Cryogenic Instrumentation Needs in the Controlled Thermonuclear Research Program

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CRYOGENIC INSTRUMENTATION NEEDS IN THE CONTROLLED
THERMONUCLEAR RESEARCH PROGRAM*

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ABSTRACT

The magnet development effort for the controlled thermonuclear research program will require extensive testing of superconducting coils at various sizes from small-scale models to full-size prototypes. Extensive use of diagnostic instrumentation will be required to make detailed comparisons of predicted and actual performance in magnet tests and to monitor the test facility for incipient failure modes. At later stages of the program, cryogenic instrumentation will be required to monitor magnet system performance in fusion power reactors. Measured quantities may include temperature, strain, deflection, coil resistance, helium coolant pressure and flow, current, voltages, etc. The test environment, which includes high magnetic fields (up to 8-10 T) and low temperature, makes many commercial measuring devices inoperative or at least inaccurate. In order to ensure reliable measurements, careful screening of commercial devices for performance in the test environment will be required. A survey of potentially applicable instrumentation is presented along with available information on operation in the test environment based on experimental data or on analysis of the physical characteristics of the device. Areas where further development work is needed are delineated.

INTRODUCTION

Recent successes with a class of magnetic plasma confinement devices called tokamaks have given plasma physicists confidence that the scientific feasibility of a controlled thermonuclear fusion reaction with net power production will be demonstrated in one or more such devices within the next several years. Following demonstration of scientific feasibility, the next step will be to demonstrate the technological and commercial feasibility of a controlled thermonuclear reactor for electrical power production. This step will require a scale of effort roughly an order of magnitude larger than the effort required for scientific feasibility and will entail construction of at least two major facilities, the Experimental Power Reactor (EPR) and the

Demonstration Plant (Demo). The EPR, scheduled for the late eighties, will contain on a reduced scale all of the essential components of a fusion power plant except the electricity generating components, including tritium handling facilities, the liquid metal heat-exchange system, etc. The Demo plant is to be a self-contained, power-generating plant scheduled for operation about 2000.

One of the major technological development items is the magnet system for confining and heating the plasma. In order to keep the power demands of the magnet system at an acceptable level, superconducting windings are mandatory for the bulk of the system. These magnets will represent a considerable advance in the state of the art in superconducting magnet technology. The magnet development effort will require extensive testing of coils at various sizes from small-scale models to full-size prototypes. Extensive use of diagnostic instrumentation will be required to make detailed comparisons of predicted and actual performance in magnet tests and to monitor the test facility for incipient failure modes. At later stages of the program, cryogenic instrumentation will be required to monitor magnet system performance in actual fusion power reactors.

DESCRIPTION OF THE TOKAMAK MAGNET SYSTEM

Figure 1 is a schematic drawing of a segment of a tokamak. The toroidal field (TF) coils produce a field B_T in the plasma chamber as shown. The ohmic heating coils, when pulsed, induce a current I_p in the plasma which simultaneously heats it and produces a field B_p which combines with the toroidal field B_T to confine it. The vertical field coils produce a field B_v which exerts an inward force on the plasma, counteracting the tendency of the plasma to expand outward. In some tokamak designs, these coils are controlled by fast circuitry which provides feedback stabilization of the plasma position. Present designs for the EPR¹ call for oval or D-shaped (TF) coils. An artist's conception of the ORNL design is shown in Fig. 2. In this design, there are 20 coils, each with a vertical diameter of 11 m and a horizontal diameter of 8 m, operating at

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Fig. 1. Tokamak section schematic.

ORNL-DWG 75-17030

Fig. 2. Oak Ridge EPR reference design.

4.5 K with a current of 20 kA. The maximum field experienced by these coils will be 11 T (110 kG). The coils are cooled by forced circulation of liquid helium through cooling passages in the windings. (In some other tokamak EPR concepts^{2,3} they are cooled by pool-boiling helium.) The ohmic heating windings are concentrated mainly in the central region ("hole of the doughnut"), forming a solenoid. In these windings, the peak field is less (7 T) than in the TF coils, but the windings must be pulsed to peak field at a rate of 7 T/sec. The TF coils, on the other hand, will be operated in constant current mode but will experience some pulsed field from the ohmic heating windings. The vertical field windings constitute the remainder of the magnet system, and in some designs are non-superconducting but operate at cryogenic temperatures.

Magnet Design and Testing Considerations

Both the toroidal field coils and the ohmic heating windings present challenging problems to the designer. A basic design criterion is that under operating conditions the superconducting windings must not "quench", i.e., undergo a runaway transition from the superconducting to the normal state, making the whole coil resistive.

The behavior of the superconductor can be described by the concept of critical current, which is defined as the maximum current a given superconducting element can carry at a given field and temperature without making a transition from the superconducting state. Critical current vs temperature curves for a typical sample of the alloy NbTi at various fields are shown in Fig. 3. A similar family of

Fig. 3. Temperature dependence of critical current density in NbTi at various fields, R. G. Hampshire et al., *Refrigeration Science and Technology*, p. 251, Intl. Inst. of Refrigeration, Belgium (1969).

curves can be drawn for the intermetallic compound Nb₃Sn, but the points for this higher temperature and field material on a given constant field line are shifted to the right relative to the NbTi data. A comparison of these two superconducting materials, which are the most important practical superconductors, is shown in Fig. 4. For fields above 10 T (100 kG),

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Fig. 4. Comparison of the critical current density dependence upon field at 4.2 K for three NbTi alloys and the inter-metallic compound Nb₃Sn (Z.J.J. Stekly, J. Appl. Phys. 42, (1) p. 65 (1971)).

use of Nb₃Sn is imperative. Below 7 T, NbTi is preferred for economic and technical reasons. The major drawback to use of Nb₃Sn is its brittleness, which makes it more susceptible to strain degradation and complicates the manufacturing process.

Magnet Design Considerations

The problem of designing a magnet to prevent a quench basically involves two interdependent considerations: (1) limiting transient heat input to the windings to a level from which windings can recover, and keeping steady-state heat loads low enough; and (2) transferring heat from the windings to the liquid helium coolant rapidly enough to prevent a quench. In all practical superconducting winding material, the superconductor itself is in the form of fine filaments (or in some cases a thin layer) surrounded by high conductivity normal material (usually copper) which is needed for magnetothermal stability. In so-called "cryostable" winding designs (required by all of the present EPR reference designs), the windings are constructed so that a small normal zone in the superconductors, if created, will shrink away and disappear. Cryo-stability requires a sufficient quantity of normal metal matrix in combination with the superconducting filaments, a sufficient rate of heat transfer to the coolant, a sufficient volume of coolant in intimate contact with the windings, and a sufficient margin between operating current and critical current at the operating temperature and field.

Sources of steady-state heat load to the magnet system are thermal conduction and radiation, as well as neutrons and gamma rays from the thermonuclear reaction. The magnitude of these loads can be calculated with a fair degree of confidence. Transient heat loads, on the other hand, are not all so easily calculated. Superconducting

windings, although resistance-free for dc constant current, exhibit heating in the presence of either changing self-field or changing external field. These losses arise from eddy currents in the stabilizing normal metal matrix and from flux flow through the superconducting filaments themselves, which exhibit hysteresis. The losses are expected to be especially severe for the central solenoid of the ohmic heating windings (see Fig. 2), which is force-cooled in the ORNL-EPR reference design. The TF coils, although operated in a constant current mode, will be subjected to a lower pulsed field from the ohmic heating and vertical field windings and from the plasma itself, but they will be heated to some degree by their combined changing field.

The second major source of transient heat input is conductor movement, which is difficult to model analytically. Conductor movement can produce heating either by the effect of movement through the magnetic field or by friction. Sudden movement of the windings can take place if a conductor suddenly slips when shear stresses exceed adhesive or friction bond strength in a particular area.

The TF coils are subjected to high radial forces which vary from a maximum in the part of the windings near the torus center to a minimum in the part of the coil away from the center. These unbalanced radial loads produce a net bending moment in the coils if they are circular; the toroidal coils shown in the EPR reference design have a minimum bending shape. The TF coils are also subjected to time-varying out-of-plane overturning forces from the vertical field. Finally, the coil support structure must be able to handle the large lateral loads to which an operating coil is subjected when the current in one or more adjacent TF coils is lowered (as in a quench). The structural design criterion in general will be more stringent than a simple mechanical yield stress limit; the structure will be required to keep conductor movement within acceptable limits from the standpoint of heat input and to maintain the integrity of turn-to-turn and winding-to-case electrical insulation.

In the case of pool-boiling designs, heat transfer from the conductor is accomplished by natural convection. In force-cooled designs, the heat transfer is enhanced by turbulent flow of the liquid helium coolant through passages. Heat transfer in pool-boiling designs is difficult to deal with analytically; the force-cooled designs are somewhat more amenable to calculation, but nevertheless are highly sensitive to the choice of input parameters such as heat transfer coefficient, friction factor, etc.

Need for Diagnostic Measurements

In general, existing magnet design knowledge is not sufficient to provide the designer with a very high degree of confidence in design calculations of either expected heat input or response to a known input. At the same time, design margins are necessarily tight in a tokamak EPR, where space for structure is competing with space for windings, blanket, etc. For this reason, an essential part of the magnet

development effort is development of a comprehensive diagnostic instrumentation system that will check model predictions and provide empirical design data when models are not available. The system should enable the coil test engineer to correlate phenomena providing heat input with the appearance of normal zones, and to observe the history of the normal zones, once created. The test stand for model TF coils will provide a background field simulating the effect of the remaining TF coils in a tokamak on a particular coil. Additional windings will be provided to produce pulsed fields. Heaters may be provided to introduce known heat pulses to the windings and to introduce normal zones. In the case of the models of the pulsed central solenoid, no background field coils will be required since the self-field of the coil dominates the total field.

Parameters Measured in the Coil Test

The basic parameters set or controlled by the test engineer in a TF coil test are test coil current, background coil current, heater current, pulsed winding current, liquid helium temperature, and, in the case of force-cooled coils, helium flow rate and inlet pressure. These variables must be continuously monitored during the test; the test thus consists of observing and recording the response of the test coil to various values of these input variables as indicated by the diagnostic variables. Of course, the designation "input variable" refers to normal operating conditions; the current in the coil and the helium temperature, for example, would change drastically during a quench. Diagnostic variables for the mechanical behavior include deflections and strains in the coil support structure and possibly in the windings. In addition, some method of detecting sudden local conductor movement is desirable.

The primary diagnostic variable for normal zones is conductor resistance, which is zero in superconducting regions and is determined by the length of the normal zone and the normal metal resistivity in normal regions. The normal metal resistivity is dependent on both field and temperature. Detection of normal zones by direct temperature measurement of the conductor is also a possibility.

Another variable, helium cryostat pressure, may be a controlled variable in pool-boiling coils because lowering the temperature of boiling helium below 4.2 K requires lowering the pressure of the vapor above the liquid. Helium cryostat pressure may also serve as a normal zone detection method, since sudden evolution of heat will produce a pressure surge in the cryostat.

Force-cooled coils present an additional set of diagnostic measurement requirements beyond those needed for coils cooled by pool-boiling helium. At the inlet of the cooling circuit, helium pressure, flow rate, and temperature will be measured as input variables, while the pressure and temperature at various points downstream will be measured as diagnostic variables.

In some proposed force-cooled designs^{1,4} the helium is maintained at supercritical pressure, i.e., at a sufficiently high pressure throughout the cooling circuit to suppress boiling. This eliminates the complication of two-phase flow measurements, but pressure and flow measurements are nevertheless difficult due to the extreme changes in thermodynamic quantities near the transposed critical line.

A number of additional diagnostic variables will be monitored during the test. During initial cooldown, temperatures in the coil windings and coil support structure will be measured. Coil ground current detectors will monitor the system for electrical insulation failure. Also, in addition to the input variables, some facility-related diagnostic variables will be monitored. These include electrical lead resistance, vacuum pressure, coolant supply line temperature, and diagnostics in the background field coils similar to those in the test coil, but more limited in scope.

Finally, a subset of the controlled and diagnostic variables for both the test coil and the facility will be designated alarm variables. These variables will provide input for initiating a protective shutdown of the coil system in the event of a quench or failure of a critical facility or test coil component. For example, if a diagnostic signal indicates that the length of a normal zone exceeds a certain limit, a system could be activated which would isolate the power supply and cause the coil energy to be dumped rapidly into a resistor external to the cryostat.

Measurement Methods and Environmental Effects

The test environment for the superconducting coils includes high static magnetic fields, pulsed magnetic fields, low temperature, large temperature gradients, and in some cases high voltages with respect to ground (in the event of a magnet system energy dump).

For sensors mounted on or near the windings, magnetic shielding is impossible because the ambient static field (up to 8-10 T) is greater than the saturation field of known ferromagnetic materials. The pulsed magnetic fields are generally of too low a frequency for effective use of eddy current shielding. The basic approach, then, must be to employ in the immediate vicinity of the test stand only sensors which are intrinsically insensitive to the static and pulsed magnetic fields but to consider shielding field-sensitive sensors for use outside the high field region.

Test and background coil current can be measured at room temperature near the power supply, where the stray field will be less than 0.01 T, by a variety of methods, including shunts, Hall effect devices, and transducers. The latter two devices are field-sensitive and would require shielding.

In pool-boiling systems, the cryostat vapor pressure is a measurement of the bath temperature under

equilibrium conditions. In single-phase force-cooled systems, pressure and temperature can generally be varied independently, necessitating direct temperature measurement.

Direct Voltage Measurements

Voltage tap measurements will be a primary method of monitoring coil behavior. The differential voltage measured across two voltage leads contacting the windings at different points is the sum of a resistive voltage (if a resistive zone is present in windings between the taps) and an inductive voltage (if the field is changing) which is produced by changing flux through the circuit formed by the section of the windings between the taps and leads themselves. The area of the pickup loop made by the leads will be minimized by twisting of the lead wires. The inductive signal can be further reduced by co-winding the voltage tap leads with the coil conductor, but this procedure may be impractical due to space limitations.

Another method of compensating for inductive signals is an analog compensation scheme, as shown in Fig. 5. A Rogowski coil measures dI/dt for each separate circuit producing a magnetic field in the test coil windings (e.g. test coil circuit, background coil circuit, and pulsed coil circuit). The dI/dt signals are multiplied by the appropriate scaling factor, according to the mutual inductance of the particular circuit with the circuit formed by the winding section and voltage tap leads. In practice, the gains will be set empirically by nulling the output while raising and lowering the current in the various circuits one at a time. The voltage tap inputs require high-voltage isolation amplifiers to handle the common mode voltages which will appear in the event of a coil dump; these voltages may be as large as 1000 V.

Fig. 5. Voltage tap inductive signal compensation scheme.

Ground fault currents can be monitored by measuring the voltage drop across a resistor to ground, since the power supply output is floating (Fig. 6). The voltage signal is amplified by a high voltage differential isolation amplifier. The contactor in Fig. 6 is closed during normal operation and is opened in the event of a fault to dump the coil energy rapidly into resistors.

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Fig. 6. Energy dump schematic. Resistors R_1 are dump resistors, R_2 is the ground current detecting resistor.

Special inductive pickup circuits can be used to detect sudden motion of windings. Investigators at Kurchatov Institute in the USSR used a system in which two arms of a bridge were formed by windings wound symmetrically on two sides of a superconducting test solenoid.⁵ In this configuration, an imbalance signal from the bridge is an indication of a change in the inductance in one of the halves of the solenoid. This change occurs when the windings move and always preceded the transition to the normal state. When balanced, the bridge output is insensitive to a change in the coil current.

Temperature Measurement

The problem of cryogenic temperature measurement in the presence of high magnetic fields has been the subject of numerous articles; anything approaching a complete listing of them would be far too lengthy to present here. A survey of the behavior of most of the available cryogenic thermometer types in high magnetic fields has been performed by Neuringer and Rubin;⁶ a later article⁷ by Sample, Neuringer, and Rubin includes data on Chromel P/Au-0.07 at.% Fe (KP-AuFe) thermocouples. Further work on these thermocouples has been performed by Chiang.⁸ A survey of instrumentation requirements for superconducting transmission line research, which includes a discussion of thermometers was made by Arp et al.;⁹ much of their work can be applied to superconducting coil testing.

Investigations of KP-AuFe thermocouples, which are the only type available with reasonably high thermopower in the entire range of 4-300 K, have shown that a thermopower change of about 15% occurs at 4 K in a field of 8 T. The effect is very difficult to correct in a practical test situation since the signal voltage is dependent upon the relation between the magnetic field and temperature distributions along the lead wires. We can conclude

that in the high field region of the test stand, thermocouples will give accurate data only during the cooldown phase of the test, before the coils are energized.

The best candidates for thermometry in the test environment are of the non-self-generating type, i.e., sensors which change in resistance or capacitance with temperature. For making a comparison of thermometers, a figure of merit has been proposed by Schlosser and Munnings¹⁰ and is given by

$$\frac{\Delta\theta/\theta}{1/\theta \, d\theta/dT} \quad (1)$$

where θ is the temperature-sensitive property of the thermometer (such as resistance, capacitance, thermoelectric voltage, etc.) and $\Delta\theta = \theta(H,T) - \theta(0,T)$. In cases where the magnetic field effect is large, $d\theta/dT$ may change significantly with field. For comparison purposes, one can use $d\theta/dT$ at zero field as long as one is consistent.

Germanium resistance thermometers, which are excellent for zero-field low temperature application, are ruled out by their extreme magnetic field sensitivity. Carbon resistance thermometers can be fabricated in a great variety of forms, varying in resistance ratio ($R_{4.2 \text{ K}}/R_{300 \text{ K}}$) from about 1.5 to almost 10. One of the most popular types of carbon resistance thermometer is the carbon composition resistor. Two types of resistor, 1/8-W Allen-Bradley^{11*} and 1/2-W Speer,¹² have been shown to retain their calibration within a few millidegrees even after repeated thermal cycling. They vary in temperature sensitivity by almost a factor of 10 at 4.2 K, according to Ref. 6, the Allen-Bradley 10- Ω resistors having the highest temperature sensitivity. The magnetically induced error for the Allen-Bradley resistor was 5% at 8 T and 4.2 K; the error becomes smaller as the temperature is increased and the field reduced, the field dependence being roughly linear at high field. Other types of carbon resistance thermometers may exhibit different magnetic field behavior; the 1/2-W Speer resistors at 4.2 K have a region of negative magnetoresistance before going positive at 10 T. The Allen-Bradley resistors have better reproducibility in magnetic field error from resistor to resistor, in addition to their higher sensitivity. Carbon resistance thermometers are also commercially available in the form of carbon dispersed in a glass matrix.¹³ These thermometers have three times as high a sensitivity at 4.2 K as the best of the resistors described in Ref. 6 and have a considerably lower magnetically induced temperature error.

Thermistors,^{10,14} which are used mainly for non-cryogenic temperature measurements, have been used to a limited extent for cryogenic measurements. They are characterized by extremely high sensitivity

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at low temperatures - in fact, such a high sensitivity that the resistance typically changes four decades in the range 4-20 K. The absolute magnetoresistance is large at 4.2 K, but the $\Delta T/T$ is small due to the high sensitivity, about a factor of three lower than in the carbon resistors. Further work remains to be done with these devices before they become generally accepted by the low temperature research community, however.

Another class of thermometers potentially applicable to magnet testing is composed of a number of diode types for which the forward voltage drop at constant current varies with temperature. Of these, the least field-sensitive at 4.2 K is the GaAs diode¹⁵ which has a 0.7-K error at 5 T, low enough for some purposes. The temperature sensitivity of the diode, however, is low at 4.2 K.

The final category of non-self-generating temperature transducers is the capacitance thermometer. Capacitance thermometers have been made from a number of different dielectric materials, but the most sensitive one for cryogenic use is the strontium titanate glass-ceramic thermometer,¹⁶⁻¹⁸ available commercially from Lakeshore Cryotronics. This device has a total capacitance of about 2000 pF and a sensitivity of 250 pF/K at 4.2 K, which is comparable to the relative sensitivity exhibited by the carbon composition resistor thermometers of Ref. 7 at 4.2 K. The device is totally insensitive to magnetic fields. The greatest difficulties associated with its use are a degree of hysteretic behavior and sensitivity to overvoltage which may cause temporary calibration changes.

Use of thermometers for direct measurement of normal zone propagation is probably unrealistic in large-scale magnet testing because of accessibility problems and space requirements, but may be considered for small scale propagation studies, etc. For this purpose, a sensor with resolution of 1 K and a fast response time (~ 1 msec) is desirable. The ideal geometry for fast response to a temperature change of a substrate is a thin film device with its face in good thermal with the substrate. Such carbon films have been fabricated by a number of investigators.^{14,19,20} Since repeatability of these sensors is usually low from sensor to sensor, a sensor which can be calibrated in a calibration fixture and then cemented in place is desirable. Capacitance thermometers have also been fabricated in thin film form,¹⁹ but have been used in applications where the film was mounted in a fluid stream rather than cemented to a substrate. For measurement of liquid helium inlet and outlet temperature in force-cooled coils, somewhat more temperature resolution (0.01 K) and similar time response are desirable. However, commercial devices such as the carbon glass thermometer (1 x 1 x 4 mm), the capacitance thermometer (1 x 3 x 1 mm), and thermistors will probably be adequate if the magnetic field error (if any) is calibrated out. For very small fluid temperature changes, the thermistor appears potentially the best choice.

Strain and Deflection Measurement

Because of the large area of contact and the magnitudes of the loads transmitted to it by the windings, the greater part of the structural support system must also be maintained at liquid helium temperature. Metal foil resistance strain gages have been used at cryogenic temperatures²¹ but there are difficulties associated with the very high zero shift from room temperature to liquid helium temperature occurring with some gage types (i.e., Constantan or Advance Alloy) and with the large temperature coefficient of apparent strain (typically $100 \times 10^{-6}/K$ with Karma alloy at 4.2 K). An additional complication is magnetoresistance. Work by this author²² which extended previous data to higher fields demonstrated a highly temperature-dependent magnetoresistance behavior in Karma alloy metal foil gages with insignificant apparent strain (magnetoresistance) at room temperature and liquid nitrogen temperature but a significant effect at 4.2 K ($\Delta\epsilon = 2 \times 10^{-4}$ at 6.5 T). These data indicate that strain gage pressure transducers made with Karma alloy gages should function satisfactorily down through liquid nitrogen temperature and, if the proper cancellation scheme is used, should not be grossly in error even at liquid helium temperature in the presence of high magnetic fields, provided proper account is taken of the gage factor shift with temperature. However, such devices will have to be tested in fields at the operating temperature before they can be used with assurance in a magnet test.

The cancellation techniques applicable to strain gage pressure transducers may not be applicable to strain measurements in magnet testing, however, due to the difficulty of maintaining a dummy gage at the same temperature as the active gage without simultaneously straining it. Although Telinde (Ref. 21) suggests simultaneous measurement of temperature at each gage location and use of a correction curve, this procedure is difficult and expensive and, in the presence of high magnetic fields, would be in error due to the temperature dependence of the magnetoresistance. The only completely satisfactory solution to the problem appears to be to find an alloy, if possible, with sufficiently low temperature variation of resistance and magnetoresistance ratio ($< 5 \times 10^{-5}$) in the range 4-20 K in fields up to 10 T.

Another strain measurement technique potentially applicable to the problem is use of a capacitive strain gage developed by Boeing.²³ This device, which is an extensometer with a fairly short (2.5 cm) gaging length, should be completely insensitive to field providing it has no magnetic parts which could be loaded by magnetic forces. The device has the disadvantages of long gaging length, bulkiness (which prevents its use in restricted geometries), and high cost relative to resistive strain gages.

Similar environmental considerations will apply to deflection-measuring devices, with the exception of certain optical methods in which an optical system is used to bring out a light beam modulated in some

way by the deflection signal. The optical methods are, in the balance, less desirable than other methods because of high cost, the complexity and bulkiness of multi-channel optical systems, sensitivity to vibrations, etc., although their lack of direct mechanical connections is a distinct advantage, especially in measurement of thermal contraction of the structure. In addition, most readout systems for optical deflection-measuring systems contain phototubes and are highly field-sensitive, requiring extensive shielding even when located out of the high-field region.

Clip gages, which are based on the measurement of strain in a calibrated elastic member attached to two points between which a deflection is to be measured, could be used, provided that proper cancellation of thermal and magnetic strain effects is accomplished. Careful attention must also be paid to thermal contraction effects in the members connecting the test points in any scheme using mechanical connections.

Conventional LVDTs, which are based on the variable coupling between primary and secondary windings provided by a moving ferromagnetic core, are unusable in the high field environment. A coreless, moving-coil LVDT, which retains the advantages of the conventional LVDT (i.e., high output, high linearity, high dynamic range, infinite resolution, standardized signal conditioning, low cost per channel), but is insensitive to magnetic fields, has been developed at Oak Ridge National Laboratory by the author and another investigator, J. F. Ellis, and is in use at Princeton Plasma Physics Laboratory in a coil test at the time of this writing. The device was previously tested in static and pulsed fields (6.5 T, 3 T/sec) and the only magnetic effect observed was an in-phase voltage (1% of reading at 6.5 T with the field along the axis, essentially zero with the field perpendicular) with a B^2 dependence, due to a mechanical vibration driven by the interaction of the excitation current and the ambient field.

Pressure and Flow Measurement

Pressure measurements (apart from vacuum system measurements) in tests of coils with pool-boiling helium coolant will probably be limited to the vapor phase above the liquid surface. As mentioned previously, the pressure measurement serves as a sensitive temperature indication under equilibrium conditions; it may also serve as a normal zone detection method, since the helium boiloff associated with the sudden appearance of a normal zone will cause a pressure surge in the cryostat. For the above purposes a pressure resolution of 5×10^3 Pa (0.05 atm) is desirable with a full scale limit of a few atmospheres to monitor the pressure during a quench. If the pressure transducer is located in the cryostat above the liquid, the ambient temperature will be somewhat above the liquid temperature, but still at a cryogenic temperature. Another alternative is to run pressure taps from the cryostat through the vacuum space to the outside of the vacuum enclosure,

permitting use of room-temperature devices. Possible disadvantages of the latter procedure are heat leaks and time lags in measurement of transient pressures; however, these may be insignificant in practice.

Pressure measurements in force-cooled systems present a more difficult set of requirements. Since the coolant is not, in general, on the liquid-vapor phase boundary, any two of the quantities of pressure, temperature, and density can be varied independently. Expected pressures range from 1 to 10 atm and temperatures from 3 to 15 K. Desired measurement accuracy is ± 0.05 atm for pressure and ± 0.05 K for temperature with a frequency response of a few milliseconds.

Pressure tap measurements are not practical for force-cooled systems because of the possibility of thermoacoustic oscillations. For this reason the transducer must be in direct contact with the coolant stream.

The operating principle of most pressure sensors appropriate to the temperature, pressure, and frequency range of interest is measurement of the deflection of an elastic member loaded by the pressure to be measured. Measurement of the deflection of the elastic member can be accomplished by bonded strain gages, inductive and capacitance methods, etc. Strain gage pressure transducers have already been discussed. Variable inductance devices are limited to types with no ferromagnetic components; all of the commercially available variable inductance devices known to the author contain ferromagnetic components. An adaptation of the moving coil LVDT described previously may be a satisfactory solution.

Two related types of pressure transducer^{9,24} based on work by C. T. Van Degrift are potential candidates for pressure measurements in force-cooled systems. The first is a tunnel diode oscillator which shifts in frequency as the capacitance in a reentrant cavity resonator changes with deflection of a diaphragm which forms the end wall of the cavity. The device works at low temperature and has been tested at room temperature to a field of 1.5 T. The device exhibited a quadratic field dependence with a 16 ppm frequency shift at 1.5 T. If extrapolated to 8 T, the shift would typically correspond to a pressure error of a few percent. A microwave cavity device, operating at considerably higher frequency and containing no nonlinear or field-sensitive elements, is being investigated by Arp et al. at NBS¹⁰ for use in superconducting transmission line work.

The problem of mass flow measurements near the transposed critical line appears difficult. Venturi meters have been used at cryogenic temperatures, and if satisfactory differential pressure transducers are available they should be considered. Under some operating conditions, it will be necessary to make a simultaneous measurement of absolute pressure and temperature and to use a previously determined calibration to derive the flow rate from differential pressure data. Turbine flow meters, which ideally

measure volume flow, have been used for cryogenic measurements but would also require simultaneous measurement of temperature and pressure to derive a density from which a mass flow could be obtained. Commercially available turbine meters, however, contain ferromagnetic elements and would not be acceptable for high field use. A number of other methods (acoustic, thermal, etc.) are potentially applicable to the problem.

Other Measurements

Other measurements required in the test are vacuum pressure, magnetic field, and, in pool-boiling systems, liquid helium level. Ionization gages are notoriously field-sensitive and cannot be used unless the field can be shielded to less than a few gauss. Thermocouple gages should be relatively field-insensitive.

For measurement of static magnetic fields, Hall probes are the best method. For measurement of pulsed field, flux coil voltage integrators are the simplest and cheapest method. Liquid helium level detection is straightforward even in fields up to 8 T with Efferson-type superconducting level-detectors.

Finally, for detection of slippage in the windings, acoustic emission techniques should be investigated. Superconducting coils frequently produce audible "cracking" noises as the current increases and the noises appear to be correlated with spikes in the voltage traces.

Signal Conditioning and Data Acquisition

The severe test environment requires that careful attention be paid to lead configurations and signal conditioning equipment. All of the sensors designated for use in the high field region are non-self-generating and require external excitation. For sensors with high level outputs for which either ac or dc excitation can be used, dc excitation is in general the preferred choice if: 1. inductive pickup can be kept to acceptable levels by twisting and/or transposition of the lead wires, and 2. thermoelectric voltages are small compared to the required voltage sensitivity. For some transducers (e.g., LVDTs), ac excitation is required by the principle of operation. For ac excitation, cable with minimum inductive and capacitive cross talk and/or loading is desirable, especially when the signal voltage has a significant out-of-phase component.

AC excitation should also be considered for sensors with low-level in-phase outputs (e.g., strain gages), because phase-sensitive detection methods filter out noise with frequency components lower than the excitation frequency. Care must be taken, however, to ensure that noise voltages at or near the carrier frequency do not mix with the carrier to produce slowly varying noise at the output. This situation can occur, for example, when a strain gage grid couples capacitively through the thin dielectric layer of backing and cement to a conductor excited with periodic voltage spikes (as from an SCR)

relative to the instrumentation ground. The SCR's, which are fired periodically, produce spikes which may contain harmonics of the carrier frequency; a slowly varying dc output is observed from the carrier amplifier as the carrier and SCR firing drift in phase relative to each other. This problem can be ameliorated by picking a carrier frequency which is not a low harmonic of the SCR spike pattern.

The large number of channels with various signal conditioning requirements (greater than 100 in the case of individual coil tests and probably even greater in magnet system tests) and the frequency response requirement lead to a choice of an amplifier-per-channel signal conditioning system with a fast (75 kHz throughput) high-level analog-to-digital converter feeding into a minicomputer system equipped with magnetic storage devices. The minicomputer should have a floating-point processor to allow real-time conversion of signal voltages into engineering units according to internally stored calibration routines and multichannel display capability.

CONCLUSIONS

Making the cryogenic measurements necessary for the development of superconducting magnet systems for the controlled thermonuclear research program will require a large-scale effort and in many cases state-of-the-art techniques. Measurement devices and techniques used in small-scale physics laboratory experiments or in other development engineering areas will have to be themselves tested before they can be used with confidence in large coil tests. In some cases (e.g., strain measurements in high fields and changing temperatures), reliable measurements do not appear possible with available techniques and further development work will have to be performed if these measurements are judged essential to the development program. Even when considering the use of proven measurement techniques, a cost/benefit analysis must be made, comparing the need of a particular measurement and the required accuracy with the required number of channels and the cost per channel.

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