length to diameter ratio is 2-4:1. For such cases, the low-frequency inductance of a single-layer coil enclosing a permeable core and having a filling factor of unity is given approximately by (15):

$$L = \frac{k\mu n^2 A}{\ell} \qquad (1)$$

where k is a constant, n is the number of turns per unit length, A is the cross-sectional area of the coil, and ℓ is its length. The thing of special interest to us in equation (1) is that L is directly proportional to μ.

For ferromagnetic samples, μ, and hence L, is a function of the magnetic field strength, H. This variation of L with H is related to the shape of the B-H hysteresis loop since the flux density, or magnetic induction, is given by $B = \mu H$. The relationship is shown graphically in Fig.10.

As a ferromagnetic sample is heated through the Curie point, its permeability changes from a large to a small and nearly constant value of about unity. The measured inductance thus exhibits a large drop followed by a flat response, and the transition should be sharp.

The experimental arrangement is similar to that for compressibility measurements. The current in the coil is adjusted for a suitable value of L. For work below about 200 C, the coil can be wound directly on the core. Above this temperature the formvar insulation on the copper wire fails, and the coil should be wound with bare wire on an insulating sleeve. This introduces a simple filling factor correction in equation (1), but this in no way influences the discussion here. Skin-depth effects are not considered because they do not influence the transition point.

To illustrate the response of the technique, data on two materials are presented. Fig.11 shows the inductance versus temperature curve of a 26-turn coil wound on a thin sleeve of pyrophyllite enclosing a nickel core. The Ni core (0.400 in. long x 0.250 in. dia) was machined from commercial rod and had an atmospheric Curie point of 340 C. The data were taken at 35 kbars and a frequency of 1 kc/sec. Temperature was measured with a Pt-Pt 13 pct Rh thermocouple, but no correction for pressure effect on emf was made. The transition is sharp and reversible.

Fig.12 shows the inductance of a coil enclosing a 70 pct Fe-30 pct Ni core as a function of ram pressure at room temperature. The alloy was prepared from commercial powders, and the experimental set-up was identical to that for Ni. Although the transition is not as sharp as in the case of Ni, it is, nevertheless, quite distinct. It is taken as the intersection of the straight line segments of the curve as indicated. The transition pressure is 27 kbars and is in good agreement with hydrostatic data obtained using different techniques (16). This corresponds to a decrease in the Curie point of ~5 deg C/kbar.

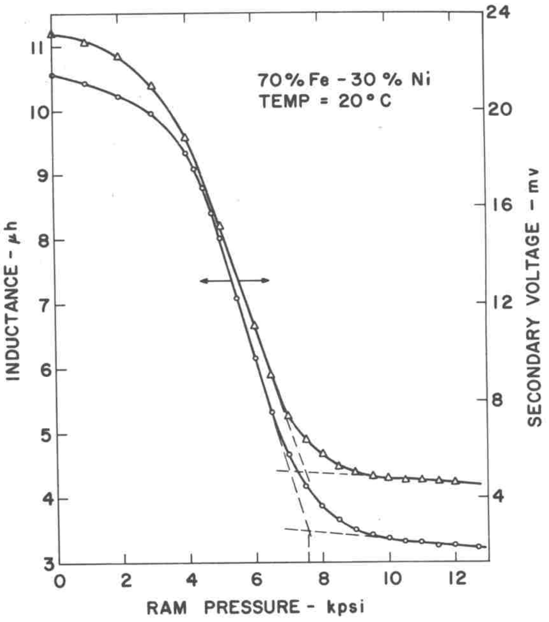

Fig. 12 Determination of the Curie point of a 70 percent Fe - 30 percent Ni alloy from inductance and secondary voltage versus ram pressure data. The two techniques give identical results. The transition pressure corresponds to 27 kbars

We have earlier used a different technique to measure the effect of pressure on the Curie point of ferromagnetic substances (10). This consists of winding two concentric coils (a primary and secondary) on the sample core. A small constant alternating current is passed through the primary coil and the induced voltage in the secondary is measured as a function of temperature and pressure. Patrick (17) used a similar method in earlier work using a hydrostatic apparatus. His sample was used as the core of a transformer. A typical example of our data on 70 pct Fe-30 pct Ni is shown in Fig.12. The shift of the Curie point is identical to that obtained using the inductive method.

The sensitivities of the single and double-coil techniques are about the same. The simplicity of the design and operation of the single coil, or inductive, method makes its usage advantageous. A further advantage, important from the standpoint of the pressure experiment, is the fact that only two electrical leads (or one coax) are needed.

Saturation Magnetization

The coil methods mentioned can be used for

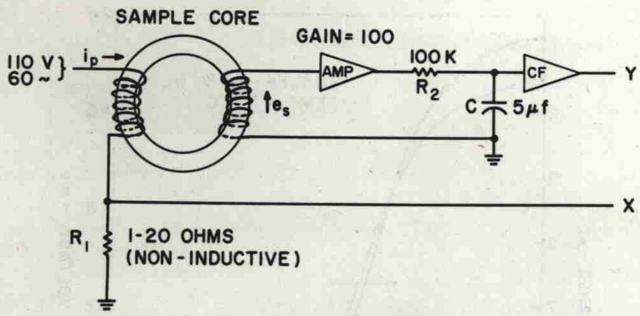

Fig. 13 Circuit diagram used for displaying ferromagnetic hysteresis loops on oscilloscope screen

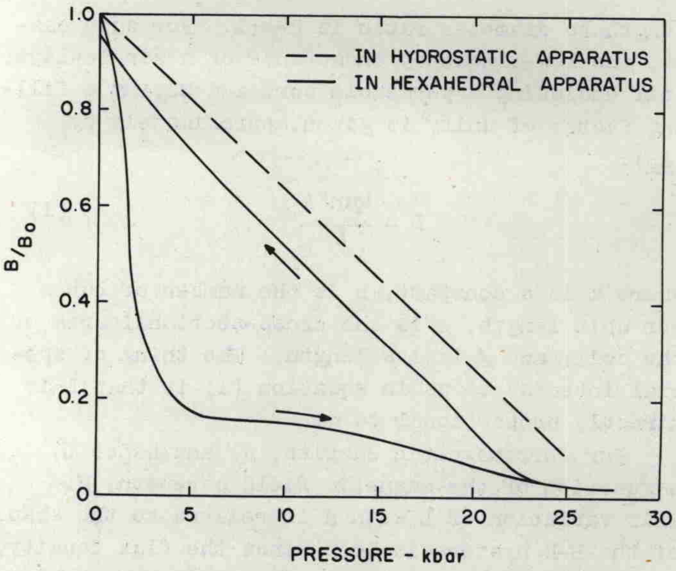

Fig. 14 Relative change in saturation magnetization versus pressure for 70 percent Fe - 30 percent Ni alloy at room temperature comparing results obtained in hydrostatic and hexahedral anvil apparatuses

studying the effects of pressure and temperature on the magnetization, or B-H, curve of a ferromagnetic material. However, precision measurements cannot be made on isolated open-ended rod specimens because of the nonuniformity of the magnetizing field along the length of the sample. A permeameter can be used to help produce a uniform field, but this complicates the design of the pressure experiment. Ring-shaped samples are the simplest, from the magnetic point of view, for use in studying magnetization curves. The field strength, H, is calculated directly from the exciting current in the primary winding, and, since there are no joints in the magnetic circuit, the flux density, B, is uniform at every point.[5]

By far, the simplest way to study the saturation magnetization of a sample is to obtain an oscilloscope display of the hysteresis loop. The circuitry for doing this is conventional and is shown in Fig.13. The excitation current in the primary, i_p (amp), establishes in the core a field given by:

$$H\ (\text{oersteds}) = \frac{0.4\pi N_p i_p}{\ell} \qquad (2)$$

where ℓ is the length of the flux path in the core (cm) and N_p is the number of turns in the primary winding. By applying to the X-axis of the scope the voltage drop e_x, produced by the current i_p in a noninductive resistor R_1, one obtains a horizontal deflection proportional to the instantaneous field intensity H.

The flux ϕ, in the core induces in the secondary winding a voltage e_s given by

$$e_s = -N_s\frac{d\phi}{dt} = -AN_s\frac{dB}{dt} \qquad (3)$$

where $\phi = BA$, A is the cross-sectional area of the core, and N_s the number of turns on the secondary winding. This voltage is amplified, integrated by the R_2C circuit, and applied to the Y-axis of the scope. By making $R_2 \gg 1/\omega C$, where ω is the radian frequency of the fundamental component of e_s, we have

$$e_Y = K\int\frac{e_s}{R_2C}dt = -\frac{KAN_sB}{R_2C} \qquad (4)$$

Hence we have a vertical deflection proportional to the instantaneous flux density B in the core, and the scope display will be a plot of B versus H.

The technique provides adequate sensitivity except when very small changes in magnetization are to be measured. In such cases, the same sample arrangement can be used with a standard ballistic galvanometer technique (18), and a point by point determination of the magnetization curve is made.

In the high-pressure experiment one is often limited by the size of sample and hence the number of turns and size of wire that can be used for the windings. The size of wire of course determines the amount of current that can be passed through the primary. For many materials, enough primary turns can be wound on a small sample to produce saturation fields without causing excessive heating of the wire. If higher fields are needed, an electronic gating circuit can be used to produce high current pulses for short duration. Such a circuit can be designed to supply the primary with a single cycle of current from the a-c line. Each

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[5] This is almost true for narrow rings; i.e., id and od not too different. For wide rings B will vary some in the radial direction.