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**WARM REINFORCEMENT AND COLD REINFORCEMENT MAGNET
SYSTEMS FOR TOKAMAK FUSION POWER REACTORS:
A COMPARISON***

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829

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TABLE OF CONTENTS

	Page
Abstract	1
Introduction	1
Description of Thermal Barrier	6
Selection of Tokamak Fusion Reactors to be Compared	10
Stress Analysis of Magnets	11
Results of Analysis	16
Magnet Construction	19
Summary and Conclusions	20
Acknowledgment	22
References	23
Tables	
Figures	

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ABSTRACT

Warm reinforcement and cold reinforcement magnets are compared for a range of tokamak fusion reactor sizes and fields for DT and catalyzed DD fuel cycles. In the conventional cold reinforcement method all magnetic forces are contained by a 4 K structure reinforced with stainless steel; in the warm reinforcement method, the magnetic forces are transmitted across a low thermal conductivity structural layer to a warm (300 K) reinforcing structure made of ordinary materials. For high-field fusion reactors, the magnets are so large that the cost of the additional refrigeration load for warm reinforcement is much less than the savings in structural costs it permits. This warm reinforcement method should permit the construction of reasonable cost (\$40/kW(e)) magnets with relatively low structural stresses for catalyzed DD reactors.

INTRODUCTION

The characteristics of large-bore, high-field magnets will be an important factor in determining the overall

technological and economic practicality of fusion reactors based on magnetic containment of plasmas, as well as in selecting the best containment concept. In addition, if practical magnets can be built for reactors based on DD fuel cycles, the complex and difficult tritium breeding blanket necessary for DT fuel cycles can be avoided.

It seems very likely these fusion reactor magnets will be entirely (or in some cases, predominantly) superconducting in order to avoid prohibitive magnet power requirements. Occasionally, it may be desirable to use a relatively limited amount of cryogenic aluminum conductor at 10 to 20 K as a high-field insert for very high-field magnets, and this appears to be practical.

The cost of superconducting laboratory magnets is strongly dominated by superconductor and refrigeration cost, while structural cost is relatively minor. It appears that this situation should be reversed for the much larger magnets necessary for fusion reactors, that is, the structural cost would become predominant while superconductor and cryogenic costs would become minor.

This is due in part to the effects of scaling factors, i.e., the amount of superconductor and cryogenic heat leak scale as the surface area of the magnet while the amount of structural reinforcement scales as the volume, but is also

due to the expected large reductions in unit costs for superconductors and refrigeration as their total requirements increase. In contrast, a unit structural cost, e.g., the cost of the unit amount of steel, should be much less sensitive to total quantity than should either superconductors or refrigeration.

The reduction in unit refrigeration cost principally results from savings in compressor cost, which is the major component of refrigeration cost. Unit costs for compressors decrease rapidly as compressor rating increases.

Large reductions in unit superconductor cost are expected to result from the much larger production volumes necessary for a fusion power reactor economy. In a previous study, hereafter referred to as the Phase I study,^(1,2) superconductor prices were projected using present processing technology, but for superconductor production plant sizes appropriate to a fusion reactor economy. Detailed plant design and cost estimating were used in these projections. It was found that large reductions in unit superconductor costs could be expected. Translated into terms of previously published fusion reactor designs, the projected superconductor cost is only a few dollars/kW(e) and is approximately an order of magnitude cheaper than the estimated structure cost.

The structures in these fusion reactor magnet designs are of the "cold reinforcement" type, illustrated in Figure 1 for a tokamak reactor. In this method all magnetic forces are contained by a cold (~ 4 K) structure, which is insulated from room temperature. Load-bearing supports are necessary to carry the structure weight, but they do not carry magnetic forces. Because of the brittle nature of ordinary structural materials at 4 K, stainless steel must be used for reinforcement of the cold structure. Since stainless steel is expensive, fusion reactor magnets are generally designed to operate with structural stresses of 50,000 to 100,000 psi to minimize structure cost. Such high stresses and consequent large strains impose severe demands on superconductors, particularly Nb_3Sn .

In this paper we examine a different method of magnet construction, the "warm reinforcement" type illustrated in Figure 2. Here the magnetic forces are carried through a relatively thin layer directly to room temperature, and the actual containment of the magnetic forces is supplied by a massive structure at room temperature which can be fabricated from ordinary carbon steel, reinforced concrete, rock, etc. The thin layer between 4 and 300 K is a "thermal barrier," and must have low thermal conductivity, high strength, and high modulus.

This type of reinforcement is impractical for small magnets but has significant advantages for large magnets of the size needed for fusion reactors. The use of cheap structural material permits large savings in magnet cost even when the extra refrigeration cost for the thermal barrier is included, and also permits much lower structural stresses, since more reinforcement can be economically used. In addition, a room temperature conductor (e.g., aluminum) circuit can be coupled closely inductively to the superconductor, permitting most of the magnet energy to be dumped at room temperature instead of 4 K if the superconductor quenches. Finally, in the special case of tokamaks, warm reinforcement permits much more pulser iron in the critical "throat" area (i.e., the inner part of the toroid). At high fields, cold reinforcement takes so much throat area that the pulser iron is insufficient to carry the pulsed field that establishes the plasma ring current, and a more costly and difficult air core transformer is required.

In the balance of this paper warm and cold reinforcement magnets for a number of different tokamak sizes are compared, for both DT and DD fuel cycles. It is found that at low fields cold and warm reinforcement magnet component costs are comparable, but for high B_0 (central plasma field) (70 kG and above) large savings can be expected with warm reinforcement.

In particular, the magnets for the catalyzed DD cycles look to be economically practical.

DESCRIPTION OF THERMAL BARRIER

Figure 3 shows an idealized view of a thermal barrier. The superconductor is wound as a simple pancake coil, one of the ~50 toroidal field coils of the tokamak reactor. (We do not consider here diverter, vertical stability, and ohmic heating coils. While important, they do not appear to be as significant economically or structurally as the toroidal field coils.) Wound on top of the superconductor coil are many interleaved layers of epoxy-fiberglass (which need not be continuous) and stainless steel strip (which must be continuous). Typically, one-third of the total barrier thickness would be stainless steel and two-thirds epoxy-fiberglass. This layered structure is assumed isotropic, with an average modulus given by the volume averaged moduli of its components. In effect, since the moduli of epoxy-fiberglass are much lower than that of stainless steel, the average modulus of the barrier is essentially that of stainless multiplied by its volume fraction.

The thermal conductivity of stainless is assumed to be effectively infinite, so that the barrier thermal conductivity is determined by the effective thermal conductivity and total

thickness of epoxy-fiberglass. In Figure 3, refrigeration power and cost for the barrier are reduced by having two intermediate heat sinks (at 20 and 77 K) between the 4 and 300 K boundary temperatures. This design is not optimized; one can further reduce considerably refrigeration power requirements by having more intermediate heat sinks. However, since refrigeration unit capital cost decreases rapidly with increasing refrigeration load, it would be better not to use separate refrigeration cycles for each heat sink but rather to use the multi-shield approach where one refrigerant cools a number of points as it climbs in temperature.

The thermal conductivity and strength of some candidate materials for the epoxy-fiberglass layer are shown in Table 1, as taken from the available literature. (3-6) Operating in vacuum results in a considerably lower thermal conductivity than in helium gas at 1 atm. Compressive strengths of epoxy-fiberglass are on the order of 100,000 psi at cryogenic temperatures and 50,000 psi at room temperature. Glass fiber-imidite resin and potassium titanate-epoxy seem to have substantially lower thermal conductivities than epoxy-fiberglass, though the mechanical strength may not be sufficient. Nylon would be of interest for the 4 to 20 K range.

The effective thermal conductivity of the laminated epoxy-fiberglass, stainless steel composite will be substantially lower than that of bulk epoxy-fiberglass because of interfacial thermal contact resistance. Mikesell and Scott⁽⁷⁾ have shown that for stacks of metal plates the effective thermal conductivity can be as low as 2% of the bulk metal conductivity. The effective value depends on the plate thickness, compressive stress, material modulus and surface cleanliness. For this paper we take the effective average thermal conductivity (including interface contract resistance) for epoxy-fiberglass sheets in vacuum to be $0.4 \text{ mW cm}^{-1} \text{ K}^{-1}$ for the 4.5 to 20 K temperature interval, $0.7 \text{ mW cm}^{-1} \text{ K}^{-1}$ for the 20 to 77 K interval, and $1.5 \text{ mW cm}^{-1} \text{ K}^{-1}$ for the 77 to 300 K interval. This corresponds to an effective thermal resistance, including interface effects of approximately double that of bulk epoxy-fiberglass.

The maximum compressive stress on the epoxy-fiberglass that would be encountered in any of the magnets considered in this paper is on the order of 10,000 psi, approximately an order of magnitude smaller than the compressive strength. At these relatively light loadings no fracture or creep problems are to be expected.

The refrigeration factors and capital costs used in this paper (summarized in Table 2) were taken from a study on

underground cryogenic power transmission lines.⁽⁸⁾ They are essentially the same as these given by Kurti⁽⁹⁾ though Kurti's capital costs and refrigeration factors both tend to be somewhat lower.

Although the refrigeration factor, $(W(e)/W(th))$, tends to drop slightly with increasing refrigeration load, the principal reduction is in capital cost $(\$/W(th))$, since the major part of the capital cost is for compressors and their unit cost decreases rapidly with increasing size. The refrigeration loads appropriate to a 1000 MW(e) fusion reactor with warm reinforcement and a first wall flux of $1 \text{ MW(th)}/\text{m}^2$ are indicated in Table 2. These loads only include heat leaks through the thermal barrier and do not include heat leaks through superinsulation, to transfer lines, etc. which will be required whether warm reinforcement is used or not. Including these refrigeration loads will further reduce unit refrigeration capital cost.

These refrigerator costs and efficiencies assume that three separate plants are built for the 4, 20, and 77 K sinks. Actually, it is much more likely that an integrated plant would be built with a common refrigerant (helium) and common compressors. The unit capital refrigeration costs should be considerably lower in this case.

Included in Table 2 are the capitalized power costs for running the refrigerators. They are comparable to the initial capital cost for the refrigerator.

The total cost from Table 2 is then used to find the optimum thermal barrier thickness, as shown in Table 3. As barrier thickness increases, refrigeration cost decreases but material costs increase. The optimum barrier thickness is determined by the minimum total cost, and is on the order of 0.5 meters. Thinner barriers (0.3 m) and thicker barriers (0.8 m) both show larger total cost.

SELECTION OF TOKAMAK FUSION REACTORS TO BE COMPARED

Five reactors using warm reinforcement magnets were selected to be paired with five reactors using cold reinforcement magnets. Each pair had the same plasma dimensions and fuel cycle. The first two pairs had DT fuel cycles with plasma minor diameters of 1.0 and 1.5 (relative); the remaining 3 pairs had catalyzed DD fuel cycles with plasma minor diameters of 1.0, 1.5, and 2.0 (relative). All reactors had the same plasma aspect ratio 3.75, and the same first wall flux, $1 \text{ MW(th)}/\text{m}^2$. A relative plasma minor diameter of 1.0 corresponds to an actual plasma minor diameter of 5.6 meters, while 1.5 corresponds to 8.4 meters, and 2.0 to 11.2 meters.

The DT case with relative plasma minor diameter of 1.0 was chosen to correspond exactly with the ORNL tokamak design⁽¹⁰⁾

except that the ORNL design had a first wall flux of $3.45 \text{ MW(th)}/\text{m}^2$. The lower wall flux of $1.0 \text{ MW(th)}/\text{m}^2$ for this paper was chosen to be conservative from a radiation damage point of view. Magnet costs in $\$/\text{kW(e)}$ for different first wall loadings can be readily calculated if desired. Plasma stability values (q , β_0) as a function of central plasma field (B_0), and plasma minor diameter (D_p) are the same as in the ORNL design, except for a scale factor change due to the lower first wall flux. The ratio of plasma diameter to first wall diameter was taken as 0.8, as in the ORNL design. DT reactors had a blanket plus shield thickness of 2.0 m, while catalyzed DD reactors had 1.0 m. The relative plasma reaction rates for catalyzed DD and DT fuel cycles were taken from Mills. (11)

STRESS ANALYSIS OF MAGNETS

Dimensions for the warm reinforcement magnets are given in Table 4. These correspond to the plasma and blanket dimensions given earlier. For all cases, the superconductor thickness is taken as 0.15 m, the thermal barrier thickness as 0.5 meters, and the aluminum thickness as 0.3 meters. The reinforcement thickness varies for each case and is fixed by the condition that the reinforcement (i.e., ordinary steel) completely fills the center of the toroid. (Because the stress analysis is 2-dimensional, the equivalent 2-D reinforcement

thickness is used for the actual wedge shape of the reinforcement at the inner part of the coil.)

Dimensions for the cold reinforcement magnets are also given in Table 4. Here several reinforcement thicknesses are analyzed for each of the five basic cases, so that all can be compared on the basis of equal maximum stress. By interpolation the reinforcement thickness corresponding to the maximum allowed stress in the stainless (for this study, 55,000 psi) is determined. This minimizes the amount of expensive stainless steel. The superconductor and stainless reinforcing strip are wound together in a circular coil (Figure 4). Extra support against coil centering forces is provided by a solid stainless support on the inside of the coil, extending along 40% of its arc length, and equal in thickness for the circular wound portion. This solid support could either be a forging or made from stacked welded plates. Central compression rings (shown in Figure 1) carry the actual centering loads. The shape of the solid support was optimized by a number of analyses of different shapes.

This cold reinforcement design differs from ORNL⁽¹⁰⁾ in that here the stainless steel reinforcing strip provides the major portion of coil reinforcement instead of an outside circular solid reinforcing ring, which appears to be more expensive.

It also differs from the Princeton "D" shaped constant tension coil ⁽¹²⁾ which in principle should require less reinforcing material, though a larger amount of superconductor.

Because of the heterogeneous structure and non-uniform loadings, it was necessary to use numerical methods for stress analysis.

Magnet stress determinations were made through the use of a computer code developed at BNL by M. Reich. The code, written for the Brookhaven CDC 6600 system, is a finite element routine designed to evaluate the stresses and deflections in any two-dimensional heterogeneous structure. It accepts as input any combination of force, displacement, and thermal boundary conditions. It provides as output a complete listing of the resultant structural deformations and stresses at all points in the structure. Previously it has been successfully employed to evaluate structures as heterogeneous as prestressed concrete reactor vessels, mine tunnel cross sections with reinforcing bolts, and concrete desalination vessels.

To use the code it is necessary to divide the structure to be analyzed into triangular finite elements. Each element is numbered and in addition each triangle vertex point (node point) is numbered. The resultant figure is referred to as the finite element grid. As it is evident that each triangular element is

delineated by its three associated nodal points only the nodal point numbering sequence is actually shown on a grid. Next the physical properties of each element (modulus of elasticity, density, etc.), the X and Y location of each node point and the desired nodal force-displacement conditions are specified and the problem is run. Since the physical properties of each element are separately specified the evaluation of heterogeneous structures are readily handled. The normal stresses in the X and Y directions, the XY shear stress and the maximum and minimum principal stresses for each element are computed. In addition, the above stresses plus the X and Y deflections of all nodal points are computed. With the present version of the code a system consisting of 2400 elements and 1400 nodes may be analyzed.

Typical finite element grid representations of the cold and warm reinforcement coils are shown in Figures 4 and 5. Obviously, the node point X and Y locations were varied from case to case and the size of elements varied so as to obtain more detailed results in regions of high stress gradient. The force distribution was taken as a radially outward (i.e., along the minor radius vector) acting load varying inversely with the toroidal major radius. It was taken as an internal pressure load in cases 47 through 55 (Table 4) and as a linearly varying body

load in cases 1 through 47 (load varying from a maximum on the inner minor radius to zero on the outer minor radius of the coil). Typical maximum principal stress contour plots are shown in Figure 6 and 7. The discontinuities apparent in Figure 6 are due to the abrupt changes in material properties inherent in the layered warm reinforcement coil structure.

The calculated stresses in the structure scale directly with $(B_0)^2$, as expected. The location of the maximum stress point does not vary with $(B_0)^2$, but can change if coil dimensions change.

Table 5 summarizes and compares the stress analyses for the basic cases. The magnets with warm reinforcement have constant reinforcement thickness and stress thus increases as B_0 increases. The magnets with cold reinforcement have constant maximum stress (55,000 psi) and the reinforcement thickness thus increases with B_0 . Even at the very highest fields, however, the stress in magnets with warm reinforcement is much less than that with cold reinforcement. For DT fuel cycles, the range of B_0 considered is 30 to 70 kG. The lower limit is set by plasma stability, the upper, by the estimate that stability does not require higher fields, even if pessimistic scaling laws are used. For catalyzed DD fuel cycles a range of 50 to 90 kG is considered; the lower limit is set by plasma stability, the upper by Nb_3Sn conductor limits for the smaller magnets.

RESULTS OF ANALYSIS

Table 6 summarizes the refrigeration parameters for the ten selected cases. The barrier refrigeration loads are well within the current state-of-the-art. The input power to the refrigerators is less than 1% of the reactor gross output electric power. Further optimization and combination of the three refrigerator cycles will substantially lower the refrigerator power input and cost.

Table 7 summarizes the magnet component costs for the ten selected cases as a function of magnetic field. Only material costs are included; these are better defined than winding and assembly costs. However, preliminary BNL studies indicate that winding and assembly costs should be small compared with material costs. The thermal barrier refrigeration costs are only about 10% of the total warm reinforcement magnet component cost.

For the cold reinforcement magnets the amount of pulser iron is set by the condition that the iron swings from +22 to -22 kG during the pulse. In two cases, there is insufficient iron in the throat to carry this pulser field. For the warm reinforcement magnets, there is much more pulser iron since it is used for reinforcement and the field change is much smaller, typically +5 to -5 kG. This permits much longer pulse operation

with warm reinforcement magnets, since the excess iron can supply the ΔH_v needed to overcome L/R decay of the plasma ring current.

Material costs reflect large volume current market prices: i.e., \$0.08/lb for pulser iron, \$0.50/lb for fiberglass roving, \$0.50/lb for epoxy, etc.

The results are presented graphically in Figures 8 and 9 as cost in \$/kW(e) as a function of B_0 . At low fields for both DT and catalyzed-DD fuel cycles, warm and cold reinforcement magnets have comparable costs. With further refrigeration optimization, the warm reinforcement costs should drop somewhat, bringing cold reinforcement and warm reinforcement costs to essentially the same value. However, at higher fields warm reinforcement magnets are considerably cheaper. Unit magnet costs increase as plasma diameter increases, as would be expected, but this is a relatively small effect.

The total magnet component cost for cold reinforcement approximately scales as B_0^2 , since additional structure is needed as field increases. However, the total cost for warm reinforcement increases only slightly with B_0 since the amount of structure is taken as independently of B_0 (i.e., the stress increases as B_0^2), and the only component of cost that increases with B_0 is the superconductor material cost.

The plasma stability parameters are shown in Figures 8 and 9 as a function of B_0 for DT and catalyzed-DD fuel cycles. For DT fuel cycles economical warm reinforcement magnets can be built even with unfavorable plasma stability parameters, i.e., $q = 3$, $\beta_0 = 2$. The cost would only increase slightly even if $q = 3$, $\beta_0 = 1$. Even lower first wall loadings (i.e., $0.5 \text{ MW(th)}/\text{m}^2$) could be used and the magnet would be still economically practical. It, thus, appears that even if one assumes very unfavorable plasma containment and very poor materials behavior, DT magnets will be of reasonable cost. For catalyzed-DD fuel cycles and reasonable stability parameters ($q = 2$, $\beta_0 = 3$) warm reinforcement magnets should be economically practical ($\sim \$40/\text{kW(e)}$). In fact, B_0 could increase to $\sim 150 \text{ kG}$ without exceeding a maximum stress of $50,000 \text{ psi}$ in the structure. However, Nb_3Sn could not be used to give B_0 much above 100 kG , even if one operated at temperatures below 4 K , because the field at the inner part of the coil would exceed the capability of Nb_3Sn . However, it appears that cryogenic aluminum could be used to produce B_0 above 110 kG if suitably reinforced against excessive compressive stress, at a relatively small additional magnet cost. Thus even with poor plasma containment ($q = 3$, $\beta_0 = 2$) it should be economically feasible to build catalyzed-DD fusion reactors.

MAGNET CONSTRUCTION

The construction of the warm reinforcement magnets should be relatively straightforward. The principal problem is to compensate for the differential shrinkage between the superconductor and the warm reinforcement. This would be done in two different ways; either by winding the superconductor and then prestressing it in compression by winding the warm reinforcement layer under tension, or by cooling down the superconductor layer to liquid N_2 temperature (far the greatest part of the contraction occurs to this temperature) and then winding on the warm reinforcement layer. In the first method, the superconductor inevitably sees a relatively high compressive stress until cool-down; in the second, it does not see a high compressive stress until warm-up. However, the compressive stresses can be readily carried by the superconductors contemplated, i.e., Nb-Ti and Nb_3Sn .

The toroidal field coils for the reactors in this paper were assumed to be simple pancakes of constant width, with a 20% gap between coils at the inner part where the major toroidal radius is the least. In actual practice, part of the steel for the warm reinforcement coils would have to be properly tapered on this inner part, so that the converging coils would fit together. This could easily be done by winding this part of the warm reinforcement steel as wire wrap in a proper coil form.

Further reductions in magnet cost could be anticipated if cheaper strong stronger structural materials than ordinary steel could be used. One such possibility would be rock, i.e., granite. The magnet coil system could be simply imbedded in a suitably shaped cavity underground, with proper shimming and/or grouting, and the rock could carry the load. Competent granite can carry 30,000 psi in compression and should be suitable for this purpose. If tension cracks do occur, the constraining nature of the surrounding rock should prevent any significant movement. This topic deserves further investigation. In conversations with W. Hassenzahl,⁽¹³⁾ it was learned that this approach has been considered for large energy storage magnets.

SUMMARY AND CONCLUSIONS

The principal conclusions of this study are:

1. Warm reinforcement should greatly reduce the cost of high field magnets for fusion reactors. The extra refrigeration cost is small compared with the savings in structure cost. The refrigeration and thermal barrier designs examined in this paper have not been optimized, and it is expected that optimization will show substantially smaller refrigeration costs for warm reinforced magnets.

2. Magnets for catalyzed-DD reactors appear to be economically practical, on the order of \$40/kW(e). This would eliminate the tritium breeding blanket necessary for DT reactors, which promises difficult technological problems.
3. For tokamak reactors, it appears possible from a structural stress standpoint to use B_0 's of up to 150 kG. This would permit economically practical magnets even if plasma containment should be very poor. Such fields could not be achieved with Nb_3Sn superconductors, however, even if they were operated below 4 K, and cryogenic aluminum or ultra-high-field superconductor inserts would be required.
4. If plasma stability and containment proves good, however, the lower fields will result in quite low structural stresses in magnets with warm reinforcement, in fact, several times less than those in magnets with cold reinforcement.
5. An intriguing possibility exists with warm reinforcement, that of using a massive rock structure to carry the magnetic forces. Such an underground structure, besides providing even cheaper material to carry the magnet forces than the ordinary steel assumed in this paper, would be useful as protective containment for the fusion reactor.

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REFERENCES

1. Powell, J. R. Costs of Magnets for Large Fusion Power Reactors: Phase I, Cost of Superconductors for dc Magnets, Brookhaven National Laboratory Informal Report, BNL 16580, Feb. 25, 1972.
2. Powell, J. R. Design and Economics of Large dc Fusion Magnets, Proc. 1972 Applied Superconductivity Conference, IEEE Pub. No. 72CH0682-5-TABSC, p. 374, May 1-3, 1972, Annapolis, Maryland.
3. Toth, L. W. Properties of Glass-Reinforced Epoxy through the 20 K Range, Modern Plastics, p. 123, Aug. 1965.
4. Campbell, M. D. et al. Thermophysical Properties of Plastic Materials and Composites to Liquid Hydrogen Temperature (-423 F), ML-TDR-64-33, Part III, Aug. 1965.
5. Hertz, J. Investigation of Potential Low Temperature Insulators, Advances in Cryogenic Engineering, 11, p. 287, Plenum Press, New York, 1966.
6. Ashworth, T., Loomer, J. E., and Kreitman, M. M. Thermal Conductivity of Nylons and Apiezon Greases, Paper F-3, Cryogenic Engineering Conference, Boulder, Colorado, 1972.
7. Mikesell, R. P. and Scott, R. B. Heat Conduction through Insulating Supports in Very Low Temperature Equipment, J. Res. of Nat'l Bur. Std. 57, 371 (1956).

8. Resistive Cryogenic Cable, Phase A and Phase B report, General Electric Company, EEI Project RP-78-6 (1969).
9. Kurti, N. Cryogenic Fundamentals, G. G. Haselden, Editor, Academic Press, 1971.
10. Lubell, M. S. et al. Engineering Design Studies on the Superconducting Magnet System of a Tokamak Fusion Power Reactor, Paper CN-28/K-10, 4th IAEA Conf. on Plasma Physics and Controlled Thermonuclear Fusion Research, Madison, Wisconsin, June 1971.
11. Mills, R. G. Catalyzed Deuterium Fusion Reactor, TM-259, Princeton Plasma Physics Laboratory, Apr. 1971.
12. File, J., Mills, R. G., and Sheffield, G. V., Large Superconducting Magnet Designs for Fusion Reactors, MATT-848, Princeton Plasma Physics Laboratory, June 1971.
13. Hassenzahl, W., Los Alamos National Laboratory, private communication, 1972.

TABLE 1

PROPERTIES OF CANDIDATE MATERIALS FOR THERMAL BARRIER

Sample no.	Type	Thermal conductivity λ to lamina (mWcm ⁻¹ °K ⁻¹)					Compressive strength λ to lamina (ksi)				Ref.
		T=4°K	20	77	300	Test atm	T=4°K	20	77	300	
1-7	Epoxy fiberglass										
1	(1581 cloth	--	--	0.79	9.8	vac	--	101	95	59	3
2	(1543 cloth)	--	--	0.90	11.0	vac	--	65	69	36	3
3	(UFW)*	--	--	1.35	10.9	vac	--	52	52	25	3
4	(BFW)**	--	--	0.92	10.5	vac	--	102	99	79	3
5	Roving	--	1.30	2.45	4.8	He, 1 atm	--	--	--	73†	4
5A	Unidirectional	--	0.58	1.73	3.3	vac	--	--	--	73	4
6	NARMCO 570/1581	--	1.10	2.10	4.3	He, 1 atm	--	134	139	76	5†
7	NARMCO 570/143	--	1.20	2.20	4.0	He, 1 atm	--	101	72	49	5†
8	KEL-F	--	0.56	1.10	1.4	He, 1 atm	--	20	17	5	5†
9	Nylon 101	--	1.00	2.50	3.4	He, 1 atm	--	--	35	10	5†
10	{ Glass fiber }	--	1.60	3.20	5.0	He, 1 atm	--	--	--	19†	4
10A	{ Imidite resin }	--	0.29	1.20	3.6	vac	--	--	--	19	4
11	{ Potassium titanate }	--	1.20	2.20	4.3	He, 1 atm	--	--	--	21	4
11A	{ Fibers-epoxy }	--	0.43	1.20	1.6	vac	--	--	--	21	4
12	Nylon	0.13	0.95	2.70	3.7	--	--	--	--	--	6

* Unidirectional filamentary winding.

** Bidirectional filamentary winding.

† Tensile strength || to lamina, compressive strength not given.

* Lower than reported in the literature, possibly poor quality.

TABLE 2

REFRIGERATION PARAMETERS FOR FUSION REACTORS
WITH WARM REINFORCEMENT

$T_c = 4.5 \text{ K}$	$P_c =$	Refrigeration load, kW		
		1	3	10^c
Refrigeration factor, $W(e)/W(th)^a$		450	380	250
Capital cost of refrigerator, $\$/W(th)^a$		470	284	132
Capitalized cost of power, $\$/W(th)^b$		98	83	55
Total refrigerator cost, $\$/W(th)$		568	367	187

$T_c = 20 \text{ K}$	$P_c =$	100^c	200	300	400
Refrigeration factor, $W(e)/W(th)^a$		45.6	45.5	43.5	42.3
Capital cost of refrigerator, $\$/W(th)^a$		20.0	12.6	9.9	8.5
Capitalized cost of power, $\$/W(th)^b$		10.0	10.0	9.5	9.3
Total refrigerator cost, $\$/W(th)$		30.0	22.6	19.4	17.8

$T_c = 77 \text{ K}$	$P_c =$	500^c	1000	2000
Refrigeration factor, $W(e)/W(th)$		9.6	7.70	7.55
Capital cost of refrigerator, $\$/W(th)^a$		2.3	1.85	1.55
Capitalized cost of power, $\$/W(th)^b$		2.1	1.70	1.65
Total refrigerator cost, $\$/W(th)$		4.4	3.55	3.20

^a Refrigeration factor and capital cost of refrigerators taken from Ref. 8.

^b Cost of refrigerator power is 4 mils/kWh; capital charges of 16%/yr.

^c Refrigeration load from thermal barrier appropriate to 1000 MW(e) fusion reactor with warm reinforcement and a first wall flux of 1 MW(th)/m².

TABLE 3

COST OF THERMAL BARRIER FOR DIFFERENT BARRIER THICKNESS

Temperature of sink (K)	Refrigeration load, W/m^2		
	$\Delta x(m) = 0.3$	0.5	0.8
4	9.3	5.6	3.5
20	50.5	30.3	18.9
77	451.0	271.0	169.0
Component	Cost of thermal barrier, $\$/m^2$		
	$\Delta x(m) = 0.3$	0.5	0.8
Refrigeration			
4	1745	1047	654
20	1515	909	568
77	1985	1191	744
Material			
Stainless	1156	1850	3083
Epoxy fiberglass	404	647	1078
Total	6805	5644	6127

$$\Delta x_{4 \rightarrow 20 \text{ K}} = \Delta x_{20 \rightarrow 77 \text{ K}} = \Delta x_{77 \rightarrow 300 \text{ K}} = 1/3 \Delta x.$$

$$\Delta x_{\text{epoxy fiberglass}} / \Delta x_{\text{stainless}} = 2/1.$$

$$\bar{k}_{\text{eff epoxy fiberglass}} = 0.4 \text{ Wcm}^{-1} \text{ K}^{-1} (4 \rightarrow 20).$$

$$0.7 \text{ Wcm}^{-1} \text{ K}^{-1} (20 \rightarrow 77).$$

$$1.5 \text{ Wcm}^{-1} \text{ K}^{-1} (77 \rightarrow 300).$$

$$\bar{k}_{\text{eff stainless}} \gg \bar{k}_{\text{eff epoxy fiberglass}}$$

Stainless strip, \$0.70/lb.

Epoxy fiberglass strip, \$0.50/lb.

TABLE 4
MAGNETS ANALYZED

Case no.	Reactor type	RF type	R_i (m)	R_o (m)	R_T (m)	ΔR thickness			B_o (kG)	Maximum principal stress			* LOC.
						RF (m)	TB (m)	Al (m)		RF (ksi)	TB (ksi)	Al (ksi)	
41	DT	warm	5.75	8.55	10.50	2.00	0.50	0.30	60.0	21.99	10.26	7.61	1104
42	DT	warm	7.49	12.00	15.75	3.71	0.50	0.30	60.0	14.65	6.52	4.90	1104
43	DD	warm	4.75	8.05	10.50	2.50	0.50	0.30	90.0	27.88	14.24	9.95	1104
44	DD	warm	6.49	11.52	15.75	4.23	0.50	0.30	90.0	22.70	10.81	7.82	1104
45	DD	warm	8.25	15.02	21.00	5.97	0.50	0.30	90.0	20.89	8.70	6.93	1104
7	DT	cold	5.60	6.74	10.50	1.14	--	--	78.5	81.21	--	--	1
8	DT	cold	5.60	6.36	10.50	0.76	--	--	78.5	130.59	--	--	1
10	DT	cold	5.60	5.98	10.50	0.38	--	--	37.0	84.74	--	--	645
12	DT	cold	5.60	6.11	10.50	0.51	--	--	37.0	50.53	--	--	658
14	DT	cold	5.60	6.62	10.50	1.02	--	--	78.5	91.60	--	--	1
17	DT	cold	7.34	7.85	15.75	0.51	--	--	37.0	68.51	--	--	645
18	DT	cold	7.34	8.10	15.75	0.76	--	--	26.2	17.60	--	--	1
19	DT	cold	7.34	8.36	15.75	1.02	--	--	37.0	24.69	--	--	1
20	DT	cold	7.34	8.85	15.75	0.51	--	--	78.5	68.97	--	--	1
21	DT	cold	7.34	9.34	15.75	2.00	--	--	78.5	49.98	--	--	840
47	DD	cold	4.60	5.36	10.50	0.76	--	--	90.0	110.42	--	--	1
48	DD	cold	4.60	5.87	10.50	1.27	--	--	90.0	68.79	--	--	801
49	DD	cold	4.60	6.38	10.50	1.78	--	--	90.0	52.17	--	--	814
50	DD	cold	6.34	7.61	15.75	1.27	--	--	90.0	84.37	--	--	1
51	DD	cold	6.34	8.12	15.75	1.78	--	--	90.0	61.90	--	--	801
52	DD	cold	6.34	8.63	15.75	2.29	--	--	90.0	50.18	--	--	814
53	DD	cold	8.10	9.88	21.00	1.78	--	--	90.0	74.25	--	--	1
54	DD	cold	8.10	10.39	21.00	2.29	--	--	90.0	58.78	--	--	801
55	DD	cold	8.10	10.89	21.00	2.79	--	--	90.0	49.66	--	--	814

R_i = minor inner radius.

RF = reinforcement.

R_o = minor outer radius.

TB = thermal barrier

R_T = radius of toroid.

B_o = central field.

* LOC is the node number on the appropriate finite element grid.

TABLE 5
COMPARISON OF SELECTED MAGNET DESIGNS

Case no.	Reactor type	RF type	R_i (m)	R_T (m)	JR RF thickness (m)				Comments
1	DT	warm	5.75	10.50	2.00				Stress = $f(B_o)$ refer to Table 4.
2	DT	warm	7.49	15.75	3.71				
3	DD	warm	4.75	10.50	2.50				
4	DD	warm	6.49	15.75	4.23				
5	DD	warm	8.25	21.00	5.97				
					$B_o = 30$	$B_o = 50$	$B_o = 70$	$B_o = 90$	
6	DT	cold	5.60	10.50	0.38	0.74	1.35	--	Stress = 55 ksi
7	DT	cold	7.34	15.75	0.47	0.86	1.52	--	
8	DD	cold	4.60	10.50	--	0.43	0.94	1.68	
9	DD	cold	6.34	15.75	--	0.57	1.17	2.02	
10	DD	cold	8.10	21.00	--	0.81	1.49	2.41	

R_i = minor inner radius.

R_o = minor outer radius.

R_T = radius of toroid.

RF = reinforcement.

TABLE 6

OUTPUT POWER AND REFRIGERATOR PARAMETERS FOR SELECTED FUSION REACTORS

Case No.	Relative* plasma diameter	Reinforce- ment	Gross** electric output MW(e)	Thermal* barrier area (m ²)	Barrier refig- erator load, kW			Power input to refrigerator MW(e)	Total* (millions)	$\frac{B_{max}}{B_o}$
					4 K	20 K	77 K			
1	1.0	warm	580	928	5.2	28.1	251	4.4	2.9	2.14
2	1.5	warm	1304	2056	11.5	62.3	557	9.7	6.5	1.88
3	1.0	warm	580	931	5.2	28.5	252	4.4	2.9	1.78
4	1.5	warm	1304	2003	11.2	60.7	543	9.4	6.3	1.67
5	2.0	warm	2320	3463	19.4	105	938	16.4	10.9	1.63
6	1.0	cold	580	--	--	--	--	--	--	2.14
7	1.5	cold	1304	--	--	--	--	--	--	1.88
8	1.0	cold	580	--	--	--	--	--	--	1.78
9	1.5	cold	1304	--	--	--	--	--	--	1.67
10	2.0	cold	2320	--	--	--	--	--	--	1.63

† Refrigeration cost includes capitalized power cost, 4 mils/kWh at 16%/yr

‡ Thermal barrier thickness = 0.5 m.

* Relative diameter of 1.0 corresponds to real diameter = 5.6 m; plasma aspect ratio = 3.75.

** First wall loading = 1.0 MW(th)/m²; thermal efficiency = 40%.

TABLE 7

COMPONENT COSTS FOR SELECTED FUSION REACTORS

Component cost*, million \$										
Case No.	B O kG	Barrier refrigerator	Super- conductor	Epoxy fiber- glass	Aluminum	Stainless strip	Support forging	Pulser iron	Total	Total \$/kW(e)
1	30	2.9	1.4	0.6	0.6	1.7	2.0	3.0	12.2	21.0
	50	2.9	3.2	0.6	0.6	1.7	2.0	3.0	14.0	24.0
	70	2.9	7.3	0.6	0.6	1.7	2.0	3.0	18.1	31.0
2	30	6.5	2.6	1.3	1.3	3.8	6.8	12.7	35.0	27.0
	50	6.5	5.5	1.3	1.3	3.8	6.8	12.7	37.9	29.0
	70	6.5	11.8	1.3	1.3	3.8	6.8	12.7	44.2	34.0
3	50	2.9	2.1	0.6	0.6	1.7	2.2	4.0	14.1	24.5
	70	2.9	4.3	0.6	0.6	1.7	2.2	4.0	16.3	28.0
	90	2.9	9.2	0.6	0.6	1.7	2.2	4.0	21.2	36.5
4	50	6.3	3.6	1.3	1.4	3.7	6.6	15.0	37.9	29.0
	70	6.3	8.6	1.3	1.4	3.7	6.6	15.0	42.9	33.0
	90	6.3	16.0	1.3	1.4	3.7	6.6	15.0	50.3	38.5
5	50	10.9	7.3	2.3	2.2	6.5	15.0	38.0	82.2	35.5
	70	10.9	14.4	2.3	2.2	6.5	15.0	38.0	89.3	38.5
	90	10.9	26.2	2.3	2.2	6.5	15.0	38.0	101.1	43.5
6	30	--	1.4	--	--	3.6	1.9	1.9	8.8	15.2
	50	--	3.3	--	--	7.4	3.9	2.0	16.6	28.6
	70	--	7.9	--	--	14.0	8.4	**	30.3	52.2
7	30	--	2.6	--	--	10.0	5.4	5.0	23.0	17.6
	50	--	5.7	--	--	20.0	10.0	5.3	41.0	31.4
	70	--	12.6	--	--	35.0	21.0	5.7	74.3	60.0
8	50	--	2.2	--	--	4.5	2.2	1.6	10.5	18.1
	70	--	4.6	--	--	10.0	5.5	1.8	21.9	37.8
	90	--	10.3	--	--	19.0	12.0	**	41.3	71.2
9	50	--	3.7	--	--	13.0	6.3	4.5	27.5	21.1
	70	--	9.1	--	--	26.0	15.0	4.9	55.0	42.2
	90	--	17.7	--	--	48.0	30.0	5.4	101.1	77.5
10	50	--	7.5	--	--	31.0	16.0	9.6	64.1	27.6
	70	--	15.3	--	--	59.0	33.0	10.2	117.5	50.6
	90	--	28.8	--	--	100.0	61.0	11.1	200.9	86.6

* Does not include coil winding costs.

** Insufficient iron in center of tokamak to supply $2H_v = 44$ kG.

Epoxy fiberglass = \$0.50/lb

Aluminum = \$0.35/lb

Stainless strip = \$0.70/lb

Support forging (iron)

Support forging (stainless) = \$1.00/lb

Pulser iron

= \$0.20/lb

= \$0.08/lb

Figure 1 Illustration of cold reinforcement magnet coil for tokamak fusion reactor.

Figure 2 Illustration of warm reinforcement magnet coil for tokamak fusion reactor.

Figure 3 Illustration of thermal barrier concept.

Figure 4 Finite element grid for 2-D stress analysis-cold reinforcement case.

Figure 5 Finite element grid for 2-D stress analysis-warm re-inforcement case.

Figure 6 Stress contours-cold re-
inforcement case.

Figure 7 Stress contours-warm re-
inforcement case.

REFNO X44

Figure 8 Magnet component cost versus on-axis magnetic field-DT fuel cycles.

Figure 9 Magnet component cost versus on-axis magnetic field-DD fuel cycles.