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Abstract. The design of solenoids with inside radii of 4 or more cm and capable of producing alternating fields of a few thousand oersted is given. It is shown that, to produce such high fields, large wire sizes are required, the ohmic resistance being the main determining factor of the field attainable. A multi-layer solenoid (5.7 cm core radius) designed to produce fields of 3,800 oersted peak on an input of 230 volts is described. Practical considerations such as field uniformity, core sizes, heating problems, high voltages and methods of preventing anhysteretic remanent magnetization are discussed. The circuit, the semi-automatic operation and other details of an apparatus consisting principally of a solenoid, a tumbler and an induction coil are given. Several workers have extensively used the apparatus for rock magnetism studies.

Résumé. Les auteurs décrivent le concept de solénoïdes à rayons intérieurs de 4 cm ou plus, pouvant produire des champs alternatifs de quelques milliers d'oersteds. Ils démontrent que l'obtention de tels champs exige des fils d'un gros diamètre, la résistance ohmique étant le principal facteur déterminant du champ accessible. Ils analysent un solénoïde à couches multiples (rayons du noyau: 5.7 cm) conçu pour produire des champs maximaux de 3,800 oersteds sur une force de 230 volts et traitent de considérations pratiques comme l'uniformité du champ, la dimension des noyaux, des problèmes de température, de haute tension et des méthodes de prévention d'aimantation rémanente anhystérétique. Ils expliquent le circuit, le fonctionnement semi-automatique et autres détails d'un appareil constitué principalement d'un solénoïde, d'un interrupteur à bascule et d'une bobine d'induction. Dans l'étude du magnétisme des roches, plusieurs spécialistes ont beaucoup utilisé l'appareil.

Introduction

Alternating magnetic field (AF) demagnetizers are commonly used in rock magnetism to examine the coercive force spectrum of the natural remanent magnetization (NRM) of rock samples. The NRM is often composed of two or more magnetizations which may have been acquired by different magnetization processes at different times in the history of the rock. Magnetizations of different origins usually have different coercive force spectra and can often be separated by AF cleaning using the following procedure. The sample is subjected to AF of, say, $\widetilde{H} = 50$ oe which is then smoothly reduced to zero in the absence of a continuous (or unidirectional) field such as the earth's field. This effectively removes the magnetization of low coercivity i.e. the lower portion of the coercive force spectrum. By treatments in successively higher $\widetilde{H}$, it is then possible to analyze the coercive force spectrum (or spectra) and determine if one or more magnetizations are contained in the rock. Rimbert (1958) has shown that many different magnetizations, viscous remanent magnetization (VRM), isothermal remanent magnetization (IRM) and thermoremanent magnetization (TRM), for example, can be successfully separated by AF cleaning in fields of 1,000 oe or less.

When magnetite is the magnetic material, fields of 1,000 oe are adequate to cover all or most of the coercive force spectrum and therefore, a large portion of the AF work is done in fields of 0 to 1,000 oe. However there are rock samples (red beds, baked contacts of igneous rocks and hematitic igneous rocks for example) where the magnetization is little affected by such fields (Opdyke, 1961; Irving *et al.*, 1972; Roy and Fahrig, 1973) owing mainly to the high coercivity of hematite which is present in most sedimentary and many igneous rocks. There is then a requirement for solenoids capable of producing higher fields so that a larger portion of spectra of high coercive forces can be uncovered.

Design requirements

The AF demagnetization must be performed in the absence of any continuous field; otherwise, an anysteritic remanent magnetization (ARM) may be acquired (e.g. see Thellier et Rimbert, 1954, 1955). It is therefore desirable to annul the earth's magnetic field. Care must be taken that the AF solenoid and other components close to the rock sample are built of sufficiently non-magnetic materials. In some instances, higher harmonics in the alternating current may produce unwanted fields at the sample. These can be virtually eliminated by filtering (As, 1957).

Smooth reduction of the alternating field is important. Three methods can be used: 1) the sample may be taken out of the solenoid, 2) the solenoid may be pulled away from the sample, or 3) the field may be reduced. In the first method, care must be taken that the earth's field is well compensated over the travel path of the sample. In the third method, the field should be reduced by means of an induction type apparatus, rather than an autotransformer, for a continuous decrease. The disadvantage of the first and second methods over the third is that the current is applied at its maximum value for a longer time. For high fields where large currents are required, the heating problems would then be accentuated. Because of the close relation between heating and current (and consequently field) the third method is to be preferred.

Rotation of the sample about 2 or 3 axes during demagnetization may be used. To provide room for these rotating apparatuses (tumblers), it is usually necessary to design a solenoid with a radius larger than would be required otherwise; in such case, the current to attain a set field needs to be larger and more heat will be generated. On the other hand, demagnetization is provided in all specimen directions and a single run is equivalent to several runs on a stationary sample placed in different orientations. Thus the heating problems arising from the use of tumblers are not as momentous as they might appear. The rotating action also diminishes the effect of continuous fields.

Solenoid design

The field $\widetilde{H}$ oe at the centre of a single-layer solenoid can be calculated from

$$\widetilde{H} = \frac{4\pi NI}{2L\times10}\cos\alpha = \frac{4\pi nI}{10}\cos\alpha \qquad .....1$$

where I is in ampere, N is the total number of turns, n is the number of turns/cm length, L is the half length and $\alpha = \tan^{-1} r/L$ where r is the mean radius (Figure 1). $\widetilde{H}$, I and V (volts) are rms values. This formula is accurate for multi-layer solenoid calculations to within a few per cent and its simplicity warrants its use for calculating the approximate field of such solenoids.

Since $\widetilde{H}$ is proportional to I and

$$W = VI = R_t I^2 \qquad .....2$$

where W is the power in watts and R_t is the total resistance (ohms) of the solenoid including dielectric losses (Terman, 1943, pp. 84-85), much heat has to be dissipated and the method of cooling is of prime importance. Water-cooled solenoids handle larger currents while air-cooled solenoids are less cumbersome and simpler to construct. In this article, we are considering air-cooled solenoids and so, because of heating problems, we regard 20 amp as a practical upper limit. Also, because the solenoid must accommodate a tumbler, 4 cm for the inside radius (r_1, Figure 1) is considered a practical lower limit.

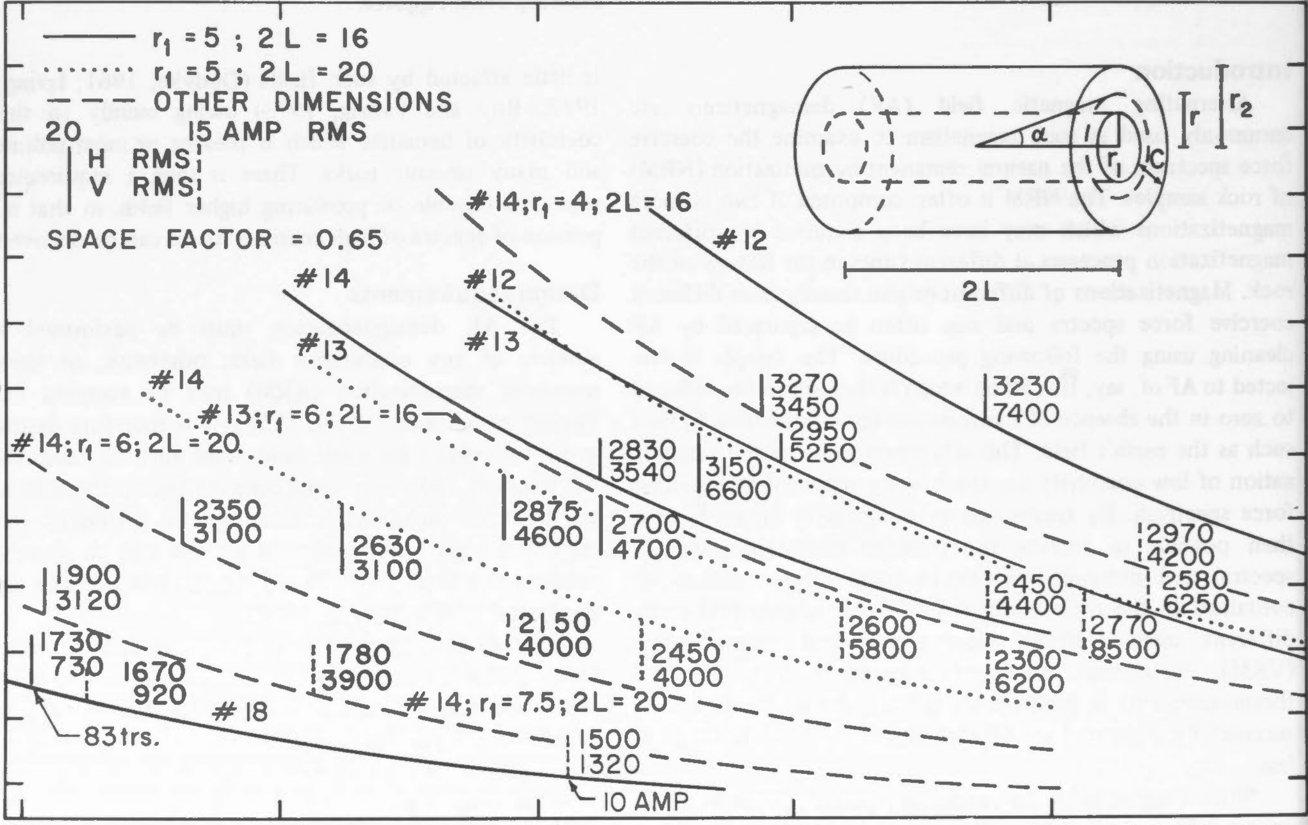

Figure 1. Curves of the ratio of the rms alternating field over total resistance of the solenoid for multi-layer solenoids of different inside radius (r_1) and length (2L) using different wire gauges (B+S). The vertical lines indicate the number of turns/cm that will let 20 or 15 amp. pass through the solenoid; the upper figure gives the alternating field H rms produced by that current; the lower figure gives the rms voltage across the solenoid for resonance tuning.

Uniformity of field

Before designing the solenoid, the uniformity of the field over the space occupied by the sample should be determined. Using formulae given by Gray 1921 (p. 222), the uniformity of the field near the centre and within a cubic space of side = 2.4 cm (comparable to the usual specimen size) has been calculated for different practical dimensions (Table I) of multi-layer solenoids. The departures of the field within that space from the field at the centre were larger axially than radially and the maximum departures calculated are given in Table I. It is evident that the uniformity of the field depends much more on the length of the solenoid than on the radius or the thickness of the windings i.e. more on L (compare Nos. 1,5,10 and 11) than on r (compare Nos. 5 and 7) or c (compare Nos. 3,4,5 and 6). Within reasonable limits, the length is almost exclusively the determining factor of uniformity and the table shows that if one chooses to build a solenoid 16 cm long, the field will be uniform to within 0.8 per cent.

Table I

[illegible]uniformity of field in a cube of side = 2.4 cm at the centre of a multi-layer solenoid. The maximum departures (from the value at the centre) shown are along the axis.

No	L	r_1	r	c	departure	mean cos
1	10	5	8	6	.0043	.7835
2	10	6	9	6	.0044	.7488
3	8	5	6.5	3	.0080	.7776
4	8	5	7	4	.0078	.7562
5	8	5	8	6	.0074	.7180
6	8	5	10	10	.0064	.6594
7	8	6	9	6	.0078	.6773
8	8	6.25	10	7	.0073	.6451
9	8	7.5	10.5	6	.0066	.6773
10	6	5	8	6	.0122	.6234
11	4	5	8	6	.0213	.4832

L, r_1, r and c in cm.

Maximum fields

The field $\widetilde{H}$ is proportional to cos α, n and I respectively (Equation 1). For given L and r_1,

$$\cos\alpha = \frac{L}{\left[L^2 + \left(r_1 + \frac{c}{2}\right)^2\right]^{1/2}} \qquad \ldots.3$$

can be increased only by reducing the thickness of the winding (c), that is by reducing either n or the wire size. A reduction of n is impractical since $\widetilde{H}$ would then be reduced (Equation 1). So a reduction of wire size as a means of increasing $\widetilde{H}$ should be investigated. Comparison of the

$$\text{means}\cos\alpha = \frac{L}{2}\left[\frac{1}{(r_1{}^2 + L^2)^{1/2}} + \frac{1}{(r_2{}^2 + L^2)^{1/2}}\right] \qquad \ldots.4$$

given in Table I shows that no drastic increases can be obtained by reducing the wire size. For example, comparing Nos. 3 and 5, the reduction of the space occupied by the wire (c from 6 to 3 cm) increases $\widetilde{H}$ by only 9 per cent. So, the variation of cos α is not an important factor in the determination of the maximum field attainable.

The following equations show that the remaining two factors – I and n – cannot be considered separately. Without tuning, the current that can be passed through a solenoid is

$$I = V/(X_L{}^2 + R_t{}^2)^{1/2} \qquad \ldots.5$$

where X_L is the inductive reactance. However the reactance can be made equal to zero by introducing in the circuit a capacitive reactance $X_C = X_L$ so that the current is effectively determined by

$$I = V/R_t \qquad \ldots.6$$

The resistance of the conductor is approximately

$$R_t = 4\pi n L\left(r_1 + \frac{c}{2}\right) R_c \qquad \ldots.7$$

where R_c is the resistance in ohm per cm of wire, so that

$$I = V/4\pi n L\left(r_1 + \frac{c}{2}\right) R_c \qquad \ldots.8$$

showing that n is inversely proportional to I. It is then evident that an appreciable increase of both n and I can be accomplished only by increasing V or reducing R_c. Practical considerations (availability of input voltage) and heating problems (Equation 2) limit the increase of V so that R_c must be given special consideration.

From equations 1 and 8, we get

$$\widetilde{H} = \frac{V\cos\alpha}{10L\left(r_1 + \frac{c}{2}\right) R_c} \qquad \ldots.9$$

showing that for a given input voltage, R_c and c remain the only (non negligible) variables and both depend on the wire gauge of the conductor.

The choice of wire gauge

When a solenoid is in operation, the temperature will vary causing the resistance to change. The variation of temperature will also affect the dielectric losses by modifying the distributed capacity between the different parts of the solenoid. Therefore, the resistance of the solenoid cannot be given a single value. However, in order to compare resistance and wire gauge, it is reasonable to assume that the variations will be approximately the same for all gauges. Hence, in subsequent calculations, R_c is considered a constant for a given gauge and is the resistance per unit length at 65°C which is taken as the upper operating temperature. The B and S (AWG) gauge system is used.

To design a solenoid capable of producing so many oersteds, the number of turns/cm is determined first. For example, to obtain 4,000 oe peak (2,830 oe rms)

$$n = \frac{10\ \tilde{H}}{4\pi\ I \cos\alpha} = 161\ \text{trs/cm} \qquad \ldots\ldots 10$$

taking I = 20 amp and cos α = 0.7 as a mean suggested from Table I. In order to admit 20 amp in the circuit, the wire gauge should be large enough (R_c small enough) to reduce R_t adequately (Equation 7).

The resistance R_t using different gauges has been calculated for different r_1 using Equation 7 and L = 8 cm; the results are given in Table II. The number of turns/cm^2 admissible for each gauge has been calculated using 0.65 as the space factor, which is the ratio of the space occupied by the bare conductor over the available space (cx2L). Such a table is useful to obtain a rough estimate of the required gauge. The thickness of insulation used and the method of winding the solenoid will affect the space factor. In general, it is relatively easy to improve upon the space factor used for compilation of Table II. However the use of the conservative space factor prevents the choosing of too small a gauge.

Table II

Resistance R_t in ohms using different wire sizes for a solenoid (length = 16 cms) of 161 trs/cm. The space factor = 0.65

				R_t when			
B+S	trs/cm^2	c	R_cX10^5	$r_1=7$	$r_1=6$	$r_1=5$	$r_1=4$
10	12.4	13.0	3.82	8.3	7.7	7.1	6.5
11	15.6	9.7	4.85	9.2	8.4	7.6	6.9
12	19.8	8.1	6.12	10.9	9.9	8.9	7.9
13	24.8	6.5	7.74	12.8	11.5	10.3	9.1
14	31.2	5.1	9.74	15.0	13.4	11.9	10.3
18	78.9	2.0	24.70	32.0	28.0	24.0	20.0

c = thickness of windings; r_1 = inside radius;
R_c = ohm/cm length.

If the input voltage is, say, 230V, R_t should be ≤ 11.5 ohms in order to admit 20 amp. Table II shows that if r_1 = 6 cm, No. 13 gauge should be chosen; No. 18 gauge, for example, would allow a current of 8.2 amp only. These observations show that great care should be given to the choosing of the wire gauge and it is evident that one should design a solenoid for maximum $\tilde{H}$/R rather than $\tilde{H}$/I as Equation 1 might lead one to believe. From Equations 1,3,6 and 7 we get

$$\frac{\tilde{H}}{R_t} = V/40\pi Ln\left[\left(r_1+\frac{c}{2}\right)^2+L^2\right]^{\frac{1}{2}}\left[\left(r_1+\frac{c}{2}\right)R_c\right]^2 \qquad \ldots\ldots 11$$

This ratio, taking V=230 volts, has been plotted against the number of turns/cm in Figure 1 for different gauges, r_1 and L. The number of turns which will allow 20 or 15 amp are shown on the individual curves by vertical lines; along these lines, the upper figure gives the rms field $\tilde{H}$ and the bottom figure the rms voltage V_c across the coil calculated from

$$V_c = (X_L{}^2 + R^2)^{\frac{1}{2}}\ I = [(2\pi fL)^2 + R^2]^{\frac{1}{2}}\ I \qquad \ldots\ldots 12$$

where f = 60 hertz.
The graph shows that the field increases with the wire diameter and that a required field (for given r_1 and L) can be reached only by choosing a wire not smaller than a certain gauge.

High voltage

The wire gauge, however, should not be larger than required because the voltage across the solenoid (Equation 12) will be larger than necessary. The solenoid inductance can be obtained from

$$L_x = \frac{rN^2}{2.54}\left[\frac{2F - 0.03193\,(0.693 + B_s)\ c}{2L}\right]\ \text{microhenries} \qquad \ldots\ldots 13$$

where F and B_s are factors given in Terman, 1943 (pp. 54 and 56) or to within 3 per cent (for the dimensions used in this paper) from

$$L_x = \frac{1.26\ \ (r\,L\,n)^2}{6\,r + 18\,L + 10c}\ \text{microhenries} \qquad \ldots\ldots 14$$

To reach a given $\tilde{H}$/R, an increase in wire size requires a large increase of n as shown in Figure 1. For example, between Nos. 12 and 13, $\tilde{H}$/R = 256 is reached for n = 188 and 162 respectively giving a ratio of 1.16. Since L_x is proportional to the square of n, the use of No. 12 instead of No. 13 will result in an increase of V_c of about 30 per cent. Unnecessary voltage increases should be avoided because of the added danger primarily; larger and/or more condensers will also be required.

Description of an AF demagnetizer

Field compensation. The earth's field and its diurnal variations are automatically compensated by a set of 3 orthogonal pairs of square (side = 244 cms) coils, which is part of an array of 5 identical sets (Roy *et al.*, 1969). Constant currents provide compensation for each component of the earth's field and a negative feedback system keeps the residual field at the centre of the coil system to within 2 γ. The field over the space occupied by the rock sample to be demagnetized is uniform to within 0.01 γ (Roy *et al.*, 1972). There are provisions for producing continuous fields for ARM experiments under controlled conditions.

Tumbler. The rock sample is rotated simultaneously about 3 axes. Primary rotation is provided by a fiberglass tube (Figure

2) which is rotated about an axis parallel to the solenoid axis (Figure 3). Its angular speed is 110 rpm and the speed ratios about the second and third axes are 0.954 and 0.896 respectively. The sample is inserted in a nylon holder (Figure 3; on the table) which fits into the opening of the inner cylinder. Except for a few brass screws on the tumbler support, the assembly is built of nonmetallic and very weakly magnetized materials – fiberglass, nylon, linen-base bakelite, and laminated beech. After machining, a component was not utilized unless the magnetic moment was so weak that the field produced at any part of the sample was less than 1 γ. Standard steel cutting tools were used but great care was taken to keep them clean at all times in order to avoid magnetic particles to become imbedded into the component. It was found that the likelihood of this occurring depends on the pliability of the material; hence greater care had to be taken with nylon than fiberglass. Cut-ins and rounding off of components provide for maximum rigidity of the assembly in the smallest possible space. The tube diameter is 9.5 cm but the bottom gear (Figure 2) describes a circle of 5.3 cm radius about the main axis. The inside radius of the solenoid is 5.7 cm leaving a clearance of 0.4 cm between solenoid and tumbler.

Solenoid. The No. 13 wire has a 'formel film' and a coat of thermosetting epoxy cement (Formset heavy insulation "H" synthetic from Canada Wire and Cable Company Ltd.). The rated maximum operating temperature is 105°C. After winding the solenoid on a form, it was heated to 200°C to set the epoxy cement. After removal on the form, 3 coats of airsetting epoxy and four strips of fiberglass were applied for additional strength. The advantages of a self-supporting over a form-supported solenoid are that the inside radius can be made smaller and that the cooling rate is faster. Particulars of the solenoid are given in Table III. Several banks of 4 microfarads (μf) condensers are used for the capacitive reactance as shown in Figure 4. The capacitance calculated from the rated value = 13.20 μf and from X_L = 13.07 μf. Fine tuning to within 0.002 of resonance was obtained experimentally by the least impedance method, i.e. by adding and removing condensers for maximum current for a fixed voltage. The condensers are rated at 2,500 V dc and 12.5 watt – second. The addition of 2 more layers of winding would, according to calculations and Figure 1, increase the maximum field (for 20 amp by 130 oe to 2,820 oe). However this would cause a large increase of 740 V to 4,800 V across the solenoid and the condenser banks.

The solenoid constant (Table III) has been calculated from the formula given by Gray, 1921 (p. 216)

$$\frac{\tilde{H}}{I} = \frac{4\pi L\, n \log}{10C} \left[\frac{r_2 + (r_2^2 + L^2)^{1/2}}{r_1 + (r_1^2 + L^2)^{1/2}} \right] \qquad \ldots\ldots 15$$

Operation. The circuit is given in Figure 4. The variac is set manually according to a chart giving variac setting vs. field. Upon switching the inductrol motor on, the field increases to the designated value where it remains after the automatic switch-off by means of a microswitch on the inductrol. The field is reduced in a like manner by manual start and automatic stop. The time of each operation can be adjusted from 15 sec to 8 min. The variac permits using the full range of the inductrol (max to min setting) even when demagnetizing in low fields. The switching on the 1 ampere meter automatically adds a 50-ohm resistance in series in the circuit. This effectively expands the variac range for more accurate setting for fields lower than 190 oe. The inductrol (Canadian General Electric) is wired so that its output/input voltage ratio is 2.0. It was found that the output-input coupling could not be reduced to zero. The ratio of the minimum and maximum couplings is 0.007; this means that if a specimen is demagnetized in a 3,000 oe field, the field remaining when the inductrol reaches its minimum coupling is about 21 oe. This field is then reduced by slowly lowering the variac setting to zero. The current and noise leaking through the variac and inductrol then corresponds to a field of 0.12 oe on high range setting and 0.03 oe on low range. The solenoid is thereafter slowly rolled away from the tumbler which at all times remains in the centre of the field compensating coils. For the time being, the maximum peak field must be limited to 3,000 oe; this limit is imposed by the capacity of the present inductrol which is rated at 2.5 kilowatts.

Table III

Particulars of the AF solenoid.	
Wires gauge B+S	13
Length (2L), cm	16
Inside radius (r_1), cm	5.7
Thickness of winding (C), cm	5.2
Turns (number of) (N)	2460.
Turns (number of/cm) (n)	153.8
Layers (number of)	30.
Space factor	0.78
Resistance (R at 65°C), ohm	9.94
Length of conductor, meter	1287.0
Mass, Kg	33.3
Current (I), ampere	20.0
Inductance (L_x), henry	0.54
Inductive reactance (X_L)*, ohm	203.
High voltage (V_c)*, volt	4060.
Field (maximum H rms)*, oe	2690.
Field (maximum H peak)*, oe	3800.
Capacitance (rated), μf	13.2
Capacitance (from X_L), μf	13.07
Constant H/I	
calculated (Equation 15), rms oe/Amp.	134.5
oerstedmeter (measured), rms oe/Amp.	135.1
gaussmeter (measured), rms oe/Amp.	133.4
average peak oe/Amp.	190.0

*calculated for I = 20 amperes.

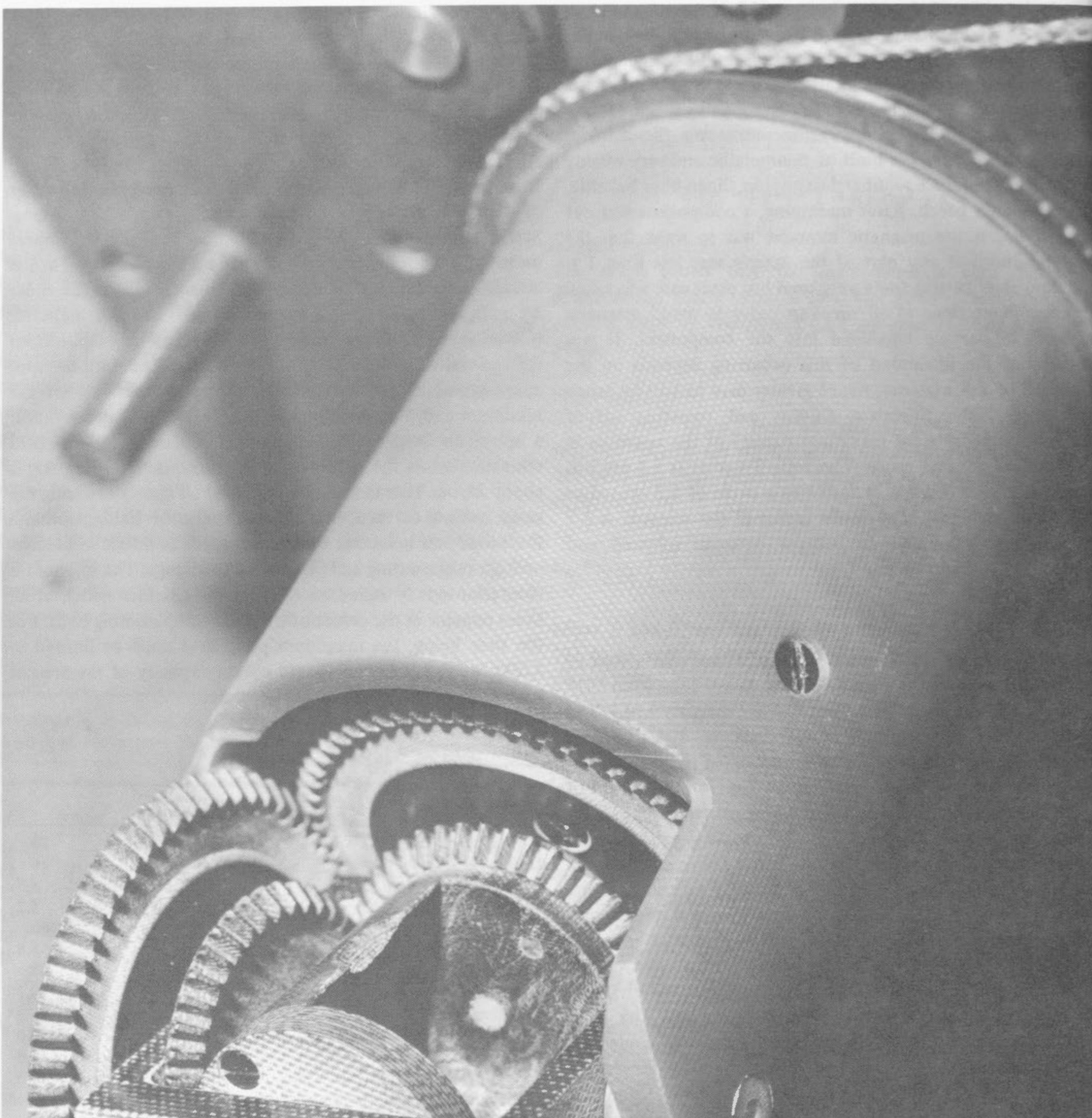

Figure 2. Rotating apparatus.

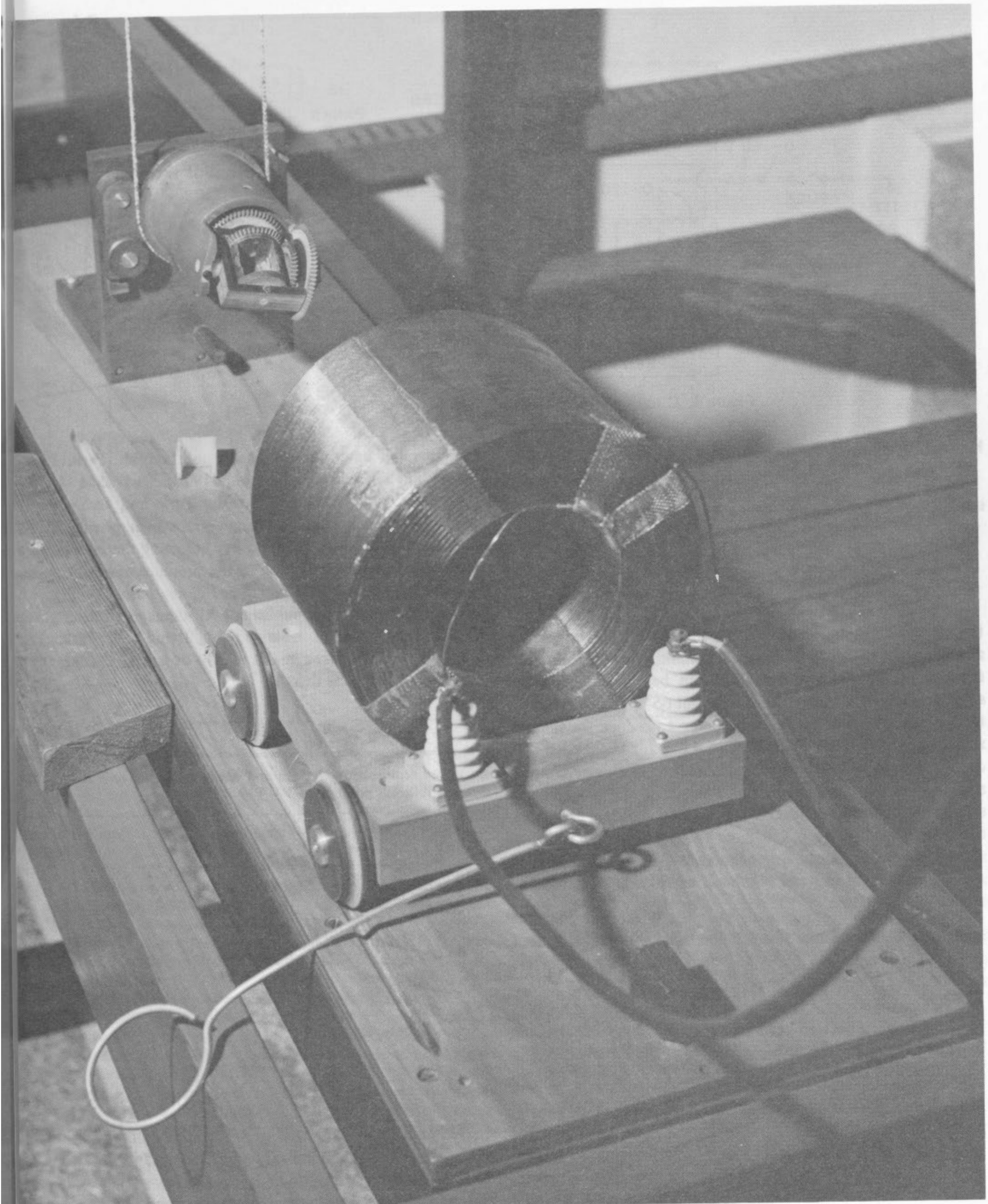

Figure 3. Solenoid on its trolley.

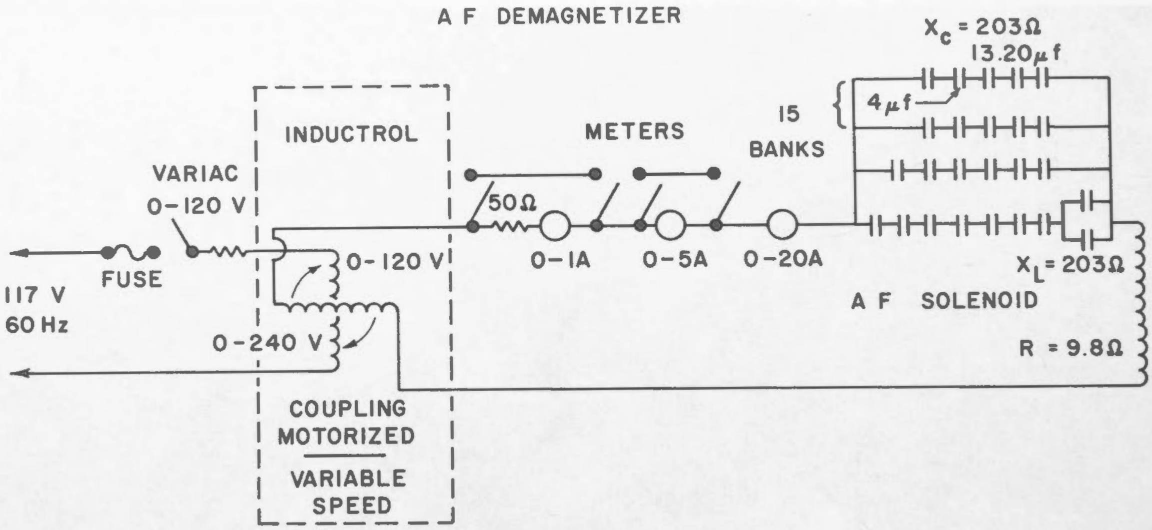

Figure 4. Circuit of the alternating field demagnetizing apparatus.

Heating. Using the following formulae

$$\text{temp. change } (^\circ\text{C}) = \frac{\text{Heat (in calories)}}{\text{mass (grams) x specific heat}} \qquad \ldots\ldots 16$$

$$\text{Heat (in calories)} = 0.24\ R_t\ I^2\ t(\text{sec}) \qquad \ldots\ldots 17$$

the increases in temperature of the solenoid can be calculated and are given in Table IV. The last column gives the estimated number of consecutive runs that can be made before the solenoid reaches a temperature of about 65°C. The increase in temperature depends on the time taken to reduce the field to zero (40 sec for $\tilde{\text{H}}$ peak $\leq$ 500 oe to 4 min for $\tilde{\text{H}}$ peak = 3,800 oe), on the pause between runs (time taken to change sample) and the continuous heat dissipation ($\simeq$ 70 watts when the solenoid temperature is at 65°C). In calculating these estimates, the rise time has been taken as 15 sec and the time at maximum field as 10 sec. Since few consecutive high-field runs are allowed, such runs can be mixed with lower field runs to increase cooling time.

Insulation. The thickness of insulation is 3.3 mils and the rated dielectric strength is 3,600 volts/mil. Since the dielectric strength is approximately inversely proportional to the square root of the thickness, the strength between 2 adjacent wires is 6,500 V. The greatest difference of voltage between 2 adjacent wires of the solenoid is at the end of 2 of the 30 layers and is 3800/15 = 253 V.

Performance. The apparatus has been in operation for over 4 years. During that time, approximately 30,000 demagnetizations have been made including a few hundred pilot or stepwise demagnetizations where progressively higher demagnetizing fields have been applied to the same sample. Numerous examples of AF demagnetization performed with the apparatus have already been published; see Park, 1970; Manzoni, 1970; Brooke *et al.*, 1970; Park and Irving, 1970; Roy and Fahrig, 1973. The Park and Irving paper shows the effectiveness of the apparatus in removing ARMs which were previously acquired by subjecting the samples to a 2,500 oe AF demagnetization in the presence of a continuous (no tumbling) 0.3 oe field (see their Figures 1 and 10). Figure 5 gives a more recent (unpublished) AF demagnetization curve of a baked sediment obtained by Irving and Park. The direction changes between 0 and 300 oe are 4° and between 300 and 3,000 oe less than 1°.

Table IV

Estimated temperature changes and demagnetization runs allowed for different applied currents.

I (amp.)	watts	temp increase °C /min*	number of runs allowed+
20	3950	18.5	2
15	2220	10.4	4
10	990	4.6	8
8	643	3.0	16
5	250	1.2	65
3	90	0.4	∞

*When corresponding current is continually applied and assuming that there is no heat dissipation.

+See text.

Acknowledgments

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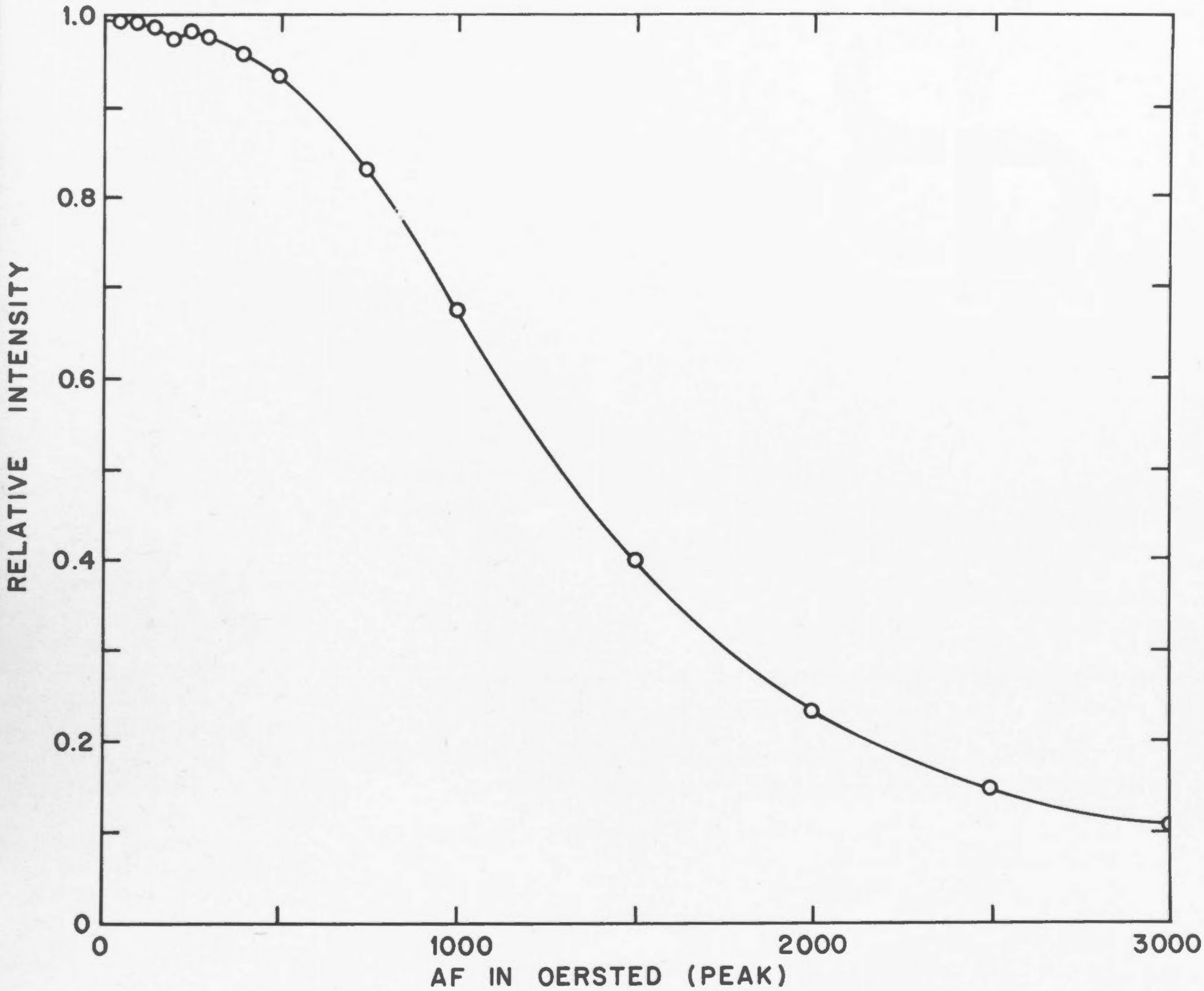

Figure 5. Alternating field demagnetization of a baked sediment (from Irving and Park).

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