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MASTER

THE USE OF HIGH CURRENT DENSITY SUPERCONDUCTING COILS IN FUSION DEVICES

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THE USE OF HIGH CURRENT DENSITY SUPERCONDUCTING COILS IN FUSION DEVICES

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Abstract

Superconducting magnets will play an important role in fusion research in years to come. The magnets which are currently proposed for fusion research use the concept of cryostability to insure stable operation of the superconducting coils. This paper proposes the use of adiabatically stable high current density superconducting coils in some types of fusion devices. The advantages of this approach are much lower system cold mass, enhanced cryogenic safety, increased access to the plasma and lower cost.

The use of adiabatic stability instead of cryostability in superconducting coils permits one to design coils with indirect forced two-phase cooling. The major problem with high current density superconducting coils is quench protection. The Lawrence Berkeley Laboratory system of quench protection is based on the use of shorted secondary windings which couple the current out of the coil and causes the entire magnet to turn normal. LBL has demonstrated this technique in a number of large test coils and in a 2.0 meter diameter by 3.3 meter long solenoid (warm dimensions) for use in a high energy physics experiment. Applications for high current density coils to fusion research are given.

Introduction

Most of the work on superconducting magnets for fusion devices has been contrived on the basis of cryostability. Virtually all large superconducting magnets with stored energies above 3 MJ use cryostabilized conductors (the CELLO magnet built by Saclay and the TPC magnet at LBL are exceptions). The concept of cryostability implies there is sufficient helium in direct contact with the superconductor to insure good heat transfer to keep instabilities in the superconductor from driving the whole magnet normal.[1]

Until recently, intrinsically stable large superconducting magnets have been considered risky. The use of high current density superconductors offers a number of advantages in large d.c. fusion devices. These advantages include:

1) Reduced cold mass and size.
2) Increased access to the experiment with neutral beams, instrumentation and shielding.
3) More efficient helium cooling with enhanced cryogenic safety.
4) Lower cost.

The use of high current densities requires careful attention to problems in quench protection, magnetic stress and strain, and training.

This paper discusses quench protection and its implications in the choice of superconductor for magnets of large stored energies. Superconductor current density and stored energy play a direct role in the stress and strain problem encountered in large coils. The maximum superconductor current density is directly related to the maximum allowable strain of the coil system. Training will be discussed along with its relationship to overall magnetic strain and the design of the coil package. Last but not least, the concept of forced two-phase cooling is discussed in relation to fusion devices.

Quench Protection

"Cryostable magnets don't quench." This statement has been uttered more than once. There is ample evidence which shows that this is not true, because a number of large cryostable magnets have quenched. Since there is the possibility of quench, even cryostable magnets must have quench protection systems. The design goal in cryostable magnets is that they will not quench. Cryostability implies a negative normal zone propagation velocity. On the other hand, adiabatically stable magnets which operate at high current densities (above $10^8 Am^{-2}$) should have maximum positive normal zone propagation rate.

The first rule for quench protection is *keep the helium out* of direct contact of superconductor.

1) Helium has a high specific heat. It will reduce the velocity of normal region propagation. When a magnet quenches, one wants the magnet to go normal as fast as possible.
2) Helium in direct contact with the superconductor can contribute to voltage breakdown. Once sparking or arcing occurs within a coil, the whole question of quench protection becomes academic; one has no coil left to protect.
3) Helium within a coil does not contribute to the strength of the coil.

In general, the higher the stored energy of the magnet the lower the current density in the superconductor matrix. The superconductor matrix current density is directly related to the magnet stored energy because of conditions imposed on the system due to the quench protection system. Figure 1 is a plot showing the matrix current density J as a function of the magnet stored energy E. Almost without exception the points in Fig. 1 lie below and to the left of a line which is the product $EJ^2 = 10^{23}\ JA^2m^{-4}$ (mks units).[2] Notable exceptions to the rule are the LBL thin solenoids.

The limit of $EJ^2 = 10^{23}\ JA^2m^{-4}$ is imposed by the burnout limits of the superconductor and the voltage and current limit which are set for various quench protection schemes[3]

$$EJ^2 = V_M I_O F^*(T_M) \frac{r+1}{r} \qquad (1)$$

where I_o is the design current in the coil, V_M is the maximum allowable voltage in the coil during a quench, r is the normal metal to superconductor ratio in the matrix, and $F^*(T_M)$ is a function which relates the hot spot temperature T_M to other parameters. Without going into alot of detail, $F^*(T_M)$ is defined as follows:

$$F^*(T_M) = \int_0^{T_M} \frac{C(T)}{\rho(T)}\, dT = \frac{1+r}{r} \int_0^{\infty} J^2 dt \qquad (2)$$

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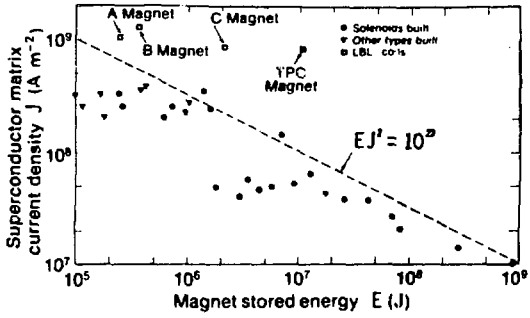

Fig. 1. Superconductor matrix current density vs. magnetic stored energy for a number of superconducting magnets.

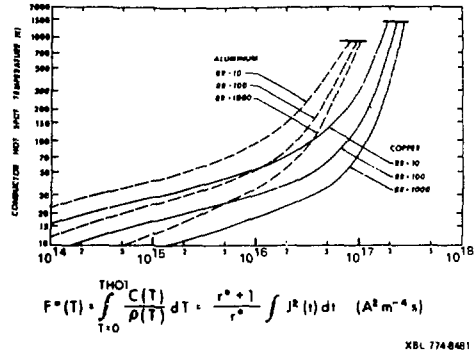

Fig. 2. Superconductor hot spot temperature T vs. F(T)*

where C(T) is the specific heat per unit volume as a function of temperature T; ρ(T) is the electrical resistivity as a function of T; t is time; r and T_M have been previously defined. Using Eq. (2), hot-spot temperature can be related directly to the decay of the current in the normal region. Figure 2 shows the relationship of F*(T) and T for various resistance ratio grades of aluminum and copper. From Fig. 2 we can see that F*(T) for safe quenching is about 10^{17} for copper based superconductors and 4×10^{16} JA^2m^{-4} for aluminum based superconductors. For typical cryostable magnets the product of $V_M I_o$ is typically 10^6W.

The EJ^2 limit can be raised above 10^{23} JA^2m^{-4} in adiabatically stabilized coils. One method is to insulate the magnet so that the maximum quench voltage can be increased. Potting the coil in epoxy and glass permits one to increase the EJ^2 limit by a factor of three to five. The use of a closely coupled secondary circuit permits one to operate well above the $EJ^2 = 10^{23}$ limit. This has been well demonstrated in the LBL thin solenoids.[2,4] It is important that the secondary circuit have a long time constant and also be well coupled to the primary circuit.

A well coupled long time constant secondary circuit will affect the quench process in the following ways:

1) During a quench, the current in the coil is shifted to the secondary circuits, reducing the integral of J^2 with time.[5]

2) The secondary circuit will absorb a substantial part of the magnet stored energy. For example, if one coil in a series multicoil magnet system quenches, the secondaries in all of the coils will absorb the stored energy.

3) Transient voltages are reduced.

4) The shorted secondary causes the magnet to become normal faster than it would through normal zone propagation. We call the process "quench-back".[6] If one coil in a multicoil magnet system quenches, quench-back would cause the other coils to quench.

5) The use of shorted secondary circuits enhances the performance of some unconventional quench protection systems, such as the varistor resistor and the so-called current pulse discharge system.[7]

Close coupling between the magnet coil circuit and the secondary circuit is important if one wants to operate a large superconducting coil at high current density in the superconductor matrix. As a general rule;

$$\varepsilon E J^2 < 10^{23}\ JA^2m^{-4} \qquad (3)$$

where ε is one minus the coupling coefficient between the primary and secondary circuits. For a simple system with two coupled circuits,

$$\varepsilon = \left[1 - \frac{M^2}{L_1 L_2} \right] \qquad (3a)$$

where L_1 is the inductance of the primary circuit, L_2 is the inductance of the secondary circuit, and M is the mutual inductance between the two circuits. Equation (3) applies to systems with dynamic quench protection systems. In at least some cases, the shorted secondary circuit is all the quench protection that is necessary. One must look at the "quench-back" process in order to determine whether or not the shorted secondary circuits alone will protect the magnet. The LBL thin coils show that a shorted secondary can be used alone when EJ^2 is substantially above 10^{23} JA^2m^{-4}.

The use of a shorted secondary circuit implies that the superconducting coil system must be D.C. If the secondary circuit is truly shorted and if it has a long time constant, the charge rate of the superconducting coil is limited by resistive heating due to currents induced in the secondary circuit. One can design a secondary circuit which has turns which are insulated from one another forming a secondary coil. Diodes put across the leads of the secondary circuit permit the magnet to be charged at a much faster rate. This approach is being used in the LBL thin solenoid for the time projection chamber (TPC) experiment.[8] It is doubtful that the shorted secondary approach is appropriate for large magnets which must be charged quickly. Experimental work at LBL suggests that the EJ^2 limit can be extedned to values as high as 10^{25} JA^2m^{-4}. The current density limit in large magnets for fusion may not be imposed by quench protection but instead magnetic stress in the coil package may become the controlling factor.

Stress and Strain

Stress in a large superconducting magnet is related directly to current density in the conductor, coil average radius (in a solenoidal or toroidal configuration) and central magnetic induction. In large high current density magnets the magnetic forces must be

carried by the superconductor and support elements. The stress problem is often reduced to one of controlling the strain. High current density potted coils can, as a general rule, carry more stress than loose cryostable coils. The superconductor yield stress is higher when the copper to superconductor ratio is low. In addition, the elastic modulus is higher in all directions. (In a solenoid the Z and R moduli are much higher when the coil is potted.)

It is difficult and often misleading to give general design rules which apply to all magnets, but one can present first order results based on experiments. In solenoids, single coils or toroidal configurations the stored energy per unit coil length along the axis E_L and matrix current density J can be related to the stress in the superconductor. To first order,

$$\Delta = E_L J^2 \approx \frac{100\ \sigma_{av}}{\mu_0} \qquad (4)$$

where σ_{av} is the design average hoop stress in the conductor and $\mu_0 = 4\pi \times 10^{-7}$ (the magnetic permeability of air). For a continuous solenoid or toriod $\Delta \approx 2 \times 10^{24}\ JA^2m^{-5}$. For a system of lumped coils which have enhanced field regions $\Delta \approx 1 \times 10^{24}\ JA^2m^{-5}$, the values of Δ given assume that strain within the coil package is limited to about 0.2%.

Equation (4) assumes that the magnetic stress is shared between the superconductor and other elements of the coil system (such as winding mandrels, cooling tubes, support structure, etc.). The superconductor is assumed to carry about 30% of the magnetic force. Thin superconducting coils built at LBL have operated safely at $E_L J^2$ limits up to $2 \times 10^{24}\ JA^2m^{-5}$.[2,4,8,9]

It should be noted that Eq. (4) is a stress limit while Eq. (2) is a quench limit. Either may be dominant in determining the design current density for the superconducting matrix. One should be careful when using Eq. (4). A detailed stress analysis (particularly in lumped coil systems) is required to make sure a large coil will stay together. It becomes very important to look at stress concentrations which have an important bearing on the training of the coil system.

Training

Training has been troublesome in high current density coils. The larger the coil the more training becomes a problem. Coils with a solenoidal configuration train less than coils of other configurations. (For example, dipole and quadrupole coils have had particularly bad training problems.) Recent studies of training have found it to be total coil strain dependent.[10,11]

There are a number of approaches to eliminating training. In general, these approaches fall into two broad categories. The first is complete impregnation of the coil so that the conductor does not move. The opposite puts liquid helium in contact with the conductor so that if motion does occur the energy is absorbed by the helium. In large coils where quench protection is a problem one cannot have helium in the winding. Therefore the method of impregnation of the coil becomes very important. The author feels that the epoxy used as an impregnant may be less important than the technique used to apply or impregnate the coil with epoxy.[12] There are other views on this matter.[13,14]

Once one has selected epoxy impregnation, one must make the structure so that stress concentration is reduced and sudden motions are avoided. The author recommends the following:

1) Vacuum impregnate the epoxy rather than using a wet lay-up technique or B stage epoxy technique.[10]

2) Choose a hard epoxy. It may be more prone to cracking but its modulus is higher and its total thermal contraction coefficient is lower.[10,12,13]

3) Fill voids in the structure. The impregnation has to be planned to make sure all voids are filled.[12]

4) Fill all unfilled regions in the epoxy (regions larger than 0.5 mm in size) with glass or dacron. This arrests crack formation and permits one to go to higher strains without training.[11]

5) Avoid sharp corners which can produce stress concentrations which will initiate cracking.[12]

6) Avoid the use of cabled or braided conductors. Monolytic conductors with rounded corners will have less stress concentration around them and will have a higher modulus in all directions.

7) Pre-strain the conductor about 0.2 to 0.3% before or during winding. It tends to get rid of the microplastic deformation of the superconductor.[11]

8) Pre-strain the whole coil structure if possible.[11]

9) Set the design current to less than 80% of the critical current along the load line if possible.

Some of the steps recommended in the previous paragraph are considered controversial. The LBL experimental solenoids use most of the steps outlined above. Training was observed in one of the solenoids when an epoxy joint failed.[4] That solenoid trained to critical current in five quenches. No training has been observed in thin solenoids since the first one was built. It is possible that the LBL thin solenoids are not large enough to see the effects of training. However, the LBL solenoids do operate near the stress limits set by Eq. (4) and they do operate at EJ^2 limits substantially above $10^{23}\ JA^2m^{-4}$.

Forced Two Phase Cooling

The major problem which is shared by all large superconducting magnetis is the cryogenic system. The conventional method used to cool most large magnets is helium bath cooling. The larger the magnet system the more cumbersome bath-cooling becomes. Many large systems have each coil in a separate cryostat. This takes space and the problem of cryogenic distribution becomes apparent. Large systems have have many thousands of liters of liquid helium which must be stored. The time needed to cool down a large bath-cooled system has been long in most of the large magnets built to date. Since the heat of vaporization and density of helium is small, a large quantity of gas is formed when the liquid helium is boiled in a quench or some other accident which results in large heat flow into the helium bath. Cryogenic safety and pressure relief systems become an important factor in the design of a bath-cooled device.

Since high current density coils do not require helium in the winding, a forced cooling system will provide all the cooling that is needed. The forced-cooled system avoids nearly all of the major problems which are encountered in a large bath-cooled system. The advantages of forced cooling are:

1) Cooldown is well controlled because the helium flows in a well defined path.

2) The mass of a forced-cooled system is less than a bath cryostat.

3) The amount of helium in direct contact with the magnet coil is minimized. Quenches are well controlled. Cryogenic safety is enhanced.

Most of the tubular cooling systems which have built use supercritical helium. (The helium pressure is above 2.25×10^5 Pa.) Two-phase cooling offers advantages over single phase cooling. They are:

1) Two-phase cooling implies boiling in the pipe. Lower operating temperatures occur in a two phase system. The system exit temperature is lower than the entrance temperature.

2) The helium mass flow in the circuit for a given amount of refrigeration is lower for a two phase system than a single phase system. The pressure drop is often lower.

3) Boiling two-phase helium can absorb large local heat fluxes without changing the temperature of the stream.

The major objections to two-phase cooling has been the problem of flow oscillations. The choice of mass flow per unit area, tube length and flow circuit configuration can eliminate flow instabilities.[15]

The most important consideration in the design of two-phase flow systems is the elimination of parallel paths. The simple series flow system is most desirable because it has almost no control problems. In order to reduce the flow circuit pressure drop, it is desirable to minimize the amount of gas phase helium into the flow circuit. Two kinds of systems can be used to circulate low quality helium (quality is defined in the same sense as it is for steam) through the magnetic cooling tube. They are: 1) a liquid pump used as a circulator, or 2) the refrigerator compressors used as a circulator. Both systems, which are shown in Fig. 3, use a heat exchanger in a helium bath to insure that the helium will enter the cooling system at or near the saturated liquid line. The pot of liquid can be used to control the cooling system, hence LBL calls this liquid dewar the control dewar.

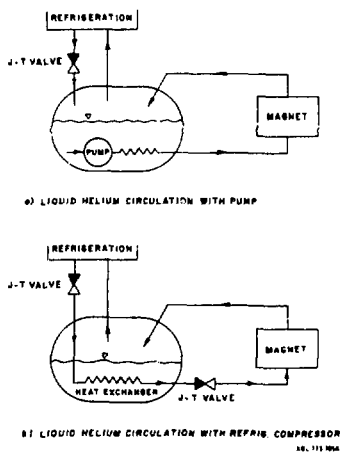

Fig. 3. A schematic of two types of two phase helium circulation for tubular cooled superconducting magnets.

The use of a control dewar with its heat exchanger eliminates the need for large quantities of liquid helium at or near the magnet coils. LBL has demonstrated that gas cooled electrical leads can be run directly off the forced flow circuit without detriment to either the refrigeration system or the leads themselves. LBL experiments have been operated with the control dewar as far away as 20 m from the magnet itself. Refrigeration can be delivered at temperatures between 4.5 and 4.8 K (when the refrigeration pressure or suction pressure is above 1 atm and the control dewar temperature is below 4.4 K) provided the mass flow in the flow circuit is high enough (about 1 gs^{-1} for each 18 W required), and the heat exchanger in the control dewar is covered with liquid helium. For example, refrigeration can be delivered to a magnet system with a helium pump alone provided the magnet system is already cold. The TPC experiment superconducting magnet, which is to be tested during the winter of 1980, has the option of using either a helium pump or the refrigerator compressor as a circulator. Both systems have been tested successfully on a dummy load.

The cooling tubes for a forced flow cooling system can be imbedded into the epoxy cast coil structure. Heat transfer to the helium is by conduction from the parts of the coil structure remote from the cooling tubes. As long as the a.c. losses or charging losses are spread throughout the coil package, this approach works. The LBL thin solenoid test magnets have successfully used cast tubes which carry the two phase helium.[4,15]

Applications of High Current Density Magnets to Fusion

This paper has shown that forced cooled high current density magnets for fusion will be smaller in both dimension and mass. Cryogenic services can be moved well away from the magnet itself. As a result, there is increased access to the plasma and there is more room available for radiation and thermal shielding. The concept of high current density conductors should be extended to magnet systems with stored energy up to and beyond 100 MJ.

Large systems of superconducting magnets can be run in series, thus eliminating extra electrical leads and refrigeration. The concept of the shorted secondary permits one to build magnet systems consisting of many coils hooked in series. A quench in one coil drives all the others normal through quench-back.

The author does not propose building magnets as large as LCP without considerable testing. More modest D.C. magnet systems look like attractive candidates for the high current density technique. Examples include the superconducting SURMAC proposed by UCLA,[16] multipole fusion systems proposed by TRW and others,[17,18] and the EBT systems now under study at a number of different places.[19]

The progress which has been made in recent years in high current density coil technology makes it worthy of consideration for study for fusion devices. The gain in accessibility to the plasma, reduction magnet system mass and a potential reduction in cost make it a worthwhile endeavor to study high current density superconducting coil technology.

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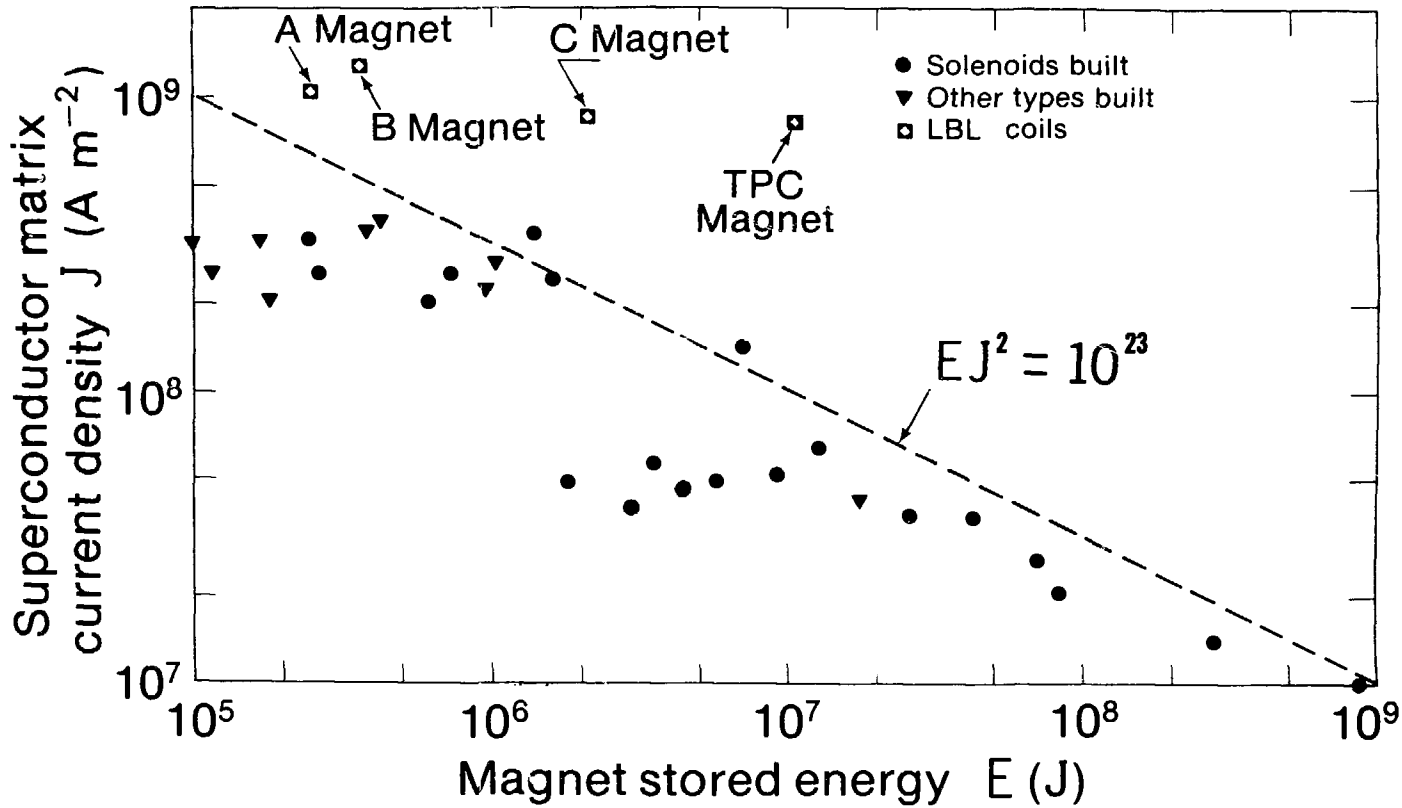

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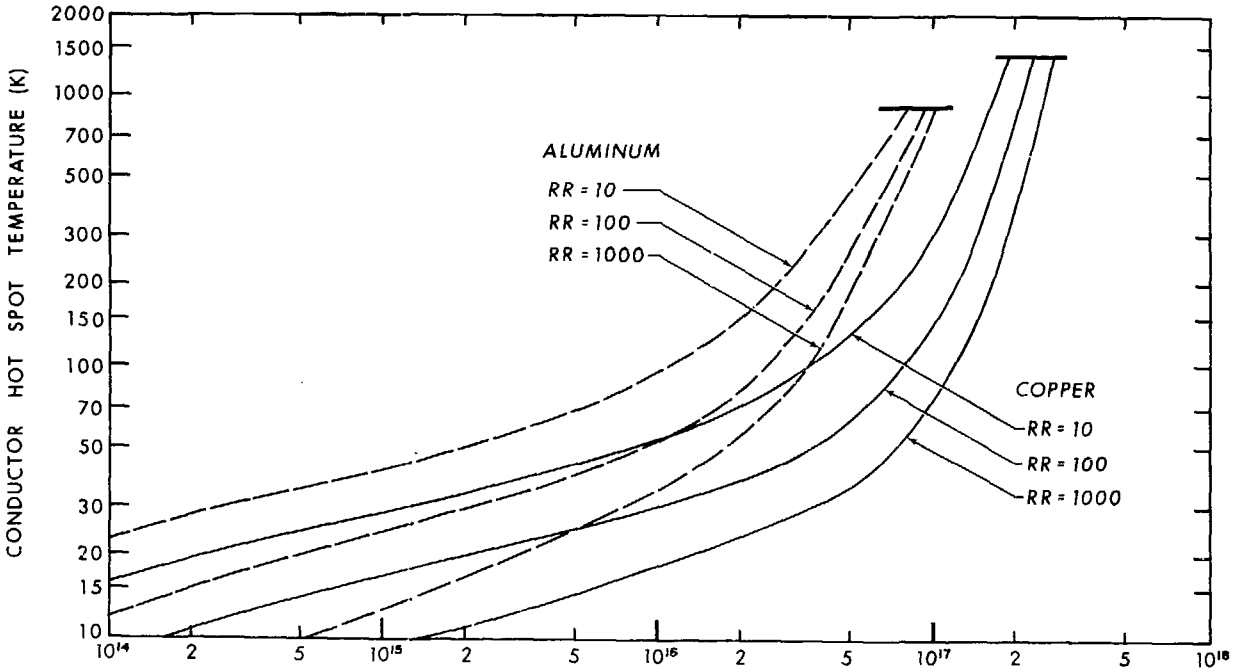

$$F^*(T) = \int_{T=0}^{THOT} \frac{C(T)}{\rho(T)}\, dT = \frac{r^* + 1}{r^*} \int J^2(t)\, dt \quad (A^2 m^{-4} s)$$

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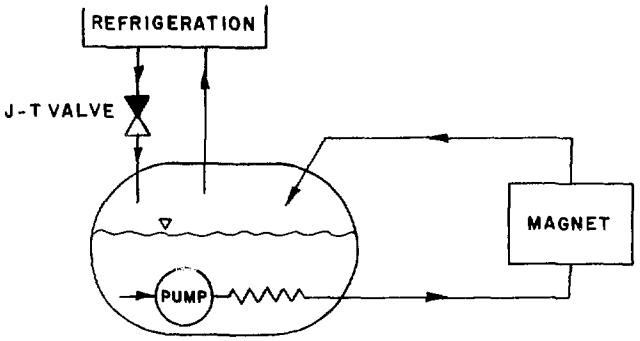
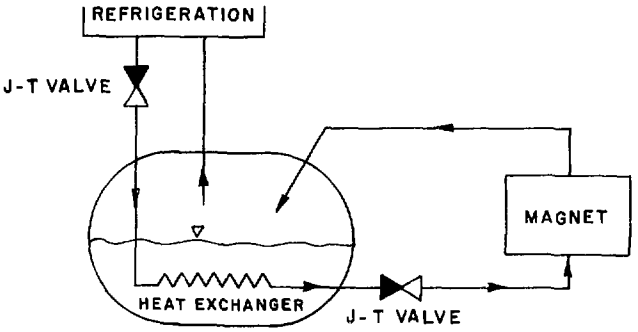


a) LIQUID HELIUM CIRCULATION WITH PUMP



b) LIQUID HELIUM CIRCULATION WITH REFRIG. COMPRESSOR

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