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PERFORMANCE OF CERAMIC SUPERCONDUCTORS IN MAGNETIC BEARINGS*

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SUMMARY

Magnetic bearings are large-scale applications of magnet technology, quite similar in certain ways to synchronous machinery. They require substantial flux density over relatively large volumes of space. Large flux density is required to have satisfactory force density. Satisfactory dynamic response requires that magnetic circuit permeances not be too large, implying large air gaps.

Superconductors, which offer large magnetomotive forces and high flux density in low permeance circuits, appear to be desirable in these situations. Flux densities substantially in excess of those possible with iron can be produced, and no ferromagnetic material is required. Thus the inductance of active coils can be made low, indicating good dynamic response of the bearing system.

The principal difficulty in using superconductors is, of course, the deep cryogenic temperatures at which they must operate. Because of the difficulties in working with liquid helium, the possibility of superconductors which can be operated in liquid nitrogen is thought to extend the number and range of applications of superconductivity. Critical temperatures of about 98 degrees Kelvin have been demonstrated in a class of materials which are, in fact, ceramics. Quite a bit of public attention has been attracted to these new materials.

There is a difficulty with the ceramic superconducting materials which have been developed to date. Current densities sufficient for use in large-scale applications have not been demonstrated. In order to be useful, superconductors must be capable of carrying substantial currents in the presence of large magnetic fields.

This paper investigates and discusses the possible use of ceramic superconductors in magnetic bearings and identifies requirements that must be achieved by superconductors operating at liquid nitrogen temperatures to make their use comparable with niobium-titanium superconductors operating at liquid helium temperatures.

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INTRODUCTION

This paper analyzes the performance of ceramic superconducting materials in a magnetic bearing application. The use of superconducting materials in magnetic bearings is justified when high performance (reduced runout) is required. The design, operation, and performance of a magnetic bearing system which employs a low temperature superconducting material (niobium-titanium) is presented as a baseline (ref. 1). The general characteristics of high temperature ceramic materials are discussed and current density is seen as the primary limit of this technology. Using the laws of electromagnetic component scaling, the performance of the baseline magnetic bearing system is estimated as a function of the achievable current density. The scaling of the auxiliary components of the bearing system to liquid nitrogen temperatures is also considered. An operating current density on the order of one tenth that of niobium-titanium superconductors appears to provide an equivalent system cost.

USE OF SUPERCONDUCTORS IN MAGNETIC BEARINGS

An opportunity exists for innovative bearing concepts to be employed in machine tool spindles. These advanced bearings concepts will allow the rotor to be more accurately positioned with respect to the stator. This reduced runout is particularly desirable in high-precision machining applications such as the manufacture of large-scale optical surfaces where rotor position accuracy on the order of a micro-inch is desired (ref. 1).

Magnetic bearings employing conventional technology have been employed in many rotating applications which require modest performance levels. Actively controlled magnetic bearings will maintain the position of the rotor to the accuracy level which can be measured by the sensors. Conventional approaches to magnetic bearing design, however, are limited in position accuracy by non-linearities, bandwidth, and the ability to apply large forces and torques.

SatCon Technology Corporation has recently completed a study directed toward investigating the role of superconducting materials in a machine tool magnetic bearing system and defining a design which could be used to roughly duplicate the air bearing system of an existing machine tool spindle in a high-precision machining operation. Superconducting magnetic bearings were shown to offer advantages in terms of linearity, bandwidth, weight, and load-carrying capability which make them superior to more conventional approaches.

The lack of a soft-iron magnetic circuit leads to a linear force versus control current characteristic and improved response time (lower inductance). The lack of soft-iron allows the weight of the magnetic circuit to be drastically reduced. The power consumption of normal control coils in a superconducting magnetic bearing is relatively modest due to the high magnetic fields produced by the superconducting source coil. There is no power consumed in maintaining this magnetic field, and the control coils which interact with it become more effective because of the elevated field levels. The development of this magnetic bearing design will provide a necessary element for high-precision machining systems when it is integrated with high resolution sensing elements.

BASELINE MAGNETIC BEARING (ref. 1)

Figure 1 shows the combination of a single superconducting coil (the "source coil") and eight non-superconducting coils (the "control coils") which comprises the system. The axis of the source coil is along the spin axis of the rotor. Four control coils are located at each end of the rotor displaced radially from the spin axis of the rotor and are spaced 90 degrees from each other. The axis of each control coil is perpendicular to that of the source coil.

The source coil operates in persistent mode (without an electrical input). This is a condition in which the current in the coil persists because of the lack of resistance in the superconducting material. Forces and torques are produced by the interaction of the current in the control coils and the magnetic field produced by the source coil.

The electromechanical interaction is independent of which of the two components (source coil or control coils) rotates. Other engineering considerations, however, affect this decision. If the superconducting coil is fixed to the rotor, then some mechanism for transporting cryogenic fluids, such as liquid helium, across the rotating interface must be designed. In addition, the stresses due to rotation will superpose on those due to the excitation of the source coil and will have to be supported by an additional structural member. If, however, the control coils are fixed to the rotor, then electrical excitation must cross the rotary interface. Signal- and power-level couplings (slip rings and brushes) have been developed for a number of applications and are considered a state-of-the-art technology. In addition, the sensors for the control system will also rotate. This simplifies the design of the control system and avoids an additional transformation of coordinates. These decisions will add some mass to the rotor.

OPERATION OF THE SYSTEM

Figures 2 and 3 show the excitation of the control coils which leads to a pure thrust force on the rotor. Figure 2 shows a section through the x-z plane, while Figure 3 shows the equivalent y-z plane section. The z-axis is defined as the spin axis of the rotor (the axis of the source coil). The figures also show the north and south poles of each of the coils. One way to visualize the interaction of the coils is to think of the attraction of opposite poles and repulsion of like poles. Figures 4 and 5 show equivalent diagrams for the cases of pure lateral loading along the x-axis and pure torsional loading about the y-axis. In these two cases, the coils whose axes lie in the y-z plane are not excited. The excitation for lateral loading along the y-axis and torsional loading about the x-axis are similar and are not shown.

PERFORMANCE OF THE BASELINE SYSTEM

Table 1 presents working and ultimate loads for the baseline superconducting magnetic bearing. These were derived from the rated loads for two typical air-bearing machining spindles at a nominal operating pressure of ten atmospheres. Table 2 presents the performance characteristics (weight and power consumption) for the superconducting magnetic bearing system. Loads of the magnitude required here would require a substantial conventional magnetic bearing structure to carry the magnetic fields at the saturation flux density of common core materials. In addition, a great deal of power would be consumed in order to provide the source field.

CERAMIC SUPERCONDUCTING MATERIALS

The most common superconducting material in use today is niobium titanium. This is a strong, ductile material which is commonly fabricated into composite conductors with pure copper or mixed copper alloy matrices. At the boiling point temperature of liquid helium (4 degrees Kelvin) critical current and flux densities are on the order of 100 MA/m^2 and 5 Tesla respectively. There is a great deal of design experience with this material. The less commonly used niobium-tin material will maintain a superconducting state up to a critical flux density of about 12 Tesla. This material, however, is extremely brittle and therefore much more difficult to fabricate into coils than niobium titanium. Extremely high performance is available from niobium germanium aluminum superconductors. This material has a critical temperature which is slightly greater than 20 degrees Kelvin, but it is virtually impossible to fabricate into wires (ref. 2).

The principal difficulty in using available superconductors is, of course, the deep cryogenic temperatures at which they must operate. Because it takes several hundred Watts of refrigerator input power to remove one Watt of thermal dissipation of heat leak from a space operating at the temperature of boiling liquid helium, the use of superconductors operating at that temperature is impractical for all but the most demanding applications.

Recent advances in "high-temperature" superconducting materials have prompted engineers to consider the use of this emerging technology in many applications including magnetic bearings. Superconducting materials could have a substantial impact on the design of these devices. Figure 6 shows a timeline of the development of superconducting materials in terms of the critical temperature (ref. 3). Since the winter of 1987, the technical (ref. 4) and popular literature (refs. 5, 6, and 7) have contained many articles which discussed progress in "high-temperature" superconductors. Critical temperatures greater than 90 degrees Kelvin have been demonstrated in a newly discovered class of superconducting materials which are, in fact, ceramics. The possibility of operating these materials in boiling liquid nitrogen (a temperature of 77 degrees Kelvin) has been raised. Physicists are quick to note that there is currently no theory which precludes a material from being a superconductor at room temperature and research continues toward that goal.

The promise of higher operating temperatures is tempered by the relatively low useful current densities which have been demonstrated and by the nature of the materials themselves. In order to be useful, superconductors must be capable of carrying substantial currents in the presence of large magnetic fields. Being ceramics, they are brittle and difficult to form into useful conductors. In addition, the class of materials which has been demonstrated is highly reactive, sensitive to water and difficult to make connections to.

Clearly there are a number of technical barriers to be overcome before ceramic superconductors may be employed in actual engineering designs. We do not focus on these technological issues however, but rather on the useful current density. We will show that substantial but not spectacular current densities are required to make useful magnetic bearings with ceramic superconductors operating at the boiling point temperature of liquid nitrogen.

SCALING STUDY

Based on the results of a detailed sizing study of the superconducting bearing, a baseline source coil design was established. This niobium-titanium source coil for the machine tool spindle bearing is described in Table 3. It is used as the "base case" for this study. For the purpose of this study it was assumed that a suitable figure of merit for the magnet is its dipole moment. Thus, the ceramic superconductors studied here all had the same dipole moment. We also assumed the same magnet shape (radius and length ratios), so that all magnet linear dimensions vary as the inverse fourth root of the current density. In this way it was possible to estimate required magnet size as a function of current density. In this exercise, no attention was paid to flux density. This is thought to be alright because the reference case operates at a relatively low flux density (a maximum of about 4 Tesla).

Coil Sizing and Conductor Cost

Figures 7 and 8 present the dimensions for the coil and the dewar as a function of the current density in the conductor. A constant insulation thickness of two inches (5 cm) in all directions is assumed. The magnet becomes quite large at current density levels less than a few thousand Amps per square centimeter.

The effective conductor density and cost were estimated to be 8900 kilograms per cubic meter and $ 220 per kilogram respectively. There is no reliable data, of course, on what stabilized ceramic composite conductor might weigh or cost. Modern metallic conductors come in a wide variety of configurations, but these numbers are thought to be not terribly far from correct. Figures 9 and 10 show the mass and material cost for the magnet coil as a function of the conductor current density. A horizontal line in Figure 10 shows the material cost for the baseline niobium-titanium coil.

Refrigerator Sizing and Cost

The refrigerator capacity was estimated by calculating the heat leak from the dewar. The largest components of the heat leak rate are thermal conduction in magnet supports (assumed to be stainless steel wires) and thermal radiation between the inner and outer walls of the dewar. Support cross-sectional area was estimated by using the maximum loads to be delivered by the bearing plus the weight of magnet and shaft system. The support length was estimated based on the thickness of the magnet and its insulating system. No intermediate support cooling was assumed. Figure 11 shows estimates for these two heat leak components and their sum.

Refrigerator input power and cost were estimated from available commercial data. It should be pointed out that there is not a lot of data on refrigerator efficiencies or costs, particularly in the very small sizes of liquid nitrogen temperature refrigerators that are predicted here. The estimates that have been made are, however, quite conservative and are shown in Figures 12 and 13. Figure 13 also shows the cost of the refrigerator for the baseline niobium-titanium coil. It should be possible to reduce the liquid helium system heat leak by careful engineering, and this would tend to reduce the apparently substantial advantage of the higher temperature materials. The bottom line seems to indicate that the cost of refrigeration does not dominate this bearing system.

Total System Cost

Figures 14 and 15 show the total cost of the ceramic superconducting source coils (conductor and refrigerator) and compares them with that of the niobium-titanium coil. Figure 14 attempts to answer the question: "What performance would a high temperature superconductor have to have to make it as attractive as niobium titanium for this application?" By trial and error, we estimate that the conductor would have to exhibit a useful current density of 9,000 Amps per square centimeter, or a little less than one tenth that of the niobium-titanium coil. Figure 15 shows that even if it were possible to make a superconductor with an operating temperature of 77 degrees Kelvin but otherwise having the properties of niobium-titanium, there would be a benefit in the refrigeration system, but that benefit would not be overwhelming.

Low performance but high temperature superconductors do not seem to be applicable here. Even at 1,000 Amps per square centimeter, the amount of superconductor required is large enough to dominate the cost of the refrigerator and make the liquid helium temperature system more attractive. It should, of course, be pointed out that this conclusion relies on the cost of superconductor. If it turns out that the high temperature superconductor can be made for, say $ 50 per kilogram, this conclusion would be different.

RESULTS

This study was only a first cut at this particular problem. We made, for example, no attempt to optimize the magnets for the high temperature materials, and it is possible that a more thorough design would have found a solution more favorable to high temperature materials. On the other hand, we were quite conservative in our estimates of low temperature heat leak in the liquid helium temperature base case.

It is also important to consider the fact that, aside from the costs which can be quantified relatively easily, there are engineering costs which increase because of the difficulties in using liquid helium. It always involves high vacuum systems, thermal radiation shields and transfer piping which is complicated. Liquid helium systems are vulnerable to contamination because all other substances are solid at such low temperatures. Air is either abrasive or obstructive, depending on which is more inconvenient. We have not attempted to estimate the increased costs associated with the complexity of the liquid helium system, nor the effects on reliability of the lower temperatures.

A most important result, however, is due to the fact that thermal isolation techniques are quite advanced, so that even coils operating at liquid helium temperatures can have very low heat loss. Because of this, the penalty associated with low temperature operation is relatively weak. The result is that, in order to offer practical benefits over niobium-titanium, ceramic superconductors must exhibit reasonably high current densities.

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7. Time Magazine, May 11, 1987, pp. 64-75.

TABLE 1. - MAGNETIC BEARING LOAD REQUIREMENTS

	Ultimate	Working
Thrust	5,340 N	2,670 N
Lateral	445 N	223 N
Torsion	180 Nm	90 Nm

TABLE 2. - BASELINE MAGNETIC BEARING PERFORMANCE

<u>Weight</u>		
Source Coil	57 kg	
Cryostat	<u>24 kg</u>	
Stator Total	81 kg	81 kg
Control Coils	105 kg	
Structure	<u>26 kg</u>	
Rotor Total	131 kg	<u>131 kg</u>
System Total		212 kg
<u>Power Consumption</u>		
Thrust Loading		750 W
Lateral Loading		390 W
Torsion Loading		425 W

TABLE 3. - BASELINE SOURCE COIL

<u>Coil</u>	
Inner Diameter	25.4 cm
Outer Diameter	31.0 cm
Axial Length	25.4 cm
Conductor Current Density	9,300 A/cm^2
Mass	57 kg
<u>Dewar</u>	
Insulation Thickness	5.1 cm
Mass	24 kg
<u>Overall</u>	
Clear Bore Diameter	15.2 cm
Outer Diameter	41.1 cm
Overall Length	34.3 cm
Mass	81 kg

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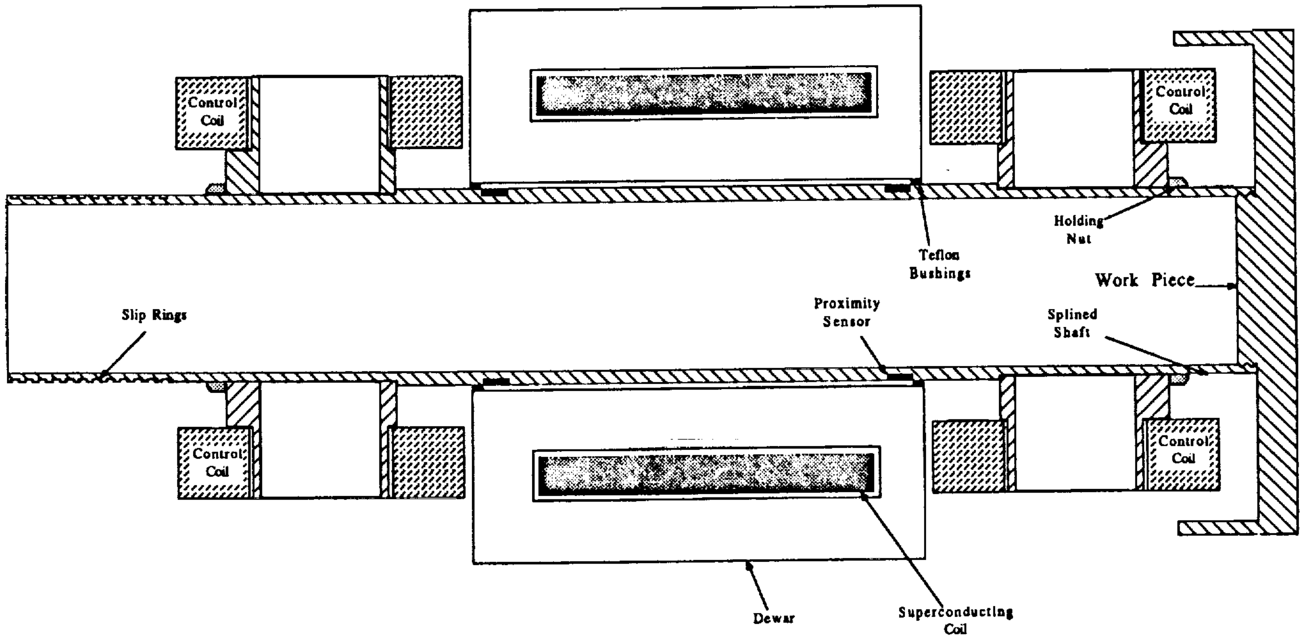

Figure 1. Baseline superconducting magnetic bearing.

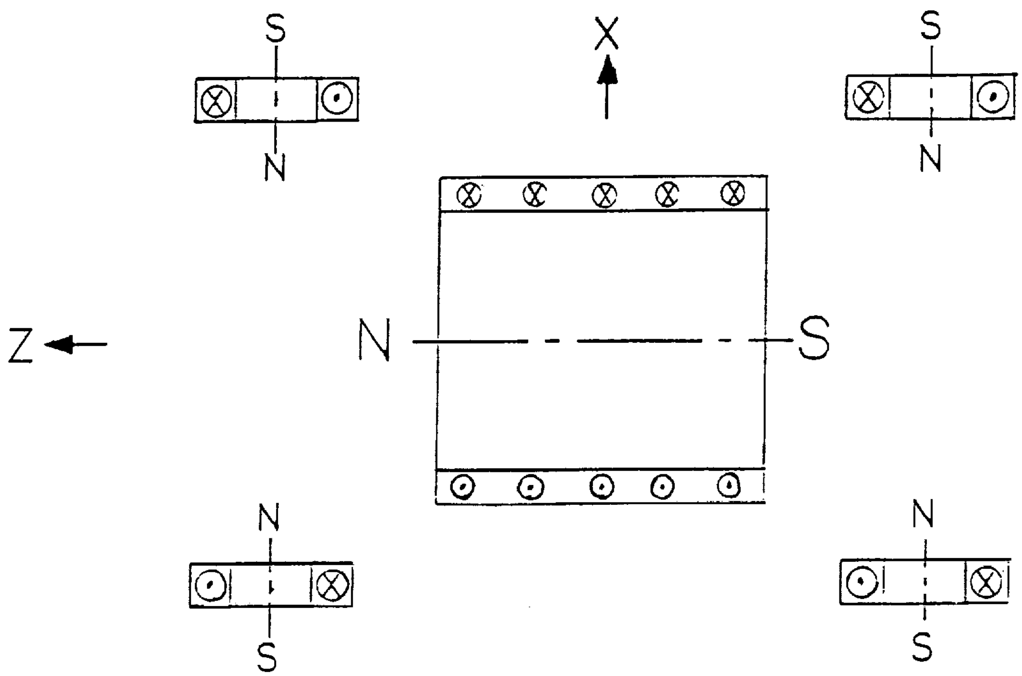

Figure 2. Coil excitation for thrust-force load (x-z plane).

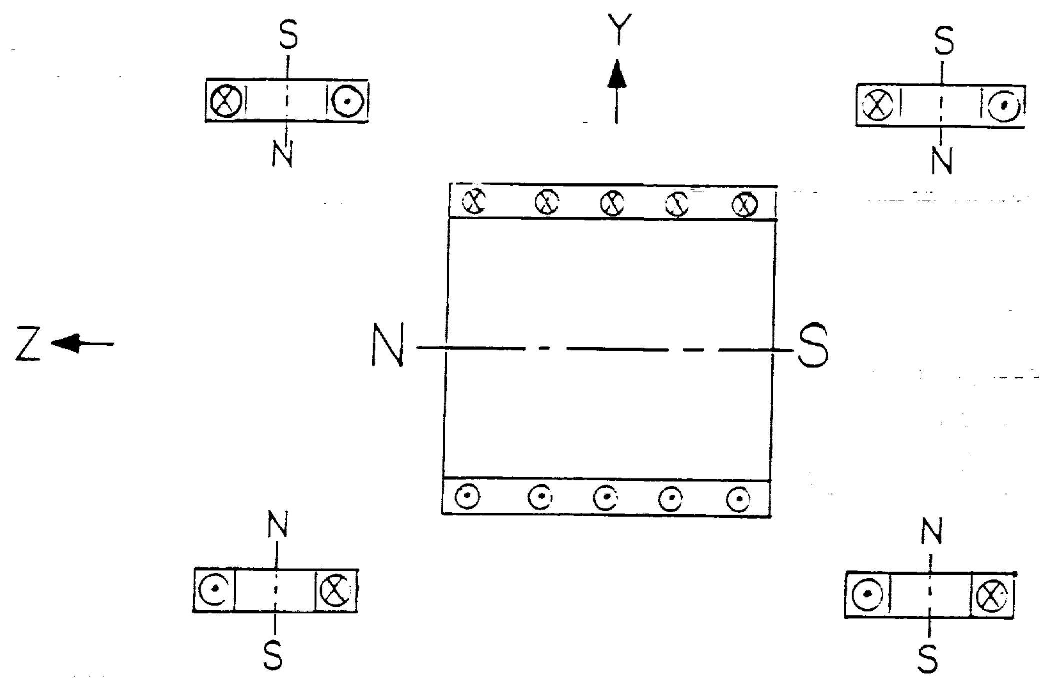

Figure 3. Coil excitation for thrust-force load (y-z plane).

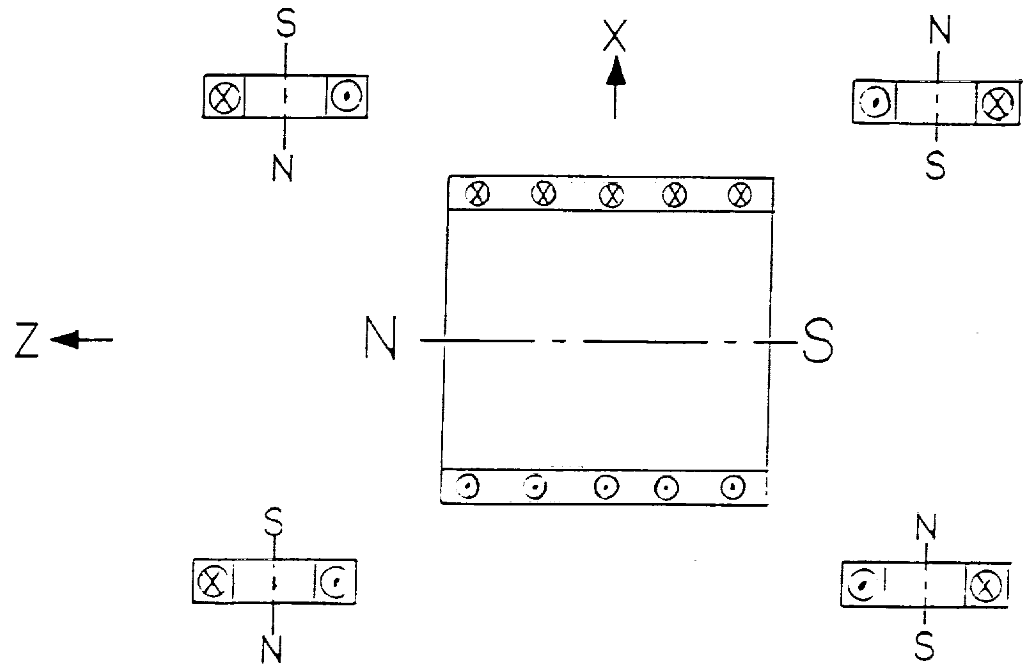

Figure 4. Coil excitation for lateral-force load.

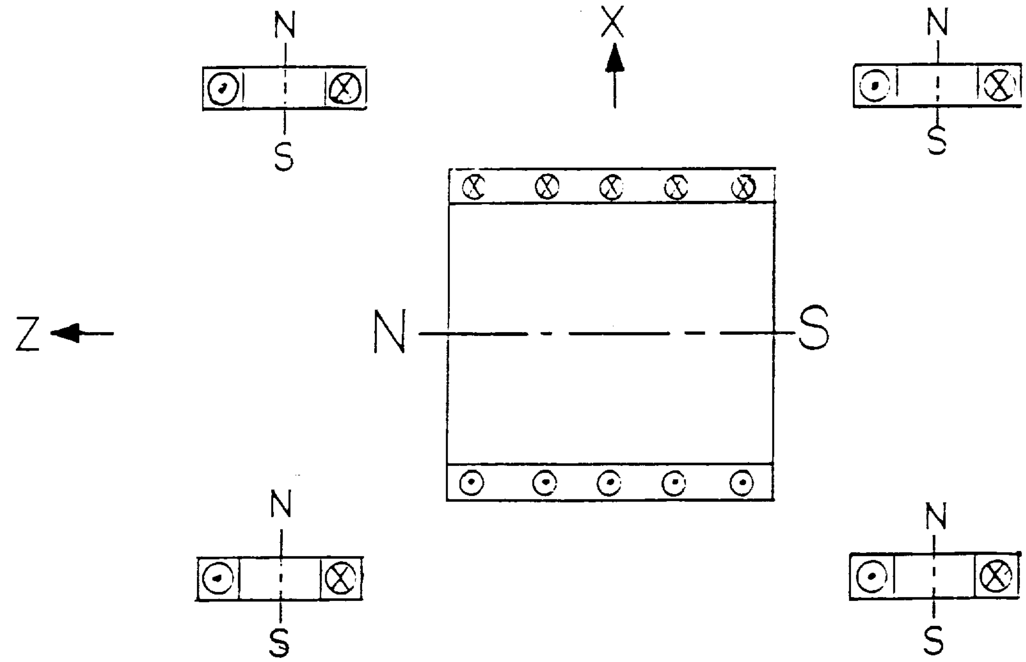

Figure 5. Coil excitation for torsion load.

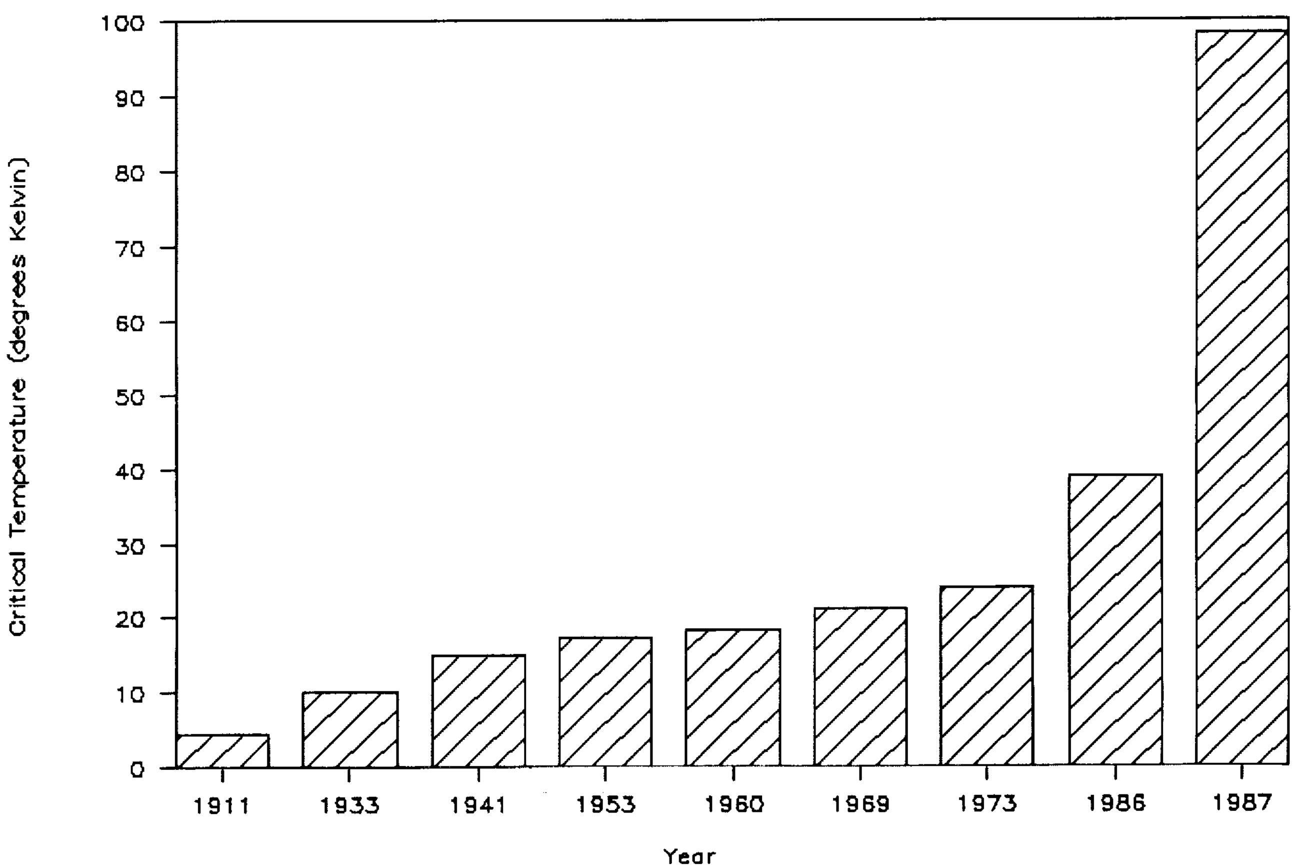

Figure 6. Progress in superconductivity.

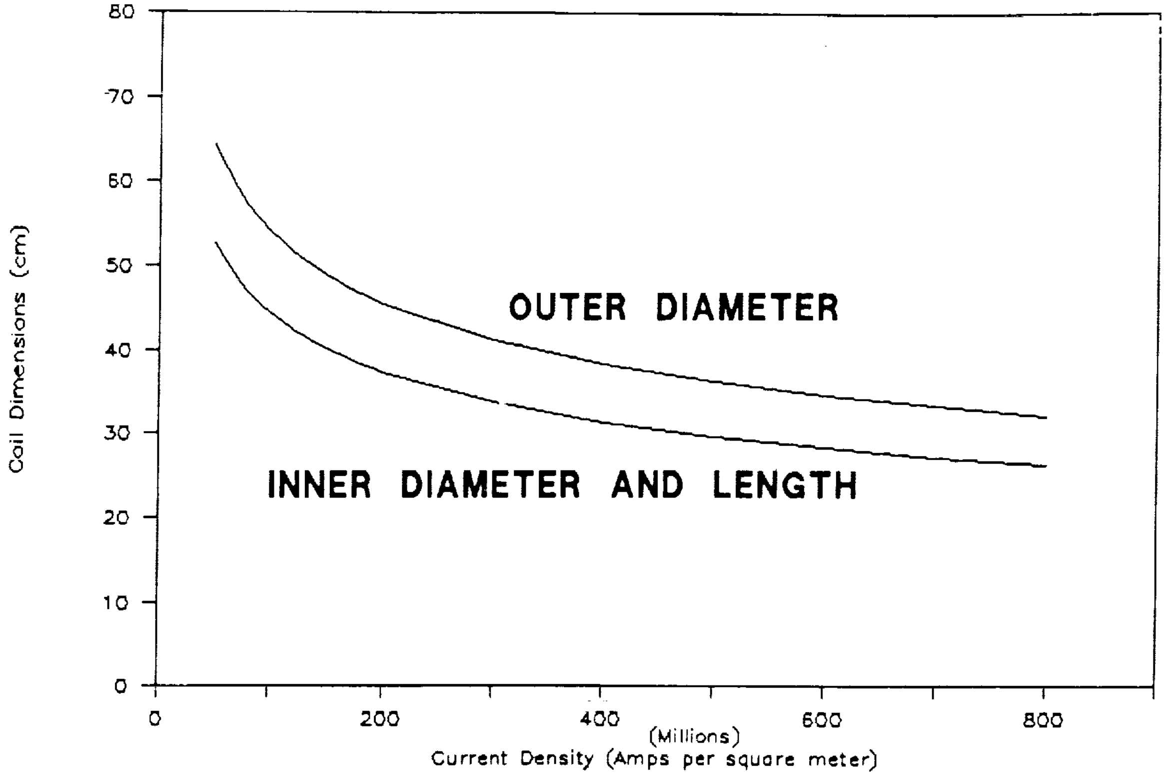

Figure 7. Source coil dimensions.

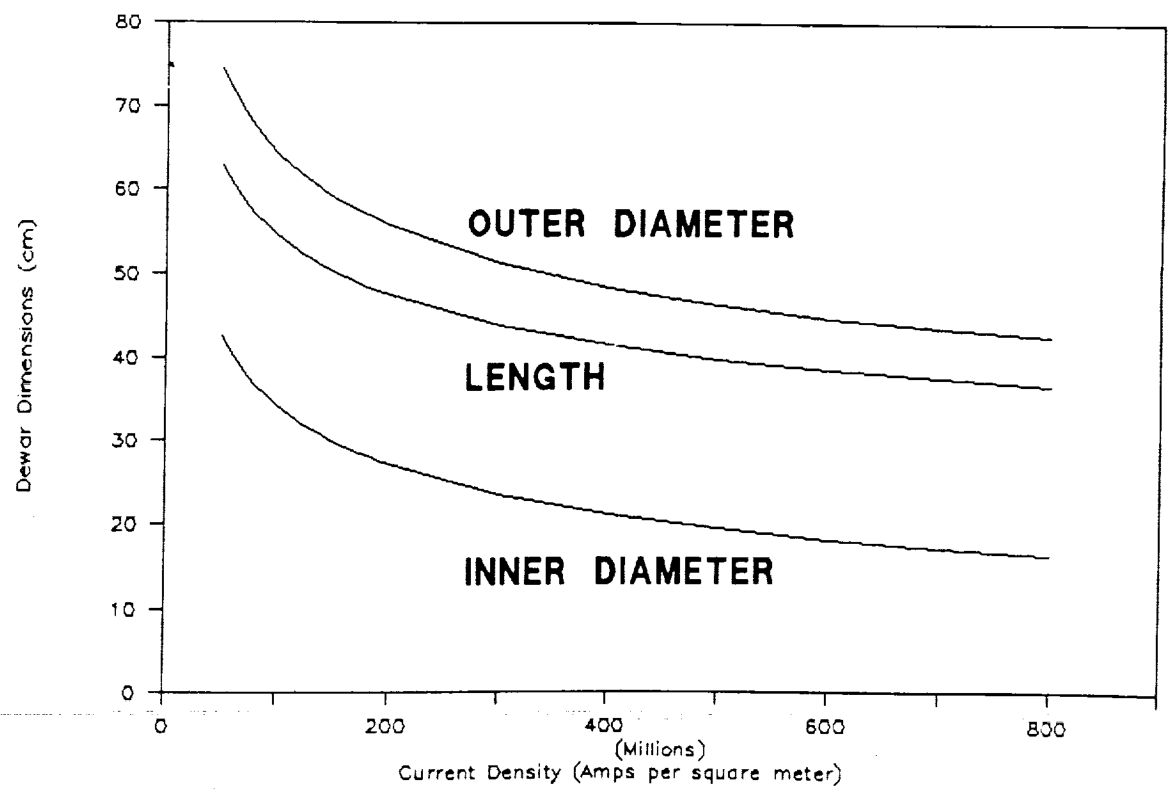

Figure 8. Dewar dimensions.

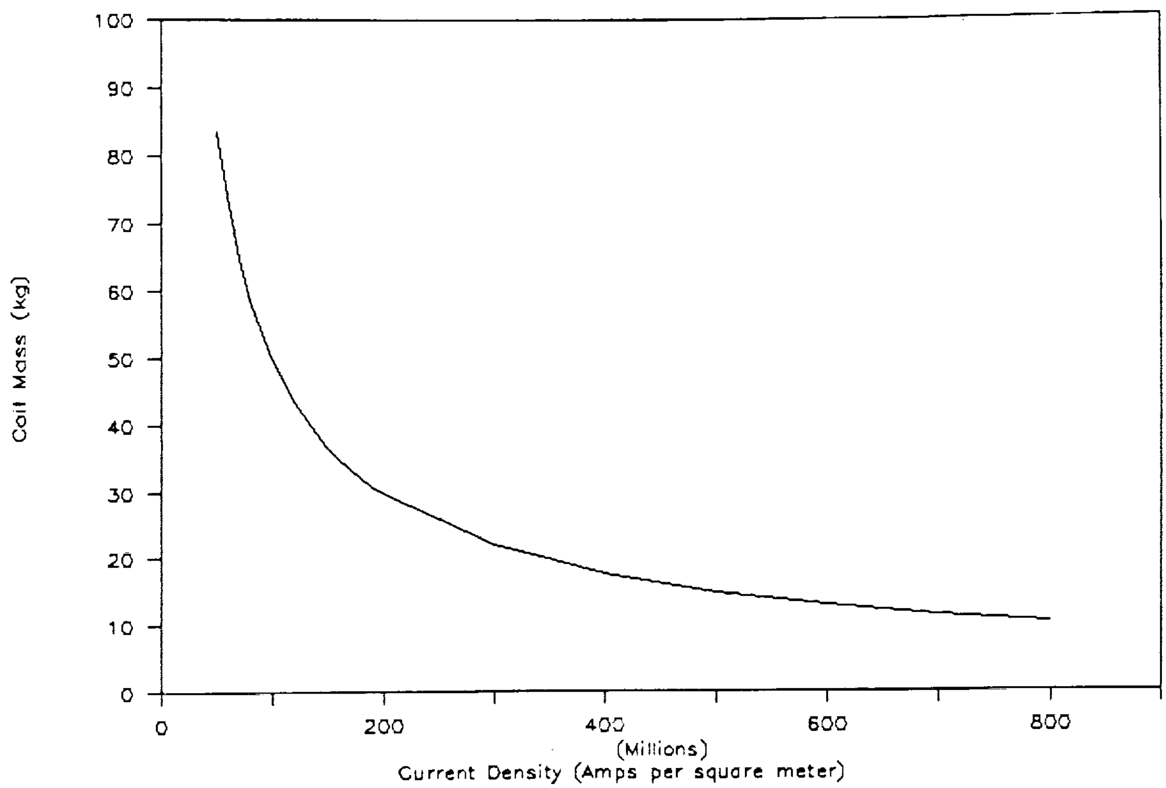

Figure 9. Source coil mass.

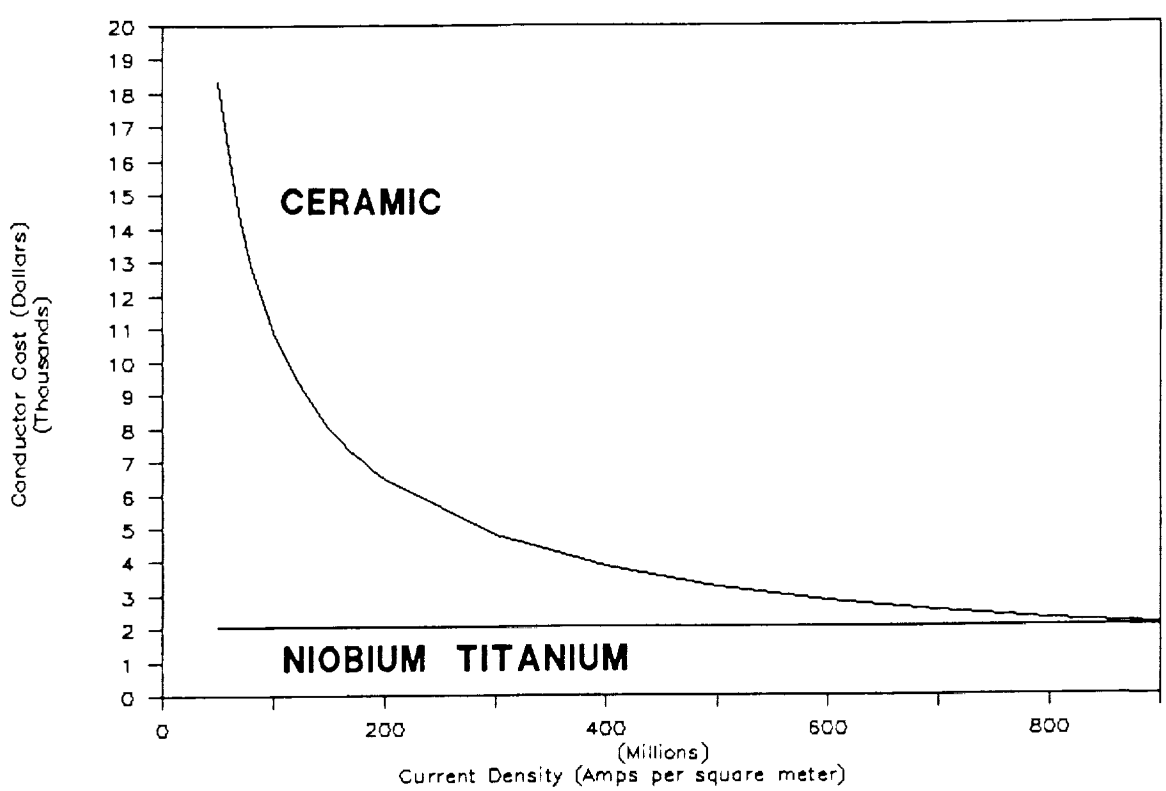

Figure 10. Source coil conductor cost.

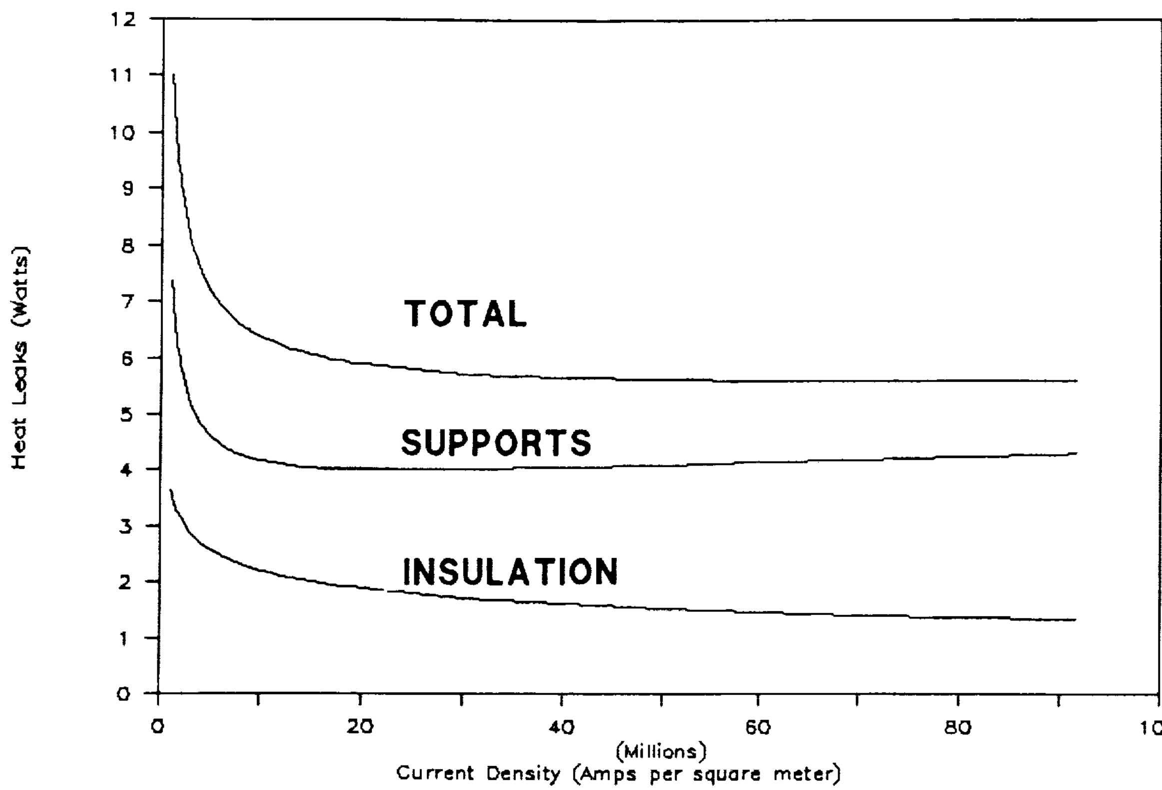

Figure 11. Dewar heat leaks.

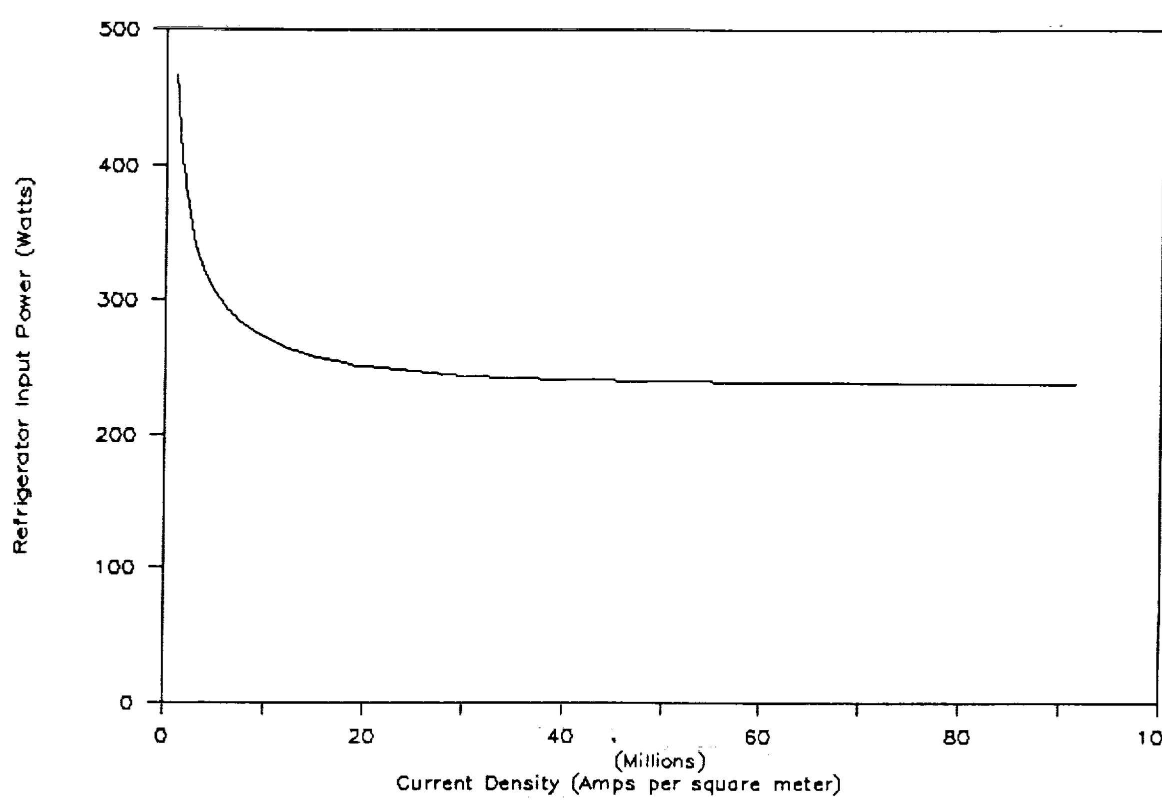

Figure 12. Refrigerator input power.

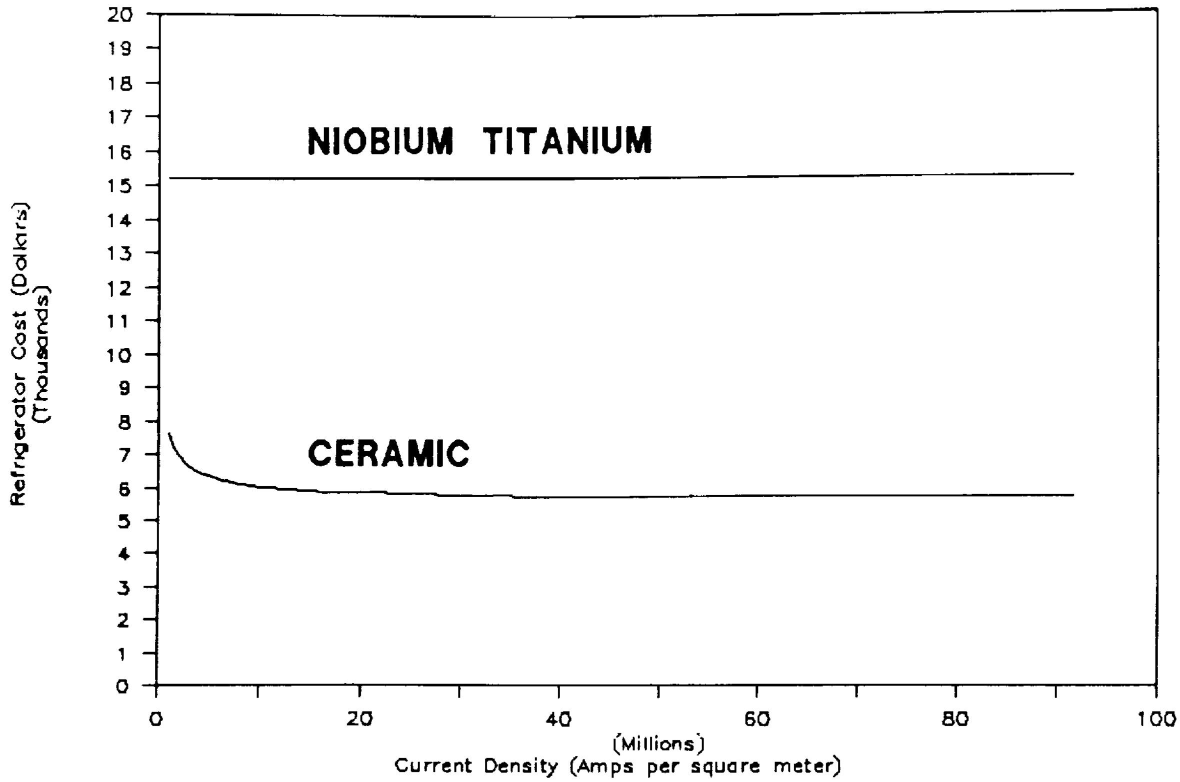

Figure 13. Refrigerator costs.

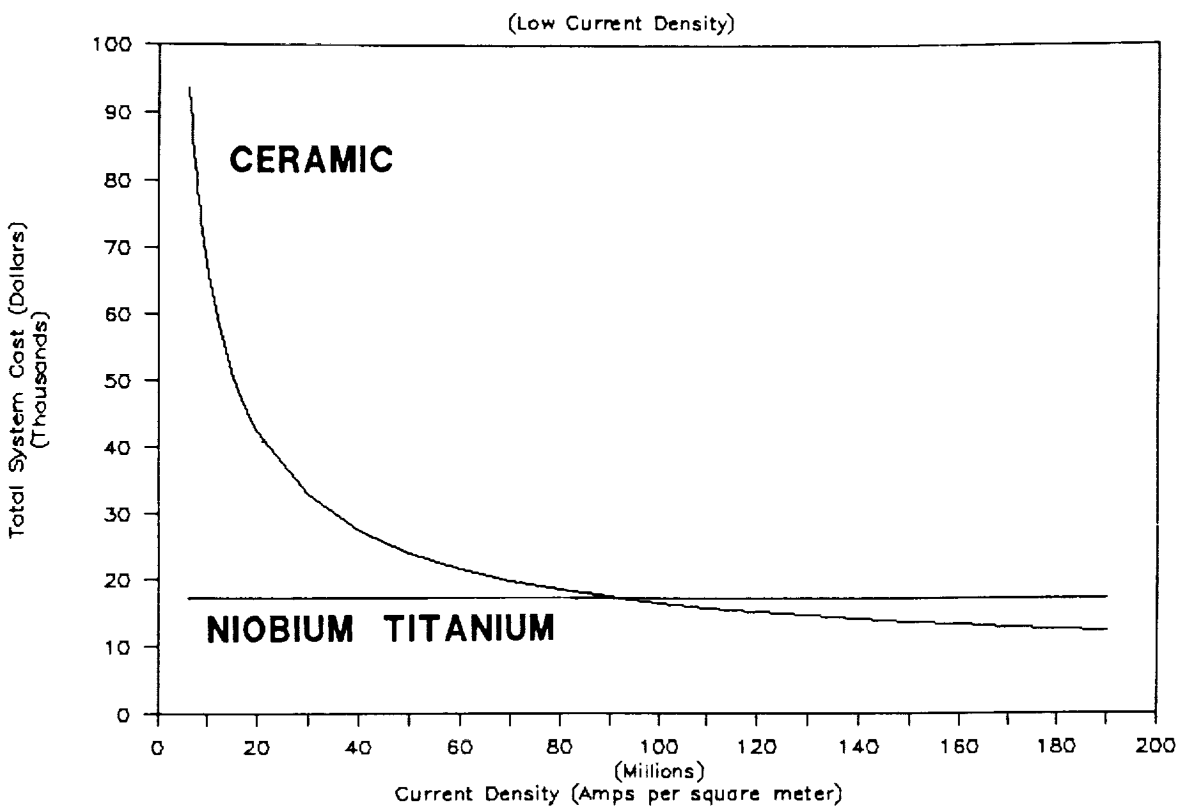

Figure 14. Total system cost, low current density.

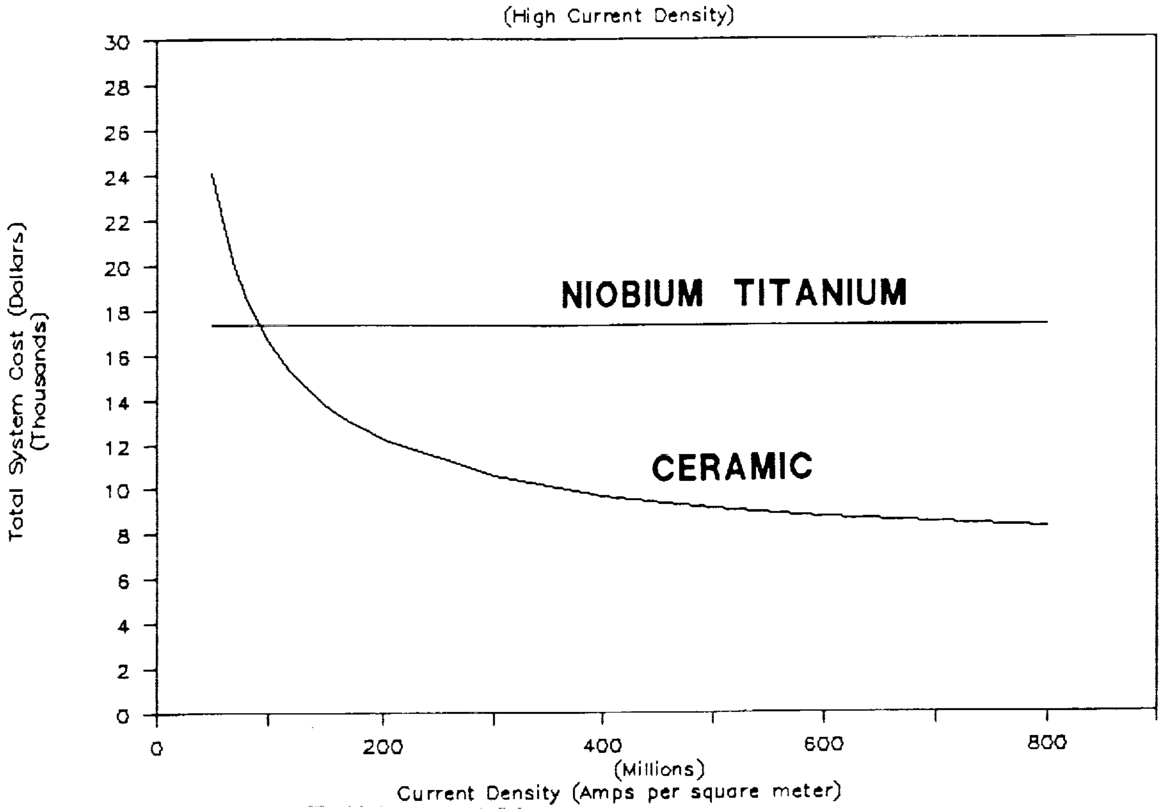

Figure 15. Total system cost, high current density.