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Transmittance measurements for a variety of x-ray/euv filter materials and pinhole leak measurements utilizing a new visible light photometer system.

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ABSTRACT

This paper describes a new visible light photometer system and presents the results of a test program where visible light transmission has been measured for a variety of materials of varying thicknesses. From these measurements, equivalent absorption coefficients are presented for some of the materials commonly used in x-ray and extreme ultraviolet (euv) filters. Also presented are some criteria for quantifying light leaks through pinholes.

1. INTRODUCTION

Most extreme ultraviolet (EUV) and soft x-ray (SXR) detectors are sensitive both to the wavelengths of interest and to visible light. If care is not taken, visible light can "swamp" the detector rendering it ineffective at the desired wavelengths. Thus, in producing filters and windows for EUV and SXR applications, it is important to test for both transmission in the bandpass of interest, and for visible light leaks. Testing for light leaks is difficult, because the light levels can be extremely low and because the testing needs to be done for light coming from all directions since pinholes are not always perpendicular pathways through the filter material.

To this end a new visible light photometer system has been built. It uses a lamp and an diffusing sphere to produce a Lambertian source. The measurement side has an integrating sphere coupled to a photomultiplier detector. The resulting system provides an excellent way of measuring light leaks through pinholes in opaque foils, as well as a way to measure the optical density of thin films that are semi-transparent.

From these measurements, equivalent absorption coefficients can be calculated and "best fit" practical values can be derived. These values can then be used to design optimal filters for SXR/EUV applications.,

2. THE PHOTOMETER SYSTEM

The photometer system will accommodate circular filters with up to two inches clear aperture, an outside diameter of up to 2.5 inches and an overall thickness of up to 0.5 inches. It has a dynamic range of 10^6. It will measure light transmittance as low as 4×10^{-10} and detect light transmission through filters with transmittances as low as 4×10^{-11}.

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2.1 Theory of Operation

Transmittance is the measure of the fraction of light passing through a filter or other optical element. Transmittance (T) is defined as the ratio of transmitted light power, PT, to incident light power, P_0.

$$T = P_T/P_0 \tag{1}$$

Thus, 'if a filter transmits 1% of the light illuminating it its transmittance is 0.01 or 1x10-2. When optical elements are placed in series, the total transmittance is equal to the product of the transmittances of each individual element:

$$Ttotal = Tl * T2 * \ldots \tag{2}$$

Optical density, O.D., is defined as the logarithm of the reciprocal of transmittance:

$$OD = \log_{10}(1/T) \tag{3}$$

Thus, the filter that transmits 1% of the incident light has an optical density of 2. A filter with a transmittance of 2.310x10-g has an optical density of 7.636. When optical elements or filters are placed in series, the total optical density is equal to the sum of the optical densities of each individual element (since the log of the product of two or more numbers is equal to the sum of the logs of each individual number):

$$OD_{total} = OD_1 + OD2 + \ldots \tag{4}$$

The photometer measures photomultiplier tube current, I, which is directly proportional to the power of the light falling on the tube's photocathode. With a light source having an output power of P_{source}:

$$I = k^*P_{source} + I_{dark} + I_{ambient} \tag{5}$$

where: I = photomultiplier current
I_{dark} = photomultiplier tube dark current
$I_{ambient}$ = photomultiplier current due to ambient light
k = overall transmittance of the optical system times the gain of the photomultiplier tube

Extensive shielding and baffling in the photometer prevents ambient light from entering the optical system. When the dark current is canceled out using the ambient suppress feature of the Photomultiplier Readout,

$$I = k^*P_{source} \tag{6}$$

If a test or calibration filter with a transmittance of T and a clear aperture area of A is inserted into the optical system, the resulting photomultiplier current will be:

$$I = k*T*A*P_{source} \quad (7)$$

When the photomultiplier current resulting from light passing through a test filter of unknown transmittance, T_t, and from light passing through a calibration filter with the same clear aperture and a known transmittance, TO, are measured, the transmittance of the test filter can be calculated:

$$I_t/I_0 = k*T_t*A*P_{source}/k*T_0*A*P_{source} \quad (8)$$

$$T_t = T_0*I_t/I_0 \quad (9)$$

For example, assuming the test and calibration filters have the same aperture, that the dark current has been adequately suppressed, and that all other conditions are the same, if the photomultiplier current with the test filter is twice the current with the calibration filter, the transmittance of the test filter is twice that of the calibration filter.

2.2 Optical Components

Figure 1 shows the layout of the optical components of the photometer. The light source is a 200 watt mercury (xenon) arc lamp which produces the fairly smooth (continuous) output across the visible spectrum of a xenon lamp along with the strong lines of a mercury source. This provides about 2 watts of power in the visible spectrum in a 32mm collimated beam. Energy in the infrared portion of the spectrum is removed with a water filter to prevent over heating of the test and calibration filters. A 90" beam turner changes the optical path to reduce the overall space needed by the optical system. A filter holder for an optional neutral density (ND) filter is provided in the event it is necessary to decrease the excitation intensity.

An 8 inch diffusing sphere diffuses the light beam to what approximates a Lambertian source (the intensity varying with the cosine of the angle to the optical axis). The diffusing sphere gives a significantly greater light transmission compared to other diffusion methods, reducing the need for higher excitation levels or greater detector sensitivity,

The test filter is held in a single, light-tight holder which can also house 2 inch round neutral density calibration filters. The holder is designed to accommodate a wide range of filter configurations using special adapter rings. Customers may specify their adapter ring configurations at the time of ordering based on specific filter sizes. The filter holder is placed in a slide which inserts it into the optical path of the instrument. "O" rings, extensive baffling, and light traps prevent excitation light from passing around the test filter and ambient light from entering the system. When the test/calibration filter slide is withdrawn, light from the source is completely blocked to prevent accidental exposure of the photomultiplier to unattenuated light.

An 8" integrating sphere provides an efficient way of collecting the light exiting the test filter for the photodetector. Because of the properties of both the diffusing and integrating spheres, the system is only minimally sensitive to path length and alignment changes, and relatively insensitive to location and configuration of flaws in the test filter and the angle of light exiting the test filter.

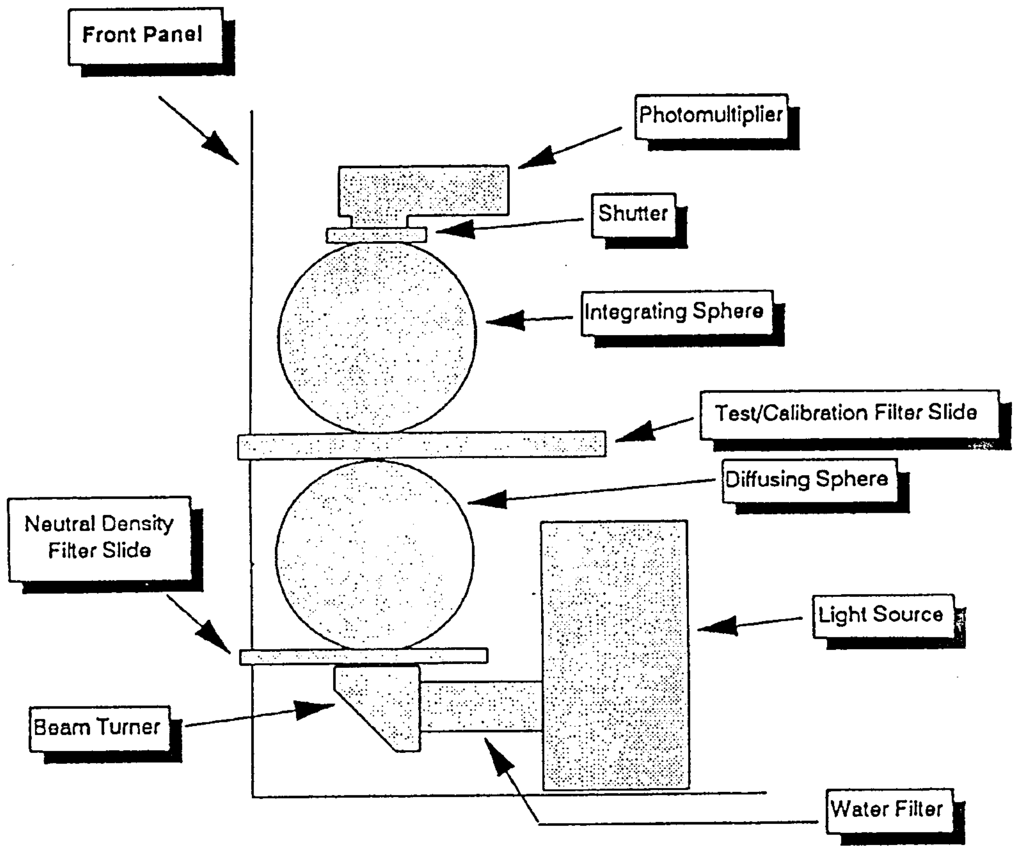

Figure 1. Layout of Optical Components

A 50mm shutter, operated manually with a cable release, protects the photomultiplier from accidental exposure. A red light-emitting diode indicates when the shutter is open. As an option, an electronic shutter can be incorporated to provide even greater flexibility in operation. The photomultiplier with the associated amplifier and power supply provide an extremely sensitive photodetector.

Neutral density filters with an O.D. of 1, 2, 3, and 4 are used to calibrate the photometer. Metalized ND filters were chosen over absorption type filters because of their greater ability to resist heat from the arc lamp source and because most XUV and SXR filters that are to be tested are reflective at visible light wavelengths. These metalized filters reduce transmittance by reflection as well as absorption.

2.3 Electronic Components

A regulated adjustable power supply provides energy to the arc lamp source. The output current is regulated and can be preadjusted before lamp ignition. The 200 watt mercury (xenon) lamp requires 9.0 amps at about 22VDC.

The Photomultiplier Readout includes an adjustable high voltage power supply for the photomultiplier tube and measures photomultiplier tube current from $1x10^{-12}$ A to $1x10^{-5}$ A. System response times of 0.1, 1, or 10 seconds can be selected depending on the desired trade-off between speed and noise. Photo-multiplier tube current resulting from internal noise ("dark current") or from ambient light leaking into the system can be canceled out using the "ambient suppress" feature.

3. TRANSMISSION MEASUREMENTS AND ABSORPTION COEFFICIENTS

Transmission measurements have been made on several hundred different filters. The photometer has been found to be reliable and accurate in that measurements are repeatable over time, assuming that a simple calibration procedure is used for each measurement session. What has been found is that Lambertian type systems require special care and considerations which are not obvious, especially since most people's experience has to do with more conventional lens and mirror optical systems.

For example, the decision was made to use reflective neutral density filters for calibration and attenuation. This was done because most of the filters under test are made from metals which are highly reflective, and because there was concern about the heat load on an absorption ND filter. It turns out that the reflective neutral density filters work fine for attenuation between the light source and the first diffusing sphere, but when used between the two spheres, other factors come into play. The calibration settings will vary depending on how much of the filter is exposed to light, and the exact configuration of the filter holder.

It was found that the filter holder for the calibration filter and the test filter need to be virtually identical in terms of their "exterior" configuration which is exposed to light within the two spheres. If the amount of light that is either reflected or absorbed (either from the filter or from it's frame) is different, the test results will be adversely affected. Intuitively, the explanation is that light that is reflected may find it's way around inside the sphere and try again to go through the filter. Thus reflected light may have more than one chance at going through the filter, and therefore, in this system, a reflective type calibration filter will measure a higher absolute transmission than an absorptive type. Light that is absorbed in either the frame or the filter is "put to rest" so to speak, and that is the end of it. Thus, everything about the geometric configuration and light reflecting properties of both the calibration and test filters, their frames and aperture sizes must be as nearly identical as possible.

For semi-transparent materials, it was found that it is best to use a neutral density filter in the lower holder to attenuate the light, and to use a blank filter frame (with exactly the same configuration as the test filter but with an open aperture) for calibration.

With the proper setup and calibration, it is possible to get accurate transmission measurements from a wide variety of filter sizes and configurations as well as a large range of thicknesses of materials. It then helps to convert transmission measurements to equivalent absorption coefficients, because for the same frequency or frequencies, the absorption coefficient should be constant for all thicknesses of material, at least for metals. Thus, a calculated equivalent absorption coefficient that varies from the norm suggests either that something is wrong with the test, or with the material itself. The most obvious material problem is pinholes, and by visually inspecting the filter under a back lit microscope, it is possible to subjectively predict when the transmission is going to be higher because of the presence of pinholes. For a further discussion on the subject of pinholes, see Section 4.

The simplest version of the formula for transmittance for a homogeneous material is:

$$T = \exp(-\mu x), \tag{10}$$

where T is the transmittance (or transmission expressed in percent), μ is the linear absorption coefficient, and x is the thickness of the filter material. The terms μ and x must be expressed in the same units. For convenience here, μ is in $Å^{-1}$ and x is in A. Sometimes the absorption coefficient is given as a mass absorption coefficient, in which case, it must be multiplied by, the density of the material.

To check linear absorption coefficients against optical constants in the literature, it is usually necessary to convert to the extinction coefficient (or absorption index) k, where:

$$\mu = 4\pi k/\lambda \tag{11}$$

Actually, the more general form of the equation for transmittance is known as Lambert's law and is usually expressed as:

$$T = \exp(-4\pi kx/\lambda) \tag{12}$$

which is convenient when k is known from the measurement of optical constants. Here the absorption coefficient μ will be used, because it is being calculated directly from transmission measurements.

Because this photometer system measures visible light transmission across the visible band from 3000 to 7000Å, the calculated absorption coefficients are an average or "best fit" value. However, since the main objective is to develop a criteria which can be used for designing SXR/EUV filters, the use of an average value is reasonable, because most of the detectors have a sensitivity across the visible spectrum, and the filter needs to reject radiation in this region.

For designing x-ray/Euv filters, a comprehensive compilation of useful information is given by Henke et al. where data that can be converted to absorption coefficients are presented for wavelengths from 10 to 1200Å.[1] Other specific measured data and design experience is covered by Powell et al. in previous work.[2] A broad range of data including optical constants from the x-ray region through the infra red has been compiled by Palik in two very useful volumes.[3-4]

The general procedure with the photometer system is to accumulate measurements from **a** large number of filters of the same material and to then calculate and compare the values of μ thus obtained. Then it is necessary to sort out which measurements are valid and why, and to come up with a best estimate of what value to use for design purposes.

For example, for aluminum, the most used filter material, over 100 measurements gave values of μ from 0.00934 up to 0.0149$Å^{-1}$. From inspection, the lower values could be attributed to pinholes or other defects. The best values in the range of 0.012 to 0.015$Å^{-1}$ could be attributed to well made material without significant defects. Numbers above 0.014$Å^{-1}$ are seen often. The Luxel specification for an aluminum filter 15008, thick is that the visible light transmission be less than 5 x 10^{-8}, and this translates to an absorption coefficient of 0.01 1$Å^{-1}$. However, the filters are generally much better than the specification, and in fact, they usually have visible light transmission of less than 5 x 10^{-9}, which translates to an absorption coefficient of 0.012681-I. Note that because of the very small numbers involved, and the exponential relationship, a variation in absorption coefficient of 14% translates to an order-of-magnitude difference in transmission. Fortunately, aluminum, which is so useful for x-ray filters for many reasons, is very dense optically.

An interesting perspective of the predicted performance of a 1500Å thick aluminum filter across a broad spectrum from 25 to 100,000Å in wavelength is shown in Figure 2. This prediction is based on work by Smith et al. from the Argonne National Laboratory.[5] There is good agreement between Figure 2, and data measured for aluminum on the photometer system, in that Figure 2 would predict a value for transmission on the order of 8^{-10} in the visible spectrum, and this translates to an absorption coefficient of 0.014$Å^{-1}$, a number often seen in the measured data. Similar results are obtained from Palik[3] where extinction coefficients that convert to absorption coefficients on the order of 0.015$Å^{-1}$ are given. Thus it has been shown that the photometer system is consistently giving reasonable and reliable results.

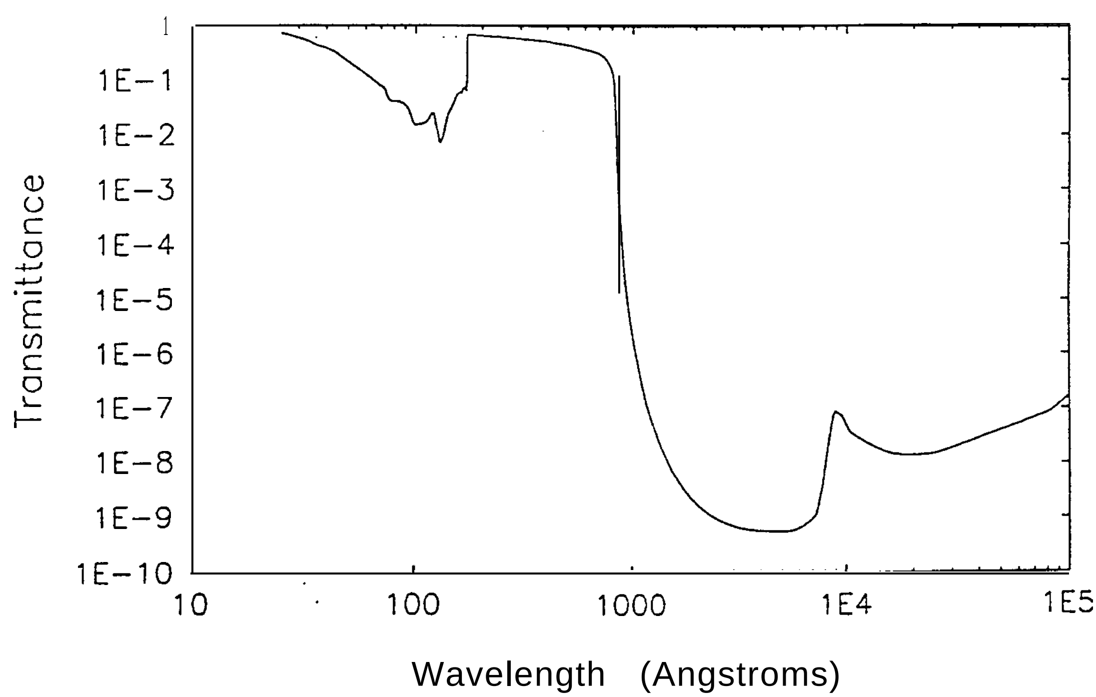

Figure 2. Transmittance for 1500Å thick Aluminum film vs wavelength

Based on confidence in the data for aluminum, a set of "practical" absorption coefficients have been developed for a number of materials as shown in Table 1. These values for the estimated absorption coefficients are conservative in that if filters are designed and built using these values, the filters should turn out to reject more visible light than predicted. Thus these values can be used for safely designing filters to provide a band pass in the SXR/EUV spectrum while rejecting light in the visible spectrum.

Material	**"Practical" Absorption Coefficient.**
Aluminum	0.0130 $Å^{-1}$
Silver	0.0055 A-1
Carbon	0.00324 $Å^{-1}$
Silicon	0.00103 A-'
Boron	0.00110 $Å^{-1}$
Indium	0.0092 A-1
Tin	0.010 A-1

Table 1. "Practical" absorption coefficients for various materials

The amount of data available for these estimates has varied considerably, and the materials are listed in the approximate order of the certainty of the estimate based on the number of samples measured, and the scatter in the data. Unfortunately, this data is hard to come by, and not as many materials are covered as had been hoped, but the.intention is to continue to build the data base as more samples become available.

The data for Silicon can be compared with optical constants from Palik[3], and this comparison shows that silicon deposited by vacuum deposition is clearly amorphous. Otherwise, it would not be as optically dense as measured since crystalline silicon is nearly transparent at the longer wavelengths.

Silver is an interesting material in that it has a distinctive light leak at 3200Å which has been 'known for a long time.[6] Filters of a thickness that would be expected to be light tight are seen to have a blue color when viewed with a strong back Iight.

4. PINHOLES

Pinholes are one of the greatest problems with ultra thin foil filters, and one of the significant reasons why sub micron foil filters generally are not as optically dense as might be expected from the data available on optical constants. Great care during manufacturing will minimize pinholes, but they are almost impossible to avoid entirely. Thus, there is a need to quantify their effect on performance. At Luxel, filters are examined for quality using a strongly back lit microscope at various powers, and when possible, they are tested on the photometer. Filters with large pin holes are rejected, both by visible inspection, and based on photometer readings. What are being called "large" pinholes may be too small to be seen with the naked eye, but if they significantly effect the visible light rejection, they will probably cause a filter to be out of specification.

A subjective measure of pinholes has been developed based on visual inspection and photometer readings. Through experience, it can be said that a pinhole with a certain appearance will affect the photometer readings in a predictable way, and a generally agreed upon rejection criteria prevails among the technicians involved.

Recently, in conjunction with the use of this new photometer system, a study was undertaken to better understand the effect of pinholes on filter performance. The results of this study are summarized in Figure 3. What is shown is the effective transmittance of pinholes of various known sizes. Note that there is good agreement between predicted and measured values except for the small size holes. It is believed that the results for pinholes of 2 and 5 microns vary from the predicted values because the test holes are in a metal foil which has a significant thickness relative to the size of the hole. Therefore, with a Lambertian light source, much of the light that should get through the hole is lost in absorption in the side walls of the hole.

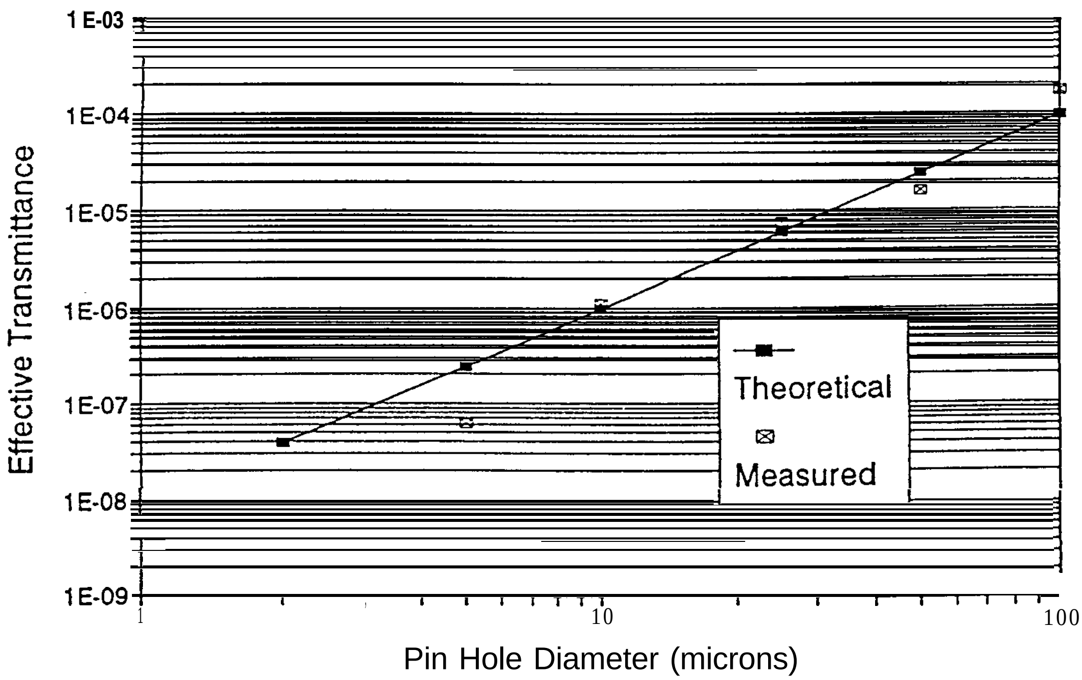

Figure 3. Effective Transmittance of a pinhole in an opaque reflective 1 cm filter

It is important to note that whereas the transmission of multilayered materials is the product of the transmittance of the individual layers (since the light must go through the materials in series), the light that goes through a pinhole adds to the transmission through the rest of the material since the light goes "around the filter" so to speak. Thus, if a filter has a transmittance of $1x10^{-8}$, and there is a *known* 2 micron pinhole present with a transmittance of $4x10^{-8}$, the transmittance of the filter will be 5x10-8. Insufficient work has been done to confirm these results for sure, but if the results shown on Figure 3 are correct, then any pinhole as large as 5 microns would cause significant degradation in any filter of the type being discussed here, Tests of a larger filter would be less affected by a pinhole of a given size than a smaller one. Thus, the data shown on Figure 3 is conservative in that the filter measured was small with an inside diameter of 1 cm.

5. CONCLUSIONS

Much has been accomplished in understanding the visible light transmission which takes place in sub micron foil filters. However, it has turned out to be a much more complex problem than originally thought. The photometer system designed and built for this purpose has proven to be reliable, and accurate, but much needs to be done yet to accumulate test data and to further refine the test methods relative to the effect of the hardware configuration on the test results. Also, data has been collected on composite and layered filter materials but the results are inconclusive at this point in time. These efforts to better understand and report on the properties of x-ray/EUV filters in the visible spectrum will be continued.

6. REFERENCES

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