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Eddy-Current Inspection of High Flux Isotope Reactor Nuclear Control Rods

J. H. Smith
L. D. Chitwood

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J. H. Smith and L. D. Chitwood

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J. H. Smith and L. D. Chitwood

ABSTRACT

Inner control rods for the High Flux Isotope Reactor were nondestructively inspected for defects by eddy-current techniques. During these examinations aluminum cladding thickness and oxide thickness on the cladding were also measured. Special application techniques were required because of the high-radiation levels (~10^5 R/h at 30 cm) present and the relatively large temperature gradients that occurred on the surface of the control rods. The techniques used to perform the eddy-current inspections and the methods used to reduce the associated data are described. This report therefore documents completed work and provides a procedural guide for future inspections.

INTRODUCTION

The High Flux Isotope Reactor (HFIR) located at Oak Ridge National Laboratory (ORNL) is controlled by two concentric, cylindrical control "rods" that are about 168 cm long, 45 cm in diameter, and 0.6 cm thick (Fig. 1). The inner control rods can be divided into four zones along the axis, each having different neutron absorption characteristics. The ends of the control rods are aluminum, which is virtually transparent to neutrons. One of the two central zones contains a dispersion of tantalum in aluminum (a moderate neutron absorber), and the other contains a dispersion of europium oxide (Eu_2O_3) in aluminum (a high neutron absorber). The entire surface of the control rod is clad with a thin layer of aluminum. The primary purpose of the aluminum cladding is to prevent the Eu_2O_3 from contacting the coolant water and resulting in a relatively violent chemical reaction. This reaction could not only ruin the control rod but could contaminate the reactor cooling system with europium.

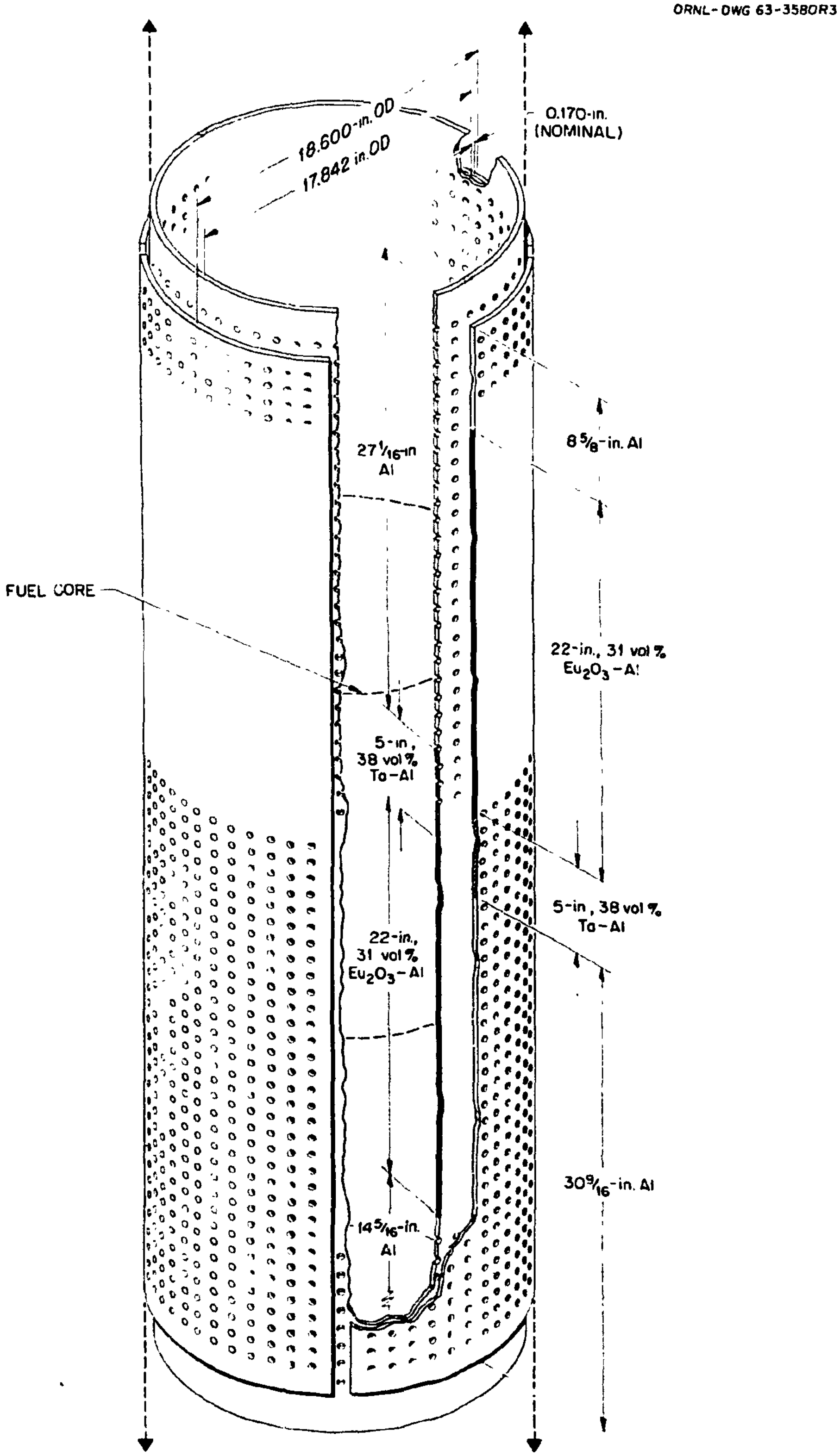

Fig. 1. Control cylinders for High Flux Isotope Reactor.

When these control rods were originally designed, they were expected to have an operational life of about one year, but experience has shown that this predicted life expectancy was conservative. Because the control rods are expensive and spent control rods must be carefully buried as radioactive waste, there are great economic and ecological incentives to use them as long as practical. The eddy-current inspection techniques described in this report were therefore developed to provide a quality assurance measure for evaluating the condition of the control rods so as to extend their operational life as long as possible without adding undue risks to the safety of the operation of the reactor. These eddy-current methods were developed by the Nondestructive Testing Group in the Metals and Ceramics Division at ORNL.[1]

Two major sources of possible damage to the control rods are (1) physical damage such as gouges and dents from handling during transportation and installation, and (2) irradiation damage from the intense operational environment of both high-gamma and neutron radiation at elevated temperatures. Results from this type of 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 density and temperature during operation). Cracks of this type would not be detrimental to operating the rod unless they penetrated the cladding over the Eu_2O_3 and allowed water to reach it. Another factor that can indirectly cause damage to the control rod is the buildup of an oxide film, which can cause high-temperature gradients, especially over the tantalum section; for example, a 0.025-mm-thick film can cause a temperature increase of as much as 17°C (30°F).

This eddy-current evaluation of these control rods consisted of two independent inspections that measured three parameters. The areas containing the tantalum and Eu_2O_3 dispersions were scanned for cracks, and the thickness of the oxide film buildup was measured simultaneously. A separate, independent examination was required to measure the thickness of the aluminum cladding over the area containing Eu_2O_3.

The HFIR control rod inspections were far from routine. In addition to the temperature gradients that existed, a used control rod can emit radiation at levels up to 10^5 R/h at 30 cm. Because of this high radiation field, the actual inspections of used control rods were performed in the reactor pool (Fig. 2) with the control rod scanning fixture and eddy-current probe located about 5 m below the surface of the water. The characteristic glow around the cylinders is Cerenkov radiation. This report describes how these tests were performed and provides guidelines for future inspections.

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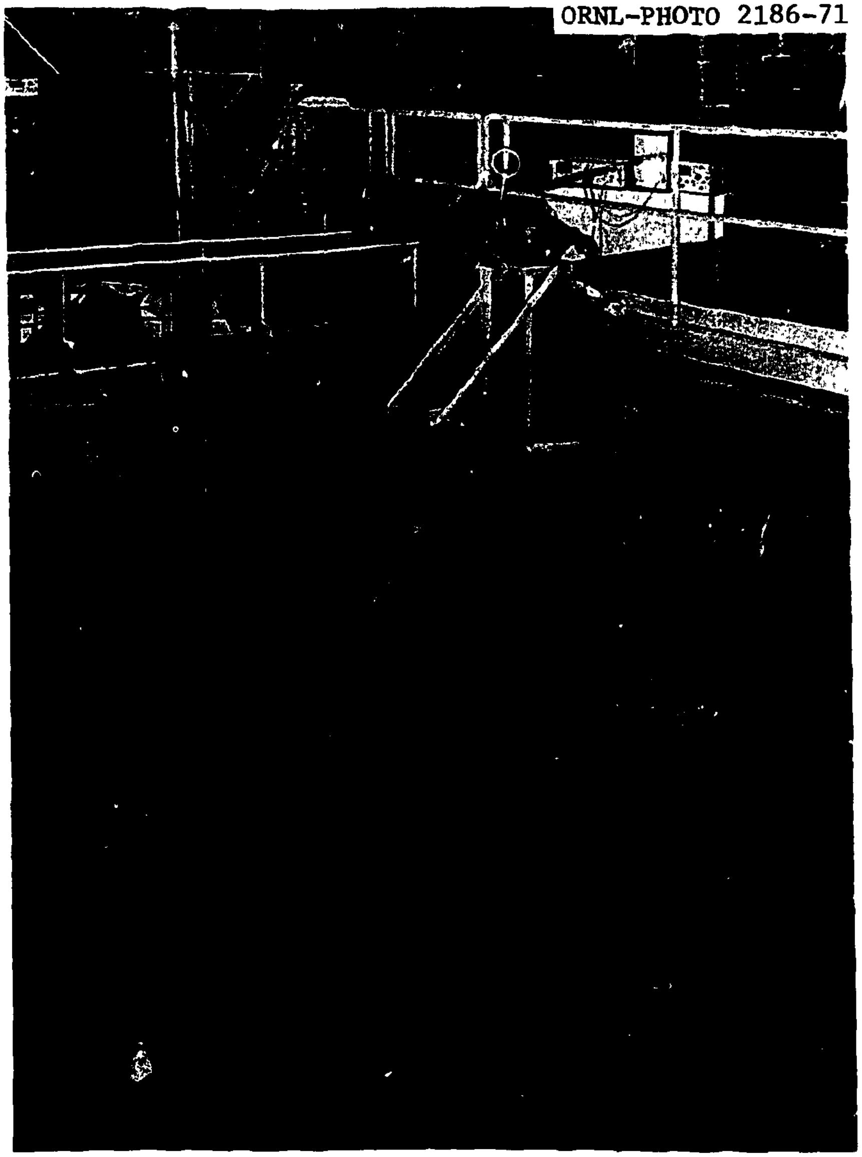

Fig. 2. Eddy-current inspection of the High Flux Isotope Reactor control rods in reactor pool.

TEST EQUIPMENT

Scanning Fixture

The scanning mechanism shown in Fig. 3 is documented in drawings ORNL-DWG E49150 through ORNL-DWG E49154. The fixture was designed to grip a control rod at the crossarm end for rotational drive and simultaneously to translate the eddy-current probe along the cylindrical axis as the part rotates. A set of rollers supports the weight of the control rod and allows it to turn freely. Heat-shrinkable plastic tubing is placed on these rollers to protect the control rod as it rotates. The eddy-current probe is supported by the arm that extends

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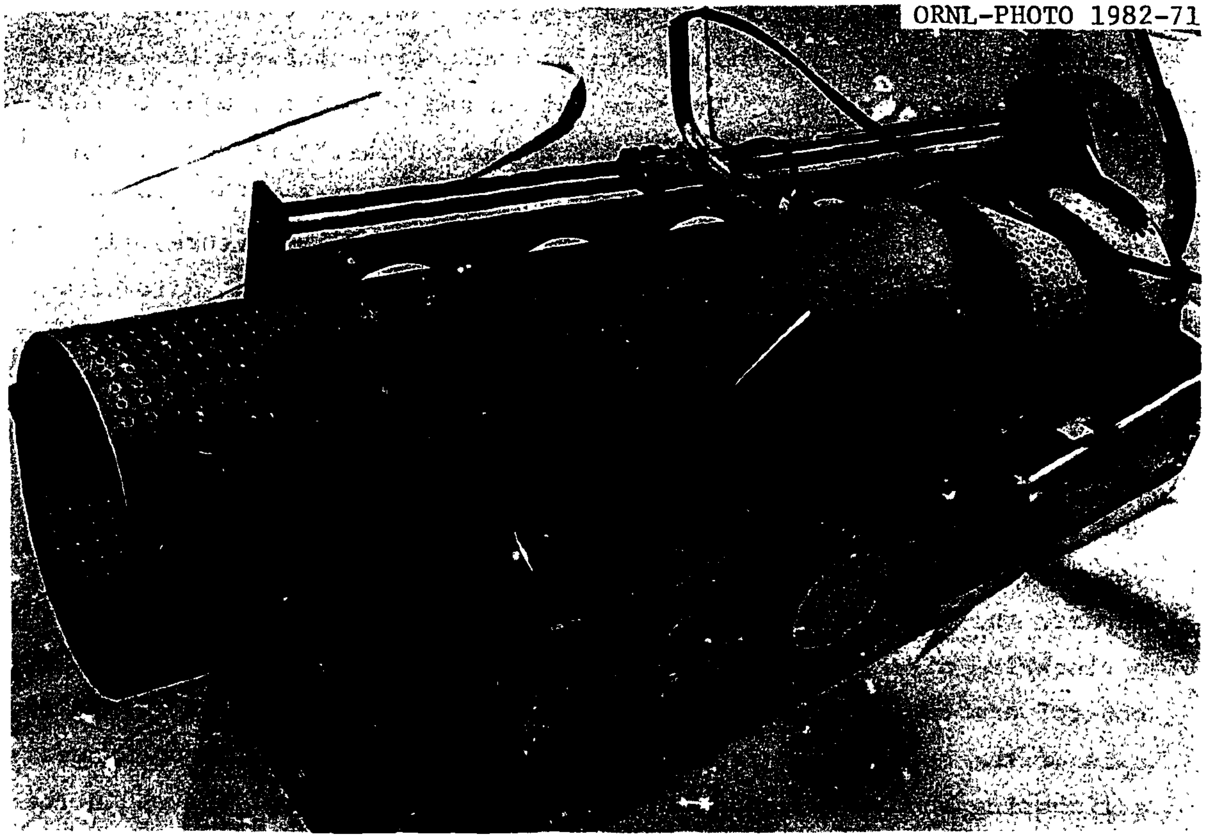

Fig. 3. Scanning mechanism for inspecting High Flux Isotope Reactor control rods.

over the top of the control rod. The probe cables are fed through the section of conduit that comprises the arm. The probe support is held against the control rod by gravity and rides on a set of rollers, which contact the part during testing. The eddy-current probe is held in the scanner head with a split clamp and a locking bolt. The probe is locked in a recessed position and does not contact the control rod during testing. A steel tape, calibrated in units of inches, has been placed on one side of the scanning fixture. This tape is used as a reference to set the scanning head in the proper position to start a test or to perform a calibration check. This tape is frequently referred to in the inspection procedures.

The entire scanning mechanism is operated outside the reactor pool for calibration purposes or to test new control rods. It is lowered into the pool for examination of radioactive specimens. This requires that the cables connecting the eddy-current instrument and probes be about 6 m long and that the electrical connections between the cables and probe be watertight. The same cables and probes are used to test all control rods whether the test is conducted inside or outside the reactor pool. The scanning fixture is decontaminated after use in the reactor pool, but it may retain some radioactivity; therefore, all appropriate safety precautions that apply to working with radioactive hazardous materials are observed while performing these inspections.

The rotational motion of the scanning fixture is controlled by a three-position electrical switch. The switch box is designated FOR (forward), OFF, and REV (reverse). When the switch is in the REV position, the control rod will rotate in a counterclockwise direction (as viewed from the driven end; with the control rod rotating in this manner, the effective scanning direction of the eddy-current probe is in a clockwise direction). At the same time, the drive screw for the control arm causes the arm and eddy-current probe to traverse along the axis of the control rod from the control arm end toward the open end. All testing should be conducted with the scanner control switch in the REV position. The manner in which the scanning mechanism is constructed requires that the surface of the cylinder rotate away from the support arm for an accurate eddy-current test. This is necessary to maintain constant lift-off and to avoid excessive bumping and bouncing of the probe. The mechanism can be rotated in the opposite direction but only to reposition the probe. The eddy-current probe and scanner head should be lifted off the part when the scanner is operated in the FOR position.

The scanner turns the control rod at approximately 4 rpm as the eddy-current probe travels along the axis to produce a helical scanning motion with a pitch of 0.64 mm (0.025 in.) per revolution. The resulting linear scanning speed is about 0.042 mm/s (6 in./h). At this speed the defect and cladding thickness inspections require about 6 and 4 h, respectively, of continuous scanning time (excluding setup and calibration time). The total axial length that the fixture can scan is about 1.14 m (45 in.); therefore, the entire surface area of a control rod cannot be inspected. The fixture was designed to scan the surface areas of particular interest, which are those areas containing Eu_2O_3 and tantalum (Fig. 1). The probe can physically scan the areas containing holes, but some information will be lost as a result of "edge effects." Signals of very high amplitude are obtained when the eddy-current probe crosses the edges of the holes. These signals can mask reflected signals obtained from cracks or other discontinuities located in these areas. The response time of the test system is such that it quickly recovers from the large signals so that we can obtain information for about 75% of the space between the holes. The areas around the holes should receive a thorough visual examination as the defect inspection is being conducted.

One inconvenience in the design of this scanner is that the probe support must be screwdriven to reposition it to start a new test. This can be quite time consuming at the single slow speed of rotation available. A clutch or split-nut assembly would greatly facilitate the repositioning of the probe and thereby significantly reduce the total time required to perform an inspection. When the scanner is operated outside the reactor pool, the probe arm can be positioned much faster by disconnecting the sprocket drive chain and turning the drive screw by hand.

When tests are conducted inside the reactor pool, a long drive shaft connects the scanning fixture to the drive motor, which is located outside the pool. This drive motor also operates a cam that in turn operates an electric microswitch once for every revolution of the control rod. An electrical signal is generated by this switch, which causes an event marker to occur on the recorder chart. The relationship between this event marker and the control rod rotation provides the means for correlating signal indications on the recorder chart to actual location on the surface of the control rod. An inner control rod comprises four sections or quadrants that are joined by four axial welds. The quadrant that contains the control rod identification has been arbitrarily selected as quadrant 1. The other quadrants are identified in increasing numerical order in a clockwise direction as viewed from the crossarm end. A few reference landmarks such as the holes and the welds occur on the control rods, but once a test is completed the only method for obtaining the location of many indications on the control rod is the relationship between the event marker and the number of rotations made by the control rod. For this reason, the quadrant in which the event marker occurs must be recorded for each test.

Eddy-Current Instrumentation

A photograph of the instrument package used for this inspection is shown in Fig. 4. The inspections were performed by use of a modular phase-sensitive eddy-current instrument, the data were recorded on a strip-chart recorder, and an oscilloscope was used for instrument setup and calibration checks. The modular phase-sensitive eddy-current instrument was designed and built at ORNL.[2] Several improvements have been made in this instrument since these tests were conducted, but we describe here the actual instrument used to perform the most recent control rod inspections. Figure 5 is a block diagram of the instrument arrangement, showing the proper electrical connections for this inspection.

The eddy-current probes, test frequency, attenuator values, and many other test parameters were designed specifically for the HFIR control rod inspection (details are in ref. 1). The same basic eddy-current instrument

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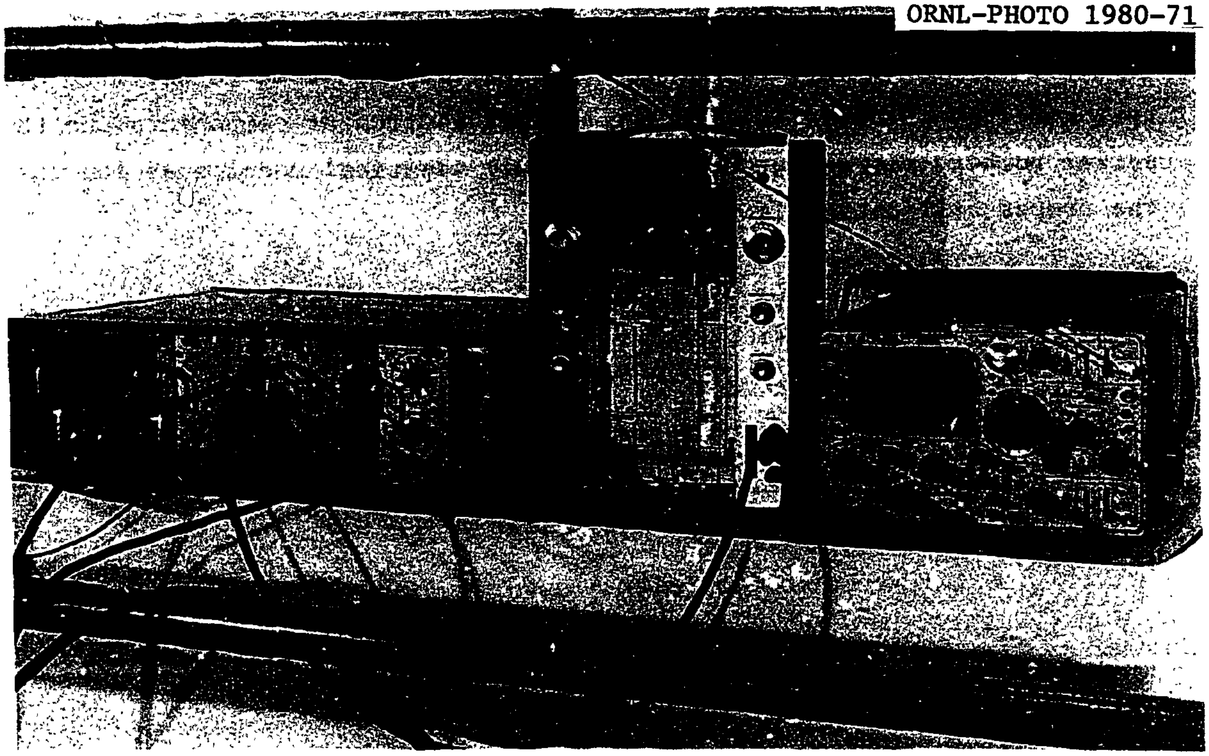

Fig. 4. Modular eddy-current instrument and associated equipment.

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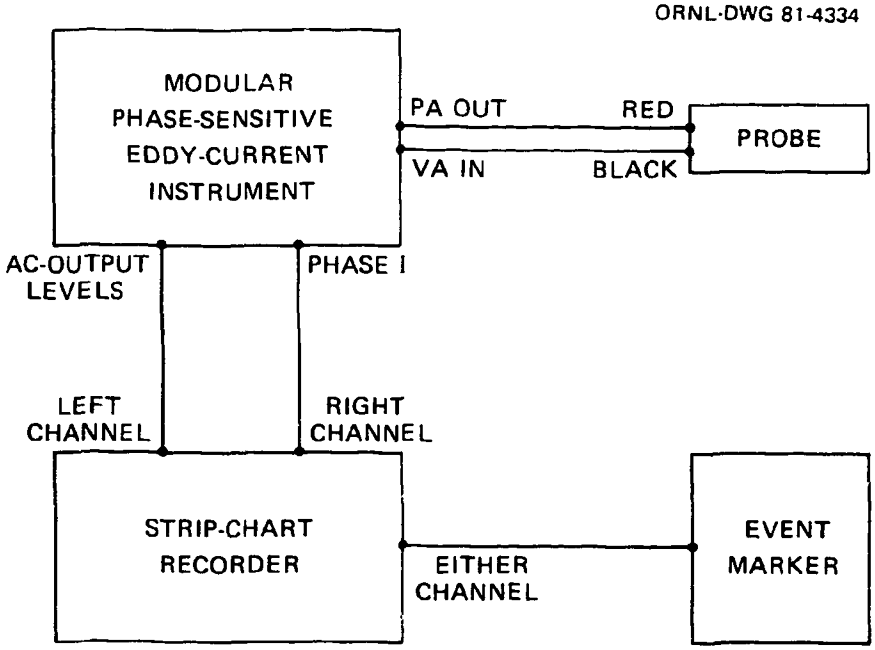

Fig. 5. Instruments and electrical connections used for High Flux Isotope Reactor control rod inspections.

was used for both the cladding thickness and defect inspections. Different probes, frequencies, and attenuators were used to optimize each test condition. Table 1 lists the modular instrument components and their serial numbers (it is not necessary to use identical modules as long as the proper calibration is performed).

Table 1. Modular components used with basic phase-sensitive eddy-current system

Component	Serial
Power oscillator	PA-101
Video amplifier	VAHF-104
Phase discriminator	DISC-102
Display module	DPM-102
Closed-loop differential amplifier	CLDA-101

Specific components and parameters used for the individual tests are given in Table 2. The cables connecting the eddy-current instrument and probes were approximately 6 m long. Shielded red Microdot type RG62-B/U cables were used, and the electrical connections between the cables and eddy-current probe were waterproofed. A piece of 0.1-mm-thick Teflon tape is placed over the face of the eddy-current probe for protection during testing except for tests performed in the reactor pool.

A two-channel strip-chart recorder (Brush model 220) is used to document the data. A recorder chart takeup reel is essential because of the large amount of data recorded. Six (122-m) rolls of chart paper are required to complete a defect inspection, but a cladding thickness inspection requires only one chart roll. The nominal sensitivity and speed settings for the recorder are also shown in Table 2 for each test. During cladding thickness and defect tests, the left channel is set to record signal magnitude, which is a measure of lift-off. The right channel

Table 2. Specific instrument parameters used on the High Flux Isotope Reactor control rod examination

Component	Cladding thickness	Defect and oxide thickness
Test frequency	10 kHz	2 MHz
Eddy-current probe	Type 83B	Type 20D
Attenuators:		
Driver resistance	500 Ω (series)	82.5 Ω (series)
Driver capacitance	0.0047 μF (parallel)	Cable only (~300 pF)
Pickup resistance	620 Ω (parallel)	133 Ω (parallel)
Pickup capacitance	0.0047 μF (parallel)	Cable only (~300 pF)
Recorder sensitivity:		
Left channel	20 mV/div[a]	50 mV/div[a]
Right channel	100 mV/div[a]	50 mV/div[a]
Recorder speed	5 mm/s	25 mm/s

[a]div = division — a unit on the recorder chart.

records signal phase, which is related to cladding thickness or to defect size, depending on how the instrument is calibrated. The magnitude data recorded during the defect test are used to determine the thickness of the oxide film over the areas dispersed with tantalum and Eu_2O_3.

CALIBRATION AND SETUP

The accuracy and repeatability of this inspection were established by optimizing the test frequency, attenuator size, and types of eddy-current probes used for each variable being measured (defect size, cladding thickness, and oxide thickness). In addition, the effects of other undesirable variables such as temperature were minimized. This optimization was performed by using established computer programs described in ref. 1. Even though the proper test parameters were selected, several instrument settings and adjustments must still be made before performing an inspection. For example, the phase output of the modular eddy-current instrument requires an internal adjustment that should be made in a laboratory environment. An electronic calibration network is used to adjust the instrument so that a 10° change in phase between the reflected and reference signals will produce a change of 1 V in the output of the phase discriminator. Because all required data for this inspection are obtained from the strip-chart recorder, an absolute phase calibration of the eddy-current instrument is not required. However, if actual phase values are desired, the instrument must be calibrated; therefore, it is advisable to perform this calculation before moving the eddy-current instrument to the inspection area. All other preinspection adjustments can be made at the test site.

Eddy-current signals are vector quantities that possess both magnitude and phase properties. The modular phase-sensitive eddy-current instrument is capable of measuring both the phase and magnitude of the reflected eddy-current signals. The term *lift-off* in eddy-current testing refers to the spacing between the coil (probe) and conductor (usually the test piece). A lift-off variation can affect both the magnitude and phase of an eddy-current signal, but a greater change will occur in the signal magnitude. When it is desirable to measure the lift-off variation, the signal magnitude is usually monitored. If signal phase is being measured, the effects of lift-off are usually suppressed. Whenever the modular eddy-current instrument is used to perform an inspection, a lift-off adjustment is required before conducting the examination. Lift-off calibration is accomplished by placing nonconducting shims of known thickness between the eddy-current probe and test piece, making the proper instrument adjustments, and locking the probe in position at the known lift-off. Typically a 0.1-mm-thick shim is used for the lift-off setting, but it is wise to check an intermediate value (around 0.05 mm) after the adjustments have been made. The techniques for performing these lift-off adjustments require a knowledge of eddy currents and familiarity with the instrument, but procedures are available.*

During the defect test, the phase of the reflected eddy-current signal is recorded on one channel of the strip-chart recorder, and the magnitude of the signal is recorded on the other. The phase signal is calibrated to indicate defect size. This signal is sensitive to defect

*C. V. Dodd and J. H. Smith, Metals and Ceramics Division, Oak Ridge National Laboratory, P.O. Box X, Oak Ridge, TN 37830.

size because of the proper selection of eddy-current probe, frequency, and attenuator values. The selection process is described in ref. 1.

The eddy-current instrument is first adjusted so that small variations in lift-off have no effect on the reflected phase signal. Nonconducting shims with thicknesses of 0.05 and 0.10 mm are alternately placed between the eddy-current probe and test piece, and the discriminator module is adjusted so that the phase signal is unaffected (see Fig. 6, which is the typical recording obtained for a lift-off calibration check). The accuracy of the defect measurement is established by scanning the eddy-current probe over the seven notches in the defect calibration standard. The indications obtained from the notches are shown in Fig. 7. These scans, as well as any other calibration checks, should be recorded and maintained for future reference.

The defect calibration standard (Fig. 3) is a used (decontaminated) control rod that is identified by the letter H. Seven notches were cut in the aluminum cladding over the Eu_2O_3 dispersion. Figure 8 is a sketch of the Eu_2O_3 area only and shows a surface view of the notch orientation and arrangement; the notch locations and dimensions are also shown. The depths of these notches were verified by optical measurements on replicas made by using a silicone rubber compound. All the notches are 25.4 mm long and about 0.127 mm wide. Notches 2 and 3 are separated circumferentially by about 12 mm, and notches 4 and 5 are separated by only about 2 mm; therefore, in addition to determining defect sensitivity, we also get a measure of resolution as the notches are scanned. Notch 6 was cut so that its major length is at an angle of 45° to the scanning direction of the eddy-current probe. This provides a measure of orientation error. The major lengths of all other notches are perpendicular to the scanning direction.

The magnitude of the reflected eddy-current signal is sensitive to lift-off variations (Fig. 6). The signal can therefore be used to measure the thickness of the oxide film that forms on the surface of the aluminum cladding (the oxide film is not an electrical conductor; therefore, it reflects only as a lift-off variation). The calibration process places nonconducting shims of known thickness between the eddy-current probe and test piece and determines the amount of deflection of the recorder pen for each shim (Fig. 6).

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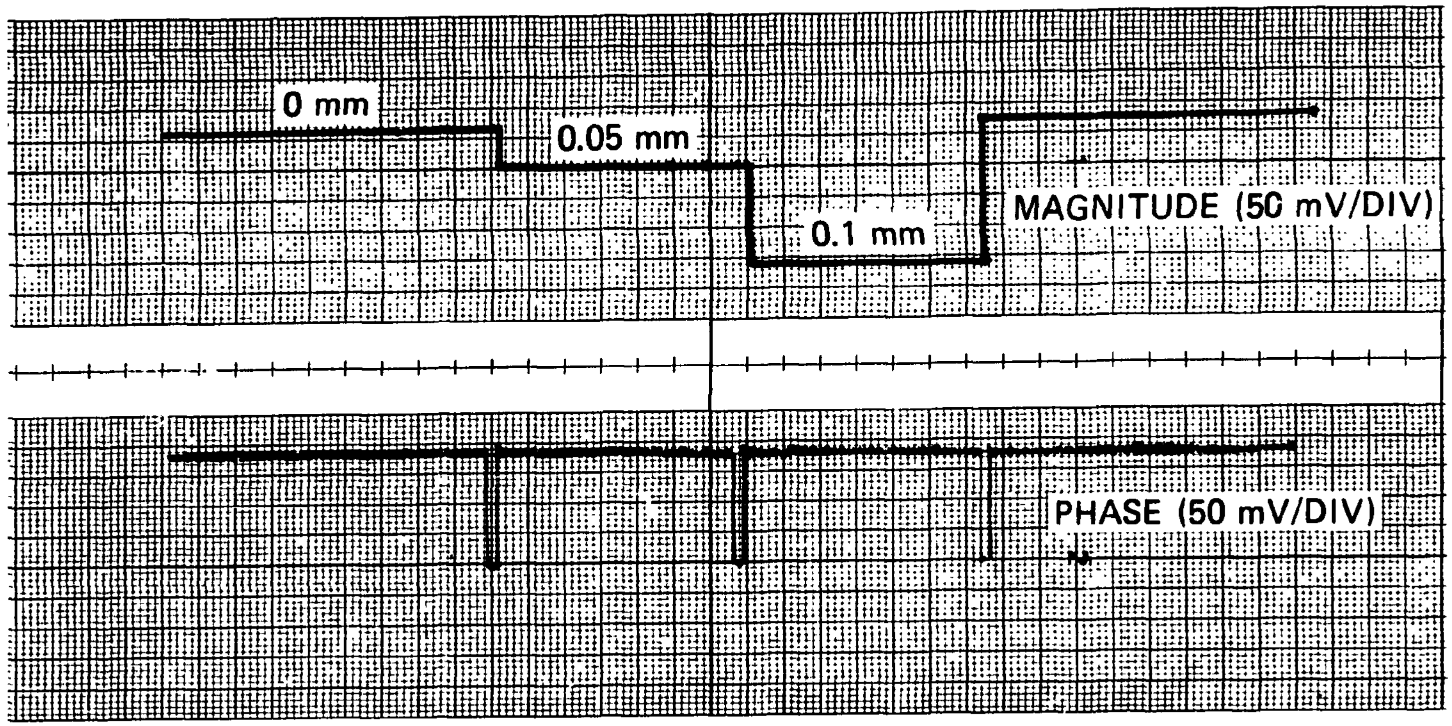


Fig. 6. Recording of lift-off calibration check for defect inspection.

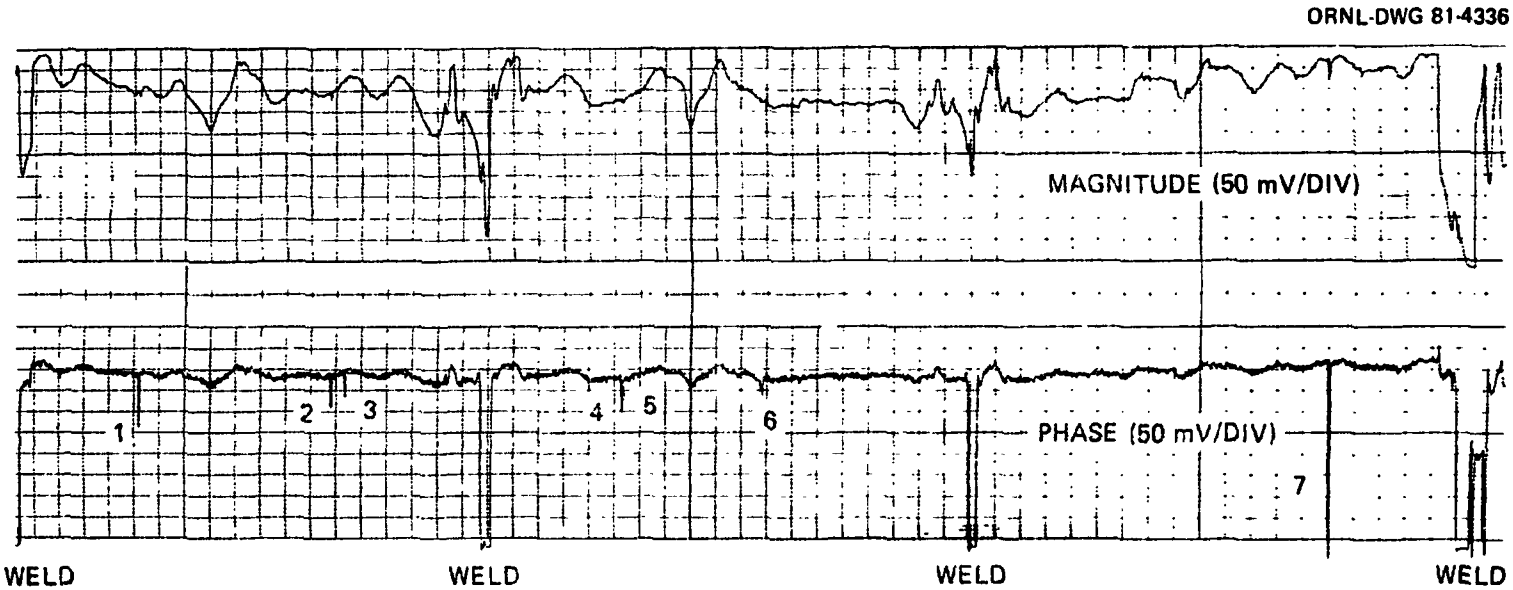
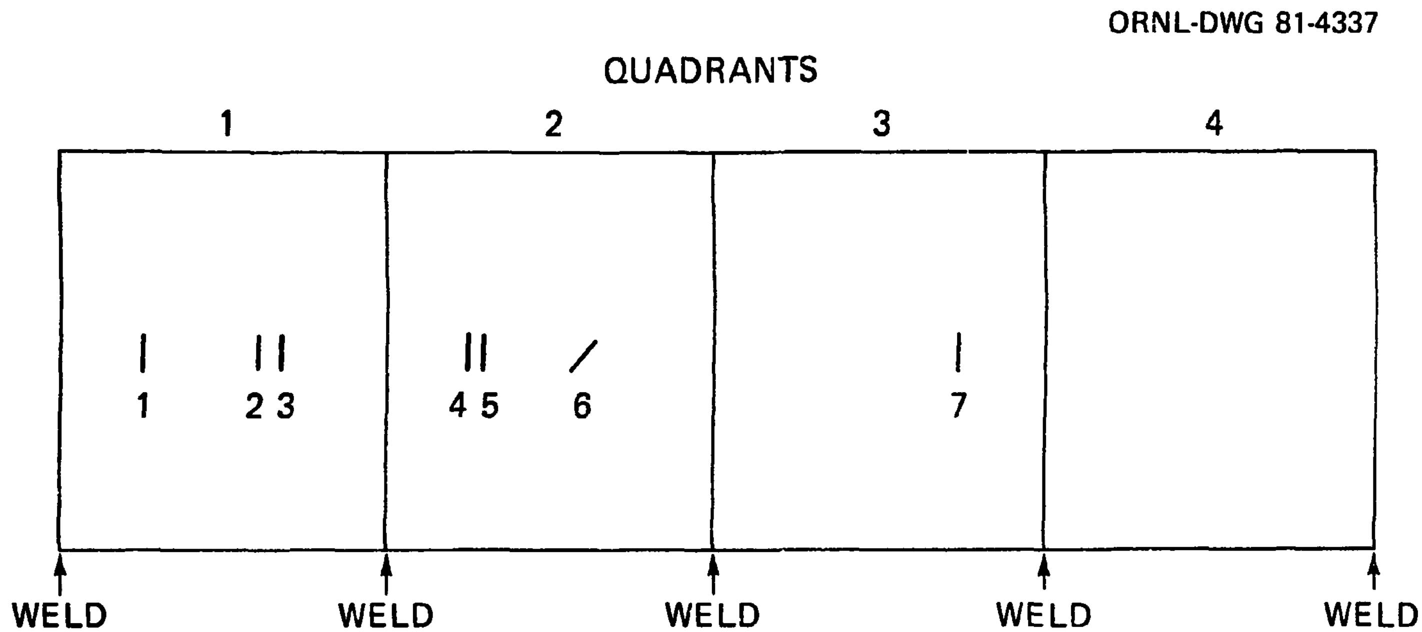


Fig. 7. Notch indications for a defect calibration check by using control rod H.



NOTCH	DEPTH mm	DEPTH in.	LOCATION (QUADRANT)
1	0.061	0.0024	1
2	0.056	0.0022	1
3	0.046	0.0018	1
4	0.056	0.0022	2
5	0.048	0.0019	2
6	0.025	0.0010	2
7	0.122	0.0048	3

Fig. 8. Planar layout of the europium oxide area on control rod H showing arrangement of the seven notches.

The oxide thickness inspection compares the nominal oxide thickness of the control rod being inspected with that of the reference standard (control rod H). In addition, variations in oxide thickness within a given control rod are determined. A probable area for oxide buildup is near the center of the Eu_2O_3 area where the radiation levels are most intense.

A curved aluminum reference sample is available for use as an oxide thickness reference when tests are conducted inside the reactor pool. This sample is a section of aluminum plate having similar curvature and electrical conductivity as the inner control rods. The eddy-current magnitude and phase response to this aluminum sample is well established and has been correlated with control rod H. The process of moving control rods in and out of the scanning fixture in the reactor pool requires several people and is quite time consuming. Therefore, whenever an oxide thickness calibration check is required for a part inside the reactor pool, the check is greatly facilitated by using the 15- by 15-cm aluminum reference sample. The curved aluminum sample is also used to set the baseline reference for the cladding thickness measurement inside the pool (Appendix C, part 2).

Phase and magnitude are also recorded on separate channels during the cladding thickness test. The phase channel is calibrated in units of thickness of the aluminum cladding, and the magnitude is calibrated in units of lift-off. The magnitude data are affected primarily by the gap between the eddy-current probe and test piece. As such, these data can be used to verify whether variations in the phase signal were caused by a cladding thickness change or by a lift-off change (lift-off changes can be caused by several other variables, for example, surface discontinuities). The discriminator module is again adjusted so that small variations in lift-off do not affect the phase signal. The recording obtained from a typical lift-off check is shown in Fig. 9.

Another variable that can affect the indicated cladding thickness value is recorder drift. This drift can be caused by inherent electrical problems in an instrument, by changes in cable capacitance, or by some shift in an electrical property anywhere in the test setup. Recorder drift will be indicated by a shift in the recorded baseline reference

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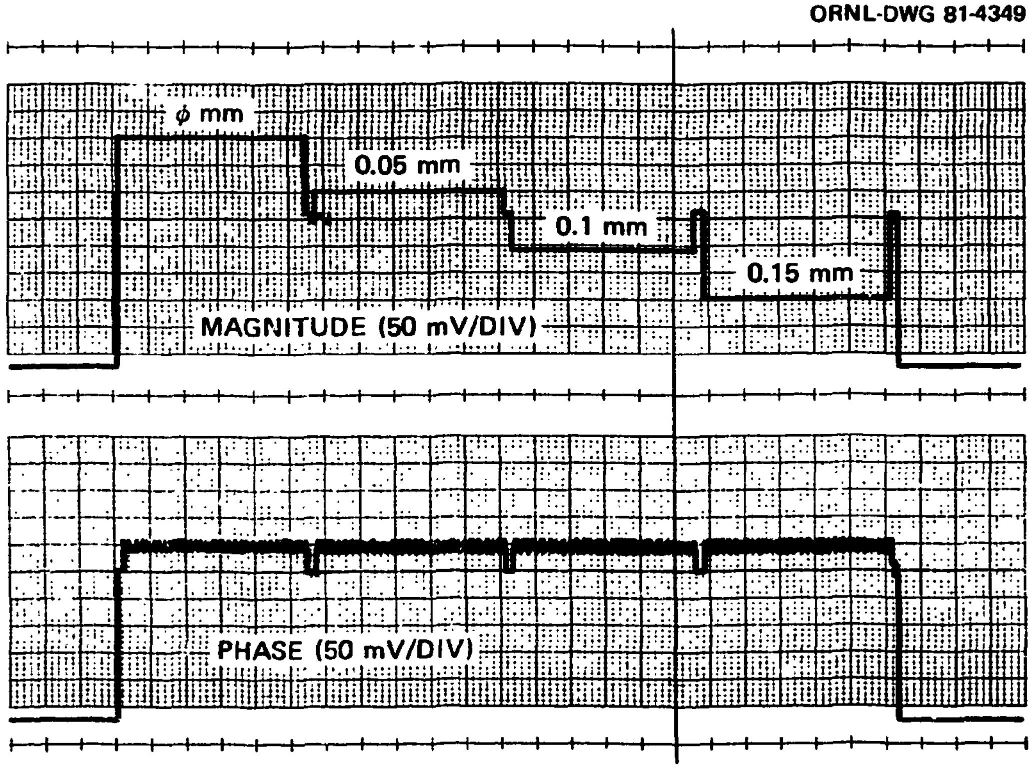

Fig. 9. Recording of lift-off calibration check for cladding thickness inspection.

value, which occurs at the solid aluminum areas on either side of the four longitudinal welds. A baseline shift can be reset using the "balance" control on the eddy-current instrument without affecting test calibration. Adjustments made for recorder drift should be identified on the recorder chart. Recorder drifts are usually small and occur gradually. Large and/or sudden drifts indicate that something is wrong with either the sample or the instrument, and these should be investigated before testing is continued.

The calibration standards for the cladding thickness measurement are samples of aluminum cladding for which the thickness is known. These cladding thickness standards were prepared by obtaining several pairs of cladding samples, of which each pair had approximately the same cladding thickness. The eddy-current response was determined for each sample, and one sample from each pair was sectioned and examined metallographically to establish the thickness of the cladding. The remaining sample was then assigned the appropriate thickness value. The cladding thickness reference samples used for this test and their respective cladding thickness values are given in Table 3. The missing consecutive identification numbers either had duplicate cladding thickness values or are samples that were sectioned for metallography.

Table 3. Aluminum cladding thickness reference samples

Identity	Thickness of aluminum cladding (mm)	Thickness of aluminum cladding (in.)
1	Infinite[a]	Infinite[a]
6	0.686	0.0270
7	0.643	0.0253
8	0.579	0.0228
10	0.533	0.0210
11	0.480	0.0189
12	0.429	0.0169

[a]Solid aluminum.

Samples 1 and 12 were used to make the necessary instrument adjustments to calibrate the test system for sensitivity to cladding thickness. The other thickness samples were measured and recorded for future reference. Figure 10 shows the typical recording obtained when the cladding thickness samples are checked.

New control rods are inspected primarily to establish baseline reference data for future eddy-current inspections. Since the new control rods are not radioactive, the inspection can be performed at any convenient location in the building. The temperature of the test area should be relatively constant because eddy-current response can be affected by temperature variations. If any sudden or large temperature variations are anticipated, a thermometer should be kept near the test site to monitor these changes (a mercury thermometer should not be used because mercury is prohibited in the reactor building).

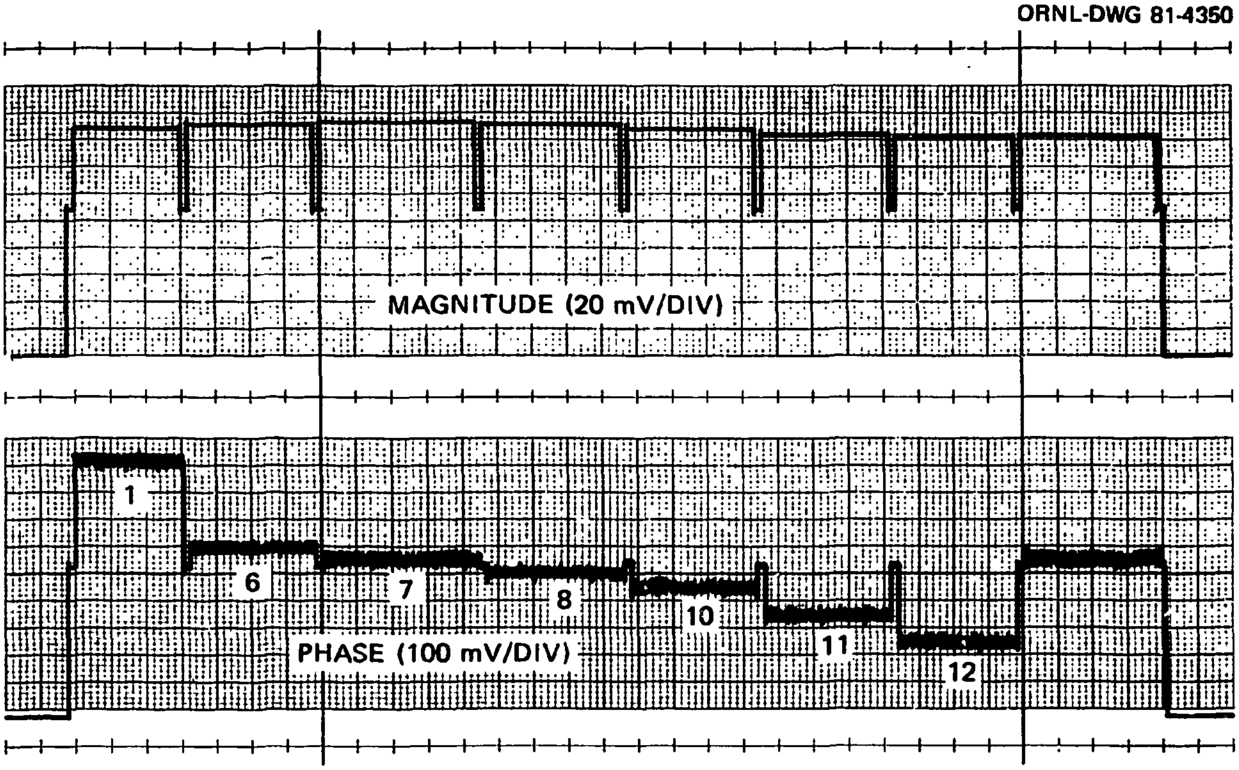

Fig. 10. Recording of cladding thickness calibration check.

Used control rods must be inspected inside the reactor pool for radiation protection. Calibration is performed at poolside; the scanning fixture must then be lowered to the bottom of the pool to conduct the test. The HFIR control room supervisor must schedule movement of the scanning fixture into or out of the reactor pool. Several precautionary measures must be taken before the scanning fixture is placed in the pool water:

1. The fixture should be cleaned and degreased.
2. The scan arm should be reset to the start position for the first inspection.
3. The protective (heat-shrink) tubing for the roller support bearings should be painted to improve visibility. This makes the wear or loss of the tubing easier to detect when the fixture is located at the bottom of the pool. (We have had good success in the past by painting the inner surface of the tubing with a yellow aerosol spray paint. Paint on the outer surface is undesirable because it wears off as the control rod rotates in the fixture.)

4. A long nylon string should be attached to the scan arm of the fixture, which will allow remote raising and lowering of the eddy-current probe with the fixture at the bottom of the pool.
5. A short nylon string should also be attached to the upper end of the coaxial cables connecting the eddy-current probe and instrument. The other end of this string is secured to help prevent the electrical cables from accidentally being dropped into the reactor pool.
6. The protective Teflon tape is removed from the face of the eddy-current probe for tests conducted in the pool. This is a safety measure to prevent the tape (which is small and difficult to see) from coming off and possibly being lost in the pool.

The order in which the tests are conducted is important only if a control rod is examined in the reactor pool. Generally it is best to perform the defect inspection first and then measure the cladding thickness. This order of test performance will minimize handling of the scanning fixture. The defect calibration can be performed at poolside by using control rod H with the scanning fixture out of the water. After the calibration has been completed, the scanning fixture can be lowered into the reactor pool and left there until all examinations on the control rod have been completed.

If the inspections are conducted in the reactor pool, the calibration checks should be performed under the same conditions (with the scanner and control rod H located in the pool). When these parts are placed in the pool, a significant temperature change occurs, which will be detected by the eddy-current system. The entire scanning system including control rod H should therefore be lowered into the reactor pool and left overnight or for about 8 h to reach thermal equilibrium before performing a calibration check.

TEST PROCEDURES

The earlier discussion in this report was presented to provide sufficient detail about the HFIR control rod inspection to allow the reader to understand the following procedures. A procedure should be thorough, but, to be effective, it must also be concise. The procedures in this report are therefore written with the assumption that the person performing these inspections is knowledgeable about both eddy-current testing and the safety procedures in the HFIR reactor building. The inspector should also be familiar with the test equipment and its operation.

These procedures were written to be independent and self-contained; therefore, some repetition occurs. But, for example, if a cladding thickness inspection is performed following a defect inspection, many of the steps required in the cladding inspection will have already been performed during the defect inspection and will not need to be repeated.

SUMMARY AND CONCLUSIONS

This report describes eddy-current inspection techniques that are capable of evaluating the condition of highly radioactive nuclear control rods for the HFIR reactor under very harsh test conditions. Cladding thickness and oxide thickness can be measured and the control rods can also be examined for defects. The tests are conducted with control rods that can emit radiation levels as high as (10^5 R/h) located approximately 6 m below the surface of the reactor pool. In addition to describing the problems and intricacies of performing tests of this type, the report provides procedures for reference in performing similar inspections.

ACKNOWLEDGMENTS

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Appendix A

PROCEDURE FOR TESTING FOR DEFECTS AND OXIDE THICKNESS ON THE HFIR INNER CONTROL ROD (OUTSIDE THE REACTOR POOL)

1. General

1.1 This procedure describes the techniques for locating surface and near-surface defects on the High Flux Isotope Reactor (HFIR) inner control rod (Fig. 1). It also describes how the thickness of the surface layer of aluminum oxide is measured simultaneously.

1.2 New control rods can be tested at nearly any convenient site in the HFIR building, but used control rods are highly radioactive and must be inspected inside the reactor pool. This procedure is written for only those tests conducted outside the reactor pool. Appendix C describes the techniques for performing an inspection inside the reactor pool.

1.3 All safety rules and precautions that apply to working with radioactive materials should be exercised when conducting this test.

1.4 The defect inspection should start between the row of screws and the first row of holes, counting from the crossarm end of the rod, and stop at the twelfth row of holes beyond the Eu_2O_3 area (Fig. 1).

2. Equipment

2.1 A modular phase-sensitive eddy-current instrument, including the following modules or equivalent:

Component	Serial
Power oscillator	PA-101
Video amplifier	VAHF-104
Phase discriminator	DISC-102
Display module	DPM-102
Closed-loop differential amplifier	CLDA-101

2.2 A 20D reflection-type, eddy-current probe with about 6 m of RG62-B/U-shielded cable and the following attenuators:

Component	Value
Driver resistance	82.5 Ω (series)
Driver capacitance	Cable only (~300 pF)
Pickup resistance	133 Ω (parallel)
Pickup capacitance	Cable only (~300 pF)

The eddy-current probe should have a piece of 0.1-mm-thick Teflon tape on its face as a protective cover.

2.3 A two-channel, strip-chart recorder (a Brush recorder, model Mark 220 or equivalent).

2.4 An HFIR inner control rod scanner assembly fixture (ORNL-DWG E49150 through ORNL-DWG E49154 or equivalent).

2.5 HFIR control rod H.

2.6 Several pieces of 0.05- and 0.1-mm shim stock made of a nonconducting material.

2.7 Optional: A thermometer capable of measuring room temperature (do not use a mercury thermometer) and a 0 to 80° phase-shift calibration box.

3. Preliminary Setup

3.1 Place control rod H in the test fixture with the crossarm end located at the scanner drive arm. The eddy-current probe and scanner head should be lifted off the part when operating with the scanner in the FOR position. All tests should be performed with the scanner switch in the REV position.

3.2 Pass the eddy-current probe cables through the conduit on the scanner arm (it may be necessary to remove the attenuators to get the cables through the conduit).

3.3 Mount the eddy-current probe in the scanner head. Leave enough slack in the cables to allow the probe and scanner head to move freely. Tighten the locking bolt only enough to hold the probe securely. DO NOT LET THE SCANNER HEAD FALL ON THE CONTROL ROD.

3.4 Firmly connect the attenuators and cables to the correct jacks on the modular eddy-current instrument (Fig. 5).

3.5 Connect the output of the AC OUTPUT LEVELS jack (in the back of the modular eddy-current instrument) to the left channel of the strip-chart recorder.

3.6 Connect the output of the PHASE 1 jack (in the back of the modular eddy-current instrument) to the right channel of the strip-chart recorder. The connections made in steps 3.5 and 3.6 determine the direction in which the recorder pens are deflected. Reversing the two "active" leads for each connection will reverse the direction of the recorder pen deflection.

3.7 Connect the event marker signal leads (from the microswitch on the fixture) to the back of the strip-chart recorder. (Usually the left recorder channel is used).

3.8 Connect the electrical power cables to all instruments and the scanning fixture.

3.9 Optional: Place the thermometer in a convenient location near the test fixture.

4. Instrument Setup and Calibration

4.1 An absolute phase calibration should be performed on the eddy-current instrument before moving it to the test site.

4.2 At the test site, make the following instrument settings:

(a) frequency control to 2 MHz (PA/OSC module),

(b) 180° phase switch (inside DISC module) in the "up" position,

(c) PA1/VA2 switch to PA1 (DPM module),

(d) PA2/VA1 switch to VA1 (DPM module),

(e) selector switch to COMP1 (DPM module),

(f) both left and right recorder channel "step" sensitivity controls to 50 mV/div, and

(g) both left and right recorder channel "variable" sensitivity controls to maximum, that is, fully clockwise.

4.3 Turn the equipment on and allow a sufficient warm-up time (at least 1 h) for all instruments to stabilize electrically.

4.4 Adjust the power amplifier gain control to get a reading of 50 mA on the PA1 meter.

4.5 Gently place the scanner head and probe in a defect-free area in the Eu_2O_3 region on the control rod H. Make sure the head and probe are properly seated, that is, not tilted. (The depth of penetration of the 20D probe at 2 MHz is less than the cladding thickness; therefore, lift-off can be set with the probe over any cladding area. The probe should be kept away from the holes to avoid edge effects).

4.6 Adjust the video amplifier gain control(s) to get a reading of 46 mA on the VA1 meter, with the probe seated on the control rod.

4.7 Loosen the probe in the scanner head and place a piece of 0.05-mm-thick nonconductive shim between the face of the eddy-current probe and the control rod.

4.8 Tighten the locking bolt on the scanner head to secure the eddy-current probe at the 0.05-mm lift-off position. (Be careful not to press down or lift up on the probe when securing it in the scanner head. One technique for maintaining the probe in a 0.05-mm lift-off position is to observe the left channel of the recorder while making this adjustment.) Remove the 0.05-mm shim after tightening the locking bolt. This adjustment, which is made with the probe head rollers in contact with the control rod, recesses the probe head for safety precautions and sets the reference lift-off position. It is necessary to press one of the speed control buttons to get a reading on the recorder. Generally the 1- or 5-mm/s speed is used during setup to conserve chart paper.

4.9 Using the procedure provided in Appendix D, adjust the lift-off controls on the discriminator module so that no significant phase shift occurs for a lift-off range of 0 to 0.1 mm. THE SHIMS MUST BE PLACED BETWEEN THE ROLLERS ON THE EDDY-CURRENT SUPPORT ARM AND THE CONTROL ROD FOR THIS ADJUSTMENT. Several steps in this procedure require "checks" of the lift-off and/or oxide thickness calibrations. These frequent checks are made to ensure that no changes have occurred in the instrumentation or equipment setup. No instrument adjustments should be made during these checks. If significant changes are detected, notify your supervisor.

4.10 Check the lift-off and oxide thickness calibration by alternately placing 0.05- and 0.1-mm shims between the probe head rollers and the control rod and by observing the reflected signal magnitude. The reflected signal phase (right channel) should remain constant during these tests. The baseline reference values for the magnitude signal (left channel) are established during this step. Make two recordings similar to Fig. 6. File one recording in the HFIR logbook along with the instrument identities, instrument settings, and the control rod identity. Leave the other recording on the chart.

4.11 Place the scanner head and probe in a position (29 5/16-in. mark on the scale) on control rod H that will allow the eddy-current probe to pass over the notches when the scanner is rotated. Make sure that the eddy-current probe is properly seated on the part. The probe arm can be positioned much faster by disconnecting the sprocket drive chain and turning the drive screw by hand.

4.12 Adjust the left and right recorder channels so that both pens write on the line 20 divisions to the left of center on the respective charts. The pen on the left recorder channel (magnitude signal) is set by using the "position" control on the recorder. Two controls will affect the phase reading on the right recorder channel; their proper setting is as follows: unplug the input to the right channel of the recorder. Using the recorder "position" control, set the pen in the center of the recorder chart and lock the control. Reconnect the input to the right channel and adjust the "balance" control on the eddy-current instrument to position the recorder pen. The sensitivity controls on the left recorder channel should be set so that the pen stays on scale for 0- to 0.1-mm lift-off signals, and the pen deflection should cover a span of at least two-thirds the width of the chart paper.

4.13 Make a defect calibration scan by simultaneously operating the REV switch on the scanner and the 25-mm/s speed button on the recorder.

4.14 Make several revolutions of the part and record the notch indications on each revolution (Fig. 7). Record the notches for a sufficient number of revolutions to obtain an average depth near the center of the notch lengths. Save these recordings.

4.15 Average the three highest depth indications obtained for each notch on the scans made in step 4.14. Record the three values and the average for each notch in the HFIR logbook. File a representative scan of the notches in the logbook along with the instrument identities, instrument settings, and control rod identification.

4.16 Check the recorder ink supply and refill if it is less than one-fourth full.

4.17 Make sure that the recorder has a nearly full roll of chart paper. If not, replace the old chart roll with a new one. Use 122-m (400-ft) chart rolls when available.

4.18 Record the following information on the chart roll:

(a) chart roll number (number the rolls consecutively as data are taken),

(b) date and initials of tester(s),

(c) control d identification number,

(d) reference page in logbook where data are filed for steps 4.10 and 4.15,

(e) the position on the inner control rod where the test started or stopped,

(f) chart speed and sensitivity, and

(g) type of eddy-current probe and serial number.

4.19 The chart paper should be attached to the take-up reel if one is available.

4.20 Repeat representative oxide thickness and defect calibration scans as described in steps 4.10 through 4.14. Leave these recordings on the chart roll.

The defect calibration check and oxide thickness (steps 4.10–4.14) calibration are required only at the beginning and end of the inspection for each particular inner control rod. The lift-off check (step 4.9) should be performed at the beginning and end of each chart roll. Any time the test is halted for an extended period of time, such as overnight, a lift-off check should be recorded at the end of testing and at the resumption of testing. The lift-off check provides assurance that no significant changes have occurred in the eddy-current instrumentation and setup.

5. Test Performance

5.1 Remove the standard H control rod from the scanner fixture and place the inner control rod to be tested in the fixture. HANDLE THE CONTROL RODS VERY CAREFULLY; AVOID DAMAGE TO THE EDDY-CURRENT PROBE.

5.2 Record the identity of the inner control rod to be inspected in the HFIR logbook. If a new control rod is being examined, record the serial numbers of the four plates that were used to make the control rod (these serial numbers are scribed on the crossarm end of the control rod). Also determine the quadrants corresponding to the four plates and record this information in the logbook.

5.3 Position the scanning arm between the 29- to 30-in. marks on the scale.

5.4 Perform a lift-off check of step 4.10.

5.5 Recall that the pens were set to record on the line 20 divisions to the left of center in step 4.12. Check the two recorder pens and note where they write on the recorder chart, then do one of the following:

(a) If the right pen (phase) is shifted slightly (<10 divisions), the shift is probably caused by a change in electrical conductivity between the control rod being tested and control rod H. Use the balance control on the eddy-current instrument to reset the pen to the line 20 division to the left of center.

(b) If the left pen (magnitude) has shifted slightly (<10 divisions), the shift is caused by a lift-off change, which is probably the result of oxide buildup in the test piece. DO NOT reset the pen. Note the difference in the logbook and on the recorder chart and continue the test by using this new reference line for oxide thickness variations within the part being tested.

(c) If either pen has shifted more than 10 divisions, check the aluminum oxide thickness reference sample to determine whether the shift is real or if an instrument problem exists. If it is an instrument problem, the entire system must be recalibrated. If the shift is real, discuss the situation with your supervisor.

5.4 Place the scanner head and probe in a position on the control rod between the screws and the first row of holes, counting from the crossarm end of the control rod.

5.5 Start the test by simultaneously operating the REV switch on the scanning fixture and pressing the 25-mm/s speed switch on the recorder.

5.6 Determine the quadrant of the control rod in which the event marker occurs and note this on the recorder chart and in the logbook.

5.7 At the beginning of the test, visually examine the control rod as it rotates in the scanning fixture and record any obvious surface irregularities such as gouges, scratches, dents, or blisters in the logbook.

5.8 Observe the recorder chart as the test progresses. Note any unusual or significant indications, and try to obtain a visual location and confirmation on the control rod. Frequent inking problems occur with these recorders. If the problem is minor, it can usually be corrected without interrupting the test. If the problem cannot be quickly corrected, stop both the recorder and the scanner drive system at the same time, correct the problem, and restart the recorder and scanner drive system simultaneously.

5.9 Six rolls of recorder chart paper (122-m length) will be required to complete this inspection. A 122-m roll of chart paper will last for about 1.5 h of continuous testing. In 1.5 h the eddy-current probe will scan approximately 22 cm along the axis of the rod. When the recorder chart paper nears the end of the roll, simultaneously stop the recorder and scanner drive system and perform the following steps:

(a) repeat the lift-off check per step 4.10,

(b) add the information required in step 4.18 on the end of the chart roll,

(c) remove the used chart roll and replace it with a new one; place the used chart roll in the box that contained the new one and identify the box,

(d) log the information required in step 4.18 on the new chart, and

(e) repeat a lift-off check per step 4.10.

5.10 Resume the test by simultaneously starting the recorder (25 mm/s) and the scanner drive system (REV). The test will be completed when the eddy-current probe reaches the twelfth row of holes beyond the Eu_2O_3 area.

5.11 At the end of the test, perform the following steps:

(a) Repeat a lift-off check per step 4.10.

(b) Record the information required in step 4.18.

(c) Remove the inner control rod from the scanner fixture and place the standard H control rod in the fixture.

(d) Move the scanning arm to the 29 5/16-in. mark on the scale.

(e) Place the eddy-current probe on the part and check the oxide thickness reference line. Both recorder pens should write on the line 20 divisions to the left of center. Record this information in the logbook and on the recorder chart. If either pen has shifted more than five chart divisions from the reference line, bring your supervisor's attention to this fact.

(f) Repeat the lift-off, oxide thickness, and defect calibration checks per steps 4.10 through 4.14.

5.12 All calibration checks should agree within 10% with those made at the start of the examination. If they do not, discuss the situation with your supervisor.

5.13 This completes the defect test. Reduce the data per Appendix E.

Appendix B

PROCEDURE FOR MEASURING CLADDING THICKNESS ON THE HFIR INNER CONTROL ROD (OUTSIDE THE REACTOR POOL)

1. General

1.1 This procedure describes the techniques used to measure the thickness of the 6061 aluminum cladding over the europium oxide (Eu_2O_3) area on the High Flux Isotope Reactor (HFIR) inner control rod (Fig. 1).

1.2 New control rods can be tested at nearly any convenient site in the HFIR building, but used control rods are highly radioactive and must be inspected inside the reactor pool. This procedure is written for only those tests conducted outside the reactor pool. Appendix C describes the techniques used to perform an inspection inside the reactor pool.

1.3 All safety rules and precautions that apply for working with radioactive materials should be exercised when conducting this test.

1.4 The cladding thickness inspection should start at the last row of holes before the Eu_2O_3 area, counting from the crossarm end of the rod, and stop at the first row of holes beyond the Eu_2O_3 area (Fig. 1).

2. Equipment

2.1 A modular phase-sensitive eddy-current instrument including the following modules or equivalent:

Component	Serial
Power oscillator	PA-101
Video amplifier	VAHF-104
Phase discriminator	DISC-102
Display module	DPM-102
Closed-loop differential amplifier	CLDA-101

2.2 An 83B reflection-type eddy-current probe with about 6 m of red Microdot coaxial cable and the following attenuators:

Component	Value
Driver resistance	500 Ω (series)
Driver capacitance	0.0047 μF (shunt)
Pickup resistance	620 Ω (parallel)
Pickup capacitance	0.0047 μF (shunt)

The eddy-current probe should have a piece of 0.1-mm-thick Teflon tape on its face as a protective cover.

2.3 A two-channel strip-chart recorder (a Brush recorder, model Mark 220 or equivalent).

2.4 A HFIR inner control rod scanner assembly fixture (ORNL-DWG E49150 through ORNL-DWG E49154 or equivalent).

2.5 A set of cladding thickness standards (Table 3).

2.6 Several pieces of 0.15-mm shim stock, made of a nonconducting material.

2.7 Optional: A thermometer capable of measuring room temperature (do not use a mercury thermometer), and a 0 to 80° phase-shift calibration box.

3. Preliminary Setup

3.1 Place the control rod to be inspected in the test fixture with the crossarm end located at the scanner drive arm. The eddy-current probe and scanner head should be lifted off the part when operating with the scanner in the FOR position. All tests should be performed with the scanner switch in the REV position.

3.2 Pass the eddy-current probe cables through the conduit on the scanner arm (it may be necessary to remove the attenuators to get the cables through the conduit).

3.3 Mount the eddy-current probe in the scanner head. Leave enough slack in the cables to allow the probe and scanner head to move freely. Tighten the locking bolt just enough to hold the probe securely. DO NOT LET THE SCANNER HEAD FALL ON THE CONTROL ROD.

3.4 Firmly connect the attenuators and cables to the correct jacks on the modular eddy-current instrument (Fig. 5).

3.5 Connect the output of the AC OUTPUT LEVELS jack (in the back of the modular eddy-current instrument) to the left channel of the strip-chart recorder.

3.6 Connect the output of the PHASE 1 jack (in the back of the modular eddy-current instrument) to the right channel of the strip-chart recorder. The connections made in steps 3.5 and 3.6 determine the direction in which the recorder pens are deflected. Reversing the two "active" leads for each connection will reverse the direction of the recorder pen deflection.

3.7 Connect the event marker signal leads (from the microswitch on the fixture) to the back of the strip-chart recorder. (Usually the left recorder channel is used.)

3.8 Connect the electrical power cables to all instruments and the scanning fixture.

3.9 Optional: Place the thermometer in a convenient location near the test fixture.

4. Instrument Setup and Calibration

4.1 An absolute phase calibration should be performed on the eddy-current instrument prior to moving it to the test site.

4.2 At the test site, make the following instrument settings:

(a) frequency control to 10 kHz (PA/OSC module),

(b) 180° phase switch (inside DISC module) in the "up" position,

(c) PA1/VA2 switch to PA1 (DPM module),

(d) PA2/VA1 switch to VA1 (DPM module),

(e) selector switch to COMP1 (DPM module),

(f) left recorder channel "step" sensitivity control to 20 mV/div,

(g) right recorder channel "step" sensitivity control to 100 mV/div, and

(h) both left and right recorder channel "variable" sensitivity controls to maximum, that is, fully clockwise.

4.3 Turn the equipment on and allow a sufficient warm-up time (at least 1 h) for all instruments to stabilize electrically.

4.4 Adjust the power amplifier gain control to get a reading of 50 mA on the PA1 meter.

4.5 Firmly hold cladding sample 1 on the face of the eddy-current probe and adjust the video amplifier gain control(s) to get a reading of 46 mA on the VA1 meter. It will be necessary to hold all cladding samples firmly against the face of the eddy-current probe to obtain consistent readings during the instrument setup.

4.6 Move the probe and scanner head to an area near the "start" position for the test (refer to step 1.4).

4.7 Gently place the scanner head and probe in a solid area on the control rod.

4.8 Loosen the probe in the scanner head and place a piece of 0.05-mm-thick nonconductive shim between the face of the eddy-current probe and the control rod.

4.9 Tighten the locking bolt on the scanner head to secure the eddy-current probe at the 0.05-mm lift-off position. (Be careful not to press down or lift up on the probe when securing it in the scanner head. One technique for maintaining the probe in a 0.05-mm lift-off position is to observe the left channel of the recorder while making this adjustment.) Remove the 0.05-mm shim after tightening the locking bolt. This adjustment, which is made with the probe head rollers in contact with the control rod, recesses the probe head for safety precautions and sets the reference lift-off position. It is necessary to press one of the speed control buttons to get a reading on the recorder. Generally the 1- or 5-mm/s speed is used during setup to conserve chart paper.

4.10 Using clad sample 6 and the 0.15-mm-thick shim, adjust the lift-off controls on the discriminator module so that no significant phase shift occurs for a lift-off range of 0 to 0.15 mm. Appendix D provides guidelines for making this adjustment. Several steps in this procedure require "checks" of the lift-off and/or cladding thickness calibrations. These frequent checks are made to ensure that no changes have occurred in the instrumentation or equipment setup. No instrument adjustments should be made during these checks. If significant changes are detected, notify your supervisor. The balance control on the discriminator module and/or the position controls on the recorder may be used to keep the recorder pen on scale. The sensitivity controls on the left recorder channel should be set so that the pen stays on scale for 0- to 0.15-mm (6-''' lift-off signals, and the pen deflection should cover a span c ıst two-thirds the width of the chart paper.

4.11 Firmly hold cladding sample 1 on the face ι eddy-current probe and adjust the recorder right channel pen "*position*" control to place the pen on the line 20 divisions to the left of center on the chart paper.

4.12 Firmly hold cladding sample 12 on the face of the eddy-current probe and adjust the recorder right channel "*variable sensitivity*" control to place the pen on the line 15 divisions to the right of center on the chart paper.

4.13 Repeat steps 4.11 and 4.12 until the recorder pen shifts to the correct positions on the chart, with no adjustments, as cladding samples 1 and 12 are alternately placed on the eddy-current probe.

4.14 Using cladding samples 1, 6, 7, 8, 10, 11, and 12, record a cladding calibration curve similar to that shown in Fig. 10.

4.15 Make a lift-off check of 0- and 0.15-mm (6-mil), using each of cladding samples 1, 6, and 12. (There should be little or no phase shift for each of these lift-off settings.) Record this lift-off check in a manner similar to Fig. 9.

4.16 File the recordings made in steps 4.14 and 4.15 in the HFIR logbook along with the instrument serial numbers (or identities) and the instrument settings. Also record the inner control rod identity.

4.17 Check the recorder ink supply and refill if it is less than one-fourth full.

4.18 Make sure that the recorder has a nearly full roll of chart paper. If not, replace the old chart roll with a new one. Use 122-m (400-ft) chart rolls when available.

4.19 Record the following information on the chart roll:

(a) chart roll number (number the rolls consecutively as data are taken),

(b) date and initials of tester(s),

(c) control rod identification number,

(d) reference page in logbook where data are filed for steps 4.14 and 4.15,

(e) the position on the inner control rod where the test started or stopped,

(f) chart speed and sensitivity, and

(g) type of eddy-current probe and serial number.

4.20 The chart paper should be attached to the take-up reel if one is available.

4.21 Repeat the cladding thickness calibration and lift-off checks described in steps 4.14 and 4.15. LEAVE THESE RECORDINGS ON THE CHART ROLL. The cladding thickness calibration check (step 4.14) is required only at the beginning and end of the test for each particular inner control rod inspection. The lift-off check (step 4.15) should be performed at the beginning and end of each chart roll. Any time the test is halted for an extended period of time, a lift-off check should be recorded at the end of testing and at the resumption of testing.

4.22 Correct for baseline differences between the materials used in the cladding samples and in the inner control rod as follows:

(a) Firmly hold cladding sample 1 on the face of the eddy-current probe and record the baseline reading on the right recorder channel. [The pen should write on the line 20 divisions to the left of center on the recorder chart (see step 4.11). If not, recheck the lift-off and cladding thickness calibrations.]

(b) Gently place the scanner head and probe down on a solid area over the 6061 aluminum on the end of the control rod (Fig. 1). Make sure that the head and probe are properly seated, that is, not tilted. (Observe the left recorder pen as the part rotates in a counterclockwise direction; the signal magnitude should remain constant.)

(c) Adjust the "position" control on the *right* channel of the recorder to place the recorder pen on the line 20 divisions to the left of center on the chart paper.

(d) Firmly hold cladding sample 1 on the face of the eddy-current probe and record the baseline reading.

(e) Identify the above adjustments and label the baselines on the chart [cladding sample 1 (before and after adjustment) and the inner control rod (before and after adjustment)]. Note on the chart the approximate location on the inner control rod where the eddy-current probe was sitting when the adjustment was made.

(f) Record the amount of baseline adjustment (in chart divisions) in the HFIR logbook.

4.23 Record any future baseline adjustments (made during the test) in the logbook and on the chart paper.

5. Test Procedure

5.1 Move the scanner head and probe to the "start" position on the control rod for this test (refer to step 1.4).

5.2 Start the test by simultaneously operating the REV switch on the scanning fixture and pressing the 5-mm/s speed switch on the recorder.

5.3 Determine the quadrant of the control rod in which the event marker occurs and note this on the recorder chart and in the logbook.

5.4 At the beginning of the test, visually examine the control rod as it rotates in the scanning fixture and record any obvious surface irregularities such as gouges, scratches, dents, or blisters in the logbook.

5.5 Observe the recorder chart as the test progresses, note any unusual or significant variation in cladding thickness, and reference the area on the control rod where the variation occurs. Frequent inking problems occur with these recorders. If the problem is minor, it can usually be corrected without interrupting the test. If the problems cannot be quickly corrected, stop both the recorder and the scanner drive system at the same time, correct the problem, and restart the recorder and scanner drive system simultaneously.

5.6 This test will be completed when the eddy-current probe reaches the first row of holes beyond the Eu_2O_3 area. This inspection requires about 4 h of continuous scanning time. One (122-m) roll of recorder chart paper will be required to complete the examination.

5.7 At the end of the test, perform the following steps:

(a) Repeat the baseline check per step 4.22(d) and identify on the recorder chart.

(b) Reset the baseline per step 4.11.

(c) Repeat the cladding calibration and lift-off checks, steps 4.14 and 4.15.

(d) Record the information required in step 4.19.

5.8 All calibration checks should agree within 10% with those made at the start of the examination; if they do not, discuss the situation with your supervisor.

5.9 This completes the cladding thickness examination. Remove the recorder chart roll, place it in a box, and identify the box.

5.10 Reduce the data per Appendix E.

Appendix C

PROCEDURE FOR EXAMINING HFIR CONTROL RODS FOR DEFECTS AND FOR MEASURING OXIDE AND CLADDING THICKNESSES IN THE REACTOR POOL

New control rods can be tested at nearly any convenient site in the HFIR building, but used control rods are highly radioactive and must be inspected inside the reactor pool. The basic objectives of the inspections are the same, but tests inside the reactor pool are more complex; therefore, special steps are required to achieve the final goals.

The order in which the tests are conducted is important. This procedure is therefore separated into two parts, which should be conducted in order and consecutively. Part 1 describes how to perform the defect and oxide thickness examination. Part 2 describes how to measure the cladding thickness.

All safety rules and precautions that apply for working with radioactive materials should be exercised when conducting this test.

1. Procedure for Testing for Defects and Oxide Thickness on the HFIR Inner Control Rod (Inside the Reactor Pool)

1.1 General

1.1.1 This procedure describes the techniques for locating surface and near-surface defects on the HFIR inner control rod (Fig. 1) when the tests are conducted inside the reactor pool. It also describes how the thickness of the surface layer of aluminum oxide is measured simultaneously.

1.1.2 The defect inspection should start between the row of screws and the first row of holes, counting from the crossarm end of the rod, and stop at the twelfth row of holes beyond the Eu_2O_3 area (Fig. 1).

1.2 Equipment

1.2.1 A modular phase-sensitive eddy-current instrument including the following modules or equivalent:

Component	Serial
Power oscillator	PA-101
Video amplifier	VAHF-104
Phase discriminator	DISC-102
Display module	DPM-102
Closed-loop differential amplifier	CLDA-101

1.2.2 A 20D reflection-type, eddy-current probe with about 6 m of RG62-B/U-shielded cable and the following attenuators:

Component	Value
Driver resistance	82.5 Ω (series)
Driver capacitance	Cable only (~300 pF)
Pickup resistance	133 Ω (parallel)
Pickup capacitance	Cable only (~300 pF)

The eddy-current probe should have no protective tape on its face when the inspection is conducted inside the pool.

1.2.3 A two-channel strip-chart recorder (a Brush recorder, model Mark 220 or equivalent).

1.2.4 A HFIR inner control rod scanner assembly fixture (ORNL-DWG E49150 through ORNL-DWG E49154 or equivalent).

1.2.5 HFIR control rod H.

1.2.6 A curved aluminum reference sample.

1.2.7 Several pieces of 0.05- and 0.1-mm shim stock, made of a non-conducting material.

1.3. Preliminary Setup

1.3.1 The initial setup and instrument checkout should be performed at poolside.

1.3.2 Place control rod H in the test fixture with the crossarm end located at the scanner drive arm. The eddy-current probe and scanner head should be lifted off the part when operating with the scanner in the FOR position. All tests should be performed with the scanner switch in the REV position.

1.3.3 Pass the eddy-current probe cables through the conduit on the scanner arm. (It may be necessary to remove the attenuators to get the cables through the conduit.)

1.3.4 Mount the eddy-current probe in the scanner head. Leave enough slack in the cables to allow the probe to move freely. Tighten the locking bolt only enough to hold the probe securely. DO NOT LET THE SCANNER HEAD FALL ON THE CONTROL ROD.

1.3.5 Firmly connect the attenuators and cables to the correct jacks on the modular eddy-current instrument (Fig. 5).

1.3.6 Connect the output of the AC OUTPUT LEVELS jack (in the back of the modular eddy-current instrument) to the left channel of the strip-chart recorder.

1.3.7 Connect the output of the PHASE 1 jack (in the back of the modular eddy-current instrument) to the right channel of the strip-chart recorder. The connections made in steps 1.3.6 and 1.3.7 determine the direction in which the recorder pens are deflected. Reversing the two "active" leads for each connection will reverse the direction of the recorder pen deflection.

1.3.8 Connect the event marker signal leads (from the microswitch on the fixture) to the back of the strip-chart recorder. (Usually the left recorder channel is used.)

1.3.9 Connect the electrical power cables to all instruments and the scanning fixture.

1.4. Instrument Calibration and Setup

1.4.1 An absolute phase calibration should be performed on the eddy-current instrument in the laboratory before moving it to the test site.

1.4.2 At the test site, make the following instrument settings:

(a) frequency control to 2 MHz (PA/OSC module),

(b) 180° phase switch (inside DISC module) in the "up" position,

(c) PA1/VA2 switch to PA1 (DPM module),

(d) PA2/VA1 switch to VA1 (DPM module),

(e) selector switch to COMP1 (DPM module),

(f) both left and right recorder channel "step" sensitivity controls to 50 mV/div,

(g) both left and right recorder channel "variable" sensitivity controls to maximum, that is, fully clockwise.

1.4.3 Turn the equipment on and allow a sufficient warm-up time (at least 1 h) for all instruments to stabilize electrically.

1.4.4 Adjust the power amplifier gain control to get a reading of 50 ma on the PA1 meter.

1.4.5 Gently place the scanner head and probe in a defect-free area in the Eu_2O_3 region on the control rod H. Make sure the head and probe are properly seated, that is, not tilted. (The depth of penetration of the 20D probe at 2 MHz is less than the cladding thickness, therefore lift-off can be set with the probe over any cladding area. The probe should be kept away from the holes to avoid edge effects.)

1.4.6 Adjust the video amplifier gain control(s) to get a reading of 46 mA on the VA1 meter, with the probe seated on the control rod.

1.4.7 Loosen the probe in the scanner head and place a piece of 0.05-mm-thick nonconductive shim between the face of the eddy-current probe and the control rod.

1.4.8 Tighten the locking bolt on the scanner head to secure the eddy-current probe at the 0.05-mm lift-off position. (Be careful not to press down or lift up on the probe when securing it in the scanner head. One technique for maintaining the probe in a 0.05-mm lift-off position is to observe the left channel of the recorder while making this adjustment.) Remove the 0.05-mm shim after tightening the locking bolt. This adjustment, which is made with the probe head rollers in contact with the control rod, recesses the probe head for safety precautions and sets the reference lift-off position. It is necessary to press one of the speed-control buttons to get a reading on the recorder. Generally the 1- or 5-mm/s speed is used during setup to conserve chart paper.

1.4.9 Using the procedure provided in Appendix D, adjust the lift-off controls on the discriminator module so that no significant phase shift occurs for a lift-off range of 0 to 0.15 mm. THE SHIMS MUST BE PLACED BETWEEN THE ROLLERS ON THE EDDY-CURRENT SUPPORT ARM AND THE CONTROL ROD FOR THIS ADJUSTMENT.

1.4.10 Check the oxide thickness calibration by alternately placing the 0.05-, 0.1-mm, and then both shims between the probe head rollers and the control rod and observing the reflected signal magnitude. The reflected signal phase (right channel) should remain constant during these tests. Make two recordings similar to Fig. 6. File one recording in the HFIR logbook along with the instrument identities, instrument settings, and the control rod identity. Leave the other recording on the chart.

1.4.11 Place the scanner head and probe in a position (29 5/16-in. mark on the scale) on control rod H that will allow the eddy-current probe to pass over the notches when the scanner is rotated. Make sure the eddy-current probe is properly seated on the part.

1.4.12 Adjust the left and right recorder channels so that both pens write on the line 20 divisions to the left of center on the respective charts. The pen on the left recorder channel (magnitude signal) is set using the "position" control on the recorder. Two controls will affect the phase reading on the right recorder channel; their proper setting is as follows: unplug the input to the right channel of the recorder. Using the recorder "position" control, set the pen in the center of the recorder chart and lock the control. Then reconnect the input to the right channel and adjust the "balance" control on the eddy-current instrument to position the recorder pen. The sensitivity controls on the left recorder channel should be set so that the pen stays on scale for 0- to 0.1-mm lift-off signals, and the pen deflection should cover a span of at least two-thirds the width of the chart paper.

1.4.13 Make a defect calibration scan by simultaneously operating the REV switch on the scanner and the 25-mm/s speed button on the recorder.

1.4.14 Make several revolutions of the part and record the notch indications on each revolution (Fig. 7). Record the notches for a sufficient number of revolutions to obtain an average depth near the center of the notch lengths. Save these recordings.

1.4.15 Average the three highest depth indications obtained for each notch on the scans made in step 1.4.14. Record the three values and the average for each notch in the HFIR logbook. File a representative scan of the notches in the logbook along with the instrument identities, instrument settings, and control rod identification.

1.4.16 Check the recorder ink supply and refill if it is less than one-fourth full.

1.4.17 Make sure that the recorder has a nearly full roll of chart paper. If not, replace the old chart roll with a new one. Use 122-m (400-ft) chart rolls when available.

1.4.18 Record the following information on the chart roll:

(a) chart roll number (number the rolls consecutively as data are taken),
(b) date and initials of tester(s),
(c) control rod identification number,
(d) reference page in logbook where data are filed for steps 1.4.10 and 1.4.15,
(e) the position on the inner control rod where the test started or stopped,
(f) chart speed and sensitivity, and
(g) type of eddy-current probe and serial number.

1.4.19 The chart paper should be attached to the take-up reel if one is available.

1.4.20 Repeat representative oxide thickness and defect calibration scans as described in steps 1.4.10 through 1.4.14. Leave these recordings on the chart roll. The defect calibration check and oxide thickness (steps 1.4.10—1.4.14) calibration are required only at the beginning and end of the inspection for each particular inner control rod. The lift-off check (step 1.4.9) should be performed at the beginning and end of each chart roll. Any time the test is halted for an extended period of time, such as overnight, a lift-off check should be recorded at the end of testing and at the resumption of testing. (The lift-off check provides assurance that no significant changes have occurred in the eddy-current instrumentation and setup.)

1.4.21 When the inspection is being conducted in the reactor pool, a lift-off calibration check can be made as follows: Gently lift the eddy-current probe with the nylon string and observe both recorder channels. When the left recorder channel (magnitude signal) has deflected the maximum number of chart divisions as was obtained on the initial oxide thickness check (step 1.4.10), hold the pen steady. Then slowly lower the pen back to the surface of the control rod and observe both recorder channels. The phase signal (right channel) should not vary. Make two recordings and identify as lift-off checks. File one in the HFIR logbook and leave one on the recorder chart.

1.4.22 At this point, the entire scanning system including control rod H should be lowered into the reactor pool and left overnight or approximately 8 h to reach thermal equilibrium. HANDLE THE CONTROL RODS VERY CAREFULLY AND AVOID DAMAGE TO THE EDDY-CURRENT PROBE.

1.4.23 After the system has reached thermal equilibrium, the magnitude (left recorder channel) should be repositioned to the line 20 divisions to the left of center using the recorder pen "position" control (step 1.4.12). The phase (right recorder channel) should be repositioned using the eddy-current instrument's "balance" control.

1.4.24 A lift-off check (1.4.21) and scan of the seven notches in control rod H should be repeated in the reactor pool and recorded on the chart roll. At this point, control rod H can be removed and the control rod to be examined can be placed in the scanner.

1.4.25 Identify the inner control rod to be inspected and record this identity in the HFIR logbook.

1.5 Test Performance

1.5.1 The control rod to be inspected should be in the scanning fixture and the scanning arm should be between the 29- and 30-in. marks on the scale.

1.5.2 Perform a lift-off check per step 1.4.21 and record the results in the logbook and on the recorder chart.

1.5.3 Recall that the pens were set to record on the line 20 divisions to the left of center in step 1.4.23. Check the two recorder pens and note where they write on the recorder chart, then do one of the following:

(a) If the right pen (phase) is shifted slightly (<10 divisions), the shift is probably caused by a change in electrical conductivity between the control rod being tested and control rod H. Use the balance control on the eddy-current instrument to reset the pen to the line 20 division to the left of center.

(b) If the left pen (magnitude) has shifted slightly (<10 divisions), the shift is caused by a lift-off change, which is probably a result of oxide buildup in the test piece. DO NOT reset the pen. Note the difference in the logbook and on the recorder chart and continue the test by using this new reference line for oxide thickness variations within the part being tested.

(c) If either pen has shifted more than 10 divisions, check the aluminum oxide thickness reference sample to determine whether the shift is real or if you have an instrument problem. If it is an instrument problem, the entire system will have to be recalibrated outside of the pool. If the shift is real, discuss the situation with your supervisor.

1.5.4 Place the scanner head and probe in a position on the control rod between the screws and the first row of holes, counting from the crossarm end of the control rod.

1.5.5 Start the test by simultaneously operating the REV switch on the scanning fixture and pressing the 25-mm/s speed switch on the recorder.

1.5.6 Determine in what quadrant of the control rod the event marker occurs and note this on the recorder chart and in the logbook.

1.5.7 At the beginning of the test, visually examine the control rod as it rotates in the scanning fixture and record any obvious surface irregularities such as gouges, scratches, dents, or blisters in the logbook.

1.5.8 Observe the recorder chart as the test progresses, note any unusual or significant indications, and try to obtain a visual location and confirmation on the control rod. Frequent inking problems occur with these recorders. If the problem is minor, it can usually be corrected without interrupting the test. If the problems cannot be quickly corrected, stop both the recorder and the scanner drive system at the same time, correct the problem, and restart the recorder and scanner drive system simultaneously.

1.5.9 A 122-m roll of chart paper will last for about 1.5 h of continuous testing. In 1.5 h the eddy-current probe will scan approximately

22 cm along the axis of the rod. When the recorder chart paper nears the end of the roll, simultaneously stop the recorder and scanner drive system and perform the following steps:

(a) Add the information required in step 1.4.18 on the end of the chart roll.

(b) Repeat the lift-off check (step 1.4.21) and record the data on the end of the chart roll.

(c) Remove the used chart roll and replace it with a new one. Place the used chart roll in the box that contained the new one and identify the box.

(d) Log the information required in step 1.4.18 on the new chart.

(e) Repeat a lift-off check (step 1.4.21) and record the data on the new chart.

1.5.10 Resume the test by simultaneously starting the recorder (25 mm/s) and the scanner drive system (REV). The test will be completed when the eddy-current probe reaches the 12th row of holes beyond the Eu_2O_3 area. If the test should be halted for any length of time with the eddy-current probe located in the area of high radiation on the control rod, lift the scanning arm (using the nylon string) to its maximum raised position until testing resumes.

1.5.11 At the end of the test, perform the following steps:

(a) Record the information required in step 1.4.18.

(b) Repeat a lift-off check (step 1.4.21) and record the data.

(c) Remove the inner control rod from the scanner fixture and place the standard H control rod in the fixture.

(d) Move the scanning arm to the 29 5/16-in. mark on the scale.

(e) Place the eddy-current probe on the part and check the oxide thickness reference line. Both recorder pens should write on the line 20 divisions to the left of center. Record this information in the logbook and on the recorder chart. If either pen has shifted more than five chart divisions from the reference line, bring the attention of your supervisor to this fact.

(f) Repeat the defect calibration scans per steps 1.4.11 through 1.4.14 and record the data.

1.5.12 The lift-off and defect calibration checks should agree within 10% with those made at the start of the examination.

1.5.13 This completes the defect and oxide thickness test. Reduce the data per Appendix E.

1.5.14 The next step in this procedure will be to measure the cladding thickness.

2. Procedure for Measuring Cladding Thickness on the HFIR Inner Control Rod (Inside the Reactor Pool)

2.1 General

2.1.1 This procedure describes the techniques used to measure the thickness of the 6061 aluminum cladding over the europium oxide (Eu_2O_3) area on the HFIR inner control rod (Fig. 1) when the tests are conducted inside the reactor pool.

2.1.2 This portion of the procedure is written with the assumption that the defect examination has just been completed and that all electrical connections are the same. Control rod H will be in the scanning fixture, and both should be in the reactor pool.

2.1.3 The cladding thickness inspection should start at the last row of holes before the Eu_2O_3 area, counting from the crossarm end of the control rod, and stop at the first row of holes beyond the Eu_2O_3 area (Fig. 1).

2.2. Equipment

2.2.1 Essentially the same test equipment is used for this inspection as was used for the defect examination. The following additional equipment is required.

2.2.2 An 83B reflection-type eddy-current probe with about 6 m of red Microdot coaxial cable and the following attenuators:

Component	Value
Driver resistance	500 Ω (series)
Driver capacitance	0.0047 μF (shunt)
Pickup resistance	620 Ω (parallel)
Pickup capacitance	0.0047 μF (shunt)

The eddy-current probe should have no protective tape on its face when the inspection is conducted in the pool.

2.2.3 A set of cladding thickness standards (Table 3).

2.2.4 Several pieces of 0.15- and 0.25-mm-thick shim stock, made of a nonconducting material.

2.3. Instrument Setup

2.3.1 Disconnect the 20D probe used for the defect examination at the eddy-current instrument and remove the associated attenuators. Secure the cables so they cannot fall into the reactor pool.

2.3.2 Connect the 83B probe and associated attenuators mentioned in step 2.2.2 to the eddy-current instrument.

2.3.3 Make the following instrument settings:

(a) frequency control to 10 kHz (PA/OSC module),
(b) 180° phase switch (inside DISC module) in the "up" position,
(c) PA1/VA2 switch to PA1 (DPM module),
(d) PA2/VA1 switch to VA1 (DPM module),
(e) selector switch to COMP1 (DPM module),
(f) left recorder channel "step" sensitivity control to 20 mV/div,
(g) right recorder channel "step" sensitivity control to 100 mV/div, and
(h) both left and right recorder channel "variable" sensitivity controls to maximum, that is, fully clockwise.

2.3.4 If electrical power has been shut off, turn the equipment on and allow a sufficient warm-up time (at least 1 h) for all instruments to stabilize electrically.

2.3.5 Adjust the power amplifier gain control to get a reading of 50 mA on the PA1 meter.

2.3.6 Firmly hold cladding sample 1 on the face of the eddy-current probe and adjust the video amplifier gain control(s) to get a reading of 46 mA on the VA1 meter. It will be necessary to hold all cladding samples firmly against the face of the eddy-current probe to obtain consistent readings during the instrument setup.

2.3.7 Using cladding sample 6 and the 0.25-mm-thick shim, adjust the lift-off controls on the discriminator module so that no significant phase shift occurs for a lift-off range of 0 to 0.25 mm. The procedure in

Appendix D provides guidelines for making this adjustment. Several steps in this procedure require checks of the lift-off and/or cladding thickness calibrations. These frequent checks are made to assure that no changes have occurred in the instrumentation or equipment setup. No instrument adjustments should be made during these checks. If significant changes are detected, notify your supervisor. The balance control on the discriminator module and/or the position controls on the recorder may be used to keep the recorder pen on scale. The sensitivity controls on the left recorder channel should be set so that the pen stays on scale for 0- to 0.25-mm lift-off signals, and the pen deflection should cover a span of at least two-thirds the width of the chart paper.

2.4 Instrument Calibration and Setup

2.4.1 Firmly hold cladding sample 1 on the face of the eddy-current probe and adjust the recorder right channel pen *position* control to place the pen on the line 20 divisions to the left of center on the chart paper.

2.4.2 Firmly hold cladding sample 12 on the face of the eddy-current probe and adjust the recorder right channel *variable sensitivity* control to place the pen on the line 15 divisions to the right of center on the chart paper.

2.4.3 Repeat steps 2.4.1 and 2.4.2 until the recorder pen shifts to the correct positions on the chart, with no adjustments, as cladding samples 1 and 12 are alternately placed on the eddy-current probe.

2.4.4 Using cladding samples 1, 6, 7, 8, 10, 11, and 12, record a cladding calibration curve similar to that shown in Fig. 10.

2.4.5 Make a lift-off check of 0 to 0.25 mm, using each of cladding samples 1, 6, and 12. (There should be little or no phase shift for each of these lift-off settings.) Record this lift-off check in a manner similar to Fig. 9.

2.4.6 File the recordings made in steps 2.4.4 and 2.4.5 in the HFIR logbook along with the instrument serial numbers (or identities) and the instrument settings. Also record the inner control rod identity.

2.4.7 Check the recorder ink supply and refill if it is less than one-fourth full.

2.4.8 Make sure the recorder has a nearly full roll of chart paper. If not, replace the old chart roll with a new one. Use 122-m chart rolls when available.

2.4.9 Record the following information on the chart roll:

(a) chart roll number (number the rolls consecutively as data are taken),

(b) date and initials of tester(s),

(c) control rod identification number,

(d) reference page in logbook where data are filed for steps 2.4.4 and 2.4.5,

(e) the position on the inner control rod where the test started or stopped,

(f) chart speed and sensitivity, and

(g) type of eddy-current probe and serial number.

2.4.10 The chart paper should be attached to the take-up reel if one is available.

2.4.11 Repeat the cladding thickness calibration and lift-off checks described in steps 2.4.4 and 2.4.5. LEAVE THESE RECORDINGS ON THE CHART ROLL. The cladding thickness calibration check (step 2.4.4) is required only at the beginning and end of the test for each particular inner control rod inspection. The lift-off check (step 2.4.5) should be performed at the beginning and end of each chart roll. Any time the test is halted for an extended period of time, a lift-off check should be recorded at the end of testing and at the resumption of testing.

2.4.12 Remove control rod H from the scanning fixture, raise the scanning fixture to the top of the pool, and leave the fixture supported by the hoist. At this point, the scanning fixture will be slightly radioactive, and all safety precautions relating to working with radioactive materials should be observed. Also take care that no tools or other items are dropped into the reactor pool while performing the following checks.

2.4.13 Remove the 20D probe and cables used for the defect test. These items will be slightly radioactive; place them in a plastic bag and identify it for decontamination.

2.4.14 Mount the eddy-current probe in the scanner head. Leave enough slack in the cables to allow the probe and scanner head to move freely. Tighten the locking bolt just enough to hold the probe securely. DO NOT LET THE SCANNER HEAD FALL ON THE CONTROL ROD.

2.4.15 Secure the upper end of the probe cables (near the eddy-current instrument) using a nylon cord.

2.4.16 Hold the scanner head and probe on the curved aluminum reference samples, and set the baseline lift-off position as follows:

2.4.17 Loosen the probe in the scanner head and place a piece of 0.15-mm-thick nonconductive shim between the face of the eddy-current probe and the curved aluminum sample.

2.4.18 Tighten the locking bolt on the scanner head to secure the eddy-current probe at the 0.15-mm lift-off position. (Be careful not to press down or lift up on the probe when securing it in the scanner head. One technique for maintaining the probe in a 0.15-mm, lift-off position is to observe the left channel of the recorder while making this adjustment.) Remove the 0.15-mm shim after tightening the locking bolt. This adjustment, which is made with the probe head rollers in contact with the curved sample, recesses the probe head for safety precautions and sets the reference lift-off position.

2.4.19 Make a cladding thickness calibration check by alternately placing cladding samples 1, 6, and 12 on the face of the eddy-current probe. Record this check similar to Fig. 10, identify, and leave on the chart roll.

2.4.20 Make a lift-off calibration check by alternately placing a 0.25-mm-thick shim between the eddy-current probe and sample for each of cladding thickness samples 1, 6, and 12. Record these data similar to Fig. 9, identify, and leave on the recorder.

2.4.21 Lower the scanning fixture back into the reactor pool.

2.4.22 Place the control rod to be inspected in the test fixture with the crossarm end located at the scanner drive arm. The eddy-current probe and scanner head should be lifted off the part when operating with the scanner in the FOR position. Use the attached nylon string to raise the arm. All tests should be performed with the scanner switch in the REV position.

2.4.23 Move the probe and scanner head to an area near the "start" position for the test (refer to step 2.1.3).

2.4.24 At this point the eddy-current probe, scanning fixture, and control rod must reach thermal equilibrium with the pool water before testing can continue. Leave the system in the pool overnight or approximately 8 h to reach thermal equilibrium.

2.4.25 After the system has reached thermal equilibrium, place the scanner head and probe on a solid area of aluminum at the end of the control rod. Then perform a lift-off check as follows: gently lift the eddy-current probe with the nylon string and observe both recorder channels. When the left recorder channel (magnitude signal) has deflected the maximum number of chart divisions as was obtained on step 2.4.20, hold the pen steady. Then slowly lower the pen back to the surface of the control rod and observe both recorder channels. The phase signal (right channel) should not vary. Identify this recording and leave on the recorder chart.

2.4.26 Correct for baseline differences between the materials used in the cladding samples and the inner control rod as follows:

(a) Make sure the head and probe are properly seated and observe the left recorder pen as the part rotates in a counterclockwise direction. The signal magnitude should remain constant.

(b) Adjust the "position" control on the *right* channel of the recorder to place the recorder pen on the line 20 divisions to the left of center on the chart paper. Identify this adjustment on the chart roll.

(c) If possible, record the amount of baseline adjustment (in chart divisions) in the HFIR logbook. Record the approximate position of the probe on the control rod when the adjustment is made.

(d) Record any future baseline adjustments (made during the test) in the logbook and on the chart paper.

The baseline reference level can shift during an examination as a result of recorder drift. Recorder drift can be identified by observing the right recorder channel as the eddy-current probe crosses one of the longitudinal welds on the control rod. The area on either side of the weld is pure aluminum and the recorder pen should write on the line 20 divisions to the left of center on the chart for a brief time as the probe traverses these areas. If it does not, the problem is probably caused by recorder drift. Use the "position" control on the right recorder channel to correct for recorder drift and identify the correction on the recorder chart and in the HFIR logbook per step (c) above.

2.5 Test Procedure

2.5.1 Move the scanner head and probe to the "start" position on the control rod for this test (refer to step 2.1.3).

2.5.2 Start the test by simultaneously operating the REV switch on the scanning fixture and pressing the 5-mm/s speed switch on the recorder.

2.5.3 Determine in what quadrant of the control rod the event marker occurs and note this on the recorder chart and in the logbook.

2.5.4 Observe the recorder chart as the test progresses, note any unusual or significant variation in cladding thickness, and reference the area on the control rod where the variation occurs. Frequent inking problems occur with these recorders. If the problem is minor, it can usually be corrected without interrupting the test. If the problems cannot be quickly corrected, stop both the recorder and the scanner drive system at the same time, correct the problem, and restart the recorder and scanner drive system simultaneously. If the test is halted for a significant amount of time (>1 h), repeat a lift-off check per step 2.4.25, identify, and leave on the chart roll.

2.5.5 This test will be completed when the eddy-current probe reaches the first row of holes beyond the Eu_2O_3 area. This inspection requires about 4 h of continuous scanning time. One (122-m) roll of recorder chart paper will be required to complete the examination.

2.5.6 At the end of the test, perform the following steps:

(a) Return the control arm to place the eddy-current probe over an area of solid aluminum (near the end of the control rod).

(b) Make a baseline reference check by recording a couple of revolutions of the control rod. The recorder pen should write on the line 20 divisions to the left of center on the chart paper. IDENTIFY THIS CHECK ON THE RECORDER CHART BUT MAKE NO ADJUSTMENTS. Small shifts (<5 div) may occur from recorder drift, etc. Report any change greater than five small divisions on the recorder chart to your supervisor.

2.5.7 Remove the control rod from the scanning fixture.

2.5.8 Raise the scanning fixture to the top of the pool and leave the fixture supported by the hoist.

2.5.9 Reset the baseline per step 2.4.1 and identify on the recorder chart.

2.5.10 Recheck the cladding thickness and lift-off calibrations by repeating steps 2.4.19 and 2.4.20. Make two recorded copies of each check. File one in the HFIR logbook and leave the other on the chart roll.

2.5.11 All calibration checks should agree within 10% with those made at the start of the examination; if they do not, discuss the situation with your supervisor.

2.5.12 Record the information required in step 2.4.9.

2.5.13 This completes the cladding thickness examination. Remove the recorder chart roll, place it in a box, and identify the box.

2.5.14 Reduce the data per Appendix E.

All materials involved with this test, including the data, must go through a decontamination procedure and a health physics check before removing them from the HFIR building.

Appendix D

LIFT-OFF COMPENSATION FOR REFLECTION-TYPE, EDDY-CURRENT COILS

The term lift-off in eddy-current terminology refers to the spacing between the eddy-current coil and the conductive material being examined.[1] Whether or not lift-off is the primary variable being measured, it must always be accounted for during an eddy-current examination. This appendix describes the techniques for reducing the effects of lift-off on the phase portion of the eddy-current signal when reflection-type coils are used with the phase-sensitive eddy-current instrument.[2–4]

Use the sample being measured as the conductor whenever possible. Access should be available to the bare surface of the conductor. If the part being measured is not accessible, a sample of material having similar geometry and electrical (magnetic) properties can be used.

The spacer or shim stock should be electrically nonconducting and should have a thickness equal to the maximum lift-off desired.

Eddy-current coils are typically sensitive to thermal variations. Take care to maintain the eddy-current probe at a uniform temperature during use.

The following steps can be used to perform the specific lift-off adjustment described above:

1. Place the eddy-current probe on a defect-free area or on the conductor and record the digital meter reading on the eddy-current instrument.

2. Place a piece of shim (of desired thickness) between the eddy-current probe and the conductor and record the digital meter reading.

3. Hold the shim between the probe and conductor and adjust the coarse and fine lift-off controls on the discriminator module to get the same reading on the digital meter as was obtained in step 1.

4. Repeat steps 1, 2, and 3 until the same digital meter reading is obtained in steps 1 and 2 with no adjustment. An initial adjustment in step 3 will reduce the number of repetitive adjustments required. The "balance" control on the discriminator module can be used to shift the meter readings without affecting the adjustment.

5. When the two readings (steps 1 and 2) are equal, repeat step 2 by using a shim thickness of half the maximum lift-off desired. This reading provides a measure of linearity for the lift-off compensation.

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Appendix E

EVALUATION OF DATA ON THE HFIR INNER CONTROL ROD

All data for these inspections are recorded; therefore, permanent records are maintained. The data should also be monitored as the test progresses. This allows the operator to detect any irregularities or unusual occurrences in the data as they occur. The indications can be quickly correlated to a given area on the control rod, and that area can be visually examined as the test progresses. It also provides for quick detection of any problem that may occur in the test setup. Any unusual event should be recorded in the data logbook for future reference.

All data are recorded in the form of analog signals on strip-chart recording paper. We now have the capability to analyze automatically these data by adding a small minicomputer to the eddy-current test system, but all data obtained to date have been evaluated manually. This appendix describes these manual techniques for data analysis.

EVALUATION OF DEFECT INSPECTION DATA

Approximately six rolls of 122-m-long (400-ft) recorder chart paper are required to complete a defect test for one control rod. There are two channels of data on each chart roll. The left recorder channel contains amplitude data that are used to determine the oxide thickness and to confirm that flaw indications occurring on the right channel are caused by lift-off variations. Defect indications occur as disturbances in the phase signal on the right recorder channel.

The major objective of this data evaluation is to determine the defect indication density D over the area inspected on the control rod. Defect indication density can be expressed as:

$$D = N/I \ , \qquad (1)$$

where N is the number of indications obtained, and I is the inspectable area within which the indications occur.

The total number of indications is obtained by manually counting them on the recorder charts. This requires a lot of rolling and unrolling of chart paper, and the data reduction time can be significantly reduced by utilizing a motorized take-up reel. The procedure used to analyze these data follows: Lay out a roll of chart paper on a long table or clean floor. Place the roll end on a spindle and attach the loose end of the chart to a driven take-up reel. Unroll the chart to locate the first event marker and identify it as zero. Then identify sequentially every 40th event marker (i.e., 40, 80, 120) on the chart. Within each set of 40 event markers, count the number of defect indications N whose depths fall in the four following ranges:

Defect indication depths, mm*

(a) >0.025 < 0.050

(b) >0.050 < 0.100

(c) >0.100 < 0.180

(d) >0.180

(Figure E.1 shows a data form that is useful for recording the above information.) In addition, the defect indication having the maximum depth within each set of 40 event markers should also be recorded along with its length. The depths of the discontinuities causing the defect indications are obtained by measuring the maximum recorder pen deflection (phase shift) for the indication and then determining the depth from the defect calibration curve, Fig. E.2 (ref. 1). The lengths of the discontinuities can be determined by counting the number of times the indication repeats on the recorder chart. The eddy-current probe travels axially 25.4 mm (1 in.) every 40 revolutions of the scanner. Each repetition of an indication represents one revolution and 0.64 mm (0.025 in.).

Several corrections are necessary to determine the true inspectable area I, which will vary over the control rod, depending on what region is being examined (Fig. 1). If the part was a smooth cylinder, the surface area could be determined by the following equation:

$$A = \pi d \cdot \ell \ , \qquad (2)$$

*To convert to inches, divide by 25.4.

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HFIR INNER CONTROL ROD DEFECT INSPECTION

CHART ROLL NUMBER	SET OF EVENT MARKERS	NUMBER OF INDICATIONS WITHIN A SET AND THE ASSOCIATED DEFECT INDICATION DENSITY (D)							MAXIMUM SIZE INDICATION	
		<0.0025 ≥0.005	$D = N/I$	<0.005 ≥0.010	$D = N/I$	>0.010 ≤0.018	$D = N/I$	>0.018	DEPTH (CHART DIVISIONS)	LENGTH (NUMBER OF REPETITIONS)
	0–40									
	41–80									
	81–120									
	121–160									
	161–200									
	201–240									
	241–280									
	281–320									
	321–360									
	361–400									
	401–440									
	441–480									
	481–520									
	521–560									
	561–600									
	601–640									
	641–680									
	681–720									
	721–760									
	761–800									

Fig. E1. Form for recording defect inspection data.

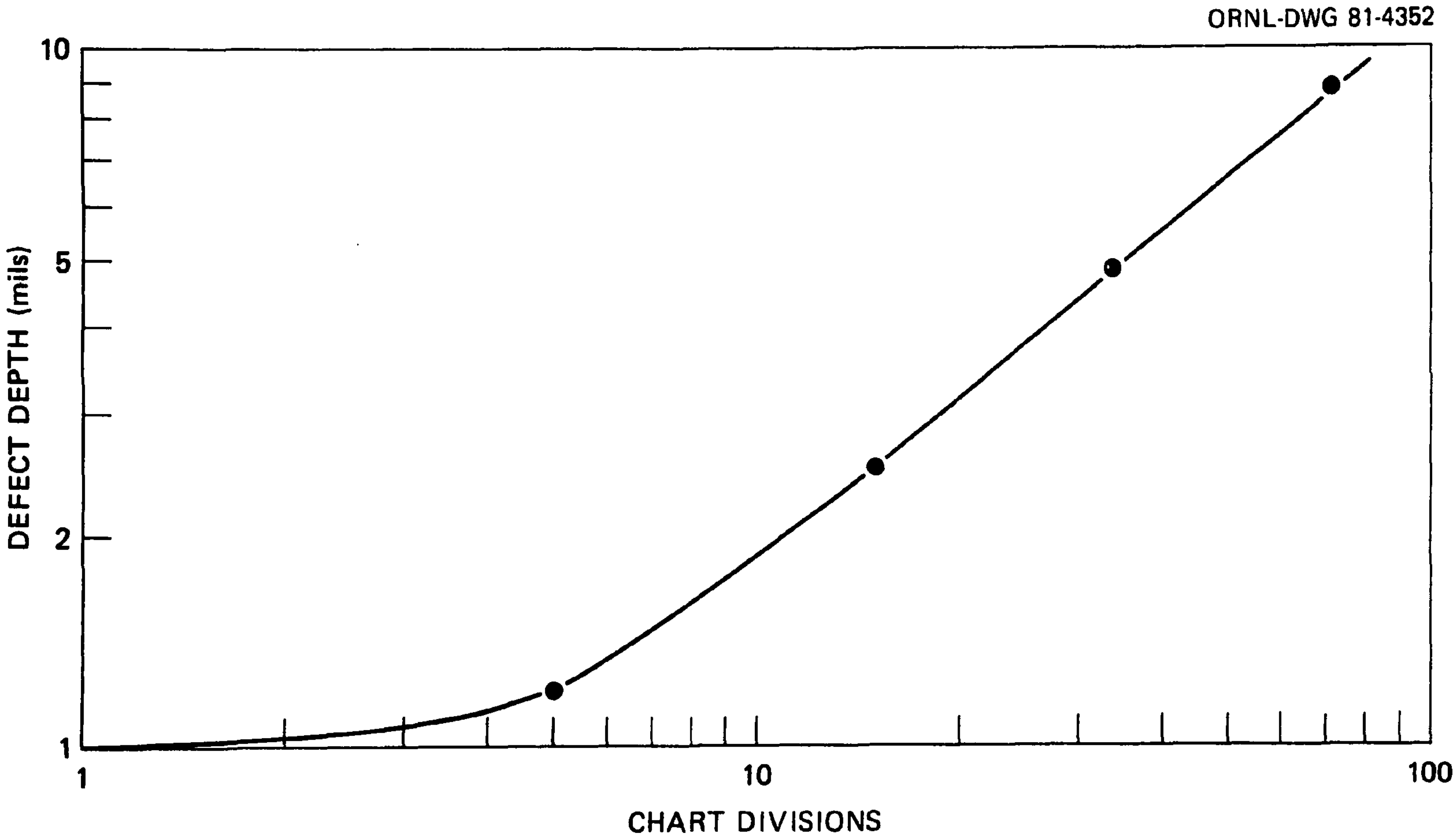

Fig. E2. Defect depth plotted versus recorder pen deflection.

where d is the outer diameter, and ℓ is the length traveled along the axis.

An inner control rod contains four longitudinal welds, each of which is about 3.2 mm (1/8 in.) wide, and an unclad area of pure aluminum about 9.6 mm (3/8 in.) wide occurs on either side of each weld. The cladding also tapers to zero thickness near these welds. Defects in these areas are not critical to the europium oxide; therefore, this area is disregarded for determining the flaw indication density. The total area to be subtracted from the circumference was determined experimentally by making several measurements on actual control rods. The average width of a single weld plus the side zones is about 25.4 mm (1.0 in.). The total length to subtract from the circumference is then 101.6 mm (4.0 in.). The equation for surface area* (mm^2) of a smooth cylinder then becomes

$$A = (\pi d - 101.6) \cdot \ell \; . \qquad (3)$$

If we then consider surface areas on the control rod containing holes, then the total area of the holes must be subtracted also. Because all holes in the control rod are drilled on 25.4-mm (1-in.) center lines, we have found that the inspectable area I is easier determined if we consider only 25.4-mm bands on the surface (i.e., 25.4-mm lengths along the axis). If we set $\ell = 25.4$ in Eq. (3) it becomes

$$A_1 = 25.4\,(\pi d - 101.6) \; , \qquad (4)$$

where diameter d is measured in millimeters. Then, if we subtract the area of the holes, the inspectable area* I (mm^2) is

$$I = A_1 - H_T = 25.4(\pi d - 101.6) - H_T \; , \qquad (5)$$

where H_T is the total area of holes in the surface band considered and

$$H_T = N(\pi d_1^2/4) \; , \qquad (6)$$

*To convert to $in.^2$, divide by 645.2.

where N is the number of holes, and d_1 is the diameter of holes.

There are 31 circumferential rows of 52 holes on one side of the Eu_2O_3 area and 11 circumferential rows of 52 holes on the other side. All holes are separated axially and circumferentially by 25.4 mm (1 in.) between their centerlines; with the exception of one row, all the holes are 6.35 mm (0.250 in.) in diameter. The sixth circumferential row of holes, counting from the Eu_2O_3 area toward the open end of the control rod, contains four 15.88-mm-diam (0.625-in.) holes that are used for lifting and handling [there are 48 6.35-mm-diam (0.250-in.) holes in the row]. The total area of holes H_T to subtract in Eq. (5) will therefore vary, depending on what area on the control rod is being inspected. There are four conditions for determining the inspectable area, and each will be described below, using Fig. E.3 as a reference.

Condition 1

Tests conducted over the Eu_2O_3 area: there are no holes in this area; therefore, the inspectable area* (mm^2) can be determined by using Eq. (4).

$$I = A_1 = 25.4(\pi d - 101.6) .$$

The outer diameter d of the inner control rod is 453.2 mm (17.842 in.) (see Fig. 1); therefore,

$$I = 33{,}583 \ mm^2 .$$

Condition 2

As the eddy-current probe approaches the first set of holes from the Eu_2O_3 area, there will be one band of surface area that extends to the centerline of the holes. This band will contain half the area of each hole or one-half the total area of all 52 holes. All holes are 6.35 mm (0.250 in.) in diameter; therefore, the total area of the holes to be subtracted, using Eq. (6), is:

*To convert to in.^{2}, divide by 645.2.

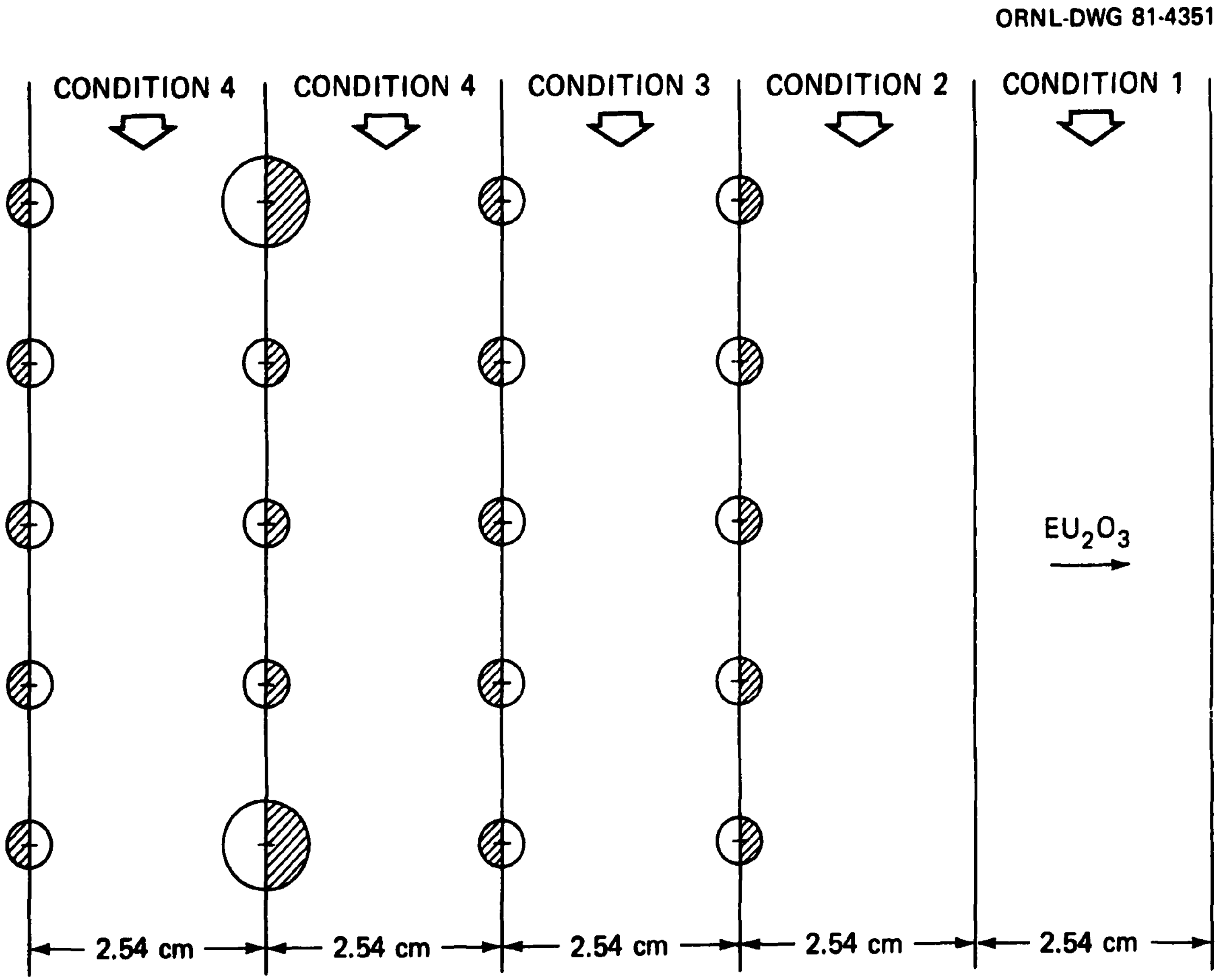

Fig. E3. Conditions for obtaining the inspectable area to determine defect indication density.

$$H_T = (52/2)(\pi/4)(6.35)^2 = 823 \text{ mm}^2 .$$

The inspectable area* (mm^2) for the condition then becomes

$$I = (33{,}583 - 823) \text{ mm}^2 ,$$

$$I = 32{,}760 \text{ mm}^2 .$$

Condition 3

Condition 3 is the area between any two sets of 6.35-mm-diam (0.250-in.) holes. The inspectable area is obtained by subtracting one-half the area of each hole or by subtracting the total area of one set of holes. The area to subtract is

$$H_T = 52(\pi/4)(6.35)^2 = 1647 \text{ mm}^2 ,$$

and the inspectable area* (mm^2) is

$$I = (33{,}583 - 1647) \text{ mm}^2 ,$$

$$I = 31{,}936 \text{ mm}^2 .$$

Condition 4

Condition 4 is the area between rows 5 to 6 and 6 to 7. [This area is different because of the four 15.88-mm-diam (0.625-in.) holes.] The hole area to subtract is

$$H_T = 48(\pi/4)(6.35)^2 + 4(\pi/4)(15.88)^2 ,$$

$$H_T = 2312 \text{ mm}^2 .$$

---

*To convert to in.^{2}, divide by 645.2.

The inspectable area* (mm^2) is

$$I = (33{,}583 - 2312)\ mm^2 ,$$

$$I = 31{,}271\ mm^2 .$$

Once the defect indications have been counted and tabulated, the inspector can select the appropriate inspectable area and calculate the defect indication density by using Eq. (1). These data should then be plotted on a graph similar to Fig. E.4, where the ordinate is defect indication density and the abscissa is length along the axis of the control rod. Any defect indication obtained whose depth exceeds 0.18 mm (0.007 in.) should be located as accurately as possible on the control rod for future reference.

EVALUATION OF OXIDE THICKNESS DATA

Oxide thickness data are obtained from the magnitude signals recorded on the left recorder channel during the defect scan. There is little reason to expect a significant buildup of oxide on a control rod, but the capability to monitor oxide thickness is available and is therefore utilized.

Oxide thickness is monitored in two ways, within a part and between parts. A localized buildup will be indicated by a localized shift in the magnitude signal when the eddy-current probe passes over the area of increased oxide thickness. A uniform buildup in oxide thickness can be detected only by comparing the magnitude signal (obtained from the control rod being inspected) with that of a standard. The oxide thickness reference standard used for these inspections was control rod H.

The main check for a uniform oxide buildup is made when the eddy-current probe is transferred from control rod H (following calibration) to the part being inspected. The left recorder channel can be monitored during the test or following the test if desired for localized oxide

*To convert to in.^{2}, divide by 645.2.

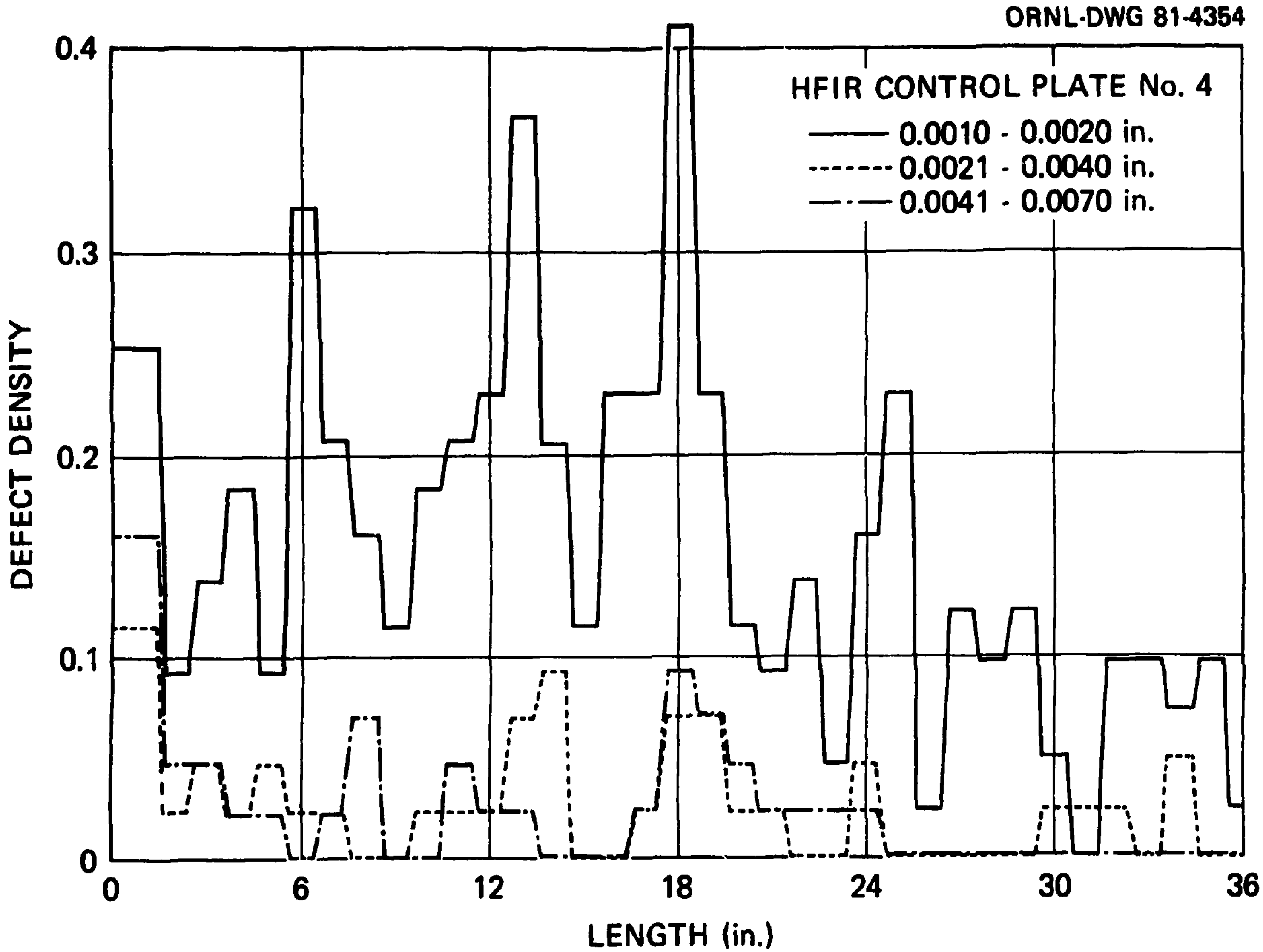

Fig. E4. Plot of defect indication density versus length along axis of control rod.

buildup. Any shift of the left recorder pen of more than ten divisions on the recorder chart will be considered significant and should be investigated. Care should be taken not to confuse other lift-off variations, such as those caused by dents, gouges, scratches, and weld seams, with oxide thickness variations. In general, lift-off variations will cause sharper and more dramatic shifts in the magnitude signal.

EVALUATION OF CLAD THICKNESS DATA

One roll of 122-m-long (400-ft) recorder chart paper is required to complete a cladding thickness test, and there are two channels of data on each chart. Cladding thickness is determined from the calibrated phase information recorded on the right channel. The left channel contains amplitude data that correspond to lift-off variations. These lift-off data can be used to confirm cladding thickness variations. For example, if a shift in the phase signal is accompanied by a significant shift in the signal magnitude, the probable cause results from a lift-off and not a cladding thickness variation. The techniques for manually resolving these data follows.

Lay out the roll of chart paper on a long clean table. Place the chart roll on a spindle and attach the loose end of the chart to a drive take-up reel. Unroll the chart to locate the first event marker and identify it as zero. Then identify sequentially every 40th event marker (i.e., 40, 80, 120, . . .) on the chart. Within each set of 40 event markers, measure and record the minimum cladding thickness in each of the four quadrants on the control rod. Also record the baseline reference signal associated with the four thickness readings. The data form shown in Fig. E.5 will be helpful for recording the above data.

After the data have been recorded, the actual cladding thickness can be converted from chart divisions to millimeters or inches by using the cladding thickness calibration curve (Fig. E.6) (ref.1).

The thickness of the aluminum cladding over the Eu_2O_3 can fall in the range of 0.61 to 1.07 mm (0.024–0.042 in.); it is usually near the lower end of the range. The four quadrants that are welded together to form a control rod are fabricated separately; therefore, the cladding thickness

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HFIR INNER CONTROL ROD CLAD THICKNESS INSPECTION

CHART ROLL NUMBER	SET OF EVENT MARKERS	SIGNAL MAGNITUDE (CHART DIVISIONS)	CLADDING THICKNESS							
			CHART DIVISIONS QUADRANT				MM OR IN. QUADRANT			
			1	2	3	4	1	2	3	4

Fig. E5. Form for recording cladding thickness inspection data.

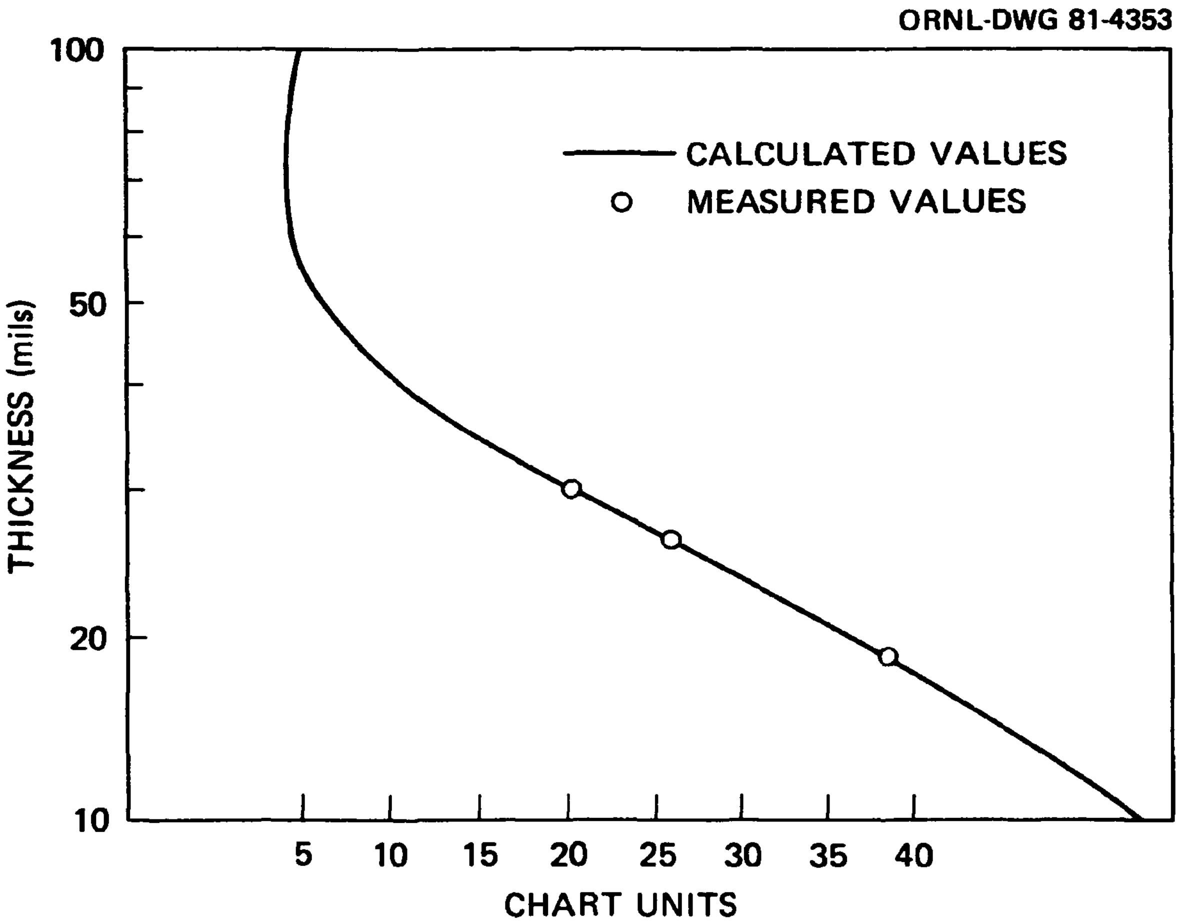

Fig. E6. Cladding thickness plotted versus recorder pen deflection.

can vary from quadrant to quadrant. There is a gradual taper of the Eu_2O_3 on both ends of this area; therefore, the eddy-current response to cladding thickness will vary for about 25.4 mm (1 in.) axially on either side of the Eu_2O_3 area. These areas are not considered for determining cladding thickness.

REFERENCE

1. C. V. Dodd, J. H. Smith, and W. A. Simpson, *Eddy-Current Evaluation of Nuclear Control Rods*, ORNL/TM-4321 (September 1973).