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Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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Nuclear Engineering Department
University of Wisconsin
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A TOROIDAL FIELD MAGNET SYSTEM UTILIZING NORMAL METAL TRIMMING COILS

P. F. Michaelson, S. O. Hong, W. C. Young, I. N. Sviatoslavsky and R. W. Conn
University of Wisconsin
Madison, Wisconsin

A conceptual design of a tokamak toroidal field (TF) magnet system with trimming coils to reduce field ripple throughout the plasma region is presented. The number and size of superconducting TF coils is reduced from conventional designs to provide more access for maintenance, blanket cooling, vacuum pumping and plasma heating schemes and to improve the operating economics. The resulting large toroidal field ripple is trimmed with normal copper coils located close to the plasma. Saddle shaped and ring shaped trimming coils are described. In addition to its primary function of trimming, a ring shaped normal coil also can be used to supply a fair amount of magnetic field strength to augment the maximum fields available from the superconducting coils. The cooling scheme, material selection, number, size, shape and placement of the superconducting coils and the trimming coils are discussed.

Introduction

In tokamak fusion power reactors the strength of the toroidal magnetic field in the plasma varies along the toroidal direction, the field being higher beneath a toroidal field (TF) coil and lower between TF coils. If this field ripple is large enough, namely, larger than 2% at the outer plasma edge, the plasma may leak out due to instabilities and thus the confinement time will be degraded.

The field ripple has been maintained at low enough values in past conceptual designs[1] by either using large TF coils with back legs far from the plasma edge or a large number of TF coils. TF coils are expensive, representing a significant fraction of the direct costs of fusion power reactors, and consequently it is worthwhile to try to reduce their size and/or number in conceptual designs. Reducing the size of the TF coils will also reduce the overall size and thus cost of the containment building. In addition, access to the plasma, blanket, and shield region of reactors is important for vacuum pumping, plasma heating and blanket cooling schemes as well as for maintenance and repair of the components in this region. Reducing the number of TF coils can greatly enhance access to the interior reactor regions. In order to maintain a low field ripple, reduce the size and number of the TF coils and increase the access to the interior reactor regions we have designed a TF coil system that includes 8 superconducting coils and 16 normal metal trimming coils, as shown in Figure 1. This coil system, after further develop-

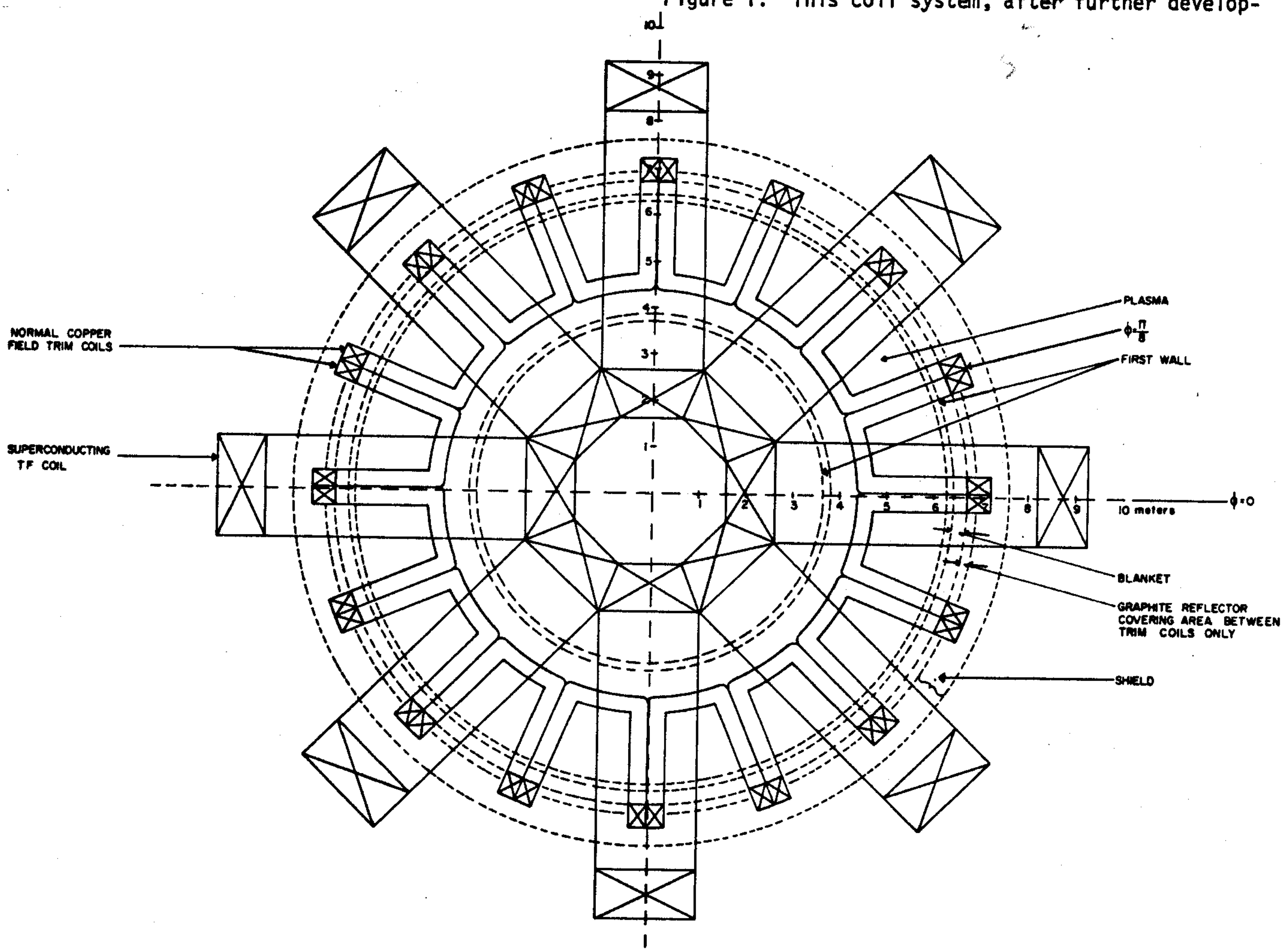

Figure 1. Top view of NUWMAK showing TF coils and saddle shaped trimming coils

ment, will be included in NUWMAK, the new tokamak fusion power reactor conceptual design study of the University of Wisconsin. NUWMAK will be a high field, small size machine in which the power output versus cost will be higher than in previous designs. Some characteristics planned for NUWMAK are listed in Table 1.

Table 1

Tentative Characteristics of NUWMAK

Major radius to plasma center	(R)	5.0 meters
Half-width of plasma	(a)	1.25 meters
Plasma height/plasma width		1.6
Thermal power	(P_{th})	2100 MW
Electric power	(P_e)	750 MW
Power incident on first wall		4.5 MW/m^2
Plasma current	(Ip)	7 MA
Plasma energy density/toroidal field energy density	(β_T)	7%
Toroidal field strength at plasma center	(B_T)	6 Tesla

We feel that a large ripple free toroidal field in a small size machine requires new and advanced design concepts. These concepts include normal metal trimming coils located close to the plasma, and superconducting TF coils using Nb_3Sn or subcooled pool boiling superfluid helium with NbTi.

Normal Metal Trimming Coils

The normal metal field trimming coils chosen for use in NUWMAK are "saddle" shaped. The current runs vertically up one coil leg shaped to fit along the outside of the blanket to a cross member at the top of the plasma region, through the cross member in the toroidal direction to the next coil leg, down the leg to a cross member at the bottom of the plasma region, and through this bottom cross member to the starting coil leg. The current paths in the 16 trimming coils are independent of each other.

The normal coils are not located close to and just inside of the superconducting coils, as is the case in a usual hybrid magnet system. In the usual hybrid system the normal coils are present to augment the field from the superconducting coils and thereby go to higher fields than would be attainable with superconducting coils alone. Such systems have operating costs that are lower than those with normal coils alone. In our proposed design for NUWMAK, the functions of the normal and superconducting coils are quite separate and distinct. The superconducting coils supply the full toroidal field. The normal coils reduce the field in some regions and add to it in others in a symmetrical way that smooths out the field, thus reducing the ripple.

Description of the Saddle Shaped Trimming Coils

This paper is a preliminary report on our coil design project, and therefore, some aspects of the coil design are not final. However, many characteristics of the trimming coils are available and are listed in Table 2.

Table 2

Characteristics of Saddle Shaped Trimming Coils

Number of Coils	16
Coil height overall	6.1 m
Coil cross-section	50 cm x 37.5 cm
Conductor material	Cold worked copper
Copper mass per coil	18,000 kgms
Structural material	316 stainless steel
Tension in coil	10. MN
Cross-section composition	50% Cu, 20% steel, 20% H_2O, 10% insulation
Coil current	0.875 M amperes
Power consumption per coil	3 M Watts
Joule heating in copper	1.5 watts/cm^3
Cooling scheme	Pumped H_2O in enclosed channels
Operating temperature	250 - 300°C
Ripple without trim coils	20%
Ripple with trim coils	2%

Originally the coil position was intended to be right behind the first wall, but radiation damage, neutron heating in the coils and the reduction in the tritium breeding ratio in the blanket behind the coils were too big and for these reasons the coils were moved back to a position just behind the blanket. We chose not to move the coils back any further than this because access would have been reduced and the current needed for ripple control, the I^2R losses and the coil mass would all have increased. Even when located behind the blanket the trimming coils still must be normal rather than superconducting because the nuclear heat load precludes cooling either cryogenic or superconducting coils economically. The neutron heating rate is estimated to be on the order of the Joule heating rate in the normal coils. The coil shape when viewed from the side is shown in Figure 2, and was chosen to conform to the plasma shape for minimum coil size at a given ripple reduction. In this configuration the forces

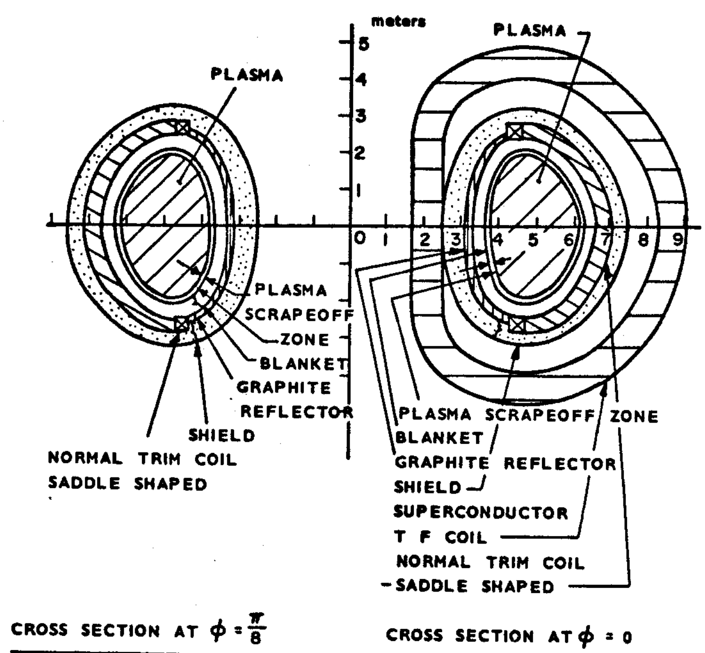

Figure 2. Side view of NUWMAK showing TF coil and saddle shaped trimming coils

are low enough and the coil mass small enough that the structure does not have to be optimized (in terms of material use) in order to reduce costs.

Material choices other than copper are being considered for the conductor such as aluminum, vanadium, or liquid sodium, which would produce low residual activity in the coils. However, copper is still the material of choice at this point because of its relatively attractive combination of high conductivity, relatively low cost, good structural strength and reasonable availability. A stainless steel ring supporting the top legs of the Cu coils, and another ring supporting the bottom legs, is used to resist the alternating inward and outward forces from the vertical coil legs. A bolted connection to the reactor shield may also be necessary for sufficient restraint against lateral bending in the vertical legs of the coils.

The choice of eight TF coils for NUWMAK is an optimized number based mainly on the competing demands of ripple correction required and access space, both as functions of coil number. As shown in Figure 3 (using for example a machine with a 4.5 m major radius and with 6T toroidal field on the plasma axis), tokamaks with fewer than 8 TF coils would have significantly more ripple, or field variation at the outer plasma edge, requiring much larger and more power consuming trimming coils.

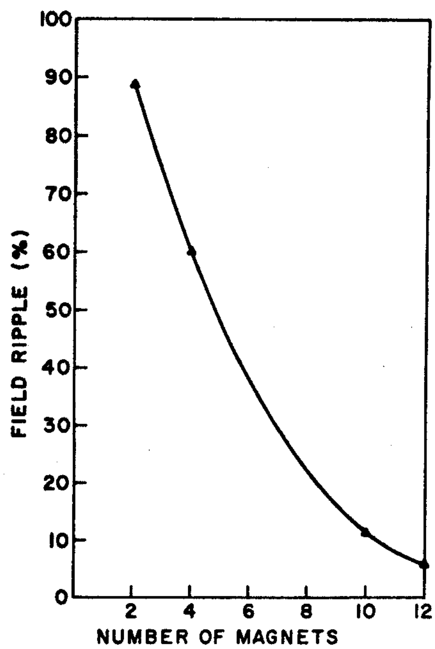

Figure 3. Results of computer calculation of toroidal field ripple for 6 Tesla, R = 4.5 meter machine

Increasing the number of TF coils above 8 does not decrease the ripple enough to be seriously considered when the loss in access is taken into account. Another machine, of different size and purpose, may have a different optimum number of TF coils.

A number of insulating materials are under consideration for use between turns of the trimming coils. These include exfoliated graphite foil,[2] Al_2O_3, mica, concrete and ceramics. The expected radiation levels are too high to allow a reasonable lifetime for organic insulations presently available. Hay and Rapperport[3] have described the experiences of many groups with other presently available insulating materials. One of their materials may prove to be suitable for use here.

The trimming coils will be cooled in a conventional way with forced flow water in the channels of the copper conductor. The recovered heat is used in a preheater for the blanket coolant. This step will return about 30% of the power consumed by the trimming coils back to the electrical output of the reactor. The operating temperature of the trimming coils may depend on the final choice of insulating material but is likely to be in the range 250-300°C. This is based on the usefulness of the coolant preheater to aid the power cycle and also on the radiation damage lifetime of the copper as a function of the copper temperature.

Advantages of Saddle and Ring Shaped Coils

The first designs considered in this study made use of ring shaped trimming coils encircling the plasma in the poloidal direction (see Figures 4 and 5). Such coils have the great advantage of making a net contribution to the toroidal field. (The saddle coils do not augment the toroidal field). This contribution would reduce the need for very high fields at the inner legs of the superconducting toroidal field coils and thus alleviate the need for exotic refrigeration schemes or superconducting materials suitable for use at high fields. Such ring coils may still have application to other experimental machines or power producing reactors. However, they are unsuitable for NUWMAK, because the width needed at the outer leg to sufficiently reduce the field ripple is so large as to restrict access to the machine between the TF coils. In addition, either the ring coils themselves or the blanket and first wall of the reactor would have to be cut in order to move the ring coils in or out for repair or maintenance. The saddle coils, in contrast, can be replaced without cutting any of these components. Another advantage of the ring coils is that they do not experience the torques which saddle coils are subjected to. These torques, however, are not high, and can be supported with a reasonable amount of structure. The ring coils do not disturb the vertical field significantly anywhere in the plasma region, while the saddle coils as presently designed produce a vertical field near the top and bottom of the plasma region that assumes values between ± 0.2 Tesla for different toroidal angles. If this vertical field ripple proves to be detrimental, the problem can be corrected by further extending the coil cross-members away from the plasma. The set of saddle coils weighs about half as much as the ring coils for a given ripple correction. They also allow good access to the top and bottom of the plasma region as well as to the entire inside of the plasma region near the central core of the reactor. The ring coils allow little or no access to these regions. Saddle coils also allow access to the outside plasma edge at places between the superconducting TF coils. Ring coils also allow access to this region, but at places under the superconducting TF coils that are harder to use effectively for vacuum pumping, plasma heating, and blanket cooling. Either of the two designs can be used to lower the capitol costs of a machine of given major radius and ripple by decreasing the size and number of superconducting TF coils needed.

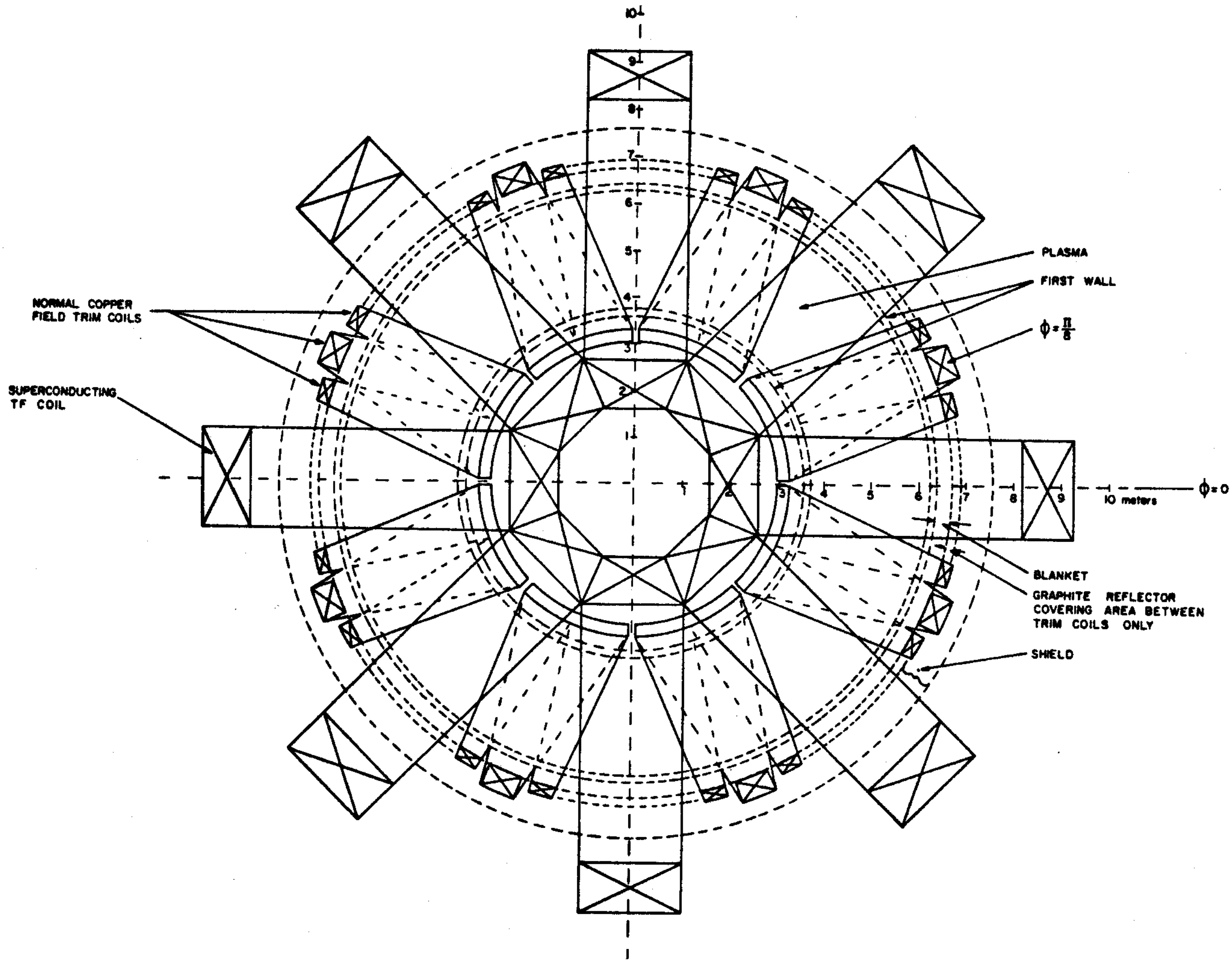

Figure 4. Top view of initial NUWMAK design showing TF coils and ring shaped trimming coils

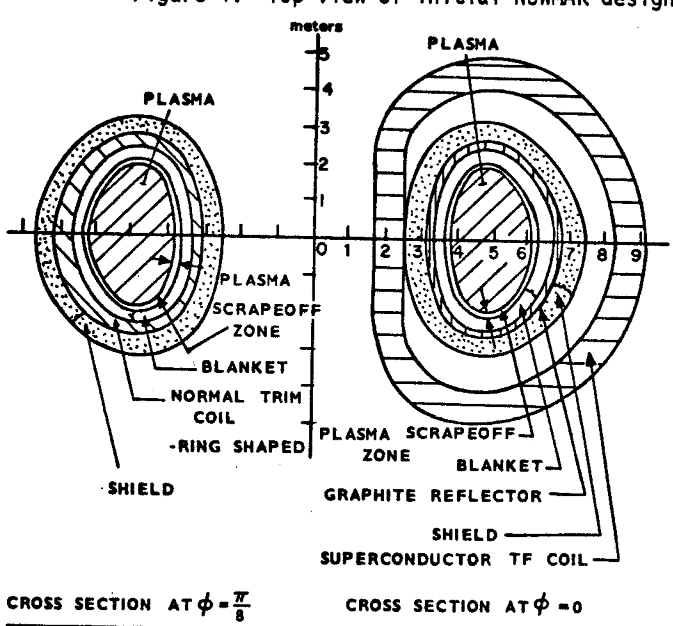

Figure 5. Side view of initial NUWMAK design showing TF coil and ring shaped trimming coils

Superconducting Toroidal Field (TF) Coils

The main toroidal field system consists if eight large superconducting magnets designed to be fully cryogenically stable. The magnet coils have a constant tension "D" shape with the conductors embedded in grooves machined in stainless steel discs with fiberglass epoxy insulation as in UWMAK series of conceptual design studies.[4] To supply 6 tesla at the plasma center at a major radius of 5 m, as the physics and economics apparently requires, the maximum field in the superconducting magnets (at a radius of 2.5 m) has to be 12 tesla. This field cannot be achieved in magnets with NbTi as the superconducting material at the boiling point of liquid helium at atmospheric pressure. There are two options for achieving the required high field which seem attractive. One is to use a NbTi superconductor at a temperature lower than 2.2 K (that is, in superfluid helium, or He II regime) in order to have a reasonably high current density in the superconductor. Pool boiling superfluid helium as a magnet coolant has been suggested by the superconductive energy storage group of the University of Wisconsin.[5] The other option is to use Nb_3Sn as the superconducting material, at 4.2 K.

Selection of Superconducting Material and Cooling Scheme

A major and important advantage of using superfluid helium is the greatly improved heat transfer characteristics as compared to the use of normal fluid helium. This and other details of superfluid helium cooling of fusion reactor magnets is discussed in paper L-2 of this conference.[6] The critical heat flux of 0.3 W/cm^2 available with boiling helium at 4.2 K may be compared to 0.5 W/cm^2 for He II at 1.8 K. This higher critical heat flux allows roughly a 1.3 times higher current density and thus economizes on space and material. Also, the thermal conductivity of He II is much higher than that of normal helium, allowing smaller cooling channels. OH coils and shields for reducing the AC losses in the TF coils due to the pulsed fields from the poloidal coils can use this saved space to advantage. However, the disadvantage of this system is that the refrigeration power at 1.8 K operation is about three times higher than at 4.2 K for a given heat load. Also, the system becomes more complicated when lower temper - tures are used because of the large amount of vacuum pumping and heat exchanger area needed. Furthermore, for a system operating with superfluid helium at saturated vapor pressure (about 12 Torr), the dielectric strength of the helium gas is low and the enthalpy stability due to the heat capacity of the helium is also low. Therefore, it is more desirable to use subcooled superfluid helium at atmospheric pressure rather than at reduced pressure. In any event, most of the thermal losses should be intercepted at 4.2 K by a normal helium or gaseous helium cooled radiation shield to keep the refrigeration power requirements low. For 1.8 K operation, special attention has to be paid to the design of the magnet discharge system during fault conditions because of the higher current density and the large stored energy in the magnet.

Superconducting Nb_3Sn available today is brittle even though the technology for producing multifilamentary Nb_3Sn has been improving significantly in recent years. It has been demonstrated that the critical current in undamaged multifilamentary Nb_3Sn produced by the diffusion process using bronze increases rather than decreases when the wire is strained. This is because the prestrain produced by the differential thermal contraction of the bronze and Nb_3Sn is being relieved.[7]

In the embedded conductor type of TF coils there exists the interesting possibility of prestressing the Nb_3Sn wires into compression during coil fabrication, with this compression being added to the compression produced by the bronze - Nb_3Sn thermal contraction mismatch. When the TF coil is energized this compression would be relieved by the magnetic forces and higher effective strain limits will result for the Nb_3Sn, greatly enhancing its suitability for these magnets. However, damage to the wire during handling in magnet fabrication is still a problem and hopefully the technological answers to these questions will become available from the Large Coil Program of the late 1970's and early 1980's. Another factor potentially limiting Nb_3Sn superconductor operation at 4.2 K is the relatively low current density in the stabilizer required (compared to operation of 1.8 K) for cryogenic stability of the magnet. The large cross-sectional area needed for the stabilizer may further encumber the already cramped TF coils and compromise adequate cooling as well as the shielding against the pulsed fields of the poloidal coils.

In general, the desired high field (12 tesla) for NUWMAK, which is assumed to be a 1st generation power reactor, may be obtained with NbTi in subcooled superfluid (1.8 K and atmospheric pressure) pool boiling liquid helium, provided the relatively high refrigeration costs involved are acceptable. As an option, the possibility of using Nb_3Sn at 4.2 K should not be eliminated until the results of the Large Coil Program become available.

In addition, there is always the possibility that other high field superconductors, such as the C-15 compounds and Nb_3Ge, may be developed.

Discussion of TF Coil Characteristics

The TF coils in Figure 1 and Figure 2 are from a preliminary design developed mainly for use in toroidal field ripple calculations. The final design will differ slightly from that shown. The constant tension "D" shape is obtained by considering only the field from the eight TF coils and not the fields from the trimming coils. The maximum current density in the conductor is about 3850 A/cm^2 at the outermost turn and the minimum is about 1750 A/cm^2 in the innermost turns. These values were chosen assuming a maximum allowable heat flux in the high field region of 0.32 W/cm^2. The stress in the steel structure with the copper stabilizer is 2×10^8 N/m^2 (about 29,000 psi) which is relatively low. This low design stress results from the restraints set by the fabrication of the grooves in the stainless steel discs.

We are also considering the use of high purity aluminum rather than copper as the stabilizing material. Since most of the cross sectional area of the TF coils is occupied by the copper stabilizer which has a high magnetoresistance at high field ($\rho = 1.8 \times 10^{-8}$ $(1 + .5B)$ ohm-cm, where B is in tesla), it may be advantageous to save space by using aluminum. Unlike copper, the magnetoresistance of aluminum saturates at high fields, such that its resistance is actually lower than copper at sufficiently high fields. We are considering the use of high purity aluminum stabilizer with high strength aluminum alloy at a strain level below 0.3%. The strain limit is needed in order to avoid an excessive increase in the resistance due to fatigue cycling.[8] This all aluminum design would require the low temperature superfluid cooling option discussed above in order to maintain a high current density, since more area is needed for structure than in a steel-structure design. The aluminum design is expected to result in a lower overall cost for the TF coils, as well as a lower residual activity, when compared with the copper and steel design.

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