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BETA BACKSCATTER MEASUREMENTS OF
ALUMINUM COATINGS ON MYLAR
SUBSTRATES

PDO 6984697, Topical Report

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Project Team:
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September 1974

MASTER

Prepared for the
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**Kansas City
Division**

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**BDX-613-1028
September 1974**

Prepared by R. V. Heckman, D/144, under PDO 6984697

A method has been developed, using specialized beta backscatter equipment, to nondestructively measure the thickness of 0- to 450-microinch (0 to 0.0114 mm) aluminum foil on an aluminum-mylar-aluminum laminate. Measurement precision is greater than 3 percent. The sensitivity of various isotope sources is discussed, and promethium 147 is shown to be the best for the application.

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**A prime contractor for the
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SUMMARY

A beta backscatter technique has been developed to provide small-area thickness measurements of aluminum coatings in the 0- to 450-microinch (0 to 0.0114 mm) range. The material of interest was a laminate consisting of a 0- to 450-microinch aluminum layer, a 0.010-inch (0.254 mm) mylar substrate, and a 0.005-inch (0.127 mm) aluminum backing. The presence of the backing complicated the thickness measurements; unless the proper isotope were used, the measurements would be affected.

A series of experiments was performed to determine the relative beta backscatter obtained from aluminum and from mylar. These experimental values were then compared with calculated values of relative backscatter. (Appendix)

In another series of measurements, the ranges of promethium 147 and thallium 204 betas were determined in aluminum and in mylar and were compared with theoretical values.

The results of the experiments indicated that promethium 147 was the isotope best suited for use with the laminate material. Thallium 204 and carbon 14 were indicated to be second and third choices, respectively. Carbon 14 was not seriously considered because its low activity requires that its source be made appreciably larger than that for promethium or thallium. The minimum area which can be measured with carbon 14 is thus limited.

Using a promethium 147 source, the sensitivity of the backscatter process was statistically measured. These results indicated that thickness measurements in the 0- to 450-microinch (0 to 0.0114 mm) range could be made with a precision of ± 3 percent. The further conclusion was reached that the inability of obtaining uniform standards was the limiting factor for making measurements to a greater precision.

Although the technique developed is capable of making thickness measurements of the laminate top foil to a precision of 3 percent, the smallest area that can be measured is one having a diameter of 0.020 inches (0.508 mm). The measurement of smaller areas might be feasible if measurement times longer than 2 minutes were used. Probes now being developed are expected to decrease the minimum aperture size from a diameter of 0.020 inches (0.508 mm) to 0.005 inches (0.127 mm).

The technique described in this report is being used to measure the foil thickness of applicable development parts.

DISCUSSION

SCOPE AND PURPOSE

This project was initiated to determine the feasibility of using beta backscatter to nondestructively measure the thickness of 0- to 450-microinch (0 to 0.0114 mm) aluminum foil on an aluminum-mylar-aluminum laminate. (Figure 1) Although no specifications for such a measurement exist at the present time, general requirements call for a nondestructive technique capable of determining the thickness of the aluminum coatings with a precision of at least 5 percent.

450 MICROINCHES (0.0114 mm) ALUMINUM

Figure 1. Cross Section
of Aluminum-
Mylar-Aluminum
Laminate

The only techniques now available for determining the thickness of the foil consist of sectioning, weight loss-or-gain measurements, and measurements of electrical resistance. All of these fail to meet the objectives in one manner or another. Sectioning is destructive and, in the thickness range of interest, is highly dependent upon the skill of the operator. The weight loss-or-gain and resistance measurements furnish only average values which cannot account for short-range variations in thickness.

Beta backscatter was chosen for investigation because, from a theoretical standpoint, it offers the highest probability for success, and because it is a fast and therefore economical method for measuring thickness. The relative interaction of aluminum foil and mylar with electrons first had to be established. Because the presence of the aluminum backing necessitated that a

source of betas be found that could penetrate the top aluminum foil without penetrating the 0.010-inch (0.254 mm) mylar layer, the sensitivity of various isotope sources was investigated. Aluminum reference foils had to be obtained to calibrate the beta backscatter equipment so that absolute thickness measurements could be made.

Work for this project was performed under PDO 6984697.

PRIOR WORK

Because of a general lack of interest and the extreme complexity of the processes involved, the theory of electron interaction with bulk material is perhaps one of the most neglected fields in modern physics. Most of the theoretical work has been concerned with describing and rationalizing the phenomena of beta decay; little work, if any, has been concerned with the interaction of moderately energetic electrons (0.1 to 1 MeV) with matter.

ACTIVITY

Theory

Expressions have been derived for the cross section of beta backscatter. The following equation is the classical expression for nonrelativistic electrons ($\beta \leq 0.5$) in the beta backscatter.¹

$$\sigma(\text{cm}^2/\text{atom}) = \pi \left(\frac{e^2}{m_0 c^2} \right)^2 Z^2 \left(\frac{1-\beta^2}{\beta^4} \right), \quad (1)$$

where

σ = cross section for backscatter,

e = charge of an electron,

$m_0 c^2$ = energy of an electron at rest,

Z = atomic number, and

β = ratio of particle velocity to speed of light.

This result is quoted to show that the beta backscatter flux is proportional to the square of the atomic number (Z^2). Thus in order to distinguish one material from another, a considerable difference must exist between the atomic numbers of the materials involved.

R. H. Muller has devised an empirical method for calculating the relative percentage of betas backscattered by specific elements and compounds.² Muller has found that within each period of elements a linear relationship can be devised to predict the backscattered percentages. He also has found that compounds can be treated successfully with the same technique provided that an effective Z value is calculated. This is accomplished by taking a weighted average of the Z values of each of the constituents and then applying a correction factor which takes into account the negative backscatter coefficient of hydrogen.

For the materials of interest in this problem, the Z of aluminum is 13 and the calculated Z for mylar is 6.46. (Appendix) By using the Muller expressions, the backscatter is 13.05 percent for aluminum and 5.36 percent for mylar. The ratio r of aluminum to mylar is therefore

$$r = 2.43.$$

From this value, beta backscatter measurements of aluminum coatings on mylar appear to be feasible.

The range of electrons in bulk material can be calculated with precision by using the range formulas. The following equation is an expression for betas in the energy range of 0.01 to 3 MeV.³

$$R_o (\text{mg/cm}^2) = 412 E^n, \quad (2)$$

where

R_o = range,

E = energy in MeV, and

$$n = 1.265 - 0.0954 \log_e E.$$

In Figure 2, the range is shown for mylar and aluminum as a function of energy. Their densities were assumed to be 1.39 g/cm³ and 2.70 g/cm³, respectively.

The general requirement for a beta source is that it be capable of penetrating the top foil in order to accurately measure the thickness; it must, however, be totally absorbed by the mylar backing material. By applying this requirement to the curves shown in Figure 2, the following observations can be made.

Figure 2. Range as a Function of Energy for Mylar and Aluminum

- The source must have an energy greater than 0.08 MeV to penetrate 0.00045 inch (0.0114 mm) of aluminum. (The range must be twice the thickness of the material since the electron must penetrate the material twice: 2×0.00045 inch = 0.00090 inch, or 0.0228 mm).
- The energy of the source should not be greater than 0.26 MeV since this energy corresponds to a beta range of 0.020 inch (0.508 mm) which, in turn, corresponds to a mylar thickness of 0.010 inch (0.254 mm).

A survey of common beta sources indicates that carbon 14 and promethium 147 meet the general requirements: carbon 14 produces a 0.155-MeV beta and promethium 147 produces a 0.220-MeV beta. Although carbon 14 is the more desirable from an energy standpoint, its long half-life (5500 years) and hence relatively low activity rules it out as a possible source, since the goal of making measurements of small areas dictates that the size of the source be minimized. Promethium 147 has a high activity with a half-life of approximately 2.6 years.

Experimental Work

Based upon the theoretical considerations previously described, a series of three distinct experiments was performed. The first two experiments were designed to verify the theoretical range and relative backscatter calculations that had been made. The third was performed to determine the statistical accuracy of the beta backscatter equipment when used on the aluminum laminate.

Geiger tubes were used for detectors in all of the experiments. Other equipment consisted of a Hewlett Packard Model 5590A Timer/Scaler and a Conberra Model 1413 Spectroscopic Amplifier. A diagram of the basic beta backscatter system is shown in Figure 3. The geometry of the test probe is shown schematically in Figure 4.

Figure 3. Basic Beta Backscatter System

Figure 4. Test Probe Geometry

Using the apparatus shown with a 50-microcurie promethium source, count rates were made from 0.060-inch (1.524 mm) thicknesses of aluminum and of mylar. The following were the average count rates obtained for 10 readings of 100 seconds duration.

Aluminum = 2202.78 counts/s, and

Mylar = 980.65 counts/s.

The ratio of these two values,

$R = 2.25$,

is close to the previously calculated theoretical value of 2.43. The cause for disagreement between the observed and theoretical values can probably be attributed to the dead time of the geiger tube. A proportional counter was used in Muller's work.⁴

The range of the 0.22-MeV electron in mylar was experimentally determined. Figure 5 shows a plot of backscattered counts as a function of mylar thickness for a promethium 147 source. The number of backscattered particles is shown to be constant for mylar thicknesses greater than 0.006 inch (0.152 mm). The range of the promethium beta would therefore be 0.012 inch (0.304 mm), which is slightly less than the 0.015 inch (0.381 mm) predicted in Figure 2 for a 0.22-MeV electron.

Figure 5. Count Rate Versus Mylar Thickness (Promethium 147 Source; 0.010-Inch or 0.254-mm Aluminum Backing)

As a check on the preceding experiment, a series of readings was made after adding increased thicknesses of aluminum to the back of 0.010-inch (0.254 mm) mylar. The data obtained is shown in Figure 6. The presence of the aluminum backing did not affect the observed count rate within the statistical limits of the experiment. From the results of the two experiments, the theory that the presence of the 0.005-inch (0.127 mm) aluminum backing does not affect the measurement of the front aluminum foil when a promethium 147 source is used was concluded to be correct.

Figure 6. Count Rate Versus Aluminum Backing Thickness (Promethium 147 Source)

The same experiments were repeated using a 0.76-MeV thallium 204 source. The bottom curve of Figure 7 shows the data obtained when no aluminum top foil was present. The count rate continued to decrease beyond a 0.028-inch (0.711 mm) thickness of mylar. The top curve shows the results obtained after adding a top coating of 512 microinches (0.013 mm) of aluminum to simulate the top foil normally present. In the latter case, the count rate appeared to stabilize at a point slightly beyond 0.010 inch (0.254 mm). The conclusion was therefore reached that the higher energy of the thallium source could be used marginally if the thickness of the top aluminum foil exceeded 512 microinches. Thallium has no advantage over promethium as a source since it is slightly less active; however, it might be useful for materials having thicker top foils than those now in use.

Figure 7. Count Rate Versus Mylar Thickness
(Thallium 204 Source)

To determine the sensitivity of the backscattered flux of 0.22 MeV electrons to changes in aluminum thickness, measurements of the count rate were made for four known thicknesses of aluminum foil placed on a piece of 0.010-inch (0.254 mm) mylar having a 0.005-inch (0.127 mm) aluminum backing. The foils were obtained from ESPI and were guaranteed uniform within 5 percent. The thicknesses used were 0.005 mm, 0.008 mm, 0.013 mm, and 0.025 mm. The count rates obtained from the four foils, shown in Figure 8, indicate that a thickness change of 0.001 mm results in a count change of 1000. With this sensitivity, a 3-percent variation in thickness would result in a count change of 300. Since the standard deviation observed in these measurements was typically of the order of ± 150 counts, a 3-percent thickness variation is essentially twice the statistical variation and therefore is observable.

From the experiment, the conclusion was reached that relative measurements of aluminum thickness can indicate a variation of 3 percent.

Absolute thickness measurements can be made with the same precision provided that precision foils having variations of less than 2 percent can be obtained. Absolute measurements are now limited by the allowable 5-percent thickness variation in the foils.

Figure 8. Sensitivity of Beta Backscatter to Aluminum Thickness Variation

ACCOMPLISHMENTS

Experimental results conclusively prove the theory that the thickness of 0- to 450-microinch (0 to 0.0114 mm) aluminum foil on a mylar substrate can be successfully measured using a promethium 147 source and a commercial geiger detector. They further show that 3-percent variations in thickness can be observed and, with suitable standards, absolute thicknesses can be measured with similar precision.

A promethium 147 source was shown both theoretically and experimentally to be the best beta source for this particular application since it had enough energy to penetrate the top foil but was not energetic enough to penetrate the 0.010-inch (0.254 mm) mylar backing.

The ability to measure the top foil of the laminate without the 0.005-inch (0.127 mm) aluminum backing affecting the measurement has been conclusively demonstrated, provided there is at least 0.005 inch of mylar separating the two foils. This conclusion is supported by the fact that aluminum has twice the stopping power of mylar; therefore, 0.0005 inch (0.0127 mm) of aluminum is equivalent to 0.001 inch (0.0254 mm) of mylar. The minimum thickness of mylar necessary to stop a 0.22-MeV beta has been shown to be 0.005 inch. If the mylar thickness were less than the latter amount, measurement of the foil might still be possible since the contribution of the aluminum backing would be small and perhaps could be disregarded.

FUTURE WORK

The primary remaining problem is the obtaining of probes capable of measuring areas having a diameter of only 0.005 inch (0.127 mm). With existing equipment, the minimum useful aperture is 0.020 inch (0.508 mm). Smaller apertures can sometimes be used, but the signal-to-noise ratio is such that precision measurements are not possible. Development work is now under way to investigate different types of detectors and to design probes specifically for small-area measurement.

Other experiments are being performed to determine the information necessary to the designing of a successful probe. These experiments include a mapping of the backscattered spatial distribution and a determination of the effect of aperture size upon the count rate. These experiments will be discussed in future reports.

A search is being conducted to locate a vendor who can supply precision foil having a thickness variation of less than 2 percent. If such a supplier can be found, adequate standards for absolute measurements can be fabricated. The existing foils are being used as working references for making relative thickness measurements of aluminum on mylar.

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¹Robley D. Evans, *The Atomic Nucleus*. New York: McGraw-Hill, 1955, p 625.

²Ralph H. Muller, "Interaction of Beta Particles With Matter," *Analytical Chemistry*, Volume 29, Number 6, June, 1957, p 969.

³Ibid.

⁴Ibid.

1

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Appendix

CALCULATION OF RELATIVE BETA BACKSCATTER FROM ALUMINUM AND MYLAR

The following is a calculation of the relative beta backscatter from aluminum and from mylar, using the empirical relationships devised by Ralph H. Muller.* The following equation is used to calculate the effective Z for a compound.

$$Z' = \frac{n(A_B \cdot Z_B) + m(A_C \cdot Z_C)}{\text{Molecular Weight of } B_n C_m}, \quad (1)$$

where

Z' = the effective atomic number of the compound,

n and m = the relative number of atoms present in the compound,

A_B and A_C = the atomic weights of the respective elements, and

Z_B and Z_C = the atomic numbers of the constituent elements.

The chemical formula for mylar is

where the atomic number Z of the atoms are

$C = 6,$

$H = 1,$ and

$O = 8.$

*Ralph H. Muller, "Interaction of Beta Particles With Matter," *Analytical Chemistry*, Volume 29, Number 6, June, 1957, p 969.

By applying these values to Equation 1, an effective Z' for mylar is obtained.

$$Z' = \frac{(10 \cdot 12.0 \cdot 6) + (8 \cdot 1.0 \cdot 8) + (4 \cdot 16.0 \cdot 8)}{192}$$

$$Z' = 6.46$$

By using a relationship derived by Muller which accounts for the absorption by hydrogen,*

$$\text{Backscatter} = 1.2311Z' - 2.157 - 10.38f_H, \quad (2)$$

where f_H is the weight fraction of hydrogen.

The following relative backscatter from mylar is then obtained.

$$\text{Backscatter} = 1.2311 \cdot 6.458 - 2.157 - 10.38 \cdot 0.0417$$

$$\text{Backscatter} = 5.36 \text{ percent}$$

The backscatter determination for aluminum is much simpler. Since aluminum is a pure element, the Z number (13) is obtained directly. Backscatter is determined by using the appropriate Muller formula for a third-period element.**

$$\text{Backscatter} = 0.96731Z + 0.476$$

$$\text{Backscatter} = 0.96731 \cdot 13 + 0.476$$

$$\text{Backscatter} = 13.05 \text{ percent}$$

The ratio R therefore is determined as follows.

$$R = \frac{13.05}{5.363} = 2.43.$$

*Muller, p 976.

**Muller, p 972.

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