A STUDY AND INVESTIGATION OF MANGANESE ARSENIDE AS A TRANSDUCER MATERIAL

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by

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Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS

United States Naval Postgraduate School
Monterey, California

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ABSTRACT

Recent research at General Electric into the physical properties of manganese arsenide has resulted in the discovery of some unique properties which suggest the use of MnAs as a transducer material.

The underlying theory behind these unique properties are described, and methods of applying these properties for use as a sonar projector as well as other applications are discussed. Actual design considerations and problems encountered in designing a working model are reported.

The writers performed their work at the General Electric Company, and wish to express their appreciation for the facilities made available to them at the Sonar Laboratory in Syracuse, New York. Special appreciation is extended to Dr. Donald Rodbell of the General Electric Research Laboratory, from whom many ideas and much of the data on the physical properties of MnAs were obtained. The writers also wish to express their appreciation for the Assistance and encouragement given them by Mr. T. C. Madison, Transducer Consultant for the General Electric Company.

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1. Introduction

Studies by Drs. D. S. Rodbell and P. E. Lawrence of General Electric Research Laboratory on the magnetic properties of manganese arsenide have resulted in the discovery that MnAs undergoes an abrupt increase in volume when subjected to a large magnetic field (30,000 oersteds) at a temperature slightly above the Curie Point. This change in volume suggested the use of MnAs as a transducer material. Further studies have shown that the volume change is a function of pressure, as well as temperature and magnetic field. Because of these unique properties, the MnAs transducer could have various modes of operation (See Section 4).

The authors have attempted to span the gap between the theoretical use of MnAs as a sonar projector and the practical design problems encountered in building a working model. The initial pages of this paper discuss the physical properties of MnAs and how they may be applied in various transducer designs. This section is followed by a report on an actual design which was used in a feasibility study. The results of this feasibility study which include design limitations, expected problems and recommendations for further experimentations are presented.

2. History of Research Into the Physical Properties of MnAs[1]

Manganese Arsenide is a metallic, ferromagnetic compound that exhibits certain interesting and unusual properties. The magnetic properties were first studied by Heusler[2], Hilpert and Dieckmann[3]. These early studies revealed that the ferromagnetism that exists at lower temperatures vanishes abruptly at 35°C. (See Figure 1).

In the usual case, a ferromagnet exhibits a continuously decreasing magnetization with increasing temperature, and the magnetization vanishes at the Curie temperature as shown in Figure 2. This transition is defined[4] as a second order phase change since there is no change in entropy, volume or latent heat.

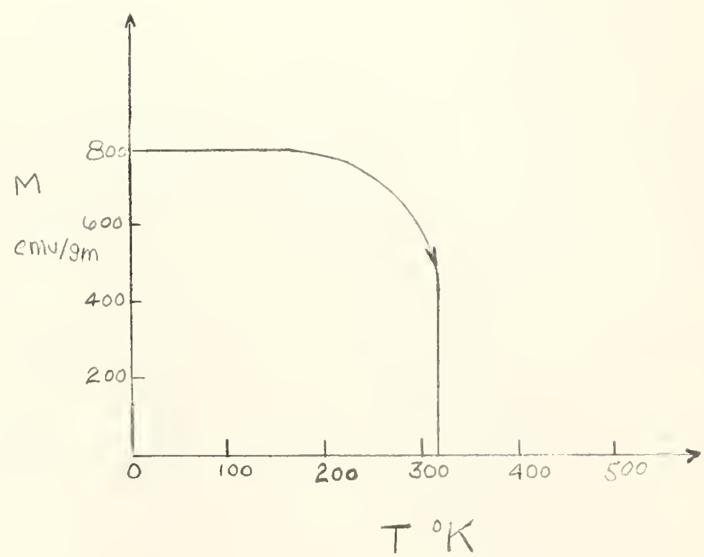


Figure 1. Magnetization vs. Applied Temperature for MnAs

In 1928, Bates[5] measured a latent heat of 1.79 cal/gram (Figure 3) and this discovery led later investigators to suspect a first order

1. Figs. 1,3,4,6,7 and 8 were obtained from GE Report No. 61-RL-2888m with permission of the Authors, C. P. Dean and D. S. Rodbell.
2. F. Heusler, Z. angew. Chem., 1, 260, 1904.
3. S. Hilpert and T. Dieckmann, Ber. Deut. Chem. Ges., 44, 2378, 2831, 1911.
4. M. W. Zemansky, Heat and Thermodynamics, p. 322, McGraw-Hill Book Co., 1951.
5. L. F. Bates, Proc. Roy. Soc., A117, 680, 1928.

phase change which would be characterized by a change in volume and entropy (crystal structure) as well as the change in latent heat. These later investigators[6,7,8] concluded that there was a change in lattice parameter (i.e., density) although they couldn't detect a change in the crystal structure. A current x-ray study by R. H. Wilson and J. S. Kasper of G. E. Research Lab has revealed that above 40°C, the crystal structure changes from a hexagonal to an orthorhombic type[9]. Associated with the crystal change is an abrupt change in atomic coordinates. (Figures 4,5).

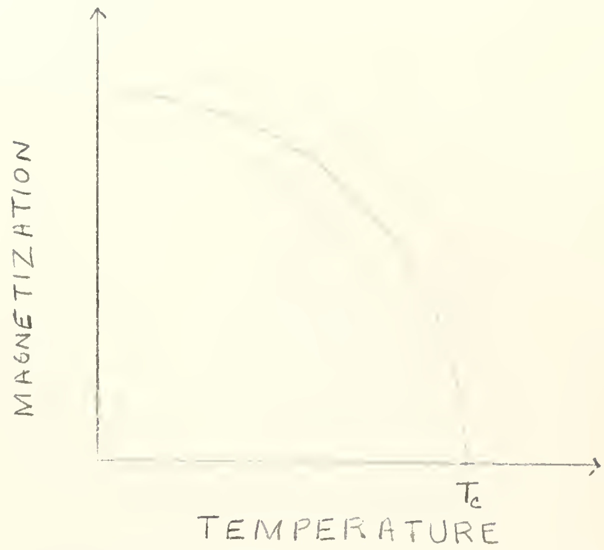


Figure 2. Ferromagnetic Magnetization Curve

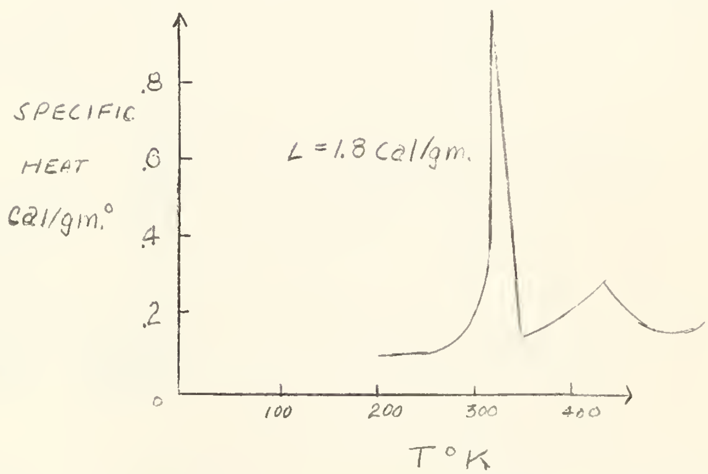
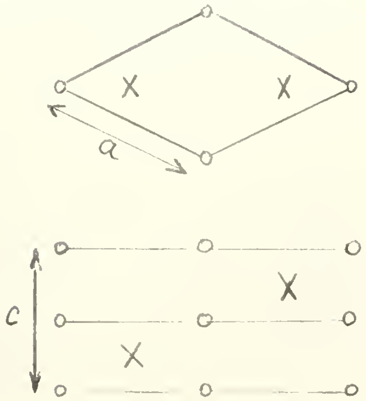


Figure 3. Specific Heat Characteristics

6. C. Guilland, thesis, Strasbourg, 1943.
7. B.T.M. Willis and H. P. Rooksby, Proc. Phys. Soc., B67, 290, 1954.
8. Z. S. Basinski and W. B. Pearson, Can. J. Phys., 36, 1017, 1958.
9. C. P. Dean and D. S. Rodbell, G. E. Report No. 61-RL-2888m, 1961.

Since the c axis undergoes no change at the transition point, the percentage change in volume is given by $\frac{\Delta V}{V} \doteq 2 \frac{\Delta a}{a} = 2\%$



O Manganese Atom

X Arsenide Atom

Figure 4. Unit Cell of MnAs

Rodbell and Lawrence[10], extending the work of Guillaud and of Meyer and Taglang[11], have shown that in very large magnetic fields it is possible to accomplish the phase transition by field alone and also to observe the large volume change (an effect that eluded earlier attempts[12] by other investigators due to insufficient fields). The measurements of Rodbell and Lawrence are given in Figure 6.

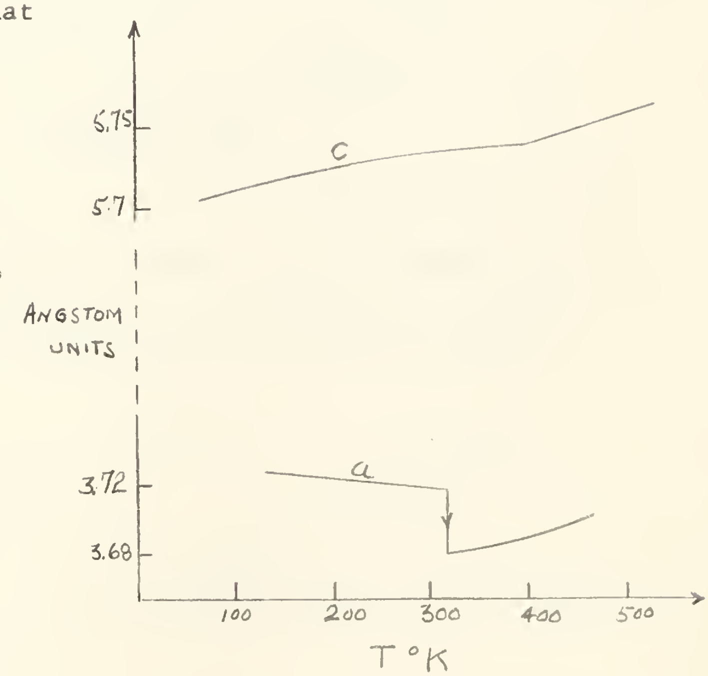


Figure 5. Atomic Coordinates vs. Temperature

10. D. S. Rodbell and P. E. Lawrence, J. Appl. Phys., 31, 275S, 1960.
11. A. J. P. Meyer and P. Taglang, J. Phys. Radium, 14, 82, 1953.
12. A. Smits, H. Gerding and F. Ver Mast, Z. Phys. Chem., 357, 1931.

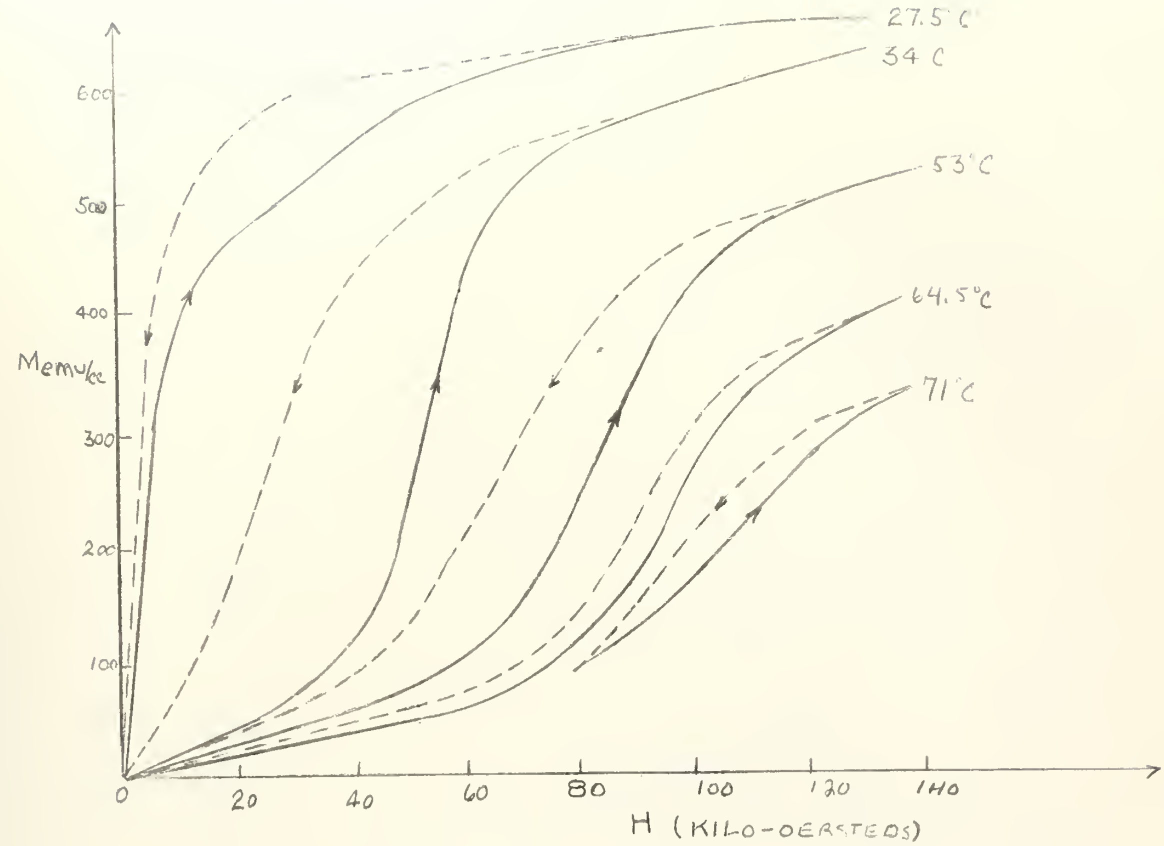


Figure 6, Magnetization vs. Applied Field for a Sample of MnAs

Figure 6 illustrates the fact that the critical field at which large magnetization changes appear depends upon the temperature, and the value of this H_{crit} vs. Temperature are plotted in Figure 7.

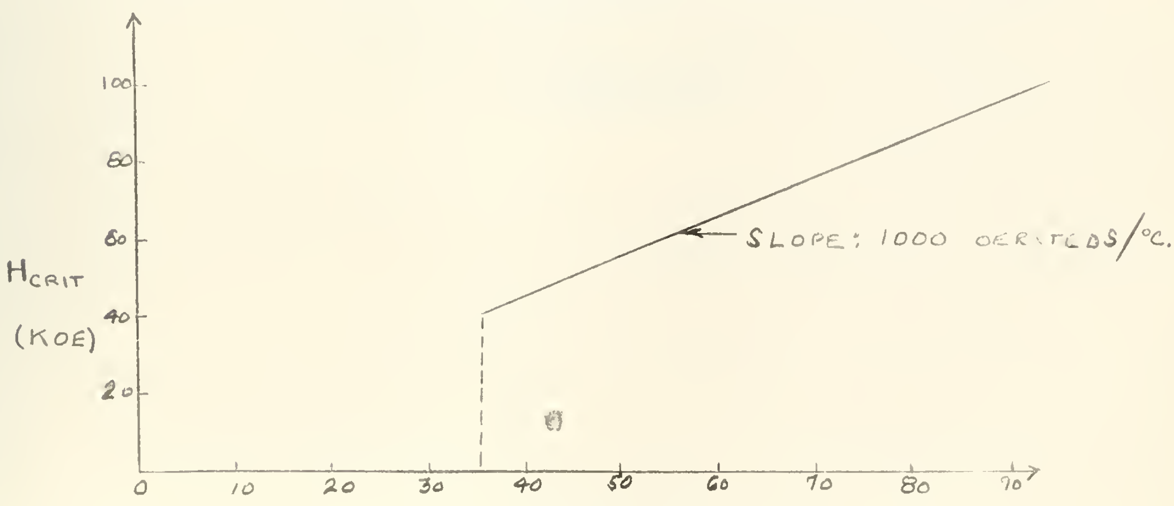


Figure 7. Critical Field as a Function of Temperature

It is believed that the phase transition occurs in the vicinity of H_{crit}, and therefore, this value represents the field required to switch MnAs from one volume state to the other. The values in Figure 7 are for atmospheric pressure. By increasing the pressure, the transition temperature (and therefore, the field requirements) are reduced as shown in Figure 8.

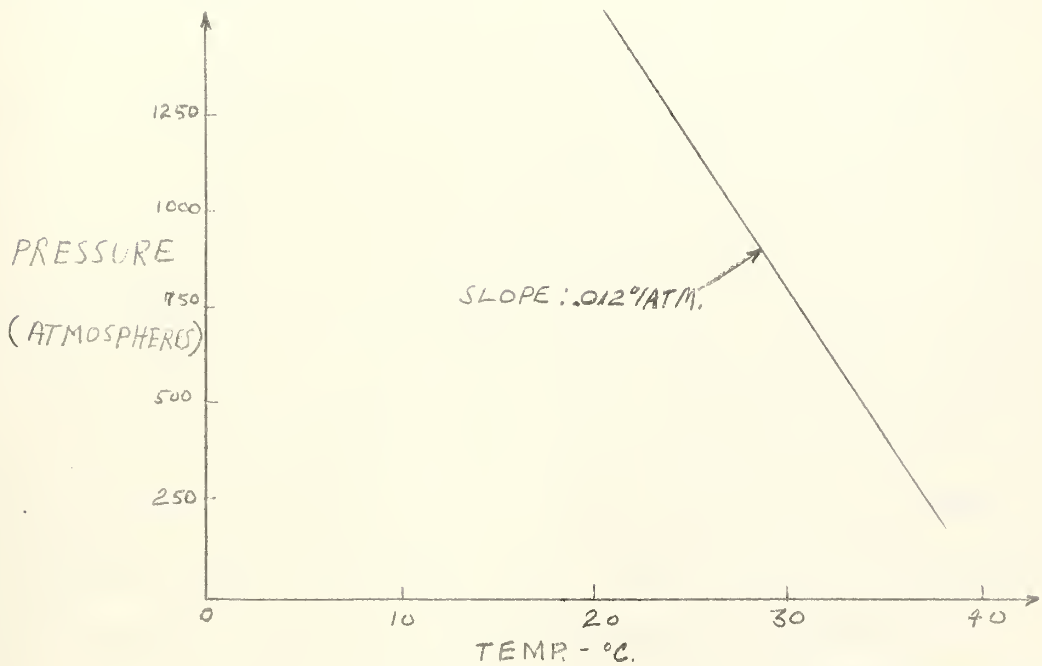


Figure 8. Critical Pressure as a Function of Temperature

3. Possible Ways of Using MnAs as a Driving Element for Transducers

The feature of MnAs of most interest, and which suggests its possible use as a transducer element, is its change in specific volume by two per cent when subjected to the proper conditions of temperature, pressure and magnetic field. This extremely large volume change can be compared to the one dimensional changes of other commonly used sonar materials to show its inherent advantages.

MnAs ------------ 10^{-2}m/m (or $2 \times 10^{-2} m^3/m^3 \frac{\Delta V}{V}$)

Nickel ----------- 4×10^{-5}m/m saturation magnetostriction

PZT -------------- 10×10^{-5}m/m at a field of $\frac{10 \text{ volts}}{\text{mil}}$

The potential advantage of MnAs is therefore 100/1 in displacement over the best currently available materials or a possible energy advantage of 10^4 to 1 in the basis of equal volume of active material.

Any one of the three parameters (temperature, pressure or magnetic field) may be varied singly, or in any combination, to trigger the MnAs from one volume state to the other. These methods are considered below to show more clearly the various mechanisms of operation.

(1) Temperature Control: Under constant pressure, MnAs could be switched from its magnetic to its non-magnetic (with accompanying volume change) state by merely raising its temperature above its critical temperature (approximately 40°C at atmospheric pressure). The reverse holds true, but when cooling the MnAs to switch it back to its magnetic state, the critical temperature is about 10° less than the temperature at which it switched non-magnetic. This is due to the hysteresis involved and is shown in Figure 9.

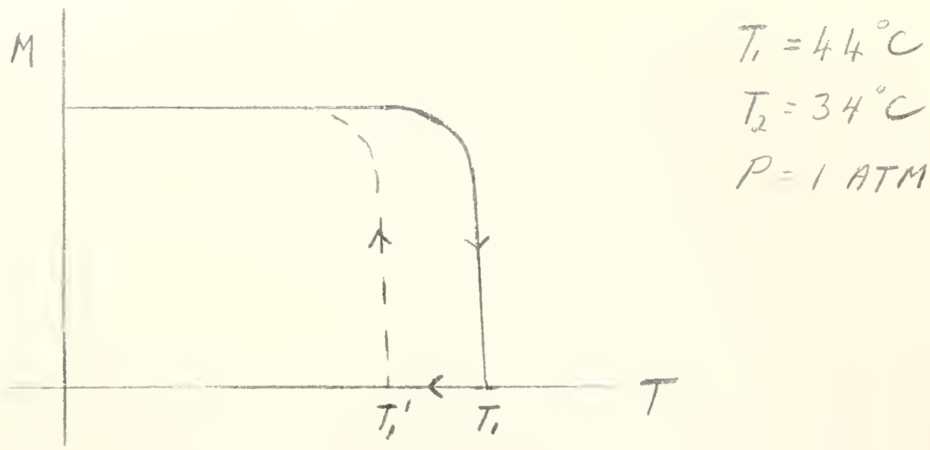


Figure 9. Temperature Hysteresis

Although this method is the easiest way to switch the material in the laboratory, it would not readily lend itself to actual transducer operation. The difficulty that would be encountered in varying the temperature at anything even approaching an acceptable frequency of operation would be prohibitive. However, the control of the static temperature is of importance because this partly determines its operating point when controlled by other methods, as will be more clearly explained below.

(2) Pressure Control: The control of pressure to switch the MnAs sample when used as a projector to transmit pressure waves is obviously not feasible. Also since by the nature of the switching action involved (step function), MnAs would be insensitive to small pressure variations and would therefore not be adaptable for use as a receiving device. However, its dependence on pressure requires that, like temperature, this parameter be controlled to set the operating point when other

switching methods are used, (See Figure 10).

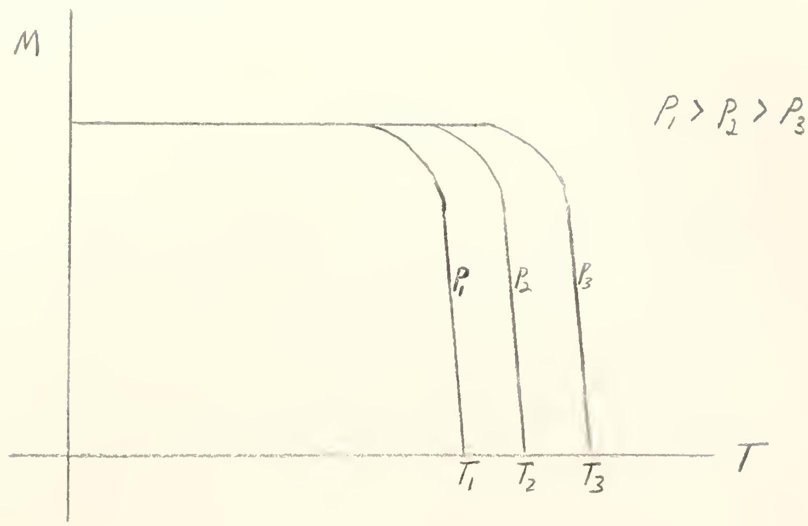


Figure 10. Pressure Dependence of MnAs

(2) Magnetic Field Control: By use of a properly designed coil placed around a sample of MnAs, and a large magnetic field in pulses of controlled length, the sample may be switched from its non-magnetic state to its magnetic state. What happens to the sample after the collapse of the magnetic field pulse is dependent upon the temperature and pressure and is discussed later. There are two major problems that are immediately evident here. One, that it is necessary to control the temperature to quite close tolerances (within a few degrees C) in order that the magnitude of the magnetic field required to switch the MnAs does not vary to any appreciable degree. (As shown by Figure 7, the magnetic field requirements are raised by 1000 oersteds for each degree of temperature increase and this represents a waste of energy).

Secondly, the design of the coil to produce the required magnetic field can present somewhat of a problem. Large fields of the order of

100,000 oersteds are readily obtainable by use of small coils (less than 5 milliameters)[13]. Fields of 125,000 oersteds were obtained by the writers with coils of one centimeter length. The generation of such fields using larger coils has yet to be developed.

Despite the problems considered above, it is considered that the most practical way to switch the MnAs is by use of applied magnetic fields. The MnAs could then be used to drive a mechanical system, resonant at the desired frequency of operation, to produce sinusoidal pressure variations into the water. (The device used by the writers, and other possibilities, are discussed later).

13. R. W. DeBlois, G. E. Report No. 61-RL-2687M, 1961

4. Modes of Operation

There are three possible ways to drive the MnAs with a magnetic field and have it complete a full cycle of operation for each pulse of magnetic field.

(1) The MnAs sample could be held at a temperature above the critical temperature, and placed under the influence of a magnetic field for one half cycle at the desired frequency of operation. For the other half cycle the magnetic field would be "off". The volume of the MnAs, when plotted against time, would be a square wave with a frequency equal to that of the sinusoidal variations into the water. This would be equivalent to class "B" operation and is a driven system rather than a resonant system. This is shown more clearly in Figure 11.

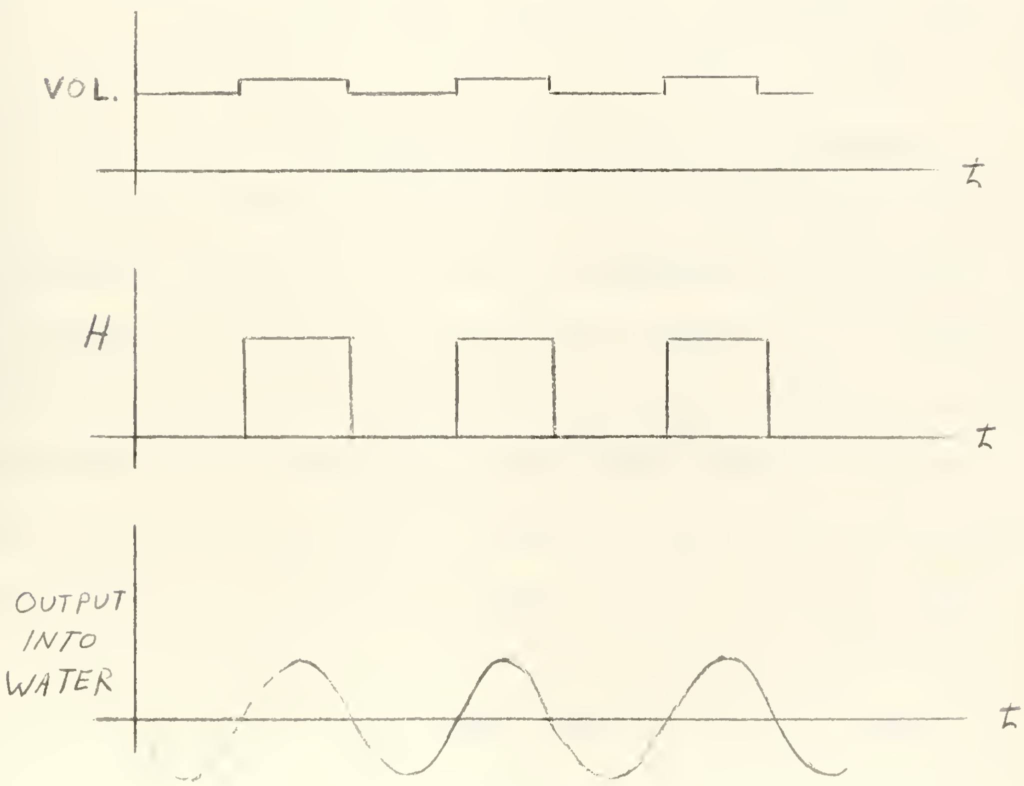


Figure 11. Magnetic Field Mode of Operation

(2) If, again, the temperature is held above the critical temperature, but the magnetic field is applied in short pulses, of the order of a few micro-seconds, the operation would be as pictured in Figure 12. The pressure pulse striking the inside of the steel cylinder would cause the cylinder to vibrate at its resonant frequency.

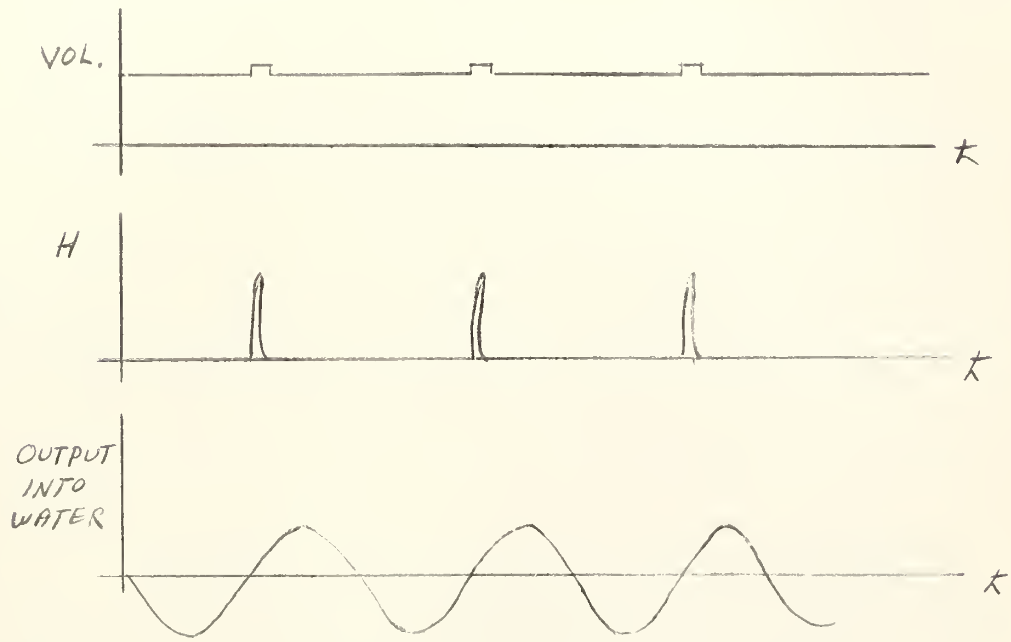


Figure 12. Resonant Mode of Operation

(3) If the MnAs is below its critical temperature, but still in its non-magnetic state, (i.e., within its temperature hysteresis) a magnetic field pulse of sufficient magnitude will switch it to its magnetic state, accompanied by the two percent volume increase. However, it will not revert back to its non-magnetic state upon removal of the field. Therefore, some other means must be brought to bear in order to switch the sample back. An increase of pressure, prior to the next pulse of magnetic field, would suffice to switch the sample and "reset" it for another cycle of operation. If the sample could be held just below its critical pressure by stringest temperature control, the initial pressure impulse

after being reflected from the inside wall of the steel cylinder would be of such magnitude to reset the MnAs. (See Figure 13).

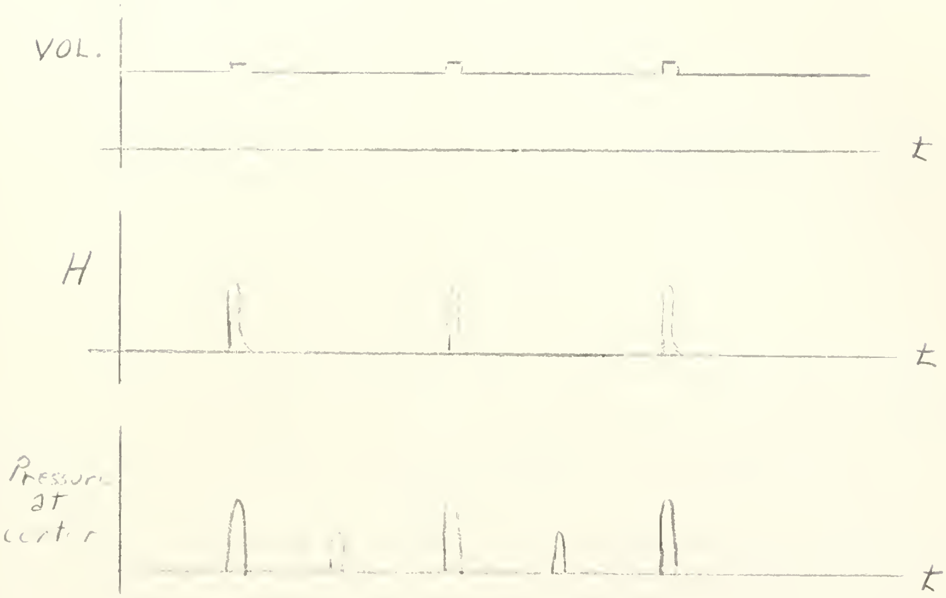


Figure 13. Pressure Reflection Mode of Operation

Mode one may be ruled out immediately since the power required and I^2R losses in a pulse of such duration would be prohibitive. Mode two and three are analogous to class C amplifier operation with its inherent higher efficiencies, and are therefore more desirable. Of these two, Mode three would give better overall results as it requires a lower magnetic field. However, this is the most difficult Mode to realize practically, as it requires the most stringent temperature control. For instance, the temperature would have to be kept almost constant at a given point, depending upon the magnitude of the reflected pressure. The lower it is, the less field is required, but at the same time, a larger pressure increase is necessary to reset the material.

5. Design of Magnetic Pulser

In order to investigate the various Modes of operation as discussed above, it was first necessary to design and build a magnetic pulser capable of producing a high energy, short duration (approximately 1-5 microseconds) "d.c." pulse of energy in a coil surrounding a sample of MnAs. From the theoretical discussion, the minimum field requirement was considered to be approximately 30,000 oersteds.

In the c.g.s. units, the field is given by $H = .4\pi \left(\frac{N}{L} \right) I$ where $\frac{N}{L}$ is the number of turns per centimeter and I is the current in amperes. Since the samples to be tested were approximately one centimeter in length and an N of 100 was considered nominal, the current requirement was calculated to be 250 amperes. The only devices capable of handling this amount of current in a cyclic manner are the gas thyratron, the ignitron, or the silicon controlled rectifier (SCR).

Since the practical use of MnAs in a sonar transducer would require the pulsing circuit to be an integral part of the sonar projector, it was considered mandatory that the circuitry should be designed using solid state devices.

At the time that this feasibility study was being made, General Electric introduced a new line of high current SCR's capable of holding back 600 volts and passing current pulses up to 600 amperes. Since these characteristics fulfilled the requirements, as previously discussed, the following circuit was designed using an SCR. (A discussion of design considerations and a complete diagram of the circuit used are given in Appendicies I and II).

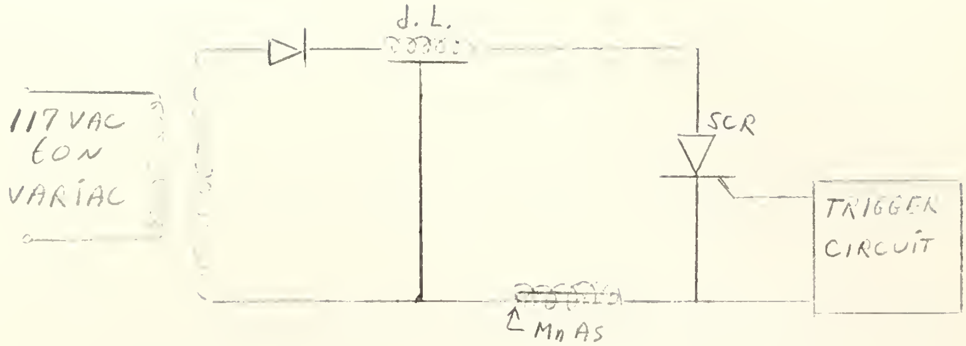


Figure 14. Abbreviated Circuit Diagram of Magnetic Pulser

The characteristic impedence (Z_o) of the delay line is designed to match the resistance of the sample. The delay line gives the current pulse a faster rise time by holding the voltage at a relatively constant level, and this insures a more uniform switching of the sample. The delay time is designed to be one half of the desired pulse length. The delay line is charged during the positive half of the a.c. swing and the trigger circuit is synchronized to fire the SCR during the negative half cycle. The switching of the SCR during the negative half cycle insures that only the energy stored in the delay line is delivered to the sample.

C. Preliminary Considerations

In order to minimize the heat problem, a low frequency of operation was considered best for investigating the samples of MnAs. Since 60 cycle voltage was readily available, it was used in conjunction with a standard plate voltage transformer to supply the power to drive the magnetic pulser.

The calculated volume change of 2% is very extreme, and it was reasoned that the MnAs would have to be used in an encapsulated powder form. Two different methods of encapsulation were used and are described below. The first samples tested were obtained from the General Electric Research Laboratory, and consisted of powdered MnAs bonded in epoxy -- the composition being about 95% MnAs and 5% epoxy. This mixture was formed into the shape of rods of varying length and in diameters of 1 mm and 1.5 mm. Later samples consisted of powdered MnAs enclosed by a stainless steel tube of 1.5 mm diameter. After the powder was packed inside the tube, it was placed in oil and put under a vacuum in order to remove the air. The samples were wound with various sizes of magnet wire from 4 to 10 mils in diameter.

The magnet wire used was insulated with Formex enamel and provided an average thickness of 20 microns between adjacent layers. Since Formex has an approximate breakdown of 20 volts per micron, adjacent windings should be protected from arcing for voltage differences up to 400 volts. However, anticipated, maximum voltages of 1000 volts across a $\frac{1}{2}$ inch coil required that great care be given to the winding of the coils. Therefore, the coils used were either single layer or formal bank (several layers, but wound progressively from one end to the other) in order to minimize the chance for voltage breakdown between windings.

The generation of heat by the current pulses required some form of temperature stabilization and the mounting of the samples in an oil bath was considered best. In order to control the ambient temperature of the oil bath (a two liter pyrex beaker), copper tubing was wrapped, in a helical manner, around the inside surface of the beaker. The copper tubing was connected to a source of hot and cold water which could be controlled to set any temperature from $15^{o}C$ to $60^{o}C$. A thin disk of barium titanate was attached to the bottom of the oil bath as a sensor to detect any shock waves or acoustical waves which would result from the switching of the MnAs from one volume state to the other.

It would be necessary to make various tests with the MnAs samples under pressure and a steel cylinder was designed which would have a resonant frequency of approximately 30 kc and be able to be pressurized up to 30,000 psi.

7. Tests Conducted in the Oil Bath

The first test conducted in the oil bath was a measurement of the temperature hysteresis of the MnAs-epoxy samples. It was found that the samples changed from a magnetic state to a non-magnetic state at approximately $45^{o}C$. The change in state was gradual starting a degree or two before $45^{o}C$ and because of this gradual change, the volume change was also gradual and no acoustic pickup was detected by the sensor. When the temperature was lowered, the change of state did not occur until a temperature of $33^{o}C$ was reached -- a 12 degree temperature hysteresis.

The next step was to try to switch the MnAs with the use of a magnetic field. The temperature of the bath was kept at $45^{o}C$ so that the MnAs would be in its non-magnetic state. Fields up to 35,000 oersteds were used with no apparent switching evident. At this point, it was considered desirable to try higher fields and our original pulser was modified to produce fields up to 125,000 oersteds (See Appendix II).

With the higher fields, indications of switching were noticed with fields in excess of 40,000 oersteds. The indication was in the form of a disturbance picked up by the barium titanate sensor. The disturbance was slight and enshrouded in noise. In order to eliminate the noise and boost the signal, a Ballantine amplifier and a Krohn-Hite bandpass filter were employed and used for all subsequent measurements. With this set up, switching was detected for momentary periods and it was suspected that the sample was heating up and was quickly reaching a temperature for which the applied field became inadequate. In order to obtain a rough indication of the amount of heating, a coil was wrapped around the base of a thermometer and current pulses of 300 amperes were applied at a 60 cycle rate. As shown in Figure 15, the temperature rise was very extreme.

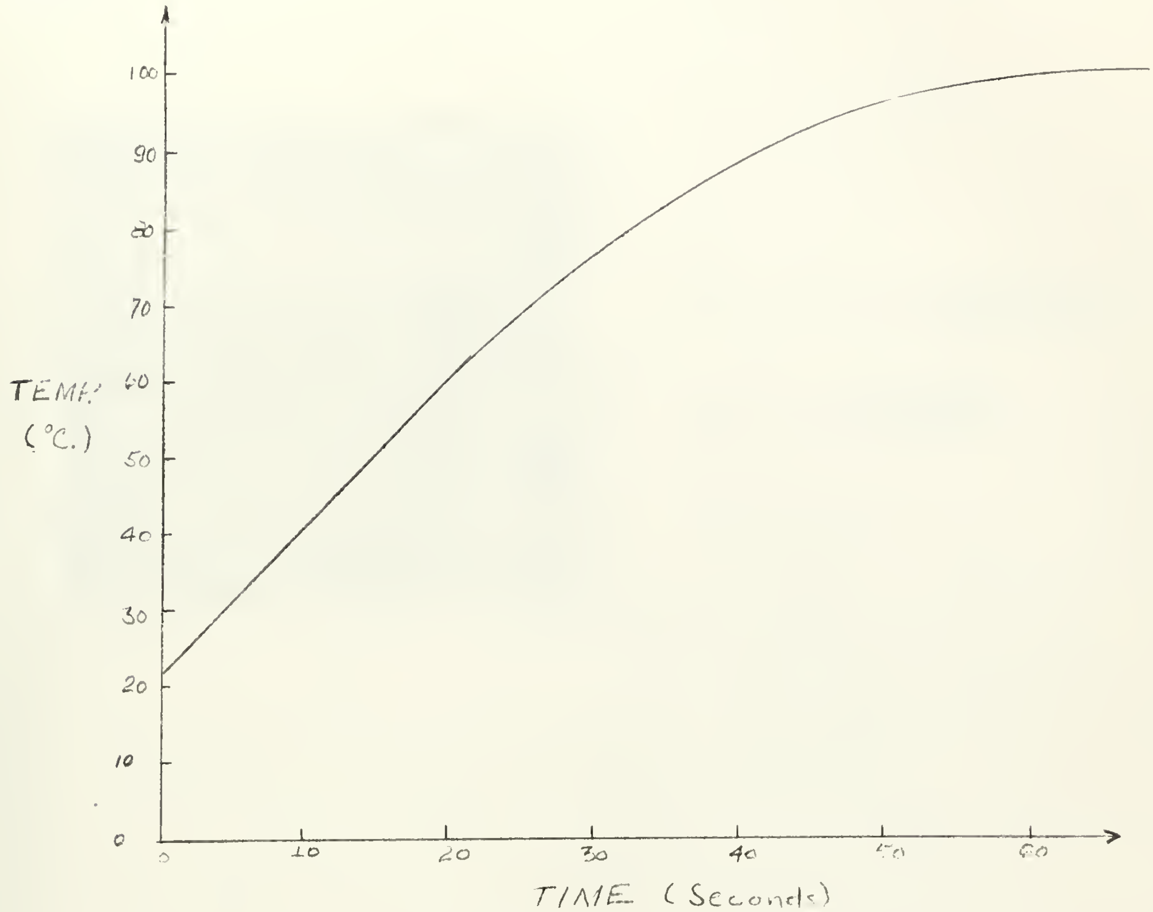
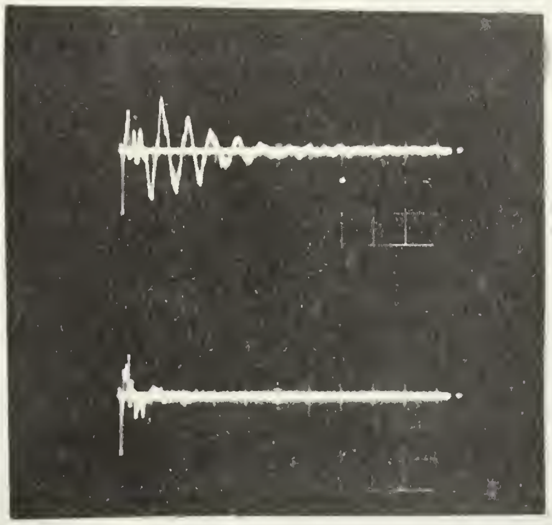


Figure 15. Coil Heating

As a result of this test, all subsequent runs were made with the circuit in operation for only a few seconds. Another indication of switching that was observed was the breaking of the MnAs epoxy samples into two pieces. When the samples were wound with a looser fitting coil, a third indication was observed and has been labeled by the authors as the "creep phenomena". In this case, the sample would creep through the coil in the direction of the magnetic field and is probably due to the effect of the field on the two magnetic states of the MnAs. An oscilloscope picture of the sensor's signal immediately before and after switching is shown in Figure 16.



Scales:

Horizontal--500 $\frac{\text{microseconds}}{\text{centimeter}}$

Vertical--1 $\frac{\text{millivolt}}{\text{centimeter}}$

Figure 16. Oscillograph of Switching in Oil Bath

8. An Experimental Transducer

A steel cylinder pressure cell was designed for the specific purpose of testing the MnAs samples under pressures up to 15,000 psi. This steel cylinder, along with two samples of MnAs powder in stainless steel tubing, is shown in the picture below.

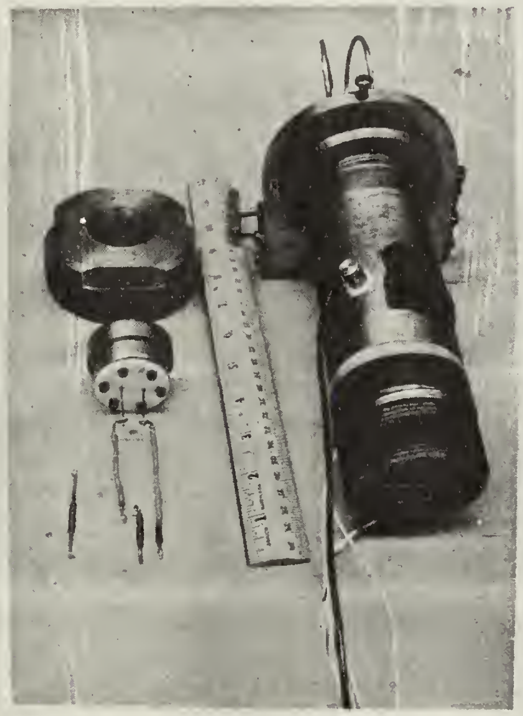


Figure 17. Cylindrical Transducer

There are two electrical lead-ins through the top of the cylinder to which the samples were mounted. Affixed to the outside of the cylinder in the area of its longitudinal center are two strain gauges and a barium titantate transducer (acting as an accelerometer).

As a first test of the system, the temperature of the cylinder was varied with a MnAs sample mounted inside under 15,000 psi. At this pressure, the critical temperature should be in the vicinity of $30^{o}C$. The strain gauges were used to try to obtain an indication of what occured as this temperature was reached. As the temperature increased, the cylinder expanded slowly as indicated by the strain gauge meter. As the temperature inside the cylinder approached the critical value(estimated), the strain gauge meter showed a series of jumps, indicating a series of small step decreases in strain as the MnAs sample switched from its ferromagnetic to its paramagnetic state. The difficulty in obtaining a uniform temperature variation over the entire MnAs sample obviated the attainment of instantaneous switching of the entire MnAs sample all at once.

Another method to attempt a strain gauge indication was to apply a single pulse of magnetic field to the MnAs sample. The discharge capacitor C_1 (see Appendix II) was first charged up, and then disconnected from the charging source. With the temperature of the MnAs samples below its critical point, the triggering circuit was activated to discharge the capacitor but no indication was observed on either the strain gauge meter or the barium titante transducer. When this process was repeated with the internal temperature of the cylinder above the critical temperature of MnAs, a definite indication was obtained on both the strain gauge and the barium titanate transducer. However, due to the highly transient nature of the MnAs expanding and contracting almost immediately, the strain gauge meter showed only a momentary flick of the needle. The output from the barium titanate transducer was a wave pattern of the same type observed and analyzed later when 60 cycle pulsing was employed.

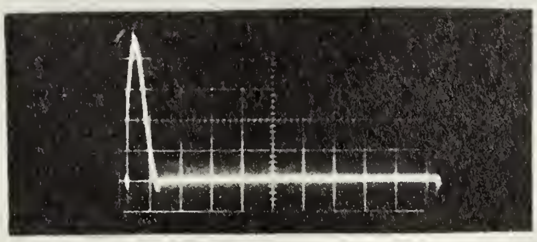
Although the strain gauge indications gave a good idea of what was going on inside the cylinder, it was limited in its ability to handle varying strains at fast rates, with its response falling off quite sharply a few cycles above d.c. Therefore, no real quantitative results could be obtained and no further use was made of it.

The next approach was to apply magnetic field pulses to the MnAs sample at a 60 cycle rate. Great care had to be taken to ensure that the 60 cycle pulses were applied in short bursts. Otherwise, as pointed out earlier, the sample would become much too hot to be effective. The best way to handle the situation in this case was to start with the samples below the critical temperature. The first few pulses of energy would heat the sample above its critical temperature and effective operation could be maintained for a short period. Even when great care was exercised, the coil around the sample would fail due to voltage breakdown and had to be continually replaced. The samples used were the stainless steel tubing filled with MnAs powder. The coils used were wound with 10 mil enamel covered copper wire. The larger wire was used because it was sturdier and easier to handle, and had less resistance than the smaller wire previously used. The windings averaged between 50 and 60 turns per centimeter with lengths of 1.5 to 2 centimeters. The d.c. resistance was about .4 ohms and the calculated average inductance was one microhenry. Various size capacitors were used for C_1 to optimize pulse length, rise time, and ringing. Capacitors of tw to four microfarads were used, for the most part. Although the current pulse rise time and magnitude were sufficient for the purpose required, the pulse length was a bit too long. The pulse length could not be shortened much more that it was with the circuit being used. From the theory, pulse lengths of one or two microseconds are sufficient to switch the material, and the excess involved in the longer pulses were merely wasted power and contributed substantially to the heating problem. The voltage pulses were in the vicinity of 700 to 800 volts.

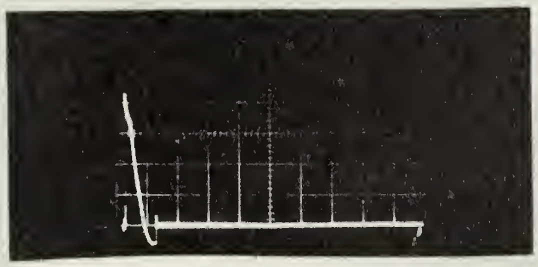
The barium titanate transducer response was observed for varying conditions of field pulsing, and various oscilloscope pictures were taken and are explained in the next section.

9. Analysis of Results

Figure 18 shows a typical current and voltage pulse delivered to a sample of MnAs. The sync circuit of the oscilloscope was triggered by



(a)



(b)

Scales:

Horizontal--10 $\frac{\text{microseconds}}{\text{centimeter}}$

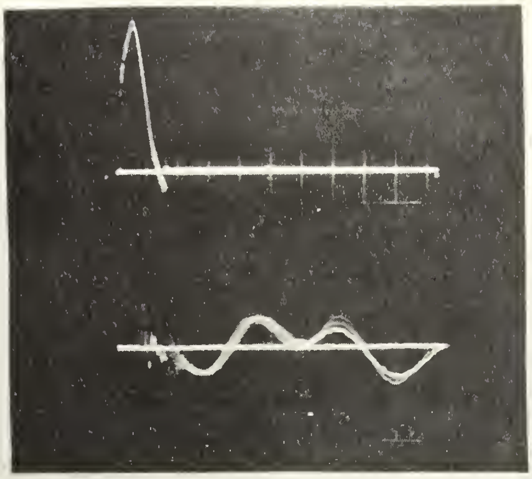
Vertical--

(a) 100 $\frac{\text{amperes}}{\text{centimeter}}$

(b) 200 $\frac{\text{volts}}{\text{centimeter}}$

Figure 18. Typical Current(a) and Voltage(b) Pulses

the current pulses and oscillographs were taken to determine the time delay between initiation of switching and reception of the shock wave at the steel surface. Figure 19 shows a comparison between the current pulse and the signal detected by the sensor. From the dimensions of the steel cylinder (Appendix III) and the velocities of sound in steel and oil, a time delay of 15.7 microseconds was computed. This compares very closely with the actual time delay. Figure 20 (a) shows the signal occuring at the 60 cycle rate and Figures 20 (b,c) show the signal on a more magnified scale.



Scales:

Horizontal-- 10 $\frac{\text{microseconds}}{\text{centimeter}}$

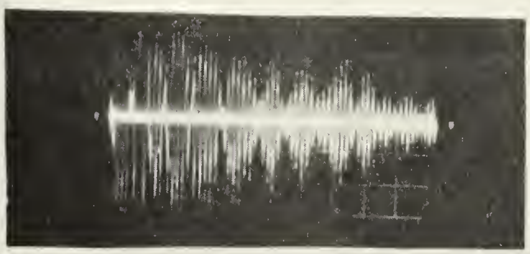
Vertical--

(a) 100 $\frac{\text{amperes}}{\text{centimeter}}$

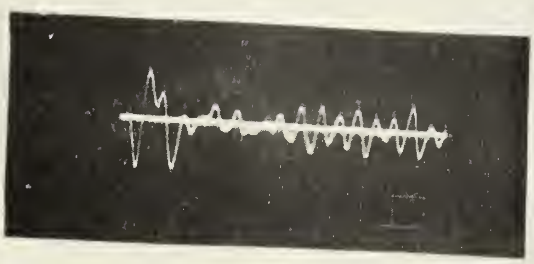
(b) 1 $\frac{\text{millivolt}}{\text{centimeter}}$

Figure 19. Time Delay Between Current Pulse and Output

(a)



(b)



(c)

Scales:

Horizontal

(a) 2 milliseconds/cm.

(b) 200 microseconds/cm.

(c) 50 microseconds/cm.

Vertical

(a) .2 millivolt/cm.

(b) .5 millivolt/cm.

(c) 1 millivolt/cm.

Figure 20. Output Response

The signals appear to be composed of two similar frequencies beating with one another. Their varying amplitudes may be explained by each frequency having a different rate of decay.

The beat frequency is approximately 2 KC and the sum frequency is about 30 kc. Therefore, the two modes of vibration are 28 kc and 32 kc.

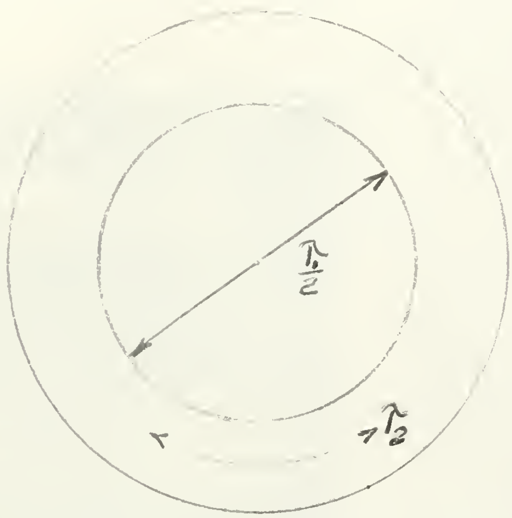


Figure 21. Modes of Vibration

The 28 kc mode may be explained as that due to the radial vibrations of the oil column. The 32 kc mode is the fundamental resonance of the cylinder and agrees almost exactly with the theoretical value.

Figure 20 can also be used to compute the peak efficiency of the cylinder. The accelerometer has a sensitivity of $.125 \frac{\text{millivolts}}{\text{unit acceleration}}$ and the peak value represents 16 g's acceleration.

$$V\ (rms) = .707\,\frac{a}{\omega} = \frac{16(980)}{2\pi(30\times10^{3})} = .059\text{cm/sec}$$

$$\text{Peak Power out} = \text{Area} \times \rho C_o \times V^2 \times 10^{-7}$$

$$= .65 \text{ watts}$$

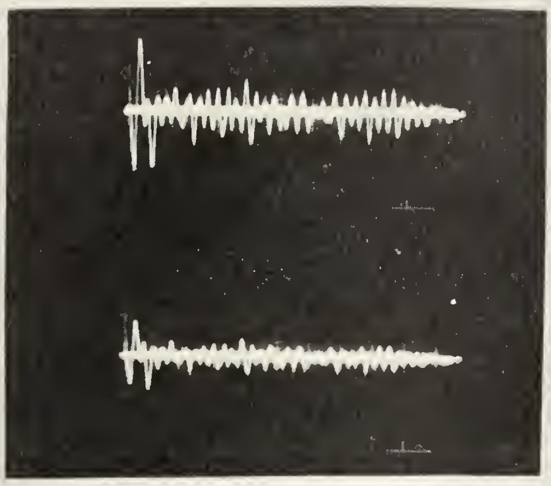
$$\text{Ave Power In} = I^2(\text{peak})R \ \frac{\text{Pulse Width}}{\text{Duty Cycle}}$$

$$= (500)^2(.3)\left(\frac{5\times10^{-6}}{16.7\times10^{-3}}\right)$$

$$= 22.5 \text{ watts}$$

$$\text{Peak eff.} = \frac{.165}{22.5} = 0.73\%$$

Although this is a very low efficiency, it is to be expected since the system has a relatively high mechanical Q and the 60 cycle operation is far removed from the resonant frequency.



Scales:

Horizontal—1 microseconds/cm.

Vertical—1 millivolt/cm.

The upper picture represents the response for an applied field of 48,000 oersteds. The lower picture shows the response for a field of 32,000 oersteds. Here the maximum amplitudes show a square relationship with applied field.

Figure 22. Amplitude Comparison for Two Different Inputs

Figure 22 shows the signal for two different values of applied fields. A series of similar photographs were taken and the data was compiled and plotted in Figure 23 to show the relative output vs. applied magnetic field. There is no output until the critical field is reached. The output appears to increase linearly with field up to a point midway between switching and saturation. After this point, the output shows a square relation tapering off as saturation is reached. The general nature of this curve is similar to the M vs. H curve and demonstrates that the volume change is only abrupt if the applied field has a sharp rise time.

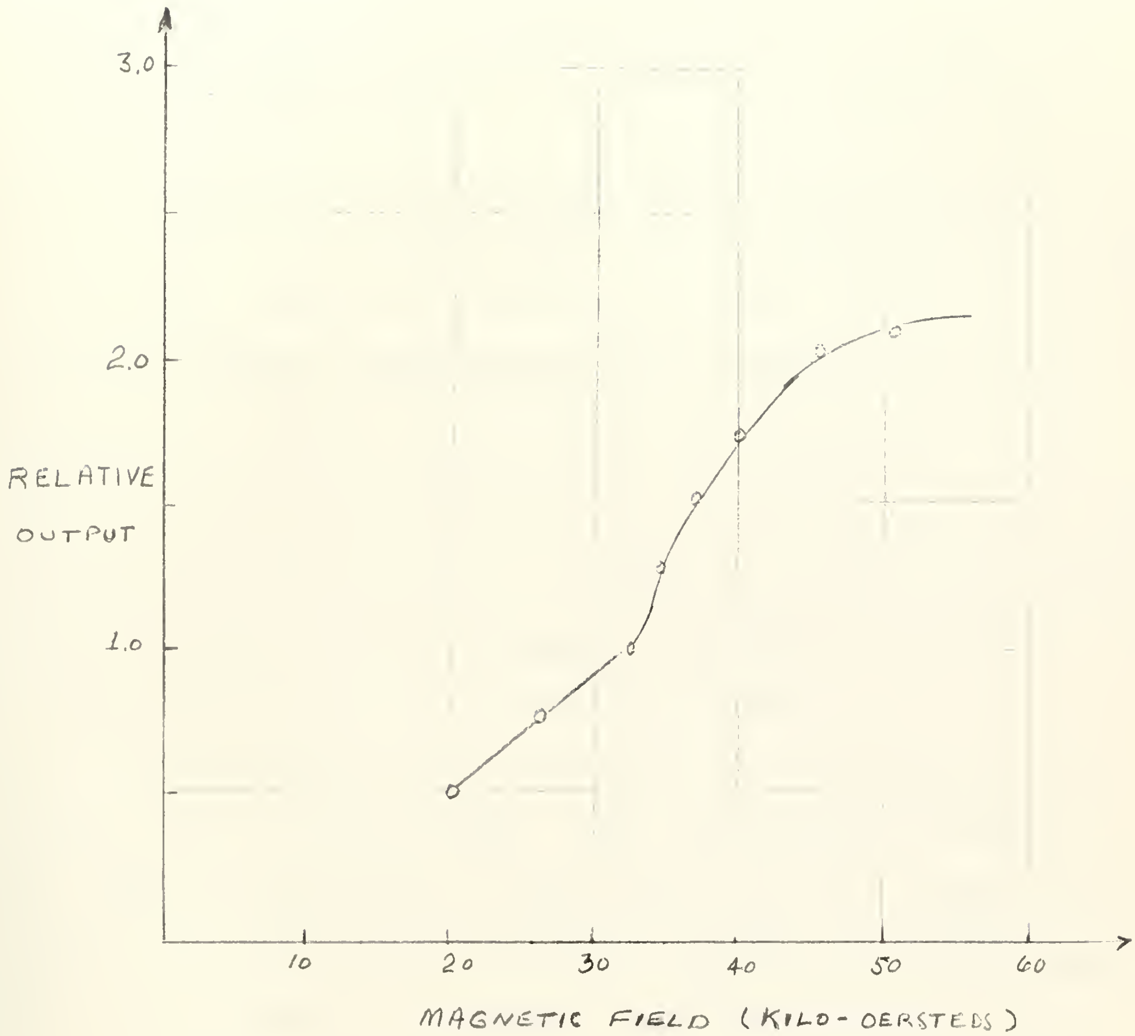


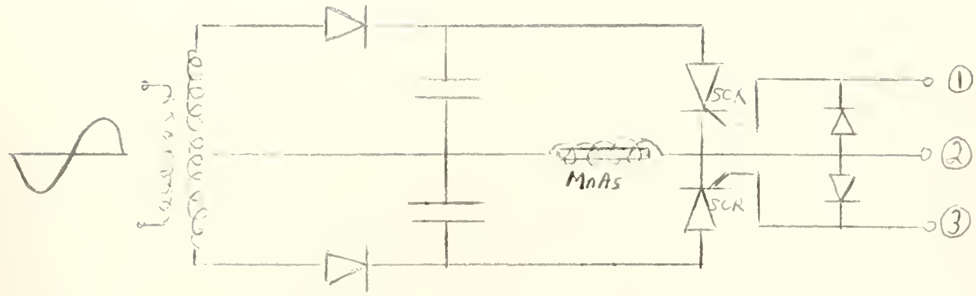
Figure 23. Plot of Magnetic Field vs. Relative Output

10. Recommendations

There are some ways in which the experimental procedure could be improved in future work. One way is to improve the pulse forming circuit into something more permanent and portable. The circuit on the following page is recommended. It is merely an extension of the circuit used by the authors, modified to send a pulse through the MnAs coil in both halves of the sinusoidal input. After work has progressed enough to try higher frequencies of operation, the whole circuit can be supplied by a variable frequency power supply. The MnAs will be pulsed at twice the incoming frequency from the power supply. For 60 cycle operation, only half the circuit need be utilized. Except for the transformers, which could be separately mounted at relatively long distances from the circuit, very little size and weight would be involved. The circuit can also be used for single pulse operation.

An attempt must be made to narrow down the current pulse to the order of one or two microseconds. Some success might be obtained in this regard by using smaller, single layer windings of perhaps 10 mil diameter wire. The number of turns per centimeter would be decreased, but the a.c. resistance and inductance of the coil would be reduced significantly. This would tend to both increase the magnitude of the current pulse and narrow it down. This might require slightly higher voltages to obtain adequate magnetic fields, so care must be taken in choosing the wire used. Therefore, in order to avoid the problem of voltage breakdown, more thickly insulated wire than that commercially available should be used.

Since heating is such a big problem when pulsing the sample, a material other than stainless steel tubing which would be a better



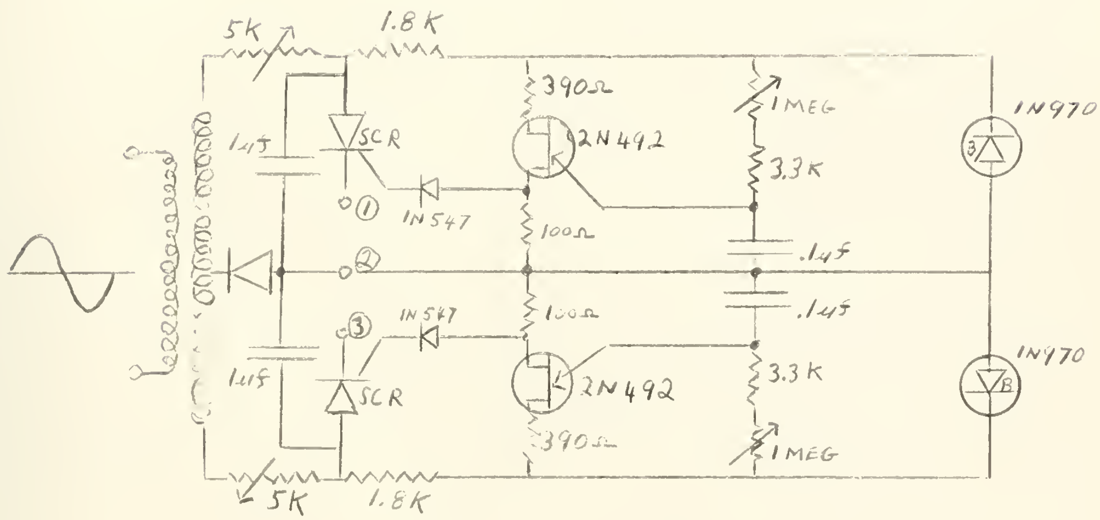


Figure 24. Recommended Pulsing Circuit

insulator should be used to hold the MnAs powder.

This combined with much reduced current pulse widths, would improve the heating problem considerably.

II. Conclusions

Although MnAs is rather difficult to work with at the present time, the authors feel that a continued effort should be made to try and develop its potentialities.

The use of MnAs as a sonar projector would bring in an entirely new mode of operation; i.e., use of volume expansion rather than the present one dimensional linear changes. This would open up new vistas in the design and construction of transducers. MnAs could be used as the driving element in an almost unlimited variety of mechanical systems. One example being the device used by the authors.

Three examples which might bring out the versatility of MnAs are shown in Figures 25, 26, and 27 below.

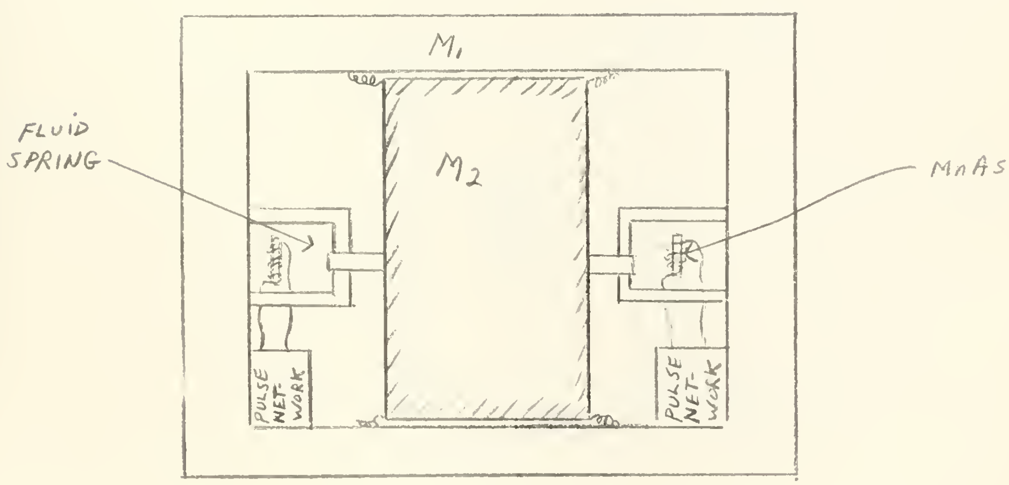


Figure 25. Shaker Box

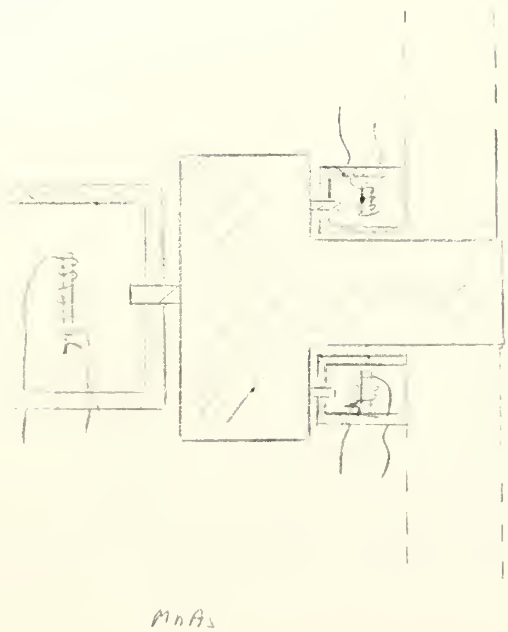


Figure 26. Push Pull Piston Radiator

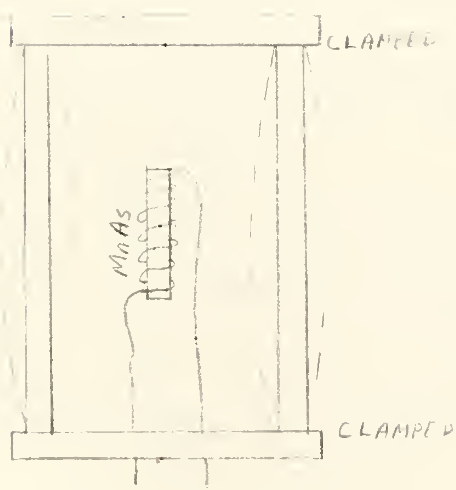


Figure 27. Bender Element

Figure 25 shows a simple [illegible] arrangement. The operation is the same as a magneto-strictive type except modified for use with MnAs. A liquid spring replaces the mechanical spring, eliminating fatigue problems. The system would be essentially class C, push pull and probably very efficient. The MnAs would be under pressure, switched by magnetic field pulses and reset by the pressure increase involved when the other side fires.

Figure 26 shows a simple driven piston arrangement, also a push pull operated device. Several could be used in an array for directional purposes.

Figure 27 shows a possibility of using MnAs as a driving element in "bender" type transducers. This type of transducer is gaining importance because of its adaptability for use with hydrofoil type ASW vessels.

Although MnAs can be operated to a limited extent today, there are steps being taken at the General Electric Research Laboratory to improve the basic material. Among these are:

1. Alloying to allow MnAs to switch under lower fields (which would ease the heating problem).
2. Alloying to exhibit a second order volume change which is proportional to the field applied but capable of a much higher "saturation" value than nickel or ceramics.
3. Investigating other materials of the same family to see if there are better materials than MnAs.

MnAs is in the same position today that ferroelectric ceramics were in about 1947. It is the first major new transduction material to be considered since barium titanate. The many possibilities of MnAs may be visualized, especially in the high power, low frequency, deep depth projectors which are becoming more and more important in combating the submarine threat.

APPENDIX I

DESIGN CONSIDERATIONS

For initial testing of the MnAs samples, the pulsing circuit shown in Figure 14 was designed. The delay line charges up during the positive half cycle. The trigger circuit is timed to gate the SCR during the negative half cycle, so only that current due to the delay line discharge will flow through the SCR and the sample coil. The delay line is for the purpose of holding up the voltage across the sample for a faster current pulse rise time. However, this leads to a slight sacrifice in current pulse amplitude and here a compromise must be made. The main requirements to be satisfied are as follows:

(1) At atmospheric pressure, the peak current through the coil must be sufficient to produce approximately 25,000 ampere turns per centimeter of coil, i.e., 30,000 oersteds to insure readhing the saturation regain. (This requirement is reduced when the sample is under pressure.)

(2) The inductance of the coil must be small enough to allow the current pulse to build up to a satisfactory value during the duration of the voltage pulse.

(3) Energy stored in the delay line must be commensurate with the magnetic energy in the coil at maximum current (to reduce ringing to a minimum).

(4) Heat dissipation in the coil should be commensurate with power delivered. Top high a temperature rise will reduce the switching ability of the MnAs. (This was quite a problem and operation was only possible for a few seconds at a time to avoid excessive heat buildup and voltage

[illegible]

Several samples were wound and their average inductance measured. From these a delay line was designed and built, as follows:

$$L = \frac{n^2 r^2}{25r + 19L} = 2.[illegible]\ \mu h \qquad r = .076 \text{ cm.} \quad L = 1 \text{ cm.}$$

In accordance with (3) above,

$$W_{mag\ field} \sim W_{delay\ line}$$

Therefore, $\frac{1}{2}L_s(I_{max})^2 = \frac{1}{2}C_t(V_{max})^2$

$$E = L\frac{di}{dt}$$

$$L\,di = E\,dt$$

$$\frac{1}{2} L_s\left(\frac{V_{max}T}{L_s}\right)^2 = \frac{1}{2} C_t(V_{max})^2 \qquad I_{max} = \frac{E_{max}}{L}T$$

Solving, $T^2 = C_t L_s$

Pulse length = $T = 2\tau n$ where n = number of delay line sections

and τ = delay time for one section = $\sqrt{L_d C_d}$

Or $\quad C_t L_s = 4 L_d C_d n^2$

And $\quad L_s = 4 n L_d$

For $\quad n = 7$, $L_d = .1\ \mu h$

For matching, set Z_o = average d.c. resistance or

$$Z_o = \sqrt{\frac{L_d}{C_d}} = .7 \text{ ohm}$$

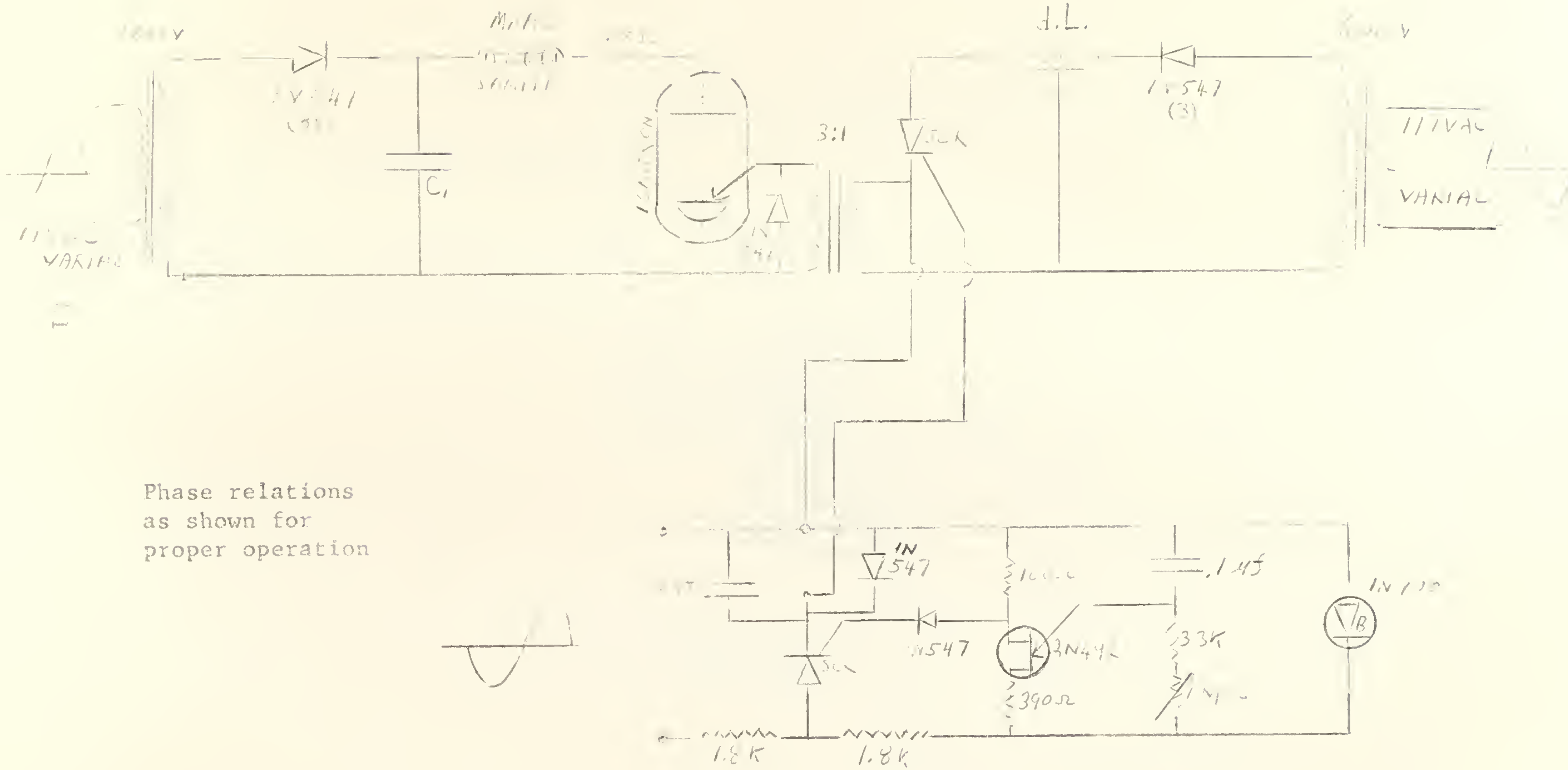
Solving, $C_d = .2\ \mu f$ and $T = 2\ \mu sec.$

Although the circuit performed satisfactorily, it was limited in its ability to put out high enough current pulses because the silicon controlled rectifier could only control a maximum of 600 volts. This, initially, seemed like enough. However, after further research into the theory of operation of MnAs, and consultation with Dr. Don Rodbell of General Electric Research Laboratory, the minimum magnetic field required for complete switching was re-evaluated to be 50,000 oersteds vice 30,000 oersteds. Two silicon controlled rectifiers in series operation could be used to obtain holdoff voltages up to 1200 volts. This would have required resistance and capacitance compensation to allow for variations in leakage current and junction capacitance. Although this is not difficult it was decided to use the Ignitron as a basis for a new circuit. This, essentially, would not limit the voltage and current pulses obtainable and would allow somewhat more freedom of operation in experimenting with the MnAs samples. The silicon controlled rectifier circuit was put to use, with no change made, as a highly satisfactory gating circuit for the Ignitron.

APPENDIX II

DIAGRAM AND DISCUSSION OF CIRCUIT USED

The Ignitron obtained was a 7703, capable of holding 20,000 volts and passing pulses of up to 100,000 amperes. Since now the voltage pulses are essentially unlimited in magnitude, no special device was deemed necessary to obtain a voltage pulse. A simple capacitor discharge arrangement was utilized, with the complete circuit diagram used shown in Figure 28. After a few trial runs, ringing did not seem to be too much of a problem. Therefore, various sizes of capacitors were used that were a compromise between giving a good impedance match ($Z_o = L/C$), and a narrow current pulse. The narrow current pulse gave a much faster rise time which is essential here in order to obtain the shock wave effect from the expansion of the MnAs. The faster the rise time, the shorter the time lapse between initial and complete switching of the MnAs. The time lapse should be no longer than a microsecond in order to produce the shock front. This in turn produces the required impulse at the steel wall to set it into motion. Otherwise, there will just be a relatively slow rise and fall of pressure within the steel cylinder with no significant results.



Phase relations
as shown for
proper operation

Figure 28. Diagram of Circuit Used in Study

APPENDIX III

DETAILED DRAWING OF CYLINDRICAL TRANSDUCER

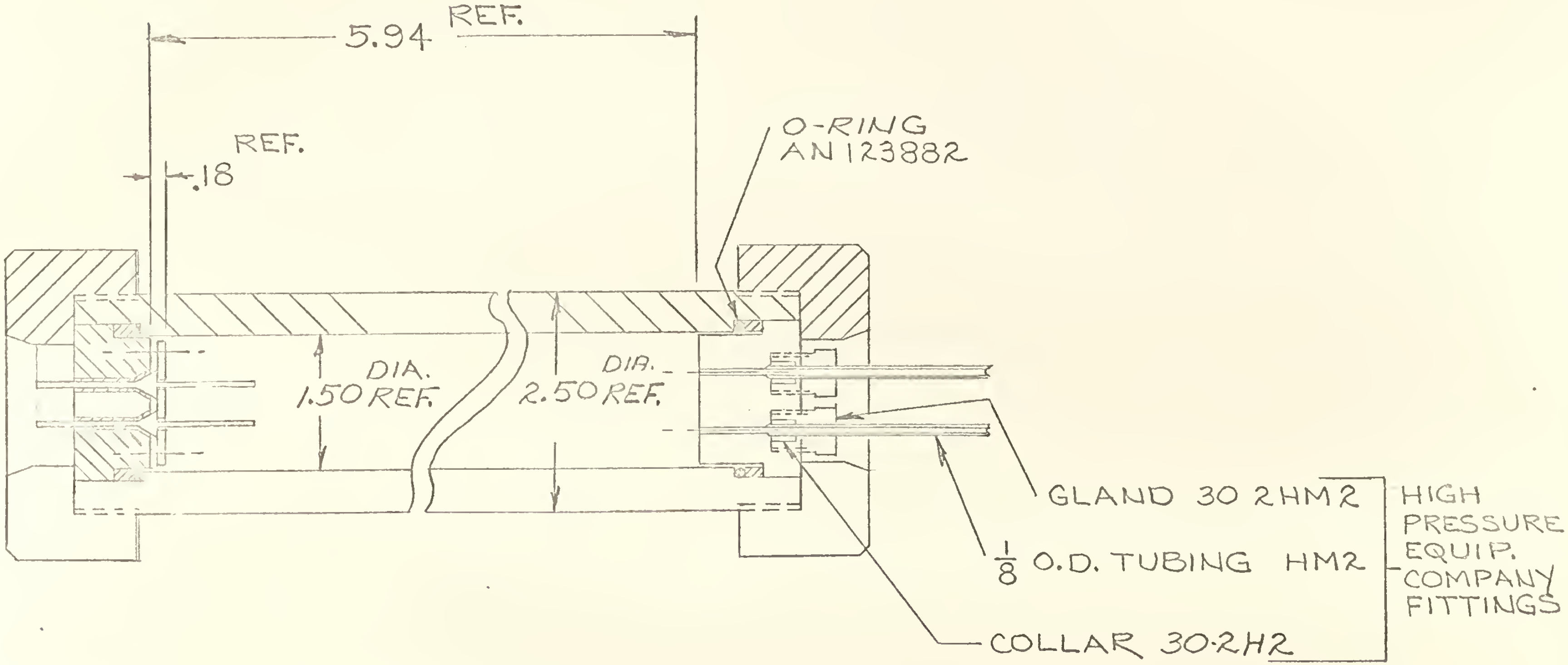


Figure 29. Detailed Drawing of Cylindrical Transducer