LIQUID METAL BEARINGS TECHNOLOGY
FOR LARGE, HIGH-TEMPERATURE,
SODIUM ROTATING MACHINERY

fourth topical report
DEVELOPMENT AND TEST OF
A HIGH-TEMPERATURE PROXIMITY PROBE
FOR USE IN LIQUID SODIUM

by
I. hoogenboom
C. kissinger

prepared for
U. S. ATOMIC ENERGY COMMISSION
Division of Reactor Development and Technology
Special Technology Branch

prepared under
contract no. AT(30-1)-3930
mti project no. 48576

JUNE 1971

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ABSTRACT

An inductance-type, proximity-probe system for measurement of bearing film thicknesses and shaft orbits in high-temperature, liquid-sodium environment has been developed, built and tested. The probe system is designed to operate at temperatures up to 1200 F and gap range of 0.004" to 0.080", with good linearity over about three-quarters of the range, when using probe pairs connected in push-pull. The probes were tested extensively in both gas and sodium environments, culminating in a 684 hours continuous test in a temperature range of 1050 F to 1170 F. The probes operated stably, repeatably and without undergoing performance changes. An electronic amplification and read-out system was specially designed for use with these probes. This electronic package was also developed, built and successfully utilized in the probe tests.
FOREWORD

This is the fourth Topical Report of the program on "Liquid Metal Bearings Technology for Large, High Temperature, Sodium Rotating Machinery." This program is currently in progress at Mechanical Technology Incorporated, under Contract AT(30-1)-3930 from the U.S. Atomic Energy Commission, Division of Reactor Development and Technology.

The program is directed at generating new technology in the areas of bearings and bearing instrumentation, that is needed for the successful development of high capacity, sodium circulation pumps and other auxiliaries of liquid metal cooled, fast breeder reactor systems. Specifically, the program comprises:

1. Extension of lubrication theory to the region of operation where bearing flow and pressure generation are governed by turbulence and convective fluid inertia forces.

2. Identification of self-acting and externally-pressurized bearing geometries that have the greatest likelihood of successful operation in high capacity sodium pumps and other auxiliaries of liquid metal cooled fast breeder reactor systems, and generation of the design data necessary for their rational design and optimization.

3. Development of accurate instrumentation for measurement of film thickness and film pressure directly in a high temperature sodium ambient.

4. Experimental evaluation of selected self-acting bearings in high temperature liquid sodium.

5. Screening, selection and evaluation of surface materials for high temperature sodium lubricated bearings.

The extension of lubrication theory, as called for in Item 1 above, was completed and described in the first topical report, NYO 3930-2. This was the basic analytical effort of the program since the sodium lubricated bearings required for high-capacity, sodium pumps will operate in the turbulent, fluid inertial flow regime by virtue of their size, geometry, surface speed, lubricant properties and Reynolds number. This regime of operation had not, in the past, received comprehensive analytical treatment in part because of its complexity, but also because of the lack of practical bearing applications in this flow regime.

The analytical development was complemented by experiments conducted with a 12 inch diameter journal bearing lubricated with a non-corrosive fluid of low viscosity to provide an early check on the validity and accuracy of the analysis. Good correlation was obtained between the calculated and measured data, as described in NYO 3930-2.

The analysis and numerical solution methods were then used to generate a broad
range of bearing design data applicable to large, self-acting sodium lubricated bearings and necessary for their rational design and optimization in specific applications. This calculated performance data for self-acting bearings operating the turbulent flow regime, was documented in the second topical report, NYO 3930-5.

In the third topical report, NYO 3930-9, the turbulent lubrication analysis was extended to cover the mode of operation of hydrostatic bearings. Calculated performance data for externally pressurized bearings operating in turbulent flow regime was generated, based on this analysis, and presented for a wide range of operating conditions.

In this fourth topical report, the development and testing of proximity probes for operation in liquid sodium at elevated temperatures, is described.

In two additional topical reports, scheduled for later this year, the remaining items of the program including the development of high temperature film-pressure instrumentation as well as the self-acting bearing tests, and the screening of surface materials will be described.

E. B. Arwas
Program Manager
Mechanical Technology Inc.
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I. INTRODUCTION

The proximity probes that are the subject of this report were developed for use in a sodium lubricated bearing test facility, to measure bearing film thickness and orbital shaft motion at operating temperatures up to 1200 F. This development was necessitated by the fact that there were no existing proximity probes capable of operation at elevated temperatures in an electrically conductive liquid gap.

Because of the highly conductive nature of the liquid in the sensing gap, an inductive sensing method was selected, as is discussed in the next section. As a result of the probe development effort, a fully developed sensing system is now available. Extensive data was obtained on the effect of temperature on system performance. The effects of the medium in the gap and of the carrier frequency on system output was investigated in detail. Limited endurance and cyclic temperature tests were also made on complete assemblies.

For the purpose of the planned sodium bearing tests, a measurement range of up to 0.040 inches had been initially required. However, other requirements of the Commission, notably related to eventual long term testing of the bearings of large sodium circulation pumps, made it desirable to develop the probes for a range of about 0.080" and to require a rugged probe construction, capable of reliable operation for extended duration in sodium at elevated temperatures. The final target specifications that were established for the proximity sensors were as follows:

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<th>sodium</th>
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<td>Temperature</td>
<td>up to 1200 F</td>
</tr>
<tr>
<td>Operating Range</td>
<td>up to 0.080 inches</td>
</tr>
<tr>
<td>Linear Range*</td>
<td>0.060 inches</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.1 volt/mil</td>
</tr>
<tr>
<td>Probe and Leadwire Temperature Sensitivity*</td>
<td>$10^{-6}$ in/°F</td>
</tr>
<tr>
<td>Readout Equipment Temperature Sensitivity</td>
<td>$10 \times 10^{-6}$ in/hr maximum</td>
</tr>
<tr>
<td>Noise</td>
<td>$30 \times 10^{-6}$ in equivalent</td>
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* When wired in "push-pull."
The transducers designed to the above specifications, were developed and extensively tested in a variety of atmospheres and temperatures, culminating in a 684 hours test in liquid sodium, as described in Section V of this report. During this period, the operating temperature cycled between the limits of 1050 F and 1170 F. Periodic measurements of the probe calibration were made incrementally over a range of ± 0.050" throughout the test, which confirmed the stability and repeatability of the transducers and the electronic system.

The probes made during the program are characterized by high stability, repeatability and sensitivity. Major factors in obtaining this performance were the overall design (aimed at ease of manufacture and assembly) and a very meticulous and consistent method of fabrication and assembly of such items as the high temperature coil, coil/core assembly, and lead connections.

An electronic amplification and read-out system was especially designed and produced for use with the probes. This system which incorporates a number of novel features, all aimed at system stability and repeatability, is described in Appendix 4 of this report.

Since the probes are currently scheduled for other uses, beyond the present sodium bearings technology test program, this report has been prepared to provide a detailed description of the development, the probe components and materials used, and the critical fabrication and assembly procedures, as well as the testing of the probes.
II. BASIS OF DESIGN FEATURES

Selection of Sensing Principle
There are numerous physical principles upon which a large variety of practical proximity sensors can be based.

In selecting the operating principle for the proximity probe for use in liquid metal at high temperature, the choice is very limited. The presence of a highly conductive medium in the sensing gap, combined with the high operating temperature leave only the inductive sensor as a possible candidate. These can be of two types as discussed below. For the reasons given in this discussion, the magnetic reluctance type of inductive sensor was chosen.

Eddy Current Proximity Probe
The principle of the inductive proximity sensor (eddy current type) is shown in Figure 1. This sensor consists of a coil, powered with alternating current, resulting in an alternating E.M. field around the probe. If a conducting (non-magnetic) surface is brought near the coil, the relationship between $\overline{E}$ and $\overline{I}$ changes. This change is the result of alternating currents (eddy currents) generated in the target by the external E.M. field of the probe. The eddy currents in turn generate an E.M. field, which opposes that of the coil.

The opposing effect of the eddy current's field causes the total field inside the target to become weaker with increasing distance from the surface. The depth at which the intensity is about 60% down from that on the surface is defined as the depth of penetration.*

The effect of the target is to reduce the inductance (L) of the coil and to increase the A.C. series resistance (R).

If the gap is filled with a conducting medium (e.g. sodium), the field of the coil is attenuated in the same way as by the target. If the field attenuation across the gap is small (< 10%), the probe can still function if the resistivity

---

* See Appendix 1 for more information on depth of penetration of A.C. magnetic field.
of the medium in the gap is much higher than that of the target. If the resistivity of the medium in the gap is the same as that of the target the probe has no output at all. If the resistivity of the material in the gap is lower than that of the target, the probe output will be reversed, that is: closer proximity will result in an increase in inductance and decrease in A.C. series resistance.

When considering a liquid metal medium in the gap, such as Na or NaK, and a 304 SS target, the high resistivity of the 304 SS (75 $\mu\Omega$ cm) and the low resistivity of Na or NaK (10 and 40 $\mu\Omega$ cm) make this an unworkable combination.

The probe can be made to work by changing to a ferromagnetic target. The effects of target conductivity on the probe (decrease in inductance $L$ and increase in series resistance $R$) remain the same, but in addition to those come the increase in probe inductance caused by the target permeability and the increase in probe resistance due to magnetic hysteresis. The effect of target permeability and hysteresis is generally greater than that of target conductivity. The effect can be increased by inserting a ferromagnetic core in the probe coil.

The probe with a core is named a magnetic reluctance probe when used with a ferromagnetic target. When used with a non-magnetic target, its characteristic is that of an eddy current probe.

**Magnetic Reluctance Proximity Probe**

The principle of this probe is illustrated in Figure 2. The field generated by the alternating current through the coil causes magnetic flux in the core. The flux passes from the core through the air gap back into the core. The air gap constitutes a major part of the magnetic reluctance of the probe. The typical increase in inductance when placing a ferromagnetic target in contact with the probe is 50 to 100%.

A probe design based on the diagram of Figure 2 is shown in Figure 3. It
**Fig. 1** Principle of Inductive Proximity Sensor (Eddy Current Type)

**Fig. 2** Principle of Inductive Probe (Magnetic Reluctance Type)
ASSEMBLE ITEM 4 IN ITEM 2 AND DRILL AND REAM FOR TAPER PIN ITEM 5 (4 HOLES LOCATE FROM ITEM 2)

Cement (see note 2)

View A
with cap pt.6 removed

FIG. 3 Proximity Probe Assembly.

NOTES

1. Fuse gold wire (Item 8) to Alumel wire (Item 11) by heating Alumel wire to 200°F.

2. "Tack" wire in place with Astroceram cement, American Thermocatalytic Corp.

3. Helium leak test per MILSTD-271, max. allowable integrated leakage shall be $10^{-3}$ micron cu ft/hr. pressure side noted.
is the final design of the probe developed in this program.

A metallographic section through such a probe is shown in Figure 4. The component parts for a probe are shown in Figure 5, and two completed probes (without sealing cap) are shown in Figure 6.

Except for minor modifications, the design in Figure 3 is identical to that of the experimental probes tested during the program.

This design has the following prominent features (see Figure 3):

1. One piece core machined from solid 430 SS, with a single radial slit extending over the full axial length of the core (part 4 of Figure 3).
2. Stainless steel casing (304 SS), (part 2).
3. Core to housing connection is made with four tapered pins very near probe sensing face, (part 9).
4. Gold wire coil with ceramic insulation, (part 5).
5. Coil form and ceramic spacers made from machinable ceramic.
6. Coil to lead connection at sensing end of probe. Connection is recessed in flange of coil form.
7. Asbestos insulated alumel lead wire, (part 11).
8. Thin (0.010") 304 SS sealing diaphragm welded to case, (part 6).

Some of the merits of these design features are discussed in the following.

Item 1
The one-piece core was chosen because it has inherently greater stability than a laminated or wire type core. The latter type of core depends upon some means of keeping the laminations (or wires) together and fixed relative to each other and the probe cases. This is difficult to achieve when operating a probe over a 1000 F temperature range. In addition to the absolute (temperature-induced) changes in inductance to be expected with a laminated core, it is unlikely that such probes when used in pairs, will track each other with temperature. When
Fig. 4  Metallographic Section of High-Temperature Probe for Use in Liquid Metals.
Fig. 5 High-Temperature Inductive Proximity Probe.
Fig. 6  High-Temperature Inductive Proximity Probe
(Complete assembly is without sealing cap and protective tubing around leads. Note recess in coil flange for lead wire connection.)
adding to these characteristics the difficulties encountered in probe manufacture and assembly, the one-piece core appears far superior to any type of laminated core. The one-piece core limits the bridge operating frequency (carrier frequency) to a lower frequency than a laminated core would. This becomes a problem only when a high frequency response is required from the probe. A practical limit with the one-piece core is a 3kHz carrier resulting in a frequency response of DC-600 Hz, which is more than adequate in the present application.

When the probe is used with liquid metal in the gap, it is desirable to use the minimum carrier frequency compatible with the desired frequency response. A lower carrier frequency reduces the effect of absence of pressure of liquid metal in the gap on the probe output. This is so because of the reduction in the magnitude of the eddy currents in the liquid metal (if present) with reduced frequency.

Items 2 and 3
The material for the housing is chosen because of its resistance to liquid metals attack. However, the difference in thermal expansion between the housing and the magnetic core is considerable. To reduce the effect of differential expansion on the probe output, the core is connected to the housing with four radial tapered pins in a plane very near the sensing end. The case does not constrain the core radially, either through the pins or by direct contact. This is important because of the notable effect of stress on the permeability of the core material.

Item 4
The gold wire is selected because of its excellent electrical stability and relatively low resistance. Also the fused joint to the alumel lead wire is very stable. The adhesion of the ceramic coating to the wire is good. The quality of the coil depends in part on a reproducible and careful winding procedure. For this reason a small, special, very low speed, winding machine was made. It is shown in Figure 7. The winding process is observed with a stereo microscope to insure uniformity of winding and to inspect the full length wire coating.
Fig. 7 Machine for Winding Coils of Ceramic-Coated Gold Wire.
Item 5
The machinable ceramic is used because of the ease with which experimental designs can be made. It is easy to machine and shrinks only little during firing. It has excellent mechanical and electrical properties.

Item 6
The joint between the lead and coil is located there because it is easily accessible for work after the coil and core are installed. There the joint can be well protected and insulated in a convenient manner. The ceramic inside the core center tube provides a sturdy strain relief, protecting the gold wire terminals of the coil. The coiled up lead wire in the cavity behind the probe is not essential. It provides stretch when e.g. bending the tube (part 10 of Figure 3).

Item 7
Alumel is chosen because of good high temperature stability. The asbestos insulation was preferred to ceramic (swaged) insulation because it tolerates cold bending to smaller radii without the danger of cracking the sheath.

Item 8
The sealing cap is necessary to obtain a hermetic case. The thickness is kept to a minimum because it reduces the available displacement range. The effect of the diaphragm on the probe output is otherwise negligible.
III. PROBE DESIGN AND FABRICATION

Probe Design

The operational and performance requirements of the probe that affect the design directly are:

1. Measuring range (0.004 - 0.080 inch)
2. Temperature range (80 - 1200 F)
3. Overall dimensions (1" diameter x 2" long)
4. Frequency response (DC-100Hz)
5. Ambient pressure (100 psi max.)
6. Accuracy, hysteresis (+ 0.001")
7. Environment (sodium)

The data in parentheses are the actual requirements for the probe.

In addition to the items listed, the electrical characteristics of the probe must be given, such as:

1. Inductance ($L_s$ = series inductance)
2. A.C. resistance ($R_s$ = series resistance)
3. Operating frequency ($\omega$)

These three quantities determine the $Q$ (quality) of the probe as an inductor. The $Q$ is the ratio of probe reactance to probe resistance: $\omega L_s / R_s = Q$. The resistance $R_s$ accounts for losses occurring through:

1. Coil: D.C. resistance (function of length and size of wire and of coil material).
2. Lead: D.C. resistance (same comments as for item 1).
3. Core: hysteresis and eddy current loss (function of core geometry, core material and operating frequency).
4. Target: hysteresis and eddy current loss (same comments as for item 3).
5. Medium in gap (if conductive): eddy current loss (function of gap size, conductivity and operating frequency).
The inductance of the probe is a function of:

1. Number of windings on coil (W)
2. Area of cross section of core (A)
3. Length of magnetic circuit (l)
4. Effective permeability of core with air gap (μ)

The probe inductance is approximately proportional to $W^2, A, \mu$, and $1/l$. The usable displacement range of the probe is a function of the difference between the core O.D. and the diameter of the core center post ($D_2 - D_1$ in Figure 2). The usable displacement range is defined as that displacement (starting from contact) resulting in 90% of the total inductance change obtainable. A rule of thumb, based on experience, gives the usable range as about 0.20 ($D_2 - D_1$).

Fitting the core in a case with an O.D. of about 1", leaves about 3/4" for the core O.D. Writing: 0.20($D_2 - D_1$) = .080" (= the range desired), results with $D_2 = .750"$, and $D_1 = .350"$. After allowing for space taken up by the coil form, the dimensions $D_1$ and $D_2$ determine the coil diameters.

One of the main design objectives is to obtain maximum Q within the probe size limitations imposed. When examining the five resistive and four inductive design parameters listed above, the following can be concluded with reference to optimizing Q:

1. The lead resistance is fixed by lead length, wire size and alloy. Little can be done to reduce it drastically once a suitable combination of these variables is chosen.
2. The eddy current losses in target and liquid metal medium cannot be influenced to any appreciable extent except by lowering operating frequency. Target material conductivity varies only little amongst magnetic alloys that can be considered.
3. Hysteresis losses in target and core cannot be influenced appreciably, except by lowering operating frequency.
4. The eddy current losses in the one piece core can be minimized by proper choice of wall thickness and by slitting in axial and radial directions.
5. The D.C. resistance of the coil is, for a given wire material and size, proportional to the coil inductance. For a given coil volume it is advantageous to use the minimum wire size compatible with manufacture and reliability, because the inductance increases with the square of the number of turns, whereas the resistance increases approximately linearly with the number of turns. As the insulation thickness is fixed (.001" - .0015"), reducing wire size excessively leads to a decrease in Q.

6. For a given wire size and turn density, the D.C. resistance of the coil is proportional to coil length, but the inductance is proportional to the square of the length (W being proportional to L). Thus increasing the coil length will improve Q.

The minimum value of Q that is still usable depends upon the type of electronics used, and on the transducer specifications concerning stability and noise. The first prototype design was made to establish a bench mark for future designs. If improvements were needed, consideration of the factors governing Q would be used as a guide.

The first design used a 416 SS pot core of a depth about equal to the core O.D. The first coil was wound with copper wire .010" diameter. The choice of the wire size was based on the need for mechanical strength, ease of manufacture and low D.C. coil resistance.

This transducer performed very well. The core was the subject of a separate evaluation program, in which the variables were the core wall thickness and various slit configurations, all aimed at improving Q.

The gold wire coil wound on a machinable (and subsequently fired) ceramic bobbin was tested extensively over a 1200°F temperature range. These tests proved the coil to be very stable and repeatable. They also proved the high quality of the fused connection between the alumel lead wire and the coil terminal (gold).

After separate evaluation and development of the core and coil, they were joined and tested as an assembly, singly and in pairs.
Test probes were made with cores of 416 SS, Hiperco, 410 SS and 430 SS. The coil development was completed early in the program and a standard coil design was adopted. Cores of different materials were tested throughout the program.

The first probe design proved to be quite acceptable. Except for testing various core materials and geometries, no changes were deemed necessary to improve Q.

Component Development Tests

Core

The choice of core material (as well as target material) is of critical importance to the functioning of the probe.

The criteria for selecting the core material are:

1. Minimum change of permeability with temperature
2. Minimum difference between permeability measured during a heating and cooling cycle
3. Minimum hysteresis losses
4. Corrosion resistance
5. Machinability

The published data available for magnetic materials was of limited help in the selection of candidate materials for the core. Therefore, extensive core tests were made, using 416 SS, Hiperco 27, 410 SS and 430 SS.

One of the few magnetic materials specifically developed for high temperature service are Hiperco 27 and Hiperco 50. They have been evaluated and accepted for use in power applications, at temperatures up to 1400 F. As Hiperco 50 has very little ductility, it was judged inferior to Hiperco 27. Therefore, Hiperco 27 (a 27% cobalt iron) was used in the first experimental probes in the program. To expedite evaluation of various core geometries, the first cores and targets were made out of readily available 416 SS, a free machining 12% chrome steel. After that, Hiperco 27 arrived and was used in subsequent tests.
It appeared that probes with Hiperco 27 cores show an inductance (L) vs. temperature (T) loop that opens up to as much as 10% of the total inductance over the 400 - 800 F temperature range. The total inductance change with temperature is, however, low. The loop in the L - T curve for Hiperco 27 cores is an undesirable characteristic, especially when the probe in use is temperature cycled in the 400 - 800 F range.

The results obtained with the early 416 SS cores, that were also tested at elevated temperatures, indicated that possibly a chrome-iron alloy should be considered for the core.

As 416 SS is not a high temperature alloy, additional tests were run on 410 SS, which is also a 12% chrome steel but without the free-machining additive (0.15% S) found in 416 SS. The maximum operating temperature of 410 SS without excessive scaling is 1250 F. It appeared desirable to obtain also data on a material with a higher operating temperature limit, for which 430 SS was chosen. It is an 18% chrome steel, with a 1550° temperature limit. The Curie point of 410 SS is about 1350 F, while that of 430 SS is 100 F lower. The Curie point of Hiperco 27 is 1700 F. The Curie point is of some value in judging whether a material will perform at elevated temperatures. By itself, however, it does not indicate whether one material is superior to another when both operate at a given high temperature, but below the Curie point.

Typical test data for the three high temperature core materials tested is given in L versus T graphs in Figure 8. Based on this data, the 430 SS was chosen as a core material because there is no loop in the L - T curve over the full cycle. The high temperature coefficient of the permeability of 430 SS was judged acceptable because the probes are used in push-pull and are always at the same temperature.

**Core Geometry**

Figure 9 shows three experimental cores used to determine the effect of wall thickness and slits on probe Q. Tables 1 and 2 show test results obtained with these cores.
Fig. 8a High-Temperature Inductive Proximity Probe.
L and Q vs. Temperature for Open and Closed Gaps.
Core Material = Hiperco 27
Target Material = 416 SS
Bridge Frequency = 2000 Hz

Fig. 8b High-Temperature Inductive Proximity Probe.
L and Q vs. Temperature for Open and Closed Gaps.
Core Material = 410 SS
Target Material = 410 SS
Bridge Frequency = 2000 Hz

Fig. 8c High-Temperature Inductive Proximity Probe.
L and Q vs. Temperature for Open and Closed Gaps.
Core Material = 430 SS
Target Material = 430 SS
Bridge Frequency = 2000 Hz
Fig. 9  High-Temperature Inductive Proximity Probe.
Three Experimental Cores of 416 SS.
### TABLE 1
COIL INDUCTANCE AND Q FOR DIFFERENT CORE WALL THICKNESSES AND SLOT CONFIGURATIONS (1,2,3,4)

<table>
<thead>
<tr>
<th>Core Wall Thickness (inch)</th>
<th>Open Gap Inductance ((L_o)) (\text{mh})</th>
<th>(Q_o)</th>
<th>Closed Gap Inductance ((L_c)) (\text{mh})</th>
<th>(Q_c)</th>
<th>Sensitivity (L_c/L_o)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Slots</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.030</td>
<td>6.0</td>
<td>4.2</td>
<td>8.0</td>
<td>3.4</td>
<td>1.33</td>
</tr>
<tr>
<td>0.050</td>
<td>6.7</td>
<td>3.4</td>
<td>9.8</td>
<td>2.4</td>
<td>1.46</td>
</tr>
<tr>
<td>One Radial Slot Through Walls Only</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.030</td>
<td>5.8</td>
<td>5.4</td>
<td>8.0</td>
<td>4.9</td>
<td>1.38</td>
</tr>
<tr>
<td>0.050</td>
<td>7.0</td>
<td>4.8</td>
<td>10.5</td>
<td>3.6</td>
<td>1.50</td>
</tr>
<tr>
<td>0.080</td>
<td>7.7</td>
<td>3.8</td>
<td>12.1</td>
<td>2.5</td>
<td>1.57</td>
</tr>
<tr>
<td>Two Radial Slots Through Walls Only</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.050</td>
<td>6.8</td>
<td>5.1</td>
<td>10.4</td>
<td>4.1</td>
<td>1.53</td>
</tr>
<tr>
<td>One Radial Slot Extending Through Walls and Web</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.030</td>
<td>5.9</td>
<td>6.7</td>
<td>8.1</td>
<td>5.9</td>
<td>1.37</td>
</tr>
<tr>
<td>0.080</td>
<td>8.1</td>
<td>4.7</td>
<td>13.4</td>
<td>2.9</td>
<td>1.65</td>
</tr>
<tr>
<td>Two Radial Slots Extending Through Walls and Web</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.050</td>
<td>7.1</td>
<td>6.7</td>
<td>11.1</td>
<td>4.9</td>
<td>1.56</td>
</tr>
</tbody>
</table>

### TABLE 2
OPEN GAP COIL INDUCTANCE AND Q FOR A CORE OF 0.050 INCH WALL THICKNESS (1,5)

<table>
<thead>
<tr>
<th>Without Slots</th>
<th>Inductance (\text{mh})</th>
<th>(Q)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One Radial Slot in Center Post</td>
<td>5.8</td>
<td>3.2</td>
</tr>
<tr>
<td>Slot Continued Across Base Web</td>
<td>6.1</td>
<td>4.0</td>
</tr>
<tr>
<td>Slot Continued Up Outer Shell</td>
<td>6.2</td>
<td>4.2</td>
</tr>
<tr>
<td>Core material - Hiperco 27; target material 416 SS</td>
<td>5.4</td>
<td>6.2</td>
</tr>
</tbody>
</table>

(1) Excitation frequency 1 kHz
(2) Cores and targets - 416 SS; results are applicable to other materials as well
(3) Measurements made using a 500 turn, 10 mil diameter copper wire coil mounted on the cores
(4) \(Q = \omega L/R\), in which \(R = \text{a.c. resistance, } \omega = 2\pi \times \text{bridge frequency}\)
(5) Core material - Hiperco 27; target material 416 SS
The data shows that the presence of a single radial slot improves $Q$. Some further improvement in $Q$ is achieved by making an additional slot but this tends to weaken the core. The effect of increasing wall thickness is to increase the inductance and sensitivity $(L_e/L_0)$, but to decrease $Q$.

The selected design has a single radial slot extending through the walls and web, and a 0.050" wall thickness. This offers a good compromise between high $Q$, sensitivity and a physically rugged design.

It should be noted that the data of Tables 1 and 2 were obtained with a 1000 Hz bridge supply frequency and are valid at or near that frequency. At much higher frequencies, the core losses rise rapidly until, at about 6000 Hz, the core, whether slotted or whole, is no longer usable because of vanishing sensitivity $(L_e/L_0)$.

**Coil and Lead - Core Materials**

**Ceramic Coated Wire**

The wire was selected on the following criteria:

1. Stability of resistance at elevated temperature
2. Corrosion resistance
3. Electrical stability of joint with lead wire
4. Adhesion of ceramic coating
5. Non-magnetic
6. Low resistance

There are two types of wire used for high temperature service, one made of a single alloy, and the other made by cladding a low resistance alloy wire with a corrosion resistant cladding. Of the latter type stainless steel clad copper and nickel clad silver are commercially available. This type of wire was not used, because of the tendency inherent in these wire types to change their characteristics due to migration of the cladding into the core and vice versa. Also, the joint to the lead wire, at which point the cladding is absent (as in a fused joint) or damaged (as in a crimped joint), was
considered a definite hazard. The use of nickel cladding would also be ruled out by the magnetic behavior of nickel.

Gold wire with a proprietary (Secon type D) coating was selected on the recommendation of the manufacturer. It was recommended for excellent stability and good adhesion of the ceramic coating. The conductivity is about equal to that of stainless steel clad copper, or 2.5 times that of pure silver. The coil terminals are joined to Alumel lead wires by fusing them together. This type of joint proved very stable. None of the more than two dozen joints made during the probe development was found to deteriorate. Figure 10 shows two experimental coils in the oven during development tests.

**Insulating Ceramic**

The ceramic material was selected for:

1. Machinability
2. Stability after firing
3. Mechanical strength

The Aremcolox grade used fully satisfied the requirements of the probe.

**Lead Material**

The lead material was selected for:

1. Stability of wire and insulation with temperature
2. Stability of joint coil wire
3. Corrosion resistance
4. Insulation thickness

The alumel (nickel base alloy, 2-1/2% Al, 1% Si) lead wire with heavy asbestos insulation was very satisfactory. The asbestos insulation would become frayed, only after a great deal of handling of the probes. This is not expected to happen when installing the probe permanently in a test setup. If lead flexibility is desired, a woven stainless steel armor around the wire can greatly increase the life of the insulation as it prevents damage of the asbestos caused by rubbing.
Fig. 10  High-Temperature Inductive Proximity Probe. Two Experimental Coils (one with core) Shown in Oven During Tests.
IV. RESULTS OF THE PROTOTYPE TESTS

The information needed to predict probe performance under actual conditions of use is briefly the following:

1. Probe inductance and Q at room temperature as a function of gap, with carrier frequency and medium in gap as test parameters.

2. Probe inductance and Q as a function of temperature at one carrier frequency.

This data permits calculation of the output generated by the probe when connected singly or in a pair to an A.C. Wheatstone bridge. The actual probe readout is an instrument containing the bridge completion elements, bridge balance controls, an amplifier, a phase-sensitive demodulator and a filter. A block diagram and functional description of the readout is given in Appendix 4.

With this system, measurements are made of:

1. Output versus gap change of one probe only with, as test parameters, the medium in the gap, the carrier frequency and the setting of the phase sensitive detector.

2. Output versus gap change of two probes in push-pull (i.e., sum of two gaps is constant) with, as test parameters, medium in gap, the carrier frequency, and the setting of the phase sensitive detector.

3. Output versus temperature for constant gap, of both probes.

This data was obtained using targets and cores made of the various magnetic alloys mentioned previously (stainless steel types 410, 416 and 430, and Hiperco 27). A large volume of test data was obtained, which is presented here in the form of summary graphs for ease of interpretation and discussion.

The tests were conducted first with a Hewlett-Packard Impedence bridge. This data is summarized in Figures 11 through 14. The effects on probe inductance (L) and probe resistance (R) that were investigated are listed below and then discussed individually:
1. Effect of frequency (Figures 11, 12 and 13)
2. Effect of temperature (Figures 8a, 8b and 8c)
3. Effect of proximity (Figures 14a, 14b and 14c)
4. Effect of highly conductive liquid in the gap (Figure 14d)

1. Effect of Frequency on Probe L and R
For a fixed current through the probe, the A.C. losses increase with increasing frequency and the inductance decreases. Both changes can be expected because intensity of the eddy currents decreases. The intensity of the eddy current determines the equivalent I²R losses in the core (and target) and thus the series resistance. The demagnetizing effect of the eddy currents (as compared to the magnetizing effect of the coil current) reduces the total (series) inductance. These effects of frequency on probe L and R are illustrated in Figure 11. In addition to a reduction in L and R, the increase of the frequency also reduces the relative change in L and R that occurs between the open and closed condition. This effect is illustrated in Figures 12 and 13.

Figure 12 shows the impedance vector of the probe for closed gap and the terminal points of the impedance vectors for an 0.050" and closed gap, all for the 5 test frequencies. When increasing the frequency, the difference vector \( \overrightarrow{Z_{closed} - Z_{open}} \) changes its direction from about 70 degrees with the resistance axis at 1/Hz to about 5 degrees at 5 kHz. That is, the change in probe reactance relative to the change in probe resistance is much reduced when increasing the frequency from 1/2 to 5 kHz. Also the total change \( Z_{closed} - Z_{open} \) relative to \( Z_{open} \) is reduced with increasing frequency, as shown in Figure 13.

In general, it is desirable to have maximum sensitivity (defined as): \( S_{co} = (Z_{closed} - Z_{open})/Z_{open} \). Therefore, as is indicated by the information in Figures 12 and 13, the operating frequency \( \omega \) is chosen as low as is compatible with the frequency response required. The frequency response obtainable with a carrier frequency "f" is DC to 0.2 f.
Fig. 11 High Temperature Inductive Proximity Probe Series Inductance and Q vs. Frequency for a Closed Gap, an .050" Gap and Open Gap at Room Temperature; Prototype #1 Hiperco 27 Core, 304 SS Cap, 430 SS Target
Fig. 12  High-Temperature Inductive Proximity Probe. Series Inductance vs. Series Resistance at 1/2, 1, 2, 3 and 5 KHz, for a Closed Gap, a .050" Gap, and an Open Gap at Room Temperature. Prototype #1, Hiperco 27 Core, 304 SS Cap, 430 SS Target Materials.
Fig. 13  Percentage Change in Probe $Z$ Between
Open and Closed Gap vs. Frequency
For the bearing experiments for which the present probe is made, a frequency response of DC-100 Hz is quite adequate. This permits operation with a carrier frequency of 500 Hz, resulting in high sensitivity.

The direction of \((Z_{\text{closed}} - Z_{\text{open}})\) is important when considering the possibility of rejecting a disturbance \(\Delta Z_n\) of the probe impedance by e.g. temperature or absence or presence of liquid metal in the gap.

To a good approximation, when using the optimum setting of the phase sensitive detector for the readout, only the component of \(\Delta Z_n\) parallel to \((Z_{\text{closed}} - Z_{\text{open}})\) will be measured as noise and the 90° component will be rejected. A more detailed analysis of effect of phase relationships in a Wheatstone bridge is given in Appendix 2. As the relative direction of \(\Delta Z_n\) to \((Z_{\text{closed}} - Z_{\text{open}})\) can be changed by using a different operating frequency, a higher operating frequency than e.g. 500 Hz could be preferable, even though the sensitivity \(S_{\text{co}}\) is reduced to reject \(\Delta Z_n\) or part of it by using a setting of the phase sensitive detector away from the optimum.

2. **Effect of Temperature on Probe L and R**

The effect of temperature on the probe L and R is the result of changes with temperature of the volume sensitivity, the effective magnetic permeability and hysteresis. This effect is illustrated for several combinations of core and target material in Figures 8a, 8b, and 8c.

Figure 8a shows inductance versus temperature through one cycle for a probe with a Hiperco 27 core combined with a 416 SS target. The core had been heat treated in a vacuum by heating it to 1500 F in 2 hours, holding at temperature for 2 hours and cooling to 80 F in 2 hours. The inductance of the probe as shown in Figure 8a changes between open and closed gap by about 70%. Over the temperature range of the test, the inductance with closed gap changes about 20% peak-to-peak, and shows a hysteresis loop of L versus T with an opening of about 10%.
Pure cobalt has a similar but larger loop than that shown in Figure 8a. The cause of the loop in Figure 8a is in the Hiperco 27 core, and not in the 416 SS target. This was proven by temperature cycling of a probe with a 416 SS core combined with a 416 SS target. The L versus T curve for this combination shows only a small loop with an opening of less than 5%, not having the prominent opening in the 400 - 800 F range. The results obtained with the 416 SS core combined with a 416 SS target were indeed very similar to those shown in Figure 8b for the 410 SS core combined with a 410 SS target. The behavior of a probe with a 430 SS core combined with a 430 SS target is illustrated in Figure 8c. The loop in the L versus T curve for 430 SS was very small, less than that for 410 SS, shown in Figure 8b.

The virtual absence of a loop in the 430 SS and 410 SS L and R curves is to be preferred to the behavior of Hiperco 27, even though the latter has the higher Curie point. The uncertainty in the probe output created by the thermal history during a temperature cycle is undesirable and can be avoided by using 430 SS or 410 SS, at the expense of greater effect of temperature on the L and R sensitivity. However, in the present application the temperature difference between the probes (used in push-pull) is not expected to be significant due to the intense heat transfer in the sodium bath. As a result of the tests reported in Figures 8a, 8b and 8c, and because of its superior corrosion resistance, 430 SS was chosen as the core and target material in preference to Hiperco 27 and 410 SS. If for reasons of manufacture 410 SS is preferred to 430 SS it can be used. There is no noticeable difference magnetically. The corrosion resistance could become a problem at temperatures over 1100 F in air. When leaving the probes at high temperature for periods of time of 10-20 hours, only a small (< 1/2%) change in inductance could be observed.

3. Effect of Proximity on Probe L and R

The magnitude of the effect of the sensing gap on probe L and R is visible in the data presented above for closed and open gap conditions. The detailed relationship between gap and probe L and R is given in Figures
14a, 14b and 14c for three bridge frequencies (0.5, 1 and 2 kHz). (In the same figures, the effect of mercury in the gap on the probe L and R is given, but this effect is separately discussed in the next section).

The "zero" on the gap scale is established by contact between the target and the core at the center of the gap. The center of the gap protrudes slightly beyond the edge (about 0.006"), because of the raised center post of the core. The center post is raised to insure good contact with the cap for support of the cap. So at contact of the target with the cap, an 0.010" gap remains in the center and an 0.016" gap remains at the edge of the core. Without cap only an 0.006" gap remains at the edge of the core, when the center post contacts the target.

The data in Figures 14a, 14b and 14c for L and Q versus gap in air shows that increasing the bridge frequency results in a reduced probe sensitivity:

\[
S_c - 100 = \frac{L_c - L_{100}}{L_c}
\]

The non-linear relationship between L and gap is typical of this type of probe. The non-linearity can be suppressed by using two probes in push-pull as will be seen later. If only a single probe can be used, a large mean gap relative to the total peak-to-peak displacement measured, reduces the non-linear content in the output.

4. Effect of Highly Conductive Liquid in Gap on Probe L and R
The presence of a highly electrically conductive medium in the gap results in a reduction in probe L and an increase in probe R, both due to eddy currents in the gap. The eddy currents create a field opposed to that of the coil, and thus reduce L. The \(I^2R\) losses due to eddy currents increase R.

* Subscript c indicates closed gap.
Subscript 100 indicates .100 inch gap
Fig. 14a Inductive High-Temperature Proximity Probe. Inductance and Q vs. Gap, With and Without Mercury in Gap.
Core Material = Hiperco 27
Target Material = 416 SS
Cap Material = .010" 304 SS
Bridge Frequency = 500 Hz

Fig. 14b Inductive High-Temperature Proximity Probe. Inductance and Q vs. Gap, With and Without Mercury in Gap.
Core Material = Hiperco 27
Target Material = 416 SS
Cap Material = .010" 304 SS
Bridge Frequency = 1000 Hz

Fig. 14c Inductive High-Temperature Proximity Probe. Effect of Mercury in Gap on Probe Inductance Plotted as Apparent Change in Gap vs. Existing Gap.
Tests with mercury in the gap were made to obtain preliminary data, before using the more complicated calibration equipment necessary for calibration in sodium. The results are shown in Figures 14a through 14d.

Figure 14d is a cross plotted from Figures 14a - 14c by taking the horizontal distance between the L curves for mercury and air (for a given frequency) at various points and plot those differences versus gap. Thus, Figure 14d gives a direct picture of the shift in output that can be used when filling the gap with mercury, if the probe inductance is used (through a suitable readout) to generate probe output. If the probe resistance is used to generate probe output, a similar effect as that in Figure 14d can be expected.

Figure 14d shows clearly that the effects of the conductive liquid in the gap are appreciable and increase rapidly as carrier frequency is increased. At 0.5 kHz, the offset caused by putting mercury in the gap is about 15% while at 2 kHz it can be as much as 45 to 50%.

However, as will be shown in the later section reporting results obtained with the Encore 902 readout, it is possible to measure a combination of probe L and R that is sensitive to displacement but (at a certain carrier frequency) not sensitive to the presence of mercury or sodium in the gap.

Apart from the zero-shift caused by filling an air gap with mercury, a change in probe sensitivity occurs. The change in sensitivity is only minor, as can be seen in Figures 14a through 14c, where inductance versus gap curves for air and mercury gaps are nearly parallel. The effect of liquid metal in the gap on sensitivity will be discussed in more detail in the section on calibrations in sodium.

The further data on probe performance was obtained with the Encore "902" readout. This readout system is described in some detail in Appendix 4. Here, only a few functions of the instrument are noted.
The instrument powers a four arm bridge with A.C. at one of three frequencies (0.5, 1 and 2 kHz). It amplifies the bridge unbalance signal and injects an adjustable balancing signal. The sum of these two signals is fed to a demodulator that can be set to be phase-sensitive or non-phase sensitive. When set at "phase sensitive" the phase of the demodulator can be adjusted from 0 to ± 90° with a ten-turn (1000 div.) control that permits accurate reading and resetting if necessary. (The sign of the phase is set with a switch).

The phase sensitive demodulator delivers a D.C. voltage proportional to the integral of the bridge unbalance signal over a period equal to 1/2 cycle of the A.C. When considering a sine wave, it can be seen that the result of integrating over a 1/2 cycle can be anywhere from + 1/2 √2 x peak value to - 1/2 √2 x peak value, depending upon the phase between the integration interval and the sine wave.

When the phase reference for the phase sensitive demodulator is set at 0, the 1/2 cycle integration interval starts when bridge supply is zero and growing positive. When set at + 90° (or 1000 on the 10 turn dial) the integration interval is moved forward in time by 1/4 cycle, and so on.

Generally, the reason for using a phase sensitive demodulator is to retain the sign of the demodulated unbalance voltage of an A.C. bridge. This is so because when the bridge unbalance changes sign (i.e., 180° phase shift), and the phase of the integration interval is left unchanged, the demodulated voltage changes sign.

More generally, for a sinusoidal bridge unbalance voltage, the output of the phase sensitive demodulator is proportional to bridge unbalance voltage multiplied by the cosine of the phase angle between integration interval and bridge unbalance voltage.

Thus, when bridge unbalanced voltage amplitude and phase both change, the resultant output of the demodulator reflects both changes. This fact must be kept in mind when inspecting the data presented in the next section.
When the phase sensitive demodulator is set in phase with the bridge unbalance voltage, the output of the demodulator is maximum. This setting is referred to as "optimum". When changing the probe gap of a single probe (or two probes in push-pull) over the full range, the phase of the bridge output voltage changes only slightly (< ± 10°)\(^{\ast}\).

The effect of ± 10° signal phase change on the output of the phase sensitive demodulator is very small (< ± 2%) when the demodulator is set "optimum". For settings away from the optimum, the effect of the ± 10° change increases. For a demodulator phase setting 90° away from the optimum the effect of ± 10° signal phase change is to change the demodulator output from zero to ± 17% of demodulator output obtained with the optimum setting. The calibration of the phase control dial is linear (1000 div. = 90°).

The probe performance data obtained with the Encore "902" readout is summarized in Figures 16 through 22. The specific investigations are listed below and then discussed individually:

1. Output of a single probe (Figures 16, 17 and 18)
2. Output of two probes in push-pull (Figures 19, 20 and 21)
3. Output change with a single probe due to the presence of highly conductive liquid in the gap (Figures 22 and 23)
4. Output change with two probes in push-pull, due to the presence of a highly conductive liquid in the gap (Figures 24, 25, 26 and 27)

1. Output of Single Probe Connected to Encore 902 Readout

The output of a single probe connected to the readout resembles the inductance versus gap curves discussed earlier (e.g. Figures 14a, b and c). The output of the readout is a function of both the probe inductance and probe resistance. The bridge dimensioning, bridge frequency and phase setting of the demodulator determine what component of the probe impedance

\(^{\ast}\) For the specific bridge used, a discussion of bridge dimensioning on phase of output voltage is given in Appendix 2.
determines the instrument output. (See Appendix 2). The bridge circuit used with the readout in obtaining all the data reported is also shown in Figure 15. It consists of two probes and two completion resistors.

The two probes have a common point, B (see Figure 15), resulting in a bridge that rejects common changes in the probes, such as caused by temperature effects. This common point is connected to the bridge supply, and the bridge output appears at the remaining leads "A" and "C" of the probes. This bridge can reject thermal and other disturbances occurring in a single probe, as is shown by the analysis in Appendix 4. The alternate way of connecting this bridge, with power to terminals "A" and "C" and output from "B" and "D" cannot reject thermal or other disturbances of a single probe.

The response obtained is shown in Figures 16, 17 and 18 for bridge frequencies of 0.1, 1 and 2 KHz, and for five settings of the phase sensitive detector.

The response is quite non-linear, as could be expected from the L and Q versus gap measurements. In Figure 16, for example, the sensitivity (phase set at optimum), varies from the contact point to 100 mils gap by a factor of 13. Due to the gap effect on phase of the bridge unbalanced voltage, the non-linearity for phase settings away from the optimum (at 100 mil gap) is different from that obtained at the optimum setting. For example, the sensitivity ratio in Figure 16, of the curve marked + 750, comparing slope at a closed gap to a slope at 100 mil gap, is only 6 which is lower by a factor of 2, when compared to the optimum response curve (marked + 230). The curve marked + 1000 in Figure 16 shows a lower sensitivity at contact than at 100 mil gap, strictly due to a small phase change of bridge output with gap. In Appendix 4 this effect is considered in some detail. The non-linearity at higher bridge frequencies is lower. In Figure 18 the sensitivity ratio of closed-to-100 mil gap is (with optimum phase) 8, and for phase set at 45° off optimum, this ratio is 6.
Fig. 15 Wheatstone Bridge with Two Inductive Probes in Parallel.

\[ |Z_a| = \sqrt{(R_1 + R_3)^2 + (\omega L_1)^2} \]

\[ |Z_e| = \sqrt{(R_2 + R_4)^2 + (\omega L_2)^2} \]

\[ R_3 = R_4 = 150 \, \Omega \]
Fig. 16  Inductive High-Temperature Proximity Probe.
Output of Encore 902 Bridge vs. Gap for Single Probe.
(See Fig. 15 for Bridge Diagram)

Core Material = Hiperco 27
Target Material = 410 SS
Cap = .010" 304 SS

(Curves are marked with phase-sensitive detector settings.)
Fig. 17 Inductive High-Temperature Proximity Probe. 
Output of Encore 902 Bridge vs. Gap for Single Probe. 
(See Fig. 15 for Bridge Diagram) 
Core Material = Hiperco 27 
Target Material = 410 SS 
Cap = .010" 304 SS 
(Curves are marked with phase-sensitive detector settings.)
Fig. 18  Inductive High-Temperature Proximity Probe.
Output of Encore 902 Bridge vs. Gap for Single Probe.
(See Fig. 15 for Bridge Diagram)

Core Material = Hiperco 27
Target Material = 410 SS
Cap = .010" 304 SS

(Curves are marked with phase-sensitive detector settings.)
2. Output of Two Probes in Push-Pull Connected to Encore 902 Readout

The bridge used is the same as shown in Figure 15. The principal difference between the response in push pull operation of two probes and the response of a single probe is the linearizing effect of push-pull on the probe response. In push-pull operation the sum of the gaps of the two probes remain constant. Therefore, the sensitivity is the sum of the sensitivities of the individual probes. In push-pull the sensitivity varies less than 10% over a total target equal to the mean gap, (that is if the travel is symmetric around the mean gap). If a single probe would be used in the same experiment, the sensitivity would typically change by a factor of 3.

Typical data obtained in push-pull operation is shown in Figures 19, 20 and 21. The data is taken with a mean gap of 0.050", three phase sensitive detector settings and at three frequencies. Linearization for an excursion of less than $\pm$ 0.025 inch from center is excellent. At the extremes of the $\pm$ 0.050 inch range, the sensitivity is about twice that at the center.

A large amount of data in push-pull was taken in the subsequent tests in sodium, using the same probes and targets that were used to obtain the data of Figures 19 through 21. The data taken in sodium is given in Section V of this report.

3. Output Change with a Single Probe Connected to Encore 902 Readout

Due to the Presence of a Highly Conductive Liquid in the Gap

The output change of a single probe due to filling the gap with mercury, converted to an equivalent gap change, is given in Figures 22 and 23 for two bridge frequencies and various phase settings of the demodulator. The bridge used is that shown in Figure 15. Both Figures 22 and 23 show that the optimum setting of the phase gives less rejection of the effect of mercury than an off-optimum setting. Especially at 2000 Hz a substantial improvement can be made by adjusting the phase from the optimum at $+535 \; (+48^\circ)$ to $+110 \; (+10^\circ)$. This is possible because of the phase
Fig. 19  High-Temperature Inductive Proximity Probe.  
Output of Encore 902 vs. Gap for Two Probes in Push-Pull.  
(See Fig. 15 for Bridge Diagram)  
Core Material = 430 SS  
Target Material = Sprayed .030" 431 SS  
Cap = 304 SS  
Temperature = 80°F, Gain = 500, Mean Gap = .050"
Fig. 20 High-Temperature Inductive Proximity Probe. Output of Encore 902 vs. Gap for Two Probes in Push-Pull. (See Fig. 15 for Bridge Diagram)

Core Material = 430 SS
Target Material = Sprayed .030" 431 SS
Cap = 304 SS
Temperature = 80°F, Gain = 500, Mean Gap = .050"
Demodulator Phase Set at -264 (maximized output*)
- Demodulator Phase Set at -0
- Demodulator Phase Set at -1000

Carrier Frequency = 2000 Hz
Bridge Phase = 0°
Null Magnitude = 0.96
Null Phase = -476

* At .050" Excursion from Mean Gap

Fig. 21 High-Temperature Inductive Proximity Probe.
Output of Encore 902 vs. Gap for Two Probes in Push-Pull.
(See Fig. 15 for Bridge Diagram)

Core Material = 430 SS
Target Material = Sprayed .030" 431 SS
Cap = 304 SS
Temperature = 80°F, Gain = 500, Mean Gap = .050"
Fig. 22  Inductive High-Temperature Proximity Probe.  
Output Change of Single Probe Connected to  
Encore 902 for Various Phase Settings of  
Demodulator Graph of Apparent Gap Change  
vs. Gap.  

Core Material = Hiperco 27  
Target Material = 416 SS  
Cap = .010" 304 SS  
Bridge Frequency = 500 Hz  

(Curves are marked with phase-sensitive detector settings.)
Fig. 23  Inductive High-Temperature Proximity Probe. Output Change of Single Probe Connected to Encore 902 for Various Phase Settings of Demodulator Graph of Apparent Gap Change vs. Gap.

Core Material = Hiperco 27
Target Material = 416 SS
Gap = .010" 304 SS
Bridge Frequency = 2000 Hz

(Curves are marked with phase-sensitive detector settings.)
relationship between bridge unbalance due to gap change versus that due to introducing mercury in the gap.

4. Output Change of Two Probes in Push-Pull Connected to Encore 902 Readout, Due to Presence of a Highly Conductive Liquid in the Gap

This was investigated in the later tests that were conducted in sodium. When operating two probes in push-pull, the effect of sodium on the output of the Encore 902 bridge amplifier is a slight change in probe sensitivity. When the gaps are equal to the mean value for which the bridge is balanced, there is of course no output and the effects of sodium in the gaps cancel out.

Away from the mean gap there is an increasing effect. A typical set of calibrations with and without sodium is shown in Figure 24. The differential between the two calibrations, measured along the gap axis can be plotted versus gap. This is done in Figures 25, 26 and 27 for three frequencies and various phase settings. Again the influence of the phase setting on the effect of liquid metal in the gap on the output can be seen. At 500 Hz, the effect of sodium can be eliminated by setting the phase somewhere between 525 and 000, at about 300. At 1000 and 2000 Hz the effect of sodium can be reduced by a phase setting somewhere below the optimum setting.

Target Material

The requirements for the target material are much the same as those for the core material. As the target material has less influence on probe performance than the core material, electrical requirements can sometimes be relaxed when compromise between, e.g., mechanical and electrical properties would be advantageous. The basic problem is the attachment of the target to the shaft. If there is substantial thermal mismatch between the suitable magnetic target material and the non-magnetic shaft material (such as a 316 series stainless steel), it has to be accommodated by proper design. Two approaches were considered. The first of these was to plasma spray a thin layer of target material on the shaft. For the reasons discussed below this proved to be un-
Fig. 24  Inductive High-Temperature Proximity Probe.
Push-Pull Calibration in Air and Sodium at 400°F, Output of Encore 902 vs. Gap.

Core Material = 430 SS
Target Material = Sprayed .030" 431 SS
Cap = .010" 304SS
Phase Setting of Demodulator at Optimum = -259
Bridge Frequency = 2000 Hz
Gain = 500
Fig. 25  Inductive High-Temperature Proximity Probe. Output Change of Two Probes in Push-Pull Due to Filling Air Gap with Sodium, at 400°F for Various Phase Settings of Demodulator. Graph of Apparent Gap Change vs. Gap. Data Obtained with Encore 902. (See Fig. 15 for Bridge Diagram)

Core Material = 430 SS
Target Material = Sprayed .030" 431 SS
Cap = .010" 304 SS
Fig. 26  Inductive High-Temperature Proximity Probe. Output Change of Two Probes in Push-Pull Due to Filling Air Gap with Sodium, at 400°F for Various Phase Settings of Demodulator. Graph of Apparent Gap Change vs. Gap. Data Obtained with Encore 902. (See Fig. 15 for Bridge Diagram)

Core Material = 430 SS
Target Material = Sprayed .030" 431 SS
Cap = .010" 304 SS
Fig. 27  Inductive High-Temperature Proximity Probe. Output Change of Two Probes in Push-Pull Due to Filling Air Gap with Sodium, at 400°F for Various Phase Settings of Demodulator. Graph of Apparent Gap Change vs. Gap. Data Obtained with Encore 902. (See Fig. 15 for Bridge Diagram)

Core Material = 430 SS
Target Material = Sprayed .030" 431 SS
Cap = .010" 304 SS
acceptable for a high temperature sodium environment. The second solution, which was adopted for sodium bearing tests despite its greater complexity is the use of a solid target material ring attached to the shaft at the probe locations.

The plasma sprayed coating, if thin enough, will adhere in spite of cyclic thermal stresses. The minimum thickness is prescribed as that required for acceptable probe sensitivity (resolution). As the target is made thinner, below a certain limit (see Appendix 1 for details), a major part of the field penetrates into the non-magnetic metal below the target. This circumstance makes the probe more sensitive to changes in the metal outside the target column (which is liquid-metal-in-the-gap and shaft material) and less sensitive to target motion. The effect of the thickness of a plasma sprayed target of 431 SS on the probe inductance for closed gap is shown in Figure 28, together with data for a 1" thick target of 416 SS. (The data is taken with a Hiperco 27 core, that causes the previously noted thermal hysteresis loop in the L versus T curve). The reduction in sensitivity caused by the reduced target thickness is, as is seen from Figure 28, about 30% for an 0.030" thick 431 SS sprayed target, and about 60% for an 0.010" thick 431 SS sprayed target. The high temperature sodium tests reported in the next section were run with two plasma sprayed targets, with 0.030" 430 SS on a base of 1/2" of 316 SS. In the same test series, samples of plasma sprayed coatings of 431 SS on a 316 SS base were also evaluated.

After completion of the tests, inspection of the targets and other coated specimens revealed an increase in the thickness of both the plasma sprayed 431 SS probe targets and other plasma sprayed 431 SS samples. Microscopic examination of metallurgical cross sections of the coated samples indicated that some oxides were present in the form of thin layers in the plasma sprayed 431 SS stainless coatings. The specimens - which were exposed to high temperature (to 1100 F) sodium - showed voids where the oxides had apparently been dissolved away. Since the coatings are normally in a stressed condition as a result of the spraying operation, it is believed that the loss of these oxide layers relieved the residual stresses and caused the dimensional changes
Fig. 28  Inductive High-Temperature Proximity Probe.  
Fourth Temperature Cycle of Flame-Sprayed Targets.  Inductance vs. Temperature for Open and Closed Gap.  
Core Material = Hiperco 27  
Target Thickness = .010" and .030"  
Flame Sprayed 431 SS
that were measured. There was also some evidence that the sodium attack of the oxides had degraded the bond between the 431 SS coating and the 316 SS substrate.

Because of this, the targets in both the calibration fixture and bearing test rig were made of solid 410 SS rather than coatings. The 410 stainless was chosen over 430 SS because it is a castable grade which could be an advantage in the design and manufacture of the ring shaped target for the bearing test rig.

When not exposed to sodium, the sprayed targets stabilized after 2 to 3 temperature cycles in air. For certain high temperature applications, sprayed targets could well be an excellent solution, but they are clearly not usable in a high temperature sodium environment.

Since some of the development test data was taken only with the 0.030" sprayed target, it has been used in this report. The main effect of the thin target is to reduce sensitivity, as shown in Figure 28. The data obtained with an 0.030" sprayed 431 SS target can be used to predict probe output for a solid, thicker 410 SS or 430 SS target, by using a sensitivity correction factor derived from the data of Figure 28.
V. SYSTEM TESTS IN SODIUM

Test Facility
Two sets of tests were conducted in liquid sodium. The first set of tests consisted of short term calibration tests of the probes over the temperature range from 400 to 1100 F. The second set was the long term endurance test in which two of the probes were operated for 684 hours during which time the sodium temperature was cycled between 1050 F and 1170 F.

The high temperature probe calibration equipment that was used in both tests is shown in Figure 29. Photographs of the complete test set-up are shown in Figures 30(a) and 30(b). The calibration fixture is a symmetric arrangement of two movable targets and two probes of which one pair is shown in Figure 29. The other pair is identical. The calibration fixture is mounted with its axis vertical, as shown in Figure 30(a).

The fixture comprises the sodium containment vessel and its cover (Part 2 in Figure 29). The probes to be tested are mounted in the vessel and the two micrometers (Part 32), that are used to position the targets (Part 12), are mounted on the vessel cover. The targets are mounted on a tie rod (Part 14) which is suspended from a pair of flexures (Part 17). The flexures in turn are mounted on the centerpost (Part 22) which is bolted to the bottom of the vessel. The purpose of the flexures is to insure parallel displacement of the target.

The extension (Parts 7 and 8) of the tie rod (Part 14) are kept in contact with the micrometer face (Part 32) by means of a compression spring (Part 29). Thus, the micrometer can be used to position the target within the range permitted by the stops (Parts 21 and 11). Both targets can be positioned independently to obtain the desired sum of the two gaps in push-pull calibration.

The initial, short-term calibration tests were conducted before the sealing caps were welded in place in the probes. For these tests, Part 11 had a built-in 0.010" thick diaphragm. The probe was clamped in place by means of
Fig. 29 High-Temperature Sodium Calibration Fixture
Fig. 30(a) High-Temperature Sodium Instrumentation Test Apparatus
Fig. 30(b) High-Temperature Sodium Instrumentation Test Apparatus
a plate (Part 9) bolted to the vessel bottom. The probe was positioned by a shim (Part 10) to allow for machining tolerances of the probe body and of Part 11. Because of concern regarding differential thermal expansion of the studs (Part 23), the probe body and the vessel wall, a modification was made to the arrangement shown, by installing a spring between Part 9 and the back of the probe. This spring was intended to keep the probe in positive contact with the shim (Part 10), and hence, the diaphragm plate (Part 11). This, however, produced an overstressing of the springs at high temperature, so that one of the probes dropped vertically 0.020".

For the 684 hours endurance test at 1050 F to 1170 F, the probe mounting arrangement was modified. First, the probes used had the sealing caps already welded on so that the diaphragm in the test fixture (Part 11) was removed. A mounting flange was welded to the lower part of the body of each test probe, as illustrated in Figure 3, and these flanges were then directly bolted to the outside of the vessel bottom.

In the endurance test, the calibration procedure was to bottom the target against the probe cap and then back it off by known amounts, as measured with the micrometer. The dial indicators (Part 35) served to provide checks on the micrometer readings.

For the sodium tests, the vessel was fully insulated and electrical heating elements were attached to the vessel surface. Thermocouples mounted in various locations monitored temperature differences between various parts of the vessel and its cover throughout the test period and, in particular, during the heating and cooling stages to assure that there were no large temperature gradients that would produce cover and flange distortions. Using the thermocouple readings as guides, the heater power was distributed amongst the various heaters so as to avoid such temperature gradients and thermal distortions.

The cover gas used in the sodium tests was nitrogen, circulated through a NaK bubbler before being introduced into the test vessel. The cover gas pressure was maintained at 5 psig throughout the tests.
Tests in Liquid Sodium

As earlier noted, two sets of tests were conducted within the probes in liquid sodium. The first set of tests composed short term calibration runs and the second was an endurance test of the probes at elevated temperature. These tests were as follows:

1. Short Term Calibration Tests
   The probes were mounted in the calibration test fixture described above. The pair of probes were mounted in push-pull, connected according to the bridge diagram of Figure 15.

   Calibration data was first obtained in gas at room temperature and at 400°F after which the sodium was introduced and the temperature raised to 1100°F, with calibration runs made at 400°F, 650°F, 850°F, and 1100°F. The temperature was then reduced back to 400°F and data taken at about the same temperatures on the way down.

   The calibrations were made using three bridge frequencies (500, 1000 and 2000 Hz) and using three different phase sensitive detector settings as follows:

   Zero = in-phase with bridge supply
   Optimum = in-phase with bridge output
   1000 = 90° out-of-phase with bridge supply

   The tests were run principally with mean gap settings of 0.050 inches, though some runs were also taken with mean gap settings of 0.020, 0.030, and 0.040 inches. At each calibration, readings were taken at 0.005 inch increments over the range.

2. Endurance Test
   Two probes were mounted in the test fixture, again connected in push-pull. After the initial calibration in gas atmosphere at room temperature and 400°F, the sodium was introduced and the temperature raised to 1050°F. Thereafter, the sodium temperature was cycled between 1050°F and 1170°F for a period of 684 hours.
It had been intended to continue this test for 1000 hours, however, a severe cover gas leak developed in the joint between the test vessel and the cover after 684 hours of cycling between 1050 F and 1170 F, resulting in high flow of cover gas. The system then cooled down and the test terminated.

The test was conducted on an around the clock basis, with the system continuously monitored. Complete calibration measurements were made daily throughout the test. This data was taken primarily at 0.050 inches mean gap with readings at 0.005" increments over the full range, i.e. from -0.050" to +0.050" about the mean position. The calibration data was taken at 500 Hz carrier frequency.

The data was screened throughout the test for consistency and to detect any indications of changes in probe performance. The probe performance was found to be completely stable and repeatable and there were no changes throughout the test. This is shown in Table 3 below which lists the calibration data obtained after 72 and 643 hours of testing. These two calibrations were made at nearly the same operating temperatures, 1150 and 1152 F, respectively.

Discussion of Test Results in Liquid Sodium

Typical results obtained are shown in Figures 31, 32 and 33. They give probe response with and without sodium in the gaps of both probes. Filling of both gaps with sodium does not affect the balance of the bridge. Filling the gap with sodium will result in a decrease or increase in output, depending upon the setting of the phase sensitive demodulator. For all these curves, the "optimum" setting of the demodulator is obtained without sodium in the gap.

All response curves show a minimum slope in the center and a notable increase in slope (sensitivity) near the ends. The non-linearity increases when a smaller mean gap is used. The non-linearity of the probes in push-pull is quite small over a displacement range of ±40% of the mean gap. In this range the slope of the response curve changes by less than 10%. After presenting
# TABLE 3
PROXIMITY TRANSDUCER CALIBRATION DATA
IN LIQUID SODIUM AT 1150 AND 1152 F

<table>
<thead>
<tr>
<th>Gap Unbalance (inches)</th>
<th>72 Hours (Data Point 11)</th>
<th>643 Hours (Data Point 46)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.050</td>
<td>(Not Recorded)</td>
<td>11.03</td>
</tr>
<tr>
<td>+ 0.045</td>
<td>9.0</td>
<td>9.0</td>
</tr>
<tr>
<td>+ 0.040</td>
<td>7.33</td>
<td>7.29</td>
</tr>
<tr>
<td>+ 0.035</td>
<td>5.98</td>
<td>5.96</td>
</tr>
<tr>
<td>+ 0.030</td>
<td>4.85</td>
<td>4.84</td>
</tr>
<tr>
<td>+ 0.025</td>
<td>3.88</td>
<td>3.87</td>
</tr>
<tr>
<td>+ 0.020</td>
<td>3.03</td>
<td>3.01</td>
</tr>
<tr>
<td>+ 0.015</td>
<td>2.23</td>
<td>2.23</td>
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</tr>
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</tr>
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<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>- 0.005</td>
<td>- 0.66</td>
<td>- 0.64</td>
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<td>- 0.015</td>
<td>- 2.13</td>
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<td>- 9.05</td>
</tr>
<tr>
<td>- 0.050</td>
<td>-11.29</td>
<td>-11.06</td>
</tr>
</tbody>
</table>
Fig. 31 Inductive High-Temperature Proximity Probe. Calibration in Push-Pull in Air and Sodium at 400°F. Output of Encore 902 vs. Gap Unbalance.

- Total Gap = .100"  
- Bridge Frequency = 500 Hz  
- Gain = 500
Figure 32a

- No Sodium
- Sodium
Demodulator Set at 000

Figure 32b

- No Sodium
- Sodium
Demodulator Set at Optimum in Air (9238)
Gain: 500

Figure 32c

- No Sodium
- Sodium
Demodulator Set at 1000

Figure 32d

- No Sodium
- Sodium
Demodulator Set at 1000

---

Fig. 32 Inductive High-Temperature Proximity Probe. Calibration in Push-Pull in Air and Sodium at 400°F. Output of Encore 902 vs. Gap Unbalance.

Total Gap = 100"
Bridge Frequency = 1000 Hz
Gain = 500
Fig. 33 Inductive High-Temperature Proximity Probe.
Calibration in Push-Pull in Air and Sodium
at 400°F. Output of Encore 902 vs. Gap Unbalance.
Total Gap = 0.100"
Bridge Frequency = 2000 Hz
Gain = 500
the high temperature probe response data a more detailed discussion of probe linearity will follow. Appendix 2 analyzes why the phase sensitive demodulator setting determines whether sodium in the gap will decrease or increase the probe output over that in air.

Typical data obtained at 650 F, 862 F and 1106 F is given in Figures 34, 35 and 36. In these figures the demodulator was set in phase with bridge output, giving maximum sensitivity. The curves in Figures 31 through 36 are all of the same shape. They only differ in total amplitude.

The probe sensitivities, in volts/mil, are plotted as functions of temperature and mean gap in Figures 37 and 38 respectively. Figure 37 shows that there is an increase in sensitivity at 900 F. This increase in sensitivity is relatively small of the order of 5% to 10% at the two higher values of bridge frequency, 2000 Hz and 1000 Hz. At the lowest value of bridge frequency, however, the sensitivity at 900 F is about 20% greater than at 400 F.

Figure 39 illustrates the difference between operation in push-pull versus operation of a single probe. The three curves in Figure 30 were made in one single test set up. The push-pull curve was made by moving the target between the two probes, with a total gap of 0.120". The two other curves were made by removing first the one and then the other probe. The gap of the removed probe is fixed at 0.060" with a second target and the gap of the remaining probe is varied to obtain the single probe response. The response curve in push-pull can be constructed from the response curves of the single probes by subtracting one from the other.

The sensitivity of two probes in push-pull at the same mean gap is twice the sensitivity of a single probe at a gap equal to the mean gap, as shown by Figure 39. The sensitivity of a single probe varies with the mean gap. To permit a quick estimate of this effect, the sensitivity of a single probe was measured at one frequency and demodulator setting. The result is shown in Figure 40. The sensitivity varies about a decade over the usable range of the probe.
Fig. 34 Inductive High-Temperature Proximity Probe.
Calibration in Push-Pull in Sodium at 650°F.
Output of Encore 902 vs. Gap Unbalance.

Total Gap = 0.100"
Fig. 35 Inductive High-Temperature Proximity Probe.
Calibration in Push-Pull in Sodium at 862°F.
Output of Encore 902 vs. Gap Unbalance.

Total Gap = 0.100"
Fig. 36 Inductive High-Temperature Proximity Probe.
Calibration in Push-Pull in Sodium at 1106°F.
Output of Encore 902 vs. Gap Unbalance.

Total Gap = 0.120"
Fig. 37  Probe Sensitivity in Push-Pull (at mean gap) vs. Temperature in Sodium.

Mean Gap = .050"
Gain = 500
Note: 1100°F data corrected for effect of increase of mean gap.

Fig. 38  Inductive High-Temperature Proximity Probe.
Probe Sensitivity in Push-Pull (at mean gap) vs. Mean Gap in Air at 400°F.
Demodulator Set at Optimum
Gain = 500
Push-Pull = Difference of Output Curves of Single Probes

"0" is with both transducers 60 mils from each side of target

Fig. 39 High-Temperature Inductive Proximity Probe. Probe Response of a Single Probe and Two Probes in Push-Pull. The Two Probes in Push-Pull Have a Mean Gap of .060". Room Temperature, Air Gap, Encore 902 Readout.
Fig. 40 High-Temperature Inductive Proximity Probe. Probe Sensitivity vs. Gap for Single Probe Connected to Encore 902. This curve represents the slope of the response curve of a single probe such as shown in Fig. 39.

- Gain = 500
- Bridge Frequency = 500 Hz
- Balance at .050" Gap
- Output at Contact = 10 Volts
Probe Location Shift in the Short Term Calibration Tests

It was noted earlier that the probe mounting system used in the early, short term calibration tests utilized a spring load on the probe and that this spring load became overstressed at the high temperature resulting in an 0.020 inch drop of one of the probes. As also noted, the probe mounting arrangement was then changed for the endurance test when the probes used already had the sealing caps welded on and the probes were bolted directly to the test vessel. This precluded any further shifting of probe position.

The data of Figure 36, which was obtained during the short term calibration tests shows the asymmetry caused by the shift in probe location. This asymmetry, which had repeated itself consistently in all the data taken between 1100 F and 400 F when coming down in temperature, provided the indication of a probe position shift.

The data recorded prior to the shift, in Figures 31 through 35, is a symmetric function of the gap unbalance. This is shown also in Figures 41 and 42 which are two typical slope versus gap unbalance curves for a normal calibration.

The slope versus gap unbalance curves for the asymmetric calibration curves, such as in Figures 36a, b and c is shown in Figures 43 and 44 for eight cases. The curves in Figures 43 and 44 are not asymmetric, but they only extend farther upward at the left hand side then at the right hand side. Otherwise, they are symmetric around an axis located at a point 0.010" - 0.011" to the right of the gap scale center. This indicated that the true mean gap was not 0.050" as set, but really 0.060" - 0.061". The greater mean gap only results in a decrease in system sensitivity, as can be calculated using Figure 38 by extrapolation of data to a mean gap of 0.060". Thus data taken between 1100 F and 400 F on the return part of the thermal cycle is valid; however, a direct comparison between this data and that taken in the first part of the test series (400 - 800 F) cannot be made because of the increased mean gap.

In order to verify that there was no change in the actual probe response, the two probes that had undergone the high temperature, calibration test in sodium
Fig. 41 Inductive High-Temperature Proximity Probe. 
Slope of Response Curve in Push-Pull vs. 
Gap Unbalance. Data Taken in Sodium Test Series.

Temperature = 80°F 
Gain = 500 
Bridge Frequency = 500 Hz 
Demodulator Set "Optimum"
Fig. 42  Inductive High-Temperature Proximity Probe.
Slope of Response Curve in Push-Pull vs.
Gap Unbalance. Data Taken in Sodium Test Series.

Temperature = 80°F
Gain = 500
Bridge Frequency = 500 Hz
Demodulator Set "Optimum"
Fig. 43  Inductive High-Temperature Proximity Probe.
Slope of Response Curve in Push-Pull vs.
Gap Unbalance. Data Taken in Sodium Test Series.
Fig. 44  Inductive High-Temperature Proximity Probe.
Slope of Response Curve in Push-Pull vs.
Gap Unbalance. Data Taken in Sodium Test
Series.

Demodulator Set "Optimum"
Bridge Frequency = 500 Hz
Gain = 200, except at DP99 Gain = 100
were removed from the test fixture and, together with two identical new probes, subjected to further testing in air. This test was conducted over the temperature range from 80 to 1200 F, with a short, about 3 hours, dwell period at 1200 F. All four probes were found to track extremely closely over the full temperature range. This data is given in Appendix 3. This test confirmed that there had been in fact, no change in probe performance during the sodium test.

**Linearity Analysis**

The non-linearity of the probes in push-pull for large excursions is evident in the graphs in Figures 41 through 44. To estimate the effect, the following approximate analysis is given:

The response curve can be represented by:

\[
E_{\text{out}} = C_1 E_{\text{supply}} (x + C_2 x^n) \quad \text{For } x > 0
\]  

(1)

and the corresponding curve is:

\[
\frac{\partial E_{\text{out}}}{\partial x} = C_1 E_{\text{supply}} (1 + nC_2 x^{n-1}) \quad \text{For } x > 0
\]  

(2)

in which \(x\) is the gap unbalance, \(E_{\text{supply}}\) is bridge supply voltage and \(C_1, C_2\) and \(n\) are calibration constants that are functions of mean gap and temperature.

The value of \(C_2\) and \(n\) determine the non-linear content (= \(C_2 x^n/x = C_2 x^{n-1}\)) of \(E_{\text{out}}\). These constants can be determined from the sensitivity plots. For example for Figure 41 the actual values are:

\[
C_2 = 0.044 \times 10^{-4}
\]

\[
n = 3.63
\]

for \(x\) in mils
With these values of \( C_2 \) and \( n \), Equation (2) closely approximates the curve shown in Figure 41. With these values, the non-linear content in Equation (1) becomes

\[
C_2x^{n-1} = 0.044 \times 10^{-4} \times 2.63
\]

For \( x = 30 \) mils, this becomes:

\[
C_2x^{n-1} = 0.044 \times 10^{-4} \times 7600 = 0.0335 \text{ or } \approx 3\%
\]

For \( x = 20 \) mils (which equals 40% of mean gap) the non-linear content is:

\[
C_2x^{n-1} = 0.044 \times 10^{-4} \times 20^{2.63} = 0.044 \times 0.26 = 0.0115 \text{ or } \approx 1\%
\]

Thus it is shown that for a total gap excursion of \( 2 \times 20 = 40 \) mils and a mean gap of 50 mils, the non-linearity in the probe output is about 1%. It is also shown that while the sensitivity may change by as much as 40% for an excursion of ± 30 mils (see Figure 41), the non-linear content in the probe response is still only about 3%.

This brief and approximate analysis is made to analyze the data of the rather curved sensitivity graphs of Figures 41 through 44. It is also easier and more accurate to use the sensitivity plot to calculate the non-linearity, than to measure non-linearity directly on the probe response curve.
When the surface of a conductive material is exposed to an A.C. magnetic field, the field penetrates into the material. The field in the material generates A.C. currents (eddy currents) that in turn generate a demagnetizing field. The result is an attenuation of the applied field. This attenuation increases with the penetration distance into the material.

When the material is also magnetic (soft), then for a given applied field the flux levels are increased by a factor \( \mu \) (= permeability, 500 - 100,000). The much higher flux levels result in much stronger eddy currents and a stronger demagnetizing field. Therefore, the attenuation of the field in a magnetic material progresses more rapidly with distance into the material.

The eddy currents induced in the material are not only a function of the change in flux, but also of the rate of change of flux, (or frequency).

The attenuation as expressed in current density is represented by:

\[
I_x = I_o e^{-x/\delta}
\]

\[
\delta = 2 \times 10^6 \sqrt{\frac{\rho}{\mu f}}
\]

in which

- \( I_x \) = current at depth \( x \) below surface
- \( I_o \) = current at the surface
- \( \delta = \text{inch} \times 10^{-3} = \text{depth of penetration (by definition)} \)
- \( \rho = \text{volume resistivity (\Omega cm)} \)
- \( \mu = \text{relative permeability (vacuum = 1)} \)
- \( f = \text{frequency (Hz)} \)

This expression accounts for the three parameters mentioned before (conductivity, permeability and frequency).
The depth of penetration of the field is defined as the distance below the surface at which the current is 37% (i.e., 100/exponential "e") of that on the surface.

Actual penetration continues beyond \( x = \delta \) and the current is down to 13% at \( x = 2\delta \) and 2% at \( x = 4\delta \) etc.

In the following an estimate of the permeability \( \mu \) existing in the probe and target will be made.

The permeability \( \mu \) is the ratio of flux density and field strength. The field in the magnetic circuit of the probe is determined by the number of windings on the coil and by the coil current. The flux density is determined by the field and the reluctance of the magnetic circuit. The reluctance of the circuit is made up of the reluctance of the core, the air gap and the target. Of these, the reluctance of the air gap is by far the largest. For the probe described in this report, the flux is as follows:

\[
F = \frac{\text{field}}{\text{total reluctance}} = \frac{.4\pi \times \text{number of turns of coil} \times \text{coil current (amps)}}{(\text{core & target}) \text{ length} / \text{core area} \times \mu + \text{air gap} / \text{core area}}
\]

Approximate data for the probe are:
- coil current = .025A (at 1000 Hz, 5 volt)
- turns on coil = 500
- core and target length = 5 cm (2"")
- core area = .6 cm\(^2\) (.1 in\(^2\))
- air gap = .1 cm (.040"")
- \( \mu = 300 \) (estimate)

\[
F = \frac{.4\pi \times 500 \times .025}{5 \text{ cm} / .6 \text{ cm}^2 \times 300 + .1 \text{ cm} / .6 \text{ cm}^2} = 80 \text{ Maxwell}
\]

and the flux density:

\[
B = \frac{F}{\text{core area}} = \frac{80}{.6 \text{ cm}} = 130 \text{ Gauss}
\]

At 130 Gauss the permeability of materials suitable for the probe core and target is low and is referred to as the "initial permeability" which is in the order of 1% to 10% of the maximum permeability that obtains at much higher flux densities. The estimated \( \mu = 300 \) (which was used in the above calculation)
is a reasonable number for 130 Gauss.

The depth of penetration is of importance in selecting the target thickness, as is pointed out in the section dealing with the target material. If the target does not attenuate most of the field, the probe sensitivity is reduced and the likelihood of noise increased (by flux penetrating into non-magnetic materials below the target).

The formula for δ given above is plotted on a log-log scale in Figure Al-1. It is given for a variety of materials that were used in the probe development program. The non-magnetic materials show a large depth of penetration, and the magnetic materials show increasingly smaller depth of penetration as the ratio of ρ/μ decreases.

For \( x = \delta \) there is still 37% of the field left and it is therefore reasonable to expect a notable loss of probe sensitivity when using a target thickness \( \delta \).

This was demonstrated by the flame sprayed targets. They were made of 431 SS which has magnetic properties similar* to those of 416 SS. For this material, the depth of penetration at 2000 Hz for a \( \mu = 200 \) is .025". The loss of sensitivity of the probe was about 30% which roughly represents the 37% field left below the target. For a target thickness of .010" the field left below the target is about 78%. The probe sensitivity with the .010" target is down to 30% of that obtained with a (1") thick target, all at 2000 Hz.

Using a value of \( \mu = 200 \) as is done above can be justified from data available for similar materials for the flux density present in the target. No standard magnetic measurements were made on any of the materials used as the information available from the literature proved to be sufficient for the qualitative judgments to be made prior to the actual use of materials in the program.

* except for the Curie point which is 700°F.
The alternating current below the surface is:

\[ I_x = I_o e^{-\frac{x}{\delta}} \]

The total current is:

\[ I_t = \int_{0}^{\delta} I x dx = 6I_o \]

\[ I_o \] = current at surface

\[ x \] = distance below surface (.001 inch)

\[ \delta \] = depth of penetration (.001 inch)

\[ \delta = 2 \times 10^{-5} \sqrt{\frac{\mu}{\rho}} \] (.001 inch)

\[ \rho \] = resistivity (Gcm)

\[ \mu \] = permeability (vacuum = 1)

\[ f \] = frequency (Hz)

<table>
<thead>
<tr>
<th>Material</th>
<th>( \mu )</th>
<th>( \rho ) Gcm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>2000-5000*</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>Cu</td>
<td>1</td>
<td>1.7 x 10^{-6}</td>
</tr>
<tr>
<td>Al</td>
<td>1</td>
<td>2.8 x 10^{-6}</td>
</tr>
<tr>
<td>304SS</td>
<td>1</td>
<td>75 x 10^{-6}</td>
</tr>
<tr>
<td>Nichrome V</td>
<td>1</td>
<td>100 x 10^{-6}</td>
</tr>
<tr>
<td>Hiperco 27</td>
<td>3000*</td>
<td>19 x 10^{-6}</td>
</tr>
<tr>
<td>12 Cr Steel</td>
<td>800-1000*</td>
<td>60 x 10^{-6}</td>
</tr>
<tr>
<td>Hg</td>
<td>1</td>
<td>95 x 10^{-6}</td>
</tr>
<tr>
<td>Na (at 208°F)</td>
<td>1</td>
<td>10^{-5}</td>
</tr>
<tr>
<td>NaK (77K)</td>
<td>1</td>
<td>4.1 x 10^{-5}</td>
</tr>
</tbody>
</table>

* Initial permeability = 200

Note: Depth of penetration is by definition the distance in to the surface at which the current is down to 37% of that on the surface.

| at \( x = \delta \) | \( I = 0.371 I_o \) |
| at \( x = 2\delta \) | \( I = 0.135 I_o \) |
| at \( x = 3\delta \) | \( I = 0.05 I_o \) |
| at \( x = 4\delta \) | \( I = 0.018 I_o \) |

Fig. AI-1 Depth of Penetration of E. M. Field in Flat Surface vs. Frequency.
APPENDIX 2
THE A.C. WHEATSTONE BRIDGE – USE OF OUTPUT PHASE DETECTION AS A MEANS TO REJECT THE EFFECT OF TEMPERATURE AND MEDIUM IN THE GAP ON SYSTEM OUTPUT

The magnetic reluctance proximity probe is a complex device when considering the fact that it can have at least three inputs (gap thickness, temperature, and gap medium) and two outputs (series inductance, L, and resistance, R).

The objective is obviously to make the probe sensitive to one input only. The degree to which this can be accomplished is very much dependent upon the relative sensitivity to the three inputs. Fortunately, the application of the probe to the measurement of bearing orbits affords an excellent opportunity to use two probes in push-pull and thus to reject common mode inputs in as much as they have an effect on the system balance (or zero). The effect of common mode inputs on the sensitivity of a pair of probes is much more difficult to reject, but it is not considered a problem for the present application.

In the following a method is described that can be used to reject probe inputs that are not common mode.

To obtain common mode rejection when using a pair of probes, the probes are connected in a Wheatstone bridge configuration. Two such configurations are shown in Figures A2-1 and A2-2. The difference between the two is that the input terminals of the one become the output terminals of the other.

The method of rejecting single mode inputs is based on the fact that the phase of the output of an A.C. Wheatstone bridge is different for the different probe inputs (gap, temperature, etc.). To be able to use this method to advantage it will be shown that the bridge with two probes in parallel should be used.

When attempting to analyze the bridge's behavior it was found that a graphical vector presentation was far more illustrative and revealing than a strictly mathematical treatment. This graphical method is, therefore, used exclusively in the following.
Ein = E_{in} \sin \omega t

$$E_{in} = E_i \sin \omega t$$

$$|Z_a| = \sqrt{(R_1 + R_3)^2 + (\omega L_1)^2}$$

$$|Z_e| = \sqrt{(R_2 + R_4)^2 + (\omega L_2)^2}$$

$$R_3 = R_4 = 150 \Omega$$

Fig. A2-1 Wheatstone Bridge with Two Inductive Probes in Parallel.
\[ E_{in} = \hat{E}_1 \sin \omega t \]

\[ |Z_b| = \sqrt{(R_1 + R_2)^2 + \omega^2(L_1 + L_2)^2} \]

\[ Z_d = R_3 + R_4 \]

\[ R_3 = R_4 = 150 \, \Omega \]

**Fig. A2-2** Wheatstone Bridge with Two Probes in Series.
The vector diagrams for both bridges are given for each case considered. The top diagram of each Figure (labeled a) is for the bridge with two probes in parallel, and the bottom diagram (labeled b) is for the bridge with two probes in series. Each of the Figures A2-3 to A2-7, is for a given set of probe conditions.

To introduce Figures A2-4 to A2-7, the diagrams for a single probe condition (i.e. open gap) is drawn in Figure A2-3, with labels on each vector to indicate their origin. The construction of these diagrams is based on the fact that for pure inductors and pure resistors in series, the voltage across the inductors leads the voltage across the resistors by 90°.

All voltages are referenced to the input voltage vector $E_{in}$, located horizontal and pointing to the right in all diagrams.

All diagrams are drawn to scale using probe inductance and resistance data measured with the Hewlett Packard Bridge.

The results obtained with the diagrams agreed with the phase readings obtained with the Encore 902 readout which used the bridge of Figure A2-1. The Encore 902 readout was not used with the bridge of Figure A2-2.

Returning to Figure A2-3a, it is constructed as follows:

1. $E_{in}$ is given an arbitrary length
2. $i_2$ (= current through bottom part of bridge) is calculated from $E_{in} = i_2 \sqrt{(R_2 + R_4)^2 + (\omega L_2)^2}$ using measured $R_2$, $R_4$ and $\omega L_2$
3. The vectors $i_2(R_2 + R_4)$ and $i_2\omega L_2$ are drawn in place
4. The vector $i_2R_2$ is measured along $i_2(R_2 + R_4)$
5. The vector $i_2\omega L_2$ is combined with $i_2R_2$, and their sum is the voltage vector across the probe

The same diagram can be constructed for probe #1 ($L_1, R_1$) in the top half of the
(a) Vector Diagram for One Half of Wheatstone Bridge with Two Inductive Sensors in Parallel. Sensing Gap is Open.

(b) Vector Diagram for Wheatstone Bridge with Two Inductive Sensors in Series. Probe #1 Sensing Gap is Open, Probe #2 Sensing Gap is Closed.

Figure A2-3
(a) Vector Diagram for One Half of Wheatstone Bridge with Two Inductive Sensors in Parallel.

(b) Vector Diagram for Wheatstone Bridge with Two Inductive Sensors in Series.

Figure A2-4
(a) Vector Diagram for One Half of Wheatstone Bridge with Two Inductive Sensors in Parallel.

(b) Vector Diagram for Wheatstone Bridge with Two Inductive Sensors in Series.

Figure A2-5
(a) Vector for One Half of Wheatstone Bridge with Two Inductive Sensors in Parallel.

(b) Vector Diagram for Wheatstone Bridge with Two Inductive Sensors in Series.

Figure A2-6
(a) Vector Diagram for One Half of Wheatstone Bridge with Two Inductive Sensors in Parallel.

GAP 1 CLOSED,
GAP 2 OPEN
$T_1 = T_2 = 700^\circ F$

(b) Vector Diagram for Wheatstone Bridge with Two Inductive Sensors in Series.

$T_1 = T_2 = 700^\circ F$
$T_2 = 900^\circ F$

Figure A2-7
bridge. If both probes are in the same condition and if \( R_3 = R_4 \), then the two vectors across the two probes are coincident, and the bridge has no output. If e.g. the gap of \#2 is open and the gap of \#1 is closed, then the probe voltage vectors are not coincident, and the bridge vector is the vector difference between \( i_2 \sqrt{R_2^2 + (\omega L_2)^2} \) and \( i_1 \sqrt{R_1^2 + (\omega L_1)^2} \).

In the diagrams in Figures A2-4 to A2-6, the locus of the terminal points of the probe vectors is shown as a dotted line, but the probe vectors themselves are not shown. The bridge output vector then is a line connecting two points of the dotted line. The direction of this (small) bridge output vector relative to \( E_{in} \) is the output phase angle, which is the main item of interest in the present analysis.

For the bridge with two probes in series, the vector diagram for a single probe condition is given in Figure A2-3b. The construction is very similar to that of the diagram in Figure A2-3a.

The diagram is drawn for the case where probe \#2 has an open gap and probe \#1 a closed gap. In Figure A2-3b to Figure A2-7b, the gap of probe \#1 is closed, and the gap of \#2 as indicated (.050" or open). The voltage across probe \#2 is \( i_2 \sqrt{R_2^2 + (\omega L_2)^2} \), and the vector difference between it and \((1/2) E_{in} \) (again \( R_3 = R_4 \)) is the bridge output. A dotted line in Figures A2-4b etc., indicates the locus of the terminal points of the vector across probe \#2. The output vector is a line between a point of this locus and the terminal of \((1/2) E_{in} \).

After this introduction to the basic bridge vector diagrams, the diagrams for four cases will be inspected. The first three cases only differ in the bridge frequency used (500, 1000 and 2000 Hz). They are shown in Figures A2-4 to A2-6. It can be seen that the locus of the probe vector is curved for bridge frequencies of 500 and 1000 Hz. This means that the phase of the output voltage varies with the output amplitude. However, this phase variation is not large enough to introduce problems. For the 2000 Hz bridge frequency the locus is a straight line, and output phase is constant.

For the bridge with two probes in parallel, the value of the bridge completion resistors \( (R_4, R_3) \) was chosen at a value centered around the probe impedance in
the frequency range used (500 - 2000 Hz). If the value of these resistors is chosen an order of magnitude higher than the probe impedance, the result will be a much reduced bridge output. Also the vector $i_2 \omega L_2$ will be nearly $90^\circ$ with $E_{in}$. Thus when using a phase sensitive detector setting of $+90^\circ$, the readout output will be proportional to the changes in probe inductance only. If, however, the bridge completion resistors are about equal to the probe impedance, then a phase sensitive detector setting of $+90^\circ$ does not detect changes in probe inductance only, as becomes obvious when inspecting the phase diagrams. This fact is mentioned here, because there seems to exist a popular misconception about the A.C. Wheatstone bridge, namely that when setting the phase sensitive detector at $+90^\circ$, only the inductive probe changes are sensed. However, this is only so for the special case where $R_2 = R_4 \gg \sqrt{R_2^2 + (\omega L_2)^2}$.

For the bridge with two probes in series (Figure A2-2) the same applies, namely that there is no single phase sensitive detector setting that will make the readout output a function of probe inductance changes only.

It should be noted here that there is no reason why the system should be made sensitive to probe inductance changes only. This is particularly so because the probe (A.C.) resistance changes are as large or larger than the reactance changes. As the probe A.C. resistance and the probe reactance are coupled through the magnetic flux, they are both affected in a similar way by such things as gap, temperature, medium in gap, etc.

Thus, rather than seek to readout only the A.C. resistance changes or reactance changes, it is more advantageous to readout the total impedance change of the probe, because it results in maximum output.

This means that the phase sensitive detector is set in phase with the bridge output. As was noticed before, the phase of the bridge output (Fig. A2-1) varies slightly with probe gap unbalance (see curvature of probe vector terminal locus) but this affects the probe calibration only slightly. To reduce this (small) effect a phase setting a little ($+10^\circ$) away from the optimum (= in phase with bridge output) can be used.

There is another reason why a phase sensitive detector setting away from the optimum can be advantageous. This is illustrated for one case in Figure A2-7 in which the vector diagrams for three probe conditions are given:
1. Both gaps are closed, both probes at 700°F
2. One gap open, one gap closed, both probes at 700°F
3. Both gaps are open, one probe at 700°F and one probe at 900°F

In Figure A2-7a it can be seen that the output due only to a temperature change of a single probe of 200°F (C-7 to C-9) is appreciable. Fortunately, however, this output is not in phase (or 180° out of phase) with the output (C-7 to 0-7) due to changing the gap of one probe from open to closed. An appreciable vector component of (0-7 to C-7) is 90° out of phase with (C-7 to C-9).

Therefore, when setting the phase sensitive detector at 90° with (C-7 to C-9), the system will be insensitive to temperature differences between the two probes, and it still has about 50% of maximum sensitivity to displacements.

This advantageous situation does not exist in Figure A2-7b. Here the outputs due to temperature change and gap change are about 180° out of phase, and it is not possible to isolate the displacement output from the temperature output with the phase sensitive detector.

As the vector diagrams are very much affected by the bridge frequency, it is quite well possible that at other frequencies than 1000 Hz the rejection of temperature effects is not as good as or better than that obtained in Figure A2-7a.

The practical proof of the scheme illustrated in Figure A2-7a is given earlier in this report, where it is shown in Figures 22 through 27 that certain phase sensitive detector settings, well away from optimum (just as required in Figure A2-7a) will make very small the effect of absence or presence of an electrically conductive liquid in the gap.
APPENDIX 3
PROBE TEST DATA FROM OVEN TEST MADE AFTER SODIUM TESTS

The two probes used in the early calibration tests in sodium and two additional probes of the same production series were subjected to an oven test, in which they were exposed to a number of thermal cycles. The maximum temperature reached was 1200°F for short periods of time (about 3 hours). The purpose of these tests was to check whether any changes in probe performance had occurred during the 1100°F calibration test in liquid sodium, thus contributing to the asymmetry observed in the sodium calibration test. The actual cause of the asymmetry was the physical shift in probe location during the sodium test. The probe performance verification tests described here showed that there had been no apparent change in probe performance.

The probe data obtained in the oven test showed that the four probes behaved identically. These tests were made at temperatures higher than any to which the probes had been exposed to before.

The data taken was:

- Probe inductance
- Coil capacitance to ground
- Coil resistance to ground

Graphs of the results are shown in Figures A3-1 through A3-3.

Figure A3-1 shows the familiar inductance versus temperature curve with and without target. The tracking of these two probes is excellent. Reproducibility of the results was excellent.

Figure A3-2 shows resistance to ground of the coil. This is an important probe parameter, as it can limit the maximum operating temperature well before, e.g., magnetic materials would do so. Judging from the trend in Figure A3-2,
it seems that temperatures somewhat above 1200 °F could be tolerated before the probe becomes inoperational due to loss of insulation resistance.

Figure A3-3 shows the capacitance to ground of the coil of probe #3. Probe #4 showed the same results. Probes #1 and #2 showed a capacitance approximately 3 times higher, possibly due to less exposure to high temperatures over long periods of time.
Fig. A3-1  High-Temperature Inductive Proximity Probe.
Inductance vs. Temperature in Air at 2000 Hz.

△ Probe #4
● Probe #3

Probe #3 and #4 were Used in Sodium Test Series
Prior to Taking Data in this Graph.
Fig. A3-2  High-Temperature Inductive Proximity Probe.  
D.C. Insulation Resistance to Ground of Coil  
vs. Temperature of Probe #3 Without Cap,  
After Sodium Test Series.  

Test Frequency = 2000 Hz
Fig. A3-3 High-Temperature Inductive Proximity Probe.
Capacitance to Ground of the Coil of Probe
#3 Without Cap, After Sodium Test Series.

Test Frequency = 2000 Hz
Several commercially available carrier-phase sensitive demodulator instrumentation systems were evaluated for use with the Inductive Proximity probes.

Since each of these systems were found to be lacking in certain respects, it was decided to draw up a set of specifications for a similar system, designed specifically to match the Inductive Proximity probe characteristics. The electronic system specifications are itemized starting on the next page. The primary features of this "special" carrier-amplifier phase demodulator electronics system are its frequency and amplitude stability (.01%), its frequency independent phase sensitive demodulator controls, its ability to accommodate a wide range of inductive transducer characteristics in 1/4, 1/2, or full bridge configurations and its precision calibrated, resettable controls. The only significant deviation from the itemized specification was the deletion of the requirement for harmonic filtering between the amplifier and demodulator. Additional testing at MTI with the proximity probes in half bridge configuration, confirmed that system linearity was acceptable without this harmonic filtering. A block diagram of the resultant electronic system is shown in Figure A4-1 and a photo of one of these units is shown in Figure A4-2.

The electronic system consists of the following: 1) a 128 KHz, crystal stabilized square wave oscillator and a divide by 64 output circuit, 2) a selectable count down logic circuit and square wave to sine wave filters for generation of 500 Hz, 1 KHz, or 2 KHz carrier frequencies, 3) a power amplifier for driving the primary of the transducer bridge supply transformer, 4) a bridge selector section which provides accommodations for 1/4, 1/2, or full bridge operation, 5) an input amplifier for amplifying the bridge unbalance signal, 6) both a non-phase sensitive demodulator and a phase sensitive demodulator for rectification of the amplified bridge unbalance signal, 7) an output section having selectable filters to provide optimum matching for the 500 Hz, 1 KHz, or 2 KHz carrier frequencies and to generate a D.C. output voltage proportional to the average level of the rectified carrier signal, 8) quadrature generator circuit to provide variable magnitude and phase reference signals for bridge nulling and for the phase
Fig. AA-1 Inductive Transducer Electronics System.
Fig. A4-2  Model 902 Inductive Transducer Readout.
sensitive demodulator timing, 9) a regulated, D.C. power supply.

Specifications - Inductive Transducer Electronics System

Description: An all solid state, bridge type, phase sensitive, carrier-amplifier electronic system for use with inductive transducers.

Power Requirements: 115 VAC ± 10%, 50 to 400Hz, 10 watts maximum

Input Characteristics:
Switchable to accommodate \( \frac{1}{4} \) bridge, \( \frac{1}{2} \) bridge and full bridge, external, and having the necessary bridge completion and balancing elements to accommodate inductive transducers ranging from 5 MH to 30 MH. The balancing controls must provide for both resistance and reactance unbalances and provide range and resolution consistent with range and sensitivity specifications.

Carrier Frequency:
1. Switchable to 500Hz, 1000Hz and 2000Hz. Frequency stability of .01%
2. Carrier output level to be 5 VRMS ± .01%

Amplifier and Synchronous Demodulator:
1. Synchronous demodulator continuously adjustable to ± 90° from carrier reference and to have fixed positions at ± 90°. Lockable adjustment.
2. Harmonic filtering between amplifier and demodulator.*
4. 10 position, switchable attenuator to reduce sensitivity to a minimum of 1000 MV.R.M.S. for full scale output.
5. Lockable vernier to provide continuously adjustable sensitivity between attenuator settings.
6. Switchable to non-phase sensitive operation.
8. Biasing or zero offset controls at amplifier input to provide for ± full scale biasing.
9. Calibration switch to connect an external reference across active or compensating bridge legs.

* Later deleted from the specification, as noted earlier.
10. System to be designed to permit common point of half-bridge external configuration to be at ground potential.
11. Linearity to within ± 0.1% of full scale.
12. Input impedance of 100K OHMS or greater.

Output-Filter Characteristics:
1. Low pass filtering of full wave demodulator to provide system response flat ± 1% to 20% of carrier frequency, with a roll off of at least 60 DB at carrier frequency.
2. Output sensitivity for full scale of amplifier to give +10 volts D.C. into a 1000 OHMS load at oscilloscope - recorder output.
3. The system shall include a 1% of full scale, panel meter for set up adjustments and readout purpose, although primary emphasis will be on reading the output on an oscilloscope or recorder.

Mechanical:
1. Modular construction to be preferred, with separate plug in units for the oscillator, amplifier-demodulator, filter and output amplifier. Unit to be rack mount adaptable and not to exceed approximately 19" wide, 7" high by 10" deep.
2. System must withstand "normal" handling shocks without showing detectable changes in performance.

Temperature:
1. System must maintain balance and sensitivity to within ± 1% of full scale on all sensitivity ranges over a temperature range of 60°F to 100°F.
2. System must maintain specification over at least a thirty day period of continuous operation.

Also quote similar alternate system with following exceptions:
1. Carrier Frequency (1) - 500 Hz carrier frequency operation only
2. Amplifier and Synchronous Demodulator (8) - Delete completely

Controls
The "Frequency and Filter Select" switch selects which of the three internally generated frequencies will be used to drive the bridge power amplifier. It also
automatically selects the proper low pass filter for obtaining the optimum frequency response and noise level for the selected bridge frequency. A feedback circuit stabilizes the output voltage from the power amplifier and maintains it at either a constant 2.5 or 5.0 VRMS. Switching to "External Oscillator" permits the power amplifier to be driven from an external source, at any frequency from approximately 100 Hz to 50,000 Hz. The three positions on the external oscillator switch selects which of the three low pass filters are in use, independently of the external oscillator frequency setting. When using an external oscillator the frequency and amplitude stability of the bridge voltage are directly determined by the characteristics of the oscillator being used.

The "Sync Select" permits phase locking of two or more units in order to minimize "beats" between adjacent channels which may occur when using long leads between the transducers and electronics.

For normal operation the "Syn Switch" is left in the "Int" position. To phase lock two or more units to a common internal oscillator, the unit chosen as the master is left in the "Sync Select-Int" position and the other units are set in the "Sync Select-Int" position. The Ext-Syn output from the master is then connected to the Ext Syn input of the slave units.

To phase lock to an external oscillator, all units are set to the "Sync Select-Ext" position and the "Ext-Bridge Drive" connector of each unit is connected to the external oscillator.

The "GAIN" switch provides calibrated steps of sensitivity, from 1000 MVAC to 2 MVAC for a 10 V.D.C. output, when the gain vernier is fully clockwise (1000 on turns counter). The gain sensitivities may be reduced proportionally by resetting the "GAIN VERNIER", as desired. "500" on GAIN VERNIER would result in all the calibrated sensitivity factors being one-half their indicated value, i.e. the 500 MV gain setting would actually be 1000 MV for full scale output.

The "Demodulator Select" switches either the non-phase sensitive or the phase sensitive detector output to the low pass filter, D.C. amplifier and output terminals.
For initial balancing this switch is usually set in the "non-phase sensitive" position since this provides a nulling indication on the output meter. It is then switched to "phase sensitive" position for operation.

The "Bridge Phase" switch selects the basic reference phase of either 0° or 180° for the phase sensitive demodulator. For example, when the red "signal" post is positive with respect to the white "signal" post, the bridge phase switch should be in the 0° position. This is equivalent to the bridge element across the green to red bridge input post being a higher resistance or impedance than the element across the green to white bridge input post. For additional information on how to determine the proper position of this control refer to the operation instructions.

**Bridge Null Controls - Magnitude and Phase**

These controls provide for electronically nulling or balancing of the transducer output. These controls inject a nulling signal into the amplifier which may be adjusted to be of equal magnitude and phase to the bridge unbalance signal. The adjustment of the magnitude and phase are best done with the "Demodulator Select" switch in the proper position of either 0° or 180° before attempting to set the bridge null controls. This can usually be determined by the response of the magnitude and null controls, i.e. if the "Bridge Phase" control is in the wrong position it will be impossible to obtain a sharp null setting. The magnitude, x1 position gives 1 volt RMS of correction at the full ten turns (1000 on DIAL) and the magnitude, x5, gives 5 volts of correction.

The "Bridge" switch selects the operating mode of the system. In the "Quarter" position, as shown in Fig.A4-3a, one transducer is connected between the green excitation terminal, and the white signal terminal. This switch position automatically connects an electrically variable inductor between the green excitation terminal and the red signal terminal. It also automatically connects 150 OHM precision resistors from each signal terminal to the black excitation terminal.

Switching the "Bridge" selector to the "Half" position removes the electrically variable inductor and requires that another transducer be connected, as shown in Fig.A4-3b. The 150 OHM, precision resistor are still internally connected from each signal terminal to the black excitation terminal.

Switching the bridge selector to the "Full" position, removes the bridge completion resistors in addition to the variable inductor, and, therefore requires that all four arms of the bridge be external to the instrument. See Figure A4-3c.
Fig. A4-3 Bridge Connections.
The "S.R. Current" and "S.R. Resistance" controls are for use only when operating with a single (1/4 bridge) transducer external. The "S.R." stands for Saturable Reactor. In the model 902 inductive transducer readout, this saturable reactor is designed specifically to match the electrical characteristic of the MTI inductive displacement probe.

Operation

Half Bridge External:

The general assumption for half bridge operation is that the two transducers are mounted diametrically opposite one another, i.e. looking at opposite sides of a shaft or target, such that when one transducer is at its minimum gap, the other is automatically at its maximum gap. The mean gap or balance point at which it is desired to have zero output is when the shaft or target is midway between the two transducers.

Half bridge operation with the two external transducers in push-pull, as described, is particularly advantageous in that it provides an inherent compensation for like variables such as temperature induced zero shifts of each transducer and also results in linearizing of the output versus gap characteristic of the overall system.

Step: (1) Set "Bridge" switch to the "HALF" position.
(2) Connect one transducer between the green excitation post and the white signal post, and connect the other transducer between the green excitation post and red signal post. See Figure 3.
(3) If using internal oscillator, set the "frequency and filter select" switch to the desired frequency on the int. drive positions.
(4) Set "Syn Select" to int.
(5) Set "Gain Vernier" to 100.
(6) Set "Gain" to 1000.
(7) Set "Bridge Phase" to 0°.
(8) Set "Demodulator Select" switch to the "non-phase sensitive" position.
(9) Set bridge null magnitude to 0 x 1 and bridge null phase to -90°.
(10) Set bridge drive to desired voltage. 5.0 VRMS is generally recommended. For transducers having an unusually low impedance (in the order of 25 OHMS or less) it may be desirable to use the 2.5 VRMS bridge drive position.
(11) After having completed the previous steps the transducer to target gap should be set at whatever distance is selected to be the mean or average gap. When using two inductive displacement transducers operating in push-pull for applications such as shaft position monitoring, the mean gap will generally be equal for each probe. When this is the case then the probe impedance will be very nearly equal to each other at this condition.

(12) Assuming the conditions are similar to those stated in step (11), the panel meter should now be reading very close to zero. The "Gain" switch may now be set to a more sensitive position until the panel meter has deflected approximately 1/2 of full scale in either the plus or minus direction.

(13) The "Bridge Null" - magnitude control should now be rotated clockwise from zero while watching the panel meter. If the meter goes away from zero as the magnitude dial increases then the "Bridge Phase" should be switched to the opposite position that it was originally in. If step (7) has been followed the bridge phase will now be in the 180° position.

(14) Reset the magnitude to zero, and again carefully increase the magnitude control. The panel meter should now start to decrease. Keep increasing the magnitude control until the panel meter goes through a null and begins to increase its deflection again. Reset the magnitude control for meter null. If this null is less than 10% of F scale the "Gain" switch may be advanced to a more sensitive position.

(15) The "Bridge Null-Phase" control should now be rotated clockwise from zero while watching the panel meter. If the panel meter goes farther off zero as the phase is increased then the phase reference switch must be reset to the +90° position. The phase control should now be rotated in either direction until the panel meter again shows a "null."

(16) By alternately adjusting the null magnitude and null phase it should be possible to obtain a null on the panel neither of less than 10% of full scale. Note: When a very small amount of null magnitude is required the null phase control will appear to be very insensitive, this is normal.
The gain vernier should now be returned to the "1000" position.

The "Demodulator Select" switch should now be set to the "Phase Sensitive" position. The panel meter should now return to very nearly zero. Any slight amount of off zero reading remaining may be cancelled out by carefully readjusting the bridge null-magnitude slightly until the panel meter reads zero.

This completes the null balancing operation. The "Bridge null magnitude" and null phase controls should be locked.

The gap between each transducer and its target should now be set to correspond to the full travel expected during actual testing. In a push-pull arrangement such as being used for this example, this will mean that the gap on the other transducer will be decreased by that same amount. After having done this the "Gain" switch should be set to obtain approximately 1/2 scale deflection on the panel meter.

The Phase Sensitive Demodulator-Phase control should now be turned clockwise away from zero and the panel meter observed until a maximum or peak reading is obtained. If the control reaches its limit of 1000 before a peak meter reading is obtained the phase sensitive demodulator of + 90° and - 90° switch must be set to opposite its original position. It should now be possible to reach a maximum peak reading on the panel meter by readjusting the phase-sensitive demodulator control.

If it is desired to adjust the output to full scale, or to obtain an even calibration factor of volts output per mil of target motion, the gain vernier may be adjusted to do so. The phase sensitive demodulator control and gain vernier should now be locked.

In steps 10 through 19, it is often helpful to connect an oscilloscope to the "demodulator output monitor jack." By doing this it is possible to observe wave shapes at the phase sensitive demodulator output. Nulling and peaking of the panel meter will be seen to correspond with nulls and peaks of the demodulator. The wave shape may also be observed for any abnormal conditions such as distortion or clipping. Figure A4-4 shows the wave shapes to be expected at the phase sensitive demodulator output for various target positions.
With "target" at one limit of its range and with phase sensitive demodulator control set for proper or optimum switching.

With "target" at opposite limit of range and same setting of phase sensitive demodulator as above.

With "target" at "mean" or equal distance from each transducer or no target present at either transducer.

With "target" at one limit of its range but with phase sensitive demodulator not set for optimum switching.

Fig. A4-4 Typical Wave Shapes at Phase-Sensitive Demodulator Output.
Quarter Bridge External

When operating with a single transducer the "Bridge" control must be set to "quarter" and the single external transducer connected between the green "excitation" terminal and the white "signal" terminal. By setting the bridge switch to 1/4, an internal, variable inductor (saturable reactor) has been inserted between the green excitation terminal and the red signal terminal.

For operation on quarter bridge follow 1/2 bridge operation procedure, steps 1 through 10. The next step will now be the adjustment of the internal inductor to match the external transducer. This is done by alternately adjusting the "S.R. Current" and "S.R. Resistance" controls to obtain a minimum null meter deflection. Steps 12 through 20 may now be followed to complete the balancing procedure.

Full Bridge Operation:
Set "Bridge" switch to "Full" and connect four transducers across the bridge terminals, as shown in Figure No. 4-3c. Follow steps 3 through 20 as described in Half Bridge Operation.

When operating with full bridge external care must be taken to insure that transducers of opposite going polarity are connected into adjacent arms of the bridge.

Operational Notes

When operating with closely matched transducers set at equal "mean" gaps, the bridge null "magnitude" setting will generally be quite small, (200 x 1, or less). If substantially larger amounts of null magnitude are required it is recommended that the set up be checked thoroughly for mis-adjustments of the transducers or electronics.

When nulling mis-matched transducers, or transducers set at unequal mean gaps, much larger values of magnitude correction may be required. In extreme cases it may be necessary to switch to the x 5 position.

When operating on 1/2 bridge external, and with the transducers at high temperature, or some other condition that may cause a drop in the insulation resistance between
the transducer and system ground, it is generally recommended that the "common" connection of the transducers be connected directly to ground. This may be done by connecting a jumper wire from the green excitation terminal to the front panel ground terminal.

The following procedure is especially useful for situations where the transducers are installed in a machine and only the two extreme positions are available for calibration. This procedure also "normalizes" the calibration curve, at the temperature, (up to approximately 1000°F) of the transducers during calibration. This permits the room temperature calibration data to be used directly, without requiring a point by point calibration at the operating temperature. This procedure assumes that the transducers are reasonably well matched and that the mean gap is defined by the shaft being at the center of the bearing, i.e. midway between the transducers, and the total range to be equal to the total diametrical clearance between the shaft and the bearing.

1) Follow step 1 through 10 in the operation section, then proceed as follows

2) With the machine at operating temperature, and the shaft not rotating, displace the shaft, to its limit, in the direction of one of the transducers.

With the transducers at this condition set the bridge null magnitude and phase controls both at zero, at the demodulator select switch at the "phase sensitive" position. Adjust the phase sensitive demodulator control to obtain a maximum reading on the panel meter. The gain may also have to be adjusted during this operation to obtain suitable meter deflection. The gain vernier may also be adjusted if it is desired to obtain exactly full scale output at full range. After making these adjustments and noting the panel meter reading or the output voltage, shaft or target is now displaced to its other limit, in the direction of the opposite transducer. Without further adjustment of the controls, the meter of output reading is again noted. It should be very nearly the same as previously obtained, but of opposite polarity. Any slight difference in the two readings is due to the transducer mismatch or fixturing errors. The net result of this will be a slight "offset" voltage when the shaft or target is at the mean gap position. If desired, this may be corrected by calculating the difference
in the output voltage at the two extreme gap settings, and then by using the bridge null magnitude control, either add or subtract this amount, as required, from the output reading. This may be done by leaving the transducers set in one or the other of the previous positions and setting in a slight amount of bridge null-magnitude correction and noting if it gives the proper direction of correction. If not, the bridge phase (0° or 180°) must be set to its alternate position. The magnitude correction should now cause the output voltage to go in the correct direction for correcting the "offset". Since the bridge phase switch will also change the polarity of the output it may be necessary to repeat the two extreme position data points and again note voltages and differences. The magnitude control should now be readjusted until the calculated voltage is obtained. At this point, the output voltage at either extreme or transducer positions should be very nearly equal, but of opposite polarity. If desired, the gain vernier may be adjusted to obtain exactly 10 volts output. When resetting the transducer gaps to the opposite positions the output voltage should also be approximately 10 volts, but of opposite polarity. The output, with both transducers at their mean gap, should now be very nearly zero.
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