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THE PERFORMANCE OF A SPECIAL DIFFERENTIAL TRANSFORMER
AND AN EDDY CURRENT COIL IN A HIGH GAMMA FLUX ENVIRONMENT

by

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TABLE OF CONTENTS

	<u>Page</u>
LIST OF FIGURES	3
ABSTRACT	4
INTRODUCTION.	4
COMPONENTS AND MATERIALS TESTED	5
INSTRUMENTATION.	7
DC Motor Control.	8
Eddy Current Instrument	8
Differential Transformer Instrument	10
Thermocouple Instrument	10
Signal and Power Transmission	11
TEST PROCEDURE AND IRRADIATION PROGRAM	11
RESULTS	12
CONCLUSIONS	14

LIST OF FIGURES

	<u>Page</u>
Figure 1 - Test Apparatus for Determination of Effects of Gamma Radiation upon a Special Differential Transformer and an Eddy Current Coil	6
Figure 2 - Containment Shell for Irradiation Test Apparatus	8
Figure 3 - Block Diagram of Test Apparatus and Control and Recording Equipment	9
Figure 4 - Control and Recording Equipment Employed in Radiation Tests upon a Special Differential Transformer and an Eddy Current Coil	10
Figure 5 - Traces of the Special Differential Transformer and Eddy Current Coil Output during High-level Gamma Irradiation	13

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ABSTRACT

The gamma activity anticipated during the refabrication of EBR-II fuel has rendered suspect many operations considered adequate in less demanding environments. Two such operations involve the use of a differential transformer to measure linear displacement and an eddy current coil to measure the internal integrity of a cast fuel pin. A test apparatus containing the above components was irradiated at between 4.7×10^5 and 1.6×10^6 rad/hr in the ANL Gamma Irradiation Facility. The electrical output of the components was periodically monitored until a total exposure of 1.24×10^9 rads had been realized. No changes in the shape of the traces recorded were noted over the entire irradiation period. With the exception of a base-line shift in the case of the eddy current output trace, the measurements were also insensitive to temperature changes of the order of 19°C . Radiation damage to paints, varnishes, conventional insulations and a radiation-resistant grease was noted, but the extent of this effect was not such that the test was affected.

It appeared that the performances of the linear transducer and eddy current device were such that they would be expected to operate successfully in an environment similar to that anticipated in the EBR-II Fuel Cycle Facility.

INTRODUCTION

The design of the EBR-II Fuel Cycle Facility and the processing equipment to be employed in this cell have been predicated upon rather unique requirements. These requirements arise from the singular purpose of this facility, namely, the reprocessing of spent reactor fuels. Since the fuels to be handled in-cell are extremely gamma active, materials compatible with this condition are required in the construction of equipment for which long life is expected. Generally, the anticipated level of gamma-radiation intensity⁽¹⁾ has precluded the use of organic materials of construction. This, of course, limits the use of electrical components because of the short life of conventional insulations within the high-intensity radiation environment.

In most cases, it has been possible to employ pneumatic equipment to achieve desired motions in process equipment; however, there are instances where mechanical linkages or pressure impulses cannot be employed conveniently. One such occasion is encountered in a balance which is to be applied in the determination of the weights of materials in various stages of manufacture. Another such example is met in the use of eddy current techniques to determine the extent of internal porosity in a fuel pin. In each of the above cases it has been deemed necessary to take an electrical signal out of the cell interior. The experimentation described in this report deals with the components and instrumentation required as auxiliaries to a balance and an eddy current porosity gage and the performance of some of these components in a high gamma flux environment.

COMPONENTS AND MATERIALS TESTED

The balance required for in-cell weighing of materials in process in the EBR-II Fuel Cycle Facility has taken the form of a single-pan, magnetically damped, 500-gram-capacity balance with a minimum precision of ± 0.03 gram. The balance was stripped of all materials of an organic nature, including nylon bumpers, paint, etc. It was decided that the off-balance movement of the balance pan during weighing would be detected by the use of a differential transformer whose armature was attached to a linkage in the beam-counterbalance system. Both the input to and output from the transformer would be impressed through an amplifier and dial indicator located remotely with respect to the balance. The voltage output from the transformer is a function of the position of the armature within the transformer coil which, in this case, is a function of the off-balance deflection of the weighing device and thereby a function of the weight of the load placed on the balance pan.

For this particular application the performance of the differential transformer in a high-flux gamma field was an unknown upon which the entire weighing operation was dependent. With this in mind a special differential transformer was obtained. This transducer, built by Automatic Timing and Controls, Inc., was designated as Class 6208K. The transformer was wound with AWG Size 40 Ceroc-insulated wire manufactured by the Sprague Electric Company. Ceroc wire is copper wire over which is laid a ceramic insulation. A layer of silicone film is deposited over the ceramic insulation to guard against abrasion due to mechanical shock. It was felt that this compromise involving the use of an organic material would be inconsequential after the wire was wound upon the coil form of a transformer. Since mechanical shock upon the insulation would not be a consideration, the loss of the silicone film due to irradiation damage was not regarded as a problem.

The second problem dealing with the transmission of an electrical signal from a high-flux radiation field to a remotely located read-out device was related to the determination of internal porosity in a fabricated fuel pin.

It was decided that eddy current techniques be employed for the determination of the integrity of a fabricated fuel pin. In this technique the item to be inspected is passed through a coil upon which is impressed a high-frequency electrical signal. Under a particular set of conditions, the character of the output from this coil is a function of the internal integrity of the section of material filling the coil. Here, again, the performance of the detecting unit in a high-flux gamma field was an unknown quantity. For this investigation the detecting unit consisted of windings of AWG Size 40 Ceroc-insulated wire upon an unfired Lava B coil form.

A test rig, shown in Figure 1, in order to determine the operating characteristics and longevity of the eddy current coil and the differential transformer in the ANL Gamma Irradiation Facility was constructed.

FIGURE 1

Test Apparatus for Determination of Effects of Gamma Radiation upon a Special Differential Transformer and an Eddy Current Coil.

The test rig consisted of a top and a bottom plate held in position by tie rods. A 250-rpm, 27-v DC electric motor (Model No. 5069600) manufactured by the Delco Appliance Div. of General Motors Corp. was mounted upon the top plate. Prior to installation, all materials of an organic nature were stripped from the motor and ceramic substitutions were made. The two exceptions were the armature windings and the Bakelite brush holders which were not altered from their original form. The gear box and bearings were washed with petroleum ether before being lubricated. The gear box was lubricated with Calresearch 159, which is a radiation-resistant grease developed by California Research Corporation, and a brush application of the base oil for the Calresearch 159 grease was applied to bearings and shafts before reassembly of the motor. The shaft of the motor was cotter-pinned to the shaft of a level wind screw which rode in a bushing on the bottom plate. The armature of the differential transformer and a uranium-5% fissium pin, 0.1445 in. in diameter and 3-3/4 in. long, were mounted upon a pin guide attached to a nut-and-thread guide mounted upon the level wind screw. Rotation of the level wind screw resulted in a reversing vertical travel of the armature and the uranium-alloy pin through the differential transformer and eddy current device, respectively. The coils of the transformer and eddy current device were rigidly mounted within the test rig framework between bearing and clamp plates.

The test assembly described above was designed to fit into two No. 2 cans. The power leads to the motor were insulated with asbestos. The signal leads from the coils were Refrasil insulated and the leads were soldered onto the lugs of Fusite octal connectors. The Fusite connectors were soft soldered into the bottom of one can and the test rig inserted into it. Another can was fitted over the test apparatus and the two soldered together. Figure 2 shows the canned apparatus just before the seal was made at the joint between the two containers. To insure leak tightness the container was tested by helium mass spectrometer methods. As a final step before irradiation the cans containing the test apparatus were flushed with dry argon and the gas lines soldered closed.

INSTRUMENTATION

The instruments employed in this experiment provided recorded information from the change in output signal of the differential transformer and from the impedance change of the flaw detector probe. In addition, the temperature within the containment shell was measured at frequent intervals.

FIGURE 2.
Containment Shell for Irradiation
Test Apparatus.

which, in turn, produce a magnetic field that cancels part of the magnetic field intersecting the pin and causes a reflected impedance change. The change in impedance produced by cracks or voids was detected by an Owen bridge circuit. This bridge was fed a signal voltage of 62 kc from the variable-frequency oscillator. The output of the bridge, which depends in part on the impedance of the coil probe encircling the specimen, is a function of the specimen resistivity. This output was amplified and rectified providing a DC output voltage. The output voltage was bucked by an external battery voltage supply and the differential voltage was adjusted to provide the sensitivity required. Using a 300-ma scale on the micro-voltmeter, the voltage was adjusted to indicate a nearly full-scale voltage for the largest flaw. The output of the microvoltmeter amplifier was connected to a Sanborne DC amplifier which fed one channel of the recorder. Stability of the eddy current instrument was maintained by the use of a regulated power supply.

A block diagram and a photograph of the instrumentation are shown in Figures 3 and 4, respectively. The instruments were operated in the following manner.

DC Motor Control

A rectifier power supply was used to produce a variable DC voltage for adjustment of the speed of the Delco motor. This motor has a permanent magnet field so that speed change could be made by varying the armature voltage. Armature current was measured to provide an indication of the condition of the motor.

Eddy Current Instrument

The detection of the flaws in the fissium pin was indicated by the Mark I eddy current instrument provided by the Metallurgy Division Nondestructive Testing Group. This instrument detects flaws by the principle of impedance change in a coil.⁽²⁾ A coil encircling the fissium pin sets up a magnetic field intersecting the pin; the flux causes eddy currents to flow in the pin,

FIGURE 3.
Block Diagram of Test Apparatus
and Control and Recording Equipment.

FIGURE 4.

Control and Recording Equipment Employed in Radiation Tests upon a Special Differential Transformer and an Eddy Current Coil.

Differential Transformer Instrument

A Sanborne strain gage amplifier was used as a source of excitation voltage for the differential transformer. It impressed a 2500-cycle excitation signal on the primary winding of the differential transformer and a signal output voltage, dependent on the displacement of the core, was induced in the secondary. This signal was amplified and rectified in the strain gage amplifier and then fed into the second channel of the recorder.

Thermocouple Instrument

The temperature within the containment shell was detected by an iron-constantan thermocouple. The EMF of the thermocouple was measured with a Model 9B Pyrotest direct-reading potentiometer.

Signal and Power Transmission

The electrical connections from the instruments through the water barrier to the connectors were made using standard, thermoplastic-insulated AWG #18 wire for the motor and flaw detector probe, and two conductor-shielded Belden 8422 cables for the primary and secondary of the differential transformer. The thermocouple was insulated with glass braid over each conductor and an over-all wrap of glass braid. The motor leads were introduced into the test assembly separate from the signal leads of the differential transformer and flaw detector probe, to avoid the possibility of stray pickup.

The hermetically sealed connectors used for entry into the containment shell were of standard octal base configuration, manufactured by Fusite Corporation, and no difficulty in electrical breakdown was experienced at the voltage levels and gamma fluxes encountered in this test.

TEST PROCEDURE AND IRRADIATION PROGRAM

The irradiation program for this investigation was carried out in the Argonne High Level Gamma Irradiation Facility. Prior to irradiation, the leads from the test apparatus to the recording and control instruments were pulled through Tygon tubing and threaded through a special urn cover. The tubing was clamped to tubulations in the urn cover, effecting a water-tight seal. The control and power leads were terminated in the octal connectors which were plugged into the proper termination on the canned test rig which was inserted into a sample urn. The cover was locked onto the sample urn and the entire assembly was lowered into an irradiation rack.

In the ANL Facility it is customary to rotate the sample urn during an irradiation to insure uniformity of irradiation and minimize the shielding effect which one component within the urn may have upon another. In this case the sample urn was placed in a pedestal cup to prevent rotation, which could not be tolerated because of the electrical leads from the urn to the controlling apparatus.

The irradiation schedule for this investigation took the form of a varying pattern over the forty-nine-day period of exposure. For twenty-eight days the test apparatus was exposed to 4.7×10^5 rad/hr during an eight-hour day of each work week. At night and on weekends the dose rate was 9.6×10^5 rad/hr. On the twenty-ninth day of continuous irradiation new fuel elements were placed in the irradiation facility and the remaining twenty-one days of exposure were carried out at increased dosages. The daytime rate was 5.2×10^5 rad/hr and the night and weekend rates were 1.6×10^6 rad/hr for this three-week period. The dose rates were determined by chemical dosimetry, employing ferrous sulfate. The gamma-radiation

energy spectra for this facility is from 0.22 to 2.5 Mev, the average being about 0.75 Mev. Although the field is essentially gamma, there is a low neutron background which was not considered pertinent to the study made.

During the irradiation study the motor within the test apparatus was operated only when a record of the output from the differential transformer and eddy current coil was required. A strip record of the operation was taken at three- and four-day intervals. During the last seven days of irradiation, however, the motor was operated continuously.

RESULTS

Figure 5 is a trace of the output of the differential transformer and the eddy current coil during irradiation. Trace "a" is the output of the differential transformer against time. The time axis is described by trace "c" upon which each pip represents one second of running time. At the top of Figure 5 is an illustration which explains the unusual shape of the differential transformer output trace. In this illustration the two heavily drawn horizontal lines represent the limits of the windings on the transformer; the series of vertical lines represents the positions of the armature in the coil at various points in its cyclic travel within the transformer coil. The horizontal centerline in this illustration represents the division between the two coils of the transformer and conforms to output zero on trace "a." Since this transducer is of the "bucking" type, when the armature is centered in the coil a null voltage is achieved. A movement of the armature out of the coil in any direction must increase the output in that direction until the core fills one set of windings only, at which time voltage in the opposite coil is zero. At this point the maximum differential voltage is reached. Continued travel in this direction reduces the length of coil filled by the armature and correspondingly decreases the magnitude of the output. This phenomenon is repeated upon reversal of travel, back to the null, and continues with a 180° phase shift in the opposite direction.

Trace "b" of Figure 5 is the eddy current coil output versus time for the cyclic travel of the fissium rod through the coil. The sharp changes in output indicated as points 1, 2, and 1 are caused by the presence of voids in the cast pin. The points 1 are the same flaw; one "seen" by the coil on the pins upward path, the other detected upon reversal of direction. Point 2, which appears to be a compound peak, is at the point of pin travel reversal which occurred at the same point in the pin as a flaw, thus the unusual shape.

Traces such as that presented as Figure 5 were taken each three or four days during the entire irradiation period. During this time the gamma flux incident upon the test apparatus was between 4.7×10^5 and 1.6×10^6 rad/hr. The test assembly was exposed to the above irradiation rates for a period of forty-nine days during which a total dosage of 1.24×10^9 rads was

FIGURE 5

Traces of (a) Special Differential Transformer and (b) Eddy Current Coil Output during High-Level Gamma Irradiation and (c) Timing Trace (1-sec intervals).

accumulated. When the motor speed was so set that the frequency of the cyclic travel of the level wind screw was constant for each data-taking interval, no changes in trace were noted over the entire irradiation period. With the exception of base-line shift in the case of the eddy current measurements, the traces were also insensitive to the temperature changes within the test apparatus containment shell, which varied from 27 to 46°C.

At the termination of the test the sample urn was transferred from the facility and the test apparatus was removed from the urn. The solder was melted away from the container and the test rig was withdrawn from the cans. The components were examined for radiation damage and the following conditions were noted: an exudation was present on the surface of the asbestos insulation, but its insulating qualities appeared unchanged. It is theorized that the material being discharged was an organic binder employed to lend adherence to the insulation. There was no apparent change in the Refrasil insulation used on thermocouple and control leads. Some rusting was noted on ferrous materials in the test rig. This was probably due to moisture entrapped in the insulation which was emitted during the test period. It was interesting to note that paint on nameplates, etc., was not noticeably changed during the irradiation, although the varnishes applied on some components did have a tendency to brown. Disassembly of the motor revealed a general darkening and embrittlement of Bakelite brush holders. The varnish used as insulation on the motor armature was darkened by the exposure to irradiation. The grease and oil used in the gear box and for lubrication of bearings had turned slightly tacky to the touch but still possessed a degree of lubricity.

CONCLUSIONS

It would appear from the results of the irradiation carried out for this investigation that the use of eddy current techniques for indicating internal porosity in cast fuel elements and the use of linear transducers of the differential transformer type is a practicality. The performances of the components tested were such that they might be expected to operate successfully in the environment anticipated in the EBR-II Fuel Cycle Facility. Although radiation damage to conventional units would preclude their use in such a facility, careful planning of design and selection of special materials of construction can and will result in acceptable performance from many components under this rather severe environment.

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