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**Cover Sheet for a Hanford
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Metal Detector Study for Hanford

TO

Nucleonics Division

FROM

W.O. Hansen, General Engineering Laboratory

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Title Page

This document consists of 13 pages. 1

AUTHOR Hansen, W. O.	SUBJECT CLASSIFICATION METAL DETECTION	NO. DF52GL120
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TITLE Metal Detector Study for Hanford		
ABSTRACT A study was undertaken to determine the possibility of detecting 3/8" boron steel control balls that become lodged within cracks between graphite blocks of an atomic pile.		
G.E. CLASS 	REPRODUCIBLE COPY FILED AT General Engineering Lab Document Control Center Schenectady, New York	NO. PAGES 13
GOV. CLASS. 		
CONCLUSIONS Spurious signals, originating from cracks between the conducting graphite blocks completely mask the signal from the ball, thereby making detection impossible. 		

Plus: Drawings as listed on Page 2

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For list of contents—drawings, photos, etc. and for distribution see next page (FN-610-2).

INFORMATION PREPARED FOR Nucleonics DivisionTESTS MADE BY S. R. Blom and W. O. HansenAUTHOR W. O. Hansen *Walter Hansen, April 15 '52*COUNTERSIGNED Dr. Ellsworth D. Cook *Ellsworth D Cook April 15, 1952*DIVISIONS General Engineering Laboratory LOCATION Schenectady, New YorkGO-1876-B (11-51)

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INTRODUCTION

This study was undertaken at the request of the Hanford Works to investigate the possibility of detecting 3/8" diameter boron-steel control-balls which become lodged within cracks between the graphite blocks of an atomic pile. The cracks concerned occur radially from 4 3/16" diameter holes which pass vertically through the pile. The problem is complicated by the following facts: The graphite blocks are conducting and will therefore give rise to spurious signals primarily due to the cracks between blocks. Numerous aluminum tubes containing water and bars of uranium pass horizontally through the pile at distances closer to the hole than the ball at its extreme position. The vertical holes themselves are warped in an arbitrary manner.

Calculations were made to determine theoretically whether or not the ball could be detected. Best operating frequency and coil design were also determined. Tests were made utilizing a specially designed search coil and a test section of graphite pile. Measurements of particle voltage vs. position relative to the coil were made and compared with that resulting from the graphite.

THEORY

The type of metal detector that was investigated is one using a mutual inductance bridge search head. This head consists of two air-core transformers spaced physically apart along the axis of the hole. By connecting the primaries in series and coupling them to a source of alternating current, equal magnetic fields are produced around each of the transformers. The secondary windings are also connected in series, but with their phases reversed so that the individual voltages cancel one another to give a net output of zero. In this manner any small change in either of the secondary voltages, will result directly as an unbalance at the output. The introduction of the steel ball into one or the other of the fields upsets the configuration of the magnetic field and has the effect of changing the voltage induced in the secondary coil. This change which appears at the output of the serially connected secondaries is amplified to the point where it can actuate an alarm or otherwise give an indication of the presence of the ball.

The amplitude and phase of this signal depend on the size and material of the particle. They also depend on the size of the coil and on the frequency and strength of the magnetic field. The amplitude of the signal will determine the amount of amplification required, while the phase characteristic dictates the type of circuit that should be used.

By following the procedures outlined by C. W. Clapp¹, it was determined that the signal from a 3/8" steel ball was almost exactly in phase with the magnetic field over a frequency range from 0 to approximately 5 Kc. The

signals arising from graphite, aluminum, water, and uranium, all of which materials are of unity-permeability, were found to approach a 90° phase relative to those due to the steel ball as the frequency approached zero. A frequency as low as possible was indicated and 25 cycles was chosen as a compromise between this and the requirements of the amplifiers. This 90° phase relationship allows considerable discrimination between the ball signal and that from the other materials by use of phase sensitive detectors.

From past experience, it has been found that spherical steel particles having a diameter one per cent of the mean coil diameter can be satisfactorily detected at the center of a stationary coil system. This sensitivity figure considers the presence of all other spurious signals resulting from instability of the electronic components, moderate vibration etc. It represents a change in voltage induced in one of the secondaries in the order of one part in 10 million; therefore, considerable care must be taken in the design to accomplish this. The signal at points other than the center of the coil will be different because of the variations in field strength with position. It can be shown⁽¹⁾ that the signal at points along the axis of the coil varies as $D^3/(D^2 + 4x^2)^3$ where D = coil diameter and x = distance from the center of the coil.

DESIGN AND CALCULATIONS

The fact that two coils make up the search head requires that it be in the form of an elongated cylinder. Since the holes are not straight, the cylinder and consequently the coils must have a diameter less than that of the hole. For the degree of curvature to be encountered, this diameter was made $3 \frac{7}{8}$ ". The mean diameter of the coils is approximately 3" which will allow detection of a particle of 0.03" diameter at its center. Figure 1 which illustrates the cross-section of the area where detection is to take place, shows that the ball can lodge a maximum of 5.4" from the center of the hole. Since the signal produced by a spherical particle is proportional to both volume and field strength, the ball would have to be larger to compensate for the reduced field at this greater distance over that present at the coil center. The ratio of ball diameters therefore would be the cube root of the ratio of the factors relating signal and field strength as follows:

$$\frac{D_{5.4''}}{D_{\text{center}}} = \sqrt[3]{\frac{(D^2 + 4x^2)^3}{(D^2)^3}} = \frac{3^2 + 4(5.4)^2}{3^2} = 14$$

The minimum diameter of a ball that would give a detectable signal at 5.4 inches from the center of the hole would be $14 \times 0.03 = 0.420$ ". This calculation indicates that, along the axis, the detection of the $\frac{3}{8}$ " steel ball will be marginal even with a stationary coil system. Movement of the coil down the hole will give rise to additional spurious vibration signals which may well mask the particle signal. Flexure of the cables may also be

troublesome. These latter effects can only be determined experimentally.

The above analysis was made assuming that the area surrounding the coil is free from any conducting or magnetic material that can have motion relative to it and thus give rise to a signal. If a homogeneous material were symmetrically disposed about the coil, its effect would be self-cancelling, however, the cracks that exist between the graphite blocks that make up the pile will affect the individual coils differently and cause unwanted signals. The construction of the area near the access hole Figure 1, is such that cracks occur between the horizontal blocks every $4 \frac{3}{16}$ ". These are sufficiently small that the balls cannot lodge in them. Wide cracks do occur between vertical blocks, 48 " long, which make up the major portion of the hole wall. Horizontal tubes of aluminum filled with uranium pass $4 \frac{3}{16}$ " from the axis of the access hole and at $8 \frac{3}{8}$ " vertical intervals. If the spacing between the coils were made $8 \frac{3}{8}$ ", these tubes and the closely spaced cracks in the graphite would influence both coils equally and largely be self-cancelling.

The physical and electrical characteristics of the search coil assembly is shown in Figure 2. The primary was designed to have a resistance of the two separate coils in series of approximately 250 ohms. Since at 25 cycles the reactance is low, impedance matching to the power amplifier is relatively simple. The secondaries were designed to have 10 times the number of primary turns to give a voltage step-up action. A resistance-capacitance network connected across the output of the secondaries allows adjustment of both phase and amplitude of the secondary voltages so as to provide complete

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balancing to a null output. A sharply tuned amplifier was constructed which combined with a vacuum tube voltmeter comprised the measurement set-up shown in Figure 3.

Because of the nature of the problem discussed above, it was decided that tests would be made utilizing an actual test section to determine the characteristics of the signals arising from the graphite cracks, etc. These could then be compared with the signal caused by the ball to determine whether or not the latter can be detected in their presence.

MEASUREMENTS

Determination of the magnetic field contours of the coil was made first by measuring the unbalance voltage resulting from a particle at various positions relative to the axis. The results which are plotted in Figures 4 and 5 were obtained in free space using a $3/4$ " ball. This large size ball was used to give signals that were large enough with respect to the drift in the null balance to give consistent data. Since the signal voltage varies exactly as the volume of the particle, a $3/8$ " ball would give $1/8$ the signal level. These contours check quite closely with those predicted by theory.

It was determined that the $3/8$ " ball signal could definitely be distinguished at distances of $5\ 1/2$ inches along the axis of the individual coils although occasional random signals caused by power line changes or other disturbances reached the same amplitude. These results therefore substantiate the calculated values for minimum detectable particle size. Detection could be obtained out to only $4\ 1/2$ inches at right angles to this axis because of the reduced field strength as shown in Figure 4. Since the farthest position in which the ball can lodge is confined to approximately a 45° angle, the coil axis having the greatest sensitivity can be pointed in this direction by keying it to the notch that is present in the graphite, Figure 1. The sensitivity at 90° to this axis will be more than sufficient by comparison.

Although it was expected that flexure of the power and signal leads from the coil might give large spurious signals, this was found to have a

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negligible effect. With careful handling of the coil it was found that vibration incidental to motion of the detector in the aperture was not a limiting factor.

Measurements were also made of the effect of the graphite material. The experimental pile supplied by the Hanford Works was 4 feet high and 2 feet square. A $4 \frac{3}{16}$ " square hole had been provided instead of the round hole, as shown in Figure 1. The coil was built up to provide a reasonably close sliding fit within the hole. A single aluminum tube was located approximately 16" from the top of the pile and $4 \frac{3}{16}$ " from the axis of the hole.

The coil assembly was inserted completely into the pile near the top and the output balanced to zero. It was then lowered in 1 inch intervals to the bottom, and the output level and phase recorded at each point. Plots of the data for the two possible orientations of the coil with and without the aluminum tube are shown in Figures 6 and 7. It was determined that the amplitude of the signal caused by the graphite crack at the center of the pile was 190 times as great as the ball signal at 5.4". The phase of the graphite signal was nominally $\pm 90^\circ$ relative to the ball signal but was observed to vary approximately ± 5 degrees. Cancellation of the signal from the cracks that occur at the $4 \frac{3}{16}$ " intervals was almost complete as expected because of the $8 \frac{3}{8}$ " spacing of the detector coils.

These measured values of the signal due to the cracks between the graphite blocks are lower than can be expected from the round $4 \frac{3}{16}$ " hole because of the greater amount of graphite that would be in the influence of the strong magnetic field near the coil.

DISCUSSION OF RESULTS

The agreement of the measured free space sensitivity and field contours with the calculated values indicates that the coil design was satisfactory and entirely suitable for the purposes of this study.

By the very nature of the problem, the signal from the crack between the graphite blocks occurs simultaneously with the ball signal. The signal at the output of the coils with the ball present is the vector sum of the two. The effect of the ball, therefore, is merely to shift the phase of the signal from the graphite. For a 190/1 ratio as measured, this change in phase is less than 0.3° . The problem would therefore become one of detecting this phase difference in a signal that varies greatly in amplitude. This would in itself be a difficult problem in instrumentation and would be possible only if the large signal from the graphite did not shift phase more than approximately 0.1° . The change in phase of the signal from the graphite alone is much larger while the influence of the aluminum and possibly the uranium would cause additional shifts.

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CONCLUSIONS

Spurious signals originating from cracks in the graphite pile are of such amplitude and phase as to mask completely any signal caused by the balls to be detected. Detection is therefore not considered possible by employing inductive principles. No other principle having sufficient merit to warrant investigation has been uncovered to date.

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C. W. Clapp "Detection of Tramp Metal" Proceedings of the National Electronics Conference, 1950.

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TITLE

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SH NO.

PLAN VIEW OF DETECTION AREA

FIRST MADE FOR HANFORD METAL DETECTOR STUDY

Note: Area completely surrounded by grahite

REVISIONS

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FIGURE 1.

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TITLE	SEARCH COIL
FIRST MADE FOR	HANFORD METAL DETECTOR STUDY

Coil Data:-

Primary Winding:- 3,750 Turns per coil,
0.0126" heavy formex, layer wound.

Secondary Winding:- 33,000 turns per coil,
0.004" heavy formex, layer wound.

FIGURE 2

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FIGURE 3

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TITLE Block Diagram of Test Set Up			CONT ON SHEET		
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142A744

CONSTANT VOLTAGE CONTOURS
For a 1/2 Diameter Steel Ball
Amplifier Gain: Approx 1500
Made by S. P. E. L. M. Date: March 11, 1952
General Engineering Lab
General Electric Company
Schenectady, N. Y.

FIG. 4.

142A744

142A745

SIGNAL VS. POSITION

For a $\frac{3}{4}$ " Diameter Steel Ball Along Coil Axis

Gain of Amplifier, Approximately 1,500

Made by S. R. Blom

Date: March 11, 1952

General Engineering Lab.
General Electric Company
Schenectady, N.Y.

FIGURE 5

142A745

142A746

GRAPHITE SIGNAL VS. COIL POSITION

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FIGURE 6

142A746

142A747

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FIGURE 1

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