SEPTEMBER 30, 1977

TNS ENGINEERING TRADE STUDY ANALYSIS

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fusion power systems department

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The results presented in this report are the culmination of many months of effort by every member of the Westinghouse Fusion Power Systems Department. The COAST code was used in the analyses, and each member of the department contributed size and cost models of components that fall into their area of expertise. D. Sink has had the responsibility for integrating the contributions into a coherent set of equations and for providing the associated logic. These equations were programmed by E. Iwinski. The ground rules and goals for the trade studies for TNS evolved from many interactions between ORNL and Westinghouse Personnel under the coordination of C. A. Flanagan and T. C. Varljen of Westinghouse and M. Roberts of ORNL.

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FOREWORD

The Division of Magnetic Fusion Energy within the U.S. Energy Research and Development Administration has initiated within the fusion development program for tokamak power reactors a series of systems studies aimed at the definition of subsequent generations of tokamak devices leading to a commercial prototype reactor. Since April, 1976, a design team composed of representatives from the ORNL Fusion Energy Division and the Westinghouse Fusion Power Systems Department has been engaged in scoping studies associated with the definition of The Next Step (TNS) in the tokamak program after the TFTR. Provisional goals established for TNS include:

- achievement of ignition
- demonstration of burning dynamics
- evaluation of design requirements and solutions for long pulse operation
- features which extrapolate to a viable power reactor
- availability in the mid-to-late 1980's

It is in this context that the work reported herein was performed.

TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
1.0	INTRODUCTION	1-1
2.0	METHOD OF ANALYSIS AND GROUND RULES	2-1
3.0	CONSTANT PEAK FIELD AT THE TF COILS	3-1
4.0	VARIABLE PEAK FIELD AT THE TF COILS	4-1
5.0	PARAMETERS AND COSTS FOR DEVICES WITH $\beta = 5\%$	5-1
6.0	COST BREAKDOWN BY COMPONENTS	6-1
7.0	SENSITIVITY STUDIES	7-1
	7.1 SENSITIVITY TO THE NUMBER OF TF COILS	7-1
	7.2 SENSITIVITY TO INCREASES IN THE PLASMA DENSITY	7-3
	7.3 SENSITIVITY TO PLASMA ELONGATION	7-3
8.0	VARIATION WITH PLASMA SCALING LAW	8-1
9.0	SUMMARY AND CONCLUSIONS	9-1
10.0	REFERENCES	10-1

LIST OF FIGURES

<u>Figure No.</u>	<u>Title</u>	<u>Page No.</u>
3-1	Cost of Cu TF coil devices vs major radius for a field at the coil $B_{\max} = 12$ T.	3-2
3-2	Toroidal beta value of Cu TF coil devices vs major radius for a field at the coil $B_{\max} = 12$ T.	3-4
3-3	Cost of Cu TF coil devices vs major radius with lines of constant beta for $B_{\max} = 12$ T.	3-5
3-4	Cost of NbTi TF coil devices vs major radius with lines of constant beta for $B_{\max} = 8$ T.	3-7
3-5	Cost of Nb ₃ Sn TF coil devices vs major radius with lines of constant beta for $B_{\max} = 12$ T.	3-8
3-6	Cost of hybrid Cu/NbTi TF coil devices vs major radius with lines of constant beta for $B_{\max} = 12$ T/8 T.	3-9
3-7	Cost of the least expensive devices for the four TF coil technologies at fixed values of $B_{\max}$ vs the toroidal beta value.	3-10
4-1	Cost of NbTi TF coil devices vs major radius with lines of constant beta for $B_{\max} = 10$ T.	4-2
4-2	Cost of the least expensive devices for the four TF coil technologies vs the toroidal beta value.	4-3
5-1	Cost of Cu TF coil devices vs major radius for $\beta = 5\%$.	5-2
5-2	Cost of NbTi TF coil devices vs major radius for $\beta = 5\%$.	5-3
5-3	Cost of Nb ₃ Sn TF coil devices vs major radius for $\beta = 5\%$.	5-4
5-4	Cost of hybrid Cu/NbTi TF coil devices vs major radius for $\beta = 5\%$.	5-5
6-1	Cost breakdown by major systems for a Cu TF coil device with $a = 1.0$ m, $R_0 = 4.0$ m, $B_{\max} = 10.4$ T.	6-2
6-2	Cost breakdown by major systems for a Nb ₃ Sn TF coil device with $a = 1.2$ m, $R_0 = 5.0$ m, $B_{\max} = 10.9$ T.	6-3
7-1	Cost of Cu and Nb ₃ Sn TF coil devices vs the number of TF coils in the device.	7-2

LIST OF FIGURES (CONTINUED)

<u>Figure No.</u>	<u>Title</u>	<u>Page No.</u>
7-2	Cost and beta value vs plasma elongation for Cu and Nb ₃ Sn TF coil devices.	7-5
8-1	Comparison of the cost of Cu TF coil devices with $\beta = 5\%$ sized with empirical plasma scaling and trapped particle mode plasma scaling.	8-2
8-2	Comparison of the cost of Nb ₃ Sn TF coil devices with $\beta = 5\%$ sized with empirical plasma scaling and trapped particle mode plasma scaling.	8-4
8-3	Comparison of the field on axis and density required for ignition vs plasma size as predicted by empirical plasma scaling and trapped particle mode plasma scaling for $\beta = 5\%$.	8-5

LIST OF TABLES

<u>Table No.</u>	<u>Title</u>	<u>Page No.</u>
1-1	SUMMARY OF GROUND RULES AND ASSUMPTIONS USED IN THE TNS TRADE STUDIES	1-2
4-1	PARAMETERS AND COST OF THE MINIMUM COST DEVICES OF EACH TF COIL TECHNOLOGY FOR DIFFERENT PLASMA BETA VALUES AT IGNITION	4-5
4-2	COMPARISON OF THE COSTS OF DEVICES WITH SUPERCONDUCTING NbTi and Nb ₃ Sn TF COILS FOR THE SAME SIZE DEVICES AND SAME PEAK FIELD AT THE COIL	4-7
5-1	COMPARISON OF REPRESENTATIVE PARAMETERS FOR FOUR TNS POINT DESIGNS	5-8
7-1	SENSITIVITY OF Cu and Nb ₃ Sn DEVICE COSTS TO OPERATION AT HIGHER DENSITIES	7-4

1.0 INTRODUCTION

In order to achieve the goal of successful operation of a commercial prototype tokamak fusion reactor, future experimental devices must be built subsequent to the Tokamak Fusion Test Reactor (TFTR). The next device in this sequence after TFTR has been designated The Next Step (TNS) tokamak. It is generally agreed that TNS should reach plasma ignition conditions with a sufficiently long pulse length to demonstrate burn dynamics. In addition to these requirements, TNS could also be designed to utilize certain advanced technology features which extrapolate to a viable demonstration reactor, although without the generation of electrical power.

Perhaps the most important consideration in analyzing the various choices for the TNS device is the cost, in terms of both the absolute cost of the TNS as well as the total cost to the fusion program of the machines between TFTR and a demonstration reactor. The two principal device parameters which will most influence the cost are the plasma size and the toroidal field (TF) coil technology. In order to consistently evaluate the relative costs and performance parameters of D-T burning tokamaks over a range of plasma sizes and TF coil technologies, a parametric trade study analysis has been performed. The results of this analyses are presented in this report, and have been used to aid in the choice of an ignition device as the basis of the ORNL/Westinghouse TNS tokamak design studies.

In performing these trade studies, certain engineering ground rules were established, which included constant-tension D-shaped TF coils; water-cooled copper poloidal field (PF) coils located within the TF coil bore; passive impurity control techniques such as wall treatment or a gas blanket; and auxiliary plasma heating by neutral beams. A summary of the ground rules and assumptions used in the study is presented in Table 1-1. It was felt to be necessary to use such basic assumptions as these in order to consistently evaluate the various TNS options without unfairly penalizing any one design type. Once the trade study analysis has narrowed the design parameter space to the most attractive regions, each of the ground rules can be examined to see how it affects the cost and performance of the particular device. In addition, sensitivity studies can be performed for certain ground rule assumptions.

TABLE 1-1

SUMMARY OF GROUND RULES AND ASSUMPTIONS USED IN THE
TNS TRADE STUDIESOPERATION

Total Number of Pulsing Cycles	10^6
Pulse Repetition Period	300 seconds
Pulse Scenario:	
Pulse OH	0-2 seconds
Neutral Beam Injection	2-8 seconds
Ignition Excursion	8-16 seconds
Burn	16-32 seconds
Quench	32-42 seconds
D-T Operation Envelope (Design Basis):	
Annual Dose at Site Boundary	≤ 5 mrem
On-site Restricted Area Annual Dose	≤ 1 rem
On-site Restricted Area Quarterly Dose	≤ 600 mrem
On-site Unrestricted Area Annual Dose	≤ 100 mrem
Copper Electrical Insulation Dose Limit	10^{10} rads

VACUUM VESSEL

Vessel Material	AISI 316-SS
Construction	I-beam stiffened shells (w/o bellows)
Vessel Cross Section	D-Shaped
Wall Thickness	Variable
Toroidal Limiter	Tungsten Segments (Radiation Cooled)
Diagnostic Penetrations	Fixed Number
Peak Bulk Wall Temperature	400°C
Vessel Coolant	Demineralized Water

TOROIDAL FIELD COILS

Number of Coils	Variable (12-28)
Conductor Type:	
TNS-1	Copper (H ₂ O cooled)
TNS-3	NbTi (L He cooled)
TNS-4	Nb ₃ Sn (L He cooled)
TNS-5	Copper/NbTi (H ₂ O, L He cooled)
Coil Shape	Constant Tension "D"
Peak Field at Conductor (Limits)	14 T Copper 10 T NbTi 14 T Nb ₃ Sn
Cooling Mode	Single Phase Forced Flow
Fault Protection	Electrical Provisions Only

POLOIDAL FIELD SYSTEM

Conductor Material	Oxygen Free High Conductivity (OFHC) Copper
Location	OH Windings Outside TF; VF Windings Inside TF
OH Flux Swing	Variable
Conductor Current Limit	20 kA
Conductor Current Density Limit	1.5 kA/cm ²
Conductor Coolant	Forced Flow Water

IMPURITY CONTROL

Wall treatment (low sputtering liner, low Z wall, etc)
 Note: It is recognized that a magnetic divertor may be necessary. This has been examined in a parallel study.

TABLE 1-1 (CONTINUED)
SUMMARY OF GROUND RULES AND ASSUMPTIONS USED IN THE
TNS TRADE STUDIES

VACUUM PUMPING

Final Pumping Stage	Cryosorption Pumps
Base Pressure (Prepulse)	1×10^{-8} torr
Outgassing Surface Area	Ten Times Smooth Area of Vessel

TRITIUM SYSTEMS

On-site/In-process T_2 Inventory	Variable
Tritium Storage	Uranium Chip Beds
Fuel Recovery-Recycling Plant	Variable Capacity (common approach)
Tritium Cleanup Systems	Variable Capacity (common approach)
Fueling	Prefill: Gaseous D-T
	Refueling: Solid T and D-T Pellets

NEUTRAL BEAM INJECTION LINES

Beam Power, Energy	Varies with Plasma Conditions
Single Arm Specifications:	
Sources	3-100 A Positive Ion
Dimensions	10.4 m long x 4 m wide x 6 m high
Number	Varies with Plasma Conditions
Vessel Aperture Per Line	Duct 40 cm wide x 90 cm high
Duct Shielding	As Required by Coil Type

HEAT DISSIPATION SYSTEMS

Final Facility Heat Sink	Mechanical Draft Evaporative Cooling Towers to Atmosphere
Vacuum Vessel Coolant	Water - Variable Capacity
Shield Coolant	Borated Water - Variable Capacity
Buffer Loop Coolant	Water - Variable Capacity
Cryogenic Refrigeration Systems	Variable Capacity
Facility Air Conditioning	Fixed Base Load, Reactor Cell Air Conditioning
	Variable
Thermal Loads	Variable - Depending on Option

OPERATIONAL DIAGNOSTICS

Number, Type, Penetrations	Constant in all Studies
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ELECTRICAL SYSTEMS

Facility Feed	Fixed Utility Constraints
S/C TF Supplies	Line-driven Rectifier Supplies (except for hybrid)
Cu TF Supplies	AC-MG Storage-Rectifier Conversion
Neutral Beam Supplies	AC-MG Storage-Rectifier Conversion
Poloidal Field Power Supplies	AC-MG Storage-Rectifier Conversion
Electrical Loads	Variable - Depending on Option
Instrumentation and Control	Fixed for all Options

ARCHITECTURAL AND FACILITY

Site	150 m Radius Site Boundary "Free-Standing"
Reactor Cell	Reinforced Ordinary Concrete
	Fixed: Walls (~ 2.9 m), Ceiling (~ 2.3 m),
	Vertical Height Fixed
	Floor Space, Basement: Variable
Electrical Power System Buildings	Variable
BOP Buildings	Fixed

Four different types of TF coil technologies have been investigated in the trade studies. The first type is water-cooled copper coils. Two superconducting material types have also been considered, NbTi and Nb₃Sn. The fourth option is a "hybrid" coil arrangement which can provide a high field at the plasma by using a normal conducting Cu coil nested within a superconducting NbTi coil. The number of TF coils in a device is a variable in the study, as is the peak field at the coil for each coil technology. In addition, all of the TF coils are of the constant-tension D-shape.

The range of device sizes considered in these trade studies for the four TF coil technologies covered a range in the plasma radius (or half-width) from ~ 0.75 m to 2.0 m, spanning the range from TFTR size plasmas to those chosen for recent Experimental Power Reactor (EPR) design studies. The device major radius was varied from ~ 8-9 m down to some lower limit which was consistent with the ground rules and still allowed a viable engineering design. In most cases the plasma elongation was kept at 1.6, although sensitivity studies of the cost vs elongation were also performed. The plasma beta value was chosen as the main parameter on which to judge the performance or "confidence of success" of each ignition device, and was allowed to vary in the range from ~ 2% to 15%. Two different plasma scalings were used to specify the physics parameters for an ignition device, empirical scaling and trapped-particle-mode scaling.

In Section 2 of this report the computer code, ground rules, and plasma scalings used in the trade studies are briefly discussed. In Sections 3-8 the results of the analyses are presented and discussed in detail. In Section 9 the results are summarized and pertinent conclusions and recommendations regarding the TNS design options are discussed.

2.0 METHOD OF ANALYSIS AND GROUND RULES

The major tool used in performing these trade studies was a computer code designated COAST, written to permit Costing And Sizing of D-T burning Tokamak systems. An extensive set of numerical calculations are performed in the code to assess the dominant features of TNS ignition tokamaks with different TF coil conductor materials. Required input data include parameters characterizing engineering constraints such as conductor current densities, magnetic field ripple limits, nuclear heating and dose limits, and power supply parameters, in addition to plasma parameters obtained independently from various scaling laws. Sizing and costing models are incorporated for various components of the tokamak system such as the copper poloidal field coils, device shielding, vacuum vessel, TF coils, and neutral beams. Sizing and costing calculations are also performed for several auxiliary components such as tritium and fueling systems, power conversion systems, heat removal systems, and the reactor cell and other facilities. The COAST code provides a generalized description of TNS and allows one to study the impact of the design features of individual components on the overall system. Further details on the COAST code are given in reference 1.

Four different types of TF coil technologies have been modeled in COAST. These include water-cooled copper coils and two types of superconducting coils, NbTi and Nb₃Sn. Both superconductors are cooled with supercritical, forced flow liquid helium. The fourth TF coil type is a "hybrid" arrangement which consists of a normal conducting Cu coil nested within a superconducting NbTi coil. The peak field at the coils is a variable for each coil technology and all coils are modeled as constant-tension D-shaped.

Required input to the COAST code includes the physics parameters such as density, temperature, and field on axis required for ignition in a given size device. In these trade studies two plasma scaling laws have been used to predict this information. The first model is based on empirical plasma scaling², which has been observed in present day resistively heated, high collisionality tokamak experiments.

The second scaling is based on a trapped-particle-mode (TPM) plasma transport model³, which involves numerically solving the spatially averaged plasma particle and energy balance equations using theoretical models for the different regimes of particle transport. Most of the trade study analysis has been done with empirical scaling, although in Section 8 of this report the results using TPM scaling are compared with those from empirical scaling. The main trends and conclusions from the study are found to be fairly insensitive to the scaling law used to specify the physics parameters of an ignition device.

For most of the studies the plasma temperature has been assumed to be ~ 13 keV, representing a volume averaged value for steady state operation under ignition conditions. From a simple energy balance equation, the required $n_e \tau_E$ product to reach ignition at this plasma temperature can be calculated to be $\sim 2.4 \times 10^{20} \text{ m}^{-3} \text{ sec}$. Hence, the physics parameters of a given size machine are selected according to one of the plasma scaling laws so as to achieve this value of $n_e \tau_E$ and reach ignition conditions.

The concept of margin in the ignition condition can also occur, e.g., a given device could be predicted by a scaling law to reach an $n_e \tau_E$ value larger than that needed for ignition. However, for most of these studies the device parameters have been chosen so as to just reach the ignition $n_e \tau_E$ value of $2.4 \times 10^{20} \text{ m}^{-3} \text{ sec}$. This was done to facilitate comparison of various TNS options of different sizes and TF coil technologies on a common basis of achieving the same $n_e \tau_E$ value. The sensitivity of the cost to operation at higher densities and $n_e \tau_E$ values has been investigated in Section 7 of this report.

For most of these studies the plasma pulse time operating scenario has been held fixed under the assumptions of a one second initiation and start-up period, a six second neutral beam injection period to reach ignition, an eight second period during which a thermal excursion occurs to reach steady state conditions, followed by a 16 second steady state burn period and then a two second quench. Hence, the total pulse length is ~ 30 seconds. The time between pulses is fixed at five minutes (300 seconds), and there are assumed to be the equivalent of 1000 full power D-T pulses per year.

The costs presented in this report for the TNS devices are those for the buildings and equipment (i.e., direct costs) in 1977 dollars. They include all of the hardware for the tokamak system and the support systems, the electrical power conversion and control systems, the neutral beam systems, and the reactor site and buildings. Not included are the costs for installation and costs for engineering, design, inspection, and administration (EDIA), which can be taken to be a percentage of the buildings and equipment cost. Also not included is a factor for contingency.

3.0 CONSTANT PEAK FIELD AT THE TF COILS

In this section the results of one aspect of the analysis are presented for the four TF coil technologies considered for the TNS design studies. In particular, here the peak field at the TF coil has been kept at a constant value as the device size and performance are allowed to vary. The chosen maximum fields for the different TF coil technologies are 12 T for the Cu, 8 T for the NbTi, 12 T for the Nb₃Sn, and 12 T/8 T for the hybrid Cu/NbTi option. Hence, here the device cost and performance trends are evaluated given that a certain field can be achieved in each technology. In subsequent sections the peak field at the coil is allowed to vary in order to evaluate the device sizes and costs necessary to achieve a certain plasma performance.

In Figure 3-1 the relative cost of devices with Cu TF coils with a field at the coil $B_{\max}$ of 12 T is plotted vs major radius R_0 for three plasma sizes: 0.8, 1.2, and 1.6 m. These are all ignition devices according to empirical plasma scaling, with a plasma elongation of 1.6 and 20 TF coils. A range of plasma sizes from 0.8 m to 2.0 m has been covered in this investigation; however, for clarity only three values are shown in Figure 3-1. These curves show the cost to be a fairly strong function of the major radius R and a weaker function of the plasma radius (half-width) a . In fact, away from devices with the smaller major radii where a minimum in the cost occurs, the cost is found to go as $\sim R^{1.5}$ for constant a and as $\sim a^{1/3}$ for constant R . The "bore size limit" in Figure 3.1 refers to the fact that there is a minimum R allowed which is set by engineering constraints. The cost increases near this minimum R due to increased costs for the OH power conversion equipment to supply the necessary flux swing through the smaller machine bore.

The key parameter not evident from Figure 3-1, which is necessary in order to consistently evaluate and compare different TNS options, is some measure of the relative performance or confidence of success of each device. One such parameter is the plasma toroidal beta, defined as the ratio of the volume averaged plasma pressure to the toroidal magnetic field pressure. The plasma β is a critical parameter for at least two reasons: because the plasma MHD stability is dependent on β , and

Figure 3-1. Cost of Cu TF coil devices vs major radius for a field at the coil $B_{\max} = 12 \text{ T}$.

because β is a measure of how efficiently the magnetic field strength is utilized. Since the primary mission of TNS will be to demonstrate ignition conditions and burn dynamics under long pulse durations, the β value for which it is designed to operate will be an extremely important quantity in judging its chances for success. Current estimates based on linear, ideal MHD stability calculations indicate that β 's in the range of 5-10% should be acceptable. Although TNS will be designed with the capability of operation at some minimum β , it can certainly also test operation at higher β 's, either by increasing the density or decreasing the field strength at the TF coil. These tests of high β operation in TNS will be extremely important in establishing what the upper limit on β is for stable plasmas, which is very important from a reactor viewpoint. However, TNS should not be designed only to operate at these high β 's, i.e., TNS should have the capability to test high β but should not rely on it for successful demonstration of ignition.

In Figure 3-2 the minimum β at ignition for the Cu TF coil devices with $B_{\max} = 12$ T is plotted vs major radius for three plasma sizes. As expected, β decreases as R_0 increases. For a fixed R_0 , β increases as a decreases since the density must increase to reach ignition, even though the field on axis, B_t , increases somewhat as a decreases because of the geometry and R^{-1} dependence of the field. However, if R_0 is sufficiently small the change in B_t can become more important so that the change in β as a changes is reduced. From plots such as these, the required a and R_0 necessary to reach a particular β value can be determined.

In Figure 3-3 the same curves as in Figure 3-1 are shown except now lines of constant β have been superimposed as determined from Figure 3-2. It can be seen that for each value of β there is a minimum cost device at a certain plasma size and major radius for a fixed field at the coil. As the plasma β decreases, the minimum cost device becomes more expensive since R_0 and a must increase in order to obtain a higher field on axis and a lower plasma density. In general, relatively low β values of 2%-3% are possible in Cu TF coil devices with a 12 T peak field at the coil.

Figure 3-2. Toroidal beta value of Cu TF coil devices vs major radius for a field at the coil $B_{\max} = 12$ T.

Figure 3-3. Cost of Cu TF coil devices vs major radius with lines of constant beta for $B_{\max} = 12 \text{ T}$.

Similar plots of the cost vs major radius for the other three TF coil technologies which were studied are shown in Figures 3-4 thru 3-6. In Figure 3-4, for the NbTi TF coils with a peak field at 8 T, relatively high plasma β values in the range of 6%-10% result due to the lower fields available. In Figure 3-5, intermediate values of β in the range 3%-5% result for the Nb₃Sn devices with $B_{\max} = 12$ T. The hybrid Cu/NbTi devices with 12 T at the Cu coil and 8 T at the NbTi coil achieve lower β values of 2%-3%, as shown in Figure 3-6. For all of the TF coil technologies, it is evident that a minimum cost device exists at a particular plasma size for each value of the plasma β at ignition.

A comparison of these minimum cost devices for each TF coil technology type is shown in Figure 3-7, where the device cost of the least expensive machine at each β is plotted vs the plasma β as obtained from Figures 3-3 thru 3-6. Here, the maximum field at the coil is 12 T for the Cu and Nb₃Sn and 8 T for the NbTi. Note that there is a rather sharp increase in cost as the β value is decreased, due to an increase in device size. Several other observations can be made from Figure 3-7; e.g., for a given cost, the Cu devices at 12 T can achieve a smaller β than the Nb₃Sn (12 T), which can achieve a smaller β than NbTi (8 T). Also, for any β value the Cu option at 12 T is less costly than the Nb₃Sn option at 12 T. For β larger than about 8%, the NbTi (8 T) is less costly than the Nb₃Sn (12 T) and for $\beta < 10\%$ the Cu (12 T) option is less costly than the NbTi (8 T) option. This is based on the fact that any of the curves in Figure 3-7 can be translated to the right (to larger β) by decreasing the current in the TF coils and running them at a lower peak field. Higher β could also be attained by running at higher density, however, then the device cost will also increase. Instead of merely translating these curves to higher β while maintaining the ability to run at 12 T for the Cu and Nb₃Sn, one could instead design the devices to be run at lower peak fields, e.g., 10 T and 8 T. This will not only move the curves to the right but also lower them since a smaller peak field at the coil will produce a less costly machine. Likewise, the NbTi coils could be designed to operate at 10 T and hence achieve a lower β value, although at a higher cost. The effect of varying the peak field at the TF coils is investigated in the next section.

Figure 3-4. Cost of NbTi TF coil devices vs major radius with lines of constant beta for $B_{\max} = 8 \text{ T}$.

Figure 3-5. Cost of Nb_3Sn TF coil devices vs major radius with lines of constant beta for $B_{\text{max}} = 12 \text{ T}$.

Figure 3-6. Cost of hybrid Cu/NbTi TF coil devices vs major radius with lines of constant beta for $B_{\max} = 12 \text{ T}/8 \text{ T}$.

Figure 3-7. Cost of the least expensive devices for the four TF coil technologies at fixed values of B_{max} vs the toroidal beta value.

4.0 VARIABLE PEAK FIELD AT THE TF COILS

As shown in the previous section, for each coil technology type and plasma β at ignition a minimum cost device with a certain minor radius a and major radius R_0 was found to occur. However, the range of β values over which a comparison of the costs could be made was limited because the peak field values of the Cu and Nb₃Sn were fixed at 12 T and the NbTi at 8 T. A wider range in β can be examined by running the coils at other peak fields, e.g., the Cu and Nb₃Sn at 10 T and 8 T and the NbTi at 10 T.

An example of this is shown in Figure 4-1, where the same type of curve as in Section 3 is plotted except now for NbTi coils at $B_{\max} = 10$ T. For this higher field the β range has been lowered (relative to Figure 3.4 at $B_{\max} = 8$ T) to 4%-7%, and again for each β a minimum in the cost is found to occur. Of course, running the NbTi coils at 10 T implies an associated technological risk which must be considered subjectively in these evaluations. The COAST code takes the higher field into account through cost models which scale the refrigeration and structural costs according to the peak field at the coil. A set of curves for the other coil technologies at various peak fields produces results similar to those in Figure 4-1.

From this data, it is evident that for each coil technology type and plasma beta at ignition there is some minimum cost device at a specific a , R_0 , and $B_{\max}$. A composite plot of these minimum cost devices vs the β value is shown in Figure 4-2. This curve is similar to Figure 3-7 except that now not only the device size (a , R_0) varies along the curve, but also the peak field at the coil $B_{\max}$ can vary. Values of a , R_0 , and $B_{\max}$ at the endpoints of $\beta = 2.5\%$ and $\beta = 10\%$ for each coil type are also shown in Figure 4-2 for reference. The hybrid Cu/NbTi curve terminates at $\beta = 7.5\%$ because the Cu coil field has been reduced to the NbTi coil field of ≈ 8 T and the need for this two coil arrangement has been eliminated. Note that there is a rather sharp increase in cost as the β value is decreased, due to the larger device sizes and peak fields. Likewise, the cost decreases for higher β because a , R_0 , and $B_{\max}$ can be decreased.

Figure 4-1. Cost of NbTi TF coil devices vs major radius with lines of constant beta for $B_{max} = 10$ T.

Figure 4-2. Cost of the least expensive devices for the four TF coil technologies vs the toroidal beta value. The device size and coil peak field vary along the curves.

Also from Figure 4-2 it can be seen that for any β the Cu TF coil devices can be built for the least cost. The Nb₃Sn coil devices are about 30% more expensive than the Cu, while the NbTi and Cu/NbTi hybrid options are about 50% more costly for most β values. A similar observation is that for the same cost, a Cu TF coil device can operate at a lower β than the other technologies. Likewise, Nb₃Sn devices can operate at lower β values than either NbTi or Cu/NbTi devices for the same cost. Note that the NbTi and Cu/NbTi devices complement each other fairly well in cost and performance, as they were intended to do.

An interesting question which can now be investigated is what are the least expensive devices for the four TF coil technology types that could be built for a specified plasma β at ignition. As stated earlier, the beta at which the TNS device will operate is an extremely important measure of the confidence of success of TNS in achieving ignition and long pulse operation.

The least cost device parameters of the four TF coil technology options for four such beta values of 2.5%, 5.0%, 7.5%, and 10.0% are presented in Table 4-1. Here the cost is shown in two ways, both in terms of the absolute cost of the buildings and equipment and also in terms of the relative cost normalized to the Cu TF coil device at $\beta = 5.0\%$. The devices shown in Table 4-1 were selected based on the least cost machines with a plasma radius of at least 1.0 meter, an aspect ratio less than 5 and a plasma current > 3 MA, based on plasma stability and α -particle confinement considerations. In addition, the plasma elongation was kept at 1.6 and all devices have 20 TF coils.

The table shows that the cost of machines which have the ability to achieve ignition at low β values can be significant, e.g., about a factor of two in the cost from $\beta = 2.5\%$ to $\beta = 10.0\%$. In fact, a rough relation which is evident from the data is that the cost of the least expensive devices is approximately proportional to $\beta^{-1/2}$. Of the machines operating at the same β , the Cu option is the least expensive, while the Nb₃Sn is about 30% more costly and the NbTi and Cu/NbTi are about 50% more costly. The $\beta = 2.5\%$ cases, which provide for a margin in the plasma physics, require high fields at the coil and achieve high fields on axis. The

TABLE 4-1
PARAMETERS AND COST OF THE MINIMUM COST DEVICES OF
EACH TF COIL TECHNOLOGY FOR DIFFERENT PLASMA BETA VALUES AT IGNITION

TF COIL	$B_{\max}$ (T)	COST (M\$)	RELATIVE COST	a (m)	R (m)	B_{axis} (T)
<u>$\beta = 2.5\%$</u>						
Cu	12.6	476	1.65	1.0	5.0	8.2
NbTi	10.0	>800	>3.0	>1.6	>8.0	-
Nb ₃ Sn	13.9	566	1.96	1.2	5.75	7.5
Hybrid	11.8	636	2.20	1.2	5.5	7.5
<u>$\beta = 5.0\%$</u>						
Cu	10.4	289	1.00	1.0	4.0	5.8
NbTi	9.9	434	1.50	1.2	5.7	5.3
Nb ₃ Sn	10.9	388	1.34	1.2	5.0	5.3
Hybrid	9.7	436	1.51	1.0	4.5	5.8
<u>$\beta = 7.5\%$</u>						
Cu	9.0	244	0.84	1.0	3.75	4.7
NbTi	9.4	362	1.25	1.0	4.75	4.7
Nb ₃ Sn	9.9	332	1.15	1.0	4.5	4.7
Hybrid	7.9	386	1.34	1.0	4.5	4.7
<u>$\beta = 10.0\%$</u>						
Cu	7.8	224	0.78	1.0	3.75	4.1
NbTi	8.1	342	1.18	1.2	4.75	3.7
Nb ₃ Sn	8.6	307	1.06	1.0	4.5	4.1
Hybrid	NOT NEEDED AT 10% β					

NbTi devices are very undesirable at this low β due to the low limit on the coil field. A more intermediate value of $\beta = 5\%$ would seem to be realizable based on current understanding of the plasma stability conditions, and allows operation with moderate field strengths except in the NbTi case. At higher β values of 7.5% and 10% the field requirements are further reduced, although with an accompanying risk in the plasma physics. Hence, there is a trade-off between technological and physics risks in considering the TNS options and their relative costs. An operating point of $\beta = 5\%$ appears to offer a good compromise between these two considerations.

As can be seen from Figure 4-2 or Table 4-1, these trade studies indicate that for the same size and field the Nb₃Sn TF coil devices are about 5%-10% cheaper than the NbTi TF coil devices. The reason for this cost difference between NbTi and Nb₃Sn is shown in Table 4.2, where the costs are compared for a typical machine with $a = 1.2$ m, $R_0 = 5.0$ m, and $B_{\max} = 9.0$ T. Note that the TF coil conductor cost is larger for the Nb₃Sn, as expected; however, the TF coil structure and dewar cost is larger for the NbTi because its radial build is larger due to its lower current density limitation. The unit costs used for the superconductor cable, based on recent vendor quotes, were \$100/kg for Nb₃Sn and \$50/kg for NbTi. The main cost item difference is in the liquid He refrigeration system costs, which are about twice as high for the NbTi due to its lower thermal operating margin. There is also a slight difference in the OH power supply cost due to the smaller machine bore space of the NbTi device. These same cost differences are found to occur in other size and field devices, so that the data in Table 4-2 is typical.

TABLE 4-2

COMPARISON OF THE COSTS OF DEVICES WITH SUPERCONDUCTING NbTi
AND Nb₃Sn TF COILS FOR THE SAME SIZE DEVICES AND
SAME PEAK FIELD AT THE COIL

a = 1.2 m, R = 5.0 m, Elongation = 1.6, B_{max} = 9.0 T

<u>ITEM</u>	<u>NbTi</u>	<u>Nb₃Sn</u>	<u>NbTi - Nb₃Sn</u>
Total Cost (M\$)	370	348	22
TF Coil Cost	85	92	- 7
- Conductor*	24	37	-13
- Structure & Dewar	61	55	6
Refrigeration System Cost	50	23	27
OH Power Supply Cost	10	8	2
TF Coil Build (m)	0.73	0.61	0.12
Device Bore (m)	1.30	1.40	-0.10

*Based on \$100/kg for Nb₃Sn and \$50/kg for NbTi.

5.0 PARAMETERS AND COSTS FOR DEVICES WITH $\beta = 5\%$

In the preceding sections the general cost and size trends have been discussed for the four TF coil technology options over a range of values in the plasma β . It was found, for example, that for each coil type and plasma β at ignition a minimum cost device occurs at a particular minor radius a , major radius R_0 , and field at the coil $B_{\max}$. As noted previously, devices with $\beta = 5\%$ appear to offer a good compromise between technological risks in the required field at the coil and physics risks in the stability of the plasma. Hence, in this section the device costs and sizes for the various coil technologies which achieve β of 5% are examined in more depth, and a detailed list of device parameters for four typical designs at a β of 5% are presented.

In Figure 5-1 the cost of devices with Cu TF coils is plotted vs major radius R_0 for different values of the plasma half-width a . These curves were obtained based on empirical plasma scaling for 20 TF coils and an elongation of 1.6. Here the plasma β is kept constant at 5% for these cases by varying the peak field at the TF coil, $B_{\max}$, for each device size. Lines of constant values of $B_{\max}$ of 9 T and 10 T are shown for reference. From the figure it can be seen that there is a minimum in the cost for each plasma radius at a certain major radius R_0 . For larger values of R_0 the overall size of the device dominates the cost, even though the field at the TF coil is decreasing in order to keep β at 5%. For smaller values of R_0 the cost also increases due to two effects - increased cost of the TF coils at the higher $B_{\max}$ values and increased power conversion costs to supply the necessary flux swing through the smaller machine bore. The curves terminate at the "bore size limit" due to the fact that there is a minimum allowable R_0 which is set by engineering constraints.

In Figures 5-2 thru 5-4, similar plots of the cost vs R_0 are shown for the other TF coil technologies for a plasma β of 5%. In Figure 5-2 for the superconducting NbTi coil devices one can see the consequences of the lower peak field limits of the NbTi conductor, namely that the relative cost is higher due to the larger machine sizes necessary to achieve $\beta = 5\%$. The curves terminate at a peak field

Figure 5-1. Cost of Cu TF coil devices vs major radius for $\beta = 5\%$.

Figure 5-2. Cost of NbTi TF coil devices vs major radius for $B = 5\%$.

Figure 5-3. Cost of Nb_3Sn TF coil devices vs major radius for $\beta = 5\%$.

Figure 5-4. Cost of hybrid Cu/NbTi TF coil devices vs major radius for $\beta = 5\%$.

limit of 10 T, with an associated technological risk for the NbTi coils. Note that 5% β devices with 8 T at the NbTi coil require relatively large plasma dimensions. In Figure 5-3 for the superconducting Nb₃Sn devices, it can be seen that peak fields in the range of 11-12 T are needed for $\beta = 5\%$ in smaller size and cost devices. The reason that the superconducting options require a higher peak field than the Cu option in order to achieve the same field on axis (i.e., same β) is the additional shielding space required to reduce the nuclear heating in the superconducting coils. This shielding space plus a dewar thickness results in a larger distance between the plasma center and the edge of the TF coil, and hence a higher peak field requirement for the NbTi and Nb₃Sn coils. Figure 5-4 for the hybrid NbTi/Cu coil option shows that peak fields at the Cu coil in the range of 9-10 T are necessary to achieve $\beta = 5\%$ in smaller sized devices. The field at the NbTi coil in these hybrid devices is held at 8 T, with the Cu coil supplying the necessary field strength above this value.

By examining Figures 5-1 thru 5-4, one can make several observations. For example, for each coil technology there is some minimum cost device at a particular a , R_0 , and $B_{\max}$ which achieves ignition at a β of 5%. Similar curves for other β values are also found to exhibit this same trend. For the Cu and Cu/NbTi options this minimum occurs at the smallest minor radius which was examined, 0.8 m. However, for the superconducting NbTi and Nb₃Sn options the least cost device does not occur for the 0.8 m plasmas. This is because the smaller plasmas must operate at higher densities in order to reach ignition, and thus require higher fields to still achieve a β of 5%. For superconducting devices the TF coils constitute a higher proportion of the total cost (see Section 6), and hence can cause smaller devices to be more expensive than slightly larger ones which achieve the same β . Of these least cost devices, the Cu TF option is the least expensive due to its ability to deliver a higher field on axis in a more compact device. These figures also are able to answer the question of what is the cheapest way to deliver a certain field on axis - by increasing the device size at lower TF coil peak fields or increasing the peak field for smaller device sizes? The results tend to show there is a compromise between the two, but in general it is cheaper to go to higher fields in more compact device sizes.

In Table 5-1 the device parameters of representative designs for each of the TF coil technology options at a β of 5% are listed. These particular devices were selected from the data in Figures 5-1 thru 5-4 as the least cost machine at $\beta = 5\%$ subject to the following considerations:

- Plasma Radius $a \geq 1.0$ m
- Aspect Ratio < 5
- Ignition According to Empirical Scaling.

From the parameters listed in Table 5-1 the relative advantages and disadvantages of each coil technology type for a TNS tokamak can be compared. Note, for example, that all have plasma currents around 4 MA and fields on axis around 5.5 T. The neutron wall loadings are in the range of 1.3-1.5 MW/m² and fusion power in the range of 550-800 MW. The ratio of the plasma energy produced to the energy consumed to operate the device during the pulse is only 0.32 for the Cu TF machine, due mostly to the resistive losses in the Cu coils. This ratio is about 1.6 for the superconducting Nb₃Sn, but is still less than one for the NbTi due mostly to the large refrigeration system load to run the coils at 9.9 T. Note that the Cu device is the least expensive, and the Nb₃Sn is about 34% more costly while the NbTi and Cu/NbTi are about 50% more costly. However, the annual utility operating cost to run the devices is largest for the Cu option. Further descriptions of these four TNS reference points for the various coil technology options are presented in reference 4.

TABLE 5-1
COMPARISON OF REPRESENTATIVE PARAMETERS
FOR FOUR TNS POINT DESIGNS

TF Coil Conductor	Cu	NbTi	Nb ₃ Sn	Cu/NbTi
Plasma Minor Radius, a (m)	1.0	1.2	1.2	1.0
Plasma Major Radius, R (m)	4.0	5.7	5.0	4.5
Plasma Elongation, δ (-)	1.6	1.6	1.6	1.6
Aspect Ratio, A (-)	4.0	4.7	4.2	4.5
Field at TF Coil, B_m (T)	10.4	9.9	10.9	9.7
Field on Axis, B_t (T)	5.8	5.3	5.3	5.8
Toroidal Beta, β_t (%)	5.0	5.0	5.0	5.0
Plasma Current, I_p (MA)	4.1	3.8	4.3	3.6
Mean Electron Density, $\bar{n}_e$ (m ⁻³)	1.6×10^{20}	1.3×10^{20}	1.3×10^{20}	1.6×10^{20}
Mean Ion Temperature, $\bar{T}_i$ (keV)	13.0	13.0	13.0	13.0
Energy Confinement Time, τ_E (s)	1.5	1.8	1.8	1.5
$\bar{n}_e \tau_E$ (m ⁻³ s)	2.4×10^{20}	2.4×10^{20}	2.4×10^{20}	2.4×10^{20}
Total Volt-Seconds	41.0	55.2	51.6	43.5
Plasma Volume, V_p (m ³)	126	259	228	142
Neutron Wall Load (MW/m ²)	1.50	1.28	1.28	1.50
Total Fusion Power (MW)	558	795	698	628
Fusion Power Density (MW/m ³)	3.7	2.6	2.6	3.7
Neutral Beam Power (MW)	40.0	57.0	50.0	45.0
Steady State Burn Time (s)	16.0	16.0	16.0	16.0
Time Between Pulses (s)	300	300	300	300
TF Coil Vertical Bore (m)	6.1	7.4	7.6	9.5
TF Coil Horizontal Bore (m)	3.8	5.1	4.9	5.7
Plasma Energy/Energy Consumed	0.32	0.85	1.57	0.51
Number of TF Coils	20	20	20	20
Cost, Building & Equipment (M\$)	289	434	388	436
Relative Cost	1.0	1.50	1.34	1.51
Annual Utility Cost (M\$)	4.1	3.0	2.0	3.4

6.0 COST BREAKDOWN BY COMPONENTS

In the previous section the parameters were presented for four reference points based on the four TF coil technologies considered. The Cu machine was the least expensive, with the superconducting options being 34% to 50% more expensive. In this section the reasons for these cost differences are investigated by breaking the cost down by components for the Cu and Nb₃Sn devices shown in Table 5-1. The cost breakdown for the other superconducting option with NbTi coils is similar to that for the Nb₃Sn device, although with some differences which were discussed in Section 4 and Table 4-2.

In Figure 6-1 the major cost contributors are shown by percentage of the total for the Cu TF coil device with $a = 1.0$ m, $R = 4.0$ m, and $B_{\max} = 10.4$ T. The two largest cost items are the power conversion equipment to run the TF coils and the TF coils themselves. Together they constitute about 39% of the total cost. The next largest cost items are the neutral beam systems and power supplies; the reactor site and buildings; the other power conversion systems for the OH and EF coils; and the tokamak system which includes the vacuum vessel, liner, structure, shielding, OH and EF coils, etc. Together these four items account for about 44% of the total. The remaining 17% of the cost is made up of the tritium handling systems, remote servicing systems, and the heat removal systems.

In Figure 6-2 a similar cost breakdown is shown for the Nb₃Sn superconducting device with $a = 1.2$ m, $R_0 = 5.0$ m, and $B_{\max} = 10.9$ T. The largest cost item, at 40% of the total, is the TF coils, which also includes the dewars, bucking cylinder, and winding station. Other large cost components are the tokamak system, neutral beams, reactor site and buildings, heat removal systems, and the OH and EF power conversion systems. Note that the TF coil power conversion equipment cost is very small for superconducting devices.

There are several obvious differences in the cost components for the Cu and Nb₃Sn devices. The TF coils are less expensive for the Cu; however, together with their

COST = BUILDINGS + EQUIPMENT = \$289 M

Figure 6-1. Cost breakdown by major systems for a Cu TF coil device with $a = 1.0$ m, $R_o = 4.0$ m, $B_{max} = 10.4$ T.

COST - BUILDINGS + EQUIPMENT = \$388 M

Figure 6-2. Cost breakdown by major systems for a Nb₃Sn TF coil device with $a = 1.2$ m, $R_o = 5.0$ m, $B_{max} = 10.9$ T.

power supplies they account for about the same fraction (40%) of the cost as do the superconducting coils, dewars, etc for the Nb_3Sn device. The heat removal systems are larger for the Nb_3Sn due to the cryogenics involved. Other components, such as the tokamak system, neutral beams, OH and EF power supplies, and reactor site and buildings, account for about the same fraction of the cost in both the Cu and Nb_3Sn devices.

7.0 SENSITIVITY STUDIES

In this section the sensitivity of the results described previously to variations in certain parameters and ground rule assumptions is investigated. The two reference configurations which are used for these sensitivities are the Cu and Nb₃Sn designs at β of 5%, which were discussed in Sections 5 and 6. Among the parameters which are varied in these sensitivity studies are:

- Number of TF Coils
- Plasma Density
- Plasma Elongation

The sensitivity of these results to the plasma scaling law used to specify the ignition parameters is investigated separately in Section 8.

7.1 SENSITIVITY TO THE NUMBER OF TF COILS

In Figure 7-1 the cost of the reference Cu and Nb₃Sn devices is shown as a function of the number of TF coils. For both machines there is a minimum in the cost for about 20 TF coils. For smaller numbers of coils the cost increases because the TF coils must be larger in order to satisfy the magnetic field ripple criterion at the outer plasma edge. Here the ripple limit has been set at 1% peak-to-average in the equatorial plane. Hence, the total amount of conductor is larger, even though the number of coils is smaller. At larger numbers of coils the cost also increases due to the larger amount of conductor. Thus, there is a trade-off between a small number of larger TF coils and a large number of smaller TF coils, with about 20 coils resulting in the minimum cost. However, devices with 16 coils are only about 3% more costly than those with 20 coils. When such things as amount of access and ease of manufacturing are considered, it is probably worthwhile to go with 16 TF coils in view of the small cost penalty relative to 20 coils.

Figure 7-1. Cost of Cu and Nb_3Sn TF coil devices vs the number of TF coils in the device.

7.2 SENSITIVITY TO INCREASES IN THE PLASMA DENSITY

The devices compared in the earlier sections were all based on achieving ignition at an $(n_e \tau_E)$ product of $2.4 \times 10^{20} \text{ m}^{-3} \text{ sec}$ according to empirical plasma scaling. This provided a common basis for comparing devices with different sizes and TF coil technologies. It is also of interest to see how the device cost varies when the plasma density is increased, so that there is a margin in $n_e \tau_E$ relative to the ignition value.

The effect of increasing the density by a factor of $\sqrt{2}$ and 2 in the reference Cu and Nb_3Sn devices is shown in Table 7-1. In each case the wall loading and fusion power increase by a factor of n^2 to fairly high values. The field on axis decreases because of the extra shield thickness needed to reduce the dose in the copper EF coils and the nuclear heating in the superconducting TF coils for operation at the higher density and wall load. Since the peak field at the TF coil is kept at the constant value, the plasma β also increases. Margin in the ignition condition exists in these higher density devices since the ratio of $(n_e \tau_E)_{\text{emp}}$ from empirical scaling to the $(n_e \tau_E)_{\text{ign}}$ value for ignition increases to 2.0 and 4.0 for the two cases considered. The increase in cost results mostly from more expensive heat removal systems to remove the extra heat generation in the vacuum vessel and shield; from increases in the OH power conversion equipment due to the smaller bore size and larger volt-seconds requirements; and from increases in the amount of shielding material needed in the device. However, the increase in cost is relatively small and hence the devices could be designed to operate at higher densities and provide a margin in the physics without a large cost penalty.

7.3 SENSITIVITY TO PLASMA ELONGATION

In Figure 7-2 the cost of the reference Cu and Nb_3Sn devices is shown as a function of the plasma elongation δ . Here the peak field at the coil has been kept at a constant value as the elongation was varied from 1.0 (circular) to 2.0, with the reference being at 1.6. The plasma density required for ignition decreases as the elongation increases according to the empirical scaling law, since an "equivalent" plasma size, which is modified by the shape factor $(\frac{1+\delta^2}{2})$ is used in the scaling.

TABLE 7-1
SENSITIVITY OF Cu AND Nb₃Sn DEVICE COSTS
TO OPERATION AT HIGHER DENSITIES

A. Cu TF COILS, a = 1.0 m, R = 4.0 m, B_{max} = 10.4 T

Electron Density, n _e (m ⁻³)	1.60 x 10 ²⁰	2.26 x 10 ²⁰	3.20 x 10 ²⁰
Neutron Wall Load (MW/m ²)	1.5	3.0	6.0
Total Fusion Power (MW)	558	1116	2232
Field on Axis, B _t (T)	5.8	5.6	5.5
Inner Shield Thickness (m)	0.17	0.23	0.28
Toroidal Beta, β _t (%)	5.0	7.4	11.1
$\frac{(n_e \tau_E)_{\text{emp}}}{(n_e \tau_E)_{\text{ign}}}$	1.0	2.0	4.0
Cost, Buildings + Equipment (M\$)	289	300	321
Percent Increase in Cost	0%	4%	11%

B. Nb₃Sn TF COILS, a = 1.2 m, R = 5.0 m, B_{max} = 10.9 T

Electron Density, n _e (m ⁻³)	1.33 x 10 ²⁰	1.88 x 10 ²⁰	2.67 x 10 ²⁰
Neutron Wall Load (MW/m ²)	1.3	2.6	5.2
Total Fusion Power (MW)	698	1396	2792
Field on Axis, B _t (T)	5.3	5.2	5.1
Inner Shield Thickness (m)	0.33	0.38	0.44
Toroidal Beta, β _t (%)	5.0	7.4	10.9
$\frac{(n_e \tau_E)_{\text{emp}}}{(n_e \tau_E)_{\text{ign}}}$	1.0	2.0	4.0
Cost, Buildings + Equipment (M\$)	388	400	419
Percent Increase in Cost	0%	3%	8%

Figure 7-2. Cost and beta value vs plasma elongation for Cu and Nb₃Sn TF coil devices.

As shown in Figure 7-2, the cost increases only slightly with the elongation. The cost difference between $\delta = 1.0$ and $\delta = 2.0$ is only about 5% for both the Cu and Nb₃Sn options. This small cost rise is due mostly to larger costs for the vacuum vessel, liner, machine structure, shielding, and the EF and OH power conversion equipment in the more elongated devices. The TF coil size and cost does not change here as δ is increased since they are of the constant-tension D-shape. As such, the TF coils provide sufficient space for an elongation up to 2.0 without requiring larger sizes.

The variation in the plasma β value is also shown in Figure 7-2 as a function of the elongation. Due to the density decrease with increasing δ , the β also decreases with increasing δ from about 6.6% at $\delta = 1.0$ to about 4.3% at $\delta = 2.0$. Note the reference point of $\beta = 5.0\%$ at $\delta = 1.6$. The field on axis also increases slightly with elongation since the lower density operation requires less shielding space on the inner part of the torus.

Hence, these results show that the TNS device cost for both Cu and superconducting TF coil types is relatively insensitive to the plasma elongation. This is an important effect, since it means that the elongation can be chosen based on plasma physics considerations without a significant cost impact.

8.0 VARIATION WITH PLASMA SCALING LAW

The results presented in the previous sections on cost and size trends for TNS tokamaks have assumed plasma ignition and burn conditions are achieved according to empirical plasma scaling, which has been observed in present-day resistively heated, high collisionality tokamak experiments. A second type of scaling which could be used to size the devices is trapped-particle-mode (TPM) scaling, which is based on theoretically predicted transport coefficients for operation in a near collisionless regime. In this section the results over a range of device sizes and fields are compared for empirical and TPM scaling.

While the empirical plasma scaling law provides relatively straightforward analytical relationships, the plasma scaling laws for TPM scaling are considerably more complicated. As used in this analysis, the TPM scaling method entails numerically solving the plasma global (space independent) diffusion equations over the regimes of different plasma transport characteristics.

Regimes of particle transport which are included in the analysis are neoclassical, trapped electron mode, and $0.1 \times$ trapped ion mode diffusion losses. A computer code has been written to solve the TPM transport equations, and is similar to the analysis described in reference 3.

In Figure 8-1 the cost of Cu TF coil devices vs major radius is compared for both empirical and TPM scaling. Here the plasma β is fixed at 5%, and the peak field $B_{\max}$ at the coil is varied so that all devices achieve an $n_e \tau_E$ of $2.4 \times 10^{20} \text{ m}^{-3} \text{ sec}$. This curve is similar to that in Figure 5-1 although now only plasma radii a of 1.0 m and 1.2 m are shown for clarity. Note that the cost for the same size (a, R_0) device which achieves ignition at $\beta = 5\%$ is somewhat larger for TPM scaling than for empirical scaling. This is because the TPM scaling, in general, requires a slightly larger density and field than the empirical scaling. Hence, the field at the coil must be larger for the TPM scaling, with a corresponding increase in the cost. For example, at the reference Cu coil case of $a = 1.0 \text{ m}$, $R_0 = 4.0 \text{ m}$,

Figure 8-1. Comparison of the cost of Cu TF coil devices with $\beta = 5\%$ sized with empirical plasma scaling and trapped particle mode plasma scaling.

and $\beta = 5\%$, empirical scaling requires a $B_{\max}$ of 10.4 T while TPM requires a $B_{\max}$ of 11.3 T. The respective costs for empirical and TPM are \$289 M and \$349 M, or a difference of about 20%. The minimum cost device for the TPM scaling occurs at $R_0 = 4.5$ m and $a = 1.0$ m with a cost of \$316 M. Thus, the net effect of using TPM scaling is to produce slightly larger device sizes at the minimum cost point, which are only about 10% higher in cost than the minimum for devices sized with empirical scaling.

The same difference between empirical and TPM scaling are also found to occur for the superconducting Nb_3Sn devices, as shown in Figure 8-2. Again, the TPM scaling produces slightly larger devices at the lowest cost point, although the difference in cost is only about 7% even for the same size machine. Note that both plasma scalings result in the same cost trends, i.e., a minimum in the cost at a certain R_0 and $B_{\max}$ for a fixed a and β . For smaller values of R_0 the cost increases due to larger fields and OH power supplies; while for larger values of R_0 the cost increases due to the larger component sizes.

The basic reason behind these differences between empirical and TPM scaling and their effect on the cost is shown in Figure 8-3. In this figure the density and field required for ignition are shown as a function of the plasma radius for both scalings. The plasma β is kept at 5%, the temperature at 13 keV, and the elongation at 1.6. In addition, the TPM curves are shown for an aspect ratio A of 4 while the empirical scaling is assumed independent of or a slowly varying function of A . Note that the TPM requires a slightly higher density and field on axis than the empirical, which results in the cost difference effects shown in Figures 8-1 and 8-2. Similar curves to Figure 8-3 are found to exist for other β values, so that the results shown in Figures 8-1 and 8-2 also occur for other β values and TF coil technologies.

The main conclusion which can be drawn from this comparison of plasma scaling laws is that the overall cost and size trends are fairly insensitive to the scaling used to predict the plasma ignition parameters. In general, the cost differences between

Figure 8-2. Comparison of the cost of Nb₃Sn TF coil devices with $\beta = 5\%$ sized with empirical plasma scaling and trapped particle mode plasma scaling.

Figure 8-3. Comparison of the field on axis and density required for ignition vs plasma size as predicted by empirical plasma scaling and trapped particle mode plasma scaling for $\beta = 5\%$.

devices sized by the two scalings are less than 10% and the trends are the same. Since there is some question⁵ concerning the validity of the theoretical models upon which the TPM scaling law is based, plus the fact that empirical scaling has been shown to exist in experimental tokamaks, it is felt to be best to base the TNS trade study results on empirical scaling. However, it is realized that the empirical law is at present strictly valid only for highly collisional plasmas.

9.0 SUMMARY AND CONCLUSIONS

In this report the results have been presented from a parametric trade study which was performed in order to consistently evaluate the relative costs and performance parameters of D-T burning tokamaks over a range of plasma sizes and toroidal field (TF) coil technologies. Four different types of TF coil technologies were investigated: water-cooled copper coils, superconducting NbTi and Nb₃Sn coils, and a "hybrid" coil arrangement consisting of a normal conducting Cu coil nested within a superconducting NbTi coil. The results of these analyses have been used to aid in the choice of an ignition device as the basis of the ORNL/Westinghouse The Next Step (TNS) tokamak design studies.

Several trends and conclusions have evolved from this study, the most important of which are given below:

- For each TF coil technology type, peak field at the coil $B_{\max}$, and plasma radius a , there exists a minimum cost device at a certain major radius R_0 . This value of R_0 is not necessarily the smallest which is feasible, due to increased costs of the OH power conversion equipment for small bore machines;
- For a fixed field at the coil, the cost is a strong function of the major radius and a weaker function of the plasma minor radius. Away from the minimum point, the cost is found to scale as $\sim R_0^{1.5}$ for constant a and as $\sim a^{1/3}$ for constant R_0 ;
- For each TF coil type and value of the plasma β at ignition, there is a least cost device at some size (a, R_0) and peak field $B_{\max}$;
- An examination of these least cost devices indicates that the cheapest way to achieve a certain β value for any TF type is

to increase the peak TF coil field for smaller device sizes rather than to increase the device size at lower peak fields. That is, in general it is cheaper to use higher fields in more compact device sizes;

- Of these least cost devices for each β value, the Cu TF coil device is the least expensive. The Nb_3Sn machines are about 30% more costly, while the NbTi and hybrid Cu/NbTi machines are about 50% more costly;
- For a fixed device cost, the Cu coil devices can operate at a lower β than the other technologies. Likewise, Nb_3Sn devices can operate at a lower β than either NbTi or Cu/NbTi for the same cost;
- The cost for any TF coil type increases rapidly with smaller β values. An approximate expression for the least cost devices is that the cost varies as $\sim \beta^{-1/2}$;
- Cu TF coil devices are the most compact in terms of providing a certain field on axis for a given plasma radius;
- NbTi TF coil devices are unattractive from size and cost considerations for operation at β values of $\sim 6\%$ or less because of the low field limitation on the conductor;
- Nb_3Sn TF coil devices are more attractive than NbTi devices from size and cost viewpoints due to the higher field capability of the conductor;
- Hybrid Cu/NbTi TF coil devices complement the capabilities of NbTi devices by providing extra field on axis for lower β operation. However, they produce higher cost devices than Cu

or Nb_3Sn in addition to the added mechanical complexity of the two coil arrangement;

- Of the four TF coil technologies at a β of 5%, the Nb_3Sn device is the only one which has a ratio of the plasma fusion energy produced during the pulse to the energy consumed during the pulse greater than one;
- For the same size device and same field at the coil, Nb_3Sn devices are about 5%-10% less expensive than NbTi devices. This is due to the lower thermal margin of NbTi which results in larger refrigeration system costs, even though the Nb_3Sn conductor cable is more expensive than the NbTi;
- A breakdown by component costs indicates that for Cu TF devices the TF coils and their power supplies are the biggest cost items and account for about 40% of the total cost. Similarly, for Nb_3Sn TF devices the TF coils and the dewars, bucking cylinder, and winding station also account for about 40% of the total cost;
- The overall cost and size trends for the various TF coil options are fairly insensitive to whether empirical plasma scaling or trapped-particle-mode (TPM) plasma scaling is used to predict the plasma parameters for ignition. In general, TPM results in slightly larger device sizes at the minimum cost point which are less than 10% more costly than those sized with empirical scaling;
- Variation in the number of TF coils in a device shows that the minimum cost occurs for about 20 coils. However, the cost is only about 3% higher for devices with 16 coils, which indicates only a small cost penalty for providing enhanced machine access;

- The cost is fairly insensitive to operation at higher densities, e.g., a $\sim 10\%$ cost increase for doubling the density;
- Variations in the plasma elongation indicate that the cost increases only slightly for larger elongations. Hence, the elongation can be chosen based on plasma physics considerations without a large cost impact;
- Devices designed to achieve ignition at intermediate β values, e.g., 5%, can also test operation at higher β values by either
 - a) reducing the TF coil current to lower the field on axis, or
 - b) maintaining the field and increasing the plasma density.

Based on these conclusions and trends, a reference design point was selected for each TF coil type at a plasma β of 5%. This value of β was selected because it represents a reasonable compromise between technological risks in the field required and physics risks in the plasma stability. Of the four design points, the Cu device is the smallest and least expensive at a cost for the buildings and equipment of \$289 M. The Nb_3Sn device is about 34% more expensive while the NbTi and Cu/NbTi are about 50% more expensive. In addition, the NbTi has the disadvantage of requiring ~ 10 T at the coil in order to have a reasonable size and cost with β of 5%.

Based on these trends and conclusions which resulted from the trade study analysis, one must next make several qualitative judgments about the role the TNS device should play in the path to commercial demonstration of fusion power.

For example, if the objective is deemed to be solely to demonstrate ignition for the least cost and in the shortest time with a minimum of development, then Cu TF coils appear most attractive. This route may not, however, result in the lowest overall program cost on the route to a demonstration plant, since more machines may be required to demonstrate all aspects of fusion power technology.

If the objective of TNS is deemed to be a demonstration of some engineering advancement and reactor technology as well as ignition and burn dynamics, then the super-

conducting option appears more attractive for TNS. This, of course, would be more expensive than the Cu option and would require more technology development. The results of this study indicate that of the superconducting options, the Nb_3Sn devices are more attractive than both the NbTi and hybrid Cu/NbTi options because of their greater field capability and lower cost. For a β of 5%, the Nb_3Sn device would be about 30% more costly than the Cu device.

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