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Part II

LIQUID-METAL-LUBRICATED BEARING INSTRUMENTATION

PART II: ADVANCED PROTOTYPE FILM THICKNESS, FILM CONTINUITY, AND FILM PRESSURE SENSORS

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Air Force Aero Propulsion Laboratory
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FOREWORD

This report was prepared by the Systems Engineering, Materials Application, and the Structural Physics Division of Battelle Memorial Institute under USAF Contract No. AF 33(615)-2812. The contract was initiated under Project 3145, "Dynamic Energy Conversion Technology, Task No. 314511, Nuclear Mechanical Power Units". The work was administered under the direction of the Air Force Aero Propulsion Laboratory, Research and Technology Division, with Mr. J. L. Morris and J. S. Cunningham acting as project engineers.

This report covers work conducted from 15 April 1965 to 15 February 1967.

This technical report has been reviewed and is approved.

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ABSTRACT

The program to develop advanced prototype instruments for the measurement of static and dynamic film thickness, film continuity, and film pressure in potassium-lubricated journal bearings has been terminated. Because of difficulties in fabricating final versions of the film-thickness transducers, no evaluations of prototype instruments were conducted in potassium. Performance data were obtained using laboratory simulation experiments.

Room-temperature simulations using metal foils were used to demonstrate the capabilities of the film-thickness-transducer design. Elevated-temperature evaluations in air or molten lead were used to examine the effects of temperature on the transducer signal. Together these experiments give promise that the prototype film-thickness transducer and ancillary instrumentation system design should have the desired performance capability.

The film-pressure-transducer performance was evaluated at room temperature and elevated temperatures by direct force loading of the transducer core. With judicious choice of the material and mechanical design of the core, the experiments demonstrated the desired sensitivity and stability.

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PART II: ADVANCED PROTOTYPE FILM THICKNESS, FILM CONTINUITY, AND FILM PRESSURE SENSORS

by

D. R. Grieser, A. F. Leatherman, R. J. Diersing, J. H. Flora, and C. M. Allen

INTRODUCTION

Current interest in high-speed turbine power systems using liquid metals as the working fluid has led to intensive research on high-speed bearings. Component capabilities and system-design requirements have resulted in the choice of liquid-metal-lubricated, fluid-film bearings for load support of the high-speed rotating elements in the power unit. Research studies of these types of bearings have revealed difficulties in achieving satisfactory stability and dynamic load capacity because of the low viscosity of elevated-temperature liquid metals and errors in turbulent-flow analysis. The difficulties of directly measuring the fluid-film behavior in the bearings during operation has forced the experimenter to evaluate bearing performance on the basis of indirect measurements such as end motion of the journal shaft and pressure of the potassium-lubricant supply. The lack of direct measurement in the bearings has made the interpretation of performance data more difficult and subject to greater uncertainty than desirable.

The present work was initiated in an effort to develop instrumentation to permit measurement of the thickness, pressure, and continuity of the lubricant film. A major goal has been the direct measurement of the film with a minimum perturbation of the film and the bearing behavior. Miniaturized transducers are required to facilitate the measurement of film thickness and pressure profiles within a single bearing. The capability of being hermetically sealed is necessary to resist attack by the liquid-metal environment. A capability for operating at elevated temperatures without cooling is desired so that the normal thermal environment of the bearing is not altered.

Two techniques were selected during the previous feasibility study as having the potential for most closely meeting the desired characteristics.(1) * An eddy-current technique was chosen for the measurement of film thickness and detection of film continuity. A technique based on the Villari effect was chosen for the measurement of film pressure.

The development of these techniques into advanced prototype measuring instruments was the objective of the present program. Bench simulation studies were performed on preliminary transducer models to assess the potentiality of the techniques for the projected bearing measurements and to obtain an empirical estimate of measurement sensitivity and temperature effects. Analytical studies have also been performed to assist in the design of prototype transducer systems. Although the past study covered the application of these techniques to the liquid-metal-film bearings in general, the

*References are listed on page 35.

present program effort was concentrated on the application to a bearing system of current interest. The prototype film-thickness instrumentation has been developed for a plain journal bearing, consisting of 1-inch-diameter tungsten carbide (K-94) sleeve and molybdenum alloy (TZM) rotor, that is lubricated with potassium and operates at a nominal temperature of 600 F. The film-pressure instrumentation has been developed for a possible future research study of liquid-metal bearing hydrodynamics. Table 1 lists the performance goals.

FILM-THICKNESS MEASUREMENT

Based on the results of an introductory survey(1) of possible approaches to thickness measurement, the most promising method was judged to be an electromagnetic induction, or eddy-current, technique. This method offered promise for (1) high-temperature service, (2) ability to make measurements in situ with detecting devices embedded within the stationary bearing, and (3) useful sensitivity.

In the electromagnetic-induction technique, a small coil of gold wire in the stationary part of the bearing serves as the sensitive member of the thickness transducer. The coil acts, in effect, as the primary winding of a small transformer in which the potassium film and electrically conductive journal serve jointly as a one-turn secondary winding. As the potassium thickness varies, the effective resistance and inductance of this secondary winding vary accordingly, causing corresponding changes in the electrical properties of the small detecting coil. These resultant changes in the electrical properties of the coil are measured by electronic instruments to provide an indication dependent on thickness.

Prototype Thickness-Transducer Design

In the development of a prototype thickness transducer, important design and construction requirements included the following.

(1) The sensing components of the transducer must be hermetically sealed against potassium and embedded within the stationary part of the bearing. Any connecting wires to instruments must also resist potassium attack.

(2) The design must permit potassium-thickness changes to be detectable without perturbing the nature of the potassium film while exposing to the film only those materials known to be promising as bearing materials in potassium.

(3) The design of the transducer and its connecting leads must be such as to permit measurement sites to be spaced as close as 0. 200 inch on centers. To correspond with this requirement a size limit of 0. 100-inch diameter by 0. 250 inch long was placed on the transducers.

For research purposes, a piece of K-94 material, to be used as the stationary part of a bearing of interest, was fabricated into a conical shape to serve as the hermetic

TABLE 1. DESIRED INSTRUMENT PERFORMANCE

Film Thickness

Lubricant Film:	Liquid potassium
Bearing Materials:	Sleeve (static member) - K-94
	Journal (rotary member) - TZM
Bearing Configuration:	Simple journal type, simulated
	Diameter - 1.00 inch
	Average radial clearance - 0.0015 inch
	Overall length - 1.0 inch, nominal
Temperature:	Operating minimum - 550 F
	Operating maximum - 650 F
	Operating control - ± 15 F
Allowable heat-up excursion - 1200 F, maximum	
Transducer:	Location - Integral with bearing sleeve (static member)
	Maximum size - 0.100-inch diameter by 0.250 inch long
Output Signal:	Linear with film thickness within ± 10 percent
	Temperature compensated within ± 10 percent over the operating range of 550 F to 650 F
	Absolute accuracy - ± 30 microinches, minimum
	Precision - ± 20 microinches at maximum film thickness, ± 10 microinches at minimum film thickness
	Dynamic response - 0 to 2000 cycles per second, ± 6 db

Film Continuity

Specifications identical with those for film thickness, except:	
Output Signal:	Distinct from film-thickness signal to avoid ambiguity
	Sensitive to gas or vapor film discontinuities comprising a minimum of 10 percent of the film volume directly in front of the transducer.

Film Pressure

Environment:	Potasssium liquid or vapor
Materials:	Sleeve (static member) - Alumina
	Journal (rotary member) - Any practical shaft material
Bearing Configuration:	Simple journal type
	Diameter - 1.00 inch
	Minimum operating clearance - 50 microinches
	Overall length - 1.0 inch, nominal
Temperature:	Operating maximum - 950 F
	Operating minimum - 500 F
	Operating control - ± 15 F
Allowable heat-up excursion - 1050 F	
Transducer:	Location - Integral with bearing sleeve (static member)
	Maximum size - 0.100-inch diameter by 0.250 inch long
	Maximum flow perturbation - 20 percent of minimum film thickness, i.e., ± 10 microinches
Output Signal:	Linear with film pressure within ± 10 percent
	Temperature compensation setable to within 10 percent over any 100 F range of operation
	Maximum pressure range - 0 to 200 psia
	Absolute accuracy - 4 psia
	Precision - ± 2 psia
	Dynamic response - 0 to 2000 cycles per second, ± 6 db

body or envelope of the transducer. In the design of a complete prototype thickness transducer, shown in cross section in Figure 1, this conical body is designated A. In use, the curved lower face of this body would be separated from a rotating shaft of TZM alloy by the film of potassium.

The detecting coil, C, consisting of several spiral turns and several helical turns of high-purity 40-gage gold wire, is wound on a coil form, D, of high-density alumina. The coil and coil form are potted by means of alumina cement within a recess drilled through an alumina (sapphire) rod insert, B, bonded by a special technique* into the K-94 body. At the lower end of the insert, B, a thin partition of the original rod material is shown intact, serving as a hermetic "window" between the coil and film.

Since the operation of the device depends on magnetic flux linkage between the sensing coil and the film, it is essentially mandatory that other electrically conductive bodies not be present in the intervening space ("window") between the coil and the film. Therefore, the design of the thickness transducer, and the design of any bearing in which the transducer is to be used, must employ nonconductive structures in certain critical areas if useful results are to be realized. The sapphire partition of Figure 1 serves as this window.

Also shown in Figure 1 are the electrical connecting wires F and L, which provide the link to outside instruments. These leads are imbedded within a specially constructed metal-clad transmission line, J, and metal sleeves, H and N, which are all brazed into a one-piece hermetic body. Thus, the only materials exposed to potassium in the completed transducer are high-purity alumina (sapphire), K-94, Kovar, Type 304 stainless steel, and the special brazing alloy employed. Details of the construction of the thickness transducer and transmission line are presented in Appendix A.

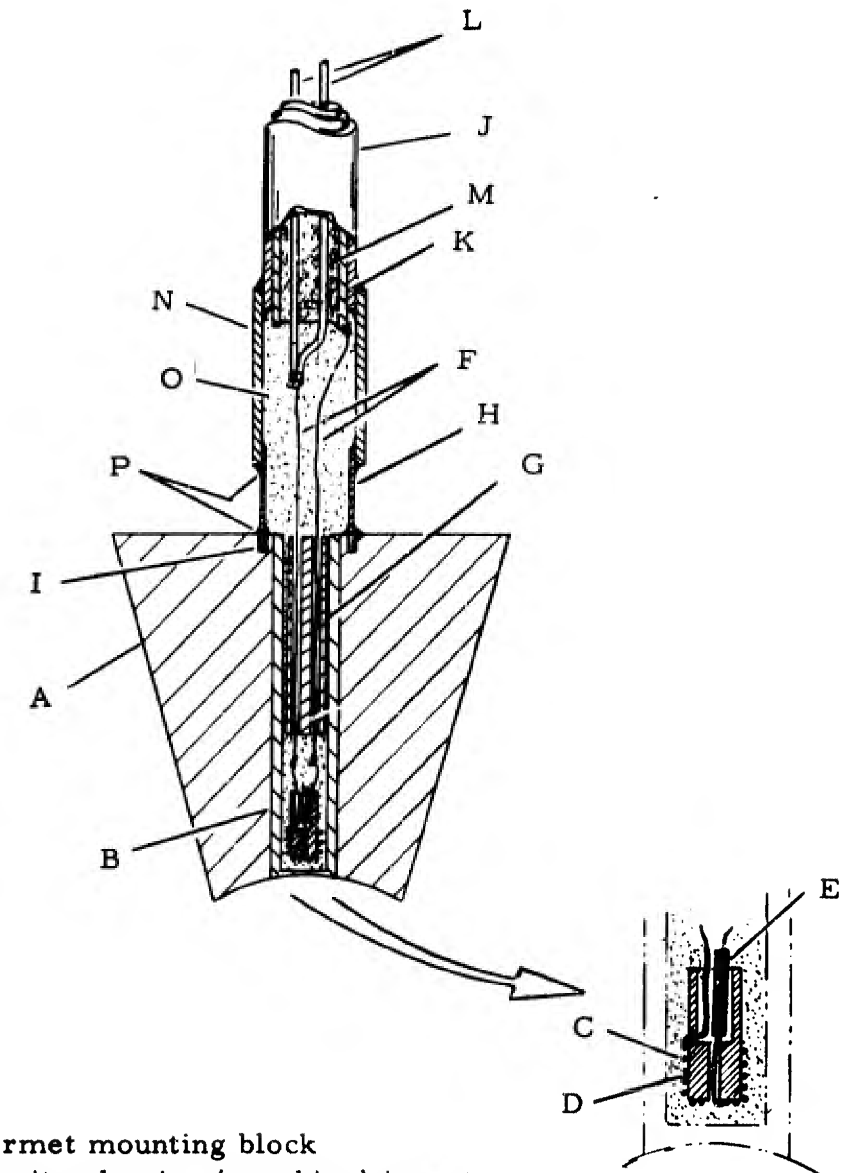
Study of the characteristics and performance of transducer designs closely approaching Figure 1 revealed that measurement of the electrical inductance of the sensing-coil circuit offered the most promise as an indication of film thickness. Further, an instrument scheme in which changes of transducer inductance produce a change in the frequency of an oscillator appear to offer the most promise for providing a useful output signal. By measurement of frequency, a theoretical resolution as high as 10,000 cycles of frequency change per mil of film thickness is offered.

In summary, the information and knowledge gained in the program can be applied in predicting the physical and operating features expected in a thickness transducer for potassium. In some cases, the experimental evidence derived from simulation of potassium operation provides a direct foundation for prediction, while in other cases the effects of some factors not thoroughly studied must be extrapolated from related experience.

The diameter of the transducer coil winding is slightly less than 0. 100 inch, with a length of about 0. 070 inch. The transducer is embedded in an alumina rod insert of 0. 160-inch diameter. The insert is diffusion bondable into a K-94 body, representing the stationary part of the journal bearing to comprise an integral unit. The alumina surface exposed to the potassium is precision ground to the curvature of the bearing for minimum flow perturbation.

Materials and construction methods suitable for temperature excursions to 1200 F or higher are employed. Test methods representing operation at 550 to 650 F with a TZM journal and average radial clearance of 0. 0015 inch produced an uncompensated

* A description of this bonding technique is given in Appendix C of this report.



A. K-94 Cermet mounting block
B. High-density alumina (sapphire) insert
C. Eddy-current thickness-detecting coil
D. Alumina-coil form
E. Quartz insulating tube
F. 31-gage lead wires
G. Alumina tube
H. Kovar sleeve
I. Circular slot
J. 304 stainless steel outer jacket of transmission line
K. Copper sheath of transmission line
L. Copper conductors of transmission line
M. MgO insulation of transmission line
N. Stainless steel sleeve
O. Alumina potting compound
P. Fillets of brazing alloy

FIGURE 1. THICKNESS-TRANSDUCER ASSEMBLY

output signal linear with film thickness to approximately ±6 percent. By means of temperature compensation it is expected that the output signals could be controlled to fall within a 10 percent variation with associated calibration data permitting the identification of film thickness within a precision of ±30 microinches over the range of zero to 3 mils with a dynamic response better than 0 to 2000 cycles per second ±6 db.

Further detailed information dealing with the transducer characteristics, measurement techniques, and simulation of bearing operation are considered in the following sections of this report.

Development of Thickness-Measurement Technique

The measurement of the thickness of metal layers by the electromagnetic or eddy-current method enjoys a recognized status.[2,3,4] However, a mathematical analysis[5] of operation under specific conditions representing the case of potassium, and experiments to simulate the operating bearing, were carefully considered during the program to identify the nature of the signals and to assure that any exceptions to ideal performance became recognized and dealt with.

The simulation experiments, considered below, were of two types. In one type, metal foils were used at room temperature to represent potassium, and, in the other type of simulation, electrical measurements were conducted at elevated temperatures with a transducer model submerged in lead and cycled from room temperature to 750 F. Data were also taken at elevated temperature in air. Description of the electronic measuring system is also included in the following paragraphs. The progress of the program did not proceed to the point at which thickness data in liquid potassium could be taken.

Simulation by Metal Foils

Simulation experiments at room temperature were employed to compare various coil designs, mechanical configurations of the transducer, and operating frequencies, and to study thickness-indicating schemes.

The best apparent coil design consisted of a winding of 40-gage bare gold wire with approximately 6 turns wound in a single-layered spiral on the flat end face of a rod of alumina and about 12 turns wound helically along the rod, as illustrated in Figure 1. For the simulation experiments, the alumina rod was mounted in a 0.160-inch-diameter hole in a flat disc of K-94 cermet about 1/2 inch thick and 1 inch in diameter. Small pieces of electrically nonconductive material were positioned as separators between the spiral portion of the winding and the metal materials representing the potassium and journal shaft. These nonconductors represented the window area of the alumina insert material of Figure 1 and acted to permit the magnetic field of the test coil to pass relatively unimpeded from the coil out into the materials representing the potassium and journal. The potassium was simulated by various thicknesses of zirconium metal foil laid on a block of 50-50 tin-lead solder which represented the TZM journal shaft. The foils and solder were selected for use at room temperature to represent potassium and TZM, respectively, at about 800 F. The selection was made from the standpoint of equivalent electrical resistivity. The test coil mounted in the K-94 block was then placed in succession upon the metal foils representing various potassium-film thicknesses.

The electrical properties of the test coils as a function of simulated potassium thickness were measured by several approaches including (1) Boonton 160-A and 260-A Q Meters modified by using a Keithley Model 660A differential voltmeter to set the oscillator drive and read the output voltage at the indicating meter, (2) a General Radio Type 916AL RF Impedance Bridge, (3) a General Radio Type 1606-A Radio Frequency Bridge, and (4) a self-resonant oscillator circuit which would change frequency as the simulated thickness was changed.

Typical data obtained by means of the Q-meter system at several frequencies are illustrated in Figures 2 and 3 showing inductance and Q*, respectively. From these relative measured values, data for circuit impedance* and a-c resistance were calculated and are shown in Figures 4 and 5. It can be noted from these four figures that the data as measured or calculated in these simple forms provide double-valued results for all properties except inductance, and consequently inductance measurement was selected for further study. Also, in the molten-lead experiments, below, inductance was revealed by an analysis to be the most reliable quantity under the influence of temperature changes, in comparison to Q, a-c resistance, and impedance.

In more advanced experiments using the same zirconium foils, solder substrate, disc-shaped K-94 transducer, and 12-inch connecting lead of metal-clad two-conductor transmission line (see below), a circuit was developed to provide an output frequency change as a function of film thickness. The transducer coil was connected as the inductance member of a parallel-resonant oscillator circuit of the two-terminal feedback type.[6] Although a series-resonant connection may have proven to be less affected by resistance changes in the measuring circuit, considerable difficulty was encountered in trying to develop such a circuit and the approach was abandoned. A parallel-resonant circuit was adopted as discussed in the following section.

Recommended Electronic Indicating System

A parallel-resonant oscillator system is recommended as the best choice of thickness-indicating schemes considering several factors. The factors considered included needed resolution, ability to detect thickness changes dynamically at up to 2 kHz, ability to "zero-set" *in situ*, amount of development effort required, ability to use commercial instruments in most or all of the system, relative stability under the effect of temperature change in the transducer, ability to measure temperature during operation, outlook for future automation of data taking, reliability of components, ability to instrument remotely for safety considerations, useful performance even though the transducer Q might be as low as 5, and possible simultaneous monitoring of other characteristics such as using amplitude as an indicator of voids.

Measuring Circuit. A block diagram of the recommended arrangement to provide recordings of signals indicative of thickness and temperature is presented in Figure 6. The transducer is shown schematically at the left in position for thickness measurement. The eddy-current test coil which responds to changes in potassium-film thickness is located inside the lower end of the cone-shaped transducer body. One side of the coil

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* $Q = \frac{X_L}{R}$; Impedance, $Z, = R + jX_L$.

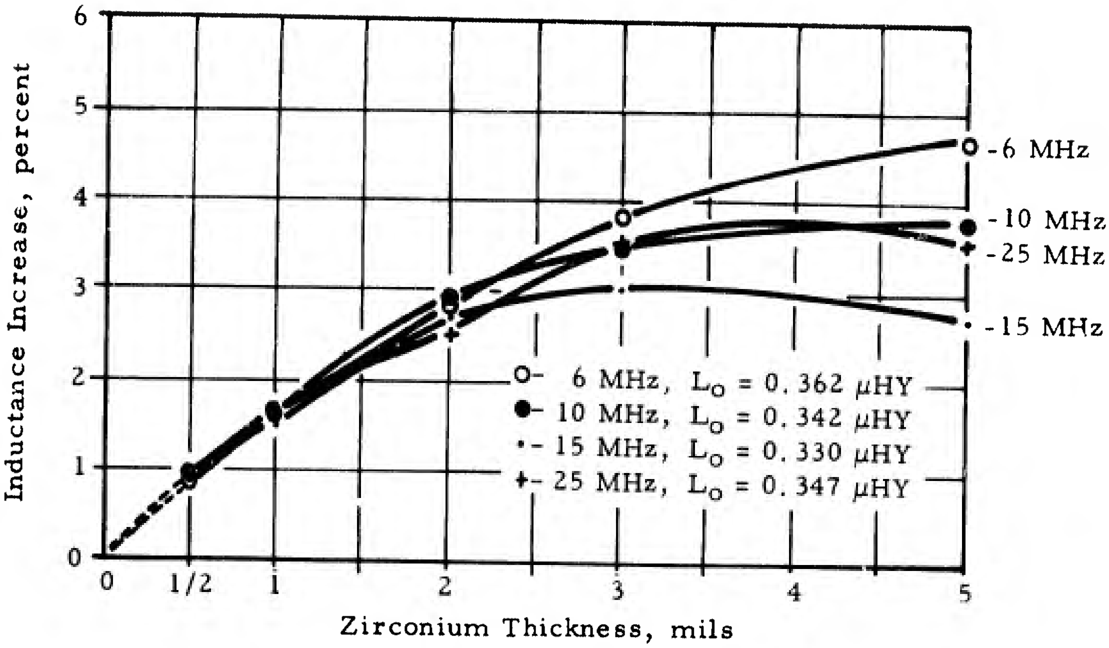


FIGURE 2. EFFECT OF FOIL THICKNESS ON TEST-COIL CIRCUIT INDUCTANCE AT 6, 10, 15, AND 25 MHz

Coil 8: 8 spiral, 12 helical turns, cup shaped; bare copper, 38-gage wire, 1.5 mils between turns; 2.5-mil partition; mounted in K-94 block.

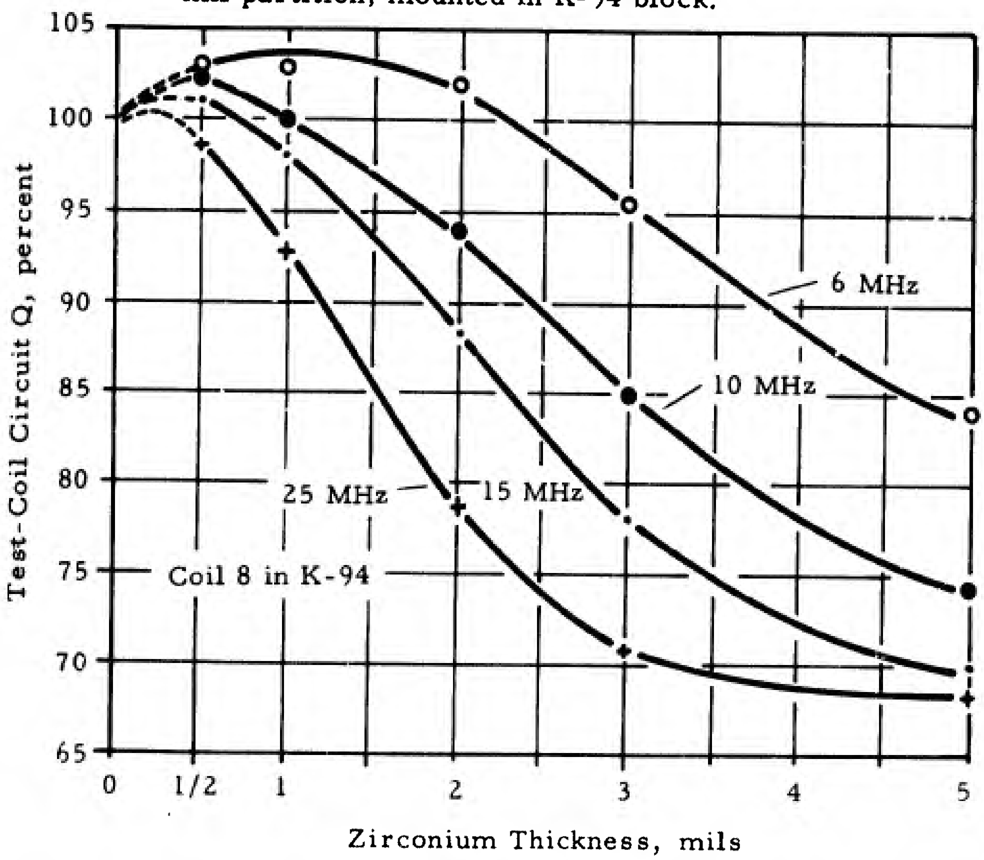


FIGURE 3. EFFECT OF FOIL THICKNESS ON TEST-COIL CIRCUIT Q AT 6, 10, 15, AND 25 MHz

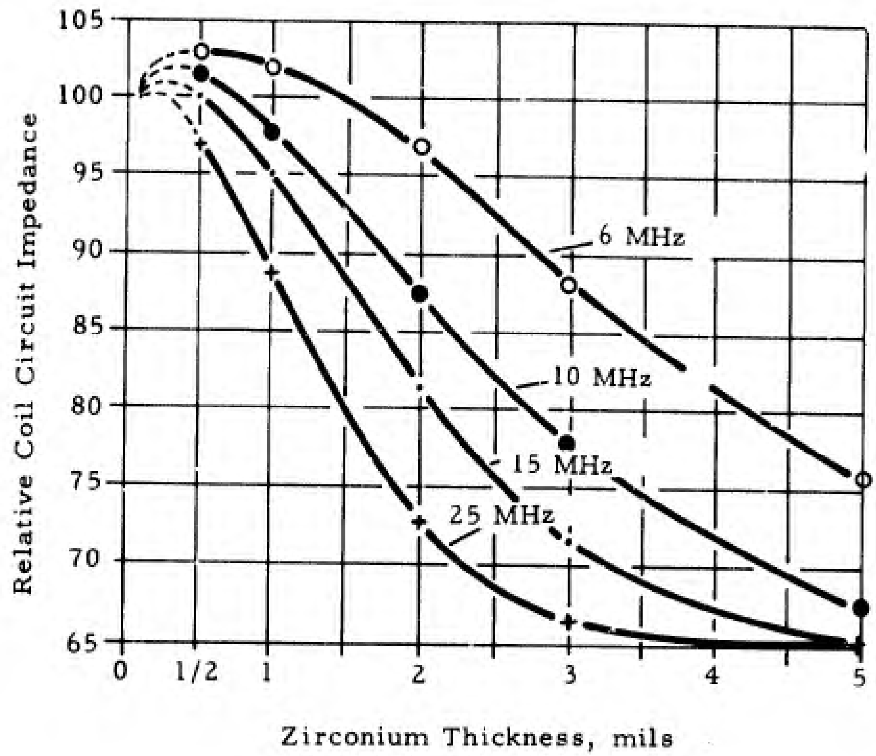


FIGURE 4. EFFECT OF FOIL THICKNESS ON CIRCUIT IMPEDANCE OF TEST COIL 8 IN K-94 AT 6, 10, 15, AND 25 MHz

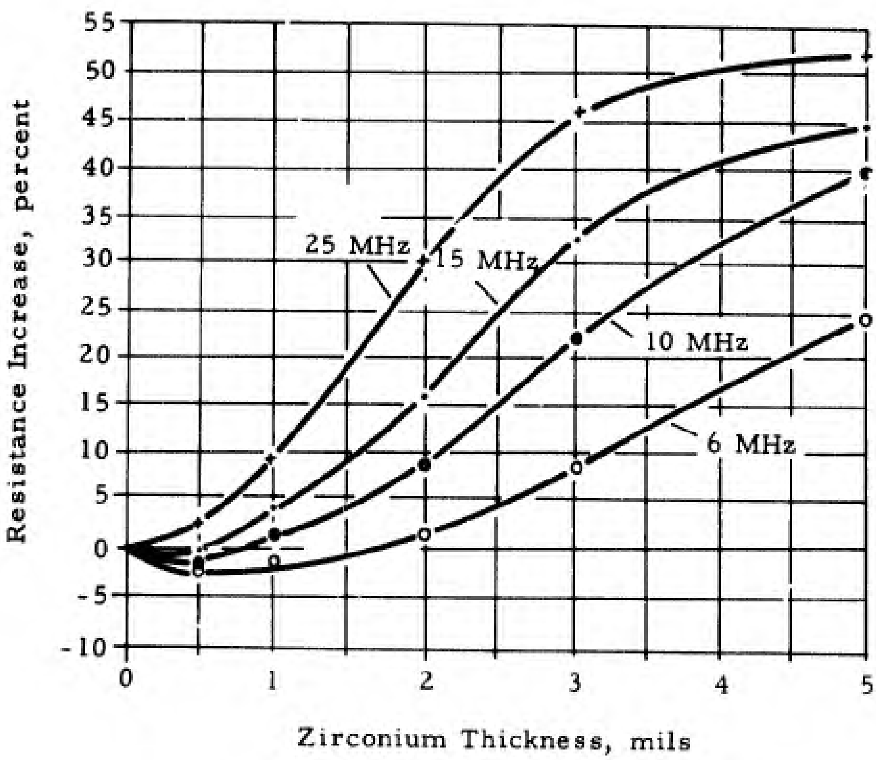


FIGURE 5. EFFECT OF FOIL THICKNESS ON A-C RESISTANCE OF TEST COIL 8 IN K-94 AT 6, 10, 15, AND 25 MHz

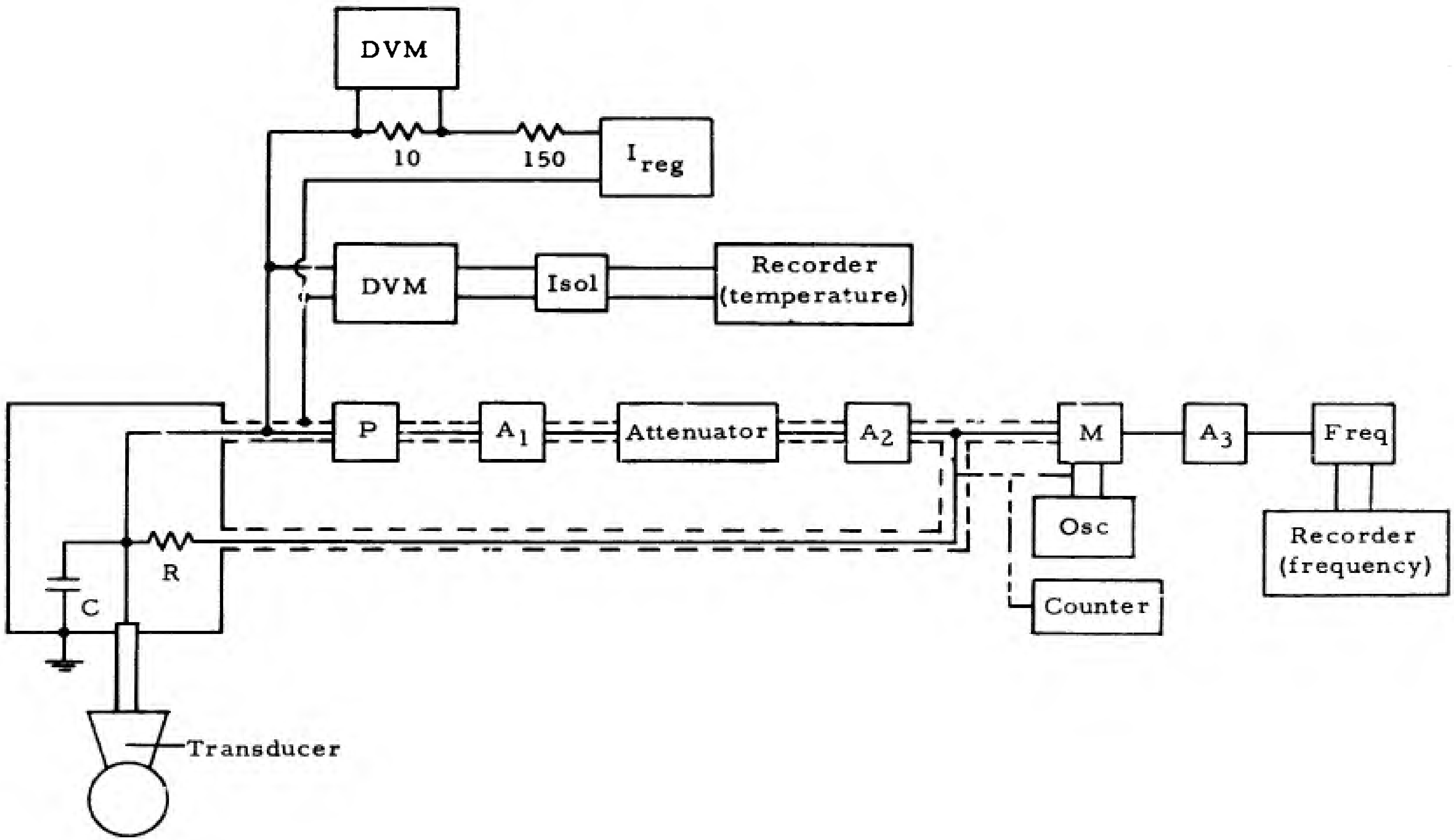


FIGURE 6. RECOMMENDED INDICATING CIRCUIT FOR THICKNESS MEASUREMENT

TABLE 2. MEASURING-CIRCUIT COMPONENTS

Component Identification in Figure 6	Detailed Identity	Purpose
C	1300 pf + 560 pf mica	To resonate transducer
P	Tektronix Probe Model 011-048	Input isolation
A_1, A_2	Tektronix Type 1121 Amplifiers	Amplification
Atten	H-P Model 355A VHF Attenuator	Gain adjustment
M	General Radio Type 1212-P3 Mixer	Heterodyne for difference freq
Osc	G. R. Type 330-A or other stable oscillator	Local oscillator for mixer
A_3	Optional IF Amplifier, 1 MHz	IF amplification
Freq	G. R. Type 1142-A Frequency Meter	Freq discrimination, d-c output
Recorder (freq)	Visicorder, Brush, or C. E. C. Optical Recorder	Record frequency
DVM	Keithley Model 660A or Fluke Model 883AB Differential Voltmeter	Measure voltage
I reg	Power Designs Model 4005 Power Supply	Regulated current source
Isol	Fluke Model A88 Isolation Amplifier	Isolation for recorder
Recorder (temperature)	Leeds-Northrup Speedo Max or other similar type	Record IR drop changes
R	Carbon-type resistor 1/2 watt 2 k to 10 k	Decoupling resistor
Counter	Beckman Universal EPUT Model 7370W or equivalent	Count frequency

circuit connects to the metal sheath of the transmission line which is at ground potential. The other side of the coil circuit connects to the central insulated lead of the metal-clad transmission line which is connected to the upper terminal of the fixed capacitor, C. This capacitor and the test coil jointly comprise a parallel resonant circuit which serves as the main frequency-determining element of a feedback-type oscillator circuit. The main path of the sine-wave oscillating signal is from capacitor C, through a cathode-follower probe P, amplifier A_1, an attenuator, amplifier A_2, and back through a de-coupling resistor, R, to capacitor C again. The circuit gain and phase are set so as to maintain oscillation under all operating conditions. Coaxial leads each 25 feet long are located between the probe and amplifier A_1, and between amplifier A_2 and the decoupling resistor. These leads help to provide the proper phase relationships while also serving to permit practically all of the measuring instruments to be located remotely from the potassium system. The other instruments in Figure 6 provide for temperature measurement by measuring and recording signals related to the test-coil d-c resistance, and provide for monitoring and recording the frequency of oscillation. These latter instruments will be described subsequently.

The room-temperature characteristics of frequency of oscillation versus simulated film thickness for the circuit of Figure 6 are presented in Figure 7. In obtaining these data, the test coil used for Figure 2 was employed at room temperature, except the simulated window thickness was 10 mils of nonconducting substance. The capacitor, C, was selected to produce oscillations at about 5.4 MHz for zero film thickness (test coil separated from solder block substrate by the layer of nonconductive material). The decoupling resistor, R, had a value of 10,000 ohms. The cascaded amplifiers were set so that A_1 provided a voltage gain of 2, the attenuator provided a gain of -5 db, and A_2 provided a gain of 10. Oscillator frequencies were determined by means of a Beckman Universal EPUT and Timer Model 7370W which counts cycles for a precise 1-second interval. This counter was connected to the output of amplifier A_2 as shown by the dotted line of Figure 6. Clearly, a counting scheme such as this, although providing a frequency-measurement resolution of ±1 part in 6 million, or ±0.18 ppm, would not be useful for the desired dynamic measurement. As various thicknesses of zirconium metal foil representing potassium were inserted between the transducer and substrate, the frequency record of Figure 7 was obtained. Actual frequency counts in Hertz (cycles per second) are noted for each data point.

The greatest frequency change per mil was found to occur at the thin-film end of the data, and a more gradual change was obtained for thicker films. The frequency was found to decrease for increasing film thickness as would be expected in referring to the inductance data of Figure 2, which show increasing inductance with thickness, and remembering that the frequency of oscillation should be approximately equal to $1/(2\pi\sqrt{LC})$.

It is most interesting that the data of Figure 7 do not show a tendency for the double-valued result for thin films, as was observed in data for Q (Figure 3), impedance (Figure 4), or a-c resistance (Figure 5). From this result, the tentative conclusion is drawn that the frequency-measurement approach is more sensitive to transducer inductance changes than it is to changes of transducer Q, impedance, or resistance. It was an objective to achieve a measurement circuit sensitive to inductance because this property appeared to be most reliable and was also single-valued. Further information leading to the choice to measure inductance is considered below.

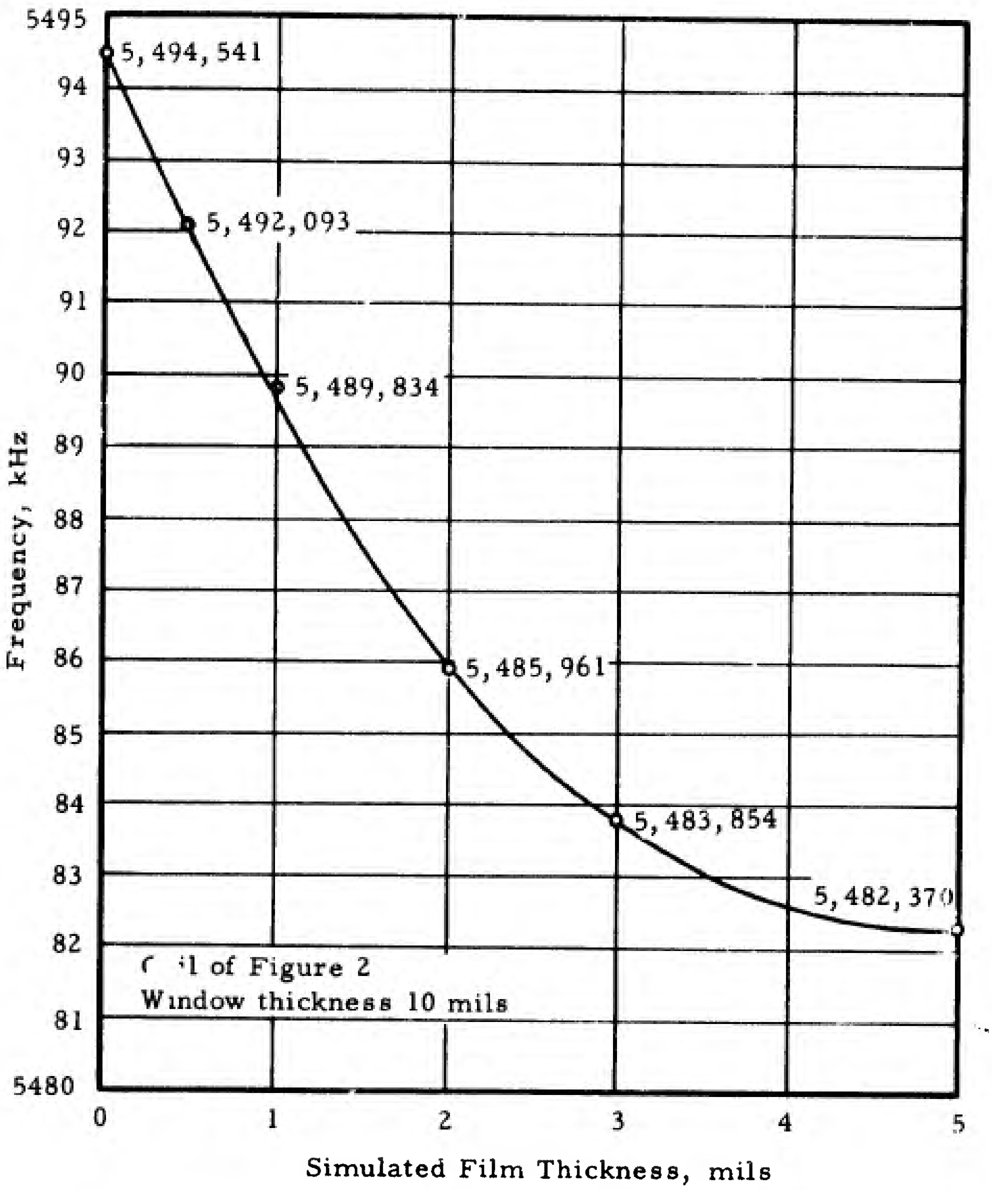


FIGURE 7. FREQUENCY OF OSCILLATION FOR CIRCUIT OF FIGURE 6 FOR FILM THICKNESSES FROM ZERO TO 5 MILS

Effect of Temperature. It was clear that since the resistance of a gold or copper transducer winding would increase with temperature, the Q of the resonant measuring circuit would decrease with temperature, perhaps as much as a factor of two from room temperature to 650 F. As Q decreases, the amplitude of oscillation of the measuring circuit can be expected to decrease leading to interruption of oscillation unless the gain in the amplifiers or feedback circuit can be increased sufficiently to overcome the increased losses.

Transducer P_2, used for the lead-bath studies below, was arranged in an oven to permit study of the effects of transducer temperature on circuit performance. With the transducer in air in the oven, the temperature was increased in steps from room temperature to 600 F. The following four results were among those noted. First, it was found that by decreasing the setting of the attenuator used, oscillation could be readily maintained at full strength to 600 F, the highest available temperature for the electronically outfitted oven used. Second, it was found that a change of only some 3 db was sufficient to make up the increased losses in the transducer at 600 F in comparison to room temperature. Measuring ranges of 150 to 200 F were available within which a given attenuator setting would serve without changing the setting. It was considered that this feature would allow measurement over the specified temperature range of 550 to 650 F to be made at a given attenuator setting. Third, it was found that changing the attenuator setting by 1 db would cause a change of about 3 kHz in the frequency of oscillation. Since all potassium data could be taken for a given attenuator setting, this irregularity was not considered limiting. Fourth, it was found that when simple resistance-type attenuators were used, increasing temperature caused a decrease in frequency as would be expected from the data of Figure 9a, showing an increase of inductance with temperature. When the attenuator of Figure 6 was used, however, (Hewlett Packard Model 355A, vhf Attenuator), the frequency tended to increase with temperature. It appeared that phase-shift considerations in the amplifier and attenuator circuits were causing a modification in the nature of performance. It is expected that additional study might reveal that a way could be found to utilize phase compensation to actually increase the available frequency shift with thickness or realize zero temperature effect. In any case, so long as the frequency-thickness characteristic is linear and reproducible as calibrated with an actual transducer in potassium, the recommended circuit can be used. The program did not advance to the point at which calibration runs in potassium could be conducted.

Components of Figure 6

In conducting the temperature-effect studies and the measurements of frequency versus thickness, Figure 7, the circuit of Figure 6 included the following typical components at least in part. Instruments of other manufacturers, with similar characteristics, probably could be substituted with the same results.

The frequency-measuring circuit was arranged so that the Type 1142-A Frequency Meter could be set to operate at the 1.0-MHz output frequency of the mixer. Using the interpolation scales of this instrument and the recorder output, a "d-c" signal would be provided proportional to the change in frequency of the oscillator measuring circuit. The resolution of the interpolation signal can be set for several choices so that the full-scale signal to the recorder might cover only 1 mil of thickness change or 3 mils, etc. The optical type of recorder is necessary to record the 2-kHz components of thickness change.

The differential voltmeters and regulated power supply are used to determine transducer d-c resistance from which transducer temperature is derived. A regulated d-c current of 50 ma from the regulated power supply is measured by means of the voltage drop across a standard 10-ohm resistor to five significant figures. The other differential voltmeter provides a measure of the d-c voltage drop in the transducer to five significant figures. In combination, the recorded signal can be arranged to indicate transducer resistance variations to four significant figures or better, from which the transducer temperature can be derived with sufficient precision for the necessary corrections to measured frequency of oscillation.

Molten-Lead Studies

In view of the precision required, plans called for careful studies to develop accurate temperature calibrations for the transducer. It was recognized that no matter what electrical property of the transducer was to be employed to indicate thickness, the characteristics of the transducer could be counted upon to vary to some extent with temperature. If these variations were reproducible, it should be possible to identify them accurately in properly designed experiments and correct either the data or the operation of the transducer accordingly. In conducting such an experiment, in which a transducer model was submerged in a lead bath, described below, it was found that useful information on thickness measurement also could be derived.

It was postulated that the electrical d-c resistance of the test coil itself could be used conveniently and accurately as an indication of temperature in eventual thickness-measurement applications. To test this theory, it was desirable to investigate the reproducibility of the transducer d-c resistance at several accurately known temperatures and to investigate the effects of temperature on any other property of the transducer that would be of interest in measurement of thickness. It was known that the melting points of several metals such as lead, tin, and zinc have been very carefully determined as temperature references. By placing a test specimen in a high-purity bath of one of these metals and causing the bath temperature to pass through melting and freezing phases, the exchange of the heat of fusion provides rather stable conditions at the melting point. Data of interest can then be measured at this known temperature.

A series of freezing-point measurements in lead were made for Transducer Model P2, which appeared in design very much like Figure 1. (The program did not advance sufficiently to call for the use of baths of additional metals.) The alumina insert for Model P2 had been previously broken, however, and the lower active "window" area exposed to the lead was provided by means of alumina cement. The test-coil winding was of electrical-grade copper. A 19-inch length of copper-clad transmission line was connected to the rear of the transducer and held in place with alumina cement rather than the brazing shown in Figure 1. Other details of the lead-bath apparatus are presented in Appendix B.

Direct-current resistance measurements were made by the four-wire method. Current was determined by voltage drop across a standard resistor. Theoretically, the instrument arrangements permitted resistance on a relative basis to be measured to ±0.00001 ohm. Knowing the temperature-resistance relationship for copper, this corresponded to a measured relative change in temperature of ±0.01 F. A residual fluctuation in the current supply limited the actual precision to about ±0.1 F, which was considered adequate for the application. A similar precision would be obtained for transducers with gold coils.

Other electrical properties of the Model P2 thickness transducer were measured with a Boonton Model 160A Q meter using Keithley Model 660A Differential Voltmeters to set the drive and read the Q indication, and a General Radio 916 AL bridge. The resultant d-c resistance data for four temperature cycles are shown in Figure 8. Inductance, a-c resistance, Q values, and impedance data determined for the range of about 500 to 700 F are shown in Figures 9a, 9b, 10a, and 10b.

Referring to Figure 8, it will be noted that considerable scatter is evident in the data. It was found that apparently the copper test-coil winding of transducer P2 was deteriorating slightly with successive temperature cycles. The slight deterioration had a large effect on the high-precision data. After considering and experimenting with a number of possible explanations for the difficulty, such as heat treatment of the winding, diffusion at silver-soldered connections, pressure effects, and oxidation, it was concluded that the lack of hermetic sealing of this transducer probably permitted enough oxidation to cause the trouble in spite of the use of protective atmosphere in the melt chamber. Although the final transducer models were to be hermetically sealed as shown in Figure 1, the use of high-purity gold wire for the transducer coil windings was adopted for advanced transducer models. Gold has very high resistance to oxidation and is a good electrical conductor. Although reproducibility to the required high precision was not realized in the resistance measurements and is attributed to the use of copper for the coil winding, excellent linearity, and general feasibility of the approach were indicated.

The electrical data of Figures 9a, 9b, 10a, and 10b illustrate the general effects of temperature on transducer properties as well as specific changes that occur at the melting point of the lead bath (621.32 F). The test-coil inductance (Figure 9a) without any lead bath present (upper curve) indicates an expected increase of inductance with temperature, amounting to about 55 parts per million per degree F. The general trend with the lead bath present (lower curve) is very nearly the same. Above the melting point of the lead, the higher inductance values can be explained by the increase of resistivity that occurs with lead upon melting (about an 86 percent increase). The increased resistivity in the lead causes a reduction in the intensity of current induced by the test coil in the lead bath resulting in an increase in test-coil inductance (via Lenz's law). The primary interest in Figure 9a (considered below) involves the magnitude of inductance change that occurs only at the melting point versus the amount of inductance change that occurs only as a result of temperature. The same consideration will apply to each of the quantities of Figures 9a, 9b, 10a, and 10b.

In Figure 9b, the a-c resistance with and without the lead bath again seems to be equally affected by temperature change, and an increase in resistance occurs at the melting point. The increase of resistance can be explained in this case by a transformer analogy: when one increases the secondary (bath) a-c resistance, decreasing the resistance load, one will obtain a decrease in the primary (test coil) a-c resistance load.

In Figure 10a, the Q values with and without the lead bath are similarly affected by temperature change, and a decrease in Q occurs at the melting point. Since $Q = 2\pi fL/R$, it can be noted that the inductance (L) values of Figure 9a are working against the a-c resistance (R) values of Figure 10a in producing the net result on the quotient, Q. It is noted that the effect of the resistance increase appears to predominate in causing a lower Q value above the melting point.

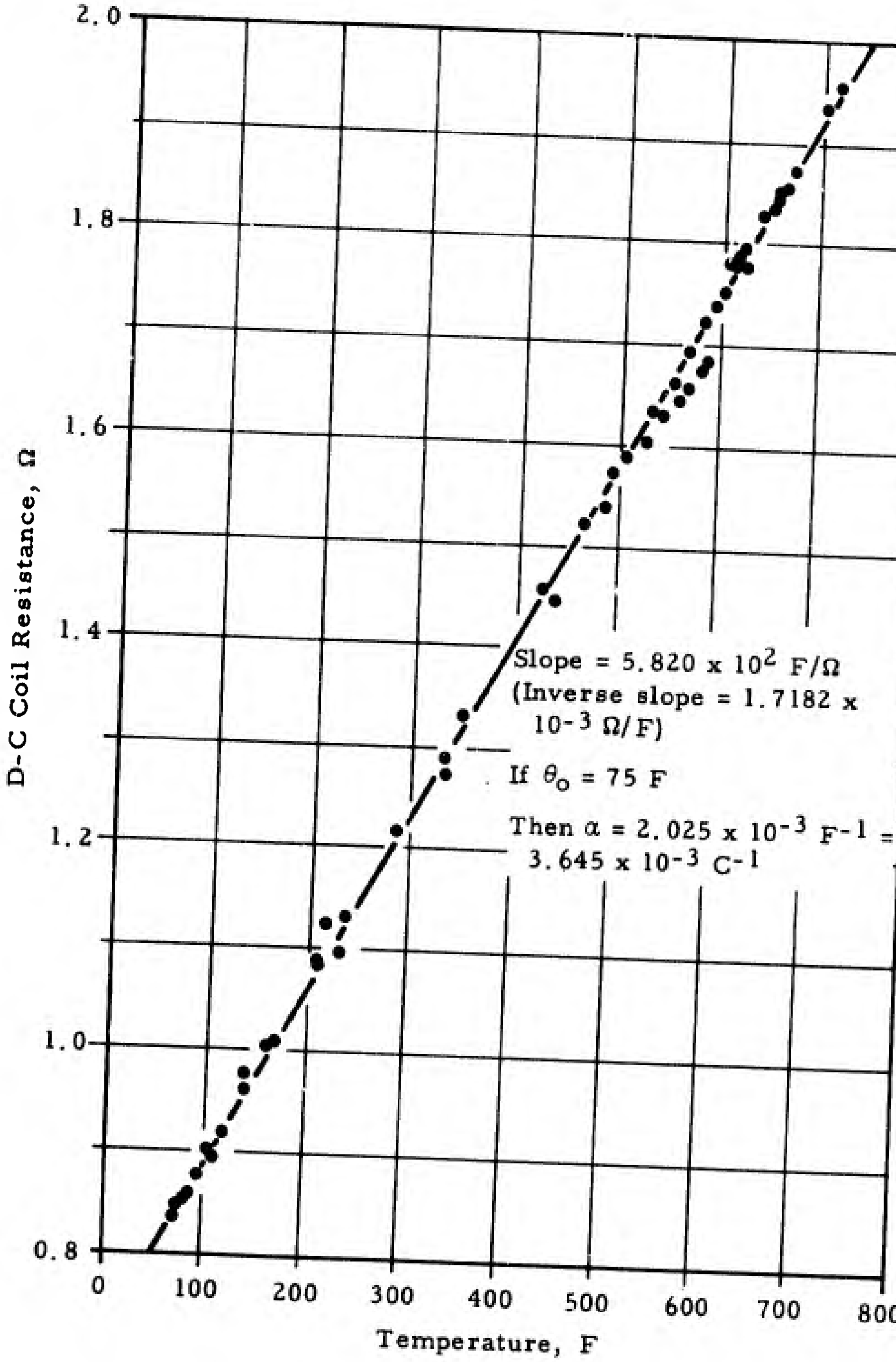
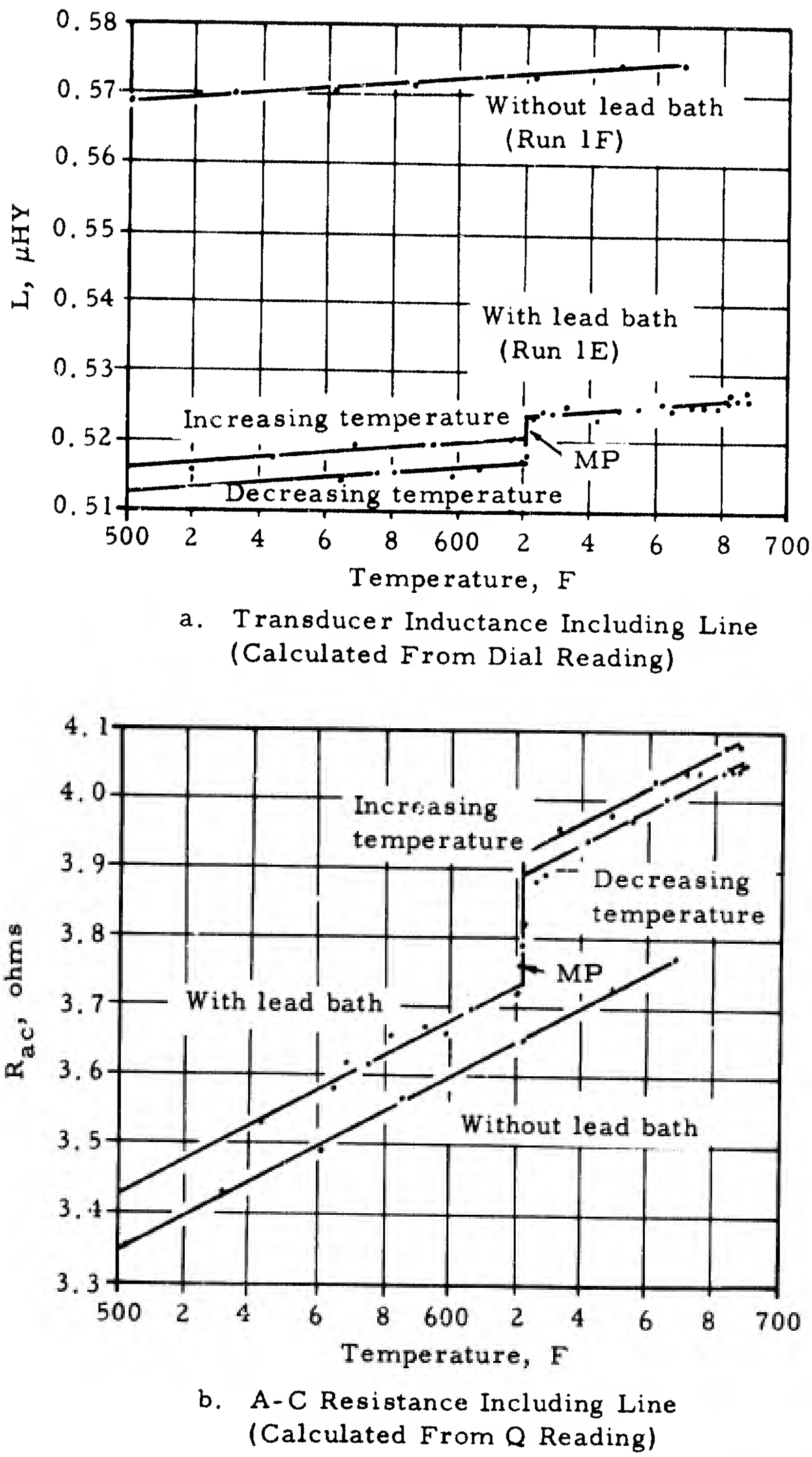


FIGURE 8. DC RESISTANCE OF TRANSDUCER P2; FOUR TEMPERATURE CYCLES, COPPER COIL

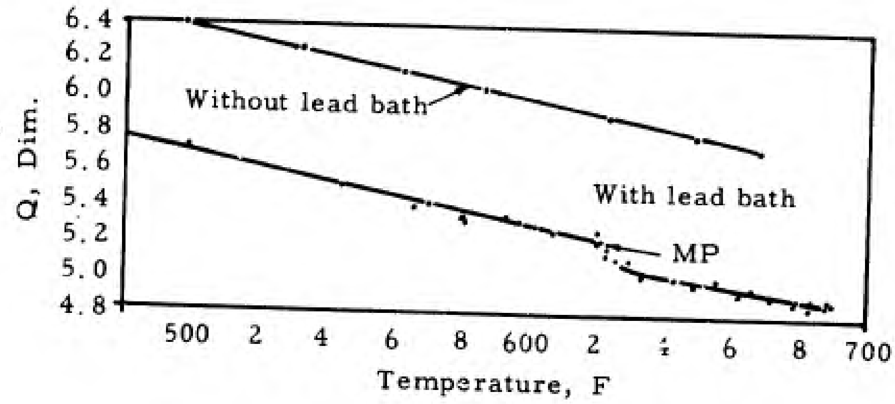


a. Transducer Inductance Including Line (Calculated From Dial Reading)

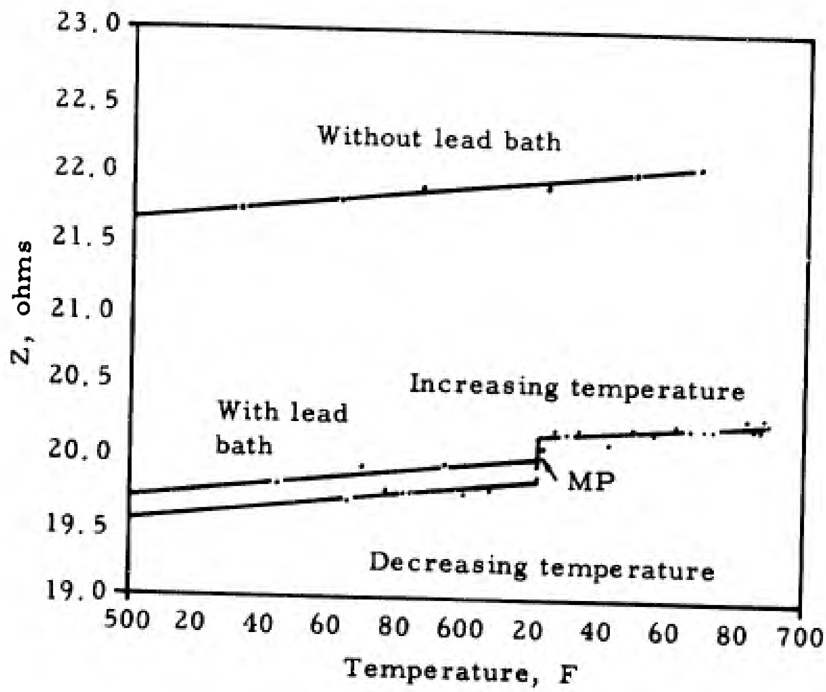
b. A-C Resistance Including Line (Calculated From Q Reading)

FIGURE 9. TRANSDUCER INDUCTANCE AND A-C RESISTANCE AT ELEVATED TEMPERATURES

Transducer P2. With and without lead baths; Runs 1E and 1F.



a. Q-Values Including Line
(From Meter and Calibration)



b. Impedance Values
(Calculated From $Z = R_{ac} + jX_L$)

FIGURE 10. TRANSDUCER Q AND IMPEDANCE AT ELEVATED TEMPERATURES

Transducer P2; lead bath; Runs 1E and 1F.

The impedance changes of Figure 10b are similarly accounted for by the changes of Figures 9a and 9b, since impedance, $Z = R + j\omega L$. For additional detail in the discussions of Figures 9a, 9b, 10a, and 10b, the reader is referred to the Quarterly Report of March, 1966.(7)

In applying the technique to a journal bearing, the change of thickness of the potassium lubricant film is expected to appear primarily as a resistance change. At the same time, temperature fluctuations may occur that also will cause a variation in resistance of the potassium and the journal. Hence, to achieve high accuracy, it is of primary importance to select a measured quantity that is affected to a relatively large degree by thickness change and to a relatively small degree by temperature change. At the melting point of lead, an 86 percent increase of resistivity occurs with essentially no increase in temperature. Therefore, it seemed reasonable to assume for simulation purposes that the resistance change upon melting represented a potassium-film-thickness change and a comparison could then be made to the effects of temperature on the same data. The measured property least affected by temperature for a given "thickness" change would be superior for thickness measurement.

To investigate the temperature effects, an analysis was made consisting of a "signal-to-noise" determination using the effective change in resistivity upon the melting of lead as the "signal" and the change in value of the measured property attributable to temperature effects over an equal temperature range as the "noise". The temperature range studied was 620 to 630 F, thus including enough of a temperature span to cover the step-shaped change in all properties at the melting point. Changes in transducer properties as a result of the temperature effect by itself were derived in each case from the essentially straight-line curves obtained for the transducer without the lead bath, especially since these curves seemed to be very nearly parallel to the curves with the lead bath. Changes in measured property upon melting of the lead and the temperature-effect values were each referred to property magnitudes at 600 F (i. e., to provide data in terms of percentage or parts per million). A 10-degree change in temperature was employed for all cases. The temperature effect on each property, the magnitude of the signal, and the resultant signal-to-noise ratios, are presented in Table 3.

TABLE 3. COMPARISON OF TRANSDUCER PROPERTIES

Transducer Property	Temperature Effect at 600 F, ppm: Per F	Temperature Effect at 600 F, ppm: Per 10 F	"Signal" Magnitude, ppm, for Melting Lead, 620 to 630 F	Signal-to-Noise Ratio for 10 F Change
Inductance	55	550	14,500 (0.0075 μhy)	26.3
A-c resistance	700	7000	56,500 (0.21 ohm)	8.1
Q	647	6470	41,800 (dimensionless)	6.5
Impedance	114	1140	17,600 (0.35 ohm)	15.5

The interesting result of the analysis summarized in Table 3 is that although the amount of inductance change seems small a different interpretation results when one considers the magnitude of error introduced by a fixed temperature change. When temperature effects are considered, the inductance property is stable to a degree to overshadow the apparently small signal size and thus to provide the best signal-to-noise ratio. This result has provided an important contribution toward the recommendation that measurement of inductance be adopted as the advanced approach to thickness measurement.

The measurements made with the lead bath illustrated that the transducer tested was capable of detecting a resistance change in a molten metal at 620 F and that this effect was measurable either by an inductive or resistive response and combinations thereof. Temperature excursions to 700 F did not damage the basic function of the device, and it is expected that the design would be useful to at least 1200 F, the upper temperature of interest to the program. An analysis of the results indicated that inductance change was apparently the most promising property to measure of the four possibilities considered.

Metal-Clad Transmission Line

Many applications envisioned for a successful potassium film-thickness transducer require that the transducer be located in a bearing surrounded with or submerged in potassium or potassium vapor. The electrical transducers studied under this program require electrical connection to instruments remotely located from the bearing site. It has been assumed that a test bearing could be mounted so as to require 12 inches or less of electrical lead wire within the potassium environment. In this view, the investigation of the performance of the thickness transducer has included study of means to achieve electrical connection in a potassium environment that would be compatible with the needs of the transducer system. Electrical lead wires hermetically enclosed in stainless steel were selected as a promising choice from the standpoint of potassium resistance. It was found that cables similar to the familiar coaxial type could be made from MI cable (mineral insulated cable) that had been clad with stainless steel tubing (see Appendix A).

The original specifications called for the use of a connecting cable that would be sufficiently flexible to operate with pad-type bearings in test. Initial plans called for the use of connecting cables sufficiently small in diameter to supply the desired flexibility. However, electrical measurements on various metal-clad electrical conductors indicated that although the inductance of such conductors was small, the electrical resistance and capacitance of cables of about 0. 060 to 0. 100-inch diameter would be high. Larger diameters would offer greater promise for success. Based on the electrical measurements of cable properties, it is recommended that cables be on the order of 0. 200-inch diameter with short reduced sections or flexible connection chambers used to achieve the desired flexibility.

Although previous plans provided for the use of two-conductor metal-clad connecting cables to permit a three-wire method for d-c resistance measurement, it now appears that sufficient accuracy of temperature measurement probably can be achieved with single-conductor metal-clad coaxial cable.

In attempting to construct a hermetically brazed final transducer model it has been learned that it may be necessary to employ gold electrical conductors throughout the transducer and metal-clad line to avoid eutectic alloying at spot welds between gold and copper. A gold-copper alloy can occur that melts at 1632 F. If a lower melting brazing alloy that resists potassium can be found and used for sealing the transducer, it may be possible to continue to use copper conductors for the metal-clad line. In another alternative, the transducer arrangement could be redesigned to physically separate the spot-weld and brazing areas so that localized heating for brazing would not injure the spot welds.

FILM DISCONTINUITY DETECTION

Several measurement approaches were conceived for detection of voids, bubbles, or other discontinuities in the potassium lubricant film, should they occur. These included (1) simultaneous measurement of two transducer properties such as inductance and Q, (2) monitoring of the rate of change of a measured value with respect to time, with the expectation that discontinuities would appear and disappear more rapidly than would film-thickness changes, and (3) the possibility that a frequency could be found that, by utilizing differences in skin-effect phenomena, would be less sensitive to film-thickness variations while remaining sensitive to voids. The first possibility in which more than one transducer property would be measured simultaneously appeared to involve considerable complexity, particularly since some of the transducer properties were double-valued, and this approach was abandoned.

The second approach, based on a time-rate of change in measured value, assumed that the voids would appear and disappear more suddenly than thickness changes would occur. This method would depend on rapid speed of response of the measuring circuit. The frequency-shift oscillator circuit for measuring thickness, discussed above, is believed to offer the necessary fast response for the success of this approach. The time-rate method should receive further consideration in any subsequent work on continuity detection.

The third method, dealing with a selective frequency of measurement, was investigated experimentally to a limited extent. Measurements at 2.1 MHz on simulated potassium film and voids indicated that either Q or a-c resistance would be possible measured quantities to distinguish film-thickness changes from voids. The use of either of these quantities, however, probably would call for a second set of instruments in addition to the equipment for the inductance measurement. Although inductance did not appear to be a sensitive property for distinguishing voids from film-thickness change at 2.1 MHz, other frequencies might be more useful. It is expected that higher frequencies will be much more sensitive than low ones for void detection by means of inductance measurement, and this possibility also should be given further consideration in any subsequent work.

FILM-PRESSURE INSTRUMENTATION

As with the film-thickness transducer, a transducer for measuring potassium lubricant film pressure should (1) be able to operate at high temperature, (2) be located in situ in the stationary part of the bearing, and (3) not interfere significantly with the normal flow pattern of the potassium lubricant. Also, any exposed materials must be compatible with potassium and any materials constituting a bearing surface should be suitable for service as a potassium-lubricated bearing.

More specifically, a pressure transducer was desired that could be mounted on 0.2-inch centers circumferentially so that pressure profiles could be investigated, a maximum operating temperature of 950 F was of interest, and the sensitivity and precision should permit measurements in the range of 200-psi film pressure with an absolute accuracy of ±4 psia. The transducer should be capable of following pressure fluctuation with a response equivalent to 0 to 2000 Hertz ±6 db*.

Based on the introductory survey(1), the most promising method was judged to be a solid-core electromagnetic induction approach using a magnetostriction-related effect. Subsequent investigation has continued to support this choice as offering sufficient sensitivity at elevated temperatures approaching 950 F.

The pressure-sensing mechanism consists essentially of two parts: A diaphragm in the bearing sleeve which converts film pressure into translational forces and the high-modulus force-measuring transducer. The core of the force transducer is fabricated from a material which exhibits a change in magnetic permeability with strain (Villari effect). A coil of wire which is electromagnetically coupled to this core material provides a means for measuring the magnetic properties of the core which vary proportionally to the forces transmitted through the diaphragm.

In using the device, no quantitative measurements are taken of the properties of the core piece, but, rather, the changes in the parameters of the sensing coil which encircles the core are measured when pressures are exerted on the transducer. An electronic bridge system containing the transducer coil as one of the bridge arms is excited by sinusoidal voltages so that changes in the parameters of the coil, namely the resistance and inductive reactance, produce voltage outputs from the bridge system. In this manner, dynamic variations in film pressure result in dynamic variation in voltage at the output of the pressure-measuring system as a result of the Villari effect acting in the core of the transducer.

In considering the available features of an advanced pressure transducer for potassium bearing service, laboratory investigations of several designs, made in part at elevated temperature and in part at room temperature, permit some expected performance characteristics to be stated with considerable certainty while others can be extrapolated or derived from related experience. At room temperature, measured data indicate that sufficient sensitivity is available to permit the desired service in a pressure range of 0 to 200 psi, ±4 psi. The linearity of available signal is within 3 percent with an overall signal hysteresis (difference in increasing and decreasing load curves) less than 3 percent. As temperature is increased to approximately 500 F, indications are that sensitivity can be expected to increase with some loss of linearity and with more hysteresis. Sensitivity would be expected to decrease with further increase in temperature. An operating limit of about 850-950 F appears to be imposed by thermal-instability effects. The electrical operating frequency of 5 kHz would be expected to permit dynamic response of 2000 Hertz, while a higher response could probably be obtained by energizing at a higher frequency. A transducer design of the desired small size was obtained including the use of potassium-resistant materials and with an alumina diaphragm exposed to the film so as to provide less than ±10 microinches of irregularity in the contour of the bearing surface.

More detailed information dealing with the pressure-transducer design, materials, and measurement techniques, is presented in the following sections of this report.

*Complete details of specified performance are listed in Table 1 of this report.

Core-Material Selection

Previous studies of the Villari effect have indicated that different magnetic materials will produce considerable differences in the response characteristics of the transducers. A selection of these materials has involved the consideration of several properties such as pressure sensitivity, hysteresis, zero shift, and magnetic stability, each being weighed according to its relative importance. Some of these special properties are defined in the following paragraphs.

1. Pressure Sensitivity. Pressure sensitivity for the present application is described in terms of the percent change in the measured electrical parameter of the transducer core with a given pressure applied. Realizing that sensitivity is dependent on many factors not necessarily related to the core material employed, such as core design and frequency of operation, efforts have been made to compare materials by holding these other factors constant. Sensitivity with respect to materials refers, therefore, to percent impedance changes for a given force, employing transducers of the same geometry, size, and having identical coil windings which are excited at the same frequency.

2. Strain Hysteresis. Hysteresis in the context in which it is used here is descriptive of the response of the transducer versus the forces applied. For example, as forces are applied to a transducer, the impedance* will change, either increasing or decreasing, depending on the type of core material employed, and as these forces are released the change in impedance is reversed for most materials. A graphical plot of these impedance changes, however, in most cases consists of points for the increasing forces which are not congruent with the points describing the decreasing forces. This difference in response is referred to as strain hysteresis.

3. Zero Shift. Zero shift might be considered as a type of hysteresis since it refers to the permanent changes in transducer impedance which occur when forces are applied to and then released from a fresh core of magnetic material. Repetition of the force cycle, however, results in a closed hysteresis loop. In this sense, the zero shift designates the change in the initial or zero force level of the impedance which occurs for a single force cycling.

4. Magnetic Stability. Magnetic stability as the term is used here refers to the ability of the core material to maintain constant magnetic properties with time, all other parameters constant. At relatively high temperatures, 900 F, for example, a transient decay in the Villari effect has been observed in certain materials. This has been demonstrated by applying a force step function to the transducer core to produce a step change in impedance, and then observing a gradual decay of the coil impedance. Other types of magnetic stability would refer to such things as the ability of the material to maintain the same magnetic properties after temperature cycling.

*Impedance - A complex quantity describing the combined parameters of the transducer coil.

Unfortunately, a very limited amount of information about these Villari-effect properties has been found in the literature. Therefore, it has been necessary to obtain samples of prospective materials and experimentally determine their characteristics in the laboratory. The candidate materials have been selected for the most part on the basis of two characteristics: (1) a Curie temperature that is above 1000 F and (2) a reasonably large coefficient of magnetostriction*, a factor which is believed to be indicative of the Villari effect. Many of the more common magnetostrictive materials have not met these characteristic requirements with the most significant limitation being the high Curie temperature.

A more recent review of the literature has substantiated the earlier findings that the alloys of iron, cobalt, and nickel are the major class of materials which offer promise toward satisfying the necessary requirements. Two additional promising materials, Hiperco 35 (35 percent cobalt, remainder iron) and Hiperco 50 (49 percent cobalt, 49 percent iron, 2 percent vanadium) were investigated in addition to the Nivco 10 and Hiperco 27 alloys which were investigated in the previous phase of study. Bobbin-core** transducers were fabricated from these materials, and pressure-response data were taken at room temperature, as illustrated in Figures 11 and 12. In particular, these experiments with a static loading device indicate Hiperco 35 to be a good Villari core material since it has displayed the greatest sensitivity, the smallest amount of hysteresis, and good linearity of response.

Each of the materials studied in these experiments has displayed a certain amount of hysteresis and zero shift. The zero shift problem, however, has been virtually eliminated with most materials by cycle loading in excess of 10 times.

After such a conditioning, the ferromagnetic specimens produce only a strain hysteresis with additional cycling.

Figures 11 and 12 illustrate some of the data taken in the core material studies and Table 4 delineates the chemical composition and the heat treatments employed, as well as other properties. Details of the experiment and the instrumentation employed are described in Appendix E. The best choice of these materials as mentioned previously appears to be the cobalt-iron Hiperco 35.

It is interesting to compare the response performance of the other varieties of cobalt-iron with the Hiperco 35, such as that of the Hiperco 27 having less cobalt than the Hiperco 35 and the Hiperco 50 having a greater percentage of cobalt. The curves of Figure 11, for example, indicate that there probably is an alloy of cobalt and iron near the composition of Hiperco 35 which would produce optimum response conditions such as maximum sensitivity, minimum hysteresis, and maximum linearity. The minimum hysteresis condition is particularly evident when noting the reversal in the direction of the hysteresis loop of the Hiperco 50 compared with the Hiperco 27.

No study was made of the high-temperature characteristics of the Hiperco 35, but crude high-temperature experiments with Hiperco 27 and 50 in previous investigations have given indications that the Hiperco 35 will function at temperatures in excess of 800 F. More refined facilities for investigating the high-temperature performance of Hiperco 35 transducers were assembled, but the intentional reduced effort in the latter portion of the pressure-instrumentation-development phase of study did not permit this experimentation to take place.

*Magnetostriction. The property of certain magnetic materials which causes them to expand or contract when magnetic fields are applied.

**Bobbin Core. The bobbin-core construction refers to a straight-core piece flanged on the ends to hold the form of the coil winding (see Figure 14).

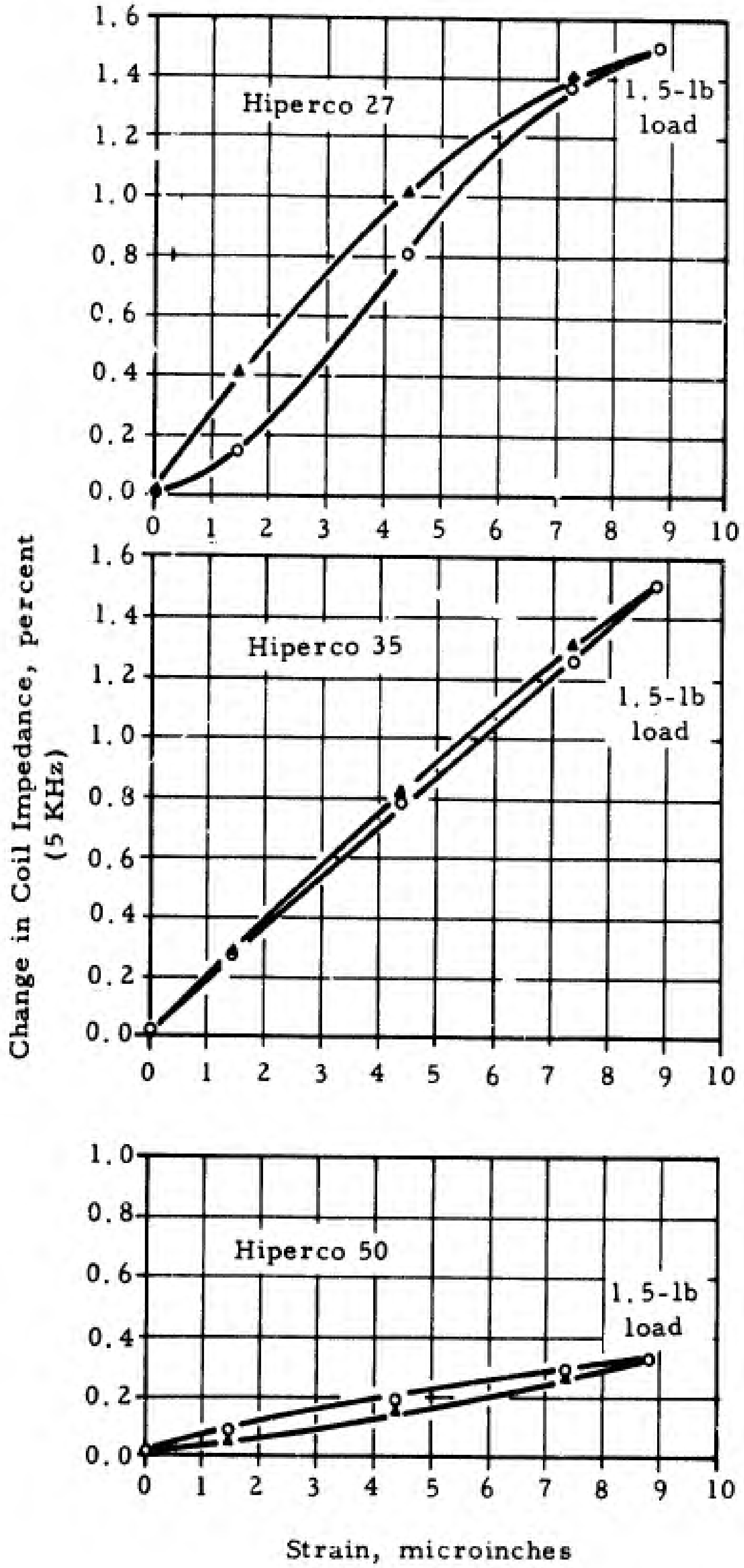


FIGURE 11. CHANGE IN COIL IMPEDANCE AS A FUNCTION OF THE COMPRESSION OF HIPERCO-ALLOY CORES AT ROOM TEMPERATURE

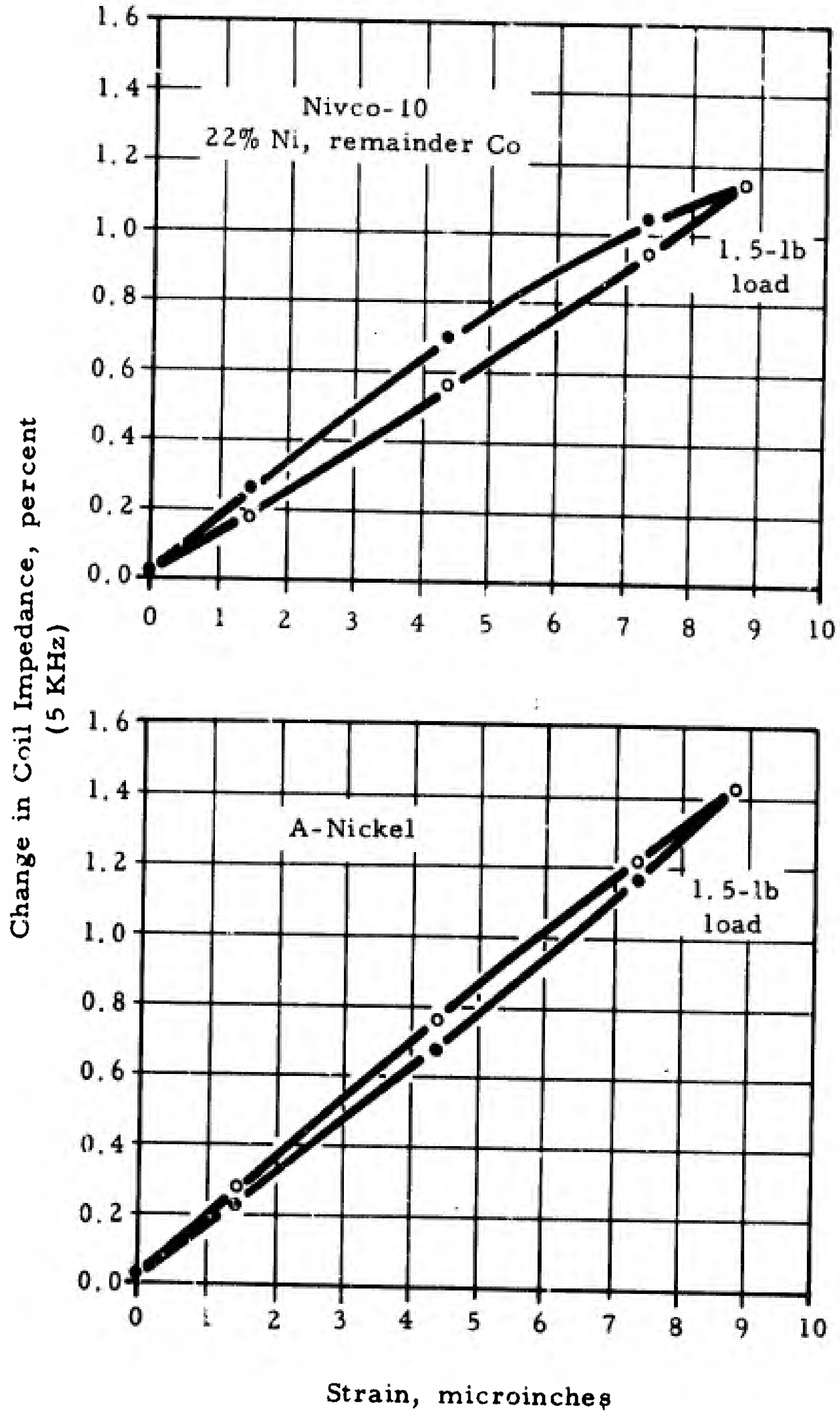


FIGURE 12. CHANGE IN COIL IMPEDANCE AS A FUNCTION OF THE COMPRESSION OF NIVCO-ALLOY AND A-NICKEL CORES AT ROOM TEMPERATURE

TABLE 4. COMPOSITION OF CORE ALLOYS

Core Material	Composition, percent: Iron	Cobalt	Nickel	Heat Treatment
(1) Hiperco 27	Remainder	26.0-28.5	0.75 max	1550 F 1/2 hour
(2) Hiperco 35	Remainder	33.5-36.5	0.70 max	1700 F 3 hours
(3) Hiperco 50	Remainder	50 percent	--	1550 F 1-1/2 hr
(4) Nivco 10	0.3	Remainder	22.5	1900 F 1/2 hour

The data illustrated in Figure 12 are descriptive of the performance of another potential core material, Nivco 10, which was believed to be particularly suitable for high-temperature work. However, the room-temperature experiments indicate a considerable amount of hysteresis in the response of the Nivco 10 transducers. Although the hysteresis was of appreciable magnitude in these experiments, previous work with the Nivco 10 transducer had indicated a much better response. Therefore, it might be concluded that such factors as original magnetic-domain alignment and heat treatment are properties which can affect the Villari effect in the Nivco 10 as well as in other materials. The investigation of these factors was to be included in the latter stages of development of the film-pressure transducers.

The response curve for the A-Nickel* cores is also included in Figure 12 as a comparison standard, but A-Nickel was not considered as a potential transducer core material for high-temperature application since the Curie temperature for nickel is approximately 650 F. A-Nickel has tranditionally been employed for the cores of magnetostriction transducers and has also had a certain amount of use in Villari-effect applications. Particular advantages exhibited with this material have been relatively good sensitivity, good linearity, and low hysteresis with strain. These A-Nickel transducers have been useful in evaluating the testing apparatus which was employed in taking response of the various core materials at room temperature. As can be seen from the A-Nickel curve, a certain amount of hysteresis could have been caused by the room-temperature testing apparatus. A subsequent section of this report describes a more sophisticated facility for testing the transducers. With this facility, the transducers are in contact with an actual diaphragm in the material to be used as the bearing sleeve.

Core-Design Studies

Analytical studies conducted early in the current program indicated that a new transducer having no air gap in the magnetic core might lead to an improved Villari sensitivity. A heightened sensitivity would permit smaller loading forces or otherwise reduce the effect of some of the undesirable characteristics such as the strain hysteresis and the zero-reference shift, which were found to be problems during the previous feasibility program. The configuration of this transducer design is much like the eye of a darning needle, as illustrated in Figure 13. Coils are wound series aiding around each of the two long sides of the core.

* A-Nickel. Commercially pure.

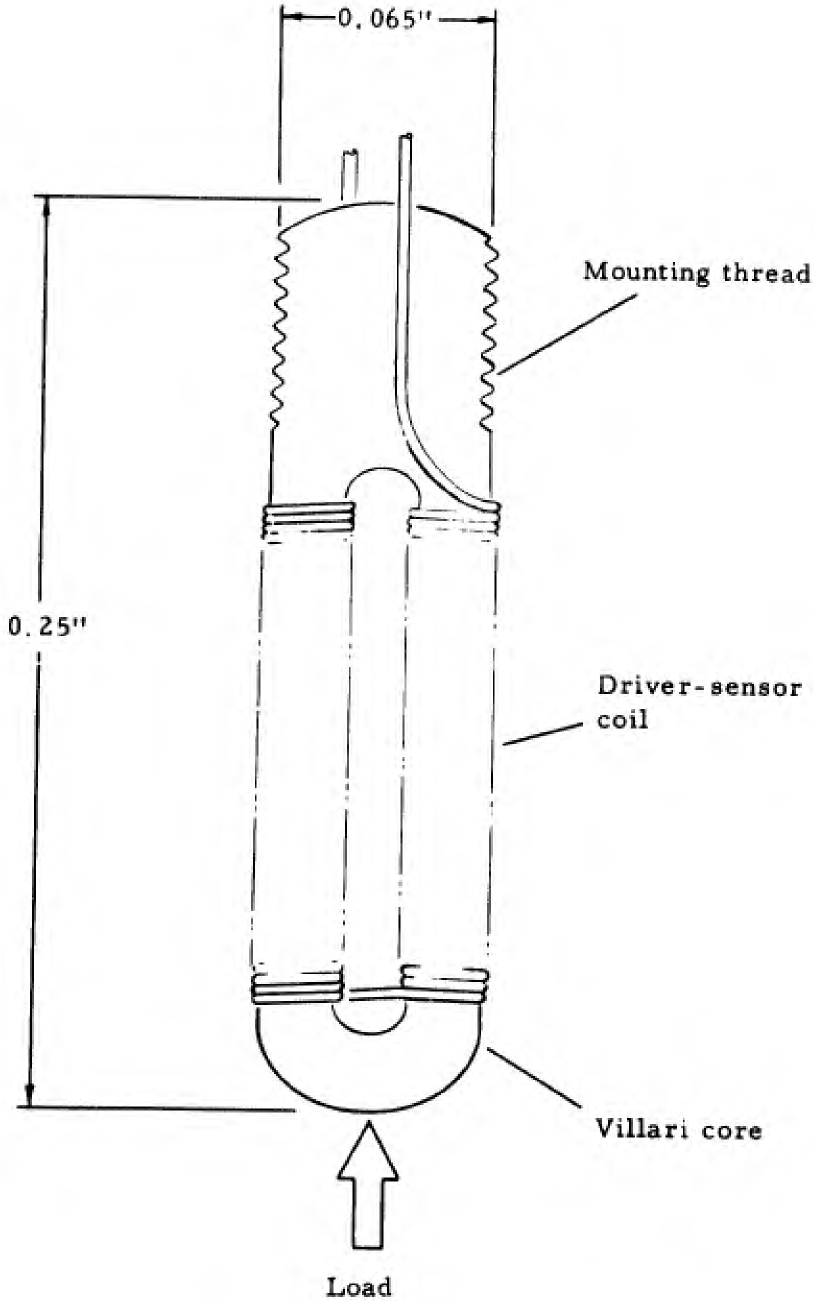


FIGURE 13. PRESSURE-TRANSDUCER-CORE DESIGN WITHOUT AIR GAP

Experimental transducers of the new design configuration were evaluated and compared with conventional-type bobbin-core transducers. Both types of transducers were constructed of Nivco 10. Nivco 10 was selected because it was considered at the time to be one of the more favorable Villari-effect materials revealed in previous work. The darning-needle transducer was fabricated by turning a small square bar of the Nivco 10 to 0.065-inch diameter, machining 0.010-inch-deep flats on opposite sides of the cylinder, and cutting the needle-eye slot by electric-discharge machining. Threads were turned on the end of the transducer to provide a means for attaching the transducers to the static loading device. The bobbin cores were fabricated by machining a 1/4-inch-long, 0.065-inch-diameter rod of the Nivco 10 to a 0.030-inch diameter over a 1/8-inch length. The transducers of both designs were heat treated for a magnetic anneal after which coils of 40-gage insulated copper wire were wound around the Villari-sensitive cores. The responses of these transducers were obtained by incrementally increasing and then decreasing the static loading up to a maximum of 1.5 pounds of force. The incremental changes in the impedance of the transducer coil were measured by detecting the change in the voltage output from a four-arm bridge network with an excitation frequency of 5 kHz*.

The results of these experiments indicated that the darning-needle design is approximately two times as sensitive as the more conventional bobbin-core configuration, but, on the other hand, there was no apparent improvement in the hysteresis and zero-shift behavior. Linearity of response was about the same for both transducers. Since the darning-needle configuration does not have an air gap in its Villari core, it was anticipated that the application of a direct-current bias to the transducer coil might be more effective in improving sensitivity than it had been previously with the bobbin-core design. Experiments conducted by Bozorth and others in which the permeability has been measured with various pressures on core pieces indicate that a d-c bias field can have a considerable effect on this d-c type of Villari effect. However, the d-c bias provided at most a meager increase in sensitivity – about 10 percent in the present application – when the 5-kHz excitation frequency was employed. Excitation at lower frequencies, on the other hand, should provide greater sensitivity and a more pronounced effect of d-c bias, but the response requirements of the pressure-measuring system would not be met by excitation frequencies much less than 5 kHz.

Although the darning-needle design exhibits a sensitivity of twice that of the plain bobbin-core design, this single characteristic may not be significant enough to warrant its use in the prototype system. In particular, the darning-needle design appears to have certain disadvantages because of the complexity of design and the fragility of construction which, from a mechanical standpoint, may make it impractical for use in the present application. Contrary to expectations, these experiments have pointed out that a flux return path may not be necessary to achieve adequate levels of sensitivity and that the simple bobbin-core configuration may be more practical for the present application. Consequently, it was decided to employ the bobbin-core transducer in laboratory investigation of materials and mechanical requirements with the assumption that darning-needle transducers could still be adopted in the final system if sensitivity became a critical factor.

A preliminary Hiperco 35 bobbin-core transducer complete with housing sleeve is illustrated in Figure 14. This transducer was prepared for experimentation with the pneumatic-pressurization facility described in the next section of this report. In a manner simulating the eventual potassium-lubricated-bearing application, the transducer

*The 5-kHz frequency was selected by judgments based on previous work and transducer requirements

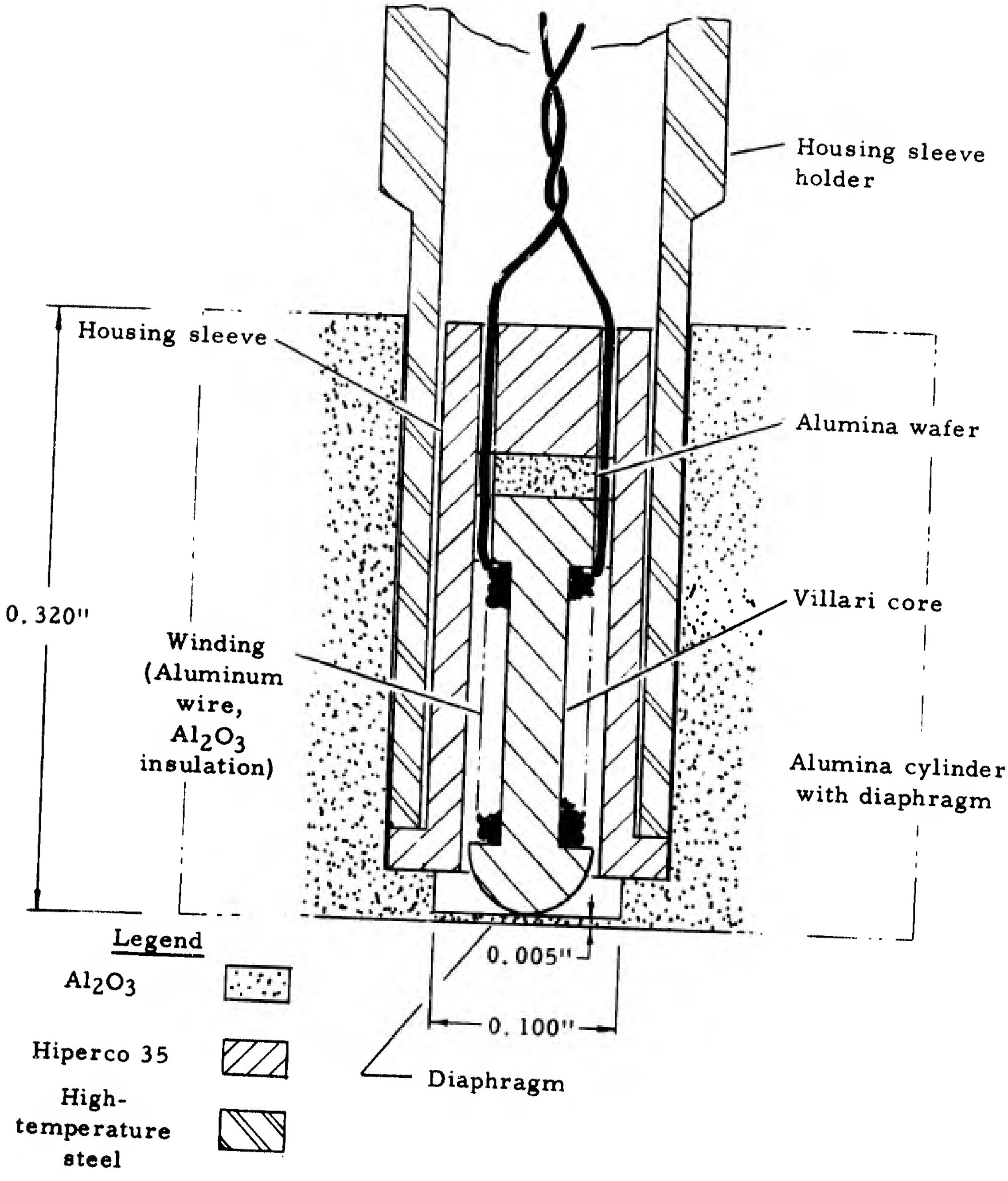


FIGURE 14. BOBBIN-CORE PRESSURE TRANSDUCER

will measure pressure through a thin alumina diaphragm which comprises the bottom of a blind hole in an alumina cylinder.

Although the preliminary transducer design of Figure 14 may not be adopted as the exact final prototype design, it is anticipated that this basic configuration will be employed. The housing sleeve is provided primarily to aid in compensation for thermal expansion, rather than to provide an improvement of sensitivity. To provide compensation for thermal expansion of the Villari core, the sleeve was mechanically referenced as close as is believed practical to the diaphragm, as shown in Figure 14. Because of the expected fragile nature of the diaphragm, the sleeve was arranged to rest against a ledge which is about 0.025 inch from the diaphragm. With this type of construction, it is believed that sufficient force can be applied to the sleeve to hold it in place without seriously endangering the diaphragm. Since the transducer core extends below the opening in the sleeve, a small alumina wafer is provided immediately above the Villari core so that the metal portion of the transducer core will be exactly the same length as the wall of the temperature-compensating sleeve. The transducer coil winding of aluminum wire with Al_2O_3 insulation enters through small holes in the rear of the housing sleeve and down through the grooves along the end shaft of the bobbin core.

Pressurization Facility

A high-temperature pneumatic pressurization facility was designed for evaluating the dynamic as well as the static response of the Villari-effect transducers for pressures transmitted through a diaphragm in an alumina block. As illustrated in Figure 15, the alumina block is to be fixed between a circular flange on the end of the stainless steel tube and a stainless steel disk having a small hole in the center. Metal gaskets provide an adequate pressure seal between the block and the flange. The transducer is held in place and clamped against the bottom of the hole in the alumina block by a thin-walled high-temperature-steel tube that is in turn held firmly by two cantilever springs producing about 2 pounds of force.

It is desirable to evaluate the prototype transducers within the pressurization facility with a testing apparatus such as a sinusoidal pressure generator.

Recently the Battelle laboratories have procured a suitable testing facility for evaluating pressure transducers which could be used, free of charge, for transducer evaluation. This device has the capabilities of generating frequencies up to 10 kHz with peak-to-peak pressure variations of 12 psi provided a 250-psi bias pressure can be applied. At 1 kHz even greater pressures of 150 psi peak-to-peak can be generated. Pressure variations subjected to the transducers can be monitored by the use of standard crystal transducers. Also available at Battelle are shock tubes in which step function pressure variations are applied to transducers to determine certain response characteristics. These facilities could be of considerable benefit in developing Villari-effect transducers.

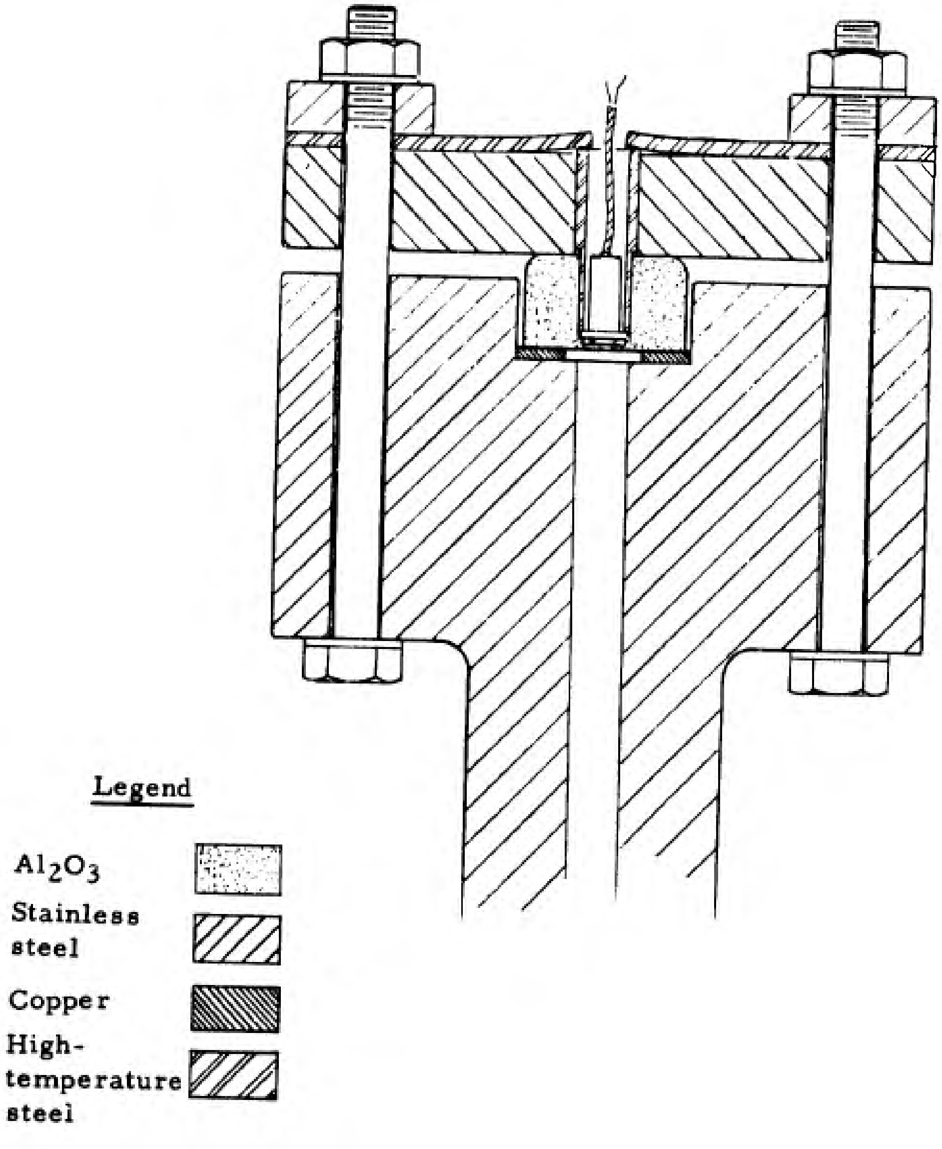


FIGURE 15. PNEUMATIC PRESSURIZATION FACILITY

SUMMARY OF PROGRAM STATUS AND RECOMMENDATIONS

The idea of using a sapphire (Al_2O_3) window to protect an eddy-current thickness-measuring coil from potassium, while avoiding perturbation of film flow during in situ film measurements, has been found to be feasible and to offer considerable promise. During attempts to finish the construction of a final transducer model for potassium, an intact sapphire window, 7.5 mils thick, was subjected to brazing temperatures of 1850-1950 F on three different occasions without apparent damage. During related procedures, the window also was subjected to mechanical loading forces of 111 grams from the inside without damage. It is expected that higher loadings could have been used successfully. Near the conclusion of the program, the window referred to became cracked during efforts to remove a failed sensing-coil element. Failed sensing-coil elements had previously been successfully removed from this transducer cavity on four occasions without damage to the window. Sufficient time did not remain to construct a new transducer body and sapphire window.

The thickness-measuring circuit using frequency of oscillation to measure inductance of the thickness transducer sensing coil has been found to be operable for transducer temperatures of 600 F with strong oscillations. The available extent of frequency shift with thickness has been found to provide between 10^3 and 10^4 cycles per second of frequency change per mil of film-thickness change. This indicated high-resolution capability offers considerable promise that the desired high resolution of measurement can be realized in potassium.

Concerning the detection of film discontinuity, the strength of oscillation of the thickness-measuring circuit has been found to vary with the Q of the sensing coil. Changes in coil Q are known to occur for simulated potassium voids. Therefore, these conditions offer promise that the thickness transducer can also be used to detect voids.

One significant problem has been discovered regarding construction of the potassium thickness transducer. There seems to be only one choice of brazing alloy that is resistant to potassium and which can be used for brazing K-94, Kovar, and stainless steel, which are also materials chosen carefully for resistance to potassium. This brazing alloy melts at about 1850 F. It has been found that spot welds between gold and copper will melt if subjected to temperatures of 1850 F although the melting points of copper and gold are 1981 F and 1945 F, respectively. An alloy of gold and copper has a eutectic point at 1632 F, which explains the difficulty. It will be necessary (1) to find a suitable lower melting brazing alloy, (2) to use gold wires and a gold sheath in the transmission lines, (3) to use copper for the sensing-coil and transmission-line wires although oxidation would be expected to cause inaccuracies, or (4) to redesign the transducer so that the final seal can be made by local heating at an area remote from copper-to-gold spot welds. The last choice is considered to be the best possibility. A concentrated type of induction brazing would be employed.

A succession of failures in attempting to complete a sealed transducer for potassium was encountered during the latter weeks of the program. These failures, except as regards the eutectic-alloy problem, are not considered fundamental. Useable transducer bodies have been made and it is conceivable that other satisfactory ones could be made again. A routine for constructing the transducer elements could be perfected that would reduce failures to a minimum. The knowledge of these procedures could then be of great value in the construction of pressure transducers as well.

It is recommended that although other materials arrangements are possible, such as an all-alumina transducer body, the problems of these alternatives can be expected to be significantly greater than the investigated approach.

The investigations of the pressure-transducer portion of the program have shown promise for the use of the Villari effect for pressure and force measurement at elevated temperatures. To reduce nonlinearity and hysteresis, and improve reproducibility, it is expected that some alloy development work should be completed before a completely suitable transducer design could become available. In cases where the transducer characteristics found are suitable, however, the investigated design could be used for pressure studies.

The potential industrial value of a high-temperature pressure transducer is probably greater than can be expected for a thickness transducer. It is recommended that serious consideration be given to means for further development of the Villari approach with the objective to produce a unit of versatile application for military, space, and industrial uses.

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DRG:AFL:RJD:JHF:CMA/mln

APPENDIX A

DESIGN AND CONSTRUCTION OF THICKNESS TRANSDUCERS

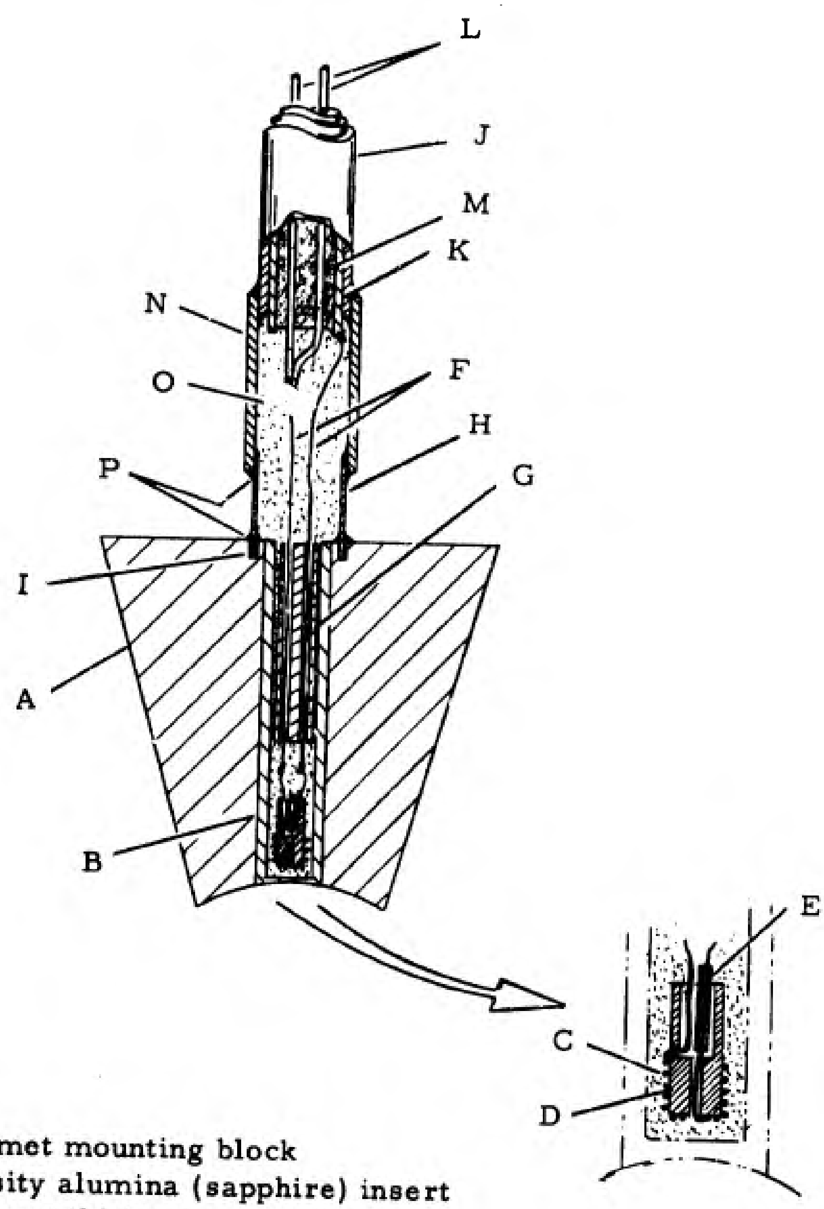
It was an objective to develop a lubricant-film thickness-detecting transducer for use *in situ* in the bearing sleeve of a potassium-lubricated journal bearing. The advanced transducer design employs a cup-shaped eddy-current test-coil winding on an alumina core, potted within a cylindrical blind hole in a high-density alumina (sapphire) insert that has been diffusion bonded into a K-94 cermet mounting block ground to the dimensions of the journal shaft and assembly flanges. The alumina insert provides a hermetic and potassium-resistant electrically nonconductive hard partition or window protecting the coil from the potassium film, but permitting it to be close enough to the film to be affected electrically by film-thickness changes. The rear of the K-94 mounting block can be provided with a mechanical seal against potassium (see Appendix D) and/or a stainless-steel-and-copper hermetic transmission line to provide electrical connection to the transducer coil. The metal-clad line is brazed to the transducer to provide the required hermetic integrity.

The design of the advanced transducer assembly is illustrated in the cross-sectional view, Figure 16. The various component parts and notes concerning them are summarized as follows, not necessarily in the actual sequence of construction. The bearing sleeve of a journal bearing is represented by the K-94 mounting block, A, ground to fit the curvature of a TZM journal shaft. The mounting block is drilled by electric-discharge machining (EDM) to provide a 0.150-inch-diameter hole into which a solid high-density alumina (sapphire) rod, B, is diffusion bonded. The bonded alumina rod, B, is ultrasonically drilled by means of a 0.098-inch-diameter tool to provide a 0.100-inch (approximate)-diameter blind hole to receive the eddy-current thickness-detecting coil, C. The coil, C, is wound with 40-gage wire in a two-part winding including 6 to 8 spiral turns and 12 to 15 helical turns on an alumina coil form, D. The wire material for the advanced design is high-purity gold. The coil form is ground to 0.090-inch OD from a solid alumina rod and then ultrasonically drilled to hollow out a 0.060-inch-diameter axial blind hole, a 0.010-inch hole in the side, and another at the center of the end, so that the coil leads may be brought out of the coil form as shown.

Details of these construction steps are as follows.

(1) Preparation of transducer cylinder with insert (see Appendix C).

The sapphire rod to become the insert is diffusion bonded full length into a hole along the axis of a K-94 cylinder. Bonding is accomplished with the cylinder in a sealed, evacuated steel can at 2250 F with 10,000 psi helium applied to the outside of the can. It is necessary to employ boron nitride or alumina powder to serve as a release agent to permit separation of the can from the exposed ends of the sapphire rod after bonding. Previously, while removing the can by grinding, the alumina rods would tend to become cracked as the can material pulled away from the rod surfaces.



A. K-94 Cermet mounting block
B. High-density alumina (sapphire) insert
C. Eddy-current thickness-detecting coil
D. Alumina-coil form
E. Quartz insulating tube
F. 31-gage lead wires
G. Alumina tube
H. Kovar sleeve
I. Circular slot
J. 304 stainless steel outer jacket of transmission line
K. Copper sheath of transmission line
L. Copper conductors of transmission line
M. MgO insulation of transmission line
N. Stainless steel sleeve
O. Alumina potting compound
P. Fillets of brazing alloy

FIGURE 16. THICKNESS-TRANSDUCER ASSEMBLY

(2) Polish the ends and inspect.

It is noted that some limited cracking of the alumina insert is encountered in nearly all of the prepared cylinders. By polishing the ends of the cylinder and inspecting visually for cracks after diffusion bonding it is possible to select the portion of the cylinder which should be removed by subsequent grinding so as to result in the best internal integrity of the resultant alumina insert. Of course, if a sufficiently large crack-free area is not found, at which the eventual partition will be located, that cylinder must be rejected.

(3) Grind to finish size.

Diamond abrasive grinding equipment is used to reduce the cylinder to finish size in a manner to leave the best quality of remaining sapphire material as noted above. It was found that grinding does not cause cracking of the alumina. Therefore, the initial front face of the sapphire window consists of material in the as-ground state. This face is diamond lapped at a later stage in the fabrication process.

(4) Drill blind hole in sapphire.

The partition window consists of the undrilled floor of a blind hole drilled almost through the length of the sapphire rod. The blind hole is drilled in two steps -

a. Ultrasonic drilling.

A flat-faced steel rod is used as the ultrasonic drilling tool. Diamond powder of 230/270 mesh is used as the abrasive with water as the vehicle. The powder must be obtained on special order because diamond abrasive in such large grit size is not generally marketed, especially in the dry state.

The transducer body must be supported for drilling in a jig that provides uniform stiff, but not hard, support to the alumina window face. This support is obtained by using optical wax as the attachment medium between the transducer surface and an aluminum block having a curved surface closely mating with the transducer curvature. After mounting the aluminum block on the transducer as is done in optical or jewelry practice, the assembly is rigidly assembled into a steel holder which has a threaded bolt that is tightened against the aluminum block to load the optical wax against the transducer surface. The bolt is tightened with a wrench snugly until solid, but not as tightly as one would assemble a bolt.

Ultrasonic drilling is continued until the sapphire window thickness, as determined by prior reference measurements, is approximately 0.020 inch thick.

b. Lapping.

The front face of the window is lapped at this time. Lapping by means of rod-shaped brass tools is also employed to reduce the window thickness to finished size. The edge of the working face of the lapping tool should be allowed to become slightly rounded to make a fillet of perhaps 5-mil radius at the bottom of the hole for better mechanical support of the window and to discourage a "punch-out" effect that seemed to be responsible for the failure of at least one otherwise successful previous lapping attempt.

(5) Attach Kovar tube.

The Kovar tube which makes a hermetic seal to the rear of the transducer body is then attached by brazing it into a slot prepared in the K-94 by EDM machining. Brazing is done by induction heating in vacuum at about 1950 F using a 91 Ni-4.5 Si-2.9 B commercial brazing powder. Additional details of this procedure are presented in Appendix D.

(6) Construct the sensing coil.

a. Prepare a mixture of 1 part of Du Pont's Duco cement to 1 part acetone. Apply 2 or 3 layers of this Duco mixture to the face of the drilled alumina coil form. Mount the alumina coil form in the chuck of a jeweler's lathe (# 24 collet) and locate in the field of a binocular microscope with the axis of the chuck vertical.

b. Place a spacing wire (#42 AWG copper) about 6 inches long and a piece of 40 AWG gold coil wire about 8 to 10 inches long through the center hole in the face of the coil form, leaving adequate lead length, and place a short piece of wire in the hole to hold the longer wires stationary. Apply the Duco mixture and let dry 5 minutes.

c. So as to proceed to attach the wires to the face of the coil by winding in a spiral, add a small drop of acetone to the face of the form. The wires will loosen but become firm again quickly. Turn the gold wire first about 90 degrees and then loosen the spacing wire with acetone and turn it 90 degrees along the side of the gold wire. Continue until the face is full. Let the face dry for about 2 minutes and then start removing the spacing wire by placing acetone on the wire as it is being removed. Too much acetone will cause the coil to unwind.

d. After removal of the spacing wire, let the coil dry for about 2 minutes and then use a razor blade to cut beneath the coil all the way around and to the center. Lift the coil and clean the Duco mixture from the core face of the coil form by means of acetone. Prepare a mixture of equal parts of water and Aremco Corp. Ceramabond No. 503, and place 1 drop of this slurry on the face of the coil form. Remove as much as possible of the Duco mixture from the spiral gold coil by means of acetone and gently press it into the slurry with a piece of cardboard.

e. Change the holding chuck to horizontal and continue the gold winding up the side of the coil form by winding 12 helical turns spaced about 3 mils. This part of the coil can be wound without a spacer wire and without continuous cementing.

Put a drop of the Duco mixture on the last turn to hold the coil in place. Feed the wire through the hole in the side of the form and apply cement slurry to the helical coil. Do not use excess cement as the coil must later fit into the K-94 body.

f. Put the coil in a 250 F oven and cure for 1 hour. Better results are found if the coil is put in a cool oven set for 250 F, and left in place while the oven heats to 250 F.

g. Cut a piece of drawn and flattened quartz or Pyrex rod and insert into the rear opening of the coil form as to separate the two lead wires. The remaining space in the coil form is then filled with slurry, using a hypodermic syringe and needle, so as to provide a handle for the coil form. As an alternative, but less desirable procedure, a piece of drawn-quartz tubing can be used to insulate the center lead wire and a piece of alumina thermocouple tubing can be cemented to the rear of the coil form to serve as a handle and to insulate the lead wires as shown in Figure 16. The craftsman may elect to interchange steps g and h.

h. Spot weld the #31 wires to the coil leads by means of a Hughes Aircraft Company Model MCW-550 electronically controlled spot welder using the following settings. For copper electrodes, use 0.50 volt for 40 milliseconds. For molybdenum electrodes, use 0.50 volt for 50 milliseconds.

i. Trim excess lead wire and apply slurry with the syringe to the spot-weld area and cement wires into position on ceramic handle.

j. Cure the assembly in a 160 F oven for a few hours and then in a 300 F oven for 2-3 days.

(7) Assemble sensing coil into K-94 body.

The clearance between the sensing-coil body and the alumina chamber into which it is to fit can be checked with the fingers. It may be necessary to hone or file excess cement from the sensing coil. Enough of a free fit must be obtained to permit the sensing coil to slide into position as close to the window partition as possible. Before cementing the sensing coil into place, the relative sensitivity of the assembly can be checked with a Q-meter and pieces of metal foil placed in front of the window. The coil is cemented in place by first putting a very small amount of cement on the inner face of the partition and placing the coil into the alumina cavity. The coil assembly can be weighted to hold it against the partition during subsequent cures. A weight of 111 grams was used without damaging the window and it appeared that 2 or 3 times this weight would not be excessive. The remainder of the cavity is filled with cement in two or three steps separated by curing procedures.

(8) Attach transducer body to transmission line.

The K-94 body containing the cemented sensing coil is joined electrically to the transmission line with the electronic spot welder. A jig was used to hold the components in position. A flattened area on the copper sheath of the transmission line was helpful in making the ground connection and provided a clearance for the stainless steel sleeve. The spot welder setting for the connection to the copper sheath is 1.3 volts and 110 milliseconds. The attachment to the center conductor is made at 0.9 volt and 100 milliseconds.

(9) Prepare for sealing.

The spot-welded wires are covered in stages with cement by using a semi-cylindrical form to retain the cement. A stainless steel sleeve to fit as a cover from the transmission line to the Kovar sleeve is machined with beveled ends into which the brazing powder can be placed.

(10) Braze to seal.

Both induction brazing in vacuum and furnace brazing in protective atmosphere were used in making experimental seals. The brazing alloy used is the only one known to the investigators that will wet stainless steel and K-94 while also being resistant to potassium. It melts at about 1850 F. It has been learned that this temperature is prohibitive if it is necessary to employ any gold to copper welds that will be exposed to this temperature. A eutectic alloy of gold and copper melts at 1632 F which means that spot welds probably will be damaged or destroyed at temperatures above 1632 F. Possible solutions include the discovery of a lower melting brazing alloy, or use of gold conductors throughout the transducer, including the transmission line.

The metal-clad transmission line, shown in the upper portion of Figure 16, is constructed as follows, assuming copper conductors are used. Commercial one-conductor or two-conductor mineral-insulated (MI) 300-volt power cable 0.246 inch in diameter is employed. This cable has electrical-grade copper conductors and copper sheath. As received, the conductors are 16-gage (0.050-inch diameter) and the copper sheath wall thickness is 1/32 inch. The interior insulation is tightly packaged MgO powder. The MI cable is straightened, and the outer surface cleaned with steel wool or sandpaper. The MI cable is then inserted in 304 stainless steel tubing which is 5/16-inch OD with a wall thickness of 0.022 inch. This loose assembly is then swaged at and near one end until the OD of the swaged area is decreased to about 0.190 inch, to provide a "pointed" end for drawing. Wire-drawing dies and a draw bench are then employed to draw the composite to size, reducing the diameter in steps of one die size at a time, to an OD of 0.194 inch.* The drawn composite is then annealed at about 1500 F, principally to benefit the copper, and the ends are cut back to eliminate any nonuniform material. To reduce adsorption of moisture into the MgO, a water quench is not employed. During storage, the ends should be capped to prevent adsorption of water by the hydroscopic MgO. Adsorbed moisture can be readily removed by baking.

The above procedure reduces the stainless steel, copper sheath, and conductors in proportion, and provides a tight mechanical fit between the steel and copper

*It is expected that modifications of the transmission-line arrangement could be employed to provide a flexible section or connector.

coverings. Referring to Figure 16, the resultant thickness of the stainless outer sheath, J, is about 0.016 inch, the copper sheath, K, is about 0.025 inch thick, and the conductors, L, are about 0.033 inch in diameter. The MgO insulation, M, does not extend beyond the lower end of the copper sheath. The sheaths are cut back to expose the inner conductors which are cleaned preparatory to spot welding. These conductors are then joined by spot welding and a stainless steel sleeve to be used in making the final seal is slipped onto the transmission line. Details of the materials and dimensions of the advanced transducer are summarized in Table 5.

TABLE 5. MATERIALS AND CONSTRUCTION PRACTICE FOR ADVANCED PROTOTYPE TRANSDUCER

Transducer Feature	Material or Design
Test-coil design	Cup-shaped
Turns	6 spiral, 12 helical
Wire	40-gage gold (99.99%)
Insulation	Bare wire potted in alumina cement
Coil form	Alumina rod, 0.09[illegible]-inch OD
Intermediate leads	31-gage gold (99.99%)
Bearing sleeve simulator	K-94
Insert	Clear Al_2O_3, diffusion bonded
Window	0.008 - 0.010 inch
Transmission line	Metal-sheathed
Outer conductor	Stainless steel swaged on copper
Stainless steel OD	0.196 inch
Copper sheath OD	0.161 inch
Inner conductors	1 - copper or gold
Insulation	Bare wire imbedded in MgO
Connection of line to K-94 bearing unit	
Wires	Spot weld
Sheath	Intermediate stainless sleeve brazed to line sheath and to Kovar tube brazed in K-94 bearing unit

APPENDIX B

FREEZING-POINT TEMPERATURE CALIBRATION AND APPARATUS

An apparatus has been constructed and commissioned for the accurate determination of the resistance-temperature behavior of film-thickness transducers. The calibrations are made using the accurately known freezing points of three high-purity metals, tin, lead, and zinc, which span the 550-650 F range of immediate interest. These metals, among others, are being actively considered by the National Bureau of Standards for use as temperature standards. The following table lists the published freezing temperatures.*

TABLE 6. FREEZING POINTS
(Degrees F)

Tin	449.38
Lead	621.32
Zinc	787.10

All of these temperatures are accredited with an accuracy of ±0.02 F. In the present work, metal baths having purities of at least 99.99+ percent are being used.

A sketch of the apparatus is shown in Figure 17. The film-thickness transducer is partially immersed in the metal bath. The metal is contained in a carbon crucible to reduce possible oxidation at elevated temperatures. The crucible is contained within a heavy-walled copper block to obtain a fairly isothermal environment for the bath. The copper block is suspended by stainless steel tubes from the lid of the stainless steel enclosure. Radiation baffles are included above the crucible to reduce the transfer of heat to the lid. During elevated-temperature operation, an inert environment of argon gas is used in the apparatus to reduce oxidation, and water cooling of the lid is used to protect the elastomer seals from elevated-temperature deterioration. Strategically located thermocouples within the enclosure permit monitoring the temperatures and gradients within the chamber.

A freezing-calibration run is performed by applying sufficient heat to the chamber to raise the bath temperature above the melting point and then allow the apparatus to slowly cool through the freezing range. Judicious application of reduced heating by the electrical ovens surrounding the chamber permits control of the cooling rate so that the freezing of the bath can be extended to 1/2 hour or longer. During this period the bath temperature drops very gradually and a sequence of precision measurements of the transducer can be made. The measured parameter is then examined either graphically or analytically to obtain a value at the initiation of freezing which then corresponds to the freezing temperature of the bath within an estimated error of ±0.05 F. Lower accuracy data can be obtained over a range of temperatures by making parameter

*McNish, A. G., "The Basis of Our Measuring System", Proc. IRE, 47 (5) (1959).

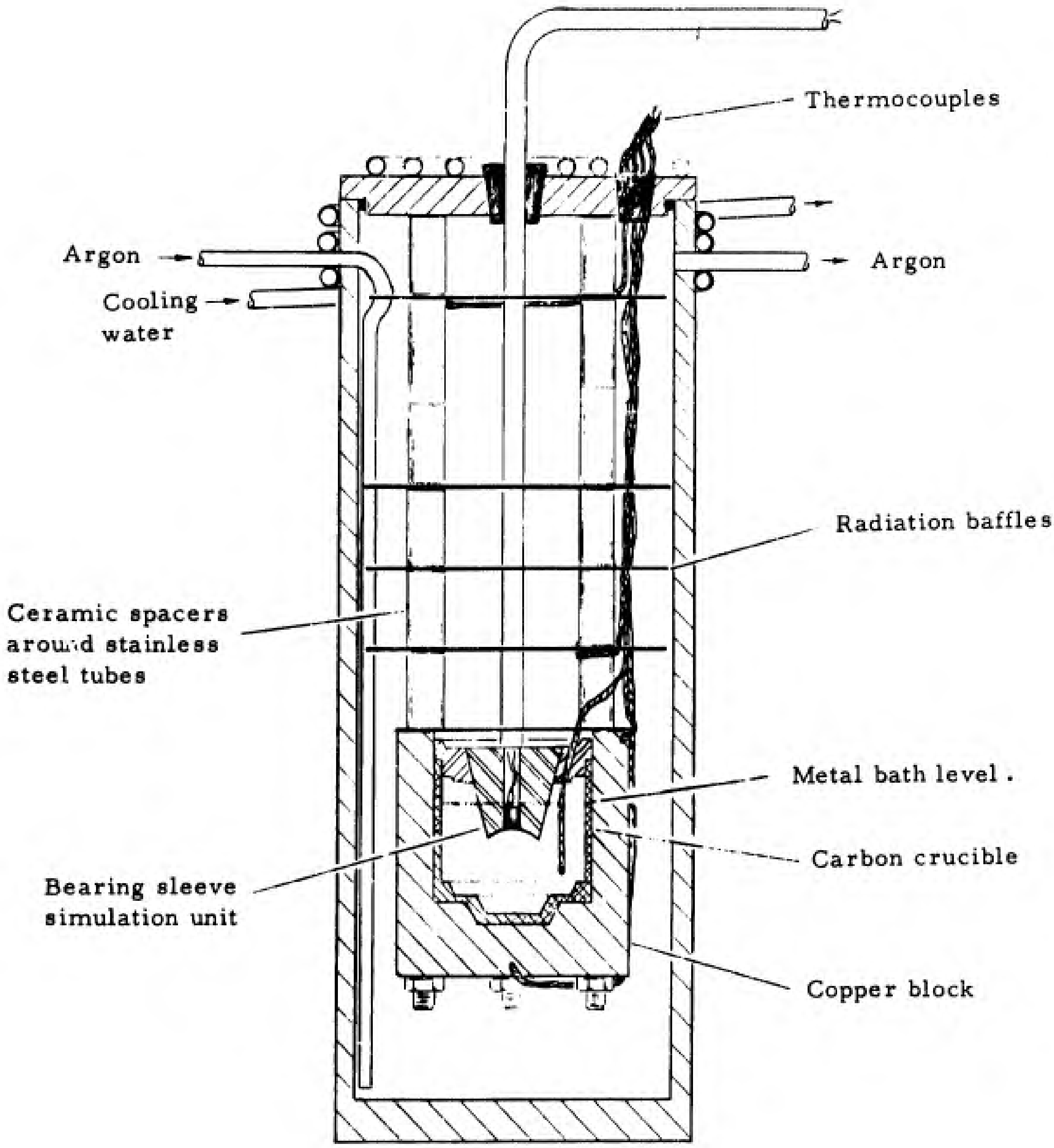


FIGURE 17. FREEZING-POINT APPARATUS

measurements during the entire heating-cooling cycle and determining the temperature with an estimated error of ±3 F from the thermocouple readings. An additional, accurate, lower temperature calibration point may be relatively easily obtained using a demineralized water-ice bath.

APPENDIX C

PRESSURE BONDING FOR HERMETIC SEALING OF SAPPHIRE TO K-94

One stringent requirement placed upon the film-thickness transducer was that it should be imbedded in the stationary member of the bearing to permit the requisite accuracy. The necessity for an electrically nonconducting window between the transducer coil and potassium film, the need for hermetic sealing of the transducer, and the necessary extreme dimensional stability of the transducer placement led to the application of pressure bonding techniques for fabricating a K-94/sapphire composite which could be subsequently fabricated to the desired final shape. The composite consists of an alumina insert rod plasma-arc sprayed with a metallic coating and solid-state bonded into a tungsten carbide (K-94) cylinder. The coatings diffuse into the tungsten carbide and alumina rod, forming a strong bond that provides hermetic sealing and that may help distribute thermal stresses during bonding and also in service. Gas-pressure bonding parameters and suitable container materials as well as methods for the preparation and assembly of the capsule components have been determined.

The Gas-Pressure Bonding Process

The gas-pressure bonding process has been developed at Battelle for densifying and bonding ceramics, cermets, and metals where dense bodies of various geometries have been required. The process employs an inert gas at high temperature and pressure to accomplish densification and bonding. The materials to be bonded and/or densified are enclosed in evacuated metal containers and inserted into a resistance heater in an autoclave pressurized with helium or argon. With the components heated to an elevated temperature, gas pressure forces the components into intimate contact, thus producing densification and bonding. An applied pressure of 10,000 to 15,000 psi, a temperature of 2000 to 3000 F, depending on the materials, and a time of several hours are usually sufficient to densify refractory metal or ceramic powder materials and bond components to each other.

The gas-pressure consolidation operation is performed in cold-wall, internally heated, high-pressure autoclaves which incorporate special features to facilitate this type of operation. A photograph of one of these autoclaves is shown in Figure 18, and a schematic drawing of the cross section is represented in Figure 19. The autoclave body is open at both ends, and a tight seal is maintained with heads that utilize a modified Bridgman seal. An internal heater incorporated in the center of the autoclave is insulated from the outer wall by bubble alumina and microquartz. The vessel has an inner liner that is spiral grooved to provide cooling of the inner wall. In the larger autoclaves, a smaller, secondary head which allows for quick and simple loading is incorporated. In this equipment, the helium or argon gas used to exert the pressure during bonding is pressurized by piston-type compressors and is reclaimed after each cycle. Autoclaves presently in use at Battelle have maximum operating pressures of 10,000, 15,000, and 50,000 psi.

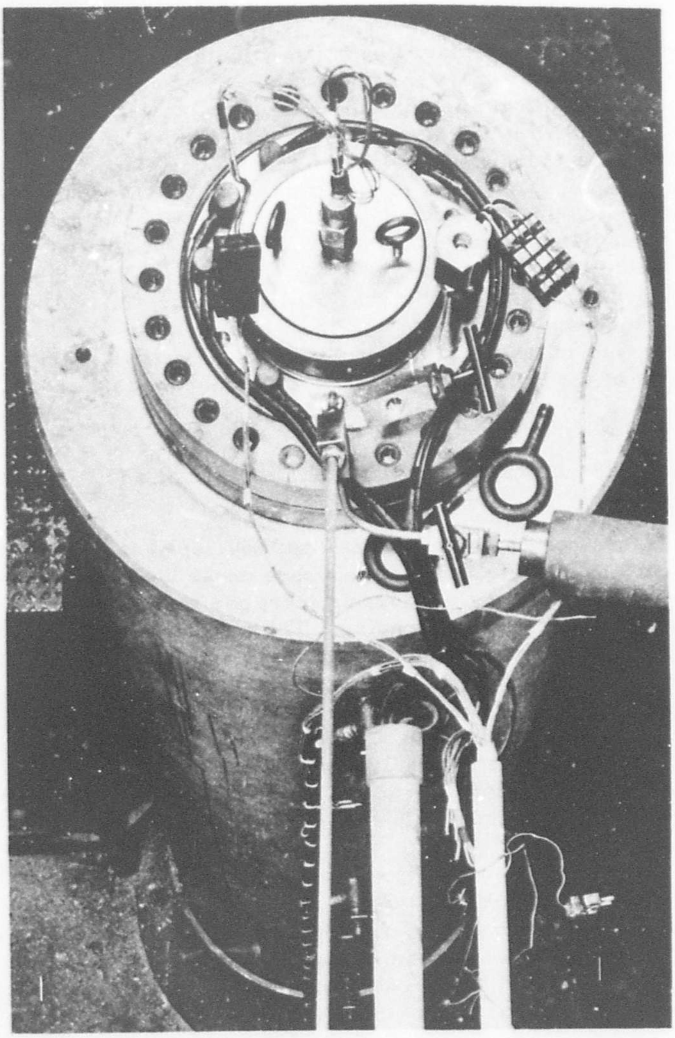


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FIGURE 18. HIGH-PRESSURE, HIGH-TEMPERATURE COLD-WALL AUTOCLAVE FOR GAS-PRESSURE BONDING

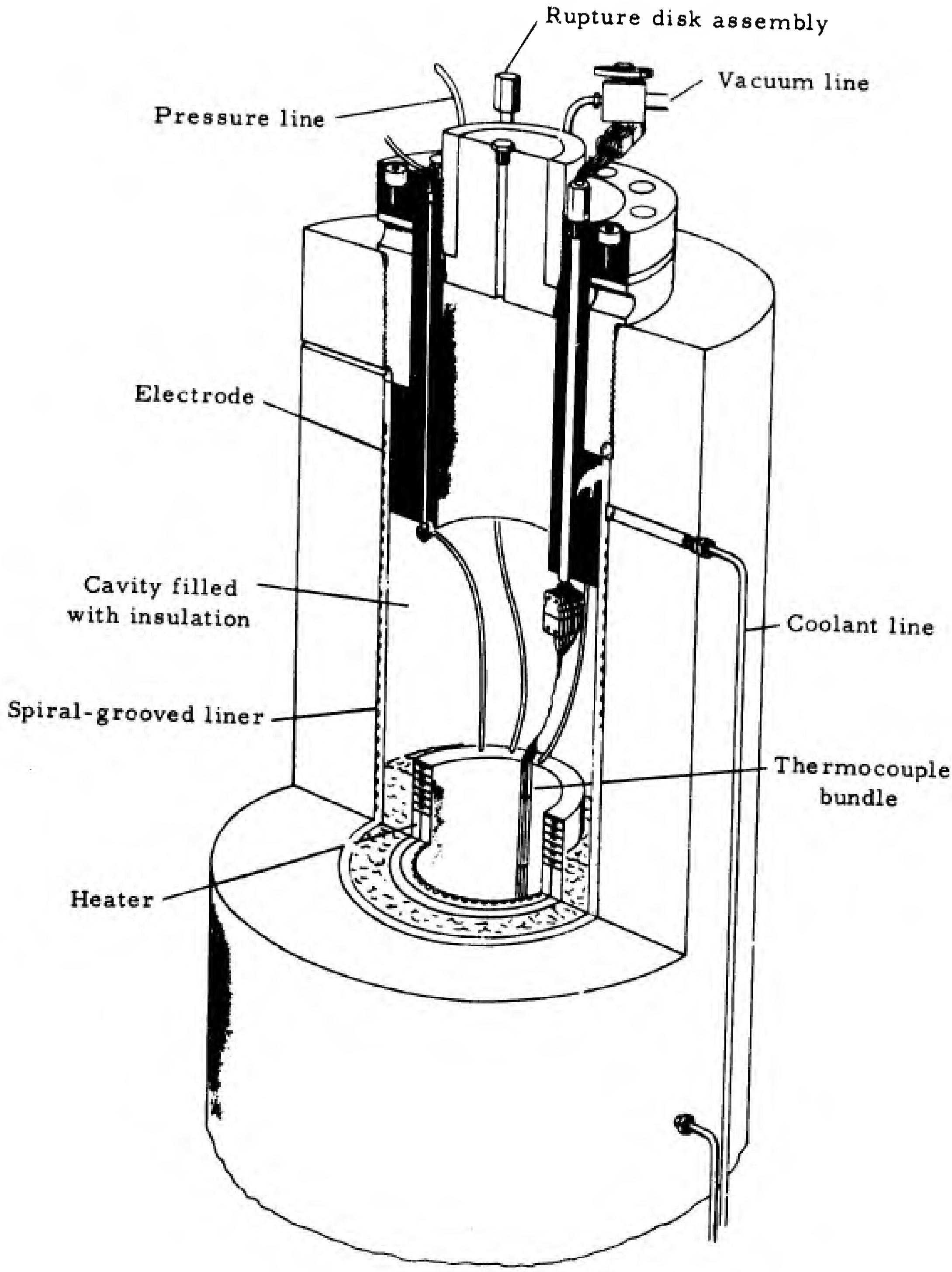

FIGURE 12. CUTAWAY DRAWING OF HIGH-TEMPERATURE COLD-WALL AUTOCLAVE

Method of Assembly of Film-Thickness Transducer Capsules

The experimental transducer composites consisted of two components, a 1-inch-long by 1-inch-diameter tungsten carbide (K-94) cylinder and a sapphire rod plasma-arc sprayed with a W-Co-Cr coating as shown in Figure 20. The sapphire rods were ground to 0.140-inch diameter and plasma-arc sprayed with a 5-mil-thick coating of W-Co-Cr. The plasma-sprayed rods were fitted into a 0.150-inch-diameter hole drilled axially in the tungsten carbide part by electrical discharge machining. To assure that the metallic diffusion layer was present at all areas of contact between the sapphire rod and tungsten carbide component, W-Co-Cr powder was vibratory compacted into any remaining voids. The specimens were then encapsulated in mild steel bonding containers, outgassed to a vacuum of 10^{-5} torr, and sealed in the electron-beam welder. A series of four units were bonded in a single run. A boron nitride or an alumina barrier layer is positioned between the mild steel end plug of the bonding container and the specimen. This eliminates bonding of the end-plugs to the specimen and facilitates the removal of the encapsulation container.

Gas-pressure bonding of the assemblies was conducted at 2250 or 2300 F for 2 hours under 10,000-psi helium pressure. Deformation of the mild steel bonding containers after removal from the autoclave indicated that an apparently satisfactory bonding run was made. The specimens were tested for leaks prior to and after the bonding operation. Selective acid leaching employing a 50 percent nitric acid bath was employed to remove the mild steel containers. The end plugs separated readily from the bonded composite because of the boron nitride and alumina barrier layers present. The specimens were metallographically polished on each end for visual and optical evaluation. Figure 21 is a metallographic section of the bond between the K-94 cermet and the W-Co-Cr coating and illustrates the diffusion of the W-Co-Cr coating into the alumina. This photomicrograph is representative of the good metallurgical bonding observed in these specimens. Visual and optical evaluation of the sapphire rods indicates that some minimal internal cracking was present in the sapphire rods. Although handbook values for thermal expansion of alumina and K-94 indicate an excellent match at room temperature, insufficient elevated-temperature data exist for evaluation and therefore a mismatch at temperatures over the bonding range to 2300 F may be a possible cause for the cracking.

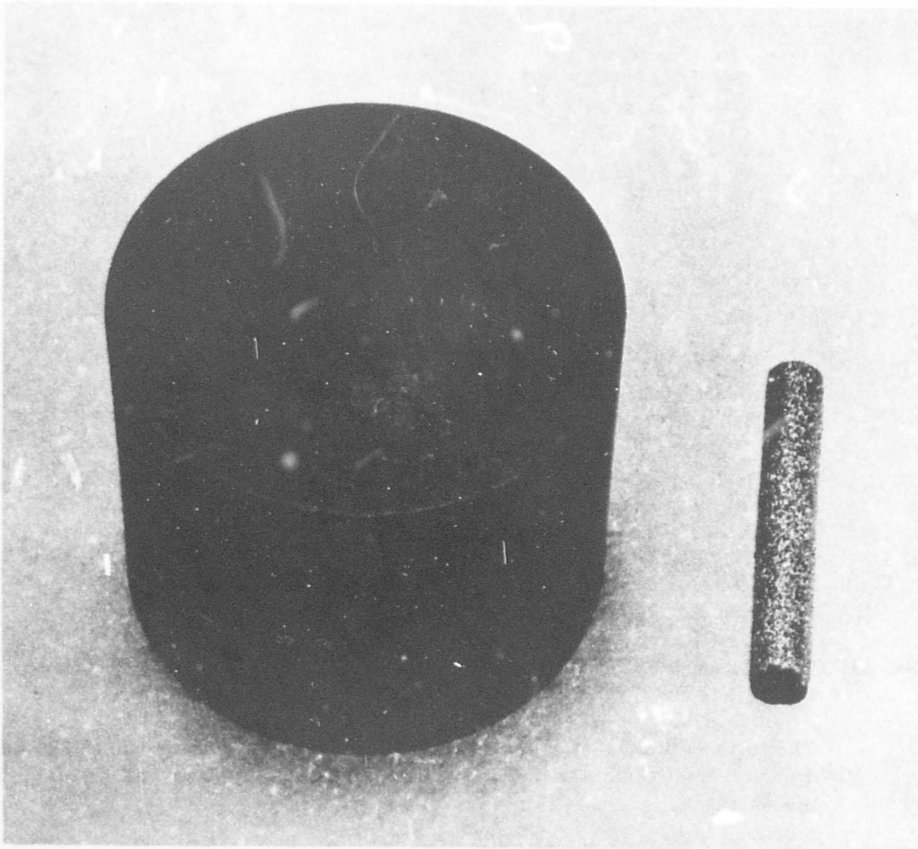

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FIGURE 20. TUNGSTEN CARBIDE CERMET (K-94) AND SAPPHIRE ROD PLASMA-ARC SPRAYED WITH W-Co-Cr COATING

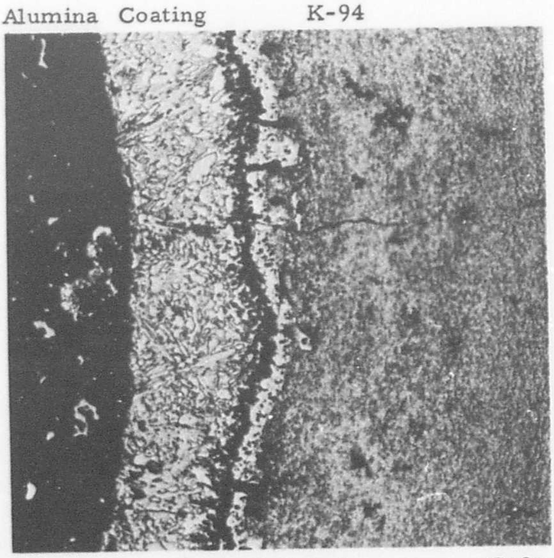

FIGURE 21. METALLOGRAPH OF PRESSURE-BONDED SPECIMEN WITH W-Co-Cr COATING BETWEEN K-94 CERMET AND ALUMINA INSERT

There is evidence of a good metallurgical bond between the K-94 cermet and the W-Co-Cr coating. The W-Co-Cr coating has diffused into the alumina.

APPENDIX D

DESIGN AND EVALUATION OF A MECHANICAL CLOSURE AND FABRICATION OF AN INDUCTION BRAZED SEAL

A small mechanical closure assembly was designed for sealing transducer-instrumented, K-94 test units into the potassium test enclosure. This closure was developed prior to the successful fabrication of an inductively brazed seal between a K-94 test piece and a Kovar tube. Both the mechanical closure and the braze seal provide a means for protecting the transducer lead wires from the potassium environment and provide for a hermetic seal for penetration of the potassium enclosure by the lead wires. The brazed seal is preferable if only compactness is considered. On the other hand, the mechanical seal provides a capability for ease of assembly and disassembly.

Mechanical Closure

This closure design is based on a static seal developed previously* for extreme environmental conditions and successfully adapted to mechanical closure of a potassium seal test chamber. The present adaptation is to the high yield strength and low thermal expansion of K-94. The basic shape of the seal is that of a ring bobbin having a Y-shaped cross section as shown in Figure 22. Sufficient uniform, axial clamping force must be used to deform the tips of the "Y" seal into the carefully machined grooves of the mating surfaces. The base of the "Y" acts to provide a stop for the axial clamping. Proper sealing requires that the clamping be just sufficient to seat the mating surfaces against the base of the "Y" without deforming the base and causing excessive stress at the junction of the base and sealing flanges of the "Y". The assembly arrangement with the transducer is shown pictorially in Figure 23.

Tests were performed on seals of the construction and size shown in Figure 22. Helium-leakage measurements at temperatures up to 1000 F showed a maximum gas leakage of 10^{-4} to 10^{-5} atm-cc per second over a 10-hour period at a nominal pressure of 100 psig, an acceptable performance. Elevated-temperature leakage measurements using molten salt showed no leakage at temperatures to 1000 F over a period of 7 hours.

Induction Brazed Seal

Induction brazing was planned for use to hermetically seal the stainless steel clad transmission lines to the K-94 bearing sleeve-simulator unit. The brazing was performed in two operations on practice specimens. First, a Kovar sleeve was brazed into a shallow groove in the K-94 unit. Subsequently, electrical connections were made between the transducer coil imbedded in the K-94 and a transmission line. A second brazing operation was used to seal a stainless steel sleeve bridging the joint between the Kovar and the stainless steel cladding of the transmission line. The braze used was a commercial product having a 91 Ni-4.5 Si-2.9 B composition, and the brazing was done

*B. Goobich, et al., "Development of AFRPL Threaded Fittings for Rocket Fuel", Tech. Doc. Rept. AFRPL-TR-65-162 (November, 1965).

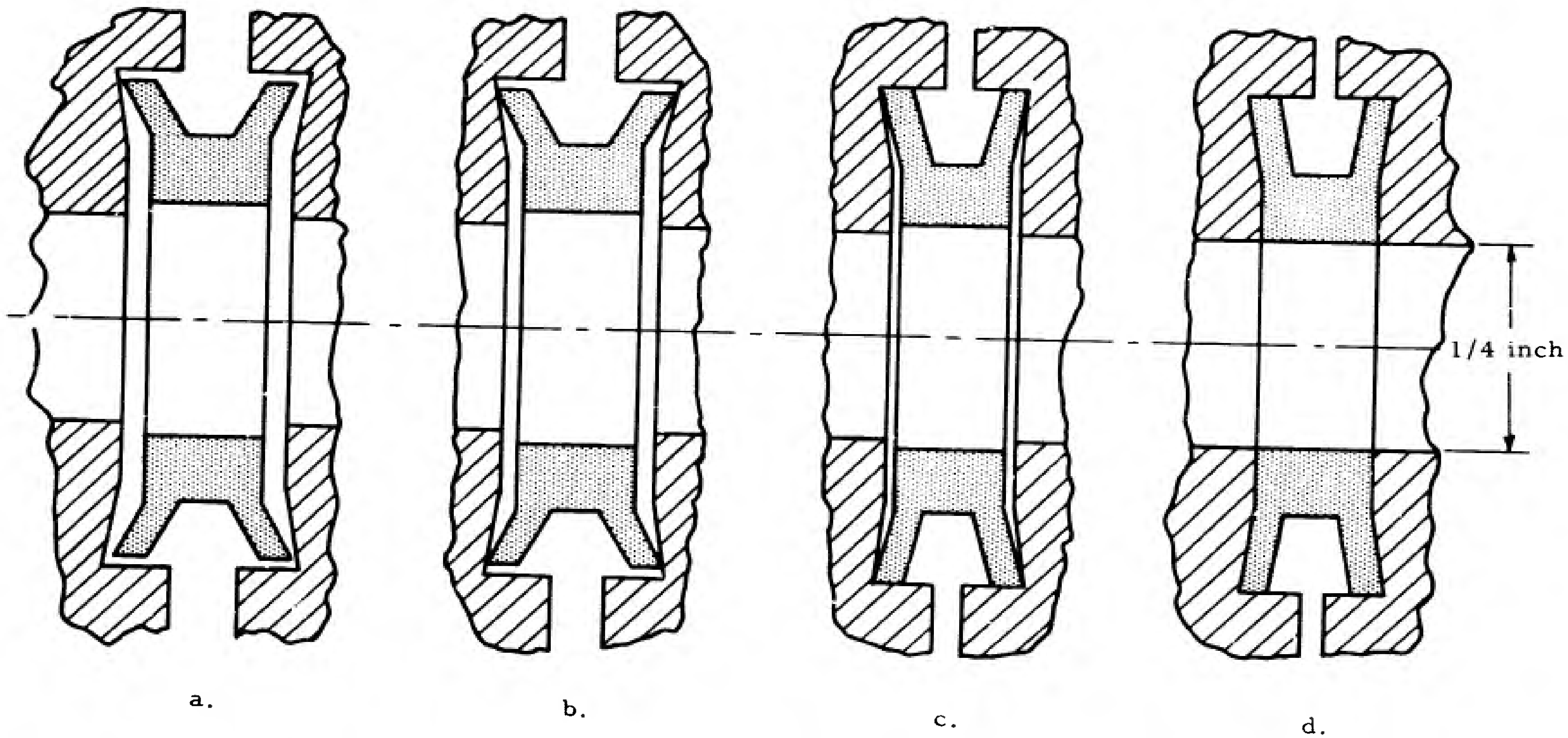

FIGURE 22. SEQUENCE OF STEPS FOR ASSEMBLY OF BOBBIN-SEAL

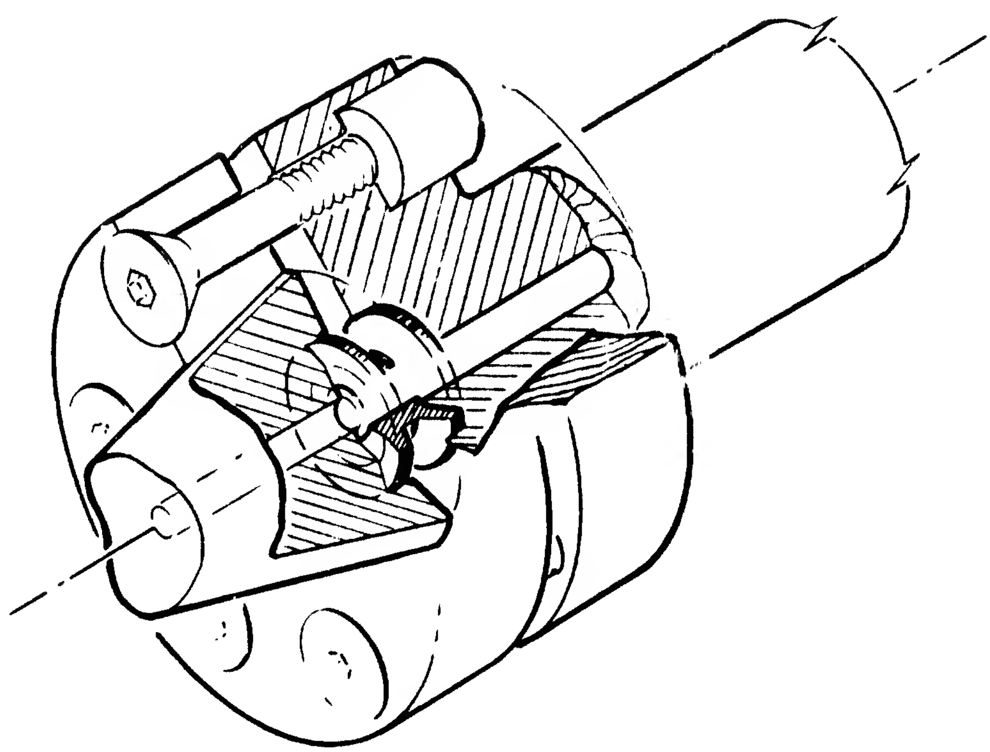

FIGURE 23. PICTORIAL VIEW OF MOUNTING OF TRANSDUCER UNIT WITH THE BOBBIN SEAL

in a vacuum at 1850 F. The braze wet K-94, Kovar, and type 316 stainless steel, and produced practice junctions exhibiting no significant leakage under helium mass-spectrometer leak checking. Problems of exposing gold-to-copper welds to 1850 F are considered in Appendix A.

APPENDIX E

PROCEDURE AND INSTRUMENTATION FOR EVALUATING PRESSURE TRANSDUCERS

The room-temperature testing facility employed for evaluating various core materials was simple in construction and consisted essentially of a lever arm, a knife edge, and support block for the transducers. The lever was supported at one end by the knife edge and at the other by the transducer, and weights were hung on a flexible cord midway between the supports. It was believed that the knife edge would offer a minimum friction resistance so that the transducers would support one-half the full load of the weights.

A preconditioning of the transducers was provided by applying a maximum weight and taking it away and repeating this cycle more than 10 times. Afterwards, the transducer response was obtained by adding incremental weights and then releasing these weights in the reverse order.

Figure 24 illustrates the electrical instrumentation employed in taking the transducer response readings. The center of the system is an a-c bridge network. A null was first obtained by balancing the bridge so that the impedance changes in the transducer caused by pressure loading would produce proportional voltage outputs. Percent changes in the magnitude of impedance were calculated by measuring the total voltages across the transducer coil. The transducer coils consisted of 160 turns of 38-gage copper wire, and each core piece of the bobbin-core type was 1/8 inch in length and 0.030 inch in diameter.

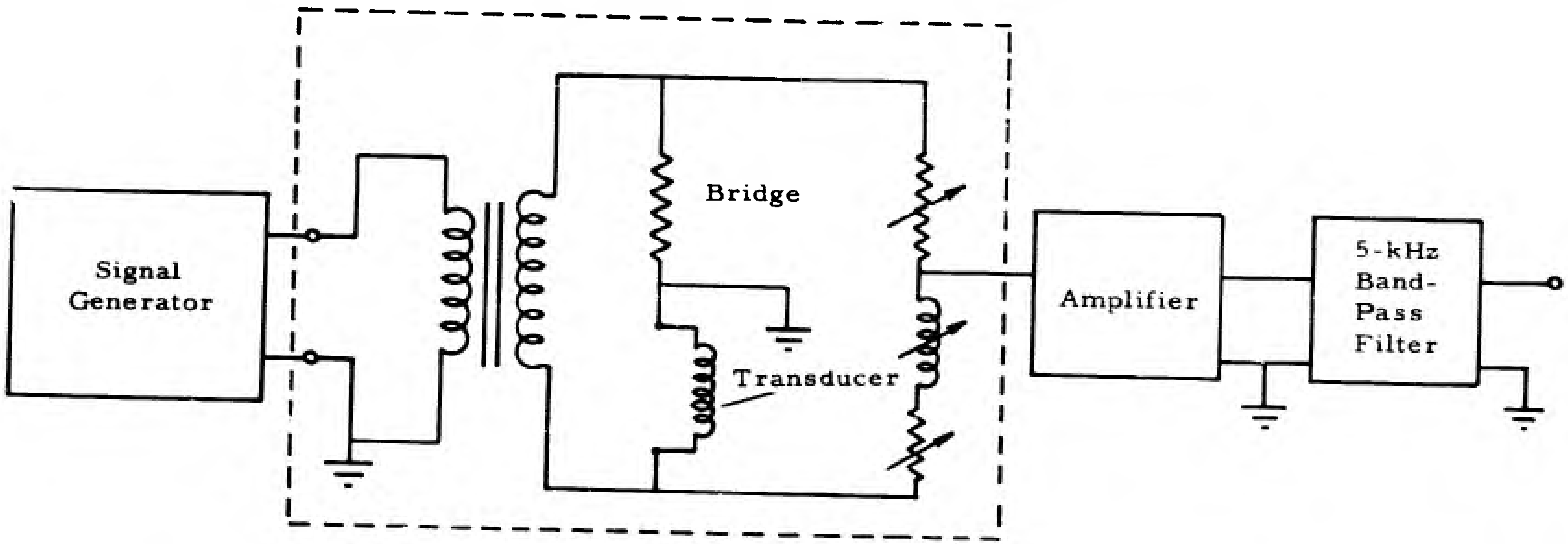

FIGURE 24. LABORATORY SYSTEM FOR EVALUATING THE PRELIMINARY PRESSURE TRANSDUCERS

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13. ABSTRACT

The program to develop advanced prototype instruments for the measurement of static and dynamic film thickness, film continuity, and film pressure in potassium-lubricated journal bearings has been terminated. Because of difficulties in fabricating final versions of the film-thickness transducers, no evaluations of prototype instruments were conducted in potassium. Performance data were obtained using laboratory simulation experiments.

Room-temperature simulations using metal foils were used to demonstrate the capabilities of the film-thickness-transducer design. Elevated-temperature evaluations in air or molten lead were used to examine the effects of temperature on the transducer signal. Together these experiments give promise that the prototype film-thickness transducer and ancillary instrumentation system design should have the desired performance capability.

The film-pressure-transducer performance was evaluated at room temperature and elevated temperatures by direct force loading of the transducer core. With judicious choice of the material and mechanical design of the core, the experiments demonstrated the desired sensitivity and stability.

14. KEY WORDS	LINK A		LINK B		LINK C	
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