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### Introduction

A Tokamak Engineering Test Reactor (TETR) will be an important component of any national or international program to achieve viable tokamak fusion power reactors. The functions of such an engineering reactor are to test blanket and shield designs, to perform materials and radiation damage studies, and to find solutions to other major engineering problems, such as remote handling, tritium extraction and tritium leakage control. A reactor designed with these goals in mind need not however be a power reactor or produce net electric power.

Recently, the design criteria for such a machine has been examined.<sup>(1)</sup> It is found that by using reaction ion beams in the two component tokamak (TCT) mode<sup>(2)</sup> together with a blanket-shield design based on the concept of internal neutron spectrum shaping,<sup>(3)</sup> a modest size reactor producing a 14 MeV neutron wall loading of about  $1 \text{ MW/m}^2$  can be achieved.

It is desirable for the toroidal field magnet to be superconducting in order to minimize the external power requirements and to achieve plasma burn times as long as 30 to 60 seconds. The design and the components of a superconducting toroidal field magnet for a TETR will be described in this paper. It consists of 18 modified constant tension "D" shaped coils each with a bore at the mid-plane of 5.55 m. With a design maximum field of 8.0 T at the winding, it provides a field of 3.8 T at the plasma center of major radius 3.05 m.

### Reactor Parameters

The system parameters for the TETR as developed by Conn and Jassby<sup>(1)</sup> are listed in Table I. The machine is designed for a plasma current of 2.4 MA at a safety factor,  $q(a)$ , of 2.5. The plasma has a noncircular cross section with a height to width ratio of 2:1 and a midplane radius of 0.55 m. The electron density-energy confinement time product,  $n_e \tau_E$ , is about  $8 \times 10^{12} \text{ cm}^{-3}$ -sec at an electron temperature of about 5 keV. The pure tritium plasma will be operated in the TCT mode using 177 MW power of 200 keV neutral deuterium beam

injection. It is to be noted that by the time a TETR could be operational (possibly in mid-1980's) all the above stated concepts - moderately noncircular plasma, TCT mode, and high powered beam injection - will have been tested several years before.<sup>(4)</sup> Therefore, a substantial extrapolation of plasma physics into untested regimes should not be required.

The thermal power output of the plasma will be approximately 185 MW, and the 14 MeV neutral wall loading is  $0.96 \text{ MW/cm}^2$  when the on axis toroidal field (TF) is 3.8 T. The area of the first wall is approximately  $150 \text{ m}^2$ , which leaves ample space for test sections. A specially designed blanket-shield combination<sup>(1,3)</sup> is incorporated on the inside of the torus such that only samples and blanket modules on the outer portion need be removed. The number of TF coils is determined as a compromise between the desire for a small field ripple (less than 1%) at the outer plasma surface and the need for working space between the coils and low capital costs. A set of 18 toroidal field magnets appears to satisfy these requirements. A vertical cross sectional view of the TETR is shown in Figure 1. Enclosed in the TF coil are the plasma, blanket, shield, and vertical field coils.

### Design Parameters

The design philosophy for the superconducting toroidal field magnet is to ensure maximum reliability and to use present day technology with little or no extrapolation where possible. The following initial choices are made:

(1) The superconducting composite consists of NbTi filaments co-drawn in a copper matrix. This alloy is chosen because it is ductile, relatively easy to handle, and there exists reliable manufacturing techniques. The large degradation of critical current density of  $\text{Nb}_3\text{Sn}$  under strain<sup>(5)</sup> and its susceptibility to radiation damage<sup>(6)</sup> also influenced the choice of NbTi. The other major consideration is the time frame such a reactor might be constructed. It is likely that a coil set as described here will be required in the mid 1980's. This also tends to dictate the choice of NbTi. On the other hand, the fusion power density in the plasma and the neutron wall loading scale as  $B_o^4$  so that if a higher field superconductor becomes available, it could be used to advantage in a tokamak engineering test reactor. The effect of higher magnetic field on reactor performance is discussed further in the last section on alternate magnet design considerations.

(2) The conductor is fully cryogenically stabilized with copper side strips. A monolithic constant cross section superconducting composite is sized to that of the outermost turn conductor. Wider and wider copper side strips are soldered onto the composite as it winds to inner turns (see Fig. 3).

(3) Conductor cooling is via liquid helium pool boiling at 4.2 K to support a maximum field of 8.0 T at the winding.

(4) The coil has a modified constant tension "D" shape. A "D" shaped coil makes the most economical use of the magnet structure because of the  $1/R$  dependence of the toroidal field.<sup>(7)</sup> The constant tension in the winding minimizes the bending moment and interturn shear. Thus, no external reinforcing

ring is necessary. However, in order to provide extra space for the removal of the outer portion of the blanket and shield while maintaining a height no more than required for the internal components, it is advantageous to deviate from a constant tension shape near the inner leg.<sup>(8)</sup> The outer surface of the plasma shown in Figure 2 has a radial distance of 3.6 m at the midplane. Allowing a 0.2 m scrape-off zone, 1.5 m blanket and shield zone plus 1.7 m extra space, a coil with midplane bore of 5.55 m is required. The extra 1.7 m space is to allow for removal of blanket-shield modules without moving a TF coil. If full constant tension is adhered to, a tall "D" shown by a broken line in Fig. 2 is necessary. By using a smaller starting radius of curvature at the far edge, a modified "D" which is constant tension from  $R=2.5$  m out is obtained. Because of the smaller coil circumference and magnet stored energy, a saving of about 15% in magnet cost is possible.

(5) The coil winding involves embedding the conductor into the premachined spiral grooves of the stainless steel structural disc. It is well known that conductor movement is a prominent cause of superconducting magnet degradation. Because of the very large tensile force involved, loose "jelly roll" type winding is not recommended. Instead, we consider a winding procedure first proposed by Young and Boom<sup>(9)</sup>. As shown in Figure 3, spiral grooves are forged or machined into both sides of a "D" shaped stainless steel disc. The preshaped conductor is spirally wrapped with fiberglass tape presoaked with epoxy before winding into the grooves. After the epoxy is cured by heat, the surface can be machined off to expose the conductor for liquid helium cooling. The fiberglass epoxy then serves as both mechanical bond and insulation between the conductor and the winding disc. Thus, the conductor is embedded in the disc in such a way that no movement can be envisioned during magnet charging, discharging or poloidal field pulsing. The completed discs of a coil are assembled by prestressed aluminum bolts with 0.45 cm thick micarta spacers covering about 50% of the surfaces between adjacent discs. Clamp joints between the conductors

of adjacent discs furnish the electrical continuity throughout the coil.

The constraints on the toroidal field magnet of a TETR are more severe than that on a larger power reactor machine. The reasons are that the size of the machine should be kept as small as possible to reduce the cost while the coils should produce a magnetic field of 3.8 T on axis which is fairly high. These constraints give rise to a higher overall current density requirement than in larger power reactor magnet systems.

#### Current Density Requirement

The minimum distance between the plasma center and the inside edge of the straight winding leg,  $r$ , is dictated by the plasma minor radius, the plasma scrape-off zone width, and the minimum shielding thickness required for a reasonably low heating and radiation loading at the magnet. The parameters listed in Table I and the special inside blanket-shield combination<sup>(1)</sup> mentioned before give  $r = 1.6$  m for an energy attenuation of  $8.31 \times 10^{-6}$ . Therefore, to obtain 3.8 T at the plasma center, a major radius,  $R_o$ , of 3.05 m is required such that the maximum field,  $B_M$ , at the winding is no greater than 8.0 T. The average winding disc current density,  $J_d$ , is related to  $R_o$ ,  $r$ , and  $B_M$  through the equation,

$$J_d = \frac{B_M(R_o - r)}{\mu_o \delta_d R_i(R_o - R_i - r)} \quad (1)$$

(See Fig. 2 for the various dimensions.)

Inside the straight winding leg, there are transformer windings, central supporting structure, and dewar. With a value of  $R_i = 1.05$  m, and an assumption of a fraction,  $\delta_d$ , of 80% of the inner toroidal circumference for winding, a disc current density of  $2750 \text{ A/cm}^2$  is required.

#### Winding Disc and Conductor Sizes

The cryogenic stability criterion and a compromise between the stress level and the ability to build the stainless steel disc determine the thickness of the disc and the size of the conductor. The winding disc thickness,  $t$ , is



limited by the volume fraction of the conductor,  $\lambda_n$ , and by  $J_d$  according to

$$t \leq \frac{2 q \delta_n \lambda_n}{\bar{\rho}_n J_d^2}, \quad (2)$$

where the average magnetoresistivity of the copper,  $\bar{\rho}_n$ , is taken at the average field,  $\bar{B}$ , across the winding

$$\bar{\rho}_n = \rho_o (1 + 0.455 \bar{B}) \quad (3)$$

We adopt a value of  $0.4 \text{ W/cm}^2$  <sup>(10)</sup> for the surface heat transfer flux,  $q$ , and a fraction,  $\delta_n$ , of 85% for the disc width occupied by the conductor. Using  $\lambda_n = 66.7\%$ , we arrive at a value of  $t = 2.1 \text{ cm}$ . The chosen  $\lambda_n$  value also gives an average stress in the disc of  $9.58 \times 10^7 \text{ N/m}^2$  (13,900 psi), and an average conductor stress of  $7.18 \times 10^7 \text{ N/m}^2$  (10,500 psi). This value is somewhat smaller than the low temperature copper yield strength,  $8.27 \times 10^7 \text{ N/m}^2$  (12,000 psi).

The conductor thickness which fulfills the cryogenic stability criterion is given by

$$t_n = \frac{q \lambda_n^2}{\bar{\rho}_n J_d^2} \quad (4)$$

and is equal to 0.83 cm. With this value of  $t_n$ , the variation of the width of the conductor,  $W_n$ , depends only on the magnetoresistivity and is given by

$$W_n = I \left( \frac{\rho_n}{q t_n} \right)^{1/2} \quad (5)$$

Using a design value of 10 kA for the conductor current, one finds  $W_n$  varies from 3.74 cm at the innermost turn to 1.74 cm at the outermost turn (see Fig. 3).

The number of conductor turns per disc is taken to be an even 24, and 14 discs for each of the 18 coils are required to get the total ampere-turns of  $58 \times 10^6$ .

### Superconducting Filaments

Assume that the thermal conductivity of the copper,  $K_n$ , follows the Wiedemann-Franz law such that

$$K_n = K_B \left( \frac{\rho_o}{T_B} \right) \frac{T}{\rho_n} \quad . \quad (6)$$

A one-dimensional heat balance equation can be solved to arrive at the temperature profile along the thickness of the conductor when the copper carries the total current. The solution is

$$T_n^2 = T_o^2 + \frac{T_B \rho_n^2 J^2}{K_B \rho_o} (2xt_n - x^2) \quad 0 \leq x \leq t_n \quad . \quad (7)$$

For a conductor surface temperature,  $T_o$ , of 4.7 K (which is consistent with the chosen value of  $q = 0.4 \text{ W/cm}^2$ ) the maximum temperature in the conductor is 4.95°K and occurs on the innermost turn. The superconducting filaments are sized using

$$N_f = \frac{I}{a_s J_c} \quad , \quad (8)$$

with  $J_c = 2.5 \times 10^4 \text{ A/cm}^2$  at  $T_s = 5.1 \text{ K}$  and  $B = 8 \text{ T}$ . The number of filaments,  $N_f$ , is 352 when 0.038 cm diameter wire is used. The number of filaments required for smooth current sharing between the superconductor and copper<sup>(10)</sup> is

$$\bar{N}_f \geq \frac{I^2 \rho_n}{32\pi K_s A_n (\bar{T}_s - T_n)} \quad , \quad (9)$$

where the average filament temperature,  $\bar{T}_s$ , has its maximum value when the current is equally shared by the superconductor and copper.  $N_f = 352$  is about  $2 \bar{N}_f$ . Therefore, under all normal operating conditions, the temperature in the superconducting filament will never go above 5.1 K, and there are enough superconductors to carry the total current such that self recovery of superconductivity is ensured.

### Summary of the Reference Design

The reference design parameters of the toroidal field magnet set are listed in Table II. The entire assembly consists of 18 cryogenically stabilized superconducting coils evenly spaced around a central support structure. This structure, which also houses the transformer coils, is kept at liquid helium temperature so that low thermal loss to the magnet is possible. The individual helium inner dewar is tightly built around each coil. A secondary vacuum wall for the plasma is built in between the coils and also serves as a lateral support. Details of the magnet assembly are similar to that given in reference (11), which also includes a structural protection scheme to guard against fault conditions.

Each modified constant tension "D" shaped coil has a bore diameter of 5.55 m at the midplane. With a design maximum field of 8 T at the winding, it supplies a field of 3.8 T at the plasma center of  $R_0 = 3.05$  m. Each completed coil has a cross section of 36.7 cm thick by 40 cm width. There are 14 discs per coil with 24 turns (12 turns on each side) on each disc. The monolithic superconducting composite, which contains 352 filaments for each disc, has a length of 550 m. Each conductor carries an operating current of 9590 A which gives a winding disc current density of  $2740 \text{ A/cm}^2$ . The average conductor size is 0.83 cm x 2.9 cm with a Cu to NbTi volume ratio of 6:1. The integration of the magnetic energy density over the torus volume gives a total energy storage of 3800 MJ.

The total materials required and the cost estimates of the reference magnet unit are itemized in Table III. The amount of materials required is calculated from the machine dimensions and a unit price is assigned to each of them. The fabrication and assembly labor cost at different stages is estimated by multiplying a unit weight cost by the weight of the components to be worked on. The total capital cost of this toroidal field magnet set reference unit is estimated to be about 11 million dollars.

### Alternative Magnet Design Considerations

In the reference design, the outside leg of the coil was extended to a radial distance of 7 m (see Fig. 2) because a 1.5 m outer blanket and shield zone was considered and an extra 1.7 m space was provided for the removal of the blanket and shield modules. If less space is required for handling these modules, the outside leg need only extend to 5.95 m. The magnet bore at the midplane would then be reduced to 4.5 m, and a full constant tension "D" shaped coil will give the same height as the reference design. The coil circumference is 18% less so that a savings of about 18% in the magnet cost is possible.

If higher magnetic field is desired, pumping on the liquid helium bath is the most straightforward alternative. For example, with the plasma height to width ratio remaining at 2:1, a maximum field of 9 T at the coil can be achieved by pumping on the helium to produce a temperature of about 3°K.<sup>(12)</sup> The axial field becomes 4.3 T, the plasma current becomes 2.7 MA and the fusion power density increases to  $6.9 \text{ W/cm}^3$ . Most importantly, the neutron wall loading becomes  $1.54 \text{ MW/m}^2$ , a 60% gain<sup>(1)</sup> over the 8 T maximum field case.

An interesting alternative is to consider the impact of a higher field superconductor, such as  $\text{Nb}_3\text{Sn}$ , on the reactor performance. If  $\text{Nb}_3\text{Sn}$  can be used in such large bore coils, and we take 12T as the field at the coil, the magnetic field on axis becomes 5.7T and the 14MeV neutron wall loading increases to  $5.05 \text{ MW/m}^2$ . At such high magnetic fields, it becomes possible to design relatively small circular tokamaks which can also achieve high neutron wall loadings.<sup>(1)</sup> A summary of the impact these alternative assumptions on magnetic field have on test reactor performance is given in table IV.

A final comment should be made on the liquid helium surface cooling flux of  $0.4 \text{ W/cm}^2$  which was used for the reference design. If a smaller value is used for the design cooling channels (1mm at the micarta spacer covered area, 4.5 mm otherwise), a smaller winding disc current density is desirable.

This can be achieved by wedging the disc at the central structure and using larger disc thicknesses where space is available.

#### Acknowledgement

The authors wish to thank Drs. R. W. Boom, W. C. Young and I. N. Sviatoslavsky for their valuable discussions. We also thank Mr. W. L. Larson of Supercon, Inc. for an independent estimate of the total conductor costs. This work was supported by the United States Energy Research and Development Administration and the Wisconsin Electric Utility Research Foundation.

Notation

|       |   |
|-------|---|
| $A_n$ | = normal conductor (copper) cross section per conductor                       |
| $a_s$ | = superconducting filament cross section                                      |
| $B$   | = magnetic field  |
| $B_M$ | = maximum field at the winding  |
| $B_o$ | = toroidal field at plasma center   |
| $d$   | = winding disc width  |
| $I$   | = conductor current   |
| $J$   | = conductor current density   |
| $J_c$ | = superconductor critical current density                                     |
| $J_d$ | = average winding disc current density  |
| $K_n$ | = copper thermal conductivity   |
| $K_B$ | = copper thermal conductivity at bath temperature and zero field = 2.5 W/cm-K |
| $K_s$ | = superconductor thermal conductivity, taken to be 0.5 mW/cm-K                |
| $N_f$ | = number of superconducting filaments per conductor                           |
| $q$   | = heat transfer flux between conductor surface and liquid helium              |
| $R$   | = radial distance from torus axis   |
| $R_o$ | = major radius  |
| $R_i$ | = inner radial distance to magnet winding                                     |
| $r$   | = plasma center to inside edge of the straight leg distance                   |
| $T_B$ | = bath temperature = 4.2 K  |
| $T_n$ | = normal conductor temperature  |
| $T_o$ | = conductor temperature at the surface  |
| $t$   | = winding disc thickness  |
| $t_n$ | = conductor thickness   |

Notation (continued)

$W_n$  = conductor width

$x$  = distance from conductor surface

$\delta_d$  = fraction of inner toroidal circumference available for winding

$\delta_n$  = fraction of disc width occupied by the conductor

$\lambda_n$  = conductor volume fraction of the winding disc

$\rho_n$  = magnetoresistivity of copper

$\rho_0$  = resistivity of copper at zero field, taken to be  $10^{-8} \Omega\text{-cm}$

$\mu_0$  = magnetic susceptibility of vacuum =  $4\pi \times 10^{-7}$

### References

1. R. W. Conn, D. L. Jassby, "A Tokamak Engineering Test Reactor" in Proc. Int'l Conf. on Radiation Test Facilities for the CTR Surface and Materials Program (Argonne National Lab., July 1975) to be published by E.R.D.A. See also, Nucl. Eng. Dept. Report FDM-119, Univ. of Wis. (March 1975) and Trans. Am. Nucl. Soc. 21, 24 (1975).
2. J. M. Dawson, H. P. Furth and F. H. Tenney, Phys. Rev. Letts, 26, 1156 (1971); D. L. Jassby, Princeton Plasma Physics Laboratory Report MATT 1072 (Oct. 1974)
3. R. W. Conn, G. L. Kulcinski, H. Avci and M. El-Maghrabi, Nuclear Technology 26, 125 (1975).
4. Pre-TETR machine includes: Tokamak Fusion Test Reactor,  $I = 2.5$  MA, operating date 1980; Doublet-III 3:1 noncircular plasma,  $I = 5$  MA, operating date 1978; Joint European Tokamak, 1.5:1 noncircular plasma,  $I_p = 5.0$  MA, operating date 1979-80, etc.
5. M. N. Wilson, to be published in the proceedings of the Fifth International Conference on Magnet Technology, Frascati, Italy, April 21-25, 1975.
6. D. M. Parkin and D. G. Schweitzer, Nuclear Technology 22, 108 (1974).
7. J. File, R. G. Mills and G. V. Sheffield, "Large Superconducting Magnet Designs for Fusion Reactors," Princeton Plasma Physics Laboratory Report MATT-848 (1971).
8. R. W. Conn, G. L. Kulcinski, M. Abdou, R. W. Boom, G. A. Emmert, Y. Eyssa, M. Hilal, J. Kesner, J. W. Lue, C. W. Maynard, A. Mense, J. Scharer, T. Sung, I. Sviatoslavsky, D. Sze, W. Vogelsang, L. Wittenberg, T. Yang, W. Young, in Plasma Physics and Controlled Nuclear Fusion Research (5th IAEA Conf., Tokyo, Nov. 11-15, 1974) to be published by IAEA, Vienna.
9. W. C. Young and R. W. Boom, in Proc. of the Fourth International Conference on Magnet Technology (Conf-720902, U.S.A.E.C., 1972) p. 244.
11. I. N. Sviatoslavsky, W. C. Young, and J. W. Lue, presented at the Cryogenic Engineering Conference, Kingston, Canada, July 22-25, 1975, paper B-9.
12. NbTi magnets with quench field up to 11 T at 2.2 K are commercially available from Intermagnetics General Corporation, Guilderland, New York.



Table I

University of Wisconsin Design- TETR System Parameters (1)

|  |  |
|--|--|
| Major radius, $R_o$  | 3.05 m   |
| Plasma radius at midplane, $a$                                 | 0.55 m   |
| Aspect ratio, $R_o/a$  | 5.5  |
| Plasma height to width ratio                                   | 2:1  |
| Plasma safety factor at $a$                                    | 2.5  |
| Poloidal beta  | 3.5  |
| Toroidal magnetic field at plasma center, $B_o$                | 3.8 T  |
| Plasma current   | 2.4 MA   |
| Plasma temperature, $\bar{T}_i \approx \bar{T}_e$              | 5 keV  |
| Electron density-energy confinement time product, $n_e \tau_E$ | $8 \times 10^{12} \text{ cm}^{-3} \text{-sec}$ |
| Fusion power density   | $4.3 \text{ W/cm}^3$                           |
| Neutral deuterium beam injection energy                        | 200 keV  |
| Injected beam power  | 177 MW   |
| Neutron production rate  | $6.4 \times 10^{19} \text{ neutrons/sec}$      |
| First wall area  | $149 \text{ m}^2$                              |
| 14 MeV neutron wall loading                                    | $0.96 \text{ MW/m}^2$                          |

Table II

Toroidal Field Magnet Parameters

|  |                                |
|--|--------------------------------|
| Major radius, $R_o$                    | 3.05 m                         |
| Magnet bore at midplane                | 5.55 m                         |
| Maximum field at winding, $B_M$        | 8.0 tesla                      |
| Field at plasma center, $B_o$          | 3.8 tesla                      |
| Number of coils                        | 18                             |
| Coil dimension                         | 36.7 cm x 40 cm                |
| Number of discs per coil               | 14                             |
| Disc cross section                     | 2.1 cm x 40 cm                 |
| Number of turns per disc               | 24 (12 on each side)           |
| Average conductor size                 | 0.83 cm (deep) x 2.9 cm (wide) |
| Winding disc current density           | 2740 A/cm <sup>2</sup>         |
| Conductor current                      | 9590 A                         |
| Total ampere-turns                     | 58 x 10 <sup>6</sup> A         |
| Cu to steel volume ratio               | 2:1                            |
| Average Cu to TiNb ratio per conductor | 6:1                            |
| Total energy stored                    | ~3800 MJ                       |

Table III

Material and Cost Estimate for Set of 18 TF Magnets

|   | <u>Weight (<math>10^3</math> kg)</u> | <u>Unit Cost (\$/kg)</u> | <u>Cost (<math>\\$10^3</math>)</u> |
|---|--------------------------------------|--------------------------|------------------------------------|
| TiNb superconductor                       | 34.7                                 | 88.00                    | 3,050                              |
| Copper (in matrix)                        | 124                                  | 4.40                     | 546                                |
| Fabrication of above                      | (159) <sup>(1)</sup>                 | 3.30                     | 525                                |
| Copper (stabilizer)                       | 146                                  | 4.40                     | 642                                |
| (Total conductor)                         | (305)                                | (15.62) <sup>(2)</sup>   | (4,763)                            |
| Stainless steel discs                     | 120                                  | 5.50                     | 660                                |
| Epoxy insulation                          | 6.2                                  | 8.80                     | 55                                 |
| Machining & winding                       | (431)                                | 6.60                     | 2,845                              |
| (Total conductor<br>embedded discs)       | (431)                                | (19.31)                  | (8,323)                            |
| Aluminum alloy bolts                      | 2.37                                 | 4.40                     | 10                                 |
| Micarta spacer                            | 11.2                                 | 17.60                    | 197                                |
| Stainless steel dewar                     | 52                                   | 5.50                     | 286                                |
| Epoxy strut                               | 0.15                                 | 8.80                     | 1.3                                |
| Cryogenic insulation                      | $800\text{m}^2 \times 5\text{cm}$    | $\$100.00/\text{m}^2$    | 80                                 |
| Magnet assembly                           | (497)                                | 1.10                     | 497                                |
| (Total magnet)                            | (497)                                | (18.90)                  | (9,395)                            |
| S.S. central structure                    | 34                                   | 16.50                    | 561                                |
| S.S. secondary vacuum<br>and support wall | 24                                   | 13.20                    | 317                                |
| Installation of the<br>system             | (555)                                | 0.50                     | 278                                |
| (Total TF magnet set installed)           | (555)                                | (19.37)                  | (10,750)                           |

(1) Numbers in brackets are the sum of all numbers above it.

(2) Unit costs in brackets are obtained by dividing the total cost by weight.

Table IV  
 Effect of Alternate Magnetic Field  
 Assumptions on Neutron Wall Loading

| <u>System</u>    | <u>Superconductor</u> | $B_M$<br>(tesla) | $B_o$<br>(tesla) | Plasma Current<br>(MA) | 14 MeV Neutron<br>Wall Loading<br>(MW/m <sup>2</sup> ) |
|------------------|-----------------------|------------------|------------------|------------------------|--|
| Reference Design | NbTi                  | 8                | 3.8              | 2.4                    | 0.96   |
| Variation #1     | NbTi                  | 9                | 4.3              | 2.7                    | 1.54   |
| Variation #2     | Nb <sub>3</sub> Sn    | 12               | 5.7              | 3.6                    | 5.05   |

Figure Captions

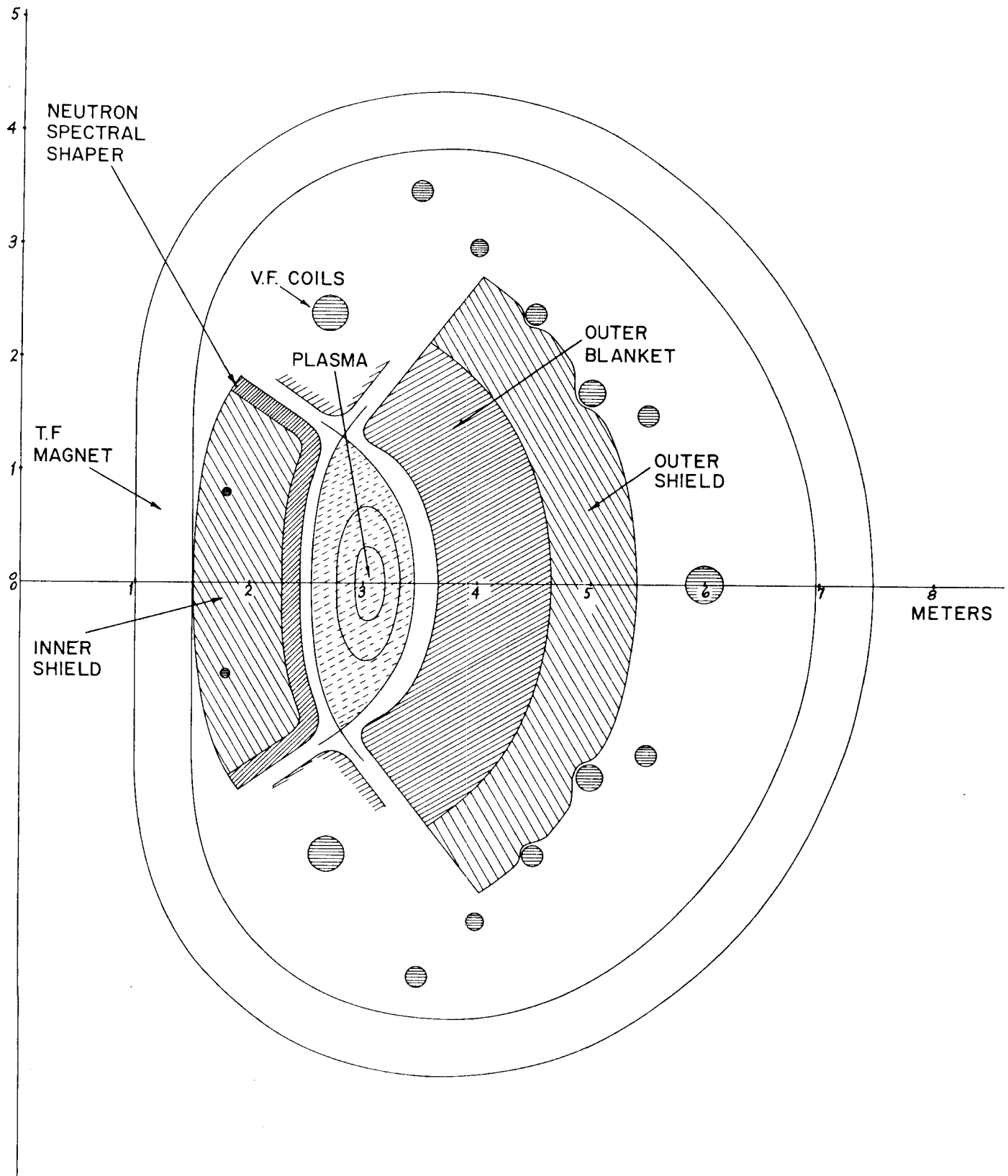
Figure 1 - A vertical cross sectional view of the Tokamak Engineering Test Reactor.

Figure 2 - A modified constant tension "D" shaped toroidal field coil.

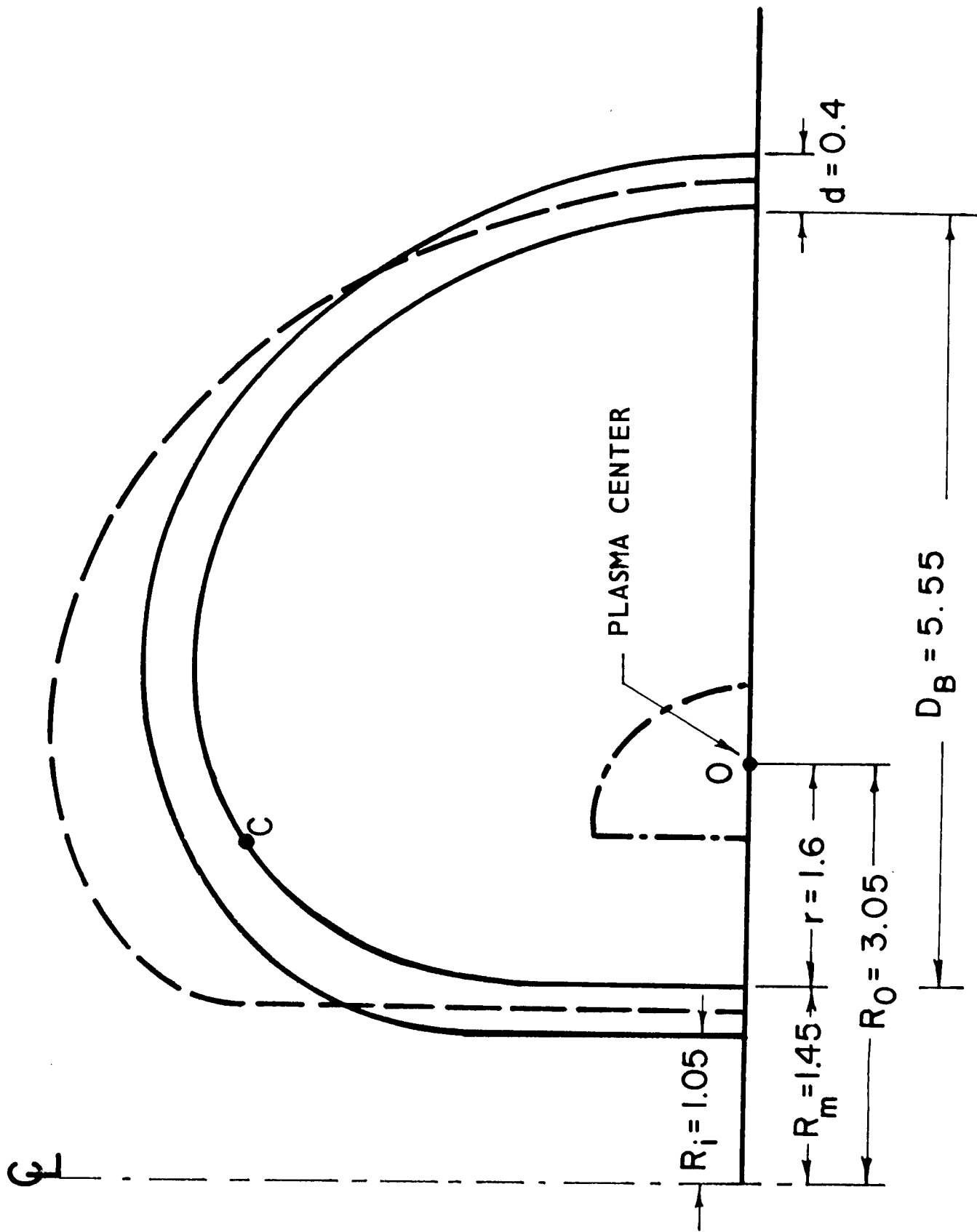
Constant tension prevails from point C out. Also shown by the dot-dashed line is the plasma surface and by the dashed line is a full constant tension "D" shape. A 4.5 m bore constant tension coil can also be used, as discussed in the section on alternate magnet design assumptions.

Figure 3 - Winding disc and the embedded conductor cross section. The NbTi + Cu superconducting composite is monolithic through the 24 turns in a disc. The NbTi filaments are sized for  $T = 5.1$  K and  $B = 8.0$  T.

# TOKAMAK ENGINEERING TEST REACTOR



ALL DIMENSIONS IN METERS



ALL DIMENSIONS IN CENTIMETERS

