

INSTRUMENTATION OF THE AUSTRALIAN NATIONAL UNIVERSITY 300 KILOGAUSS EXPERIMENTAL MAGNET

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December, 1969

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Research School of Physical Sciences

THE AUSTRALIAN NATIONAL UNIVERSITY

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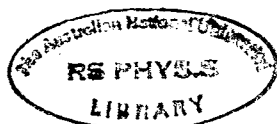
by

P. O. CARDEN and R. E. WHELAN

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SUMMARY

The basic features of the Australian National University magnet are described, introducing critical parameters intended to be measured.

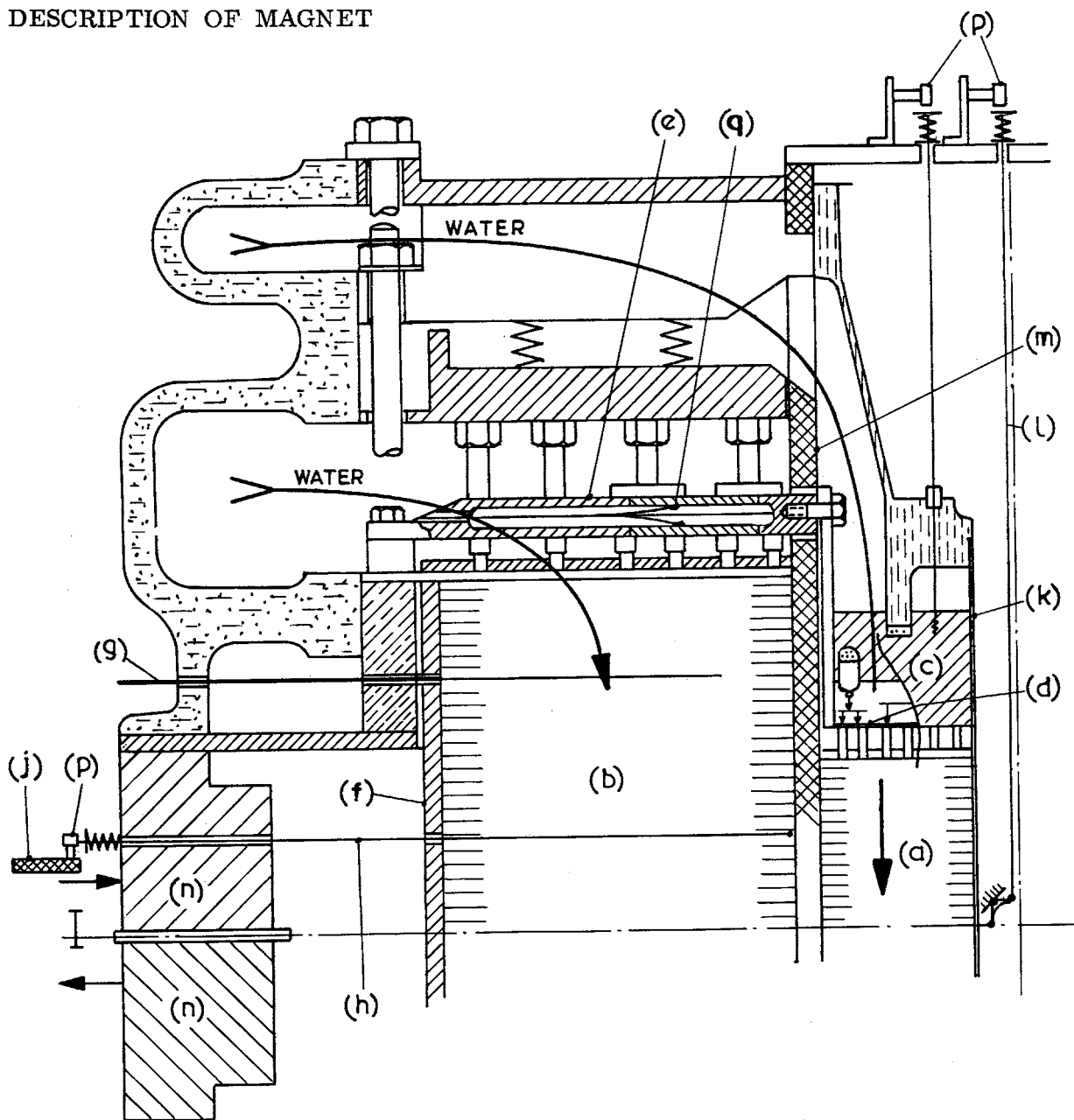
Description of the design and construction of instruments to indicate mechanical stress, temperature, pressure, relative motion, current and magnetic field, is given.

ACKNOWLEDGEMENTS

Chapter 5 is freely adapted from more complete information compiled by R. McMurtrie of the Magnet Laboratory Group, based on the work of the authors.

Figures 6 and 7 have been prepared by Mr. A. Collins, also of the group, from computed field data.

DESCRIPTION OF MAGNET



Section of Magnet

- | | | | |
|---|----------------------------|---|--------------------------------|
| a | Inner Coil | h | Displacement Wires, Outer Coil |
| b | Outer Coil | j | Reference Frame |
| c | Inner Terminating Assembly | k | Core Tube |
| d | Electrodes in (c) | l | Axial Molybdenum Transfer Wire |
| e | Resistors | m | Clamp Tube |
| f | Torsion Jacket | n | Current Distributing Rings |
| g | Thermocouple Probes | p | Bentley Gauges |
| | | q | Thermocouples in Resistors |

1. INTRODUCTION

In 1967 work began at the A.N.U. on the design of a 300 kilogauss experimental magnet. No other such device existed, so that new ground had to be broken in theory and technology before the project looked like culminating in the creation of a practical device.

This magnet should therefore be looked upon, not merely as a new more powerful research instrument to serve, in particular, the discipline of solid state physics, but also as a piece of engineering research in its own right.

This is certainly the attitude of its builders, and it is because of this that the provision of adequate instrumentation has been regarded as a most important aspect of the work.

2. DESCRIPTION OF MAGNET

The magnet, a section of which is shown opposite, consists essentially of two concentric coils, named inner and outer, connected electrically in parallel.

The outer coil is basically a homogeneous plane helix of 48 turns, the dimensions, field rating, power consumption and cooling requirements of which are listed in Table I. The construction is based on the Bitter principle⁽⁵⁾ of

TABLE I

	Inner Coil	Outer Coil	Total
Inside diameter	2.22 inch	10.5 inch	
Outside diameter	9.2 inch	26.8 inch	
Length	8.0 inch	16.25 inch	
Field Contribution	135 kilogauss	165 kilogauss	300 kilogauss
Power	4 MW	25.5 MW	29.5 MW
Cooling water	0.9 cubic ft/sec	6.5 cubic ft/sec	7.4 cubic ft/sec
Current	26.7 kA	168 kA	194.7 kA
Voltage	150 V	150 V	

interleaved split discs, but the principle has been developed well beyond previous practice and more is expected of the structure in terms of strength than has previously been the case. The expected stresses based on calculations derived after References 1 and 2 are graphed in Figure 1.

The inner coil is essentially a plane helix of 96 turns and is of consid-

erably different pitch from the outer coil. However it is not mechanically homogeneous, consisting in fact of eleven concentric sub-coils all of the same

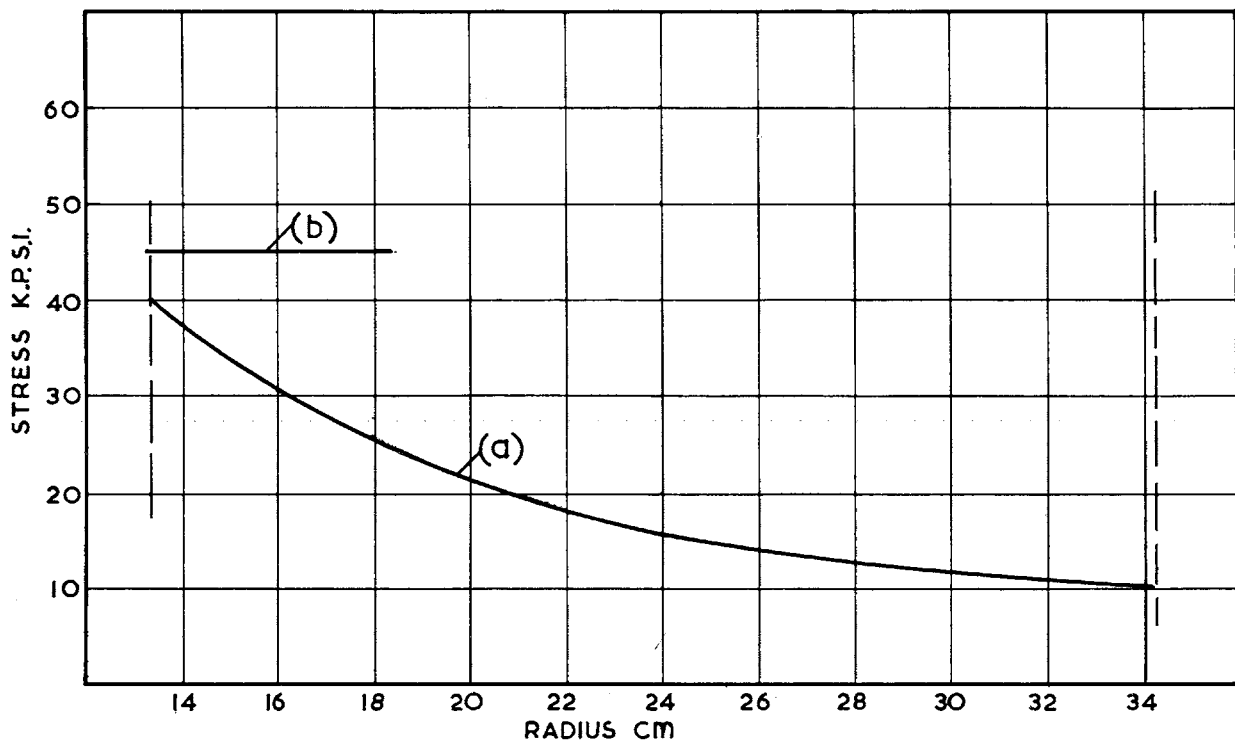


Figure 1. Stresses in outer coil. Material is .07% Ag-Cu hard temper.
 (a) expected azimuthal stress.
 (b) expected 0.1% proof stress.

pitch and electrically in parallel throughout the composite structure. The non-homogeneity of the inner coil is beneficial to azimuthal stress distribution which is expected to be as graphed in Figure 2. Main parameters are listed in Table I as for the outer coil.

Cooling of both coils is by means of axial water passages - punched holes in the discs of the outer coil, and milled slots on the outer surface of each of the sub-coils of the inner coil. With the design water flow and maximum field, temperatures in the outer coil are expected to be as shown in Figure 3 and those in the inner coil as in Figure 4.

Since the design of the magnet is based on new theory and innovations not previously verified experimentally, and since its safety depends on certain

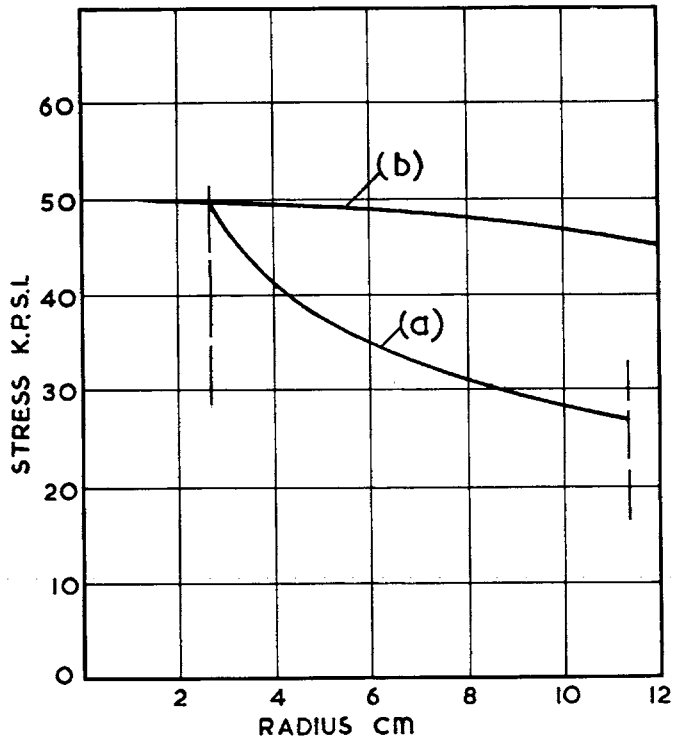


Figure 2. Stresses in inner coil. Material 0.25% Zr-Cu hard temper.
 (a) expected azimuthal stress.
 (b) expected 0.1% proof stress corrected for operating temperature.

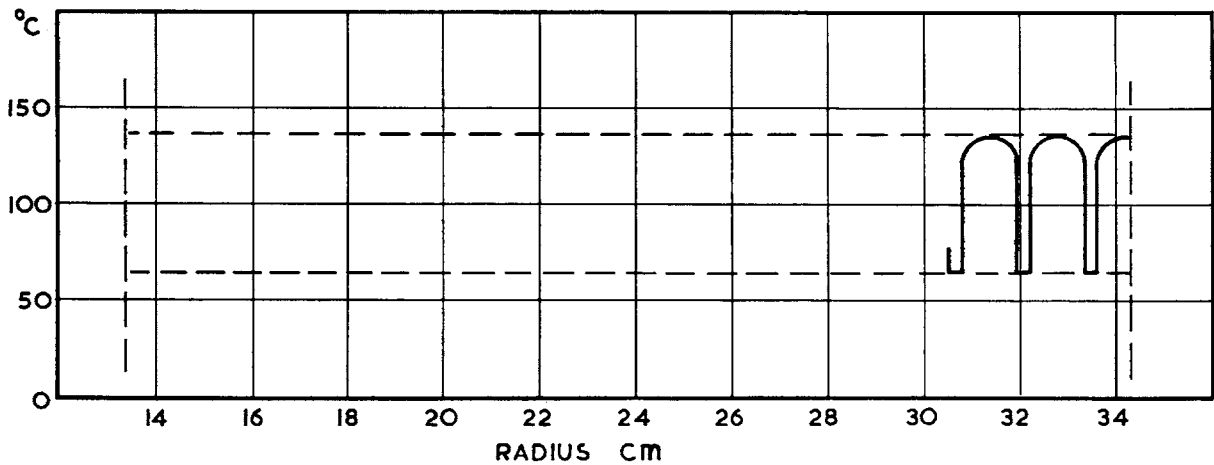


Figure 3. Temperature profile - through cooling holes, outer coil.

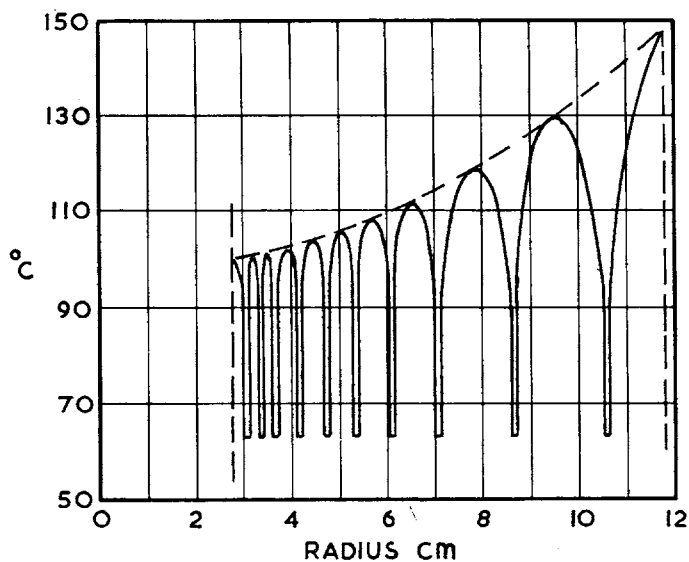


Figure 4 Temperature profile, inner coil.

critical parameters not exceeding known limits, it was considered desirable to incorporate adequate instrumentation into the magnet structure. Section 3 gives an account of the principal variables in the magnet and the practical means adopted for monitoring these variables. As will be seen, in some cases it was found impracticable to measure the desired variable directly, or in as many locations as one would like.

3. PRINCIPAL VARIABLES

3.1 Maximum magnetic field

Measurement of this variable is an obvious necessity and is readily accomplished by means of an inductive pick-up coil in the high field region of the magnet, coupled to an electronic integrator.

3.2 Voltage applied to magnet

This is monitored and usefully correlated with magnetic field.

3.3 Stress

Estimation of this variable, which is a function of position, is most important from the point of view of verifying theory, and for safety of the structure. However, the only stresses found possible to derive even approximately are the azimuthal stresses at both cylindrical surfaces of the outer coil and at the

inner surface of the inner coil. These may be derived from measurements of radial strain, using the fact that radial stress here is zero, making a reasonable assumption as to axial stress. The relevant relation is:(1,2)

$$t_{\theta} = Ee_{\theta} + \frac{1}{m} t_z$$

where t_{θ} and t_z are the azimuthal and axial tensile stresses respectively, e_{θ} is the azimuthal strain, equal to $\frac{\text{measured radial displacement}}{\text{radius}}$, and m is the reciprocal of Poissons ratio - approximately 3.3 .

The value of t_z assumed depends on other assumptions about the rigidity of the coil structure. Certainly a negative (compressive) component of t_z can be simply calculated from the known axial clamp force and the electromagnetic axial clamping force $j_{\theta} \times B_r$. There is, however, a tensile component which, for rigid long solenoids, approaches a limiting value given by the equation for $\frac{t_z}{p_m}$ in Reference 2 . The appropriate value for t_z calculated from this equation for the inner surface of the outer coil is approximately 5,500 p.s.i. which makes the maximum uncertainty in t_{θ} from this source of the order of 1,600 p.s.i.

3.4 Forces

There are many forces about which one would like to have knowledge, but few which one can measure. The inner coil is hydraulically clamped so that there is at hand a ready means of measuring the axial force on the inner coil from hydraulic pressures. Such information is useful in determining whether the inner coil is in the magnetic centre of the outer coil and in verifying the contact and clamping force applied to the inner coil.

The current distributing rings encircle the magnet and hence experience induced currents and radial forces either inwards or outwards. In passing, it should be explained that these currents are beneficial in so far as they allow the applied current to be distributed to points around the magnet which are essentially at equal potential. This is of prime importance especially for the inner coil where the flow of current in or out of the end turns has been carefully controlled to avoid large unbalanced forces. However, it is difficult to calculate the size of the circulating currents with accuracy, and it is prudent to monitor them as directly as possible. Since for the ring

$$E = j\rho \quad ,$$

where E is the induced electric field ,
 j the current density ,
 and ρ the resistivity of the ring copper ,

it is possible to derive j from a measurement of E . This is done by placing a single inductive measuring loop in a representative location on the ring surface. For a loop of length l and induced voltage v ,

$$E = \frac{v}{l}.$$

The location of the loop is important because the shape of the current distributing rings is such as to suggest that there will be considerable variation in current density. The loop therefore must be located in a region where the local induced current density might be expected to be about equal to the average current density in order that the results will lead to an estimate of total induced current and net force acting on the distributing system. The location was chosen after a computer study of fields produced by the magnet and by circulating currents in the rings.

3.5 Movement between adjustable parts

The inner coil may be moved axially by hydraulics. This ability is primarily due to the system chosen to apply axial force to the inner coil and allows adjustment of the position of the inner coil to the magnet centre of the outer coil which should enable minimisation of forces acting on it. Once the adjustment is possible, a means of monitoring must be incorporated. Such means also allows a check on axial deflection under load.

3.6 Temperatures

Together with stresses, temperatures constitute the most critical variables of the magnet because the strengths of materials used are a function of temperature. Temperatures are relatively easily measured by means of thermocouples but there is a problem of inductive pick-up in the signal leads to be investigated.

The strength most critically dependent on temperature is that of the glue bond of the inner coil. In Figure 5 is shown a graph of stress vs temperature upon which is drawn an envelope containing all points of the inner coil glue bond under all conditions of field strength up to the maximum. Also drawn is the experimentally determined strength of the composite bond developed for these coils. Clearly, a 10 or 20 degrees variation will have far more effect on the glue bond than on the strength of the metals employed. The hottest parts of each of the inner sub-coils - the top ends - are measured, using two thermocouples for each measurement to enable cross checking or to allow for a loss due to breakage during assembly of the magnet.

The outer coil is monitored by a number of fixed thermocouples and also by radially movable thermocouple probes operating in a number of slightly enlarged slits between discs of the outer coil.

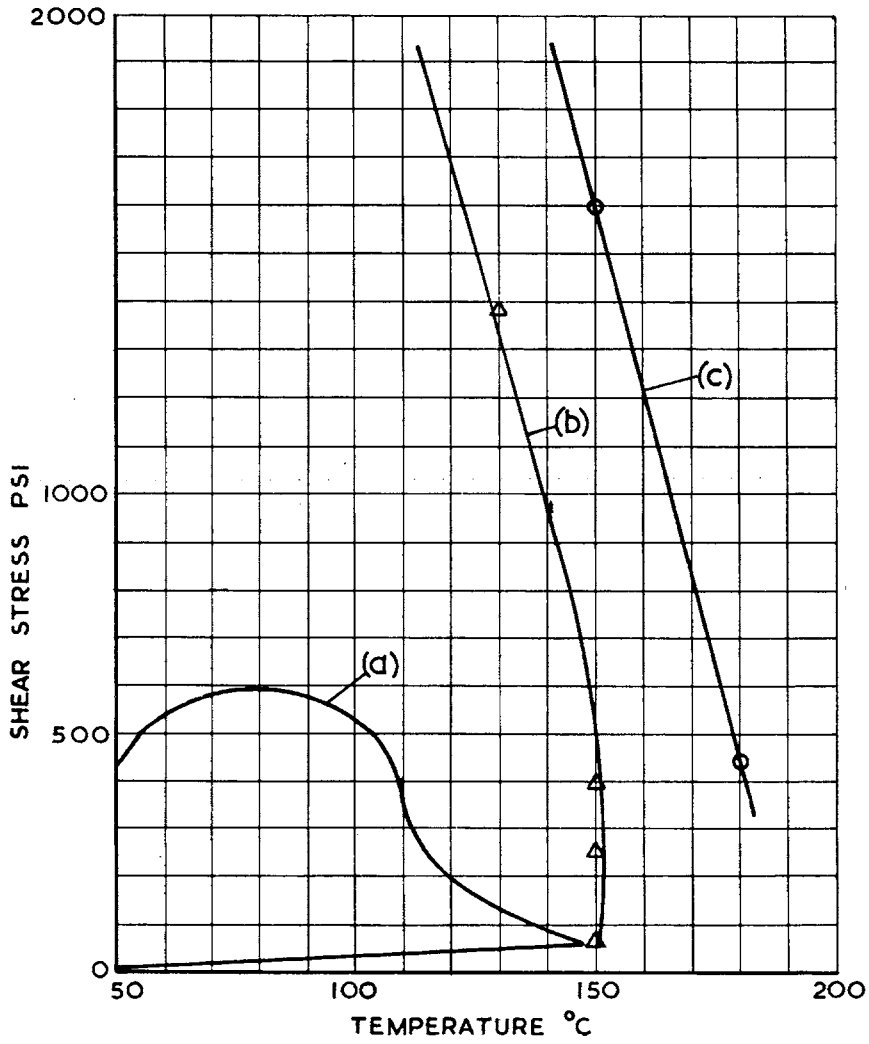


Figure 5. Inner coil glue shear stresses.

- (a) envelope for all parts of the coil under all conditions of energisation.
- (b) } two types of epoxy resin tested.
- and }
- (c) }

Certain special situations require monitoring where the cooling is rather complex. All such situations have been checked experimentally by model but there is always the possibility that the model was inadequate. The resistors feeding the inner coil are a case in point. They lie radially in the water space above and below the outer coil. The gross velocity of water here is zero at the inner end of the resistors, so one must turn to secondary effects such as turbulence caused by efflux from the outer coil channels or by natural convection. If these effects prove to be insufficient, it would be simple - but time consuming - to add circulating vanes. However, model experiments show that natural convection alone should be adequate, so it is easier to do nothing except monitor temperature (hoping, with good ground, that nothing extra will be required).

A similar situation occurs in relation to the copper distributing fingers feeding from the resistors to the ends of the inner sub-coils. Due to compactness, it was found impossible to provide direct cooling to all surfaces of these components, and one must rely on secondary effects. Again, model experiments indicate the secondary effects to be adequate, but it is prudent to monitor this area, nevertheless.

3.7 Current Distribution

A large part of the complexity of the magnet design has arisen because of the complex and potentially dangerous situation at the ends of the coils. In the body of the coils, equipotential surfaces are almost vertical planes across a turn, and perpendicular to the direction of j . Fortunately, in the body of a coil, forces are very favourably balanced. It is essential to preserve this state of affairs at the ends of the coil, and this can be done only by preserving the vertical equipotential surfaces as closely as possible. This is made possible by distributing current to the first turn uniformly around it in equal, discrete, and evenly spaced increments. Twelve distribution points are used for the inner coil and four for the outer.

Monitoring of this distribution is achieved by measuring appropriate resistive voltage drops. The resistors are the obvious measuring places for the inner coil. In the outer coil the end turns are four-start and a convenient check is the voltage drop across these four sections.

3.8 Magnetic Field Distribution

The relative contributions of the two coils to maximum magnetic field is important to know since both coils are designed near the limits of strength and it would be desirable therefore not to energise the combination to full field at the expense of overloading one coil. Known variations of conductivity from the specifications suggest that there will be small differences in the contributions of field from what was intended. On the other hand it may turn out that in practice one coil is stronger than expected (the strain may be less, or the cooling better than

anticipated) enabling the contributions to be optimised for maximum central field.

The field distribution may be checked by using an inductive loop around the outer coil in conjunction with the maximum field pick up coil. The ratio of these two measurements may be correlated with the theoretical steady state ratio of the two coil currents. Figure 6 shows the approximate theoretical correlation. These measurements should also give us an indication of the transient division of currents between the two coils.

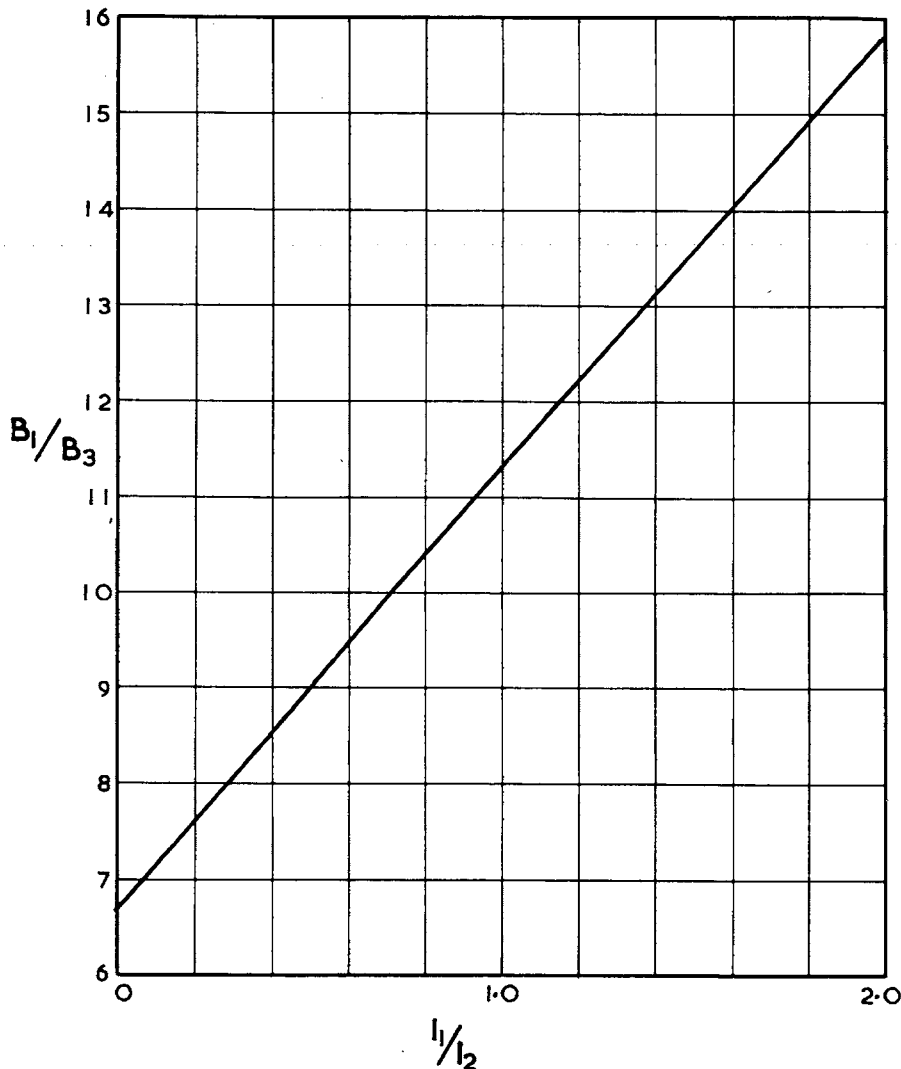


Figure 6. Theoretical relation between the average fields measured by two pick-up coils and the current distribution between the two magnet coils. B_1 is the average field in a pick-up coil in the middle of the magnet with diameter 5 cms. B_3 is the average in a coil 12 cms away from the median plane of the magnet with diameter 92 cms. I_1 and I_2 are the inner and outer currents, each normalised with respect to the design values.

3.9 Cooling Channel hydraulic characteristics

The heat transfer characteristics of the cooling channels depend on the flow velocity through the channels. The best way to monitor instantaneous water velocity is to establish the correlation between water velocity and pressure drop by a series of tests where water velocity is kept steady. The quantity of water flowing in a given time may be measured and hence the channel water velocity derived.

This correlation may be done for each of the coils separately and, once done, allows independent adjustment for each coil by means of the series valves provided.

The design pressure drop is 100 p. s. i. but large deviations are expected because of the small size of the cooling channels in relation to the manufacturing and assembly tolerances which were determined on practical and economic grounds. The hydraulic characteristics of the complex groove shape for the inner coils have been checked experimentally.

Pressures at the tops and bottoms of the coils are transferred by means of small pipes to transducers operating on the strain gauge principle.

4. THE MEASURING SYSTEMS - DESIGN CONSIDERATIONS

It is evident from the previous section that in many cases the principal variable cannot be measured directly, but must be derived from measurement of another more accessible variable. The distinction must therefore be made between "principal" variable and "measured" variable. All the principal variables discussed can be either measured directly, and therefore are themselves measured variables, or can be derived from a measured variable. Table II lists the principal variables and the associated types of measured variable. It will be seen that there are in all just four types of measured variable, and therefore four types of measuring system, which may be called

1. temperature
2. displacement
3. voltage
4. pressure

The design of these four systems will now be discussed.

TABLE II

Principal variable	Measured variable
maximum (central) magnetic field	voltage
magnet voltage	voltage
stress	displacement
force	pressure
	voltage
movement	displacement
temperature	temperature
current distribution	voltage
magnetic field distribution	voltage
cooling channel hydraulic characteristics	pressure

4.1 Temperature

All temperatures are measured by thermocouples using .003" or .008" diameter copper-constantan wires. The sensitivity of these thermocouples is only 4.2 m.V. per 100°C so that voltages induced in the signal leads and in the thermocouple itself must be kept quite small. Thermocouples located in or on conductors must have no contact with the conductor to avoid currents that might be flowing in the conductors also partially flowing in the thermocouple. Twisted copper-constantan pairs are used to carry the signal voltage through the varying magnetic environment. A carefully twisted pair of constant pitch p (distance between cross over points) and wire diameter d may be considered as a succession of positive and negative inductive loops of area pd (actually $\frac{2pd}{\pi}$) connected in series. Two adjacent loops will have fluxes Bpd and $-(B + \frac{dB}{ds} \cdot p)pd$ respectively,

where B is the field perpendicular to the direction of the wire and s is the distance along the wire. Hence the rate this flux is added to by successive pairs of loops is

$$\frac{d\phi}{ds} = - \frac{pd}{2} \frac{dB}{ds}$$

Integrating between points 1 and 2 on the twisted pair we have

$$\phi_2 - \phi_1 = - \frac{pd}{2} (B_2 - B_1)$$

This is correct provided an even number of loops lie between 1 and 2. If there is an odd number, then an extra flux component must be added equal to $-B_1 pd$ or $+B_2 pd$ depending on which end of the twisted pair the extra loop is considered to be added. The two cases are of course similar, except that one case is equivalent to the wire being twisted 180° throughout, compared with the other.

Adding the extra flux component for the odd loop case, we find

$$\phi_2 - \phi_1 = \pm \frac{pd}{2} (B_1 + B_2)$$

so that the general case may be written

$$\phi_2 - \phi_1 = \pm \frac{pd}{2} (B_1 \pm B_2)$$

The induced voltage in a twisted pair cannot therefore be greater than that induced in a single loop of that twisted pair placed in the maximum field through which it is routed.

If $p = 1$ cm, $d = 0.07$ m.m. and $\frac{dB}{dt}$ as high as 300 kilogauss per second, the induced voltage will not be greater than $\frac{1}{60}$ m. volt, equivalent to about $\frac{1}{2}^\circ\text{C}$.

4.2 Displacement

Measurement of displacement is centred around a commercial device - a Bentley Proximator. It operates on the principle that the close proximity of a metal surface to a high frequency coil alters the coil's tuning characteristic. It has been verified experimentally that steady fields of a few thousand gauss have no effect on the proximator's calibration, but it is uncertain what effect higher fields, of the order of a hundred thousand gauss, may have, especially on the inbuilt solid state electronics. This, together with the size of the proximator ($\frac{1}{4}$ " diameter x 1" long) makes it desirable to locate it well outside the structure.

The real problem with displacement measurement is then in the transfer from the point of interest within the magnet structure to the proximator. The displacement of the inner surface of the outer coil, for example, needs to be transferred through a temperature and field environment varying in time and space. Fortunately the slits between discs provide an ideal radial channel which can be made to accommodate a transfer wire of up to 0.020 inch diameter. Invar wire, 36%

Ni-Fe with a temperature coefficient of expansion of only 0.8×10^{-6} , (Reference 3) has been used under a known tension, to nullify the effects of the temperature environment, but unfortunately invar is magnetic. This property has two general effects in a space-varying magnetic field: it algebraically adds to the applied tension in the wire and it causes a side-ways force which, with the action of friction, causes an uncertainty in the tension.

The effects can be examined theoretically. We assume that the invar is magnetically saturated with a magnetisation of M_s which is fixed in value but locally takes the direction of the field B . It follows that, if B has a direction θ with the axis of the magnet (the z axis), the component of magnetization along the wire - r direction - is $M_r = M_s \sin \theta$ and the resulting longitudinal force at each point in the wire is

$$\frac{dF}{dV} = \frac{M_s \sin \theta}{\mu_o} \times \frac{dB_r}{dr},$$

where V is volume.

Hence the tension at any point at radius r in the wire, additional to the applied tension at radius r_2 may be expressed.

$$F_r = \frac{M_s a}{\mu_o} \int_r^{r_2} \sin \theta \cdot \frac{dB_r}{dr} \cdot dr \quad \dots \dots \dots (1)$$

where a is the cross-sectional area of the wire.

Similarly the sideways force per unit length of wire may be derived, which results in an uncertainty in tension in the wire due to friction of

$$|T_r| < \frac{\gamma M_s a}{\mu_o} \int_r^{r_2} \left| \cos \theta \cdot \frac{dB_z}{dz} \right| dr \quad \dots \dots \dots (2)$$

where γ is the coefficient of friction.

Here the integral of the modulus is taken because the wire is not rigid enough to allow a sideways force in one direction to be offset against a sideways force in the opposite direction several wire diameters along the wire from the first force.

The integrals in equations 1 and 2 may be obtained from computed field components of the magnet. Figure 7 shows how $\theta, \frac{dB_z}{dz}$ and

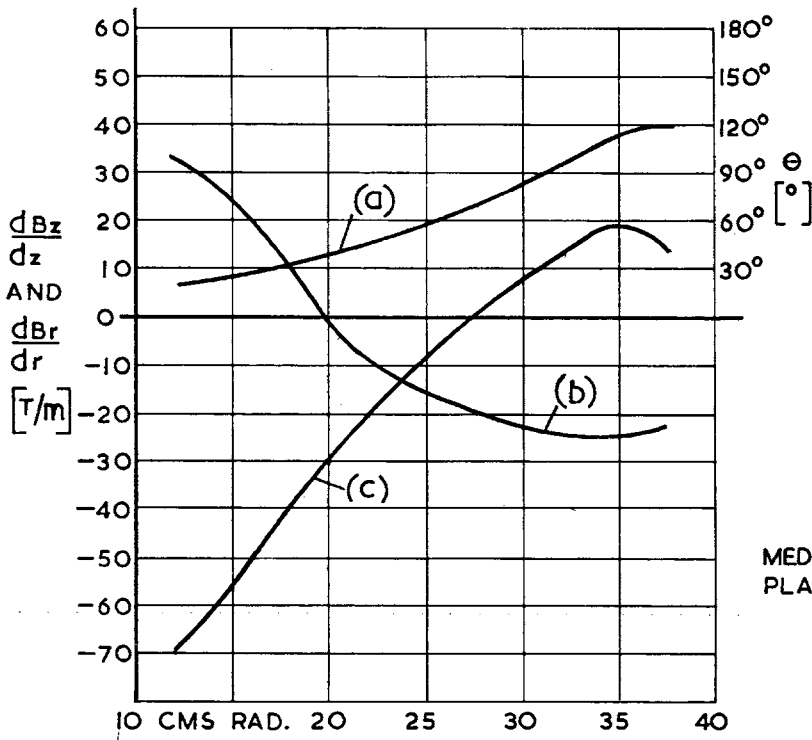


Figure 7(a)

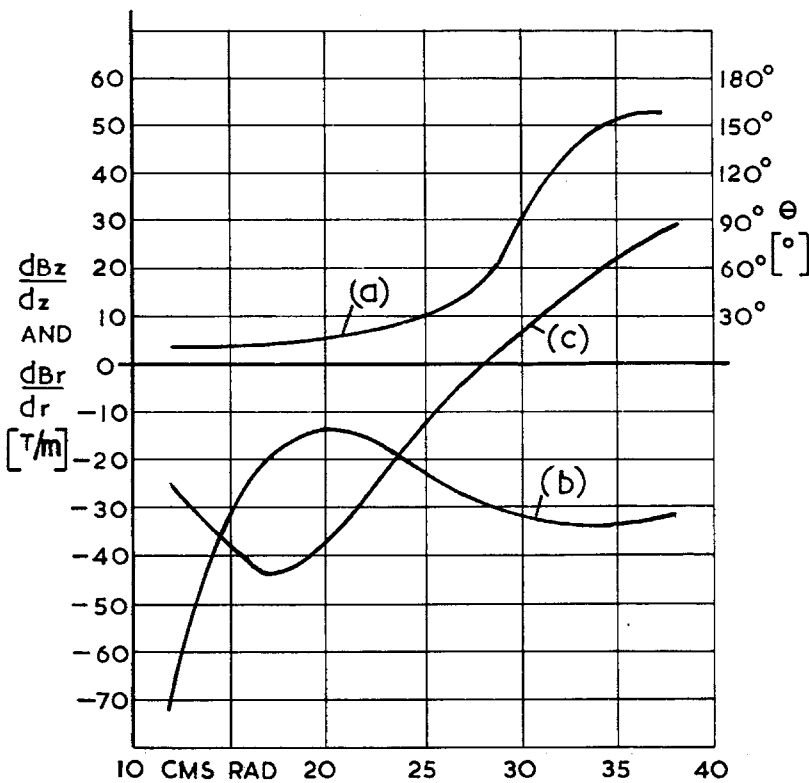


Figure 7(b)

Direction of field and magnitude of field gradients along displacement measuring channels in outer coil.

7(a) for channels 18 cms from median plane.

7(b) for channels 8 cms from median plane.

(a) angle θ } The diagram defines the axes used.
 (b) $\frac{dB_r}{dr}$
 (c) $\frac{dB_z}{dz}$

$\frac{dB}{dr}$ vary along the radial channels. The values of the two integrals over the length dr of the channel are as shown in Table III .

TABLE III

$\int_{r_1}^{r_2} \sin \theta \frac{dB}{dr} \cdot dr$ (Wb/m ²)	$\int_{r_1}^{r_2} \left \cos \theta \frac{dB}{dz} \right dr$ (Wb/m ²)	Distance of channel from median plane of magnet. (cms.)
- 0.7	- 1.1	8
- 2.6	- 5.3	18

The magnetisation of invar may be determined experimentally as a function of applied field. This was done by placing samples of invar, some weighted with copper, in a field gradient adjusted so that the upward force

$$\frac{M}{\mu_0} \cdot \frac{dB}{dz} V$$

just balanced the gravitational force. $\frac{dB}{dz}$ was determined from a field plot

using a magnet which produced magnetic intensities of about 8×10^4 A/m (actually 940 to 1040 oersted in the region of interest). According to Brailsford⁽⁴⁾ this is well in excess of what is required - about 500 A/m - to produce saturation in invar (or any ferromagnetic material).

Values of M_s (Wb/m²) calculated from these experiments ranged between 1.38 and 0.72 and compare favourably with the results given by Brailsford⁽⁴⁾ of $M_s = 1.4$. Substituting this value, the values of the definite integrals in Table III, $a = 0.2 \times 10^{-6} \text{ m}^2$ and $\gamma = .2$ in equations 1 and 2 , it is found that the resulting maximum components of wire tension occur in the 18 cms channels, their magnitudes being:

$$F_r \int_{r_1}^{r_2} = 0.13 \text{ lb. force towards magnet centre}$$

$$T_r \left. \begin{array}{l} r_2 \\ r_1 \end{array} \right\} = \pm 0.053 \text{ lb. force.}$$

These forces will cause strains which will change the length of the wire even though the applied force at the outer end is constant. The change in length for an average force of 0.05 lbs. over a wire length of 10 inches ($E = 21 \times 10^6$ p. s. i.) is about $\frac{1}{12}$ mil. (0.00008 inch) which would result in an error of 300 p. s. i. in calculated azimuthal stress at the inner radius of the outer coil if unaccounted for. It can be concluded therefore that the magnetic forces on the invar wires may be neglected and will lead to errors not exceeding a few hundred p. s. i.

Brailsford⁽⁴⁾ also gives magnetostriction coefficients which suggest that an increase in wire length of up to about 0.2 mil. might be expected. This may also be considered insignificant, especially when it is opposite in effect to the magnetic force.

Displacement measurements of the inner coil offer a different problem. Axial displacement may be transferred from the terminating assembly at either end of the coil through either cooling water or structural material of fairly constant temperature. The radial displacement of the inner surface of the inner coil may be transferred radially inwards into the access hole. In both cases therefore the environment through which displacement is to be transferred is magnetic - with much higher field gradients than for the outer coil - but not severely thermal. Molybdenum wire was chosen for its availability, non ferro-magnetic properties and sufficiently low thermal coefficient of expansion (4.9×10^{-6}) - Reference 3 .

4.3 Voltage

The monitoring of voltage, either induced or as a resistive drop, presents no problem as the levels are usually of the order of a volt or so. Substantial twisted pairs are used and the problem of induced noise, discussed under "temperature", is relatively insignificant.

4.4 Pressure

No particular problems arose in the design of pressure monitors. In general, pressures have been transferred through small diameter tubing to localities outside the magnet structure suitable for the installation of commercial pressure transducers. Hydrostatic pressure measurement in high velocity flows required suitably shaped pitot heads designed after N. P. L. standards.

The remainder of this paper deals with technical detailed descriptions of the instruments including the routing of signal wires and transfer devices.

5. DESCRIPTION OF INSTRUMENTS AND ROUTING OF WIRES

It will be found useful to refer to the sectional drawing of the magnet included at the beginning of Chapter 2 .

This section is divided into four sub-sections, each headed by one of the four measured variables discussed in the previous sections, viz. ,

1. temperature
2. displacement
3. voltage
4. pressure

5.1 Temperature

Measurement of the temperatures of the inner and outer coils and the electrodes and resistors feeding the inner coil, is here described.

In general, thermocouples are made from .008 inch diameter copper-constantan thermocouple wire formed into a regularly twisted pair.

5.1.1 Inner coil

Each inner sub-coil is terminated at either end with a 1/8 inch thick fibre glass insulating ring (to prevent thermal discontinuities due to end cooling) through which current is taken via cylindrical contact pins. Four temperatures of each sub-coil are taken, two at each end under the fibre glass rings. This number was chosen because it is expected that there will be a significant difference in temperature between the bottom - where cooling water enters - and the top, where water exits, and because a redundancy of two is advisable for such important measurements using such fragile instruments.

The construction of each of these thermocouples is illustrated in Figure 8 . First two small holes are drilled through the fibre glass ring at right angles to each other and at 45° to the coil axis, the two holes meeting close to the end surface of the coil. The separated wires of a pair are then passed along these holes to meet again where the holes coincide. Here the joint is formed using 157PA high temperature solder, and the whole made firm and insulated by means of araldite. This method of construction provides the advantage of firm anchorage. The small loop so formed is oriented so as to have no coupling with the magnetic field.

After emerging from the insulating rings, the twisted pairs are routed radially outwards to the vicinity of the outer edge of the coil, being

fixed by means of lacing twine.

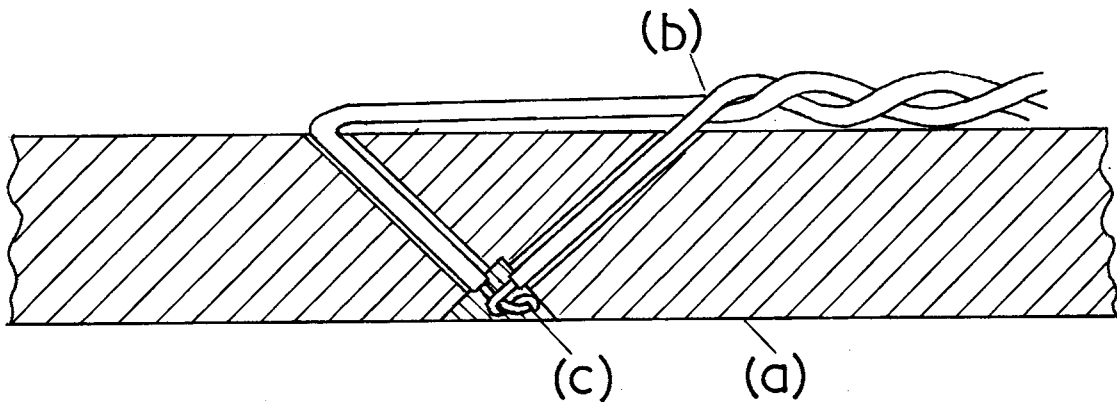


Figure 8. Construction of thermocouples for the ends of the inner coil.

- (a) 1/8" fibre glass ring (section)
- (b) .008" thermocouple wire
- (c) araldite

The inner coil is terminated at each end by an assembly whose purpose is to provide independent contact pressure to the current-carrying contact pins, to carry the current through semiflexible conductors, and to distribute cooling water to the sub-coils. These assemblies, known as the terminating assemblies, are housed in a stainless steel body and it is through this body that the thermocouple pairs pass in 1/4" x 1/8" channels, two to an assembly. From there the wires pass through fibre glass tubes and water seals to the outside. Miniature connectors adjacent to the water seals allow ease of assembly.

5.1.2 Electrodes

Within the terminating assemblies for the inner coil described above, are twelve semiflexible conductors known as electrodes. The purpose of these is to provide connections to each of the 132 contact pins even though these may move axially as a result of temperature and stress changes. The electrodes are rather thin in order to enhance flexibility and hence tend to be hotter than most other conductors. Their temperature is monitored by means of two thermocouples to each electrode, each thermocouple being mounted on a 0.0005" mylar strip and glued to its own electrode. These pairs are routed to the channels in the terminating assemblies and thence follow the inner coil thermocouples.

5.1.3 Resistors

Feeding the electrodes, which in turn feed the inner coil, are 24 resistors, 12 at each end of the coil. These resistors are made from

stainless steel tube and copper tube, hard soldered together in various proportions to obtain the desired resistances. The purpose of the resistors is to distribute current evenly from twelve equally spaced points around each end of the coil. Actually there are only twenty-two resistors since two contain no stainless steel. Each of the twenty-two contains inside its bore, two thermocouples (a redundancy of one) insulated by 0.0005" mylar and araldited to phosphor bronze springs which press the thermocouples against the inside surfaces of the stainless steel parts of the resistors. An enlarged view of one of these thermocouples is shown in Figure 9.

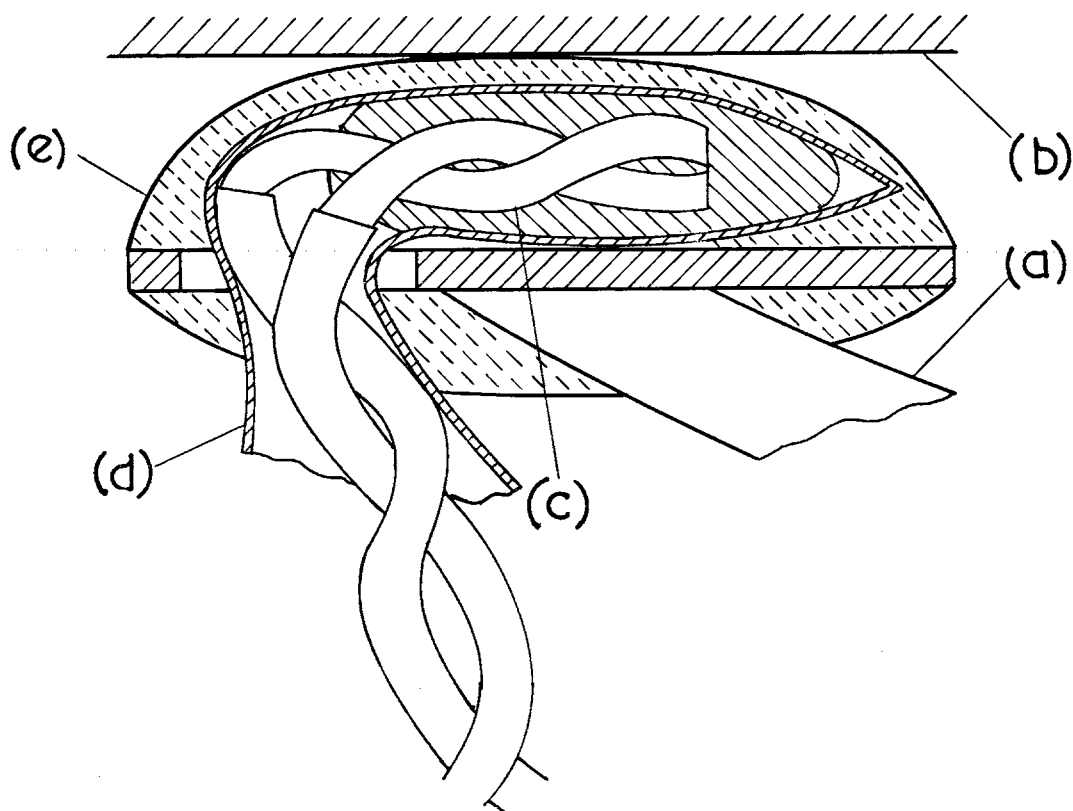


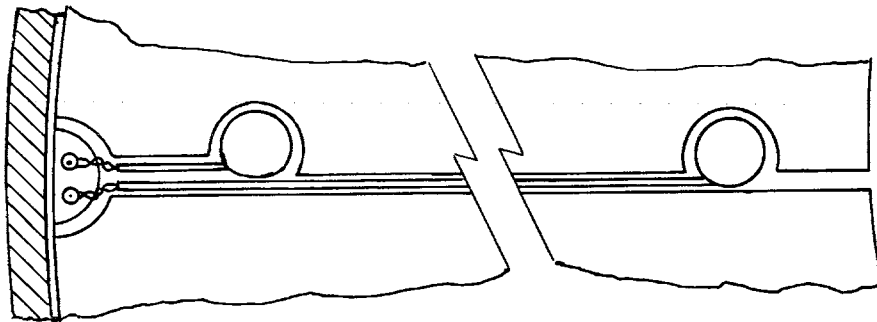
Figure 9. Construction of thermocouples used for measuring the temperature of resistors (greatly enlarged). The 0.035" phosphor bronze wire (a) presses the thermocouple (c) against the inside surface of the $\frac{1}{2}$ " diameter bore of the resistor (b) .
 (d) mylar
 (e) araldite

5.1.4 Outer Coil

The thermocouples in the outer coil may be divided into two groups - fixed and moving. The fixed thermocouples, eight in all, monitor temperature at the inner and outer edges of the coil near the top and bottom faces.

There is again a redundancy of two.

The routing for the inside thermocouple pairs is along slits formed by two butting discs from which the coil is constructed. The discs are over 0.020 inch thick and their edges have been trimmed to provide a .025" wide rectangular section channel through which each pair runs, encased in a .020" diameter stainless steel tube. Near the outer edge, the channel is widened to take a second thermocouple. From there on, the routing for both inside and outside thermocouples is the same. They travel axially along a channel formed by scallops punched from the edges of the discs and pass through holes in the encasing stainless steel torsion jackets. Figure 10 shows the location and routing of these thermocouples.



SECTION A-A

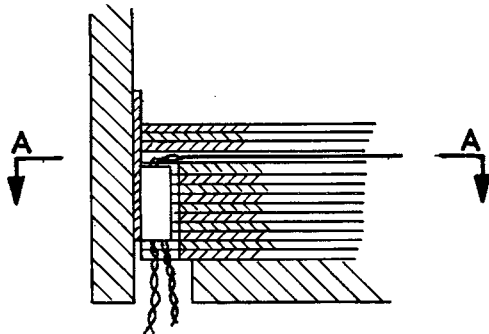


Figure 10. Construction and routing of the outer coil fixed thermocouples.

The moving thermocouples or "probes" are essentially similar to the inside fixed thermocouples but they are routed in a straight radial line to the outside of the magnet. This enables them to be moved along the .025" wide channels thus providing a complete temperature profile.

There are four levels where probes may be inserted, there being in general four positions at each level at intervals of 90° around the magnet.

Each probe comprises a .020" diameter stainless steel tube in which is a thermocouple pair soldered together at the end of the tube. The thermocouples are insulated from their tubes. The construction of these probes is shown in Figure 11. Each probe is mounted on a $\frac{1}{4}$ " diameter brass tube with provision for a water seal and a means of indicating the position of the thermocouple within the coil.

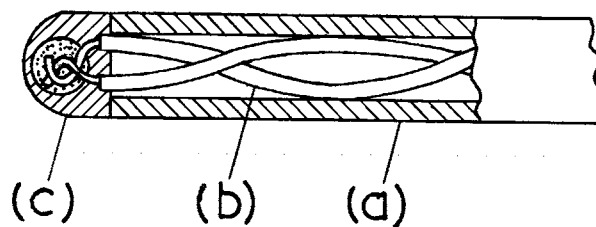


Figure 11. Thermocouple probes
 (a) .020 inch diameter stainless steel approximately 8 inches long.
 (b) copper-constantan thermocouple wire .003 inch diameter.
 (c) hard soldered thermocouple joint in epoxy resin tip.

The route for the probes beyond the .025" wide channels is through insulated holes in the torsion jackets and through holes in the surrounding conductors. The entrances to the .025" wide channels are flared out a little to make insertion of the probes a little easier.

5.2 Displacement

Measurements are taken of the radial position of the inner and outer regions of the outer coil; the radial position of the inside surface of the inner coil and the axial position of the inner coil. In the case of the outer coil, the measurements are with respect to a circular reference frame which surrounds the magnet and which is supported independently.

5.2.1 Outer Coil

Thirty-two measurements are made, eight at each of

four levels in the coil. Of the eight at each level, four are of the inner regions and four of the outer surface of the coil, in each case spaced at 90° intervals around the coil.

For the inner regions, transfer of radial position is by means of .020 inch diameter invar wires threaded at the inner end. The outer coil is prepared with .025 inch wide radial channels similar to those used for the temperature probes. In addition, at the inner end of each of these channels is a small threaded tag formed from a disc of the coil. The invar wires may be inserted into the channels and screwed into the tags after the magnet is assembled. A wire screwed into its tag is shown in Figure 12 .

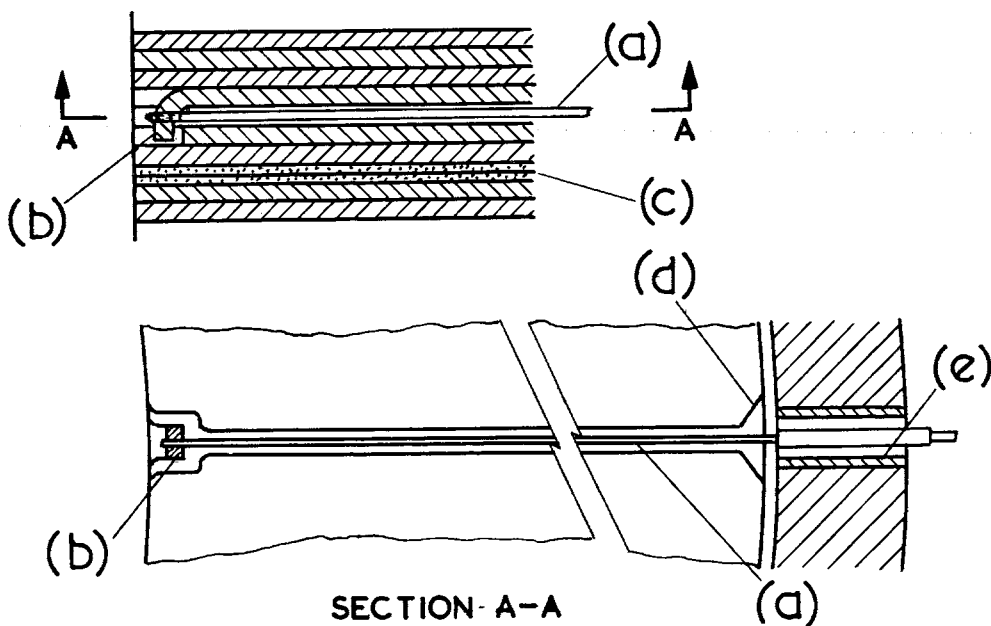


Figure 12. Details of invar displacement transfer wire from inner edge of outer coil.

- (a) invar wire .020" diameter
- (b) threaded tag
- (c) insulation in outer coil
- (d) discs shaped for easy entry of probe
- (e) insulation lining access holes in torsion jacket.

At the outer edge, position is sensed by the bakelite tip of a spring loaded pusher. This is illustrated in Figure 13 . Again the position is transferred by means of invar wire through the surrounding structure to the exterior of the magnet.

In all cases, the invar wire is held under constant

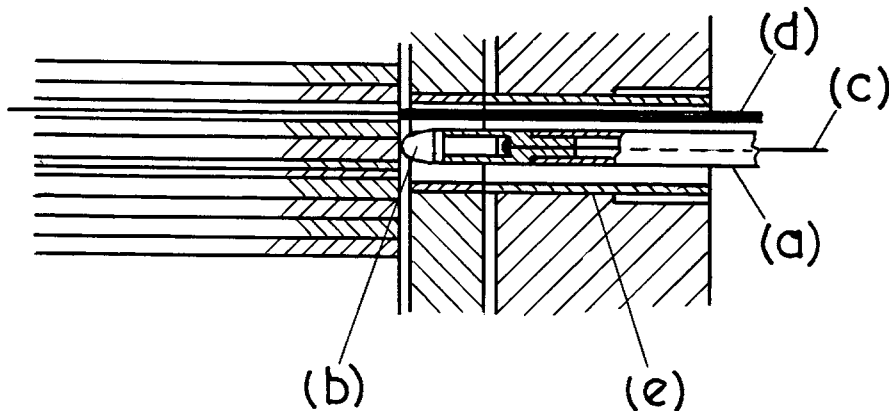


Figure 13. Detail of displacement probe for outside edge of outer coil.

- (a) spring loaded push rod
- (b) bakelite sensing tip
- (c) invar transfer wire .020" diameter
- (d) inner transfer wire teflon covered
- (e) fibre glass insulating tube.

tension applied from the magnet structure, and the position of the outer end of the wire is measured off the circular measuring frame by means of a Bentley Proximator. The invar wires, at the potential of the coil, pass through insulated holes in the surrounding structure. Where they must leave the cooling water environment, effective low friction seals are formed simply by passing the wires through slightly larger diameter holes in teflon plugs. Figure 14 shows the means of applying force to the pusher which is pressed against the coil, and the teflon water seal.

5.2.2 Inner Coil

During the testing of the magnet it is intended to measure the radial position of the inside surface of the inner coil at four points spaced 90° . These measurements will be relative to a compact central measuring frame placed in the access hole of the magnet. It does not seem possible to provide an alternative means of making these measurements when the access hole is required by experimenters.

The magnet access hole is within a tube, known as the core tube, placed inside the inner coil. Radial position of the coil is sensed by four small springloaded probes which pass through teflon seals in this tube. Bell cranks with jewel bearings translate radial motion from these probes to vertical motion which is transferred out of the access hole by means of four molybdenum rods.

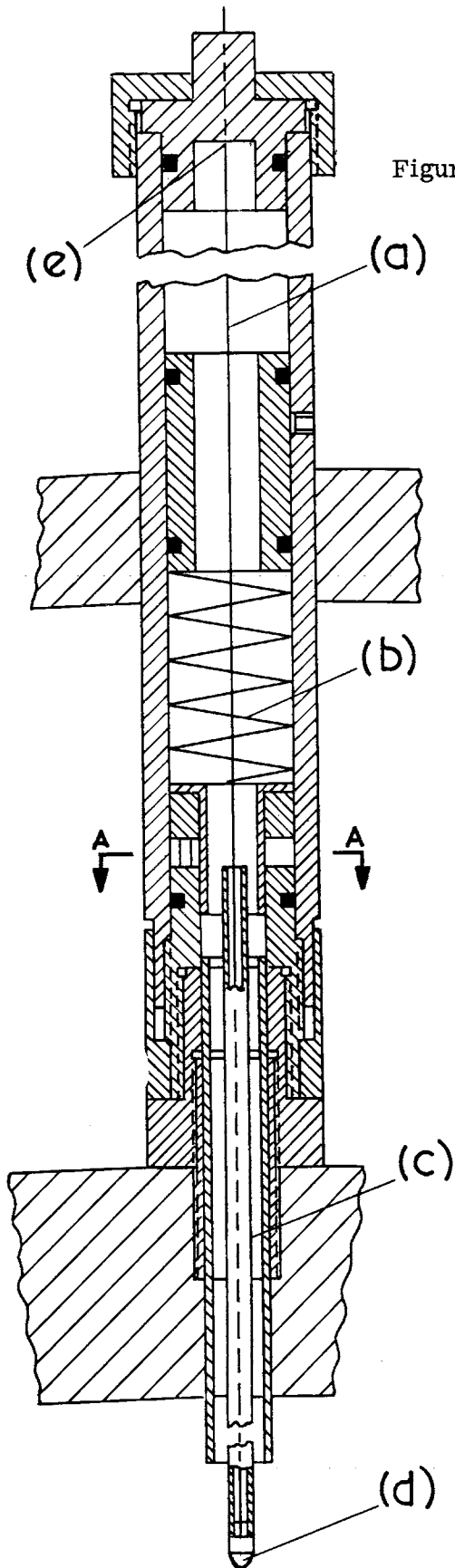
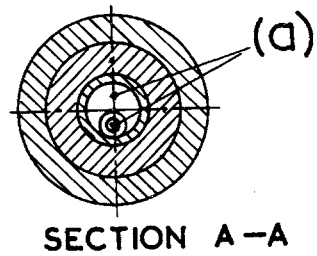


Figure 14. Detail of displacement transfer wires from the magnet.

- (a) invar wires
- (b) spring pushing stainless steel probe tube (c) and tip (d) against outer surface of coil.
- (e) teflon water seal.



The axial position of the inner coil is determined from measurements of the axial position of the stainless steel bodies of the two terminating assemblies. Two molybdenum wires, 0.021" diameter, are attached to each terminal assembly and are taken in an axial direction through water seals to the exterior of the magnet. The wires are placed under tension and the position of their ends measured, by Bentley proximators, relative to the clamp tube which is the central supporting structure of the magnet.

5.3 Voltage

Several voltages are measured within the magnet for various purposes viz., to determine current distribution or to correlate with current in a resistive circuit; to determine, by integration, an average field strength; and to determine induced circulating current.

In the first category comes the measurement of magnet voltage itself which is done by means of a twisted pair of leads connected across the two current distributing rings which are separated by a quarter inch of insulation.

The current distribution to the inner coil is checked by measurement of voltage drop across the feeder resistors. Each of these resistors is hollow, enabling an insulated lead to be brought through the middle to connect to the inner end of the resistor. At the outer end of the bore of the resistor, another connection is made, the two leads leaving the resistor as a pair.

The current distribution within the outer coil is checked by measuring the voltage drop in each of the four "starts" for about a turn at each end of the coil. Soldered connections are made to the outer edges of appropriate discs and the leads taken axially along a channel formed by scalloping the coil discs similar to that described for the outer coil fixed thermocouples. These voltage leads, those from the resistors, and the resistor and outer coil fixed thermocouples all subsequently travel the same route to the exterior of the magnet.

In the second category, field strength, there is a coil wound on a bakelite former mounted within the core tube, and a number of single turn loops placed within the current distribution rings which surround the magnet. The latter may be used also for measurements in the third category - determination of circulating currents from direct measurement of the induced electric field.

5.4 Pressure

Two ranges of pressure are measured and may be classified as low pressure and high pressure. The low pressure measurements are all concerned with the cooling water system. In general, pressure is tapped off at the points of interest using a 3/16" O.D. Nylon tube which transfers it to Consolidated Electrodynamic Corporation (C. E. C.) pressure transducers mounted external to the magnet.

Pressures are monitored at both ends of both coils.

The high range covers water pressures, normally 2000 p.s.i. to 3000 p.s.i., which are associated with a commercial hydraulic unit used to apply the squeeze forces to both coils. Only the inner coil pressures are monitored continuously by means of C. E. C. transducers. Other hydraulic pressures are monitored by means of bourdon tube type gauges.

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