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Argonne National Laboratory

AN INDUCTION PROBE FOR MEASURING LIQUID LEVELS IN LIQUID METALS

by

T. R. Johnson, F. G. Teats,
and R. D. Pierce

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IN NUCLEAR SCIENCE ABSTRACTS

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Chemical Engineering Division

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ABSTRACT

A mutual-inductance probe has been developed to determine the location of the interface between gas and liquid metal and between liquid salt and liquid metal. The probe is a bifilar winding of Nichrome wire on an alumina form contained in a Type 304 stainless steel or a ceramic well. A high-frequency voltage supplied to one winding induces a voltage in the second winding, that can be related to the depth of liquid surrounding the coil. Probes, approximately 5 and 14 in. long, have been calibrated in liquid cadmium, bismuth, and sodium over the range from 200 to 700°C. The output signal was only slightly affected by the metal resistivity over the range from 20 to 140 $\mu\text{ohm-cm}$. The response was influenced by the temperature of the probe. A simplified procedure for calibrating the probe is discussed.

Although developed primarily for use in nuclear-fuel recovery processes that employ liquid metals as solvents, the device has several important advantages over other means of measuring liquid levels. It is compact, rugged, reliable, and reasonably accurate. The average deviation in measured liquid level was 2 to 3% of probe length. The instrument is well adapted to operations in remotely operated facilities, because it has no moving parts and can be replaced easily.

I. INTRODUCTION

Reactor-fuel recovery processes¹ that are being studied at Argonne National Laboratory use liquid metals and liquid chloride salts as solvents for uranium, plutonium, and fission products. The metals are mixtures of magnesium, zinc, and cadmium, and the salts are the chlorides of magnesium, sodium, potassium, and calcium. For these pyrochemical processes, the depth of the liquid metal and the location of the interface between the

liquid metals and salts often must be determined in the processing vessels. The method of detection should have a reproducibility and accuracy in the range of 1/8 in., be able to operate under vacuum and pressure in gas-tight systems and at temperatures up to 900°C, and be able to withstand the corrosive effects of the metal and salt solvents. The measuring device must be small enough to fit into confined areas and be usable in remotely maintained and operated facilities. It is preferable that the device have no moving parts. The probe itself should have a high degree of reliability and be of a design to make replacement easy. A mutual-inductance probe has been developed which fulfills these requirements satisfactorily.

Other types of liquid-level indicators were considered but were thought to have limitations that would impair their usefulness in pyrochemical processes. Sight glasses in which the liquid level is determined visually were eliminated from consideration because of design and mechanical difficulties and because visual sighting in shielded facilities can be difficult. Also, liquid metals containing magnesium attack glasses that contain silica.

Float gauges can be fabricated of corrosion-resistant materials, but other than visual means of indicating the float position must be used. Mechanical linkages moving an external indicator are unattractive in gas-tight systems. A radiation source cannot be used to locate the position of a float or of the liquid surface because of the high gamma-ray field intensity associated with nuclear-fuel recovery processes.

If the liquid density is known, the position of the liquid-gas interface can be determined by a pressure measurement at a known location in a vessel. Diaphragm pressure transducers suitable for use in liquid metals^{2,3} and salts⁴ have been built and used successfully. However, they were considered to be insufficiently rugged and too bulky for use in pyrochemical process vessels. Pressure measurements suitable for the location of liquid levels can also be made by determining the pressure required to expel gas from a tube immersed in the liquid. Such devices, bubbler gauges,⁵ have been applied in liquid-metal and salt systems. The very pure inert gas needed to prevent contamination of the molten solutions, and the vaporization and entrainment of volatiles in the gas stream, are problems that reduce the desirability of this method of measurement. A very slow bubble rate minimizes these difficulties, but at lower gas flow rates, the instrument cannot record rapid changes in liquid level and will give inaccurate readings. In metal or salt systems, precautions must be taken to prevent the fluid from entering the dip leg, reaching a cold region, and solidifying.

Electrical types of liquid-level measurement devices fall into four classes: resistance, capacitance, inductance, and dielectric. Of these, the inductance and resistance types are most applicable to liquids having high electrical conductivities. A capacitance type of level indicator measures the change of capacitance between two plates as they become immersed

in the liquid. Instruments based on this principle cannot be used with liquid metals and salts because of the high conductivities of these materials. Instruments based on dielectric losses cannot be used in liquid metals and salts because of the low polar moments and high conductivities of these materials.

Resistance devices usually consist of a fixed or moving electrode inserted into the containment vessel but insulated from it. When the liquid touches this electrode, a circuit is completed. The movable type, which is generally necessary for continuous liquid-level measurements, is difficult to manipulate in remotely operated facilities. Another disadvantage of this type of probe is the condensation of metal vapors that accumulate in cool regions, such as around the insulation separating the probe from the containment vessel. The gradually accumulating condensed material ultimately causes short circuits and false signals.

A fixed-resistance probe that can measure liquid levels continuously has been developed for use in liquid-alkali metals.⁶ It is reported to be accurate, to withstand temperatures up to 900°C, and to have a high degree of reliability. This probe must be carefully calibrated because of the small changes in circuit resistance that are measured. The liquid metal must completely wet the probe to insure a reproducible contact resistance between the probe and the liquid. A device of this type, which is capable of measuring two levels in molten fluoride salts, has also been developed at Oak Ridge National Laboratory.⁷ The liquid-metal solutions used in the Argonne fuel processes do not wet surfaces as well as do the alkali metals and fluoride salts. Because contact resistances can be large and variable, this type of probe cannot be used.

Induction devices measure the change in coil inductance caused by changes in the position of a conductor such as the liquid itself. In order to make a significant change in the coil impedance, a material that has a high electrical conductivity or magnetic permeability must be near the coil. The liquid depth in a "sight glass" can be determined by wrapping an inductance coil around this tube. This induction device offers the advantage over the ordinary sight glass that the tube can be made of metal and thus is more compatible with high-temperature systems. However, attaching the "sight glass" to the vessel is still a problem.

A similar device⁸ has been used successfully by Oak Ridge National Laboratory in liquid fluoride salts. A float, which rises and falls with the liquid level, moves within a differentially wound, saturated transformer and changes the impedance of the coil, depending on the position of the float. With an extension of sufficient length on the float, the coil can be located in a cooler zone. If this type of probe is to be used with volatile liquid metals and salts, precautions must be taken to prevent condensing vapors from

entering the space between the coil and the float. This instrument was felt to be too bulky and complicated for use in the small equipment for pyrochemical processes.

An induction probe contained in a corrosion-resistant well, which is immersed directly in the liquid, is compact and uncomplicated. It is easy to replace, has no moving parts, is easily fabricated, and is readily adaptable to remote operation in high-radiation fields. The adaptation of this promising type of probe for use in high-temperature processes for the recovery of reactor fuels is described in this report. This device consists of a bifilar winding of Nichrome wire on a ceramic insulator that is contained in a protection well. The fluctuating magnetic field created by the alternating current in the primary coils of the probe induces eddy currents in any nearby conductor including the secondary coil, the protection well, and the liquid surrounding the well. The presence of a conducting material near the coils tends to decrease the mutual inductance between the coils and thus to decrease the voltage induced in the secondary coil.

The inductance principle of measuring the presence of conducting liquids is well known and has been used successfully in many applications. Indeed, a probe similar to that described in this paper was used successfully by Davidson⁹ to measure the depth of liquid sodium in small cylindrical tanks. Induction devices have been developed and employed commercially to measure defects in metal parts and have been applied especially to detecting flaws in the cladding for nuclear fuel pins and for measuring the level and integrity of the sodium bond in fuel pins.¹⁰ A commercial instrument based on the inductance principle for measuring liquid levels is available from the MSA Research Corporation. However, this device has the disadvantages, for small remotely operated equipment, that it is a search-type coil and has a fairly large (1-in.-diam) well. A very high-frequency (6-Mc), flat, spiral coil has been developed to measure the dynamic film thickness in potassium-lubricated journal bearings at elevated temperatures.¹¹

The available reports contain little information on the response of induction probes to metals other than sodium or on the stability of the instruments at high temperatures and over long times. The circuits employed for the instruments reported tended to be quite complicated. It was of interest to investigate the use of a simple circuit for the eddy-current, liquid-level probe.

II. DESCRIPTION OF EQUIPMENT

A. Electronics

A circuit diagram of the equipment used is shown in Fig. 1. The high-frequency signal was generated by an audio oscillator, which had a range of output frequencies from 5 to 600,000 cps and a maximum signal output of 10 V rms. A Class A power amplifier was connected to the output

of the audio oscillator. The high frequency was fed from the amplifier to the primary, or inducing coil, of a probe. The secondary, or sensing coil, of the probe was connected to a full-wave bridge rectifier. A 1.34-V battery was used as a source of bucking voltage to enable the voltage from the secondary coil to be read on a 0-20-mV single-point recorder.

Fig. 1. Circuit Diagram of Induction Probe

The small changes in the magnetic field of the primary coil caused by the eddy-current strength in the metal surrounding the coil changed the mutual inductance of the system and were detectable as a change of voltage induced in the secondary winding. The output signal was sensitive to the voltage supplied to the primary coil and to changes in the resistances of the probe coils. Davidson⁹ used a more complicated circuit, which was insensitive to changes in the coil resistances and compensated for changes in temperature. However, the simpler circuit had very good stability and accuracy, and proved to be well adapted for use in the present study. The instrument had to be zeroed at a standard liquid level and temperature before it could be used. Liquid depths were determined by the change in output signal from this arbitrary standard. Because of the good stability of the circuitry, the zero had to be set only once during a series of runs with a single probe. Since there was some aging of the electronic components, the device had to be rezeroed approximately every 1000 hr to obtain accurate measurements.

The circuit was tuned by adjusting the capacitance in the primary circuit to obtain the maximum output signal. This adjustment was required whenever the input frequency was changed or whenever the probe was changed.

B. Probe

The probe (Figs. 2 and 3) was a dual-wound coil of 20-gauge Nichrome wire wrapped into grooves on an alumina form, which had an

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Fig. 2. Induction Probe

103-7898

Fig. 3. Induction Probe, Close-up View

outside diameter of $3/8$ in. The grooves were 0.040 in. wide and 0.062 in. deep and were separated by 0.026-in. alumina webs. There were 7.7 turns per inch in each coil. The grooves were deep enough to prevent contact of the coil with the sides of the containment well, allowing for the thermal expansion of the Nichrome wire. The lead wires terminating at the bottom of the probe were drawn through the center of the alumina form and were protected from contact with the bottom of the containment well by an alumina protrusion extending $1/8$ in. below the first coil. The four wires from the top of the form were protected by a four-hole, $1/4$ -in. alumina rod that extended to the top of the containment well.

In tests with cadmium, magnesium, sodium, bismuth, and chloride salts, the containment well was Type 304 stainless-steel tubing, which was $1/2$ -in. OD, 0.032-in. wall, sealed at one end with a 0.032-in. plate. A tantalum well of similar dimensions or a ceramic well ($3/4$ -in. OD) was used in tests with liquid zinc.

A probe, which had windings insulated and supported on an alumina insulator by a ceramic cement (Melbond),* was built and tested earlier by I. O. Winsch and D. Benzing¹² of ANL. This type of probe had been used successfully on a cadmium-distillation pilot plant by I. G. Dillon and P. A. Nelson.¹³ However, the cemented probe was less reliable and much less rugged than the probe having uncemented windings contained in grooves on an alumina insulator. The ceramic cement tended to break away from the windings, allowing the wires to contact the containment well. Above 800°C , the electrical resistivity of this cement decreased significantly.

C. Auxiliary Equipment

During the collection of most of the data presented in this report, the crucible containing the liquid was located in a gas-tight, resistance-heated furnace tube, which consisted of a 6-in. stainless-steel pipe 20 in. long. The furnace tube was connected to vacuum-inert gas manifold. The experiments were performed in a helium atmosphere at a pressure of about 10 psig to prevent oxidation of the liquid metals and to reduce the vaporization of the volatile liquids. The cover flange of the furnace tube was equipped with a port for charging materials to the crucible and with fittings for a thermocouple well, the probe-containment well, and a movable resistance probe to determine the actual depth of the liquid. This reference probe was a $1/8$ -in. rod that entered the furnace tube through a vacuum-tight fitting that insulated the rod from the furnace tube. To locate the liquid level, the rod was moved until contact with the liquid surface completed the circuit between the rod and the furnace tube. The resistance probe could locate the liquid level within $1/16$ in., provided that the condensed metal vapors

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*Product of Melpar Inc., Falls Church, Va.

were cleaned from the rod and from the insulator every few hours. Three heat shields were located in the hot zone above the crucible to insure that the entire length of the induction probe windings were in a zone of uniform temperature.

For the calibrations in sodium of a probe having $5\frac{1}{8}$ -in.-long windings, and in cadmium of a 14-in. probe, a two-compartment furnace tube was used in which the liquid-metal level around the probe could be raised or lowered by transferring liquid from one vessel to the other. A large temperature gradient near the top of this equipment caused a 200-300°C temperature difference across the top few inches of the longer probe. As the liquid level was raised, this temperature gradient would vary, causing small errors in the level measurements.

III. EXPERIMENTAL PROCEDURE

To determine the effect of liquid depth on the strength of the output signal, the liquid level was varied by adding increments of metal while the probe and its containment well remained in a fixed position with respect to the crucible. The empty crucible and the other necessary equipment were put into the furnace tube; the tube was evacuated and filled with helium.

The electronic circuits were allowed to warm up for at least 1 hr before data were taken. The proper capacitance had been wired previously into the circuit to match the impedance of the probe to the oscillator output impedance. The oscillator was set at the desired frequency (usually 50 kc) and voltage output (~ 7 V rms), and the amplifier was set at maximum gain. The bucking voltage was set at a value that had been determined previously to give an output signal that could be conveniently recorded on a 0 to 20-mV recorder.

After the electronic components had been adjusted and had warmed up, and the furnace tube had been heated to the desired initial temperature, the output signal of the induction probe was recorded at intervals of 50°C. These readings were taken to be the signal at zero liquid depth. The furnace was then cooled, an increment of metal was added to the crucible, and the furnace tube was reheated. Readings of the output signal were recorded again at intervals of 50°C. The liquid-metal depth was measured at each temperature with the resistance probe.

To simulate changes in liquid depth in preliminary tests, the induction probe was moved up and down in a fixed well located in a given amount of liquid metal. Because of the varying effect of the bottoms of the crucible and well, signal versus immersion-depth curves obtained in this manner differed from those obtained by leaving the probe in a fixed position.

IV. EXPERIMENTAL RESULTS

A. Results with Liquid Cadmium

The effects of the depth of immersion of the windings into the liquid cadmium and of the temperature of the probe on the output signal are shown in Fig. 4 for a probe having windings $5\frac{1}{8}$ in. long, and in Fig. 5 for a probe having windings 14 in. long. The probes and the stainless-steel wells were

Fig. 4

Calibration of 5-in. Induction Probe in Cadmium

Oscillator output frequency 50 kc
 Oscillator voltage 7.0 V rms
 Bucking voltage 4.64 mV
 Well 304 SS, 0.032-in.
           wall x 1/2-in. OD
 Crucible 304 SS, 10-in. high x
           5-5/8-in. ID
 Liquid metal Cadmium
 Length of winding 5-1/8 in.

Fig. 5

Calibration of 14-in. Induction Probe in Cadmium

Oscillator output frequency 50 kc
 Oscillator voltage 7.0 V rms
 Well 304 SS, 0.032-in. wall,
           0.50-in. OD
 Crucible 304 SS, 6-in. ID
 Liquid metal Cadmium
 Length of winding 14 in.

kept in a fixed position as close to the bottom of the crucible as possible. The isotherms for the longer probe were somewhat distorted, probably because of the large temperature gradient across the top of the windings. The data obtained with the longer probe were more scattered than those obtained with the shorter windings.

The response of the instrument to changes in liquid level increased slightly as the probe windings became longer. At liquid depths approximately equivalent to one-half the winding length, where the graph of the output signal versus depth was most nearly a straight line, the slopes of output isotherms for the $5\frac{1}{8}$ -in. and 14-in. probes were -0.60 and -0.74 mV/in., respectively. When the liquid level was within 1 in. of the top or bottom of the windings, the signal responses of both probes exhibited deviations from linearity that were attributed to end effects of the coil. At the bottom of the probe, there was also the unsymmetrical influence of the bottoms of the crucible and well.

The effect of a change in temperature as shown in Fig. 4 was essentially to shift the entire line of the signal versus depth. The amount of this shift varies only slightly with depth for the 5-in. probe as shown in Fig. 6. For the shorter probe tested, the probe can be compensated conveniently for changes in the melt temperature by changing the bucking voltage as a determined function of temperature. For example, if the bucking voltage were adjusted to a value that depends on the temperature as shown in Fig. 6, the 550°C isotherm in Fig. 4 can be used with cadmium at any temperature over the range of 400 to 700°C with an error equivalent to 2% of the probe length, in addition to other experimental and calibration errors. The anomalous influence of temperature on the output of the 14-in. probe was felt to be due to a large and changing temperature gradient in the top of the furnace tube used to calibrate the longer probe. In the absence of this gradient, a temperature correction could also be made for the longer probe.

Fig. 6

Temperature Compensation of 5-in.
Liquid-level Probe in Cadmium

Correction to bucking voltage required to use 550°C
calibration isotherm at another temperature

Oscillator output frequency	50 kc
Oscillator voltage	7.0 V rms
Crucible	304 SS, 10-in. high x 5-5/8-in. ID
Well	304 SS, 0.032-in. wall, 0.50-in. OD
Liquid metal	Cadmium
Length of winding	5-1/8 in.

The temperature effect was presumably due to a combination of causes. The changes in resistivity of the liquid metal with temperature had a noticeable effect indicated by the influence of melt depth on the temperature coefficient of the output signal. The resistance of the Nichrome wire changes very little with temperature in the range of 400-700°C.¹³ The most important effects causing the influence of temperature on the output signal are the increase of mutual inductance of the bifilar coil with temperature and the increase in the resistance of the stainless-steel well. An increase in mutual inductance of the coils that results from expansion of the coil diameter with increasing temperature will cause an increase in voltage induced in the secondary by the primary. An increase in the resistance of the stainless-steel protection well will decrease the eddy currents, and this will increase the voltage induced in the secondary coil. Calculations showed that each of the three causes (resistances of liquid metal and well, and mutual inductance of coils) contributed about equally to the measured temperature effect.

B. Effect of Other Liquids

As the electrical resistivity of the liquid surrounding the probe decreased, the output signal would be expected to decrease. The resistivities of most low-melting liquid metals¹⁴ fall in a narrow range between those of the alkali metals ($\sim 10 \mu\text{ohm-cm}$ for sodium at 100°C) and those of the heavy metals bismuth, lead, and mercury ($\sim 120 \mu\text{ohm-cm}$).

The $5\frac{1}{8}$ -in.-long probe was calibrated in bismuth and sodium, and their 550°C isotherms are compared to that of cadmium in Fig. 7. Although

Fig. 7

Response of Probe in Various Liquid Metals

Oscillator output frequency	50 kc
Oscillator voltage	7.0 V rms
Bucking voltage	Adjusted to make S(0) coincide
Well	304 SS, 0.032-in. wall x 1/2-in. OD
Crucibles	304 SS
Length of winding	5-1/8 in.

Liquid Metal	Temperature, °C	Resistivity, $\mu\text{ohm-cm}$
Cadmium	550	34.5
Bismuth	525	147
Sodium	550	(26)

the resistivity of bismuth is about four times that of cadmium and that of sodium is significantly less than that of cadmium, the curves for the three metals are quite similar. The change in signal per inch of depth decreases as the metal resistivity increases. The resistivity of sodium at 550°C was estimated by extrapolating the data given for temperatures below 400°C.¹⁴ At temperatures below 250°C, because of a layer of sodium that adhered to the protection tube as the sodium level was lowered, the calibration isotherm for sodium showed a hysteresis effect as the sodium level was changed. At higher temperatures, the sodium drained cleanly from the tube, and the hysteresis effect was not measurable.

The effect of temperature of the bismuth on the output signal, shown in Fig. 8, is essentially identical to the temperature coefficient in cadmium. The temperature effect in sodium was somewhat larger than that found for bismuth and cadmium. The larger temperature effect seen in sodium was attributed to the very large temperature coefficient of resistivity of sodium as well as the changes in the resistance of the well and in the mutual inductance of the coils. The temperature compensation determined for the probe in cadmium and bismuth would be applicable, in general, to other liquid metals whose temperature coefficients of resistivities were similar to those of cadmium and bismuth.

Fig. 8

Temperature Compensation of 5-in. Liquid-level Probe in Bismuth

Correction to bucking voltage required to use 550°C calibration isotherm at another temperature

Oscillator output frequency	50 kc
Oscillator voltage	7.0 V rms
Crucible	304 SS, 10 in. high x 5-5/8-in ID
Well	304 SS, 0.032-in. wall, 0.50-in. OD
Liquid metal	Bismuth
Length of winding	5-1/8 in.

When the probe was tested with a liquid salt (50 m/o MgCl_2 , 30 m/o NaCl , 20 m/o KCl) that had a resistivity approximately 1000 times¹⁵ as much as that of cadmium, the change in signal with liquid depth could not be detected because the eddy currents induced in the salt were negligible with respect to those induced in the stainless-steel protection tube. When 1 in. of a salt (50 m/o MgCl_2 , 30 m/o NaCl , 20 m/o KCl ; or 54 m/o MgCl_2 , 45 m/o CaCl_2) was added to a 4.5-in.-deep cadmium melt, the output signal did not differ detectably from the signal with the metal present alone.

Thus, the probe enclosed in a stainless-steel well could be used to detect the level of the liquid-liquid interface in a liquid metal-salt system.

The probe in a stainless-steel well was also tested in liquid magnesium at temperatures up to 800°C. The results were similar to those found for liquid cadmium and bismuth. The stability of the probe at 800°C was excellent.

C. Effect of Surroundings

Because the probe was sensitive to the presence of any nearby conductor, the characteristics of the probe depended to some extent on its surroundings. The electrical conductivity and magnetic permeability of the containment well would have the greatest effect on the probe characteristics. If the containment well were made of a material having a high conductivity or permeability, conductors outside the well would be effectively shielded from the magnetic field generated by the primary coil and have little or no effect on the current induced in the secondary coil. In Fig. 9, a calibration curve of the probe in a 1/2-in.-OD, 30-mil-thick, tantalum

Fig. 9. Effect of Well Material on Liquid-level Probe
(Probe moved in well)

	X	Δ	o
Oscillator output frequency, kc	50	50	50
Oscillator voltage, V rms	7.0	7.0	7.0
Bucking voltage, mV	1.50	14.92	0.0
Temperature, °C	500	460	460
Well material	304 SS	Ceramic	Ta
Well OD, in.	0.50	0.75	0.50
Liquid metal	Cd	Zn	Zn

tube immersed in zinc is compared to data obtained with a ceramic well immersed in zinc and with a stainless-steel well immersed in cadmium. Zinc, which has a resistivity similar to that of cadmium, should have given results similar to those for cadmium in a similar environment, but because of the low resistance of the tantalum well ($20 \mu\text{ohm-cm}$ at 460°C^{16}), the change in signal with change in depth of the zinc was very small. With the probe in the ceramic well ($3/4$ -in. OD), a large change in output signal was found. Because of the larger outside diameter of the ceramic well, the data taken in the ceramic well are not comparable directly to the data taken in the metal wells.

With the probe sheathed in the 32-mil, Type 304 stainless-steel well, the presence of conductors farther away than $3/4$ in. from the centerline of the probe had negligible effects on the output signal. If a conducting body, such as the wall of the containment vessel, were closer than $1/2$ in. to the containment well there was a measurable influence on the output signal. For the data shown above for cadmium, bismuth, and sodium, the probe was resting on the bottom and was in the center of a $5\frac{5}{8}$ -in.-ID stainless-steel crucible. These calibration data would be valid only for the situation in which the probe was resting on the vessel bottom and was not near a wall of the vessel.

D. Input Frequency

The input frequency must be selected for the particular probe design to maximize the effect of liquid depth on the output signal and to minimize the effect of extraneous signals and noise. The optimum operating frequency depends primarily on the coil design and the type of protection well, but other considerations, such as circuit characteristics and external noise, may also be important. In general, at fixed input voltages, as the input frequency increases, the current induced in the secondary increases, but the effective depth of penetration of the magnetic flux through a containment well decreases. At high frequencies (above 100 kc), wells must be made of very thin metal or of nonconducting materials. A high-frequency probe would be sensitive to thin films of liquid adhering to the protective well, causing a hysteresis similar to that observed for sodium at low temperatures. At low frequencies, the voltage output from the secondary coil would be small unless the number of turns in the coil were increased. A low-frequency probe would tend to be more sensitive to vessel walls and other extraneous conducting objects.

For the probe with its intended uses and with an austenitic stainless-steel protection well as described in this report, an input frequency of 50 kc seemed to be optimum. The output voltage of the amplifier with the probe as the load in a tuned circuit was found to be reasonably constant over a frequency range of 10 to 100 kc and to have a peak voltage at 120 kc. At higher frequencies, the voltage decreased rapidly. The influence of the protection

well on the output signal is shown in Fig. 10. The probe was tuned at each frequency by changing the capacitance in the primary-coil circuit to obtain the maximum output. The scatter in Fig. 10 was due partly to the limitations in tuning of the circuit with fixed capacitors, but there is some indication of two resonances (at 60 and 120 kc) in the apparatus. The effect of the metal wells was to decrease the output signal, especially at the higher frequencies. Although the output signal increased up to 120 kc, the signal change per change in liquid depth decreased rapidly above 60 kc. At frequencies below 40 kc, although this signal change was reasonably large, a high noise level prevented the use of lower frequencies. This noise may have been caused by induction heating units, located in the laboratory, that operated at 10 kc.

Fig. 10

Effect of Frequency and Well Material
on Output Signal of Liquid-level Probe

Probe length 6 in.
Frequency Varied
Bucking voltage 0.0 mV
Oscillator voltage 7 V rms
Temperature 30°C

○ Probe, no well, in air
× Probe, SS well (32-mil wall), in air
+ Probe, tantalum well (30-mil wall), in air

V. CALIBRATION

It was virtually impossible to make two probes having the same characteristics. Figure 11 shows calibration curves obtained from two probes that were made with their physical dimensions as nearly

Fig. 11

Comparison of Similar Liquid-level Probes
(Probe moved in well)

Oscillator output frequency	50 kc
Bucking voltage (Probe No. 1)	7.41 mV
Bucking voltage (Probe No. 2)	9.40 mV
Well	304 SS, 0.032-in. wall, 1/2-in. OD
Crucible	304 SS, 10-in. high x 5-5/8-in. ID
Liquid metal	Cadmium
Temperature	485°C
Length of winding	6-1/16 in.

identical as practical. Both had the same d.c. resistances (5.5 ohms) and the same overall length. In Fig. 11, the bucking voltages were adjusted so the signals at zero depth coincided, but the bucking voltages required differed by 1.99 mV. These data were taken by moving the well and probe and are not comparable to data taken with the probe in a fixed position.

If a high degree of accuracy is required, complete calibrations at several temperatures must be made for each probe. A quicker procedure described below can be used if an accuracy of only $\pm 5\%$ is required. The procedure is quicker because it requires measuring the signal output at only a few points, and experimental data can be smoothed by means of the empirical equation.

The calibration isotherm of signal versus liquid depth can be represented reasonably well by the equation

$$S(\ell) = S(0) + A\{[(R^2 + \ell^2)^{1/2} - R] - [(R^2 + (L - \ell)^2)^{1/2} - (R^2 + \ell)^{1/2}]\}, \quad (1)$$

where

L = length of probe windings,

ℓ = distance measured from bottom of windings,

$S(\ell)$ = output signal when windings are immersed to depth ℓ ,

A and R are arbitrary constants, and $S(0)$, the output signal when $\ell = 0$, is also arbitrary since it can be set at any value by the bucking voltage. The form of the equation can be rationalized by the following arguments:

The magnetic field along the axis of a single turn of radius r carrying a current i is¹⁷

$$H = \frac{2\pi r^2 i}{10(r^2 + x^2)^{3/2}}, \quad (2)$$

where x is the distance along the axis from the coil. If the single turn is considered a differential section of a solenoid (see Fig. 12) carrying the

Fig. 12

Magnetic Field along
Axis of Solenoid

current $di = I dx$, where I is the current per unit length, then

$$dH = \frac{2\pi r^2 I dx}{10(r^2 + x^2)^{3/2}} \quad (3)$$

Integrating Equation (3) yields the magnetic field along the axis of a solenoid:

$$H(\ell) = \frac{2\pi I r^2}{10} \left\{ \int_0^{L-\ell} \frac{dx}{(r^2 + x^2)^{3/2}} + \int_0^{\ell} \frac{dx}{(r^2 + x^2)^{3/2}} \right\} \quad (4)$$

or

$$H(\ell) = \frac{2\pi I}{10} \left\{ \frac{L - \ell}{[r^2 + (L - \ell)^2]^{1/2}} + \frac{\ell}{(r^2 + \ell^2)^{1/2}} \right\} \quad (5)$$

In the center of the coil, if $L - \ell \gg r$ and $\ell \gg r$, then Equation (5) reduces to the familiar expression¹⁷ for the field of a solenoid along its axis,

$$H(\ell) = \frac{4\pi I}{10} \quad (6)$$

Assume that the field is not disturbed by the presence of conductors, that the field external to the coil is similar to field along the axis, and that the signal change of the secondary winding is proportional to the magnetic field in the metal. Then

$$S(\ell_2) - S(\ell_1) = A \int_{\ell_1}^{\ell_2} H(\ell) d\ell;$$

$$S(\ell) - S(0) = A \int_0^{\ell} \left\{ \frac{L - \ell}{[r^2 + (L - \ell)^2]^{1/2}} + \frac{\ell}{(r^2 + \ell^2)^{1/2}} \right\} d\ell \quad (7)$$

$$= A \{ [(r^2 + L^2)^{1/2} - r] - [(r^2 + (L - \ell)^2)^{1/2} - (r^2 + \ell^2)^{1/2}] \}. \quad (8)$$

The form of Equation (8) is the same as that of Equation (1), the equation used to represent the signal isotherm. In Equation (1), R can be seen to represent an effective radius of the coil. As shown below, R does not correspond to the physical radius of the coil as indicated in Equation (8). Equation (1) was fitted to the experimental data for the $5\frac{1}{8}$ -in.- and 14-in.-long probes in cadmium at 500°C, by taking R equal to 0.45 in. The results are shown in Fig. 13. The data points for liquid depths less than $3/4$ in. do not fit well because of the distortion of the magnetic field caused by the crucible and well bottoms.

Fig. 13

Empirical Curves Fitted to Experimental Data

Oscillator output frequency	50 kc
Oscillator voltage	7.0 V rms
Well	304 SS, 0.032-in. wall, 0.50-in. OD
Crucible	304 SS
Liquid metal	Cadmium
Temperature	500°C
Experimental points	○ 14-in. Probe □ 5-1/8-in. Probe

Values for the parameter A for other liquid metals are listed in Table I. Equation (1) can be used to reduce the amount of data required to obtain a calibration curve for a new probe. A technique for obtaining the constants $S(0)$, R , and A is as follows: The data are plotted, and the "best" straight line is drawn through the data points for liquid depths near the center of the winding where the calibration curve is most nearly a straight line. In the central region, where R is negligible with respect to l and $L - l$,

$$S(l) \approx S(0) + 2Al.$$

TABLE I. Slope Parameters for Equation (1) for Various Liquid Metals

Liquid Metal	Temperature, °C	Electrical Resistivity, $\mu\text{ohm-cm}$	Length of Probe, in.	A , mV/in.
Cd	500	34	$5\frac{1}{8}$	-0.60
Cd	700	36	$5\frac{1}{8}$	-0.66
Cd	500	34	14	-0.74
Bi	500	140	$5\frac{1}{8}$	-0.58
Na	500	25	$5\frac{1}{8}$	-0.69

From the straight line, a value for A and a preliminary value for $S(0)$ are obtained. Values for R are assumed, and by trial and error, the data for liquid depths near the ends of the windings are fitted. It then will be necessary to adjust $S(0)$ slightly.

For precise work, the effect of temperature on the signal must be determined for each probe in each liquid over a range of liquid levels. However, a temperature correction determined at one liquid depth in any liquid metal can be used with reasonable accuracy at other liquid depths and in other liquid metals because the effect of the liquid on the temperature coefficient was small.

VI. ACCURACY AND REPRODUCIBILITY

The stability of the important characteristics, the change in signal with the depth at a constant temperature and the change in signal with temperature at constant depth, was excellent. During a calibration run that lasted approximately 17 days and included 102 hr at temperatures above 350°C and at least 17 cycles of heating to 700°C and cooling to room temperature, the reproducibility was within $\pm 1/8$ in. of cadmium. As the electronic components aged, the important operating characteristics of the probe (change of output signal with liquid depth and temperature) remained reasonably constant. The principle effect of the inevitable aging of the oscillator and amplifier was to change the bucking voltage. After about 1000 hr of operation, it would be necessary to zero the instrument by measuring the signal output at one known liquid depth and temperature.

For the $5\frac{1}{8}$ -in.-long probe, the average deviation of the experimental points from the curve drawn through the data was about $1/8$ in. The same deviation for the 14-in. probe was approximately $5/16$ in., and the maximum deviation was $3/4$ in. The longer probe did not possess the absolute accuracy and reproducibility of the shorter device. The average relative accuracy and precision (error/winding length) was about 2.5% for both probes.

VII. CONCLUSIONS

The mutual-inductance probe has been a reliable and useful instrument for measuring liquid depths in a variety of molten metals at temperatures up to 800°C . The necessity of calibrating each probe against liquid level and temperature was the principle disadvantage. With proper calibration, the instrument was capable of making measurements with an accuracy of better than 3% of the length of the windings. The calibration is reasonably independent of the surroundings of the probe and of the composition of the liquid metal. A simplified method is described by which a reasonably accurate calibration can be obtained with a minimum of data. Once calibrated,

the instrument was useful for more than 1000 hr with only minor recalibrations required to adjust the bucking voltage. The relatively simple electronic circuitry employed was satisfactory. The sensing element is simple, stationary, heat-resistant, and isolated from the fluid. It can be easily removed for inspection or replacement. Because of these advantages, the induction liquid-level probe should have a wide range of applications in a variety of systems employing liquid metals at elevated temperatures.

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