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FUEL ELEMENT COOLANT CHANNEL AND OTHER SPACING MEASUREMENTS BY EDDY-CURRENT TECHNIQUES

C. V. Dodd

R. W. McClung

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ABSTRACT

The problem of making measurements of restricted spaces is presented and eddy-current techniques are proposed as a possible solution. Very elementary theory is presented for orientation of those who are unfamiliar with eddy currents. The design philosophy of test probes is discussed. Several probe styles are described and their application to inspection problems is shown.

INTRODUCTION

In the nuclear industry, as in the aircraft and missile industries, the solutions to design problems are often realized by operating materials and components only marginally below their ultimate capabilities. Frequently, the attainment of such high performance is dependent upon very close dimensional control of the various components and assemblies. For instance, in most nuclear reactors, the fuel assemblies are arrays of fuel-bearing plates or rods with coolant channels between each member. A constant flow of coolant through the reactive core maintains a dynamic balance of heat production and removal. It is evident that too little coolant flow could cause excessive temperatures and subject structural materials to conditions beyond design limits. Excessive channel spacing could be cumulative and prevent the maintenance of overall dimensional requirements. Similarly, there are many applications in which tubing diameters must be very carefully controlled. Obviously, the imposition of close tolerances demands accurate methods for measuring these various dimensions.

Recent developments at the Oak Ridge National Laboratory (ORNL) have demonstrated that eddy currents can be used to provide rapid and accurate techniques for performing such measurements. This report gives a brief introduction into the problems of measuring restricted spaces by nondestructive means. Included is the elementary eddy-current theory from an empirical viewpoint and a description of the methods and applications of eddy-current spacing methods at ORNL. This report was prepared as an introduction for those who are unfamiliar with nondestructive testing and, in particular, eddy-current phenomena.

GENERAL THEORY

Basic principles of physics reveal two phenomena relative to the flow of an alternating electrical current through a coil of wire.

1. The current will produce a magnetic field which will induce electrical currents into any conductor within its influence. The induced currents, better known as eddy currents, are influenced by the geometry, magnetic permeability, electrical conductivity and discontinuities of the conductor, and the frequency and intensity of the alternating field. The eddy currents will, of course, establish a magnetic field in opposition to the primary field.

2. The coil itself will exert an influence on the alternating voltage which is driving the coil. This influence is known as the impedance of the coil.

These two effects are related in that the secondary magnetic field which will be established by the eddy-current flow will alter the impedance of the coil. Therefore, the coil impedance will be a function of the aforementioned properties of the conductor, the frequency and intensity of the driving voltage, and the distance or lift-off between the coil and the conductor.

Impedance can be expressed as the vector sum of a resistive component which resists the current flow and a reactive component which stores the current allowing it to flow at a slightly different time. Ohm's law provides the expression

$$\bar{V} = I \bar{Z}$$

where

$\bar{V}$ is the voltage,

I is the current, and

$\bar{Z}$ is the impedance.

Thus it can be readily seen that for constant current the voltage is proportional to the impedance. From this, it follows that measurements of coil impedance may be made by placing a large resistor in series with the coil to provide constant current and then monitoring the amplitude and phase of the coil voltage. This information may be plotted with the amplitude of the voltage representing the length of the impedance vector and the phase representing the angular displacement (or storage time) from the positive real axis (phase of the driving voltage).

Figure 1 shows a general plot of coil impedance as the frequency conductivity and coil-to-conductor spacing or lift-off vary. The curve has been normalized by subtracting the resistance of the coil in air and dividing both the coordinates by the reactance of the coil in air.

A major problem in the utilization of eddy-currents is to fix the other variables and to measure only the one of interest. One of the parameters which is difficult to hold constant when measuring conductivity or clad thickness is that of lift-off on coil-to-metal spacing. However, for spacing measurements, the proper frequency and coil design are chosen to give a large ratio of impedance change to spacing change and the variables other than lift-off must be fixed.

INSTRUMENTATION

Figure 2 is a block diagram of a basic eddy-current instrument. It incorporates an oscillator, a power amplifier, and an impedance bridge. The test coil is placed in one leg of the bridge and the other leg of the bridge may be electrically balanced for a null output. This impedance change in the test coil will unbalance the system and can be detected as voltage changes. A number of commercial instruments are available using this and other circuitry by which impedance variations can be measured. Two such instruments used at ORNL for spacing measurements are the Dermitron[1] and the Laminagage.[2]

PROBE DESIGN

Probably the most important element in successful spacing measurement by eddy-current techniques is the test probe. The test probe

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[1]Manufactured by Unit Process Assemblies of 61 E. 4th St., New York, New York.

[2]Licensed for manufacture by General Motors Corporation, Detroit, Michigan.

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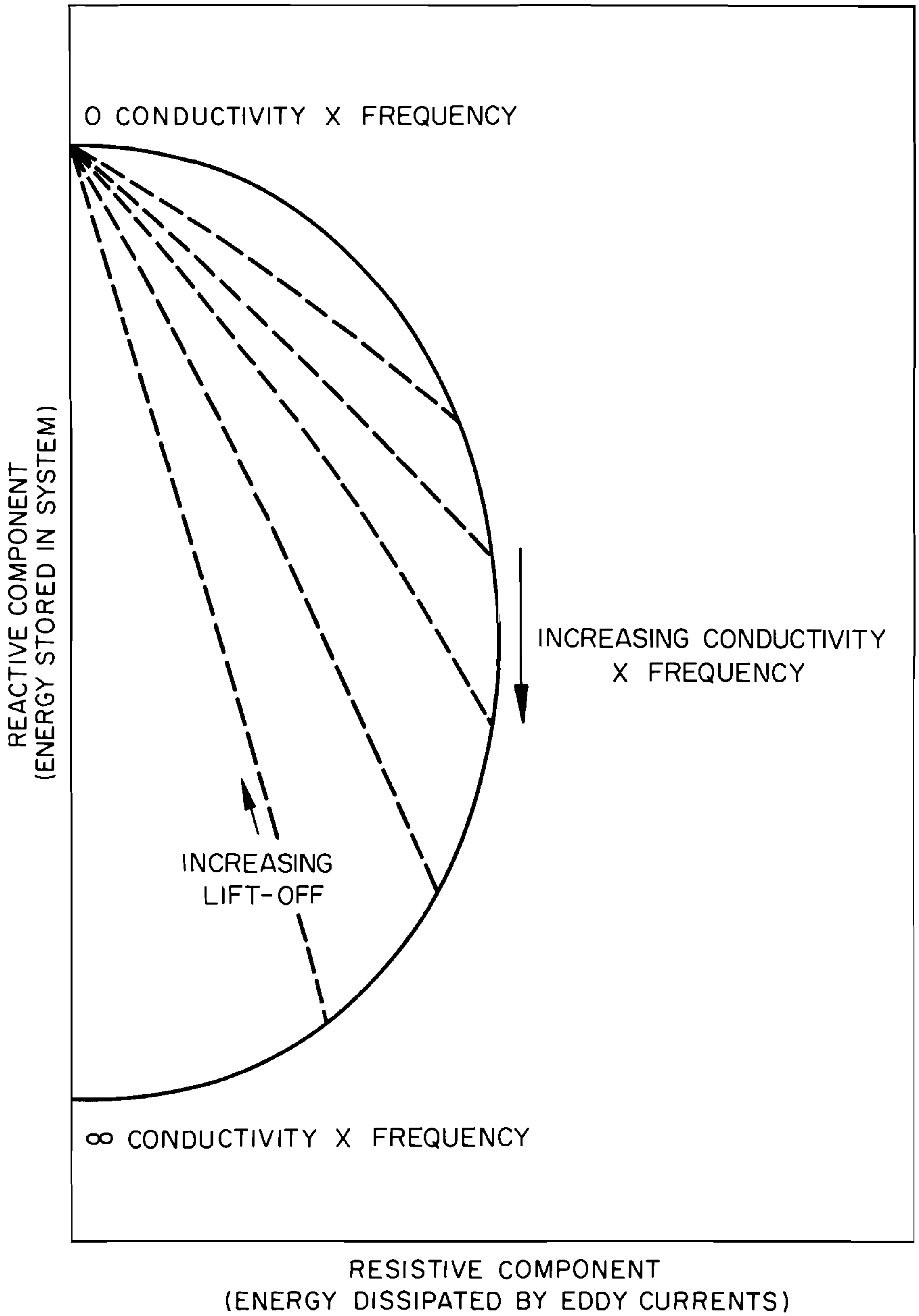

Fig. 1. Impedance Plane for General Case.

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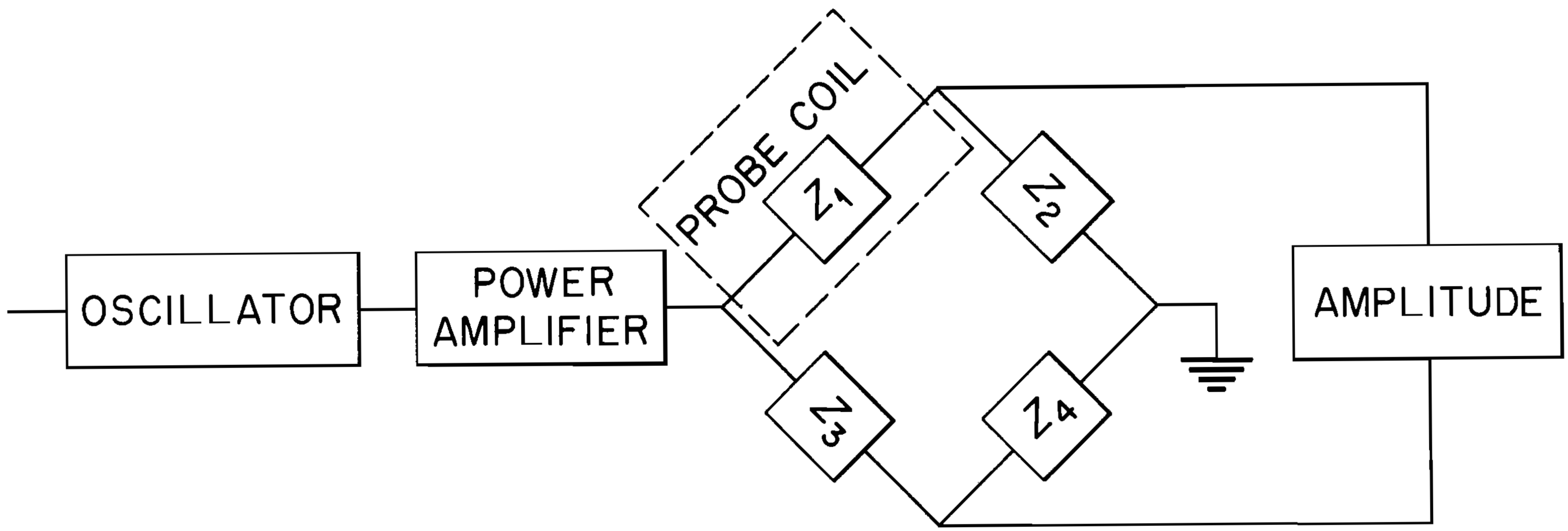

Fig. 2. Eddy-Current System.

consists of the coil and the mechanical features to position the coil and fix the other variables. A number of different test probes have been designed and constructed for several different applications and a variety of different coils have been wound.

Probes for Flat-Plate Fuel Elements

In order to keep the variables in the fuel plate from influencing the coil impedance, an indirect method of measuring the spacing is used. The type of probe shown in Fig. 3 has been employed to measure the spacing between relatively flat fuel plates. The coil is mounted on a long, thin handle and is shielded by a leaf spring which overhangs the coil. Thus, as the probe is inserted between the plates, the spring action presses the coil and spring against opposite sides of the channel. The changes in coil impedance are a function of the coil-to-spring spacing, and, of course, the plate spacing determines the spring spacing. When minimum spacing permits, small projections may be placed on top of the spring and on the bottom of the holder to measure the spacing directly over the coil and allow more localized variations to be detected. Ferromagnetic steel which is used for these probes has been chosen because it effectively shields the coil from the surrounding media, gives an effective signal increase, and is durable. The design of the test coil itself plays an important role in successful spacing measurements. For example, Fig. 4 shows the normalized fields of two general coils plotted along the axis of the coil. One coil is a short solenoid in a ferrite cup and the other is a flat coil, spirally wound with flat wire. It can be readily seen that the coil in the ferrite cup will have the largest range of spacing measurements due to its extended field. However, the flat coil will fit into smaller spaces and can be more sensitive over a narrow range. Figure 5 shows how the impedance varies with lift-off. The test coil was placed directly on a flat piece of ferromagnetic material, and the spacing varied to a second piece of identical material. This was done over a range of frequencies. Thus it simulates the basic probe-coil design. It is evident that the impedance is a nonlinear function of the lift-off, and that the amount of impedance change varies

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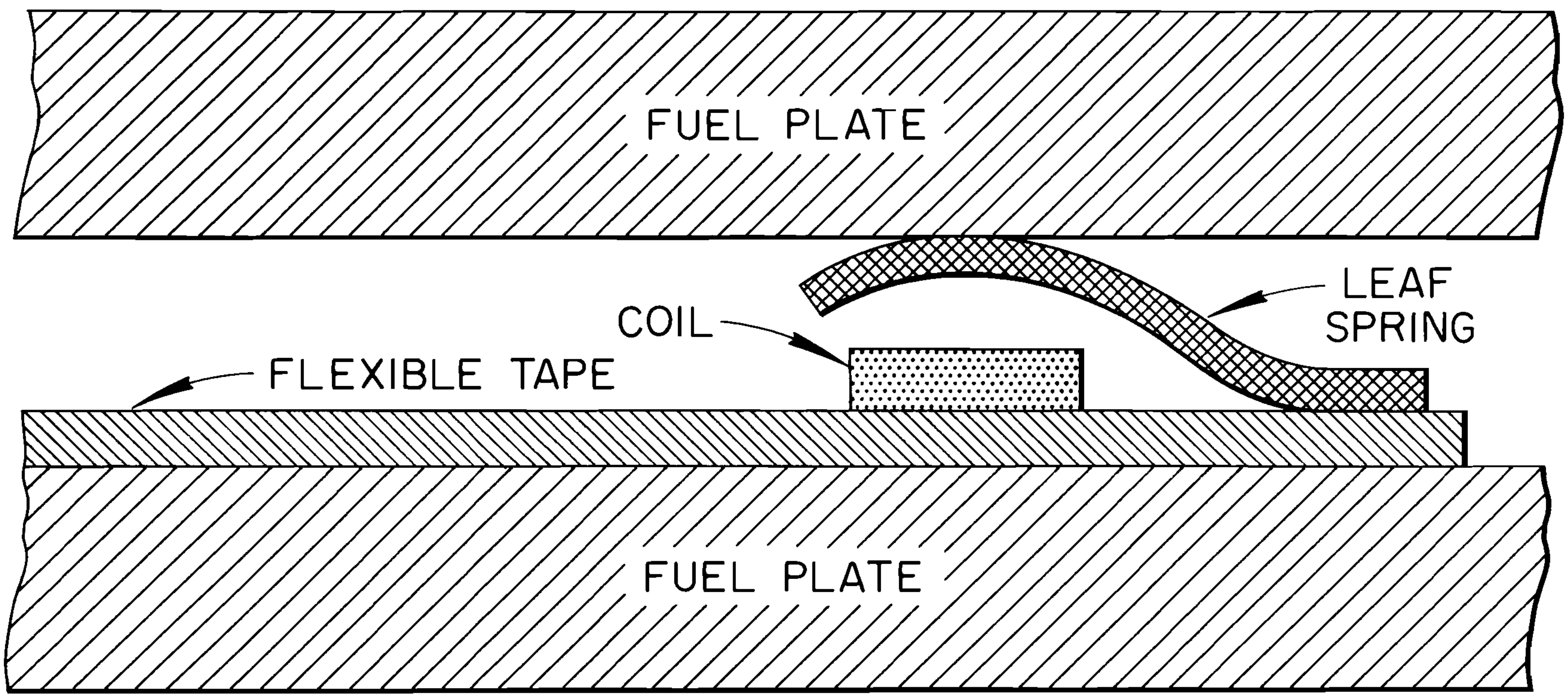

Fig. 3. Flat-Plate Channel-Space Measuring Probe.

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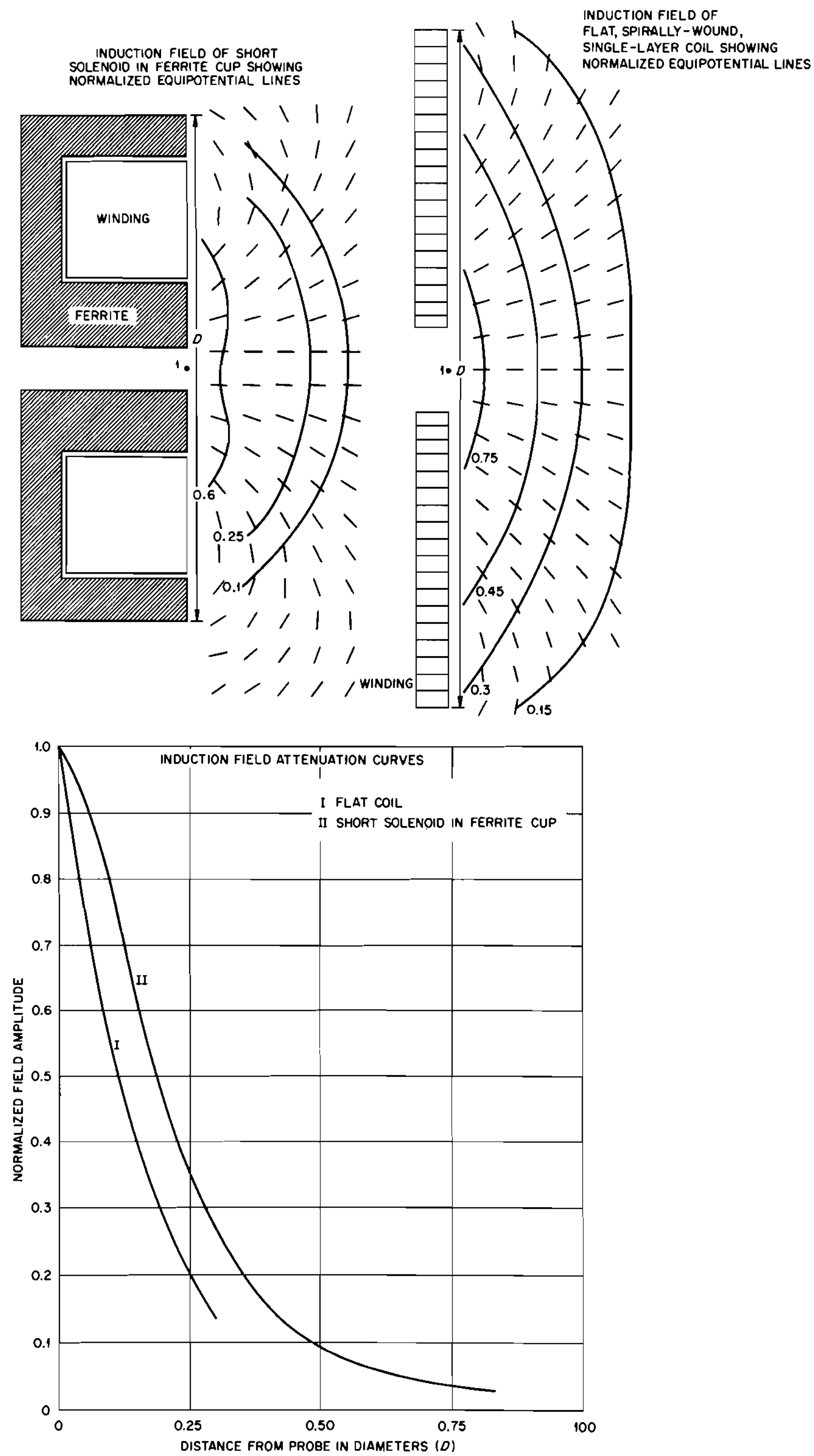

Fig. 4. Induction Fields of Probe Coils.

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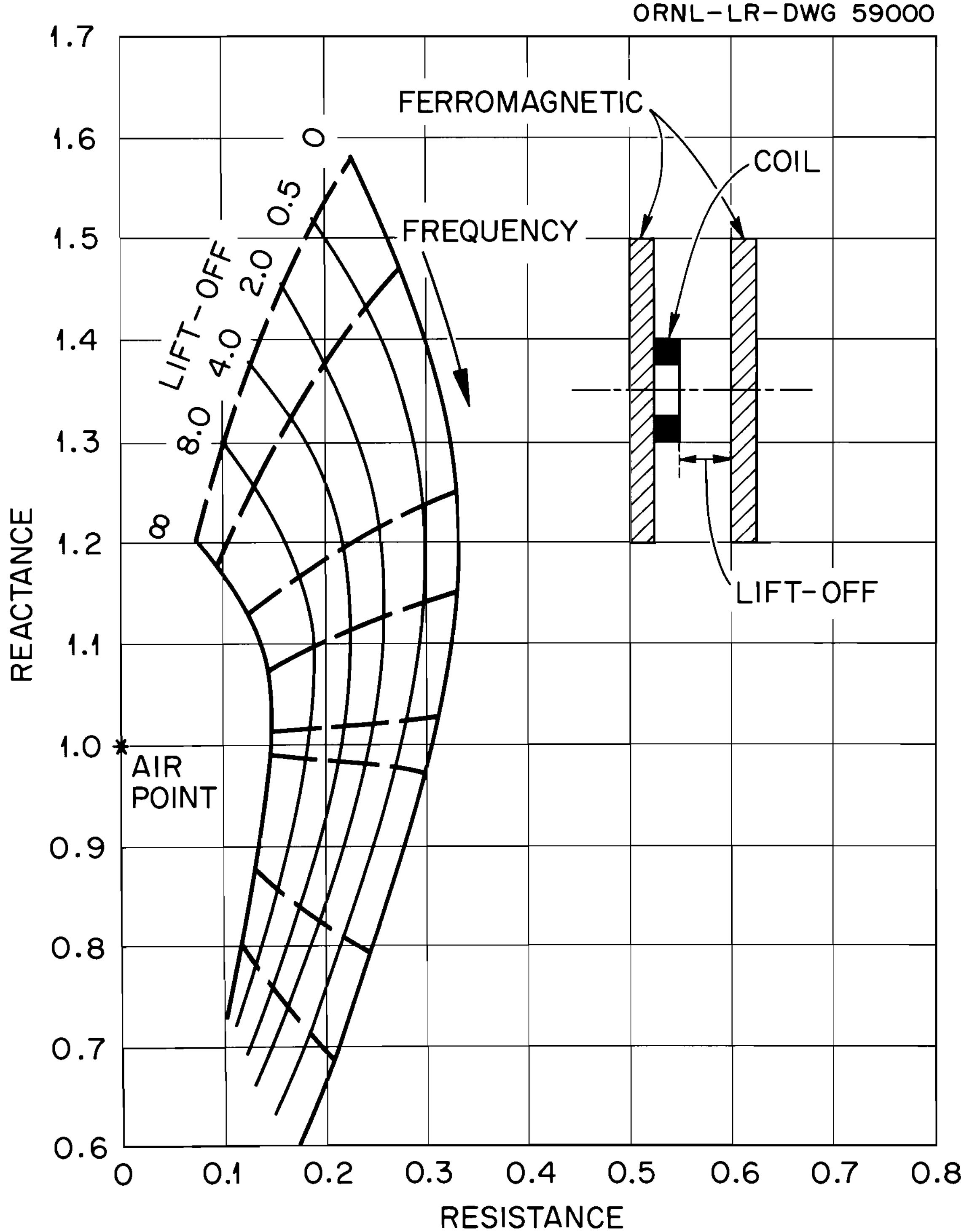

Fig. 5. Normalized Impedance Plane for Flat-Plate Spacing Measurements.

with the frequency. When the frequency is too low, the ferromagnetic material becomes a poor shield and the overall coil impedance is small compared to the residual coil resistance.

Probes for Tubular Fuel Elements

A probe designed and constructed to measure the spacing between tubular fuel elements is shown in Fig. 6. This probe measures the spacing between the fuel elements directly. Early attempts to utilize a leaf-spring probe were somewhat unsuccessful for several reasons, including difficulties in positioning the probe between the rods and the fact that long, flexible rods tended to move slightly with the spring insertion. As with plate-type elements, the impedance changes are not linearly related to coil-to-specimen spacings. Thus the coil cannot be allowed to move freely across the measured space. The modified V shape of the probe shown in Fig. 6 holds the coil equidistant from the measured rods and controls the amount of coil insertion between the rods as a function of rod spacing. This latter movement will cause an impedance change which can be calibrated in terms of inter-rod spacing.

Probes for Inside-Diameter Measurement

Figure 7 shows a type of probe designed to measure the inner diameter of tubing. The probe head is inserted into the tubing by means of a long handle. As the probe is moved longitudinally or circumferentially through the tube, inner-diameter variations will cause lateral movement of the spring-loaded ferromagnetic feeler. The shank of this feeler is surrounded by a solenoid coil. The feeler variations will be reflected as impedance changes in the solenoid coil. A metallic shield surrounds the coil and isolates it from changes in the tube other than the diameter. Probes of this type have been constructed to make measurements in tubing with boxes as small as 0.4 in.

APPLICATIONS

These spacing measuring devices have been used in several projects at ORNL. A typical example is the High Flux Isotope Reactor (HFIR) fuel element. This is a cylindrical assembly composed of 0.050-in.-thick

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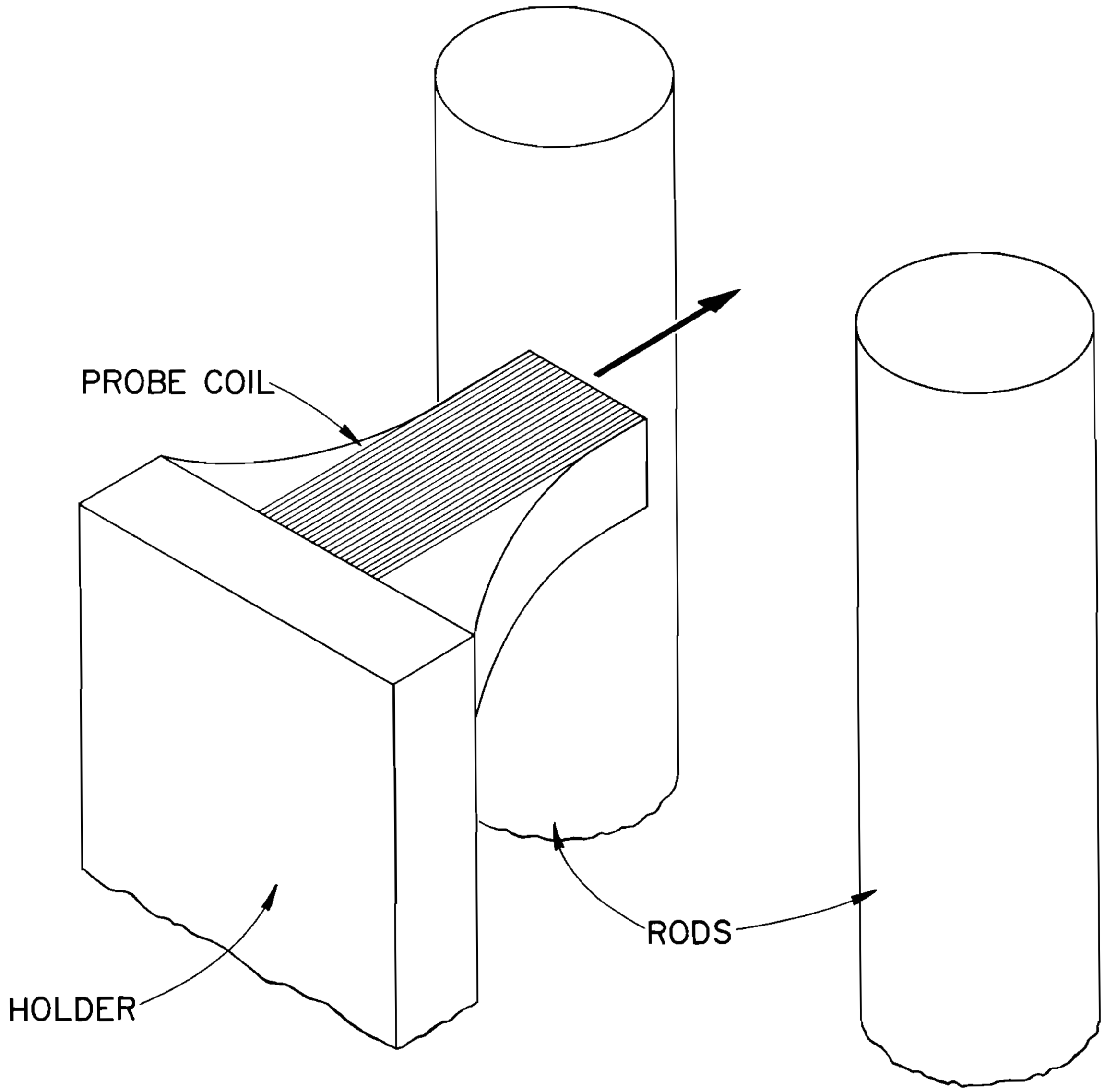

Fig. 6. Inter-Rod Probe.

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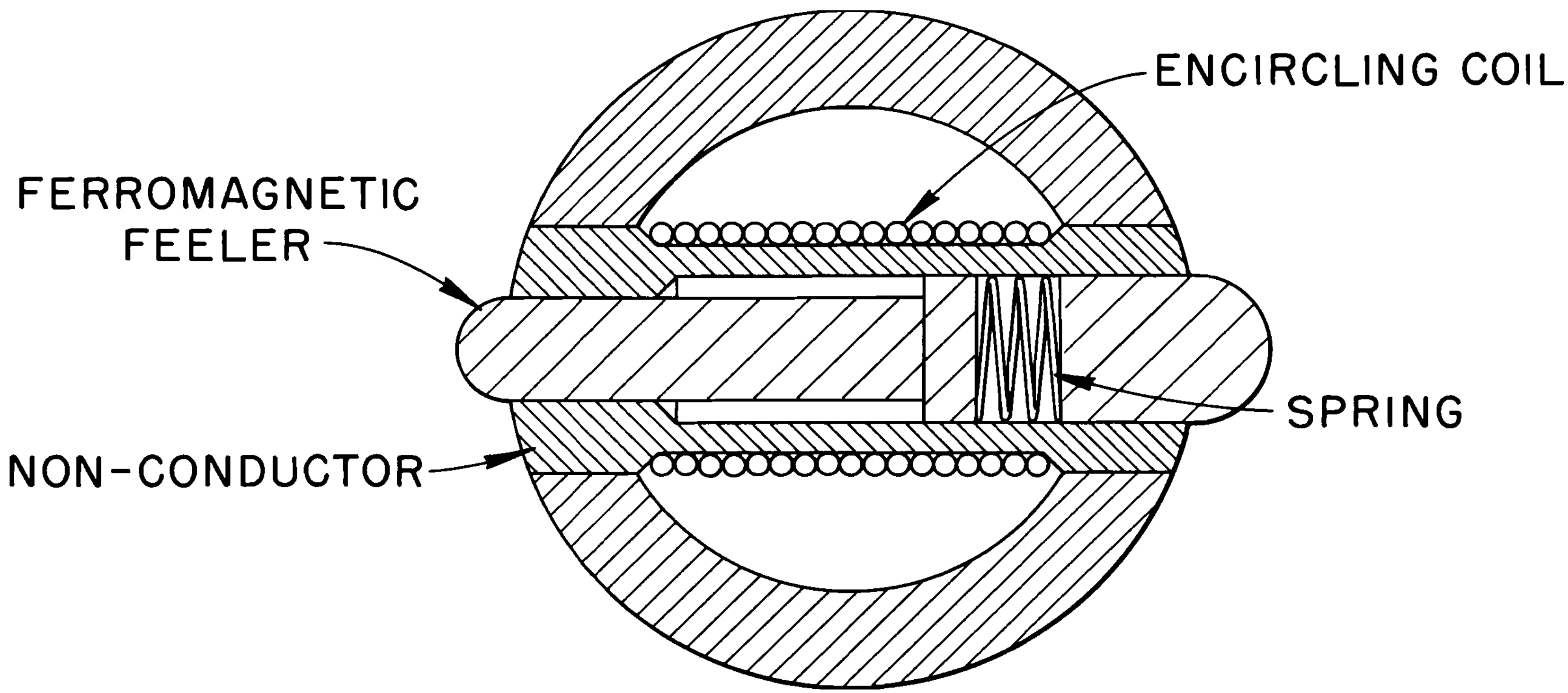

Fig. 7. Tubing Inside-Diameter Gage.

aluminum-base fuel plates with alternate coolant channels nominally 0.050 in. wide. The plates are curved into an involute shape. Figure 8 shows the probe used to measure the spacings in the HFIR fuel element. It consists of a coil placed on a steel tape with a leaf spring which has been spot welded to hang over the coil. Because of the very restricted space, the coil was a single layer, spiral-wound coil 1/4 in. in diameter. The curved tape was chosen because its radius of curvature was smaller than that of the smallest radius in a coolant channel. This, of course, prevents "wedging" the probe in the narrow curved channel. Also, the distance of insertion into the element could be read directly from the probe. This probe was used with the Laminagage. Figure 9 shows how the probe was inserted into the HFIR fuel element. The particular system has a range of spacings from 0.030 to 0.070 in. and an accuracy of ± 0.001 in. This type of probe has been used to make thousands of measurements in the fabrication development of the HFIR fuel element.

A very similar type of probe was used to measure the coolant channel spacings in an Enrico Fermi Reactor Core B fuel element constructed with stainless steel. This probe is used with the Dermitron and has a range of 0.050 to 0.060 in. with an accuracy of 0.000 5 in. This system with the Fermi element is shown in Fig. 10. The spacing was wide enough to permit shielding to be used on the leads. A large number of these measurements was made and Fig. 11 is a typical plot of the data obtained on a prototype element. This is a Gaussian (bell-shaped) distribution around a mean which would be expected. These measurements were checked a month later and agreed to within ± 0.0005 in.

Measurements of the type described lend themselves very well to mechanization, recording, and even remote operation. Such measurements have been made on an irradiated Army Package Power Reactor fuel element which is somewhat similar to the Fermi element except that the spacing range was 0.110 to 0.160 in. These measurements were made under hot-cell conditions. It was suspected that there were permeability variations throughout the element due to radiation effects, so thicker leaf springs were used to provide extra shielding for the coil. Also, this space was

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Fig. 8. Photograph of Probe for Measuring Coolant-Channel Spacing of HFIR Fuel Element.

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Fig. 9. High Flux Isotope Reactor Fuel Element with Probe Inserted.

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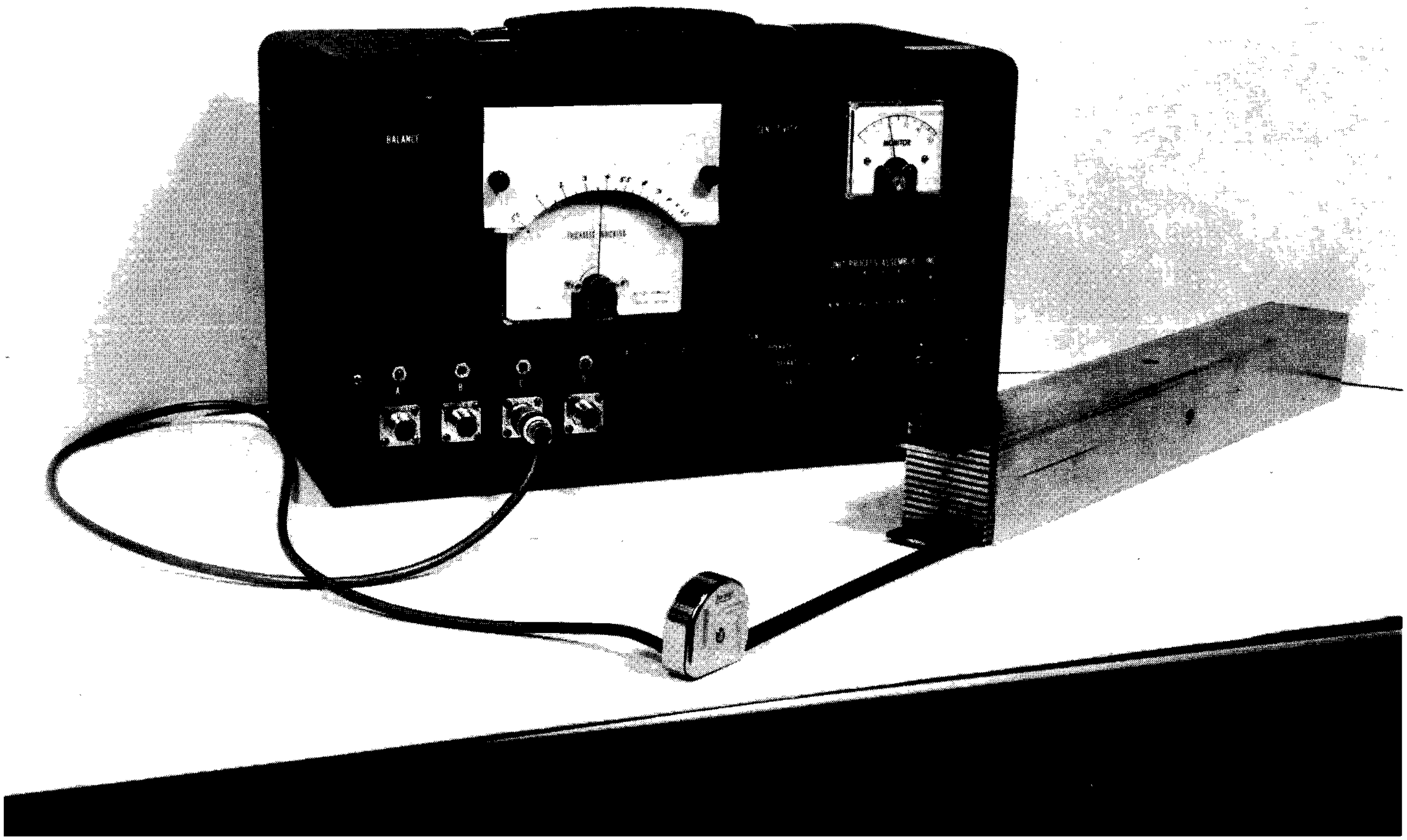

Fig. 10. Measurement of Fermi Fuel Element Channel Spacing.

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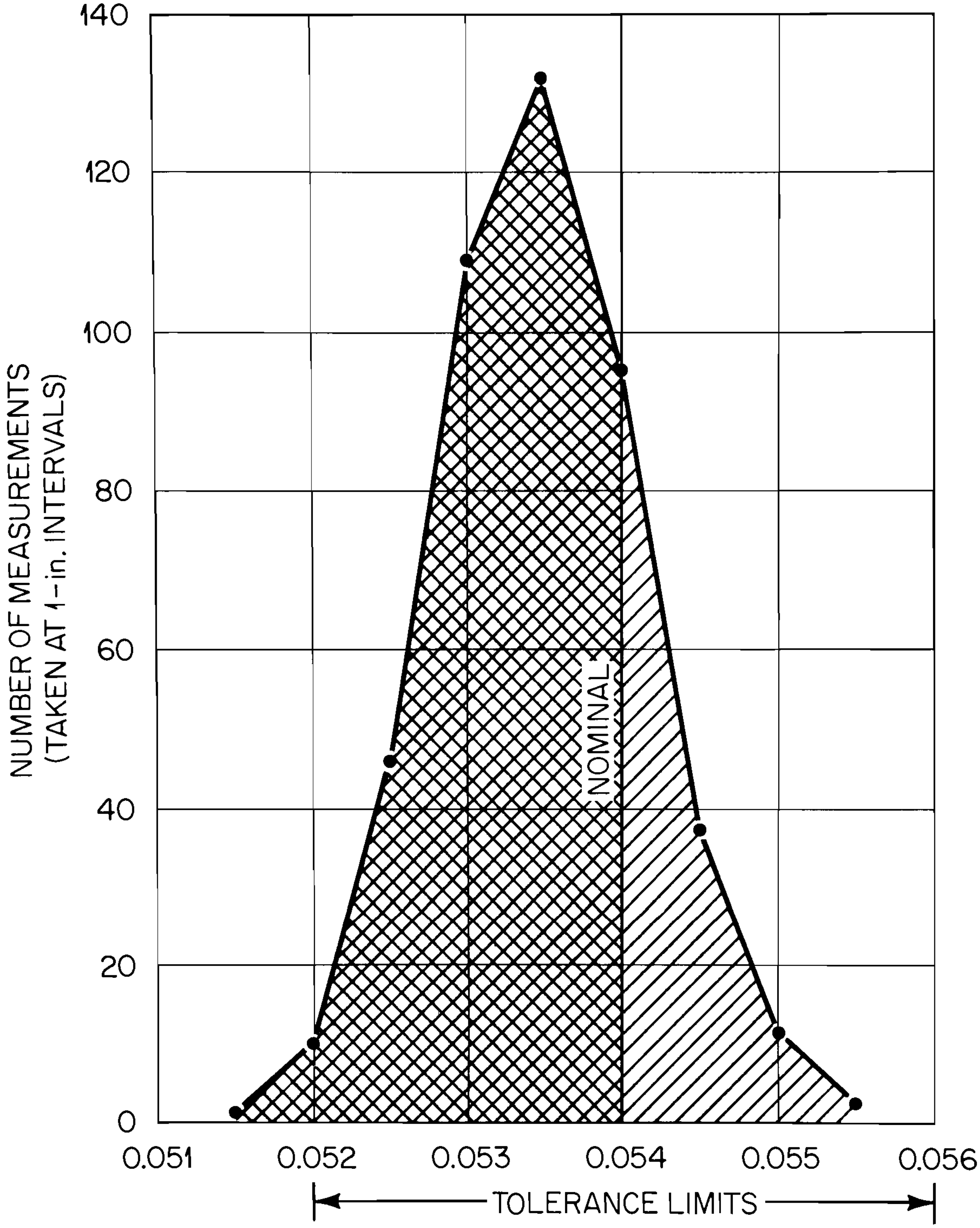

Fig. 11. Fermi Core B Dummy Element No. 2 Dermitron Data of Channel Spacing.

wide enough to permit small feeler projections above and below the coil to permit measurement of very localized variations. The element was clamped to the bed of a milling machine in the cell and driven mechanically past the fixed coil. The output of the Dermitron was fed to a strip-chart recorder. In this way, a continuous contour of the channel spacing was recorded. A block diagram of this system is shown in Fig. 12. The channel spacings were measured within ± 0.003 in. with eddy currents and were checked with a mechanical device with an accuracy of ± 0.005 in. The readings checked within the limits of error.

CONCLUSIONS

The eddy-current method of spacing measurements has proven to be very successful with plate-type fuel elements. Some of the problems such as durability of the probes have been overcome. Others, such as construction and maintenance of good standards and manual errors near the ends of the element, still exist. The use of eddy currents for inter-rod and tubing inside-diameter measurements has not yet been developed to the same extent as for flat-plate fuel elements, but early studies are very promising. The eddy-current methods are rapid, accurate, can be readily automated for a permanent recording, and can be used in areas of limited access. While other methods may be used to make these measurements, it is believed that eddy-current methods, because of their versatility, will be more widely employed in critical applications.

ACKNOWLEDGMENT

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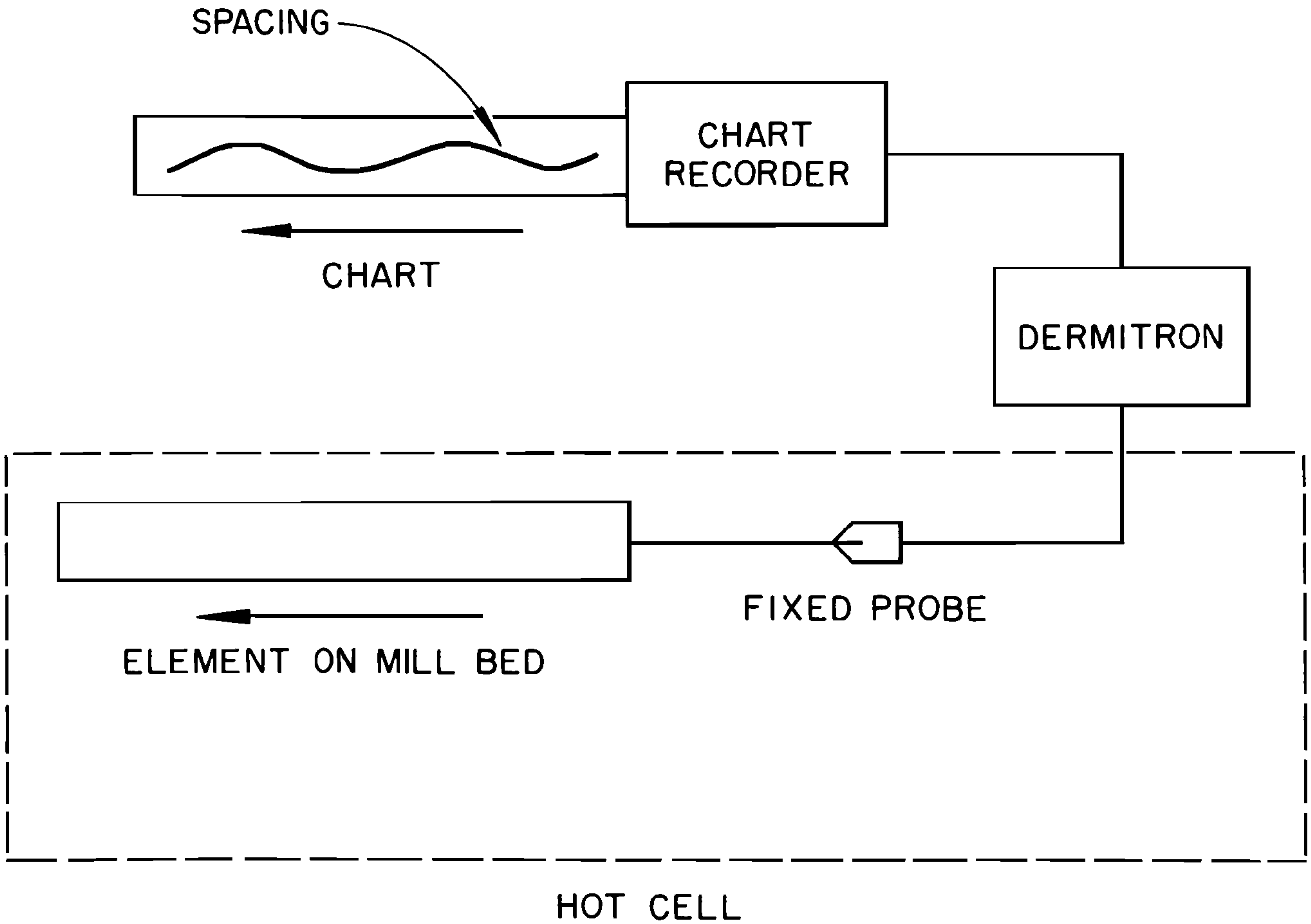

Fig. 12. Remote Measurement of Irradiated Element.

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