Calibration of the AXAF-HRC UV/Ion shields at the Osservatorio Astronomico di Palermo G.S.Vaiana: IV - UV rejection measurements.

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ABSTRACT

The AXAF-HRC UV/Ion shields have to provide high UV rejection from diffuse background and bright UV sources (e.g. rejection greater than 10^7 at wavelength longer than $\sim 300 Å$ for the HRC-I). In the framework of the AXAF-HRC calibration program we have conducted UV (300-2500 Å) and FUV/Visible (1900-10000 Å) transmission measurements on the baseline design UV/Ion shields based on Lexan and aluminum. The results of these measurements, here reported, have shown that the baseline design UV/Ion shields did not meet the scientific requirements of UV opacity and as a consequence, the UV/Ion shields were redesigned. UV tests of new UV/Ion shields, based on new materials, is in progress.

KEY WORDS: X-ray, Astronomy, Instrumentation, AXAF

1 INTRODUCTION

Key components in the full exploitation of the capabilities of the AXAF[1,2] High Resolution Camera (HRC)[3] are the UV/Ion shields that protect the MCP based detectors from UV radiation and low energy ionized particles. Light rejection higher than 10^7 in the wavelengths range 300-3500 Å is required.

The original baseline design of the HRC UV/Ion shields was based on Lexan membranes coated with aluminum.[4] Lexan ($C_{16}H_{14}O_3$, bisphenol-A polycarbonate) is a plastic material whose soft x-ray properties are well known.[5] Nevertheless, in some cases where aluminum coated Lexan filters have been employed as UV blocking filters for soft x-ray detectors, leaks in the UV band have been detected during the in orbit operation. This was particularly evident and puzzling in the ROSAT mission where the HRI detected unexpectedly high count-rates from hot stars.[6]

In this paper we report on UV and visible transmission measurements conducted on aluminum coated Lexan filters initially developed for the AXAF-HRC UV/Ion shields. We show the occurrence of interferences in transmission, due to the multilayer design of coated plastic membranes, that significantly reduce the UV opacity at resonant wavelengths. In addition, the oxidation of the exposed surfaces of aluminum and/or the occurrence of chemical interactions between aluminum and the plastic support also affect the UV/Visible opacity.

The measured UV performance did not meet the scientific requirements of UV opacity and thus the HRC UV/Ion shields had to be redesigned. We have reconsidered the opportunity to use Polyimide in place of Lexan, the former being more opaque than Lexan in the wavelength range 2000-3500 Å . The new UV/Ion shield design, based on polyimide, carbon and aluminum, is more widely discussed in another paper.[7]

In section 2 and 3 we describe the vacuum UV and in air FUV/Visible transmission measurements conducted in this work. In section 4 we discuss a possible interpretation of the observed filter performances. In section 5 we present results on a comparison between Lexan and Polyimide, and show the FUV/Visible performance of the new design HRC UV/Ion shields. Summary and conclusions are given in the last section.

2 VACUUM UV TRANSMISSION MEASUREMENTS

All measured samples, manufactured by the Luxel Corporation (Friday Harbor, WA) , are listed in table 1 giving sample number (column 1), manufacturer ID number (column 2), sample material (column 3), manufacturer nominal thickness (column 4).

Vacuum UV transmission measurements were conducted at the XACT facility of the Osservatorio Astronomico di Palermo G.S. Vaiana[8] on sample 1 (see table 1) which was initially baselined as UV/Ion shield for the HRC-I detector on AXAF.[3] The adopted instrumental set-up is briefly described below, while a more detailed description of the instrumental set-up is given elsewhere.[9]

- a 1.0 m diameter grazing incidence monochromator;
- a hollow cathode source to cover the wavelength range 200-2500 Å, and a mercury lamp which provides a bright calibration lines at 2537 Å;
- two interchangeable photon counting detectors: 1) a KBr coated microchannel plate (MCP) for wavelengths shorter than $\sim$ 1200 Å, and 2) a Far-UV photo-multiplier tube (FUV PMT) with cesium telluride photocathode for use at longer wavelengths;
- Two neutral density meshes[1] of nearly 1% transmission, which can be inserted in the beam one at a time or together to reduce the flux intensity.

Source power (dependent on gas pressure and high voltage supplied) and monochromator slits are set in order to never exceed the maximum count rate that the detectors can manage ($\sim$ 30000 cts/s for the MCP and $\sim$ 50000 cts/s for the FUV PMT). With these choices of slit aperture, the typical pass band of the monochromator is about 5 Å FWHM. Data acquisition time intervals are typically in the range 1-100 minutes to gather at least 10000 counts.

The transmission of the UV/Ion shield may be much higher at higher orders wavelengths with respect to transmission at the wavelength of interest. For this reason, contamination from higher orders may significantly affect the measurement. In order to reduce this effect the OFF-LINE[2] count rate is subtracted from the ON-LINE count rate as described in.[10]

Before starting the sequence of measurements required to determine the UV/Ion shield transmission at a selected wavelength, the transmission of the neutral density meshes must be measured at the wavelength of

[1] In order to measure the transmission of UV blocking filters, high fluxes are required that could saturate the detectors. Neutral density meshes can be placed in the beam line to reduce the incident flux when the UV blocking filters are out.

[2] Before starting the transmission measurement, the source is slide along the monochromator Rowland circle in order to approach the chordal position theoretically predicted for the line of interest. A scan is then performed around such position in order to find the line peak position (in the following ON-LINE position) and a close position out of the line where the flux is basically due to the continuum (in the following OFF-LINE position)

interest. In order to do this the source flux is reduced so that the count rate with only one mesh in the beam is within the dynamic range of the detector. The following sequence of measurements is conducted:

1. ON-LINE, Mesh #1 and #2 ON, UV/Ion Shield OFF;
2. ON-LINE, Mesh #1 OFF, Mesh #2 ON, UV/Ion Shield OFF;
3. ON-LINE, Mesh #1 ON, Mesh #2 OFF, UV/Ion Shield OFF;
4. BACKGROUND MEASUREMENT.

No OFF-LINE measurement is conducted since the mesh transmission is not dependent on wavelength. Since the source is very stable with time no measurement is repeated to conduct time averages. The source flux is now increased until the count rate reaches the maximum that the detector can manage with the meshes in the beam ($\sim$ 30000 cts/s for the MCP and $\sim$ 50000 cts/s for the FUV PMT). The UV/Ion shield transmission measurement is then performed conducting the following sequence of measurements:

5. ON-LINE, Meshes #1 and #2 ON, UV/Ion Shield OFF;
6. OFF-LINE, Meshes #1 and #2 ON, UV/Ion Shield OFF;
7. ON-LINE, Meshes #1 and #2 OFF, UV/Ion Shield ON;
8. OFF-LINE, Meshes #1 and #2 OFF, UV/Ion Shield ON.

The measurements conducted with the MCP detector have in principle spatial resolution over an illuminated area of nearly $1 \times 1\ cm^2$. For the purpose of this work we have only computed average transmission in the illuminated area (i.e. summing up all counts in this region). The following expression has been used to calculate the transmission of each of the two meshes:

$$T_{M1} = (\frac{cnt_1}{lt_1} - \frac{cnt_4}{lt_4})/(\frac{cnt_2}{lt_2} - \frac{cnt_4}{lt_4}) \tag{1}$$

$$T_{M2} = (\frac{cnt_1}{lt_1} - \frac{cnt_4}{lt_4})/(\frac{cnt_3}{lt_3} - \frac{cnt_4}{lt_4}) \tag{2}$$

where cnt_i and lt_i are the counts and live time for the measurements 1. to 4. listed above. The transmission of the two meshes together ($T_{M1,2}$) is the product of the individual values T_{M1} and T_{M2}.

The measured transmission of the UV/Ion shield (T_S) in the surveyed position is analogously computed as follows:

$$T_S = T_{M1,2}\,(\frac{cnt_7}{lt_7} - \frac{cnt_8}{lt_8})/(\frac{cnt_5}{lt_5} - \frac{cnt_6}{lt_6}) \tag{3}$$

where cnt_i and lt_i are the counts and live time for the measurements 5. to 8. listed above. The 1 σ statistical uncertainty on UV/Ion shield transmission has been calculated adopting standard error propagation analysis and assuming Poissonian statistics on detected counts.

At a few wavelengths the transmission of the UV/Ion shield is very low and the number of transmitted photons is within the statistical fluctuations of the background. For these cases we can only quote a 3 σ upper limit on transmission calculated as follows:

$$UPL = \frac{3 \sqrt{(\frac{cnt_4}{lt_4})\ lt_7}}{((\frac{cnt_5}{lt_5})\ lt_7)}\ T_{M\,1,2} \tag{4}$$

The upper limit scales as one over the square root of the live time duration of the measurement taken with no meshes and the shield in front of the detector.

Table 2 lists the measured transmission of sample 1 at the surveyed wavelengths together with the detector, source, and gas. Column 6 in table 2 reports expected transmission based on a simple slab transmission model adopting known linear attenuation coefficients of Lexan and aluminum[11] and film thickness derived from x-ray transmission measurements,[12] namely 6290 Å for Lexan and 730 Å for aluminum. The measurements and expectations based on the above described model are also plotted in figure 1. We notice that the measured transmissions at wavelengths where the opacity is mainly due to the Lexan ($\lambda < 2000$ Å) are in good agreement with predictions. At longer wavelengths, where Lexan becomes transparent and the opacity is mainly due to aluminum, the measured transmissions are significantly higher than expected. The transmission value measured at 2537 Å (Hg Lamp) is 9×10^{-4}, about 100 times higher than expected. The transmission measured at 2300.6 Å (hollow cathode source, CO line) is 1.6×10^{-6} also about 100 times higher than expected.

In order to verify that our results were not affected by stray light we repeated the measurement with a thick aluminum plate in place of the filter, and there we measured no transmission. We also repeated the measurement at several filter positions, and got transmission values consistent to each other. An inspection of the above measured sample was then conducted with a microscope with 1 μm resolution to check the uniformity of the aluminum coating. This inspection showed that the aluminum coating was very uniform with no evidence of micro pin-holes that could be responsible for the observed higher UV transmission.

3 FUV/VISIBLE TRANSMISSION MEASUREMENTS

Puzzled by the unexpected results reported above, we made a series of additional and independent transmission measurements at the Physics Department of the University of Palermo. These measurements were performed in air using a Jasco model 5500 spectrophotometer covering the wavelength range 1900-8000 Å. The slits aperture of the plane grating monochromator have been set in order to get a 10 Å FWHM pass band. Wavelength scans were taken with 20 Å steps and 400 Å/min speed. Samples 1, 2 and 3 in table 1 have been examined. Sample 2 has characteristics similar to sample 1, but with the aluminum coating only on one side. Sample 3 is a Lexan film with no coating.

Figure 2 shows the measured FUV/Visible transmission for sample 1 double-side aluminum coating (solid line), and sample 2 single-side aluminum coating (dashed line). Superimposed data points are the measurements taken at the XACT facility on sample 1. We notice that the measurements taken at XACT on sample 1, at wavelength longer than 2300 Å, are in very good agreement with measurements taken at the Physics Department (figures 2) and confirm the unexpected high transmission of the sample filter. The spectrophotometer is not able to measure transmission below $\sim 10^{-5}$, therefore, solid and dashed lines below 2300 Å are indeed upper limits. In addition, we notice that the transmission as a function of wavelength shows peaks and dips typical of interference effects (much more pronounced on sample 1). It is evident that multilayer structures like those of our samples behave like Fabry-Perot interferometers. In such systems, at resonant wavelengths, transmission can be higher than the product of the transmission of each individual layer.

In another paper[13] we describe a model of transmission for multilayer structures based on Born and Wolf (1984)[14] and Heavens (1985).[15] In the following we compare predictions based on this model with measured transmissions. Figure 3 and figure 4 show the transmission measurements taken in the 1900-6000 Å range (solid line) together with the predictions (dashed line) based on the above referred model[13] and x-ray derived thickness of Lexan and aluminum.[12] Also superimposed in figure 3 and figure 4 are the predictions based on the same transmission model where Lexan thickness was interactively changed in order to have resonance peaks at the same position as the measured ones and aluminum thickness was also interactively changed in order to match the measured transmission level. The best-fit model parameters obtained by interactive adjustments are summarized in table 3 lines 1 and 2. Lexan thickness derived above are in reasonable agreement with those derived from x-ray measurements[12] (namely, 6290 ± 100 Å for sample 1, and 5990 ± 30 Å for sample 2), while derived thickness of aluminum are significantly lower (x-ray derived values are namely, 730 ± 10 Å for sample 1, and 610 ± 10 Å for sample 2).

Figure 5 shows the FUV/Visible transmission measurements taken with the spectrophotometer (solid line) on sample 3 (see table 1) consisting of a pure Lexan membrane. Interference effects due to reflections at the interface between the plastic film and air are still present, but much less significant. The superimposed dashed line curve is the model for a single layer of Lexan with Lexan thickness derived from x-ray measurements[12] (6150 ± 30 Å). This thickness is very close to that derived optimizing the interferences model to fit the FUV/Visible transmission measurements (see table 3, line 3), thus proving the validity of our FUV/Visible modeling approach. Notice that at wavelength shorter than 2600 Å the refractive index of Lexan is only poorly known.

4 DISCUSSION OF RESULTS

One possible interpretation of the significant discrepancy between thickness of aluminum derived from x-ray measurements and those derived from FUV/Visible measurements is that oxidation of the exposed surface of aluminum alters its properties; the oxide layer being more transparent in the UV/visible wavelength range, and thus reducing the effective (in terms of UV rejection) layer of aluminum. We also cannot exclude the possibility that chemical reactions occur at the plastic-aluminum interface that also affect the optical properties of aluminum.

In the extreme hypothesis that only oxidation is responsible for the observed higher FUV/Visible transmission, and aluminum oxide is completely transparent to FUV/Visible radiation, aluminum thickness derived from FUV/Visible measurements (table 3), compared to those derived from x-ray measurements,[12] are consistent with a layer of oxide of 110 Å on each exposed surface of aluminum for sample 1, and an oxide layer of 85 Å on the exposed surface of aluminum on sample 2.

The oxidation of aluminum does not change the x-ray transmission property of aluminum, but the addition of oxygen, in principle, does. In another paper[12] we show that including aluminum oxide significantly improves the quality of the x-ray transmission model. There we find that the χ^2 of the fitting is significantly lower when aluminum oxide is included in the transmission model. Furthermore, the amount of aluminum oxide in sample 1, found with the x-ray measurements (110 Å), is more than twice that found in sample 2 (40 Å) thus confirming the results of the FUV/Visible transmission measurements. The fact that absolute values of aluminum oxide thickness derived from x-ray and FUV/Visible measurements do not match each other, may be due to the actual density of aluminum oxide being lower than the adopted value of 3.97 $g\ cm^{-3}$. We cannot, however, exclude that some interaction at the interface between plastic and aluminum occurs that also affects the UV/Visible opacity of aluminum.

These measurements supported by simulations on the HRC UV count-rate due to point sources and diffuse background[16] indicate that this UV/Ion shield design with double side coating of aluminum does not meet the scientific requirements and might result in a significant UV leak of the HRC detectors.

The single coating design has a higher opacity but not sufficient to withstand the scientific requirements and furthermore would not avoid charge accumulation on one of the two shield sides. Still maintaining the double-coating design with aluminum an increase in aluminum thickness of nearly a factor 2 would be required which would significantly depress the soft X-ray transmission of the shield below the carbon edge (at 150 eV the transmission would decrease from nearly 20% to nearly 2%).

As possible solution to improve UV opacity at longer wavelengths we have reconsidered the opportunity of using Polyimide plastic film in place of Lexan. Previous measurements conducted at Berkeley SSL on different plastic films as part of the HRC UV/Ion shield development program[4] have shown that Polyimide is significantly more opaque than Lexan at wavelengths longer than about 2000 $\AA$. Following this hint we have decided to further investigate the differences in UV response between Lexan and Polyimide. We have measured the two samples of Lexan and Polyimide (sample 4 and 5 in table 1), previously measured at Berkeley, with the spectrophotometer of the Physics department at the University of Palermo. Figure 6 gives the measured transmission in the wavelength range 1900-10000 $\AA$ (solid line for Polyimide, and dashed line for Lexan) together with data points taken at Berkeley (plus symbols for Polyimide and triangles for Lexan). As it is evident Polyimide is much more opaque in the region 2100-3500 $\AA$ where aluminum is more transparent then expected.

The new design of the HRC UV/Ion shields, based on Polyimide, carbon and aluminum is widely discussed in another paper.[7] Here we report a plot (figure 7) of measured FUV/Visible transmission for a witness sample (TF101-969) of the new HRC-I UV/Ion shield consisting of 725 Å aluminum - 5000 Å Polyimide - 200 Å carbon (solid line). For comparison superimposed (dashed line) is also the measured FUV/Visible transmission of the old design HRC-I UV/Ion shield witness sample (TF101-952). Transmission of the new design HRC-I UV/Ion shield at wavelengths shorter than 3800 Å is lower than the limiting sensitivity of the spectrophotometer (10^{-5}). At longer wavelengths transmission is always lower than 10^{-4}.

5 SUMMARY AND CONCLUSIONS

The reported UV transmission measurements conducted on two samples of aluminum coated Lexan show that the UV rejection at wavelength longer than about 2300 Å is significantly lower (more than two orders of magnitude) than the expected performance. On the basis of EUV measurements conducted on sample 1 at 256, 304, 584 Å, where aluminum is basically transparent, and of FUV/Visible measurements conducted on sample 3 the performance of Lexan turns out to be nominal. Transmission significantly higher than expected occurs at wavelengths ($\lambda > 2300$ Å) where Lexan is nearly transparent and opacity is due to aluminum. Inspections conducted with a microscope with 1 μm resolution have shown that the aluminum coating is very uniform with no evidence of micro pin-holes that could be responsible for the observed higher UV transmission.

Constructive interferences in transmission occur at resonant wavelengths due to the multilayer design of coated membranes. Interference effects in transmission occur in all samples analyzed, being more prominent in the sample with an aluminum coating on both sides (figure 2 solid line), but still present in the sample with aluminum coating only on one side (figure 2 dashed line), and, to a lesser degree, in a plastic membrane with no aluminum coating (figure 5).

Modeling the observed FUV/Visible transmission of coated Lexan samples taking into account interferences due to the multilayer design of the filters, we have found that, in addition to a decrease of average opacity due to interference effects, aluminum UV/Visible opacity is significantly lower than expected. As a possible interpretation we suggest that oxidation of exposed aluminum surfaces significantly affects UV opacity while x-ray transmission is affected only by the presence of the small amount of oxygen in the aluminum oxide.

The results of this work conducted in the framework of the AXAF-HRC calibration program have led to a redesign of the HRC UV/Ion shields. The new shields design, widely discussed in another paper,[7] is based on Polyimide, carbon and aluminum.

An interesting byproduct of the results reported here is the possible explanation of the leaks at UV wavelengths observed in the ROSAT HRI (Zombeck 1995). This issue is discussed in another paper.[17]

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TABLES AND FIGURES

Table 1: List of Measured Film Samples

Sample	ID. Num.	Material	Nominal Thickness (Å)		
			Al	Plastic	Al
1	TF101-952	Al-Lexan[1]-Al	360±35	6065±100	345±35
2	TF101-542	Al-Lexan[1]	710±50	5805±100	
3	TF110-380	Lexan[1]		5740±100	
4	TF110-377	Lexan[1]		2816±50	
5	TF110-382	Polyimide[2]		2745±50	

[1]General Electric RL5002.

Table 2: Vacuum UV Transmission Measured at XACT on sample 1

Detector	Source	Gas	λ (Å)	Meas. Transm.	Expect. Transm.
MCP	Hollow Cath.	He	256.3	$(8.5 \pm 0.5)\ 10^{-6}$	$1.5\ 10^{-5}$
MCP	Hollow Cath.	He	303.8	$(1.5 \pm 0.1)\ 10^{-7}$	$1.8\ 10^{-7}$
MCP	Hollow Cath.	He	584.3	$<\ 4.5\ 10^{-9}$	$3.1\ 10^{-18}$
MCP	Hollow Cath.	Ar	919.8	$<\ 6.7\ 10^{-9}$	$5.6\ 10^{-19}$
FUV PMT	Hollow Cath.	He	1640.5	$<\ 9.5\ 10^{-6}$	$3.3\ 10^{-9}$
FUV PMT	Hollow Cath.	CO	1657.2	$<\ 1.41\ 10^{-6}$	$3.3\ 10^{-9}$
FUV PMT	Hollow Cath.	CO	2190.4	$<\ 3.14\ 10^{-6}$	$3.2\ 10^{-10}$
FUV PMT	Hollow Cath.	CO	2300.6	$(1.6 \pm 0.3)\ 10^{-6}$	$1.2\ 10^{-8}$
FUV PMT	Hg LAMP		2536.5	$(9.3 \pm 0.9)\ 10^{-4}$	$9.3\ 10^{-6}$

Table 3: Thicknesses derived from the modeling of the FUV/Visible transmission measurements

Sample	Thickness (Å)	
	Al	Lexan
1	510	6130
2	525	5990
3		6130

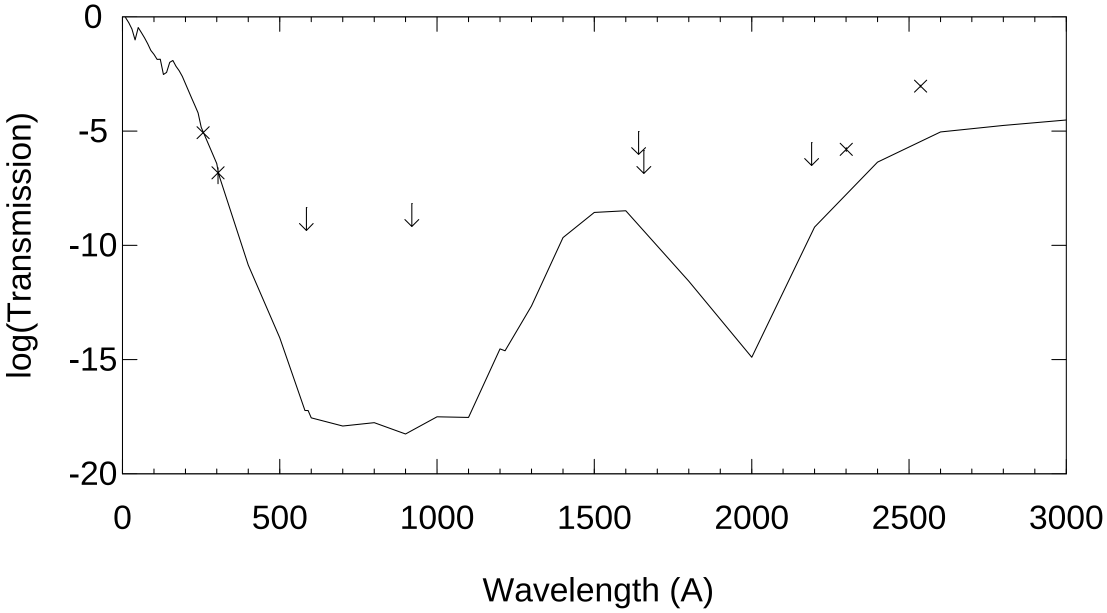

Figure 1: Measured UV transmission vs. wavelength for sample 1. Arrows indicate upper-limit to the transmission measurements. The superimposed curve is a simple slab transmission model obtained adopting known linear attenuation coefficients and x-ray derived thickness for Lexan and aluminum.

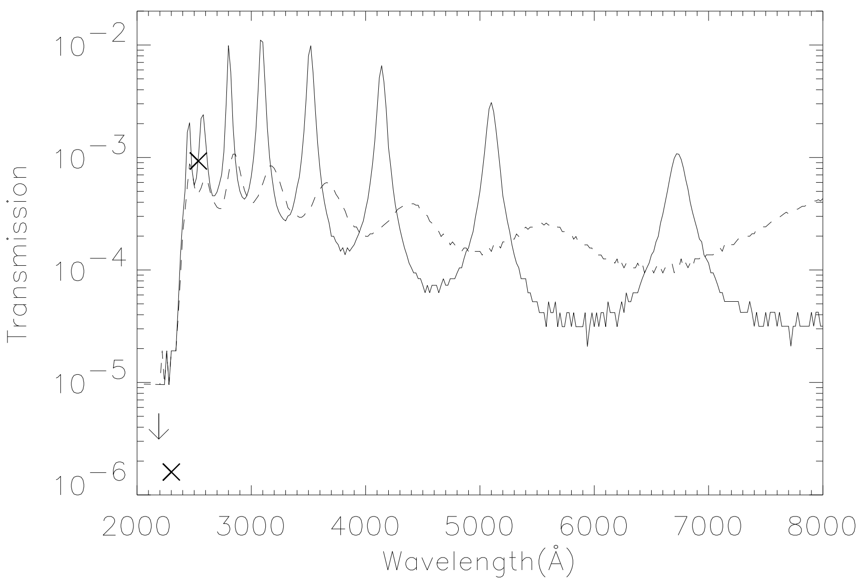

Figure 2: Measured FUV/Visible transmission vs. wavelengths for the double-side coating sample (sample 1, solid line), and the single-side coating sample (sample 2, dashed line). Superimposed are the measurements taken on sample 1 at XACT facility (x for measurements and arrow for an upper-limit).

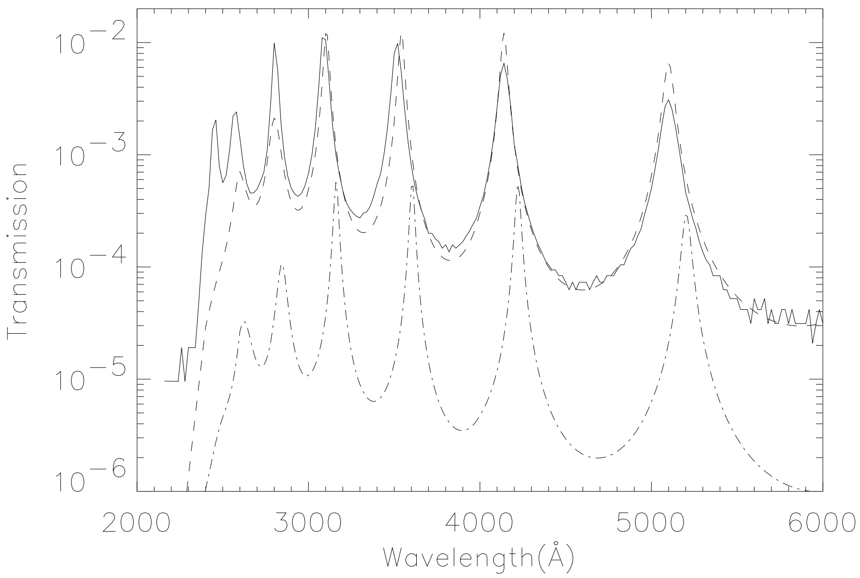

Figure 3: Measured transmission in the wavelength range 1900-6000 Å for the double-side coating sample (sample 1, solid line). Superimposed is the model transmission with nominal thickness of Lexan and aluminum (dotted-dashed line), and the best-fit model transmission (dashed line).

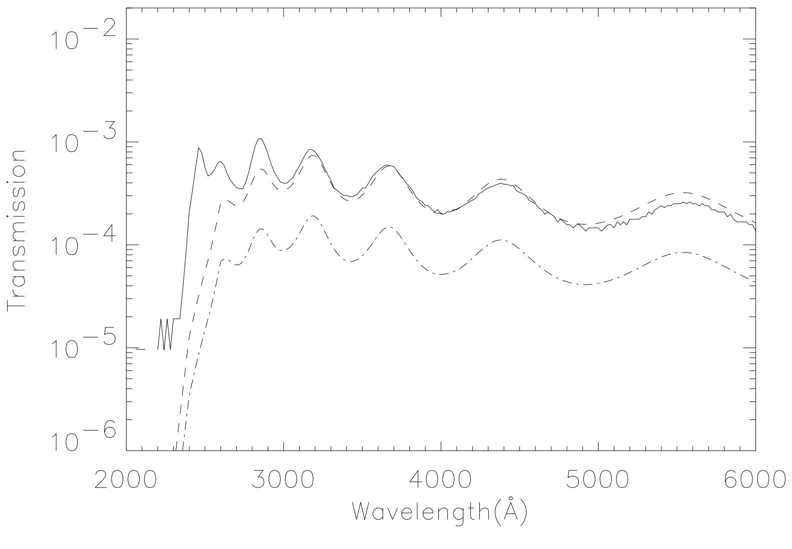

Figure 4: Measured transmission in the wavelength range 1900-6000 Å for the single-side coating sample (sample 2, solid line). Superimposed is the model transmission with nominal thickness of Lexan and aluminum (dotted-dashed line), and the best-fit model transmission (dashed line).

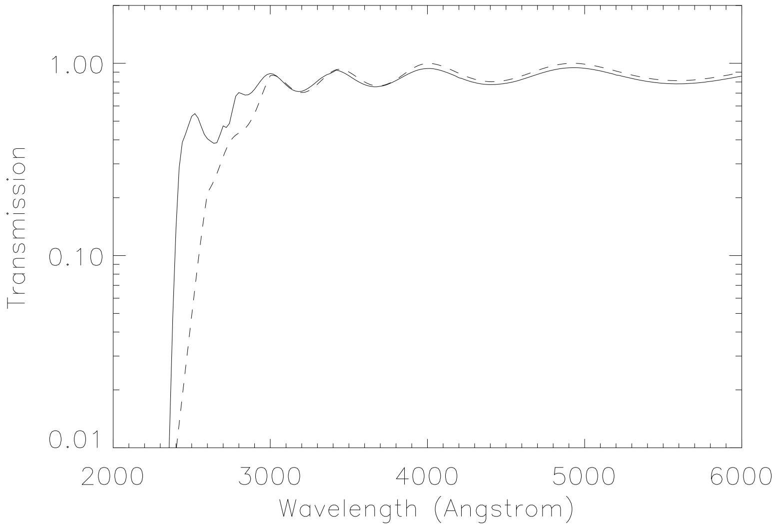

Figure 5: Measured transmission in the wavelength range 1900-6000 Å for a Lexan sample (sample 3, solid line). Superimposed is the best-fit model transmission (dashed line).

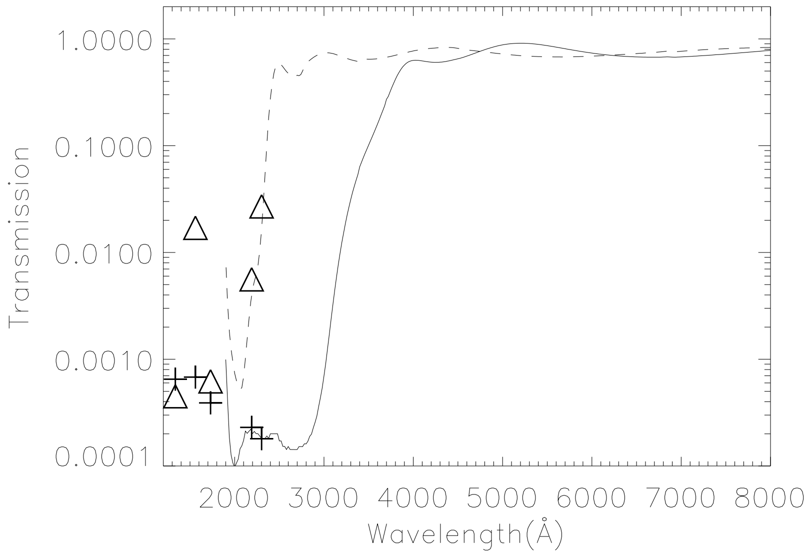

Figure 6: Measured FUV/Visible transmission vs. wavelengths for a sample of Polyimide 2745 $\AA$ thick (TF110-382, solid line) and a sample of Lexan 2816 $\AA$ thick (TF110-377, dashed line) in the wavelength range 1900-10000 $\AA$. Superimposed are also the measurements taken at Berkeley SSL on the same samples in 1994 (plus symbols for Polyimide and triangles for Lexan).

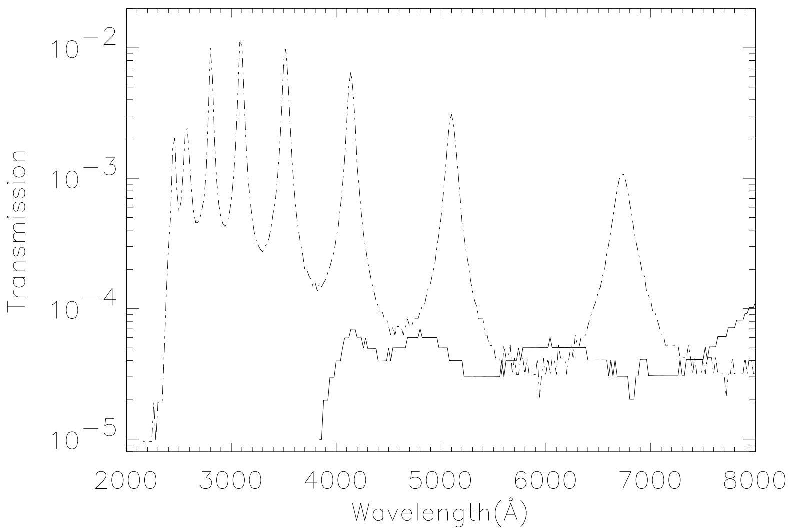

Figure 7: Measured FUV/Visible transmission vs. wavelengths for a witness sample (TF101-969) of the new HRC-I UV/Ion shield consisting of 725 Å aluminum - 5000 Å Polyimide - 200 Å carbon (solid line). Superimposed is the measured transmission of the old design HRC-I UV/Ion shield witness sample (TF101-952, dashed line).