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CHARACTERIZATION OF IRRADIATED FUEL RODS USING PULSED EDDY CURRENT TECHNIQUES*

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I. INTRODUCTION

Aerojet Nuclear Company (ANC) at the Idaho National Engineering Laboratory (INEL) is conducting fuel rod behavior studies as part of the Nuclear Regulatory Commissions' Water Reactor Safety Fuel Behavior Program. Data on fuel rod performance are being obtained under a wide range of normal, off-normal and accident conditions in order to provide information for further development and verification of fuel rod behavior models.

A number of irradiated fuel rods and unfueled zircaloy cladding tubes ("water tubes") were obtained from the Saxton reactor through arrangements with the Westinghouse Electric Corporation for use in subsequent irradiation effects and fuel behavior programs. A comprehensive nondestructive and corroborative destructive characterization program was undertaken on these fuel rods and tubes by ANC to provide baseline data on their characteristics prior to further testing and for comparison against post-post data.

As in standard pressured water reactor (PWR) fuel rods, the cladding is Zircaloy-4; the fuel consists of UO_2 pellets loaded to a stack height of 35-36 inches. Fuel enrichments, internal gas pressure, and burnup varied among the rods. Although some destructive examinations

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were performed, and because of the limited number of fuel rods and "water tubes" available, great emphasis was placed on a thorough nondestructive testing program. This report deals primarily with one portion of the NDT program performed remotely in the hot cells. The portion of interest in this paper is the pulsed eddy current inspection used in the nondestructive phase of the work.

The pulsed eddy current (PEC) method was selected for use in the nondestructive inspection of irradiated Saxton fuel rods and water tubes for internal and external surface defects, cladding thickness and rod deformation. This method was developed at the Argonne National Laboratory (ANL) and has also been used by General Electric (GE) at the Vallecitos[1,2,3] Nuclear Center to inspect irradiated fuel rods.[4]

The PEC method of inspection was appropriate for the inspection of these rods since it would:

(1) detect microcracking,
(2) detect fuel-cladding interaction,
(3) determine cladding thickness, and
(4) operate in a dry environment and therefore be readily adaptable to hot cell installation and usage.
(5) provide simultaneous data on rod diameter and rod bowing with the incorporation of appropriate sensors.

For the purposes of this paper, the term "defect" refers to any phenomenon which results in an indication on the PEC readout. Included are scratches, grooves, wear marks, adherent corrosion products, scuff marks, subsurface hydriding, etc.

II. SUMMARY AND CONCLUSIONS

The pulsed eddy current system has proven to be an excellent technique for nondestructive examination of irradiated fuel rods.

The contribution of the PEC examination to the overall fuel rod characterization program is considerable and does provide important information upon which to make selection of test rods for PBF.

Unfueled zircaloy tubes irradiated in the same environment as fueled tubes show appreciably less damage, emphasizing, as may be expected, the added damage of service in conjunction with nuclear fuel.

An interesting result from this work is the wear on the fuel rods caused by the support grids. Defect indications observed by PEC were resolved to be primarily the grid wear marks and corrosion on the outer surface. The wear marks were only 0.0005 to 0.00075 in. deep and 0.005 to 0.006 in. wide. Bowing on the rods and water tubes varied from negligible to 0.012 inch from centerline. Cladding and tubing thickness variations noted were small, less than .001 inch for most of the tubes and only a few fuel rods had up to .003 inch variation. Diametral variations were similarly minor (<0.0005 in.), except for some high burnup rods which showed increased ovality (±0.010 in. from nominal diameter).

The pseudo-mapping technique provided an excellent overview of the cladding defects, and permitted ready identification of the wear marks. Severity and extent of the defects, as well as location and patterns of grouped indications can be easily assessed with this technique.

III. PEC SYSTEM OPERATION

1. Description of Equipment

The operating principle of the PEC inspection system is similar to conventional eddy current testing. The data analyses in the calculation of field strengths and the transducer design are complicated by the use of pulsed driving currents, but the advantages of the pulsed system greatly outweigh these additional problems. In theory at least, the wide band signal of the pulsed system permits extraction of all possible information from the test specimens by eddy currents. The high peak energy but low duty cycle permits design of components, especially the sensors, having a degree of resolution and ruggedness not possible in conventional eddy current equipment.

The PEC system consists basically of four major components:

a. The first component is the electro-mechanical scanning fixture (Figure 1A) which goes into the hot cell. This unit was designed and built by Aerojet Nuclear Company. After fuel rod testing under off-normal reactor conditions, the rods may be bowed, ballooned, or otherwise distorted. In order to keep the sensor coil-to-cladding distance constant, a servo-mechanism (Figure 1B) was designed which will automatically position the PEC sensor coil laterally. This servo-mechanism uses two opposing linear variable differential transformers (LVDT's) as sensors. In addition to providing input to the servo-mechanism, the LVDT's also produce information on the rod diameter and extent of bowing.

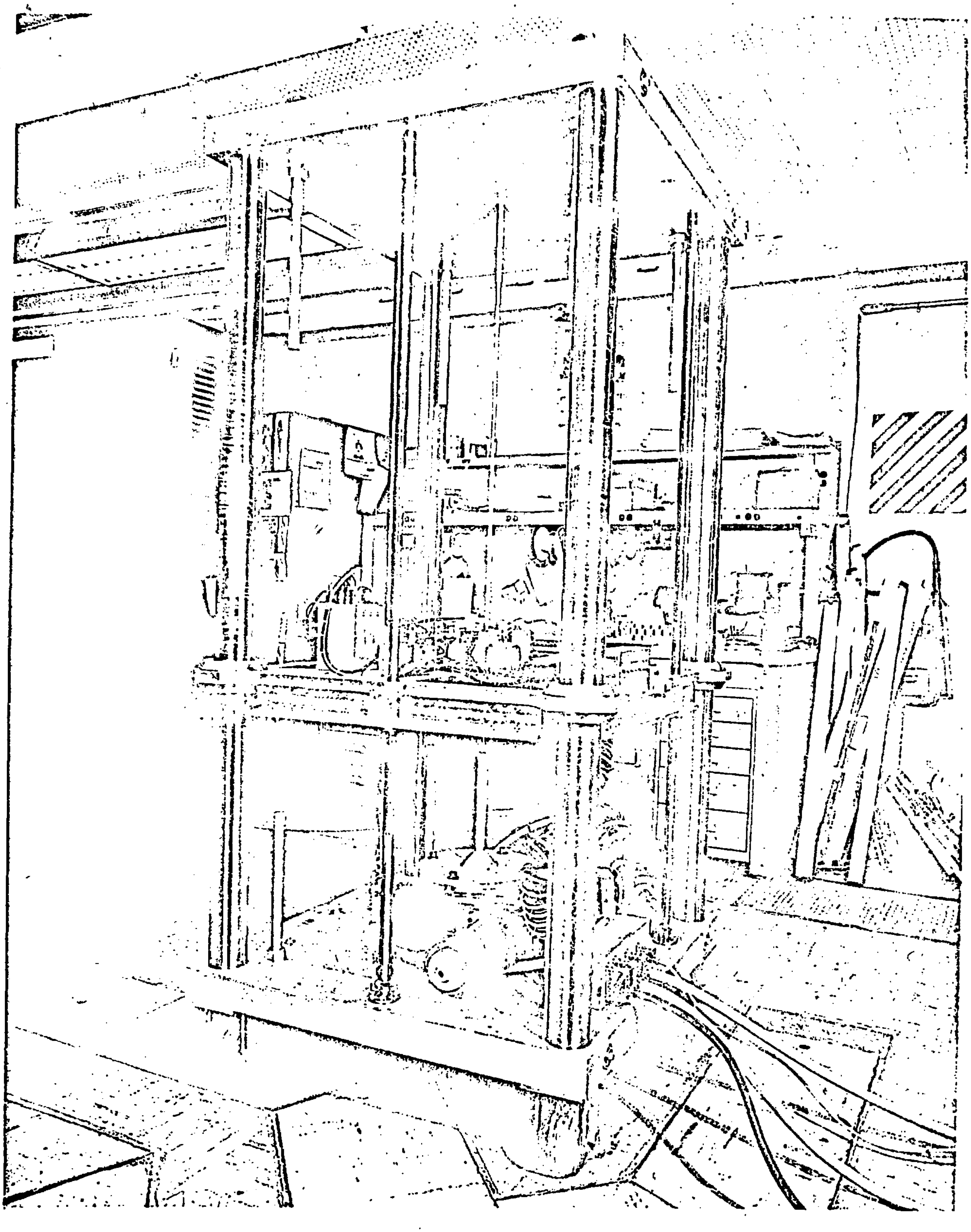

Figure 1A - Electro-mechanical scanning fixture for in-cell use.

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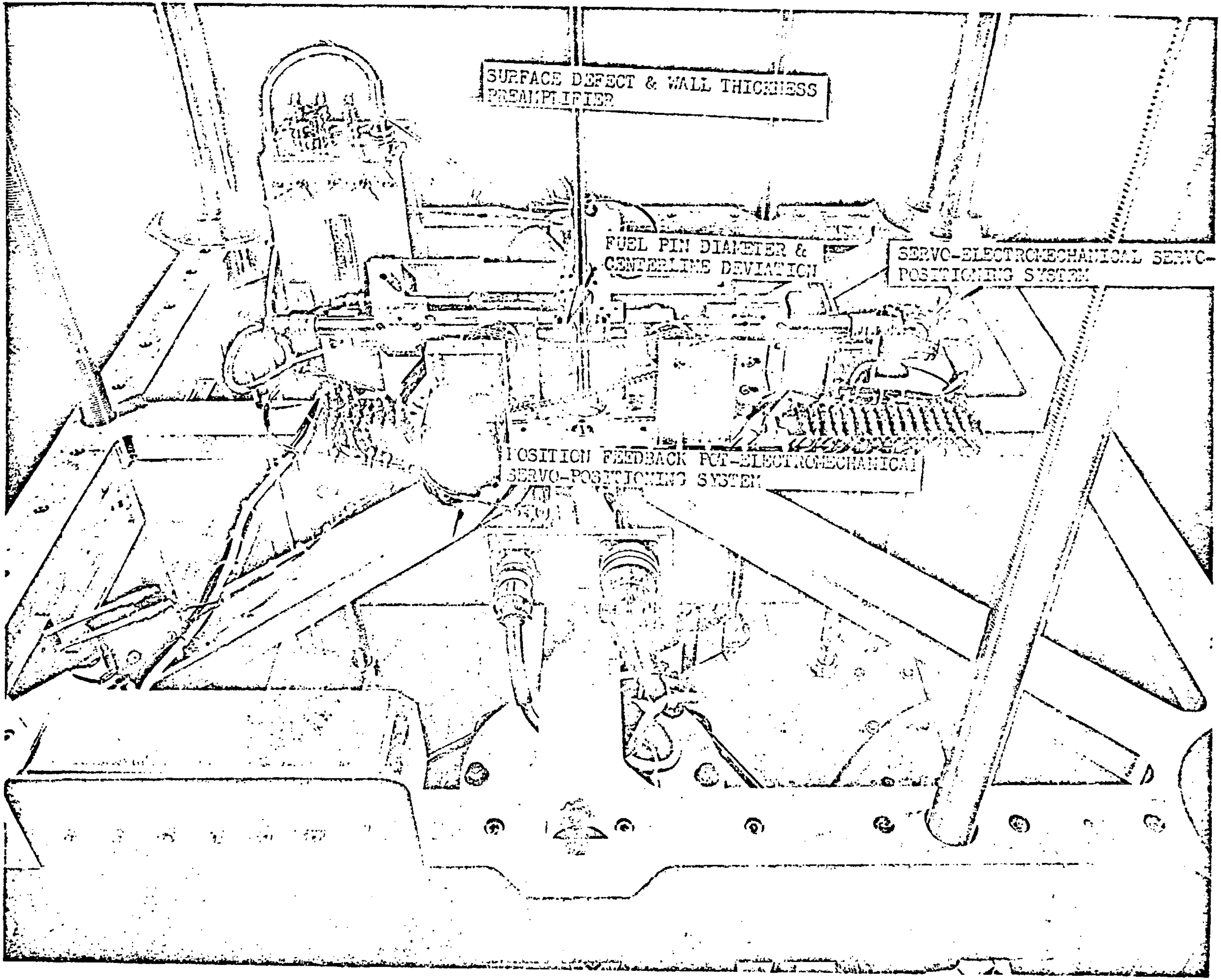

Figure 1B - Scanning bridge with servo-positioning devices and dummy fuel rod in place.

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The fuel rod is scanned in the vertical position with the sensors being moved past the rod.

b. The second item comprises the PEC sensors (Figure 1C) made by Argonne National Laboratory (ANL). These coils must match the electronics package and are "tailor-made" for each fuel rod design that is to be inspected. The top sensor measures the thickness of the zircaloy cladding, the lower sensor contains two coils to detect inner and outer surface defects in the cladding. The axial and azimuthal orientation of the sensors and LVDTS is illustrated in Figure 1D.

c. The electronics package is the third component (Figure 2). The rack-mounted electronics furnish the power and control for the scanner axial drive and rotational movements, pulse power for the sensors, and signal processing for data presentation.

d. Lastly, a six-channel Brush 260 recording oscillograph (Figure 2) provides the readout of the data.

2. Calibration and Test Procedure

2.1 Calibration

As with other NDT methods, the pulsed eddy current inspection technique is strongly dependent on accurate calibrating standards. Considerable care was therefore employed in fabricating standard specimens for thickness correlation, fuel rod straightness and for ID and OD defect calibration.

2.1.1 Wall Thickness Calibration Standard

When the PEC equipment at ANC became operable, some of the first measurements were made on the cladding thickness of unirradiated material

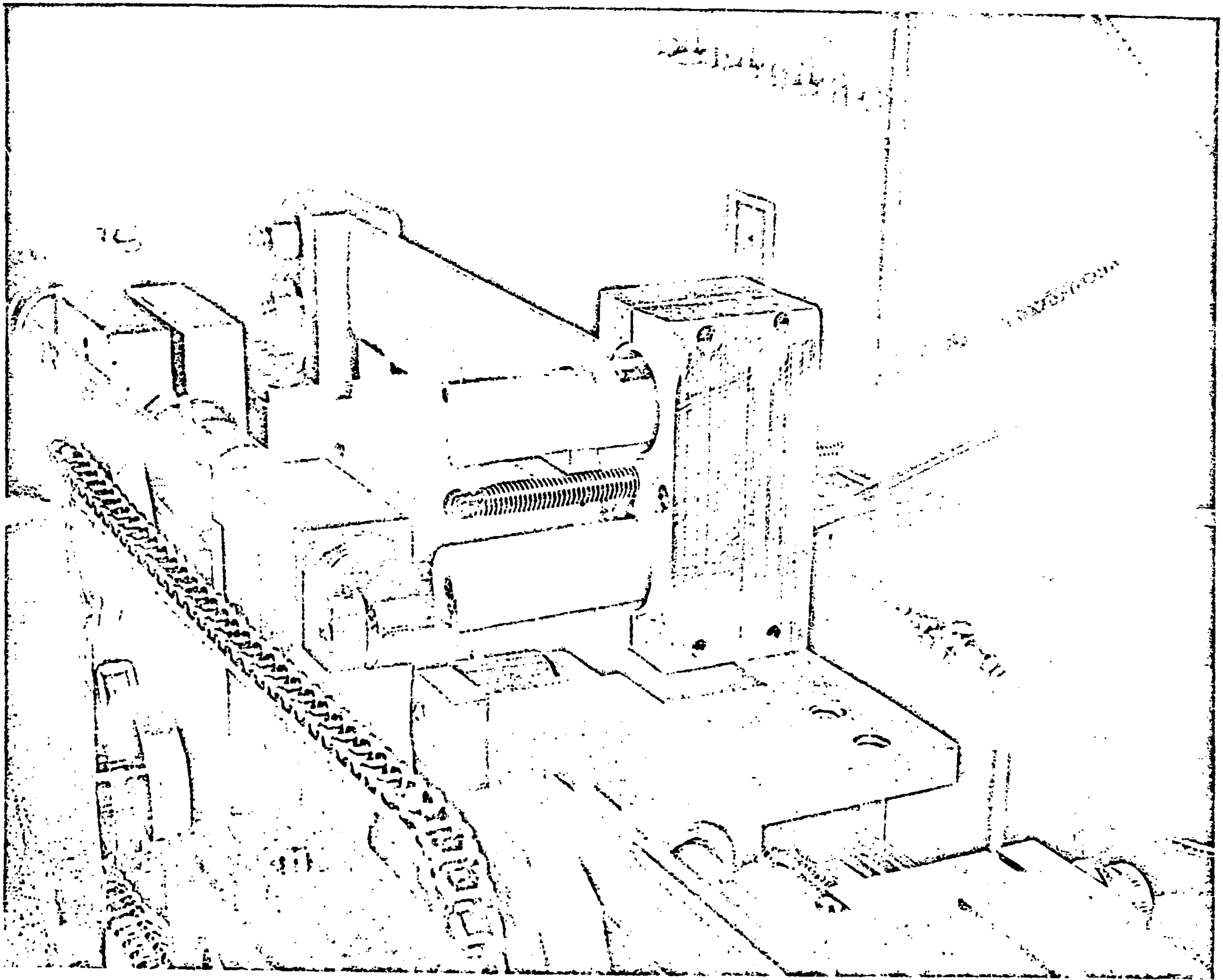

Figure 1C - Pulsed eddy current (PEC) sensors and diametral measuring LVDT's.

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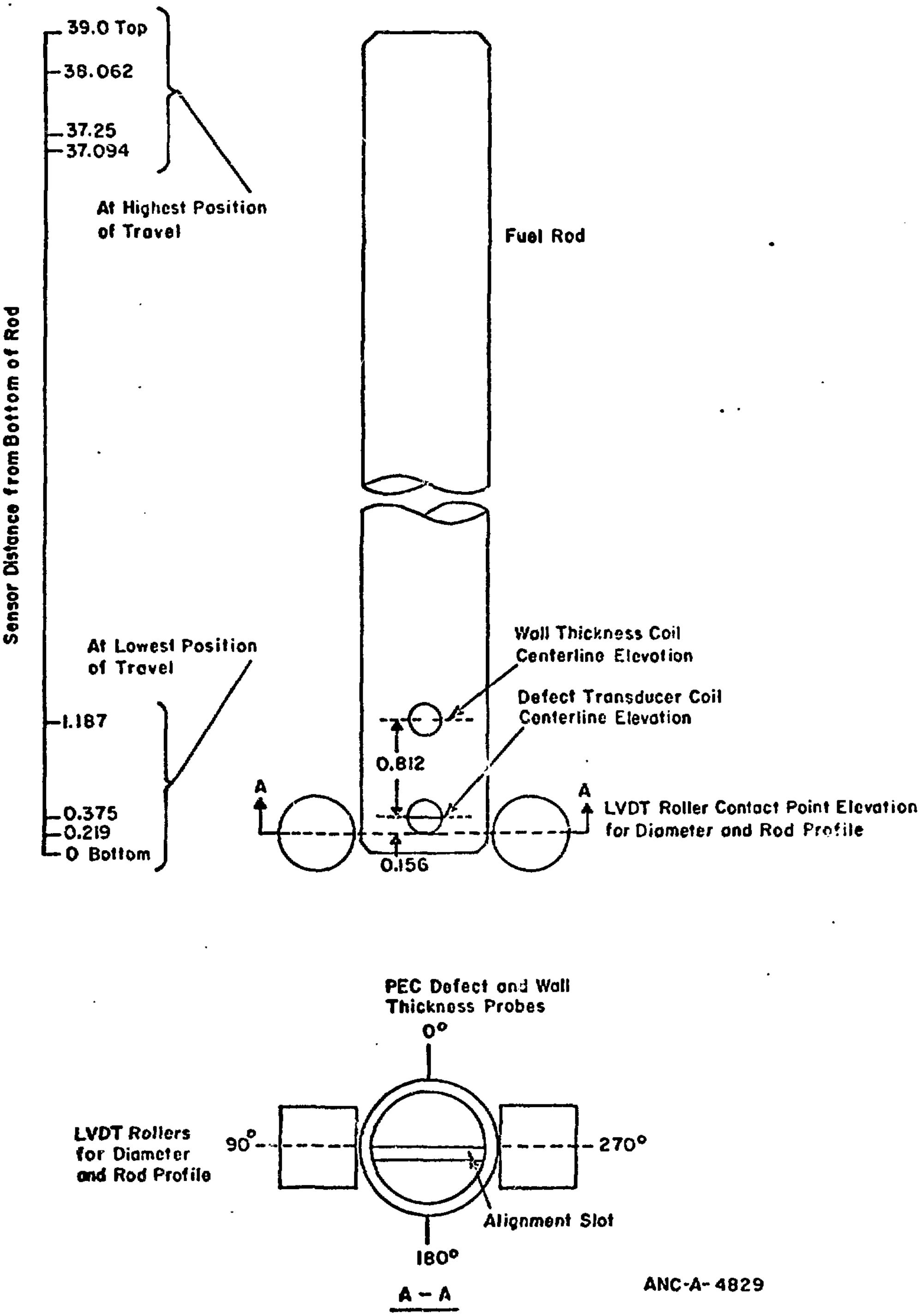

Figure 1D - Axial and azimuthal orientation of PEC sensors and LVDT's.

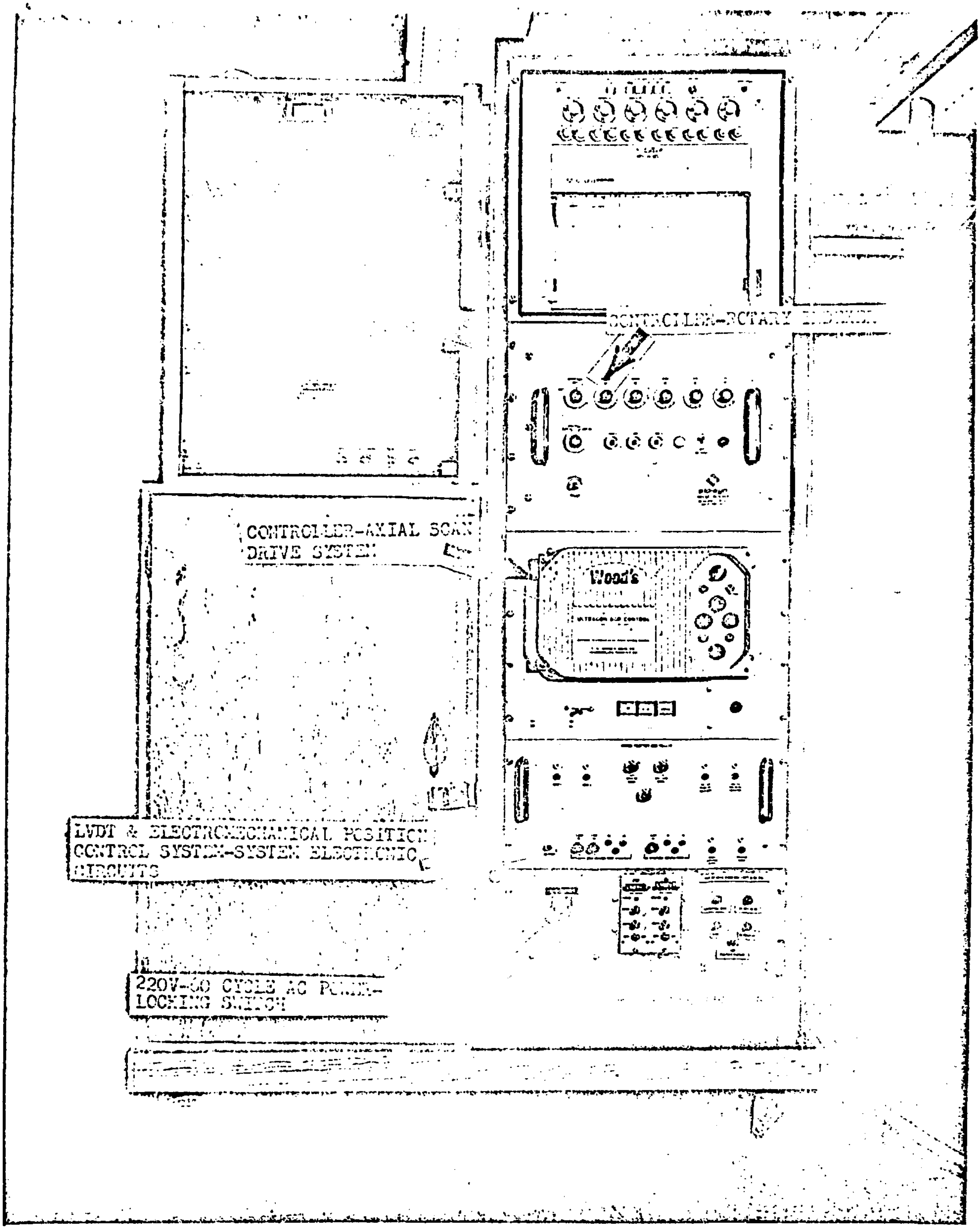

Figure 2 - Out-of-cell electronics package. High-speed recorder at upper left.

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to compare with the measurements made by mechanical techniques. A calibrating standard was prepared using Saxton-type zircaloy tubing of nominal 0.391 inch OD, machined internally to provide nominal .020, .022, .024 inch thickness standards. The actual values obtained (.021, .022, and .0238 inch wall) and the assembly of the calibrating section are shown in Figure 3. The thickness taper indicated in the figure was readily observed in the PEC scan and complicated the assignment of absolute values in fuel rod scanning. Variations in thickness over the fuel rod length, however, were easily detected.

2.1.2 Fuel Rod Straightness Standard

A calibrating rod for straightness was fabricated from Invar 36 stock which was rough machined, normalized in a controlled atmosphere, hard chrome-plated and finish ground. The maximum centerline deviation measured by the INEL Standards Laboratory is 0.0053 inch, but in two of the scanning orientations the maximum bow is less than .0005 inch.

In addition to locating and measuring variations in rod straightness (bowing), it was also desired to determine bulging or collapse of the fuel rod cladding. By the use of opposing LVDT's, this measurement is readily made. The sensitivity was adjusted to provide 0.00024 inch per minor chart division in order to detect small variations in fuel rod diameter such as ridging and pitting.

2.1.3 Fuel Rod Defect Standard

Three standards were prepared by EDM. Each standard consisted of a zircaloy tube, 6 inches long, 0.391 in. OD and 0.021 in. wall thickness. These standards involved 0.100 inch long by 0.006 inch wide longitudinal and transverse notches on both OD and ID surfaces. Three notch depths, nominally 0.002, 0.004, and 0.006 inch were prepared by EDM. The notch dimensions were certified by means of replication with GE RTV

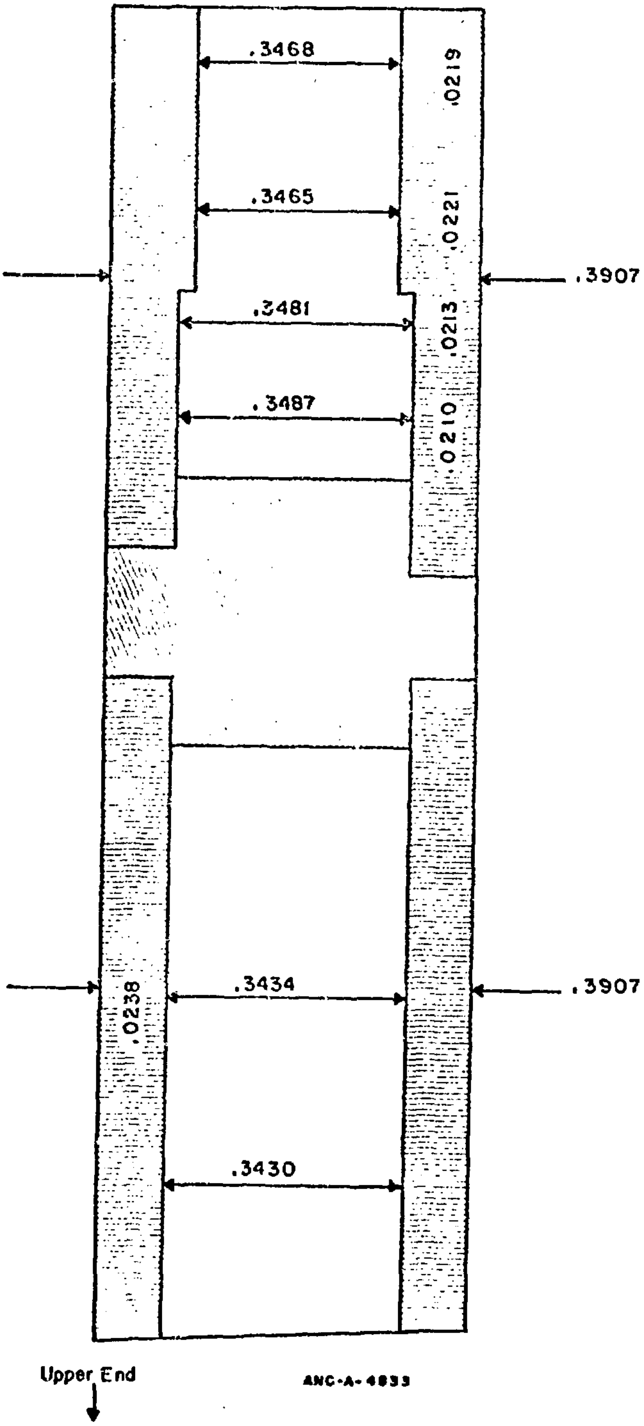


Figure 3 - ID-machined wall thickness standard.

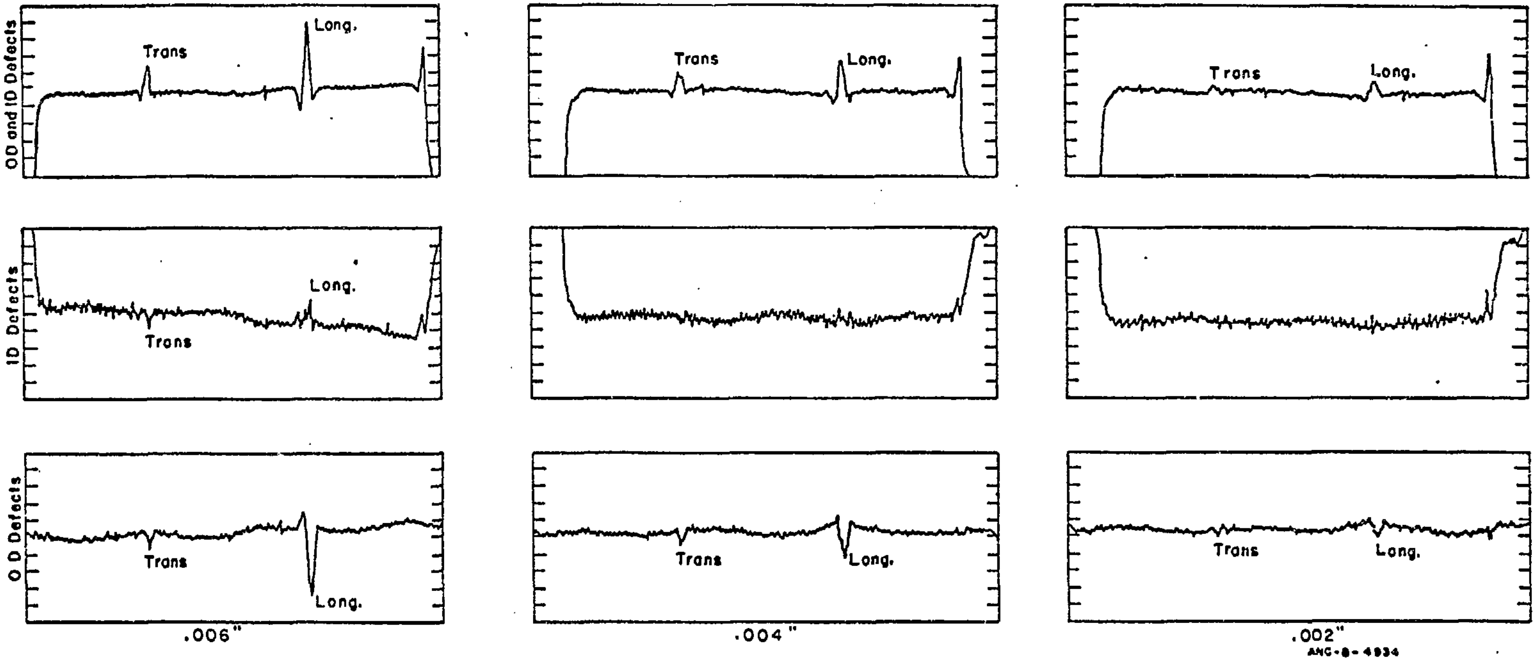
liquid silicone rubber. Figure 4 shows the PEC scans of the defect standards.

2.2 Test Procedure

Approximately 100 irradiated fuel rods and "water tubes" were scanned using the PEC equipment. The entire PEC examination, including limited destructive examination for correlation purposes, required nearly two months. Normal procedure required scanning of the calibrating standards before inspecting each of the irradiated rods or tubes. The PEC scanning equipment was operated in close accordance with the written procedures in the Operating Manual prepared by Instrumentation and Measurement Branch, ANC.

Thirty-four irradiated fuel rods and sixty-six irradiated water tubes were examined remotely using the ANC PEC inspection equipment. Thirty-seven chart scans (the 0° and 360° were deliberate duplications), each with six traces, were obtained for each fuel rod and water tube. Two fuel rods and one water tube were subsequently selected for destructive examination; the PEC scan results of these rods and tubes are summarized in this report and compared with the results of the destructive examination.

Each fuel rod scan and each water tube scan was examined in detail by qualified personnel from either ANC's Materials Technology Branch or Quality Division. These people were qualified to ASNT's TC-1A Level III inspection[5]. The scans from each rod or tube were further reduced to the chart form illustrated in Figure 5. These charts provided a simple visual presentation of the location, extent and size of the indications observed in the PEC scanning. A quick reference on the same chart is also available for cladding thickness, straightness and diameter variations.



PEC Calibration Rod for Surface Defects and Clad Thickness
50° Orientation for OD Defects

Figure 4 - PEC scans of EDM-produced defect standards.

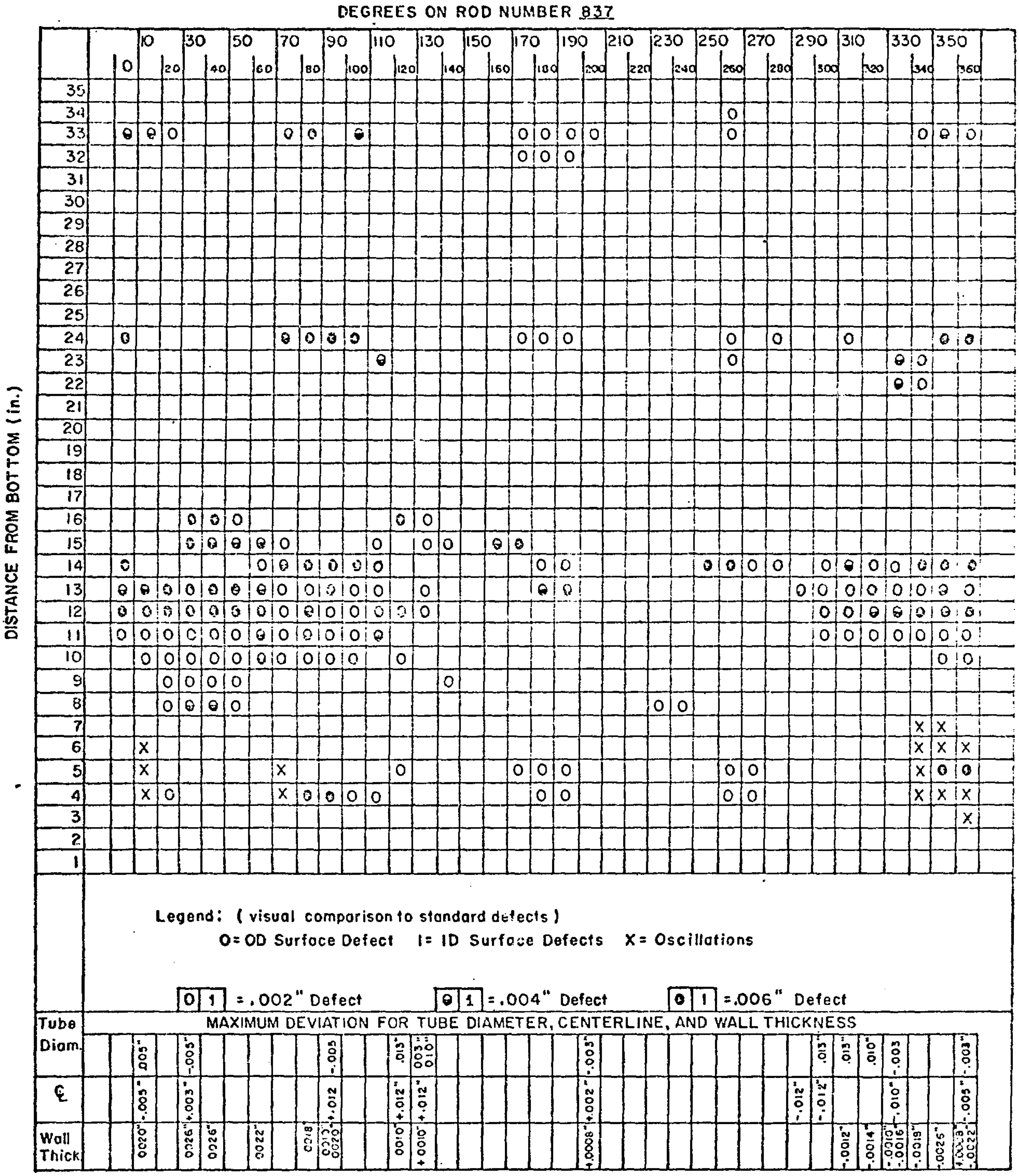


Figure 5 - PEC summary chart condensed from 37 six-channel scan charts for each rod.

IV. TEST RESULTS

1. General

From Figure 4, it can be seen that the PEC instrument is more sensitive to longitudinal defects than to transverse defects and that both types of defects are more readily observed on the outer surface than on the inner surface. The 0.002-inch deep defects in both longitudinal and transverse directions can be readily observed on the outer surface standard but only the longitudinal defect of this size can be detected on the inner surface of the standard.

The voluminous data generated for a complete PEC scan of a single rod (37 charts, containing 6 traces each) makes correlation of data difficult and an "overview" of defect patterns virtually impossible. In order to circumvent those problems, a three-dimensional mapping technique was attempted. The length and angular displacements of the scans defined a plane, and the relative magnitude of the indication defined a point above or below the plane for OD or ID defects, respectively. This approach was used to generate the pseudo-maps shown in Figures 6 and 7. Using Figure 6 as an example, it is readily apparent that the major OD defects frequently appear in four adjacent scans (i.e., through 40°) located approximately 90° apart. By superimposing the centerline locations of the four spacer grids, a correlation can be seen indicating wear as a possible cause for these defects. The possibility is shown more graphically in Figure 7. In this case, the wear marks associated with the paired wear pads on the spacer grid are readily identifiable in at least two positions. Each pair of wear pads is located in each of

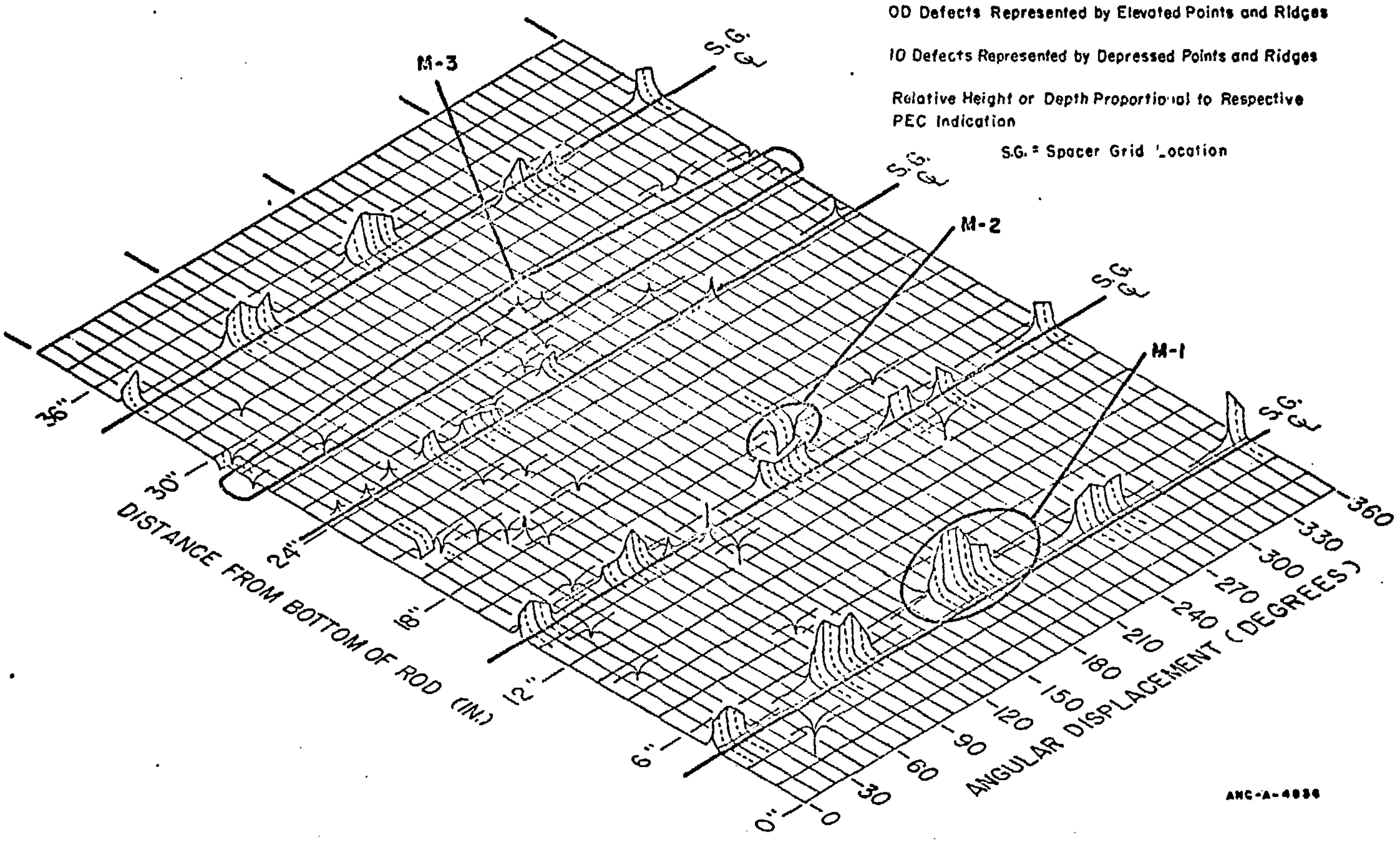


Figure 6 - Pseudo-map of defect indications on water tube Std. 50. M-designations show areas destructively examined.

OD Defects Represented by Elevated Points and Ridges

ID Defects Represented by Depressed Points and Ridges

Relative Height or Depth Proportional to Respective PEC Indication

S.G. = Spacer Grid Location

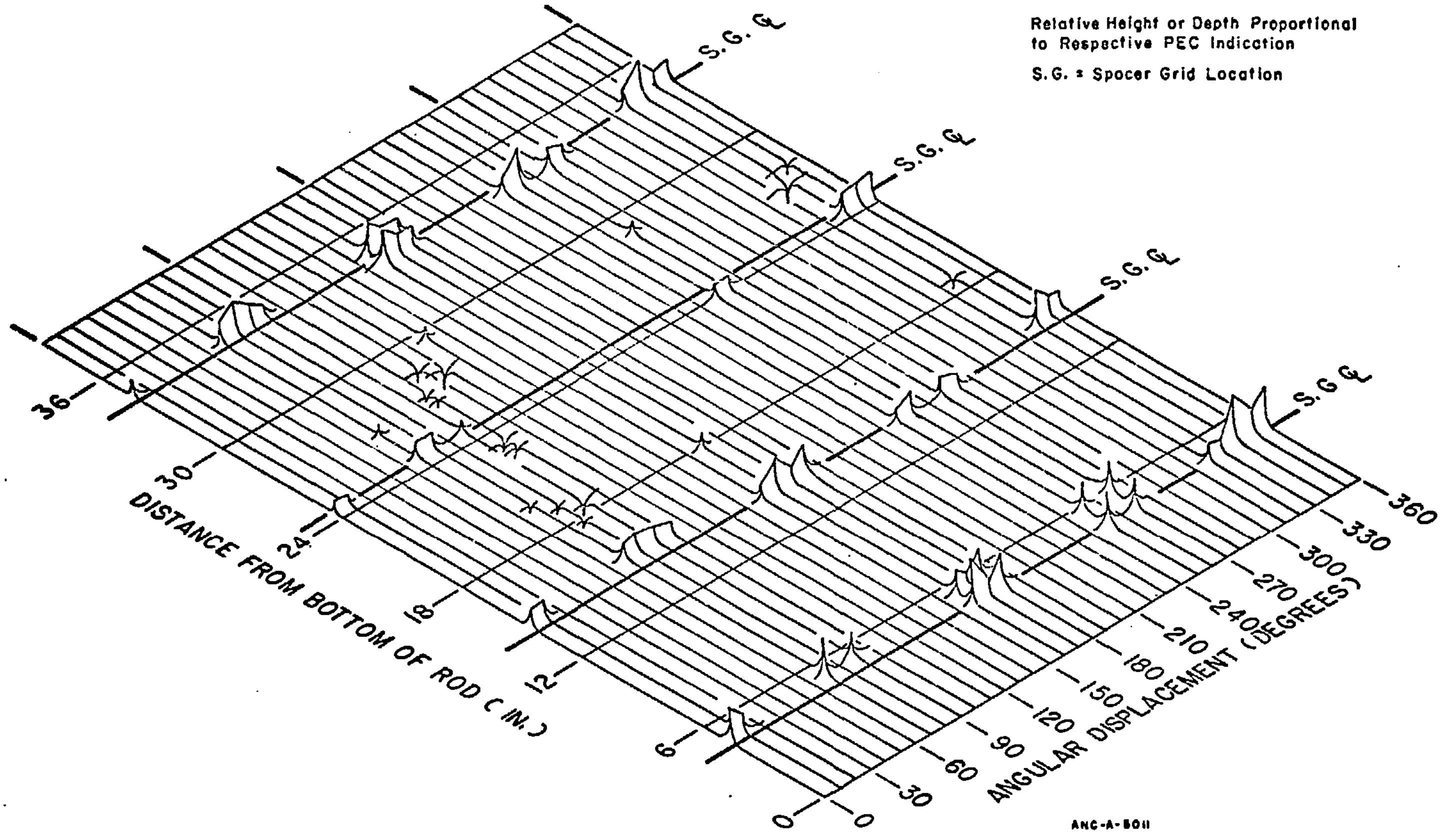


Figure 7 - Pseudo-map of defect indications on water tube No. 5.

two positions, 90° apart for each spacer grid. In the case of the lowermost grid, the pseudo-map for water rod No. 5 (Figure 7) shows that the pairs of pads were initially in contact at 160° and 250°, and that at some point the rod was rotated approximately 20°, bringing the wear pad to 180° and 270° for the balance of the rod's exposure (or vice versa).

Nearly all of the fuel rods and water tubes gave well defined OD "defect" indications at four axial locations and spaced at 90° intervals around the rod at each of the axial locations. The axial distances between these indication groupings were approximately 10 inches. These OD indications were readily correlated with the grid spacings in the fuel assembly and thus appeared to reflect wear areas on the fuel rod or water tubes from vibration against the grids. When these OD "defect" indications were subtracted from the total indications most of the fuel rods and water tubes were relatively free of defect indications.

One peculiarity in the combination of the PEC characteristics and the mapping technique should not be overlooked. The circumferential extent of defects can be estimated from the recurrence of the indication at the same position on adjacent scans. At this time, no similar capability exists to estimate longitudinal extent. While circumferential defects may appear as ridges on the pseudo-map, longitudinal defects will appear as spikes.

Variations in cladding thickness were generally quite small. The vast majority of the rods showed thickness variations of <±0.001 in., with the worst cases (some of the high burnup rods) showing variations of ±0.003 in. Centerline variations similarly showed more bowing on the high burnup rods (up to 0.012 in.) than the low burnup rods and water tubes.

Diametral variations were generally minor on the water tubes and low burnup rods (<0.0005 in.). Some of the high burnup rods showed some ovality changes which resulted in a ±0.010 in. diametral variation.

2. Destructive Correlation

Two fuel rods and one water tube were selected for destructive examination. In addition to confirming the results of the PEC examination, some of the samples were selected to evaluate other parameters which could not be determined nondestructively. Only the former will be discussed in this paper.

A total of ten areas were examined metallographically. These areas were repeatedly polished and examined until the largest portion of the defect was located. No defects were found which would represent a threat to rod integrity or compromise the use of the rod in the fuel behavior tests. Indeed, most of the "defects" were smaller than anticipated, based on the relative signal intensity of the PEC scan. As stated in the Introduction, the term "defect" refers to any condition which deviates from ideal cladding, and includes scratches, grooves, wear marks, adherent corrosion products, subsurface hydride accumulations, etc., as well as cracks.

Examination of the metallography specimens revealed only the former phenomena; no cracking was found in any of the areas examined. The wear marks caused by the spacer grids were comparatively easily located, both on the pseudo-maps and in the metallography specimens. A double set of wear marks is shown in Figure 8. This set and similar observations on other rods are shallow (0.00050 to 0.00075 in. deep), fairly broad (0.005 to 0.006 in.), and flat bottomed. The comparatively

Figure 8 - Double-set of spacer grid wear marks found on water tube Std. 50 at 200° in metallography mount M-3.
As-polished 200X

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large indications on the PEC scans are thought to be the result of the width of the "defect", rather than the depth as with a crack or scratch.

Other "defects" which were located metallographically are shown in Figures 9-11. Figure 9 shows a section through a longitudinally oriented groove on the rod OD, approximately 0.004 in. wide by 0.001 in. deep. Figures 10 and 11 illustrate two conditions not normally identified as defects, but which caused a "defect" indication in the PEC system. Neither condition was common, and the majority of the defects examined were of the types shown in Figures 8 and 9, or surface "scuffing" which resulted in very broad but very shallow deformation. Figure 10 shows very minor surface irregularities (too small to be detectable) underlaid with a 0.0035 in. layer of hydride concentration. Figure 11 shows a 0.0025 in. thick layer of adherent corrosion products which caused a momentary lift-off of the PEC sensing coils and resulted in a "defect" signal on the output recorder. Isolated buildups like this one were rare becuase the rods and tubes had been "decrudded" prior to the PEC examination. The type of "defect" indication produced by these buildups is generally identifiable and distinguishable from the type of indication produced by cracks, scratches, etc. "Defect" signals are produced on both the OD and ID channels, with that of the OD channel being somewhat larger, and the indications show limited axial length as opposed to individual spikes for more conventional defects.

The results of the destructive examination were positive. No "defects" of any kind were found outside the PEC-indicated regions in either these

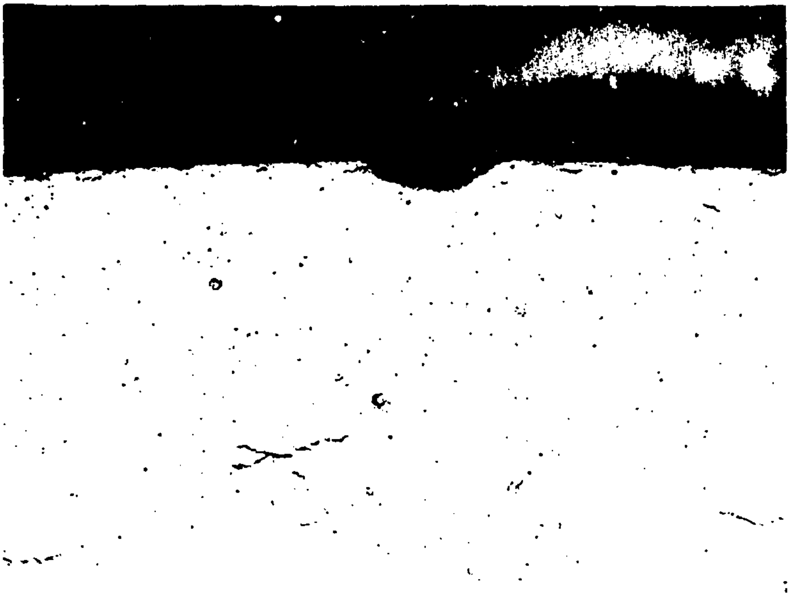

Figure 9 - Longitudinally-oriented groove found on the OD surface of fuel rod 837.
As-polished 200X

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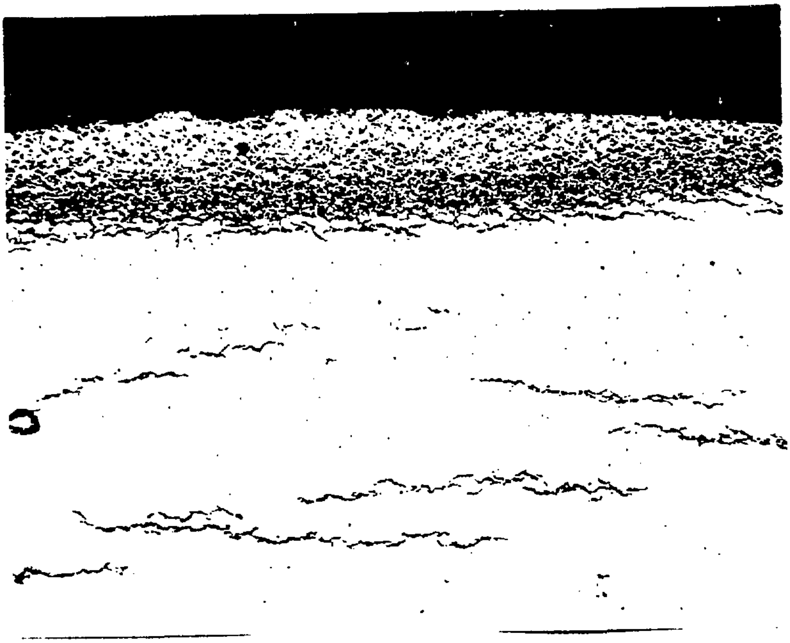

Figure 10 - Subsurface hydride concentration found on fuel rod 837 in area of defect indication.

As-polished 200X

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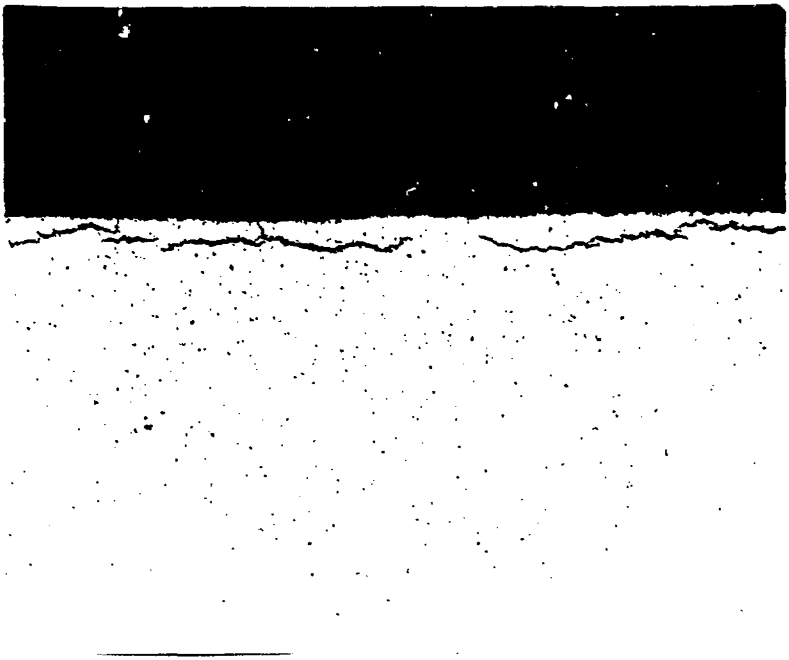

Figure 11 - Adherent corrosion product buildup found on fuel rod 864. Material caused distinct defect indication on PEC output recorder.

As-polished 200X

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ten samples or in the other five samples which were taken for other purposes. Conversely, with the exception of one area, "defects" of one type or the other were observed in all the suspect areas. The one exception was a sample taken in a region of the rod where the PEC system showed a step in the readout as opposed to a spike (the usual defect indication). It was believed that the step was an electronic anomaly, but a specimen from this region was examined to verify this assumption.

V. LIMITATIONS OF PEC

Our experience with the PEC technique and the equipment designed at INEL and ANL was generally most satisfactory. The combination of diameter, profile, wall thickness, and defect data all in one scan was an ingenious design saving countless hours of examination. Nonetheless, there are some inherent limitations in the PEC technique and some deficiencies in the as-built equipment which merit noting. These are discussed here primarily to indicate some improvements which may be made in the existing equipment or which may be incorporated in a future design.

1. Limitations of Techniques

The PEC technique is predominantly sensitive to defects lying in the longitudinal plane with respect to the scan direction and considerably less sensitive to transverse defects. In our equipment it was difficult to observe a .002 inch deep machined notch in the transverse plane. This limitation could possibly have been eliminated by scanning in a spiralling motion but interpretation of the data would almost certainly have required a computer.

Sensitivity of the PEC detection is a function of the scanning speed. In the design and in laboratory pre-operational testing the scan velocity must be optimized for maximum sensitivity. Because of the high scanning speed required for sensitivity (approximately 2 inches/sec), it is not possible to slowly search back and forth over a suspected defect for enhanced characterization.

Defect size estimation is based on comparison with calibrating standards. Actual defects lying in other than purely longitudinal or transverse planes can only be evaluated of being "at least" equal to a certain size of standard; the actual size of a diagonal defect could be somewhat larger. This deficiency may well be applicable to all NDT techniques scanning in an axial mode.

Axial scanning provided relatively good resolution of the extent of a defect in angular displacement but very little information on the extent of the defect in the axial direction.

2. Equipment Limitations

   a. Correlations of the start, stop and linearity of the axial scan of the strip chart recording with the PEC equipment was difficult and subject to some judgment errors. Use of a stepping motor to control the axial traverse and the use of start and stop reference calibration marks on the strip chart would resolve this deficiency.

   b. The acme-threaded lead screws for the axial drive train required frequent oiling. Providing adequate oil for smooth motion to reduce drag was difficult to accomplish remotely in the hot cell. Too little oil appeared to result in slower and somewhat non-uniform axial traverse; too much oil resulted in splatter on equipment and even on the walls of the hot cell.

   c. The voluminous data (37 strip charts each with six data scans for each rod) made "hand" reduction a lengthy, tedious operation. Recording of the data redundantly on magnetic tape which could then be evaluated by an appropriately developed computer program would be a real advantage in examining the large number of fuel rods and "water tubes" involved in our program and in reducing the potential of human error.

   d. The thickness sensor and the defect sensor are separated axially by about 0.8 inch; both sensors are separated angularly by 90^0 from the LVDT's. These off-sets make correlations of the six line scans on each chart difficult. The computerized data handling proposed above could provide automatic axial and azimuthal correlation of the data.

e. Most of the fuel rods to be used in subsequent tests will have instrument leads emerging from the top end cap and most will also include surface thermocouples. Present PEC equipment has no provision for handling this instrumentation. We believe that relatively minor equipment changes would permit scanning rods with top end cap leads, but surface instrumentation presents a more difficult problem. At best it appears that the latter rods can only be scanned in regions free of surface instrumentation.

f. As in most NDT techniques the evaluation of data is largely dependent on the use of good calibration standards. We believe the defect and centerline (straightness) standards adequately met the requirements but the thickness standard left something to be desired. The steps were not sufficiently uniform that calibration with PEC response could be readily established. This problem was at least partly the result of our decision to machine the thickness steps on the inside surface while retaining the constant outer surface for ease in traversing.

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