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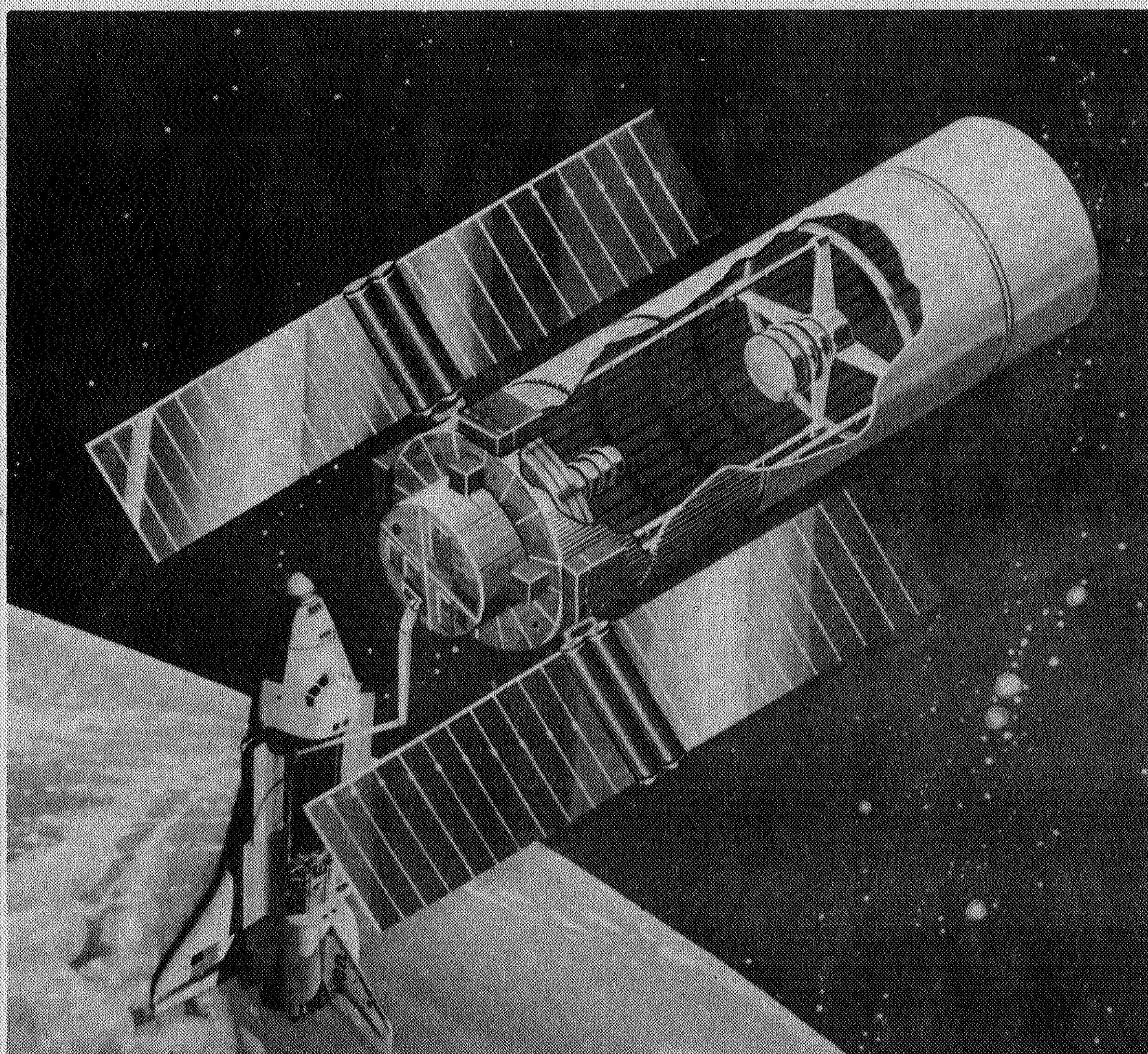
OPTICAL COATING IN SPACE
FINAL REPORT



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Abstract:

This report constitutes a technological appraisal of the steps required to approach the goal of in-situ optical coating, cleaning and re-coating the optical elements of a remote telescope in space. Emphasis is placed on the high ultraviolet throughput that a telescope using bare aluminum mirrors would offer. A preliminary design is suggested for an Orbital Coating Laboratory to answer basic technical questions.

PREFACE

The work described in this report was performed by the Space Science Division of the Perkin-Elmer Corporation. The work was sponsored by the National Aeronautics and Space Administration (NASA) under a program called "Innovative Uses of the Space Station".

A few words of guidance: In this report, all references are collected together in Section 8 and numbered. The first 133 of these are arranged alphabetically. The remaining references are arranged in no particular order, except roughly as they are cited in the text. Citations throughout the text refer to these references by numbers in parentheses, such as (18, 19).

A separate appendix provides a bibliography covering the particular subject of the use of mirrors in space for ultraviolet wavelengths and the effects of degradation of reflectivity of such mirrors. This bibliography (Appendix E) duplicates many of the references in Section 8 and is included as a potentially useful reference tool which can be separated from this report.

In this report we will be found guilty of using the unconventional acronym FUV for the far ultraviolet spectral region ($\lambda \approx 900$ Å - 1800 Å), as this is a useful shorthand for the spectral range where pure aluminum offers a significant advantage in mirror refelctivity. Other acronyms are listed in Appendix A.

The optical constants (n and k) at far ultraviolet wavelengths for some of the optical materials considered in this study are tabulated as a function of wavelength for reference in Appendix C.

Finally, an index (Appendix F) is offered to assist the reader in finding some discussion of a few particular subjects.

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SECTION 1

INTRODUCTION

This report documents the results of a six month study into the advantages, feasibility and possible techniques of applying optical coatings in space.

This study was conducted as a part of NASA's "Innovative Use of the Space Station" Program. The intent of this NASA program was to solicit novel ideas from a wide community of parties interested in the uses of space, as a part of a larger investigation into the potential requirements for and attributes of a permanently manned space station, as it might be used for science, applications, technology development, commercial utilization and national security. NASA's goal is to solicit the best possible advice before committing to a specific functional architecture for the space station (134).

Although a baseline design for the space station does not yet exist, the attributed of the system design are likely to include (134):

- o A permanent manned presence in space
- o Both manned and unmanned elements
- o Low-Earth orbit for the first manned element
- o Delivery to space from the Space Shuttle
- o An operational phase of the space station which might begin as early as 1990

Corollary attributed specifically related to science, applications, and technology utilization may also include (134):

- o Permanent facilities for conducting research
- o The potential for continuous manned interaction with research facilities which are in close proximity to the manned elements

- The potential for repetitive (if not continuous) manned interaction with unmanned research facilities in earth orbit at any altitude or inclination.

The present study is motivated by scientific goals--the desire to produce efficient space telescopes for astronomy, particularly for ultraviolet wavelengths--but the connection to the space station is that we will discuss an unmanned research facility in earth orbit that is operated by men in space. Later phases of a program to develop optical coating in space may involve manned interaction with a space station facility that would constitute a production facility rather than a research laboratory.

The author would like to acknowledge the help, ideas and advice of Bruce Tirri, Alan Wissinger and Arthur Vaughan, all of Perkin-Elmer, Jim Heaney and John Osantowski of Goddard Space Flight Center, George Hass, formerly of Night Vision Laboratories, Professor Bob Wilson of University College London, Michael Sanford, Peter Barker and William Burton of Rutherford Appleton Laboratory and A. V. Bruns of the Crimean Astrophysical Observatory. These and many other individuals contributed their thoughts generously to this study.

1.1 MOTIVATION AND GOALS

One of the most important and scientifically rewarding portions of the electromagnetic spectrum in astrophysics is the far ultraviolet--800 Å to 1200 Å. Molecular hydrogen, a major constituent of the interstellar gas, and deuterium, a crucial probe of cosmological questions, can be studied in detail only at these wavelengths. Furthermore, hot plasma in the interstellar medium, in the atmospheres of hot stars and in other objects ranging from planets to quasars, with temperatures between 200,000K and 2,00,000K, is studied best with observations in this wavelength range (Figure 1). The interstellar OVI absorption lines discovered by OAO-Copernicus at 1032 Å and 1038 Å represented an important new phase of the gas in our galaxy (7, 135).

Except for the one mission, OAO-Copernicus, which fluorished from 1972 to 1980, and a few solar physics instruments, no space astronomy project has included this important spectral region. OAO-2, the European TD-1, the International Ultraviolet Explorer, the Spacelab ultraviolet telescopes scheduled to fly on OSS-3, and the Space Telescope all were not designed to include this spectral range. The reason is straightforward. There

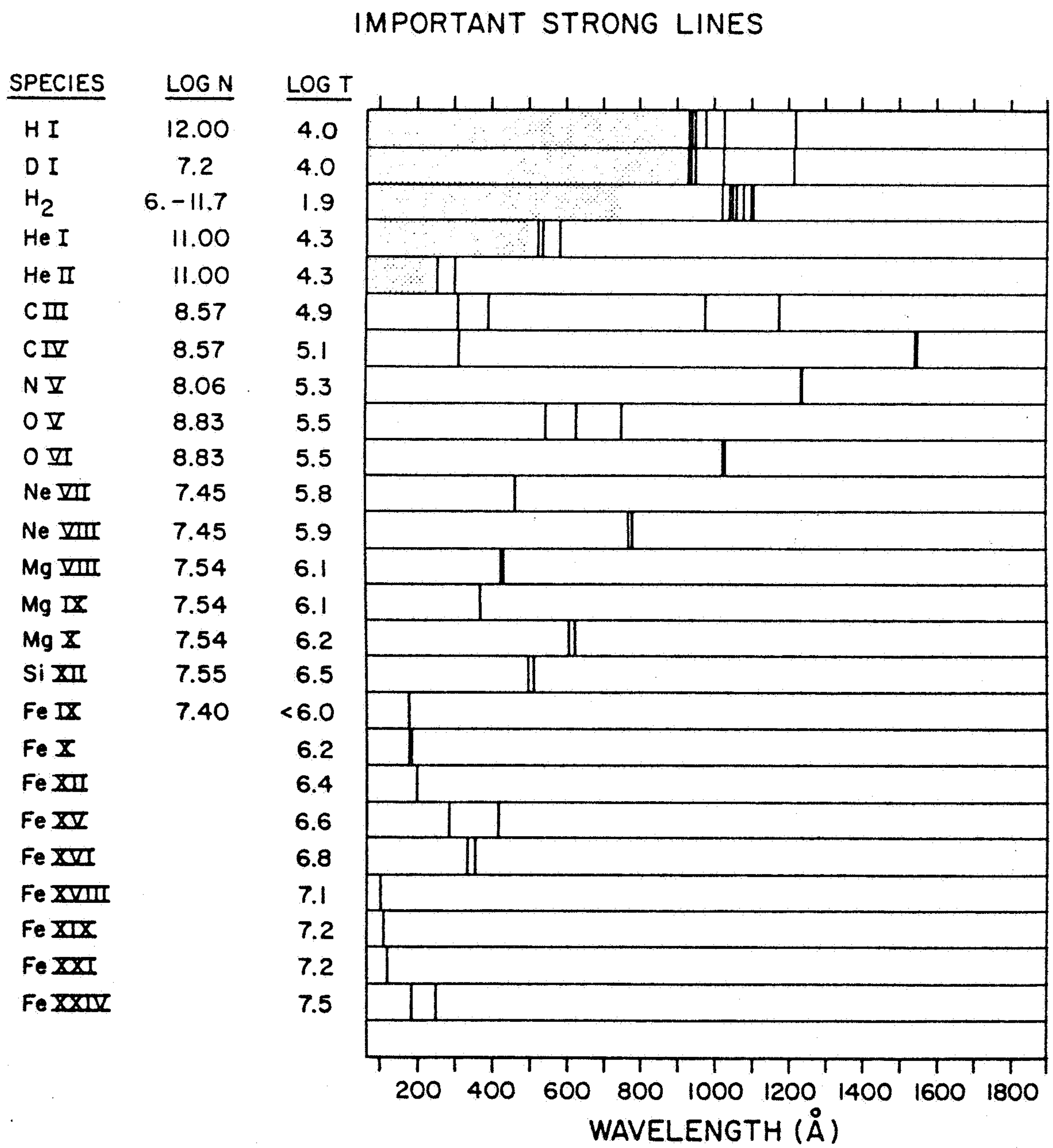


Figure 1. Wavelengths of Important Spectral Lines in the Far Ultraviolet. From Reference 7.

is only one telescope mirror material that has a high reflectivity in the spectral range from 800 Å to 2000 Å at near-normal incidence, and hence high telescope throughput, and that is pure aluminum. However, aluminum is very reactive and in a terrestrial environment it quickly forms an oxide layer of Al_2O_3 with a serious loss of reflectivity at all wavelengths shorter than 2000 Å. Therefore, aluminized mirrors are usually overcoated with MgF_2 or LiF to protect the aluminum from oxidation. This allows retaining high reflectivity from 1200 Å to 2000 Å, but at the cost of introducing a strong absorption edge at 1150 Å (MgF_2) or 1000 Å (LiF).

The gain in reflectivity that is possible with a pure aluminum mirror coating over other coatings commonly used or suggested for the far ultraviolet is shown in Figures 2-4.

If a pure aluminum mirror (or grating) coating could be achieved in a space telescope, one gain would then be a significant increase in spectral range, including the scientifically very important 800-1200 Å regime. Therefore, one motivation for developing the techniques for applying optical coatings in space, in an environment where aluminum will not quickly oxidize, is to open this new spectral region to study in astronomy with high throughput instrumentation, permitting spectroscopy with high spectral resolution and the study of faint objects. Several recent proposals or plans for future space astronomy programs are based on the desire to observe in this spectral range: the Far Ultraviolet Spectroscopic Explorer (FUSE) (7, 135), the international mission "Columbus" based on the FUSE concept (147), the United Kingdom proposal for an Ultraviolet Space Observatory (UVSO) (129, 135), the Hopkins Ultraviolet Telescope (HUT) scheduled for flight on the Shuttle's OSS-3 mission (136), the "Magellan" mission studied by the European Space Agency (137), the Grazing Incidence Solar Telescope (GRIST) also studied by ESA (138), the Solar XUV Facility studied by NASA-GSFC in 1976 (139), among others.

A second motivation for developing the capability for coating optics in space comes from the desire to recover from a condition of degraded reflectivity that might be caused by mirror contamination. Throughout the ultraviolet region from 900 Å to 3000 Å, the reflectivity of mirror surfaces can be easily spoiled by outgassed organic vapors, photopolymerization or even oxidation. Examples of these effects are described further in Section 2.1. As telescopes become larger in size and are designed for longer

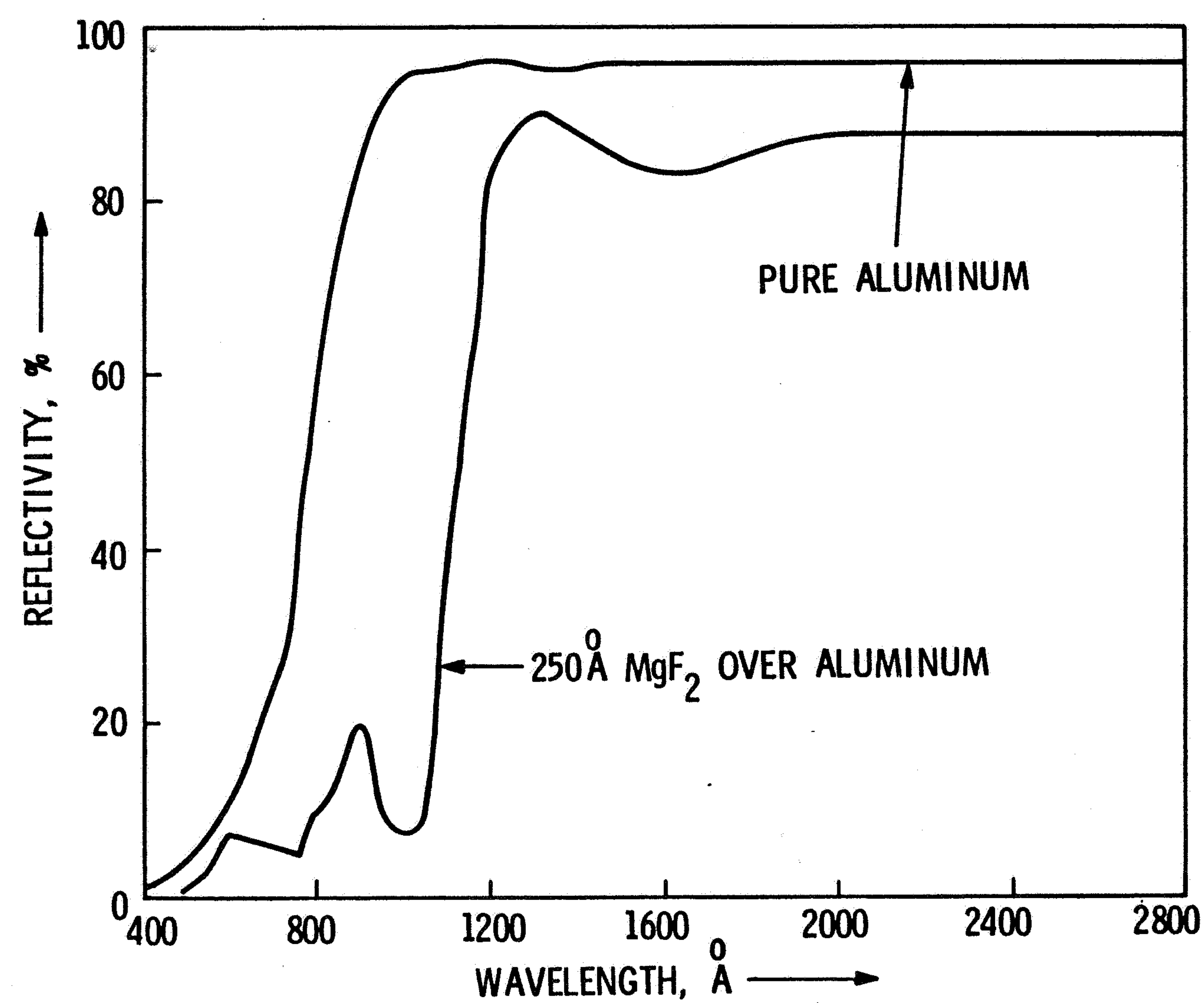
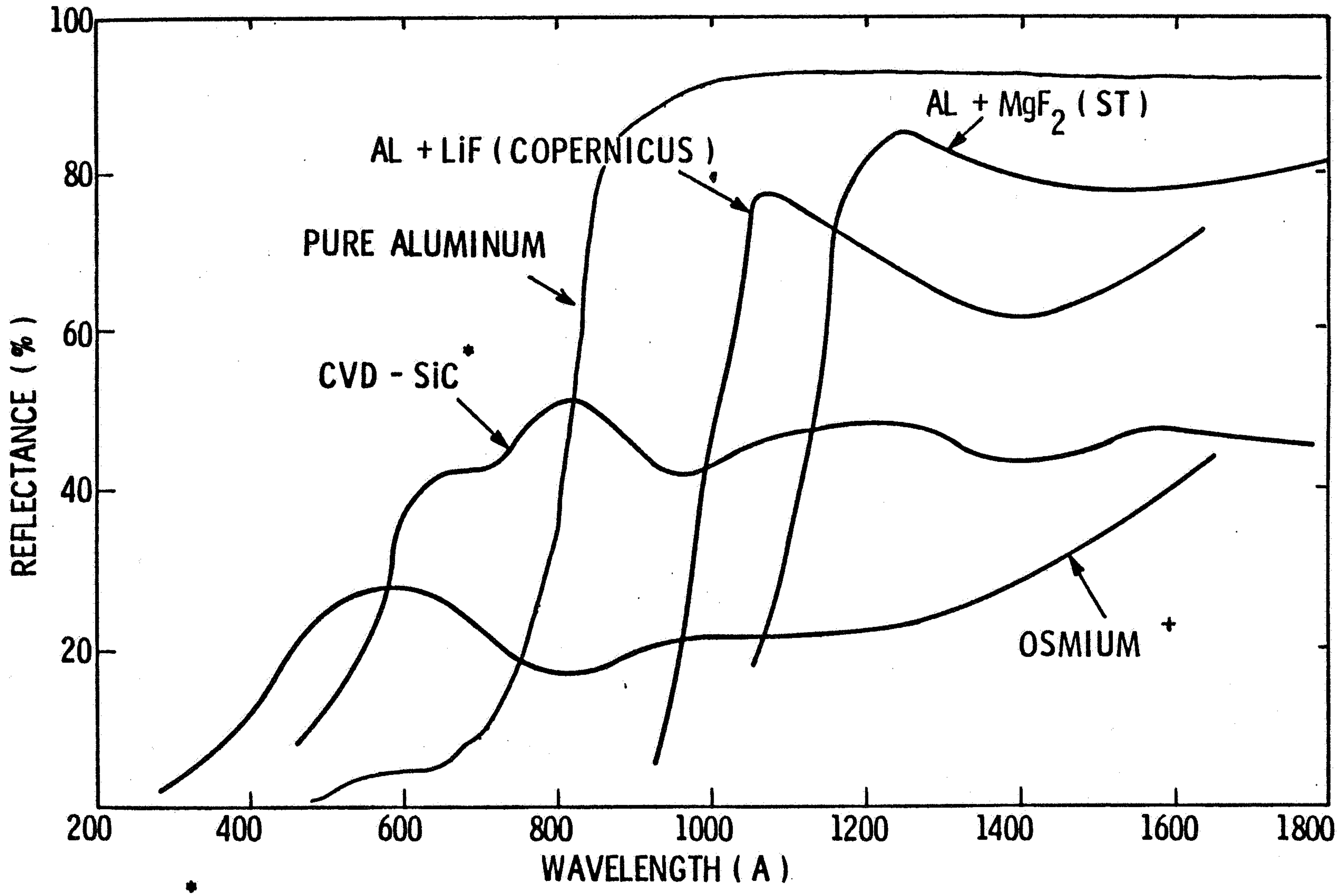


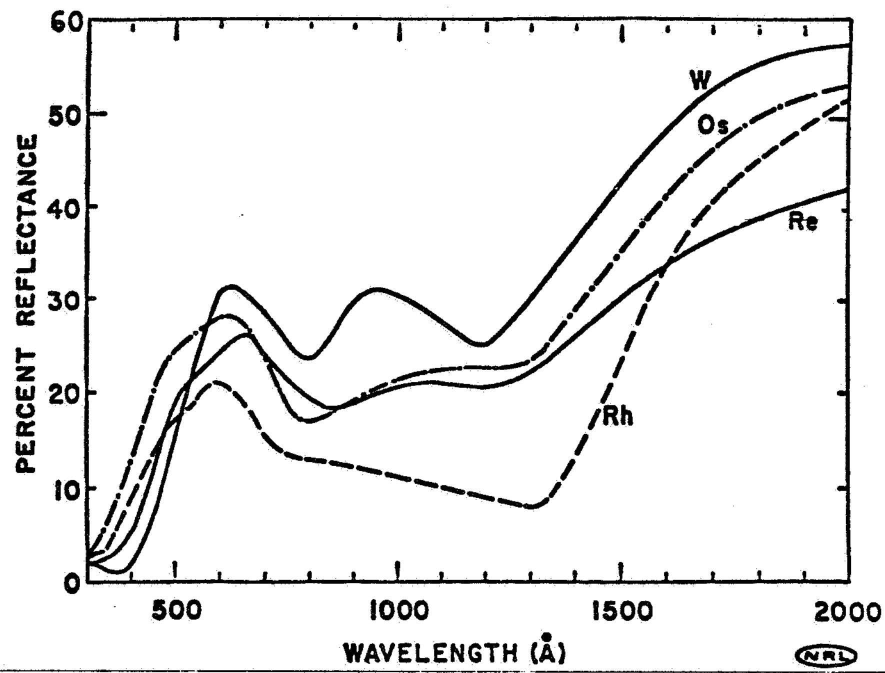
Figure 2. Reflectivity at Normal Incidence of Pure Aluminum (39, 59, 63, 129) and of Aluminum with the Usual 250Å MgF_2 Protective Coating (18, 63, 135).



* W. J. CHOYKE ET AL. APPL. OPT. 16, 2013 (1977)

\+ J. T. COX ET AL. J. OPT. SOC. AM. 63, 435 (1973)

Figure 3. Far Ultraviolet Reflectivities at Normal Incidence of Aluminum, Aluminum + MgF_2 as Used in Space Telescope, Aluminum + LiF as Used in OAO-Copernicus, Chemically Vapor Deposited Silicon Carbide, and Osmium. The Data for Aluminum is calculated in Appendix B.



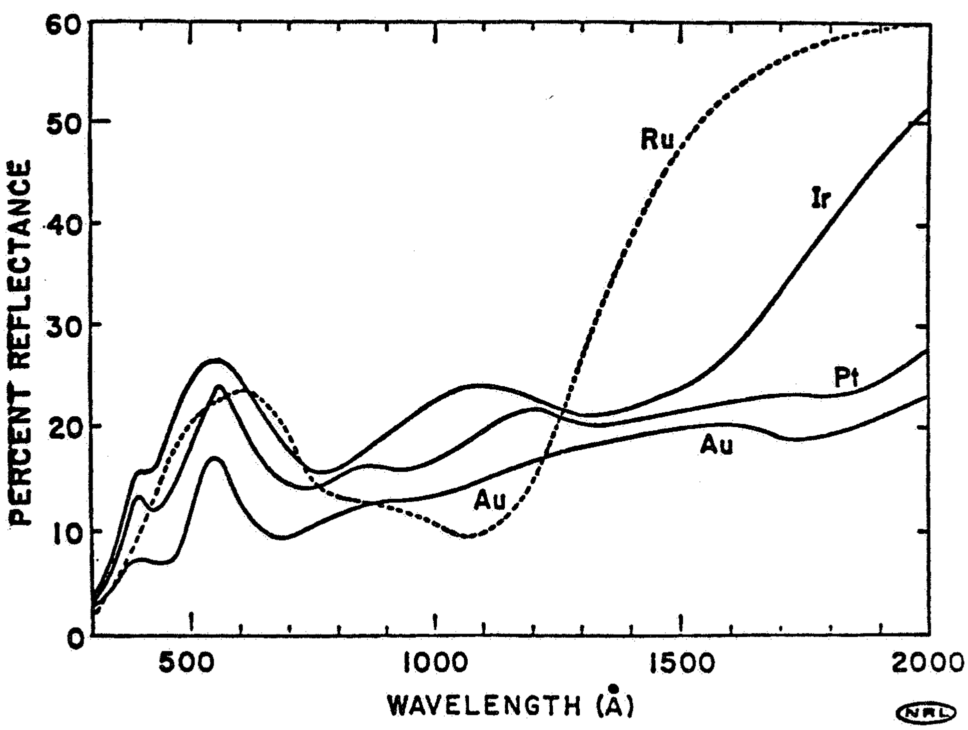


Figure 4. Far Ultraviolet Reflectivities at Normal Incidence of Tungsten, Osmium, Rhenium, Rhodium, Ruthenium, Iridium, Platinum and Gold (63, 71, 135).

lifetimes, aging effects may degrade the optical surfaces sufficiently that re-coating is desireable. If telescope optics can be re-coated in space, the costly and time-consuming process of returning the telescope to earth, refurbishment, and re-boosting the telescope to orbit is avoided. For telescopes in geosynchronous orbit, from which we do not yet have the capability to retrieve satellites, or deep space, the motivation for in-space refurbishment is particularly strong.

Even in the absence of aging or degradation effects in space, there is a motivation to avoid coating the mirrors for a sophisticated space telescope years before they will be used. In a major space telescope program, the long pre-launch environment poses risks to the mirror surface quality which could be avoided by applying the final coating after the telescope is in space.

Solar telescopes have a particular risk of degradation of reflectivity because of the posssibility of solar ultraviolet-induced photopolymerization of organic "tars" on mirror surfaces which are exposed simultaneously to intense ionizing radiation and organic gases (satellite outgassing). See References 16, 17, 61, 65, 66, 69, 72, 75, 110 130.

A cleaning and re-coating capability might be particularly useful on a deep-space telescope such as might be included on Solar Probe (142, 143) or Star Probe (140, 141), coming within $\sim$0.1 AU of the Sun.

These are the circumstances motivating the development of techniques for optical coating in space. The eventual goals of such a development program are:

1. The construction of future space telescopes whose optical elements have the full reflectivity from 700 Å to 3000 Å of the highest curve in Figure 2.
2. The construction of future space telescopes with a built-in capability for refurbishing their throughput through renewed optical coatings.

The purpose of the present study is to plan a path towards the above goals, identifying the problems, the questions to be answered and the techniques that might be used.

There may in fact be other applications for applying optical coatings or thermal coatings in a space environment besides the above applications to ultraviolet astronomy. There may be other coating materials useful in other wavelength regions which, like aluminum, react too readily in a normal earth environment.

1.2 REQUIREMENTS FOR COATING IN SPACE

To achieve the goals discussed in the previous paragraphs, a space-based coating system would have to satisfy the following requirements:

1. The optical surfaces must be cleanable to the extend required for successful re-coating.
2. The design should allow for repeated re-deposition of a new optical coating, up to, say, 10 occasions.
3. The coatings must adhere to the substrate or to the previous layer and be resistant to the normal thermal changes of the substrate.
4. The surfaces must be reasonably smooth to ensure low-scatter performance.
5. The applied coatings must fully cover the desired optical surface to a reasonably uniform thickness.
6. The applied coatings must not extend beyond the target mirrors to reach critical surfaces in a telescope assembly where the evaporated material would spoil the absorbing properties of an optical baffle or the insulating properties of a high voltage insulator, for example.
7. It must be possible to monitor the thickness and/or reflectivity of the deposited coatings.
8. The coating system should not require excessive power.
9. The coating system should be capable of operating without manned intervention, at least without manned access to the heart of a delicate telescope assembly.
10. The following materials are considered potentially useful: aluminum, iridium and lithium fluoride (See Section 3.4.3). The coating system should be capable of depositing these materials.
11. The coating process must be reliable.

Concerning Point No. 5 above, the simultaneous achievement of high reflectivity over a large surface area and state-of-the-art (~3%) thickness uniformity in an optical coating may be very difficult in a space environment, especially in an in-situ telescope situation. In a diffraction-limited ultraviolet telescope such as the Space Telescope, the requirement on coating thickness uniformity is strict because gradients in the coating thickness could actually disturb the mirror figure. In this study, our concern is more with large far-ultraviolet throughput than with diffraction-limited performance.

Concerning Point No. 10 above, we will consider in this report the particular cases of aluminum over iridium and lithium fluoride over aluminum.

We are not considering in this report multi-layer coatings such as are used to achieve particular sharply-tuned interference effects or filters.

The above list of requirements would apply either to a space-based optical coating facility, that is, a general-purpose coating chamber to which mirrors or gratings could be brought to receive a new coating, or to a coating arrangement built into a next-generation space telescope for in-situ optical coating.

1.3 QUESTIONS ADDRESSED IN THIS STUDY

This study constitutes a technological appraisal of the steps required to approach the goal of in-situ optical coating, cleaning and re-coating the optical elements of a remote telescope in space. What prevents us from designing such a telescope today?

For one thing, a space telescope designed to be coated in space represents a costly investment with a high level of risk, until the techniques have been successfully demonstrated. Moreover, there are a number of technical questions that need to be answered before one could completely plan for such a space observatory. The significant open questions include the following:

1. How high in altitude does a telescope with bare aluminum mirror surfaces need to be, to avoid rapid oxidation from residual atmospheric oxygen?
2. What are the effects of the orbital velocity through the residual atmosphere on the lifetime of an aluminum surface being used as a far ultraviolet reflector?

3. Can a coating source be designed that satisfies requirements no. 2 (re-usable), 5 (uniform), and 6 (no spill-over) of Page 9?

4. What are the effects of repeated coating, oxidation, re-coating, on VUV mirror reflectivity, roughness and scatter?

5. Are there alternate ways to achieve long-life high ultraviolet reflectivity surfaces, or to extend the lifetime of a bare aluminum surface in Earth orbit?

6. How much does the inevitable environment of spacecraft outgassing limit the lifetime of a bare aluminum ultraviolet mirror surface?

Some of the above questions may be answerable by means of carefully designed ground laboratory experiments. Some of the others (for example, items 1, 2 and 6 above) may best be answered in space orbital laboratory experiments. Certainly the need to successfully demonstrate in-orbit coating techniques requires an orbital coating laboratory.

Besides the ground-based laboratory experiments, we may envision three categories or stages of space-based experimentation leading to our final goal of in-situ coating of optics in space observatories (see Figure 5):

Stage 1: Orbital Coating Laboratory Experiments. Controlled experiments and demonstration tests designed to answer the above questions.

Stage 2: Space Station Coating Facility. A semi-permanent "coating chamber" built into a manned space station (for example) that serves to utilize the vacuum of space and the earth orbital environment to coat or re-coat telescope mirrors without the costs of transportation to and from Earth, and without the dust, humidity and handling problems of the Earth environment. This facility would be flexible enough to handle mirrors and mirror segments of all sizes and a variety of coating materials. Removal of mirrors and mirror segments from a telescope assembly and re-installation into a telescope assembly might be required.

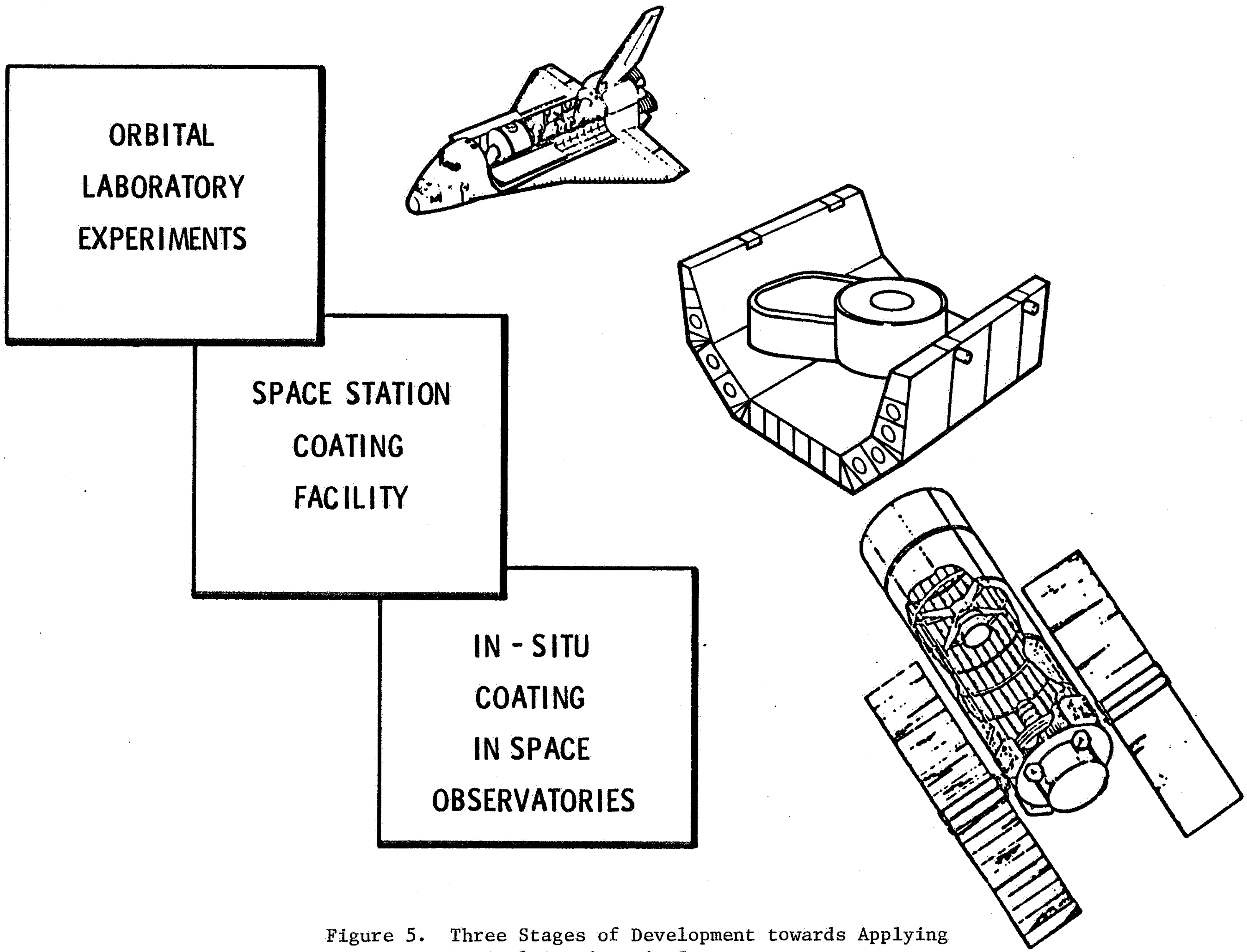


Figure 5. Three Stages of Development towards Applying Optical Coatings in Space.

Stage 3: In-situ Coating in Space Observatories. Built-in apparatus for coating and re-coating gratings and/or mirror elements in space telescopes. This category of coating operation would be controlled in real time by remote control and would not require removal or handling of the optical components.

This report will examine these three categories of optical coating operations in a space environment. Some hardware design ideas that might be appropriate will be suggested. The most immediate need in a program of development of these concepts are the laboratory experiments and demonstration tests that serve to answer the basic questions posed on Page 10. Therefore a major topic of this study will be the conceptual design of an orbital coating laboratory versatile enough to perform a variety of useful experiments and demonstrations, with a description of some of the important experiments to be carried out with such a laboratory.

SECTION 2

HISTORY

Ultraviolet astronomers have considered the merits of optical coating with pure aluminum in the vacuum of space for many years (144). The high vacuum ultraviolet reflectance of aluminum and the rapid rate of oxidation in air were both certainly recognized prior to 1956 (145). There was little active development of the idea for several reasons: (1) Optical coating is a power-hungry procedure. Early space astronomy missions could not contemplate using 500-5000 watts for thermal evaporation. (2) Even the earliest suggestions to coat mirrors in space included the caveat that the presence of high altitude oxygen would restrict the use of bare aluminum to high Earth orbits.

The earliest published discussion of mirror aluminizing in space of which I am aware is the Perkin-Elmer final report (reference 1) of a feasibility study for the "Princeton Advanced Satellite" (which later became OAO-Copernicus). This 1965-66 report identified most of the advantages and disadvantages of coating optics in space which are still the main considerations today. A concluding paragraph from this discussion is reproduced here (1):

> "The possibility of coating optics in space in order to achieve a pure aluminum film having a much higher reflectivity in the 900 Å to 1200 Å region than overcoated films is extremely attractive. For a near earth orbit (125 miles to 500 miles) the pressure varies from 10^{-6} to 10^{-9} mm Hg which is similar to pressures achieved with present coating facilities. Oxygen contamination in near earth orbits is, therefore, likely to be as serious a problem as it is in earthbound faciities and no advantage is apparent in this case. For a 20,000 mile synchronous orbit the pressure is below 10^{-12} mm Hg and some advantage may be obtained with a space coating facility provided that outgassing from the satellite did not nullify the effect of a higher orbital altitude. A space coating facility would require a minimum of 5 KW of power for approximately 10 seconds

to evaporate the aluminum and a motorized mask assembly to achieve a uniform distribution. In order to prevent a reflective coating being applied to the telescope tube, this structure would probably have to be separated from the primary during the coating process. In conclusion, optical coating in space is unlikely to be attractive until manned missions to synchronous altitude and beyond are contemplated. The advantages to be gained with a spaceborne coating facility, even under the most advantageous conditions, such as with a contaminated or abrased mirror surface, are not readily apparent. They will depend in part of advances in the state-of-the-art with earthbound coating facilities and in part on feasibility experiments aimed at cleaning and coating optical surfaces by future high altitude manned missions."

A later (1967) design study (Reference 2) by Perkin-Elmer for a segmented 2-meter telescope, proposed to fly as a part of the Apollo Extension System program, arrived at a design for an Orbital Mirror Recoating Facility (OMRF), to be attached to the Saturn SIV-B orbital workshop, wherein mirror segments could be cleaned and re-coated by remote control, with all mirror processing controlled and monitored by astronauts in the workshop. Coating experiments were suggested for this facility. See Figure 6. The workshop later became "Skylab", but without the 2-meter telescope or the OMRF.

Later studies (Reference 3) developed these coating concepts for a 2-meter astronomical telescope design that would later become the Large Space Telescope.

A key paper by Hass and Hunter (59) concluded that only at altitudes greater than 1500 km could a mirror coating lifetime of a year or more be achieved. These authors also pointed out that the lifetime would strongly depend on the angle made by the telescope tube with the flight vector of an orbiting space vehicle, both because of the increased pressure on the leading side and became of the higher "sticking probability" of atoms at higher kinetic energy.

An important series of measurements was carried out by James B. Heaney in 1967-68 aboard the geosynchronous satellite ATS-3 (65). The specular reflectance versus wavelength of various coatings and mirror surfaces including MgF_2, aluminum, Al_2O_3 and SiO_2 were monitored for radiation-induced degradation over a two year period. The effects of solar ultraviolet radiation and charged particle radiation were separated by

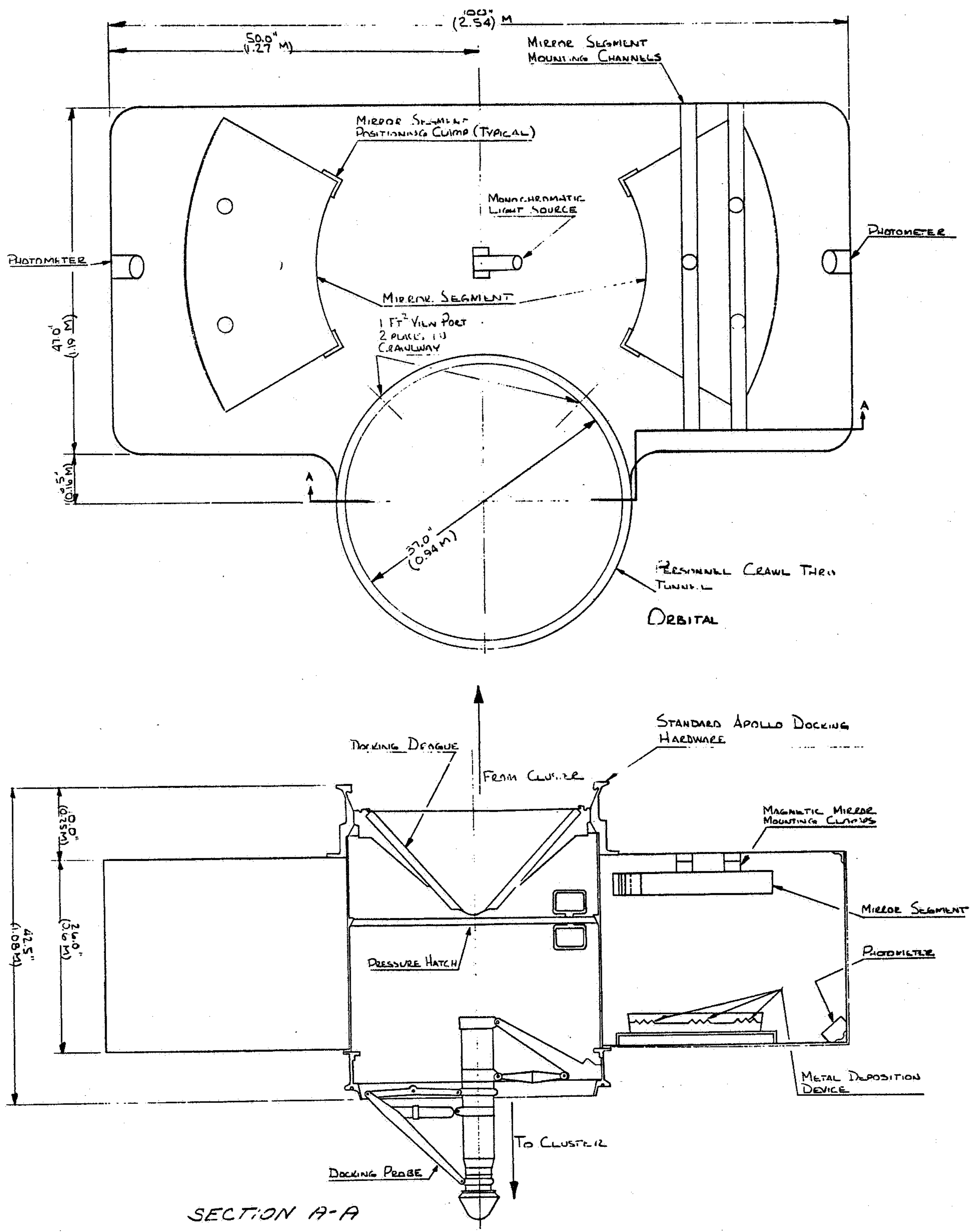


Figure 6. A Concept for an Orbital Mirror Recoating Facility (OMRF), from a Perkin-Elmer/Lockheed 1967 design study (2).

the use of transmitting quartz shields (which passed the ultraviolet radiation for $\lambda > 1600$ Å but stopped the particles). This experiment showed substantial losses in uv reflectivity for all samples after ~1½ years, especially for those samples that were exposed to the $\lambda < 1600$ Å solar radiation and charged particle radiation. The unshielded vapor-deposited aluminum (uncoated but naturally oxidized) suffered up to 90% loss of reflectance in the 3000 Å to 4000 Å band. The observed degradation may have been due to a uv-induced contamination (photopolymerization) in the case of the shielded samples, and an erosion of the coatings (charged particle induced sputtering?) in the case of the unshielded samples.

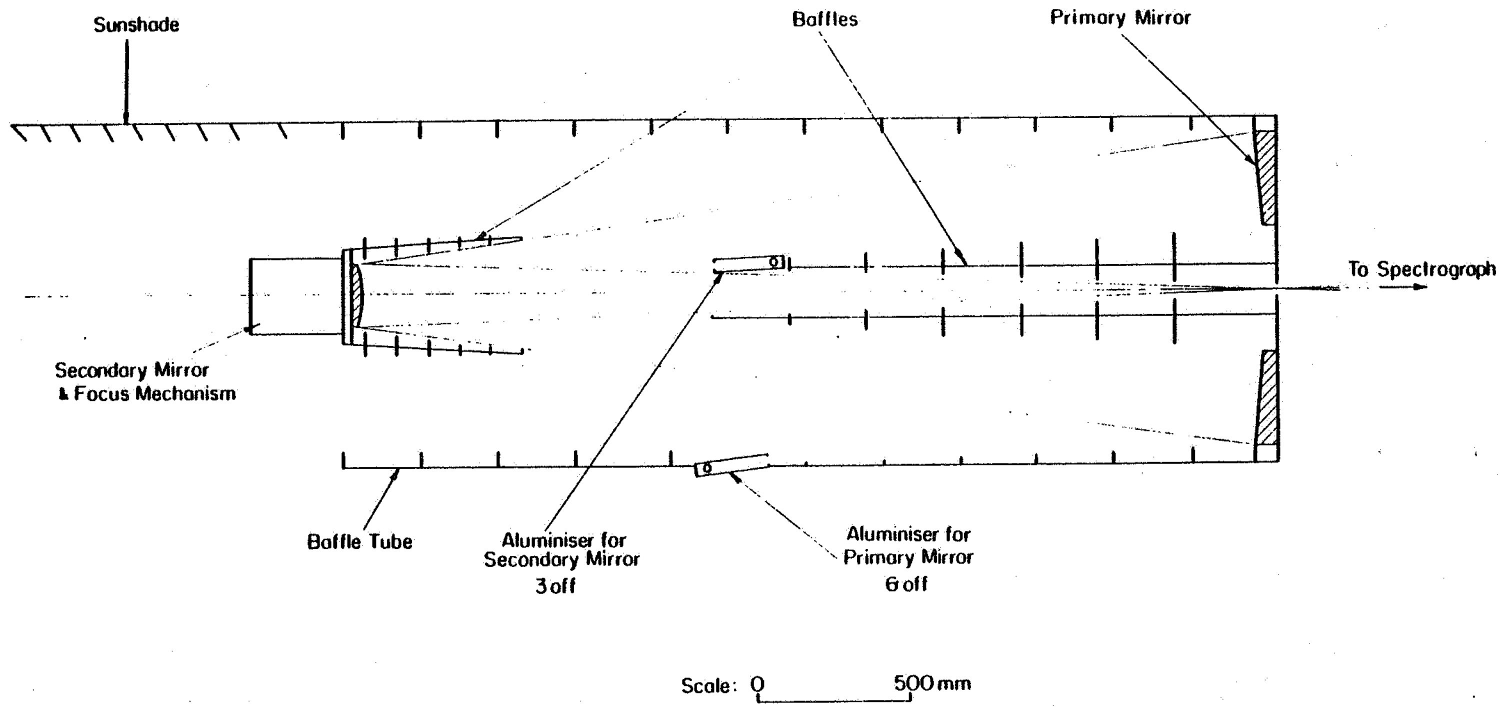
In 1981, Heaney and Herzig (151) proposed a study of both plasma gun cleaning and re-coating of optical components in a space environment. This proposal was motivated partly by the wish to investigate a potential long-run cost savings for the Space Telescope program, but Heaney and Herzig also pointed out that procedures developed for in-orbit cleaning might also find application in extending the lifetime of solar cell arrays and thermal control surfaces.

Recently, the concept of applying aluminum mirror coatings in space received new attention in a proposal (135, 129) for an Ultraviolet Space Observatory (UVSO) from Professor Robert Wilson of University College London and colleagues in Great Britain.

This proposal sketched a design for a one-meter Ritchey-Chretien telescope for $\lambda = 900$ Å to 1200 Å astronomy, to be flown as a free-flyer in geosynchronous orbit. The authors suggested that the primary and secondary mirrors could be aluminized before launch and either be allowed to naturally oxidize or be overcoated with a temporary protective MgF_2 coating (146) and then re-aluminized in orbit by means of barrel-shaped aluminum evaporator guns for each of the two mirrors. See Figures 7, 8 and 9.

A laboratory program to experiment with evaporator gun design, baffling, and re-usable aluminum evaporators is being carried out at Rutherford Appleton Laboratory to answer some basic design questions (146, 148).

Moreover, Wilson and his colleagues have suggested (129, 146) that the optics and gratings in a ultraviolet spectrograph for such a telescope would be even more amenable to aluminizing in orbit, as the reflectivity of the gratings is just as



UVSO Telescope

Figure 7. UVSO Telescope Concept with a Ring of Six Aluminizers for the Primary Mirror and Three Aluminizers for the Secondary Mirror (129)

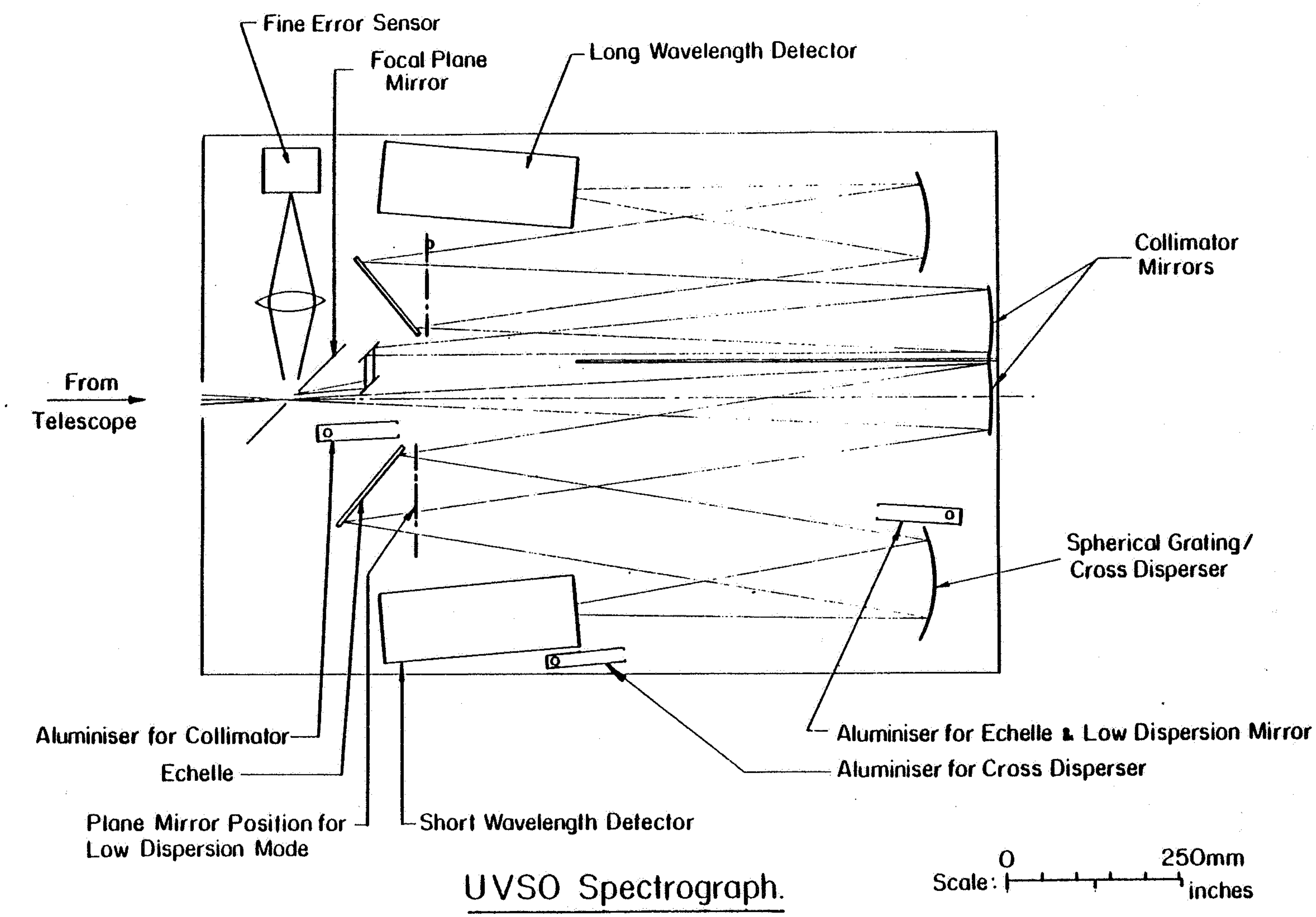


Figure 8. Concept for the UVSO Spectrograph with Aluminizers for the Gratings, Low Dispersion Plane Mirror and Collimator Mirror Used for λ = 900 -1200Å (129).

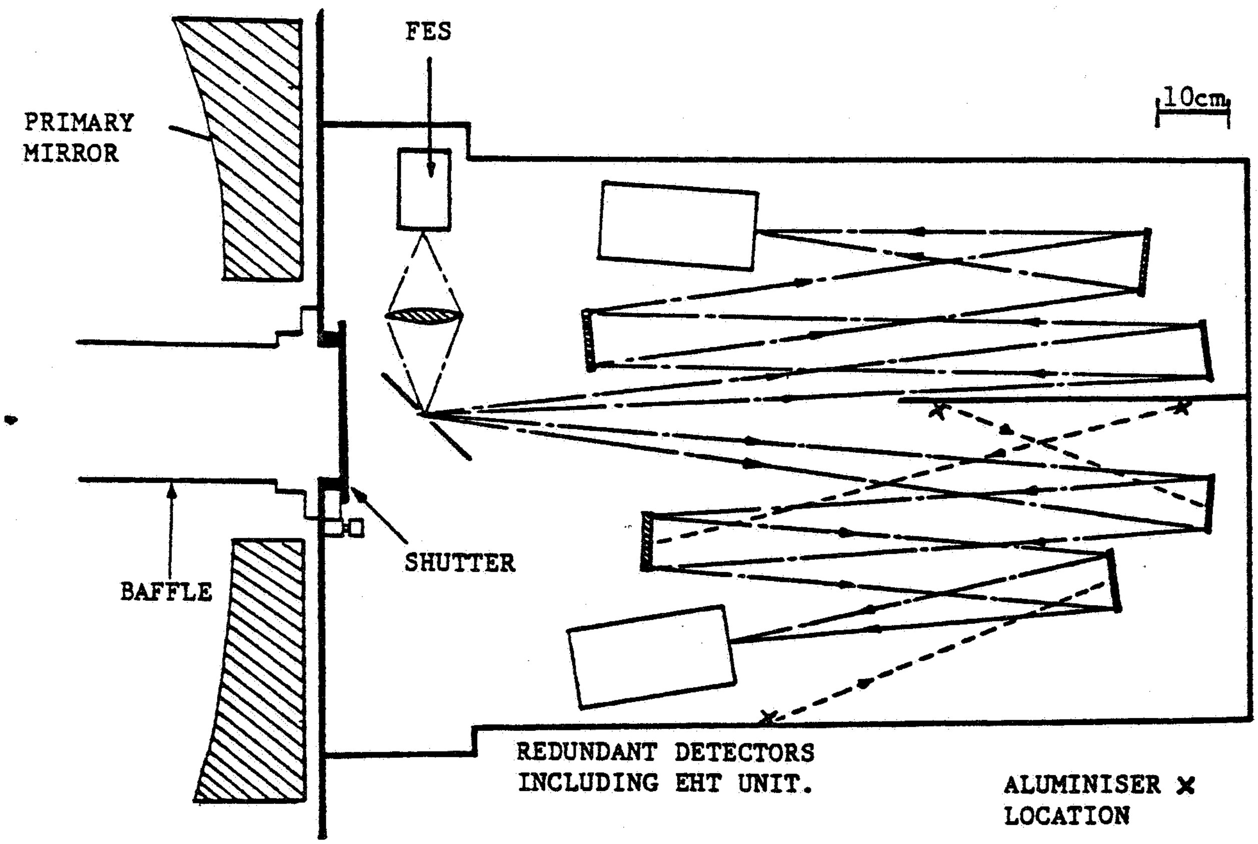


Figure 9. Layout Showing Dimension of UVSO Spectrograph and Alternate Positions for Aluminizers (129).

important to system throughput as the telescope optics and their smaller size makes the coating job easier. This possibility is also being considered for the "Columbus" Far-Ultraviolet Spectrographic Explorer mission, formerly known as "FUSE" (7, 135, 146, 147).

An alternative concept for achieving unoxidized aluminum mirror surfaces for high FUV reflectivity is being studied by William M. Burton and colleagues at the Rutherford Appleton Laboratory in Great Britain. In this concept (23, 24, 148), a mirror is first coated with pure aluminum is an ultra-high vacuum evaporator in a ground-based coating chamber and then immediately overcoated with a thin protective layer of zinc or cadmium (or other suitable volatile material) to prevent oxidation of the aluminum during the time interval prior to achieving earth orbit. Once in space, the volatile protective film would be removed by controlled heating (or possibly by ion bombardment or plasma etching or some other technique) to expose the original clean pure aluminum mirror surface. The re-evaporated protective coating would be condensed on a collector surface placed over the mirror for this purpose. Burton calls this concept of a Removable Volatile Aluminum Protection coating which is "revaporated" in a high vacuum space environment a "REVAP" coating (23, 24). Figure 10 (23, 24) illustrates a laboratory demonstration of this technique. A glass surface was coated with two partially overlapping regions of aluminum and zinc with an estimated thickness of ~500 Å. After an initial microdensitometer scan (solid line) the coating was heated in a vacuum to 200°C - 300°C to "revaporate" the zinc. The final microdensitometer scan (dotted line) shows that the zinc coating appears to have totally disappeared.

This concept is, of course, a promising approach to achieving unoxidized aluminum mirror surfaces in space. A program of laboratory experiments at Rutherford Appleton Laboratory is in progress to further develop this technique (23, 24, 148). Some of the questions that will have to be answered are: (1) Can a protective "REVAP" material be found that will not diffuse into the aluminum in the several months between deposition and re-evaporation? (2) Will the last few angstroms of the protective coating evaporate along with the bulk material or may surface bonding effects make removal of these last atomic layers more difficult? (3) Will the final reflectivity in the far ultraviolet be close to the theoretical value for pure aluminum? (4) Can a completely smooth, low scatter, aluminum surface be achieved? (5) Does the mirror heating cause any

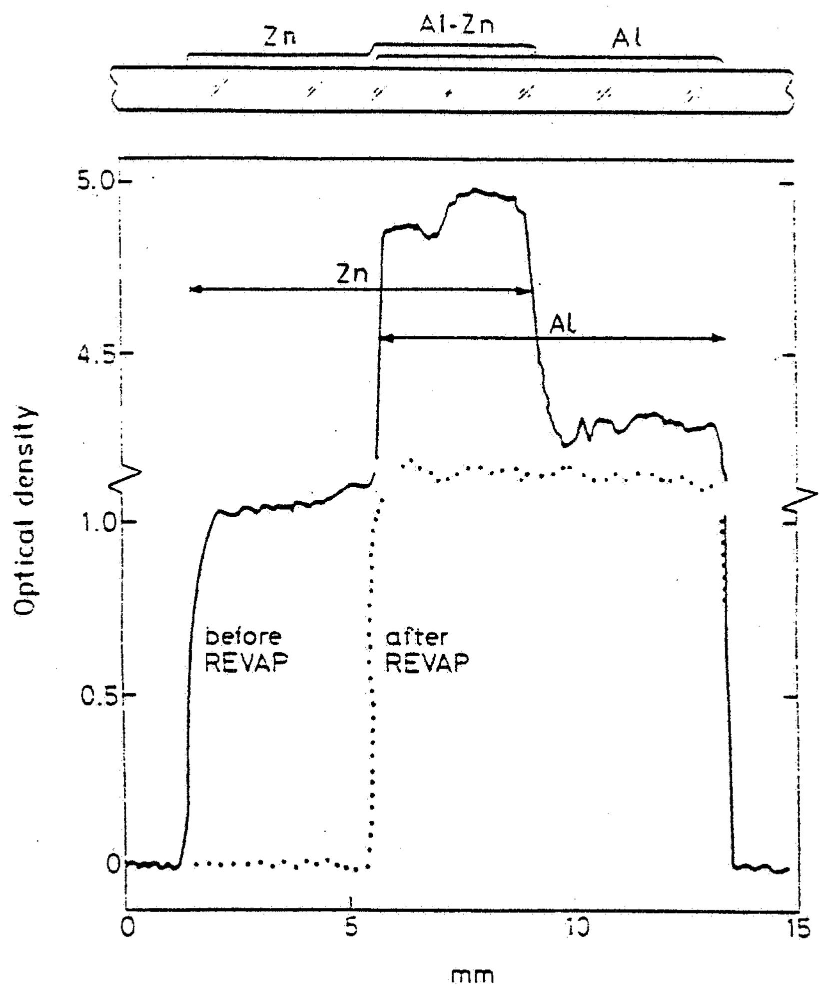


Figure 10. Microdensitometer tracings of a glass plate used as a substrate for the experimental REVAP mirror coating. The structure of the composite coating is shown above the optical density scan curves. The lower curve (dotted) shows the scan made after revaporation of the zinc coating (23, 24).

unwanted effects to either the mirror or the desired final coatings? (6) Can the "REVAP" coating be completely collected and removed from the telescope environment without condensing on inappropriate surfaces?

In connection with this last question, it is worth noting that low vapor pressure metal coatings such as cadmium was formerly used in space hardware (on electrical connectors, for example) and was notorious for its tendency to evaporate in flight and re-deposit elsewhere, such as on high-voltage feedthroughs (149).

2.1 LABORATORY EXPERIMENTS

A number of important experiments have taken place in ground-based laboratories over the past 20 years to shed some light on the lifetime of bare aluminum coatings and contamination effects that can degrade the far ultraviolet reflectivity of mirrors.

Madden et al (91, 92) showed that at the shortest wavelengths they studied (1025 Å) a loss of reflectivity of pure aluminum due to oxidation can be seen within 30 seconds of time in a vacuum of $\sim 1 \times 10^{-6}$ torr. Figures 11 and 12 show the short-term ($p \approx 1 \times 10^{-6}$ torr) and the longer term ($p \approx 3 \times 10^{-7}$ torr) rate of loss in ultraviolet reflectivity (40, 91, 92). The implication from these data is that at $\lambda = 1025$ Å and at 1×10^{-6} torr, the expected time to suffer a drop of reflectivity from 86% to 20% is about one hour (62, 63). During the initial 30 seconds or so of this period, an oxide layer forms on pure aluminum at a rate on the order of one monolayer (~ 1 Å) per second at $p \approx 1 \times 10^{-6}$ torr (91, 150). This rate of penetration then slows down, the total oxide layer thickness asympototically approaching ~ 40 Å (57, 59, 63) with a time constant on the order of one hour (77, 81, 92). Presumably the mechanism for the oxidation of the first 2 monolayers is different from subsequent oxidation. In the case of the first monolayers, every oxygen atom which strikes the surface reacts with a probability near 1. As the oxide thickness approaches 30 or 40 Å, however, the penetration of the oxygen must proceed by a diffusion reaction, a place-exchange process between the chemisorbed oxygen and the underlying aluminum atoms (39, 81, 83, 92).

Figure 13 shows the calculated reflectivity at normal incidence for Al + Al_2O_3 as a function of oxide thickness at 4 different far ultraviolet wavelengths (57, 59, 62, 63, 92). From this figure, we can see that whereas ~ 3 Å of Al_2O_3 can be tolerated on the

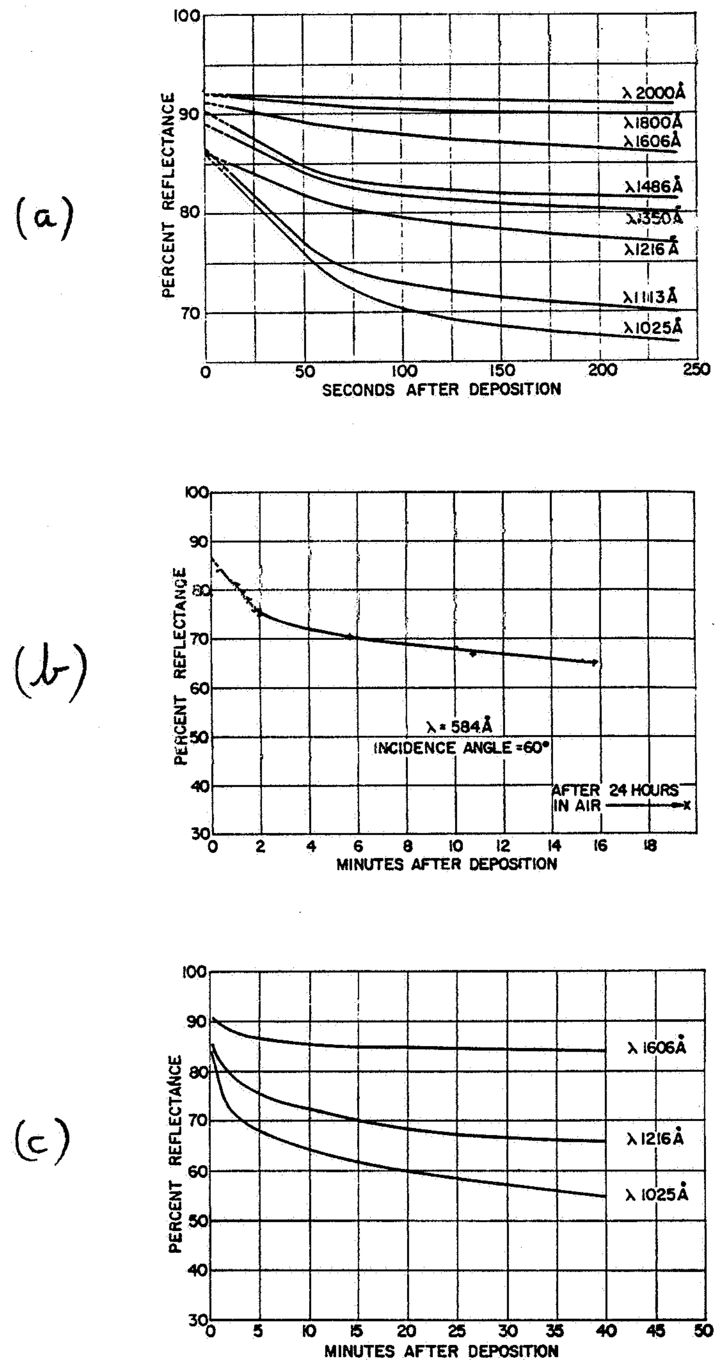
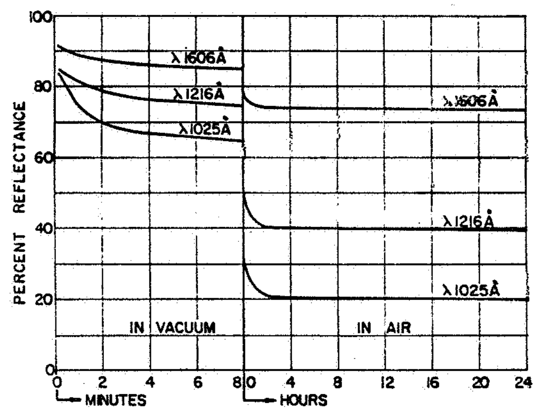
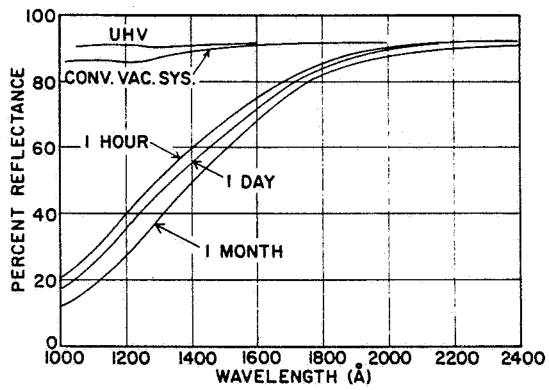


Figure 11. The Initial Reflectance Decrease of Freshly Deposited Aluminum Films in Vacuum in the Ultraviolet as a Function of Time, (a) the First 250 Seconds, at a Pressure $\sim 1 \times 10^{-6}$ Torr, (b) the First 16 Minutes, at a Pressure $\sim 4 \times 10^{-7}$ Torr, at an Incidence Angle of 60° for λ = 584Å, (c) Over 40 Minutes Time, at a Pressure of 3-5 x 10^{-7} Torr (92).

(a)



(b)



REFLECTANCE OF EVAPORATED ALUMINUM FILMS BEFORE & AFTER 1 HOUR, 1 DAY & 1 MONTH EXPOSURE TO AIR IN THE WAVELENTH REGION FROM 1000Å TO 2400Å.

Figure 12. The Effect of Aging in Vacuum and in Air on the Reflectance of Evaporated Aluminum, as a Function of Time and Wavelength. (a) These films were exposed to air after 8 minutes (92). (b) Reflectance of evaporated aluminum films before, and after 1 hour, 1 day and 1 month exposure to one atmosphere of air (77).

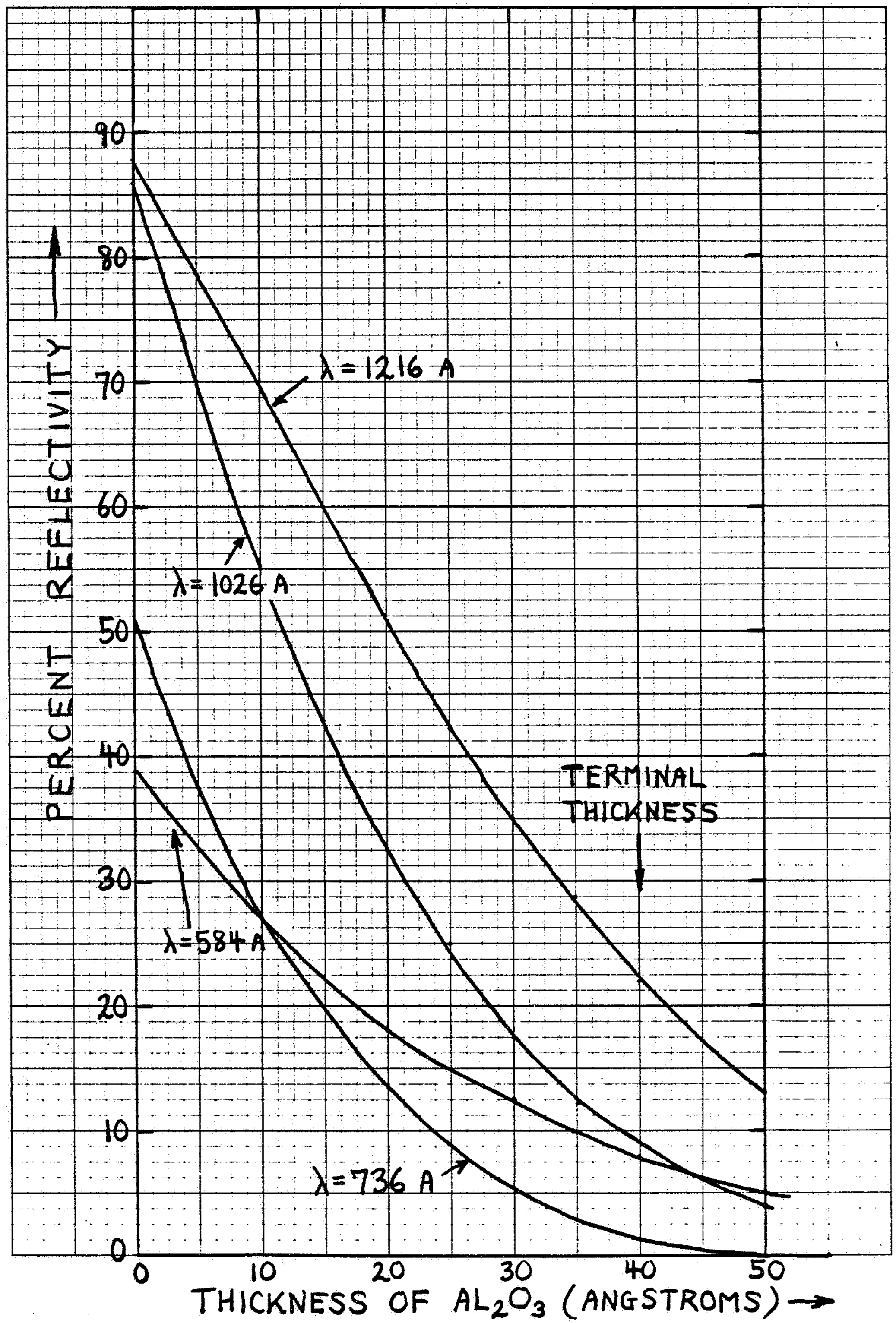


Figure 13. The calculated effect of oxide films of various thicknesses on the reflectance of aluminum at 584, 736, 1026 and 1216 Angstroms. Adapted from Hass and Hunter (59, 62, 63). The terminal (maximum) $A\ell_2O_3$ thickness for naturally oxidized aluminum is about 40 Angstroms (62, 92, 150).

surface of an aluminum mirror for far ultraviolet use, a thickness of ~5 Å of Al_2O_3 causes a ~15% drop in reflectivity at $\lambda = 736$ Å. We may therefore take 5 Å as the maximum tolerable oxide thickness on bare aluminum and as the point at which recoating with fresh aluminum would become desireable.

It has also been shown in the laboratory (62, 91, 92) that a high rate of aluminum deposition yields a higher ultraviolet reflectivity than a slow rate (Figure 14). According to Madden et al (92), for a given partial pressure of oxygen, the higher the aluminum deposition rate, the less oxygen will be trapped into the film to produce the strongly absorbing aluminum oxide. Moreover, a higher deposition rate results in a tighter, more compact film structure which is more resistant to later oxidation.

In addition to aluminum oxide, other strongly uv-absorbing contaminant films have been studied, in both laboratory and space flight environments, which may be more or less independent of the material of the substrate. Hass and Hunter (61) and others (50, 66, 76, 49, 98, 115, 128) have shown in laboratory demonstrations that uv-absorbing films of organic high vapor pressure residue can build up on mirror surfaces when both organic gases and ionizing radiation (either ultraviolet radiation or charged particles) are present at the mirror surface. The mechanism is thought to be radiation-induced cross-linking or photopolymerization of organic molecules striking the mirror surface (49, 56, 61).

Laboratory efforts at removal of such chemically-altered deposited films have shown that heating the substrate to encourage evaporation, and even liquid solvent cleaning, are generally ineffective at removing polymerized contaminant films (49, 66, 98). The film may be removed by polishing the surface with a mild abrasive such as calcium carbonate (49, 66), but this brute-force technique is not very practical for a space telescope. Two techniques for restoring the ultraviolet reflectivity of polymer-contaminated mirrors have been proven in the laboratory: (1) plasma etching and (2) exposure to atomic oxygen. Plasma etching or atom bombardment cleaning (51, 150, 152, 153) sputters away a surface film by mechanically milling away the undesired layer atom by atom, using either ions or neutral atoms (eg. argon) of typically 2 keV kinetic energy. Atomic oxygen (Figures 15-17) adds the chemical effect of oxidation, which converts a contaminant polymer film into volatile compounds which then evaporate (49,

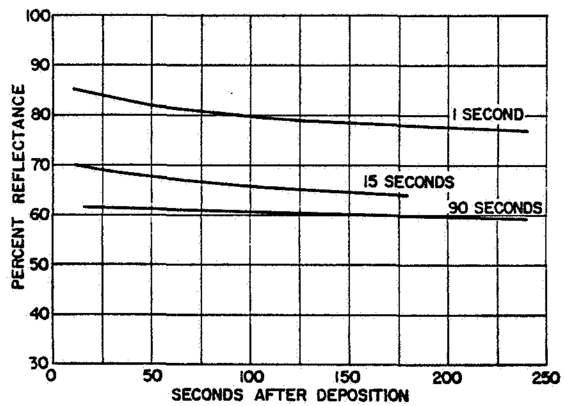


Figure 14. Effect of the speed of evaporation on the reflectance of freshly deposited aluminum films before exposure to air at λ 1216Å. The times indicated on the curves represent the duration of the evaporations. All films were 700-900Å thick (92).

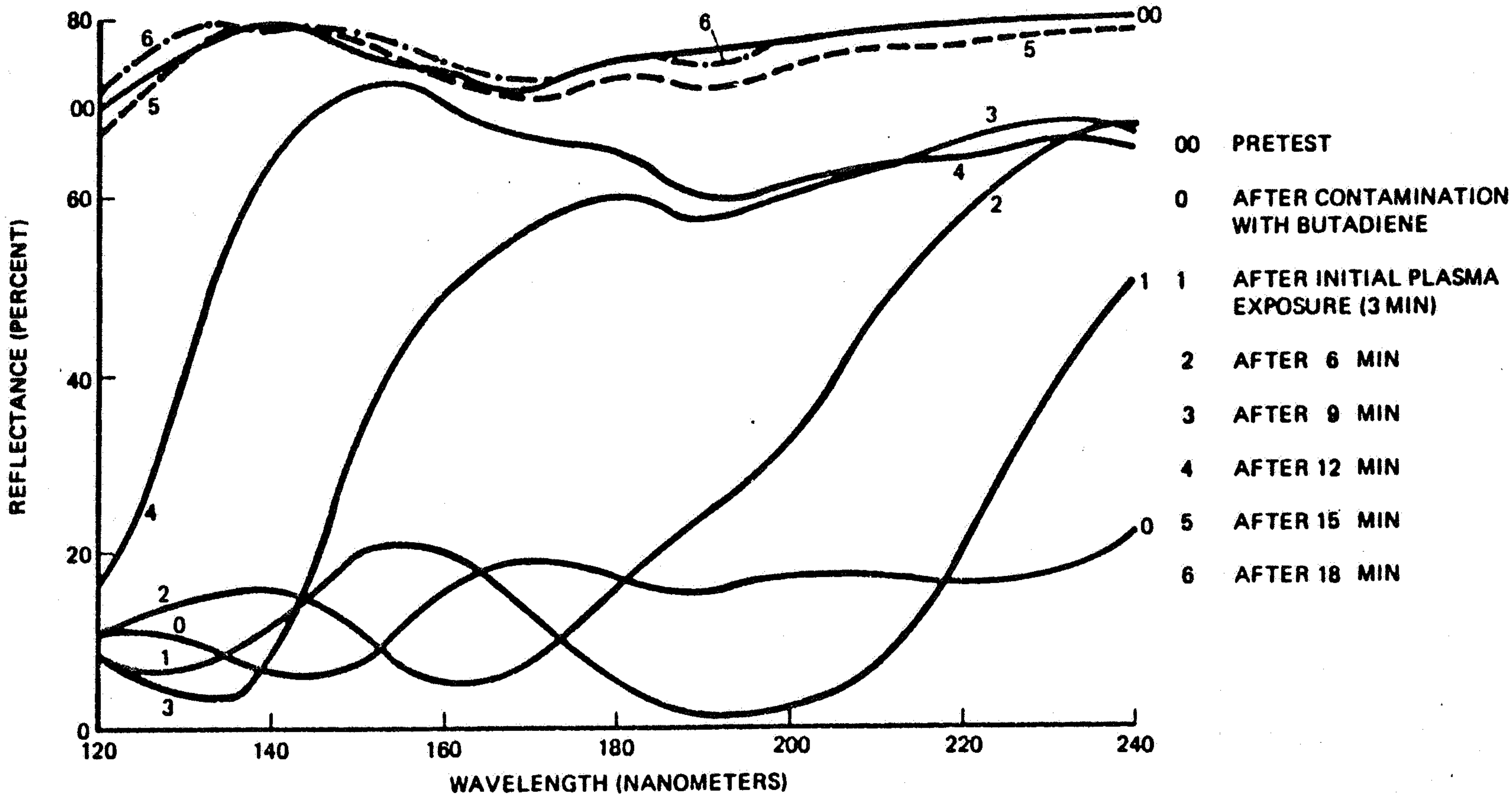


Figure 15. Effect of Butadiene Contamination and Plasma Exposure on Reflectance of 1/2λ MgF_2 Over Aluminum Coated Mirror. The Plasma was Produced by Ionizing Molecular Oxygen at ~0.45 Torr with an RF Field (49, 50, 153).

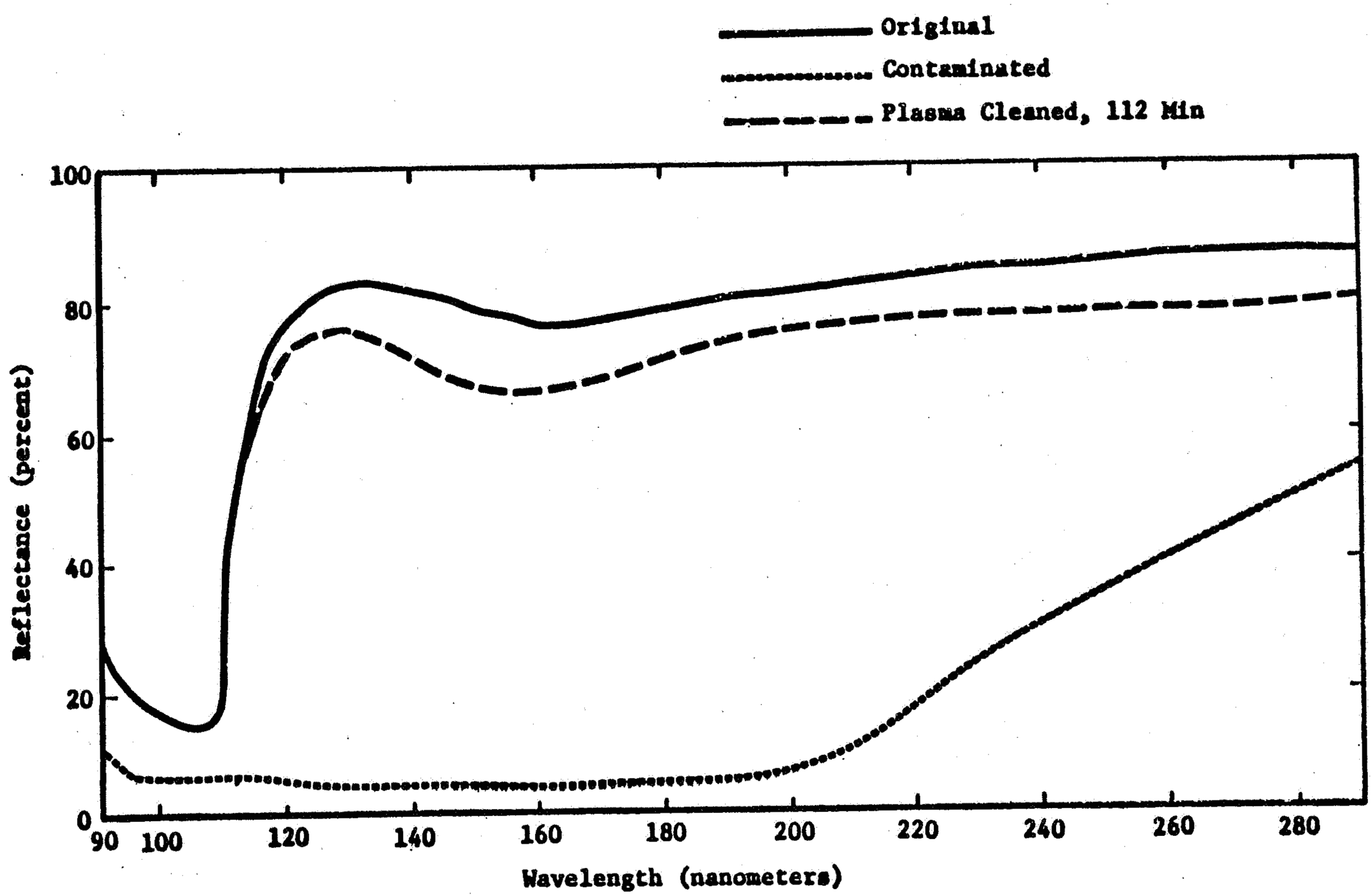


Figure 16. Effect of Butadiene Contamination and Plasma Cleaning on Reflectance of $1/2\lambda$ MgF_2 Over Aluminum-Coated Mirror, for Wavelengths from 90-280 nm (49, 50, 153).

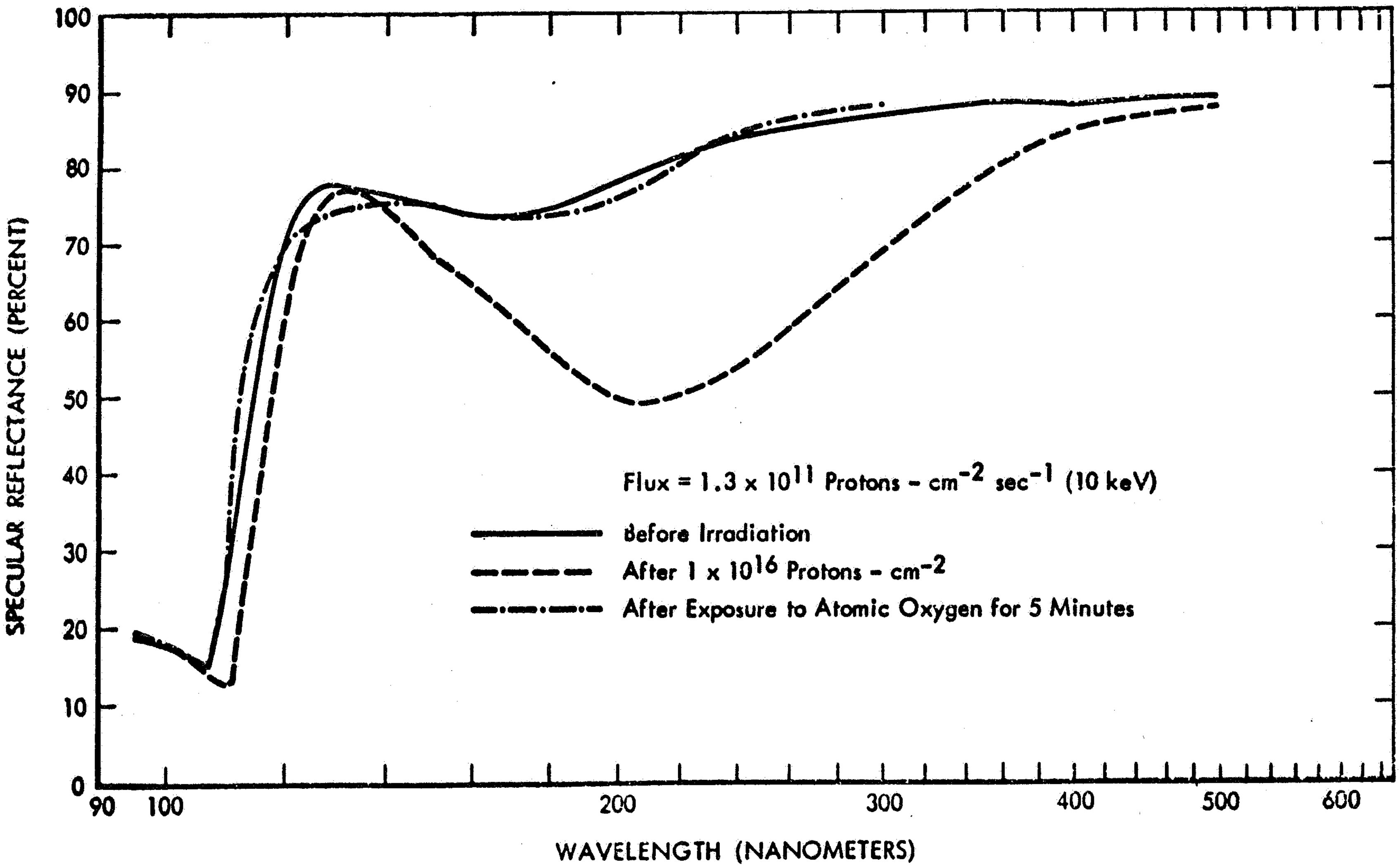


Figure 17. Reflectance Recovery of an Irradiated MgF_2/Alum-Coated Cer-Vit Mirror Exposed to Atomic Oxygen. A contaminant film of thickness 40-50Å formed in the presence of hydrocarbon molecules only on the proton-irradiated portion of the surface (49, 50).

50). These are the same techniques used in coating chambers and in semiconductor production facilities to prepare a substrate for the deposition of a thin film. The contaminant removal rate is much higher when an oxidation reaction is involved. Furthermore, atomic oxygen cleaning has the chemically selective property of removing hydrocarbons without removing more stable compounds such as MgF_2 (49). Figure 17 shows the recovery of the ultraviolet reflectance of a proton-induced polymer contaminated mirror exposed to un-accelerated atomic oxygen at $\sim$0.45 torr (49). The ion gun technique has the property of spatial selectivity; that is, the ion beam can be steered to remove material in one area while avoiding another area.

2.2 SALYUT 4 SOLAR TELESCOPE

Optical coating in orbit has actually been accomplished once, in 1975 on the Orbiting Solar Telescope (OST) on board the Soviet manned space station Salyut 4 (19, 20, 21, 154). The solar astronomers who designed this ultraviolet telescope (A.V. Bruns, A.B. Severny and others) realized that the ultraviolet reflectivity of the two principal mirrors could be severely degraded by the combination of ionizing (solar ultraviolet) radiation and organic contaminants (21). They therefore arranged to have aluminum evaporators mounted in front of both a 28 cm flat pointing mirror and a 25 cm parabolic main mirror which could be activated in flight to refresh the coatings. Salyut 4 was launched into a 337-350 km altitude, 51.6° inclination orbit on December 26, 1974 (Figure 18). The parabolic main mirror (Figure 19) was re-aluminized with about 800 Å of thermally-evaporated aluminum once during January-February 1975 and the flat pointing mirror was re-aluminized once during June-July 1975 (19, 154). This demonstration had a mixed success. As an engineering demonstration, the coating experiment worked well. However, there was no improvement of ultraviolet reflectivity observed, presumably because of a rapid oxidation of the aluminum by oxygen atoms present in the telescope area.

The coatings on the OST optical elements are summarized in Table 1. The parabolic main mirror was launched with a Ge+ZnS optical coating (57) so as to have low reflectance in the visible spectrum and thus reduce the visible and near ultraviolet stray light entering the OST ultraviolet spectrograph. The in-orbit aluminizing of the main mirror had the interesting secondary effect of evaporating the contaminant film

ОРБИТАЛЬНЫЙ СОЛНЕЧНЫЙ ТЕЛЕСКОП СТАНЦИИ САЛЮТ-4

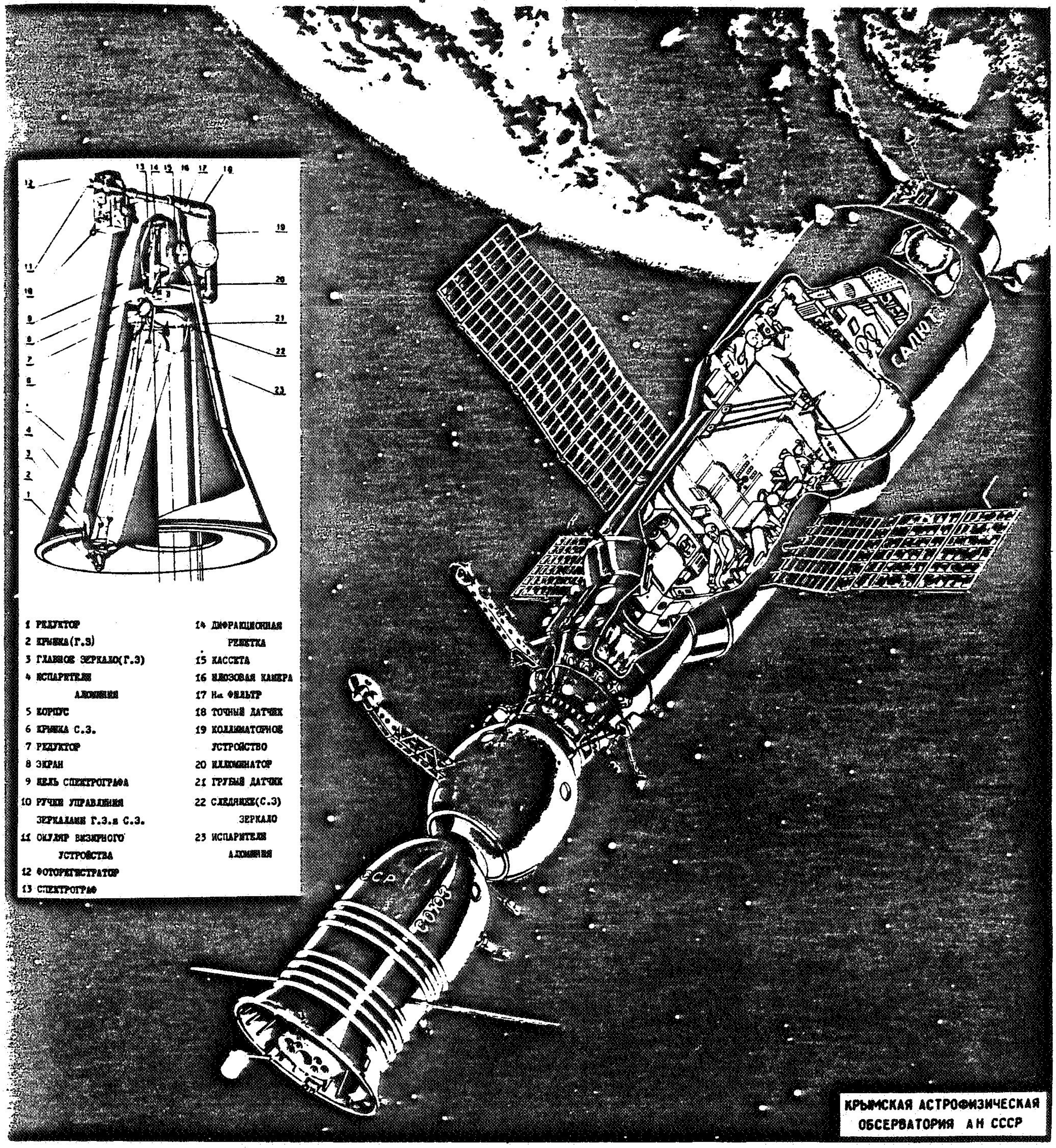


Figure 18. Orbiting Solar Telescope on the Space Station Salyut-4 (154).

ORBITING SOLAR TELESCOPE (OST)

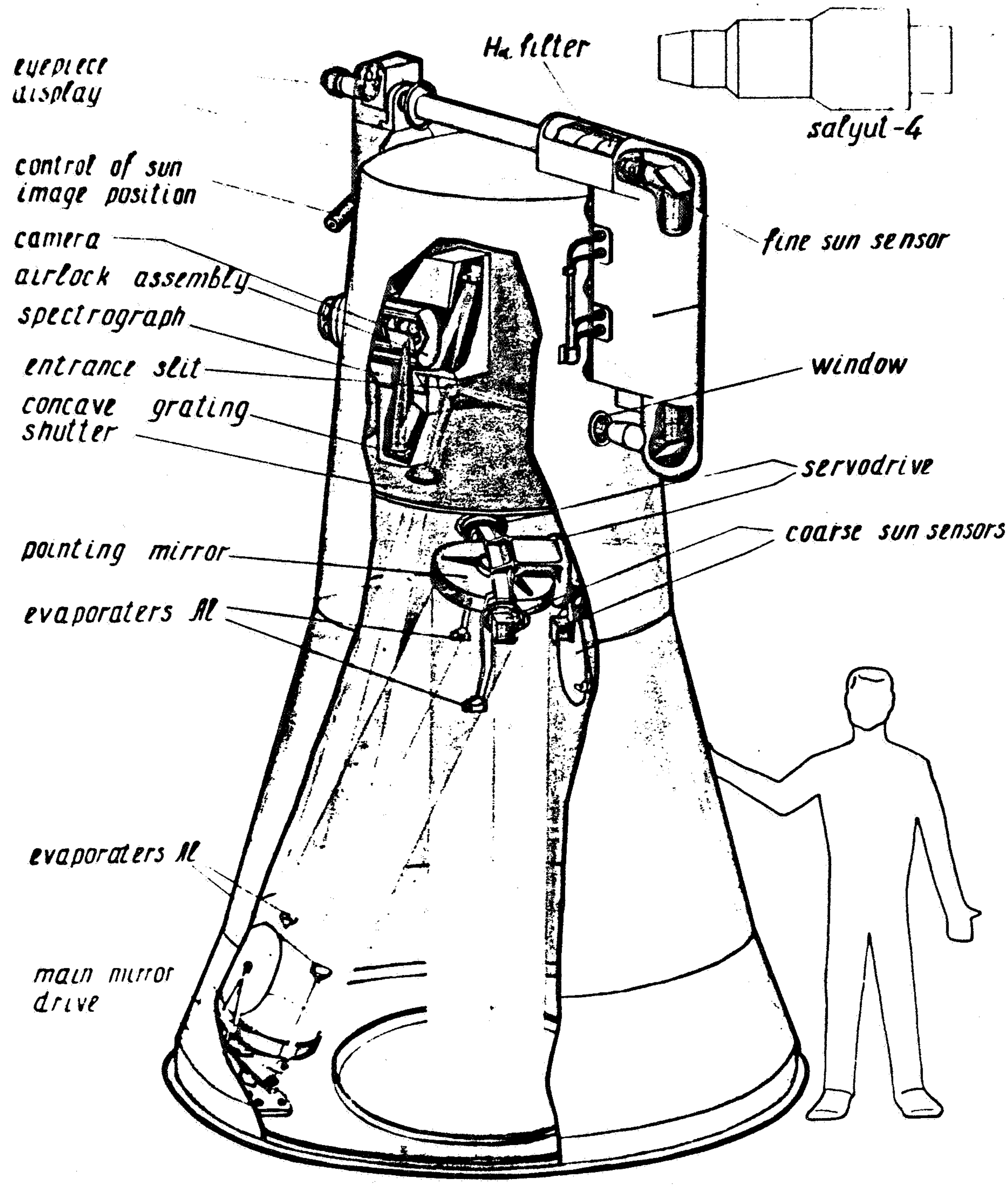


Figure 19. Layout of Orbiting Solar Telescope on Salyut-4, Showing Location of Main Mirror, Pointing Mirror, and Aluminum Evaporators (21, 154).

TABLE 1

Salyut 4 OST Telescope Optics

Mirror	Substrate	Coatings
Pointing Mirror (off-axis parabola)	Sytal (Zerodur)	At launch: Al (1000 Å) + LiF (160 Å) + MgF_2 (15 Å) Added in flight: Al (~800 Å)
Main Mirror (flat)	Sytal (Zerodur)	At launch: Al (1000 Å) + Ge (~600 Å) + ZnS (~450 Å) Added in flight: Al (~800 Å)
Spectrograph Gratings		At launch: Al + Ge + ZnS

from a badly contaminated reflective slit jaw, due to the increased heat dumped on the slit jaw by the newly-aluminized Ge+ZnS mirror.

Some other design details of the Salyut 4 solar telescope are worth noting. The aluminum evaporators were designed to be reusable, although in flight each mirror was coated only once (154). The flight mirrors were mounted into the instrument only at the last possible opportunity after all ground testing was complete. (Qualification mirrors were used for prior testing.) The back and side surfaces of the flight sytal (zerodur) mirrors were polished and aluminized to provide a higher normal operating temperature and thus minimize the amount of condensation of contaminants on the mirror faces. To further protect the mirrors from condensation, especially during the period immediately after insertion of the telescope into orbit, which was considered to be the most risky period for potential contamination of the optics, both the main mirror and the pointing mirror were equipped with clean metal protective covers, which were opened when observations were begun (21). Both the protective cover and the two symmetrically placed aluminum evaporators can be seen in Figure 20. Finally, to protect the hydroscopic LiF-coated pointing mirror from possible degradation due to humidity, this mirror was given a very thin (15 Å) coating of MgF_2 over the LiF. Moreover, the instrument was kept in a dry atmosphere during pre-launch testing, and a cannister of 3 kgm of silica gel was used for backup protection during particularly risky periods such as transportation.

The conclusions that may be drawn from the Salyut 4 OST experience are (1) clean protective covers for contamination-sensitive optics are effective at minimizing condensation, as seen by comparison of the unprotected reflective slit jaw to the protected main mirror and pointing mirror on OST, (2) 350 kilometers is an insufficient altitude for pure aluminum mirror coatings, and (3) a large, complex manned space station such as Salyut 4 is certain to create its own atmosphere of outgassed vapors. It is not clear whether spacecraft outgassing or residual Earth atmosphere was the primary limitation to the aluminizing experiments on Salyut 4. A.V. Bruns suggests that spacecraft outgassing may have been the real limitation to the lifetime of the bare aluminum (Reference 21, Section III). In any case, it is clear that telescopes using bare aluminum mirrors require an extremely low outgassing environment and a geometry

(a)

(b)

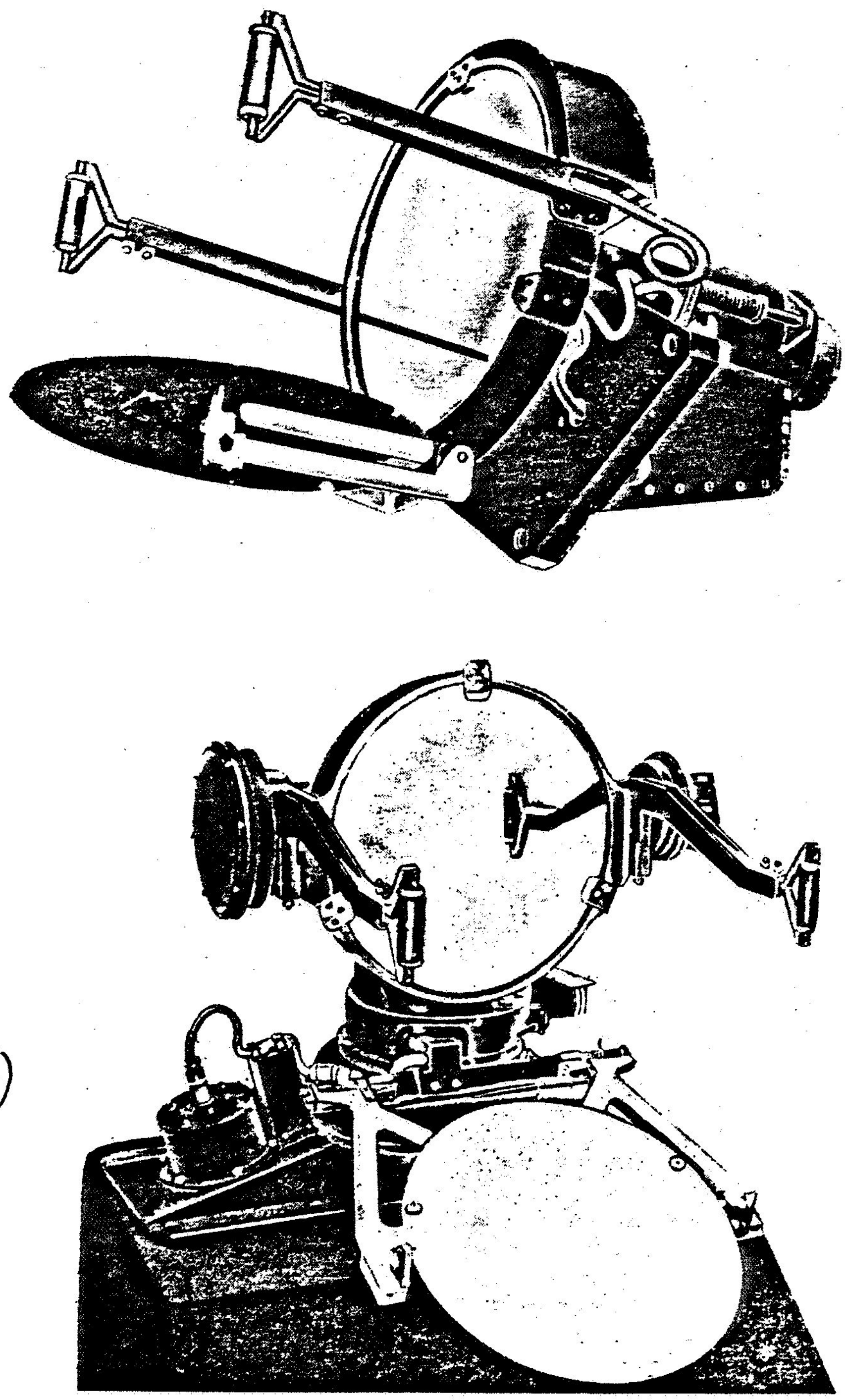


Figure 20. OST Telescope Optics.
(a) Main Mirror Module Showing Protective Cover and Two Aluminum Evaporators.
(b) Pointing Mirror Module Showing Protective Cover and Two Aluminum Evaporators (21).

that permits rapid venting of outgas products and that avoids intercepting residual atmosphere.

To the best of our knowledge, the in-orbit aluminizing procedure has not been repeated by the Russian astronomers.

For comparison, two normal-incidence solar instruments for FUV and EUV wavelengths flew on the large manned Skylab mission at an altitude of 435 km in 1973-74. These instruments were the Extreme Ultraviolet Spectroheliometer, S-055, for wavelengths from 300 to 1340 Å (11, 157, 159, 160) and the NRL EUV and Ultraviolet Spectroheliographs, S-082A and S-082B, for wavelengths from 175 Å to 615 Å and 970 Å to 3940 Å (76, 155, 156, 158, 159). The mirrors and gratings in these instruments used iridium (S-055), gold (S-082A) and MgF_2 (S-082B) optical coatings. Although these instruments did not have to contend with bare aluminum coatings, they did face the risk of photopolymerization on the optical surfaces from the combined effects of outgassing and solar ultraviolet. No significant in-flight degradation of throughput was observed in any of these instruments (155, 157), presumably because of a vigorous and thorough program of contamination prevention in both the selection of materials and handling of the instruments (11, 76).

2.3 SPACE SHUTTLE COATING DEGRADATION EXPERIMENTS

The first few flights of the U. S. Space Shuttle have been at altitudes of 200-315 kilometers. At these low altitudes the density of residual atmospheric atomic oxygen is high. (The number density of atomic oxygen at 200 km is $\sim 4 \times 10^9$ atoms cm^{-3}; the total atmospheric density is $\sim 10^{10}$ cm^{-3} or $\sim 2.8 \times 10^{-7}$ torr.) Many observations of the degradation of various coatings on the Shuttle have now been recorded. This degradation appears to be due in part of the high atomic oxygen density, high light velocity into the atmospheric gas, and in some cases the simultaneous exposure to solar ultraviolet radiation. Some of the observations on Flights STS-1 through STS-4 and proposed mechanisms are listed below (5, 87, 161, 162, 164).

- o Polymer films such as kapton, paint binders, torlon thermal blanket buttons, were oxidized and/or removed by sputtering. Kapton (polyamide) erosion was as much as 0.1 mil (2.5μ) in 6-day mission.

- Loss of material from mylar sample on STS-4 was 0.07 mil (1.8μ).
- Loss of material from teflon sample on STS-4 was 0.003 mil (0.08μ).
- Carbon coatings and aquadag suffered complete loss (2000 Å), presumably oxidized to CO and evaporated.
- Osmium coatings suffered complete loss (120-2000 Å), presumably oxidized to osmium tetroxide (OsO_4) and evaporated.
- Silver coating suffered complete oxidation to Ag_2O. Coating changed color but did not evaporate.
- The above reactions were accelerated by both exposure to the vehicle ram direction (flight vector) and to direct solar exposure, as evidenced by observed shadowing effects.
- No degradation of MgF_2, iridium, gold, platinum or aluminum surfaces have yet (October 1983) been observed on Shuttle flights, presumably due to the chemical stability of these materials.
- Metallic coatings of aluminum, gold or platinum served to completely protect surfaces of kapton, mylar, kevlar from oxidation, even for metal film thicknesses of only 250 Å.
- When material erosion measurements are normalized into a measure of reactivity, namely (material loss (in cm))/(fluence = atoms impinging on surface per cm^2), this reactivity is more or less a constant for a given material, for example: the reactivity of kapton is 1 to 2 x 10^{-24} cm^3 per oxygen atom.
- A baffled pressure gauge on the STS-3 flight showed pressure increases up to a factor of 200 over the expected normal ambient atmospheric pressure, due to ram effects of the vehicle's 7.55 km/sec motion into the atmospheric gas (162).
- The temperature-controlled quartz crystal microbalances (TQCM's) on the Contamination Monitor Package on STS-3 showed accretion rates as high as 29 angstroms per hour (at -30°C) of molecular contaminants during portions

of this 241 kilometer altitude mission, and evaporation rates as high as 37 angstroms per hour (at +60°C) during "bakeout" periods (163, 164).

- Observations of the diffuse glow surrounding the Orbiter surfaces which faced into the direction of motion of the vehicle are consistent with an interaction of atmospheric O with the vehicle surface or with adsorbed OH in the vehicle surfaces. At a 240 km altitude, the flux of oxygen atoms striking the exposed surface areas of the Orbiter is $\sim 1.4 \times 10^{15}$ atoms $(cm^2\ sec)^{-1}$ (6, 12, 94, 95, 112, 116, 121, 131, 132).

The lessons learned from these Space Shuttle experiments conducted to date include: (1) Reactive optical coatings (such as osmium and presumably aluminum) will oxidize very quickly in a Space Shuttle environment at altitudes $\lesssim 315$ km, (2) the rate of reaction is greatly enhanced by exposure of the surface to the vehicle flight direction, (3) the Shuttle is a major source of outgassing itself, so that even surfaces sheltered from the vehicle ram direction still suffer oxidation.

SECTION 3

THE DESIGN OF AN ORBITAL COATING LABORATORY

The real purpose of an Orbital Coating Laboratory is to assess the viability of coating, cleaning and re-coating reflective elements for use in the far ultraviolet in a space vacuum environment. In this section we will derive a conceptual design for an orbiting laboratory that is capable of both coating experiments and feasibility demonstrations. We will list the research questions that could be addressed with a versatile coating laboratory, the requirements on the vehicle carrying such a laboratory, and describe a possible experimental layout.

3.1 RESEARCH QUESTIONS TO BE ANSWERED

The principal research question to be studied in an orbiting optical coating laboratory is the lifetime of the far ultraviolet reflectivity, determined by oxidation, of pure aluminum optical coatings deposited in the vacuum of space. We need to understand the way in which this lifetime may be maximized by careful selection of the range of telescope pointing direction with respect to the orbital flight direction and by other geometrical shielding techniques. The goal of these lifetime measurements is to provide sufficient data to allow extrapolation to a real orbiting telescope configuration, so as to allow estimation of lifetime for a real FUV telescope in a particular orbit. A related research question of interest for future solar-pointed telescopes is to investigate the dependence of the rate of oxidation of aluminum on incident solar radiation.

Another research problem to be studied is the reflecting properties of an aluminum coating that has been deposited on top of a thin oxide layer or even a built-up sandwich of many Al + Al_2O_3 layers, all produced in a space vacuum environment. The ability of such a mirror or grating to continue to provide high reflectivity and low scatter at all wavelengths needs to be tested.

Secondary research goals for an orbiting optical coating laboratory are concerned with the build-up and removal of contaminating films which again can spoil the far ultraviolet reflectivity of optical surfaces. Whereas a fresh aluminum coating is known to adhere well to an Al_2O_3 film, most evaporated coatings do not adhere well to an organic polymer film and therefore an organic contaminant layer must be removed before re-coating. One possible cleaning technique that cannot easily be simulated in a ground laboratory test is exposure of the contaminated surface to the flow of atomic oxygen in the residual Earth atmosphere, which has high oxidizing power at an orbital velocity of 7.6 km/sec (4.8 electron volts of kinetic energy). Atomic oxygen cleaning by either a built-in atom bombardment source or by the orbital ambient oxygen flow can be expected to literally burn off an organic contaminant layer but also of course oxidize an aluminum surface. The experiment that needs to be conducted is to learn whether aluminizing which follows such a cleaning process can yield a high-reflectivity low-scatter mirror for ultraviolet observations.

Finally, experiments on the rate of degradation of reflectivity due to photolytically-reacted outgas contaminants are possible in the same orbital laboratory, since the natural "oil-free high vacuum system" of space provides a controlled enviornment for measuring the rate of degradation versus ultraviolet flux, substrate temperature and ambient gas density. Such experiments are of key interest to future solar telescopes such as for the telescope optics and the heat rejection mirrors for NASA's Solar Optical Telescope (56, 165, 167, 168).

Other uses for a space-based "vacuum research facility" have been described in a very interesting 1979 JPL study on "Instrumentation Concepts and Requirements for a Space Vacuum Research Facility" (166).

3.2 ORBIT

How high an orbit is required to perform useful in-space coating experiments, and how high an orbit will probably be required to provide 6 months of useful life for an actual bare aluminum telescope? We will consider the second question first.

From the material reviewed in Section 2.1, we concluded that an Al_2O_3 thickness of ~ 5 Å was the maximum tolerable oxide thickness if significant loss of far ultraviolet reflectivity is to be avoided. We have used a general purpose computer program ("OPTCOAT", Appendix B) to calculate the normal incidence reflectivity of thin layers of Al_2O_3 over aluminum for the full wavelength range from $\lambda = 500$ Å to 1800 Å, as a function of oxide thickness. For these calculations, we used optical constants for aluminum from the Deutsche Physikalische Gesellschaft "Physics Data" compilation (169) and optical constants for Al_2O_3 from the Hamburg Electron Synchrotron (DESY) group (170). These calculations (Figure 21) show that a 5 Å Al_2O_3 thickness (about 5 monolayers) leads to a ~30% loss in "figure of merit" for a bare aluminum mirror. (The figure of merit here is defined as a weighted average of the normal incidence reflectivity from $\lambda = 500$ Å to 1800 Å, with extra weight on the astrophysically significant 900 Å to 1216 Å region.)

There are many sources of data on what oxygen exposure is required for an Al_2O_3 build-up of the above amount (39, 46, 57, 59, 62, 63, 77, 81, 83, 92). Estimates of this exposure based on these data range from 15 to 3000 Langmuirs* of oxygen exposure. At the low end of this scale, the data of Madden, Canfield and Hass (92) indicate that a 20% drop in reflectivity at $\lambda = 1025$ Å is reached with an air exposure of only 100 seconds at $p \approx 8 \times 10^{-7}$ torr, suggesting a useful lifetime of only ~16 Langmuirs. At a high end of the scale, the data of Krueger and Pollack (83) show ~2 Å of oxide on exposure to 5×10^{-7} torr of dry O_2 for 100 minutes, ie. 3000 Langmuirs. The data of Kirk and Huber (81) which suggests an oxide thickness of 2 Å after 16 minutes of 2×10^{-7} torr (200 Langmuirs) may be representative of data close to the geometric mean between these two extreme estimates.

It is clear from all data sources that the first ~2 monolayers of oxide are produced very quickly with a high oxygen sticking efficiency while deeper penetration of the oxide layer occurs with a much reduced oxygen sticking efficiency (39, 83, 81, 92). See Figure 22.

Taking 200 Langmuirs as a rough estimate of the maximum allowable oxygen exposure, a 6 month lifetime corresponds to 1.27×10^{-11} torr of oxygen, which occurs at an altitude of ~760 km. Since there is at least an order of magnitude possible error in this

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* One Langmuir=10^{-6} torr-seconds, that is, one second at 10^{-6} mm Hg, or 10 seconds at 10^{-7} mm Hg, for example.

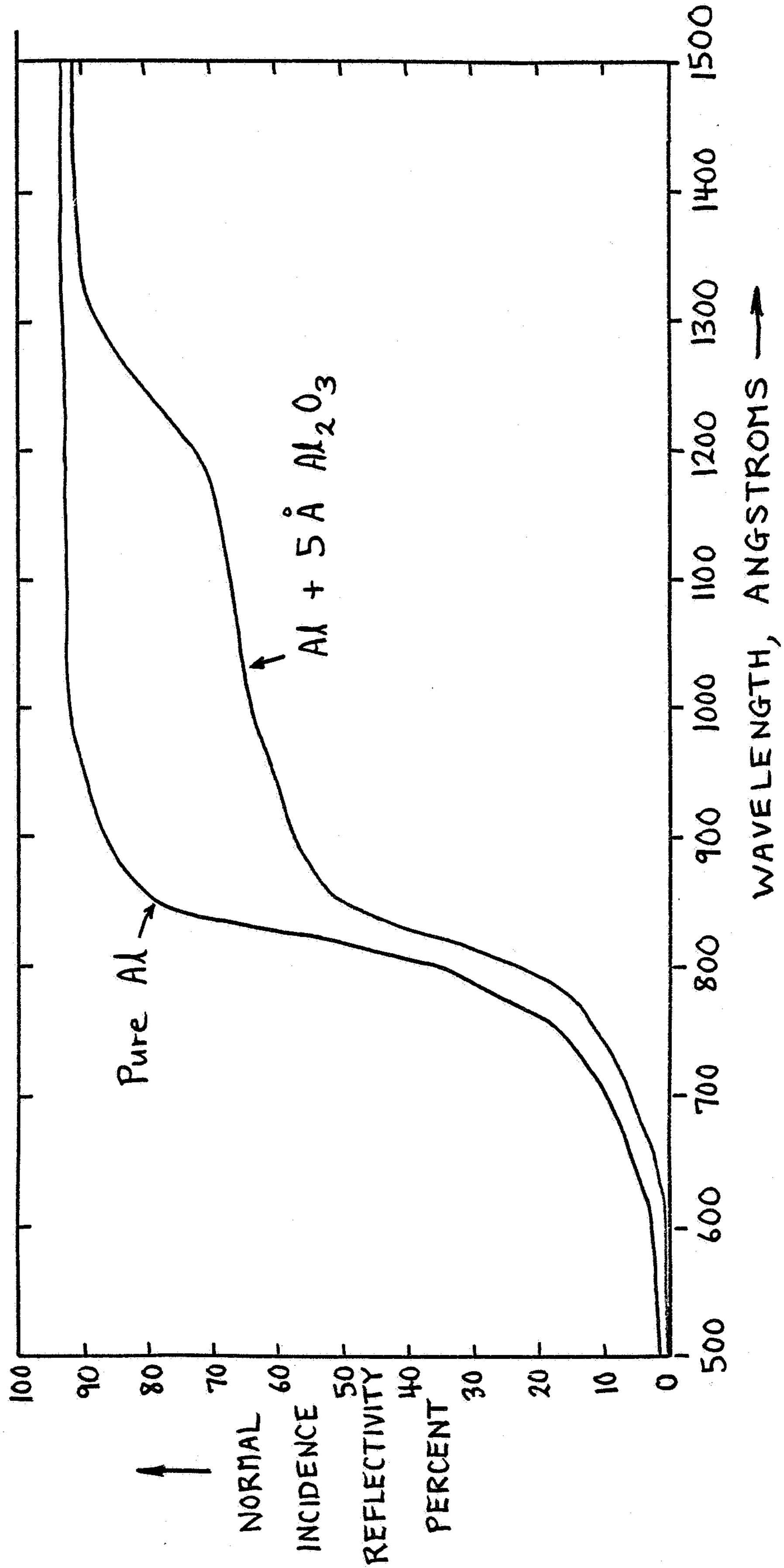


Figure 21. Calculated Normal Incidence Reflectivity of Aluminum, With and Without 5Å Oxide Layer, Using Optical Constants of Appendix C and "OPTCOAT" Program of Appendix B.

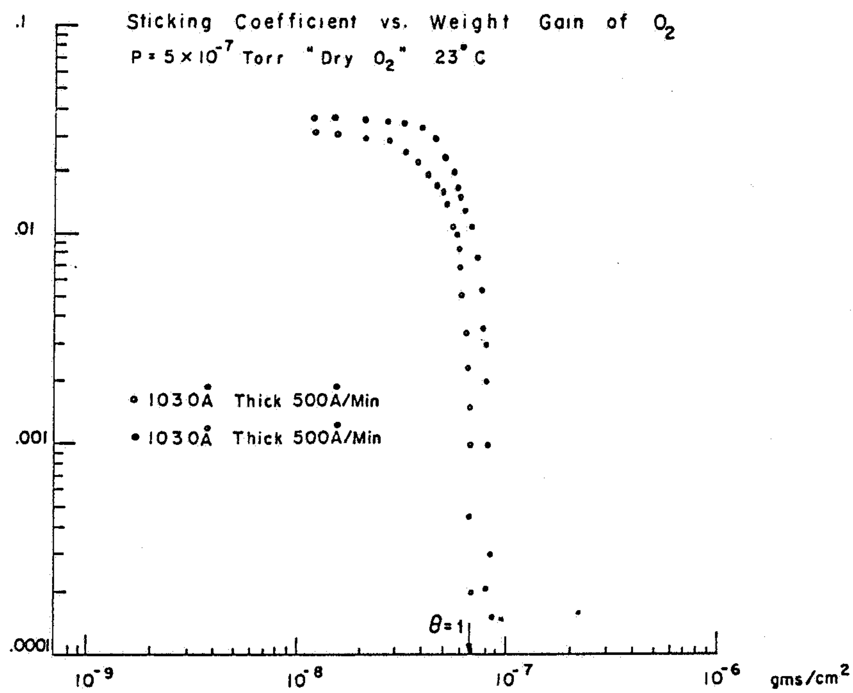


Figure 22. Sticking Coefficient of Oxygen or Aluminum as a function of total oxygen weight gain. A monolayer of oxygen atoms on each available site corresponds to $\sim 7.0\text{x}10^{-8}$ gm/cm^2. From Krueger and Pollack (83).

exposure estimate, the minimum allowable altitude could be as high as 900 km (166, 171, 172). Although this estimate is somewhat more optimistic than the estimate of 1500 km for required perigee altitude given by Hass and Hunter (59), the estimate of $\sim$900 km still poses a dilemma for the concept of flying bare aluminum optics in Earth orbit. Altitudes no higher than 900 km (486 nautical miles) can be tolerated in order to avoid interference with the trapped radiation belts and the South Atlantic Anomaly (7). The detectors typically used in far ultraviolet astronomy are sensitive to charged particles and the fraction of the Earth's surface that is free from high energy particles shrinks as the altitude increases (7, 173). So to avoid a high level of particle background, an ultraviolet space telescope must either be placed below 900 km or in a circular or somewhat eccentric geosynchronous orbit. The geosynchronous orbit is almost certain to provide a sufficient lifetime against oxidation, provided the instrument and spacecraft are designed to release extremely low levels of outgassed oxygen or water vapor.

The one exception to the minimum altitude requirement imposed by oxidation considerations is the molecular shield situation, discussed in the next section.

The above orbital altitude requirements for a long-lived ultraviolet telescope using bare aluminum optics do not apply to the Orbital Coating Laboratory. The in-space optical coating experiments that we envision can best be done at a much lower altitude where the time constants of oxidation reactions can be more easily measured. The important constraint is only that the measurements can be extendable to allow predicting lifetimes for higher orbits. In order that a lifetime of, say, 90 minutes (one orbit) or more can be achieved with an oxygen concentration equal to the ambient density, an oxygen partial pressure of $\lesssim 3.7 \times 10^{-8}$ torr is necessary, and an altitude $\gtrsim$ 360 km is required (166, 171, 172). See Figures 23 and 49.* This is in the range of current Space Shuttle altitudes such as the Long Duration Exposure Facility (LDEF) mission (463 kilometers). The preferred orbit for an Orbiting Coating Laboratory would be

* For an ideal gas, p (torr) = 1.03×10^{-19}. n (atoms/cm^3). T (^{o}K).

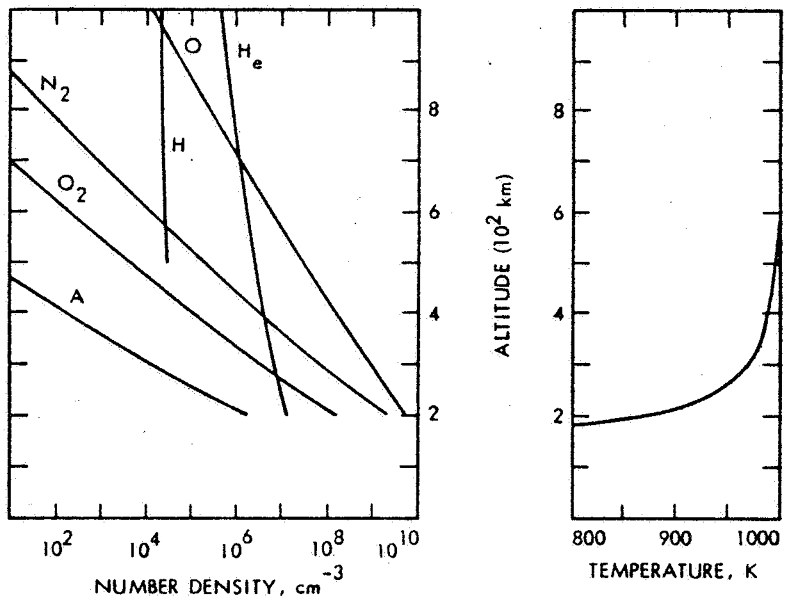


Figure 23. Constituent Number Density and Temperature as a Function of Altitude for a Terrestrial Atmospheric Model with an Exospheric Temperature of 1000°K (166).

elliptical, spanning altitudes between ~400 km and ~900 km, because with this range of altitudes sampled, the ambient atmospheric density is a variable that can be put to use in experiments, as was done with Atmospheric Explorer satellites (121, 132).

In fact, atmospheric density and the atomic oxygen concentration are a strong function of solar activity (Figure 24) and of time in the solar cycle (Figure 25). An orbital aluminizing laboratory and an aluminum-coated space telescope must be designed for the worst case concentration (135, 172).

In Section 3.4 of this report, we suggest that the Sun be used as a relatively constant ultraviolet source for the purpose of measuring reflectivity and also for contamination experiments involving photopolymerization. Therefore there is an optimum orbital configuration for an Optical Coating Laboratory: the Sun should be near an orbital pole, so that the line of sight into the laboratory's optical measurement chamber is roughly perpendicular to the flight vector for reflectivity measurements, and never need be closer than 90° to the flight vector at other times. This suggests that the orbital plane should be as close as possible to perpendicular to the ecliptic plane, (inclination $\geqslant 56^{\circ}$).

3.3 THE MOLECULAR SHIELD CONCEPT

A concept which has real potential merit is the idea of using a molecular shield in low Earth orbit to block the flow of atmospheric gas due to a spacecraft's orbital velocity, thereby achieving a large reduction in pressure over the natural ambient pressure at that altitude. This concept has been recently studied by workers at NASA's Jet Propulsion Laboratory and Langley Research Center (161, 171, 174, 175, 176, 177).

The concept is simple: Since the orbital velocity of a low Earth orbit satellite (~7.6 km/sec) is much higher than the Maxwellian speed of the atmospheric atoms (typically ~1.2 km/sec), there is virtually no probability for an atmospheric atom to enter an instrument compartment from the hemisphere on the "wake" side, opposite the flight direction. This fact has led researchers to consider the design of experiments in a "Space Vacuum Research Facility" (166) to use this unique opportunity of an ultra-high vacuum together with a collimated 5 eV atomic beam (the atmospheric flow). Experiments that have been suggested for such a facility include surface physics

ATOMIC OXYGEN CONCENTRATION AND ATMOSPHERIC DENSITY AS A FUNCTION OF ALTITUDE

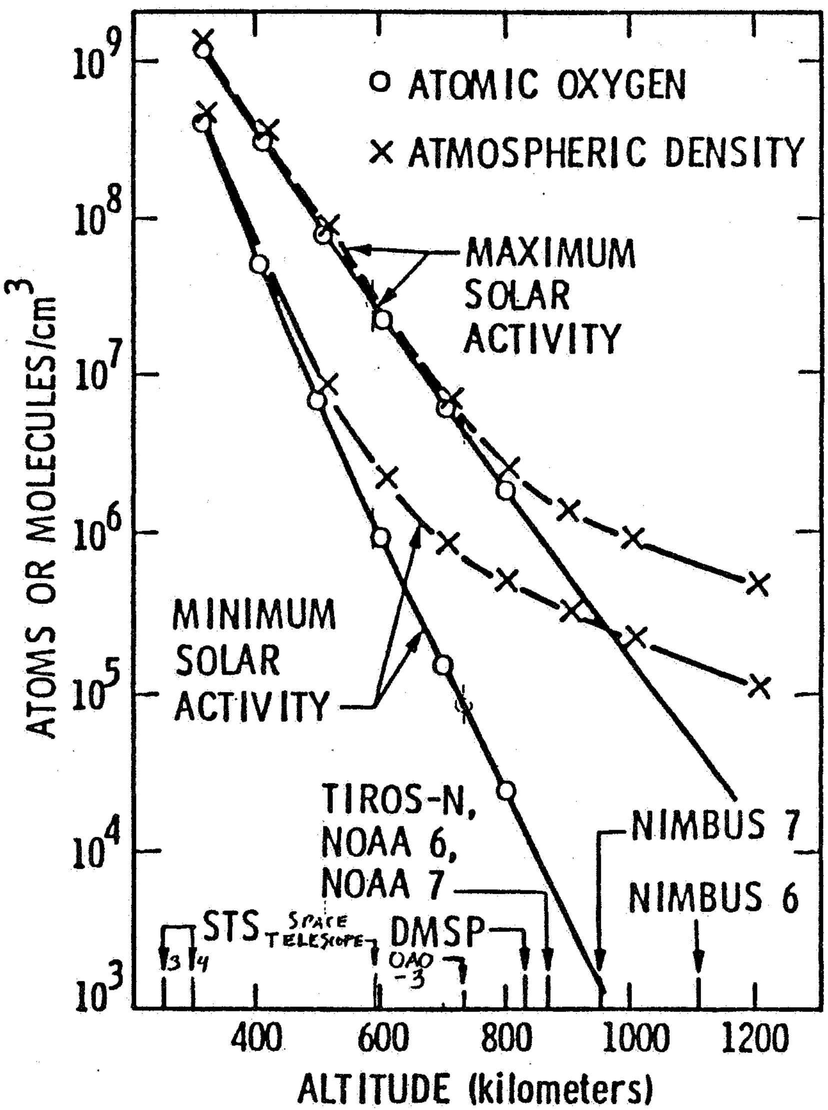


Figure 24. Atomic Oxygen Concentration and Atmospheric Density as a Function of Altitude and Solar Activity, from Reference 135. STS-3 and -4 show the altitudes for two early Shuttle flights.

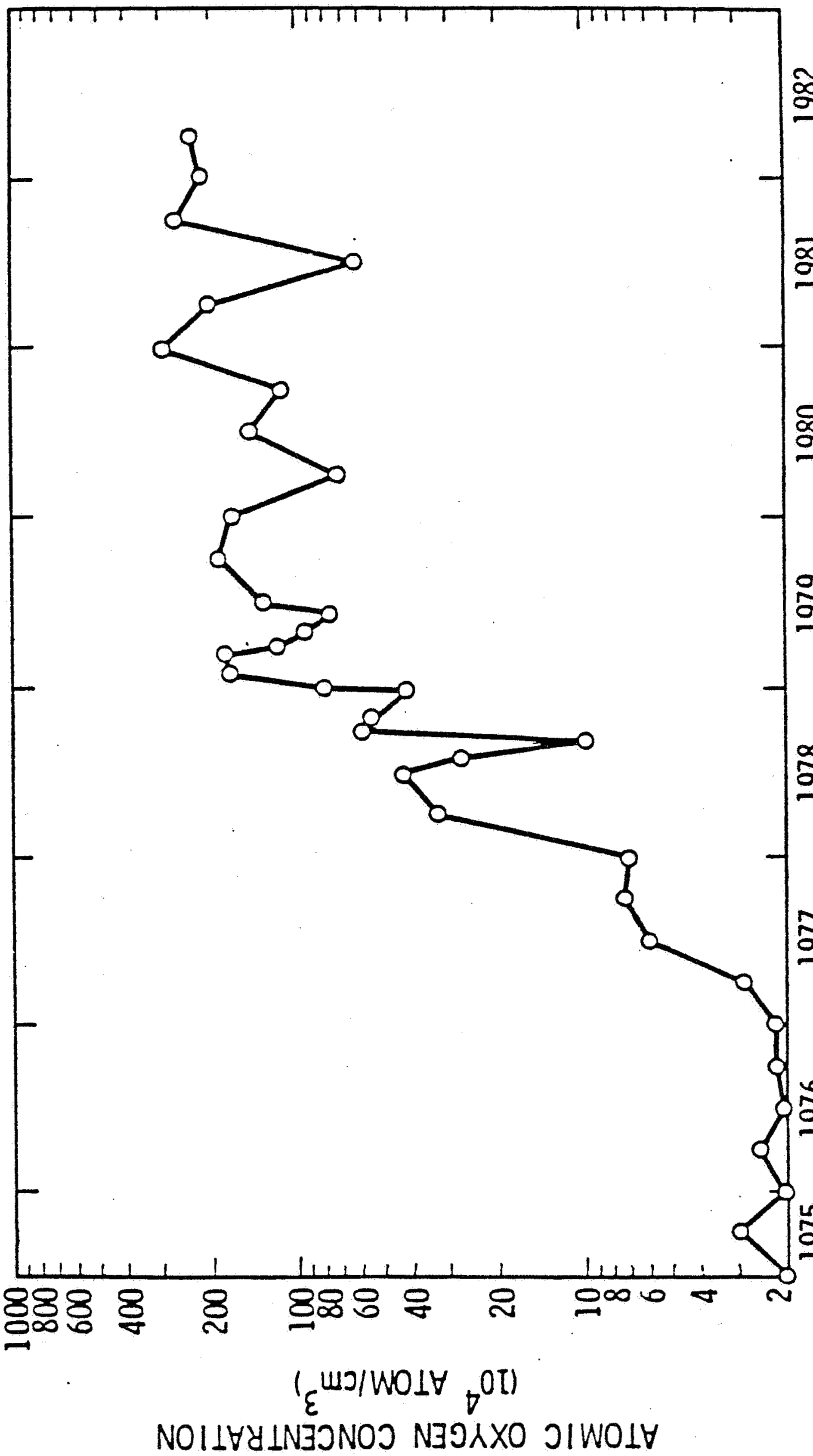


Figure 25. Rise in Atomic Oxygen Concentration from 1975 to 1982 at an 800 km Altitude, from Reference 135.

studies, electron spectroscopy for chemical analysis (ESCA), molecular beam experiments, gas dynamics and thin film research. The shield material need be no more substantial than aluminum foil. Since the mean free path at altitudes of 200 km or more is 0.4 km or greater, all atoms or molecules may be considered to follow straight line trajectories.

Figure 26 (166) illustrates schematically the molecular shield concept.

We have written a general purpose computer program (Appendix D) for calculating the pressure or the residual density at a test point that is surrounded by an arbitrary geometry of shielding in a Maxwellian gas drifting at an arbitrary velocity. Calculations with this program show that even for the worst case atmospheric model (exospheric temperature = 2100°K), a factor of 10^8 reduction in pressure is theoretically achieved by a shield which covers only 2.6 steradians in front of the test point. See Figure 27.

Of course this full pressure reduction will never be achieved in practice because of gas released by the payload itself (207). However, with proper care in the selection of materials and the timing of gas-venting activities and providing a geometry for rapid venting of released gases, it seems likely that a factor of 200 reduction in atomic oxygen flux can be achieved with a shield that blocks no more than 50% of the sky from view. This would be an acceptable compromise for a far ultraviolet telescope. A bare aluminum telescope could then survive for $\gtrsim$6 months at an altitude of 600 kilometers, close to the planned altitude of Space Telescope.

What will be the ultimate pressure achievable in a satellite due solely to outgassing? Clean satellites have measured gas densities as low as 2×10^4 atoms/cm^3 ($\sim 2 \times 10^{-12}$ torr). This may be close to the limit attainable with a space telescope. Fortunately the lifetime of bare aluminum coatings at this density is $\gtrsim$3 years.

We propose that the molecular shield concept be applied in the Orbital Coating Laboratory. In this case the shield need consist of little besides a solid surface facing the flight direction and a small shield to shadow any apertures opening to the ambient vacuum.

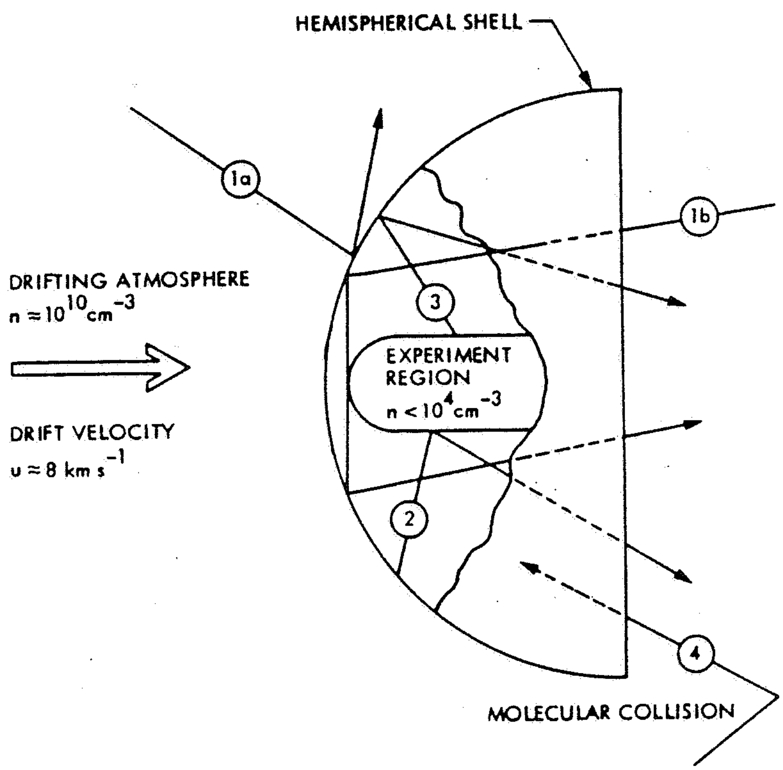


Figure 26. Schematic representation of the molecular shield geometry in the drifting gas, illustrating typical molecular trajectories: (1a) and (1b) are free-stream molecules where the flux of (1a)-type molecules is much greater than the flux of (1b)-type molecules; (2) are desorbed molecules from the shield; (3) are desorbed molecules from the experiment; and (4) are molecules scattered from the Orbiter (from Reference 166).

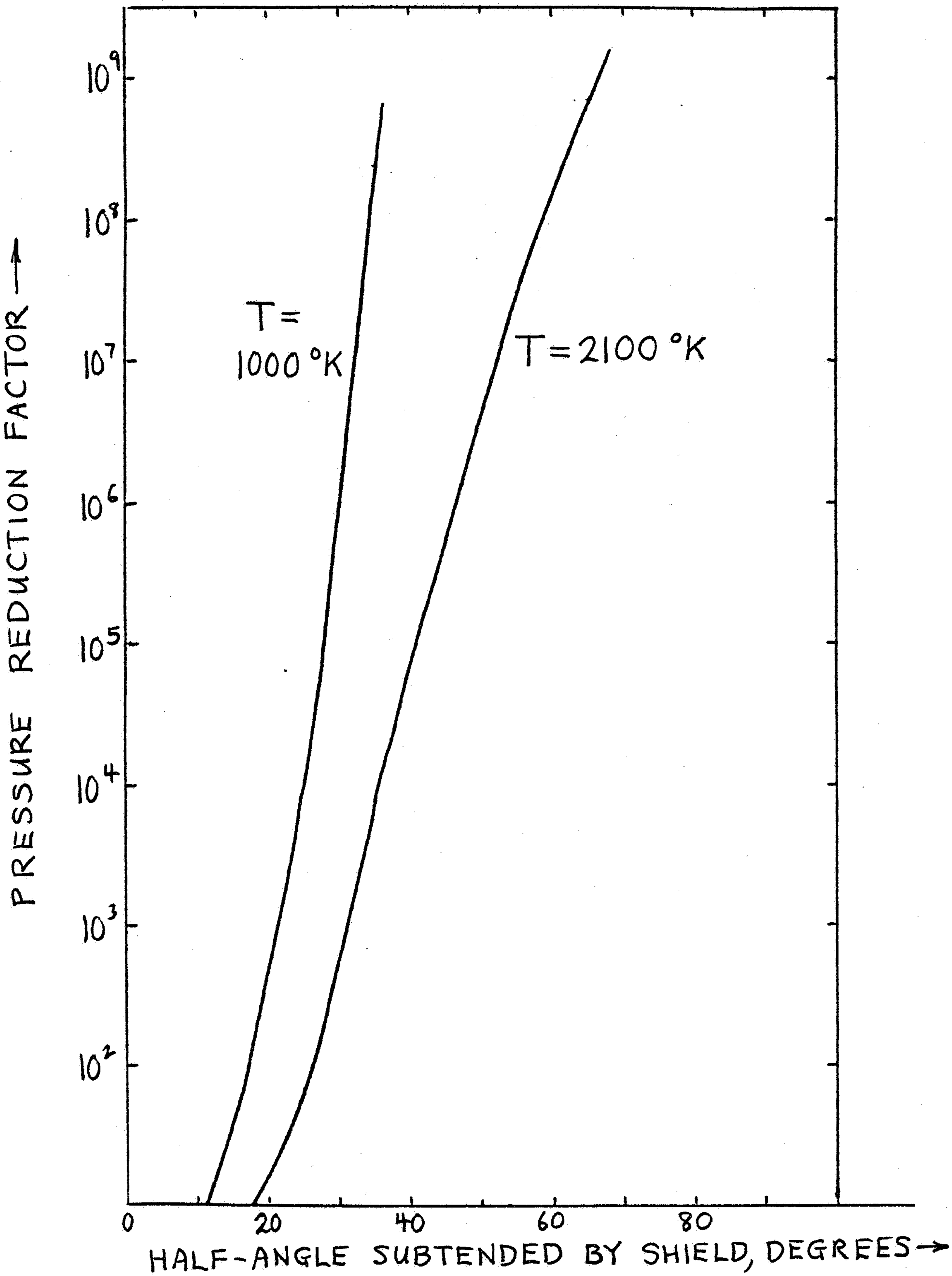


Figure 27. Pressure Reduction Factor Resulting from a Molecular Shield of Various Solid Angles Placed Ahead of a Test Point Moving at 7.55 km/sec, for Different Exospheric Temperatures, T.

3.4 LABORATORY DESIGN

In the following paragraphs, we will consider some aspects of the conceptual design of an orbiting optical coating laboratory. These concepts are obviously very preliminary; a more thorough study would undoubtedly find improvements. The dual goals here are to conduct a realistic demonstration of the techniques of in-space optical coating with pure aluminum, and to carry out experiments that will answer many of the research questions discussed in Section 3.1.

3.4.1 Requirements and Constraints

In Section 1.2, we listed the general requirements for optical coating in a remote space environment. Here we will list some of the requirements and constraints for the particular case of a versatile experimental laboratory on a Space Station or platform or independent free-flyer.

1. Low outgassing hardware: The payload must be designed for the lowest possible level of in-orbit outgassing. The Space Shuttle may be an incompatible vehicle for these experiments unless the laboratory is carried at the end of a long boom (166). A more appropriate platform for this laboratory will probably be a clean, unmanned space platform (178, 179, 180, 181, 200) or an automonous "SPARTAN" mission (182).

2. Heaters: The laboratory should be equipped with heaters to drive off adsorbed gases from any adsorption-prone materials. The mirrors should be provided with heaters to allow variation of substrate temperature over the range 0 to +80^{o}C.

3. Pointing: The laboratory's entrance aperture will need to be pointed towards the Sun (to within $\pm 1/4$ degree) and held for several minutes for some experiments. A two-axis steering system and a solar aspect sensor will be needed.

4. Coating Runs: Up to 16 independent coating runs must be accommodated. The amount of material deposited on each mirror must be somewhat controllable.

5. Reflectometer-Monochromator: The Laboratory must have provision for measuring broad band ($\Delta\lambda \sim 50$ to 100 Å) reflectivity over the range from $\lambda \cong 700$ Å to 2200 Å.

6. Sensitivity: Reflectivities will be measured ranging from 92% to ~0.1%. The reflectometer must be capable of sensing changes in reflectivity of 3% (minimum) and a factor of 100 (maximum).

7. Pressure Measurements: The Laboratory should be equipped with a device to monitor pressures in the optical measurement compartment in the range 10^{-10} to 10^{-5} torr.

8. Venting and Outgassing: The laboratory must be sufficiently well vented to the ambient vacuum that a high pumping speed is achieved following a coating or a cleaning operation.

9. Coating Monitor: A quartz crystal microbalance is needed to monitor the amount of evaporant deposited on each mirror at each coating operation.

10. Atom Beam Cleaning: The laboratory must be equipped with a means of cleaning contaminant films from each mirror prior to re-coating.

11. Scatter: Repeated re-coating of a test mirror with intervening oxidation may lead to a roughness build-up of the mirror surface (183). Although the measurement of mirror scatter is not a primary goal here, the facility should have some power to characterize a serious change in mirror scatter.

12. Mission Duration: The laboratory should be capable of performing all or most of the experiments suggested in section 4 within a period of ~28 days.

3.4.2 Layout

Three particularly significant design details need to be decided at the start: (1) whether to work with numerous small mirror test samples or a few large "telescope-like" mirrors, (2) the choice of technique for applying an optical coating (thermal evaporation, electron-beam evaporation, sputtering, plasma ion deposition), and (3) the choice of FUV light source for the measurement of reflectivity.

An in-flight optical coating feasibility demonstration has also recently been proposed by Dr. William M. Burton of Rutherford Appleton Laboratory (148) and called "Aluminum Coating Experiment" (ACE). Burton's concept called for a number (~eight) of small (~3 cm) mirror samples. We have chosen the alternate concept of two larger mirrors to provide a larger amount of coated surface area and perhaps better demonstrate the coating of large telescope mirrors.

The case for thermal evaporation as the means of depositing coatings in space is discussed further in Section 3.4.4. Basically, thermal evaporation is known to provide smooth and uniform optical coatings with good adhesion properties. Although some thermal evaporation techniques (designed for ground laboratories) depend on gravity, evaporator designs exist which do not rely on gravity (21).

Concerning the choice of constant broad-band ultraviolet light source for the measurement of reflectivity, we have selected the relatively simple expedient of using the Sun: an intense, more or less constant and reliable source to which the laboratory will have access most of the time. Table 2 shows some estimates of the short-term time variability (1 minute-1 hour) of the integrated flux from the disk of the Sun at various wavelengths (17, 184, 185, 186, 187). The coronal emission lines show the most variability, but even for these the whole Sun flux changes by $<10\%$ in 24 hours and $\ll 5\%$ in one hour. Since in the concept we are describing, all reflectivity measurements come from ratios of measurements made a few minutes apart, the variability of the light source on longer time scales is not important.

The concept sketched in Figure 28 is a 48 x 36 x 65-inch experiment housing mounted in a 2-axis gimbal mount. The experiment system is designed for the direction of atmospheric flow to always be within a few degrees of the vector shown. The sides marked A, B, C, D, have solid metal walls to block the flow of atmospheric gas. The rest of the assembly is well-vented to the "wake" side of the flow. The side, bottom and back walls have a louvre baffle arrangement, G, to shield the interior from the bulk flow of the atmospheric gas and from major stray light sources (sunlit Earth, moon) while allowing outgas products from the experiment cannister to escape. Items E and F are molecular shields to shield the side and bottom walls and the optical aperture. A solar aspect sensor H senses the angular coordinates of the Sun with respect to the experiment cannister.

TABLE 2

ESTIMATED VARIABILITY OF THE SUN

Continuum Above $\lambda = 2100$ Å	$< 1\%$
Continuum 1520 Å - 2100 Å	$< 1\%$
C IV (1550 Å)	$< 5\%$
Continuum 1216 Å - 1520 Å	$< 1\%$
Lyman -α (1216 Å)	$\lesssim 1\%$
Continuum 800 Å - 900 Å	$< 5\%$
Helium I 584 Å	$< 5\%$
Continuum 400 Å - 600 Å	$< 5\%$
Helium II 304Å	$< 5\%$

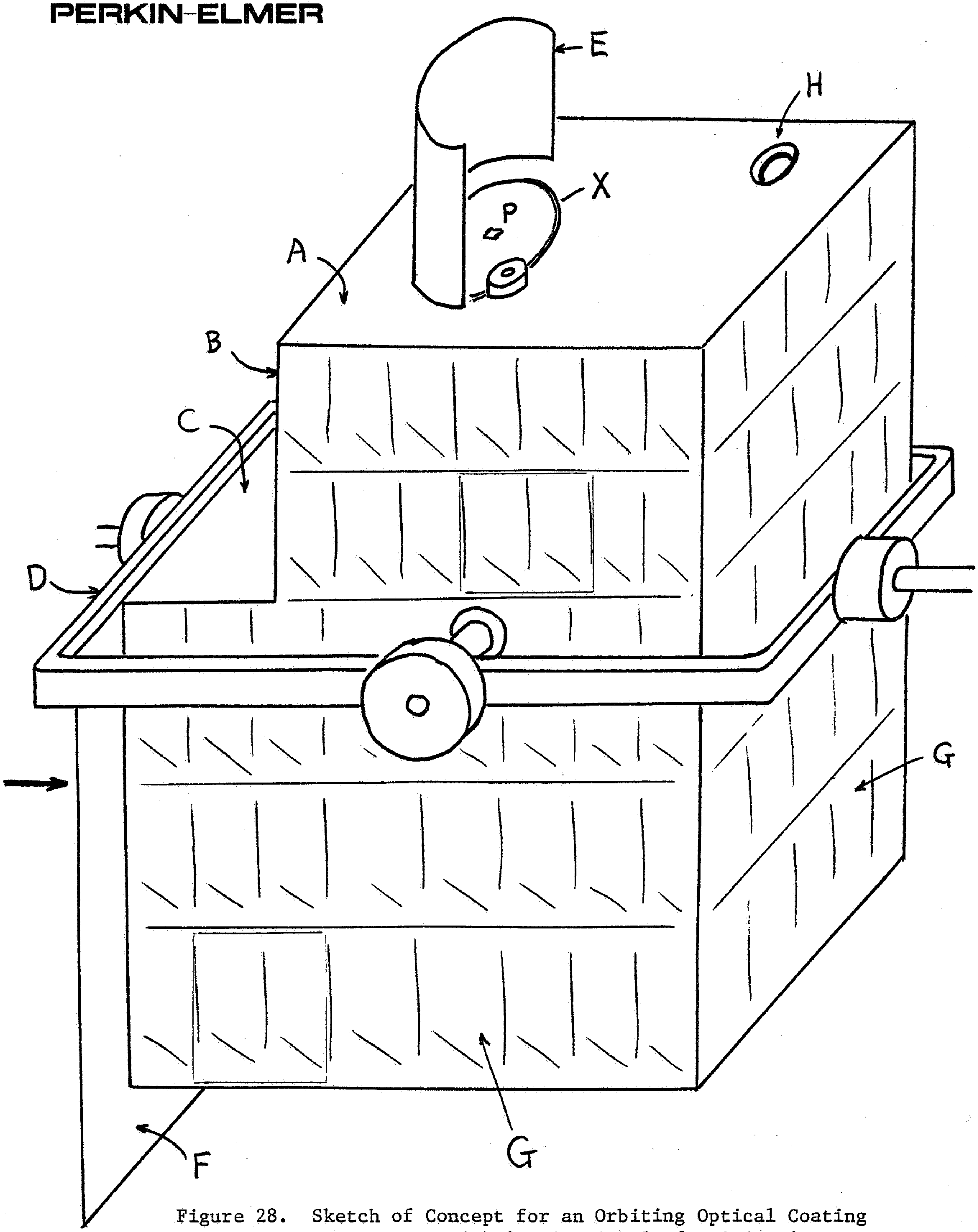


Figure 28. Sketch of Concept for an Orbiting Optical Coating Laboratory, with 2-Axis Gimbals for Orienting. The heavy arrow indicates the direction of atmospheric flow. Items E and F are shields to shadow the Laboratory from this flow.

It is important that this experiment chamber be mounted (on a space platform, free flyer, or on the end of a long arm from the Space Shuttle) so as to minimize or eliminate any direct lines of sight from any spacecraft surfaces which are exposed to the ram flow, through the baffles into the optical coating laboratory. Surfaces exposed to the ram flow of atmospheric gas become themselves secondary sources of atomic oxygen flux and sources of contaminant gases.

The interior is sketched in Figure 29. Two large flat mirrors, 1 and 2, provide a total of 4 mirror surfaces (2x2) for coating experiments. The experiment cannister is divided into 3 separate compartments: the top coating chamber J, the bottom coating chamber K, and the optical measurement L. Each of these compartments is sealed off from each other with a solid wall but all three are well vented to the exterior towards the "wake" side. No combinations of lines of sight exist between the upper coating chamber and the lower coating chamber except via 3 or more bounces.

Each of the two mirrors 1 and 2 can be rotated by 180° around the axes shown, M, so as to turn either face A or face B towards the optical measurement chamber. The "butterfly valve" sealing rings, N, provide a geometrically tight (but not hermetically tight) seal around each mirror while still allowing the mirrors to rotate. The mirrors are driven by sealed DC torque motors.

Reflectivity measurements are via a multiple bounce reflectometer, using the Sun as a source. The principle is illustrated in Figure 30. A small aperture, P, allows sunlight to illuminate the lower mirror. By tilting the assembly with respect to the Sun line over a total range of ~22°, any number between 1 and 6 reflections can be achieved from the two mirrors. The ratio of signals recorded with different numbers of reflections allows solving for R_1, R_2, R_2^2, R_2^2, and so on, where R_1 and R_2 are the reflectivity of the two mirrors, independent of the intensity of the source and the sensitivity of the detector. For the geometry shown, the angle of incidence on each of the parallel mirrors for n reflections is given by

$$\cot \theta_n = \frac{h}{w}\left[1 + \frac{d}{h}(2n-1)\right]$$

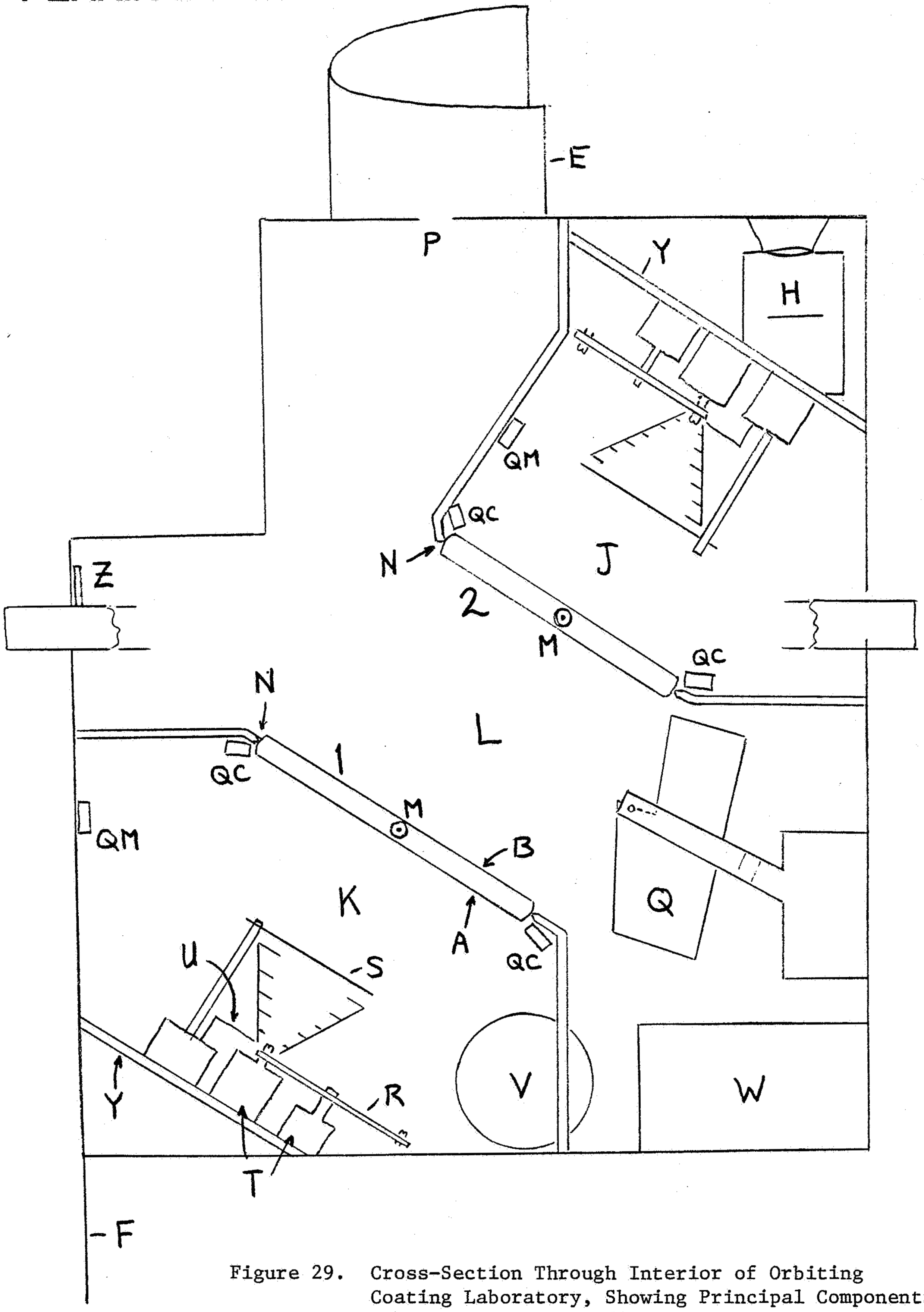
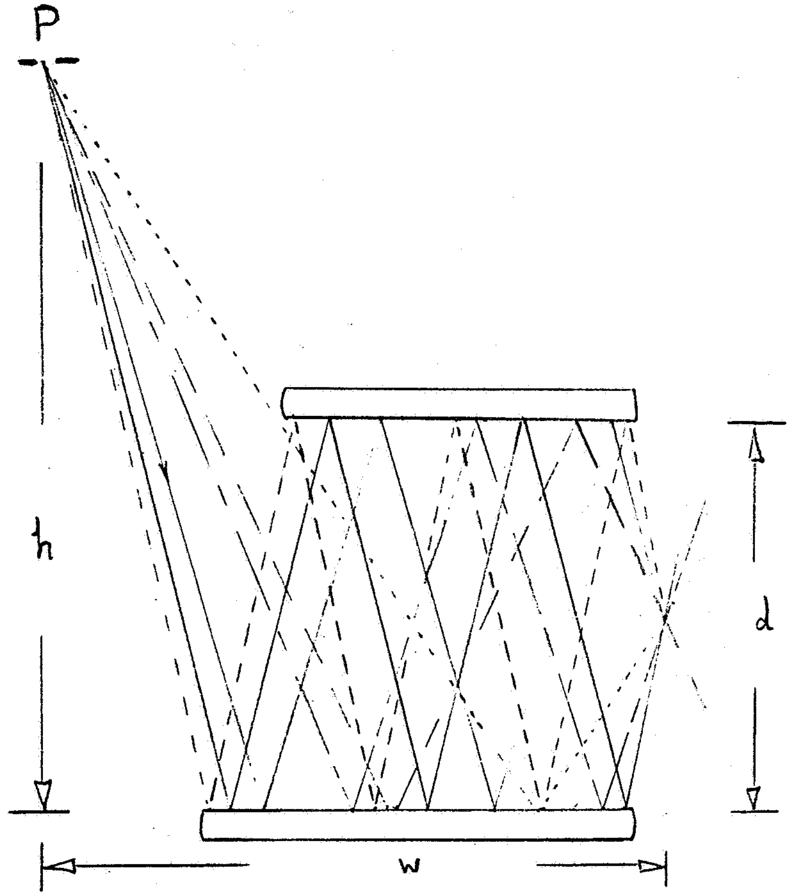


Figure 29. Cross-Section Through Interior of Orbiting Coating Laboratory, Showing Principal Components. Labeled items are defined in text.



$$S_1 = I_0(\lambda)\, R_1 \cos\theta_1$$
$$S_2 = I_0(\lambda)\, R_1 R_2 \cos^2\theta_2$$
$$S_3 = I_0(\lambda)\, R_1^2 R_2 \cos^3\theta_3$$
$$S_4 = I_0(\lambda)\, R_1^2 R_2^2 \cos^4\theta_4$$
$$S_5 = I_0(\lambda)\, R_1^3 R_2^2 \cos^5\theta_5$$

} Ratio gives R_2 (S_1, S_2)

} Ratio gives R_1 (S_2, S_3)

Figure 30. Reflectivity Measurement Scheme Using Reflected Sunlight from Both of Two Mirrors.

The benefits of multiple reflections are (1) to allow solving for the individual reflectivities, (2) to increase the sensitivity to changes in reflectivity, and (3) to allow sampling other portions of the mirror surfaces.

The reflected radiation is passed through the entrance aperture of a moveable objective grating monochromator, Q, whose plane of dispersion is close to the plane of incidence of the last reflection. The monochromator selects a spectral band of bandwidth $\Delta\lambda$ = 50-100 Å to be fed through an exit slit to a detector. The entrance aperture, exit slit and detector are all fixed inside the monochromator compartment, and the concave reflection grating rotates to scan the wavelength range. The entire monochromator assembly must have three degrees of freedom of motion: (1) pivoting through a range of $\sim 22^{\circ}$ to accept the different multiply-reflected rays, (2) swivelling through 180° to view each of the two mirrors, and (3) translation (perpendicular to the page in Figure 29) to sample different lateral positions on the test mirrors.

Each of the two optical coating chambers contain a multi-source rotatable wheel of aluminum-loaded heater filaments (R), a coating mask (S), motor drives (T) and a fast atom bombardment (FAB) neutral oxygen atom beam source (U) for the mirror cleaning (152, 196), all mounted on a base plate, Y. None of these devices requires a pressurized compartment to operate, so the coating compartments are fully vented to the outside. The items marked QC are temperature-controlled quartz crystal microbalances (TQCM's) for monitoring the coating thickness immediately next to each mirror. Additional monitors QM in other locations serve to test for evaporant deposition in other parts of the chamber away from the mirror.

Finally, in Figure 29, item V is a pressurized sphere of oxygen to supply the atom beam cleaning units, and item W is a microprocessor-based control unit and data processing unit. Item X in Figure 28 is a moveable door (containing the small aperture P) which can be swung open to illuminate a large fraction of both mirrors with one Sun, to test for solar-induced degradation. Small filters can also be conveniently located at location P. A thin fused silica filter here would allow separating the solar far-ultraviolet from the near-ultraviolet entering the system. Z is an aperture that can be opened on command to expose mirror 2 to the flux of high kinetic energy (5 eV) atomic oxygen from the orbital flow.

Not shown in Figure 29 are high-vacuum pressure monitors, sensitive over the range 10^{-10} torr to 10^{-5} torr, in each of the three compartments.

Figures 31 and 32 provide additional views of this arrangement. Figure 31 is a top view showing the projection of the two mirrors and the small aperture from the top, and showing a cross-section of one possible arrangement for baffles at the side and back walls. Figure 32 shows one of the interior solid separation walls, separating the optical measurement compartment from the lower coating chamber. Cables inside the hubs on which each mirror pivots carry power to controllable heaters for each mirror, so that substrate temperature can be controlled in experiments where this is desireable.

3.4.3 Coating Materials

What coating materials should an orbiting coating laboratory be prepared to evaluate? No single film material exists with a higher reflectivity over the broad far-ultraviolet region of interest to ultraviolet astronomy than pure aluminum. Hass and Hunter (59, 63) have shown that iridium overcoated with 265 Å of unoxidized aluminum gives a significant boost to the 500-800 Å reflectivity, over that of pure aluminum, while the reflectivity of this combination from λ = 900 Å to 1500 Å is not greatly reduced from that of pure aluminum. We have verified the results of Hass and Hunter using the program of Appendix B and the optical constants of Appendix C, finding an optimum aluminum thickness of ~280 Å to maximize a "figure of merit" for far-ultraviolet astronomy.

Unfortunately, iridium has a very high melting point and therefore would introduce difficulties including a much higher power requirement than aluminum. As there seems to be no compelling reason to apply iridium, tungsten, or the other refractory metals in space, we will not consider these further.

Silicon carbide has recently received much attention as a high-reflectivity material for the far ultraviolet and extreme ultraviolet (44, 77, 88, 108, 109, 135, 201-205). It has a reflectivity over the λ = 500-900 Å region (Figure 3) which compares well with the transition metals (202, 203) and it can form an extremely smooth surface (201). However, the process of deposition is complex and requires very high temperatures (204, 205). Although a fine mirror substrate material, SiC is not yet a viable coating material.

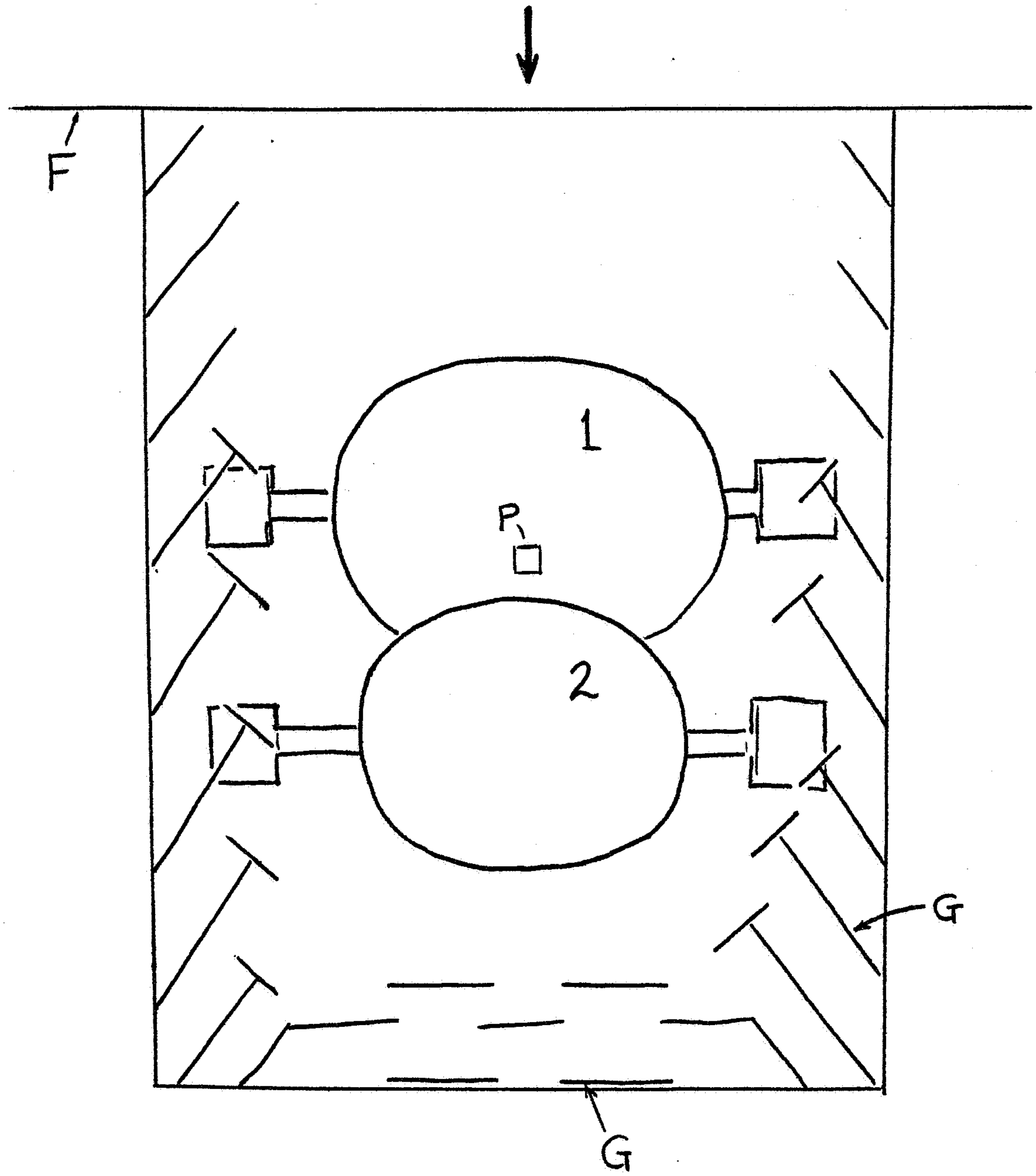


Figure 31. Top View of Orbital Coating Laboratory, Showing Internal Baffle Arrangement. The Flow of Atmospheric Gas is from the Top.

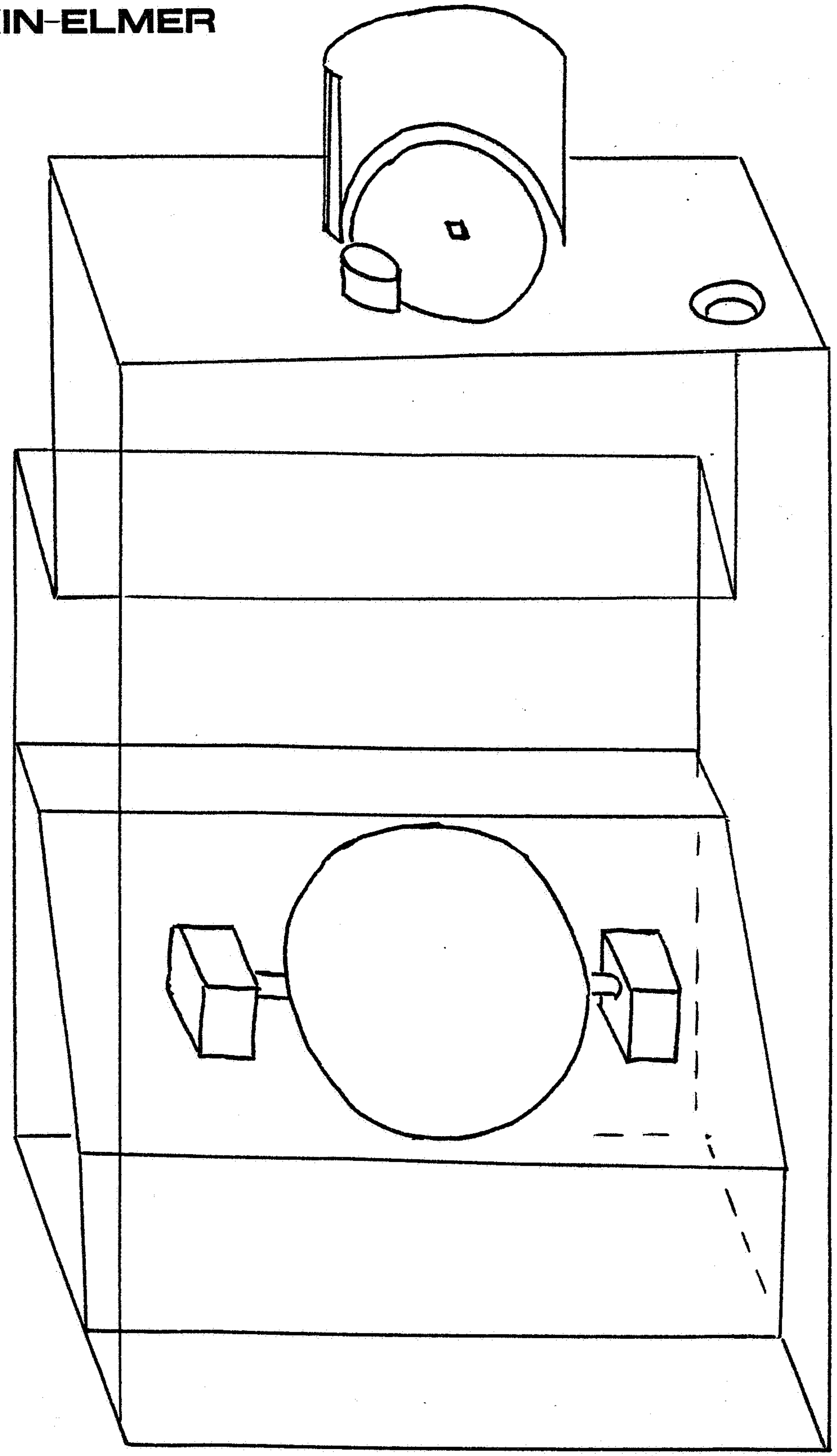


Figure 32. Isometric Sketch of Interior of Orbiting Coating Laboratory, Showing One of the Solid Walls Separating Interior Compartments, in which is Mounted One of the Rotatable Test Mirrors.

Is there a "magic" protective material which could be used, in a very thin film, over pure aluminum, which might retard the rate of aluminum oxidation somewhat without destroying the far ultraviolet reflectivity? We have not found such a material. Using the optical constants for lithium fluoride from Roessler and Walker (188) (Appendix C), we have found that even as little as 10 Å of LiF over aluminum spoils the "figure of merit" (page 43) by ~35%.

Because all fluorides and oxides will have similar deep absorption bands in the ultraviolet, such materials are unacceptable for protective coatings over aluminum.

A thin metallic protective overcoating, if one existed that did not decrease the net reflectivity of aluminum, would also be likely to diffuse together with the aluminum over a period of months, spoiling the advantage of the two-metal coating (62).

3.4.4 Evaporators

We have examined several options for depositing a clean, smooth aluminum coating of ~500 Å on mirrors of 16 to 19 inches in size: thermal evaporation, electron-beam evaporation, sputtering, and chemical reduction (2, 189).

Thermal evaporation, the process of heating a crucible or a helix of tungsten wire until the aluminum melts and evaporates, is a well-understood technique which does not require gravity to be effective (19, 21). The power requirements are not severe. Electron-beam evaporation in principle might be more efficient than thermal evaporation because an electron beam can heat and vaporize a small section of the material at a time. However, the rate of evaporation cannot be controlled as well as for thermal evaporation, heat loss from the cruicible forces the power requirement up, the resulting coated surfaces are often not as smooth, and the required high voltage is an additional risk (150).

Biassed sputtering involves ion bombardment of the target material. The disadvantage of this technique is that the coating thickness uniformity is never as good as for thermal evaporation. Sputtering works best with a small aperture (small solid angle) while a larger solid angle is required here. While conventional diode sputtering (involving two electrodes) is a very difficult technique to use for optical coating, a variation called plasma ion sputtering may be more viable.

However, it is our conclusion that thermal evaporation provides the highest reflectivity, the best smoothness, the best uniformity, and the highest degree of thickness control of the available techniques. Aluminum wets a hot tungsten ribbon very effectively and provides the opportunity for either slow or fast evaporation.

How often can a tungsten wire be re-wetted with fresh aluminum and thereby re-used? Eventually the aluminum and tungsten will begin to alloy and the tungsten becomes brittle. The probable life of a tungsten coil is only 2 or 3 uses. Therefore we recommend a turntable of ~16 pre-loaded evaporators, each consisting of multistrand helical tungsten coils, and each of which would be used only once. As the turntable is rotated, a new tungsten filament is brought into position under a conical "coating gun" and is connected to the power supply.

Laboratory experimentation with optimizing the design of a coating gun is needed. A few concepts are sketched in Figure 33. If aluminum vapor were to specularly reflect from the walls of a coating gun (which it does not), then the "Winston cone" (compound parabolic concentrator, Figure 33(a) might provide the basis for a good coating gun design, as this figure provides a uniform beam which is spread uniformly over a desired solid angle with no rays outside this solid angle (190, 191, 192). Figure 33(b) shows a large solid angle conical gun with internal masks to define the area covered. Figure 33(c) shows a straight "gun barrel" design that might be appropriate for coating mirrors in-situ in a space telescope, when the coating guns could be placed at a large distance from the mirror. It is known that better smoothness and higher reflectivity (higher packing density of the coated material) are achieved when the evaporated material is incident on the substrate at near-normal incidence.

3.4.5 Stray Light Control

A major concern of those who have considered coating telescope mirrors in place in space has been whether or not the stray light characteristics of the telescope can be maintained after the telescope barrel has been filled with aluminum vapor. Inter-beam collisions of aluminum atoms in the vapor beam can lead to a diffuse distribution of a small fraction of the evaporant beam. In solar telescopes where the flux of visible light is orders of magnitude stronger than the flux of EUV radiation, and in celestial

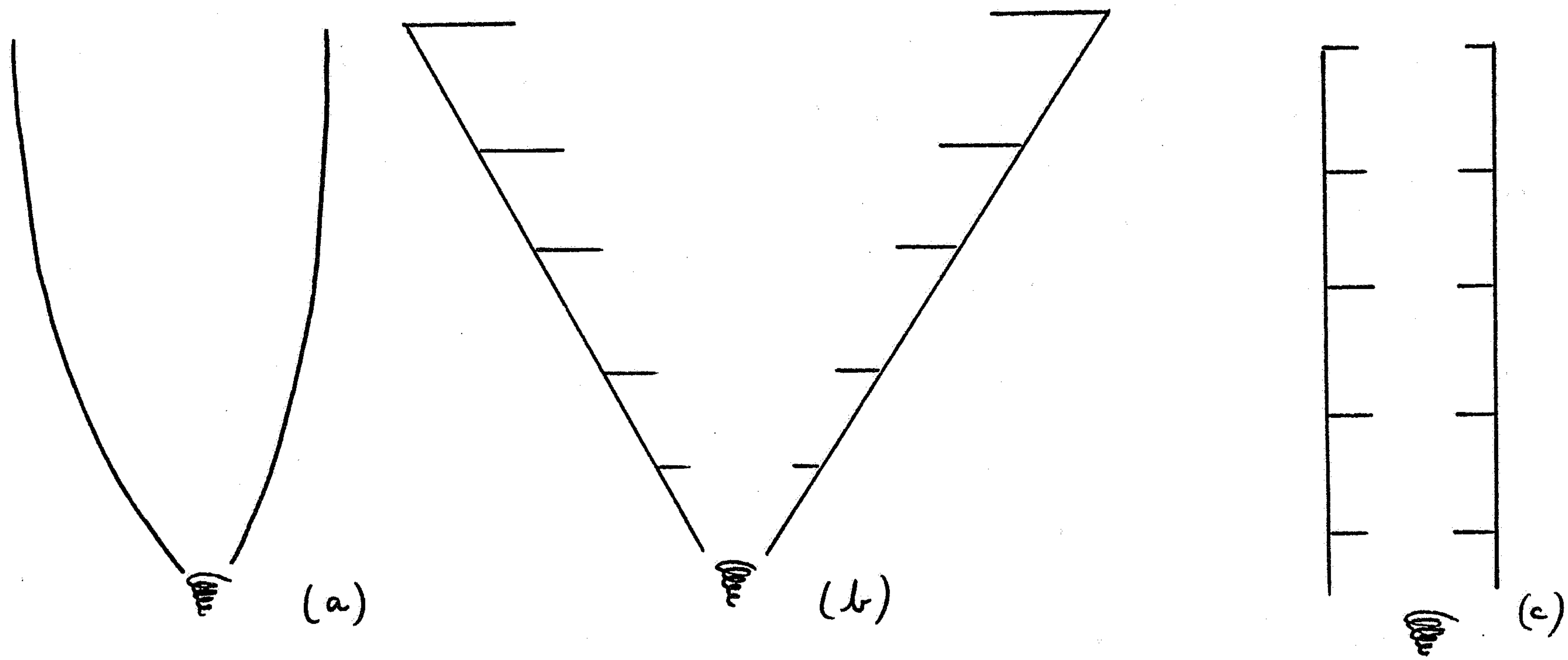


Figure 33. Three Concepts for the Design of an Evaporator Collimator. (a) Compound Parabolic Concentrator, (b) Large Solid Angle Cone with Angle-Defining Baffles, (c) Straight "Gun Barrel" with Internal Baffles.

astronomy, where 26th magnitude stars are to be studied in the presence of a full moon 30° away in the sky, the control of stray light requires painstaking care in design.

This subject can certainly be studied by ground laboratory experiments. Information available today indicates that , at pressures $\lesssim 10^{-6}$ torr, the sharpness of the edge of a shadow formed by a mask in a coating chamber is very fine. But we are not aware of experiments that have been aimed at characterizing the amount of scattered vapor or at optimizing the design of a coating system to minimize the amount of stray vapor at large angles from the desired direction.

Aluminum coating in ground-based coating chambers is usually applied at a high deposition rate to minimize the amount of oxidation (92, 63, 145). It may be possible to achieve a significantly better and more oxygen -free vacuum in a space coating facility and therefore use much lower deposition rates. In this case, the inter-beam collisions are greatly reduced and the amount of stray vapor expected is much less.

It is possible that a small amount of stray aluminum deposited on black baffles does very little harm in terms of scattered ultraviolet light, provided that the black surfaces are rough. The roughness of most black surfaces ensures that any deposited aluminum will be non-continuous and that any scattered light will still be trapped by the geometry of the rough surface (150).

In the design of an orbital coating laboratory, TQCM's should be arranged to monitor the amount of stray aluminum received during the evaporation process in directions well away from the mirror being coated.

The control of stray light in the actual reflectometer arrangement suggested in Figure 29 must also be considered. Since the Sun is much brighter than any other sources of possible light entering the optical measurement chamber, L, baffles like those sketched in Figures 28 and 31 should be sufficient protection for this chamber. The location most sensitive to stray light in reflectivity measurements is within the monochromator, Q, where a particular wavelength interval is fed to a detector. Therefore the entire monochromator is enclosed in a light-tight box which accepts only light from the appropriate direction.

3.4.6 Reflectometer

The method of measuring reflectivity suggested in Section 3.4.2 and sketched in Figure 29 is to allow unfocused parallel sunlight from a small aperture to reflect from the one or two test mirrors and enter a concave objective reflection grating monochromator. The suggested configuration is a pseudo-Rowland circle configuration in which the grating is rocked to scan in wavelength but the total included angle, $\alpha+\beta$, is held constant (Figure 34).

The entrance aperture to the monochromator is roughly the same size as the entrance aperture into the optical measurement chamber. With a grating of 600 lines/mm and a total included angle $\alpha+\beta = 35^{o}$ and with a radius of curvature of 200 mm, the range of wavelengths 440 Å to 2200 Å can be scanned by rotating the grating through 10^{o}, with a dispersion of ~35 Å/mm. A fixed exit slit of ~1.5 mm width is placed ahead of the detector, which could be a National Bureau of Standards windowless Al_2O_3 far ultraviolet photodiode (193, 194). This detector serves well from the shortest wavelengths to Lyman-α (1216 Å). Longward of Lyman-α, the efficiency of this detector falls off and an alternate detector might be required.

The only moving part within the monochromator is the 10^{o} scan motion of the grating, controlled by a sealed DC stepper motor. However, three degrees of freedom of motion are required for the entire monochromator package: (1) rotation through a range of ~ 22^{o} to change the line of sight, (2) 180^{o} inversion to face the other test mirror, and (3) a lateral motion to scan different portions of the test mirrors. These motions are indicated schematically in Figure 35 and are also controlled by sealed DC stepper motors.

3.4.7 Plasma Discharge Cleaning

The usual means of preparing a substrate for optical coating is to establish a glow discharge in the vicinity of the optic by allowing a pressure of ~50 microns Hg (0.05 torr) of argon or oxygen (49, 51, 57, 91, 153, 195). This procedure apparently oxidizes and vaporizes all oxidizable contaminants on the mirror surface. See Figures 15-17. The effect is to improve the adhesion of the coating and increase the reflectivity of the resultant coated mirror.

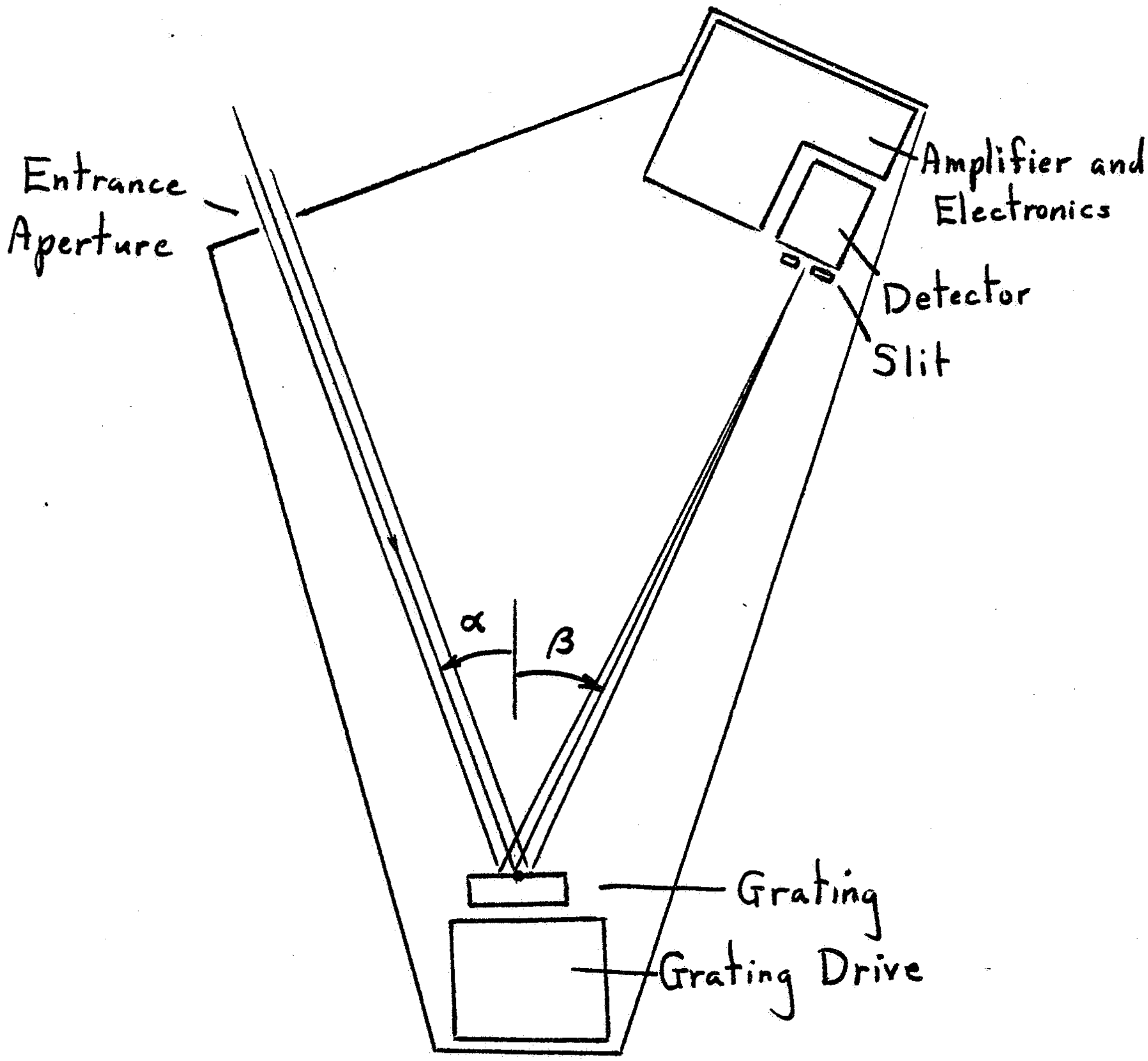


Figure 34. Schematic Diagram of Monochromator for Measuring Reflectivity. Parallel Sunlight from the Flat Mirrors Enters the Enclosure. The Concave Grating is Rocked about an Axis Perpendicular to the Page to Scan Wavelength.

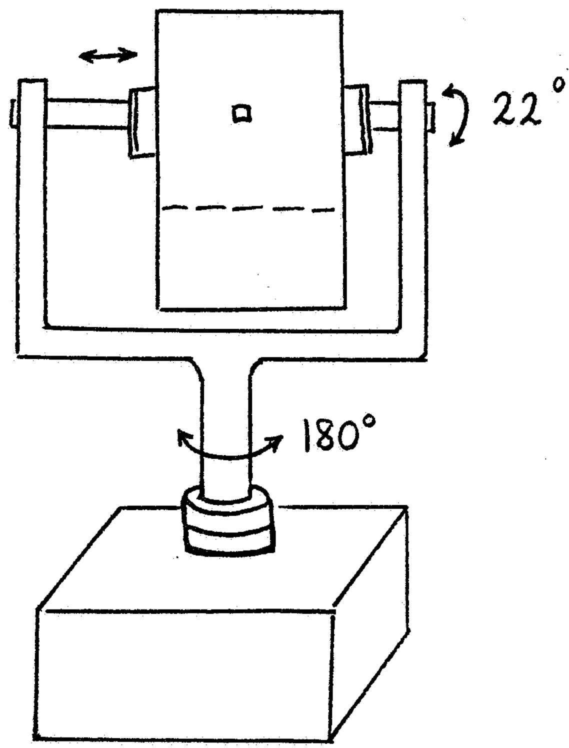


Figure 35. Top View of the Monochromator Package Showing the Desired Three Degrees of Motion: (1) Rotation through ∿ 22° to Change Line of Sight, (2) 180° Reversal, to View Other Mirror, (3) Sideways Motion to Change Strip of Mirror being Tested.

However, the need to pressurize the mirror compartment and the somewhat indiscriminant nature of the plasma cleaning process, which can attack other surfaces near the mirror, makes this technique unattractive for use in a space telescope.

An alternative to the plasma discharge is the more highly controlled, high vacuum, technique of an argon or oxygen ion gun, defocused so as to spread the ion beam over an area on the mirror surface, which is then scanned over the entire mirror area, and removes contaminants by a sputtering mechanism. But again the presence of an intense level of ions may be incompatible with a sophisticated telescope environment.

The cleaning technique which possibly offers the best advantage is the fast atom bombardment (FAB) gun technique (152, 196) in which a beam of high kinetic energy energetic neutral atoms of a chosen gas is directed at a target to be cleaned. This technique is used in the semiconductor industry where a concern for ion beam-induced substrate ion migration argues against ion glow discharge or ion gun techniques. In the FAB technique, atoms are ionized, accelerated and neutralized as they are emitted by the atom gun. The device is compact and uses only DC voltages. This device could be made to scan over an entire mirror surface area just as an ion gun.

Oxygen is a preferred material for the FAB beam as its reactivity provides extra cleaning power over an argon beam. The required voltage is 500-2000 volts; the required current is 5 to 50 milliamperes. Therefore, the required power is only 2.5 to 100 watts (152).

All of the above cleaning techniques remove only oxidizable or loosely-bound chemicals from a mirror surface. An aluminum oxide layer is very resistant to attack and is not removed by any of these techniques. Our approach here is to let the Al_2O_3 layer remain and clean this surface for subsequent aluminization.

3.4.8 Atmospheric Oxygen Cleaning

An interesting question is whether the high velocity (7.6 km sec^{-1}; 4.8 electron volts) atomic oxygen flow streaming past a telescope in low earth orbit can be put to use in lieu of the above neutral atomic beam technique described above. This concept can be easily tested in the orbital coating laboratory configuration described here. When the small door shown (Z) in Figure 29 on the forward side of the structure is opened to the atmospheric flow, a beam of predominantly oxygen atoms is directed against one of the mirrors. The ability of the atmosphere itself to remove a polymerized organic film has in essence already been demonstrated by the materials studies carried out on the early Shuttle flights (Section 2.3).

3.4.9 Liquid Cleaning

Cleaning telescope mirrors by means of liquids seems quite incompatible with the in-situ re-coating of telescope mirrors. The absence of both gravity and air pressure makes the handling of liquids very awkward, and we will therefore not consider the use of liquids in an orbital coating laboratory.

Liquid cleaning might possibly find a use in a separate dedicated orbital coating facility, in which a raw mirror blank is handled in a sealed container (2,3).

The one type of cleaning in which liquids might be desireable is the removal of dust particles. Clearly the need for a dust-free substrate is just as important when a mirror is re-coated in space as when it is originally coated in a ground-based coating chamber. How may dust be removed in an orbiting telescope environment? This is a question that needs to be further studied. Anti-static sources such as ultraviolet light sources, piezoelectric crystals, alpha particle emitters may be considered. However, the best baseline plan would seem to be to avoid carrying dust into orbit at the beginning.

3.4.10 Power Supplies

Although the power requirements for evaporating aluminum in a space telescope may have been one factor deterring investigators from attempting optical coating in orbit in the past, the power is no longer a concern by the standards of todays' spacecraft and future space telescopes and space platforms. Since we are considering, for a space telescope, re-coating operations at very infrequent intervals (~6 months or more), the average power is of course negligible.

For the Orbital Coating Laboratory, the power estimate during each coating operation is 30 to 150 watts for a maximum of 2.5 minutes. The maximum current and voltage might be ~30 amperes of unregulated power at 5 volts. The precision of the coating thickness deposited is determined by the open and close timing of a mask, and not by the control of power to the tungsten filaments.

3.4.11 Pointing System

The requirements for pointing the Orbital Coating Laboratory with respect to the flight vector and the Sun line have been discussed in the introductory paragraphs of section 3.4. The need to avoid a high flux of atmospheric atomic oxygen into the laboratory requires that the "optical axis" of the laboratory lie within the 55°-wide cone with respect to the instantaneous flight vector shown in Figure 36. Reflectivity measurements can only be made when the Sun is in the figure of revolution generated by this cone (that is, a 55°-wide band around the sky). A high inclination orbit can satisfy this requirement for a larger fraction of the time.

Of course, the celestial co-ordinate of the flight vector is constantly changing. Therefore, the Sun may not be visible by the reflectometer for more than ~ 15 minutes at a time. The pointing of the laboratory is controlled to track the Sun during reflectometer measurements (that is, to control the location of the spots illuminated on the two test mirrors). At other times, the pointing is controlled to track the flight vector. All of this pointing control is managed by the Orbital Coating Laboratory's microprocessor. When the Sun is in view, the exact solar aspect is measured by a 2-dimensional imaging solar aspect telescope, co-aligned with the laboratory's "optical axis", which has a field of view of $\sim 55^{\circ}$ width.

Since a set of reflectivity measurements covering the entire wavelength range 400 Å to 2200 Å takes only 10 minutes, the finite duration of the solar exposure is not a problem.

The (θ,ϕ) tilt of the laboratory with respect to the Sun is controlled by the 2-axis gimbal arrangement shown in Figure 28. The pointing of the "windward" side of the laboratory with respect to the flight vector is controlled by the orientation of the vehicle carrying the laboratory, in this concept.

3.5 ASTRONAUT INVOLVEMENT

The concept for an Orbital Coating Laboratory that we have described is for a remotely-controlled laboratory in which scientists or payload specialists control the

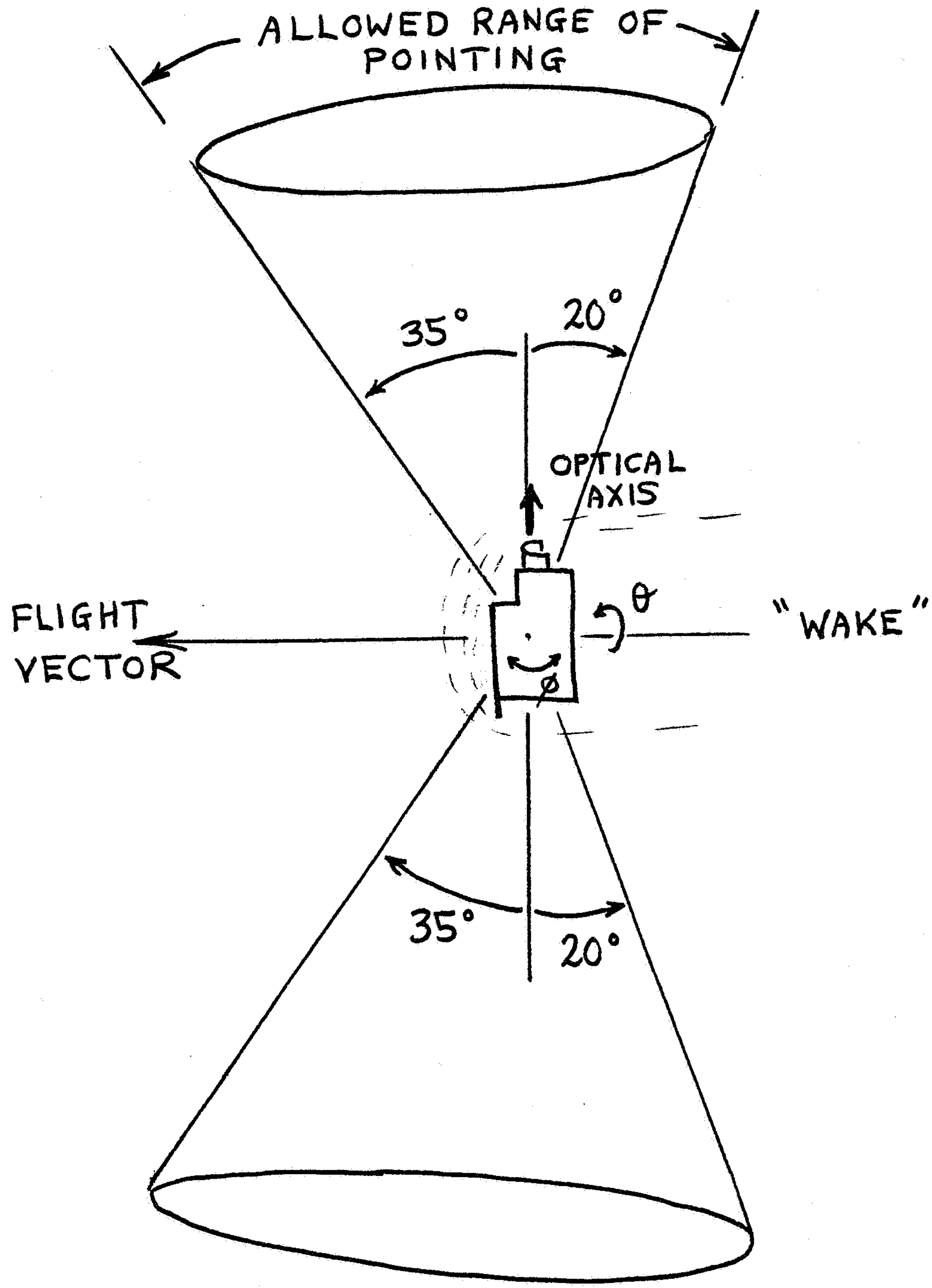


Figure 36. Constraint on Pointing of Orbital Laboratory Due to Flux of Atmospheric Atomic Oxygen. The Optical Axis of the Laboratory can Point into the Figure of Revolution Generated by a 55°-wide Cone. Reflectivity Measurements can be Made Only when the Sun is Within this Allowed Range.

experiments and receive the data in near-real time. The role of astronauts is largely in extra-vehicular activity (EVA) servicing. The most important need for astronaut involvement is in changing the two evaporant source disks, which are accessible through service doors just visible in Figure 28. Provision for these replaceable units will be useful for testing new coating materials or changing the quantity of evaporant loaded into the laboratory.

Astronauts might also be required to deploy or modify the arrangement of a large external molecular shield, which could serve to reduce still further the oxygen atom flux in the vicinity of the laboratory in low Earth orbit (166, 174, 175, 177).

SECTION 4

EXPERIMENTS WITH AN ORBITAL COATING LABORATORY

Assuming that an optical coating laboratory in space similar to the concept described in the preceding sections is available, we now will discuss some of the demonstrations and experiments that can be carried out. In this section we will briefly describe the procedures to be followed for each experiment.

4.1 RATE OF ALUMINUM OXIDATION

A key experiment or series of experiments is the measurement of the rate of degradation of far ultraviolet reflectivity, as a function of wavelength and as a function of environmental conditions.

A coating and reflectivity measurement is typically carried out as follows, assuming a clean aluminum or oxidized aluminum substrate is available:

A. Coating Procedure

1. Position laboratory to optimize "molecular shield" geometry. Sun aperture closed or pointed away from Sun.
2. Rotate aluminum source wheel to position source in evaporation position.
3. Rotate one or both of desired mirror test surfaces toward Coating Chambers.
4. Set substrate temperature to desired temperature.
5. Measure status of all thermistors and TQCM's.
6. Pre-heat tungsten filament to outgas source, with mask over source gun.
7. Full evaporation power to filament.

8. Open and close mask for set period of time (typically 30 seconds).
9. Filament power off.
10. Measurement status of all thermistors and TQCM's.
11. Substrate heater power run-down.
12. Rotate freshly-coated mirror surface into optical measurement compartment (Sun aperture closed or pointed away from Sun).
13. Allow entire laboratory to outgas in optimum "molecular shield" geometry for 30 minutes - 12 hours (depending on orbit).

B. Reflectivity Measurement Procedure

1. Open Sun aperture.
2. Fine-tune the angular position of mirrors 1 and 2 if desired.
3. Point laboratory optical axis in (θ,ϕ) to the "R_1", position (see Figure 30).
4. Use solar aspect camera to "lock-on" to this orientation of laboratory.
5. Position monochromator to the "R_1" position.
6. Scan grating angle to record once-reflected solar spectrum.
7. Re-point laboratory optical axis to the "R_1R_2" position.
8. Use solar aspect camera to lock-on to this orientation.
9. Position monochromator to the "R_1R_2" position.
10. Scan grating to record twice-reflected solar spectrum.
11. Compute reflectivities. Compare to previous measurements.
12. Proceed to $R_1^2R_2$, $R_1^2R_2^2$ etc. positions if desired.

The coating procedure is estimated to require 5 minutes. The above reflectivity measurements require about 6 minutes. Much of the above procedures is automatically controlled by the laboratory microprocessor to minimize the elapsed time.

The measurement of coating lifetime is then made by repeating the above reflectivity measurements at frequent intervals. The laboratory microprocessor records the pressure in the optical measurement compartment versus time and keeps a running measure of the ambient gas exposure age in Langmuirs (torr-seconds). The microprocessor is also, at all times, keeping a running tally of the Sun exposure of each area element of all four optical test surfaces.

This sequence of optical coating with aluminum followed by reflectivity measurements is the kernel of the in-orbit aluminizing demonstration that is one of the main purposes of this orbital coating laboratory .

4.2 SHUTTLE/SPACE STATION RAM FLOW EFFECTS

Another class of experiments that can be carried out with an Orbital Coating Laboratory is the examination of the effects of the highly asymmetric (non-isotropic) distribution of flux of atmospheric gas. What reduction in pressure can actually be achieved when the laboratory is shielded from the direct flow? How does the net pressure in the optical measurement compartment depend on the attitude of the laboratory with respect to the flight vector? The goal of these studies is to aid in the design of future bare aluminum telescopes. What latitude in pointing direction will such telescopes have, to avoid the risk of mirror oxidation?

Two methods are available to answer the above question. One method is simply to measure pressure by an auxilliary ionization gauge located in the optical measurement compartment. This gauge would have a range of $\sim 10^{-4}$ to 10^{-10} torr. As different laboratory attitudes are samples (and altitudes as well, if this variable is available), the laboratory can be characterized in terms of its ability to shield the region inside from molecular flow coming from various directions. The second method, which could be used for net pressures in the range of $\sim 10^{-10}$ to 10^{-13} torr range, is to use the rate of oxidation of aluminum as a highly sensitive measure of the amount of oxygen reaching the mirrors.

These experiments are intended to provide a real experimental check of the theoretical calculations of gas density in a shielded geometry (174, 175). At the same time, these measurements will aid in the characterization of the oxygen component of the atmosphere in the altitude range 400-1000 km.

Experiments in which the forward side aperture door (facing the atmospheric flow) is opened to allow the 5 eV atomic oxygen beam to directly irradiate a freshly aluminized mirror will allow testing the linearity condition (that a high flux for a short time produces the same oxidation as a low flux for a long time). The atmospheric atomic beam also provides an opportunity for studying basic surface physics questions that cannot easily be studied in ground laboratories. Does irradiation of pure aluminum by 5 eV oxygen atoms lead only to oxidation, or is material actually removed by sputtering? Examining the scatter performance of the test mirrors may help to answer this question. (See Section 4.4).

4.3 RATE OF PHOTOPOLYMERIZATION

A secondary purpose of the Orbital Coating Laboratory is to characterize the rate of photopolymerization when sunlight is incident on a freshly-coated aluminum mirror in the presence of hydrocarbon gases. In a sense, this surface reaction is the opposite of oxidation, as it can occur in the complete absence of oxygen, and in fact may be cured by the addition of oxygen. This reaction is of interest for estimating the lifetime of a solar-pointed ultraviolet telescope using bare aluminum-coated mirrors. The photopolymerization reaction has been observed in solar space telescopes and in ground laboratory experiments and can be visualized as the formation of long-chain hydrocarbons formed on a mirror surface in the presence of both organic gases and intense ionizing radiation (16, 61, 65, 66, 69, 75, 110, 130, 72, 17, 49, 50, 56, 115). However, it is not known what role, if any, the substrate material plays in catalyzing this reaction.

Two experiments can be conducted. One experiment is to test for the build-up of a polymer film due to the natural outgassing of the laboratory and surrounding hardware. The second experiment is to introduce a known amount of a known compound (say, propane or butane) and thus provide a much better controlled experiment. The procedure might go as follows:

1. Orient the laboratory to maximize "molecular shield" effect.
2. Coat both mirrors according to procedure on Page 78.
3. Measure reflectivity versus wavelength according to the procedure on Page 79.
4. Point the laboratory optical axis to the Sun.

5. Open the large aperture door to illuminate a maximum area of both mirrors.
6. Expose mirrors for ~1 hour of integrated solar exposure.
7. Switch to small solar aperture.
8. Measure reflectivity versus λ.
9. Open large solar aperture door to the Sun.
10. Introduce a small flow, say 10^{-1} standard cm^3 per minute, of hydrocarbon gas from storage bottle.
11. Monitor temperature of substrate versus time.
12. Measure reflectivity every ~4 hours.

If degradation in reflectivity is observed, then one must determine whether it is due to oxidation or to the deposition of an absorbing contaminant. One test is the particular shape of the degraded reflectivity curve, which tends to be quite different from that of Al_2O_3. Figures 37 (16) and 38 (130) show examples of the short-wavelength degradation of two solar-pointed space telescopes. Note that the loss of throughput at λ = 1200 Å is a remarkable 3 to 4 orders of magnitude.

The second test of the source of an observed degradation is to put the mirror(s) in question through the atom beam cleaning procedure described on Page 91. If the reflectivity partially recovers or converts to the Al_2O_3 curve, then the original degradation was not simply due to oxidiation.

Figure 39 shows the effect on reflectivity at λ = 1236 Å of thin films of various common oils found in manufacturing areas (168). Figure 40 shows that the equilibrium thickness of one of these oils (without polymerization) is a strong function of substrate temperature, and may approach a monolayer at a sufficiently high temperature (168).

4.4 RE-ALUMINIZING DEMONSTRATION

The purpose of this experiment is to demonstrate the repetitive process of cleaning and re-aluminizing a mirror and to measure the cumulative degradation, if any, that occurs when this re-coating process is repeated several times. This experiment is a key one to the coating-in-space concept. Although this experiment can (and should) be first

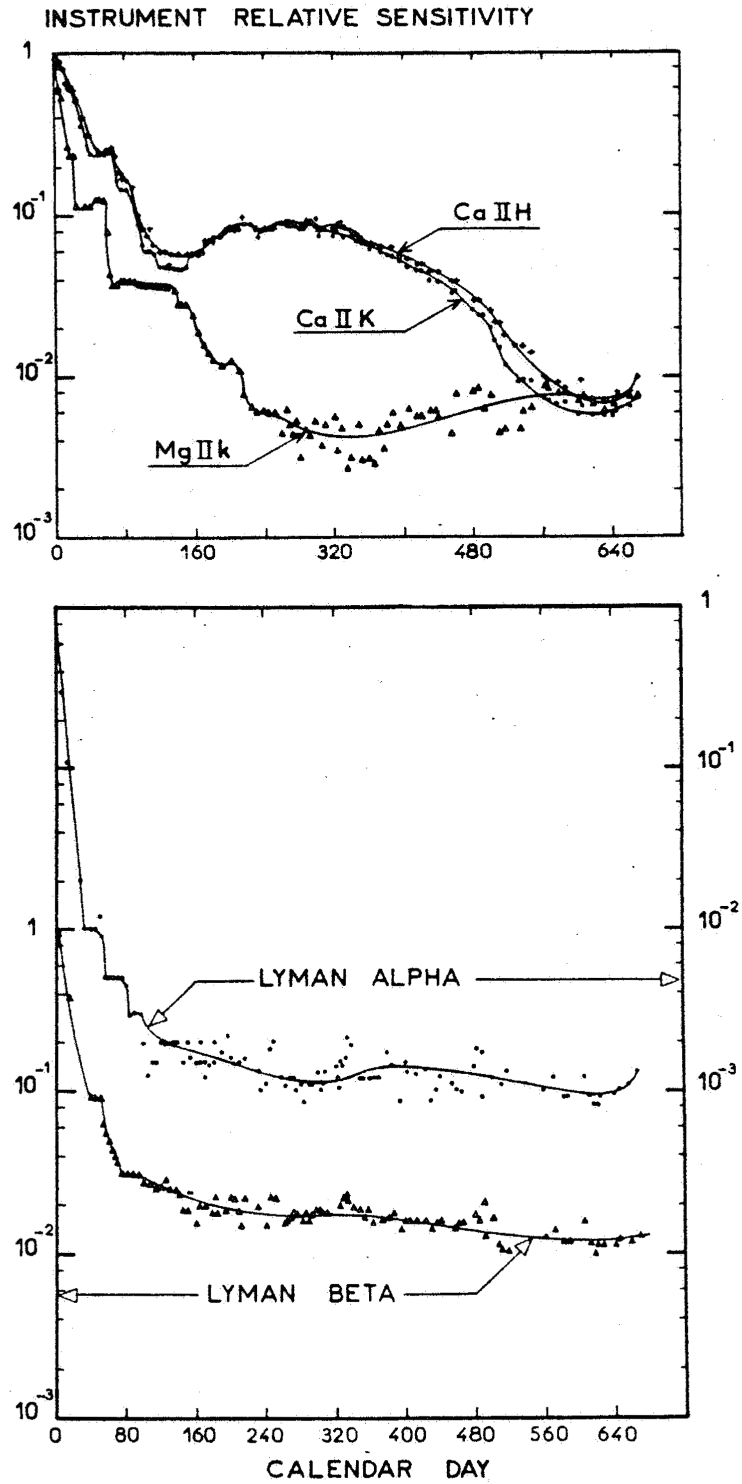


Figure 37. Variations of the Sensitivity of the Solar Pointed LPSP (Laboratoire de Physique Stellaire et Planetaire) Instrument on OSO-8 Versus Time After Launch in Days. Lyman Beta = 1025Å Lyman Alpha = 1216Å Mg II = 2800Å, Ca II = 3950Å. At least part of this degradation is attributed to Molecular Contamination (16).

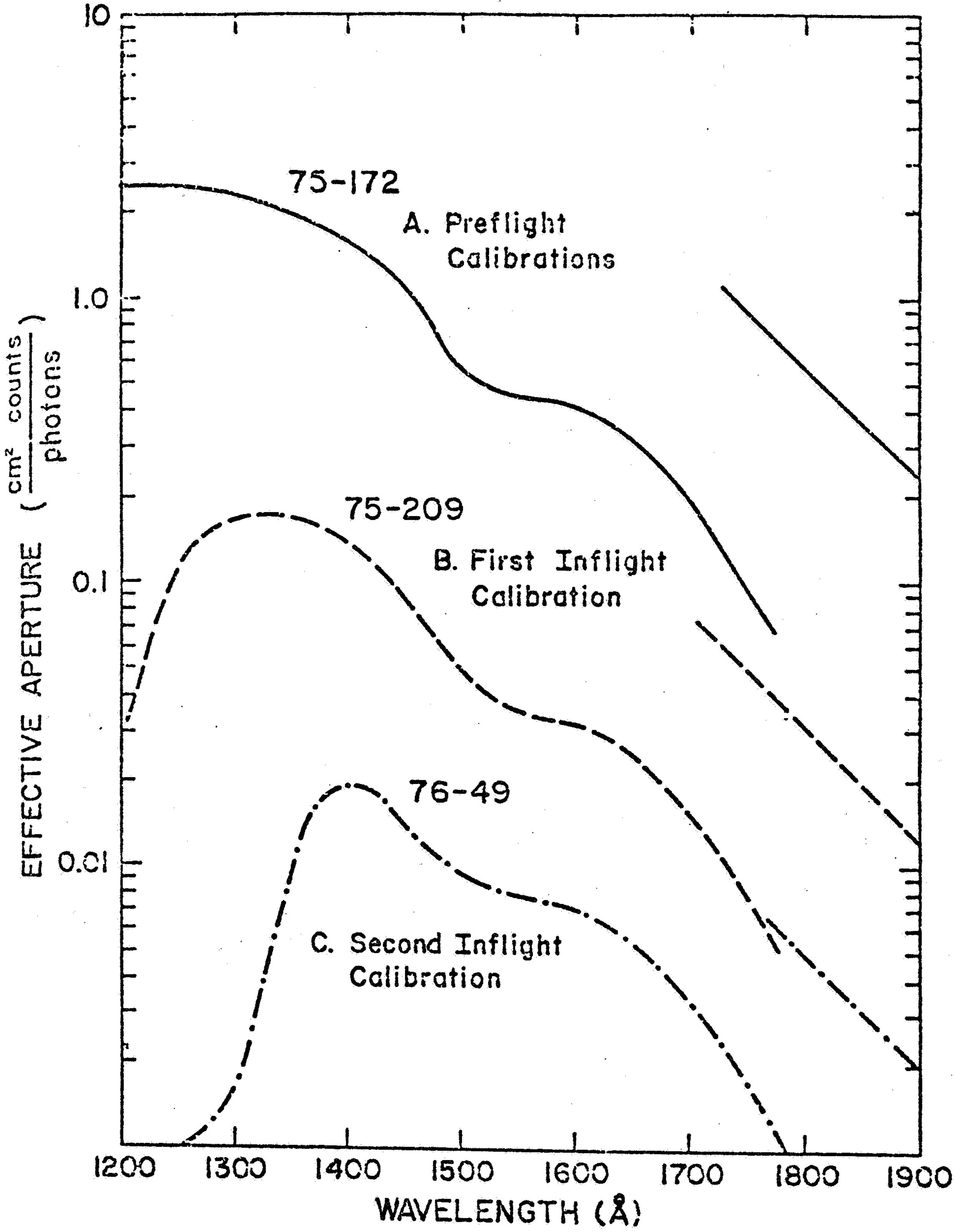


Figure 38. Deterioration of the Sensitivity of the University of Colorado Solar-Pointed Telescope on OSO-8 with Time. The date 75-172 is Day 172 of 1975. Part of this degradation is assumed to be due to the build-up of molecular contaminants on the telescope mirrors (130).

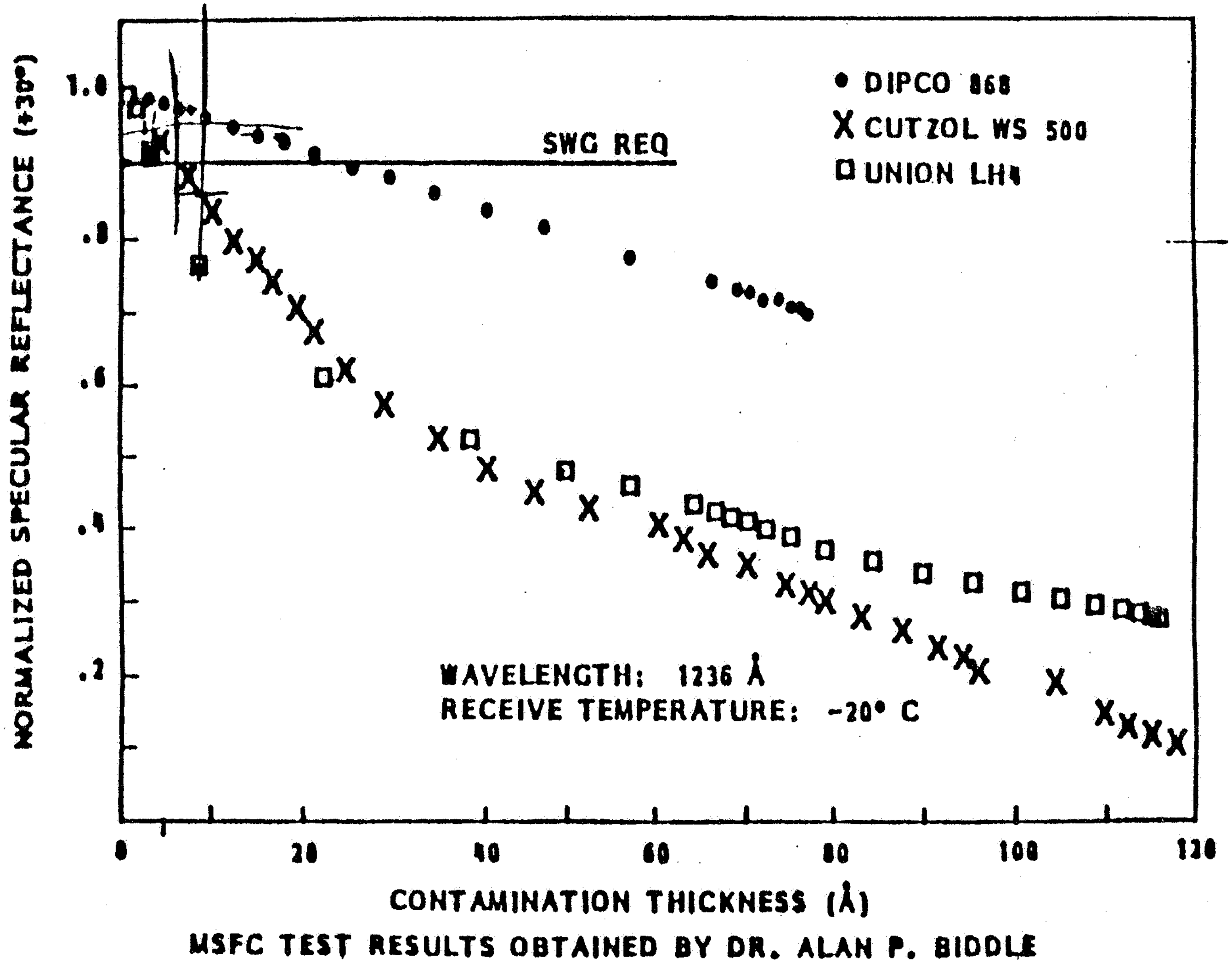


Figure 39. The effect on Reflectivity at λ 1236Å of Thin Films of Various Common Oils Found in Manufacturing Areas (168).

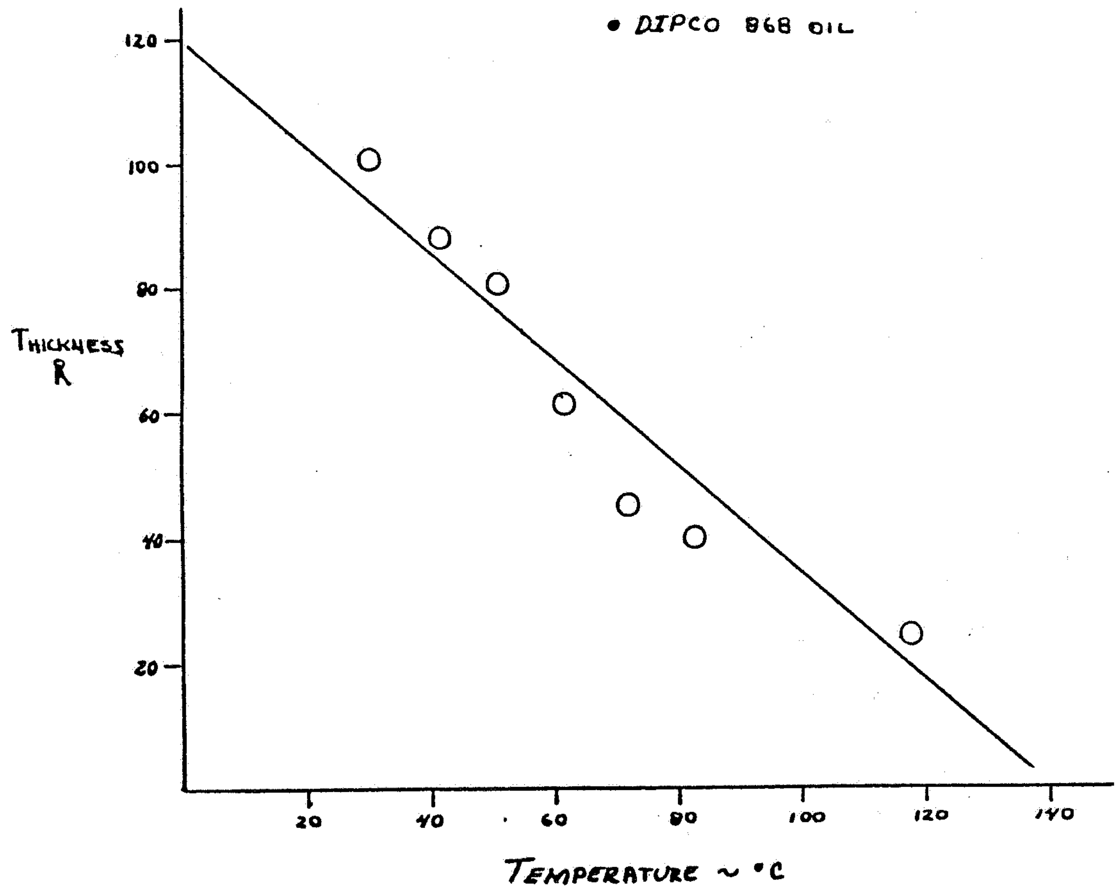


Figure 40. Thin Film Equilibrium Thickness Versus Temperature for Dipco 868 Oil (168).

conducted in a ground laboratory, the impurity-free, ultra-high vacuum of the space laboratory could conceivably lead to quite different results.

The procedure to be followed is a simple combination of the cleaning, coating, and reflectivity measurement procedures described elsewhere in this chapter. If the orbiting laboratory is in a sufficiently high orbit that oxygen is very sparse, the oxidation may be accelerated by tipping the laboratory vents toward the flight vector or by opening the "oxygen beam door" on the forward wall (Figure 29).

Suppose that 495 Å of fresh aluminum are deposited with each coating, of which 45 Å oxidizes to Al_2O_3, leaving a sandwich of 450 Å of aluminum and 45 Å of Al_2O_3. We have run the "OPTCOAT" program of Appendix B, using optical constants for Al_2O_3 from Reference 170 and for aluminum from Reference 169, to predict the net effect of this sequence of layers on the reflectivity of a mirror. The surprising result is that this multilayer actually has a normal-incidence reflectivity "figure of merit" for far ultraviolet astronomy which is slightly higher than that of pure aluminum. The data are included here on the following pages (Table 3).

One important test for the re-coating concept is whether the level of scatter from the mirror surface signifgicantly worsens after a few re-coatings. Scattered light can be measured by the apparatus described here as follows:

As seen in Figure 41, the aperture to the optical measurement compartment of the laboratory is slighty smaller than the aperture to the monochromator. The pool of light with little or no scattered light falls within the aperture of the monochromator and is analyzed. But with larger amounts of scattering the pool of light reaching the monochromator is spread over a larger area. This is tested by tilting one of the mirrors (or the entire line of sight) slightly so as to displace the monochromator entrance aperture with respect to the reflected beam of light (dashed lines in Figure 41). A non-zero measurement here is a measure of the scattered light.

4.5 ATOM BEAM CLEANING DEMONSTRATION

In Section 3.4.7, we described one technique for an high velocity impact oxidation reaction cleaning which does not require pressurizing the compartment containing the mirror. The procedure for this atom beam cleaning demonstration is as follows:

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Table 3

Reflectivity of Aluminum Over a Al_2O_3 Multilayer Sandwich

ANGLE = 0.0 DEGREES

WAVELENGTH MICRONS	REFL AVERAGE	TRANS AVERAGE	ABSORP AVERAGE	REFL S-POL	TRANS S-POL	ABSORP S-POL	REFL P-POL
0.0113000	0.0156	22.2305	77.7539	0.0156	22.2305	77.7539	0.0156
0.0493920	1.5753	26.5932	71.8315	1.5753	26.5932	71.8315	1.5753
0.0506040	2.6417	24.5871	72.7712	2.6417	24.5871	72.7712	2.6417
0.0516380	3.9893	21.7514	74.2593	3.9893	21.7514	74.2593	3.9893
0.0523100	3.6181	21.3452	75.0367	3.6181	21.3452	75.0367	3.6181
0.0525840	3.8119	20.9552	75.2329	3.8119	20.9552	75.2329	3.8119
0.0528330	4.4666	20.0975	75.4359	4.4666	20.0975	75.4359	4.4666
0.0530130	4.7370	19.7835	75.4795	4.7370	19.7835	75.4795	4.7370
0.0532410	5.2373	19.2906	75.4721	5.2373	19.2906	75.4721	5.2373
0.0534710	5.6553	18.9141	75.4306	5.6553	18.9141	75.4306	5.6553
0.0537870	5.9099	18.3895	75.7006	5.9099	18.3895	75.7006	5.9099
0.0538040	6.0845	18.5424	75.3731	6.0845	18.5424	75.3731	6.0845
0.0540220	6.3171	18.3878	75.2951	6.3171	18.3878	75.2951	6.3171
0.0541900	6.6482	18.2099	75.1419	6.6482	18.2099	75.1419	6.6482
0.0543770	7.1428	17.9146	74.9426	7.1428	17.9146	74.9426	7.1428
0.0546080	8.3754	17.2826	74.3419	8.3754	17.2826	74.3419	8.3754
0.0552480	9.5483	16.7334	73.7183	9.5483	16.7334	73.7183	9.5483
0.0555470	10.8026	16.2026	72.9948	10.8026	16.2026	72.9948	10.8026
0.0560550	11.8286	15.6317	72.5397	11.8286	15.6317	72.5397	11.8286
0.0565720	12.8195	15.1784	72.0020	12.8195	15.1784	72.0020	12.8195
0.0571980	13.6338	14.8113	71.5549	13.6338	14.8113	71.5549	13.6338
0.0579350	14.2329	14.5282	71.2389	14.2329	14.5282	71.2389	14.2329
0.0590390	14.6698	14.2131	71.1171	14.6698	14.2131	71.1171	14.6698
0.0604780	12.9806	14.4851	72.5342	12.9806	14.4851	72.5342	12.9806
0.0619900	8.7368	14.7716	76.4916	8.7368	14.7716	76.4916	8.7368
0.0635790	3.9076	14.9307	81.1617	3.9076	14.9307	81.1617	3.9076
0.0652530	1.0472	13.5667	85.3861	1.0472	13.5667	85.3861	1.0472
0.0666560	2.4102	11.7841	85.8057	2.4102	11.7841	85.8057	2.4102
0.0670139	3.3738	10.6989	85.9273	3.3738	10.6989	85.9273	3.3738
0.0678800	4.3722	10.0213	85.6065	4.3722	10.0213	85.6065	4.3722
0.0687490	5.6551	9.3423	85.0026	5.6551	9.3423	85.0026	5.6551
0.0688780	9.6886	7.3772	82.9342	9.6886	7.3772	82.9342	9.6886
0.0703450	14.0375	5.8037	80.1588	14.0375	5.8037	80.1588	14.0375
0.0704430	15.8814	5.1104	79.0082	15.8814	5.1104	79.0082	15.8814
0.0708460	17.7127	4.6039	77.6834	17.7127	4.6039	77.6834	17.7127
0.0711539	18.7232	4.3064	76.9704	18.7232	4.3064	76.9704	18.7232
0.0716660	21.7511	3.6039	74.6450	21.7511	3.6039	74.6450	21.7511
0.0733610	28.4334	2.3168	69.2498	28.4334	2.3168	69.2498	28.4334
0.0755979	38.7004	1.1945	60.1051	38.7004	1.1945	60.1051	38.7004
0.0765310	42.8930	0.8815	56.2255	42.8930	0.8815	56.2255	42.8930
0.0770060	45.0735	0.7634	54.1631	45.0735	0.7634	54.1631	45.0735
0.0774979	47.1619	0.6530	52.1851	47.1619	0.6530	52.1851	47.1619
0.0779780	49.3598	0.5550	50.0852	49.3598	0.5550	50.0852	49.3598
0.0784680	51.7683	0.4754	47.7563	51.7683	0.4754	47.7563	51.7683
0.0789680	53.8799	0.4004	45.7197	53.8799	0.4004	45.7197	53.8799
0.0799570	58.3682	0.2834	41.3484	58.3682	0.2834	41.3484	58.3682
0.0810330	62.8843	0.1805	36.9352	62.8843	0.1805	36.9352	62.8843
0.0821060	66.6621	0.1053	33.2326	66.6621	0.1053	33.2326	66.6621
0.0826530	68.4973	0.0775	31.4252	68.4973	0.0775	31.4252	68.4973
0.0832080	70.2369	0.0575	29.7056	70.2369	0.0575	29.7056	70.2369
0.0843400	73.9918	0.0307	25.9775	73.9918	0.0307	25.9775	73.9918
0.0849180	75.0651	0.0239	24.9110	75.0651	0.0239	24.9110	75.0651
0.0855430	76.1795	0.0188	23.8017	76.1795	0.0188	23.8017	76.1795

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Table 3 (Continued)

0.0860969	77.2088	0.0152	22.7760	77.2088	0.0152	22.7760	77.2088
0.0866989	78.0990	0.0127	21.8883	78.0990	0.0127	21.8883	78.0990
0.0873100	78.8574	0.0106	21.1319	78.8574	0.0106	21.1319	78.8574
0.0879290	79.8516	0.0088	20.1395	79.8516	0.0088	20.1395	79.8516
0.0885569	80.6777	0.0074	19.3148	80.6777	0.0074	19.3148	80.6777
0.0888750	80.8255	0.0072	19.1673	80.8255	0.0072	19.1673	80.8255
0.0891940	81.3623	0.0063	18.6314	81.3623	0.0063	18.6314	81.3623
0.0895160	81.8024	0.0058	18.1918	81.8024	0.0058	18.1918	81.8024
0.0898409	82.2425	0.0053	17.7522	82.2425	0.0053	17.7522	82.2425
0.0901670	82.5521	0.0049	17.4430	82.5521	0.0049	17.4430	82.5521
0.0904959	82.8853	0.0045	17.1102	82.8853	0.0045	17.1102	82.8853
0.0908279	83.2193	0.0042	16.7765	83.2193	0.0042	16.7765	83.2193
0.0911620	83.5275	0.0039	16.4686	83.5275	0.0039	16.4686	83.5275
0.0914980	83.8625	0.0036	16.1339	83.8625	0.0036	16.1339	83.8625
0.0918370	84.1971	0.0033	15.7996	84.1971	0.0033	15.7996	84.1971
0.0921750	84.4686	0.0031	15.5283	84.4686	0.0031	15.5283	84.4686
0.0925220	84.7344	0.0029	15.2627	84.7344	0.0029	15.2627	84.7344
0.0928690	85.0042	0.0027	14.9931	85.0042	0.0027	14.9931	85.0042
0.0932180	85.2688	0.0025	14.7287	85.2688	0.0025	14.7287	85.2688
0.0935700	85.5354	0.0023	14.4622	85.5354	0.0023	14.4622	85.5354
0.0939240	85.7407	0.0022	14.2571	85.7407	0.0022	14.2571	85.7407
0.0942810	85.9478	0.0021	14.0501	85.9478	0.0021	14.0501	85.9478
0.0946410	86.1500	0.0019	13.8481	86.1500	0.0019	13.8481	86.1500
0.0950040	86.3537	0.0018	13.6445	86.3537	0.0018	13.6445	86.3537
0.0953690	86.5527	0.0017	13.4456	86.5527	0.0017	13.4456	86.5527
0.0957370	86.8172	0.0016	13.1812	86.8172	0.0016	13.1812	86.8172
0.0961090	87.0794	0.0015	12.9191	87.0794	0.0015	12.9191	87.0794
0.0964820	87.3143	0.0014	12.6843	87.3143	0.0014	12.6843	87.3143
0.0968590	87.5042	0.0013	12.4944	87.5042	0.0013	12.4944	87.5042
0.0972390	87.7349	0.0013	12.2639	87.7349	0.0013	12.2639	87.7349
0.0976220	87.9657	0.0012	12.0332	87.9657	0.0012	12.0332	87.9657
0.0980080	88.2134	0.0011	11.7855	88.2134	0.0011	11.7855	88.2134
0.0983970	88.4392	0.0010	11.5598	88.4392	0.0010	11.5598	88.4392
0.0991340	88.8812	0.0009	11.1179	88.8812	0.0009	11.1179	88.8812
0.0999340	89.1803	0.0008	10.8189	89.1803	0.0008	10.8189	89.1803
0.1007970	89.4712	0.0007	10.5280	89.4712	0.0007	10.5280	89.4712
0.1016230	89.7525	0.0007	10.2468	89.7525	0.0007	10.2468	89.7525
0.1026000	90.0469	0.0006	9.9525	90.0469	0.0006	9.9525	90.0469
0.1033170	90.3132	0.0005	9.6863	90.3132	0.0005	9.6863	90.3132
0.1053149	90.8381	0.0004	9.1614	90.8381	0.0004	9.1614	90.8381
0.1064000	91.0783	0.0004	8.9213	91.0783	0.0004	8.9213	91.0783
0.1078089	91.3232	0.0003	8.6765	91.3232	0.0003	8.6765	91.3232
0.1100000	91.5333	0.0003	8.4664	91.5333	0.0003	8.4664	91.5333
0.1102040	91.4747	0.0003	8.5249	91.4747	0.0003	8.5249	91.4747
0.1127090	91.6176	0.0003	8.3821	91.6176	0.0003	8.3821	91.6176
0.1149999	91.5868	0.0003	8.4129	91.5868	0.0003	8.4129	91.5868
0.1190760	91.5774	0.0004	8.4222	91.5774	0.0004	8.4222	91.5774
0.1216000	91.5638	0.0007	8.4355	91.5638	0.0007	8.4355	91.5638
0.1239800	91.6196	0.0010	8.3794	91.6196	0.0010	8.3794	91.6196
0.1300000	92.3695	0.0006	7.6299	92.3695	0.0006	7.6299	92.3695
0.1377560	92.5399	0.0002	7.4599	92.5399	0.0002	7.4599	92.5399
0.1400000	92.5729	0.0001	7.4270	92.5729	0.0001	7.4270	92.5729
0.1549750	92.5821	0.0000	7.4179	92.5821	0.0000	7.4179	92.5821
0.1600000	92.5824	0.0000	7.4176	92.5824	0.0000	7.4176	92.5824
0.1771140	92.5634	0.0000	7.4366	92.5634	0.0000	7.4366	92.5634

108 WAVELNGTHS, SUM OF REFL= 9415.500 FIG OF MRT= 87.181

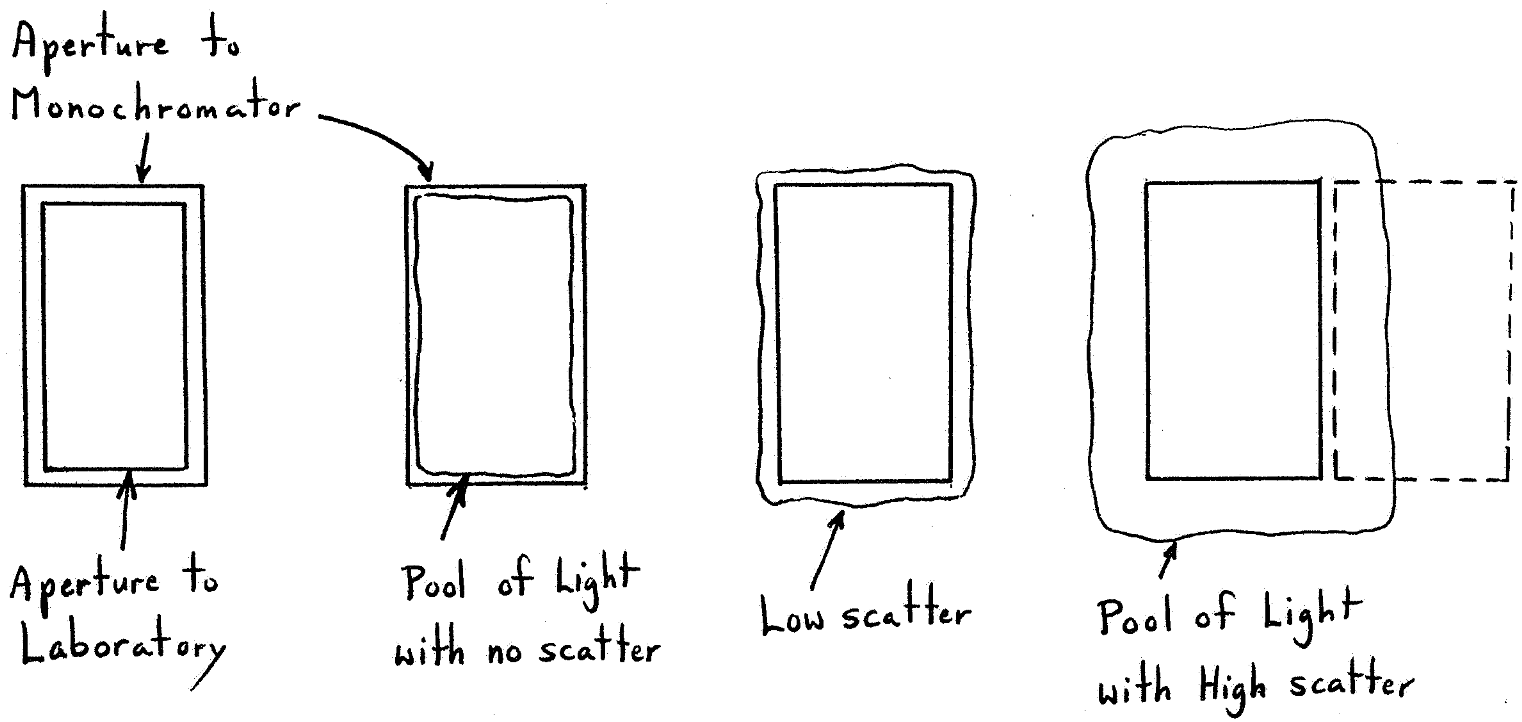

Figure 41. The Effect of Increasing Scatter on the Size of the Light Bundle Reaching the Monochromator.

1. Allow one mirror surface to become contaminated with a molecular film, by exposure to solar ultraviolet and an organic gaseous contaminant simultaneously, or by some other method.*
2. Measure reflectivity versus wavelength.
3. Rotate mirror surface to face atom beam gun.
4. Monitor all TQCM's.
5. Turn on atom beam gun.
6. Raster scan atom beam gun over surface of mirror.
7. Turn off atom beam.
8. Monitor all TQCM's.
9. Rotate clean mirror surface to optical measurement compartment.
10. Re-measure reflectivity versus wavelength.

An even more dramatic demonstration of the atom beam cleaning method would be to remove a contaminant film which had failed to evaporate following a long heating of the contaminated substrate.

4.6 CONCLUSIONS AND RECOMMENDATIONS

We have described a conceptual design for an orbital laboratory which features the capability to demonstrate in-orbit optical coating, particulary for pure aluminum, and also allows for a variety of basic experiments which are stepping-stones to the in-situ coating of future large space telescopes.

The design we have described makes use of the highest level of contaminant-free vacuum available in a near-Earth orbit. Alternate designs or refinements to this design are certainly possible. The major disadvantage of the design sketched in this chapter is

* Concentrated solar ultraviolet is known to accelerate the rate of degradation due to photopolymerization. A uv-transmitting lens built into this orbital laboratory could therefore serve to accelerate the build-up of a contaminant film on one illuminated area, by providing a factor ~ 5-10 concentration of the sunlight.

the number of moving parts, always an element of risk in any design. The advantages of the design include a considerable level of versatility, so that experiments even beyond those described in this chapter could be attempted.

There is nothing that is technically very difficult about building the instrumentation described here. This laboratory could be flown today. The most difficult aspect of the construction of this hardware would probably be the selection of acceptable materials to minimize the outgassing of oxygen, water or organic gases in space.

A logical plan for the initial launch of this experimentation would be to launch both mirrors with an initial coating of iridium. Iridium has a high FUV reflectivity and is not subject to atomic oxygen effects. Therefore the initial response of the system would be calibrated. An initial "heat soak" of the laboratory and an outgassing period of a few days after reaching orbit before opening the aperture to the Sun is advisable.

This orbital coating laboratory would be best flown on an unmanned Space Platform at an altitude of 600-1000 km which is periodically visited by astronauts. The astronauts serve to replace key components such as the evaporators and the contamination monitors.

An orbiting laboratory of the kind described here needs to be located at a remote corner of the platform, away from all sources of outgassing or contamination, particularly sources of oxygen, water, other oxidants, or compounds which could decompose into O or OH ions, as these are the substances which will most severely shorten the life of a highly reactive aluminum mirror. A location on the end of an "outrigger" beam on a Space Platform would be appropriate (Figure 42). This laboratory also requires a particular controlled alignment with respect to the vehicle flight vector, and in addition a frequent controlled alignment with respect to the Earth-Sun line. These motions could be accommodated by swivelled stage holding a two-axis gimbal mount for the laboratory payload.

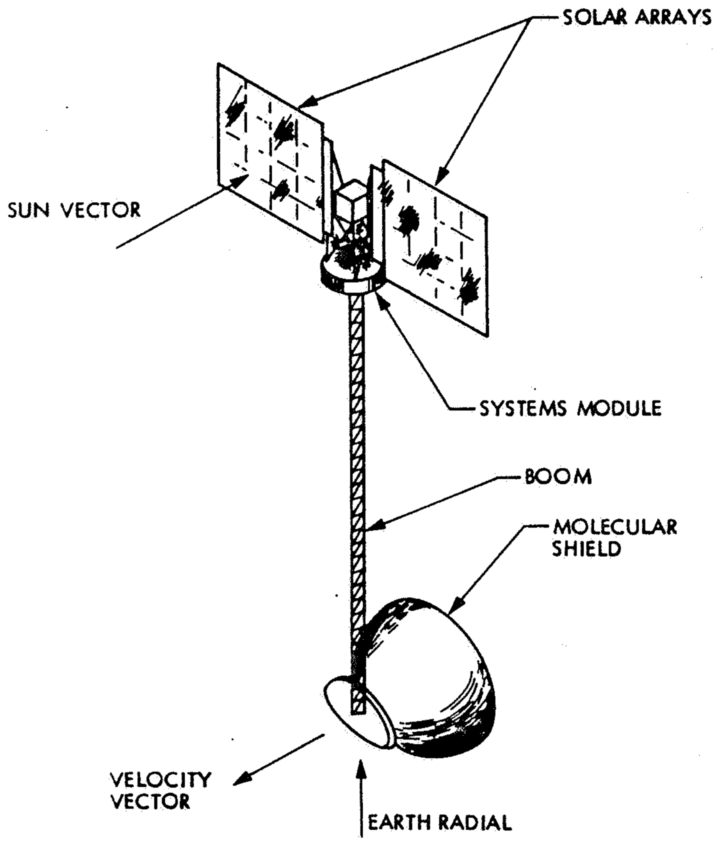

Figure 42. Concept for a High-Vacuum Orbital Laboratory, with Molecular Shield, Located on Long Boom Extending from Free-Flyer Platform (from Reference 166).

SECTION 5

A SPACE STATION COATING FACILITY

Much of what has been discussed so far in this report constitutes a technological appraisal of the steps required to approach the goal of in-situ optical coating of the optical elements of a remote telescope in space. A quite different approach to re-coating mirrors in space, and one which will be the more viable route for certain large systems where in-situ coating is ruled out, is the concept for an optical coating facility, possibly an adjunct to a manned space station in low or moderately low Earth orbit. This facility could be a general-purpose operation capable of handling a variety of ultraviolet, infrared or special-purpose coating materials, toxic materials such as osmium, and capable of repairing damaged mirrors by completely stripping their existing coatings. Such a facility would be a generalized and updated version of the Orbital Mirror Recoating Facility conceived in 1967 (Reference 2) to be a part of the Apollo Applications Program Orbital Workshop. See Figure 6.

Figure 43 is a block (or task structure) diagram indicating the general organization and makeup of an envisioned 21st century Space Station Coating Facility. The diagram is intended to represent all of the principal subsystems making up the SSCF, and their capabilities and interrelationships. Such a diagram can serve as a guide in planning the engineering design of the SSCF and in extending or modifying its specifications. The following is a brief discourse on each element of the system as presently envisioned.

5.1 SPACE STATION INTEGRATION (010)

The SSCF is considered to be an integral or adjunct part of a permanent Manned Space Station (MSS) in Earth orbit at an altitude of about 600 km (See Figure 44). Optical components of up to 2 meters in size would be brought to the SSCF by a space transport craft, introduced into the SSCF through an interlock port, tested, stripped, cleaned, recoated with aluminum or another coating, and then returned to use in high orbital space observatories. The principal motivation for establishing the SSCF is to eliminate

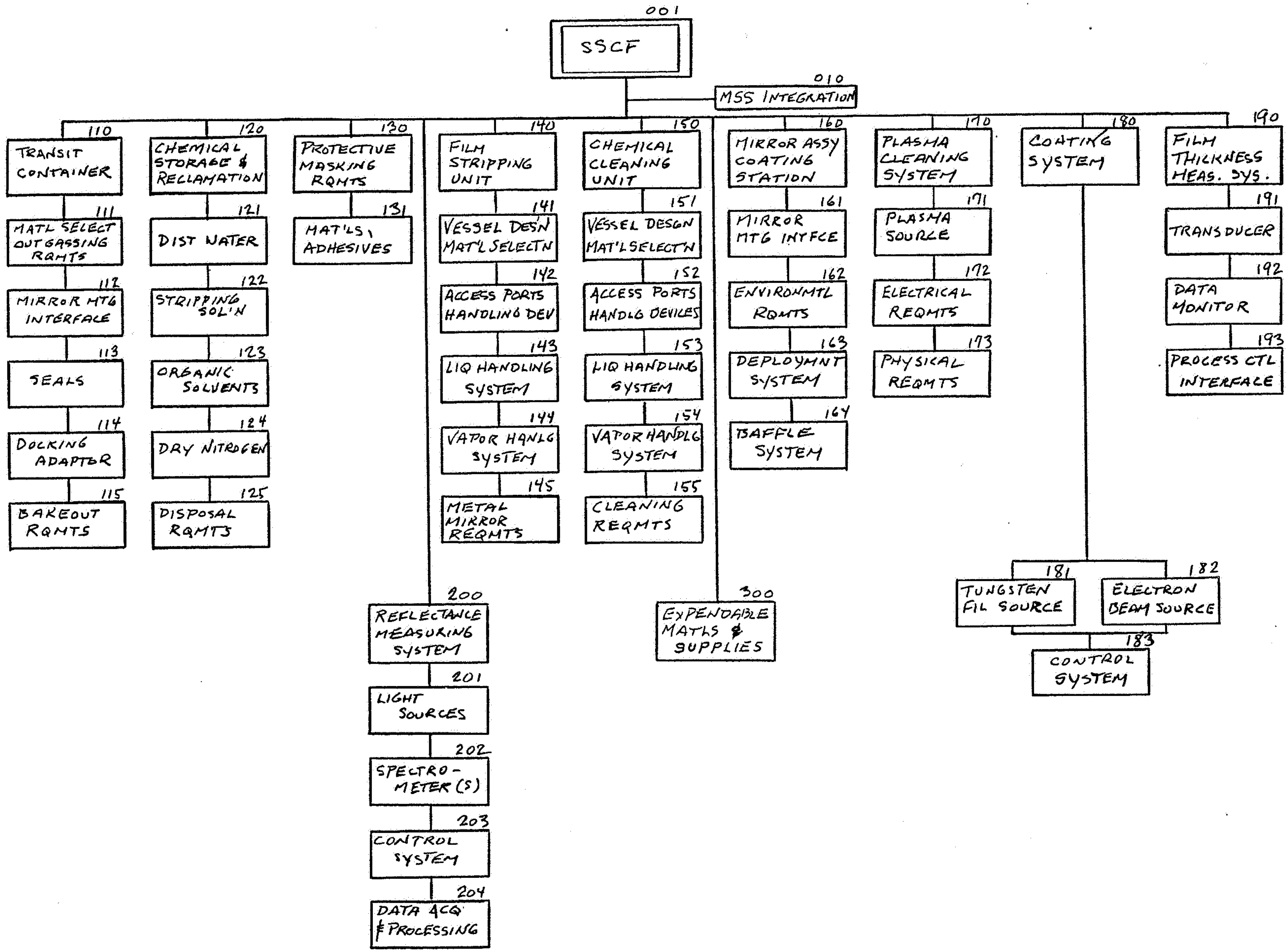

Figure 43. Task Structure Block Diagram Showing All the Principal Subsystems for a Semi-Permanent Space Station Coating Facility.

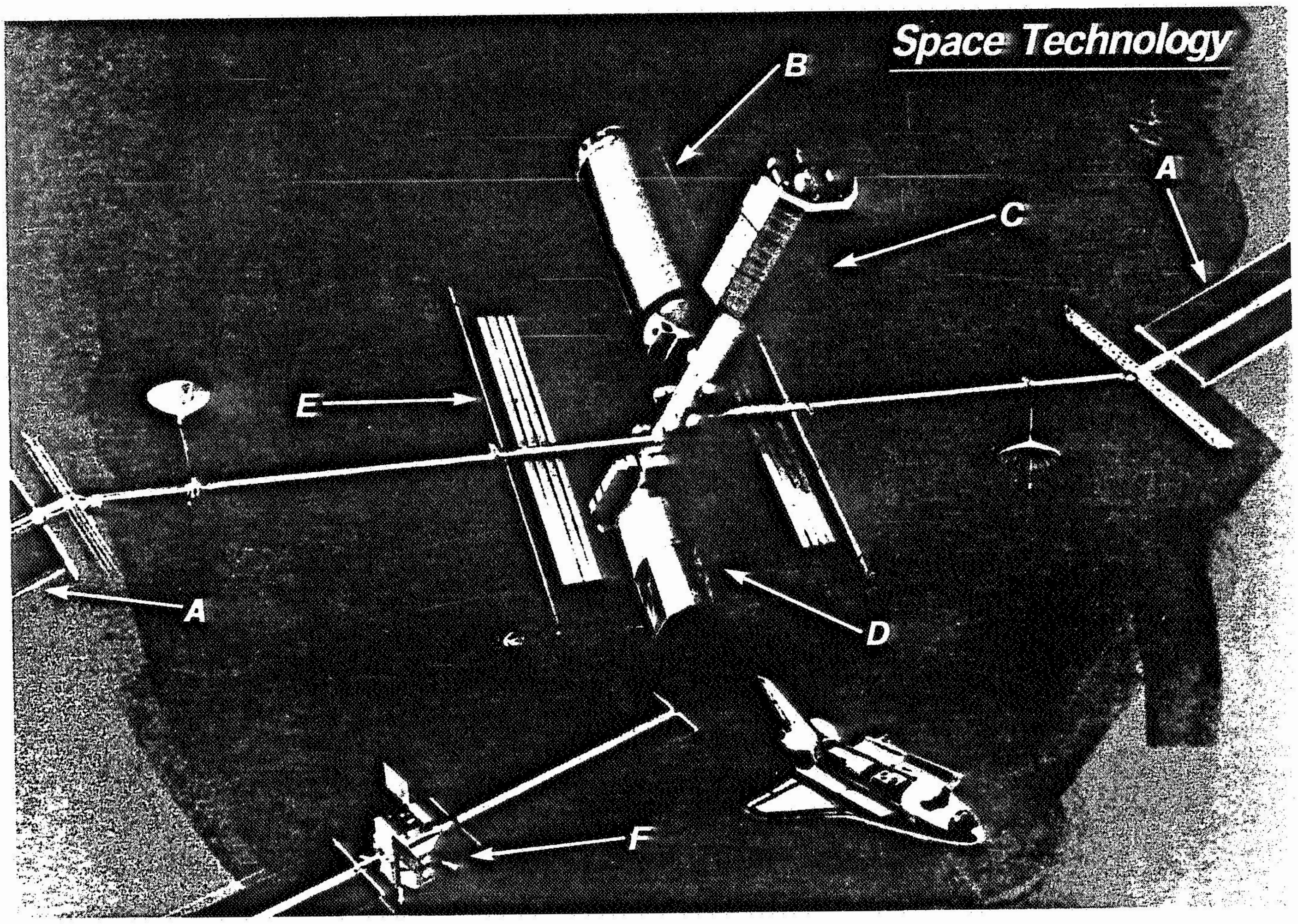

Figure 44. Artist's Concept for a Future Space Station Including Materials Processing Facilities such as an Optical Coating Facility. (Johnson Space Center drawing, Reference 206).

the expense of returning space observatory optical components to Earth for periodic recoating, and to take advantage of the vacuum of space to produce pure aluminum coatings with high reflectance in the extreme Ultraviolet. An objective of the overall SSCF design is to achieve a processing turnaround time of less than the lifetime of a pure aluminum coating at the altitude of the SSCF - about 16 days.

The MSS is assumed equipped with all necessary primary electrical power sources, a clean room interior environment, access ports and air locks, and astronauts equipped for EVA as necessary. Some of the activity of the SSCF is conducted inside the MSS in a 1 atmosphere air environment. Actual coating of mirrors will be conducted externally to the MSS under remote control from operating centers in the SSCF. The detailed arrangement of the MSS is not now known. It is possible that some of the subsystems envisioned as part of the SSCF will already be provided by the MSS itself. For example, the MSS may have a liquid handling system (or chemical storage and recovery facility) that would be sufficient for the needs of the SSCF. However, this this not assumed in the present discourse. Also, the MSS may provide artificial gravity. In the following, however, operations are assumed to take place in a zero gravity environment in which special procedures are required, for example, in the handling of liquids.

The Space Station Coating Facility should be located on the Space Station at a remote end of the structure, both so that the coating chamber is removed from sources of outgassing elsewhere in the MSS, including leading-edge surfaces facing the ram flow, and also so that its own effluent gases are dissipated away from other parts of the Space Station.

5.2 TRANSIT CONTAINER (110)

An important requirement of the SSCF is the design of the containers used to transport mirrors (or other optical components) back and forth between the SSCF and their parent spacecraft. The transit container must be configured to fit and hold securely a particular component. The container must be made of a material whose outgassing will not damage the newly coated mirror in the return voyage to the parent spacecraft. The container must be able to be handled and docked at the SSCF. A number of tasks are envisioned in designing and developing these containers.

Material Selection - Outgassing Requirements (111)

The material must not introduce reactive (oxidizing or UV-absorbing) contamination in the course of a voyage. The material may have to be capable of being baked if the container handling involves exposure to the interior environment of the MSS.

Mirror Assembly Mounting Interface (112)

The container must have hold-down fasteners for the optical component or assembly it carries. In some cases, a mirror will have attached metal mounting hardware of some kind which practically cannot be detached; the particular component configuration will dictate the detailed design of the mounting interface.

Transit Container Seals (113)

Seals for the cover of the container must be operable by an astronaut during EVA and must provide a seal against contamination during a return voyage.

Docking Adaptor at SSCF (114)

The container will be reloaded externally to the SSCF immediately after a mirror is recoated. This external EVA is required in order to avoid damage (oxidation or contamination) of the mirror in the MSS. Thus, the container is envisioned to be docked securely outside the SSCF.

Bakeout Requirements (115)

In case it is impossible to avoid an objectionable amount of contamination of the container, bakeout may be a requirement prior to a return voyage. This may take place in a bakeout oven belonging to the SSCF. Alternatively, the container may have a self-baking capability when furnished with external electrical power.

5.3 CHEMICAL STORAGE AND RECLAMATION FACILITY (120)

The use of liquids appears difficult to avoid in the processing (stripping and cleaning in preparation for recoating) of mirrors. In some cases, new coatings might be applied to previously uncoated mirrors or new coatings might be laid down over old ones without necessarily requiring the use of liquids. In general, however, the best results will be obtained if standard reagents (and distilled water) can be used. (See Reference 125.)

Distilled Water (121)

Distilled water would be used in final stages of mirror preparation after stripping. Relatively large quantities of distilled water (5-10 gallons or more) could be required in the preparation of a 2 meter mirror for coating. The consumption of water may necessitate a reclamation (re-distillation and re-use) processing facility (such a facility may already be provided by the MSS).

Stripping Solution ($HCl + CuSO_4$) (122)

Up to a gallon of stripping solution may be consumed per mirror. Suitable conditions and facilities for handling of this chemical are a requirement. Possible reclamation and re-use of the solution or its ingredients should be investigated.

Organic Solvents (123)

Organic solvents (acetone, alcohol, and various composite organic solvents) are used to remove hydrocarbon (oil, etc.) contaminants which are not dissolved by other means. Means for safe transport to the MSS and for storage, use, and possible reclamation in the MSS should be considered. Possible contamination of the MSS atmosphere could pose a hazard.

Dry Nitrogen (124)

Used for flushing the stripping and cleaning units.

Chemical Disposal Requirements (125)

In case it is not possible to reclaim and recycle reagents various methods of containing or disposing of them must be considered, including, possibly, ejection into high orbit, ejecting them locally, or returning canisters to the ground.

5.4 PROTECTIVE MASKING REQUIREMENTS (130)

In some instances parts of a mirror (such as metal mounting hardware cemented to the mirror) must be protected from exposure to liquids (especially corrosive liquids). Possibly the necessary masking can make use of an impregnable fabric that can be fastened and sealed (with an adhesive) to the edge of a mirror.

5.5 FILM STRIPPING UNIT (140)

The FSU is envisioned as a sealed (probably lightweight stainless steel or suitable plastic) vessel within which a mirror can be stripped and washed by personnel of the SSCF. The FSU would operate with an internal air atmosphere at close to the MSS atmospheric pressure. It would have a window, and (possibly) an internal manipulator or operator gloves extending into the vessel enabling the operator to perform various stripping and cleaning actions. The FSU will have a water dispensing and flushing system. and a purging system capable of eliminating all unwanted liquids and vapors prior to reopening the vessel. Several necessary design considerations are envisioned.

Vessel Design and Material Selection (141)

Design objectives include lightweight construction and resistance to damage by the reagents used.

Access Ports and Handling Devices (142)

Design objectives include suitability for a wide range in size and configuration of mirrors to be processed, and ease of operation by facility personnel.

Liquid Handling System (143)

The system must be suited to handing of liquids (including corrosive liquids) in a zero gravity environment. The possible use of a centrifuge system should be considered.

Vapor Handling System (144)

The vapor handling system is the interface between the atmosphere within the FSU and the MSS atmosphere.

Metal Mirror Requirements (145)

Metal mirrors cannot be stripped by the same methods used for glass or ceramic mirrors. Metal (for example, aluminum) mirrors are often used for heat rejection in solar instrumentation. Such mirrors are usually nickel- and chromium-plated to form a substrate suitable for adherence of the aluminum film. Development of a suitable stripping procedure for such mirrors may become a requirement for the SSCF.

5.6 CHEMICAL CLEANING UNIT (150)

The CCU provides an enclosed atmosphere for final cleaning of the mirror with distilled water and various organic solvents. This unit might possibly be virtually identical to the FSU except as modified for the handling of the particular chemicals used. Separation of the CCU and FSU is considered necessary to prevent cross-contamination between the stripping and final cleaning materials. Possibly (especially in the interest of economy and weight-saving) procedures will be devised that enable only one processing unit to be called for.

Vessel Design and Material Selection (151)

As required for the use of organic solvents.

Access Ports and Handling Devices (152)

Operation in principle the same as for the FSU.

Liquid Handling System (153)

Appropriate for Organic solvents and distilled water.

Vapor Handling System (154)

Special precautions are needed to control possible explosion hazard from organic vapors.

5.7 MIRROR ASSEMBLY COATING STATION (160)

Actual coating of the stripped and cleaned mirror will necessarily be done in free space outside the MSS to prevent immediate contamination of the fresh aluminum by outgassing products. The MACS is considered to consist of a structure for holding the mirror during the coating operation, together with any necessary shields or baffles to contain the evaporated aluminum stream and protect the mirror from the ram flow of upper atmospheric gas.

Mirror Mounting Interface (161)

Standard or customer designed jigs or other tooling will attach the mirror to the MACS.

Environmental Requirements (162)

Consideration must be given to the effect of the proximity of the MSS or other spacecraft at the time of coating. The mirror should face away from the ram direction during and after coating. Stray evaporated aluminum must not coat the spacecraft (particularly windows, electrical or communications devices, solar panels).

Deployment System (163)

The deployment system carries the mirror from final processing inside the SSCF to the external Coating Station and, after coating, places the mirror into its transit container under remote control without astronaut EVA.

5.8 PLASMA CLEANING SYSTEM (170)

The PCS is the SSCF equivalent of the gas discharge cleaning cycle used in ground-based coating facilties. It is envisioned as consisting of a plasma source (ejecting a stream of oxygen ions directed at the mirror) and associated monitor/control instrumentation. The plasma cleaning cycle will be performed with the mirror attached to the Mirror Assembly Coating Station.

Plasma Source (171)

Ion density, particle kinetic energy, geometry, cycle duration TBD.

Electrical Requirements (172)

The design must include consideration of possible effects on MSS communications.

5.9 COATING SYSTEM (180)

The coating system is considered to consist of the evaporators for aluminum, and associated control system within the SSCF. The evaporator may have either a tungsten filament source or an electron beam source. A tungsten source might possibly introduce contamination that would be objectionable in the EUV. An electron beam source could utilize billets of pure aluminum and might best serve for depositing large amounts of aluminum in repeated coatings.

Tungsten Filament Source (181)

Wire gauge, aluminum charge weight, loading procedure and tooling, melt-in requirements TBD.

Electron Beam Source (182)

Beam source, geometry (bending magnet), boat design, electrical requirements TBD.

Control System (183)

Must monitor beam or filament current, voltages, and possibly interact with film thickness monitor.

5.10 FILM THICKNESS MEASURING SYSTEM (190)

Because the coatings of primary interest are opaque aluminum, film thicknesses will be monitored by a piezoelectric transducer system. The transducer (along with possible witness samples) will be deployed with the mirror at the coating station. Such equipment is standard in ground based coating facilities, but must be hardened as necessary for the SSCF. Requirements include consideration of the following:

Transducer Design (191)

Sensitivity, accuracy, signal-to-noise.

Data Monitor (192)

Provides operator real time information on progress of coating operation.

Process Control Interface (193)

Possible automation of the coating cycle should be considered.

5.11 REFLECTANCE MEASURING SYSTEM (200)

The RMS must be capable of reflectance measurement (to about 1 percent accuracy if possible) as a function of wavelength over a minimum bandwidth extending from 800 Å to 1200 Å (and probably into the visible and near infrared range as well). The system should be capable of evaluating mirrors of arbitrary size, shape, and surface figure, both before and after recoating. Probably the RMS must be deployed outside the SSCF for this purpose. The RMS is considered to include the following subassemblies and components.

Light Sources (201)

Selection of artificial EUV light sources TBD. The Sun could possibly serve as a source for reflectance measurement in some spectral regions. The entire surface of a mirror would not necessarily have to be illuminated for a reflectance measurement. Thus, a suitable shield or baffle could allow a relatively narrow beam of sunlight to strike the mirror under test. Similarly sunlight might be admitted into the SSCF for a secondary RMS that might be located there.

Spectrometer (202)

A Spectrometer suitable for use in measuring the reflectance of aluminum could have a relatively wide bandwidth (assuming there are no narrow reflectance anomalies of interest). A grazing incidence optical system is probably necessary.

Control System (203)

The RMS will be operated remotely by personnel within the SSCF.

Data Acquisition and Processing System (204)

Permanent record-keeping and data analysis by computer is assumed.

Expendable Supplies (300)

A considerable store of expendable supplies specifically needed for the SSCF can be envisioned.

5.12 OPERATION OF A SPACE STATION COATING FACILITY

To summarize the handling and processing tasks involved in re-coating a large telescope mirror or mirror segment in this facility, the following key steps are involved:

1. Receive and dock transit container. Astronaut EVA may be required.
2. Transfer optical assembly (eg. mirror segment) to MSS/SSCF.
3. Inspection of optical component: Visual; Physical; Optical Measurements.

4. Preparation and application of protective masking, if necessary.

5. Stripping of coating:

   Pre-clean (water and detergent are possible agents)

   Strip/Swab

   Rinse/Flush

   Purge the Film Stripping Unit

6. Chemical cleaning:

   Rinse/Swab/Flush

   Purge the Chemical Cleaning Unit

7. Move cleaned optic to coating station.

8. Vent all gas from the coating station.

9. Plasma cleaning.

10. Coating operation.

11. Re-install mirror in high-vacuum transit container.

5.13 SUMMARY

The above description of a Space Station Coating Facility is based on the anticipated requirement to perform the same general-purpose coating facility operations that are presently handled in ground laboratories. The key elements of the Space Station facility are

- o Avoidance of costly return to Earth of large optical components,
- o Using the vacuum of space as a clean "roughing pump",
- o Permitting the application of reactive coatings such as bare aluminum, which can then be quickly ferried to higher orbit.

The design of the transit container would be a challenging aspect of this concept. To be able to carry aluminum-coated mirrors without a measureable amount of oxidation, it may require an internal vacuum which is better than that of the surrounding space in low Earth orbit.

A manned space station facility of the kind described here also offers a tremendous opportunity for research. When senior scientists can travel at reasonable cost and comfort to a space station to supervise or conduct experiments, then research which utilizes the unique benefits of the space environment will have advanced to a new era, and a resulting enhancement of scientific yield may be expected.

SECTON 6

IN-SITU COATING OF LARGE SPACE TELESCOPE MIRRORS

The final phase of an experimental space coating program will be in-situ application of an aluminum film to a large primary mirror and its associated secondary mirror. The advantages of this approach have been discussed earlier in this report. Experimental verification of the technique during the previous phases of the program will prove feasibility.

In-situ coating capability for a large astronomical telescope system in space would have to be incorporated into the design of the system during the early conceptual phases. Baffling, power systems and on-board instrumentation would all have to be compatible with this process. Proper integration of a coating system into the telescope assembly would make coating in space both feasible and practical in applications where optical throughput in the vacuum ultraviolet must be maintained for extended periods of time.

Several assumptions will serve as guidelines for this study. Our system will be in geosynchronous orbit where ambient pressures will be 10^{-12} torr or lower. At this pressure a bare aluminum film without a protective overcoat will be sufficient. We also assume that all coating work is to be performed automatically. Astronauts will not be available to manipulate mirrors, sources or baffles.

6.1 SYSTEM DESCRIPTION

For our telescope we will choose a design similar to the Space Telescope - a 100 inch primary mirror with a 15 inch secondary (Figure 45). Located at the outer diameter of both mirrors are stray light baffles. The primary mirror also has a central baffle located at approximately a 24 inch diameter. The surfaces of the primary mirror and secondary are separated by approximately 20 feet. These are the only optics in the system that we will consider coating. We will also consider recoating of these optics several times.

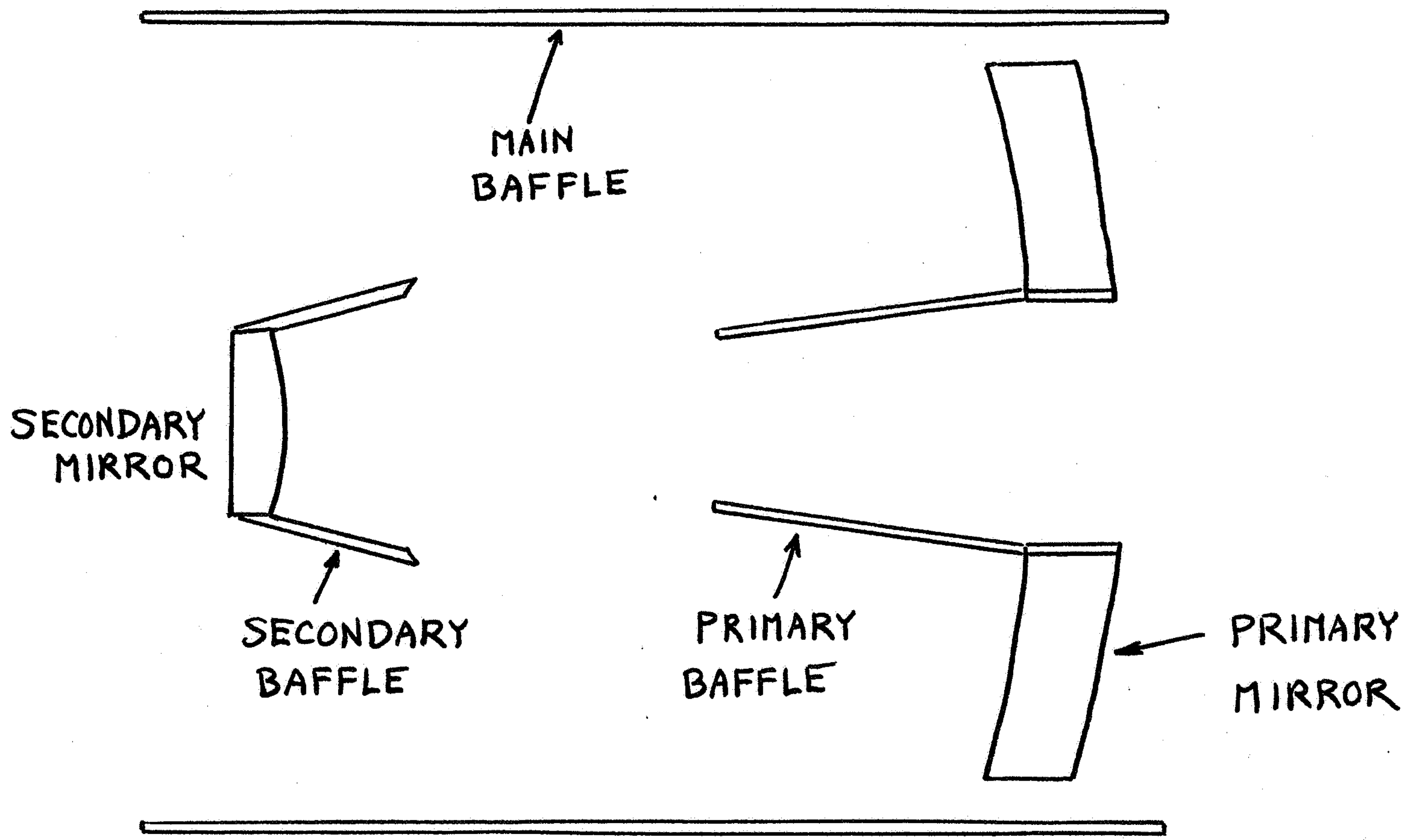

Figure 45. Baseline Optical System for a Large Space Telescope Requiring In-situ Coating.

6.2 EVAPORATOR DESCRIPTION

The type of evaporators and their location are critical to the feasibility of this approach. Power requirements play a primary role in determining evaporator type and size. The location and number of evaporators determine film uniformity.

There are two types of sources which may be used to thermally evaporate aluminum: resistance heating and electron beam gun heating. We will not consider electron beam gun sources because of the large powers required (several kilowatts). Resistance sources can be designed to operate at low voltages and therefore low powers (tens of watts). In addition resistance sources can be pre-shaped and pre-charged to give a wide range of vapor distribution patterns and pre-determined mechanical thickness. A large number of sources can be arranged in a distributed geometry to simulate an extended source.

Tungsten stranded wire can be formed into large helical coils and precharged with aluminum (Figure 46). This geometry gives excellent uniformity in two directions. The source can be made simple, compact and mechanically sound. The tungsten filaments can be pre-charged with aluminum prior to launch. Multiple evaporation can be accommodated by using several sources with a multiple tap switching mechanism. This technique is used routinely in conventional deposition systems.

6.3 UNIFORMITY AND THICKNESS CONSIDERATIONS

The performance of the telescope system is very dependent upon the uniformity and thickness of the aluminum film applied to the optical surfaces. A non-uniform film on either the primary or secondary mirror can seriously degrade the optical figure. The mechanical thickness of aluminum specified will be 600 Å. This value is a lower limit. Thicker films (<1000 Å) can be used without a serious increase in surface roughness.

If telescope mirrors or other components to be coated were to be used at other than normal incidence, special care would be required in choosing the thickness of aluminum in order to prevent unwanted polarization effects.

The sources for the primary mirror coating are arranged on a circumference outside the clear aperture of the main baffle (Figure 47). Shielding and baffle opening are such that only the mirror surface is in the line of sight of the source. The angle α is a

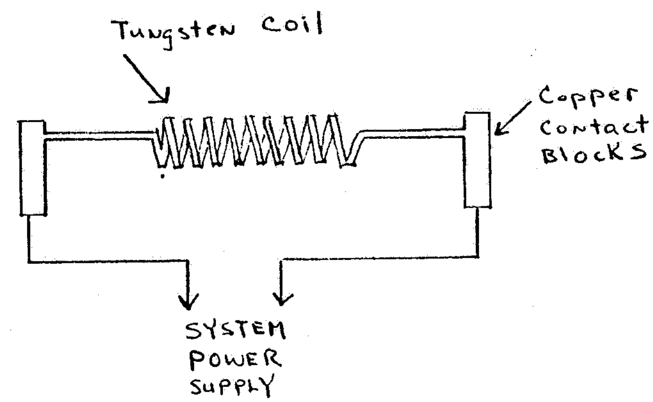

Figure 46. Tungsten Stranded Wire Helical Coil Source.

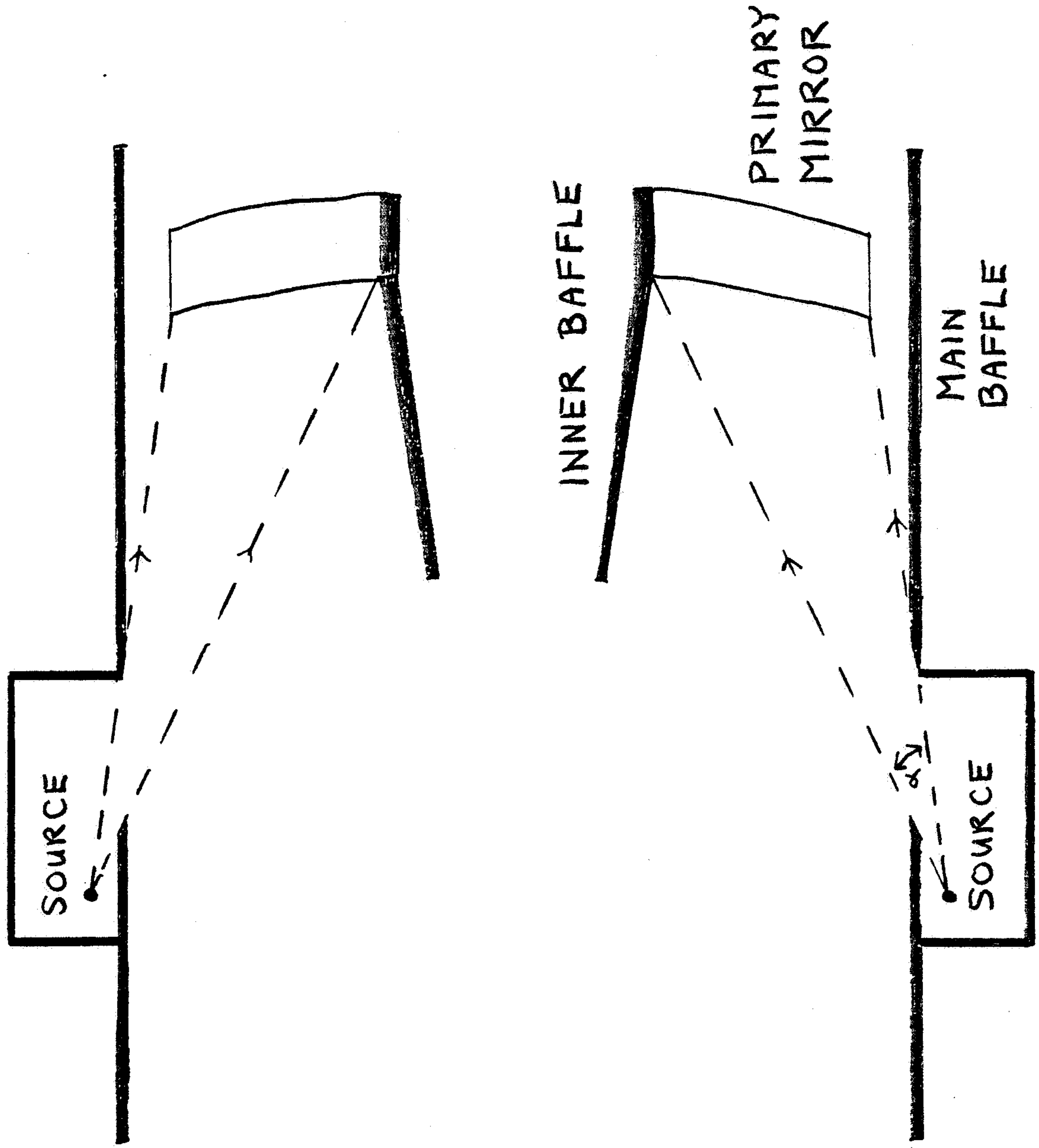

Figure 47. Primary Mirror Evaporator Configuration.

function of the source distance from the primary mirror plane. The further away the source is from this plane the smaller is and the better the uniformity across the mirror in the radial direction. However, the tradeoff in locating sources far from the primary mirror is in the amount of energy which must be expended. More aluminum must be evaporated as the solid angle coverage decreases. For a continuous ring source the azimuthal uniformity is very good. Since discrete sources must be used, azimuthal uniformity deteriorates. A tradeoff study must again be made to determine acceptable uniformity versus power expenditures.

The secondary mirror presents more of a problem than the primary mirror because of the difficulty in locating the sources in a position which will not obscure the optical path. One possibility (Figure 48) is to locate the evaporators at the extreme end of the primary mirror central baffle. This position is far enough away from the secondary mirror to insure a uniform coating yet in a position that would not present a large obscuration to the optical path.

Proper thickness control can be achieved by evaporating to completion a pre-set charge of aluminum. This technique can be used as long as the evaporators are used once. For multiple evaporations new sources are switched in sequentially. If sources are to be used more than once, it will be necessary to monitor the deposition for thickness control. One simple method is to photometrically monitor the system throughput at 1216 Å. As the aluminum film is deposited, throughput will increase to a value limited by the film reflectance at 1216 Å. When throughput ceases to increase the deposition can be terminated. It is a simple technique which would require no additional instrumentation.

6.4 SUMMARY

In-situ coating of large optical systems appears to be very feasible. Detailed work must be performed to accurately determine film uniformity requirements for the mirrors and the source geometry necessary to achieve these uniformities. Power requirements do not seem to be severe and process monitoring does not appear to be critical. If the early experiments on coating in space prove successful the application of this technology to a large system would be the next logical step.

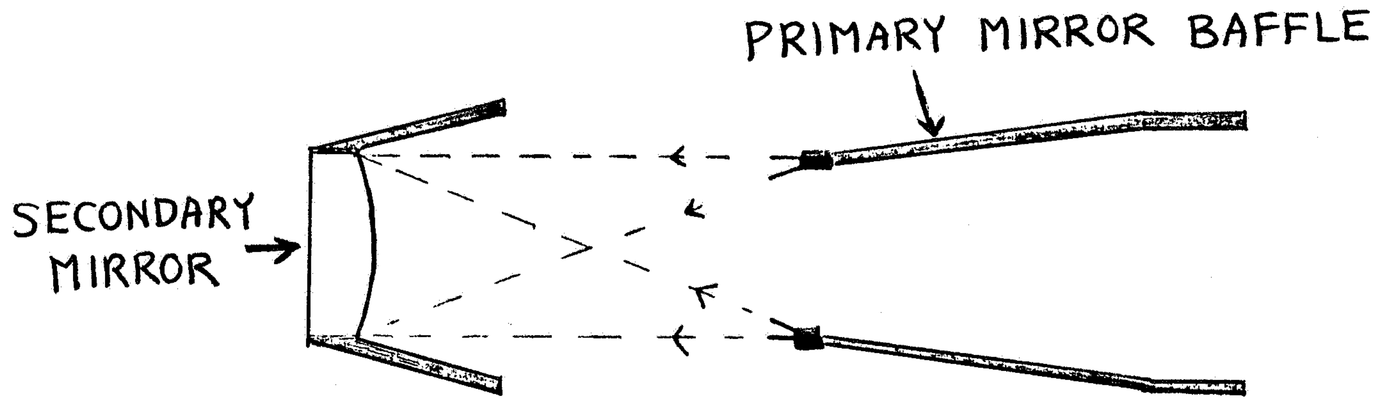

Figure 48. One Possible Configuration for Locating Secondary Mirror Evaporators.

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

In this study we have given some thought to the steps required to approach the goal of in-situ optical coating, cleaning and re -coating the optical elements of a space telescope. We have concentrated our attention on the desire to achieve high reflectivity with normal incidence telescope mirrors. In general, grazing incidence mirrors such as are used for X-ray and EUV astronomy (7, 135, 138, 139, 147) are more tolerant of small amounts of surface contamination and there is therefore less gained by coating these in space. In particular, we have considered the case of bare aluminum coatings, which offer a tremendous advantage to far ultraviolet astronomy. We have suggested some design ideas for an optical coating laboratory in space, flown either on a space platform or as a "Spartan"-type free flyer, for conducting experiments and demonstrations that can set the stage for a future telescope with built-in aluminum evaporators.

Some prerequisite experiments should be carried out in ground-based laboratories before a final design of an orbital coating laboratory can be made. The recommended work is listed here:

1. Experimental tests of evaporator gun design. A design for a vapor collimator must be found that provides an optimum "top-hat function" (uniform distribution over an area and zero vapour outside that area) and that does not clog up with condensed aluminum after multiple uses.
2. Measurements of the angular distribution of the evaporant as received on a substrate behind a mask, as a function of evaporation rate and local pressure. This data is needed to find the optimum deposition rate and the maximum allowable chamber pressure to avoid stray vapor beyond the desired target areas.

3. Measurements of the amount of stray vapor scattered at large angles out of a thermally evaporated aluminum beam.

4. Experiments on repeated coating, oxidation, and recoating of aluminum mirror surfaces. How does the scattered light performance change with increasing number of Al_2O_3/Al layers? How many repetitions of this process can be allowed before a mirror is no longer satisfactory?

5. Measurements of the adhesion of new aluminum layers over oxidized aluminum as a function of various parameters such as temperature, deposition rate.

6. Experiments on ways to remove dust from a mirror in a vacuum by an automated, remote technique.

7. Search for a "magic" material that, when deposited as a very thin film over pure aluminum, retards the rate of oxidation of aluminum without significantly losing the advantage of high far-ultraviolet reflectivity that aluminum offers.

8. Experiments with fast atom beam cleaning of polymerized hydrocarbon films on coated mirrors, using neutral oxygen atoms in high vacuum.

However, ground-based experiments cannot replace experiments and observations made directly outside the Earth's atmosphere. The true test of the techniques considered here for coating in outer space can only be made on a spacecraft, and best on a platform which samples various orbital altitudes over a period of time.

In all likelihood, the coating of large optics in space is the approach that will in fact be taken for the next generation of large space telescopes in the twenty-first century. The technology exists to develop this approach today.

SECTION 8

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APPENDIX A

DICTIONARY OF ACRONYMS

AE	Atmospheric Explorer
ATS	Applications Technology Satellite
ATM	Apollo Telescope Mount (on Skylab)
CCU	Chemical Cleaning Unit
CVD	Chemically Vapor Deposited
ESA	European Space Agency
EUV	Extreme Ultra-violet .Wavelength range from ~100 Å to 1000 Å
EVA	Extra-vehicular Activity
FSU	Film Stripping Unit
FUSE	Far Ultraviolet Spectroscopic Explorer
FUV	Far Ultraviolet. Wavelength range from ~900 Å to 1800 Å.
GAS	Get Away Special (NASA cannister for self-contained Space Shuttle experiments)
GRIST	Grazing Incidence Solar Telescope (ESA program)
HUT	Hopkins Ultraviolet Telesope (Johns Hopkins University)
JPL	Jet Propulsion Laboratory
LDEF	Long Duration Exposure Facility
LPSP	Laboratoire de Physique Stellaire et Planetaire (C.N.R.S., France)
MACS	Mirror Assembly Coating Station
MSFC	Marshall Space Flight Center
MSS	Manned Space Station
NRL	Naval Research Laboratory
OAO	Orbiting Astronomical Observatory
OMRF	Orbital Mirror Recoating Facility
OSO	Orbiting Solar Observatory
OSS	Office of Space Science (NASA office)
OST	Orbiting Solar Telescope (on Salyut 4)

PCS	Plasma Cleaning Sation
REVAP	Removeable Volatile Aluminum Protection
SOT	Solar Optical Telescope
SPARTAN	Shuttle Pointed Autonomous Research Tool for Astronomy (free flying payload dropped and retrieved by Shuttle)
SSCF	Space Station Coating Facility
ST	Space Telescope
STS	Space Transportation System (Space Shuttle)
TBD	To Be Determined
TQCM	Temperature Controlled Quartz Crystal Microbalance
UVSO	Ultraviolet Space Observatory (U.K. proposal)
VUV	Vacuum Ultraviolet. Wavelength range from ~900 Å to 2000 Å.
XUV	Extreme Ultraviolet. Wavelength range from ~100 to 1200 Å.

APPENDIX B

FORTRAN OPTICAL COATING REFLECTIVITY PROGRAM

The program "OPTCOAT" which is listed on the following pages, was created to compute the reflectivity versus wavelength of a multi-layer coating at any desired angle of incidence. The program assumes that data files exist containing lists of wavelength (in microns) and n and k values, where the complex index of refraction is

$$g = n - ik.$$

The program also assumes, for multilayer calculations, that there is a one-to-one correspondence of the wavelengths in each list of optical constants being used, in other words, that the data files for each material have the same number of entries and are "synchronized" in wavelength.

The input data are: Mode (different printout options), Number of films (above the substrate material), the angle of incidence in degrees, and the physical thickness of each layer in Angstroms, starting with the layer adjacent to the substrate.

The output data include wavelength (in microns), s-polarization and p-polarization reflectivities, average reflectivity, transmittance and absorptance.

This program is adapted from one of John S. Loomis, Air Force Weapons Lab, Kirtland Air Force Base (reference 90). We gratefully acknowledge this help.

As examples of runs made with this program, a computation of the normal incidence reflectivity of pure aluminum, using the optical constants of Appendix C, and the normal incidence reflectivity of 280 Å aluminum over an iridium substrate, follows the Fortran program listing. (A plot of this pure aluminum data appears in Figure 3).

Program "OPTCOAT" Fortran Listing

```
C       PROGRAM OPTCOAT FORTRAN
C       OPTICAL COATING CALCULATIONS OF R, T, A
C       ADAPTED FROM JOHN LOOMIS, AWFL, 1975 PAPER
C       THIS VERSION BY ALAN BUNNER, 4 AUG 1983
C       UNIT 10 CONTAINS SUBSTRATE OPTICAL CONSTANTS
C       UNITS 11, 12, ... CONTAIN COATING OPT. CONSTANTS, BOTTOM TO TOP
C
       COMMON /FILM/ LAYER,WDD,UZ,HS,TS,USS,VSS,HF(4),TF(4),UFF(4),
     +  VFF(4)
       DIMENSION UF(4,110),VF(4,110),WD(110),US(110),VS(110),THIK(4)
       DIMENSION TITLE(20)
       DATA UZ/1.0/
       DATA PI/3.1415927/
       NWAVES=110
       UZ = 1.0
       WRITE (5,200)
 200      FORMAT(1X,' OPTICAL PROPERTIES OF THIN FILMS OVER SUBSTRATE',/,
     +       ' MODE=1 FOR SHORT PRINT OUT',/,
     +       ' MODE=2 FOR SPECTRAL SCAN ONLY',/,
     +       ' MODE=3 FOR ANGLE SCAN ONLY',/,
     +       ' MODE=4 FOR FULL PRINT OUT',/)
       WRITE (5,201)
 201      FORMAT(1X,' ENTER MODE,DESIGN WL,OPERATING WL,WL STEP,',
     +       ' NO. OF FILMS & ANGLE OF INC IN DEGREES',/)
C     ANGLE OF INCIDENCE IS MEASURED FROM NORMAL
       READ (5,100) MFM, WA, WB, WI, NFL,PHI
 100      FORMAT (I4,F8.3,F8.3,F8.3,I3,F8.5)
       MODE = MFM
       LAYER=NFL
       WRITE(5,203) MODE,WA,WB,WI,LAYER,PHI
 203   FORMAT(1X,' HAVE MODE= ',I3,1X,3(F9.6,1X),
     + ' NFL= ',I3,' ANGLE= ',F5.2)
C      NOW READ SUBSTRATE OPTICAL CONSTANTS DATA FILE
       READ (10,101) TITLE
 101      FORMAT (20A4)
       WRITE (5,102) (TITLE(KK), KK=1,16)
 102      FORMAT (1X,' SUBSTRATE IS ', 16A4)
       DO 103 I= 1,NWAVES
          READ (10,106) WD(I), US(I), VS(I)
          IF (WD(I) .LT. 0.) GO TO 104
 103   CONTINUE
 104   CONTINUE
 106      FORMAT (3F15.0)
C      NOW HAVE READ IN SUBSTRATE DATA FILE
       IFIN = I-1
       WRITE(5,151) IFIN
 151   FORMAT(1X,' HAVE READ IN ', I4,' LINES FOR SUBSTRATE')
       HS = TITLE(1)
       IF(LAYER.EQ.0) GO TO 500
C      NOW READ IN COATINGS DATA FILES
C    J=1 IS BOTTOM COAT, LAST =LAST (TOP) LAYER
       DO 500 J=1, NFL
       IUNIT=10+J
       READ (IUNIT,101) TITLE
```

```
      WRITE (5,105) J, (TITLE(KK), KK=1,15)
 105     FORMAT (1X,' COAT NO. ',I3,' IS ', 15A4)
      WRITE (5,107)
 107     FORMAT(1X,' INPUT PHYSICAL THICKNESS OF THIS LAYER IN ANGSTROMS
     +    AND NAME')
      READ (5,108) THIK(J), HF(J)
 108     FORMAT (F15.5,A4)
         DO 495 I=1, NWAVES
         READ (IUNIT,109) WL, UF(J,I), VF(J,I)
 109        FORMAT (3F15.0)
            IF (WL .LE. 0.) GO TO 496
 495     CONTINUE
 496     CONTINUE
         IFIN=I-1
      WRITE(5,152) IFIN
 152  FORMAT(1X, ' HAVE READ IN ',I4,' LINES FOR COATING')
 500  CONTINUE
C     NOW WE HAVE READ IN ALL COATING FILM DATA
C     NOW WE WILL CALL FILMD FOR ONLY ONE WAVELENGTH AT A TIME
C     ASSUME DATA FILES ARE SYNCHRONIZED IN WAVELENGTH
C
      WRITE (5,130) PHI
 130  FORMAT (' ANGLE=',F6.1,' DEGREES'/
     +   '0WAVELENGTH',3(5X,'REFLT',5X,'TRANS',4X,'ABSORP')/
     +   4X,'MICRONS',3(3X,'AVERAGE'),3(5X,'S-POL'),3(5X,'P-POL'))
      SIGMAR =0.
      DO 505 I=1, IFIN
         WDD=WD(I)
         WL=WDD
         WA=WDD
         WB=WDD
         WI=0.
C        MODE=0.
         USS=US(I)
         VSS=VS(I)
      IF(LAYER.EQ.0) GO TO 504
      DO 503 J=1,NFL
         TF(J)=THIK(J)*UF(J,I)/(WDD*1.E4)
         UFF(J)=UF(J,I)
         VFF(J)=VF(J,I)*40000.*PI/WDD
 503  CONTINUE
 504  CONTINUE
      CALL FILMD (MODE,WL,PHI,WA,WB,WI,RR)
      IF((WL.GT..09).AND.(WL.LT..122)) RR=2.*RR
      SIGMAR= SIGMAR + RR
 505  CONTINUE
      IF(IFIN.LE.1) IFIN=1
      FOM=SIGMAR/IFIN
      WRITE(5,507) IFIN,SIGMAR,FOM
 507  FORMAT(1X,I4,' WAVELNGTHS, SUM OF REFL= ',F12.3,
     + ' FIG OF MRT= ',F8.3)
      END
C
```

```
C
      SUBROUTINE FILMD (MODE,WL,PHI,WA,WB,WI,RR)
C
      COMMON /FILM/LAYER,WD,UZ,HS,TS,US,VS,HF(4),TF(4),UF(4),
     +   VF(4)
      DIMENSION PF(4), R(3), T(3), A(3)
C        TITLE
      IF(MODE.EQ.2) GO TO 910
      WRITE (5,909) WD
  909    FORMAT (1X,' COATING DESIGN WAVELENGTH ', F10.7,' MICRONS'/
     +    '0 N',5X,'NAME',13X,'OPT',7X,'THK',5X,'INDEX',6X,'BETA')
  910 CONTINUE
      IF (LAYER .EQ. 0) GO TO 30
      DO 20 I=1, LAYER
   20 PF(I)= TF(I)*WD/UF(I)
      IF(MODE.EQ.2) GO TO 117
C        PRINT FILM CONSTRUCTION
      DO 310 I=1, LAYER
      N= LAYER-I+1
  310 WRITE (5,110) N,HF(N),TF(N),PF(N),UF(N),VF(N)
  110    FORMAT (1X,I2,5X,A4,6X,2F10.5,F10.4,F10.3)
   30 CONTINUE
      IF(MODE.EQ.2) GO TO 117
      WRITE (5,111) HS,US,VS
  111    FORMAT (8X,A4,6X,20X,F10.5,F10.5,'  KAPPA')
C           SHORT DESIGN PRINTOUT
      CALL FILMS (LAYER,PF,UF,VF,PHI,WL,US,VS,UZ,R,T,A)
      WRITE (5,115) WL,PHI, R(1),T(1),A(1)
  115    FORMAT ('0 WAVELENGTH=',F10.7,' MICRONS',10X,'ANGLE=',F6.1,
     +' DEGREES'/10X,'REFLT',5X,'TRANS',4X,'ABSORP'/6X,3F10.4)
      IF (PHI .GT. 0.0) WRITE(5,116) R(2),T(2),A(2),R(3),T(3),A(3)
  116    FORMAT (' S-POL',3F10.4/' P-POL',3F10.4)
  117 CONTINUE
      IF (MODE. EQ. 1) RETURN
C        CALCULATE ANGLE PHOTOMETRY
C
      IF (MODE .LT. 3) GO TO 25
      WRITE(5,120) WL
  120    FORMAT ('1 WAVELENGTH=',F10.7,' MICRONS'/
     +   5X,'ANGLE',3(5X,'REFLT',5X,'TRANS',4X,'ABSORP')/
     +    4X,'DEGREES',3(3X,'AVERAGE'),3(5X,'S-POL'),3(5X,'P-POL'))
      DO 400 I= 1,90
      J=I-1
      ANGLE=J
      CALL FILMS (LAYER,PF,UF,VF,ANGLE,WL,US,VS,UZ,R,T,A)
      WRITE(5,125) J,(R(K),T(K),A(K), K=1,3)
  125    FORMAT (1X,I10,9F10.4)
      IF (I .EQ. 46) WRITE(5,120) WL
  400 CONTINUE
C           CALCULATE SPECTRAL PHOTOMETRY
   25 IF (MODE .EQ. 3) RETURN
      IF (MODE.EQ.2) GO TO 131
```

```
          WRITE (5,130) PHI
    130   FORMAT (' ANGLE=',F6.1,' DEGREES'/
         +    'OWAVELENGTH',3(5X,'REFLT',5X,'TRANS',4X,'ABSORP')/
         +    4X,'MICRONS',3(3X,'AVERAGE'),3(5X,'S-POL'),3(5X,'P-POL')
    131    CONTINUE
          W=WA-WI
    40    W=W+WI
          IF (W .GT. WB) RETURN
          CALL FILMS (LAYER,PF,UF,VF,PHI,W,US,VS,UZ,R,T,A)
          WRITE (5,135) W,(R(K),T(K),A(K), K=1, 3)
    135      FORMAT (1X,F10.7,9F10.4)
          RR=R(1)
          IF(WI.LT.1.E-5) RETURN
          GO TO 40
          END
  C
  C
          SUBROUTINE FILMS (LAYER,TK,UX,VK,ANGLE,WAVE,US,VS,UZ,R,T,A)
          DIMENSION TK(3),UX(3),VK(3),R(3),T(3),A(3)
          DIMENSION G9(8),G17(8),G25(8),GB(8),U(8)
          DATA TWOPI/6.283185307179/
          DATA U(1),U(2),U(3),U(4),U(5),U(6),U(7),U(8)/1.,
         + 0.,0.,0.,0.,0.,1.,0./
          DO 1 I=1,8
          GB(I)=U(I)
    1     G17(I)=U(I)
          PISIG=TWOPI/WAVE
          XK=-VS
          AX=0.017453293*ANGLE
          CX=SIN(AX)*UZ
  C       WRITE(5,603) UZ,CX
  C603    FORMAT(1X,' UX= ',E15.8,' CX= ',E15.8)
          USS=CX*CX
          AX=COS(AX)
  C       WRITE(5,602) I,LAYER,AX,BX
  C602    FORMAT(1X,' IN FILMS,I= ',I3,1X,I3,1X,E15.8,1X,E15.8)
          UY2=UZ/AX
          UY3=UZ*AX
          IF(LAYER .EQ. 0) GO TO 3
          DO 2 I= 1, LAYER
          J= LAYER-I+1
          QX=TK(J)*PISIG
          IF(QX .EQ. 0.0) GO TO 2
          DX=-0.00005*VK(J)/PISIG
          PX=QX*UX(J)
          CX=QX*DX
          CALL COSCM (UX(J),DX,COSR,COSJ,USS)
          DH=PX*COSR-CX*COSJ
          AJ= PX*COSJ+CX*COSR
          CALL COSSN (DH,AJ,G9(1),G9(2),RS,SJ)
          CALL DVC(UX(J),DX,COSR,COSJ,AX,BX)
```

```
      CALL MLC (RS,SJ,AX,BX,G9(3),G9(4))
      CALL DVC (RS,SJ,AX,BX,G9(5),G9(6))
      G9(7)=G9(1)
      G9(8)=G9(2)
      CALL MLC (UX(J),DX,COSR,COSJ,AX,BX)
      CALL MLC (RS,SJ,AX,BX,G25(3),G25(4))
      CALL DVC (RS,SJ,AX,BX,G25(5),G25(6))
      G25(1)=G9(1)
      G25(2)=G9(2)
      G25(7)=G9(1)
      G25(8)=G9(2)
      CALL MXM (G17,G25,G17)
      CALL MXM (G8,G9,G8)
    2 CONTINUE
    3 CALL COSCM (US,XK,COSR,COSJ,USS)
      CALL DVC (US,XK,COSR,COSJ,AX,BX)
      CALL RFTR (G8,AX,BX,UY2,T(3),R(3))
      CALL MLC(US,XK,COSR,COSJ,AX,BX)
      CALL RFTR (G17,AX,BX,UY3,T(2),R(2))
      R(1)= 0.5*(R(2)+R(3))
      T(1)= 0.5*(T(2)+T(3))
      A(1)= 100.-R(1)-T(1)
      A(2)= 100.-R(2)-T(2)
      A(3)= 100.-R(3)-T(3)
      RETURN
      END
C
      SUBROUTINE COSSN (DX,XIMAG,RCOS,XICOS,RSIN,XISIN)
      XD=DX
    1 REAL=XD
      CS=COS(REAL)
      SN=SIN(REAL)
      E=0.5*EXP(-XIMAG)
      CSH= 0.25/E
      SNH=CSH-E
      CSH=CSH+E
      RCOS=CS*CSH
      XICOS=-SN*SNH
      RSIN=-CS*SNH
      XISIN=SN*CSH
      RETURN
      END
C
      SUBROUTINE DVC (A,B,C,D,E,FA)
      X=C*C+D*D
      IF(X) 2,1,2
    1 X=1.E-30
    2 EW=(A*C+B*D)/X
      FA=(B*C-A*D)/X
      E=EW
      RETURN
      END
C
```

```
      SUBROUTINE MLC (A,B,C,D,E,FA)
      AW=A*C-B*D
      FA=A*D+B*C
      E=AW
      RETURN
      END
C
      SUBROUTINE MXM (A,B,C)
      DIMENSION A(8),B(8),C(8),D(8)
      D(1)=A(1)*B(1)-A(2)*B(2)+A(5)*B(3)-A(6)*B(4)
      D(2)=A(1)*B(2)+A(2)*B(1)+A(5)*B(4)+A(6)*B(3)
      D(3)=A(3)*B(1)-A(4)*B(2)+A(7)*B(3)-A(8)*B(4)
      D(4)=A(3)*B(2)+A(4)*B(1)+A(7)*B(4)+A(8)*B(3)
      D(5)=A(1)*B(5)-A(2)*B(6)+A(5)*B(7)-A(6)*B(8)
      D(6)=A(1)*B(6)+A(2)*B(5)+A(5)*B(8)+A(6)*B(7)
      D(7)=A(3)*B(5)-A(4)*B(6)+A(7)*B(7)-A(8)*B(8)
      D(8)=A(3)*B(6)+A(4)*B(5)+A(7)*B(8)+A(8)*B(7)
      DO 1 J=1,8
    1 C(J)=D(J)
      RETURN
      END
C
      SUBROUTINE COMSQ (A,B,C,D)
      HR=SQRT(.5*(ABS(A)+SQRT(A*A+B*B)))
      IF (HR) 1,3,1
    1 HI=.5*B/HR
      IF(A) 4,4,2
    2 C=HR
      D=HI
      RETURN
    3 HI=0.
      GO TO 2
    4 C=ABS(HI)
      IF (B) 5,6,6
    5 D=-HR
      RETURN
    6 D=HR
      RETURN
      END
C
```

```
C
      SUBROUTINE RFTR (G,SUB,XK,UY,TT,RR)
      DIMENSION G(8)
      ER=G(5)*SUB-G(6)*XK+G(1)
      EJ=G(5)*XK+G(6)*SUB+G(2)
      HR=G(7)*SUB-G(8)*XK+G(3)
      HJ=G(7)*XK+G(8)*SUB+G(4)
      G51 = ER*UY
      G52 = EJ*UY
       G61 = G51 + HR
      G62 = G52 + HJ
      G63 = G51-HR
      G64 = G52-HJ
      G48 = G61*G61 + G62*G62
C     WRITE(5,601) SUB,XK,G61,G62,G48
C601  FORMAT(1X,5(E15.8,1X))
      TT = 400.*SUB*UY/G48
      RR =100.*(G63*G63 + G64*G64)/G48
      RETURN
      END
C
C
      SUBROUTINE COSCM (UR,UJ,COSR,COSJ,USS)
    1 CALL MLC(UR,UJ,UR,UJ,A,B)
      CALL DVC(USS,0.,A,B,C,D)
      CALL COMSQ(1.-C,-D,COSR,COSJ)
      RETURN
      END
```

Table 4
Normal Incidence Reflectivity of Pure Aluminum

ANGLE= 0.0 DEGREES

WAVELENGTH MICRONS	REFLT AVERAGE	TRANS AVERAGE	ABSORP AVERAGE	REFLT S-POL	TRANS S-POL	ABSORP S-POL	REFLT P-POL	TRANS P-POL	ABSORP P-POL
0.0113000	0.0073	99.9928	-0.0000	0.0073	99.9928	-0.0000	0.0073	99.9928	-0.0000
0.0495920	1.1246	98.8755	-0.0001	1.1246	98.8755	-0.0001	1.1246	98.8755	-0.0001
0.0506040	1.2582	98.7418	-0.0000	1.2582	98.7418	-0.0000	1.2582	98.7418	-0.0000
0.0516580	1.4022	98.5979	-0.0000	1.4022	98.5979	-0.0000	1.4022	98.5979	-0.0000
0.0523120	1.5240	98.4761	-0.0001	1.5240	98.4761	-0.0001	1.5240	98.4761	-0.0001
0.0525340	1.5398	98.4602	0.0000	1.5398	98.4602	0.0000	1.5398	98.4602	0.0000
0.0529830	1.6196	98.3804	0.0	1.6196	98.3804	0.0	1.6196	98.3804	0.0
0.0532100	1.6358	98.3642	-0.0000	1.6358	98.3642	-0.0000	1.6358	98.3642	-0.0000
0.0534400	1.7018	98.2982	-0.0000	1.7018	98.2982	-0.0000	1.7018	98.2982	-0.0000
0536710	1.7355	98.2645	-0.0001	1.7355	98.2645	-0.0001	1.7355	98.2645	-0.0001
0537870	1.7525	98.2475	-0.0000	1.7525	98.2475	-0.0000	1.7525	98.2475	-0.0000
0.0539040	1.7696	98.2304	-0.0000	1.7696	98.2304	-0.0000	1.7696	98.2304	-0.0000
0.0540220	1.7866	98.2134	-0.0000	1.7866	98.2134	-0.0000	1.7866	98.2134	-0.0000
0.0541400	1.8211	98.1790	-0.0001	1.8211	98.1790	-0.0001	1.8211	98.1790	-0.0001
0.0543770	1.8559	98.1441	-0.0000	1.8559	98.1441	-0.0000	1.8559	98.1441	-0.0000
0.0548580	1.9630	98.0370	-0.0000	1.9630	98.0370	-0.0000	1.9630	98.0370	-0.0000
0.0553480	2.0552	97.9448	0.0	2.0552	97.9448	0.0	2.0552	97.9448	0.0
0.0558470	2.1694	97.8306	-0.0000	2.1694	97.8306	-0.0000	2.1694	97.8306	-0.0000
0.0563550	2.2682	97.7318	-0.0000	2.2682	97.7318	-0.0000	2.2682	97.7318	-0.0000
0.0568720	2.3900	97.6100	-0.0000	2.3900	97.6100	-0.0000	2.3900	97.6100	-0.0000
0.0573980	2.5158	97.4842	-0.0000	2.5158	97.4842	-0.0000	2.5158	97.4842	-0.0000
0.0579350	2.6458	97.3542	-0.0000	2.6458	97.3542	-0.0000	2.6458	97.3542	-0.0000
0.0590380	2.9654	97.0346	0.0	2.9654	97.0346	0.0	2.9654	97.0346	0.0
0.0604780	3.4116	96.5884	-0.0001	3.4116	96.5884	-0.0001	3.4116	96.5884	-0.0001
0.0619900	3.9869	96.0132	-0.0001	3.9869	96.0132	-0.0001	3.9869	96.0132	-0.0001
0.0635790	4.6530	95.3470	0.0000	4.6530	95.3470	0.0000	4.6530	95.3470	0.0000
0.0652530	5.5346	94.4654	-0.0000	5.5346	94.4654	-0.0000	5.5346	94.4654	-0.0000
0.0666560	6.4044	93.5957	-0.0001	6.4044	93.5957	-0.0001	6.4044	93.5957	-0.0001
0.0670159	6.6463	93.3537	-0.0001	6.6463	93.3537	-0.0001	6.6463	93.3537	-0.0001
0.0673800	6.8949	93.1053	-0.0002	6.8949	93.1053	-0.0002	6.8949	93.1053	-0.0002
0.0677490	7.1923	92.8078	-0.0002	7.1923	92.8078	-0.0002	7.1923	92.8078	-0.0002
0.0688780	8.0948	91.9053	-0.0001	8.0948	91.9053	-0.0001	8.0948	91.9053	-0.0001
0.0700450	9.0228	90.9773	-0.0001	9.0228	90.9773	-0.0001	9.0228	90.9773	-0.0001
0.0704430	9.5436	90.4566	-0.0001	9.5436	90.4566	-0.0001	9.5436	90.4566	-0.0001
0.0708460	10.0285	89.9715	-0.0001	10.0285	89.9715	-0.0001	10.0285	89.9715	-0.0001
0712529	10.2504	89.7497	-0.0000	10.2504	89.7497	-0.0000	10.2504	89.7497	-0.0000
0.0716650	11.2321	88.7679	-0.0000	11.2321	88.7679	-0.0000	11.2321	88.7679	-0.0000
0.0733610	13.4797	86.5204	-0.0001	13.4797	86.5204	-0.0001	13.4797	86.5204	-0.0001
0.0755979	17.8669	82.1331	-0.0001	17.8669	82.1331	-0.0001	17.8669	82.1331	-0.0001
0.0765310	20.3114	79.6887	-0.0002	20.3114	79.6887	-0.0002	20.3114	79.6887	-0.0002
0.0770060	21.6780	78.3222	-0.0002	21.6780	78.3222	-0.0002	21.6780	78.3222	-0.0002
0.0774879	23.2284	76.7717	-0.0001	23.2284	76.7717	-0.0001	23.2284	76.7717	-0.0001
0.0779750	24.9802	75.0200	-0.0002	24.9802	75.0200	-0.0002	24.9802	75.0200	-0.0002
0.0784680	26.9532	73.0468	-0.0000	26.9532	73.0468	-0.0000	26.9532	73.0468	-0.0000
0.0789680	29.1936	70.8065	-0.0001	29.1936	70.8065	-0.0001	29.1936	70.8065	-0.0001
0.0799870	35.0391	64.9610	-0.0001	35.0391	64.9610	-0.0001	35.0391	64.9610	-0.0001

Table 4. (Continued)

0.0810330	43.5077	56.4924	-0.0000	43.5077	56.4924	-0.0000	43.5077	56.4924	-0.0000
0.0821060	54.9653	45.0349	-0.0002	54.9653	45.0349	-0.0002	54.9653	45.0349	-0.0002
0.0826530	61.2112	38.7887	0.0000	61.2112	38.7887	0.0000	61.2112	38.7887	0.0000
0.0832080	66.7621	33.2381	-0.0002	66.7621	33.2381	-0.0002	66.7621	33.2381	-0.0002
0.0843400	75.8754	24.1247	-0.0001	75.8754	24.1247	-0.0001	75.8754	24.1247	-0.0001
0.0849180	77.9065	22.0937	-0.0002	77.9065	22.0937	-0.0002	77.9065	22.0937	-0.0002
0.0855030	79.6463	20.3538	-0.0002	79.6463	20.3538	-0.0002	79.6463	20.3538	-0.0002
0.0860969	81.0813	18.9188	-0.0001	81.0813	18.9188	-0.0001	81.0813	18.9188	-0.0001
0.0866989	82.1940	17.8062	-0.0002	82.1940	17.8062	-0.0002	82.1940	17.8062	-0.0002
0.0873100	83.0120	16.9880	-0.0001	83.0120	16.9880	-0.0001	83.0120	16.9880	-0.0001
0.0879290	84.1084	15.8916	-0.0001	84.1084	15.8916	-0.0001	84.1084	15.8916	-0.0001
0.0885569	84.9081	15.0921	-0.0002	84.9081	15.0921	-0.0002	84.9081	15.0921	-0.0002
0.0888750	85.0732	14.9269	-0.0001	85.0732	14.9269	-0.0001	85.0732	14.9269	-0.0001
0.0891940	85.5094	14.4907	-0.0002	85.5094	14.4907	-0.0002	85.5094	14.4907	-0.0002
0.0895160	85.9040	14.0960	0.0	85.9040	14.0960	-0.0000	85.9040	14.0960	-0.0000
0.0898409	86.3156	13.6845	-0.0001	86.3156	13.6845	-0.0001	86.3156	13.6845	-0.0001
0.0901670	86.5542	13.4458	0.0	86.5542	13.4458	-0.0000	86.5542	13.4458	-0.0000
0.0904959	86.8202	13.1798	-0.0000	86.8202	13.1798	-0.0000	86.8202	13.1798	-0.0000
0.0908279	87.0849	12.9151	0.0	87.0849	12.9151	-0.0000	87.0849	12.9151	-0.0000
0.0911620	87.3388	12.6614	-0.0002	87.3388	12.6614	-0.0002	87.3388	12.6614	-0.0002
0.0914980	87.6005	12.3996	-0.0001	87.6005	12.3996	-0.0001	87.6005	12.3996	-0.0001
0.0918370	87.8607	12.1394	-0.0002	87.8607	12.1394	-0.0002	87.8607	12.1394	-0.0002
0.0921780	88.0584	11.9417	-0.0000	88.0584	11.9417	-0.0000	88.0584	11.9417	-0.0000
0.0925220	88.2551	11.7450	-0.0001	88.2551	11.7450	-0.0001	88.2551	11.7450	-0.0001
0.0928690	88.4507	11.5494	-0.0001	88.4507	11.5494	-0.0001	88.4507	11.5494	-0.0001
0.0932180	88.6451	11.3550	-0.0002	88.6451	11.3550	-0.0002	88.6451	11.3550	-0.0002
0.0935700	88.8382	11.1619	-0.0001	88.8382	11.1619	-0.0001	88.8382	11.1619	-0.0001
0.0939240	88.9730	11.0272	-0.0002	88.9730	11.0272	-0.0002	88.9730	11.0272	-0.0002
0.0942810	89.1070	10.8931	-0.0001	89.1070	10.8931	-0.0001	89.1070	10.8931	-0.0001
0.0946410	89.2404	10.7597	-0.0001	89.2404	10.7597	-0.0001	89.2404	10.7597	-0.0001
0.0950040	89.3732	10.6269	-0.0001	89.3732	10.6269	-0.0001	89.3732	10.6269	-0.0001
0.0953690	89.5052	10.4949	-0.0001	89.5052	10.4949	-0.0001	89.5052	10.4949	-0.0001
0.0957370	89.7143	10.2857	-0.0001	89.7143	10.2857	-0.0001	89.7143	10.2857	-0.0001
0.0961090	89.9217	10.0783	-0.0001	89.9217	10.0783	-0.0001	89.9217	10.0783	-0.0001
0.0964820	90.1018	9.8984	-0.0002	90.1018	9.8984	-0.0002	90.1018	9.8984	-0.0002
0.0968590	90.2292	9.7708	-0.0000	90.2292	9.7708	-0.0000	90.2292	9.7708	-0.0000
0.0972390	90.4066	9.5935	-0.0002	90.4066	9.5935	-0.0002	90.4066	9.5935	-0.0002
0.0976220	90.5823	9.4178	-0.0001	90.5823	9.4178	-0.0001	90.5823	9.4178	-0.0001
0.0980080	90.7647	9.2354	-0.0001	90.7647	9.2354	-0.0001	90.7647	9.2354	-0.0001
0.0983970	90.9372	9.0629	-0.0001	90.9372	9.0629	-0.0001	90.9372	9.0629	-0.0001
0.0991840	91.2774	8.7227	-0.0001	91.2774	8.7227	-0.0001	91.2774	8.7227	-0.0001
0.0999840	91.4662	8.5339	-0.0001	91.4662	8.5339	-0.0001	91.4662	8.5339	-0.0001
0.1007970	91.6523	8.3477	-0.0000	91.6523	8.3477	-0.0000	91.6523	8.3477	-0.0000
0.1016230	91.8359	8.1641	-0.0000	91.8359	8.1641	-0.0000	91.8359	8.1641	-0.0000
0.1026000	92.0317	7.9684	-0.0001	92.0317	7.9684	-0.0001	92.0317	7.9684	-0.0001
0.1033170	92.2022	7.7979	-0.0000	92.2022	7.7979	-0.0000	92.2022	7.7979	-0.0000
0.1055149	92.5325	7.4675	-0.0000	92.5325	7.4675	-0.0000	92.5325	7.4675	-0.0000
0.1064000	92.6799	7.3201	-0.0000	92.6799	7.3201	-0.0000	92.6799	7.3201	-0.0000
0.1078089	92.8524	7.1476	0.0000	92.8524	7.1476	0.0000	92.8524	7.1476	0.0000
0.1100000	92.9347	7.0654	-0.0001	92.9347	7.0654	-0.0001	92.9347	7.0654	-0.0001
0.1102040	92.8755	7.1246	-0.0001	92.8755	7.1246	-0.0001	92.8755	7.1246	-0.0001
0.1127090	92.9125	7.0875	-0.0001	92.9125	7.0875	-0.0001	92.9125	7.0875	-0.0001
0.1149999	92.8574	7.1426	-0.0001	92.8574	7.1426	-0.0001	92.8574	7.1426	-0.0001
0.1180760	92.8551	7.1449	-0.0000	92.8551	7.1449	-0.0000	92.8551	7.1449	-0.0000
0.1216000	92.8721	7.1280	-0.0000	92.8721	7.1280	-0.0000	92.8721	7.1280	-0.0000
0.1239800	92.8964	7.1036	-0.0000	92.8964	7.1036	-0.0000	92.8964	7.1036	-0.0000
0.1300000	92.8836	7.1164	-0.0000	92.8836	7.1164	-0.0000	92.8836	7.1164	-0.0000
0.1377560	92.7290	7.2710	0.0001	92.7290	7.2710	0.0001	92.7290	7.2710	0.0001
0.1400000	92.7275	7.2725	-0.0000	92.7275	7.2725	-0.0000	92.7275	7.2725	-0.0000
0.1549750	92.6432	7.3568	0.0000	92.6432	7.3568	0.0000	92.6432	7.3568	0.0000
0.1600000	92.6326	7.3674	0.0000	92.6326	7.3674	0.0000	92.6326	7.3674	0.0000
0.1771140	92.5945	7.4055	0.0000	92.5945	7.4055	0.0000	92.5945	7.4055	0.0000

108 WAVELNGTHS, SUM OF REFL= 9264.559 FIG OF MRT= 85.783

Table 5
Computation of Reflectivity of 280Å Aluminum Over Iridium

```
15:27:02 >OPTCT2
FI 10 DISK IRRID2 OPTCON A1 ( RECFM FB LRECL 80 BLKSIZ 800 DISP MOD PERM )
FI 11 DISK ALUM2 OPTCON A1 ( RECFM FB LRECL 80 BLKSIZ 800 DISP MOD PERM )
FI 12 DISK LIF OPTCON A1 ( RECFM FB LRECL 80 BLKSIZ 800 DISP MOD PERM )
FI 8 PRT
FI 6 TERMINAL
LOAD OPTCOAT ( CLEAR
START
EXECUTION:
 OPTICAL PROPERTIES OF THIN FILMS OVER SUBSTRATE
MODE=1 FOR SHORT PRINT OUT
MODE=2 FOR SPECTRAL SCAN ONLY
MODE=3 FOR ANGLE SCAN ONLY
MODE=4 FOR FULL PRINT OUT

 ENTER MODE,DESIGN WL,OPERATING WL,WL STEP, NO. OF FILMS & ANGLE OF INC IN DEGREES

>2, 0., 0., 0., 1, 0.,
*HAVE MODE=   2  0.0        0.0        0.0        NFL=    1 ANGLE=   0.0
 SUBSTRATE IS IRRI N AND K, 108 VALUES, 113-1771 A
 HAVE READ IN  108 LINES FOR SUBSTRATE
 COAT NO.    1 IS ALUM N AND K, 108 VALUES, 113-1771 A
 INPUT PHYSICAL THICKNESS OF THIS LAYER IN ANGSTROMS    AND NAME
>280.,ALUM ,
 HAVE READ IN  108 LINES FOR COATING
ANGLE=   0.0 DEGREES
```

WAVELENGTH MICRONS	REFLT AVERAGE	TRANS AVERAGE	ABSORP AVERAGE	REFLT S-POL	TRANS S-POL	ABSORP S-POL	REFLT P-POL	TRANS P-POL	ABSORP P-POL
0.0113000	0.0583	68.7663	31.1754	0.0583	68.7663	31.1754	0.0583	68.7663	31.1754
0.0495920	12.1521	72.1912	15.6566	12.1521	72.1912	15.6566	12.1521	72.1912	15.6566
0.0506040	11.8196	71.9426	16.2379	11.8196	71.9426	16.2379	11.8196	71.9426	16.2379
0.0516580	10.9811	71.4551	17.5638	10.9811	71.4551	17.5638	10.9811	71.4551	17.5638
0.0523120	10.7891	70.7369	18.4740	10.7891	70.7369	18.4740	10.7891	70.7369	18.4740
0.0525340	10.8376	70.4402	18.7222	10.8376	70.4402	18.7222	10.8376	70.4402	18.7222
0.0529830	10.8557	69.8588	19.2855	10.8557	69.8588	19.2855	10.8557	69.8588	19.2855
0.0532100	10.9405	69.6358	19.4236	10.9405	69.6358	19.4236	10.9405	69.6358	19.4236
0.0534400	10.8909	69.3143	19.7948	10.8909	69.3143	19.7948	10.8909	69.3143	19.7948
0.0536710	10.9855	68.9786	20.0359	10.9855	68.9786	20.0358	10.9855	68.9786	20.0358
0.0537870	11.0949	68.7326	20.1726	11.0949	68.7326	20.1726	11.0949	68.7326	20.1726
0.0539040	11.1589	68.5517	20.2894	11.1589	68.5517	20.2894	11.1589	68.5517	20.2894
0.0540220	11.2068	68.4910	20.3022	11.2068	68.4910	20.3021	11.2068	68.4910	20.3021
0.0541400	11.2653	68.3954	20.3394	11.2653	68.3954	20.3394	11.2653	68.3954	20.3394
0.0543770	11.4086	68.2364	20.3550	11.4086	68.2364	20.3550	11.4086	68.2364	20.3550
0.0548580	11.8100	67.6981	20.4919	11.8100	67.6981	20.4919	11.8100	67.6981	20.4919
0.0553480	12.2488	67.2169	20.5343	12.2488	67.2169	20.5343	12.2488	67.2169	20.5343
0.0558470	12.7467	66.6481	20.6051	12.7467	66.6481	20.6051	12.7467	66.6481	20.6051
0.0563550	13.2252	65.8247	20.9501	13.2252	65.8247	20.9501	13.2252	65.8247	20.9501
0.0568720	14.0696	64.8016	21.1288	14.0696	64.8016	21.1288	14.0696	64.8016	21.1288
0.0573980	15.0518	63.6901	21.2581	15.0518	63.6901	21.2581	15.0518	63.6901	21.2581
0.0579350	16.1589	62.5030	21.3381	16.1589	62.5030	21.3381	16.1589	62.5030	21.3381
0.0590380	18.9206	59.7424	21.3370	18.9206	59.7424	21.3370	18.9206	59.7424	21.3370
0.0604780	22.6916	56.3264	20.9820	22.6916	56.3264	20.9820	22.6916	56.3264	20.9820
0.0619900	26.9370	52.1473	20.9156	26.9370	52.1473	20.9156	26.9370	52.1473	20.9156
0.0635790	31.0421	49.2110	19.7469	31.0421	49.2110	19.7469	31.0421	49.2110	19.7469
0.0652530	35.3918	45.7153	18.8929	35.3918	45.7153	18.8929	35.3918	45.7153	18.8929
0.0666560	38.7276	43.3062	17.9662	38.7276	43.3062	17.9662	38.7276	43.3062	17.9662
0.0670159	39.5141	42.7034	17.7825	39.5141	42.7034	17.7825	39.5141	42.7034	17.7825
0.0673800	40.2630	42.0996	17.6374	40.2630	42.0996	17.6374	40.2630	42.0996	17.6374
0.0677490	41.1461	41.5098	17.3441	41.1461	41.5098	17.3441	41.1461	41.5098	17.3441
0.0688780	43.3044	39.8512	16.8444	43.3044	39.8512	16.8444	43.3044	39.8512	16.8444
0.0700450	44.9569	39.0452	15.9979	44.9569	39.0452	15.9979	44.9569	39.0452	15.9979
0.0704430	45.6770	38.3567	15.9664	45.6770	38.3567	15.9664	45.6770	38.3567	15.9664
0.0708460	46.5145	37.8367	15.6487	46.5145	37.8367	15.6487	46.5145	37.8367	15.6487
0.0712529	46.7425	37.7631	15.4944	46.7425	37.7631	15.4944	46.7425	37.7631	15.4944
0.0716650	48.2959	36.6238	15.0803	48.2959	36.6238	15.0803	48.2959	36.6238	15.0803
0.0733610	51.0468	34.5329	14.4203	51.0468	34.5329	14.4203	51.0468	34.5329	14.4203
0.0755979	55.1186	31.4227	13.4587	55.1186	31.4227	13.4587	55.1186	31.4227	13.4587
0.0765310	56.6789	29.9963	13.3248	56.6789	29.9963	13.3248	56.6789	29.9963	13.3248

Table 5. (Continued)

0770060	57.5309	29.3915	13.0776	57.5309	29.3915	13.0776	57.5309	29.3915	13.0776
0.0774879	58.3125	28.7249	12.9626	58.3125	28.7249	12.9626	58.3125	28.7249	12.9626
0.0779750	59.1106	28.1413	12.7481	59.1106	28.1413	12.7481	59.1106	28.1413	12.7481
0.0784680	60.0791	27.6427	12.2782	60.0791	27.6427	12.2782	60.0791	27.6427	12.2782
0.0789680	60.8541	27.0831	12.0628	60.8541	27.0831	12.0628	60.8541	27.0831	12.0628
0.0799870	62.7822	25.9106	11.3072	62.7822	25.9106	11.3072	62.7822	25.9106	11.3072
0.0810330	64.6598	24.8240	10.5162	64.6598	24.8240	10.5162	64.6598	24.8240	10.5162
0.0821060	66.4664	23.5077	10.0259	66.4664	23.5077	10.0259	66.4664	23.5077	10.0259
0.0826530	67.3737	22.9066	9.7197	67.3737	22.9066	9.7197	67.3737	22.9066	9.7197
0.0832080	68.3135	22.3093	9.3773	68.3135	22.3093	9.3773	68.3135	22.3093	9.3773
0.0843400	70.3871	21.1479	8.4650	70.3871	21.1479	8.4650	70.3871	21.1479	8.4650
0.0849180	70.9787	20.5069	8.5143	70.9787	20.5069	8.5143	70.9787	20.5069	8.5143
0.0855030	71.5994	19.9277	8.4728	71.5994	19.9277	8.4728	71.5994	19.9277	8.4728
0.0860969	72.2342	19.3631	8.4027	72.2342	19.3631	8.4027	72.2342	19.3631	8.4027
0.0866989	72.8724	18.7947	8.3329	72.8724	18.7947	8.3329	72.8724	18.7947	8.3329
0.0873100	73.4318	18.2209	8.3474	73.4318	18.2209	8.3474	73.4318	18.2209	8.3474
0.0879290	74.1753	17.6785	8.1462	74.1753	17.6785	8.1462	74.1753	17.6785	8.1462
0.0885569	74.8153	17.1336	8.0511	74.8153	17.1336	8.0511	74.8153	17.1336	8.0511
0.0888750	74.9527	17.0300	8.0174	74.9527	17.0300	8.0174	74.9527	17.0300	8.0174
0.0891940	75.3913	16.6205	7.9883	75.3913	16.6205	7.9883	75.3913	16.6205	7.9883
0.0895160	75.7546	16.3381	7.9073	75.7546	16.3381	7.9073	75.7546	16.3381	7.9073
0.0898409	76.1166	16.0915	7.7920	76.1166	16.0915	7.7920	76.1166	16.0915	7.7920
0.0901670	76.3951	15.8347	7.7703	76.3951	15.8347	7.7703	76.3951	15.8347	7.7703
0.0904959	76.6920	15.5818	7.7263	76.6920	15.5818	7.7263	76.6920	15.5818	7.7263
0.0908279	76.9923	15.3310	7.6767	76.9923	15.3310	7.6767	76.9923	15.3310	7.6767
0911620	77.2693	15.1168	7.6138	77.2693	15.1168	7.6138	77.2693	15.1168	7.6138
.0914980	77.5647	14.8808	7.5545	77.5647	14.8808	7.5545	77.5647	14.8808	7.5545
0.0918370	77.8627	14.6469	7.4904	77.8627	14.6469	7.4904	77.8627	14.6469	7.4904
0.0921780	78.1168	14.4299	7.4534	78.1168	14.4299	7.4534	78.1168	14.4299	7.4534
0.0925220	78.3598	14.2286	7.4117	78.3598	14.2286	7.4117	78.3598	14.2286	7.4117
0.0928690	78.6167	14.0156	7.3676	78.6167	14.0156	7.3676	78.6167	14.0156	7.3676
0.0932180	78.8752	13.8045	7.3203	78.8752	13.8045	7.3203	78.8752	13.8045	7.3203
0.0935700	79.1322	13.5990	7.2688	79.1322	13.5990	7.2688	79.1322	13.5990	7.2688
0.0939240	79.3397	13.4107	7.2496	79.3397	13.4107	7.2496	79.3397	13.4107	7.2496
0.0942810	79.5574	13.2148	7.2279	79.5574	13.2148	7.2279	79.5574	13.2148	7.2279
0.0946410	79.7751	13.0211	7.2038	79.7751	13.0211	7.2038	79.7751	13.0211	7.2038
0.0950040	79.9907	12.8331	7.1762	79.9907	12.8331	7.1762	79.9907	12.8331	7.1762
0.0953690	80.1990	12.6532	7.1478	80.1990	12.6532	7.1478	80.1990	12.6532	7.1478
0.0957370	80.4657	12.4712	7.0630	80.4657	12.4712	7.0630	80.4657	12.4712	7.0630
0.0961090	80.7231	12.3008	6.9761	80.7231	12.3008	6.9761	80.7231	12.3008	6.9761
0.0964820	80.9731	12.1215	6.9054	80.9731	12.1215	6.9054	80.9731	12.1215	6.9054
0.0968590	81.1872	11.9450	6.8679	81.1872	11.9450	6.8679	81.1872	11.9450	6.8679
0.0972390	81.4421	11.7655	6.7924	81.4421	11.7655	6.7924	81.4421	11.7655	6.7924
0.0976220	81.6936	11.5919	6.7145	81.6936	11.5919	6.7145	81.6936	11.5919	6.7145
0.0980080	81.9727	11.3900	6.6373	81.9727	11.3900	6.6373	81.9727	11.3900	6.6373
0.0983970	82.2217	11.2221	6.5562	82.2217	11.2221	6.5562	82.2217	11.2221	6.5562
0.0991840	82.7177	10.8910	6.3913	82.7177	10.8910	6.3912	82.7177	10.8910	6.3912
0.0999840	83.1078	10.5625	6.3297	83.1078	10.5625	6.3297	83.1078	10.5625	6.3297
0.1007970	83.4693	10.2689	6.2618	83.4693	10.2689	6.2618	83.4693	10.2689	6.2618
0.1016230	83.8202	9.9890	6.1907	83.8202	9.9890	6.1907	83.8202	9.9890	6.1907
0.1026000	84.2008	9.6910	6.1083	84.2008	9.6910	6.1083	84.2008	9.6910	6.1083
1033170	84.5332	9.4299	6.0370	84.5332	9.4299	6.0370	84.5332	9.4299	6.0370
0.1055149	85.3259	8.7573	5.9168	85.3259	8.7573	5.9168	85.3259	8.7573	5.9168
0.1064000	85.6904	8.4575	5.8522	85.6904	8.4575	5.8522	85.6904	8.4575	5.8522
0.1078089	86.0263	8.2084	5.7653	86.0263	8.2084	5.7653	86.0263	8.2084	5.7653
0.1100000	86.4290	7.7756	5.7954	86.4290	7.7756	5.7954	86.4290	7.7756	5.7954
0.1102040	86.3864	7.7691	5.8445	86.3864	7.7691	5.8445	86.3864	7.7691	5.8445
0.1127090	86.7332	7.3641	5.9027	86.7332	7.3641	5.9027	86.7332	7.3641	5.9027
0.1149999	86.8977	7.0644	6.0380	86.8977	7.0644	6.0380	86.8977	7.0644	6.0380
0.1180760	87.0551	6.8255	6.1195	87.0551	6.8255	6.1195	87.0551	6.8255	6.1195
0.1216000	87.2289	6.5623	6.2088	87.2289	6.5623	6.2088	87.2289	6.5623	6.2088
0.1239800	87.4111	6.3376	6.2513	87.4111	6.3376	6.2513	87.4111	6.3376	6.2513
0.1300000	87.9242	5.6331	6.4427	87.9242	5.6331	6.4427	87.9242	5.6331	6.4427
0.1377560	88.2686	4.9796	6.7518	88.2686	4.9796	6.7518	88.2686	4.9796	6.7518
0.1400000	88.4860	4.7088	6.8052	88.4860	4.7088	6.8052	88.4860	4.7088	6.8052
0.1549750	89.5651	3.3170	7.1179	89.5651	3.3170	7.1179	89.5651	3.3170	7.1179
1600000	89.9341	2.8796	7.1863	89.9341	2.8796	7.1863	89.9341	2.8796	7.1863
0.1771140	90.8166	1.8892	7.2942	90.8166	1.8892	7.2942	90.8166	1.8892	7.2942

108 WAVELNGTHS, SUM OF REFL= 9485.328 FIG OF MRT= 87.827

APPENDIX C

TABLES OF OPTICAL CONSTANT

The tables on the following pages list the optical constants n and k for coating materials that we have considered in this study, aluminum, aluminum oxide (Al_2O_3), iridium and lithium fluoride, for wavelengths from $\lambda = 113$ Å to 1771 Å (7 eV to 110 eV), with frequent values given for $\lambda = 500$ Å to 1200 Å. The data for aluminum is from Physics Data, Volume 2 (169), with some interpolations. The data for Al_2O_3 and for iridium are from a 1982-83 compilation by Michael Hettrick (University of California, Berkeley) based on an exhaustive survey of experimental and theoretical literature (71, 199). We are grateful to Hettrick for this data. The constants for lithium fluoride are largely from Roessler and Walker (188), with some interpolations, and are based on bulk LiF rather than thin film data. This data was considered more reliable than that of Kato (197, 198).

Although not tabulated in this Appendix, we have also used n and k data for magnesium fluoride (MgF_2) from Gillette (50) and from a Perkin-Elmer optical constant data file.

The complex index of refraction g = n - ik is related to other commonly used optical constants by the following inter-relationships:

$n \equiv$ real index of refraction

$k \equiv$ extinction coefficient or absorption index

$K =$ complex dielectric constant $= (1-\delta-ik)^2$

$K = \varepsilon_1 + i\varepsilon_2$

$\beta \equiv$ absorption coefficient (cm^{-1})

$\varepsilon_1 = (1-\delta)^2 - k^2$

$\varepsilon_2 = -2k(1-\delta)$

$\beta = 4\pi k/\lambda$

$\delta = 1-n$

Table 6
Optical Constants of Aluminum in Far Ultraviolet

OPTICAL CONSTANTS OF ALUMINUM IN FAR UV

WAVELENGTH(A)	N	K
113.00	0.9880	0.0120
495.92	0.8090	0.0180
506.04	0.7990	0.0180
516.58	0.7890	0.0190
523.12	0.7810	0.0196
525.34	0.7800	0.0199
529.83	0.7750	0.0202
532.10	0.7740	0.0203
534.40	0.7700	0.0206
536.71	0.7680	0.0208
537.87	0.7670	0.0209
539.04	0.7660	0.0210
540.22	0.7650	0.0210
541.40	0.7630	0.0210
543.77	0.7610	0.0210
548.58	0.7550	0.0211
553.48	0.7500	0.0212
558.47	0.7440	0.0214
563.55	0.7390	0.0220
568.72	0.7330	0.0224
573.98	0.7270	0.0228
579.35	0.7210	0.0232
590.38	0.7070	0.0240
604.78	0.6890	0.0250
619.90	0.6680	0.0270
635.79	0.6460	0.0280
652.53	0.6200	0.0300
666.56	0.5970	0.0315
670.16	0.5910	0.0320
673.80	0.5850	0.0326
677.49	0.5780	0.0330
688.78	0.5580	0.0350
700.45	0.5390	0.0361
704.43	0.5290	0.0375
708.46	0.5200	0.0380
712.53	0.5160	0.0384
716.65	0.4990	0.0395
733.61	0.4640	0.0432
755.98	0.4070	0.0500
765.31	0.3800	0.0550
770.06	0.3660	0.0570
774.88	0.3510	0.0600
779.75	0.3350	0.0630
784.68	0.3180	0.0650
789.68	0.3000	0.0690
799.87	0.2580	0.0780
810.33	0.2070	0.0940
821.06	0.1510	0.1280
826.53	0.1250	0.1530
832.08	0.1040	0.1810
843.40	0.0730	0.2430
849.18	0.0670	0.2730

Table 6. (Continued)

855.03	0.0620	0.3010
860.97	0.0580	0.3270
866.99	0.0550	0.3500
873.10	0.0530	0.3730
879.29	0.0500	0.3950
885.57	0.0480	0.4170
888.75	0.0476	0.4220
891.94	0.0466	0.4370
895.16	0.0456	0.4480
898.41	0.0445	0.4580
901.67	0.0440	0.4680
904.96	0.0434	0.4780
908.28	0.0428	0.4880
911.62	0.0422	0.4970
914.98	0.0416	0.5070
918.37	0.0410	0.5170
921.78	0.0406	0.5264
925.22	0.0402	0.5358
928.69	0.0398	0.5452
932.18	0.0394	0.5546
935.70	0.0390	0.5640
939.24	0.0388	0.5730
942.81	0.0386	0.5820
946.41	0.0384	0.5910
950.04	0.0382	0.6000
953.69	0.0380	0.6090
957.37	0.0375	0.6180
961.09	0.0370	0.6270
964.82	0.0366	0.6360
968.59	0.0364	0.6450
972.39	0.0360	0.6540
976.22	0.0356	0.6630
980.08	0.0352	0.6730
983.97	0.0348	0.6820
991.84	0.0340	0.7000
999.84	0.0338	0.7180
1007.97	0.0336	0.7360
1016.23	0.0334	0.7540
1026.00	0.0332	0.7740
1033.17	0.0330	0.7910
1055.15	0.0330	0.8370
1064.00	0.0330	0.8580
1078.09	0.0330	0.8830
1100.00	0.0341	0.9280
1102.04	0.0345	0.9310
1127.09	0.0360	0.9790
1150.00	0.0380	1.0250
1180.76	0.0400	1.0760
1216.00	0.0424	1.1370
1239.80	0.0440	1.1780
1300.00	0.0490	1.2860
1377.56	0.0560	1.4020
1400.00	0.0580	1.4390
1549.75	0.0720	1.6630
1600.00	0.0770	1.7380
1771.14	0.0950	1.9830

Table 7
Optical Constants of Aluminum Oxide (Al_2O_3) in Far Ultraviolet

OPTICAL CONSTANTS OF AL2O3 IN FAR UV

WAVELENGTH(A)	N	K
113.00	0.7680	0.0233
495.92	0.7350	0.4442
506.04	0.7285	0.4722
516.58	0.7220	0.5020
523.12	0.7254	0.5227
525.34	0.7305	0.5296
529.83	0.7347	0.5434
531.10	0.7369	0.5502
534.40	0.7370	0.5572
536.71	0.7411	0.5641
537.87	0.7430	0.5710
539.01	0.7432	0.5717
540.22	0.7443	0.5757
541.40	0.7454	0.5796
543.77	0.7476	0.5876
548.58	0.7519	0.6034
553.48	0.7563	0.6193
558.47	0.7606	0.6351
563.58	0.7650	0.6510
568.73	0.7744	0.6654
573.98	0.7838	0.6798
579.35	0.7932	0.6942
590.38	0.8130	0.7230
604.78	0.8410	0.7470
619.90	0.8620	0.7690
635.79	0.8800	0.7940
652.53	0.8960	0.8250
666.56	0.9060	0.8420
670.16	0.9211	0.8674
673.80	0.9263	0.8763
677.49	0.9313	0.8852
688.78	0.9470	0.9120
700.45	0.9728	0.9370
704.43	0.9814	0.9453
708.46	0.9900	0.9536
712.53	0.9994	0.9621
716.65	1.0088	0.9705
733.61	1.0463	1.0043
755.98	1.1028	1.0408
765.31	1.1254	1.0554
770.06	1.1367	1.0627
774.88	1.1480	1.0700
779.75	1.1625	1.0770
784.68	1.1770	1.0840
789.68	1.1915	1.0910
799.87	1.2205	1.1000
810.33	1.2495	1.1190
821.06	1.2735	1.1330
826.53	1.2930	1.1400
832.08	1.3103	1.1440
843.40	1.3346	1.1520
849.18	1.3618	1.1560

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Table 7. (Continued)

855.03	1.3790	1.1600
860.97	1.3970	1.1600
866.49	1.4160	1.1600
873.10	1.4342	1.1600
879.29	1.4526	1.1600
885.57	1.4710	1.1600
888.75	1.4794	1.1610
891.94	1.4878	1.1620
895.16	1.4962	1.1630
898.41	1.5046	1.1640
901.67	1.5130	1.1650
904.96	1.5214	1.1660
908.28	1.5298	1.1670
911.62	1.5382	1.1680
914.98	1.5466	1.1690
918.37	1.5550	1.1700
921.78	1.5643	1.1710
925.22	1.5740	1.1710
928.69	1.5830	1.1720
932.18	1.5920	1.1720
935.70	1.6013	1.1730
939.24	1.6108	1.1730
942.81	1.6204	1.1740
946.41	1.6299	1.1740
905.04	1.6395	1.1750
953.69	1.6490	1.1750
957.37	1.6592	1.1750
961.09	1.6695	1.1750
964.82	1.6797	1.1740
968.59	1.6900	1.1740
972.39	1.7002	1.1730
976.22	1.7108	1.1730
980.08	1.7213	1.1720
983.97	1.7319	1.1720
991.84	1.7530	1.1710
999.84	1.7760	1.1710
1007.97	1.7990	1.1710
1016.23	1.8220	1.1700
1026.00	1.8496	1.1700
1033.17	1.8680	1.1700
1055.15	1.9411	1.1650
1064.00	1.9715	1.1620
1078.09	2.0170	1.1600
1100.00	2.1069	1.1400
1102.04	2.1151	1.1347
1127.09	2.2180	1.1100
1150.00	2.3400	1.0290
1180.76	2.4840	0.9510
1216.00	2.5436	0.7358
1239.80	2.5820	0.5970
1300.00	2.4400	0.2350
1377.56	2.2970	0.0875
1400.00	2.2612	0.0803
1549.75	2.0580	0.0280
1600.00	2.0236	0.0206
1771.14	1.9240	0.0082

Table 8
Optical Constants of Iridium in Far Ultraviolet

OPTICAL CONSTANTS OF IRRIDIUM IN FAR UV

WAVELENGTH(A)	N	K
113.00	0.9489	0.0348
495.92	0.6890	0.7850
506.04	0.7000	0.8300
516.58	0.7300	0.8700
523.12	0.7480	0.9000
525.34	0.7540	0.9100
529.83	0.7660	0.9280
532.10	0.7720	0.9360
534.40	0.7780	0.9420
536.71	0.7840	0.9500
537.87	0.7870	0.9560
539.04	0.7900	0.9600
540.22	0.7950	0.9630
541.40	0.8000	0.9660
543.77	0.8100	0.9720
548.58	0.8300	0.9840
553.48	0.8500	0.9920
558.47	0.8700	0.9960
563.55	0.8900	1.0000
568.72	0.9100	1.0080
573.98	0.9300	1.0160
579.35	0.9500	1.0240
590.38	0.9900	1.0400
604.78	1.0400	1.0500
619.90	1.1000	1.0600
635.79	1.1600	1.0375
652.53	1.2200	1.0150
666.56	1.2550	0.9850
670.16	1.2620	0.9775
673.80	1.2700	0.9700
677.49	1.2780	0.9600
688.78	1.3000	0.9300
700.45	1.3000	0.8850
704.43	1.3000	0.8700
708.46	1.2950	0.8600
712.53	1.2900	0.8500
716.65	1.2800	0.8400
733.61	1.2550	0.8250
755.98	1.2300	0.8200
765.31	1.2200	0.8250
770.06	1.2150	0.8270
774.88	1.2100	0.8300
779.75	1.2080	0.8300
784.68	1.2050	0.8300
789.68	1.2030	0.8300
799.87	1.1970	0.8360
810.33	1.1930	0.8370
821.06	1.1880	0.8500
826.53	1.1850	0.8550
832.08	1.1820	0.8620
843.40	1.1790	0.8710
849.18	1.1750	0.8750

Table 8. (Continued)

855.03	1.1730	0.8770
860.97	1.1700	0.8800
866.99	1.1670	0.8880
873.10	1.1650	0.8950
879.29	1.1620	0.9030
885.57	1.1600	0.9100
888.75	1.1610	0.9150
891.94	1.1630	0.9200
895.16	1.1640	0.9250
898.41	1.1650	0.9300
901.67	1.1660	0.9350
904.96	1.1670	0.9400
908.28	1.1680	0.9450
911.62	1.1700	0.9500
914.98	1.1710	0.9540
918.37	1.1720	0.9580
921.78	1.1730	0.9620
925.22	1.1750	0.9650
928.69	1.1760	0.9690
932.18	1.1770	0.9730
935.70	1.1790	0.9770
939.24	1.1800	0.9800
942.81	1.1810	0.9840
946.41	1.1820	0.9880
950.04	1.1840	0.9920
953.69	1.1850	0.9950
957.37	1.1860	0.9990
961.09	1.1870	1.0020
964.82	1.1880	1.0060
968.59	1.1900	1.0100
972.39	1.1920	1.0150
976.22	1.1950	1.0200
980.08	1.1970	1.0250
983.97	1.2000	1.0300
991.84	1.2050	1.0400
999.84	1.2100	1.0500
1007.97	1.2180	1.0580
1016.23	1.2250	1.0650
1026.00	1.2350	1.0750
1033.17	1.2400	1.0800
1055.15	1.2550	1.1020
1064.00	1.2750	1.1150
1078.09	1.2950	1.1250
1100.00	1.3300	1.1270
1102.04	1.3400	1.1280
1127.09	1.3800	1.1300
1150.00	1.4070	1.1050
1180.76	1.4350	1.0800
1216.00	1.4450	1.0300
1239.80	1.4500	1.0100
1300.00	1.4100	0.9650
1377.56	1.3300	0.9400
1400.00	1.3000	0.9450
1549.75	1.1300	1.0300
1600.00	1.0650	1.0800
1771.14	0.9700	1.3400

Table 9
Optical Constants of Lithium Fluoride (LiF) in Far Ultraviolet

OPTICAL CONSTANTS OF LITHFLUORIDE IN FAR UV

WAVELENGTH(A)	N	K
113.00	0.0167	0.0117
495.92	0.4700	0.2300
506.40	0.4400	0.3100
516.58	0.4300	0.4200
523.12	0.4200	0.5000
525.34	0.4300	0.5600
529.83	0.4300	0.5900
532.10	0.4400	0.6200
534.40	0.4500	0.6600
536.71	0.4600	0.7000
537.87	0.4700	0.7200
539.04	0.4800	0.7400
540.22	0.5000	0.7600
541.40	0.5100	0.7800
543.77	0.5500	0.8100
548.58	0.6200	0.8700
553.48	0.7000	0.9100
558.47	0.8000	0.9400
563.55	0.9100	0.9300
568.72	0.9900	0.8800
573.98	1.0400	0.8400
579.35	1.0800	0.8000
590.38	1.1400	0.7300
604.78	1.1800	0.6500
619.90	1.2000	0.5800
635.79	1.2100	0.5300
652.53	1.1900	0.4700
666.56	1.1700	0.4400
670.16	1.1500	0.4400
673.80	1.1400	0.4400
677.49	1.1300	0.4500
688.78	1.1100	0.4800
700.45	1.1300	0.5200
704.43	1.1400	0.5200
708.46	1.1600	0.5300
712.53	1.1800	0.5200
716.65	1.1900	0.5100
733.61	1.2000	0.4700
755.98	1.1600	0.4000
765.31	1.1200	0.3900
770.06	1.0900	0.3900
774.88	1.0600	0.4100
779.75	1.0200	0.4200
784.68	0.9900	0.4700
789.68	0.9800	0.5200
799.87	1.0000	0.5900
810.33	1.0400	0.6400
821.06	1.0800	0.6800
826.53	1.1000	0.6950
832.08	1.1200	0.7100
843.40	1.1700	0.7300
849.18	1.1900	0.7400

Table 9. (Continued)

855.03	1.2200	0.7400
860.97	1.2500	0.7300
866.99	1.2700	0.7200
873.10	1.3000	0.7100
879.29	1.3200	0.6800
885.57	1.3200	0.6400
888.75	1.3200	0.6200
891.94	1.3200	0.5900
895.16	1.3100	0.5600
898.41	1.2900	0.5200
901.67	1.2400	0.4600
904.96	1.1500	0.4200
908.28	1.0500	0.4300
911.62	0.9500	0.5000
914.98	0.8800	0.5800
918.37	0.8400	0.6700
921.78	0.8200	0.7600
925.22	0.8100	0.8400
928.69	0.8000	0.9200
932.18	0.8000	1.0100
935.70	0.8000	1.1000
939.24	0.8100	1.2000
942.81	0.8400	1.3300
946.41	0.9100	1.4300
950.04	0.9700	1.5300
953.69	1.0400	1.6400
957.37	1.1300	1.7700
961.09	1.2600	1.9000
964.82	1.4200	2.0200
968.59	1.6400	2.1300
972.39	1.9200	2.2000
976.22	2.2400	2.1900
980.08	2.5700	2.0800
983.97	2.8900	1.9000
991.84	3.3400	1.1700
999.84	2.9300	0.4800
1007.97	2.6800	0.3300
1016.23	2.5100	0.2300
1026.00	2.4000	0.1600
1033.17	2.2800	0.1100
1055.15	2.0800	0.0400
1064.00	2.0100	0.0470
1078.09	1.9400	0.0090
1100.00	1.8400	0.0440
1102.04	1.8400	0.0090
1127.09	1.7700	0.0090
1150.00	1.7000	0.0370
1180.76	1.6700	0.0090
1216.00	1.7000	0.0300
1239.80	1.6000	0.0090
1300.00	1.6000	0.0090
1377.56	1.5300	0.0090
1400.00	1.5080	0.0160
1549.75	1.4900	0.0090
1600.00	1.4618	0.0090
1771.14	1.4600	0.0050

APPENDIX D

FORTRAN MOLECULAR FLUX PROGRAM

A simple Fortran program for computing the (non-Maxwellian) velocity distribution of a Maxwellian gas moving at a constant drift speed V_o is listed on the following pages. The program integrates this probability distribution over all possible directions in space and all possible speeds to derive the net flux of particles reaching a particular point from a given range of directions. That is, if a target point is shielded from a given range of directions (defined in terms of "latitude" and "longitude") the program sums, over all possible remaining directions and velocities, the probability that an atom from that direction at that velocity would exist. The resulting sum is proportional to the total mass flux or particles $(cm^3\ sec)^{-1}$ passing through the test point.

All atoms are assumed to be oxygen atoms. The mass of the oxygen atom and Boltzmann's constant are written into the program. Input data include the drift velocity (km/sec), grid spacing for the numerical integrations (degrees), velocity spacing for the numerical integration and the number of velocity increments to make, the gas temperature, and the size and shape of the latitude, longitude region from which to accept atomic trajectories. Straight-line trajectories are assumed, that is, the mean-free path is assumed much larger than the size of the experimental target region, and no return flux or outgassing is added.

The gas is assumed to be approaching from the direction of of latitude = 0^o, longitude = 180^o.

Therefore the program can calculate a number proportional to the pressure in a space shielded from a drifting Maxwellian gas by a shield of arbitrary size and shape. To normalize the calculation to absolute numbers, the numerical integrations must be repeated over 4π steradians.

The absolute density of major constituents of the ambient neutral atmosphere are shown in Figure 49, as functions of solar activity (105).

Program "MOFLUX" Fortran Listing

```
C     PROGRAM MOFLUX
C     PROGRAM FOR CALCULATING MOLECULAR FLUX INTO ARBITRARY GEOMETRY
C     EXPERIMENT MOVING AT SPEED VO THRU RARIFIED ATMOSPHERE.
C      ALAN BUNNER, PERKIN-ELMER, OCT. 10, 1983.
       PI = 3.1415927
       RA = .01745329
       CM = 2.6556E-23
       CX = 1.38E-16
       WRITE(5,10)
   10  FORMAT(1X,' READ IN VO(KM/S), GRID(DEG), VINCR(KM/S)),',
      + ' NVMAX,TEMP(K),KEY')
       READ(5,11) VO,GRID,VINCR,NVMAX,TEMP,KEY
C      KEY = 0 MEANS 4*PI COVERAGE (ALL SKY NORMALIZATION)
C      KEY = 1 MEANS CIRC APERTURE
C      KEY = 2  OTHER APERTURES
 11     FORMAT(3F15.8,I4,F15.7,I3)
       NLAT = INT(180./GRID + .01)
       IF(NLAT.LT.1) NLAT=1
       IF(KEY.EQ.0) WRITE(5,21)
   21   FORMAT(1X,' ALL SKY FLUX CALCULATION:')
       IF(KEY.NE.1) GO TO 60
       WRITE(5,201)
  201   FORMAT(1X,' CIRCULAR APERTURE, READ IN CLONG,CLAT AND RADIUS ',
      + 'IN DEG')
       READ(5,202) CLONG,CLAT,RAD
  202  FORMAT(3F15.8)
       WRITE(5,203) CLONG,CLAT,RAD
  203  FORMAT(1X,' ACCEPTING TRAJECTORIES IN CIRCLE OF RADIUS ',F5.1,
      + ' DEG, CENTER AT LONG= ',F5.1,' LAT= ',F5.1)
       RCLONG=RA*CLONG
       RCLAT=RA*CLAT
       RRAD=RA*RAD
   60  CONTINUE
       CON1=(CM*1.E10)/(2.*CX*TEMP)
       CON2=1.E40*((CM/TEMP)**1.5)
       SUMSUM=0.
       ANRMSM=0.
       NLTP1=NLAT+1
       WRITE(5,65) NLAT,NLTP1,NVMAX
   65  FORMAT(1X,' NLAT= ',I5,' NLTP1= ',I5,' NVMAX= ',I5)
       WRITE(5,70)
   70  FORMAT(1X,' LAT(DEG) LONG(DEG)',6X,'PROB',9X,'PROBSM',10X,
      + 'SUMSUM',9X,'ANRMSM')
       NPTS = 0
       DO 100 LAT=1,NLTP1
       ALAT=(LAT-1)*GRID - 90.
       RALAT=RA*ALAT
       NLONG=INT(360.*COS(RALAT)/GRID + .01)
       IF(NLONG.LT.1) NLONG=1
       IF(LAT.EQ.1) WRITE(5,75)NLONG
   75  FORMAT(1X,' ENTERING LOOPS, FIRST NLONG= ',I5)
```

```
      NPTS=NPTS+NLONG
      DO 200 LONG=1,NLONG
      LNG=LONG-1
      RALONG = 2.*PI*LNG/NLONG
      ALONG=RALONG/RA
C   NOW TEST FOR ACCEPTANCE OF GRID POINT
C    IF CIRCULAR APERTURE NOT WANTED, GO TO 230
      IF(KEY.NE.1) GO TO 230
C   THIS IS CIRCULAR APERTURE TEST
      COSRX=SIN(RALAT)*SIN(RCLAT)+COS(RALAT)*COS(RCLAT)*
     + COS(RCLONG-RALONG)
      RX=ACOS(COSRX)
      IF(RX.GT.RRAD) GO TO 250
      GO TO 240
  230 CONTINUE
  231 CONTINUE
C   THIS SPACE FOR ALTERNATE TESTS
C
  240 CONTINUE
      PROBSM = 0.
      DO 300  NV=1,NVMAX
      NNV=NV-1
      V=NNV*VINCR
C   NOW COMPUTE VX, VY, VZ FOR NET VELOCITY
C   ASSUME ALL V VECTORS ARE AIMED AT THE ORIGIN
      VX=V*SIN(RALONG)*COS(RALAT)
      VY= -V*SIN(RALAT)
      VZ= -V*COS(RALONG)*COS(RALAT)
C   NOW COMPUTE PROBAB AND PROB SUM
      EXPO=CON1*(VX*VX+VY*VY+(VZ-VO)*(VZ-VO))
      PROB=CON2*EXP(-EXPO)
      PROBSM=PROBSM+PROB
  300 CONTINUE
      SUMSUM=SUMSUM+PROBSM
C     WRITE(5,305)ALAT,ALONG,PROB,PROBSM,SUMSUM
  305 FORMAT(1X,F6.1,2X,F6.1,2X,E15.7,1X,E15.7,1X,E15.7)
  250 CONTINUE
  200  CONTINUE
   100 CONTINUE
C  ALL DONE
      VMAX=V
      WRITE(5,399) VMAX
  399 FORMAT(1X,' VMAX= ',F9.5,' KM/S')
      WRITE(5,398) NPTS
  398 FORMAT(1X,' NO. OF GRID PTS= ',I8)
      ANRMSM = SUMSUM/(NVMAX*NPTS)
      WRITE(5,400) SUMSUM,ANRMSM
  400 FORMAT(1X' HOFLUX DONE, SUMSUM= ',E15.7,' ANRMSM= ',E15.7)
      RETURN
      END
```

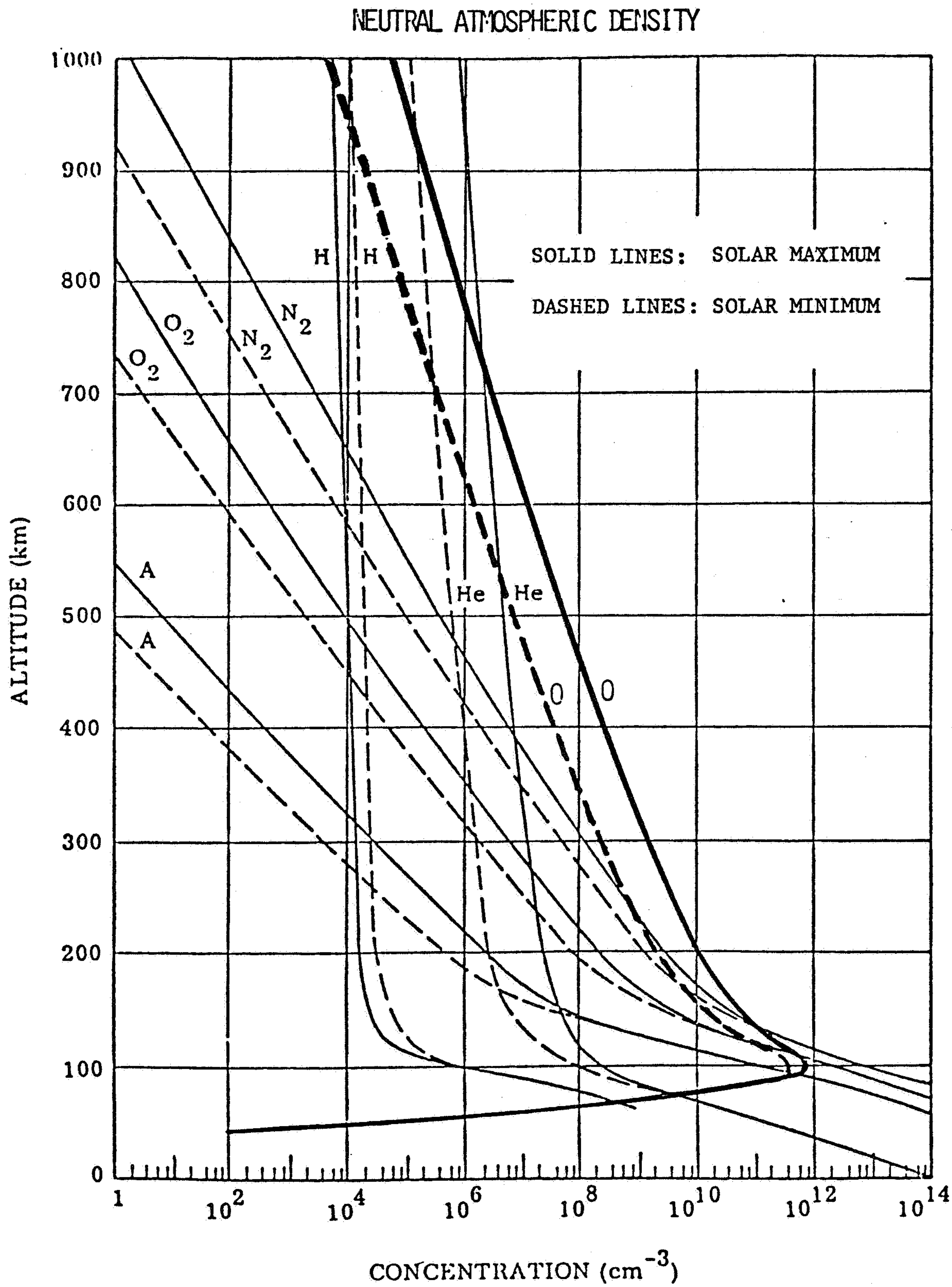

Figure 49. Distribution of Major Constituents of Neutral Atmosphere at Extremes of Solar Activity (105).

APPENDIX E

BIBLIOGRAPHY ON THE CONTAMINATION AND DEGRADATION OF MIRRORS AND OPTICAL ELEMENTS IN A SPACE ENVIRONMENT

Alan N. Bunner

Perkin-Elmer

October 14, 1983

The attached bibliography, arranged alphabetically by author, covers primarily published papers and reports related to mirrors used for ultraviolet wavelengths in a space environment and considerations related to the degradation of their reflectivity. The subject matter categories provide a key for a selection of references that may be useful for a particular question. In this key, degradation means loss of reflectivity or transmissivity; contamination means the deposition of foreign material; optical coatings means thin films; ultraviolet includes EUV wavelengths. Very few references on infrared reflectivity or the degradation of infrared mirrors are included.

<u>Subject Matter Categories</u>

A. Ultraviolet

B. Reflectivity

C. Optical Constants

D. Mirrors

E. Degradation

F. Contamination

G. Optical Coatings

H. Cleaning

I. Radiation Damage

J. Transmitting Elements

K. Thermal Coatings

L. Coating in Space

M. Upper Atmospheric Oxygen

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2.	_____, Optical Technology Apollo Extension System (OTES) Phase A Study Final Report, Perkin-Elmer/Lockheed, Perkin-Elmer Engineering Report ER-8900, October 1967.	A	B		D	E		G	H				L	M
3.	_____, Large Telescope Experiment Program (LTEP), Perkin-Elmer Engineering Report No. ER-9800, April 1970.	A	B		D	E		G	H				L	M
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APPENDIX F

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