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DETECTION OF LAND MINES

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ABSTRACT

The General Theory of Metal detection is given in the earlier portion of the paper. The conflicting influences of conductivity and ferromagnetism are stressed and the difficulty of detecting metallic mines in magnetic soils is explained.

The latter half of the paper deals with the principles of operation, description and comparative performances of a few mine detectors now in service use. Towards the end mention is made about the possibilities of tackling the problem of non-metallic mine detection.

One of the new primary aids to defence is the large scale use of Landmines. A field of such mines distributed in depth, covered by artillery fire is a very formidable defence line indeed. Military Science has yet to disprove the statement that the advantages are always on the side that lays these deadly charges. Until then we can hold Dr. Bush's view that in the conflict between landmines and the means for removing them, the mines have won out.

During the last war the allied progress in the Libyan desert, and in southern Italy was seriously hampered by the German Minefields. The development of portable devices for detecting these metallic mines was one of the urgent problems confronting the British and the American Scientists at that time. The detection of metallic mines is a comparatively simple matter due to the fact that the electrical properties of metals differ sharply from those of the surrounding media. Some of these properties are the high electrical conductivity of the non-ferrous metals and the magnetic susceptibility of ferrous metals. But at present the main problem connected with mine warfare is the detection of the non-metallic mines. The difficulty is that the properties of non-metallic mines do not differ markedly from those of the surrounding soil. Detection of these must therefore be based on totally different principles, and future military research must be directed to the discovery and application of these principles.

The earlier portion of this paper deals with the general theory of metal detection and the latter describes the various types of portable mine detectors which are now being used by the Indian Army.

THE DETECTION OF THE METALLIC MINES

General Principles

Ideas which are responsible for the detection of Metallic bodies are based on certain properties of metals, namely :—

(i) Electrical conductivity.
(ii) Magnetic permeability.
(iii) High density.
(iv) Radioactivity.

Detection of a material of high density may be achieved through the use of an ultrasonic beam which will be reflected by any irregularity in a homogeneous medium. This principle can be used also in the detection of non-metallic mines which have densities differing from that of the earth.

Radioactive metals may be detected by Gieger Muller counters, and this method has been used in the location of Uranium ore fields.

The mine detectors under discussion are based on either magnetic or the electrical properties of the material under consideration.

The introduction of a metallic particle into an alternating magnetic field distorts the symmetry of the field. Therefore, if a system of coils is constructed to radiate an alternating field (let us call it the primary field) any metallic particle in the region of the field acquires a magnetic dipole moment on account of the eddy current and magnetic polarisation induced by the field. The distortion of the primary field by a metallic particle ultimately depends upon the nature of the metal under investigation. The ferrous metals (iron, cobalt and nickel) have a high magnetic susceptibility in addition to high electrical conductivity. On the other hand non-ferrous metals (Aluminium, Copper, etc.) have only a high degree of electrical conductivity with very little magnetic properties. Thus an alternating magnetic field will be distorted in the presence of a metallic mine by the eddy current produced in its conducting parts and by the magnetic polarisation induced in those regions of high magnetic susceptibility.

Consider two coils A and B, which are so wound that the mutual inductance between the two is zero. In other words the coefficient of coupling is zero since $M = K\sqrt{L_1 \ L_2}$, where L. & L. are the self inductances of coil A and coil B respectively. If now Coil A is connected to an oscillator, it produces a magnetic field, but the voltage induced across the terminals of coil B is zero as there is no coupling between A and B. If a metallic particle is now introduced into the region of this primary field, Coil B can pick up a small voltage by two possible ways. Each of them will be discussed separately.

1. If the particle is of a purely magnetic material with zero electrical conductivity (this is a hypothetical case since there is no metal which is purely magnetic and completely non-conductive) then the particle acts like a core in a transformer whose primary is coil A and the secondary is B. The transfer of flux from the primary to the secondary can occur now through this core. The coefficient of coupling has now become finite and a small voltage is induced in the secondary. The amount of voltage induced in the secondary for a given particle at a particular distance from the primary coil is a measure of the sensitivity of the arrangement. It may be expected in the above example that the sensitivity is independent of the frequency employed in the primary coil. The increase in frequency will not in any way increase the secondary voltage if the distance of the particle from the coil is kept constant. It has been shown that the co-efficient of coupling between the two coils is given by the expression

$$\frac{16}{9}\left\{\frac{\sqrt{ab}}{d}\right\}^{6} \text{ where}$$

a = diameter of each coil.
b = diameter of the metallic particle under consideration.
d = distance of the metallic particle from the primary coil.

From this one can readily see that the voltage in coil B varies inversely as the sixth power of the distance between coil A and the particle and is directly proportional to the third power of the diameter of the particle. Hence the sensitivity of the detector should fall off very rapidly as the distance d increases.

2. If the particle introduced is a purely conductive one it dissipates energy, thereby decreasing the energy in the field. It acts like a shortcircuited secondary of the transformer which has the coil A as its primary. The magnitude of the current flowing in the particle depends upon its resistance and the extent of its coupling with the exciting coil. These eddy currents in turn radiate a relatively weaker field which due to its linkage with the coil B induces a small voltage. Now the eddy currents in the particle increase as the square of the frequency employed in the exciting coil and hence we can expect a rapid increase in the sensitivity of the arrangement if the frequency is raised.

In the case of steel mines both the above effects are present since steel has both magnetic and conducting properties. The secondary voltage in coil B is therefore comparatively small in magnitude since the voltage due to the eddy current effect tends to cancel out that due to the magnetic effect as they are opposite in direction.

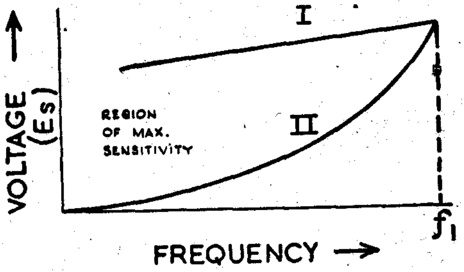

FIG. 1

In the figure, curve I shows the variation of induced voltage with frequency for a magnetic substance and it will be seen that as the oscillator frequency is increased, there is practically no change in the voltage picked up by B.

On the other hand for a particle which is purely conductive the voltage induced varies as the square of the frequency as shown in curve II. For steel and other ferrous substances however, the induced voltage will be denoted by the difference in the ordinates of the two curves. It will be seen that the maximum sensitivity for these substances will be in the low frequency region. This is one of the reasons why a low frequency is employed in many of the mine detectors. From the figure it is also evident that there is a critical frequency f_1, at which the detector will be practically insensitive to ferrous metals.

In metal detection one of the fundamental problems is the calculation of the strength of the dipole-moment induced in the particle by the primary field. It is a classic problem in magneto-statics—the calculation of the magnetic polarization induced in a homogeneous spherical particle when placed in a uniform magnetic field of strength **H.**

In solving this problem it is found that the field external to the particle may be considered as the linear superposition of the original field H, and the field of a magnetic dipole of strength 'm' located at the centre of the particle, the dipole strength being given by

$$\overline{m} = \frac{3}{4\pi} \frac{\mu - 1}{\mu + 2} V\overline{H}$$

where V = volume of the spherical particle.

μ = permeability of the sphere.

The solution of the same problem for a more general case where the applied magnetic field is alternating has been worked out by Poritsky. According to him when the applied magnetic field is He^{wt}, the complex induced dipole moment is given by

$$\overline{m} = \frac{3}{8\pi} \left\{ \frac{2\mu + 1 - W}{\mu - 1 + W} \right\} V\overline{H}$$

where $$W = \frac{(\gamma + i\gamma)^2 \tan h\, \gamma + i\gamma}{\gamma + i\gamma - \tan h\, \gamma + i\gamma}$$

and $$\gamma = \pi d \sqrt{\mu \sigma f} \times 10^{-9}$$

σ = conductivity of sphere.

μ = permeability of sphere relative to free space.

$f = \frac{\omega}{2}$ = frequency of applied field.

d = diameter of sphere in cms.

$$\frac{\overline{m}}{V\overline{H}} = \frac{3}{8\pi} \left\{ \frac{2\mu + 1 W}{\mu - 1 + W} \right\} = x + iy \text{ say}$$

Here x and y are both functions of γ and μ

Thus we see that vector m is completely determined by the two quantities γ and μ both of which are dependent on the intrinsic properties of the material under investigation, *viz.* :—

1. The permeability of the metal relative to free space.
2. The conductivity of the metal.
3. The frequency employed.

C. W. Clapp has shown that the voltage induced in the passive secondary coil which is subject to the flux of this dipole is given by

$$e_s = -i w \frac{3V}{8\pi} (x + iy)(\overline{H}_p \cdot \overline{H}_s)\, 10^{-8} \text{ Volts}$$

where H_p is the magnetic field strength in lines per square cm. caused by a current flow of 1 amp in the primary coil and H_s is the magnetic field intensity in lines per sq. cm. caused by 1 amp flowing in the secondary coil. In other words the mutual impedance between the two coils which was originally zero has now become

$$\triangle Z = iw\,\frac{3V}{8\pi}\left(\chi + i\gamma\right)\bar{H}_p\,\bar{H}_s \times 10^{-8}\ \text{Ohms.}$$

$$\text{If } H_p = H_s \simeq \frac{4\pi n}{10D}\left(\begin{array}{l} n = \text{No. of turns of coil} \\ D = \text{diameter of coil} \end{array}\right)$$

$$\triangle Z = iw\,\frac{6\pi n^2 V}{D^2}\left(\chi + i y\right)10^{-10}\ \text{Ohms}$$

This expression $\triangle Z$ forms a convenient figure of merit for a metal detector.

Description of Mine Detectors

Mine detectors operating on the above principles can be broadly divided into three classes :—

(i) Detectors operating on the Felici Mutual inductance bridge method, *e.g.*, SCR 625, Polish detector No. 1 and No. 2 and No. 3, British Mine Detector No. 5 and German Detector Frank Furt 42.

(ii) Detectors working on the Heterodyne method, *e.g.*, the German Mine Detectors, Neptune, Aachen, the Berlin 40.

(iii) Detectors working on the regenerative amplifier principle, *e.g.*, British Metallic Mine Detectors No. 3A, 6A and No. 4.

Bridge Type Detectors

The SCR 625

Principle of operation

The detector works on the principle of the Felici inductive bridge, a sketch of which is given below :—

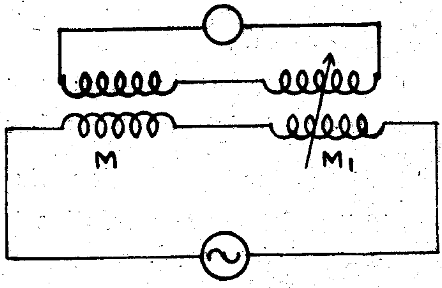

FIG. 2.

M is a fixed mutual inductor whose primary is connected to an oscillator in series with the primary of another variable mutual inductor M_1. The secondaries of M and M_1 are connected in opposition so that when $M = M_1$ no current flows through the secondary circuit. When there is a slight change in M the balance is upset and the sensitive galvanometer shows a deflection.

This circuit has been adopted in the SCR 625 and other bridge type detectors. The SCR 625 consists of two identical coils L_1 and L_2 connected in series but with their fields opposing. Another coil L_3 which may be called the receiving coil is connected to an amplifier. The output of the two stage amplifier feeds a resonator, and a meter, by means of which we get audio as well as visual response to any unbalance in the circuit. Another variable mutual inductor inserted for achieving perfect balance in the system is housed in a separate box called the control box. The value of this mutual inductance can be changed at will by means of knobs provided in the front panel of the box. The simplified circuit diagram of the SCR 625 is shown below and one can at once notice its similarity to the Felici bridge.

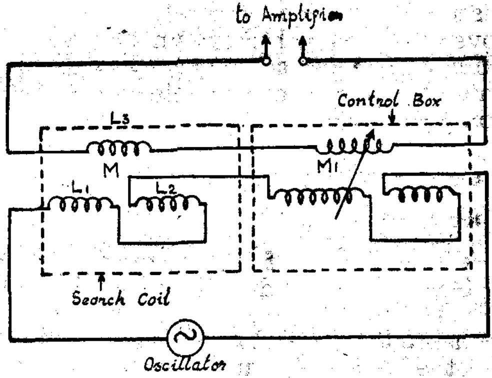

FIG 3

It will be evident from the diagram that the mutual inductance M and M_1 that we are dealing with are quite small. They will be of the order of a few microhenries. The oscillator works at thousand cycles.

Finer Adjustments in the SCR 625

Reverting back to the Felici bridge (see Fig. 2) perfect balance cannot sometimes be achieved even if $M = M_1$. If the current flowing in the primary circuit is i_1 then normally we would expect the secondary voltage of M to be $iwM\ i_1$ and that in M_1 is iwM_1i and since the secondaries are connected in opposition there must be balance. But it is only in an ideal instrument that the voltage induced in the secondary is $iwMi_1$ in quadrature with i_1 in the primary. The above equations will hold good only when there are no eddy currents and no displacement or capacity currents in the system. But these always exist and Vs and i_1 are strictly in quadrature and we must write

$$V_s = \left\{ \sigma + iw(M + \Delta M) \right\} i_1$$

where σ may be called the impurity and ΔM the frequency correction. It must be remembered that not only does each coil possess self capacitance, but the two coils are also linked by a distributed mutual capacitance. The mutual inductor is therefore more complicated than a self inductor. So, for balance, we should not only make Vs and V_1 equal in magnitude but make them exactly 180° out of the phase. The latter can be achieved by varying the value of M_1, *i.e.*, by varying the eddy current losses in M_1. For this reason a brass core is provided and by a variation of the resistance of this core the eddy current losses can be increased or decreased. The exact theory of phase alteration by variation of eddy current losses is given in the appendix.

The Heterodyne Detectors

These detectors were used only by the Germans during the last war. Since the Bridge type detectors, and detectors working on the regenerative principle were much more sensitive than those working on the heterodyne principle little effort was made by the Americans and the British to develop them. High frequency detectors cannot be very successful against Ferrous Metals and the reasons for these have already been discussed in the general theory underlying mine detectors. Moreover experience has shown that better stability, sensitivity and reliability can be achieved by low frequency bridge detectors and almost all operational detectors in England and America are now-a-days of this type.

The German Detector Neptune

Principle of Operation

The "Neptune" was one of the several heterodyne detectors developed by the Germans early during the war and used by them in North Africa. Its circuit is built round a single hexagrid valve. A Colpitts oscillator using grids 1 and 2 has the search coil for its inductance. There is another fixed oscillator also of the Colpitts type which is connected between the grid 4 and the anode. The mixed signal is fed through a step up transformer to headphones.

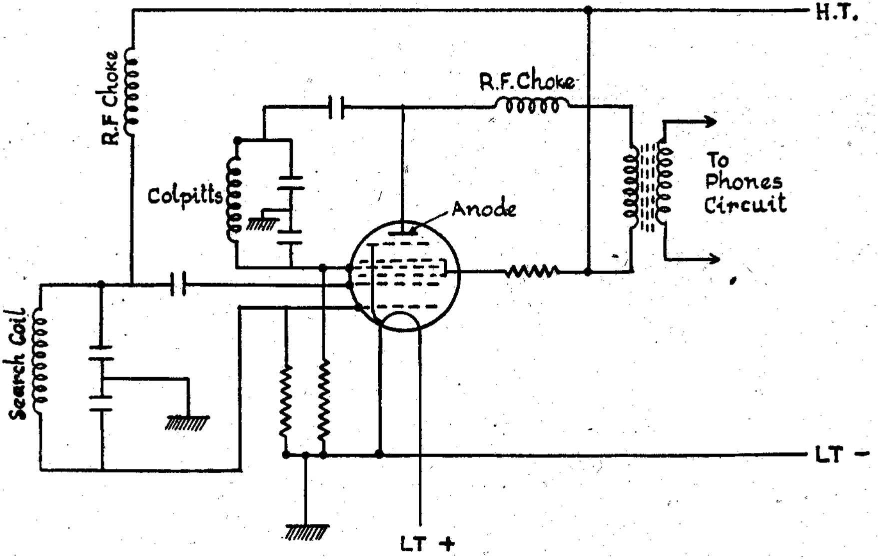

FIG. 4

It is well known that if two waves almost of the same frequency, say $E_1 \cos w_1 t$ and $E_2 \cos w_2 t$ are mixed the mixed signal will be of the form ${}^2E_2 \cos\left(\frac{w_1-w_2}{2}\right)t \cos\left(\frac{w_1+w_2}{2}\right)t + (E_1-E_2)\cos w_1 t$

If for simplicity we assume $E_1 = E_2$ and $\frac{w_1+w_2}{2} = w$ then the mixed signal will be of the form $e = 2E_2 \cos\left(\frac{w_1-w_2}{2}\right) t \cos w t$

The component of the beat frequency $\frac{1}{2\pi}\left(\frac{w_1-w_2}{2}\right)$ can be obtained only through the distortion of the above wave form through some nonlinear process such as that involved in a demodulator of the beat frequency oscillator. There are numerous tubes which perform mixing and detection at the same time. The hexagrid valve with the circuit connection usually employed in the Heterodyne detectors is shown in the figure.

The frequencies of the two oscillators are so adjusted that an audible note of very low pitch is heard in the headphones. Any metallic particle in the vicinity of the search coil changes its inductance and hence the frequency of the tuned circuit. A noticeable change in the pitch of the note is produced. The H.F. Oscillators work at a frequency of 70 Kc/s.

Sensitivity

It appears to be the characteristic of all Heterodyne detectors that their sensitivity to large metallic objects is fairly good, but to small pieces of metal it is poor. All non-magnetic metals, and large steel objects produce signals in the form of an increase in pitch. On the other hand ferrous rock was indicated by a lowering of the pitch. The detector is practically insensitive to small pieces of iron and steel.

Detectors Working on the Regenerative Amplifier Principle

The first detector working on the above principle was produced in July, 1944. Its principle is based on that of a feed back oscillator.

If the coupling between the output and the input circuit is very low the tendency to oscillate is controlled. In other words the oscillations are infinitely weak. Let us assume that the frequency of these oscillations is f_0. Increasing the coupling disturbs the balance and this departure will increase the amplitude of oscillations. The frequency will also differ from f_0, becoming smaller or greater according to the nature of the coupling. The simplified circuit diagram of the British Metallic Mine Detector No. 3A is shown in Fig. 5.

L_1 and L_2 are the two coils constituting the search coil. From the figure it may be noticed that the input and output circuits are coupled through these coils whose mutual inductance is adjusted to be zero before the beginning of an operation. Reducing the coupling to a very low value is of paramount importance if the amplitude of oscillations has initially to be small.

In practice it is very difficult to achieve this because there are always eddy currents, leakage and capacity currents in the system.

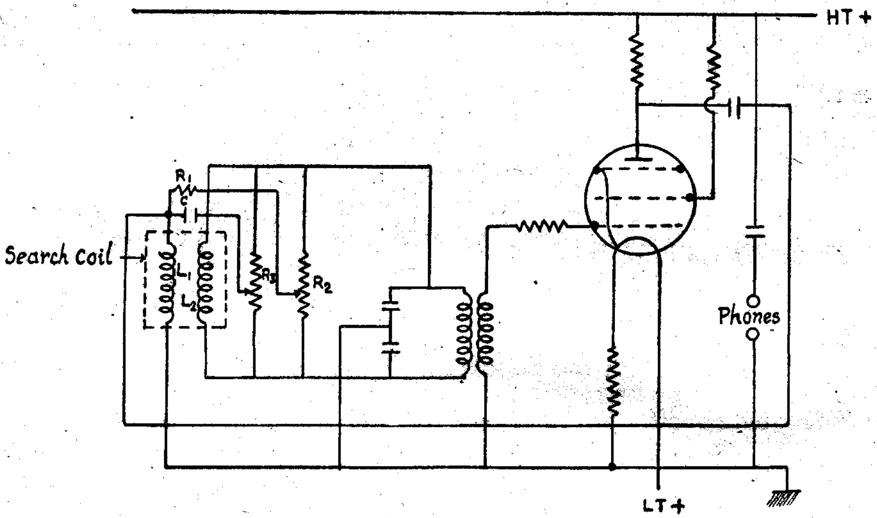
HT +
R1
C
Search coil
L1
L2
R3
R2
Phones
LT +

Fig. 5

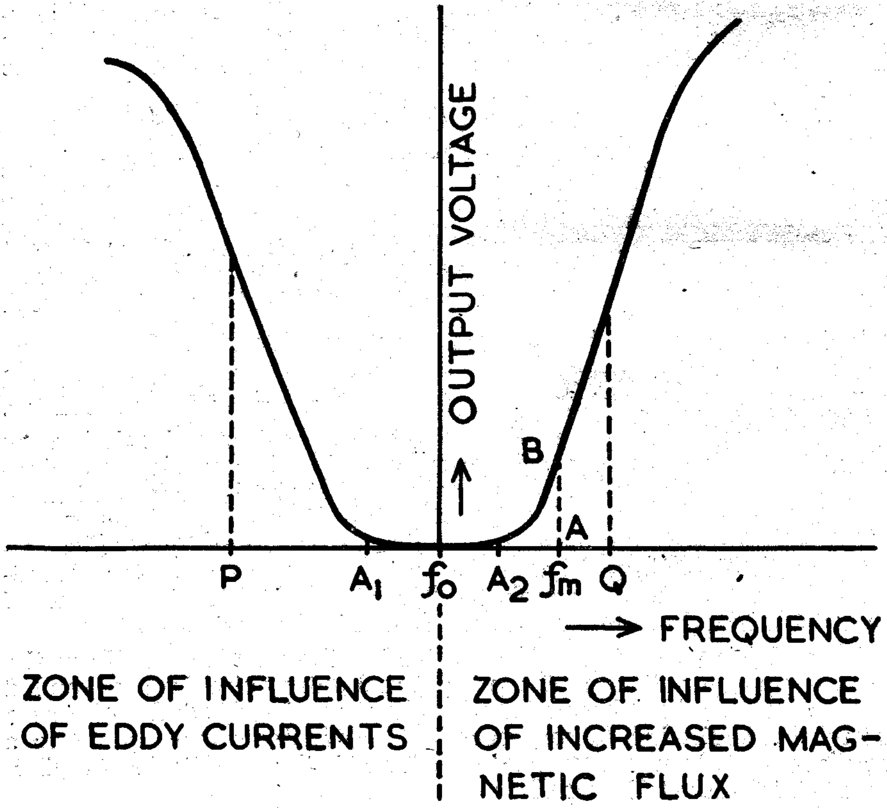
OUTPUT VOLTAGE
B
A
P
A1
fo
A2
fm
Q
→ FREQUENCY
ZONE OF INFLUENCE OF EDDY CURRENTS
ZONE OF INFLUENCE OF INCREASED MAGNETIC FLUX

FIG. 6.

To ensure zero coupling, therefore, an additional net work is provided consisting of resistances R_1 and R_2 and R_3 and a condenser C. By the adjustments of the resistance R_1 and R_2 we can make the coupling practically zero. Any metallic particle in the vicinity of the search coil alters the coupling and hence the amplitude of the oscillation increases. A slight shift in the frequency is noticed. It is of very great interest to study this phenomenon of the variation in the frequency and amplitude. The sensitivity of the detector depends only on the increase in amplitude.

Figure 6 shows the graph of frequency shifts versus amplitude Referring to figure the magnetic materials such as pave, clinker or magnetite will shift the frequency from f_0 to f_m giving an appreciable output AB. In the case of large metallic bodies where appreciable eddy currents exist the working point will be shifted to the left of the working frequency, *i.e.*, towards lower frequencies. The detector is practically insensitive from A_1 to A_2 and any shift in the frequency between these limits do not affect the detector. This region between A_1 and A_2 is known as the dead zone. A large metallic mine will shift the working point to P and a small magnetic mine in which eddy currents are small and the magnetic effect therefore predominates will shift the point to Q giving appreciable change in the output.

The frequency of the 3A detector is arranged to be approximately 1100 c.p.s. There is a pair of headphones connected to the amplifier output. Even when there is no coupling between the coils there is still a small signal due to stray disturbances and this is heard as a back ground rustle. One advantage of the above detector is that its characteristic can be changed by shifting the initial working point from one dead zone to the other. This adjustment enables the instrument to discriminate the Metallic Mines against Pave, Magnetite or clinker.

Comparative sensitivities of the different types of mine detectors discussed in this report

Type of Mine	Regenerative Amplifier	Bridge type detectors	Heterodyne type
	Distance in Inches	Distance in Inches	Distance in Inches
Tellermine	24	24 to 28	21
S—Mine	18	13—15	12
British Mark	21	18	18
Ferrous Rock (Pave)	9	13	7

Data taken from SRDE Reports

A study of the above table reveals that all the detectors are quite sensitive to large mines even at distances of the order of two feet.

In the case of large mines eddy current effects play a large part, being relatively great compared to the magnetic effects. The difficulty of detection is felt only in the case of small steel mines like the

'S' mine, for example, where the magnetic and eddy current effects try to cancel each other. It is in the detection of such mines that instruments employing the regenerative amplifier principle score over the other types.

Another remarkable feature about this detector is its ability to discriminate between magnetic and non-magnetic substances. This assumes an enormous importance especially when the detection has to be done in soils abounding in magnetite or pave as it is often referred to and clinker (abounding in feo). All the latest British detectors (*e.g.*, No. 6A) work on the regenerative principle. So far the problems concerned with the detection of metallic mines have been discussed in detail. But during the last war, non-metallic mines were also used by some countries. Methods of their detection are of great importance.

Detection of Non-Metallic Mines

The problem of the non-metallic mine has been attacked principally through detectors utilizing the variations in the acoustic, electrical and radioactive properties in the ground produced by any buried object. The name non-metallic mine detectors is somewhat a misnomer since all non-metallic mine detectors would also detect the metallic mines. Some of the techniques used in the last war to detect non-metallic mines will be described below.

The AN-PRS-I Detector

This was developed by the RCA Victor division towards the end of 1943 and shortly thereafter was approved by the National Defence Research Committee. A three hundred mega cycle oscillator radiated energy into the ground and utilized variations of the loading in the antenna to detect any discontinuity. This instrument gave good response to large anti-tank mines, but was much less sensitive to anti-personnel mines. One of the major drawbacks in this method was that it gave a number of false indications when the stones, roots and cavities in the ground were encountered.

The Brewster Angle Detector

This is based on the principle that when an electro magnetic wave suitably polarized was incident on a boundary between two dielectric media, there was a critical angle of incidence beyond which the waves would be totally reflected. If there was a disturbing object beneath the ground it would reflect the refracted ray completely and this reflected ray could be used to activate a suitably placed receiver. A transmitter radiated a ten centimeter wave into the ground through a parabolic reflector. A similar antenna array was used in the detector head, and a specially designed amplifier actuated an indicator system. Actual use in the field revealed that this detector was far from reliable. It is yet to be perfected for field use.

Seismic Detectors

These were also developed by the Victor division RCA. They generated acoustic waves by means of an Oscillating mass, held in contact with the ground. The detector and the ground immediately underneath constituted a resonant system and this resonant frequency was determined by soil conditions. If this frequency was lowered, it was either due to the presence of a mine or due to disturbed earth. The detector weighed about 6 lbs. and hence it was dangerous to use it in a mine field strewn with highly sensitive anti-personnel mines. Moreover since the detector required point to point contact with the ground it proved to be less rapid than simple prodding with an iron probe.

The conclusion seems therefore inevitable that no successful solution of the non-metallic mine problem was ever reached during the last war. The astounding success that characterized many of the projects in the fields of electronics, acoustics and instrument technology was significantly absent in the land mine programme of the National Defence Research Committee. The explanation may most probably be found in the unpredictable tactics of the enemy. The requirements for land mine counter-measures has to be repeatedly changed to suit the varying tactics of the enemy. Until a really effective means of clearing mine fields is developed the advantages will always remain with the users of the deadly charges.

Note.—Figures 4 and 6 have been taken from S.R.D.E. Reports.