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**FEASIBILITY STUDY OF PROBE-TYPE
LIQUID METAL FLOWMETERS
FOR FTR SUBASSEMBLIES**

FEBRUARY 1969

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FEASIBILITY STUDY OF PROBE-TYPE LIQUID METAL
FLOWMETERS FOR FTR SUBASSEMBLIES

By

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ABSTRACT

Results of a feasibility study of probe-type liquid metal flowmeters are presented. A comparison of inside-channel eddy current flowmeters and inside-channel eddy current-ultrasonic flowmeters indicates that the eddy current flowmeter is most suitable for the proposed application in the FTR subassemblies. Experimental results using liquid Wood's alloy as the liquid metal medium indicate a sensitivity of 18 $\mu\text{V}/\text{ft}/\text{sec}$ velocity per volt bridge drive for a 1 in. diameter eddy current probe. Low impedance makes the eddy current probe compatible with cabling able to withstand radiation levels encountered in the reactor environment.

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FEASIBILITY STUDY OF PROBE-TYPE LIQUID METAL FLOWMETERS FOR FTR SUBASSEMBLIES

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INTRODUCTION

The purpose of this report is to present the results of a feasibility study of probe-type liquid metal flowmeters made in support of conceptual design planning relating to the Fast Flux Test Facility back-up (vertical core) design.

The study was conducted to determine the feasibility of monitoring coolant flow with a sensing probe placed in the center of the flow channel in contrast to the previously evaluated flow-through type.⁽¹⁾ The need to consider the inside type sensor (center of flow channel type) arises from the inherent design of the back-up system where the insertion of sensors into the open end of the coolant channel is planned.

Use of eddy current⁽²⁾ and ultrasonic⁽³⁾ effects in the detection and measurement of flow of conducting liquids has been reported in the technical literature, but design information applicable to specific problems is not readily found. Thus, the feasibility determination must be based on a study of matching the proposed technique to the specific environment and other special requirements of the reactor.

For the purpose of this study, the following design conditions are assumed:

Coolant	Liquid Sodium
Maximum coolant temperature	1200 °F
Inside diameter of coolant channel at sensor location	2.5 in.
Maximum diameter of sensor body	1.0 in.
Velocity of coolant flow	0 to 20 ft/sec
Jacket of sensor	0.015 in. thick stainless steel

SUMMARY AND CONCLUSIONS

Two types of liquid metal flowmeters were studied for possible use within the coolant flow channel in the FTR sub-assemblies back-up design. Laboratory measurements using eddy current and ultrasonic transducers with solid metal specimens showed the eddy current method to possess greater potential than the ultrasonic method for this application.

A mock-up simulating the flow of liquid metal past the sensing probes by moving a probe mount through a stationary column of molten Wood's metal at about 1.4 ft/sec was fabricated. Tests at temperatures of about 175 °F, approximately 17 °F above the melting point of the Wood's metal, were conducted. Safety features were built into the equipment to prevent toxic vapors generated by excessive temperatures. Results showed that an eddy current probe of 1 in. diam, operating in a bridge circuit at 800 Hz and with an impedance of approximately 14 ohms, would have a sensitivity of about 18×10^{-6} V/ft/sec velocity per volt bridge drive. The low impedance is considered favorable for this technique within the reactor environment where radiation effects on electrical characteristics of cables adversely affect the accuracy of high impedance sensors.

Additional study is needed to determine the effects of the variation of coolant temperature and coolant turbulent flow on the performance, and to provide a probe design for use in the reactor environment.

PRINCIPLES OF OPERATION

The principles of operation of the eddy current flowmeter and ultrasonic flowmeter differ greatly because in the former the energy transport is through the electromagnetic field whereas in the latter it is through material elastic waves.

EDDY CURRENT FLOWMETER

The eddy current flowmeter for electrically conducting materials may consist of two or more coils arranged so that movement of the conducting fluid unbalances a condition of symmetry existing under conditions of no movement. This type of flowmeter, described by Lehde and Lang,⁽²⁾ is proposed for use in a reactor by Evans.⁽³⁾ The principle on which these flowmeters operate is discussed by Graneau⁽⁴⁾ in reference to the effect of sample movement in some eddy current nondestructive tests. He shows the velocity effect to be due to the generation of currents within the moving conductor as it moves through the radial components of the magnetic field. The effect is not observed when using a single induction coil as illustrated in Figure 1. Eddy currents are induced in a conductor (here represented by a tube around the coil) by currents flowing in a single coil. The axial and radial components of the magnetic field of the coil will generally be as shown at points P_1 and P_2 . Under stationary conditions, only the axial field components, H_z , will cause induction of eddy currents in the tube. However, movement of the tube through a radial component of the magnetic field will induce a voltage around the tube wall and, since the radial fields on each side of the coil are opposite in direction, the flow of these currents on each side of the exciting coil are opposite in direction. These currents, of course, are also proportional to the magnitude and phase of the primary field and, thus, have the same frequency as the excitation current.

For the case where the product of operating frequency and coolant conductivity is small, the axial field induced currents lag the exciting current by about 90 electrical degrees, and the velocity induced currents are either in-phase or 180 degrees out-of-phase with the exciting current depending upon the motion direction of the conductor. As the operating frequency

FIGURE 1. Induction of Eddy Currents in a Conductor (Tube) Using a Single Induction Coil

increases or conductor conductivity increases, the field within the conductor lags in phase and becomes a complex function of depth within the conductor, thus affecting the resulting flow of velocity-induced currents. It is helpful in visualizing these effects to apply the principle of superposition. The total current flow is a summation of those due to the axial components of the ac magnetic field and those due to the motion of the conductor through the radial components of the field.

Since the induced voltage due to motion of the conductor through the radial component of the field is proportional to the conductor velocity, the resulting current flow is also proportional to velocity. The voltage induced in the coil due to these currents is zero because of the opposite direction of flow on each side of the coil. Thus, the effect, though present in the conductor, is not observed at the coil. However, the desired velocity effect may be observed with the three coil system shown in Figure 2 or the two coil bridge system shown in Figure 3. In both of these multiple coil systems, the respective sensing coils are closer to (and thus more sensitive to) currents on one side (upstream or downstream) of the excitation coil. In Figure 3, each coil performs both excitation and sensing functions.

Eddy current flow density in the conductor region in the vicinity of the excitation coil or coils varies greatly. Flow density is greatest near the coils and becomes smaller as distance from the coils increases. Assuming uniform geometrical conditions and uniform electrical characteristics of the conductor, two factors affect the current distribution. The current will be greatest near the excitation source due to the first factor (skin effect). This effect increases with increase in frequency and conductor conductivity and, at the higher frequencies, shows very little current penetration into the conductor. The second effect, due to the geometry of coils,

FIGURE 2. *Three-Coil Eddy Current System for Observing Velocity Effect*

FIGURE 3. *Two-Coil-Bridge Eddy Current System for Observing Velocity Effect*

has considerable effect on relative current density within the conductor. This effect at lower frequencies can limit the relative depth of current penetration and determine the general area in which currents flow.

Since eddy current density does vary in the conductor (fluid), the output of the sensor represents, even under ideal uniform flow across the cross section of the conductor, a weighted average of the flow velocity. Actually, one cannot depend upon uniform flow across the cross section of the flow channel, and distribution of flow across the cross section would be expected to vary with flow rate and temperature. One reference⁽³⁾ states that the eddy current flowmeter can be calibrated in position as a function of flow, but that no simple relation exists between output and total flow. The output sensitivity also varies with conductivity of the fluid which, in turn, varies with temperature. For example, the electrical resistivity of sodium⁽⁵⁾ varies approximately from 14 $\mu\text{ohm-cm}$ at 400 °F to 23 $\mu\text{ohm-cm}$ at 800 °F, and to 36 $\mu\text{ohm-cm}$ at 1200 °F. It is important that the sensing probe exhibit stable performance over the operating temperature range. Null balance drift can appear as an error in velocity readout.

Temperature differentials in the coolant between the two sensing coils also will yield an output error.

ULTRASONIC FLOWMETER

Due to the high operating temperature, development of an ultrasonic flowmeter using conventional transducer techniques⁽¹⁾ was expected to require considerable work. Because of its potential structural simplicity, consideration of an eddy current ultrasonic transducer based on principles previously demonstrated at Hanford⁽⁶⁾ was proposed. This transducer operates on the principle that vibrations are generated in a metal due to forces between the induced eddy currents and the

external electromagnetic field. Generation can be accomplished either with or without a dc magnetic field, although detection of vibrations within the metal by this method requires the use of an external field at the receiver. Also, when no polarizing field is used at the transmitter, double frequency components are present in the transmitted acoustic wave. The method is characterized by its low efficiency and the resulting low sensitivity compared with piezoelectric transducers. The generation of acoustic waves by rf fields is also discussed in relation to helicon waves.⁽⁷⁾

The measurement of coolant velocity using the ultrasonic method, except for the novel use of eddy current ultrasonic transducers, would follow conventional principles based upon differences of acoustic wave transit times in the direction of flow and counter to the direction of flow. One proposed arrangement is shown in Figure 4. Transducers A and B each operate as transmitter and receiver. Each is driven with a sending pulse simultaneously. The time of transit of the ultrasonic wave in the coolant depends upon the direction and velocity of coolant flow. Measurement of the difference of transit times gives a measure of the velocity. For example, with transducer spacing, d , ultrasonic velocity, c , and coolant velocity, v , the downstream transit time is:

$$t_1 = \frac{d}{c + v} \quad (1)$$

The upstream transit time is

$$t_2 = \frac{d}{c - v} \quad (2)$$

The time difference is

$$t_2 - t_1 = \frac{d}{c - v} - \frac{d}{c + v} = \frac{2dv}{c^2 - v^2} \quad (3)$$

FIGURE 4. Eddy Current - Ultrasonic Method for Observing Velocity Effect

or,

$$t_2 - t_1 \approx \frac{2dv}{c^2} \quad (4)$$

The time difference, under the conditions that $c = 2.4 \times 10^5$ cm/sec, $d = 30.48$ cm, and $v = 1$ ft/sec = 30.48 cm/sec, is found to be

$$\Delta t = t_2 - t_1 = 32.3 \text{ nsec/ft/sec} \quad (5)$$

or,

$$\Delta t = 0.0323 \text{ } \mu\text{sec/ft/sec} \quad (6)$$

In an alternate electronic configuration, the transducers would be driven by a synchronized burst of a 1 MHz signal. The time difference would be determined by phase comparison of the received signals. In this method, each 10° phase difference would be equivalent to a coolant velocity of about 3 ft/sec.

DESCRIPTION OF EXPERIMENTAL APPARATUS

In order to evaluate the two types of liquid-metal flow-meters considered in this report, a suitable experimental apparatus was required for simulating flow of liquid metal past the probes. Two alternate experimental arrangements were possible. The first involved pumping a suitable liquid metal past the stationary probes in some form of closed-loop pumping system. The second approach involved mechanically translating the probes through a stationary column of liquid metal, thus simulating flow of the metal past the probes. Although closed-loop liquid sodium systems were available at PNL, the inherent problems associated with operating the experimental apparatus in such an environment were deemed too difficult to overcome in the short time available. Hence, the aforementioned second approach was selected. This section will describe the experimental apparatus constructed, and outline the various measurements made with the two probe-type flow meters.

The choice of a suitable liquid metal environment for use in performing measurements on the probe-type flowmeters will first be considered. As mentioned earlier, liquid sodium, although obviously the desired choice, is difficult to contain and potentially dangerous. Hence, a search for a low melting point, relatively nontoxic metal to use as a substitute was undertaken. Mercury was considered, since it is liquid at room temperature. Due to its high toxicity, however, a less dangerous metal was sought. After further investigation, Wood's metal was chosen.

Wood's metal, a bismuth-lead-tin-cadmium alloy with a melting point of 158 °F, is convenient to use and is safe at temperatures below 250 °F but hazardous to life at higher temperatures. Extremely toxic vapors are produced at temperatures in excess of 250 °F due to oxidation of the cadmium in the

alloy. Hence, the apparatus used to contain the liquified metal requires built-in safety features designed to prevent temperature excursions which could cause oxidation of the cadmium in the alloy.

With the foregoing in mind, details of the apparatus used to contain the liquid metal and to simulate flow of the metal past the probes will be considered. Figures 5 and 6 are photographs of the apparatus. Basically, the device consists of a 2 1/2 in. ID schedule 80 stainless steel tube approximately 4 ft long surrounded by a brass water jacket (see Figure 7 for a section view). Water contained in the water jacket surrounds the stainless steel inner tube. A laboratory heating tape wound around the outside of the water jacket heats the water which, in turn, heats the inner tube containing the Wood's metal. The water temperature, and thus the temperature of the molten Wood's metal, is controlled by means of a temperature monitor and a Variac autotransformer controlling current flow through the heating tape. The temperature of the molten metal can thus be maintained a few degrees above the melting point to insure that the alloy remains melted but does not exceed the oxidation temperature of the cadmium in the alloy. The water jacket is kept full at all times by means of water, gravity fed from a container (visible in Figures 6 and 7). Any steam forming in the jacket is vented through a standpipe in the top flange of the jacket. These provisions were necessary to prevent a lowering water level and consequent local heating of regions of the liquid metal column sufficient in intensity to oxidize the cadmium in the Wood's metal. The Wood's metal is introduced into the stainless steel inner tube and maintained in the molten state in the manner just described.

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FIGURE 5. Front View of Liquid Metal Apparatus Showing Drive Motor and Electronics System

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FIGURE 6. Rear View of Liquid Metal Apparatus Showing Mechanical Probe Drive and Liquid Metal Vessel

FIGURE 7. *Liquid Metal Vessel and Water Jacket*

Choice of probe designs and the manner in which they are translated through the column of liquid Wood's metal will be considered next. Since two basic eddy current-effect flowmeters were considered in this study, suitable probes to examine each effect were required. Construction of the probes necessitated taking into account both the electrical requirements of a probe suitable for studying each effect, and the physical and mechanical constraints imposed by the vessel in which they were to be moved. A suitable mechanical drive scheme was, in turn, constrained by the physical design of the probes. Every effort was made to make the drive (translating mechanism) compatible with both probes so that they could readily be interchanged to facilitate study of both the eddy current and eddy current-ultrasonic effects. Due to lack of time, measurements were not made on the eddy current-ultrasonic probe in the liquid metal. This matter will be discussed more fully in a later section.

Figure 8 is a photograph of the probes fabricated for use in this study. The top probe is the eddy current-ultrasonic probe, while the bottom two probes were designed for evaluating the straight eddy current-effect flow measurements. The middle probe in the photograph was not utilized because machining difficulties during its construction resulted in a probe too large to fit the inside diameter of the stainless steel liquid metal vessel. Hence, all measurements taken in the liquid metal of the eddy current-effect flowmeter were made using the probe shown at the bottom of the photograph.

Figures 9a and 9b depict schematically the eddy current and eddy current-ultrasonic probes, respectively. The eddy current probe consists of two coils wound adjacent to one

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FIGURE 8. Eddy Current Effect and Eddy Current-Ultrasonic
Effect Flow Measuring Probes

(a) Eddy Current Probe

(b) Eddy Current-Ultrasonic Probe

FIGURE 9. *Schematic Representation of Eddy Current and Eddy Current-Ultrasonic Probes*

another on a phenolic coil form. The form is inserted in a stainless steel cladding jacket affixed to the connecting rod as shown. The positioning fins serve to keep the probe in the geometric center of the liquid metal vessel so that eddy currents induced in the walls of the vessel will not affect the probe differently as a function of probe-to-wall spacing. Electrical leads from the coils are fastened to the connecting rod and brought out to the electronics system processing the electrical signals from the coils. The leads are not shown in Figure 9 for the sake of clarity. The mounting plate shown at the left end of the probe assembly attaches to the drive mechanism.

The eddy current-ultrasonic probe (Figure 9b) differs considerably from the eddy current probe in its construction. In this probe, separate transmitting and receiving coils are positioned with respect to one another as shown in the Figure. The coils themselves are wound on permanent magnets contained in stainless steel enclosures. The magnets are used to enhance the induced eddy currents. Provision has been made to accommodate several different thicknesses of stainless steel (the windows in Figure 9b) between the exciting coils and the liquid metal in order to evaluate the effect upon the final measured results. As in the case of the eddy current probe, a connecting rod fastens the coils to the mounting plate which is attached, in turn, to the drive mechanism. Positioning fins are again used to center the assembly within the liquid metal vessel.

The drive mechanism used to translate the probes through the liquid metal will now be considered. The mechanism is visible in Figures 5 and 6. Figure 10 shows an exploded view

FIGURE 10. Probe Drive Mechanism

for the sake of clarity. Probe drive is accomplished by actuating the stepping motor, thus driving the pinion gear through the drive gears and mainshaft combination. The pinion gear causes the rack gear to translate in the guide assembly. Cam followers located in the guide assembly serve to align and constrain movement of the rack gear in a vertical path. The probes are then fastened to the probe mounting plate and translated through the liquid metal vessel as the stepping motor runs. Limit microswitches and an associated electronics system actuate and reverse the stepping motor as the probe reaches the limits of its translation path through the vessel. In this manner, periodic motion of the probe through the liquid metal is achieved and flow past the probe is thus simulated.

The electronics systems used with the probes to measure flow velocities are described in the following section.

EXPERIMENTAL RESULTS

Most of the effort was placed on the eddy current flowmeter because, as measurements progressed, this method appeared to have the greater potential of the two considered. Time was not available to bring the measurements of the eddy current-ultrasonic study to an equivalent stage of progress.

EDDY CURRENT FLOWMETER

Preliminary measurements were made to demonstrate the method and to determine performance of several types of eddy current test coil configurations. These tests and results are described in Appendix A. From these tests and the incorporation of the liquid metal system and probe translating equipment described in the previous section was evolved the final test system shown in diagram form in Figure 11. A photograph of the system appears in Figure 12. A sketch of the cross section of the final eddy current probe used is shown in Figure 13. Each of the two windings were 250 turns of No. 30 magnet wire, with

FIGURE 11. Block Diagram of Final Test System

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FIGURE 12. Test System Instrumentation

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Coil Width: 0.25 in.
Gap Between Coils: 0.031 in.

FIGURE 13. Eddy Current Probe No. 8 with Stainless Steel Sheath

inductances of 794 μH and 859 μH and resistances of 5.4 ohms and 5.5 ohms, respectively. The operating frequency was 800 Hz and the bridge circuit was that used by Robinson and Perriam⁽⁸⁾ in the inspection of tubing. The bridge output, brought to a null balance with the Wood's metal column in liquid state, was amplified, filtered by band pass filters, and viewed on an oscilloscope and a vector impedance locus plotter. The locus plotter was connected to display the voltage vector locus of the signal labeled E_{out} . Permanent records of the tests were made by a chart recorder, with recording channels as follows:

<u>Channel</u>	<u>Signal Recorded</u>
1	Output of one channel of vector locus plotter.
2	E_{out} (Input to vector locus plotter)
3	60 Hz timing signal
4	Output of stepping motor used as a probe position (velocity) indicator

In operating the stepping motor drive system (Figure 10), the motor was found to have insufficient power to drive the probe assembly at the desired velocity. With time unavailable for procuring a larger motor, the probe rack gear assembly was moved up and down manually during the tests. The stepping motor then acted as a generator and its output was calibrated and recorded for use in computing probe velocity.

A typical record of the tests is shown in Figure 14. The top trace is the 60 Hz timing signal, the next is E_0 (the ac signal at the input of the vector plotter), the next is the output of one of the two output channels of the vector plotter with baseline added, and the lower trace is the output of the stepping motor used for determining the probe velocity.

Similar charts without the E_0 signal and at 10 times the chart speed of 50 in./sec are shown in Figure 15 (region of maximum velocity on upward stroke) and Figure 16 (region of maximum velocity on downward stroke).

FIGURE 14. Record of Typical Test Run with Eddy Current Flowmeter

FIGURE 15. *Eddy Current Flowmeter Output: Region of Peak Probe Velocity During Upward Stroke. (Time scale expanded).*

FIGURE 16. Eddy Current Flowmeter Output: Region of Peak Probe Velocity During Downward Stroke (Time scale expanded).

As shown in Appendix B, the velocity sensitivity for this run, corrected for the displacement effect of the probe, is

$$V_V = 18.4 \times 10^{-6} \text{ V peak-to-peak at bridge output per volt bridge drive per ft/sec flow velocity.}$$

EDDY CURRENT ULTRASONIC TEST RESULTS

For the first test, a coil was hand-wound on one leg of a horse-shoe magnet. Twenty turns of No. 28 magnet wire were placed on separate magnets for the transmitter and for the receiver coils.

The block diagram appearing in Figure 17 illustrates how the coils were driven electrically. A time mark generator pulsed the Arenberg pulsed oscillator (tuned to 10 kHz) which, in turn, drove the transmitter coil. The receiver coil fed into an Arenberg preamplifier also tuned to 10 kHz. The output was then viewed on an oscilloscope.

Twenty turns of wire proved insufficient to produce any signal, so the number of turns was increased to 50. This increase still did not produce any output signal. The receiving coil was replaced by a 10 kHz piezoelectric crystal transducer and some signal could be detected.

The same number of hand-wound turns were tried on a round bar magnet 1/2 in. in diameter and 1 in. long. Although no signal was brought in by the coil, a small signal was detected by means of the 10 kHz crystal.

The next step was to wind coils on a form 3/8 in. in diameter and 1/8 in. long. Fifty turns of No. 34 magnet wire were used for the first coils. These coils were then molded with RTV-102 flush to the end of one of the horseshoe magnet legs. The magnets and coils were then close-coupled to the metal sample. It was still difficult to note any output signal. However, with the 10 kHz crystal replacing the receiving coil, a strong signal was detected.

FIGURE 17. Block Diagram of Eddy Current-Ultrasonic Transducer Test

The next step was to use two coils in series, each with 50 turns of No. 34 magnet wire wound on the previously used forms. The two coils were molded one each on each leg of the horseshoe magnet flush with the magnet end to assure close coupling with the sample. One set of coils was used for the transmitter coil and one set for the receiver coil. A signal due to the transmission of the longitudinal acoustic wave through an aluminum sample was observed with this arrangement. Eight internal reflections of the first longitudinal acoustic wave also were detected. The signal-to-noise ratio was noted to be approximately 2 to 1.

DISCUSSION

The tests using the eddy current flowmeter method show good potential. Although the bridge output for the flow rate of 1.6 ft/sec (at the probe position) was only 18.4 μ V peak-to-peak per volt bridge drive, flows in the reactor are expected to exceed this by a factor of 10 or more. Apparent sensitivity may also be increased somewhat by increasing the bridge drive power.

A two coil probe system requiring 3 or 4 leads to carry both excitation and signal currents as is customary in the applicable bridge circuit was used. In view of the large temperature variations expected, use of a 3 coil system (Figure A-7) may be desirable. This arrangement, although requiring three pairs of leads, is desirable from the standpoint that signal excitation currents do not flow through the signal leads. In addition, current flowing in the signal leads can be kept low.

Over the operating temperature range of the reactor, the sodium coolant will have approximately 2 1/2 to 6 times the electrical conductivity of the Wood's metal used in these simulation tests and, at the 800 Hz operating frequency, would

retard the penetration of eddy currents in the coolant and provide a higher sensitivity to flow. However, the smaller depth of penetration would weight the flow measurement more towards the region near the probe. It may be more desirable, by lowering the operating frequency and foregoing the increase in sensitivity, to effect about the same depth of penetration obtained in the Wood's metal at 800 Hz. In any event, measurements will still vary considerably due to the wide temperature variation. This and the effect of the temperature variations on the performance of the probe system will require further study.

RECOMMENDED FUTURE WORK

The following future flowmeter studies, conducted in the order of listing, are recommended.

1. Firm the design of a prototype probe and determine readout equipment requirements.
 - a. Further explore test coil configuration for use in design of probe.
 - b. Design a probe and connecting leads suitable for operation at the reactor operating temperature.
 - c. Study the effects of cross talk between adjacent probes in a multiple flow channel installation. Evaluate need for a range of operating frequencies to reduce cross talk.
 - d. Study readout equipment alternatives. Evaluate use of a multiplexing system to reduce duplication of readout equipment.
 - e. Measure, by the use of metal sleeves of different electrical conductivities, the effect on the velocity calibration of coolant conductivity change resulting from temperature variation.

2. Build and test a prototype probe at about 180 °F.
 - a. Build a prototype probe and selected amplifier detector circuit.
 - b. Check probe operation at about 180 °F using Wood's metal mock-up.
 - c. Determine sensitivity of probe to flow velocity profile.
 - d. Measure sensitivity to cross-talk using a simulated second probe system.
 - e. Check velocity sensitivity and stability at 180 °F.
3. Test the prototype probe at proposed operating temperatures without and with simulated coolant.
 - a. Test in a furnace the prototype probe for null stability and integrity over the proposed operating temperature range without real or simulated coolant.
 - b. Test the prototype probe, inserted in a metallic sleeve simulating the coolant, over the proposed operating temperature range.
 - c. Modify the design of the probe as needed to meet in-service requirements.
4. Related research of interest.
 - a. Evaluate use of pulse excitation of the eddy current flowmeter.
 - b. Obtain more definitive results for possible future application by completing eddy current ultrasonic flowmeter tests.

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APPENDIX A

PRELIMINARY MEASUREMENTS FOR EDDY CURRENT COIL DESIGN

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PRELIMINARY MEASUREMENTS FOR EDDY CURRENT COIL DESIGN

Measurements were first made to determine sensitivity to velocity and to compare the performance of different coil arrangements as design aids for the eddy current coil assembly.

The velocity effect was first observed using the circuit shown in Figure A-1 with the coil assembly Probe No. 1. Flow of material past the coils was simulated by moving the probe, consisting of two form-wound coils, inside a section of Schedule 80, 304 LC stainless steel pipe of 1.35 in. OD, 0.179 in. in wall thickness, and about 4 ft in length. In these tests, a null was first obtained by balancing the bridge with no probe movement. Then, as the probe was moved in the pipe, a deflection apparently proportional in magnitude to probe velocity was observed on the vectorscope.

Various probe configurations were tested by the probe motor drive system shown in Figure A-2. The same bridge electrical drive voltage was used for each coil configuration. The resulting vectorscope deflections were compared for each probe as the probe was translated at a velocity of about 2 ft per sec.

Several different coil configurations were tested with this system. Figures A-3 through A-7, and Figures A-9 and A-10 illustrate the various coils. Figure A-8 is a ring demodulator circuit used to test eddy current probe No. 5 for indications of phase and amplitude shift.

Various observations employing each of these coils led to the final configuration chosen for tests in the liquid Wood's metal vessel. These observations are described for the reader's information as follows:

FIGURE A-1. Bridge Circuit for Eddy Current Probe Tests

FIGURE A-2. Motor Drive and Probe Arrangement for Probe Comparison Tests

COIL FORM

Length: 3.5 in.
 Diameter: 0.87 in.

COILS

Length (each): 1.5 in.
 Two Layers #30 Magnet Wire, 300 Turns Each
 Spacing Between Coils: 0.0625 in.
 Inductance (each): $\approx 700 \mu\text{H}$
 Resistance (each): $\approx 8 \text{ ohms}$

FIGURE A-3. Eddy Current Probe No. 1

COIL FORM

Length: 3.0 in.
Diameter: 0.87 in.

COILS

Length (each): 0.125 in.
L1: 54 Turns #30 Magnet Wire
L2: 59 Turns #30 Magnet Wire
Inductance: L1 = 103 μ H
 L2 = 125 μ H
Resistance (each): $\approx$ 3 ohms
Spacing Between Coils: 0.0625 in.

FIGURE A-4. Eddy Current Probe No. 2

COIL FORM

Length: 3.0 in.
Diameter: 0.87 in.

COILS

Length (each): 0.094 in.
Spacing Between Coils: 0.031 in.
7 Turns per Coil #30 Magnet Wire
Total Inductance (each 3 coil set): 11 μ H
Total Resistance (each 3 coil set): $\approx$ 2.2 ohms

FIGURE A-5. Eddy Current Probe No. 3

COIL FORM

Length: 3.5 in.
Diameter: 0.87 in.

COILS

193 Turns per Coil, #30 Magnet Wire
Inductance (each): 270 μ H
Resistance (each): 6.4 ohms
Both Coils Single Layer

FIGURE A-6. Eddy Current Probe No. 4

COIL FORM

Length: 3.5 in.
Diameter: 0.87 in.

COILS

No. 1: 89 Turns, #30 Magnet Wire
Resistance: 3.4Ω
No. 2: 85 Turns, #30 Magnet Wire
Resistance: 3.65Ω
No. 3: 85 Turns, #30 Magnet Wire
Resistance: 3.75Ω
Inductance (each): $\approx 104 \mu\text{H}$

(a) Eddy Current Probe No. 5

(b) Three-Coil System

FIGURE A-7. Eddy Current Probe No. 5 and Three-Coil Wiring Diagram

A-7

FIGURE A-8. Ring Demodulator Circuit

BNWL-911

COIL FORM

Length: 5 in.
Diameter: 0.87 in.

COILS

Length (each): 2.0 in.
No. of Turns (each): 345, #30 Magnet Wire
Inductance (1): 950 μ H
Inductance (2): 910 μ H
Resistance (each): 10.5 ohms

FIGURE A-9. Eddy Current Probe No. 6

COIL FORM

Length: 3 in.
Diameter: 0.87 in.

COILS

Length (each): 0.25 in.
No. of Turns (each): 250, #30 Magnet Wire
Inductance (1): 1420 μ H
Inductance (2): 1240 μ H
Resistance (1): 7.3 ohms
Resistance (2): 6.8 ohms

FIGURE A-10. Eddy Current Probe No. 7

Probe No. 1 A velocity effect was observed with this coil. To determine any deviations in the sensitivity of the coil to velocity effects, the leads of one of the coils were reversed to alter the coil phasing. This procedure did not produce any indication of an effect on the velocity sensitivity of the probe.

Probe No. 2 A power amplifier to drive this coil configuration employed higher current levels than were used with Probe No. 1. The velocity effect observed on the vectorscope was very small compared to the observed effect with Probe No. 1. This effect was to be expected, however, as much smaller coils were employed in Probe No. 2.

Probe No. 3 This probe was constructed to observe the effect of multiple coils, closely wound along the same coil form. Six coils, with every other coil connected together as shown in Figure A-5, were used. No velocity effect was observed in this scheme and, hence, it was abandoned.

Probe No. 4 The effect of overlapping the two induction coils was investigated with this probe arrangement. A velocity effect was observed, but the sensitivity was marginal.

Probe No. 5 A three-coil arrangement was evaluated with this probe. One of the coils was used as the driver coil and the other two as pickup coils. Figure A-7b illustrates the necessary modification of the bridge circuit used with the pickup coils. Much easier bridge nulling was achieved and the sensitivity of the probe to the velocity effect was equal to the best results obtained with previous configurations even though the bridge drive voltage was reduced slightly. The ring demodulator circuit shown in Figure A-8 was used to observe phase and amplitude shifts in the probe output signal.

Probe No. 6 This two-coil probe was constructed to determine the effect of gap width between the coils on the velocity effect. One coil was made stationary, while the other was

moveable to facilitate altering the gap. Gap widths of $3/32$ in., $1/4$ in., $1/2$ in., and $3/4$ in. were tested. An increase in the gap width was observed to decrease the observed velocity effect. Thus, close spacing of the coils was determined necessary to achieve maximum probe sensitivity.

Probe No. 7 This two-coil probe was also constructed to allow gap spacing between the coils to be altered. The coils themselves, however, were considerably shorter than those used in Probe No. 6 and, in addition, consisted of many layers of wire and considerably more turns. Velocity effects observed with this probe were from two to four times as great as with Probe No. 6, even though the same drive voltage level and amplification were used.

APPENDIX B

DATA AND COMPUTATIONS RELATING
TO CALIBRATION OF EDDY CURRENT FLOWMETER

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STEPPING MOTOR DATA

The name plate information states that the stepping motor, Figure 10, rotates at 72 rpm with 60 Hz input. It was determined by measurement that when the shaft was rotated one revolution, 50 pulses were observed at the motor terminals. This output is in agreement with the name plate information since

$$\text{Pulses per revolution} = \frac{\text{Cycles/min}}{\text{Revolutions/min}} = \frac{60 \times 60}{72} = 50 \quad (\text{B1})$$

With the gearing arrangement shown in Figure 10, it was determined by measurement that rotating the stepping motor shaft one revolution would move the rack gear carrying the probe mount by 6.5 in. The probe travel per cycle, P_t , was thus determined to be:

$$P_t = \frac{6.5}{50} = 0.13 \text{ in.} \quad (\text{B2})$$

Letting v_p = probe velocity (fps) and t_c = elapsed time between output pulses when the stepping motor is used as a tachometer, we find that

$$v_p = \frac{P_t}{12t_c} = \frac{0.13}{12t_c} = \frac{0.0108}{t_c} \quad (\text{B3})$$

The time between pulses, t_c , may be obtained from the chart records (Figures 14, 15, and 16) in the following manner:

$$t_c = \frac{\ell_s}{\ell_{60}} \times \frac{1}{60} \quad (\text{B4})$$

where ℓ_s and ℓ_{60} are the measured lengths along the chart of one cycle of the stepping motor output and the 60 Hz timing signal, respectively.

Equations (B3) and (B4) may be combined to give the probe velocity, v_p :

$$v_p = 0.0108 \times \frac{\ell_{60}}{\ell_s} \times 60 = 0.648 \frac{\ell_{60}}{\ell_s} \quad (B5)$$

The velocity sensitivity may be computed from the data in Figures 14 and 15. At the peak velocity of the probe, ℓ_s is measured to be 0.380 in. and ℓ_{60} is 0.820 in. Then using Equation (B5),

$$v_p = 0.648 \times \frac{0.820}{0.380} = 1.40 \text{ ft/sec} \quad (B6)$$

SIGNAL VOLTAGE CALIBRATION

The measured value of the voltage gain between bridge output and vector locus plotter was

$$\frac{E_o}{E_B} = 370 \quad (B7)$$

Deflection sensitivity of the vector locus plotter was 1 in. deflection for a signal input, E_o , equal to 0.149 V peak-to-peak. For this same deflection (1 in.), the chart record deflection was also 1.0 in. Figures 14 and 15 show the peak-to-peak deflection of the signal to be 1.8 in. From the foregoing, the overall voltage velocity sensitivity, V_v , of the probe expressed as volts peak-to-peak at the bridge output for a probe velocity of 1 ft/sec, and for the bridge drive voltage equal to 12 V peak-to-peak is:

$$V_v = \frac{0.149}{370} \times \frac{0.9}{1.40} = 259 \times 10^{-6} \text{ V peak-to-peak} \quad (B8)$$

A correction factor can be applied to this sensitivity factor to account for the actual increase in flow velocity due to the displacement of the probe. The velocity factor is

given as

$$F_v = \frac{D_1^2}{D_1^2 - D_2^2} \quad (B9)$$

where

D_1 = inside diameter of flow channel and

D_2 = outside diameter of eddy current probe.

F_v is thus found to be

$$F_v = \frac{(2.5)^2}{(2.5)^2 - (0.95)^2} = 1.17 \quad (B10)$$

Since the uncorrected velocity was found to be 1.4 ft/sec (Equation B6), the corrected velocity is thus

$$v_c = v_p F_v = (1.4) (1.17) = 1.64 \text{ ft/sec} \quad (B11)$$

Similarly, the corrected voltage velocity sensitivity is given as

$$V_{vc} = \frac{V_v}{F_v} = \frac{259 \times 10^{-6}}{1.17} = 221 \times 10^{-6} \text{ V peak-to-peak} \quad (B12)$$

If V_v is expressed in volts peak-to-peak at the bridge output per volt bridge drive per ft/sec velocity, we find that $V_v = 18.4 \times 10^{-6}$ V peak-to-peak per volt bridge drive per ft/sec flow velocity.

IMPEDANCE OF COILS USED IN PROBE

$$L_1 = 794 \text{ } \mu\text{H} \quad , \quad R_1 = 5.4 \text{ } \Omega$$

$$L_2 = 859 \text{ } \mu\text{H} \quad , \quad R_2 = 5.5 \text{ } \Omega$$

Thus, $L_{\text{total}} = 1653 \text{ } \mu\text{H}$ and $R_{\text{total}} = 10.9 \text{ } \Omega$. The reactance of L_{total} at the 800 Hz operating frequency is found to be

$$\begin{aligned} X_L &= \omega L = (6.28) (800) (1.653 \times 10^{-3}) \\ &= 8.31 \text{ } \Omega \end{aligned} \quad (B13)$$

The total impedance is given as

$$Z = \sqrt{R^2 + X_L^2} = \sqrt{(10.9)^2 + (8.31)^2} = 13.7 \, \Omega \quad (B14)$$

Thus, the total series coil impedance is found to be approximately 14 ohms.

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