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ELECTRICAL AND MECHANICAL PROPERTIES OF A SUPERIOR HIGH-TEMPERATURE COBALT-IRON MAGNETIC MATERIAL

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ABSTRACT

The alternating-current electrical and mechanical properties of high-purity alloys of 9 weight percent iron, the balance being mostly cobalt, were determined at temperatures from 25° to 1000° C. Data are presented for four thicknesses from 0.002 inch (0.005 cm) to 0.012 inch (0.030 cm) and at six frequencies from 60 to 3200 hertz. The results of the measurements and comparisons with a commercial alloy indicate that the material is one of the best magnetic materials for high-temperature transformer-core applications.

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SUMMARY

The alternating-current electrical and mechanical properties of high-purity alloys of 9 weight percent iron, the balance being mostly cobalt, were determined at temperatures from 25° to 1000° C. Data are presented for four thicknesses from 0.002 inch (0.005 cm) to 0.012 inch (0.030 cm) and at six frequencies from 60 to 3200 hertz. The results of the measurements and comparisons with a commercial alloy indicate that the material is one of the best magnetic materials for high-temperature transformer-core applications.

INTRODUCTION

The space power conversion and conditioning equipment requirements (refs. 1 and 2) for very-high-temperature magnetic materials have revived interest in the lesser known high-Curie-point alloys of cobalt-iron. The binary alloys in the range of 5 to 21 percent iron have not only a high Curie point but also a high permeability at 25° C (refs. 3 and 4). The maximum permeability according to Bozorth (ref. 5) occurs at approximately 8 percent iron after annealing at 1000° C. The alloy also has a high saturation magnetization (ref. 5), and there are no phase changes or order-disorder transformations (ref. 6).

In a previous report (ref. 6), the dc magnetic properties were presented for an alloy of 9.3 percent iron, the balance being cobalt. The magnetization curves and hysteresis loop were given from room temperature to 1000° C. The purposes of the present investigation were (1) to determine the ac magnetic properties as a function of temperature, frequency, and material thickness and (2) to determine the mechanical properties as a function of temperature.

The iron content of the alloys described in the report is 9 weight percent, the balance being largely cobalt. The ac magnetic properties and mechanical properties were measured from room temperature to 1000° C. The results were also compared with a commercial alloy at selected temperatures.

TEST SAMPLES AND PROCEDURE

A very-high-purity alloy was obtained by selection of high-quality starting materials and purification by electron-beam float-zone techniques. The refinement was obtained by subjecting the starting materials to three zone passes in a vacuum of 10^{-6} torr (1×10^{-8} N/cm^2). This reduced the impurities to a total of less than 90 parts per million. The materials were then alloyed by arc melting the beam-refined metals in purified argon. Five approximately 3/8- by 3/8-inch- (1- by 1-cm-) thick rods were prepared with iron contents of 9 percent, the balance being cobalt. For electrical testing, four of the rods were cold rolled to 0.012-inch- (0.030-cm-), 0.008-inch- (0.02-cm-), 0.004-inch- (0.01-cm-), and 0.002-inch- (0.005-cm-) thick strips. For mechanical testing, one of the rods was cold rolled to a 0.012-inch- (0.030-cm-) thick strip. An additional rod of approximately the same size was prepared with an iron content of 8.8 percent and a tungsten content of 0.8 percent. This rod was cold rolled to a 0.012 inch (0.030 cm) strip for electrical testing. All specimens received a final stress-relieving anneal for 4 hours at 1020° C, a temperature which is approximately 20° C under the Curie point. Total impurities of the final product were less than 250 parts per million, as measured by emission spectrographic and other chemical analysis techniques (see table I).

For the electrical tests, the alloy strips were coated with an insulator consisting of an aluminum oxide - phosphoric acid cement. The alloy strip was spirally wound into a toroid with an inside diameter of 2.0 inches (5.1 cm). A test transformer was made by winding coils around the toroid. Nickel wire was used for the electrical winding, and boron nitride and aluminum oxide insulators were used throughout. The sample was tested in an argon atmosphere furnace from room temperature to 1000° C. The temperature was measured by a Chromel-Alumel thermocouple welded to the magnetic core. The temperature was indicated on a continuous balance precision indicator. A minimum time of 1 hour was allowed at each temperature for stabilization.

The ac magnetic properties for all thicknesses were measured by the usual ASTM wattmeter method (ref. 7) except that a Roland ring was used instead of an Epstein frame. The field applied to the specimen was in the direction of rolling. An electronic wattmeter with an accuracy of 3 percent was used to measure the core loss. The rms exciting current was measured with an instrument that has an accuracy of 1 percent of full scale. The flux-measuring voltmeter had an accuracy of 1 percent of full scale.

The mechanical properties were determined by the ASTM tension testing method (ref. 8) except that the 0.012 inch (0.030 cm) tensile specimens had a gage length of $1\frac{1}{2}$ inches (3.8 cm) instead of 2.0 inches (5.1 cm). The change in strain was measured by an automatic recording extensometer with a maximum strain error of 0.0002. The load was measured by a dynamometer with an accuracy of 3 percent. The strain rate was kept at 0.005 per minute to yielding and 0.05 per minute thereafter. The samples were tested in an argon atmosphere from room temperature to 1000° C.

RESULTS OF ELECTRICAL TESTS

Alternating current data were taken at temperatures of 25°, 250°, 650°, 800°, 900°, and 1000° C. Core loss and exciting current measurement were made up to an induction of 1.4 teslas (14 000 gauss) and at frequencies of 60, 400, 1000, 2000, and 3200 hertz. Complete data were obtained for each thickness. Exciting volt-amperes were calculated by multiplying the rms exciting current and the induced primary voltage.

Figure 1 presents the core loss curves for the alloy with a 0.002 inch (0.005 cm) thickness. The core loss has units of watts per kilogram, while the induction is measured in teslas. For any given temperature, the core losses increase with increasing frequency. Generally, at a given frequency, the core loss decreased as temperature increased.

Figure 2 shows the exciting volt-ampere curves for the 0.002 inch (0.005 cm) alloy. The exciting volt-amperes have units of the volt-amperes per kilogram. For any given temperature, the exciting volt-amperes increased with increasing frequency. For a given frequency, the exciting volt-amperes decreased with increasing temperature except at 1000° C. The curves at 1000° C (fig. 2(f)) increased sharply with increasing induction because the temperature is only 40° C under the Curie point with a resultant low saturation magnetization.

Core loss curves for the 0.004-inch- (0.01-cm-) thick material are shown in figure 3. Figure 4 gives the corresponding exciting volt-ampere curves. All these curves behaved in the same way as the curves for the 0.002 inch (0.005 cm) alloy.

Figure 5 presents the core loss curves for the 0.008 inch (0.02 cm) alloy. The exciting volt-ampere curves are shown in figure 6. Again the behavior is the same as the 0.002 and 0.004 inch (0.005 and 0.01 cm) thicknesses.

The 0.012 inch (0.030 cm) alloy with a composition of 9 percent iron, balance cobalt, has core losses as shown in figure 7. Generally, the behavior is the same as the other thicknesses. An exception is the 1000° C plot (fig. 7(f)), where, at higher frequencies, the core losses are somewhat higher than at 900° C. Figure 8 shows the exciting volt-ampere curves which behave again in the usual manner. The core loss curves for the 0.012 inch (0.030 cm) alloy with a composition of 8.8 percent iron, 0.8 percent tungsten, balance cobalt are shown in figure 9. The curves behave generally in the same way as the other 0.012 inch (0.030 cm) material (fig. 7). The addition of tungsten however has lowered the core losses. This may be explained in part by the fact that the room-temperature resistivity was raised approximately 35 percent when the third element was added. It is known that eddy current losses are influenced by changes in resistivity. The corresponding exciting volt-ampere curves, illustrated in figure 10, generally behaved in the usual way, but like the core losses were also lower than the curves for the material without tungsten.

The effect of temperature on the core loss properties is shown in figures 11 and 12. Figure 11 shows a comparison of core losses for various temperatures at a frequency of 2000 hertz and 0.008 inch (0.02 cm) thickness. At 1000° C, the core loss at 0.6 tesla is approximately 20 percent that of room temperature. Figure 12 shows a comparison of core losses for various thicknesses at an induction of 0.6 tesla and a frequency of 2000 hertz. The addition of tungsten to the 0.012 inch (0.030 cm) material decreased the core losses by an average of approximately 22 percent. In a NASA sponsored study (ref. 9, p. 33), the only commercial alloy recommended for service above 600° C as both a transformer core and machinery rotor alloy is a material of 27 percent cobalt, the balance being mostly iron. In figure 13, the 0.008-inch (0.02-cm) 27-percent-cobalt alloy (ref. 9, pp. 336 and 338) is compared with the new 0.008-inch (0.02-cm) 91-percent-cobalt material at frequencies of 800 and 3200 hertz. The 25° C curves (fig. 13(a)) show that the 27-percent-cobalt alloy has lower core losses than the 91-percent-cobalt alloy. At elevated temperatures (figs. 13(b) and (c)), the new alloy has lower core losses than the commercial alloy. At 0.6 tesla, the new alloy has approximately 25 percent less core loss than the commercial alloy. These curves show that the new 9-percent-iron - 91-percent-cobalt alloy is superior to the 27-percent-cobalt commercial alloy for high-temperature transformer-core applications. The new alloy can also be utilized at higher temperatures than the commercial material since it has a Curie point of approximately 1040° C compared with 925° C (ref. 9, p. 293) for the commercial alloy.

RESULTS OF MECHANICAL TESTS

Tension test data for two specimens were taken in the direction of rolling at temperatures of 25°, 250°, 650°, 800°, 900°, and 1000° C. Yield strength at an offset of 0.2 percent, ultimate tensile strength, elongation, and reduction in area were determined at all temperatures. Since the modulus of elasticity of the testing machine was not known at high temperature, the modulus of elasticity of the sample was determined at 25° C only. Numerical values obtained from the data are included in table II. The high values of the percent elongation and percent reduction in area at 25° C indicate the ease of fabricability of the alloy into thin sheets. Moreover, it is as easily cold rolled as conventional 3 to $4\frac{1}{2}$ percent silicon-iron. The low values of yield strength and ultimate tensile strength at high temperatures indicate that the present composition is not suitable for heavy, high-speed machinery rotors at these temperatures.

CONCLUSIONS

The magnetic and mechanical properties of an alloy of 9 percent iron, the balance being cobalt, have been determined for various thicknesses and at temperatures from 25° to 1000° C. The formation of a ternary alloy by the addition of 0.8 percent tungsten further improved the electrical properties. Comparisons with a commercial alloy indicate that the new alloy is one of the best magnetic materials for high-temperature transformer-core applications.

Results of the mechanical testing explains the ease of fabricability of the alloy into thin sheets. The low values of mechanical strength at high temperatures also indicate that the composition is not suitable for heavy, high-speed-machinery rotor applications.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 2, 1968,
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TABLE I. - TYPICAL ANALYSIS OF FINAL ALLOY

Element	Content, ppm	Analysis method
Nitrogen	15	Kjeldahl distillation
Hydrogen	45	Hot extraction
Oxygen	45	Inert gas fusion, gas chromatographic
Carbon	50	Combustion, gas chromatographic
Copper	50	Spectrographic, sustaining arc excitation, photographic detection
All others	Total less than 45	Spectrographic, sustaining arc excitation, photographic detection
Total of all elements	Less than 250	

TABLE II. - MECHANICAL PROPERTIES OF 9-PERCENT IRON, BALANCE COBALT, AT VARIOUS TEMPERATURES

Temperature, °C	Specimen	Yield strength for 0.2 percent offset		Ultimate tensile strength		Elongation for 1.5 in. (3.8 cm) gage length, percent	Reduction in area for an original cross section of 0.006 in.^{2} (0.04 cm^2), percent	Modulus of elasticity	
		psi	N/m^2	psi	N/m^2			psi	N/m^2
25	1	17 900	123×10^6	61 600	425×10^6	58.4	27.5	24.1×10^6	166×10^9
	2	15 900	110	68 800	474	54.2	36.0	23.8	164
250	1	13 200	91.0	50 800	350	29.2	28.9	--------	-------
	2	13 200	91.0	58 400	403	33.3	28.3	--------	-------
650	1	12 400	85.5	31 800	219	16.7	15.6	--------	-------
	2	15 700	108	27 100	187	12.5	8.8	--------	-------
800	1	9 000	62.1	17 000	117	10.4	10.3	--------	-------
	2	9 300	64.1	16 100	111	8.3	10.3	--------	-------
900	1	10 700	73.8	15 200	105	13.6	7.2	--------	-------
	2	11 100	76.5	14 600	101	12.5	8.8	--------	-------
1000	1	2 980	20.5	6 470	44.6	14.6	13.2	--------	-------
	2	5 300	36.5	6 600	45.5	8.3	7.4	--------	-------

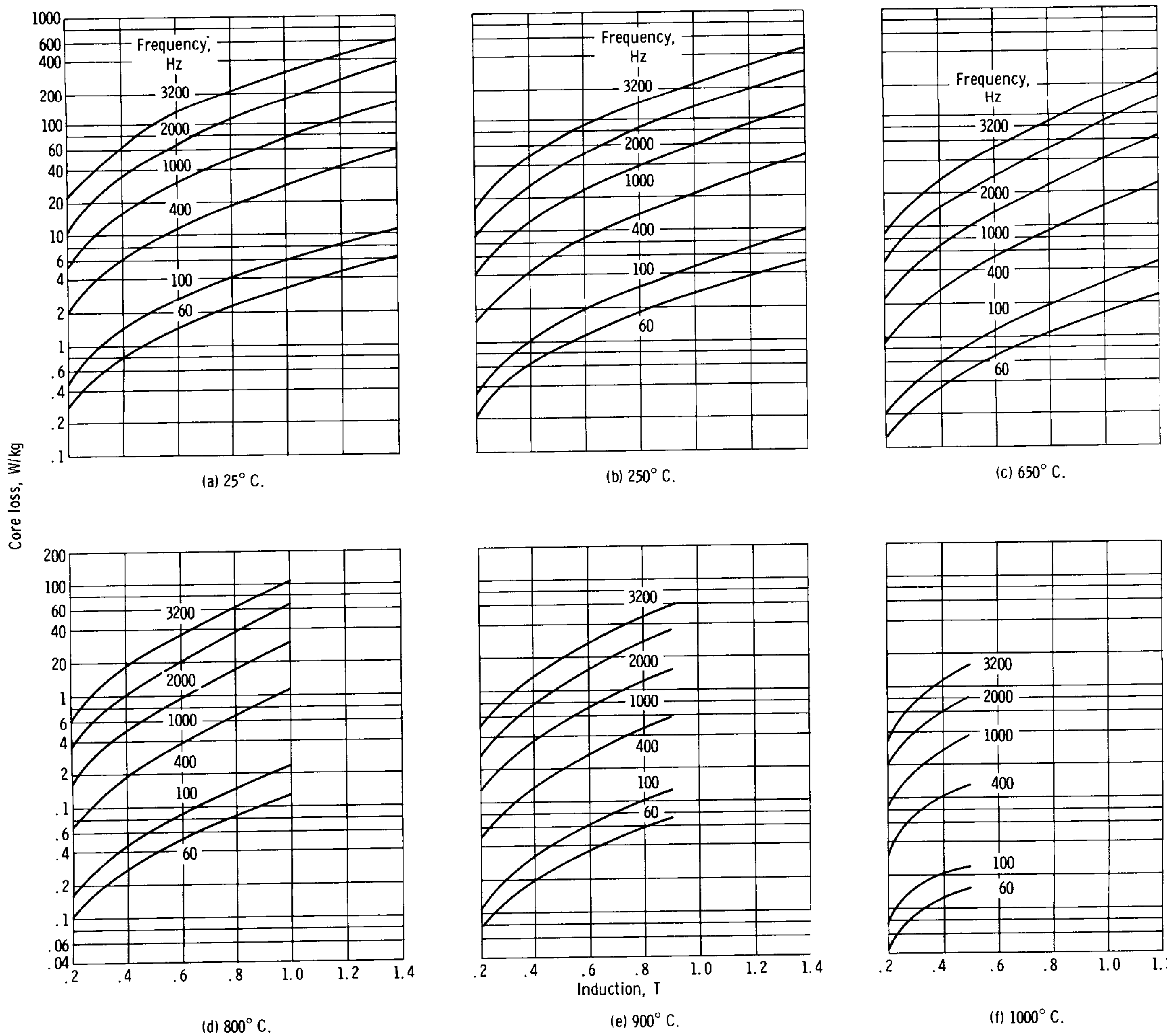


Figure 1. - Core loss for 0.002 inch (0.005 cm) alloy.

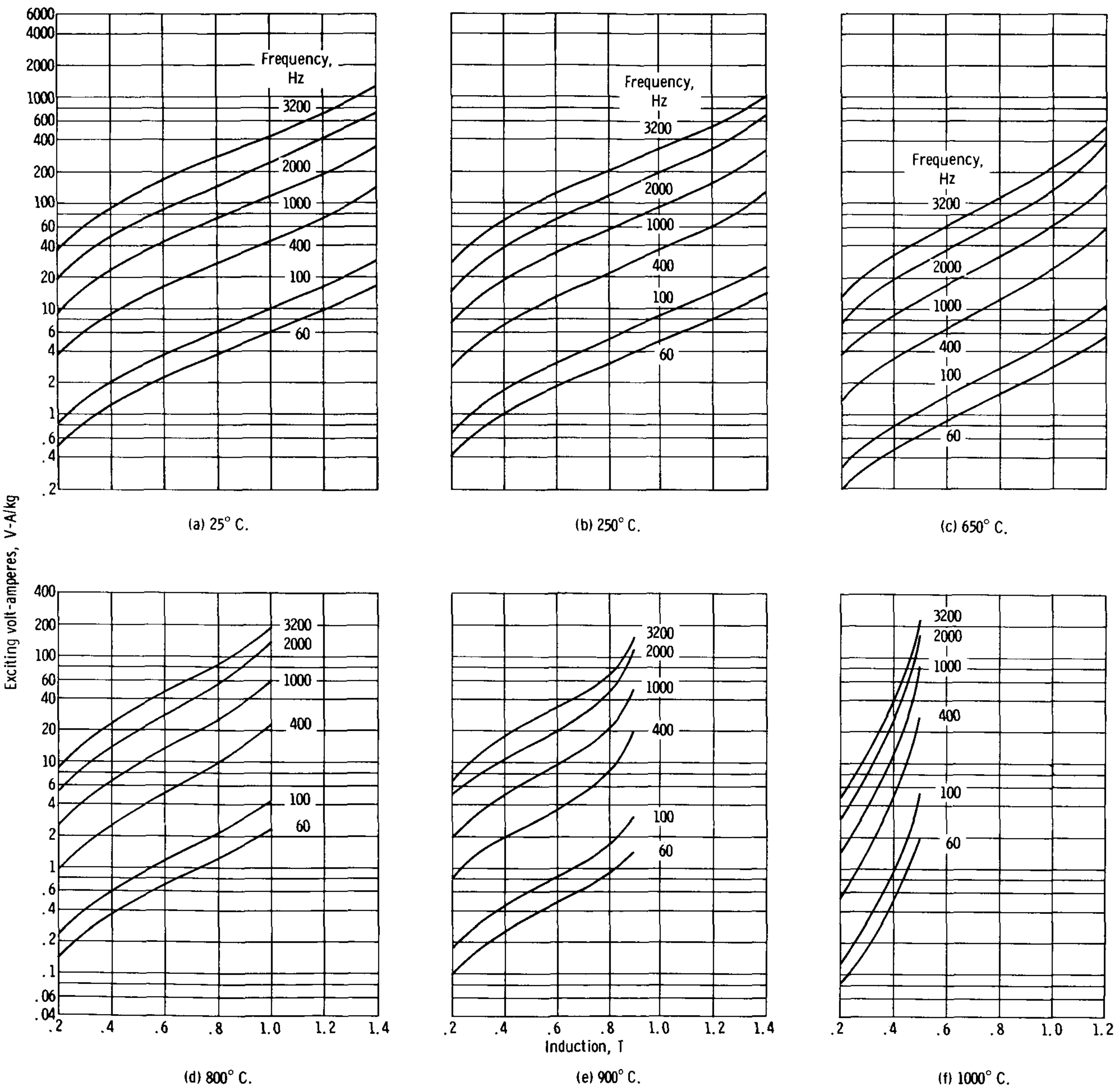
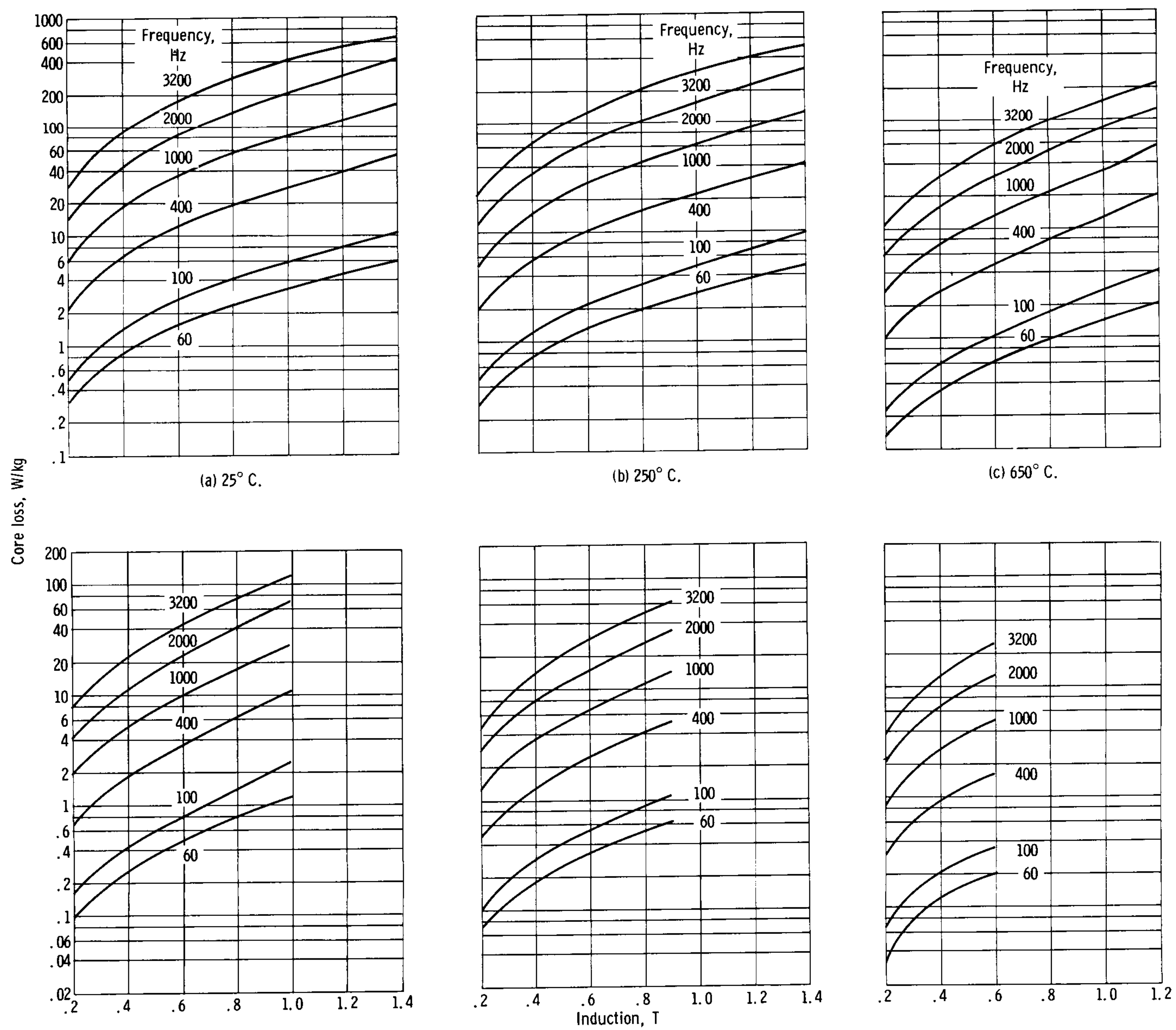


Figure 2. - Exciting volt amperes for 0.002 inch (0.005 cm) alloy.



(a) 25° C.

(b) 250° C.

(c) 650° C.

(d) 800° C.

(e) 900° C.

(f) 1000° C.

Figure 3. - Core loss for 0.004 inch (0.01 cm) alloy.

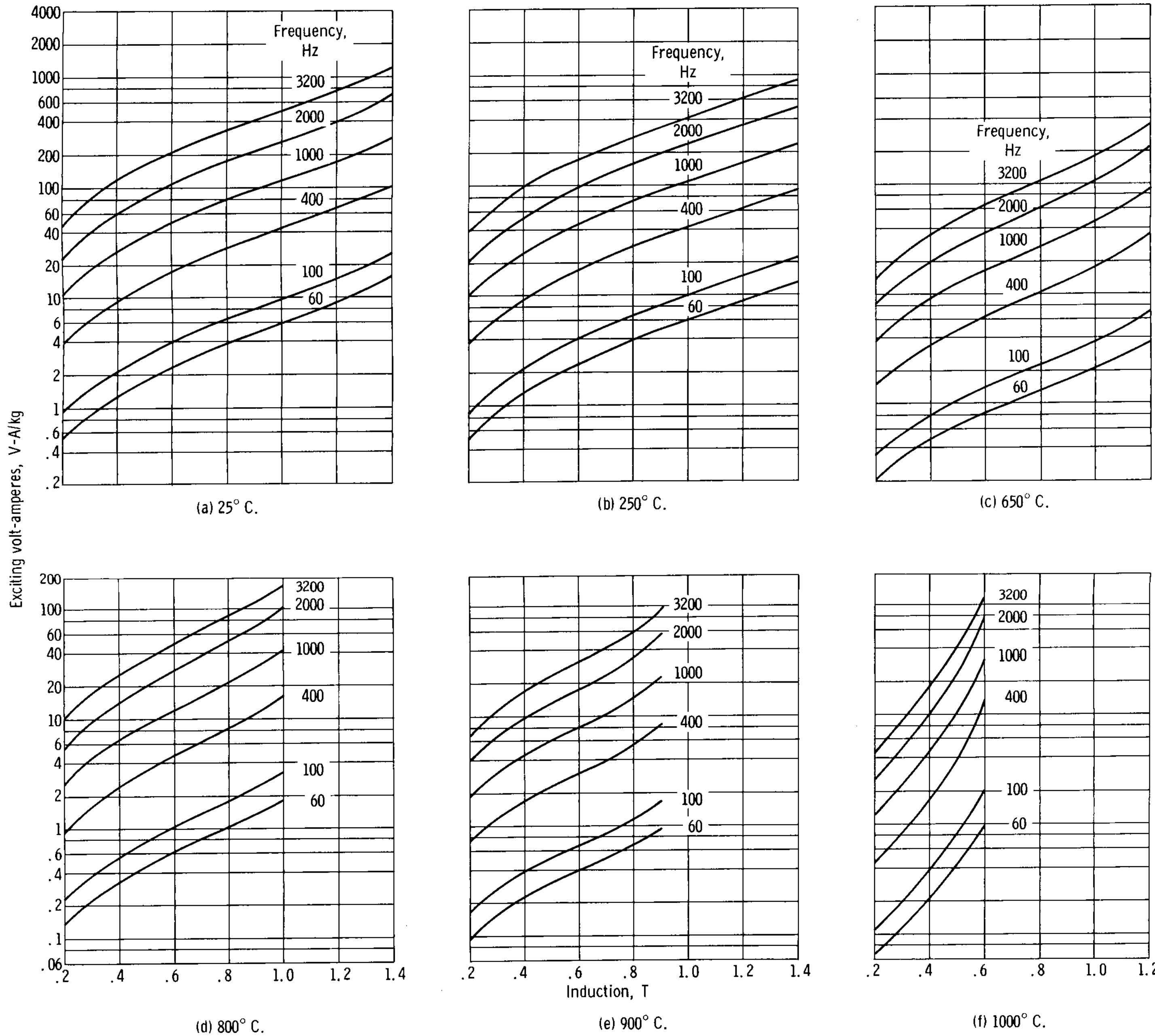


Figure 4. - Exciting volt-amperes for 0.004 inch (0.01 cm) alloy.

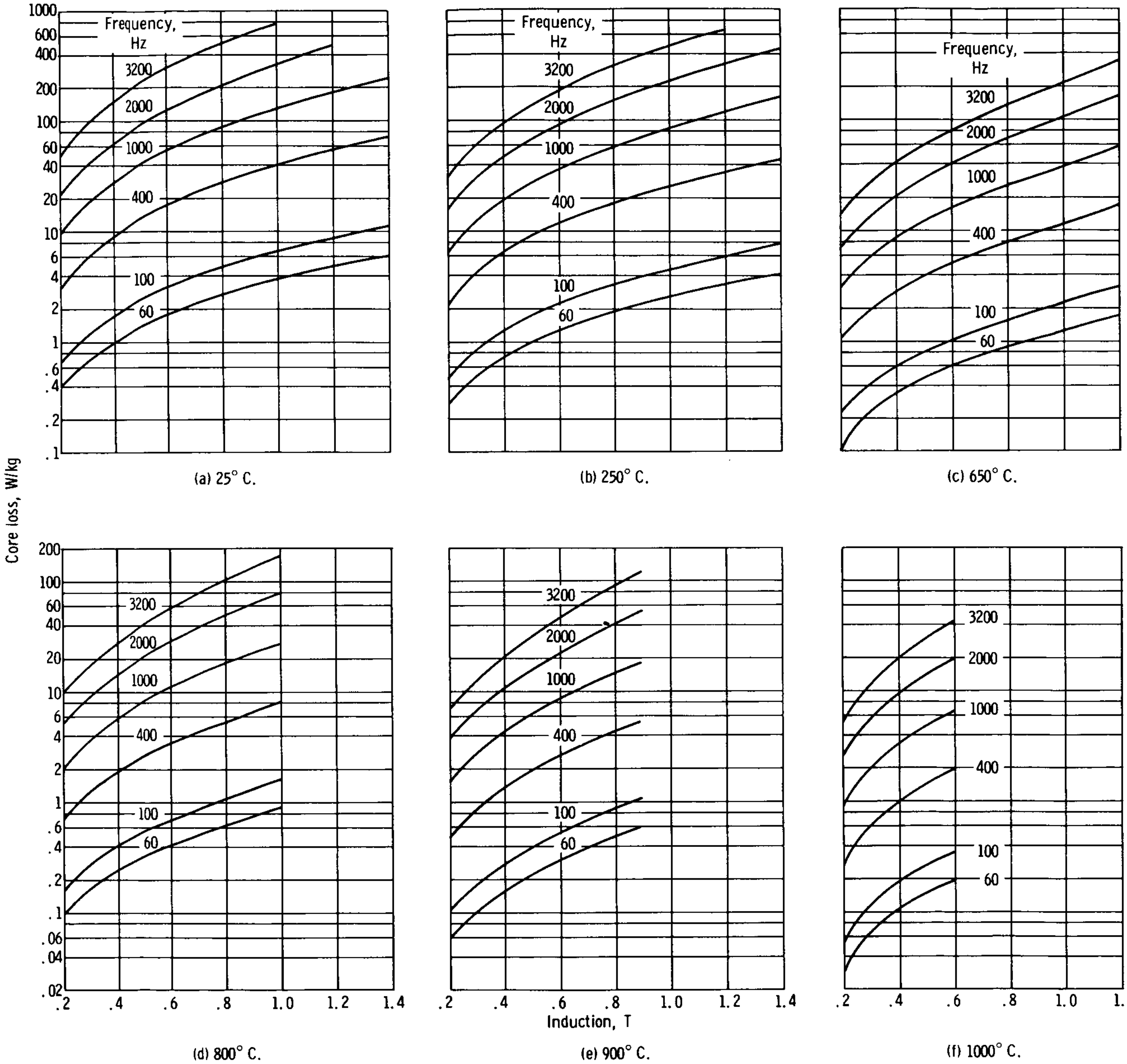


Figure 5. - Core loss for 0.008 inch (0.02 cm) alloy.

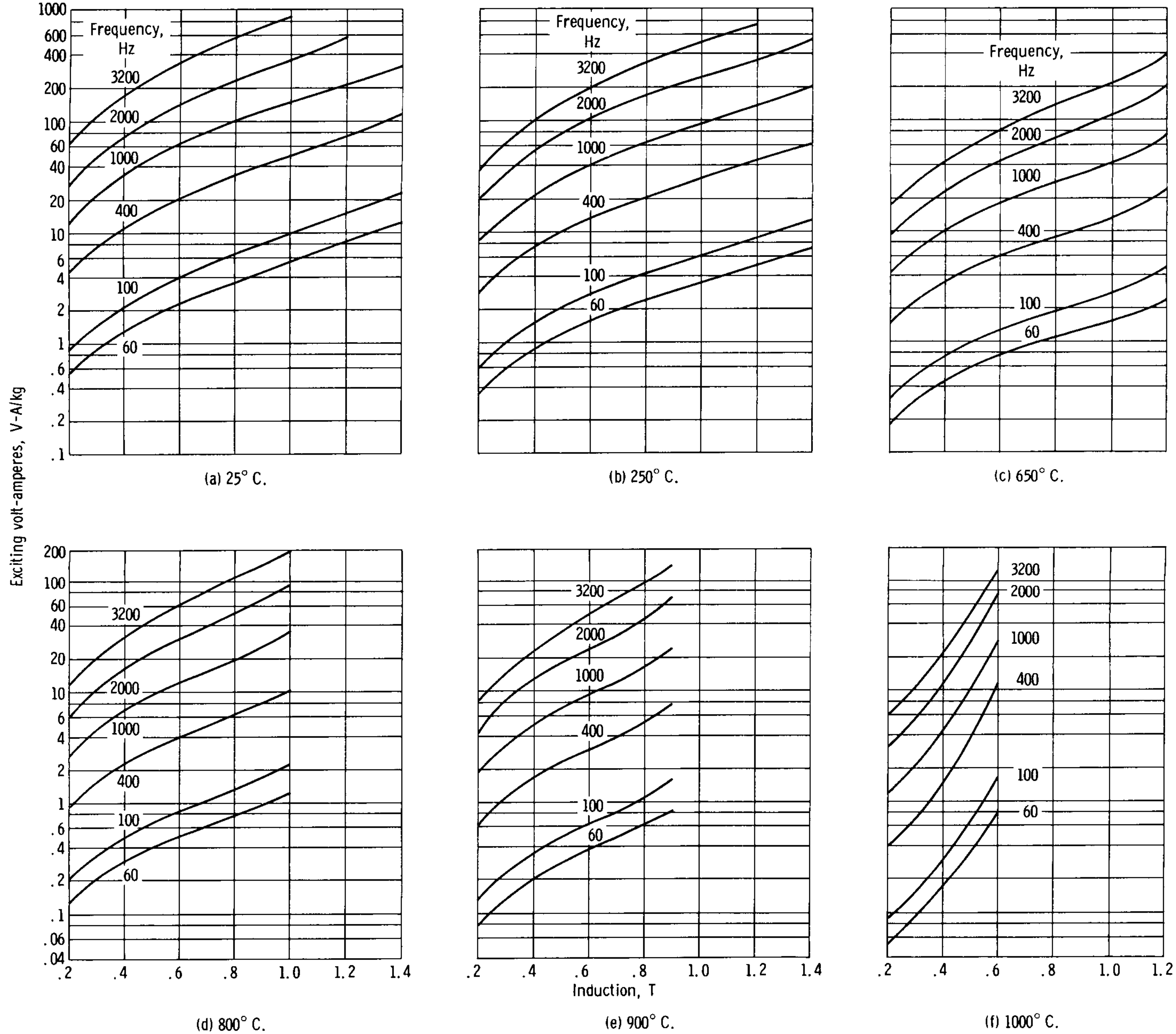


Figure 6. - Exciting volt-amperes for 0.008 inch (0.02 cm) alloy.

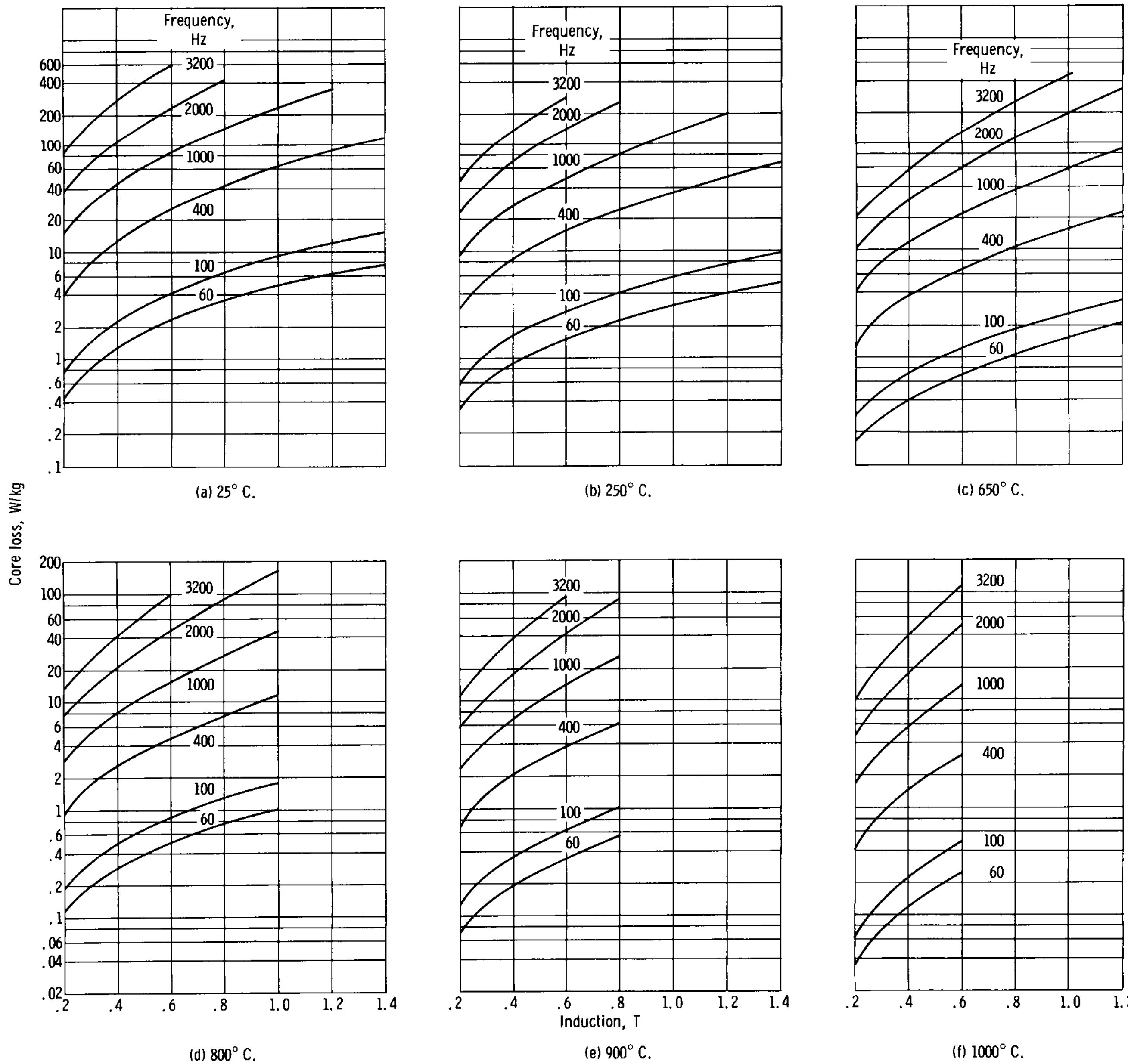


Figure 7. - Core loss for 0.012 inch (0.030 cm) alloy.

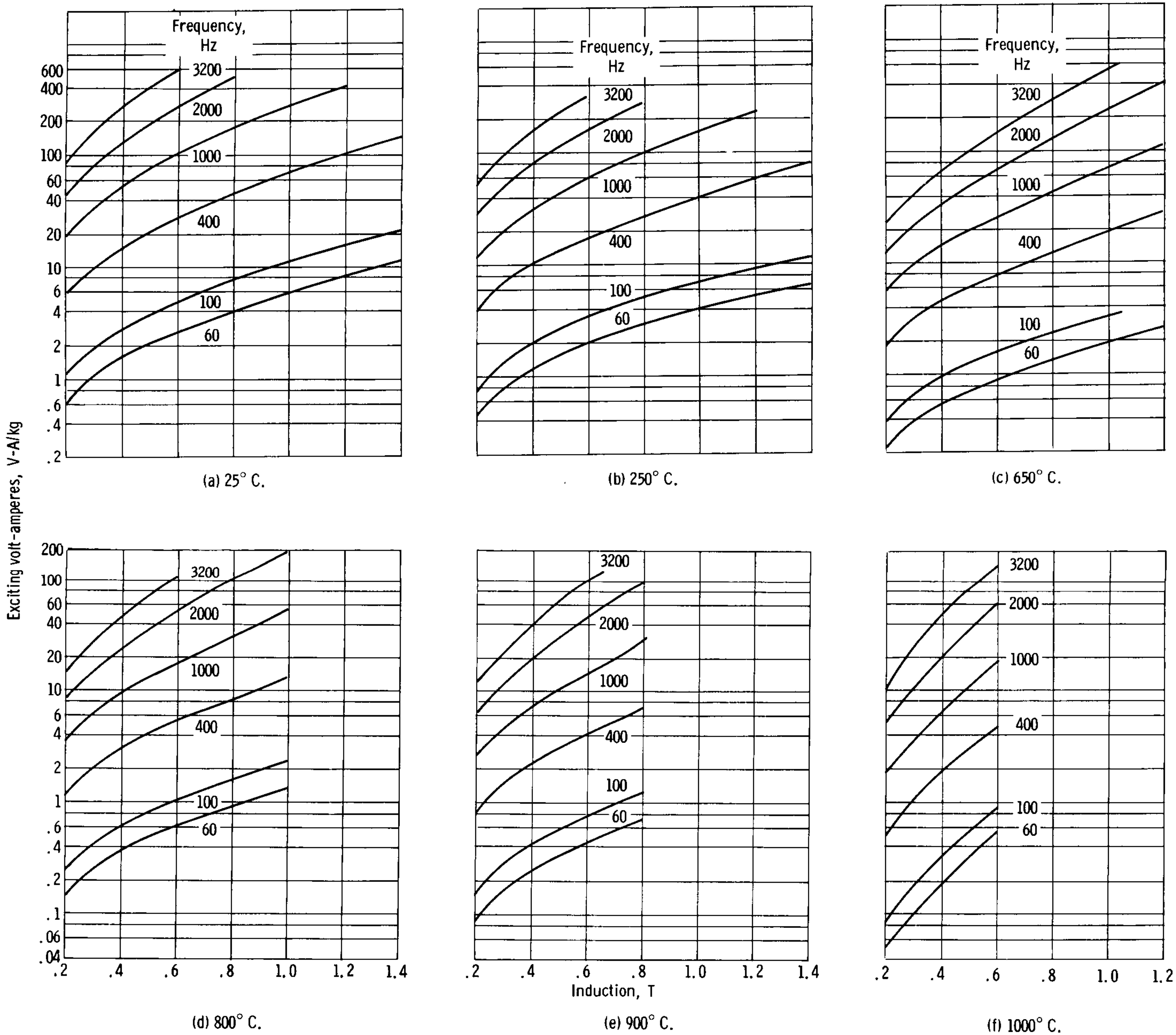


Figure 8. - Exciting volt-amperes for 0.012 inch (0.030 cm) alloy.

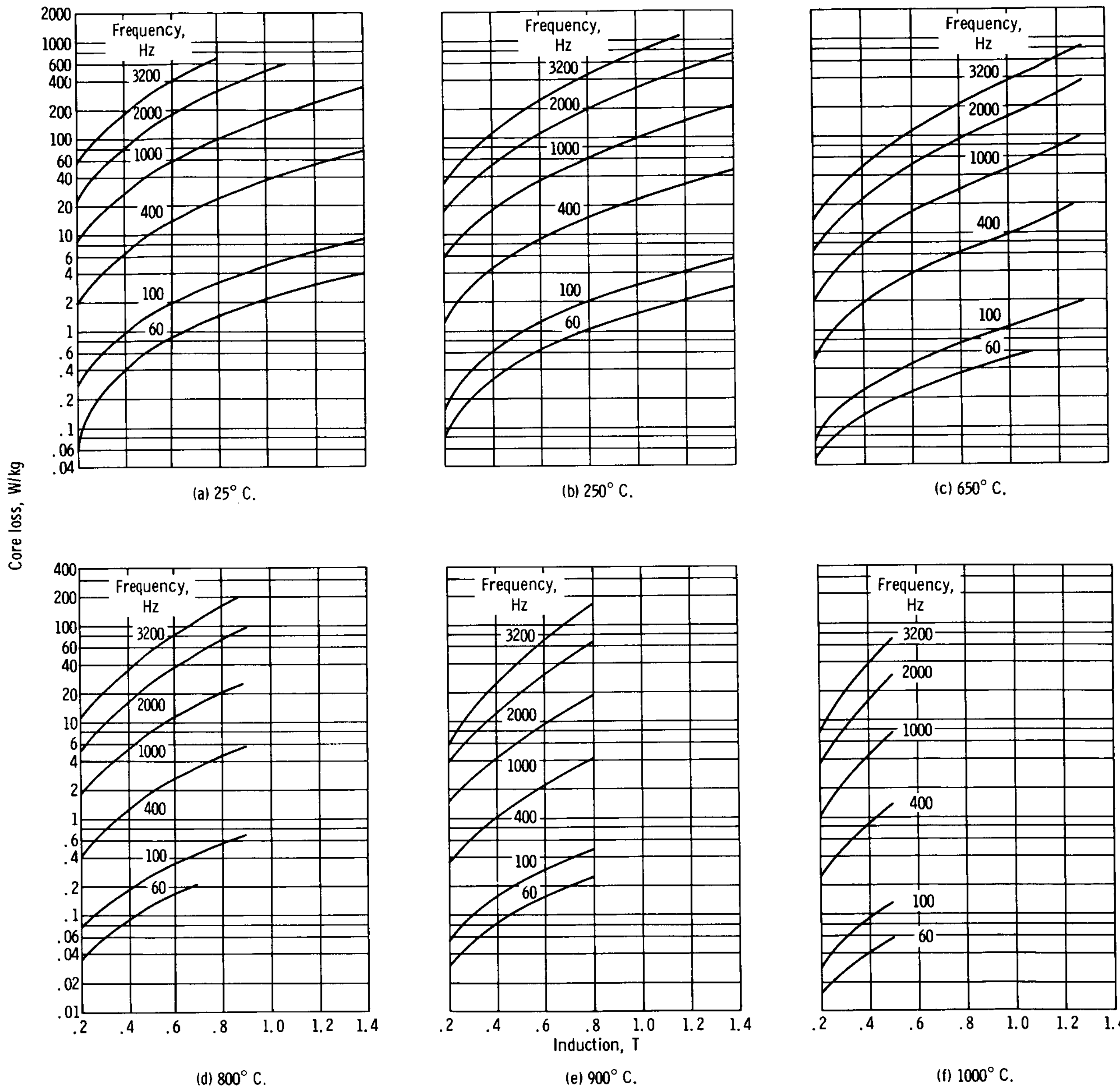


Figure 9. - Core loss for 0.012 inch (0.030 cm) alloy with tungsten.

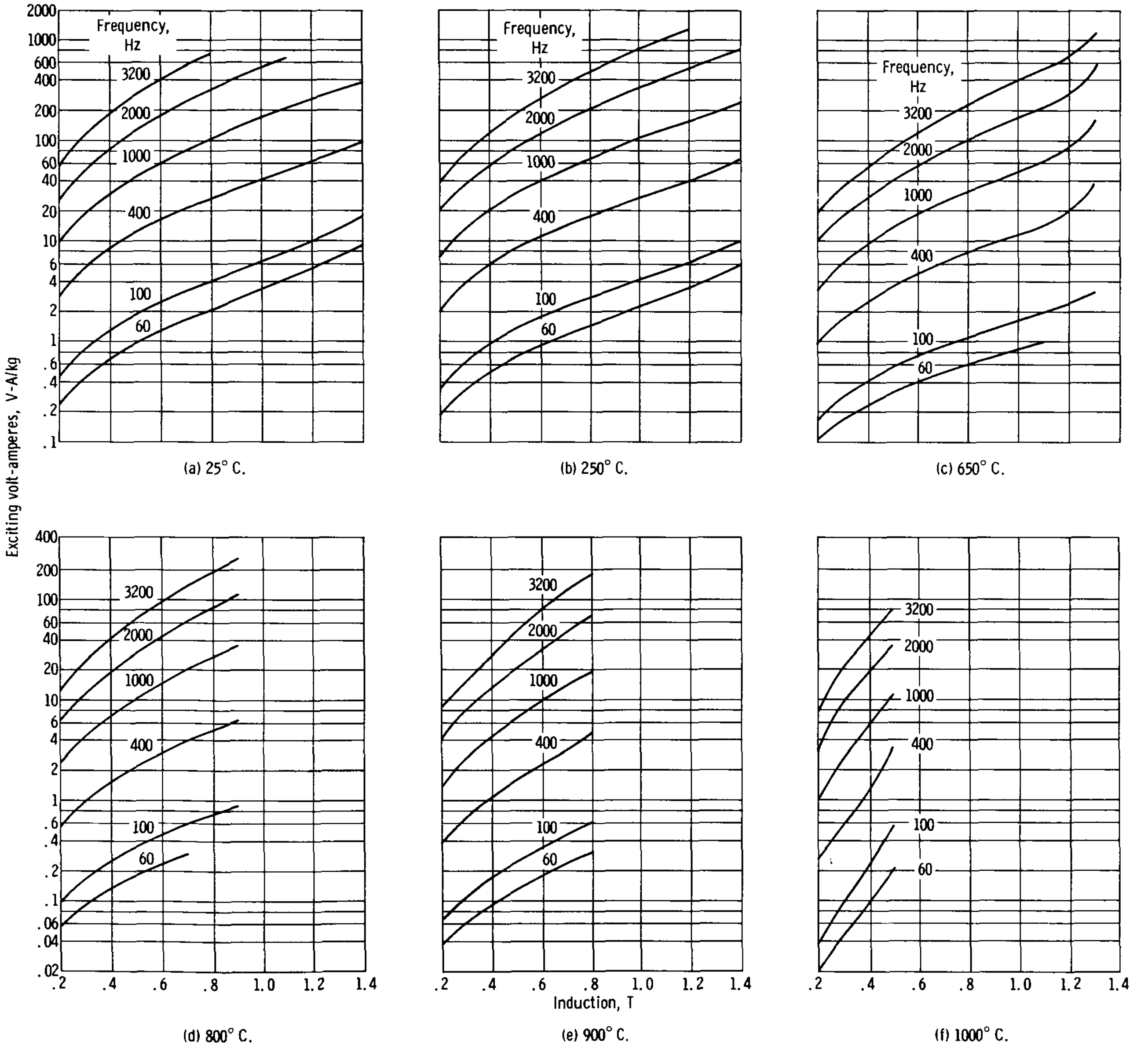


Figure 10. - Exciting volt-amperes for 0.012 inch (0.030 cm) alloy with tungsten.

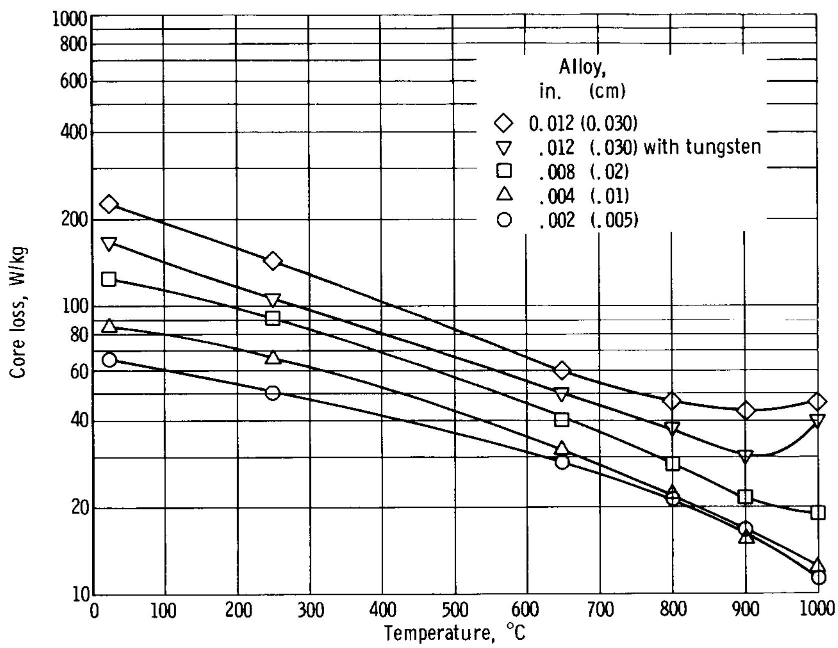


Figure 11. - Comparison of core losses for various thicknesses at an induction of 0.6 tesla and a frequency of 2000 hertz.

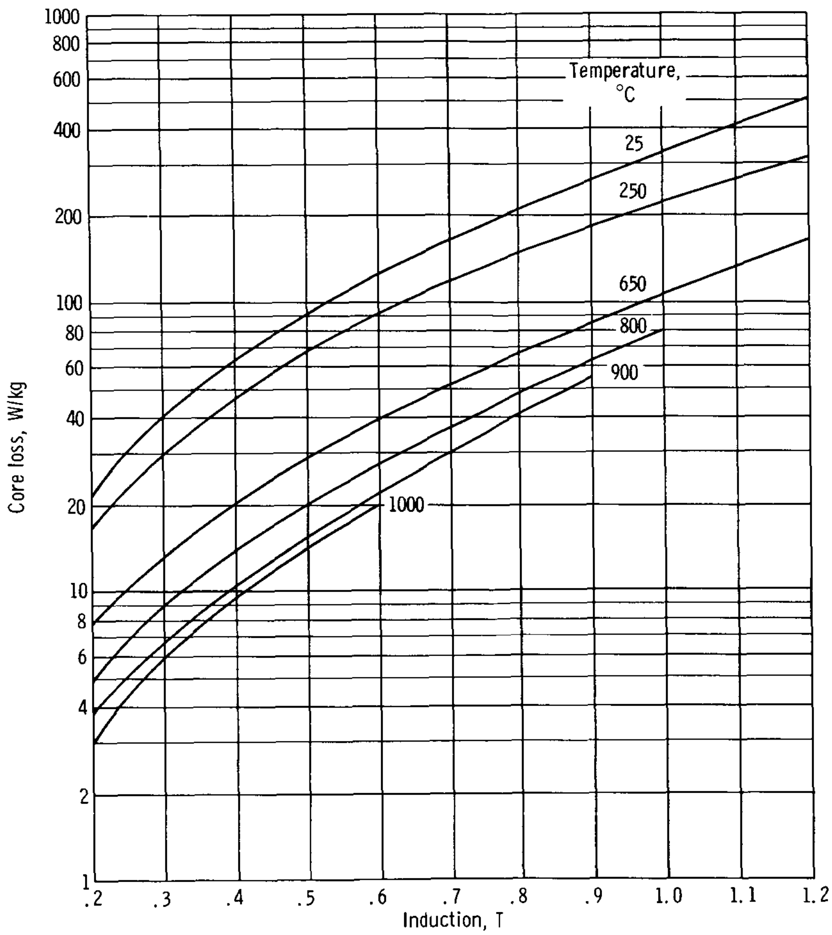
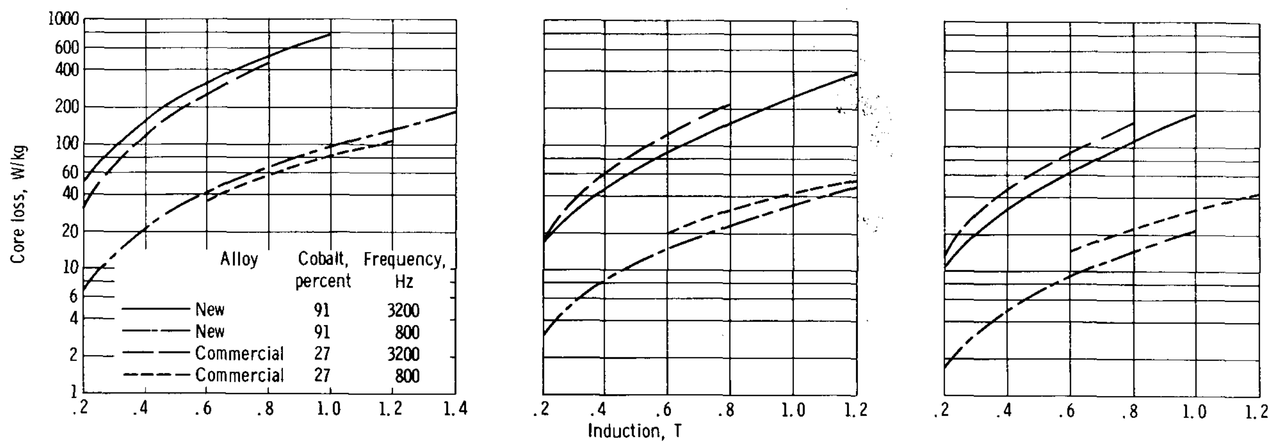


Figure 12. - Comparison of core losses for various temperatures at a frequency of 2000 hertz and 0.008 inch (0.02 cm) thickness.



(a) 25° C.

(b) 593° C.

(c) 760° C.

Figure 13. - Comparison of interpolated core losses for 0.008 inch (0.02 cm) alloys of 91 percent cobalt and commercial 27 percent cobalt.

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