GEMINI
8-M Telescopes
Project

REV-TE-G0007

Coating Plant, *In-Situ* Cleaning Program, And Low-Emissivity/Protected Silver Coatings Program
Design Review Document

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Contents

Acronym Glossary

5N, 6N - Five or Six "nines" of purity, meaning 99.999% pure or 99.9999% pure
ACT - Airco Coating Technologies
Ag - Silver
Al - Aluminum
BT - Blue Toad
CFHT - Canada-France-Hawaii Telescope
CO_2 - Carbon Dioxide
DSI - Deposition Sciences, Inc.
EMU - Emissivity Measuring Unit
ESO - European Southern Observatory
HfO_2 - Hafnium Dioxide, or Hafnia
IR - Infrared wavelength range
ISO - International Standards Organization
LUT - Loughborough University of Technology
MMT - Multiple Mirror Telescope
NIR - Near Infrared wavelength range
NIST - National Institute of Science and Technology
NOAO - National Optical Astronomy Observatories
NPL - National Physical Laboratory
NSF - National Science Foundation
ODA - Optical Data Associates
ppm - Parts Per Million
ppt - Parts Per Trillion
PSCP - Protected Silver Coatings Program
PVD - Physical Vapor Deposition
R - Reflectance
RGO - Royal Greenwich Observatories
Si_3N_4 - Silicon Nitride
SRD - Science Requirements Document
TBD - To Be Determined
UV - Ultraviolet wavelength range
Vis - Visible wavelength range
UHV - Ultra High Vacuum
UKIRT - United Kingdom Infrared Telescope
UW - University of Washington
WHT - William Herschel Telescope

List of Figures

1. Introduction

(a) This report describes the plans and the current status for:

- The 8m coating plant;
- In-situ primary mirror cleaning;
- Protected silver coating development.

(b) Section 2 describes the science requirements that affect the above systems, together with a brief description of how the requirements influence the designs.

(c) Section 3 describes Gemini plans for the 8-m coating plant. The Royal Observatories in the UK have been allocated a work package to design, procure, install and commission the 8-m coating plants. Prior to completing the design and specification of the Coating Plant, Royal Greenwich Observatory (RGO) will undertake a comprehensive development program including involvement of consultants at Loughborough, Leicster, Cambridge, and Balzers to investigate and establish optimal deposition process parameters. In addition RGO will be undertaking large scale sputtering tests in the 4.2m WHT chamber on La Palma.

(d) Section 4 describes Gemini's in-situ mirror cleaning program. We are investigating the relative performance, cost and implementation of both Excimer laser cleaning and carbon dioxide (CO_2) snow cleaning. We have contaminated aluminum samples on Mauna Kea and cleaned the samples with the two cleaning methods. Emissivity measurements before and after cleaning have yielded some interesting results.

(e) Section 5 describes the protected silver coating development program. Here we have contracted Optical Data Associates (ODA) to co-ordinate a program with coating specialists sub-contractors, Airco Coating Technologies (ACT) and Deposition Sciences, Inc. (DSI), to develop two commercially marketed industrial silver coatings for Gemini's application. With this method we can compare the performance of the two coatings, which are based on silicon nitride (ACT) and hafnia (DSI), side by side using independent (from ACT and DSI) characterization instruments and environmental tests.

2. Science Requirements[2-1]

2.1 Coating Plant

2.1.1 Requirement: *"For full realization of their scientific potential, the Gemini telescopes will need high throughput from ultraviolet wavelengths longer than 0.3 μ m through the visible and infrared bands to at least 30 μ m. In order to achieve high performance across this very broad wavelength band, capability for a variety of mirror coatings is required."*

2.1.2 We are providing coating facilities capable of depositing high quality silver (Ag), aluminum (Al), and dielectric coatings. Initially, the coating plants will deposit Al, but they are being designed for the ability to be upgraded to deposit protected silver coatings. The coating plant program is described in Section 3.

2.2 In-Situ Cleaning

2.2.1 Requirement: *"A frequent, regular and efficient primary mirror cleaning program and careful contamination control at the observing facility will be critical to meeting this [low emissivity] requirement. The required cleaning frequency is estimated to be about once/week."*

2.2.2 We are investigating two methods for cleaning the primary mirror in-situ: CO_2 snow cleaning and excimer laser cleaning. Both could be performed on a regular basis during daytime, without affecting the telescope availability for observing. The in-situ cleaning program is described in Section 4.

2.3 Low Emissivity/Protected Coatings

2.3.1 Requirement: *"The fully optimized IR configuration will have a telescope emissivity, including scattering and diffraction, of 4% with a goal of 2% immediately after coating or recoating optics, with 0.5% maximum degradation during operations, at any single wavelength beyond 2.2μ m. [... This] leads to the need for low emissivity coatings on the primary mirror."*

2.3.2 A low emissivity, protected, durable silver coatings program is currently being investigated by the Project. The protected coatings program is described in Section 5.

2.4 References

[2-1] Gemini Science Requirements Document Version 2.0, April 1994, SPE-PS-G0001

3. Coating Plant

3.1 Introduction and Project Plan

(a) In late 1993 RGO was awarded a work package for design and procurement of the 8m Coating Plants. Their main objectives are:

- A process development program, including a Sputtering Development Program;
- Tests in the William Herschel Telescope's (WHT) coating chamber (covered in Section 3.4.3);
- Design and specification of the coating plants, to include:
  - A design requirements document;
  - Vacuum system requirements;
  - Vessel design;
  - Magnetron design;
  - Power supply design;
  - Cooling water supply design;
  - Sputter parameter definitions;
  - Cost estimates.
- Procurement of both plants;
- Transportation of both plants to sites;
- Installation of both plants and training of personnel.

3.2 Gemini Specifications

(a) The Functional Specification for the Gemini Coating Plants is contained in Appendix 1.

3.3 Coating Processes

(a) There are two major physical vapor deposition (PVD) processes that could be used for coating 8m mirrors: evaporation and sputtering. Current 4m mirrors are coated using thermal evaporation. Since the 4m chambers were built, industry has developed the sputtering process to the stage that it is now the industry standard process for coating optics and low emissivity architectural glass. Figure 3-1 shows a graph of the reflectance of evaporative versus sputtered silver films.

3.3.1 Evaporation

(a) Thermal evaporation is a subdivision of PVD in which changes of state characterize the condensation of the coating material. Metals, and many dielectrics, are vaporized from the source. After vaporization, the particles condense on the substrate and elsewhere in the chamber as the desired coating material.

(b) Salient points regarding evaporation are as follows:

- Very high deposition rates can be sustained using evaporation; these can overwhelm oxidation tendencies in most metals and deposit highly reflective, relatively pure metal layers.
- Uniformity of coatings depends on equal distances between the source and the substrate. Because evaporative sources tend to be small in area, multiple sources and a larger distance between the substrate and the source are required to cover large areas evenly. This results in a very large coating plant.
- Thermal evaporation sources work best when the evaporative flux flows upwards from the sources. However, due to the size of the Gemini mirrors and the fact they cannot be inverted, an evaporative coating plant would have to be designed for downward deposition (as in the Mayall [4m] evaporative coating plant).
- The large chamber requires a larger, more expensive building, and a larger power supply to evaporate the filaments.

(c) Thermal evaporation has been the conventional method for coating large mirrors since the 1930's.

3.3.2 Sputtering

(a) In the sputtering process, the source material is mobilized not by heating, but by ion impact on a large solid plate of source material, known as the target. The incident ions impact surface atoms in the target, which then produce further collisions within the target until target atoms are ejected. Ions are then generated in a discharge that fills much of the chamber. Figure 3-2 illustrates this concept.

(b) Salient points regarding sputtering are as follows:

- Sputter targets can have much larger surfaces than evaporative sources. This simplifies problems of coating uniformity.
- Since the target is large, a relatively small distance to the substrate is required; this results in a smaller, cheaper coating plant.
- The solidity of sputtering targets permits, theoretically, operation at any angle.
- Since the distance between the targets and the substrate is reduced, a high degree of control can be maintained over grain diameter, and consequently reflectance.
- By having two or more different target sources (such as silver and another protective material) present in the chamber during the process, a metal alloy can be deposited with ease.
- Reactive processes can be easily done by sputtering a metallic target while reactive gases are introduced into the chamber, to enable oxides, nitrides, etc., to be deposited.

(c) Sputtering has been universally applied in the semiconductor production area, and in producing low emissivity coated architectural glass.

3.4 Progress To Date

3.4.1 Interface Control Document

(a) An interface specification which defines the interfaces between the coating plant and the support facility has been provided by RGO. The Preliminary Building Interface Document is contained in report #RGO-N-027 (Gemini #ICDG0010).

(b) The Coating Plant layout is shown in Figure 3-3. The Coating Plant room layout in the enclosure base is shown in Figure 3-4.

3.4.2 Aluminum Sputtering Program

(a) In early 1992 RGO investigated and demonstrated the feasibility of a low-emissivity sputtered durable coating[3-1]. RGO selected as subcontractors the University of Cambridge's Department of Materials Science and Metallurgy, Loughborough University of Technology (LUT), and the National Physical Laboratory (NPL).

(b) The purpose of the work was to optimize sputtering parameters to enable a thin film of aluminum to be deposited with emissivities as low as 1.8%. The main objectives of the program were:

- Build an instrument to enable IR emissivity measurements to be made on sample coatings, based on the NOAO Blue Toad (BT) instrument (see Section 4.2.1.2).
- Direct LUT and Cambridge to evaluate the effect of varying sputtering parameters on film emissivity. Parameters included (but were not limited to) the sputtering rate, distance of target from surface, target purity, gas type, and pressure.
    - Direct LUT to evaluate the effect of varying the sputtering environment.
    - Direct Cambridge to evaluate the effect of varying the target purity.
    - Direct both LUT and Cambridge to prepare coated samples for evaluation.
    - Direct NPL to determine whether the crystalline film structure was related to film emissivity.
- Measure all provided samples using the IR emissivity measuring instrument.
- Provide reports of all tests and measurements.

3.4.2.1 Results[3-2]

(a) The findings of the study were that a sputtered aluminum coating can be deposited in a high vacuum environment with high reflectivity and low film scatter. Several samples were made under many different sets of conditions. All emissivity measurements were made with RGO's Emissivity Measuring Unit (EMU), a duplicate to the NOAO BT described in Section 4.2.1.2.

(b) The progress to date finds that a base pressure of 10^{-7} torr with a low partial pressure of water vapor and a target purity of at least 99.999% (5N's) purity will result in samples with emissivities from 2.0-2.1% at 3.8μ. However, at a base pressure of 10^{-9} torr and using a target with 6N's purity sputtered at the lowest argon pressure result in 1.8-1.9% emissivity results. In practice, the limitation in the 8m plant "will be pumping capacity, and [it is] not possible to duplicate the UHV figures in a chamber of this size"[3-3]. Results can be seen in Table 3-1.

Table 3-1. Comparative emissivity results, RGO sputtered aluminum tests[3-3]

Sample	***Emissivity, %***	***Comments***
NPL Standard	1.8	
WHT Samples	1.85-1.9	No process parameters given
Balzers Samples (4)	2.25-2.27	Substrate ULE, Vacuum system Rotary/Cryo, Base pressure 10^{-6} mbar, Balzers standard planar magnetron, Target 5N's purity
AIRCO Samples (2)	2.20-2.25	Base pressure $1.3x10^{-6}$ torr, target 4N's purity, standard 817 planar cathode, argon pressure 2.8mtorr
TEER Samples (7)	2.44-3.50	Base pressure < 10^{-5} torr Note: This company has not had previous experience with optical coatings but RGO felt it might be worth obtaining samples with a high gauss magnetron to see whether this offered any significant advantages.
Cambridge 5989 Samples (5)	2.00-2.06	Thicknesses ranging from 0.05-1.50µ Target 5N's purity
Cambridge 6030 Samples (5)	1.81-2.10	Thicknesses 0.3-0.4µ, pressure varied from 0.16-5.0 Pa Target 6N's purity
Cambridge 6048 Samples (5)	1.80-2.07	Thicknesses 0.3-0.4µ, pressure varied from 0.16-5.0 Pa Target 6N's purity
Cambridge 6038 Samples (5)	1.88-2.00	Thicknesses 0.12-1.5µ, pressure constant at 0.16Pa Target 5N's purity
Cambridge 6043 Samples (5)	1.81-1.97	Thicknesses 0.12-5m, pressure constant at 0.16 Pa Target 5N's purity

3.4.3 WHT Test Program

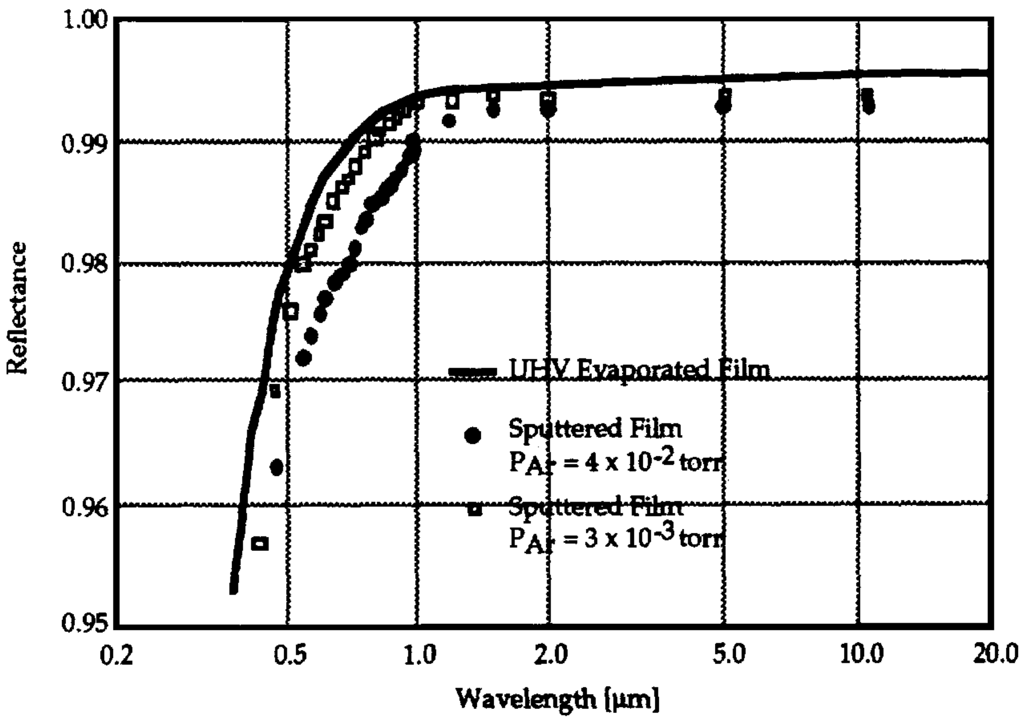
(a) As part of the work on the 8m Coating Plants, RGO has secured time for the use of the William Herschel Telescope's (WHT) 4.2-m evaporative coating tank at La Palma. This tank will be modified to enable a sputtering process to be run.

(b) The purpose of these tests will be "to demonstrate that 8-m primary mirrors can be coated to the required specifications using the sputtering process"[3-4]. Specifications to be determined during these tests are:

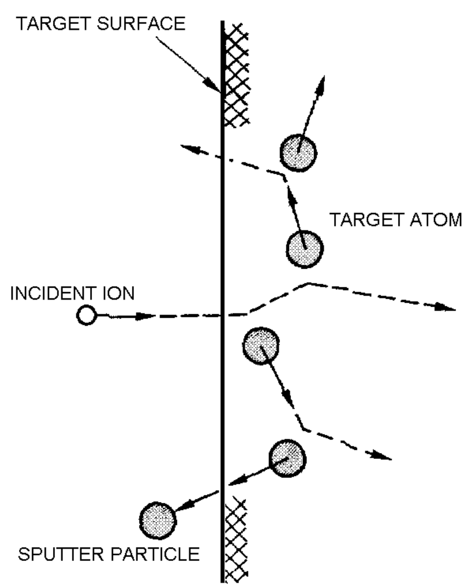
- The required vacuum quality and pump down time;
- Coating uniformity and overlap control;
- Optimum magnetron size;
- Magnetron power requirements.

(c) RGO will measure the adhesion, emissivity, film thickness, and surface roughness characteristics of the deposited films.

3.4.4 Schedule



(a) The full schedule for all work on the 8m coating facilities is due to be completed in late



1998. Milestones in the schedule are:

- WHT tests completed and final report due December 1994

- Design and specification of coating plants complete in March 1995
- Procurement date for both plants is December 1996
- Installation at Mauna Kea scheduled for March 1997
- Installation at Cerro Pachon scheduled for August 1998

3.5 References

[3-1] RGO, The Investigation and Demonstration of the Feasibility of Low Emissivity Durable Coatings", Workscope GTL00001.
[3-2] RGO, "Technical Report on the Evaluation of the Effect of Varying Sputtering Parameters on the Film Emissivity", RGO-N-012.
[3-3] RGO Coating Plant Progress Report #3, 6 May 1994.
[3-4] Gemini-RGO Work Package Definition Paper for the Primary Mirror Coating Plant Development and Fabrication, GEM-01006.

3.6 Figures

Figure 3-1. Reflectance of evaporated versus sputtered silver films.

Figure 3-2. Illustration of sputtering process.

4. In-Situ Cleaning

4.1 Introduction

(a) Traditional methods of removing the mirror from the telescope and hand-washing it are impractical for Gemini. Two methods that are better suited to in-situ cleaning of 8m mirrors are being investigated by the project; CO_2 snow cleaning, and laser cleaning.

4.1.1 CO_2 Snow

(a) This method is used on many 4-m class telescopes such as the CFHT and MMT, and is also used on the Keck telescope.

(b) Carbon dioxide jet flush cleaning occurs when pressurized liquid CO_2 is exhausted to ambient conditions, where it expands and undergoes a phase change. The resultant spray is a mixture of gaseous and solid flakes of CO_2, called dry ice or CO_2 snow. Particulates on the surface to be cleaned are blown away through impact with these flakes, which transfer enough momentum to dislodge the particles from the surface. This method leaves behind no residue on the surface, since the solid flakes sublime directly into a gaseous state; it also imparts no scratch damage to the surface, since the particles glide across the surface on this sublimated cushion. Very pure carbon dioxide is needed for this method, as any impurities in the liquid will be imparted to the mirror surface.

(c) Items needed for the implementation of CO_2 snow cleaning are:

- An adequate amount of at least 99.99% pure CO_2 at approximately 800 psig;
- A cleaning nozzle or delivery system;
- An appropriate delivery platform for reaching the entire mirror surface.

Reference 4-1 suggests that the surface to be cleaned must be heated to about 30-35^{o}C to minimize moisture condensation. However, other tests have found no such requirements.

(d) CO_2 snow cleaning has been found to be very efficient when cleaning particulate contamination from mirrors. Some type of molecular contaminants are also partially removed using CO_2 snow; however, removal of these types of contaminants is not as effective or as thorough as removal of particulate contaminants.

(e) Tests conducted at the MMT, the CFHT, and the Lick Observatory were conducted in 1990 using CO_2 snow cleaning. In general, results from all three test series show that particulates and macrocontaminants are easily and effectively removed using CO_2 cleaning[4-2]. These and other tests performed indicate that CO_2 cleaning is as effective as other conventional techniques[4-3].

(f) The CO_2 jet method imparts a very low thermal shock to the surface, and no evidence of scratching from this method has been found.

(g) A large amount of CO_2 is needed for this method, as only about 0.1% of the original CO_2 ends up as flakes which actually reach the surface to be cleaned[4-2].

(h) The main cost for this method is the cost of the CO_2. Very pure gas is needed in order to avoid the potential organic contamination problem; and the cost of CO_2 gas increases with purity (see Figure 4-1)[4-2].

(i) Based on CO_2 cleaning programs currently in use at the CFHT and MMT, a conservative estimate of 200 lbs of CO_2 is needed per cleaning[4-4,4-5]. Using Figure 4-1, that comes to an operations cost of approximately $400 per cleaning, or $19,200 per year for the CO_2 alone. This does not take delivery costs of CO_2 into account.

(j) Man-power estimates to clean an 8-meter mirror is one day, involving two or three people.

(k) Implementation of this method for Gemini is described in Section 4.3.1.

4.1.2 Laser

(a) If a pulsed ultraviolet laser beam (typically 1 cm^2) is scanned across a mirror surface, the beam will remove particulate and molecular contaminants. The laser cleaning process involves different mechanisms for removal of different contaminations. For molecular contaminants, the contaminant photothermally absorbs the UV energy and is vaporized, or the molecular bond of the contaminant and the bonds between the contaminant and the surface are broken photochemically. For particulate contamination, removal is accomplished by absorption of the laser light leading to vaporization, and by the generation of a photoacoustic stress wave in the mirror substrate that breaks the electrostatic contaminant-surface bond and "bounces" the particle off the surface[4-6,4-7]. A pulsed laser is essential for creation of this photoacoustic effect. The laser fluence required for removal of both types of contamination is well below the damage threshold for both the mirror and the reflective coating.

(b) Excimer lasers are ideal lasers for this purpose, as they are readily available commercially and have a history of reliability and ease of use. It is important for the laser beam profile to be uniform; another advantage of excimer lasers are that the laser output is already incoherent. The beam is easily made uniform by sending it through an optical beam homogenizer, which redistributes the energy into an uniform rectangular beam. Excimer lasers are also capable of high pulse repetition rates, thereby directly reducint the cleaning time.

(c) Items needed to implement this method are[4-8]:

- An excimer laser system (laser, valves, RS-232 port),
- A gas handling system (cabinets, regulators, exhaust system),
- A scanning mirror system (rotation stages, cradles, hardware)
- A focusing telescope (mirrors, mounts, translation stages),
- An optical table system,

- A laser alignment system (laser, beam splitter, mounts),
- Steering mirrors and mounts,
- A 486 PC.

(d) The cleaning of mirrored surfaces by this method is very effective in removing molecular and particulate contaminants. Water spots, oils, fingerprints, pump oils, dust, and other contaminants are removed cleanly and quickly, without damage to the surface[4-6,4-7]. UV laser cleaning has also been found to be effective in removal of thick contaminant layers, large particles, and tightly bound contaminants[4-7].

(e) Operating costs for this process are very low: laser fill, optical solvent for cleaning the resonator mirrors, and soda lime to fill the halogen gas trap. The cost to fill the laser is approximately $140 per fill, and each fill is good for about 4 cleanings, or one month. The optical solvent and soda lime costs approach $100. That brings the annual operating costs to approximately $2000.

(f) Manpower estimates are one man for one day, since the system will be automated and run from the PC.

(g) Implementation of laser cleaning for Gemini is discussed in Section 4.3.2.

4.2 Test Programs

4.2.1 UKIRT/Gemini Contamination & Measurement Program

4.2.1.1 Program outline

(a) An extensive program to contaminate a set of mirror samples at a representative observatory site was implemented in 1992 by Gemini. The mirrors were exposed on Mauna Kea, Hawaii and returned to Gemini, where their emissivities were measured. One half of each set was then cleaned using a CO_2 snow jet; the other half were cleaned using an UV excimer laser.

(b) The samples used were 10-cm (4-inch) diameter polished silicon wafers, 0.5mm thick, coated with 1000 $\mathring{A}$ of aluminum. They were mounted in a specially-made sample exposure box.

(c) The samples were exposed on the crossbeams of the United Kingdom Infrared Telescope (UKIRT) Samples were exposed for differing durations (from 3 to 84 days, with 7 days intervals) before being sealed and returned to Gemini for emissivity measurements and subsequent cleaning tests.

4.2.1.2 Emissivity Measurements

(a) The emissivities of the contaminated samples was measured both before and after cleaning, using an NOAO instrument nicknamed the "Blue Toad".

(b) The BT is an InSb photometer, with an input window to the top of the instrument rather than to the side. It was designed for use on the 2.1m and 4m telescopes, but is also heavily used to measure the emissivity of reflective samples.

(c) The technique used to measure the mirror sample emissivity on the BT is to make a direct measurement of the thermal emission from the mirror surface and then calculate using

$$E_{mir} = \frac{(V_s - V_{int})}{(V_{bb} - V_{int})}$$

where:

- E_{mir} is the emissivity of the mirror sample,
- V_s is the voltage output for the mirror surface,
- V_{int} is the voltage output for a small gold-coated mirror mounted on the underside of an aluminum cup containing LN_2,
- V_{bb} is the voltage output for an ambient temperature black body.

(d) Measurements were made on the exposed samples as the individual sample boxes were returned to Gemini. Each mirror was measured before cleaning, and then again after cleaning. One sample, labeled GEM CTRL, was neither exposed or cleaned and was used as a base emissivity value.

4.2.1.3 CO_2 cleaning

(a) The CO_2 cleaning system utilized at Gemini was a smaller version of the system seen in Figure 4-2. A 40-lb tank of pressurized CO_2 gas with a hose nozzle attached was used, and the samples were cleaned at an approximate distance of 24 inches from the nozzle.

4.2.1.4 Results

(a) Figure 4-3 shows the plot of pre-cleaning emissivities of all the mirror samples. Figure 4-4 shows a plot comparing the pre-clean and the post-CO_2 clean emissivities.

(b) Based on the emissivity results of the before- and after-CO_2 cleaning, for low exposure times (one week or less) CO_2 jet cleaning returned the emissivity of the samples to near the original emissivity.

4.2.2 STI tests

4.2.2.1 NSF-funded work

(a) In April 1991 STI Optronics (located in Bellevue, Washington, USA) and the University of Washington (UW) co-submitted a grant proposal to the National Science Foundation (NSF). The purpose of the grant was to demonstrate that UV laser cleaning was a safe, effective method for cleaning astronomical mirrors[4-9]. Gemini was able to arrange a program with STI Optronics for laser cleaning tests specific to Gemini's requirements, which built on the program funded by the NSF.

(b) Under the direction of Dr. Wayne Kimura, a complete laboratory was set up at STI Optronics to include all lasers and appropriate equipment, computers, video systems, optical tables, lab space, and office space. All actual laser work was performed at this facility.

(c) Dr. Bruce Balick of UW acted as a scientific advisor and coordinator of all activities between STI, UW, other observatories involved, and the astronomical community. He was also responsible for all surface analysis work using scanning electron microscopes (SEMs) and other types of analysis instruments on the UW campus.

4.2.2.2 Gemini-funded work

(a) Under the Gemini contract, STI Optronics was responsible for the following[4-8]:

- A laser cleaning design study to determine how best to implement laser cleaning for Gemini;
- A costing study based on the design study;
- Laser cleaning tests (to include optimization, laser cleaning, and scatterometry measurements), to include cleaning the UKIRT contaminated samples.

4.2.2.2.1 Laser setup

(a) Most of the equipment can be located on a 4-foot by 8-foot optical table. Positioned next to the table would be a support I-beam approximately 12 feet tall. Figure 4-5 shows the layout of the setup. The setup was designed assuming that further experiments would show that an optical beam homogenizer (further discussed in Section 4.2.2.2.2) would not be needed, since preliminary tests indicated that the output beam of the laser was already fairly uniform.

(b) The UV laser beam exits the excimer laser and reflects off of a dichroic beam splitter. This dichroic beam splitter is highly reflective at 308 nm and highly transmissive at 632.8nm, allowing the red light from a HeNe laser to be efficiently transmitted through the beam splitter and combined with the UV laser beam. An expansion telescope on the HeNe laser enlarges the size of the beam exiting the HeNe laser to better match the size of the UV laser beam. The dichroic beam splitter allows the two laser beams to be aligned collinear to each other, making it easier to see the UV laser beam.

(c) The two beams then pass through a focusing telescope that focuses the beams to the proper spot size on the primary mirror surface. A periscope mirror sends the beams up to the scanning mirror on top of the support I-beam, which is mounted on a motorized cradle that is situated on a motorized rotation stage. This allows the laser beams to be swept across the mirror surface in both the vertical and horizontal planes.

(d) The entire top of the laser table is covered with a protective enclosure consisting of blue-tinted acrylic panels. These panels are lockable and slideable for table-top access. The top of the enclosure will have box fans to create a slightly positive air pressure within the enclosure, preventing dust from entering and contaminating the optics. The enclosure will also perform as a safety system for the laser table, permitting no laser light to escape it.

4.2.2.2.2 Homogenizer tests

(a) It is important to have a flat beam profile for laser cleaning. For some systems, an optical beam homogenizer is needed to "flatten out" the profile of the beam. Without a relatively flat beam, the outer edges of the beam do not impart as much energy as the central part, and particles around the edges of the beam area could be simply charred instead of vaporized away from the surface. These charred particles are then harder to remove at a later time. However, if the mirror is cleaned frequently, then the beam quality requirements become less stringent and the system becomes simpler.

(b) Preliminary tests indicated that the beam from the UV excimer laser may already be "flat" enough for Gemini's purpose. Figure 4-6 shows the beam profiles of the laser system with and without a homogenizer.

(c) Four sample mirrors were exposed at the UKIRT for 21 days, then taken to STI for testing in the system with and without an optical beam homogenizer. Two samples were cleaned with a homogenizer in the system, and two were cleaned without the homogenizer.

(d) Results indicate that, for Gemini's purposes, the system cleans just as effectively without a homogenizer in the system. Figure 4-7 shows a plot of the two sets of samples.

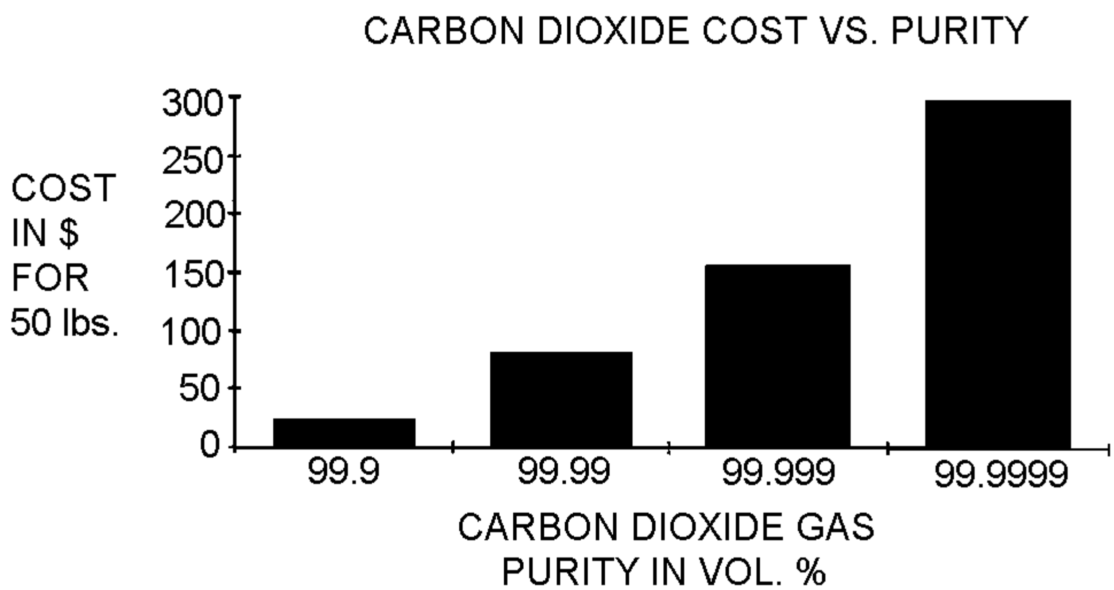
4.2.2.2.3 Scatterometry measurements

(a) A particle measurement system was developed at STI to provide quantitative information on cleaning effectiveness. Contaminants on the mirror surface cause scattered light that is easily seen by a CCD camera. Light from a high-intensity microscope lamp shines directly on the mirror sample, with specular reflection being directed away from the CCD camera so that only scattered light is seen. Figure 4-8 shows a schematic plan of this system.

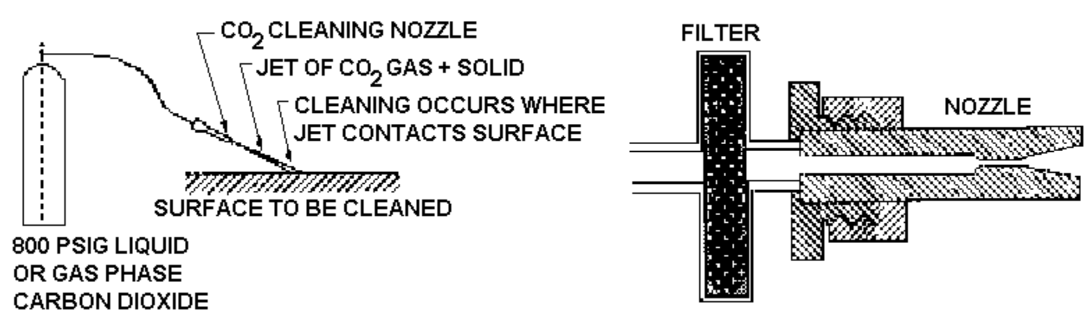
(b) Readings were taken of pre-clean, 4-shot, 8-shot, and 12-shot cleaned samples, plus the samples that were CO_2 cleaned by Gemini personnel.

(c) The video images of the scattered light were analyzed by subtracting a filtered image showing only background material from the raw video image, leaving only an image of the isolated particles left on the mirror surface. A software program then counted the number of particles in the image, and sorted them by size. The results of this is a count of the number of particles per unit area, the area of the mirror covered by particles, and the distribution of particles by size.

4.2.2.3 Results

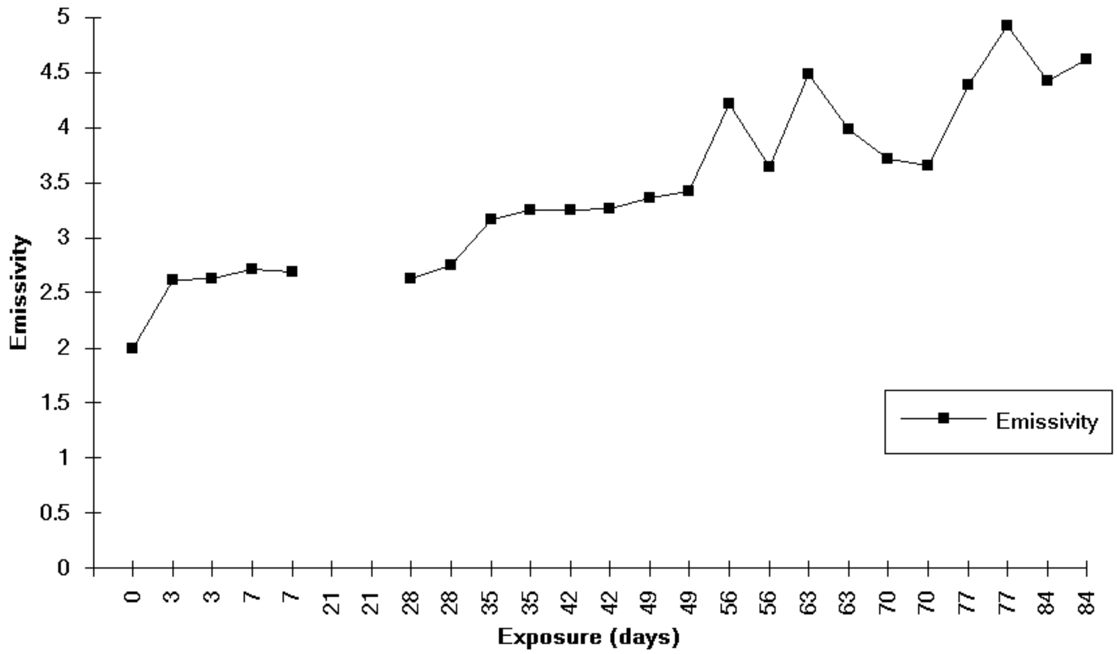


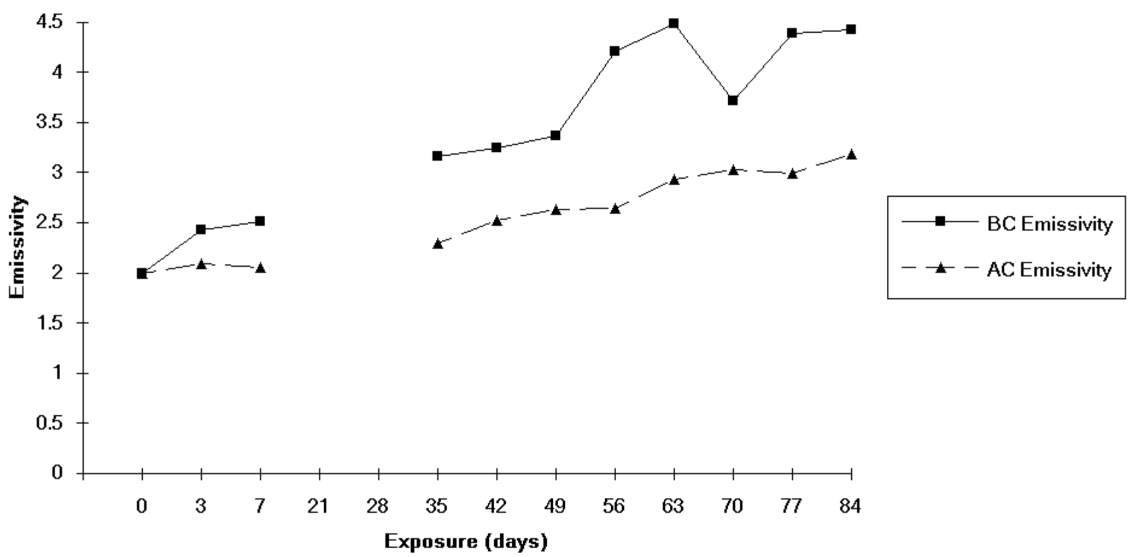
(a) Results from the laser cleaning program at STI Optronics are very promising compared to the CO_2 cleaning results. In every case, the laser cleaning system returned the emissivity of the



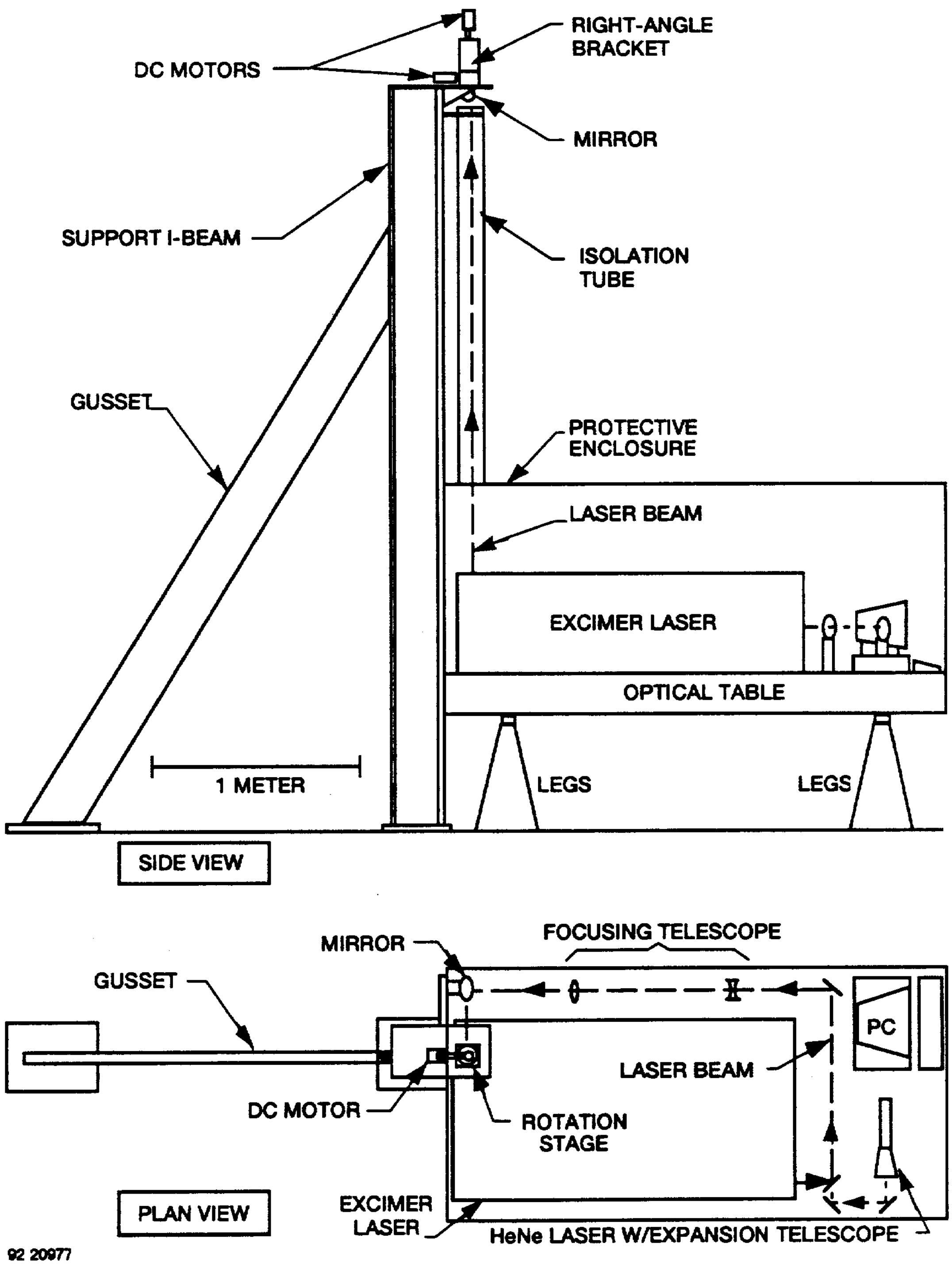
samples to almost the starting level. A great deal of minute substrate surface damage was seen on several of the samples; this may account for why the laser did not return the samples to their exact starting emissivity.

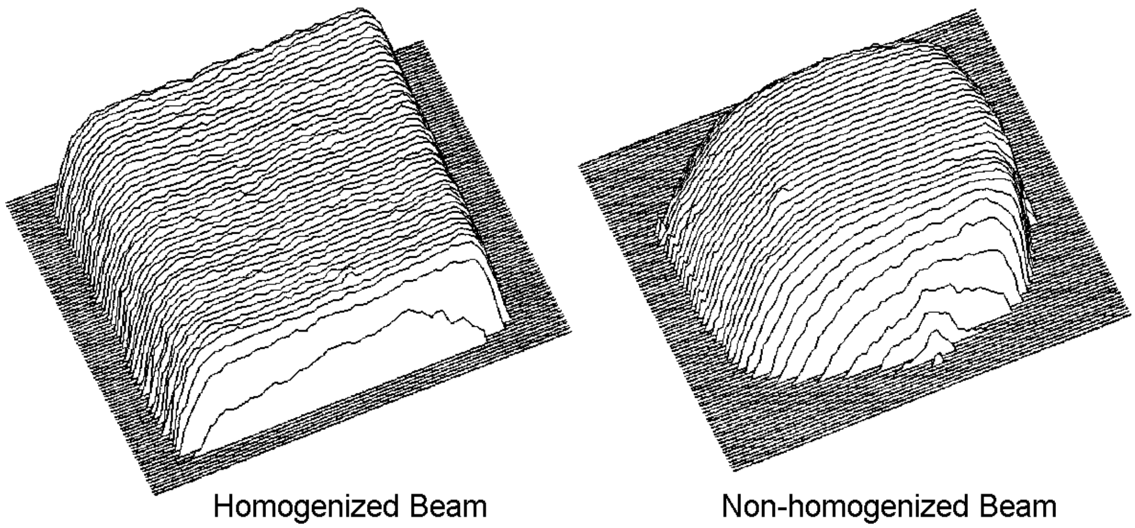
(b) Figure 4-9 shows a plot of emissivity versus exposure time, for both the CO_2 cleaned and the laser cleaned samples. This plot is based on data from the BT emissivity measurements.



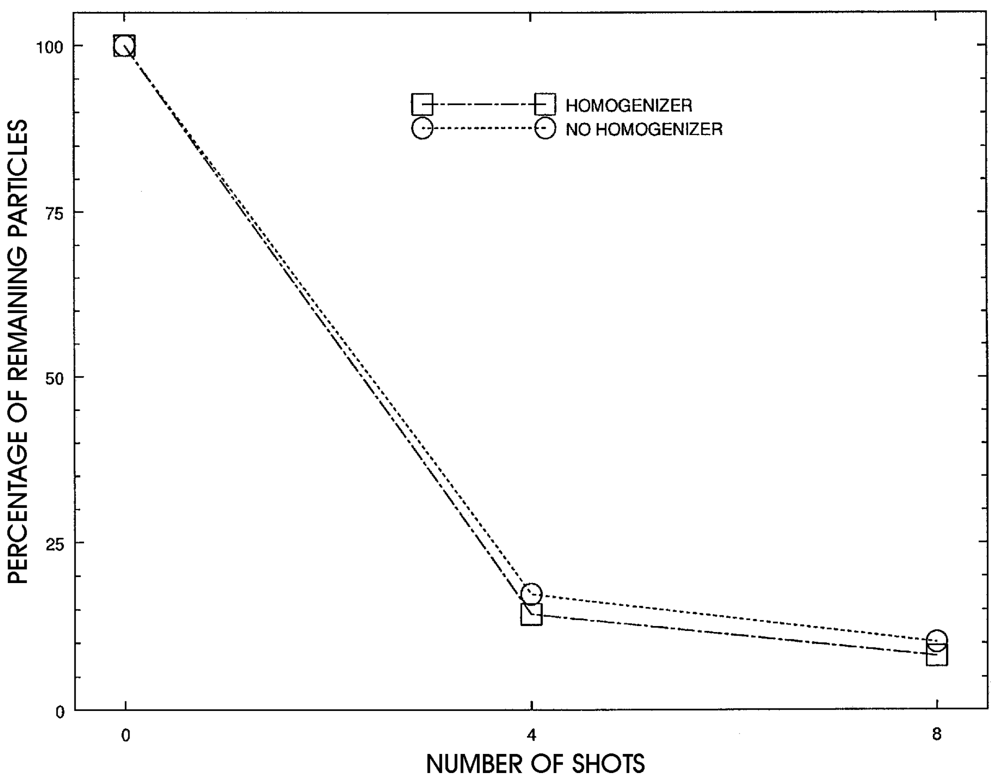


(c) Figure 4-10 shows a plot of remaining contaminated area relative to a contaminated mirror versus exposure, for both CO_2 cleaned and laser cleaned samples. Data for this plot was obtained through the STI video scatterometry measurements.


RIGHT-ANGLE BRACKET
DC MOTORS
MIRROR
SUPPORT I-BEAM
ISOLATION TUBE
GUSSET
PROTECTIVE ENCLOSURE
LASER BEAM
EXCIMER LASER
OPTICAL TABLE
1 METER
LEGS
LEGS
SIDE VIEW
MIRROR
FOCUSING TELESCOPE
GUSSET
PC
LASER BEAM
DC MOTOR
ROTATION STAGE
PLAN VIEW
EXCIMER LASER
HeNe LASER W/EXPANSION TELESCOPE
92 20977

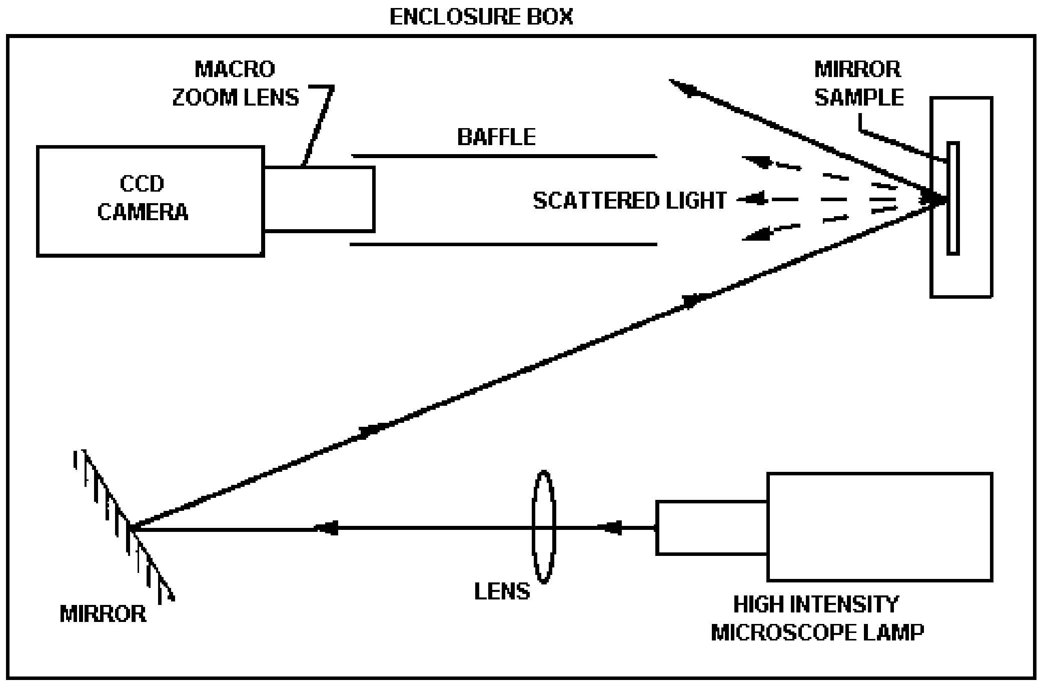


(d) Both test systems indicate that the laser cleaning system is more efficient in returning a mirror contaminated with both molecular and particulate contamination to its original emissivity

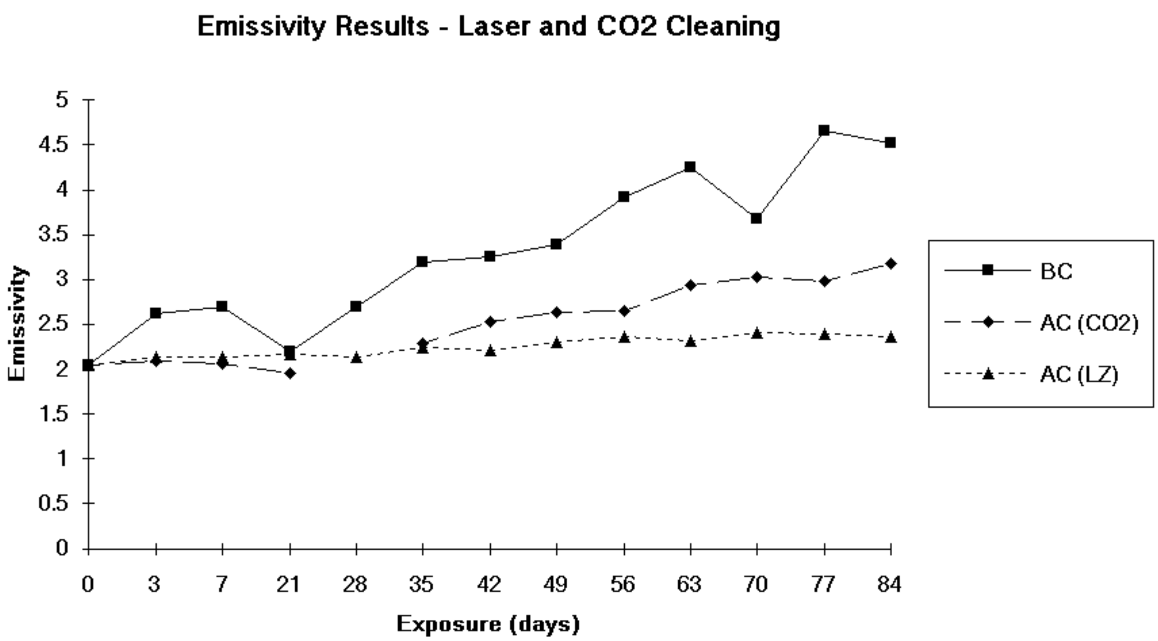


or state of cleanliness.

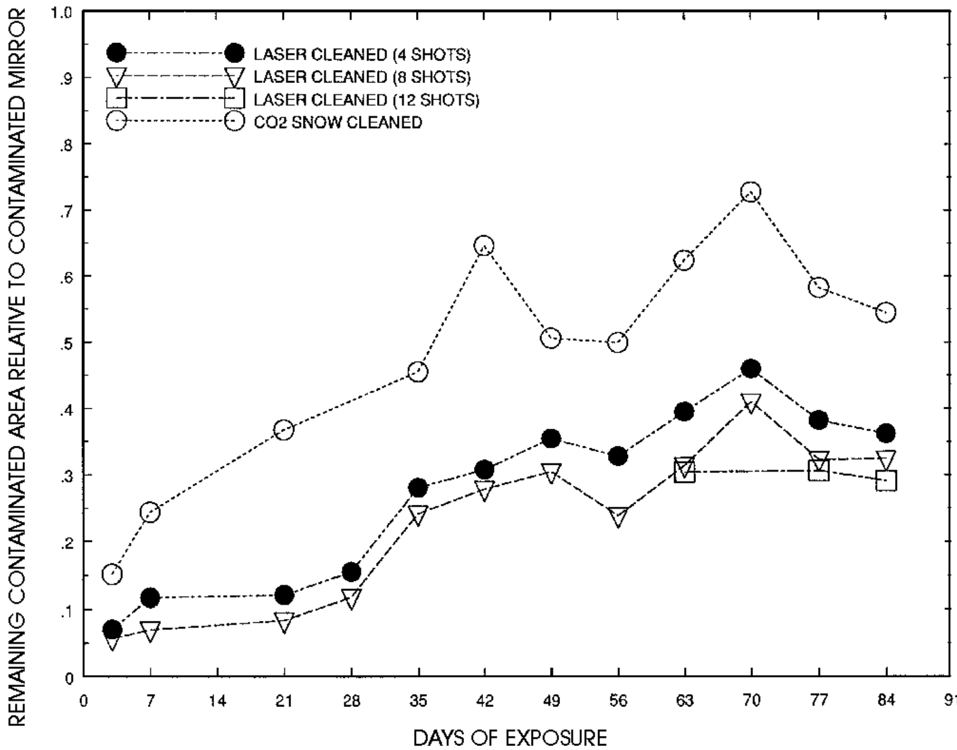
4.3 Implementation in Gemini Facility



4.3.1 CO_2 Layout



(a) The most basic implementation for CO_2 jet cleaning would be manual operation from a raised platform, using a system similar to that seen in Figure 4-2. The telescope could be tilted to

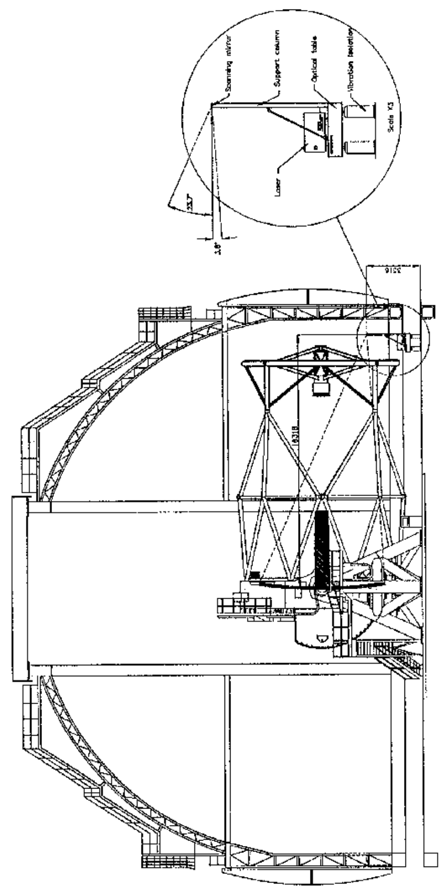


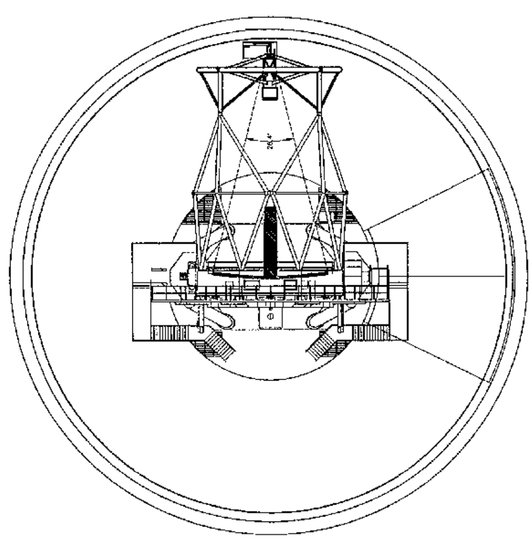
the horizon-pointing position, and a lift could be utilized along the face of the mirror. Theoretically, two people with a sufficiently-sized CO_2 tank would be sufficient for the job. The operators would work in tandem to cover the mirror surface using a horizontal, slightly-downward-pointing movement of the delivery nozzle system, while arranging the lift system as needed. Drawbacks to this mode of operation include potential danger to the primary mirror from the nozzle delivery system.

(b) Another potential implementation for Gemini is to install a multiple nozzle system into the mirror covers of the telescope. The telescope could be tilted to the horizon-viewing position with the lower shutter fully extended and the upper shutter fully open. The upper shutter could slowly close, cleaning the upper half of the mirror; then the lower shutter could slowly open, cleaning the other half of the mirror. If the nozzles point respectively slightly downward, this would also cause any collected material to be swept to the bottom section of the mirror cell, where it could be easily removed.

4.3.2 Laser Layout

(a) The concept layout of the system designed by STI Optronics was discussed in Section 4.2.2.2.1. Implementation of that system within the Gemini facility would involve actual installation of the optical table and components and the support I-beam. Figure 4-11 shows a top- and side-view of the possible layout within the telescope enclosure.





(b) The current layout would involve the mirror being set to the horizon-pointing position, then the laser system being activated with the laser beam being scanned across the mirror surface, In order to clean the part of the mirror obscured by the optical baffle, the telescope would have to be azimuthally rotated 10 o *in either direction.*

4.4 Future Plans

(a) Once the protected silver coating program (see Section 5) is complete, samples of the candidate protective overcoatings will be laser cleaned.

4.5 References

[4-1] R. Weiss, "Changing Optical Surfaces with Snow", OE Reports pg. 4, April 1994
[4-2] R. Zito, "Cleaning Large Optics with CO_2 Snow", SPIE 1236, 1990
[4-3] M. Frink and R. Laybon, "CO_2 Jet Flush Cleaning Performance Monitored by Surface Scatter Measurements", SPIE Presentation 1992
[4-4] B. McGrath, CFHT, private communication
[4-5] R. Kindred, MMT, private communication
[4-6] Kimura et. al., "Comparison of Laser and CO_2 Snow Cleaning of Astronomical Mirror Samples", SPIE **2199**, *1994*
[4–7] Ρ.Α. Οσιεχκι ανδ Τ.ϑ.Μαγεε, ∀Υλτραϖιολετ Λασερ Χλεανινγ οφ Μιρρορεδ Συρφαχεσ∀, ΣΠΙΕ **1329***, 1990*
[4–8] ΣΤΙ Οπτρονιχσ, ∀Λασερ Χλεανινγ Συστεμ φορ Γεμινι 8–μ Τελεσχοπεσ Προφεχτ∀, #47990–ΓΕΜ00043, Αυγυστ 1993
[4–9] Β. Βαλιχκ ανδ Ω. Κιμυρα, ∀Σαφε ανδ Εασψ Χλεανινγ οφ Αστρονομιχαλ Μιρρορσ∀, ΝΣΦ Γραντ Προποσαλ, Απριλ 1991.

4.6 Figures

Figure 4-3. Pre-clean emissivity of contaminated samples.

Figure 4-4. Plot of pre-clean versus post-CO_2 clean emissivities.

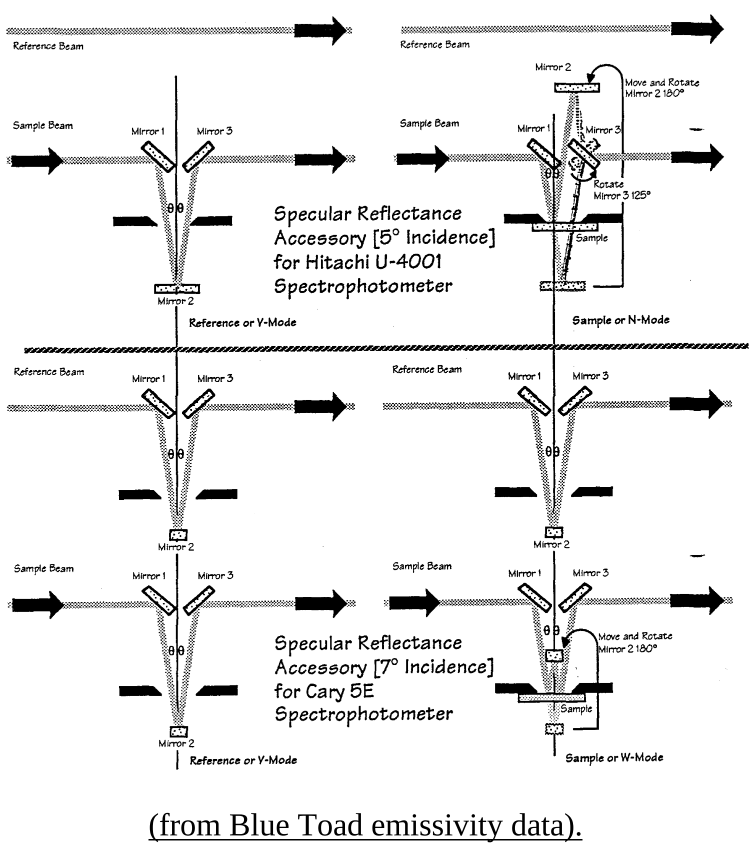
Figure 4-5. Layout of proposed laser optical table.

Figure 4-6. Laser beam profiles with and without an optical homogenizer.

Figure 4-7. Plot of samples cleaned with and without an optical homogenizer.

Figure 4-8. Layout of video scatterometry system.

Figure 4-9. Emissivity versus exposure time for both CO_2 and laser cleaned samples



(from Blue Toad emissivity data).

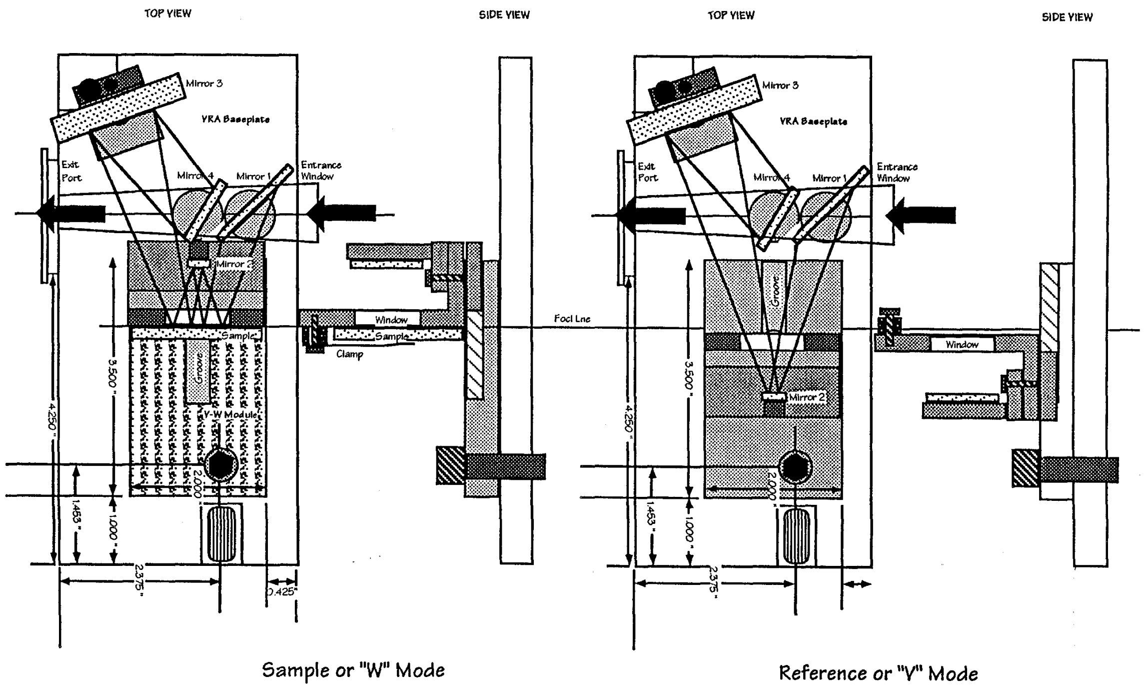
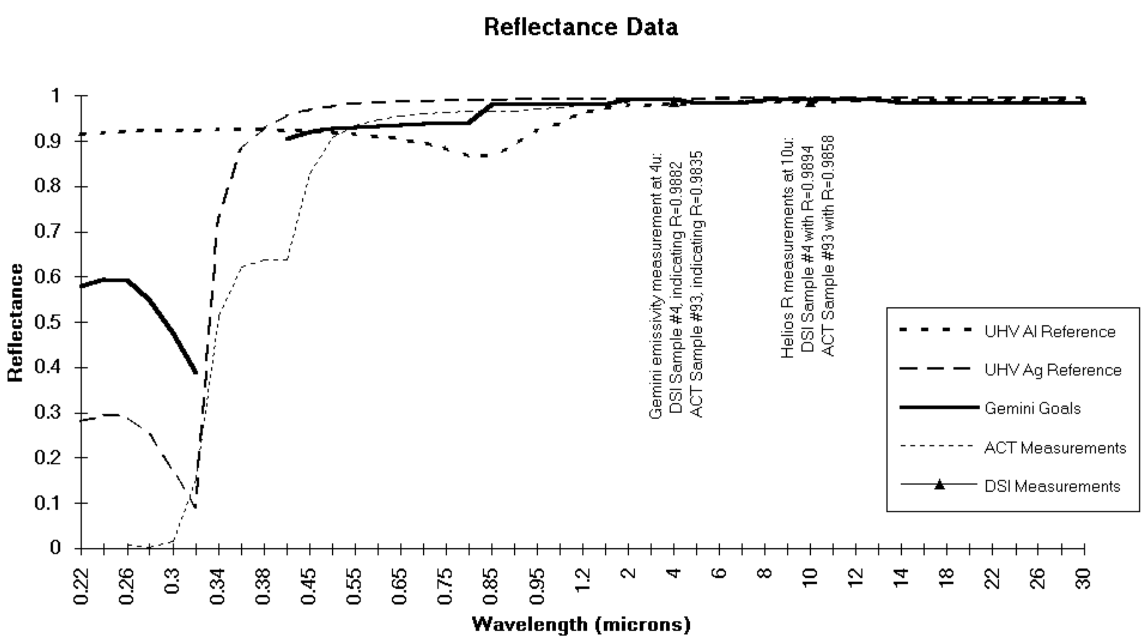


Figure 4-10. Remaining contaminated mirror area versus exposure for both



CO_2 and laser cleaned samples (from STI video scatterometry data).

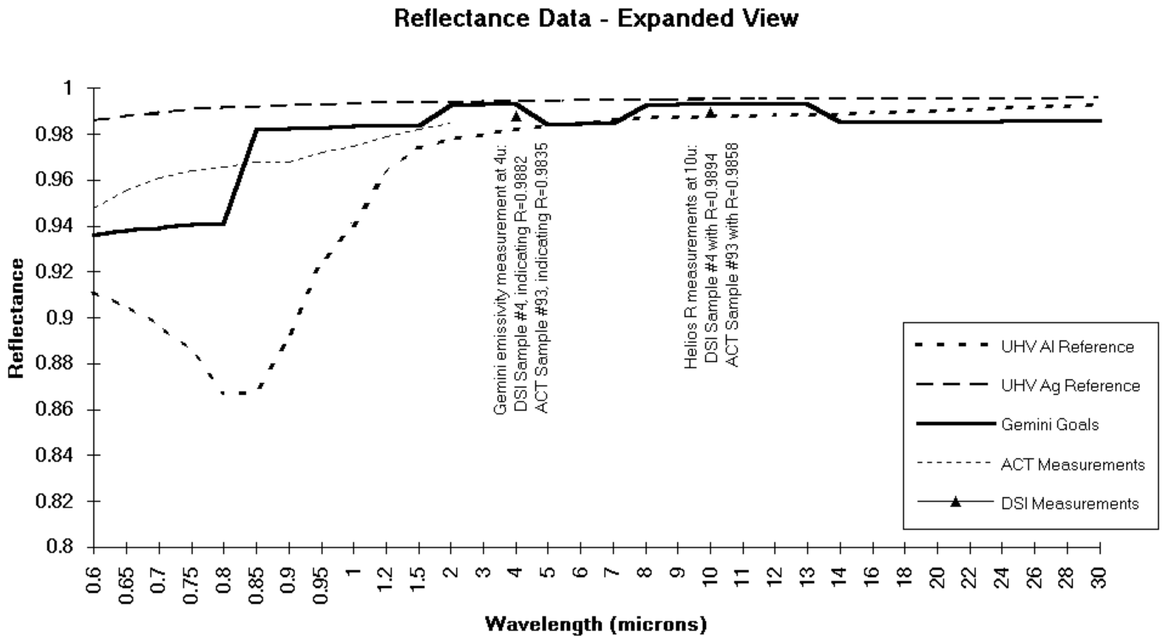


Figure 4-11. Layout of possible implementation in the Gemini enclosure.

5. Low Emissivity/Protected Silver Coatings

5.1 Introduction

(a) The top-level Gemini Science Requirements specify a goal of 2% for the telescope emissivity. This can only be achieved by coating the primary and secondary mirror with silver, as can be seen in Table 5-1. However, silver will tarnish if unprotected, and the emissivity and reflectivity will subsequently rapidly degrade. Figure 5-1 shows a graph of the UV-Visible reflectance of silver and aluminum, plotted against each other.

Table 5-1. Emissivity error budget for the Gemini telescope.

Emissivity error budget	Ag	Al
Primary mirror budget	0.8%	
Secondary Mirror Surface (Ag)	0.7%	
Secondary Outer Bevel	0.16%	
Secondary Inner Bevel	0.03%	
Secondary Vanes (by reflection)	0.2%	
Secondary Vanes (by scattering)	0.06%	
All other sources	0.05%	
Total	2.0%	4.0%

(b) It became important to identify and test the most appropriate coatings for Gemini to ensure that this goal is met, and to ensure the coating plant is specified to enable protected silver coatings to be deposited at a future date with minimum modifications.

(c) In 1991 the GSC requested that the Project investigate the feasibility of the development of a sputtered protected silver coating. Proposals were received in late 1991, and a source selection committee chose ODA of Tucson to undertake the program.

(d) The program was divided into two phases. Phase 1 investigated prior work performed in this field and ran computer simulations to predict candidate performances. A report was circulated to the GSC for comments prior to starting the next phase. Phase 2 is for actual deposition, characterization, and optimization of silver and protected silver coatings.

5.2 Progress to Date

5.2.1 ODA Literature Search and Computer Simulations

(a) The first phase of the investigative program included an exhaustive literature search to determine the best candidate protective coatings for silver. Properties and requirements for silver

were investigated, including the physical, chemical, and optical properties. Computer simulations were undertaken to predict the optical properties and performances of the candidate coatings. The top four candidates identified were silicon nitride (Si_3N_4); hafnium dioxide, or hafnia (HfO_2); tantalum pentoxide, or tantala (Ta_2O_5); and yttrium sesquioxide, or yttria (Y_2O_3).
(b) Work on this first phase has been completed, and a final report was submitted in September 1992[5-1]. The Gemini Project decided to further investigate the top two candidate coatings, silicon nitride and hafnia.

5.2.2 Phase 2 of ODA Program[5-2]

(a) The second phase of the program involved deposition, characterization, and optimization of bare silver and silver protected with the candidate overcoatings, followed by environmental tests of temperature/humidity, salt fog exposure, abrasion, adhesion, and sulfide exposure. ODA subcontracted to ACT to perform the Si_3N_4 work, and DSI for the HfO_2 *development. ODA would perform the optical characterization tests for reflectance across the required wavelengths. Both firms license these coatings commercially, and the Gemini program was designed to optimize these coatings to meet the Gemini specifications. In this manner, Gemini is building on a wealth of industrial experience.*

(b) The goals of this phase are twofold: (i) to produce a coating with a reflectivity as seen in the attached figures, which at 11 μm is 99.3% or better; and (ii) to boost UV reflectance between 0.3 μm and 0.38 μm by 30%.

5.2.2.1 ACT Work

(a) The base design for the coatings at ACT is S/PA/Ag/PA/Si_3N_4, where S is the substrate (either Pyrex or ULE*TM*), and PA is a proprietary adhesor layer. The overall strategy was to vary the thicknesses of the layers, as well as the deposition process parameters, to determine the optimal process requirements and stack designs.

(b) ACT has scheduled 2 runs of 2 weeks each in one of their industrial sputtering plants. The first run was in December, 1993; the second run is scheduled for late June, 1994. Between runs, coating characterization tests and environmental tests were conducted.

(c) Tests from the first run of samples indicate that the first adhesor layer is necessary for the integrity of the silver stacks. Optimally, the layer should be less than 1nm thick. The second adhesor layer, between the Ag and the Si_3N_4, may or may not be required, depending on a tradeoff between reflectance and durability. The reflective Ag layer was varied between 75 and 200nm, with a reflectance variance of only 0.1% at 10 μm. However, the raw reflectance of the silver was lower than the UHV deposited Ag values in the visible range.

5.2.2.2 DSI Work

(a) The base design for the coatings at DSI is S/Ag/HfO_2, where S is the substrate (either glass, quartz, silicon, or ULE**TM**). The overall strategy was similar to ACT's.

(b) DSI is using a smaller coating chamber for their test programs, and their program involves continuous coating and testing of samples.

(c) Initial tests indicated that, for these stacks, an optimum thickness for the silver layer was 150nm. Again, the raw reflectance of bare silver was lower than the UHV deposited Ag values, but reflectances of 99.19% have been reported. Stack development with hafnia at a 50nm thickness was encouraging.

5.2.3 Measurements

(a) Accurate measurements are achieved by a combination of instruments with accessories and optical standards. Optical measurements at ODA, DSI, and ACT are primary performed on the instruments found in Table 5-3. Measurements at Gemini are made on the Blue Toad, described in Section 4.2.1.2. Comparison measurements have been done on all systems, and all four sets of systems provide data in agreement**5-3**

Table 5-3. Optical Instruments at ODA, ACT, and DSI

Wavelength Range	**Organization (bracketed number = number of systems)**		
	ODA	**ACT**	**DSI**
UV-Vis-NIR	Cary 5E [1]	Hitachi 4001 [1]	Cary 5E [1]
R Accessories	V-W R Absolute	V-V R Absolute	V-W R Absolute
R Standards	NIST 2003 Al	NIST 2011 Au	NIST 2003 Al NIST 2011 Au
IR	PE 983G [2]	PE 983G [1]	PE 983G [3]
R Accessories	PE R Relative	PE R Relative	PE R Relative & Proprietary Units

(b) Reflectance measurements are generally made with respect to standards, unlike transmittance measurements. Measurements of the UV-Vis-NIR reflectances are performed by ODA and DSI using the Strong (V-W) specular reflectance accessories, and by ACT using a V-V accessory. Figure 5-2 shows the layouts of both accessories. The V-W accessory measures R^2, and is best suited for the high R measurements found in this program.

(c) Measurements of the IR reflectances are performed with the same system at all three organizations: the Perkin-Elmer 983G spectrophotometer, using a Strong V-W accessory (shown in Figure 5-3). This accessory measures absolute reflectance, and is the same basic design as the V-W accessories employed in the UV-Vis-NIR.

(d) Helios, Inc. of Longmont, CO, has been used by ODA to perform absolute reflectance measurements in the IR at 10.6 μ, using a laser reflectometer . This gives exact reflectance measurements in the critical IR window.

(e) Reference standards for the UV-Vis-NIR and NIR are NIST Al and Au calibrated standards. However, in the IR, there are no conventional standards available. ODA has had gold standards prepared by Epner Technology in New York, the same firm that does the gold standards for the NIST. These samples were electroplated gold, on diamond-turned nickel, on a beryllium-copper alloy substrate. These standards then had absolute reflectance measurements performed by Helios. ODA is in the process of distributing these IR standards to all involved in the program.

5.2.5 Environmental Tests

(a) All coatings are required to undergo environmental tests specified by the International Standards Organization[5-4] (ISO). These tests are, in the ISO recommended sequence and with the parameters used, as follows::

- ISO 9022-2: Moderate to severe water solubility (humidity) test. This consists of 16 hours of exposure to $55^{\circ}C$ with RH=95%.
- ISO 9022-4: Salt mist test. This consists of 120 hours exposure of 20% salt fog at $35^{\circ}C$.
- ISO 921--4: Moderate abrasion test. This consists of 40 strokes using approximately 10N force.
- ISO 9211-4: Moderate adhesion test. This consists of a snap pull of adhesive tape, ~25mm/second speed.
- ISO 9022-20: Chemical durability test. This consists of an atmospheric H_2S test with 10 ppm concentration. (A note must be inserted here: The concentration of sulfur on Mauna Loa has been measured quite extensively by the Mauna Loa Observatory at 70-80 ppt. Prevailing wind flow patterns over Mauna Kea and Mauna Loa lead to the belief that concentrations of sulfur at the summit of Mauna Kea will certainly be several orders of magnitude lower than those measured at Mauna Loa. The ISO tests call for a very high sulfur strength, and are being used mostly for comparitive performances of the samples.)

(b) In general, ACT samples with no protective overcoats did not pass most of the environmental tests. Samples without the second adhesor layer also failed most of the tests, in particular adhesion and abrasion. With the second adhesor layer, the samples passed most of the environmental tests, but with an additional loss of about 0.1% reflectance. The same environmental tests were performed on the DSI samples. At the time of this report, all of the samples passed the adhesion test, but did not pass the other environmental tests.

5.2.6 Schedule/Future Plans

(a) After two quarters (of six) of investigation, sample results from both ACT and DSI fall short of the R_{NIR} **goal of 99.2% by about 0.4%. However, the protective overcoatings themselves appear to account for only a fraction of the deficiency; it is the as-deposited silver films that are deficient. In the next quarter, a primary objective will be to improve the deposition process and improve the raw reflectance of the silver layer. Other goals for the next quarter are to improve the durability of the protected coatings, at least for the nondestructive environmental tests**

(adhesion and abrasion), and investigate boosting the UV reflectance. Figures 5-4 and 5-5 show a comparative plot of reflectances of the silver baseline, the aluminum baseline, the Gemini goals for protected silver, and the best ACT and DSI coatings to date[5-5]

(b) Coating removal will be investigated in the later quarters of the program, with results included in the Final Program Report.

(c) The full schedule for the protected silver investigation program is due to be completed in March of 1995. Milestones in the program are listed below:

- **The third Quarterly Report, covering further** Si_3N_4 *and* HfO_2 multilayer coating tests, preliminary optical properties, and durability properties, in late June 1994.
- The fourth Quarterly Report, covering further multilayer tests, refined multilayer coating measurements, and a preliminary report on long-term durability , in late September 1994.
- The fifth Quarterly Report, covering a final tabulation of multilayer tests, a report on refined long-term durability test results, and an outline of support for the 8m coating facility work, in late December 1994.
- A final program Report, containing all aspects of the program, in late March 1995.

5.3 References

[5-1] ODA, "The Investigation and Demonstration of the Feasibility of Low Emissivity Durable Coatings, Subtask A-1", under Contract 47990-GEM00032.
[5-2] ODA, "Investigation and Demonstration of the Feasibility of Low Emissivity Durable Coatings", #47990-GEM00057, July 1993.
[5-3] ODA First Quarterly Report, December 1993.
[5-4] ISO TC172 9211 and 9022, January 1992.
[5-5] ODA Second Quarterly Report, March 1994.

5.4 Figures

Figure 5-1. Reflectance of aluminum and silver in the UV-Vis range.

Figure 5-2. Diagram of UV-Vis-NIR Specular Reflectance Accessories.

Figure 5-3. Diagram of IR Reflectance Accessory.

Figure 5-4. Comparative plot of aluminum baseline, silver baseline, Gemini silver coating goal, and the best ACT and DSI samples to date.

Figure 5-5. Expanded plot of Figure 5-4.

Appendix 1 - Gemini Functional Specification for the 8m Coating Plant

1. General.

1.1 This section describes the functional specification of the Coating Plant(s). Engineering specifications will be developed by Royal Observatories during the design phase.

1.2 The Coating Plant(s) will be used primarily for coating the primary and secondary mirrors.

2. Primary Mirror Considerations.

2.1 The mirror(s) will be coated with the primary optical surfaces facing vertically.

2.2 The primary mirror(s) will be between 8.1m and 8.4m diameter. The Coating Plant(s) must be capable of coating a Corning ULE meniscus mirror.

2.3 Mirror handling arrangements will be specified and designed by the Gemini Project.

3. Interfaces.

3.1 The interfaces between the coating plant and the enclosure are detailed in the RGO Gemini Coating Plant Building Interface Document (RGO-N-027, Gemini ICDG0010).

4. Coatings.

4.1 The Coating Plant(s) will be designed to deposit aluminium at the time of build and commissioning of the Coating Plant at the Sites. The reflectivity of the aluminium is specified in Table 1.1. The coating plant must be designed to readily allow an upgrade (at some unspecified time in the future) to deposit the protected silver coatings being developed under contract to ODA.

4.2 Initial coating uniformity requirements are $\pm$ 5%, with a coating thickness of approximately 1000 angstroms.

4.3 Scattering. (TBD)

5. Future Upgrades.

5.1 The Coating Plant(s) must be capable of being upgraded to a high vacuum plant (10^{-7} torr) with minimal modifications. This will probably require, but may not be limited to, the use of stainless steel for the initial fabrication of the vacuum chamber(s) and the inclusion of additional ports that would initially be blanked off but would allow additional pumps to be connected to the chamber to provide higher pumping capacity at a later date.

5.2 As the Coating Plant(s) may be used for depositing interference films (at some later date) the uniformity requirements may become more strict. To accommodate this possibility the plant equipment for depositing the coating, such as the sputtering head support and rotation system, should be as modular as possible and be designed to allow upgrades, at minimal cost, to allow better uniformity to be achieved at a later date.

6. Operation.

6.1 The Coating Plant(s) must be fully automatic in operation, with manual overrides where appropriate. Mimic displays will be required on the control console showing the plant status.

7. Safety and Standards.

7.1 Ρεθυιρεμεντσ φορ σαφετψ ιντερλοχκσ ωιλλ βε δετερμινεδ δυρινγ τηε δεσιγν σπεχιφιχατιο πηασε.

7.2 Τηε Χοατινγ Πλαντ(σ) μυστ χονφορμ το ΑΣΜΕ ανδ ΒΣ στανδαρδσ.

7.3 Οπερατιον οφ τηε Χοατινγ Πλαντ(σ) μυστ χονφορμ το ΟΣΗΑ ανδ ΥΚ Φαχτορψ Αχτ σαφε στανδαρδσ. Γεμινι ωιλλ προϖιδε α λιστ οφ σολυτιονσ υσεδ το στριπ χοατινγσ (ΤΒΔ).

7.4 Τηε Χοατινγ Πλαντ(σ) μυστ βε δεσιγνεδ το οπερατε σαφελψ υνδερ τηε σιτε σεισμιχ λοαδινγ βυιλδινγ ρεθυιρεμεντσ

8. Maintenance.

8.1 The Coating Plant(s) must be designed to allow all necessary maintenance procedures to be performed efficiently with minimum manpower requirements.

9. Environmental.

9.1 The Coating Plant(s) will operate at the summit of Mauna Kea (13,800 ft) in Hawaii and Cerro Pachon (9000 ft) in Chile . Environmental conditions are listed below.

General:

Mauna Kea:

Seismic ground acceleration:	Zone 3 Requirements given in the Uniform Building Code
Min and Max Air Temperature Range	-15 ^{o}**C to +25**^{o}C (+5^{o}***F to +77*** ^{o}Φ)

Min and Max Air Humidity Range:	5% to 100%
Min and Max Air Pressure Range:	600 mb to 700 mb

Cerro Pachon:

Seismic ground acceleration:	Zone 4 requirements given in the Unifrom Building Code
Min and Max Air Temperature Range	-15°C to +30°C (+5°F to +86°F)
Min and Max Air Humidity Range:	5% to 100%
Min and Max Air Pressure Range:	700 mb to 800 mb

Operating Conditions :

Mauna Kea

Operating temperature range:	-15°C to +20°C (+5°F to +68°F)
Operating humidity range:	5% to 90%
Air Pressure range:	600 mb to 700 mb

Cerro Pachon

Operating temperature range:	-15 °C to +25°C (+5°F to +77°F)
Operating humidity range:	5% to 95%
Air Pressure range:	700 mb to 800 mb

Table 1.1
REFLECTANCE VALUES FOR ALUMINUM

l (m)	R, Al*
0.3000	0.9208
0.3500	**0.9205**
0.4000	0.9194
0.4500	0.9175
0.5000	0.9162
0.5500	**0.9157**
0.6000	0.9117
0.6500	0.9057
0.7000	0.8977
0.7500	0.8862
0.7800	0.8773
0.8000	0.8676
0.8300	**0.8657**
0.8500	0.8677
0.8800	**0.8744**
0.9000	**0.8908**
0.9300	***0.9075***
0.9500	0.9243
1.0000	*0.9402*
1.2000	0.9637
1.5000	0.9742

λ (μ)	***R***, Al*
2.0000	0.9779
3.0000	0.9805
4.0000	0.9826
5.0000	0.9843
6.0000	**0.9856**
7.0000	**0.9866**
8.0000	0.9872
9.0000	0.9874
10.0000	0.9876
11.0000	0.9879
12.0000	0.9882
13.0000	0.9884
14.0000	**0.9886**
16.0000	0.9892
18.0000	**0.9896**
20.0000	**0.9902**
22.0000	***0.990***
24.0000	0.9912
26.0000	*0.9918*
28.0000	0.9923
30.0000	0.9928

The Gemini Aluminum Coating Goal is to allow a maximum reflectance decrease of the values in the above table as follows:

- For λ ***between 0.30 and 0.38 μm, the goal is to decrease by no more than*** 0.05 *(5 %).*
- *For* λ between 0.38 and 0.8 μm, a decrease of *0.03* (3%) is allowed.
- For l between 0.8 and 2.0 *m* m, an decrease of *0.01* (1%) is allowed.
- For *l* between 2.0 to 2.5 μ**m, 3.4 to 4.4 μm, and 8.0 to 13.0** *m* m, a decrease of 0.002 (0.2 %) is allowed.
- For other λ between 2.0 and 25 *m* m, a decrease of 0.01 (1%) is allowed.

UHV Evaporated Aluminum information from "IR Reflectance of Aluminum Evaporated in Ultra-High Vacuum", Bennett et. al.,* **Journal of the Optical Society of America, 53, *1089-1100, 1963.*

Table 1.2

EMITTANCE VALUES FOR SILVER

λ (μm)	E, Ag * (fresh UHV evaporated silver)	λ (μm)	E, Ag* (fresh UHV evaporated silver)
0.3000	0.8240	**2.0000**	**0.0060**
0.3500	0.1945	**3.0000**	0.0058
0.4000	*0.0436*	4.0000	*0.0056*
0.4500	*0.0294*	5.0000	0.0054
0.5000	0.0214	6.0000	0.0052
0.5500	**0.0169**	7.0000	0.0050
0.6000	0.0140	8.0000	0.0049
0.6500	0.0120	9.0000	0.0048
0.7000	0.0106	10.0000	0.0047
0.7500	0.0090	11.0000	0.0046
0.7800	0.0087	12.0000	0.0046
0.8000	0.0084	13.0000	0.0045
0.8300	0.0082	14.0000	0.0045
0.8500	0.0080	16.0000	0.0044
0.8800	0.0075	18.0000	0.0044
0.9000	0.0071	20.0000	0.0044
0.9300	0.0070	22.0000	*0.0044*
0.9500	0.0070	24.0000	0.0043
1.0000	0.0064	26.0000	0.0043
1.2000	0.0062	28.0000	0.0042
1.5000	0.0061	30.0000	*0.0042*

The Gemini Protected Silver Coating Goal is to allow a maximum emissivity change of the values in the above table as follows:

- For λ between 0.30 and 0.38 μm, the goal is to decrease by no more than *0.30 (30%).*
- *For* λ between 0.38 and 0.8 μm, an increase of 0.05 (5%) is allowed.
- For λ between 0.8 and 2.0 μm, an increase of 0.01 (1%) is allowed.
- For λ between 2.0 to 2.5 μ***m, and 3.4 to 4.4*** μm, an increase of 0.001 (0.1%) is allowed.
- For λ between 8.0 and 13.0 μ***m an increase of*** 0.002 (0.2%) is allowed.
- For other λ between 2.0 and 25 μm, an increase of 0.01 (1%) is allowed.

*UHV Evaporated Silver Information from "IR Reflectance and Emittance of Gold and Silver in Ultra-High Vacuum", Bennett et. al., *Applied Optics*, 4:221-4, 1965.