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A TRAMP-METAL DETECTOR

by

M. H. Goosey

Instrument Development Division

October 1955

E. I. du Pont de Nemours & Co.
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ABSTRACT

An instrument is described which detects small pieces of "tramp" iron in an aluminum alloy.

Iron-particle volumes of 3×10^{-4} cubic inches are readily detected inside an alloy rod one inch in diameter.

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A TRAMP-METAL DETECTOR

INTRODUCTION

During the casting of aluminum alloy billets, failure of the furnace thermocouple housings causes the inclusion of "tramp" metal which appears in the final extruded pieces. The presence of this extraneous material, which is primarily iron, is undesirable for process reasons. It was thus desirable to devise a nondestructive test that would quickly and simply examine each aluminum rod for "tramp" metal.

SUMMARY

A Tramp-Metal Detector, utilizing an inductance bridge circuit, was built and successfully applied. The instrument indicates 30 per cent of full scale for pieces of soft iron wire 1/10 inch long and 1/16 inch in diameter located on the longitudinal axis of aluminum alloy rod one inch in diameter. Auxiliary alarms can be operated for defects of this size.

DISCUSSION

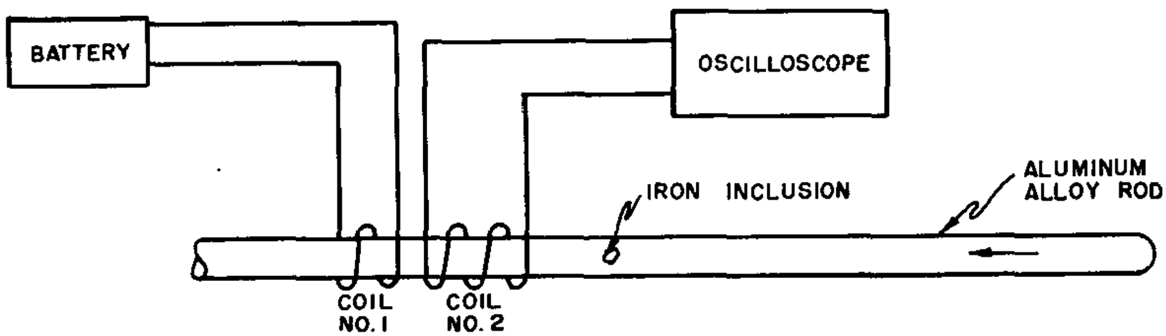
The problem to be solved was that of detecting small particles of iron embedded in aluminum alloy. It was desired that the test be rapid and of nondestructive nature and that it could be applied without the need for additional operators or process time. The instrument utilizes the large difference in the magnetic permeabilities of iron and aluminum.

THEORY

The permeability of the aluminum alloy is approximately that of free space or 10^{-6} hy/m, while the permeability of iron is of the order of 10^{3} hy/m. This large difference in permeability was used as the basis for the proposed tester.

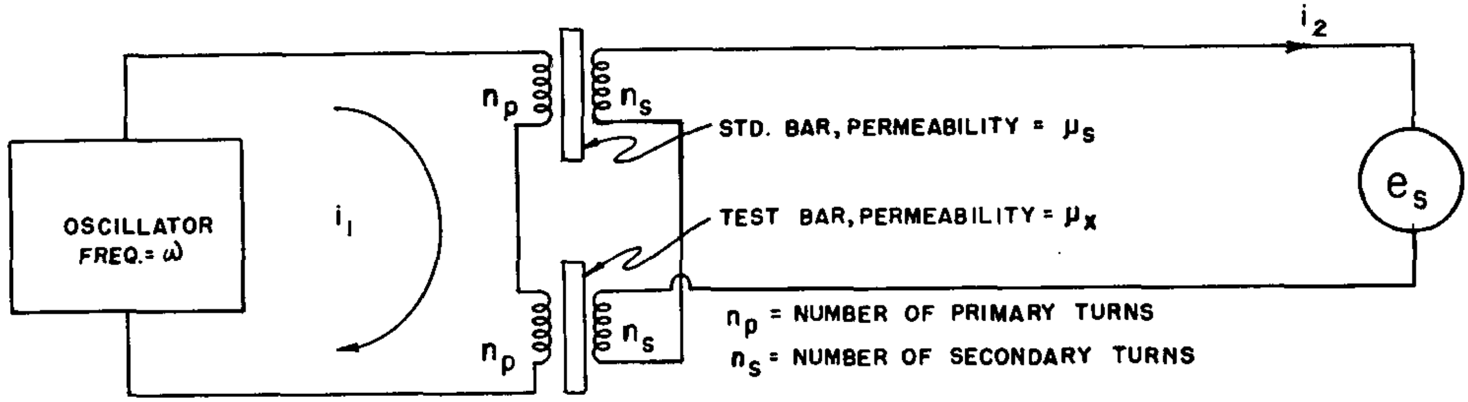
Two methods by which the permeability difference might be used were investigated: (1) the use of a constant magnetic field applied to the aluminum sample and of a pickup coil to detect relative changes in the magnetic induction due to the presence of extraneous iron; and (2) the use of an alternating magnetic field and of a pickup coil to detect changes in the induced voltage. Both methods are similar in principle and involve the transfer of energy from the magnetic field to the detecting device through the ferromagnetic properties of the iron.

The principle involved in the first method is that if the magnetic induction, B, in the region of a coil of wire changes, a voltage will be induced in the coil. Shown below is a diagram of the apparatus used to investigate this method:



The battery supplies current to Coil No. 1, which produces a magnetic field in the region of Coil No. 2. When the iron inclusion enters this magnetic field the magnetic induction in the region of Coil No. 2 changes and so induces a voltage in this coil. The magnitude of the voltage induced is a function of the number of turns on Coil No. 2, and the rate of change of the magnetic induction. The rate of change of the magnetic induction in turn is a function of the velocity of the iron inclusion in the region of the coil. It is apparent then that to obtain an output signal proportional to the size of the inclusion a constant-velocity feed mechanism is necessary. In view of the fact that the second method investigated eliminates the need for such a feed mechanism, investigation of the first method did not proceed beyond this point.

The difference between the second method and the first is that the motion of the inclusion is replaced by a change in space and time of the magnetic field. The second method was set up as a comparison inductance circuit whose essential features are indicated below:



The analysis given in the Appendix shows that the parameters are related by the following equation:

$$e_s = k\omega n_p n_s(\mu_x - \mu_s)i_1$$

which neglects ohmic and eddy-current losses.

It appears from this relation that a larger signal voltage, e_s, could be obtained by using a higher frequency, ω; however, the obtainable signal is limited by eddy-current losses which increase with frequency. Initial experiments revealed that the magnetic flux distribution was distorted at frequencies above 200 cycles per second. In order to keep the magnetic flux distribution as uniform as possible and to avoid beats with 60-cycle line harmonics, a test frequency of 135 cycles per second was selected.

The number of turns in each of the primary coils was fixed since it was necessary to match them to the audio oscillator output. They were wound with a length of #30 enamel wire having a D.C. resistance of 11 ohms.

The number of secondary turns in the coils was made as high as possible within the physical size limitations which limited the number to 2400 turns of #36 "Formex" wire.

DESCRIPTION OF INSTRUMENT

The Tramp-Metal Detector, with the exception of the coils, is housed in a cabinet 14-3/4 x 22 x 14 inches. Both of the coils are mounted on a "Lucite" plate 3/4 x 5 x 10 inches in which tapered guide holes have been drilled. Figure 1 is a photograph of the instrument and coils. Figure 2 is a photograph of the chassis in which all tubes and controls are marked.

Figure 3 shows a schematic diagram of the circuit. A 6SJ7 is employed in a phase-shift oscillator of conventional design. The phase-shift oscillator is simple to construct for fixed-frequency operation and features good stability and sine-wave output provided that the "Oscillator Gain" control is set so as to just maintain the oscillations. Sine-wave output is necessary in this application because the balance in the coil system is frequency-dependent, and if the output has a large harmonic content, it will not be possible to achieve a high sensitivity.

The 6SJ7 is followed by a 6AQ5 power amplifier operating into a universal audio output transformer. The secondary winding of this transformer (from terminals 1 to 6) has an impedance of about 11 ohms with which the primary windings of the search coils were designed to match. The signal voltage from the secondary windings of the coils is connected to the grid of a 6SJ7 voltage amplifier through a one-megohm gain control. The highest gain is normally used for those applications in which a sufficiently good balance may be achieved in the detector coils. The 6SJ7 is followed by two more stages of voltage amplification in a 12AU7 dual triode. The output voltage at the plate of the last triode is read by a diode voltmeter.

The 0 to 100-microamp "Simplytrol" meter incorporates both the measuring and the alarm facilities in one unit. The meter span is 0 to 50 volts. Lock-in current for the "Simplytrol" is supplied in series with a 10,000-ohm relay from a 45-volt battery contained under the chassis.

Mal H. Goosey Jr.
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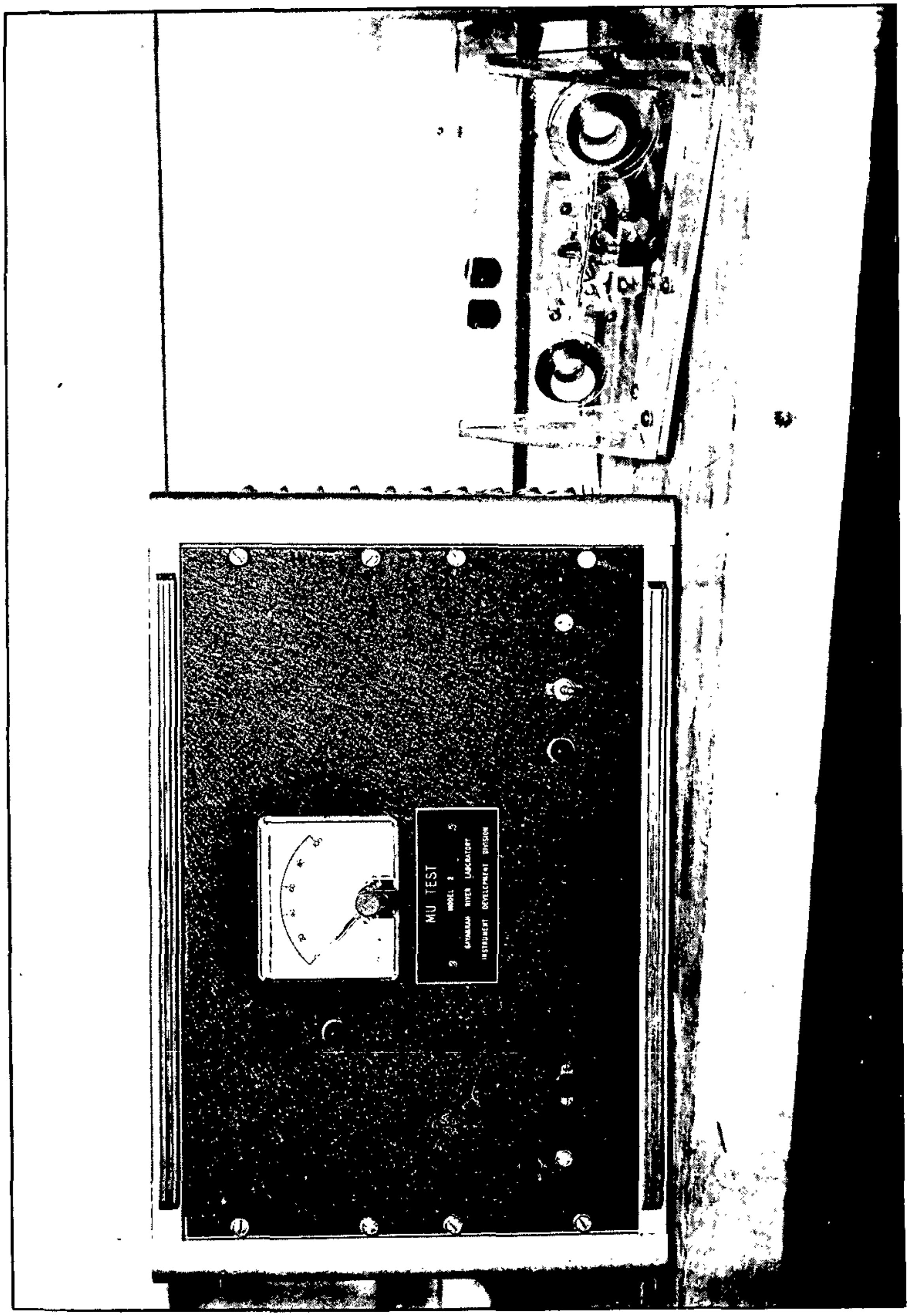
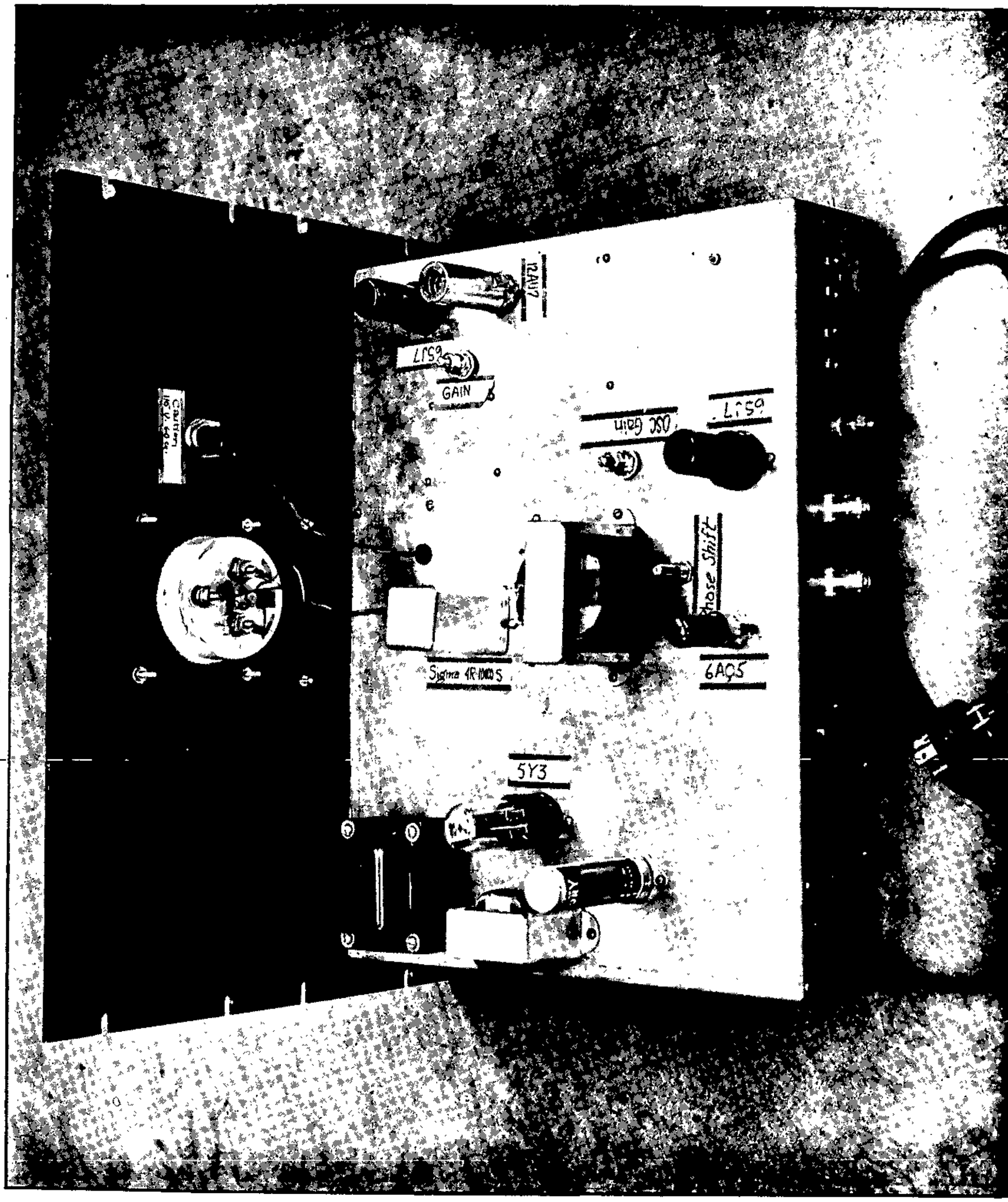
FIGURE 1



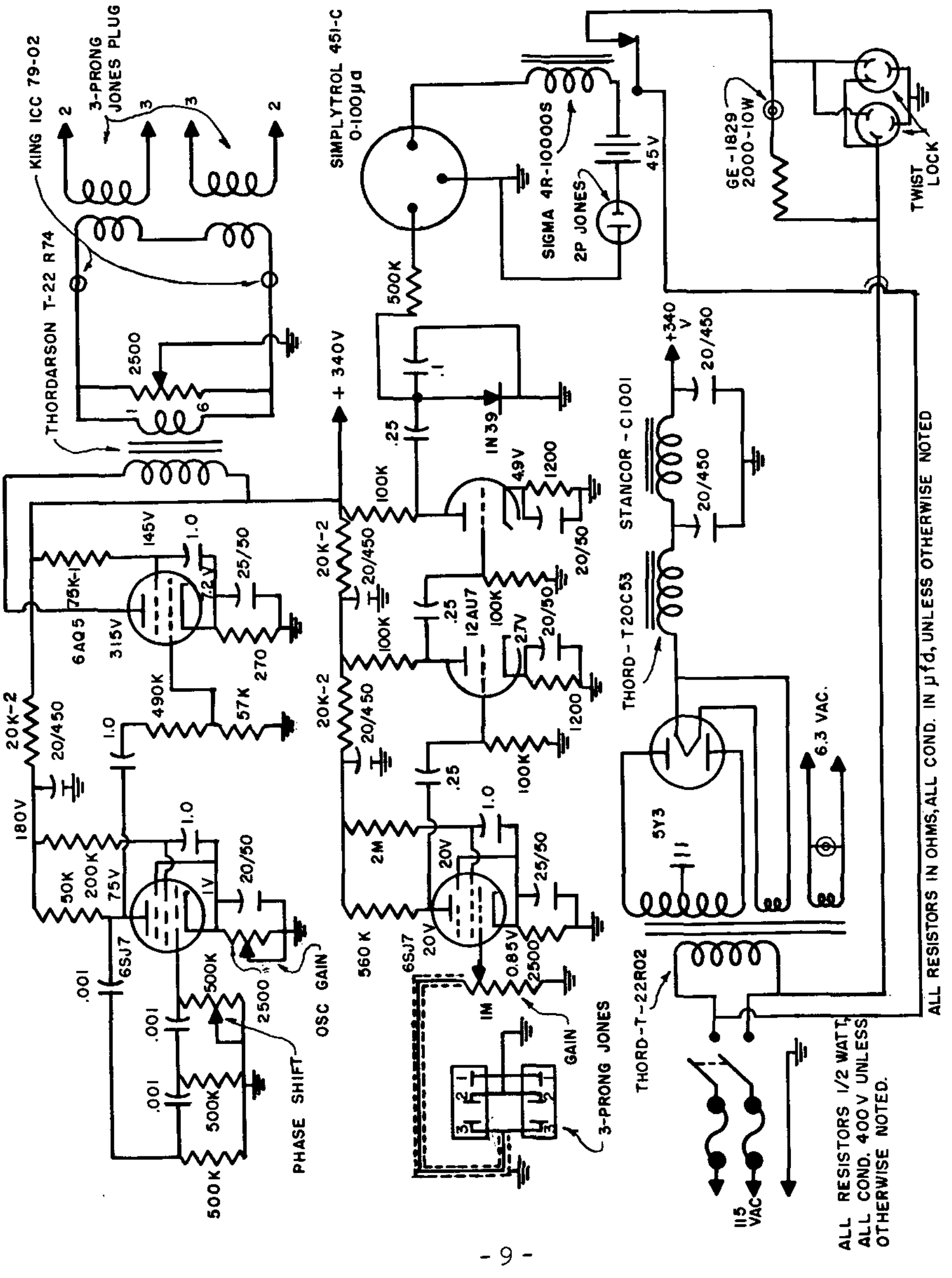
FRONT VIEW OF TRAMP-METAL DETECTOR AND COIL ASSEMBLY

FIGURE 2



CHASSIS OF TRAMP-METAL DETECTOR SHOWING TUBE AND CONTROL LOCATIONS

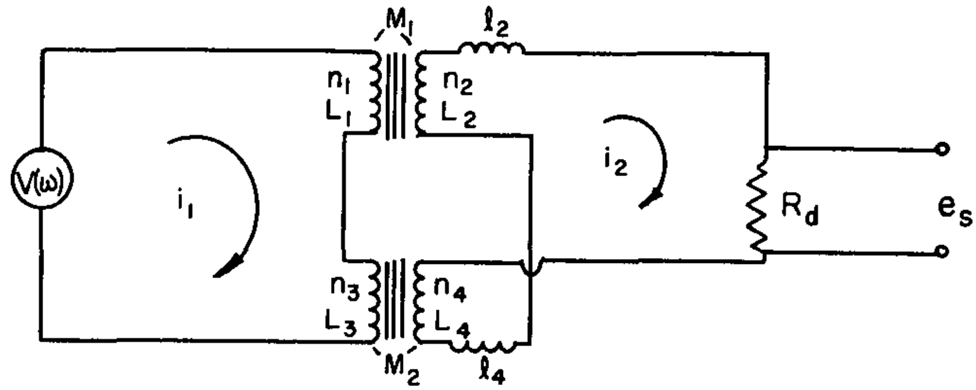
FIGURE 3



SCHEMATIC DIAGRAM OF TRAMP-METAL DETECTOR

APPENDIX

CIRCUIT ANALYSIS



If ohmic and eddy-current losses are neglected, the equation for the complex voltage of the secondary circuit is

$$0 = -j\omega M_1 i_1 + j\omega M_2 i_1 + j\omega \ell_2 i_2 + j\omega \ell_4 i_2 + R_d i_2 \qquad (1)$$

where i_1 = current in the primary coil circuit

i_2 = current in the secondary coil circuit

ω = angular frequency of the current

L_i = inductance of individual coils

ℓ_i = leakage inductance of secondary coils

M_i = mutual inductance of the coil pairs

R_d = detector input resistance

$j = \sqrt{-1}$

Rearranging Equation 1 gives

$$j\omega(M_2 - M_1)i_1 = j\omega(\ell_2 + \ell_4)i_2 + R_d i_2 \qquad (2)$$

The term $j\omega(\ell_2 + \ell_4)i_2 + R_d i_2$ represents the voltage drop in the secondary circuit, but $\omega(\ell_2 + \ell_4)$ is small compared to R_d and may be neglected. The term $j\omega(M_2 - M_1)i_1$ represents the voltage source in the secondary circuit and may be equated to the voltage drop to obtain

$$e_s = j\omega(M_2 - M_1)i_1 \qquad (3)$$

where e_s = the signal voltage = $R_d i_2$

Now $M_1 = K_1 \sqrt{L_1 L_2}$ and $M_2 = K_2 \sqrt{L_3 L_4}$, where the K_i's are the coefficients of coupling between the coil pairs. The L_1's are proportional to the n^2 and μ where n_p and n_s are the number of turns on the primary and secondary coils, and μ_s and μ_x are the effective permeabilities of the standard and test bars. Therefore, for equal coils

$$e_s = k\omega n_p n_s (\mu_x - \mu_s) i_1 \qquad (4)$$

where k is a constant.

OPERATIONAL DETAILS

When the instrument is being put into service for the first time in a new location, the coils should be connected and the 115V A.C. power turned on. Allow at least a five-minute warm-up period to stabilize the oscillator.

Insert two identical aluminum alloy bars into the coils and adjust the balance control on the rear chassis wall for a minimum meter reading. If the meter will not read less than full scale for any balance control setting, reduce the amplifier gain by turning the "Gain" control until the meter reading comes back on scale, and then proceed with the balance control adjustment. This adjustment compensates for small resistive unbalances in the coil system.

In order to compensate for inductive unbalances caused by nearby masses of metal, bring up a small amount of iron (a screwdriver will do) to each of the coils in turn and observe the meter. The reading will increase with one coil and decrease with the other. Mount the iron compensator on the coil that gives the decreased meter reading. This compensator consists of an annular piece of iron mounted on two brass screws. The coil-holder is drilled and tapped at the two coil positions to accept the mounting screws. Vary the distance between the coil and the compensator by turning the mounting screws into the coil-holder while observing the meter. As the compensator is brought closer to the coil, the meter reading will decrease to a minimum and then rise again. Adjust the compensator position for minimum meter reading.

The two adjustments just described (i.e., the balance control and the compensator) interact so that it is necessary to repeat the adjustments several times. As the instrument is brought into balance, the gain may be increased by turning the "Gain" control the other way.

The instrument is now ready for iron detection and may be operated thereafter without repeated adjustments. A piece of iron in the test specimen will cause the meter to deflect upward to a maximum reading which is reached when the iron particle is located in the plane of the coil. The rejection level may be set by means of a knob on the meter face. When this preset level is exceeded, the alarm lamp lights and 115V A.C. is supplied to two twist-lock outlets on the rear chassis wall. These may be used to provide power for an aural alarm or for a mechanical rejection device.

Once the alarm circuit has been actuated, it remains operative until the iron particle has passed through the coil and the alarm circuit has been reset. The alarm circuit is terminated at a two-prong Jones plug located on the front panel to allow remote resetting. A cable supplied with the instrument connects to this plug and the other end may be connected to a normally closed switch in a location convenient to the operator, or secured in such a way to the feed mechanism that the instrument is reset automatically after inspecting each piece.

MAINTENANCE AND SERVICING

The vacuum tubes in the Tramp-Metal Detector should be checked after every 1000 hours of operation. It may be necessary to go through the balance procedure explained in the Operational Details section if the meter begins to drift upscale after the instrument has been in service for a long time. The relay is sealed and needs no adjustment.

An audio signal generator will facilitate checking the amplifier stage of the instrument. In the event that the oscillator refuses to operate and/or the oscillator tube is replaced, it may be necessary to adjust the "Oscillator Gain" control. To do this, plug the normal search coils into the instrument and connect a Model 260 Simpson meter to the output terminals 1 and 6 of the output transformer. With the Simpson meter switch on "AC" and "10" volts, adjust the "Oscillator Gain" control to obtain a reading of 3.4 volts.