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THIN FILM FILTER PERFORMANCE FOR EXTREME ULTRAVIOLET AND X-RAY APPLICATIONS

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Abstract. Substantial work has been done to characterize filter materials for the vacuum ultraviolet and x-ray regions of the electromagnetic spectrum. This paper summarizes the theoretical basis for predicting performance and compiles the results of different measurement programs for comparison. Recent work that better quantifies transmission as a function of wavelength for various filter and window materials is reported. Other applications of thin films in which these optical properties are important include photocathodes and x-ray laser targets. Of particular interest are figures giving linear absorption coefficients as a function of wavelength for commonly used filter materials. Also included are recent data on the effect of aging on aluminum filters, plus test data and comments on the use of composite materials designed to adjust the bandpass of a filter to meet particular research requirements. The data are presented so that the reader may more easily design and predict the performance of filters and windows for specific applications.

***Subject terms:** x-ray/EUV optics; x-ray filters; EUV filters; x-ray telescopes; x-ray astronomy; thin foils; thin films; filter transmission.*

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CONTENTS

1. INTRODUCTION

Commonly mentioned references for thin film filter performance in the vacuum UV spectrum are a paper by Hunter et al.,[1] Samson's text[2] for experimental data, and Henke's many publications on optical constants. A representative sample of Henke's work is listed in Refs. 3 through 6. Some of these data are correlated with x-ray attentuation cross sections in work by Saloman et al.[7] Other sources of optical constants include Hagemann et al.[8] and Palik's extensive handbook.[9] Also useful are a summary book of facts published by the Center for X-ray Optics at the Lawrence Berkeley Lab.[10] and Zombeck's handbook.[11]

Invited Paper XR-111 received Jan. 2, 1990; revised manuscript received Feb. 10, 1990; accepted for publication April 6, 1990. This paper is a revision of Paper 1160-04, presented at the SPIE conference X-Ray/EUV Optics for Astronomy and Microscopy, Aug. 7–11, 1989, San Diego, Calif. The paper presented there appears (unrefereed) in SPIE Proceedings Vol. 1160.

Data on filter performance are generally presented in terms of transmittance and/or linear absorption coefficient as a function of wavelength for particular materials or combinations thereof. Transmittance data are easiest to assimilate, but linear absorption coefficient data are more useful for the design of new filters. While filter performance is sometimes the primary subject of a paper,[12] the data are often presented in connection with other research.[13,14] Frequently, measurements go unpublished. Thus, it is generally difficult to find filter performance data. This work is an attempt to bring some of the existing data together to aid in filter design. While this paper presents some of the authors' transmittance data, there has also been an effort to collect and correlate relevant filter performance data from other sources.

2. GENERAL CONSIDERATIONS

Generally, only a single formula is needed for the design of a vacuum UV filter. The transmittance T (a dimensionless ratio of transmitted energy to incident energy) of a filter at a particular wavelength is determined by the relationship

$$T = \exp(-\mu x) , \tag{1}$$

where μ is the linear absorption coefficient at the chosen wavelength and x is the thickness of the material. Sometimes data are presented as τ, the mass absorption coefficient in cm^2/g. In these cases τ is multiplied by the density of the material, δ, in g/cm^3 to get μ ($\mu = \tau\delta$); thus, the units of the linear absorption coefficient μ are cm^{-1}, and the thickness of the material must be converted to centimeters. For convenience, the units for the linear absorption coefficient are often given in inverse micrometers: the thickness in this case must be in micrometers. These

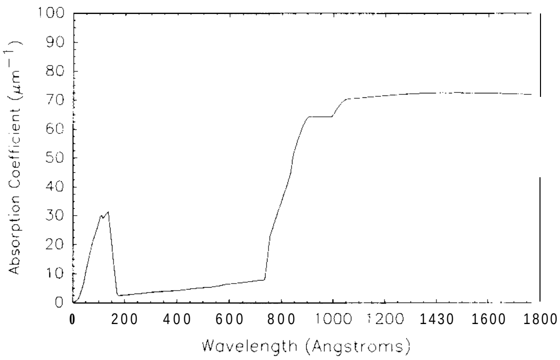

Fig. 1. Linear absorption coefficient for aluminum (UCB) as a function of wavelength.

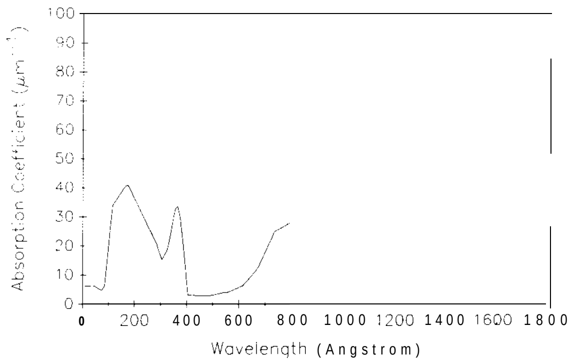

Fig. 2. Linear absorption coefficient for antimony as a function of wavelength.

are the units used in this paper. To make conversions from wavelength to photon energy one needs the relationship

$$\text{wavelength (Å)} = \frac{12,398}{\text{energy}} \text{ (eV)} . \qquad (2)$$

Rarely are the films produced in a vacuum as dense as the material in the bulk. When synthesis is done by vacuum deposition, most metals have a density around 90% of theoretical, whereas many compounds such as the fluorides have densities as low as 50% of theoretical. To accurately predict filter performance, density factors based on experimental measurements must be used.

It is possible to make theoretical predictions of filter transmittance for elemental materials using optical constants, and the results are generally good except for occasional anomalies near absorption edges. However, real filters are never composed of entirely pure materials, and the effects of oxidation and impurities must be taken into account.

Filter performance for compounds can be predicted by assuming that the filter is made up of the individual elements taken in proportion to the percentage by weight of each element present. The transmittance of each element is determined separately, and the individual transmittances are multiplied to get a composite transmittance. However, the results of these predictions are not always reliable because of interactions that can occur between atoms within the compound.

Composite filters of layers of elemental materials can be predicted more accurately than compounds. Generally, the overall transmittance of such filters can be computed as the combined product of the predicted transmittance of each layer, but oxidation and impurities will affect the results. Also, intermetallic compounds may be formed at the interface between layers, and this may reduce the accuracy of predicted performance. Intermetallic compounds may also affect the mechanical properties of the filter, and care should be taken to guard against unexpected differences in properties that may result from the formation of such compounds.

Testing of filter materials is essential to the understanding of their performance. From good test data, empirical models of linear absorption coefficients as a function of wavelength can be derived. Filter performance can then be predicted with fairly good accuracy for different thicknesses of the material.

In the Extreme Ultraviolet Explorer (EUVE) project at the University of California, Berkeley (UCB) Space Sciences Laboratory, linear absorption coefficients have been derived for the various materials used in the EUVE filters. The basic equation given previously is used, but it is modified by a multiplicative factor f_{ox} to account for the possible presence of oxide layers, for instance, on aluminum or titanium. This technique makes the simplifying assumption that the f_{ox} factor will adequately account for the effect of the oxides present. For composite filters, $T_{filter} = T_1 T_2 T_3 \ldots T_n$ is assumed, and with some thought for the materials used, interface alloys are ignored.

The transmissions of many filters with varying thicknesses have been measured at the Space Sciences Laboratory over the past several years. By taking the ratios of transmissions for different filters, the linear absorption coefficient μ can be computed. When different composite filters are measured where one of the materials has the same thickness, μ can be computed for the other material, which has different thicknesses. For example, for two aluminum/carbon filters with thicknesses 4000 Å/300 Å and 1500 Å/300 A, respectively,

$$\frac{T_1(4000/300)}{T_2(1500/300)} = \frac{f_{ox}\exp[-4000\mu(\text{Al})]\exp[-300\mu(\text{C})]}{f_{ox}\exp[-1500\mu(\text{Al})]\exp[-300\mu(\text{C})]} = \exp[-2500\mu(\text{Al})] . \qquad (3)$$

Using this technique, linear absorption coefficients have been derived for aluminum, antimony, boron, Lexan (GE trademark name for polycarbonate), tin, and titanium. These data have been augmented with linear absorption values from the literature,[2,4] particularly for the soft x-ray wavelengths.

These derivations yield absorption coefficients only at the discrete wavelengths at which the transmission data were taken. Between these wavelengths, the data can be linearly interpolated. This causes some roughness in what might be expected to be smooth parts of the curve. The effect is particularly obvious in the aluminum data at wavelengths larger than 700 A. In the future, continuum data will be used to “fit the curve” between the discrete wavelengths.

3. LINEAR ABSORPTION COEFFICIENTS

Figures 1 through 7 are graphs of the EUVE linear absorption coefficient data previously discussed. Smoothing is appropriate when these data are used for filter design, especially in the region from about 700 Å to 850 A.

Because aluminum is such an excellent filter material, work has been done at Stanford’s Center for Space Science and Astrophysics to model aluminum and aluminum oxide in great detail (3400 data points). The results of this effort are shown in Figs. 8 and 9. The aluminum curve in Fig. 8 is based primarily on

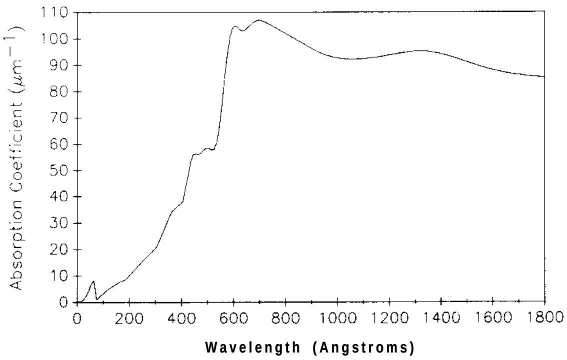

Fig. 3. Linear absorption coefficient for boron as a function of wavelength.

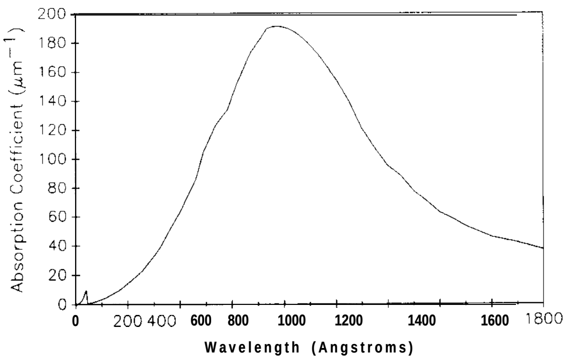

Fig. 4. Linear absorption coefficient for carbon as a function of wavelength.

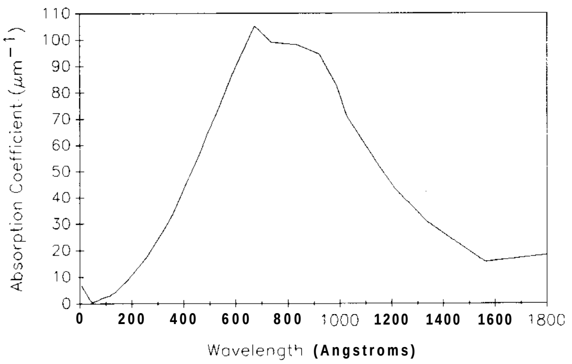

Fig. 5. Linear absorption coefficient for Lexan as a function of wavelength.

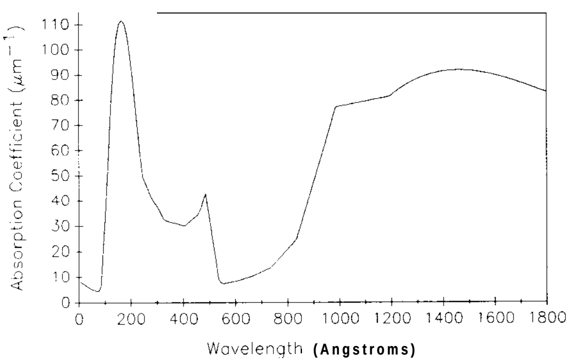

Fig. 6. Linear absorption coefficient for tin as a function of wavelength.

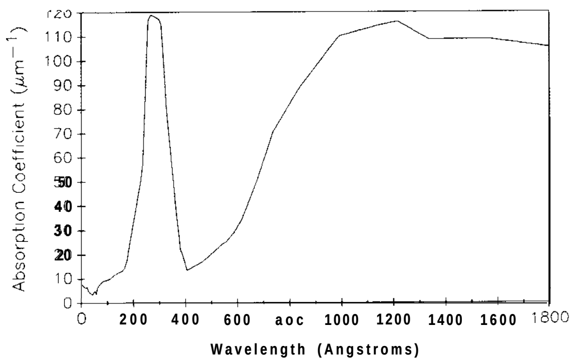

Fig. 7. Linear absorption coefficient for titanium as a function of wavelength.

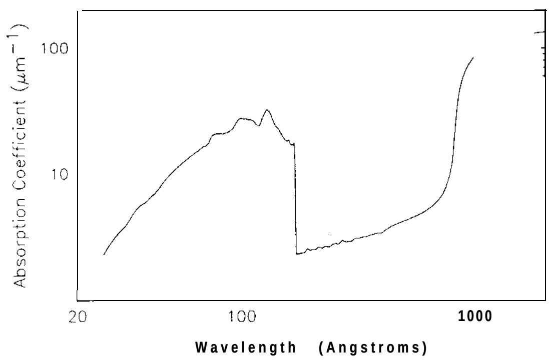

Fig. 8. Linear absorption coefficient for aluminum (Argonne, 1983) as a function of wavelength.

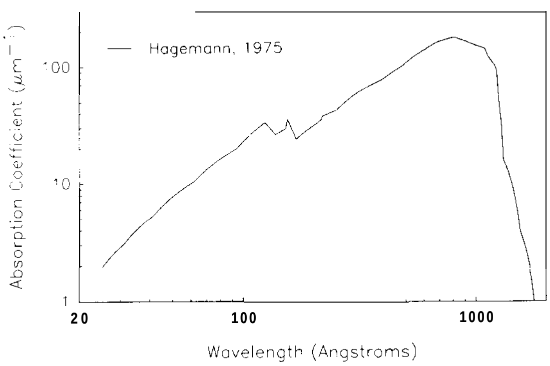

Fig. 9. Linear absorption coefficient for aluminum oxide as a function of wavelength.

Argonne National Laboratory data,[15] although it also agrees with recent Henke data. Figure 9, for aluminum oxide, is based partly on a calculated combination of Argonne data for aluminum and Henke optical constants for the oxygen at short wavelengths. However, Hagemann[8] (assuming a density of 3.17 g/cm^3) gave the best results, and this was adopted for the model. These linear absorption coefficients have been used to confirm aluminum test data from a variety of sources (see following section). Figure 10 compares the linear absorption coefficient for aluminum derived from the UCB test program with the Stanford model. The UCB data do include a small amount of aluminum oxide. The correlation is good except for the region above 700 Å.

Figure 11 gives the linear absorption coefficient for indium. The data are based on published test results of Hurwitz et al.[16]

In support of the Stanford/Marshall Space Flight Center Multi-

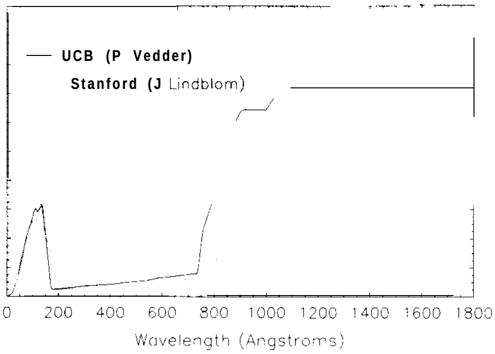

Fig. 10. Comparison of linear absorption coefficients for aluminum as a function of wavelength.

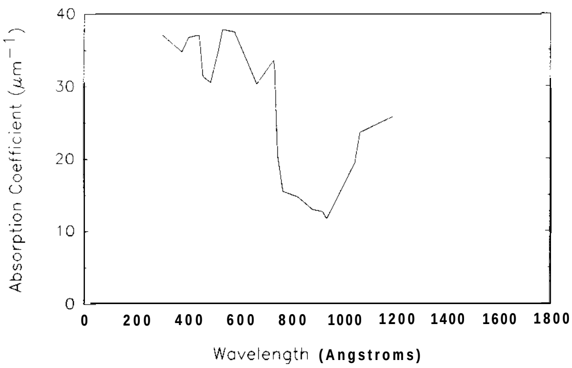

Fig. 11. Linear absorption coefficient for indium as a function of wavelength.

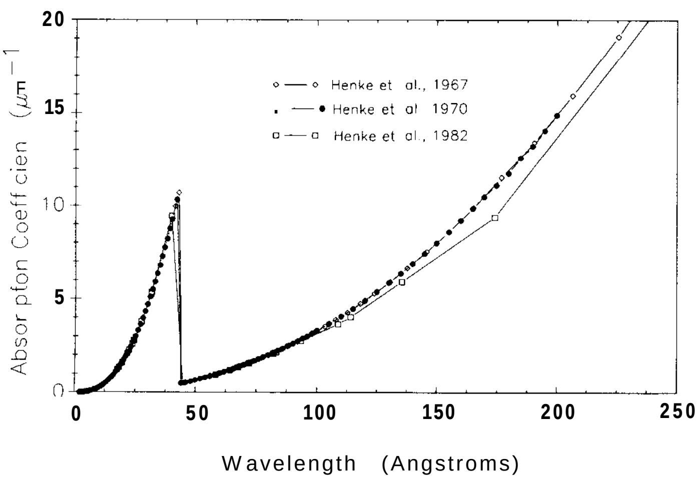

Fig. 12. Linear absorption coefficient for carbon (Henke) out to a wavelength of 250 Å.

Spectral Telescope Array project, an extensive literature search was done on carbon as a filter material. Since the references describe several decades of investigation, including recent work, measurement techniques were quite varied.[4,6,8,17–25] The principal references cited are noted in Figs. 12 through 15, which plot the linear absorption coefficients of carbon over various ranges of wavelength. This effort gives a good perspective of the kinds of differences that show up in various measurement programs. Naturally, the discrepancies are the greatest at the highest values of the absorption coefficient when the transmittance is the lowest or weakest and thus most difficult to measure accurately. The UCB data have been included in these carbon plots for comparison. In general, the data are consistent and the work supports the use of the EUVE data on carbon for filter design.

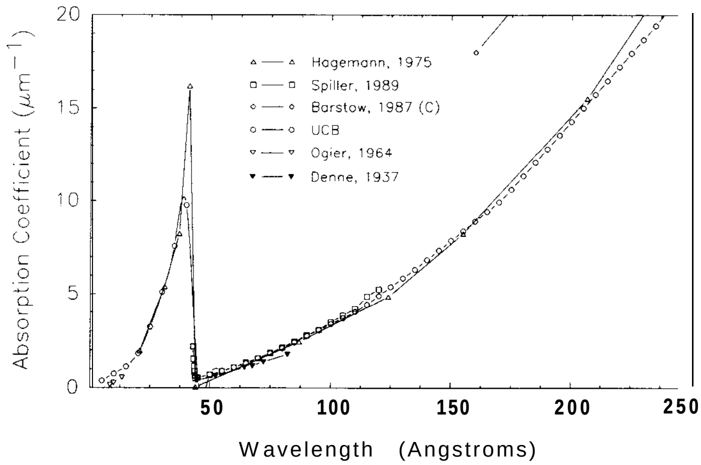

Fig. 13. Comparison of linear absorption coefficients for carbon out to a wavelength of 250 Å.

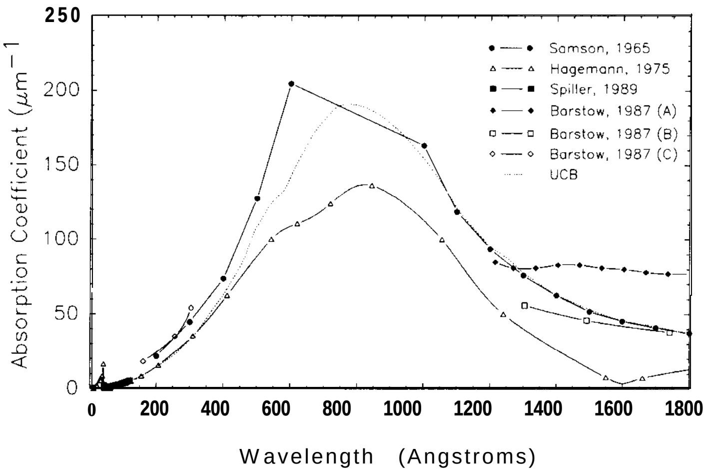

Fig. 14. Linear absorption coefficient for carbon out to a wavelength of 1800 Å.

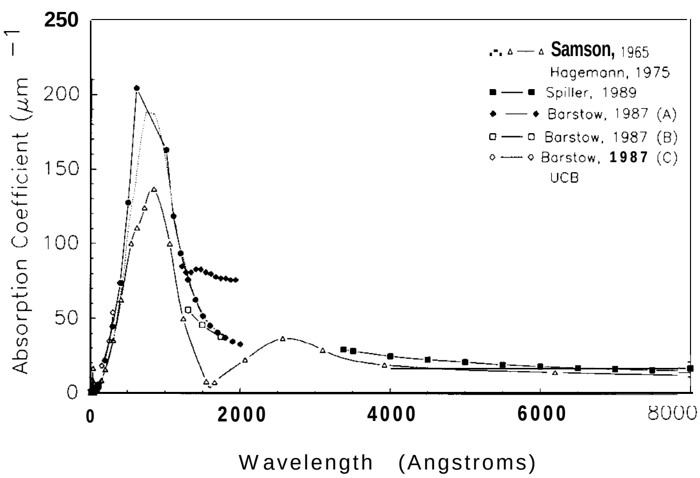

Fig. 15. Linear absorption coefficient for carbon out to a wavelength of 8000 A.

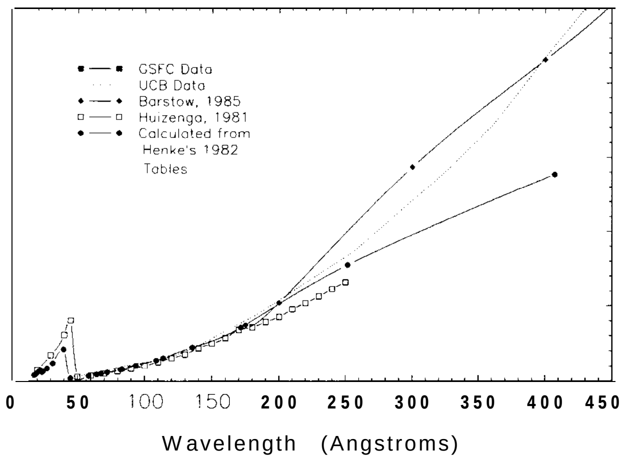

Fig. 16. Linear absorption coefficient for Lexan out to a wavelength of 450 A.

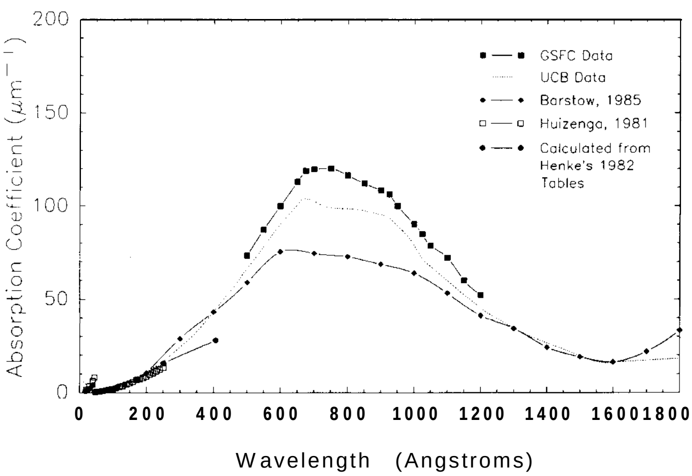

Fig. 17. Linear absorption coefficient for Lexan out to a wavelength of 1800 Å.

Based on the work on carbon, linear absorption coefficients were calculated for three organic compounds, assuming a composite of elemental materials present in proportion to their respective weights. These calculations went out to a wavelength of 400 Å, where the Henke data terminated. The results for Lexan are shown in Figs. 16 and 17 along with data available from the literature.[26–29] The agreement with the EUVE data is very good, particularly at wavelengths less than about 300 Å, where the transmission is more than 1% for typical filter thicknesses. As with carbon, variation in the data is expected when the transmittance is very low, as is clearly the case at wavelengths from about 500 Å to about 1200 Å.

Linear absorption coefficients have been calculated for Parylene N. Calculated and measured[30] data are shown together in Fig. 18.

Lastly, Fig. 19 shows calculated values for phthalocyanine (a blue dye) compared with Henke data for pure carbon. Phthalocyanine is of interest because of the desire to achieve maximum transmittance in the 44 Å to 68 Å region of the spectrum while also rejecting visible light when photographing the sun. Since

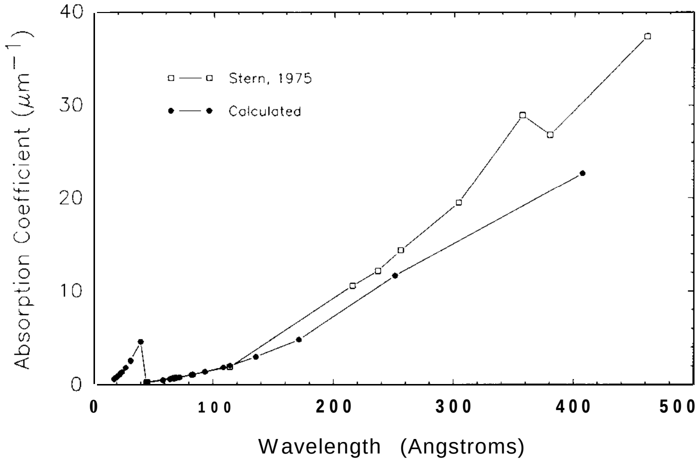

Fig. 18. Linear absorption coefficient for Parylene N as a function of wavelength.

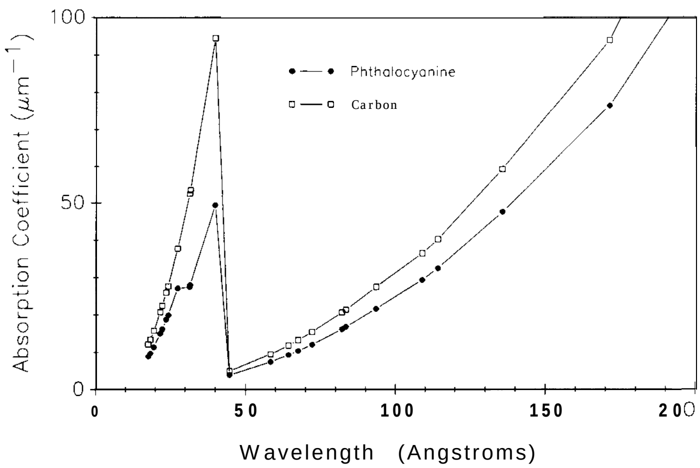

Fig. 19. Linear absorption coefficient for phthalocyanine as a function of wavelength.

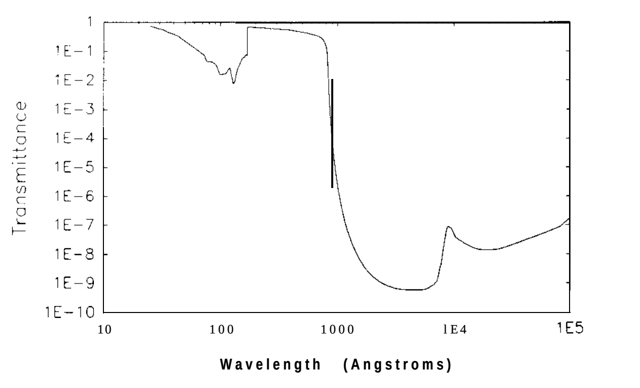

Fig. 20. Transmittance of a 1500 Å aluminum foil with 15 Å Al oxide as a function of wavelength.

carbon cannot be deposited in a single layer with sufficient thickness for this purpose, it must be built up in separate layers. The question becomes, "What is the best material to use as a spacer between layers?" It is possible to use a clear plastic such as Parylene or Lexan, but if phthalocyanine is used as the spacer, the visible light rejection is enhanced. Using this scheme, a

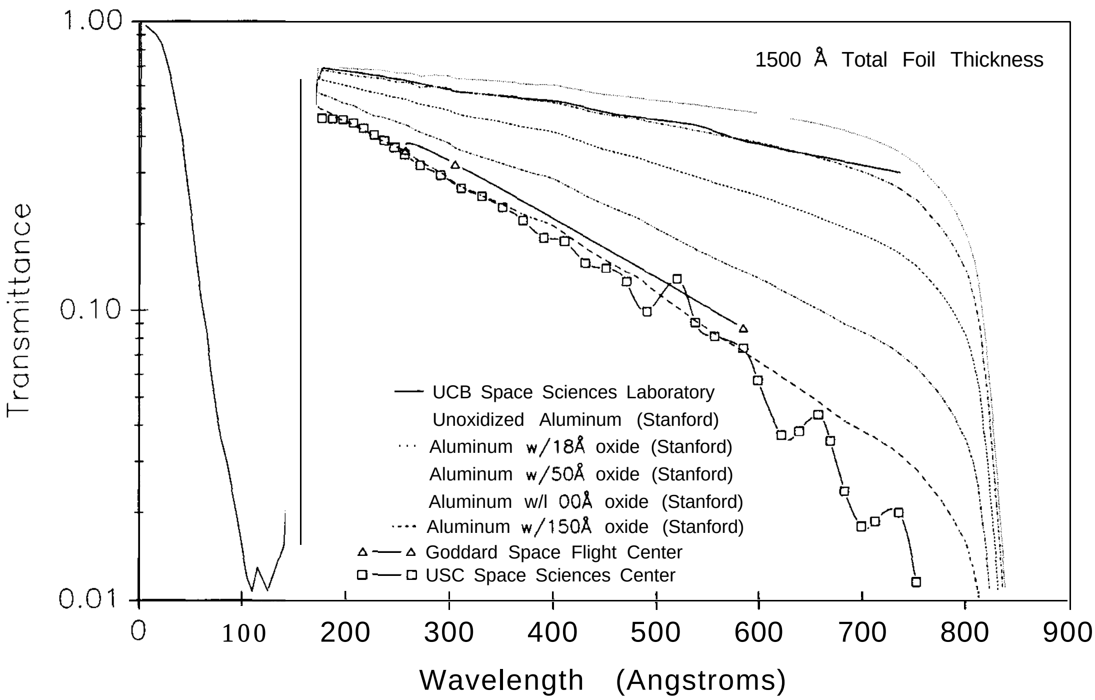

Fig. 21. Comparison of transmittance of aluminum foils with various amounts of aluminum oxide as a function of wavelength.

higher transmittance in the region of interest can be obtained while also achieving the required visible light rejection. The technique for producing carbon/phthalocyanine filters has been developed at the Luxel Corporation. (See also E. Spiller et al., "Filters for soft x-ray solar telescopes," in this issue, for actual test data on carbon/phthalocyanine filters.)

It is the authors' intention to keep a current library of tables 'of digital data on linear absorption coefficients. These data will be available through the Luxel Corporation on request.

4. FILTER PERFORMANCE FOR SELECTED MATERIALS

4.1. Aluminum

Aluminum is one of the best and most frequently used filter materials. It is relatively durable and is easier to process than are many other filter materials. It has a wide bandpass (from 170 Å to about 800 A) and is excellent for visible light rejection. As an example, mesh-supported 1720 Å thick aluminum filters yielded excellent high-resolution pictures of the sun at 173 Å and 256 Å.[31] The filters provided visible light rejection in the range of 10^{-9}. Recently, continuing work at Stanford's Center for Space Science and Astrophysics has produced predictions of light rejection as a function of wavelength based partly on data produced by Smith et al. from the Argonne National Laboratory? Figure 20 gives an interesting broad picture of predicted transmittance for a 1500 Å aluminum filter from 10 A to 100,000 Å in wavelength. Although the level is very low, there is a peak in transmission occurring at 9000 Å. Somewhat similar and consistent results were obtained from tests by J. W. Kohl at the request of R. W. McEntire at Johns Hopkins University Applied Physics Laboratory's Optical Calibration Facility. The unpublished results showed a peak in the transmission at about the same wavelength. In their case, the filter was Parylene with 420 Å of aluminum on both sides. Since the aluminum was thinner, the measured transmittance was somewhat higher, but the general shape of the curve is the same. Parylene and Lexan are both commonly used in filters, with aluminum on both sides. The advantage of putting the aluminum on both sides is that it usually reduces the possibility of pinholes.

Work somewhat similar to that done by R. B. Hoover et al. has been done by A. M. Umov et al. at the P. N. Lebedev Physical Institute of the USSR Academy of Sciences. In their TEREK experiment on board the Phobos satellite,[32] both grazing incidence and normal incidence optics produced solar images using various types of aluminum filters to eliminate visible light. Other work on multilayer mirrors used in x-ray astronomy has been published by Haisch et al.[33]

As detectors become more and more sensitive, energy rejection outside the band of interest becomes more important and filter design must be tailored to meet the researcher's needs over a very broad spectrum. Since multilayer mirrors by their nature provide a very narrow bandpass in the region of interest, the design of the filters to be used in conjunction with them may be somewhat different than it is for other optical systems.

An important question regarding aluminum filters is how aging affects their performance. Figure 21 summarizes the current understanding of what occurs. All curves are for a 1500 Å thick foil and are corrected to exclude the effect of mesh (which is usually 85% transmitting). (Meshless aluminum filters have some applications, but they cannot be very large and special care must be taken during their manufacture and use.) The top curve, marked unoxidized aluminum, shows an approximate upper limit of performance for pure aluminum with no oxides present, based mostly on Argonne data with some smoothing. The rest of the Stanford curves are based mostly on Argonne data for aluminum and on Hagemann[8] data for aluminum oxide. The curve that includes 18 Å oxide is the nominal performance predicted by

TABLE I. Aluminum filter transmission data at three wavelengths.

Wave-length	Measured Trans.	Mesh Trans.	Foil Thick.	Adjusted Trans.	Average Trans.
256Å	.466	.85	1100Å	.35	
	.407	.85	1530	.41	
	.487	.85	1000	.34	
	.532	.925	1031	.35	.3571
	.507	.9	1000	.3433	
	.607	1.0	924		
	.503	.82	1004	.38	
304A	.420	.85	1100Å	.31	
	.361	.85	1530	.37	
	.445	.85	1000	.30	
	.478	.925	1031	.30	.3214
	.467	.9	1000	.31	
	.580	1.0	924	.32	
	.477	.82	1004	.35	
584Å	.163	.85	1100Å	.08	
	.147	.85	153	.15	
	.164	.85	1000	.07	
	.168	.925	1031	.07	.0871
	.172	.9	1000	.08	
	.242	1.0	924	.08	
	.180	.82	1004	.08	

the authors for aluminum filters at or near the time of manufacture. It is based on the feedback received from many different users over the years. Note that it corresponds very closely to EUVE (UCB) data calculated from the linear absorption coefficients discussed earlier, out to about 700 Å.

Table I presents some aluminum filter test data supplied by R. Keski-Kuha of NASA's Goddard Space Flight Center. The tests were conducted over a two-year period on a variety of filters. Generally, each data point shown is the average performance of two similar filters made from the same materials. The data have been adjusted by calculation to show performance normalized to a common baseline of 1500 Å thickness without mesh, The average data fall just above the Stanford curve with 150 A of oxide, indicating that the filters were fairly well oxidized at the time of the tests.

The University of Southern California (USC) curve presents some very interesting new and unpublished data. D. McMullin of the USC Space Science Center found an aluminum filter that had been manufactured in 1980; it had not been stored in any special way. He had it tested at the National Institute of Standards and Technology. The results of that measurement program are presented as the USC curve, including individual data points. The closeness of the correlation with the Stanford curve with 150 Å seems quite remarkable. Also, a check against Hunter's' data adjusted for mesh and thickness gives the same close correlation. It would lead one to believe that the lower curves represent a reasonable lower limit on aging effects for an aluminum foil.

It is interesting to note that the longer the wavelength, the greater the effect of aging; this same phenomenon has been observed in other materials, such as silicon.[12] It is generally believed that the effect is directly related to the amount of oxygen present. It is not being suggested that a fully oxidized aluminum foil has precisely 150 A of oxide present, but rather that calculating filter performance based on this empirical model gives consistent results; thus, new filters designed using this same model can be expected to perform in a quite predictable way.

It can be concluded that aluminum filters have a reasonably long useful life. Nevertheless, it is best to minimize oxidation of the surface for optimum performance. All filters should be stored either in dry nitrogen or in a dry box with desiccant, if possible. For applications such as aerospace, where filters may be mounted in a spacecraft payload for a relatively long time before launch, care should be taken to use the most recently manufactured and/or the most carefully stored material available. Usually, performance comparable with that predicted by the UCB curve can be obtained. If the filters have aged for a year or more, then decreased performance similar to that shown for 50 A to 100 Å should be expected.

Aluminum is also useful at shorter wavelengths (shown approximately in Fig. 21), where it begins to transmit again at about 100 Å. Its transmittance is generally greater than 90% below about 20 Å. There is another absorption edge at 8 Å, but this edge has little effect for filters that are only a few thousand angstroms thick. An aluminum/carbon composite is often used when only short wavelength transmission is desired. Another useful combination is aluminum and titanium.

Other filter materials have very different aging characteristics. For example, tin and indium age quite quickly, whereas carbon and Lexan show virtually no signs of aging.[34] Precise work on the aging of tin and indium has been done by Hurwitz et al.[16] They concluded that the best way to store sensitive filters is in a high vacuum and even then, after 10 months, the transmission was only 70% of the original value. However, many people have reported good results for tin and indium used within a few months of fabrication.

With better test equipment and methods, a number of researchers have reported a fine structure in the transmittance of aluminum on the shorter wavelength side of the absorption edge at 171 Å. An extensive analysis of the phenomena has been

TABLE II. Solar A Soft X-ray Telescope Mission witness filter transmission measurements.

Filter No.	Filter Material	Measured Transmission Transmittance		Wavelength		
		13.3Å	44.7Å	67.67Å	304.0Å	584.0Å
1	Al/Ti/Lex	.68	.313	.090		
2	Al-12μm	.0070				
3	C/Al/Si/C	.745	.335	.1318	.163	.0042
6	Al/C	.76	.295	.101	.270	.031
7	Al/Ti/Lex	.668	.34	.108		
8	Al/Mg/Mn/C	.452	.0190	.00050		
9	Al/C	.77	.31	.1220	.492	.228

done by Paerels et al.[35,36] using star emissions as observed through different filters on the European X-ray Observatory Satellite. They derived mass absorption coefficients in the region from about 60 Å up to the edge at 171 A. While the variation was not large, there was a noticeable effect, presumably due to the material's failure to behave as free atoms (an assumption made in many models). There is measured data and a discussion of these effects in Ref. 7.

4.2. Polycarbonate (Lexan)

Various plastic films, including polypropylene and Parylene, have been used as filter materials for some time. They are mostly carbon, and therefore they have bandpass performance somewhat similar to carbon, but they are generally much stronger and less brittle than pure carbon. Since they do contain other elements, they have somewhat different bandpass characteristics than carbon alone. If these differences are acceptable, the mechanical advantages make them preferable as filter materials.

Lexan is finding wider use as a filter material. It is very strong (as demonstrated in bulletproof windows), and its thickness can be controlled precisely, even down to thicknesses as small as 500 A. Filters have been made in a wide spectrum of thicknesses. Pure Lexan, obtained from the manufacturer, is used to ensure uniform and repeatable filter performance. It is believed that some of the variation in Lexan filter performance measurements is caused by the presence of additives. Lexan can be coated on one or both sides with other filter materials, such as aluminum, especially if light rejection is required. Lexan's strength is quite beneficial when a pressure differential must be withstood.

Lexan is an organic compound ($C_{16}H_{14}O_3$) whose chemical name is bisphenol-A polycarbonate. Its density is 1.2 g/cm^3. Because of its nature, it is somewhat difficult to predict absorption coefficients as a function of wavelength. The need for a good empirical model for Lexan was one of the driving forces behind the EUVE test and data analysis project.

5. COMPOSITE FILTERS

Many of the more commonly used filter materials have been discussed. Although the materials that nature provides possess a variety of bandpasses, there is always the desire for a more refined window, and to this end, researchers are taking advantage of the cumulative effects of multiple bandpasses in series.

UCB's EUVE astronomical satellite will be using composite filters to separate spectral bands between 68 Å and 912 Å.[34,37] The composite filter types have evolved to be (1) Lexan/boron, (2) aluminum/carbon, and (3) titanium/antimony/titanium/aluminum. These will be used in various combinations with single layer tin and aluminum filters to achieve the desired separation of signals. The titanium/antimony/titanium/aluminum filter presented a special challenge in that the antimony provides the desired bandpass but is not an acceptable filter material by itself because of its mechanical and chemical nature. However, by sandwiching it between two titanium layers and overcoating with aluminum, the desired bandpass was achieved with sufficient chemical stability and strength.

Acton et al. at the Lockheed Palo Alto Research Laboratory are developing composite filters for use in the Soft x-ray Telescope for the Solar A Mission.[38] They have evolved to be entrance filters of Lexan/titanium/aluminum used in conjunction with analysis filters in a filter wheel of (1) titanium/magnesium/titanium, (2) aluminum/magnesium/manganese/carbon, (3) 12 pm aluminum, (4) 1400 A aluminum, and perhaps one or two other types yet to be decided. The entrance filters present special mechanical design problems because of their high aspect ratio shape required to match the entrance slit of the grazing incidence telescope. R. C. Catura, J. R. Lemen, and W. A. Brown have provided unpublished test data on witness filters in Table II. The accuracy of the data is reported to be 1% or better, and the correlation with predicted results based on calculations using mass absorption coefficients is quite good.

A composite of 2000 A tin and 2000 Å aluminum is being used by B. J. Kent from the Rutherford Appleton Laboratory. From unpublished test results, he reports transmittance measurements of 2.32~ 10^{-2} at 67 Å and 3.21 x 10^{-4} at 462 A. These are average results taken from 14 different filter cells; the data were quite consistent. These filters are a part of a set for the ROSAT satellite[27,39] using composites of carbon/boron/Lexan, beryllium/Lexan, and aluminum/Lexan as well as the tin/aluminum. M. A. Barstow from the University of Leichester and M. V. Zombeck from the Harvard-Smithsonian Center for Astrophysics provided unpublished linear absorption coefficients in the form of the Wide Field Camera database. In particular, there is good agreement with the UCB model for Lexan.

6. GENERALIZED THIN FILM FILTER PERFORMANCE

Figure 22 provides a generalized overview of the transmittance that can be expected from commonly used filter materials. Normalized and smoothed curves are given for eight different materials; transmittance is plotted as a function of wavelength. The addition of silicon (1%) to aluminum, germanium (3%) to tin, and titanium (1%) to indium is done to enhance mechanical strength.

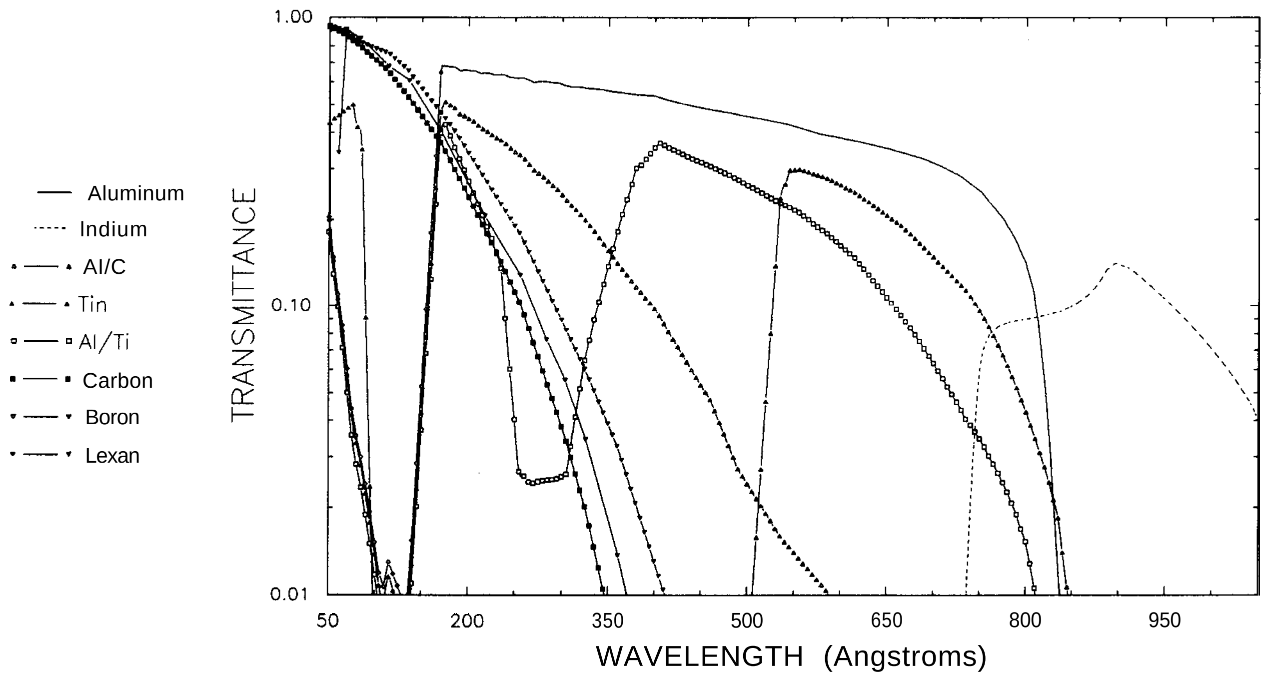

Fig. 22. Transmittance of eight different foils and foil combinations as a function of wavelength.

Figures 23 through 30 give some further detail on each of the eight filter types. Figure 23 shows both UCB and Stanford predictions for aluminum. Figure 26 shows both UCB data and data from Labov et al. [12] for boron. The Labov data are smoother and may be the preferred model for some situations. These figures show a broader range of transmittance for completeness. Sometimes, as in the case of tin, there is some additional zone of transmittance, which may be important if the detector to be used in a particular application is very sensitive.

7. PHOTOCATHODES AND LASER TARGETS

From the standpoint of design and fabrication, a photocathode is not unlike a composite filter. It consists of several layers of materials, each of which performs a particular function. A popular design consists of Lexan overlaid with a very thin layer of grounded aluminum and either cesium iodide or potassium bromide, depending on the application. Cesium iodide and (to a lesser extent) potassium bromide are both prone to absorb moisture; hence, considerable care must be taken during the manufacturing process. On completion of the last deposition, the films are packaged in dry nitrogen immediately after removal from the vacuum chamber.

Laser targets use many of the same materials as UV filters, in addition to others. X-ray laser work by Matthews and Rosen at University of California Lawrence Livermore National Laboratory[40] involves the use of materials such as selenium, tungsten, tantalum, gold, silver, germanium, magnesium fluoride, sodium fluoride, yttrium, and molybdenum. Each of these materials has special properties of interest in producing the plasmas needed for x-ray lasing. G. Stone, W. Junk, V. Gregory, M. Moran, and others at Livermore are investigating a number of areas, including vacuum barrier windows that can stand up to 50 Ton of pressure. Their measurements on Lexan coated with aluminum confirm the properties of Lexan already discussed.

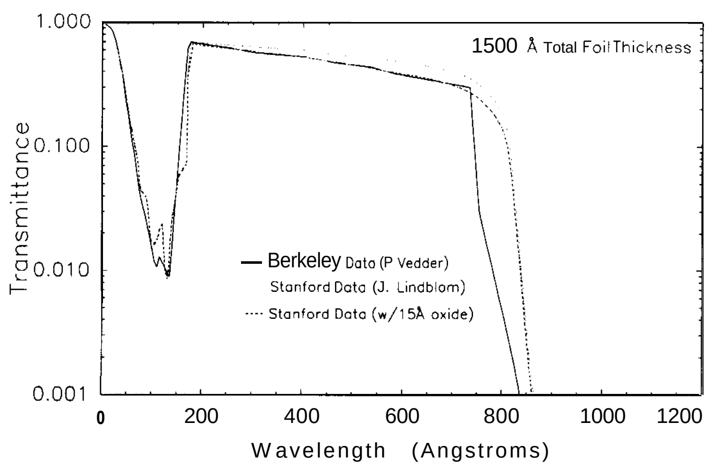

Fig. 23. Comparison of transmittance of aluminum foils from two different data sources.

8. CONCLUSIONS

The body of knowledge on UV filter performance, ranging from the aging of metal foils to the use of plastic films in filters, is improving as the number of applications increases. The current state-of-the-art in filter design includes an expanding list of materials in practical use, plus many new composite designs. Reliable values for linear absorption coefficients are available for many materials.

Today's instrumentation and measurement techniques enable a measurement error in filter transmittance to about ±1%, but in practice it is generally not possible to predict filter performance to better than about ± 3% to ± 5%. One of the biggest uncertainties is mesh transmission, since it is difficult to procure mesh with lot to lot consistency. It is safest to plan for an uncertainty

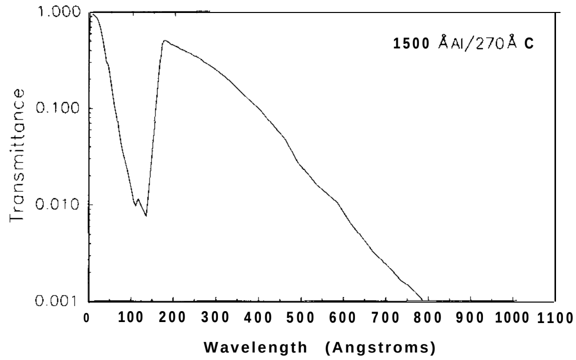

Fig. 24. Transmittance of an aluminum/carbon foil as a function of wavelength.

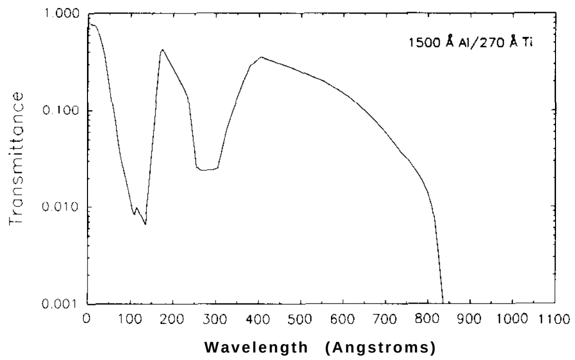

Fig. 25. Transmittance of an aluminum/titanium foil as a function of wavelength.

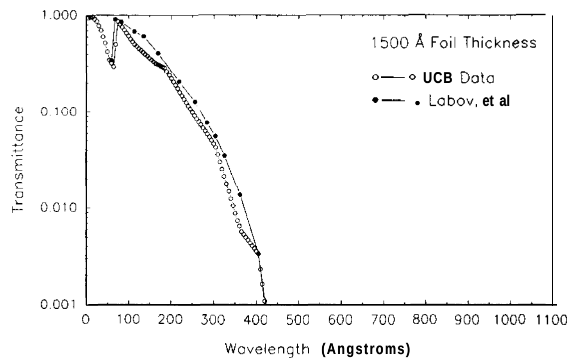

Fig. 26. Transmittance of a boron foil as a function of wavelength.

of at least ±10%, and if that amount of uncertainty causes system design problems, then the filters should be built far enough in advance that measured performance can be used for setting expected signal levels in detectors.

9. ACKNOWLEDGMENTS

The authors wish to thank those named in this paper, plus all of the others who have volunteered their efforts to help make this work possible. The cooperation in this endeavor to collect and correlate data has been excellent, and it is much appreciated. Many references have been omitted for the sake of conciseness. It is the authors' intent to continue working along these lines and to make the combined results available.

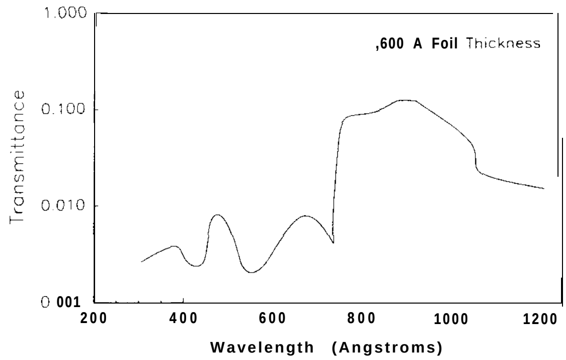

Fig. 27. Transmittance of an indium foil as a function of wavelength.

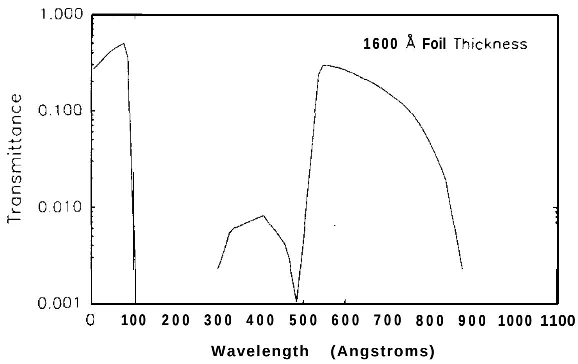

Fig. 28. Transmittance of a tin foil as a function of wavelength.

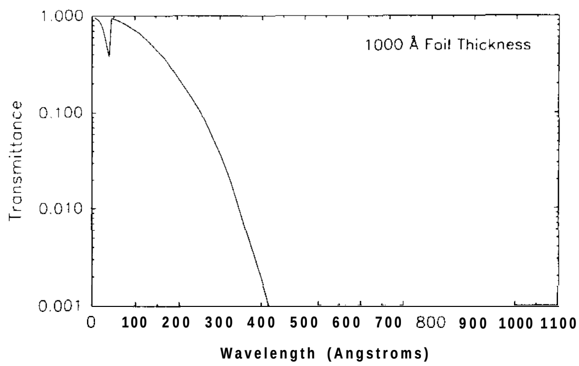

Fig. 29. Transmittance of a carbon foil as a function of wavelength.

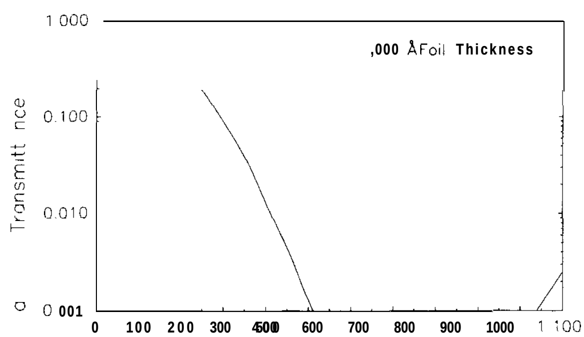

Fig. 30. Transmittance of a Lexan foil as a function of wavelength.

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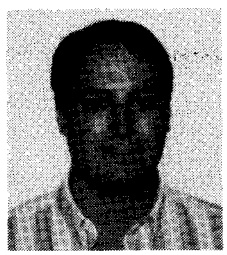

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