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**Oak Ridge TNS Program:
System Studies of the
Toroidal Field Coils**

R. L. Reid

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OAK RIDGE TNS PROGRAM: SYSTEM STUDIES
OF THE TOROIDAL FIELD COILS

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ABSTRACT

The interaction of toroidal field coil parameters on magnetic field ripple at the plasma edge, on accessibility to the torus for segment removal, on size, and on cost of the Reference Design is presented in this document.

INTRODUCTION

The Next Step (TNS) represents that phase of fusion energy development in which the major emphasis would be directed towards engineering testing and demonstration. The objective of the TNS studies (initiated by the Department of Energy's Office of Fusion Energy) has been to define the characteristics and requirements of a facility dedicated to the engineering testing phase of fusion power development. For this reason, the TNS study results are providing a basis for defining an Engineering Test Facility (ETF). Because the scientific basis required for a TNS/ETF will first be available for the tokamak concept, the reactor core of the facility has been based on the tokamak concept. However, the commitment to an ETF with a reactor core based on the tokamak concept does not represent a commitment to tokamaks as the ultimate power reactor concept.

The TNS studies at Oak Ridge National Laboratory (ORNL) were initiated in FY 1977. During FY 1977 the Oak Ridge effort pursued scoping studies in three broad areas: plasma engineering, systems modeling, and program planning. Based upon the findings of the FY 1977 efforts, it was judged that continued activities in the Oak Ridge TNS program should be directed towards a preconceptual design with particular emphasis placed on engineering feasibility. As a point of departure for the FY 1978 activities, a Baseline Design was selected, based on the systems modeling effort of FY 1977. The primary objective of our FY 1978 TNS effort has been to evolve the Baseline Design towards a preconceptual design. However, it is emphasized that the FY 1978 effort was not intended to lead to a completed preconceptual design. Therefore, the design resulting from this year's effort is referred to as a reference design rather than as a preconceptual design.

This document defines the effects of variations to the toroidal field (TF) coil configuration on accessibility to the torus for segment removal and on tokamak system cost while maintaining a value of magnetic field ripple within limits compatible with plasma physics considerations.

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1. EFFECTS OF RIPPLE ON PLASMA PHYSICS PARAMETERS

The discrete nature of the toroidal magnetic field coils of a tokamak introduces a small, but finite, amplitude modulation on the toroidal magnetic field. These modulations, called ripples, destroy the axisymmetry of an ideal tokamak and lead to large particle excursions and hence to particle and energy losses. Ripple is defined as $\delta \equiv (B_{\max} - B_{\min}) / (B_{\max} + B_{\min})$, which is the ratio of the amplitude of the modulation (relative to the average magnetic field) to the average magnetic field. Criteria for the analysis of maximum tolerable ripple within the limits of plasma physics considerations include: (1) plasma energy transport, (2) loss of fast ions, i.e., injected particles and/or alpha particles, and (3) injection angle in the case of near perpendicular injection.

A computer module "RIPPLE" for ripple analysis was developed¹ and coupled into the one-dimensional (1-D) transport simulation code to study the magnetic field ripple effects on plasma transport and scaling. Calculations include both radial and poloidal variations in the magnitude of the field ripple as well as the effects of high- β operation.¹

Superthermal ions (injected and/or alpha particles) are the species most affected by the ripple. Although the ripple enhances the radial diffusion of all particles in the plasma, it causes a convective loss of some of these high energy particles. This loss must be accounted for in the design of the injection system, and it should be considered when studying alpha particle dynamics in a reactor plasma. The fast ions near the outside of the plasma where the ripple is large are most affected due to the ripple loss region. Perpendicular injection puts the fast ions directly in the loss region and probably provides unacceptable losses. Some alpha particles will also be lost by a similar process. However, because the 3.5-MeV alphas are primarily born near the plasma center and slowdown, it appears that they deposit their energy before they escape from the system (the lost alpha energy is ~ 10 -20%).

The results of the present calculations show that allowable ripple at the plasma edge is ~ 2 -2.5% with an injection angle (θ), in the near perpendicular case, $> 10^\circ$ ($\theta > \tan^{-1} \sqrt{2\delta}$).¹

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2. EFFECTS OF RIPPLE AND NUMBER OF TF COILS ON COIL SIZE AND SYSTEM COST

The TF coil configuration of the FY 1977 Baseline Design, based primarily on system studies, was characterized by 20 D-shaped constant tension coils with a coil bore of 5.0 m which resulted in a magnetic field ripple at the plasma edge of 1.0%. In this study perturbations were made to the FY 1977 TF coil configuration in order to produce a more feasible design from an engineering viewpoint, particularly in the area of torus replacement and maintenance. The following tokamak system parameters, defined during the FY 1977 study, were maintained during this year's study.

Plasma radius, $a = 1.2$ m

Field on axis, $B_T = 5.3$ T

Max field at TF coils, $B_m = 10.9$ T

Major radius, $R_o = 5.0$ m

Aspect ratio, $A = 4.17$

The relationship between number of TF coils, coil bore, percent ripple, midplane access, and relative system cost generated by using the COAST computer code,² is shown in Figs. 1-3. This code uses an empirical relationship, derived from the computed ripple for a number of coil sets, to relate ripple to the number of TF coils, the plasma edge location, and the outer TF coil leg location.³ At a given percent ripple, as the number of coils is decreased, the coil bore, the midplane access, and the relative system cost increase. As an example, at 2% ripple, decreasing the number of TF coils from 16 to 12 increases the coil bore approximately 1 m (from ~5.0-6.0 m) as shown in Fig. 1, increases the midplane access from 1.55-2.40 m as shown in Fig. 2, with an increase in system cost of ~5.0% as indicated in Fig. 3. Also note that for a fixed number of coils, the rate of reduction in coil size and cost decreases with increasing value of ripple. The curves on Fig. 1 which present coil bore as a function of ripple for various numbers of coils do not all terminate at the same value of ripple. For 12 coils the variation in ripple shown is from 1-5% with a steadily decreasing coil bore. For 16 coils the maximum value of ripple shown is ~2.7% due to the fact that

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Fig. 1. Coil bore as a function of magnetic field ripple and number of toroidal field coils.

Fig. 2. Midplane access between toroidal field coils as a function of magnetic field ripple and number of coils.

Fig. 3. Relative reactor cost as a function of magnetic field ripple and number of toroidal field coils.

space for the blanket and shield, i.e., machine space, requires a larger TF coil than is required by the ripple criteria for values of ripple $>2.7\%$ for 16 coils. For 20 coils the minimum coil bore is set by neutral beam access between coils assuming a beam injection angle of 16° .

Twelve TF coils at a clear horizontal bore of 6.2 m were selected for the Reference Design. This selection was based on a maintenance requirement that a 1/16-torus segment be extractable between two fixed TF coils and that the maximum magnetic field ripple at the plasma edge be $<2.5\%$. A 16-segment torus was chosen based on the following considerations. A torus with fewer segments (e.g., 12) would require larger TF coils (consequently higher system cost) in order to provide access for segment removal. A torus with a greater number of segments (e.g., 32) would require twice as many mechanical seals and twice the time to replace the entire torus, but would allow smaller TF coils. Thus a trade-off must be made between capital costs and operating costs; a 16-segment torus was selected as a reasonable compromise. Sixteen segments also yield a segment size which is compatible with the geometric requirement of the neutral beam duct — a neutral beam duct penetrates only one torus segment. Removal of the 1/16-torus segment requires a clearance between TF coils of ~ 2.8 m at the midplane of the tokamak. Figure 2 shows that this value of access, 2.8 m, is obtained for 12 coils at a ripple value of 1.5% with the corresponding coil bore (see Fig. 1) of 6.2 m. With 16 coils, 2.8 m of access is achieved with a coil bore of 8.2 m resulting in a value of ripple of 0.05%; with 10 coils the access is in excess of the value of 2.8 m through the maximum value of ripple shown on the figure, 5%. However, plasma physics considerations limit the value of ripple to 2.5%; therefore, with 10 coils and 2.5% ripple, the corresponding coil bore is 6.5 m. Correlating the ripple values that correspond to 2.8 m access or to the plasma physics limit with cost as a function of ripple and number of coils indicates that 12 coils is the optimum TF coil configuration, based on total systems cost, for the Reference Design. Table 1 summarizes the values of system costs, coil size, midplane access, ripple, and number of TF coils required for a 1/16-torus segment removal or for the maximum allowable ripple, whichever is the limiting consideration.

Table 1. Cost of the Reference Design as a function of the number of TF coils

Number of coils	10.0	12.0	16.0
Bore, m	6.5	6.2	8.2
Ripple, %	2.5 ^a	1.5	0.05
Midplane access, m	3.6	2.8	2.8
System cost, relative	1.10	1.07	1.27

^aLimiting value of ripple used for this study.

3. EFFECTS OF TF COIL DESIGN PARAMETERS ON TOKAMAK SIZE AND SYSTEM COST

The Reference Design TF coils are based on a coil design proposed by Westinghouse for their coil entry into the Large Coil Project (LCP). This design uses grooved plates in which the coil windings are embedded, stacked in pancake fashion, and bolted together. This results in a coil which has a relatively high structure-to-conductor area ratio. In order to determine if this coil design would unduly impact the overall tokamak configuration and cost of the Reference Design, three tokamak reactors were modeled by the COAST computer code, each with different TF coil design parameters. The TF coil design parameters were those submitted for the LCP by Westinghouse, General Dynamics, and General Electric. As previously stated, the Westinghouse design uses machined plates stacked as pancakes, whereas the General Electric and General Dynamic designs use layer wound coils enclosed in a steel case. All three coil designs are for a field of 8 T at the coil winding. The three tokamak models used a common set of system parameters with the exception of those related to the TF coils. Note that the Westinghouse coil uses a Nb₃Sn superconductor, and the General Electric and General Dynamic coils use NbTi superconductors.

The overall impact of the coil design relative to overall tokamak cost and size is shown in Table 2. The higher structure-to-conductor ratio of the Westinghouse coil is balanced by a higher conductor current density so that the net effect is that the cost of a tokamak reactor modeled with a Westinghouse coil lies between those modeled with General Electric and General Dynamic coils. The spread in cost among tokamaks

Table 2. Tokamak size and cost as a function of TF coil parameters

Parameter	LCP coil type		
	GD	GE	W
Field at the coil, $B_{\max}$ T	8.0	8.0	8.0
Superconductor	NbTi	NbTi	Nb ₃ Sn
Structure/conductor	0.72	1.6	2.2
Conductor average J, MA/m ²	24.5	24.6	40.0
Packing factor	0.57	0.65	0.60
Relative tokamak cost	1.00	1.14	1.03
OH bore, m	3.26	2.72	3.12
Tokamak outer radius, m	9.51	9.65	9.55

utilizing the three-coil design configuration is 14%; the reactor employing the General Dynamic coil design is the least expensive and the reactor with the General Electric coil design is the most expensive. Coil costs were estimated based on \$50/kg for NbTi conductors, \$100/kg for Nb₃Sn conductors, and \$44/kg for the stainless steel structure. For comparison purposes, all coils were assumed to be cooled by forced-flow helium. In the actual LCP coil designs, the General Electric and General Dynamic coils employ pool boiling techniques. The difference in cooling techniques would have an effect on tokamak cost which is not accounted for in this study. Here, the main concern was the impact of the bolted plate coil fabrication technique compared with the layer wound encased coils.

4. CONCLUSIONS

1. The maximum magnetic field ripple at the plasma edge is limited to 2.5% due to plasma physics.
2. Twelve 6.2-m horizontal bore TF coils is the optimum even number of coils to allow for 1/16-torus segment removal for the Reference Design. Magnetic field ripple for this coil configuration is 1.5%.
3. The Reference Design is not penalized, based on overall reactor size and cost, because of the machined, stacked plate TF coil design advocated by Westinghouse rather than alternative TF coil designs.

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