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INSTRUMENT SYSTEM FOR DETERMINING TEMPERATURE EFFECTS ON MAXIMUM INDUCTION OF MAGNETIC MATERIALS

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SUMMARY

An instrument system for continuous measurement of maximum induction of magnetic materials as a function of temperature is described. To obtain continuous data, sinusoidal alternating-current excitation of the magnetic materials was used. An experimental evaluation of the effect of losses on overall accuracy was made. The hysteresis loss had no measurable effect which means that both hard and soft magnetic materials may be tested with this system. The eddy current loss does cause an error in maximum induction; however, this error can be minimized by operation at the proper frequency. The final result is a system that can continuously record maximum induction as a function of temperature with an error of $<\pm 1$ percent of full scale.

INTRODUCTION

The exploration of outer space will require large amounts of power for electric propulsion (ref. 1) and long distance communications (ref. 2). A strong contender to produce this power will be a closed-loop turboalternator system (ref. 3). The only means of heat rejection in a closed system is by radiation to space. In order to keep the size of the radiator within reasonable limits (ref. 4), it will be necessary to operate these power systems at high temperatures (above 1000° F), because the radiator size is an inverse function of its absolute temperature to the fourth power (ref. 5). If the electrical apparatus (alternator and transformers) could be operated at cycle heat rejection temperature, their losses could be rejected by the same radiator. Thus, the separate lower temperature radiator system now required would be eliminated or substantially reduced (ref. 6). In order to evaluate the operation of electromagnetic equipment at high temperatures, it is necessary to determine the high-temperature properties of magnetic materials.

The objective of this testing is to determine how temperature affects the properties of magnetic materials, and also to aid in the development of new magnetic materials, especially for high-temperature operation. For a given volume of magnetic material, the power handling capability is proportional to maximum induction. Because the main concern is space electric power systems, maximum induction has been chosen as the parameter to be tested. In the method of reference 7 for making this measurement, the material to be tested is used as the core of a two-winding transformer. The direct current in the primary of the transformer is reversed, and the voltage pulse induced in the secondary is integrated by a ballistic galvanometer that gives a deflection proportional to the maximum induction (ref. 8). These data can be obtained as a function of temperature by heating the material sample to each temperature level and taking measurements by the method of reference 7 as was done in the investigation of reference 9. The temperatures at which the measurements are to be made, however, cannot be chosen at random since maximum induction as a function of temperature does not result in a smooth curve for all materials. Some materials exhibit phase transformations and order-disorder phenomena that cause humps or rapid changes in the curve (ref. 10). To ensure that these data are not missed, the approach of reference 7 would require a prohibitive number of data points. Since a great number of man-hours would be required and the data would be subjected to human error both in reading the galvanometer and in plotting, it was decided to develop a continuous recording system. Instead of driving the sample transformer in the manner of reference 7, the sample was driven with sinusoidal alternating current. Thus, a continuous voltage was induced in the secondary of the sample that could be averaged to produce a signal proportional to the maximum induction (ref. 11). By feeding this signal along with the temperature of the sample into an X-Y recorder, a continuous plot of maximum induction as a function of temperature is obtained. By driving the sample transformer with alternating-current excitation, however, errors due to hysteresis and eddy current losses may have been introduced. The effects of these losses were determined by making a comparison of direct-current with alternating-current magnetization curves and also maximum induction as a function of frequency curves. The direct-current curves were obtained by the method of reference 7 and are considered the standard for comparison. The equipment errors were determined experimentally.

SYMBOLS

A cross-sectional area of transformer core, cm^2

B_m maximum induction in transformer core, kG

f excitation frequency, cps

H_m maximum magnetizing force driving sample, Oe

I_m maximum value of exciting current, A

K_e eddy current loss constant for sample, cm^4/ohm

L mean length of transformer core, cm

N_p number of turns on sample transformer primary

N_s number of turns on sample transformer secondary

P_e eddy current loss in transformer core, W

V_{av} average value of voltage induced in sample secondary, V

μ permeability

INSTRUMENT SYSTEM

The equation, $V_{av} = 4B_m N_s Af \times 10^{-5}$, derived directly from Faraday's law (ref. 11), is the basis for the instrument system. This equation relates the average value of the voltage induced in the secondary of an unloaded transformer to the maximum induction in the core of that transformer. By using the test material to form the core, its maximum induction can be tested. The samples used were in the form of a toroid because it has the smallest error due to leakage flux and nonuniformity of magnetizing force (ref. 12). The magnetizing force driving the sample is calculated from the equation $H_m = 0.4\, \pi N_p I_m/L$, where the current used is the maximum value of the exciting current.

A complete circuit diagram of the instrument system is shown in figure 1. A sine wave is fed from the oscillator to the input of the power amplifier that drives the sample with a constant amplitude sinusoidal current throughout the test. A precision resistor is placed in series with the sample primary so that the maximum value of the exciting current can be metered to calculate the maximum magnetizing force. The signal from the sample is fed into a high input impedance amplifier to prevent loading of the secondary. The true value of the induced voltage from the sample is thus obtained. The signal is then fed through an isolation transformer to the input of a full-wave bridge rectifier. The

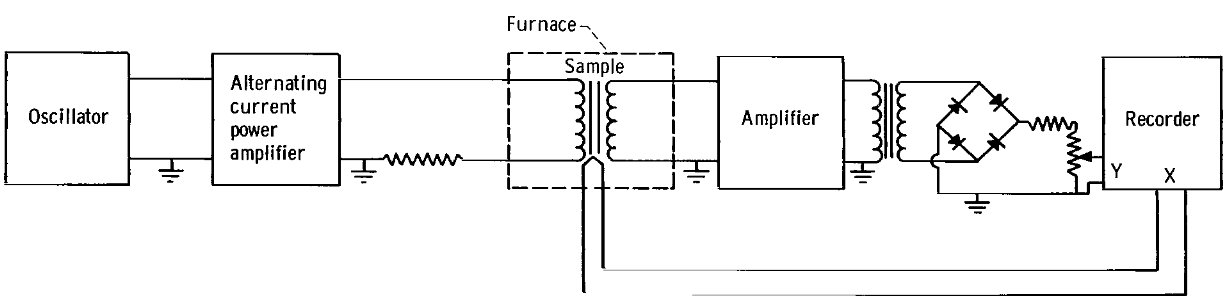

Figure 1. - Circuit diagram of instrument system used to plot maximum induction as function of temperature curves of magnetic materials.

transformer steps up the signal to a high value to make the effect of the rectifier forward voltage drop small. The signal is then fed through a voltage divider to the Y-axis of a direct-current X-Y- strip-chart recorder. The recorder will give a deflection proportional to the average value of the signal. Since maximum induction is proportional to the average value of the voltage induced in the sample, the deflection is proportional to maximum induction. The system can be calibrated by reading the average voltage at the secondary of the sample with an average responding meter and by adjusting the voltage divider to give the desired deflection in B_m by using the equation $V_{av} = 4B_mN_sAf\times10^{-5}$. The temperature of the sample is obtained from a thermocouple welded to the sample and connected to the X-axis of the recorder, which is calibrated to read temperature. The result obtained from the system is a continuous plot of maximum induction as a function of temperature as the sample is excited by a constant amplitude sinusoidal current.

EFFECT OF HYSTERESIS AND/OR EDDY CURRENT LOSS ON ACCURACY

The instrument system was devised to determine the effect of temperature on the maximum induction of magnetic materials. During a test, therefore, all quantities (except temperature) that affect B_m must be accurately known and held constant. This can be done easily for all quantities except the maximum magnetizing force H_m. With the use of alternating current to excite the magnetic material for testing purposes, hysteresis and eddy current losses are present in the material. A current flows in the primary of the sample transformer to supply each of these losses. The maximum magnetizing force is calculated by using the equation $H_m = 0.4\,\pi N_pI_m/L$, where I_m should be the maximum value of the magnetizing current. However, since it is not possible to measure only the magnetizing current, the maximum value of the exciting current is used instead. The exciting current contains the magnetizing current as well as the currents that supply the core losses. If the core loss currents affect the maximum value of the exciting current, there will be an error in the maximum magnetizing force. In order to determine if there are errors, H_m should be evaluated both with and without the loss currents present. This should be done over a wide range of values to determine whether the level of H_m has any effect on errors. Since the loss currents are not present in the determination of H_m by the method of reference 7, a comparison of H_m values between the method of reference 7 and the alternating-current method would reveal any errors. The comparison must be made at equal B_m values that can be obtained accurately by either system. A comparison of H_m values with equal B_m values over a wide range of H_m levels can best be done by comparing magnetization curves obtained by both methods, because the normal magnetization curve is a locus of B_m as a function of H_m points. Since core losses tend to decrease with increasing temperature, the testing was done at room tem-

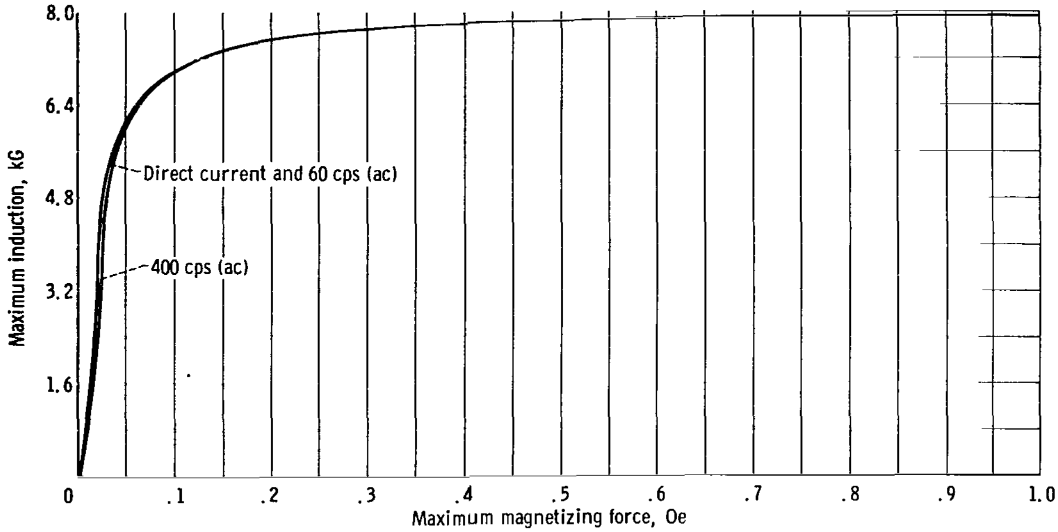

Figure 2. - Comparison of direct-current and alternating-current test methods with low loss magnetic material.

perature where the errors would be more apparent than at high temperature. The direct-current magnetization curves were obtained by using the standard methods of reference 7. The alternating-current curves were obtained by measuring the average value of the induced voltage on an average responding voltmeter, and the maximum exciting current on an oscilloscope by comparing it with a known direct-current voltage.

In order to determine whether the direct-current and alternating-current methods give comparable data, it would be desirable to test a magnetic material that had no losses. To approximate this condition, a 1-mil nonoriented 78-percent nickel-iron material was used because it has the lowest losses of any commercial material. The curves of figure 2 show no detectable difference between the direct-current and 60-cps-alternating-current curves and only a slight difference for the 400-cps alternating-current curve, which indicates that the two systems give comparable data.

In order to determine whether eddy current loss has any effect on the maximum magnetizing force, it would be desirable to test a material with high eddy current loss and no hysteresis loss. The 78-percent nickel-iron material used in the first test had low enough losses at 60 cps to give no measurable effect. The eddy current loss could be increased by using a thicker lamination (14 mil) and no insulation between laminations. These changes should have little or no effect on the hysteresis loss. The curves of figure 3 show a considerable difference between the direct- and alternating-current curves, which indicates that eddy current loss can have a significant effect on the maximum magnetizing force. This, however, is an extreme case used only for the separation of hysteresis and eddy current loss effects.

In order to determine whether hysteresis loss has any effect on the maximum magnetizing force, it would be desirable to test a material with high hysteresis loss and no eddy

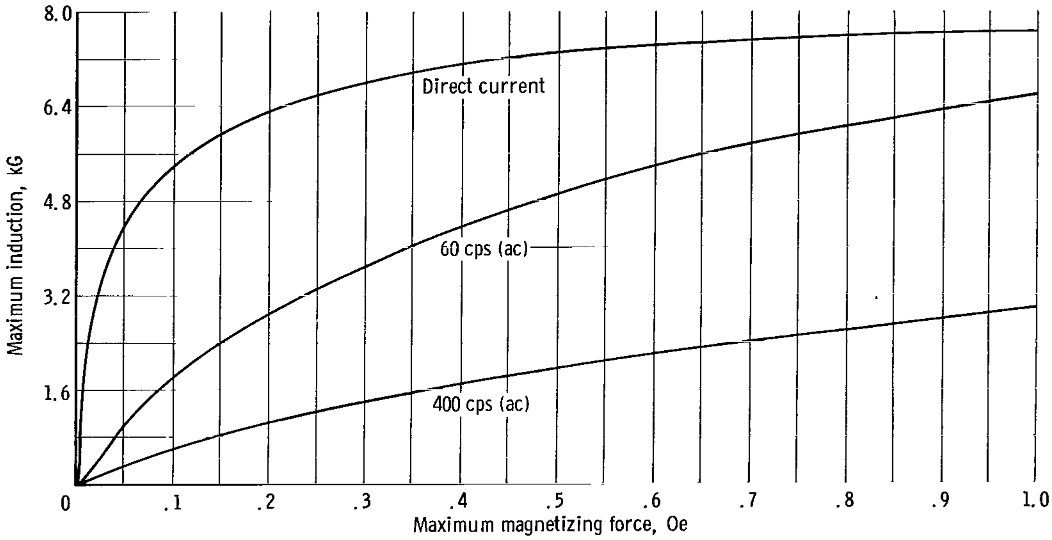

Figure 3. - Effect of high eddy current loss on alternating-current testing.

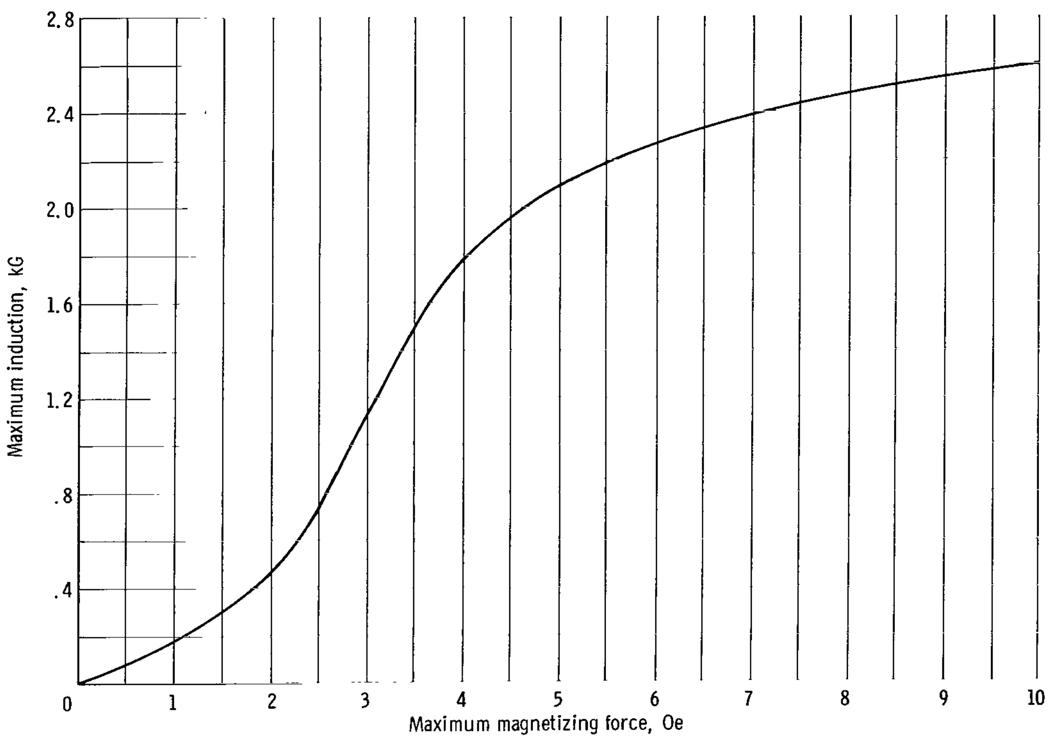

Figure 4. - Effect of high hysteresis losses on alternating-current testing. Curve shows identical results for direct current, 60-cps, and 400-cps alternating current.

current loss. Eddy current losses can be made small by using very thin laminations. The extreme case is to use a powdered material such as a ferrite that has almost no eddy current loss but can be obtained with substantial hysteresis losses. The results from a ferrite core are shown in figure 4. There is no measurable difference between the direct-current, 60-cps-, and 400-cps-alternating-current curves, which indicates that hysteresis loss has no apparent effect on the maximum magnetizing force. The hysteresis loss at 400-cps alternating current for the ferrite was an order of magnitude larger than the eddy current loss at 60-cps alternating current for the material of figure 3. The results in figure 4 indicate that hard as well as soft magnetic materials can be tested by alternating-current methods.

The sample used to determine the effect of high eddy current losses on alternating-current testing of magnetic materials was an extreme case used to obtain a large difference between hysteresis and eddy current losses. To get a better picture of the actual errors due to eddy current loss, a standard 4-mil silicon-iron sample was tested. The curves of figure 5 show that large errors can occur even with moderate eddy current losses; however, it also shows that the more saturated the sample, the less the error. In figure 5 the error is no longer detectable above $H_m = 1.2$ oersteds for either of the two frequencies used.

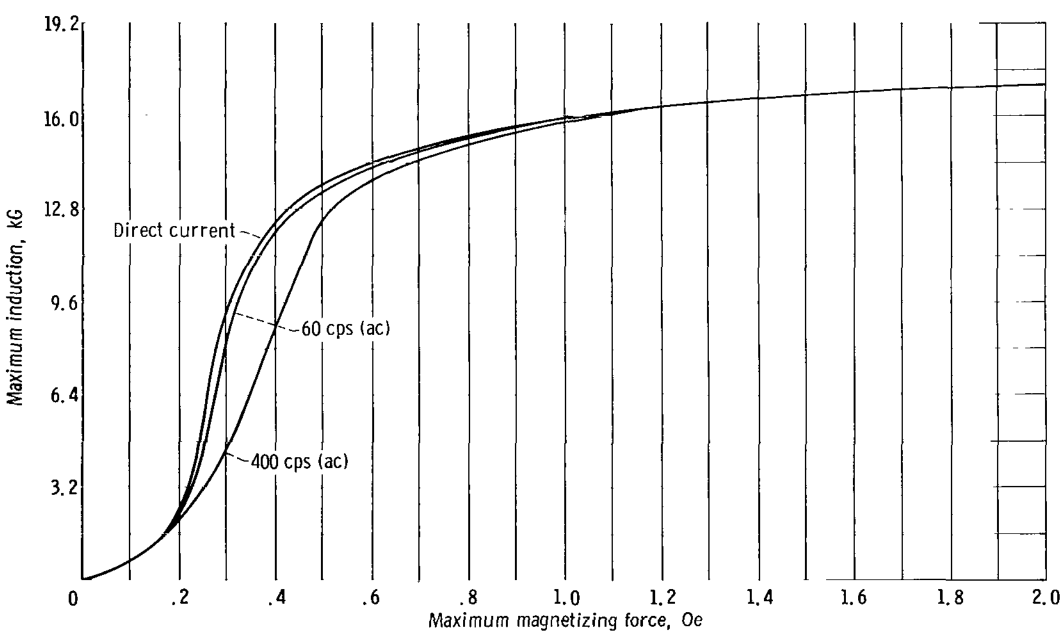

Figure 5. - Effect of moderate eddy current losses on alternating-current testing.

CONTROLLING EFFECT OF EDDY CURRENT LOSS ON ACCURACY

If alternating-current testing is to be used, the error in H_m due to eddy current loss must be controlled. Since the parameter to be tested is B_m, the major concern over the H_m error is how much it will affect the accuracy of B_m. The two quantities are related by the equation $B_m = \mu H_m$. Since permeability is a variable quantity, it would be difficult to determine the error in B_m even if the H_m error were known. Therefore, it is better to determine directly the effect of eddy current loss on the accuracy of B_m. From the equation $P_e = K_e f^2 B_m^2$ (ref. 13) it can be seen that eddy current loss is proportional to frequency squared. This would indicate that the sample should be tested at a very low frequency to eliminate eddy current loss. At very low frequencies, however, the signal from the sample becomes quite small, and also the equipment used to test the sample has a low frequency operating limit. Therefore, some operating frequency range that would minimize the eddy current error and be above the lower frequency limitation of the equipment must be found. This can be done by plotting maximum induction as a function of frequency. The curves in figure 6 show the results from the 4-mil silicon-iron sample tested previously. On the flat portion of the curves, the error due to eddy current loss is no longer detectable. To make space power systems lightweight, it will be necessary to operate the magnetic materials at a high H_m level to obtain a high B_m. This area is represented by the top two curves in figure 6, which are flat over

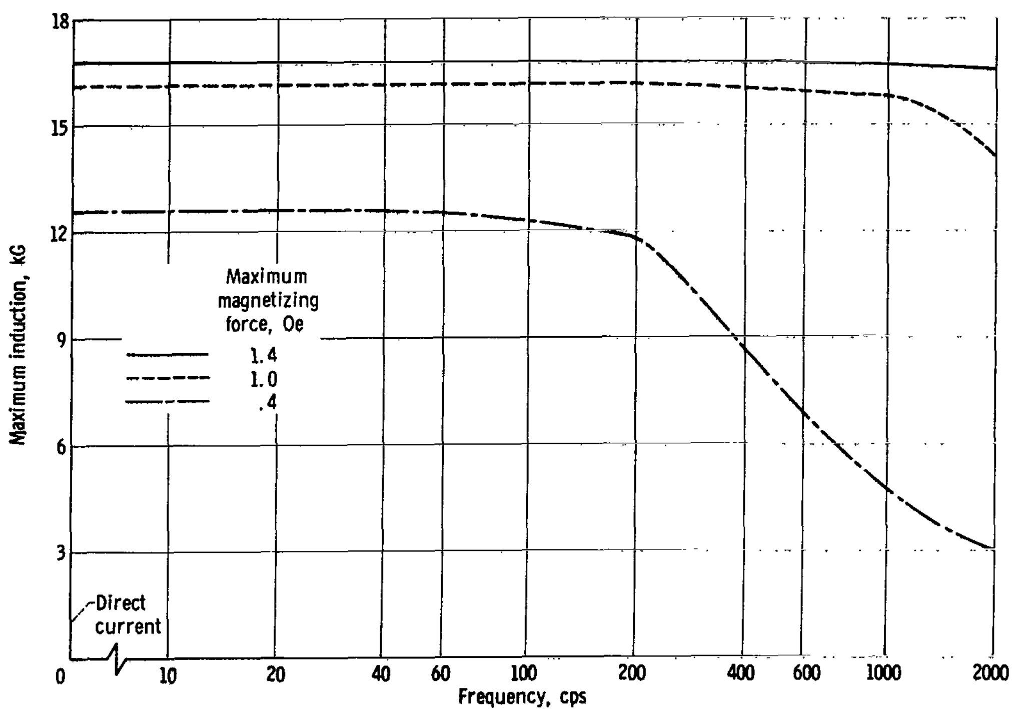

Figure 6. - Determination of operating frequency range to minimize eddy current loss error.

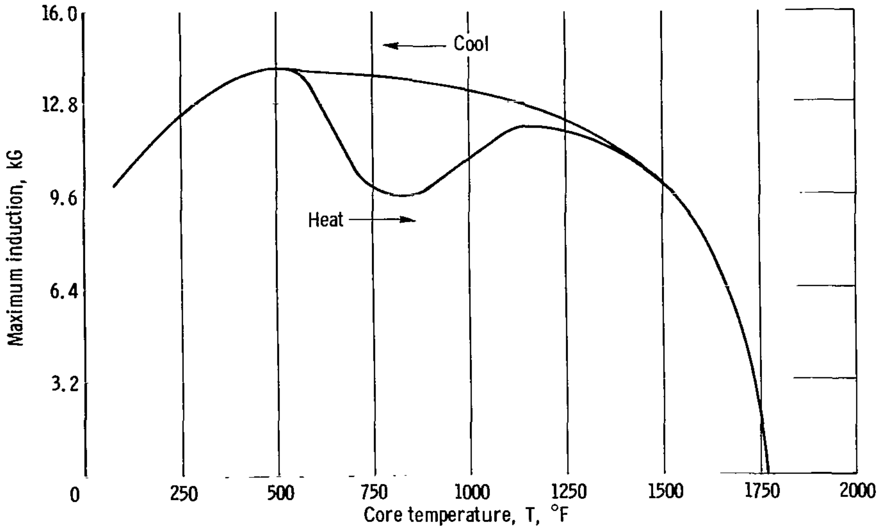

Figure 7. - Type of data obtained by instrument system.

a large frequency range. Thus, the error due to eddy current loss will be easily controllable.

The basic difference between direct- and alternating-current testing is the error due to eddy current loss. In order to control this error during actual testing of magnetic materials, the following steps should be taken: On each general type of material (such as silicon-iron, cobalt-iron, etc.) a curve for maximum induction as a function of frequency should be plotted at the minimum H_m to be used to indicate the frequency range over which the material can be tested. Each particular composition (such as 3 percent silicon-iron) can be checked by measuring B_m at two frequencies that lie in the general operating range. Accurate measurement can be made by using a digital voltmeter with an average responding alternating-current converter to measure the average voltage at the sample secondary. Then the maximum induction can be calculated. In this manner, the error due to eddy current loss can be made negligible compared with the equipment errors in the system. All this testing can be done at room temperature, since the eddy current loss will be less at high temperatures because of the increased resistivity of the magnetic material. An indication of the type of data obtained by the system is shown in figure 7.

EXPERIMENTAL EVALUATION OF INSTRUMENT SYSTEM

In the previous sections, the error due to eddy current loss was discussed and evaluated. There are also errors due to the equipment used that must be evaluated in order to determine the overall accuracy of the system. The evaluation of the instrument system is separated into three sections: first, the portion of the system that excites the sample; second, the portion of the system that measures and records the temperature; and, third, the portion that averages the induced voltage and records maximum induction.

The sample, in the form of a two-winding transformer, is driven by a constant current amplifier that receives its signal from an oscillator. Since the system is calibrated by using the equation $V_{av} = 4B_mN_sAf\times10^{-5}$, any error in the oscillator frequency will be reflected in B_m. The frequency error of the oscillator used is ±0.1 percent. Variations in exciting current were traceable to drift in oscillator amplitude, amplifier gain, and variation in load. The maximum value of the exciting current was recorded during an 8-hour temperature test, and the total error was <±0.3 percent.

The temperature of the sample is measured by a thermocouple welded to the core sample. Its output is fed to the X-axis of a potentiometric X-Y recorder that has a calibrated temperature range. The total error including thermocouple error is <±0.5 percent of the maximum temperature.

The signal from the secondary of the sample is amplified, fed through an isolation transformer, full-wave bridge rectifier, voltage divider, and to the Y-axis of a potentiometric X-Y recorder. Since the sample is a nonlinear device being driven by a sinusoidal current, the secondary voltage will be distorted. In order to test the effect of distortion on the operation of the system, the secondary of the sample was replaced by a function generator that produces three waveforms: sine, triangle, and square. These waveforms were used to present a wide variation in harmonic content and rise time to the system. A fourth waveform was obtained from an actual transformer sample to compare normal operating conditions to the other test waveforms. No difference was found between the various waveforms, indicating that distortion, within the frequency limitations of the equipment, has no effect on the ability of the system to obtain the average value of the induced voltage. The system is calibrated by measuring the average voltage at the secondary of the sample, calculating maximum induction, and then adjusting the voltage divider to give the proper deflection on the recorder. The average voltage can be measured with an error of ±0.04 percent by using a digital voltmeter with an average responding alternating-current converter that makes the calibration error negligible. The nonlinearity in the equipment was checked by measuring the secondary voltage with an average responding voltmeter and by calculating maximum induction. The calculated value was then compared with the maximum induction indicated on the recorder while the amplitude of the secondary voltage was set at various levels. The errors were <±0.8 percent of full scale if the induction level varied in the range of 10 to 90 percent of full scale and <±0.4 percent of full scale if the induction level varied in the range of 30 to 70 percent of full scale with the system calibrated at midscale.

The maximum probable error in any point on the curve for maximum induction as a function of temperature will be <±1 percent of full scale if the induction level varies over

80 percent of the recorder range. All the errors previously discussed are included, but any errors associated with the sample such as flux leakage and errors in area measurement are not included.

SUMMARY OF RESULTS

An instrument system was investigated that would determine and record the effects of high temperature on the maximum induction of magnetic materials. In order to accomplish this, the transformer sample was driven by a sinusoidal alternating current. By comparison of direct-current with alternating-current magnetization curves of four materials, it was found that hysteresis loss had no effect on the measurement of maximum induction but that eddy current loss does. By plotting a curve of frequency as a function of maximum induction for one of these magnetic materials, it was determined that this error can be made negligible by operation in the proper frequency range. The equipment errors due to drift, nonlinearity, regulation, and waveform distortion were determined experimentally. The final result is a system that can continuously record the maximum induction of hard and soft magnetic materials as a function of temperature with an error of $<\pm 1$ percent of full scale.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 2, 1966,
120-27-04-18-22.

REFERENCES

1. Mickelson, William R.: Electric Propulsion. Space/Aeronautics R & D Technical Handbook Issue 1964/1965, vol. 42, no. 4, pp. 50-53.
2. Thatcher, John W.: Deep Space Communication. Space/Aeronautics, vol. 42, no. 1, July 1964, pp. 54-63.
3. English, Robert E.; Slone, Henry O.; Bernatowicz, Daniel T.; Davison, Elmer H.; and Lieblein, Seymour: A 20,000 Kw Nuclear Turboelectric Power Supply for Manned Space Vehicles. NASA MEMO 2-20-59E, 1959.
4. Osmun, William G.: Space Nuclear Power: Snap-50/Spur. Space/Aeronautics, vol. 42, no. 7, Dec. 1964, pp. 38-45.

5. Mackay, D. B.; and Bacha, C. P.: Space Radiator Analysis and Design. Part I. Rep. No. SID 61-66 (AFASD TR 61-30, pt. I), North American Aviation, Apr. 1, 1961.

6. Anon.: Electrical Power Generation Systems for Space Applications. NASA SP-79, 1965, p. 15.

7. Anon.: Standard Methods of Test for Normal Induction and Hysteresis of Magnetic Materials. ASTM Designation: A341-64, Sec. 7-11. ASTM Standards, Part 8, Nov. 1965, pp. 33-35.

8. Harris, Forest K.: Electrical Measurements. John Wiley & Sons, 1952, pp. 342-395.

9. Pasnak, Michael; and Lundsten, R. H.: Effects of Extremely High Temperatures on Magnetic Properties of Core Materials, NAVORD Rep. 6132, Naval Ordnance Laboratory, July 10, 1958.

10. Bozorth, Richard M.: Ferromagnetism. D. Van Nostrand Co., Inc., 1951, p. 17.

11. Mueller, George V.: Alternating-Current Machines. McGraw-Hill Book Co., 1952, pp. 9-10.

12. Harris, Forest K.: Electrical Measurements. John Wiley & Sons, 1952, pp. 369-370.

13. Mueller, George V.: Alternating-Current Machines. McGraw-Hill Book Co., 1952, pp. 14-16.

NASA-Langley, 1966 E-3342