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X-RAY FLUORESCENCE TECHNIQUE FOR MEASURING COATING THICKNESS

J. E. Coulter

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OAK RIDGE Y-12 PLANT
OAK RIDGE, TENNESSEE

*prepared for the U.S. ATOMIC ENERGY COMMISSION
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ABSTRACT

An X-ray fluorescence technique has been evaluated for measuring the coating thickness of two coating-substrate combinations. A quantitative theory has been developed in conjunction with the experimental data to support the results of the investigation.

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SUMMARY

An X-ray fluorescence technique has been evaluated, at the Oak Ridge Y-12 Plant,^(a) for measuring the coating thickness of several coating/substrate combinations. The fluorescence technique consists of using the monochromatic radiation from an isotopic source to generate fluorescent radiation in both the coating and substrate and then taking the ratio of the coating-to-substrate fluorescence to provide independence of source intensity and source and detector geometry. A macroscopic quantitative theory has been formulated, and experimental data were taken to support the results of the theory. Employing the X-ray fluorescence method, plating thickness measurements were made on plated coupons and a plated test cylinder to determine the accuracy and precision of the measurement technique.

(a) Operated by the Union Carbide Corporation's Nuclear Division for the US Atomic Energy Commission.

INTRODUCTION

X-ray fluorescence has become a valuable nondestructive testing method for measuring coating thickness (or mass per unit area). Two X-ray fluorescence methods are in common use⁽¹⁾ for measuring the thickness of a coating on a substrate. One method consists of measuring the intensity of fluorescent radiation from the coating; the other method measures the intensity of the fluorescent radiation which is produced in the substrate and then attenuated by the coating. An X-ray beam of polychromatic radiation is normally used to produce the characteristic X-ray fluorescence in both the coating and substrate. However, the polychromatic radiation from an X-ray tube not only generates fluorescent X rays in the media but also produces a continuum of scattered radiation which creates a high "background" level in the resultant X-ray energy spectrum.

An alternative to the X-ray tube is to use the monochromatic radiation from an isotopic source for the generation of fluorescent radiation. Using the monochromatic radiation from an isotopic source and then taking the ratio of the coating fluorescent radiation to the attenuated substrate fluorescent radiation offers several distinct advantages. For example, the "background" level of the fluorescent energy spectrum is significantly reduced. Also, the ratio of coating fluorescent radiation to substrate fluorescent radiation is independent of the intensity of the source and, to some extent, is independent of the source and detector geometry. This particular X-ray fluorescence technique facilitates the interpretation of the resultant fluorescence data and allows the use of a quantitative macroscopic theory to predict coating thickness data for various combinations of coating and substrate materials.

Based on the X-ray fluorescence technique just described, a quantitative macroscopic theory has been formulated (see the Appendix) according to the relative atomic numbers of the coating and substrate. The quantitative results of the theory have been tested for two particular cases: (1) a zinc coating on an iron substrate, where the atomic number of the coating is greater than the atomic number of the substrate; (2) a nickel coating on a uranium substrate, where the atomic number of the substrate is greater than the atomic number of the coating.

An experiment was also conducted to determine the feasibility of the X-ray fluorescence technique for measuring the thickness (or mass per unit area) of plated nickel on a uranium substrate where metal foil standards were used for the thickness calibration. Plating thickness measurements were made on plated coupons and on a plated test cylinder to determine the accuracy and precision of the measurement technique.

X-RAY FLUORESCENCE TO MEASURE COATING THICKNESS

EXPERIMENTAL METHOD

Figure 1 presents a block diagram of the X-ray fluorescence system used to measure coating thickness. The 40-keV gamma rays from a 500-millicurie gadolinium-153 source generate the characteristic fluorescent radiation in both the coating and substrate. The 30-mm² lithium-drifted silicon detector converts the fluorescent radiation into electrical pulses where the amplitude of the pulses is proportional to the fluorescent energy. The pulses are then shaped and amplified by the preamplifier [mounted on the Si (Li) detector] and amplifier. The multichannel analyzer counts the pulses according to the pulse height (energy), and a printout of the fluorescent energy spectrum data (counts, time, channel number) is obtained via a teletypewriter.

Figure 1. X-RAY FLUORESCENCE THICKNESS MEASUREMENT SYSTEM.

EXPERIMENTAL CONFIRMATION OF THE THEORY

Zinc Coating on an Iron Substrate

Zinc metal foils of known thickness (or mass per unit area) were placed on an iron substrate having a thickness of approximately 0.1 inch. Forty-keV gamma rays from a 500-millicurie gadolinium-153 source were used to excite the K_{α} X rays in both the zinc and iron. From

Equation A-10 in the Appendix, the theoretical ratio of coating fluorescent radiation to substrate fluorescent radiation is given by:

$$\frac{I_{D(c)}}{I_{D(s)}} \cong \frac{G_{I_O(c)} [\mu_{I_O(s)} + \mu_{F_S(s)}] \left\{ 1 - e^{-[\mu_{I_O(c)} + \mu_{F_C(c)}] \rho(c)t} \right\}}{G_{I_O(s)} [\mu_{I_O(c)} + \mu_{F_C(c)}] e^{-[\mu_{I_O(c)} + \mu_{F_S(c)}] \rho(c)t}} \quad (1)$$

Derivation of Equation 1 and definitions of the various symbols can be found in the Appendix. Theoretical and experimental data are given in Figure 2 where the zinc coating thickness is plotted as a function of the ratio of zinc K_α fluorescence to iron K_α fluorescence. The solid line in Figure 2 represents the theoretical data from Equation 1 and the data represented by circles are actual experimental results from the observed zinc and iron fluorescence. Data from Equation 1 were calculated using theoretical values⁽²⁾ for the mass attenuation coefficients and fluorescence yields of the media.

Figure 2. COATING THICKNESS AS A FUNCTION OF THE RATIO OF ZINC (COATING) K_α FLUORESCENCE TO IRON (SUBSTRATE) K_α FLUORESCENCE.

Nickel Coating on a Uranium Substrate

If the atomic number (Z) of the substrate is higher than the atomic number of the coating, the substrate fluorescent radiation can produce additional fluorescent radiation in the coating, providing the energy of the substrate fluorescence is above the K or L absorption edge of the coating. For the particular case of a nickel coating (metal foils) on a uranium substrate, the 40-keV gammas from the isotopic source excite the K_{α} X rays in the nickel coating and the L_{α} and L_{β} X rays in the uranium substrate. The L_{α} and L_{β} substrate fluorescence can then generate additional K_{α} fluorescence in the nickel coating. From Equation A-15, the additional coating fluorescent radiation, generated by the substrate fluorescence, is given by:

$$I'_D(c) = G_{I_O}(s) G_{F_S}(c) I_{Oe} \left[\mu_{I_O}(c) + \mu_{F_C}(c) \right] \rho(c) t \left\{ 1 - e^{-[\mu_{F_S}(c) + \mu_{F_C}(c)] \rho(c) t} \right\} \quad (2)$$

$$[\mu_{I_O}(s) + \mu_{F_S}(s)] [\mu_{F_S}(c) + \mu_{F_C}(c)]$$

Derivation of Equation 2 and definitions of the various symbols can be found in the Appendix. Equation 1 for the ratio of coating fluorescent radiation to substrate fluorescent radiation now becomes:

$$\frac{I_D(c)}{I_D(s)} \rightarrow \frac{I_D(c) + I'_D(c)}{I_D(s)} \quad (3)$$

Theoretical and experimental data are illustrated in Figure 3, where the nickel coating thickness is plotted as a function of the ratio of nickel K_{α} fluorescence to uranium L_{α} fluorescence. The dotted line in Figure 3 shows the theoretical data obtained from Equation 1 and does not include the additional nickel K_{α} fluorescence generated by the substrate fluorescent radiation. The dashed line represents the theoretical data from Equation 3, but only includes the L_{α} substrate contribution to nickel K_{α} fluorescence. The solid line, however, includes both the L_{α} and L_{β} substrate contributions in Equation 3. Data represented by the circles are the experimental results from the observed nickel and uranium fluorescence.

X-RAY FLUORESCENCE THICKNESS MEASUREMENTS

In order to evaluate the X-ray fluorescence technique just described, coating thickness measurements were made for an electroplated nickel coating on a uranium substrate. Nickel metal foils were used as standards, where the equivalent thickness of each standard was determined by weight-area measurements. Thickness calibration consisted of placing each nickel foil on a 0.1-inch-thick uranium substrate and using the method of least squares to fit the resultant fluorescence data [nickel thickness versus ratio of K_{α} (nickel) to L_{α} (uranium)]. An example of typical thickness calibration data is given in Figure 3.

Forty keV gamma rays from the 500-millicurie gadolinium-153 source were collimated to obtain an effective 0.35-inch-diameter beam spot. The detector-to-coating distance was maintained at approximately two inches. However, the ratio of coating-to-substrate

Figure 3. COATING THICKNESS AS A FUNCTION OF THE RATIO OF NICKEL (COATING) K_{α} FLUORESCENCE TO URANIUM (SUBSTRATE) L_{α} FLUORESCENCE.

fluorescence is independent of the source intensity and, to some extent, is independent of the source and detector geometry; therefore, the detector-to-coating distance could vary by as much as ± 0.2 inch without noticeable error other than that due to statistics of counting. Resolution of the silicon (Li) detector was of the order of 200 ev at 5.9 kev, and all data were taken in 100-second (live time) counting intervals.

X-ray fluorescence thickness measurements were made on five nickel-plated uranium coupons. The coupons were then sectioned for destructive analysis. Employing a metallographic imaging method, plating thickness measurements were made at two-mil intervals along a one-inch cross section of each coupon. Results of the fluorescence and metallographic measurements are reported in Table 1. Nickel-plating thicknesses, as determined by the fluorescence technique, are biased (on the average) about 70 microinches below the average thicknesses measured by the metallographic process. However, the plating thickness, as measured by the metallographic imaging method, varied (across the coupon) by as much as ± 100 microinches from the average thickness given in Table 1. This variation in thickness is due to the diffusion of nickel into the uranium substrate, thus causing a "hill and valley" effect across the coupon.

A six-inch-diameter uranium cylinder was machined to a 0.1-inch wall thickness and an 8-inch length. The outer surface of the cylinder was then electroplated with nickel where the plating thickness was specified to be 1 ± 0.2 mil. Using the X-ray fluorescence technique, the thickness of electroplated nickel was measured every 90 degrees circumferentially at one-inch intervals along the length of the cylinder. To determine the reproducibility of the fluorescence method, a second set of thickness measurements were made at the same locations on the cylinder. The results of these two separate sets of plating thickness measurements are given in Table 2. The average difference for the two sets of measurements is 14 microinches; the largest difference is 33 microinches.

Table 1
COMPARISON OF X-RAY FLUORESCENCE AND
METALLOGRAPHIC THICKNESS MEASUREMENTS
ON NICKEL-PLATED COUPONS

Coupon Number	X-Ray Fluorescence Plating Thickness (μin)	Metallographic Average Plating Thickness (μin)	Difference (μin)
1	260	340	-80
2	455	460	- 5
3	571	660	-89
4	713	780	-67
5	903	1000	-97

Table 2
X-RAY FLUORESCENCE PLATING THICKNESS MEASUREMENTS ON
A NICKEL-PLATED URANIUM CYLINDER

Distance from End of Cylinder (inch)	Circumferential Position (degrees)	Plating Thickness		Difference (μin)
		Trial 1 (μin)	Trial 2 (μin)	
0.5	0	804	782	22
	90	813	796	17
	180	799	793	6
	270	782	785	3
1.5	0	1025	1001	24
	90	1030	1011	19
	180	994	986	8
	270	1010	998	12
2.5	0	986	960	26
	90	988	950	30
	180	981	964	17
	270	986	979	7
3.5	0	960	967	7
	90	975	953	22
	180	960	953	7
	270	966	962	4
4.5	0	910	885	25
	90	913	912	1
	180	922	899	23
	270	926	915	11
5.5	0	902	894	8
	90	896	873	23
	180	898	902	4
	270	887	883	4
6.5	0	830	810	11
	90	833	800	33
	180	807	799	8
	270	820	807	13
7.5	0	817	814	3
	90	804	780	24
	180	826	795	31
	270	811	805	6

CONCLUSIONS AND RECOMMENDATIONS

Use of a monochromatic isotopic source rather than a polychromatic X-ray beam may appear to be quite limited in the energy range of fluorescence excitation; however, the 40-kev gammas from a collimated Gd-153 source provided adequate generation of the K_{α} of iron at 6.4 kev and K_{α} of nickel at 7.5 kev, where the respective count rates exceeded 10,000 counts per minute. The X-ray fluorescence system described here is portable and, therefore, amenable to on-site inspections. If the ratio of coating-to-substrate fluorescence is used, then sample geometry and positioning are not as critical for making reliable coating thickness measurements. Metal foils are available with a purity of 99.95 percent and a thickness uniformity of 2.5 percent of the nominal thickness; and, in general, metal foils are more reliable than plated standards for determining mass per unit area. Precision of the X-ray fluorescence technique is very good, and the accuracy of the technique depends mainly upon the quality of the standards and density uniformity of the coating for a linear thickness measurement. With the aid of the quantitative macroscopic theory, theoretical calculations can be made to determine the practical thickness range and measurement feasibility for a particular coating and substrate combination.

REFERENCES

- (1) Ogburn, F. and Smit, J.; "Fluorescent X-Ray Methods for the Measurement of Coating Thickness", *Plating*; February 1973.
- (2) Storm, E. and Israel, H.I.; *Photon Cross Sections from 0.001 to 100 Mev for Elements 1 through 100*, LA-3753; Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico; November 1967.

APPENDIX

FLUORESCENT RADIATION FROM DIFFERENT MEDIA

Fluorescent Radiation from a Single Medium

In Figure A-1, monochromatic radiation from an isotopic source impinges on a medium of thickness, t , to produce fluorescent radiation. Intensity of the source radiation at a distance, z , in the medium is given by:

$$I(z) = I_0 e^{-\mu_{I_0} \rho z} , \quad (A-1)$$

where:

I_0 represents the initial intensity of the source radiation,

ρ the density (gms/cm³) of the medium, and

μ_{I_0} the total mass attenuation coefficient (cm²/gm) for the medium at the energy of the source radiation.

Intensity of the fluorescent radiation produced in the element, dz , by the source radiation is:

$$I_F(z) = (G_{I_0} \rho dz) I(z) , \quad (A-2)$$

where:

$$G_{I_0} = \mu_{PI_0} Y , \text{ and} \quad (A-3)$$

μ_{PI_0} represents the total photoelectric mass attenuation coefficient (cm²/gm) for the medium at the energy of the source radiation, and

Y the fluorescence yield of the medium for the particular type (K or L) of fluorescent radiation.

Therefore, the intensity of fluorescent radiation seen by the detector after attenuation by the medium thickness, z , is:

$$I_D(z) \propto I_F(z) e^{-\mu_F \rho z} , \quad (A-4)$$

where μ_F represents the total mass attenuation coefficient (cm²/gm) for the medium at the energy of the fluorescent radiation. Integrating Equation A-4 over the total thickness, t , of the medium gives:

$$I_D \propto G_{I_0} \rho I_0 \int_0^t e^{-(\mu_{I_0} + \mu_F) \rho z} dz , \text{ or} \quad (A-5)$$

$$I_D \propto \frac{G_{I_0} I_0}{\mu_{I_0} + \mu_F} \left[1 - e^{-(\mu_{I_0} + \mu_F) \rho t} \right] \quad (A-6)$$

If the medium is of infinite thickness, Equation A-6 becomes:

$$I_D \propto \frac{G_{I_0} I_0}{\mu_{I_0} + \mu_F} \quad (A-7)$$

Fluorescent Radiation from a Two-Layer Medium (Z of the coating $>$ Z of the substrate)

In Figure A-2 monochromatic radiation from an isotopic source impinges on a two-layer medium to produce fluorescent radiation in both the coating and substrate materials. From Equation A-6, intensity of the fluorescent radiation (as seen by the detector) from the coating material is:

$$I_{D(c)} \propto \frac{G_{I_0(c)} I_0}{\mu_{I_0(c)} + \mu_{F_c(c)}} \left\{ 1 - e^{-[\mu_{I_0(c)} + \mu_{F_c(c)}] \rho(c) t} \right\} \quad (A-8)$$

The initial source radiation, I_0 , is attenuated in the coating material before reaching the substrate to produce the substrate fluorescent radiation. Also, the substrate fluorescent radiation is attenuated in the coating material before reaching the detector. Using Equation A-7 for the case of a medium having infinite thickness and correcting for the attenuation of the source radiation and substrate fluorescent radiation in the coating material, the intensity of the fluorescent radiation (as seen by the detector) from the substrate material is:

$$I_{D(s)} \propto \left[\frac{G_{I_0(s)} I_0}{\mu_{I_0(s)} + \mu_{F_s(s)}} e^{-\mu_{I_0(c)} \rho(c) t} \right] e^{-\mu_{F_s(c)} \rho(c) t} \quad (A-9)$$

Therefore:

$$\frac{I_{D(c)}}{I_{D(s)}} \cong \frac{G_{I_0(c)} [\mu_{I_0(s)} + \mu_{F_s(s)}] \left\{ 1 - e^{-[\mu_{I_0(c)} + \mu_{F_c(c)}] \rho(c) t} \right\}}{G_{I_0(s)} [\mu_{I_0(c)} + \mu_{F_c(c)}] e^{-[\mu_{I_0(c)} + \mu_{F_s(c)}] \rho(c) t}} \quad (A-10)$$

Fluorescent Radiation from a Two-Layer Medium (Z of the substrate $> Z$ of the coating)

If the atomic number, Z , of the substrate is higher than the atomic number of the coating, the substrate fluorescent radiation can produce additional fluorescent radiation in the coating providing the energy of the substrate fluorescent radiation is above the K or L absorption edge of the coating material. Using Equation A-7, the fluorescent radiation from the infinite substrate becomes an additional source, I_s , capable of producing fluorescent radiation in the coating, where:

$$I_s \propto \frac{G_{I_0}(s) I_0 e^{-\mu_{I_0}(c) \rho(c) t}}{\mu_{I_0}(s) + \mu_{F_s}(s)} \quad (A-11)$$

In Figure A-3, intensity of the coating fluorescent radiation (as seen by the detector) produced in an element, dz , in the coating by the substrate source radiation, I_s , is given by:

$$I'_D(z) \propto I_s e^{-\mu_{F_s}(c) \rho(c) z} [G_{F_s}(c) \rho(c) dz] e^{-\mu_{F_c}(c) \rho(c) (t-z)} \quad (A-12)$$

where:

$$G_{F_s}(c) = \mu_{PF_s}(c) Y(c) \quad (A-13)$$

Here, $\mu_{PF_s}(c)$ is the total photoelectric mass attenuation coefficient (cm^2/gm) for the coating at the energy of the fluorescent radiation from the substrate, and $Y(c)$ is the fluorescence yield of the coating for the particular type (K or L) of fluorescent radiation produced in the coating. Therefore:

$$I'_D(c) \propto I_s G_{F_s}(c) \rho(c) e^{-\mu_{F_c}(c) \rho(c) t} \int_0^t e^{-[\mu_{F_s}(c) - \mu_{F_c}(c)] \rho(c) z} dz, \quad (A-14)$$

or

$$I'_D(c) \propto \frac{G_{I_0}(s) G_{F_s}(c) I_0 e^{-[\mu_{I_0}(c) + \mu_{F_c}(c)] \rho(c) t} \left\{ 1 - e^{-[\mu_{F_s}(c) - \mu_{F_c}(c)] \rho(c) t} \right\}}{[\mu_{I_0}(s) + \mu_{F_s}(s)] [\mu_{F_s}(c) - \mu_{F_c}(c)]} \quad (A-15)$$

Equation A-10 for the ratio of the intensities of the coating and substrate fluorescent radiation now becomes:

$$\frac{I_D(c)}{I_D(s)} \rightarrow \frac{I_D(c) + I'_D(c)}{I_D(s)} \quad (A-16)$$

Figure A-1. MONOCHROMATIC RADIATION FROM AN ISOTOPIC SOURCE IMPINGING ON MATERIAL OF THICKNESS, t , TO PRODUCE FLUORESCENT RADIATION.

Figure A-2. MONOCHROMATIC RADIATION FROM AN ISOTOPIC SOURCE IMPINGING ON A TWO-LAYER MEDIUM THAT CONSISTS OF A COATING MATERIAL OF THICKNESS, t , AND A SUBSTRATE MATERIAL OF INFINITE THICKNESS.

Figure A-3. FLUORESCENT RADIATION FROM AN INFINITE SUBSTRATE PRODUCES ADDITIONAL FLUORESCENT RADIATION IN THE COATING MATERIAL OF THICKNESS, t .

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