EDDY-CURRENT EVALUATION OF NUCLEAR CONTROL RODS^a

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ABSTRACT

An eddy-current technique was developed and performed to detect cracks and measure thickness of cladding and oxide thickness on new and used nuclear control rods for the High Flux Isotope Reactor at the Oak Ridge National Laboratory. A computer design was performed for coils to maximize sensitivity to surface cracks and cladding thickness variations and minimize effects due to lift-off and temperature variations. In spite of radiation levels measured to be 10^5 R/h at 1 ft from the surface and temperature variations of 5°C on used control rods, flaws as small as 0.001 in. were detected and the cladding thickness was measured to within 0.001 in.

INTRODUCTION

The High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory (ORNL), as its name implies, is used to produce transplutonic isotopes by subjecting the heavier elements (e.g., plutonium) to very intense neutron radiation. This reactor is immersed in water and controlled by two concentric, cylindrical control "rods". This paper describes a method for the inspection of these rods. The control rods, shown in Fig. 1, are clad with aluminum and are approximately 18 in.

^aResearch sponsored by the U.S. Atomic Energy Commission under contract with Union Carbide Corporation.

Fig. 1. Control Cylinders for the High Flux Isotope Reactor.

in diameter, 66 in. long, and 1/4 in. thick. They are divided axially into regions having three different neutron absorption characteristics. The aluminum regions on the ends of the rod are virtually transparent to neutrons. One of the two central regions contains a dispersion of tantalum in aluminum, which is "gray" to thermal neutrons (moderate absorption), and the other region contains a dispersion of Eu_2O_3 in aluminum, which is "black" to neutrons (high absorption). These rods were originally designed to have a service life of one year, which would be limited by the decrease in nuclear worth (relative ability to absorb neutrons) of the control rod (caused by the decrease in the cross section of the europium). However, a destructive analysis revealed that the rods experience little decrease in nuclear worth for several years of operation, and the lifetime of the rods is actually limited by irradiation damage to the aluminum. The results of this damage are most likely to appear as surface cracks in the aluminum cladding over the tantalum region of the inner control rod (the region of highest neutron flux and temperature during operation). The cracks are not detrimental to the operation of the rod until they penetrate the cladding over the Eu_2O_3 region and allow water to reach the Eu_2O_3 . The resulting water-oxide reaction will soon destroy the control rod, contaminate the reactor coolant system with europium, and shut the reactor down. Since the control rods cost approximately \$60,000, and the old control rods must be carefully buried as radioactive waste, there is a great economic and ecological incentive to extend the life of these rods as long as practical, without risking a reactor shutdown.

Three eddy-current tests were developed, the first to detect flaws that extend to depths of 0.001 in. or greater and the second to measure

the thickness of cladding in the Eu_2O_3 section. Third, a measurement is made of an oxide film that forms 0.003 to 0.005 in. thick over the tantalum section. A 0.005-in.-thick film causes the control rod temperature to increase to nearly 150°C , accelerating the growth of oxide and causing excessive increases in temperature. To assure reasonable working temperatures on the rod, the oxide film thickness is measured at the same time as the scan for flaws.

This inspection was designed around the ORNL-developed modular phase-sensitive eddy-current instrument because of its good stability and high sensitivity. Because of the intense gamma radiation level of 10^5 R/h at 1 ft, the inspection of used control rods had to be performed with the rod and inspection probes under 15 ft of water. This in turn required the leads from the instrument to the probe to be approximately 25 ft long. Also, a special radiation-resistant insulation consisting of a polyimide resin was used on the wire in the coils. A computer analysis was performed to determine the optimum operating parameters for both the detection of discontinuities and the measurement of cladding thickness.

DETECTION OF FLAWS

The problem of flaw detection was solved before the problem of measuring cladding thickness. An eddy-current probe was first designed by computer techniques. Then the probe was constructed, tested on electroetched flaws, and finally used to inspect an irradiated control rod.

Analysis of Flaw Problem

The mathematical model for analysis of the problem represented a reflection-type coil above a clad conductor, as is shown in Fig. 2. The cladding material is aluminum alloy 6061; the base material can be a tantalum dispersion or aluminum. The base material has no effect on the problem at the operating frequencies required for good flaw detection. This problem was analyzed using the equations and programs contained in another report.¹ The first analysis was for the mutual coupling of the coil above a conductor with spherical flaws. The coil is assumed to have an infinite impedance in the driving and pickup circuits. Spherical flaws are used since they can be analyzed to a higher degree of accuracy than cracklike discontinuities. A system optimized to detect spherical flaws will also be quite sensitive to cracklike discontinuities. The phase shift of the eddy-current signal in radians for spherical flaws with three different diameters is plotted against the dimensionless parameter $\omega\mu\sigma_1\bar{r}^2$ in Fig. 3, where ω is the angular frequency, μ is the magnetic permeability, σ_1 is the electrical conductivity of the cladding material, and $\bar{r}$ is the mean radius of the driver coil. The flaws are assumed to be 0.0015 in. beneath the surface and are varied in size from 0.001 to 0.003 in. in diameter. For each of these flaws there is a maximum phase shift for a given value of $\omega\mu\sigma_1\bar{r}^2$, and this maximum occurs at the same value of $\omega\mu\sigma_1\bar{r}^2$ for all three flaws. An operating frequency of 2 MHz and a coil mean radius of 0.020 in. were chosen as an optimum compromise. A smaller coil would have had a greater sensitivity to discontinuities, but would have required a higher operating frequency, been more sensitive to lift-off variations, required a

Fig. 2. Reflection-Type Coil Above a Section of a Control Rod of the High Flux Isotope Reactor.

longer scanning time, and been much harder to construct. Because of the 25-ft length of cable required for inspecting the irradiated rods, 2 MHz was the practical limit for the operating frequency. For 2 MHz and a 0.020 in. (mean radius) coil, the value of $\omega\mu\sigma_1\bar{r}^2$ is approximately 100.

The lift-off, or coil-to-conductor spacing, was varied in the calculations from 0.003 to 0.005 in. for various values of $\omega\mu\sigma_1\bar{r}^2$, and the phase shift due to the variation in lift-off is also plotted as a function of $\omega\mu\sigma_1\bar{r}^2$. We can see from Fig. 3 that the phase shift induced by lift-off is equivalent to a 0.0015-in. flaw at the optimum operating value of $\omega\mu\sigma_1\bar{r}^2$. This curve provides a close approximation to the optimum operating conditions and sensitivity that can be achieved. However, for complete design we must also add the external circuit as shown in Fig. 4 and calculate the optimum values of the circuit and coil parameters.

Table I gives the parameters of the coil and the external circuit as determined by computer calculations.

The addition of the external circuit has had the effect of decreasing the phase shift due to the flaw and increasing the phase shift due to lift-off variations. The large shunt capacitance (due to the long cables) in the driving and pickup circuits has caused most of these effects. The phase shift due to lift-off is now larger than that produced by a 0.003-in.-diam spherical discontinuity and about equal to that produced by a 0.001-in.-deep cracklike flaw. However, in practical examinations, discrimination between signals due to lift-off or flaws is simplified since a flaw produces a very rapid shift in the base line, but lift-off produces a slow variation in the base line.

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Fig. 3. Phase Shift Plotted Against $\omega\mu\sigma_1\bar{r}^2$ for Various Size Flaws and for Lift-off.

- V_0 DRIVING VOLTAGE
- R_0 SERIES RESISTANCE IN THE DRIVING CIRCUIT
- C_6 SHUNT CAPACITANCE OF THE DRIVING CIRCUIT
- R_6 D.C. RESISTANCE OF THE DRIVER COIL
- Z_D IMPEDANCE OF THE DRIVER COIL
- M MUTUAL IMPEDANCE BETWEEN THE DRIVER AND PICK-UP COILS
- Z_{PU} IMPEDANCE OF THE PICK-UP COILS
- R_7 D.C. RESISTANCE OF THE PICK-UP COILS
- C_7 SHUNT CAPACITANCE OF THE PICK-UP CIRCUIT
- R_9 AMPLIFIER INPUT IMPEDANCE

Fig. 4. Simplified Circuit Diagram for an Eddy-Current Reflection-

Type Probe.

Table I. Calculated Coil and Circuit Parameters for
Flaw Detection on HFIR Control Rods

Driver coil, in.

0.030 ID, 0.050 OD, 0.018 long, wound with 45 turns of No. 46 wire

Pickup coils (two required), in.

0.014 ID, 0.028 OD, 0.006 long, wound with 65 turns each of

No. 54 wire

Driving circuit series resistance, Ω	82.5
Driving circuit shunt capacitance, pF	300
Pickup circuit shunt resistance, Ω	133
Pickup circuit shunt capacitance, pF	300
Operating frequency, MHz	2
Resistivity of cladding material, $\mu\Omega\text{-cm}$	3.632
Phase shift due to a 0.003-in.-diam flaw, °	0.023
Phase shift due to a 0.0032-in. lift-off variation, °	0.15

The phase shifts caused by variations in a number of parameters were also calculated. The instrument is calibrated, and then the parameter varied, and the phase shift produced without recalibration is recorded as the "drift." These values are shown in Table II.

All the parameters are varied 1%, and the drift in degrees is quite linear over this range. The resistance of the driver and pickup coils may vary more than 1% because of the gamma heating of the copper wire in the coils. The remainder of the parameters will vary less than 0.05% and are not significant. Also, these drifts cause only a slow shift in the base line and are not likely to be confused with the rapid shifts in the base line produced by discontinuities. The test probe was built using the above coil and circuit parameters. The intense gamma radiation was expected to change the resistance of the coils and break down the insulation on the wire in the coils, causing turn-to-turn shorting. This was overcome, however, by using a special polyimide resin for insulation on the wire. Irradiation tests on typical coils in an intense gamma radiation field to an accumulated dose of approximately 10^7 rads indicated no significant coil degradation and an expected life of at least 3 days in the anticipated radiation field. The probe was then tested on a section of a control cylinder containing electroetched notches of various known depths. Figure 5 is a plot of phase shift versus notch depths. As we can see from the figure, the phase shift produced by a 0.001-in.-deep cracklike flaw with a length exceeding the coil diameter is much larger than the phase shift produced by a spherical flaw 0.003 in. in diameter.

Table II. System Drifts for Flaw Detection of HFIR Control Rod
for a 1% Parameter Variation

Parameter Varied	Drift (°)
Driver coil resistance	-0.023
Pickup coil resistance	-0.029
Driving circuit series resistance	0.143
Driving circuit shunt capacitance	-0.042
Pickup circuit shunt resistance	0.087
Pickup circuit shunt capacitance	-0.092
Applied voltage	-0.069
Frequency	-0.068
Mean radius	-0.068

Fig. 5. Phase Shift Versus Notch Depth.

While the phase of the signal was used to detect flaws, the magnitude of the signal was used to measure the lift-off. (This can be related to the thickness of the nonconducting oxide film.) The variation in magnitude with lift-off was calibrated against a set of nonconductive shims. In the actual scanning for discontinuities, the signals for both the magnitude and phase were recorded on a two-channel recorder, giving information about both flaws and lift-off (or oxide coating). The accuracy of the lift-off measurements was 0.0002 in.

Scanning of Rods for Flaws

A scanning mechanism was constructed to grip the cylinder at one end for rotation and simultaneously translate the probe along the cylinder, as shown in Fig. 6. This action produced a helical scan with a pitch of 0.050 in. for each revolution. A set of rollers supports the weight of the cylinder and allows it to turn freely. The probe support is held against the cylinder by gravity and rides along on a set of rollers. The mechanism can be operated above the shielding water for calibration scans using an unirradiated control rod containing electroetched notches and then lowered into the pool for examination of radioactive specimens.

Both used and new control rods were inspected, and the data for both calibration and inspection were recorded on a strip chart recorder. The first inspection was made only over the tantalum section and a small part of the europium oxide region of a unit that had been in use for 650 days. Figure 7 shows a plot of the density of flaws along the scanned region. As expected, there is a greater density of large

Fig. 6. Mechanism for Scanning the Control Rods.

Fig. 7. Flaw Density Along the Control Rod.

discontinuities over the tantalum section. However, there was a greater density of small flaws over the europium oxide region, and this density did not decrease as expected with distance away from the tantalum-europium oxide interface. Since there was no similar examination performed on the unit before service, it was impossible to determine whether the flaws were preexistent or resulted from service. Therefore, we decided to scan as much of the control rod as possible (40 in.) and perform a "base-line" flaw scan on all new control rods. Further, since the important parameter is the thickness of the residual cladding under the discontinuities in the europium section, it was determined that techniques should be developed to measure the thickness of cladding over the area containing europium oxide. With this information, one can monitor (by scans at intervals) the growth of cracks and tell when they are close to penetrating the aluminum cladding in the europium oxide region. Scans of new control cylinders made thus far show a lower flaw density, indicating the possibility that some of the flaws in the used rod may be due to irradiation damage.

MEASUREMENT OF CLADDING THICKNESS

After it had been determined that cracklike flaws of 0.001 in. and greater could be detected in the irradiated control cylinders and discontinuities were detected in the europium oxide region, a program to measure the cladding thickness was initiated to aid in the determination of the significance of the discontinuities. An eddy-current reflection-type probe was first designed by computer techniques. The probe was then constructed and measurements were made on calibration

standards whose thickness was verified by metallography. Finally, scans were made on actual control rods.

Analysis of Cladding Thickness Measurement Problem

The mathematical model for measurement of clad thickness again assumed the reflection-type coil above a clad conductor, as shown in Fig. 2. The cladding material is 6061 aluminum alloy with a resistivity of $3.632 \mu\Omega\text{-cm}$, and the base material is europium oxide-aluminum dispersion having a resistivity of $5.393 \mu\Omega\text{-cm}$. In this case the resistivity of the base material is important to the calculation and subsequent inspection. The optimum operating parameters were reported previously² and are summarized in Fig. 8 (σ_1 and σ_2 are the conductivities of the cladding and base materials, respectively). From the curves in Fig. 8, we first determine that the optimum value of thickness/ $\bar{r}$ is 0.3 for a ratio of σ_1/σ_2 of 1.5. For a nominal cladding thickness of 0.028 in., this gives a coil mean radius, $\bar{r}$, of 0.093 in., and we choose a 0.08325-in. coil since it is one that we have established as standard. The optimum value of $\omega\mu\sigma_1\bar{r}^2$ is 9 for a σ_1/σ_2 ratio of 1.5. Since μ , σ_1 , and $\bar{r}$ are known, we can determine the optimum frequency as 9.25 kHz, and we choose 10 kHz since it is readily available in the instrument. Finally we see that if we use optimum $\bar{r}$ and $\omega\mu\sigma_1\bar{r}^2$ values, we should get a change in phase of 0.0075 rad or 0.43° for a variation of 10% in cladding thickness.

After using Fig. 8 for the preliminary design, as discussed for flaw detection, the design is completed by adding the external circuit and calculating the optimum values of the circuit and coil parameters.

Fig. 8. Optimum Values of the Parameters Cladding Thickness/ $\bar{r}$

and $\omega\mu\sigma, \bar{r}^2$ for Maximum Sensitivity and the Phase Shift at Maximum Sensitivity due to a 10% Change in Cladding Thickness, Plotted Against the Ratio of Cladding to Base Material Conductivity.

Table III summarizes the parameters of the coil and the external circuit as determined by computer calculations.

Calculations were also made of the relative effect (phase shift) of a variation in any given parameter. These are shown in Table IV. Primarily by the use of a lower frequency, the drifts could be reduced more here than in the defect problem. The drifts due to variations in the resistance of the driver and pickup coils were greatly reduced by proper matching of the resistance and capacitance in the driving and pickup circuits. The only parameter variations expected to cause drifts greater than 0.01° are the resistivities of the cladding and base materials.

Calibration of Thickness Measurements

The test probe was built and tested with the above circuit parameters. The calibration proceeded as follows:

1. A series of phase measurements was made on a number of clad samples. After the phase measurements some of the samples were sectioned, and metallographic measurements were made on the cladding thickness.
2. A curve of phase shift versus cladding thickness was determined by computer calculations.
3. A correction was made on all phase measurements that gave a least-squares fit to the calculated curve.

This general statistical technique takes advantage of the fact that a functional relation between cladding thickness and phase shift is known and gives a more accurate measurement than trying to fit any arbitrary curve to the experimental data. For both the calculations

Table III. Calculated Coil and Circuit Parameters for Measurements of Cladding Thickness on HFIR Control Rods

Driver coil, in.	
0.125 ID, 0.208 OD, 0.030 long, wound with 360 turns of No. 46 wire	
Pickup coil, in.	
0.060 ID, 0.116 OD, 0.008 long, each wound with 410 turns of	
No. 54 wire	
Driving circuit series resistance, Ω	500
Driving circuit shunt capacitance, μF	0.0047
Pickup circuit shunt resistance, Ω	620
Pickup circuit shunt capacitance, μF	0.0047
Operating frequency, kHz	10
Resistivity of cladding material, $\mu\Omega\text{-cm}$	3.632
Resistivity of base material, $\mu\Omega\text{-cm}$	5.393
Phase shift due to a 10% thickness	
change, $^{\circ}$	0.38
Phase shift due to 0.008 in. lift-off	
change, $^{\circ}$	0.008

Table IV. System Drift Variations for a 1% Parameter Variation
(for Cladding Thickness in a HFIR Control Rod)

Parameter Varied	Drift (°)
Driver coil resistance	-0.001
Pickup coil resistance	-0.004
Driving circuit series resistance	0.063
Driving circuit shunt capacitance	-0.013
Pickup circuit shunt resistance	-0.034
Pickup circuit shunt capacitance	-0.048
Applied voltage	-0.43
Frequency	-0.340
Mean coil radius	-0.426
Cladding resistivity	0.149
Base resistivity	0.047

and the measurements, a phase shift of zero corresponds to a sample with infinite cladding thickness, and all phase shifts represent the difference between the phase for infinite cladding and the phase for any finite cladding. As we will see later, this significantly reduces the effects on the measurements of resistivity variations in the cladding material.

From the computer calculation we determined a functional relationship between the calculated phase and thickness:

$$T = f(X) ,$$

where X is the calculated phase, T is the calculated thickness and f is the functional relationship. This relationship can be a plotted curve or any complicated nonlinear function. In the actual problem we used the function

$$T = \sum_{i=1}^7 C_i (\log 3/X)^{i-1} ,$$

where the constant coefficients, C_i , were determined by calculating X for seven different T values and then solving the seven equations for the seven unknown coefficients.

We then made j experimental measurements of phase and thickness, designated P_j and T_j , and made calculations of the phase, designated X_j , for each value of T_j . Next we made a base line and gain correction to give the minimum standard deviation, using the relationship

$$X_i = b_1(P_i + b_0) ,$$

where b_0 is the base line correction and b_1 is the gain correction:

$$b_0 = -P(\text{infinite cladding}); b_1 = \frac{\sum_{j=1}^n P_j X_j + n b_0 \bar{X}}{\sum_{j=1}^n (P_j + b_0)^2}.$$

The data used to determine the correction factors are given in Table 5.

For the correction factors we may calculate:

$$b_0 = -0.01; b_1 = 0.9925.$$

Figure 9 shows a plot of the calculated phase, X_c , versus thickness, with the corrected measured points shown on the plot. The sensitivity at nominal cladding thickness is $1^\circ/0.0075$ in.

If both the calculations and the measurements could be made with absolutely no error, then the factors b_0 and b_1 would be 0 and 1, respectively. The fact that the correction factors are almost their ideal values shows how accurate both the calculations and measurements are. The individual cladding thickness readings varied considerably because of the roughness of the interface between the cladding and base regions. In fact, the average variation between the maximum and minimum readings was 0.0035 in., or approximately 10% of the cladding thickness. However, by using these statistical methods we can generate a calibration curve that has a standard deviation equivalent to 0.00015 in. Since the shape of the curve was already known, fewer metallographic samples were needed to establish confidence in the measurements.

The used control rods varied in temperature because of gamma self-heating, and this caused changes in the resistivity of the cladding

Table V. Summary of Measured and Calculated Results

T (measured) (in.)	Standard Deviation (in.)	Values (°)			
		P_i (measured)	Standard Deviation	X_i (calculated)	$X_i - b_1(P_i + b_0)$
250×10^{-3}	0.1×10^{-3}	0.010	0.007	0	0
29.9	0.19	1.528	0.007	1.540	0.033
26.1	0.33	2.095	0.007	2.067	-0.002
19.0	0.24	3.367	0.003	3.352	-0.014

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Fig. 9. Calculated Values of Phase Shift for Different Values of 6061 Aluminum Alloy Cladding Thickness.

and the base materials. The calculated phase shift due to a 1% resistivity increase in both the cladding and base materials is approximately $\pm 0.196^\circ$. Using a temperature coefficient for resistivity of $+0.35\%/^\circ\text{C}$, the calculated phase shift caused by temperature variation was $0.069^\circ/\text{C}$. The measured phase shift caused by variation in temperature for cladding with thicknesses of infinity, 0.0299 in., and 0.019 in. was 0.055, 0.066, and $0.070^\circ/\text{C}$, respectively. However, in our manner of calibration we use the infinite cladding as the base line, and thus the drifts in base line data tend to track the drifts for the cladding. The differential drift between the infinite cladding and the nominal cladding is $0.011^\circ/\text{C}$. Since the infinite cladding material was adjacent to the finite cladding material, they were at approximately the same temperature, and errors in measurement of cladding thickness caused by variations in temperature were estimated to be less than 0.0004 in.

Scanning of Rods for Cladding Thickness

The scanning mechanism was the same used for the flaw scan. The scans were also made similarly, except that only the region containing europium-oxide was scanned. The measured thickness of cladding on actual control cylinders varied from 0.0255 to 0.0345 in. There has been no indication to date that the cladding thickness decreases significantly with irradiation.

SUMMARY AND CONCLUSIONS

Accurate eddy-current inspection techniques were developed to allow interim monitoring of the growth of flaws (0.001 in. deep or greater) in the HFIR control rods and allow measuring the cladding

thickness of a section of these rods to within approximately 0.001 in. In addition the thickness of the oxide film was measured to within 0.0002 in. Computer-aided design of these techniques resulted in more accurate inspections at a lower cost and increased the confidence in the measurements. The effects of radiation (minimized by computer design) on these tests was very small, particularly considering the high level of the radiation.

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