A STUDY OF INTENSE MAGNETIC FIELDS FOR HIGH ENERGY FORMING AND STRUCTURAL ASSEMBLY

INTEREM REPORT

by

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INTRODUCTION

The purpose of this study is to determine the maximum force on a static sheet of aluminum subjected to the magnetic field of the hammer coil now being used at the Marshall Space Flight Center at Huntsville, Alabama. Although movement of the metal sheet does take place as a result of this force, the present use of the hammer coil is in smoothing metal surfaces. This allows only a differential movement which can be closely approximated by a static sheet. If true forming is attempted, the movement of the metal sheet would create voltages due to motion of a conducting material in a magnetic field. The only voltages considered in this study are those created in a stationary conducting material subjected to a time varying magnetic field. If the force created in a true forming operation is to be determined, the current due to both induced voltages would have to be considered.

This study is directly concerned with the forces produced on four thicknesses of six different aluminum alloys. The thicknesses under consideration are 0.060, 0.375, 0.500 and 0.750 inches. The alloys and some of their characteristics are listed in Table I. The values of the electrical and magnetic properties were furnished through the courtesy of the Aluminum Company of America.

Two methods of determining the force exerted on the aluminum sheet are suggested in this report. One method requires a determination of the magnitude of the currents induced in the aluminum as a function of the current in the coil. The interaction of the fields produced by these two currents will then be used to determine the force exerted on the sheet. The other method is to determine the self and mutual inductances of the

Alloy	Temper	Relative Magnetic Permeability	Conductivity@20c	Resistivity@20c
			% International Annealed - Copper Standard (Equal Vol)	(Microhm-centimeter)
2219	T87	1.0000196	32	5.4
7075	T6	1.0000159	33	5.2
7075	T651	1.0000159	33	5.2
6061	T6	1.0000199	43	4.0
5456	H343	*1.00002	29	5.9
5456	H321	*1.00002	29	5.9

*Estimated Value

Characteristics of Aluminum Alloys

Table I

coil and the aluminum sheet. From a system of equations having these inductances as coefficients, an equation for the force exerted as a function of current will be developed. At the present time there is no indication which, if either, of these two methods are better or more accurate.

Investigation of Hallen's Equation

An investigation was made of the equation

$$\bar{T} = 1/2\ \bar{B}\ (\bar{n} \cdot \bar{H}) + 1/2\ \bar{H} \times (\bar{B} \times \bar{n}) \qquad (1)$$

where $\bar{T}$ is the total force per unit area acting on the elemental surface, $\bar{n}$ is the unit vector in the direction of the outward normal to the elemental surface, and $\bar{B}$ and $\bar{H}$ are the magnetic field quantities immediately outside the elemental surface of a magnetized body immersed in a fluid such as air.[1] It was determined that this equation only applied to a ferromagnetic material and was not applicable to this investigation.

The study of this equation was performed by using a balance to measure the force exerted on a sheet of metal when subjected to a time varying magnetic field. A photograph of this balance is shown in Figure I. The sheet of metal was balanced without any magnetic field being applied. A magnetic field was then applied energizing a coil directly beneath the sheet. The sheet was balanced and a reading was made of the difference in weight required to balance the material with and without the presence of the field. Readings were also made of the voltage, current, and power input to the coil. These readings are shown in Table II.

The curves of Figures 2 and 3 show the variation of power dissipation and reflected resistance as a function of the thickness of the sheet.

Figure 4 shows the force exerted on different thicknesses of aluminum as a function of thickness. All points in Figure 4 were made with a coil current of four amperes.

Eddy Current Method

An inspection of Figure 4 indicates that a limit is approached in the force exerted as the thickness of the metal increases. This is due to the so called penetration depth of the magnetic field in the metal. The time varying magnetic field induces a voltage in the metal which creates a current. This current is in such a direction as to oppose the change in the applied magnetic field. It, therefore, tends to cancel out the magnetic field, and, as a result, the magnetic field reaches zero magnitude at some point within the metal. The penetration depth is dependent on frequency as given by the equation

$$\delta = \frac{1}{\sqrt{f \Pi \mu \sigma}} \qquad (2)$$

where f is the frequency, μ is the permeability of the material, σ is the resistivity of the material, and δ is the depth at which the induced voltages is $1/_e$ times the value of induced voltage at the surface.[2]

From photographs taken of the current wave of the hammer coil, the natural frequency is approximately 3.3 KHz. This frequency is being used in the preliminary calculations to determine the penetration depth. This gives a depth of 0.100 inches which indicates that only one of the proposed thicknesses need investigation. All sheets thicker than 0.100 inches should have the same induced current.

It is proposed to divide the sheet into concentric circular segments about the center line of the coil. From the cross-section area, length, and penetration depth, the resistance of the segments will be calculated. The current flow in the segment due to the induced voltage will then be determined. From the value of the induced current and the value of the coil current, force will be determined in an equation of the form

$$F = KI^2 \tag{3}$$

where I is the current in the hammer coil, K is a constant which includes the rise time of this current, and F is the force exerted on the aluminum sheet. An attempt will also be made to express this force in terms of the applied voltage.

Equivalent Circuit Method

This method also necessitates dividing the sheet into concentric circular segments and determining the currents in each segment as a function of time. The equilibrium equation for the hammer coil then becomes

$$\begin{aligned} e_1 = \{ \, & [L_1 \frac{di_1}{dt} + L_2 \frac{di_2}{dt} + \dots + L_{16} \frac{di_{16}}{dt}] \\ & \mp M_{1a} \frac{di_a}{dt} \mp M_{1b} \frac{di_b}{dt} + \dots \mp M_{1n} \frac{di_n}{dt} \\ & \mp M_{2a} \frac{di_a}{dt} \mp M_{2b} \frac{di_b}{dt} \mp \dots \mp M_{2n} \frac{di_n}{dt} \\ & \quad \vdots \qquad\qquad \vdots \qquad\qquad \vdots \\ & \mp M_{16a} \frac{di_a}{dt} \mp M_{16b} \frac{di_b}{dt} \mp \dots \mp M_{16n} \frac{di_n}{dt} \, \} + Ri. \end{aligned} \tag{4}$$

Equation 4 is based on approximating the hammer coil by sixteen circular conducting paths each carrying the hammer coil current and on dividing the aluminum sheet into N concentric circular segments. The self inductance of each segment is indicated by L and the segment identified by a single subscript. The mutual inductances between two segments is indicated by M and the circuits involved are identified by a double subscript. The Ri term in equation 4 is the resistance drop in the hammer coil.

For the individual segments in the metal sheets, a family of equations may be set up as shown in equations 5.

$$0 = \sum_{k=1}^{k=16} M_{ak} \frac{di_k}{dt} + \sum_{n=a}^{n=N} M_{an} \frac{di_n}{dt} + R_a i_a$$

$$0 = \sum_{k=1}^{k=16} M_{bk} \frac{di_k}{dt} + \sum_{n=a}^{n=N} M_{bn} \frac{di_n}{dt} + R_b i_b \qquad (5)$$

$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots$$

$$0 = \sum_{k=1}^{k=16} M_{nk} \frac{di_k}{dt} + \sum_{n=a}^{n=N} M_{Nn} \frac{di_n}{dt} + R_n i_n$$

where it is taken in each respective equation that $M_{aa} = L_a$, $M_{bb} = L_b$, . . . , and $M_{NN} = L_N$.

Equation 5 is a family of differential equations using the inductances as constant coefficients. It is believed that the mutual inductances will be a function of separation only. Once this relationship is definitely determined, the solution of these equations should be obtainable by use of the digital computer.

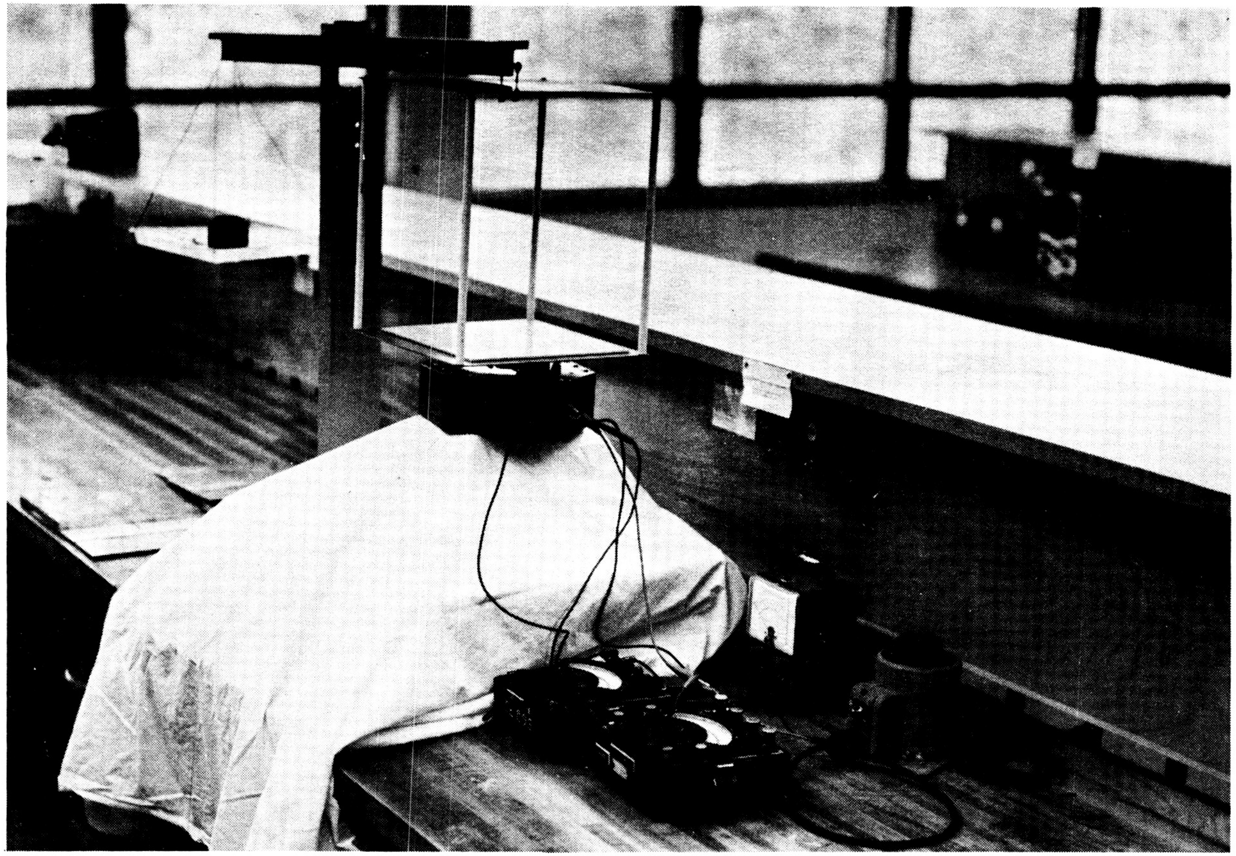

FIGURE I. BALANCE ARM MEASURING DEVICE USED TO DETERMINE MAGNETIC FORCE IN PRELIMINARY INVESTIGATION

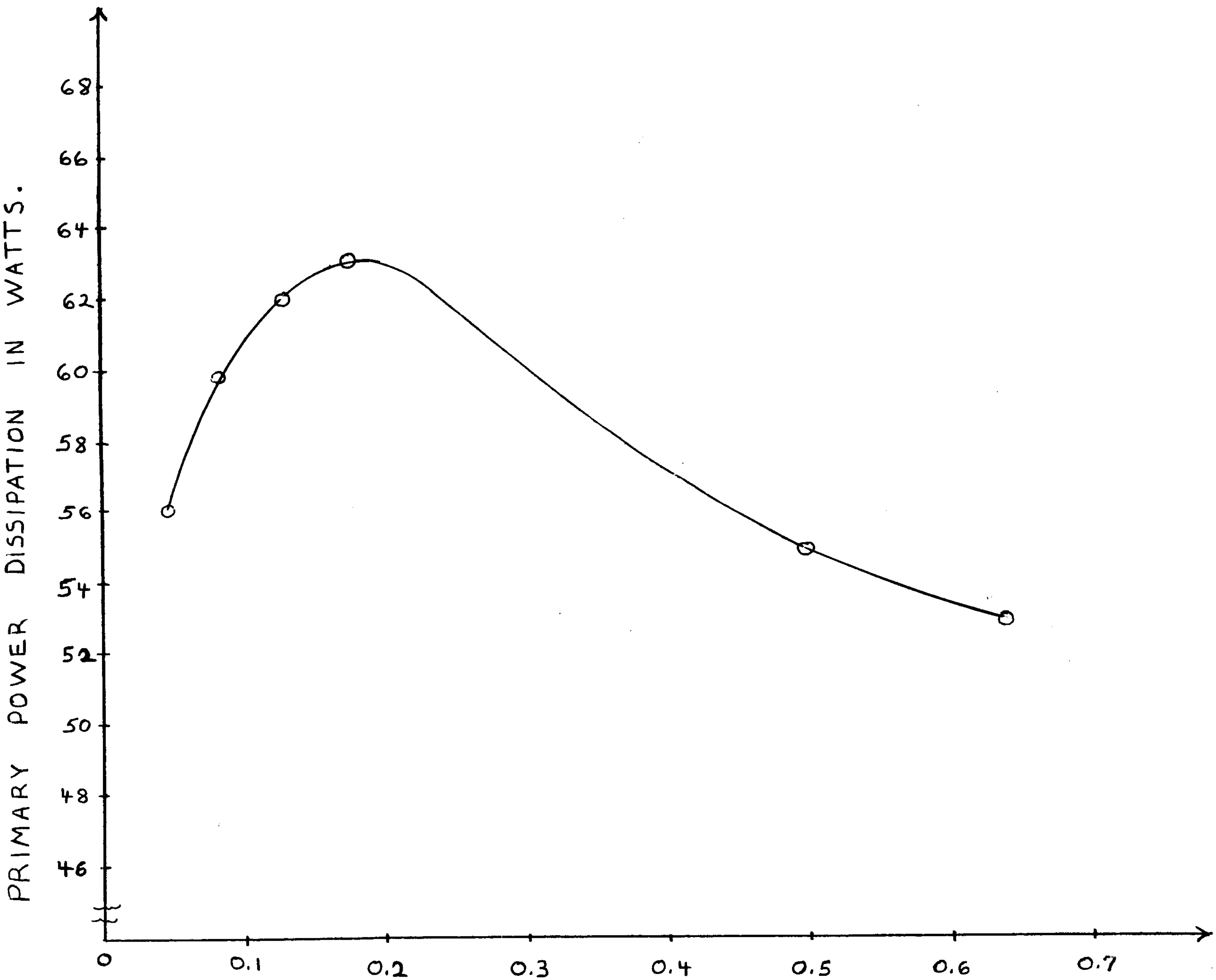

FIGURE 2. THICKNESS OF MATERIAL IN INCHES.

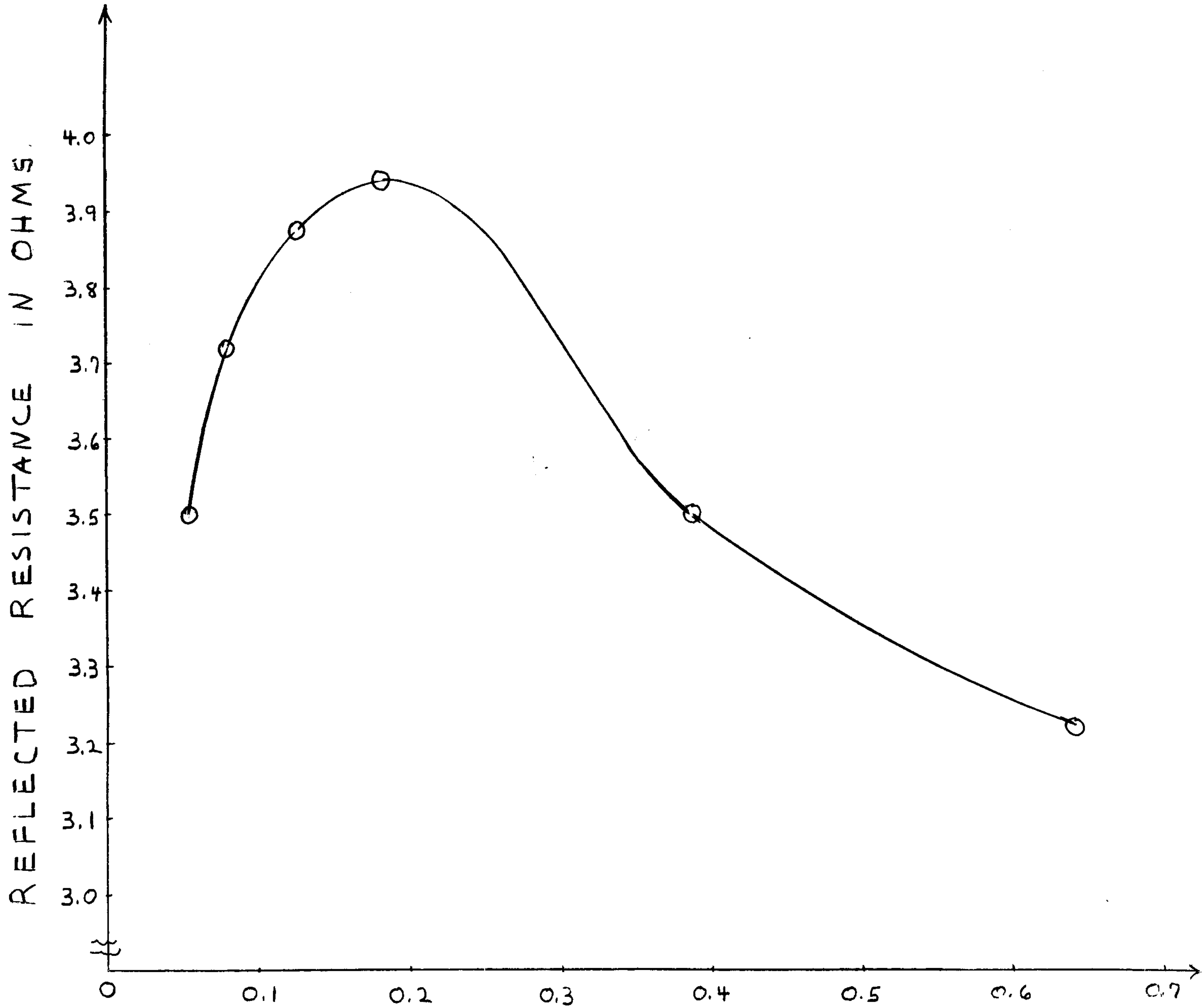

FIGURE 3. THICKNESS OF MATERIAL IN INCHES.

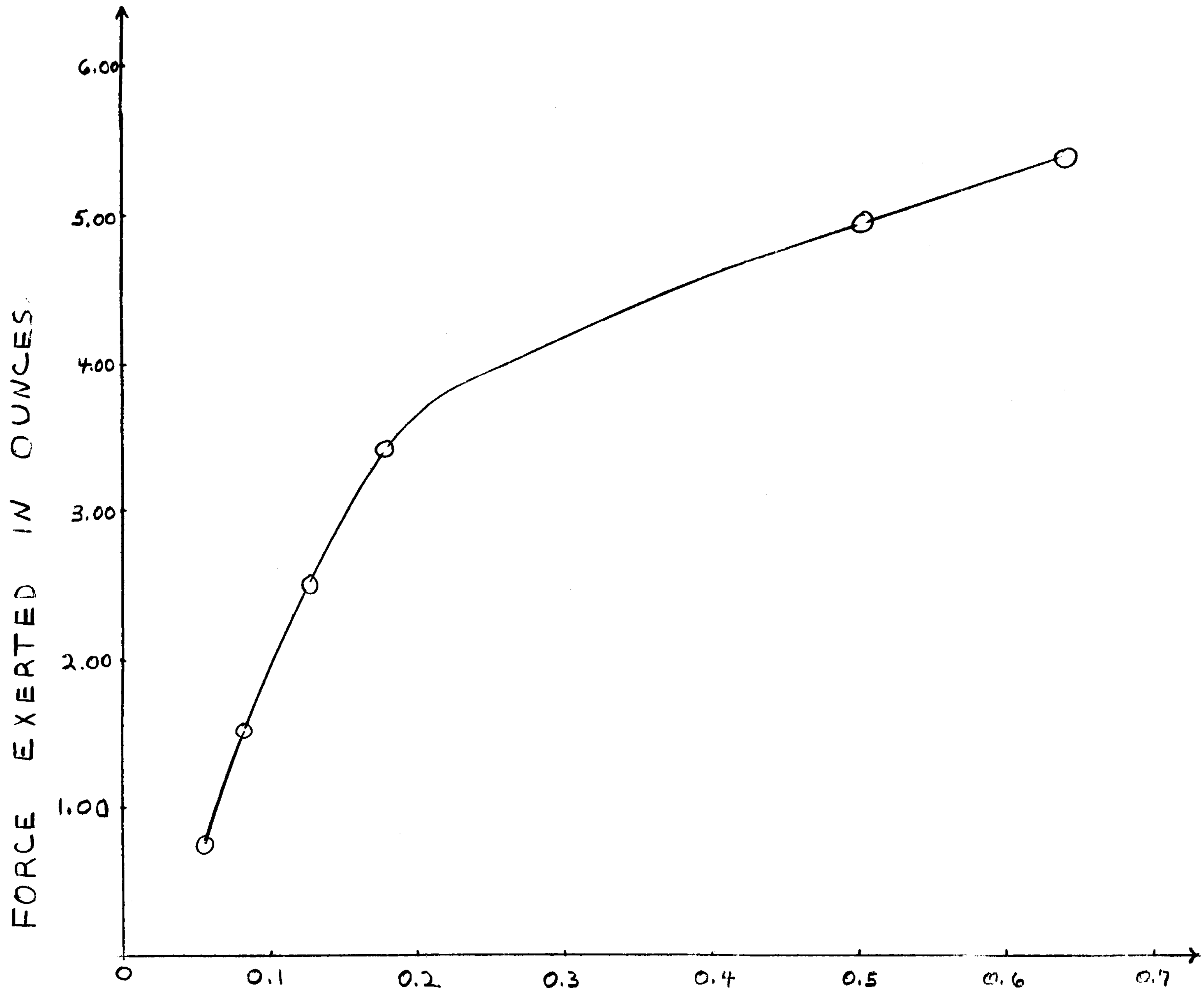

FIGURE 4. THICKNESS OF MATERIAL IN INCHES.

Thickness (inches)	Force (ounces)	Frequency (Hz)	Current (amperes)	Voltage (volts)	Power (watts)	Resistance (ohms)
0.054	0.72	60	4	116	56.0	3.50
0.080	1.50	60	4	115	59.5	3.72
0.125	2.45	60	4	114	62.0	3.87
0.175	3.40	60	4	113	63.0	3.94
0.375	4.20	60	4	110	56.0	3.50
0.500	5.00	60	4	108	55.0	3.44
0.6375	5.50	60	4	106	53.0	3.21
0.54	0.36	60	3	86	28	
0.375	2.25	60	3	82	30	
0.375	1.00	60	2	54	14	
0.375	0.25	400	.87	202		
0.6375	0.25	400	.87	202		

Data Obtained as Function of Thickness of Material

Table II

The value of each inductance term may be determined by

$$L_a = \frac{2\pi\mu r\ A_{a\ max}}{I_a} \quad . \tag{6}$$

In equation 6, μ is the permeability of the surrounding medium, r is the radius of the conductor, $A_{a\ max}$ is the vector magnetic potential at the center of the conductor "a" due to the current in the conductor ,I_a, and L_a is the self-inductance.

$$M_{ab} = \frac{2\pi\mu r\ A_{ab\ max}}{I_b} \tag{7}$$

In equation 7, the symbols have the same meaning except that A_{max} is the vector magnetic potential in conductor "a" due to the current in conductor "b", I_b,and M_{ab} is the mutual inductance between conductor "a" and "b".

The force on conductor segment "a" in the metal sheet may then be found by

$$\bar{F} = \bar{i}_1\ \bar{i}_a \left(\frac{\bar{i}}{d_{1a}} + \frac{\bar{i}}{d_{2a}} + \ldots + \frac{\bar{i}}{d_{16a}} \right) + \frac{i_a i_b}{d_{ab}} + \frac{i_a\ i_c}{d_{ac}} + \ldots \frac{i_a i_n}{d_{an}} \ . \tag{8}$$

where $\bar{F}$ is the vector force on segment "a", i_1, is the current in the hammer coil, $\bar{i}_a$ is the current in segment "a", and d_{ab} is the separation between segments "a" and "b".

Equation 8 could then be used to find the force on each segment in the aluminum sheet.

CONCLUSION

As previously stated, it is not known at the present time which of the two methods will give better or more accurate results. At the present time, no equipment is available for checking experimentally the theoretical results obtained. A much better evaluation of the theoretical results would be possible if a hammer coil and power supply were available.

The use of the magnetic vector potential,A, to obtain values of inductance is the result of a previous study made at Mississippi State University under the sponsorship of N.A.S.A., Marshall Space Flight Center. At the present time, a paper is being prepared for possible publication on this subject. This paper will be a joint effort of some of the Electrical Engineering staff at Mississippi State University and the technical staff at Marshall Space Flight Center.

The present plans are to continue investigation of both methods outlined. If both methods should prove successful, an evaluation will then be made as to which is the more practical approach.

REFERENCES

1. Hallen, Eric, Electromagnetic Theory. New York: John Wiley & Sons, Inc., 1962.

2. Kraus, John D., Electromagnetics. New York: McGraw-Hill, 1953.

3. Wier, D. D., Ball, B. J., Catledge, C. G., and Hill, L. J., Development of a Valid Mathematical Formula or Group of Formulas to Establish Within an Accuracy of 5% the Inductance Audio Range Resulting in Beryllium Coil Assemblies, Final Report, unpublished, Mississippi State University, 1966.