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PRODUCTION OF 400 MIRRORS WITH HIGH VUV REFLECTIVITY FOR USE IN THE SLD ČERENKOV RING IMAGING DETECTOR*

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THE SLD CRID COLLABORATION

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ABSTRACT

The Stanford Large Detector for experimental particle physics detection at the SLAC Linear Collider contains a Čerenkov Ring Imaging Detector (CRID). The barrel CRID mirrors have been successfully produced and installed. The industrial mirror production process, the quality control of the mirrors produced, and the results of the vacuum ultraviolet (VUV) reflectivity and mirror-shape accuracy are described. An average reflectivity of at least 80% for light at 160 nm and 85% for light in the 180–230 nm wavelength range has been achieved in the production of over 400 mirrors of a typical size of 30 by 30 cm. The surface roughness and optical distortion measurements imply that the light loss due to scattering is a few percent of the incident light and the angular error due to shape distortion is less than 1 mrad.

1. INTRODUCTION

A large Čerenkov Ring Imaging Detector (CRID)[1,2] is currently under construction to be included in the Stanford Large Detector for experimental particle physics detection at the SLAC Linear Collider (SLC). This CRID consists of a cylindrical barrel and two endcaps, as shown in fig. 1(a). This device is capable of determining the actual radius of the Čerenkov ring associated with each charged particle which, along with a momentum measurement, provides particle identification.

In a gas ring imaging detector[3,4] the Čerenkov light emitted by a relativistic charged particle traveling through the radiator medium is reflected by a mirror to focus a ring image onto the photosensitive detector plane. The single-photon position detector consists of Time Projection Chambers (TPCs) with the photosensitive additive tetrakis[dimethylamine]ethylene (TMAE, with an ionization threshold of 5.4 eV) as the photocathode mixed with the drift gas. The TPCs (drift boxes) use quartz windows that are transparent to VUV light. This apparatus permits the reconstruction in three dimensions of the position where the photon ionized a TMAE molecule. The angle of Čerenkov radiation emission, from which the velocity of the relativistic particle can be determined, is found by reconstructing the ring image as registered by the photodetector for all the photons associated with a given charged particle.

The SLD barrel CRID includes both liquid and gas radiators, spherical focusing mirrors, long drift boxes of the TPC type containing gaseous TMAE as the photocathode, and proportional chambers with charge division readout, as shown in fig. 1(b). Each barrel half is divided into 10 azimuthal sectors which contain 2 drift boxes and their associated liquid radiators and 20 mirrors. Each drift box detects light from 2 rows of 5 mirrors and all of the 10 mirrors have a unique shape. The SLD barrel CRID contains a total of 400 spherical mirrors.

The gas radiator perfluoro-n-pentane[5] (C_5F_{12}) in which the Čerenkov light is emitted is only transparent for light of wavelengths longer than 165 nm, whereas the photocathode (TMAE) has a significant quantum efficiency only at wavelengths below 220 nm. In order to detect as large a number of photons as possible within the constraint of a reasonable cost, it was necessary to require the reflectivity of the mirrors to be not less than 85% for light in the range of 180–220 nm.

The accuracy with which the CRID measures the Čerenkov angle of a particle from the gas radiator is determined by the contributions from five separate sources of error: chromatic aberration in the gas radiator, measurement, multiple scattering, geometric, and momentum smearing.[6] The angular reflection error of less than ± 1 mrad for the two focal lengths of the mirrors of 479 mm and 508 mm ensured a small geometric contribution from optical distortions to the allowed overall photoelectron spatial reconstruction uncertainty of about 1–2 mm[3]. The focal properties and surface quality of mirrors which are suitable for ring imaging work are not as demanding as those for an astronomical telescope mirror, but are difficult to maintain in large quantities with thin mirrors and reasonable cost.

A total of 472 mirror substrates, of which 430 were coated, were successfully completed by the University of California, Santa Barbara (UCSB) for the SLD barrel CRID. The 400 mirrors that best met our acceptance criteria have been installed into the CRID vessel. We describe the mirror production process, the quality control of the mirrors produced, and the results obtained of VUV reflectivity.

2. MIRROR SUBSTRATE

2.1 Mirror Substrate Manufacturing

The mirror substrate was required to have a surface finish which would limit scattering to a few percent of the incident light. This requirement is due to the small number of photons produced, typically 10 or so. In addition, the mirror substrate was required to give an angular reflection error of <1 mrad. These requirements were achieved in a two-step manufacturing process.[7]

(i) The 6 mm × 1 m × 1 m glass blanks were "slumped." (In the slumping process, soda-lime float glass was heated and pulled into spherical molds under vacuum while soft.)

(ii) The spherical blank was ground and polished to produce a substrate with surface roughness $\leq$3 nm (rms).

After passing visual inspection, the mirror substrate was cut into one of the 10 different mirror sizes, and the edges were chamfered 0.16 cm or less. The mirror substrate was placed into a size gauge to easily verify that the dimensions were kept to within ±0.076 cm of the specifications. The 10 mirror sizes varied from approximately 26 × 23 cm to 35 × 28 cm.

2.2 Mounting Fixtures and Epoxy

After the mirror substrate passed the visual inspection and dimension check at UCSB, an annealed aluminum mounting spool was epoxied onto the substrate. Approximately 0.15 mm of DP190 epoxy was used with a gluing jig designed to ensure careful spool placement. Figure 2 shows the mounting spool shape used on all mirror substrates.

Before settling on the use of 3M DP190 epoxy to hold the mirror to the mounting spools, rigorous testing was carried out. The epoxy was required to adhere well to both glass and aluminum, not to outgas by-products that absorb UV light in the range of 160–220 nm, and to have an acceptably small thermal expansion coefficient. The choice of DP190 was made from a small list of possible adhesives that had been previously tested for outgassing and approved by the SLD CRID group. The epoxy was further tested at UCSB by gluing a spool to a mirror substrate, and hanging weights from the spool over a long period of time.

In the course of production, it was noticed that mirror substrates that had undergone a normal gluing procedure and had been subjected to high temperatures, developed voids in the epoxy-glass interface. The epoxy released totally from only one mirror substrate. The epoxy thickness used in this normal gluing process was not controlled so a new gluing procedure was developed in which the glue thickness was increased to a minimum of 0.15 mm using a spacer in the gluing jig. The epoxy strength was then tested in an oven at the CRID operating temperature (40°C) with weights ranging from 0.91 kg (approximate mirror substrate weight) to 4.5 kg attached to the spool. Small voids (about 1 mm^2) evolved into large voids (about 1 cm^2) in the epoxy-glass interface after a week, but all epoxy bonds held.

The area of the epoxy was also increased to give further confidence in the mounting spool-mirror substrate connection. To increase this area without a complete redesign and reassembly of the mirror support system, an epoxy injection method was made to introduce 1 cc of epoxy to fill the region between a previously glued spool's feet. A coated mirror after injection showed no change when the optical distortion was remeasured. Such spools did not develop voids in the injection regions while voids did develop on the foot regions under low-weight oven tests. A dramatic test of this increased adhesion was provided by taking an injected and an uninjected mirror substrate and subjecting both of them to a 22.7 kg weight at 40°C. Within 24 hours the uninjected mirror substrate released the spool, while the injected one still remains attached 1 year later. One cc of epoxy was injected beneath the spool for all mirrors as a result. The most probable cause of release is that the mismatched coefficients of expansion of the glass, aluminum, and epoxy conspired with the minimal adhesive thickness to stress the interfaces into developing voids.

As an additional protection against a mirror detaching from its spool and falling in the detector, a secondary restraint system was designed and installed on all mirrors. The secondary restraint system consisted of four wires connecting clips on the corners of the mirror and the mirror spool. This restraint system was designed to keep any mirror whose glue joint failed from doing further damage, but not to hold it in a sufficiently rigid position to be useful for focusing.

2.3 Surface Roughness

Surface smoothness of better than 3 nm (rms) is necessary in order to keep the light loss due to scattering to below approximately 5%. The surface profile of about 70% of the mirrors was tested[8] using a WYCO[9] 3-D Micro-Surface Measurement System with a 5× magnification lens. The method makes use of an interferometer technique and an online computer to provide real time 3-D displays of the surface structure. This type of measurement is vastly superior to a traditional stylus profilometer in many respects. At the beginning of each testing session, the WYCO system was calibrated using a reference with a known surface roughness of 0.24 nm. Each tested mirror was measured at two or three different locations, and the peak to valley and surface statistics were calculated at each location. Figure 3 shows an example of the surface roughness profile of a typical mirror substrate.

The acceptance criterion of an rms surface roughness of less than 3 nm, and a surface roughness of nowhere greater than 5 nm, was met by 91% of all the tested mirrors. The mirror substrates that failed the acceptance criterion were repolished or replaced at no additional cost.

2.4 Optical Distortion

The optical distortion of each mirror was measured by placing a mask with a grid of accurately positioned holes of a diameter of 1 cm (made on a numerically controlled milling machine) in front of the mirror and illuminating it with a point light source at the center of curvature (approximately 1 m away). The image of the grid pattern was projected onto a frosted glass screen, which was set a distance of 10 cm behind the center of curvature. This provided a demagnification of 10 : 1 of the grid pattern. This image was then photographed with a 1 : 1 macro lens (see fig. 4). An ideal mirror would produce light spots which fell exactly on the grid points scribed on the frosted glass. Departures from the ideal curvature, corresponding to angular errors of approximately 1 mrad at the ground glass screen, were easy to see. The photographed patterns were measured and compared to the ideal pattern to give the reflection error averaged over between 20 and 36 spots for each mirror. Two photographs corresponding to different masked positions of the mirror were taken. The requirement that the average angular reflection error be $\leq$1 mrad implied that the average deviation of a light spot from its corresponding grid point be $\leq$1 mm on the negative. After the film was developed it was easy to measure deviations at the 0.2 mrad level.

For an ideal mirror illuminated by a point light source placed very close to the center of curvature of the mirrors, the square grid pattern of the mask would create an undistorted square grid image pattern. To make the measurement of the imaged pattern possible, the point light source was situated off-axis below the mirror centerline by a few centimeters, and the frosted glass was above the centerline. A computer simulation with ray tracing was run to duplicate the actual positioning of elements. The off-axis positioning of the light source and the frosted glass cause the expected square grid to become slightly rectangular, with the longer side in the vertical direction. The ideal image pattern was taken to be this computed rectangle, and any other effects found were due to imperfections in the mirror.

The acceptance criterion of a maximum average reflection error of 1 mm on each negative was satisfied by 96.5% of all the mirror substrates. The mirror substrates that failed the acceptance criterion were replaced again at no additional cost.

3. COATING AND REFLECTIVITY

3.1 Coating

Before coating, the mirror substrates were cleaned by conventional methods. After extensive testing of coatings by many vendors, Acton Research Corporation's[10] standard coating ARC1600 was chosen. The mirror substrates were coated with approximately 80 nm of ultra-high purity aluminum and 40 nm of magnesium fluoride (MgF_2) overcoat under high vacuum (approximately 10^{-7} T). The mirrors were held by the spool pieces so no shaded areas were left on the mirrors. The aluminum was deposited in a few seconds and followed immediately by the MgF_2 to minimize oxidation of the reflective surface. The depositions took place as the mirrors rotated to insure an even coating. Figure 5 shows the minimum reflectance specifications ($\geq$80% at $\lambda = 160$ nm and $\geq$85% for $\lambda \geq 180$ nm). After coating, the mirrors were stored in a dry-air clean room with less than 15% relative humidity at 20°C.

3.2 Reflectivity Testing

Three spherical mirror substrates and one planar witness coupon (5.1 × 5.1 cm) were coated in each batch by Acton Research Corporation. The reflectivity of the witness coupon was measured by the vendor using the Acton Model VRTMS-502 Vacuum Measurement System at 10 wavelengths ranging between 160 and 230 nm. If the reflectivity of the witness coupon was above the minimum specifications, as shown in fig. 5, the reflectivity of the full-size spherical mirrors was assumed to be acceptable and the mirrors were shipped. Witness coupons were necessary because the Acton VUV spectrometer was not large enough to contain the full-size spherical mirrors.

After delivery to UCSB, the reflectivity of each full-size spherical mirror was measured at eight different wavelengths ranging from 160 to 230 nm relative to a standard whose absolute reflectivity was well measured. A custom instrument was designed and constructed to measure the relative reflectivity of each full-size mirror (see fig. 6). It consisted of a large vacuum box with steering mirrors, stands, and stepper motor rotators which permitted the reflectivity of the full-size mirror to be compared to the standard small mirror mounted in the box. A McPhearson 218 vacuum UV monochromator with a deuterium lamp[11] directed a narrow beam of light onto the test mirror, which reflected the light into a photomultiplier tube that was coated with p-terphenyl wave shifter.[12] The full-size test mirror could be pivoted about its center of curvature, and rotated about its center point, allowing any point on the mirror surface to be tested. All the motors and settings were computer controlled via CAMAC. At each wavelength, three positions of each full-size mirror were tested. The light from the full-size test mirror was compared to that from a curved standard (5.1 cm diameter) to determine the relative reflectivity of the test mirror. The absolute reflectivity of the curved standard was tested at least monthly using a second custom instrument described later; thus the absolute reflectance of the full-size spherical mirrors could be calculated rather accurately.

After delivery to UCSB, the reflectivity of the witness coupons were measured at the same 10 wavelengths as chosen by Acton in the range 160 to 230 nm. This was done using a custom instrument, which was built to measure absolute reflectivity of small mirror samples. This instrument was pumped down to a high vacuum (approximately 10^{-6} T) so no VUV absorption from oxygen or water vapor could occur. A second McPhearson 218 VUV monochromator with a deuterium lamp directed a narrow beam of light onto the test mirror. The test mirror reflected the light onto a standard mirror, which reflected the light into a photomultiplier. The light from this measurement was then compared to the light obtained when the standard mirror was pivoted into a position to reflect the narrow beam from the deuterium lamp directly into the same photomultiplier. The same position on the standard mirror was illuminated by the narrow beam in both cases; thus the absolute reflectance of the mirror sample was determined directly.

3.3 Reflectivity Results

Figure 5 shows the average reflectivities, measured at UCSB, of all 430 full-size coated mirrors at 8 wavelengths in the range of 160 to 230 nm. The reflectivity steadily increases from 84% at 160 nm to 89% at 220 nm. The reflectivities of all 430 mirrors are presented at four wavelengths in fig. 7 as histograms showing the number of mirrors N having reflectivity R in percent.

The average reflectivities of the witness coupons for all 430 mirrors as measured at UCSB are shown in fig. 8. The agreement between the measurements of the witness coupons by UCSB and Acton Corp. is good for the wavelengths ranging from 180 to 230 nm. However, the UCSB averages are as much as 3.6% lower than those made by Acton Corp. for wavelengths in the range of 160 to 175 nm (as shown in fig. 8). The average results are in agreement well within the measuring errors over all wavelengths.

The agreement between the reflectivity measurements of the witness coupons at UCSB and those of the associated full-size mirrors at UCSB is good at all wavelengths (see fig. 5). The average reflectance of the full-size mirrors and the witness coupons differ by a maximum of 1.5% (which occurs at 190 nm).

4. ALIGNMENT

4.1 Mounting Spool

The mirror alignment process involved the rotating and bending of the mounting spools (see fig. 2). The spools were machined from 6061T–6 aluminum and then fully annealed. The purpose of the spool design was to allow the bending of the stem to orient the mirror in any direction with high precision. It had to satisfy the double constraint of not bending too easily (to prevent droop or accidental bumps) but easily enough to make small adjustments without springing back to the original position.

The effect of a variable torque on the spools was tested, measuring the amount of deflection when the torque was applied and the ability of the spool to return to its original position when the torque was removed. It was found using a stem diameter of 7.62 mm that the elastic limit was reached at 3.1 kg. Since the average mirror weighed less than 1 kg, this was deemed adequate to prevent droop yet also permit alignment changes of 1 or 2 mrad.

4.2 Mirror Alignment

An alignment table was designed to simulate the position of the mirror array as if it were in the SLD CRID vessel. In the CRID each mirror type focuses light towards a different position along a drift box. The alignment table had two sides, the mirror array side and the point light source side, as shown in fig. 9. An array consisted of two ladders attached to a permanently mounted mirror main channel. Each ladder had 5 mirrors mounted via mirror arms onto a side mount channel. The arms were made of stainless steel tubing cut and welded to nominally orient the mirror. The source side of the alignment table had a point light source-screen assembly, that could be accurately and reproducibly positioned by means of precision alignment holes in the table to bring the source to the center of curvature of each of the 10 mirrors in turn. Each mirror was then illuminated by the point light source, and the image projected onto a frosted glass screen. The radius of curvature was measured by moving the screen position along the axis of the mirror until the image reached its smallest point. Aligning was done by rotating and bending the spool stem (see sec. 4.1 and fig. 2). Typical adjustments needed were of the order of 10 mrad. The alignment was done to a typical accuracy of ± 2 mm (± 2 mrad) from the center of the screen. A secondary restraint system was installed on each mirror at the time of alignment to provide further protection against a mirror releasing from its spool (see sec. 2.2).

After all 5 mirrors were aligned, the ladder with its side channel was detached from the mirror main channel of the alignment table and mounted in a shipping box to be sent to SLAC. Special shipping boxes were designed and tested in order to comply with the requirements pertaining to transport-environment resistance, cleanliness, and shock-absorbing ability. Tests indicated that driving over rough roads did not affect the alignment. The steam-cleaned aluminum boxes contained several small packets filled with a desiccating agent; the boxes were then filled with dry nitrogen. The desiccant packets were replaced and the shipping box was purged with dry nitrogen after each use.

4.3 Mirror Ladder Installation

After their arrival at SLAC, the mirror ladders were placed in clean, dry (15% RH at 20°C) storage shelves. Previously, 40 main mirror channels identical to the one on the alignment table had been mounted onto the inside surface of the liquid argon calorimeter vacuum jacket. Installation consisted of placing the ladders onto the main channels. This was done by means of a sophisticated instrument mounted on a large turret. The turret allowed access to all positions around the barrel. The instrument itself permitted translation along three directions and rotations about two axes. This freedom of motion was required to accurately mate the ladder to the main channel without bending. The ladder was held onto the instrument by a compressed air system which could be remotely released after the ladder was in place. The final step was to wedge a bar between the ladder and the channel by means of a screw which drove the bar and locked the assembly in place.

4.4 "In-Place" Mirror Measurement

Alignment was done on a bench as described to an accuracy of approximately ±2 mrad. We expected the actual deviation in the CRID barrel to be considerably larger—the contributing factors may include minor misalignments of the main or side channels which would be magnified by a factor of 100 or so due to the long lever arm. In addition, we wanted to determine where each mirror pointed onto the particular drift box to which it was focused. This would remove any deviations in mechanical tolerances of the barrel structure itself.

We have constructed a device which is rigidly supported at the same three points as the particular drift box associated with a ladder of mirrors. The device is very simple in concept. A laser beam is directed at a small mirror which is free to pivot about two axes so as to direct the beam onto the mirror being measured. The steering mirror is positioned so that the reflected beam from the measured mirror bounces off the steering mirror and back into the laser opening. By determining the position and angles of the steering mirror, we can easily compute the direction in which the measured mirror is pointing. In practice, each mirror was measured at three well-spaced points to determine the focal length of the mirror to an accuracy of ±1 or 2 mrad.

The actual measurements indicated that the average deviation from the original aimed-for spot was ±20 mrad, approximately. This posed no problem for us since we now have the actual direction of pointing to an order-of-magnitude better accuracy, but it stressed the need for making an "in-place" measurement.

5. CONCLUDING REMARKS

A mirror slumping, grinding, and polishing process at Lancaster Glass Company and a coating process at Acton Research Corp. have been successfully implemented to produce more than 400 spherical mirrors for the SLD Barrel CRID counter. The quality control measurements performed at Acton Research Corp. and at UCSB show good consistency and confirm that the average reflectivity is at least 80% for light at 160 nm and 85% for light in the 180–230 nm wavelength range for these mirrors. The surface roughness and optical distortion measurements imply that the scattering is limited to a few percent of the incident light and the angular reflection error is less than 1 mrad.

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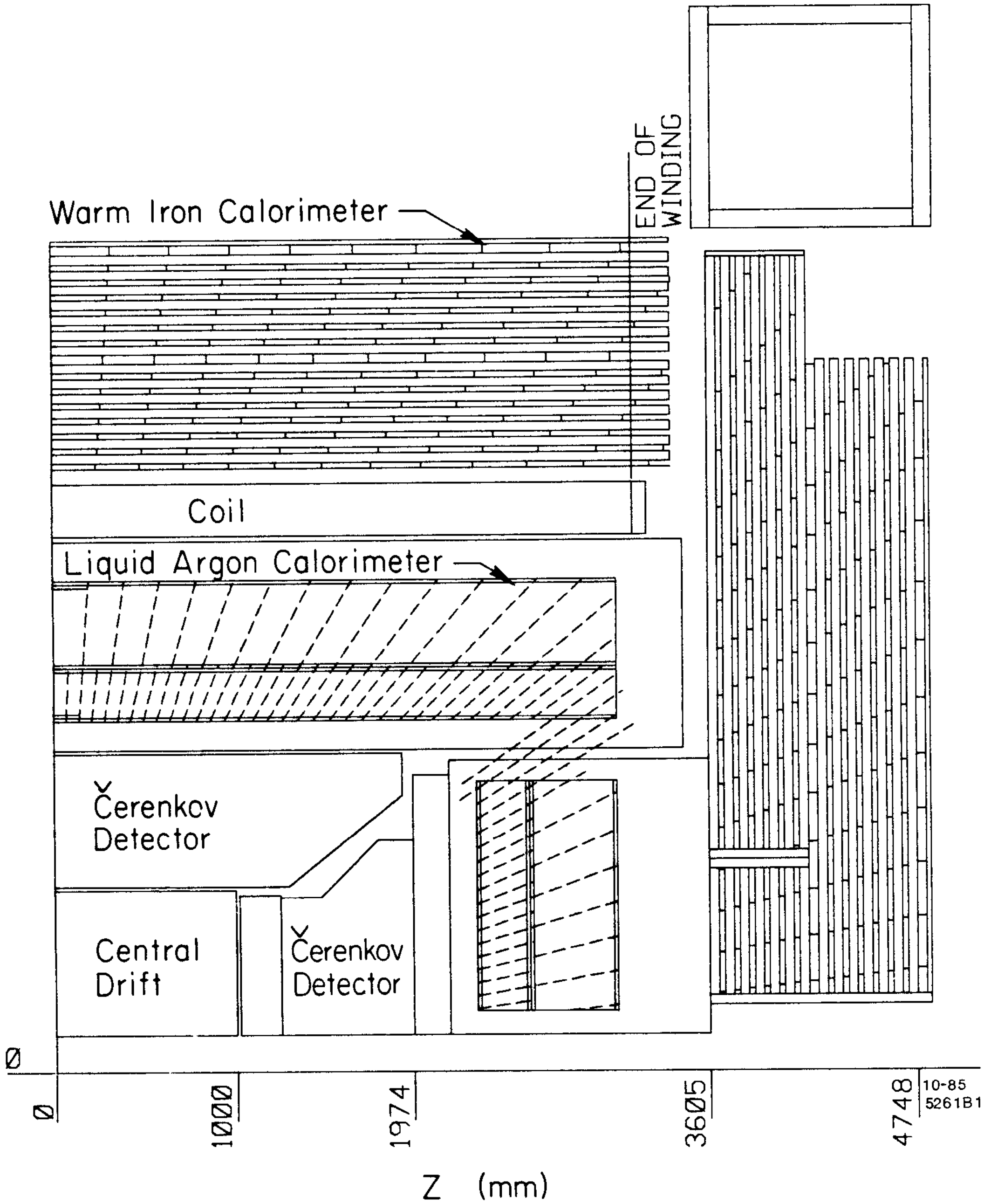
9. WYCO Corp., 1955 East 6th St., Tucson, AZ, 85719.
10. Acton Research Corp., Acton, MA 01720.
11. Hamamatsu L879-01, with MgF_2 window. Originally both the deuterium lamp and the monochromator were brought under vacuum but a short deuterium lamp lifetime resulted. The lamp was then closed in a container with a continuous nitrogen flow; thus the lifetime of the deuterium lamp was extended.
12. There was a gradual loss of the p-terphenyl wave shifter coating on the MgF_2 window since it was within the vacuum chamber. The p-terphenyl coating was frequently replaced to ensure maximum light output.

FIGURE CAPTIONS

1. (a) Vertical section in the plane including the $e^{\pm}$ beams of one quadrant of the SLD detector. (b) Schematic of CRID barrel longitudinal section with Čerenkov photons pictured. See (a) for scale.
2. Aluminum mounting spool epoxied onto the back of the mirror substrate.
3. Surface roughness profile of a typical mirror substrate, showing a 2×2 mm area with a surface roughness of 1.91 nm (rms) and a curvature of 1.020 m.
4. Bench setup used to measure the optical distortion from each mirror.
5. The average VUV reflectance results as measured by UCSB for the witness coupons and full-size mirrors, and the minimum acceptable reflectance specifications.
6. The custom instrument used to measure the relative reflectivity of all full-size mirrors: (a) light path schematic, and (b) photograph of device.
7. Results of the reflectivity measurement of the full-size mirrors for all 430 mirrors at UCSB for the light at wavelength (a) 160 nm, (b) 180 nm, (c) 200 nm, and (d) 220 nm.
8. Results of the reflectivity measurement of the witness coupons for all 430 mirrors at Acton Corp. and UCSB for the light at wavelengths 160 thru 230 nm.
9. Table used to align mirrors on a ladder, as discussed in text.


Warm Iron Calorimeter
END OF WINDING
Coil
Liquid Argon Calorimeter
Čerenkov Detector
Central Drift
Čerenkov Detector
Ø
Ø
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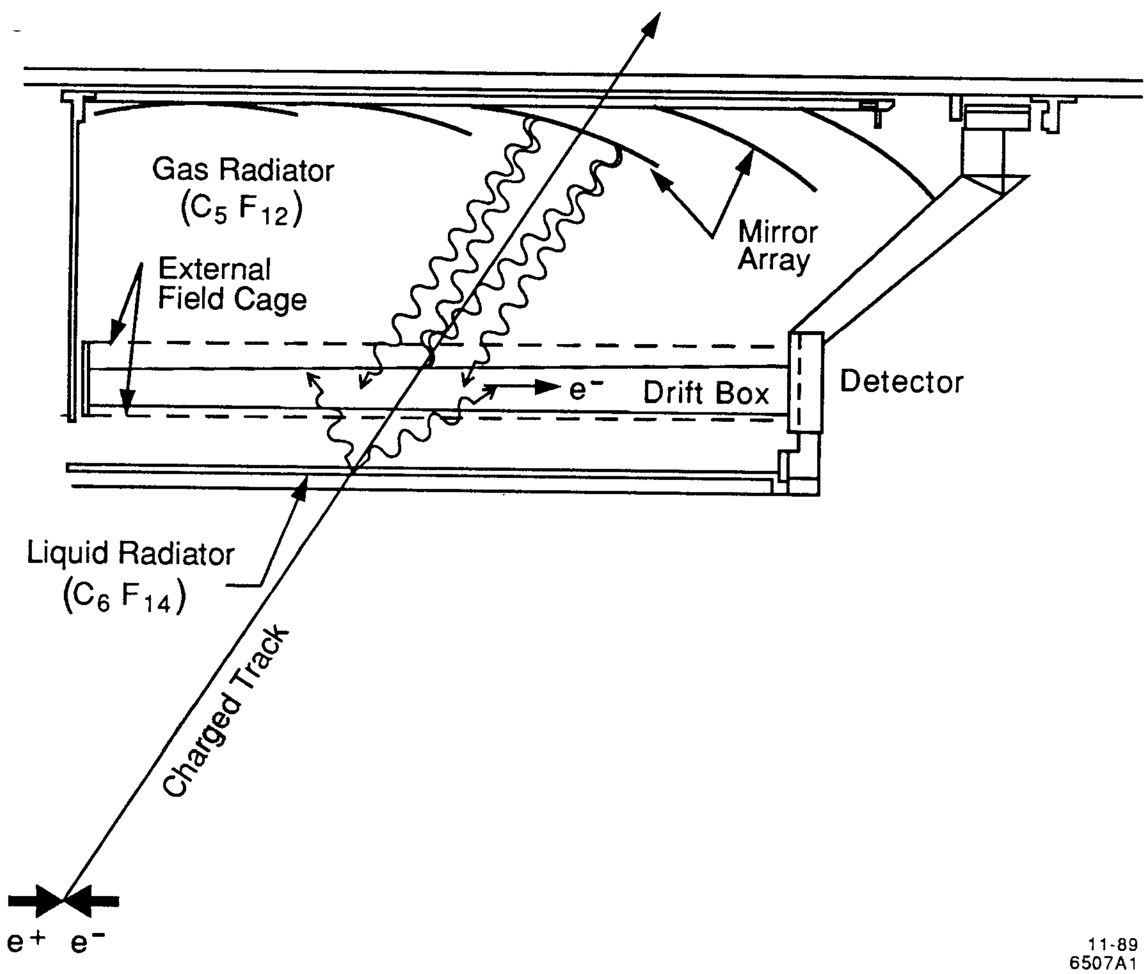
1974
3605
4748
10-85
5261B1
Z (mm)

Fig. 1a



Gas Radiator
(C_5F_{12})
External
Field Cage
Mirror
Array
e^-
Drift Box
Detector
Liquid Radiator
(C_6F_{14})
Charged Track
e^+ e^-
11-89
6507A1

Fig. 1b

SPOOL PIECE

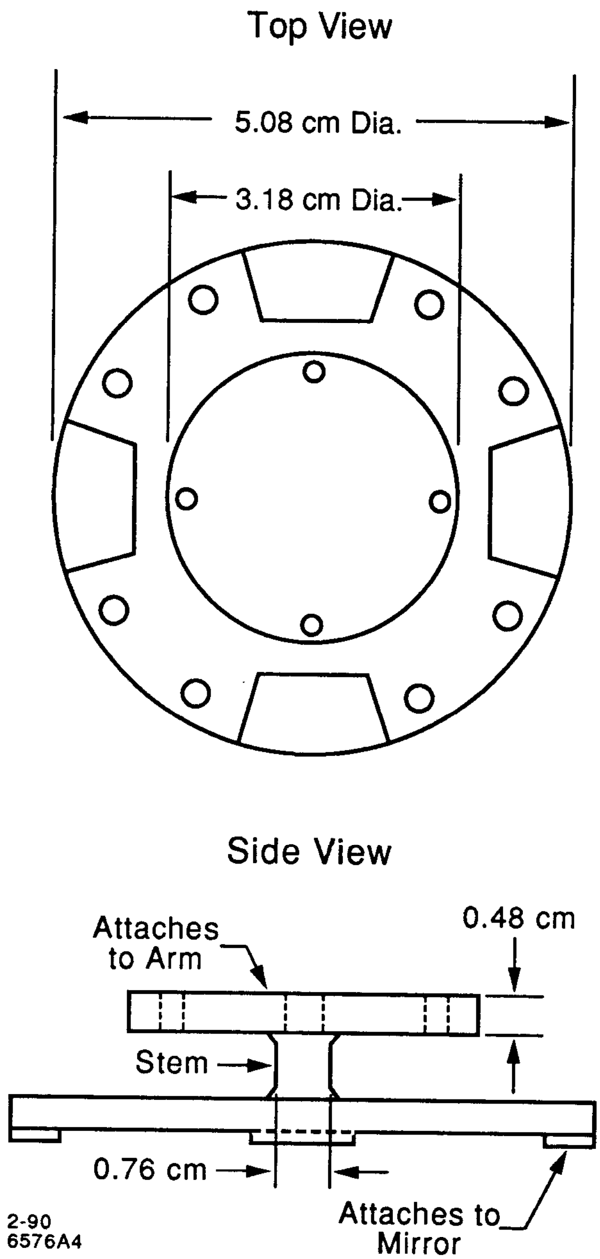
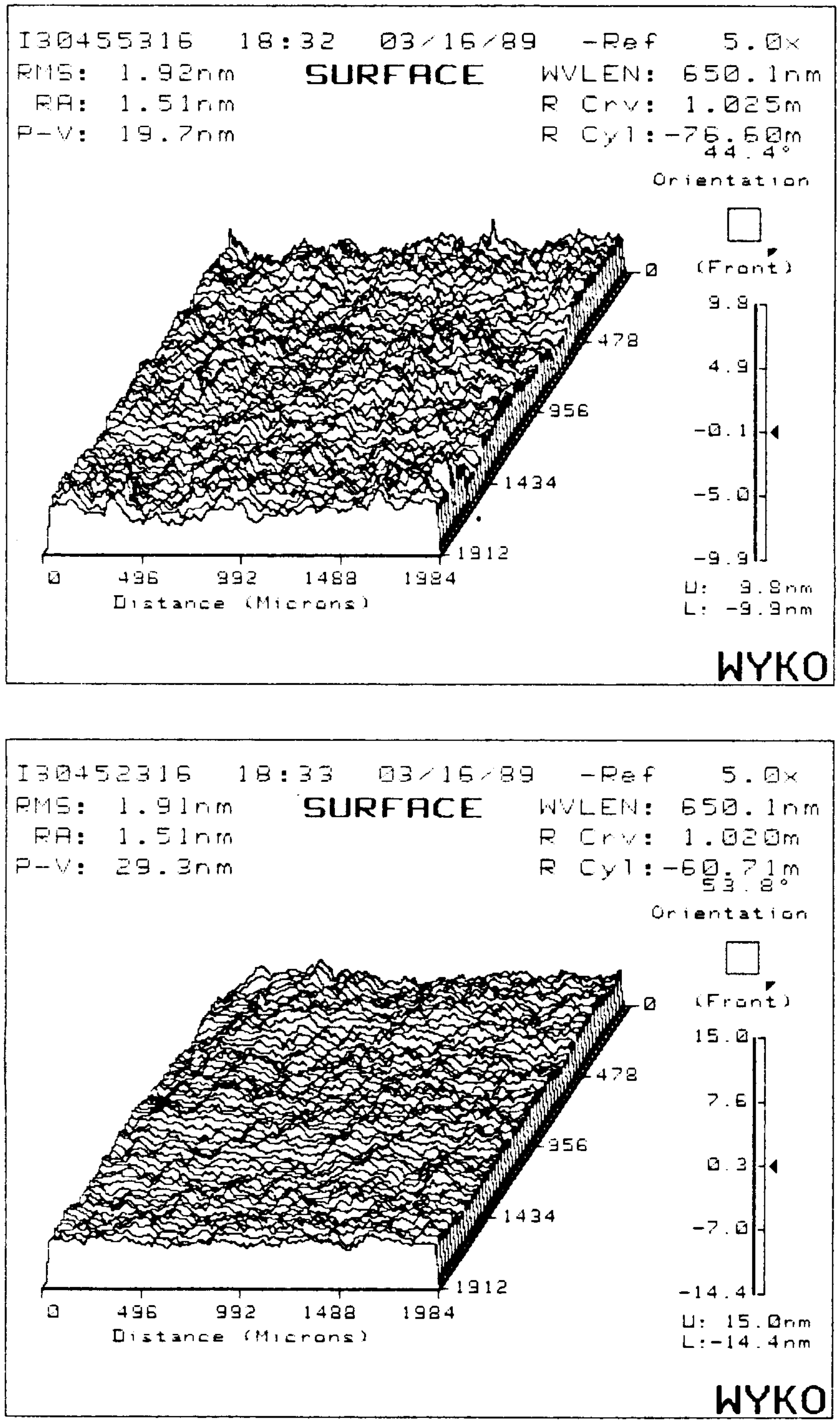
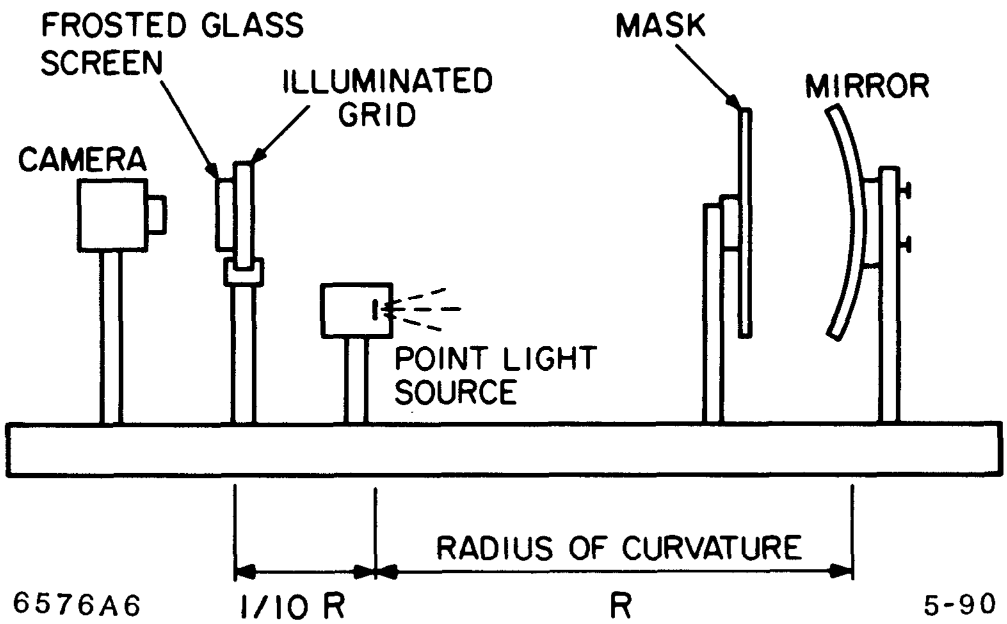


Fig. 2



5-90 6576A5

Fig. 3


FROSTED GLASS
SCREEN
ILLUMINATED
GRID
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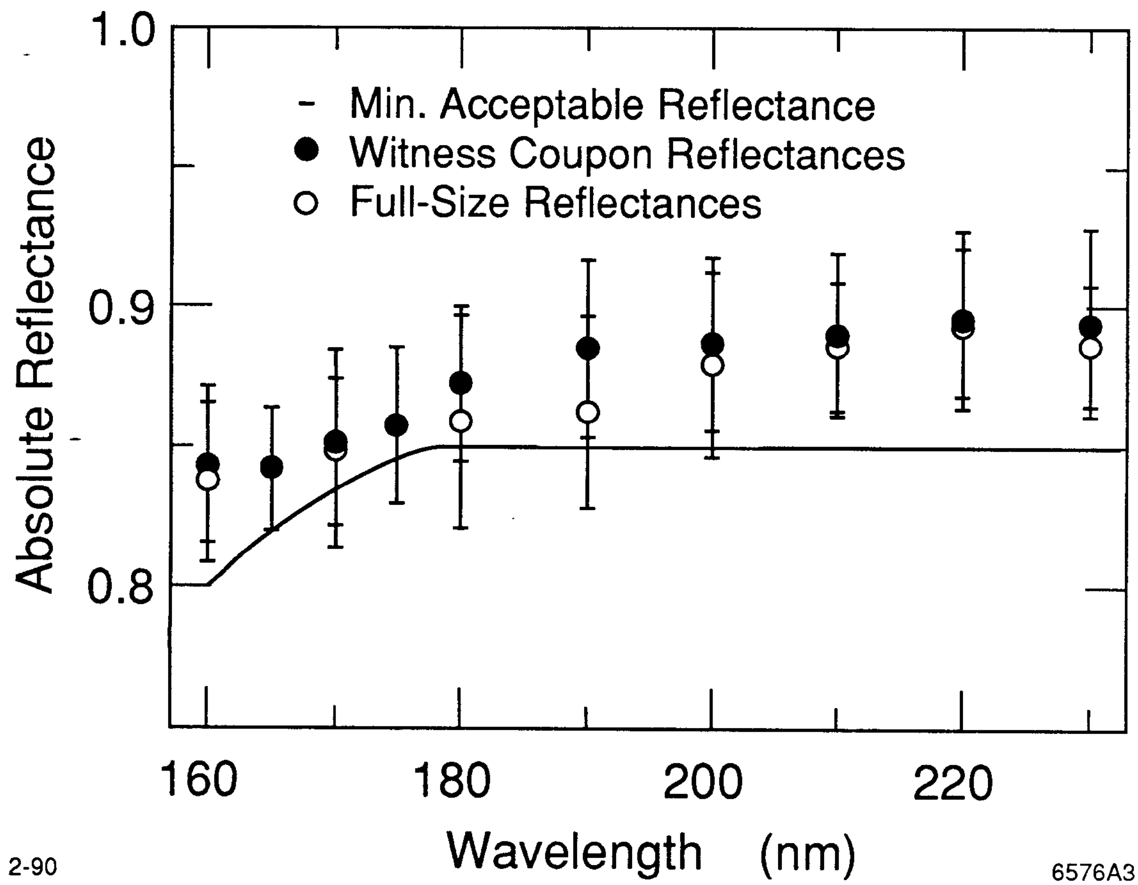
MIRROR
POINT LIGHT
SOURCE
RADIUS OF CURVATURE
6576A6
1/10 R
R
5-90

Fig. 4


1.0
0.9
0.8
Absolute Reflectance
- Min. Acceptable Reflectance
● Witness Coupon Reflectances
○ Full-Size Reflectances
160
180
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Wavelength (nm)
2-90
6576A3

Fig. 5

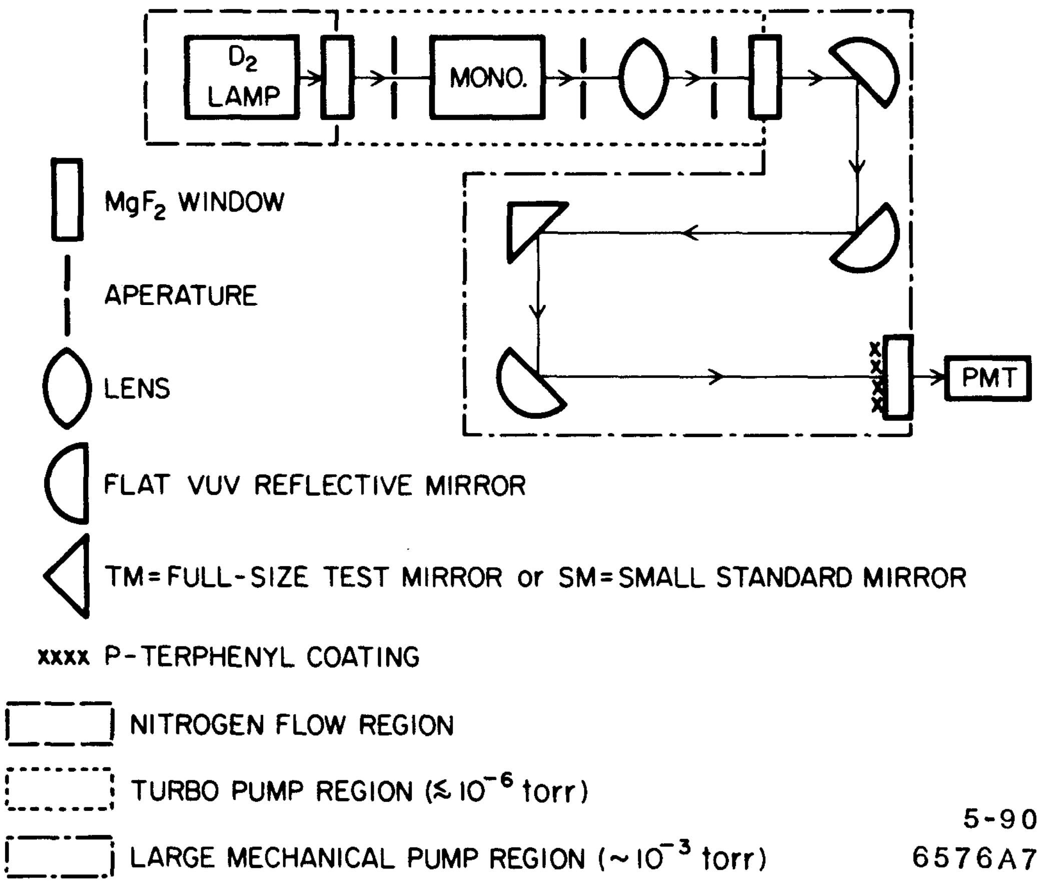
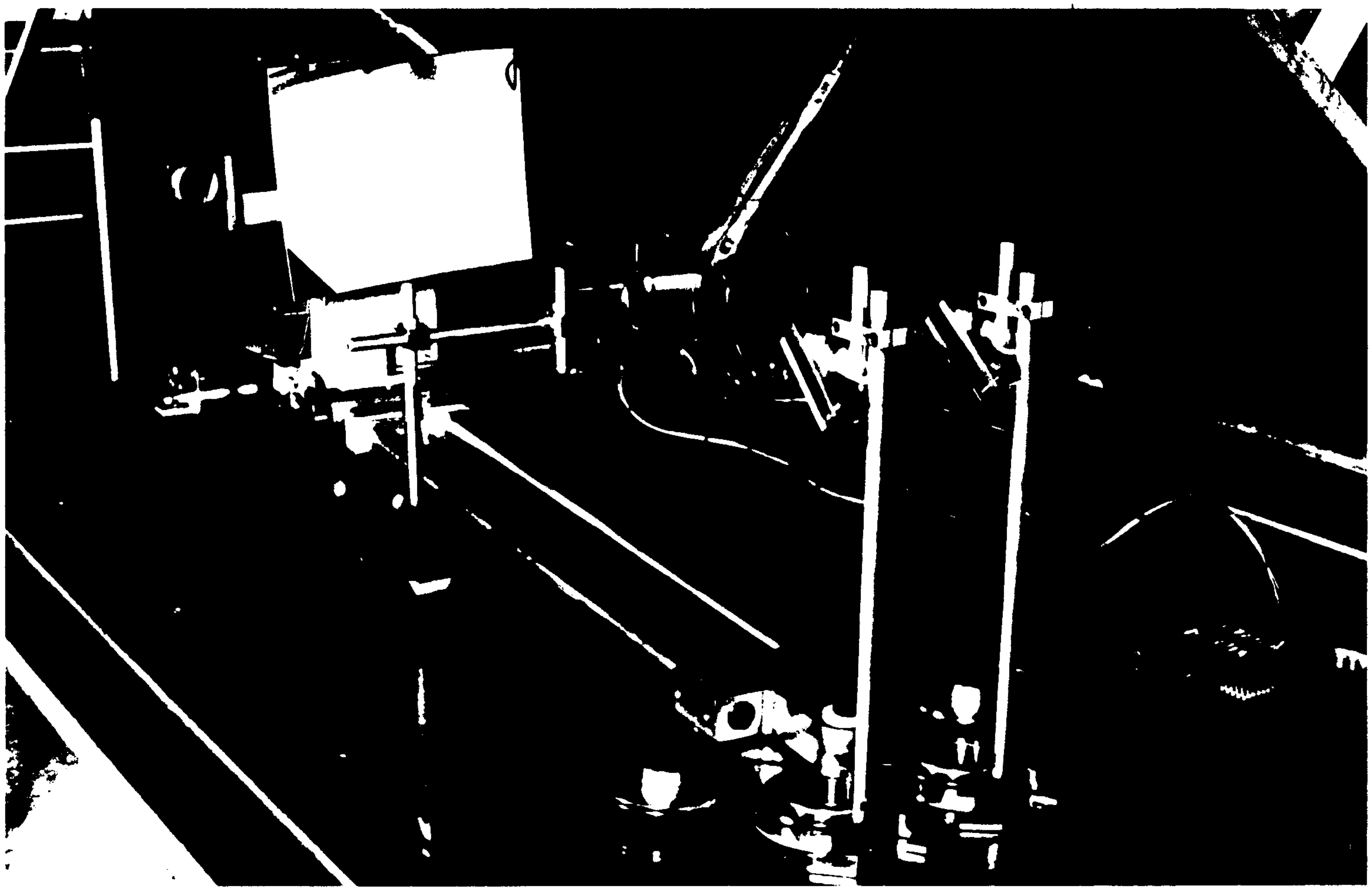

D_2 LAMP
MONO.
PMT
MgF_2 WINDOW
APERATURE
LENS
FLAT VUV REFLECTIVE MIRROR
TM=FULL-SIZE TEST MIRROR or SM=SMALL STANDARD MIRROR
xxxx P-TERPHENYL COATING
NITROGEN FLOW REGION
TURBO PUMP REGION ($\lesssim 10^{-6}$ torr)
LARGE MECHANICAL PUMP REGION ($\sim 10^{-3}$ torr)
5-90
6576A7

Fig. 6a



5-90 6576A8

Fig. 6b

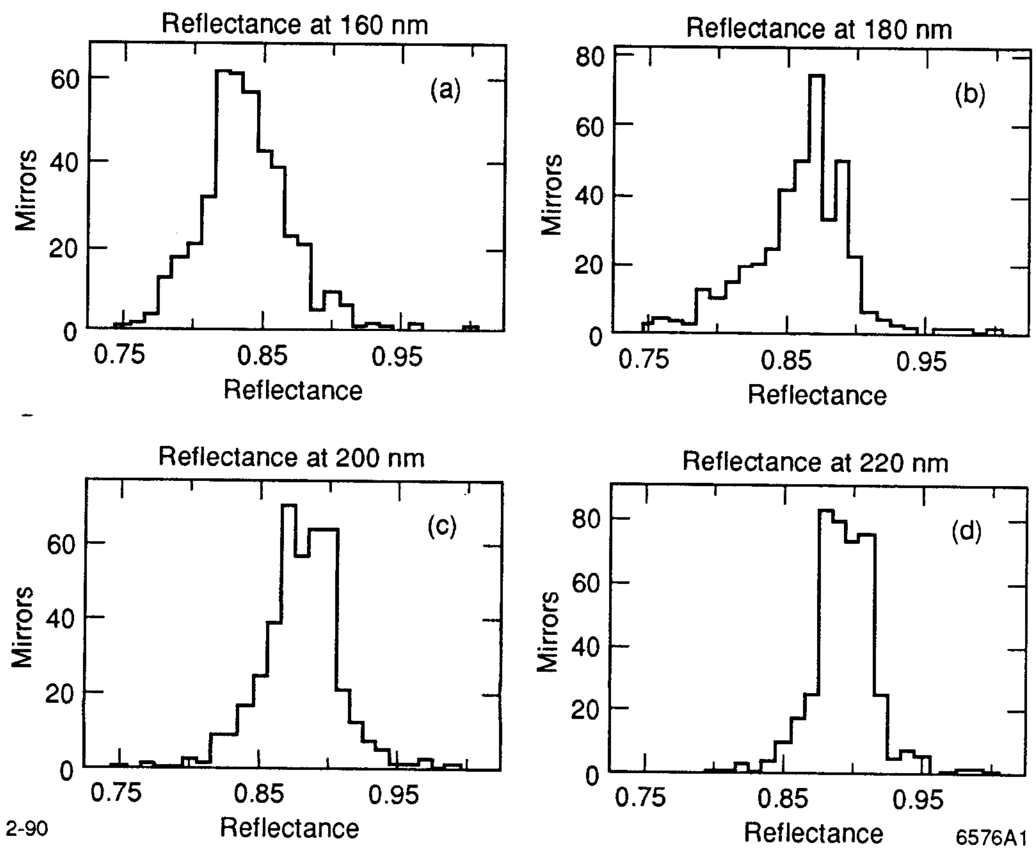

Reflectance at 160 nm
(a)
Mirrors
0
20
40
60
0.75
0.85
0.95
Reflectance
Reflectance at 180 nm
(b)
Mirrors
0
20
40
60
80
0.75
0.85
0.95
Reflectance
Reflectance at 200 nm
(c)
Mirrors
0
20
40
60
0.75
0.85
0.95
Reflectance
Reflectance at 220 nm
(d)
Mirrors
0
20
40
60
80
0.75
0.85
0.95
Reflectance
2-90
6576A1

Fig. 7

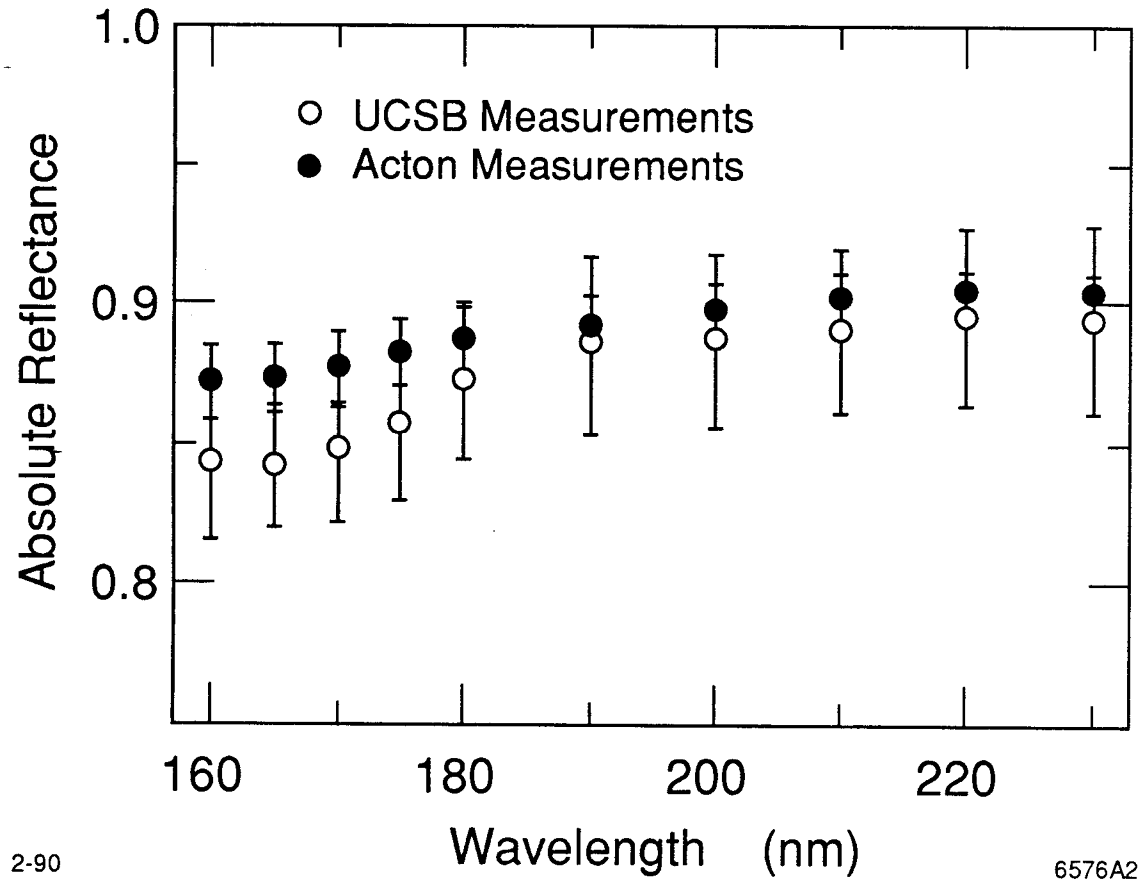

1.0
0.9
0.8
Absolute Reflectance
UCSB Measurements
Acton Measurements
160
180
200
220
Wavelength (nm)
2-90
6576A2

Fig. 8

5-90 6576A9

Fig. 9