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fusion power systems department

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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.

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Summary

A series of parametric trade studies was performed 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 Nb_3Sn coils, and a "hybrid" coil arrangement consisting of a normal conducting Cu coil nested within a superconducting NbTi coil. Results of the analysis indicate for TNS operation, for example, that for a given plasma beta at ignition, the Cu TF coil devices are least expensive, followed by the Nb_3Sn, NbTi, and NbTi/Cu options. Other conclusions and trends resulting from the study are presented and analyzed.

Introduction

There are a number of distinctly different options in the plasma size and toroidal field (TF) coil technology which could satisfy the objectives of The Next Step (TNS) tokamak. The plasma size is a very important parameter because it directly translates into machine and plant size and cost. In addition, the plasma size is a key parameter in evaluating the flexibility of the system to achieve the objectives. The TF coil technology is important because available options exhibit a certain range in the maximum magnetic field and a wide range of system complexities. Accordingly, a parametric trade study was performed to consistently evaluate the relative costs and performance parameters for D-T burning tokamaks over a range of plasma and machine sizes and TF coil technologies. The results of this analysis are presented in this paper, 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 for TNS tokamaks, 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. 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.

Four different types of TF coil technologies have been investigated in the trade studies. These include water cooled copper coils and two types of superconducting coils, NbTi and Nb_3Sn. 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 number of TF coils in a device is a variable in the analysis, as is the peak field at the coil for each coil technology.

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 limits which were consistent with the ground rules and still allowed a viable engineering design. In most cases the plasma elongation was kept at 1.6, based on physics considerations. 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.

Method of Analysis

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.

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 scaling[2], 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 model[3], which involves numerically solving the spatially averaged plasma energy balance equations using theoretical models for the different regimes of particle transport. 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. The plasma temperature has been assumed to be 13 keV, representing a volume averaged value for steady state operation under ignition conditions.

For most of these studies the plasma pulse time operating scenario has been held fixed under the assumptions of a 1 second initiation and startup period, a 6 second neutral beam injection period to reach ignition, an 8 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 2 second quench. Hence the total pulse length is ≈30 seconds. The time between pulses is fixed at 5 minutes (300 seconds), and there are assumed to be the equivalent of 1,000 full power D-T pulses per year.

The costs presented in the next section for the TNS devices are those for the buildings and equipment 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.

Analysis Results

In this section the results of an analysis using the COAST code are presented and discussed for the four TF coil technologies considered for the TNS design studies. In order to consistently evaluate and compare the relative costs and sizes of different TNS options, it is necessary to also consider some measure of the confidence of success of each device. An important device parameter is the plasma 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 also 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 the long pulse durations, the minimum β 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 1 the relative 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

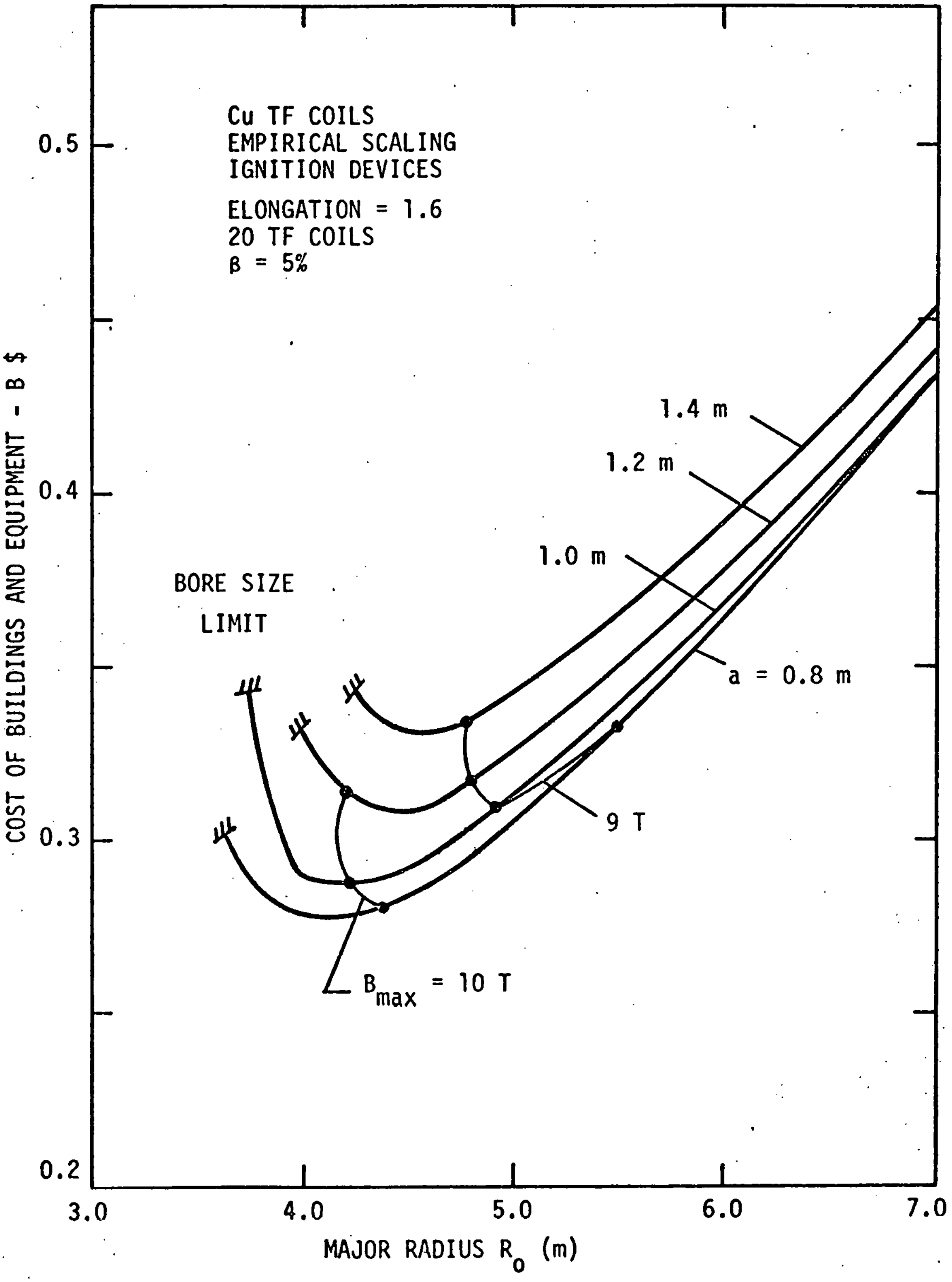

Figure 1. Cost of Cu TF Devices at β = 5%

1.6. 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 Figure 2 and 3 similar plots of the cost vs. R_0 are shown for the superconducting TF coil technologies for a plasma β of 5%. In Figure 2 for the 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 β = 5%. The curves terminate at a peak field 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 very large and costly sizes. In Figure 3 for the Nb_3Sn devices, it can be seen that peak fields in the range of 11 - 12 T are needed for β = 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 Nb_3Sn coils. Similar curves for the hybrid NbTi/Cu coil option show peak fields at the Cu coil in the range of 9 - 10 T are necessary to achieve β = 5% in smaller sized devices.

By examining Figures 1 - 3, 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

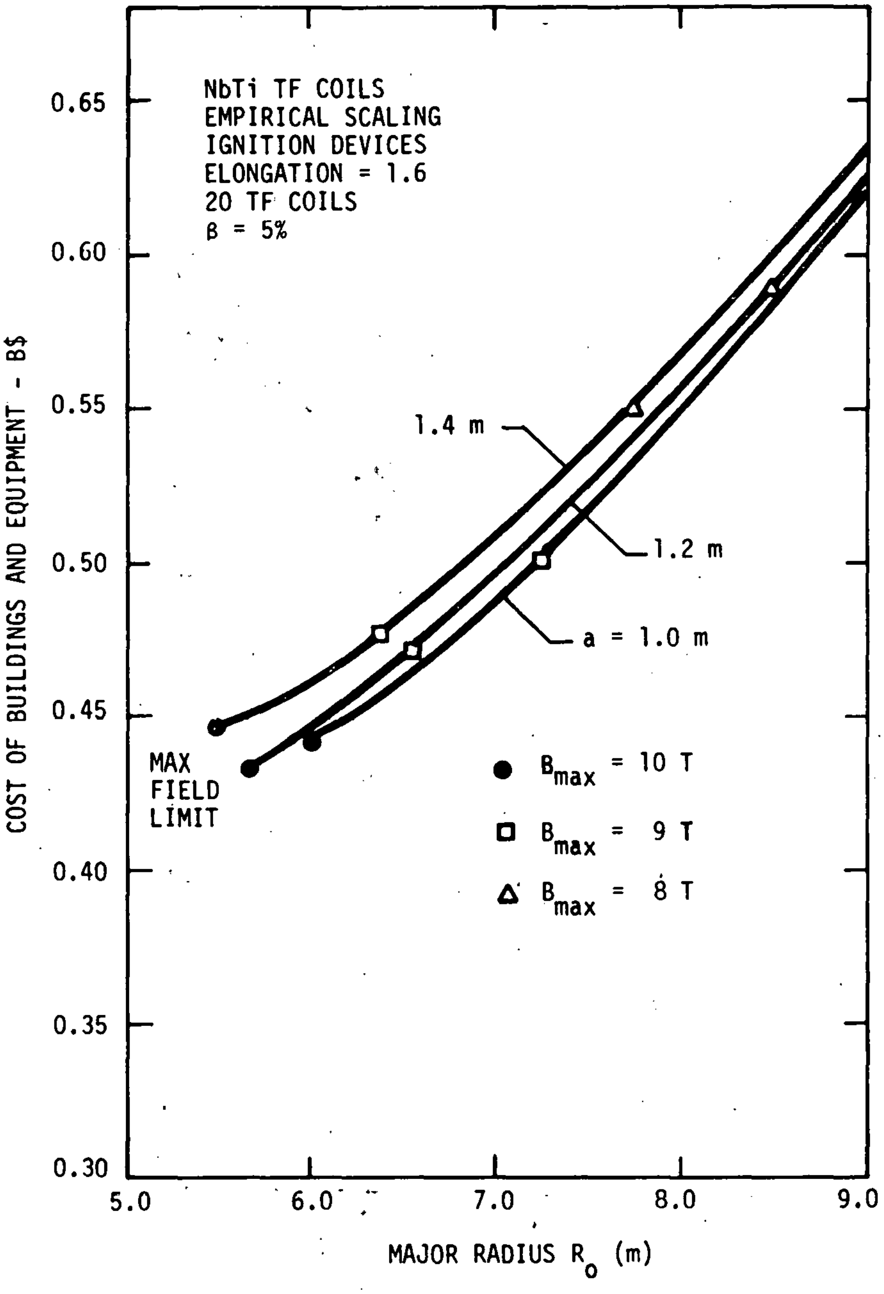

Figure 2. Cost of NbTi TF Devices at β = 5%.

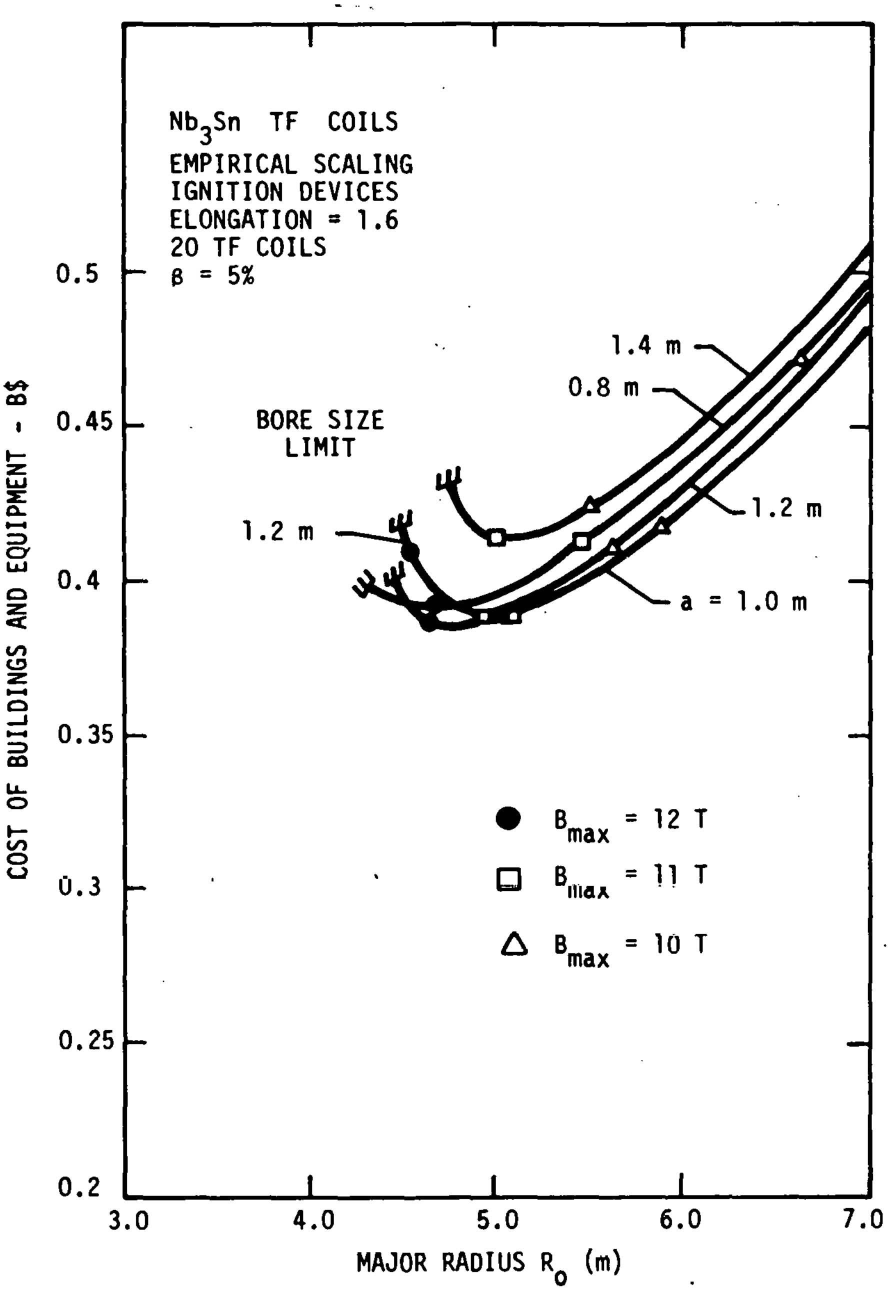

Figure 3. Cost of Nb$_3$Sn TF Devices at β = 5%.

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 Nb_3Sn 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, and hence can cause smaller devices to be more expensive than slightly larger ones which achieve the same β. Of these minimum 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.

As noted above, for each coil technology and plasma beta at ignition there is some minimum cost device at a specific a, R_o, and B_{max}. A composite plot of these minimum cost devices vs. the operating β value is shown in Figure 4 for the four TF coil technology options. Values of a, R_o, and B_{max} at the end points of β = 2.5% and β = 10% for each coil type are also shown in Figure 4 for reference. 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_o, and B_{max} can be decreased. Also from Figure 4, it can be seen that for any β the Cu TF coil devices can be built for the least cost. The Nb_3Sn 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, Nb_3Sn 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.

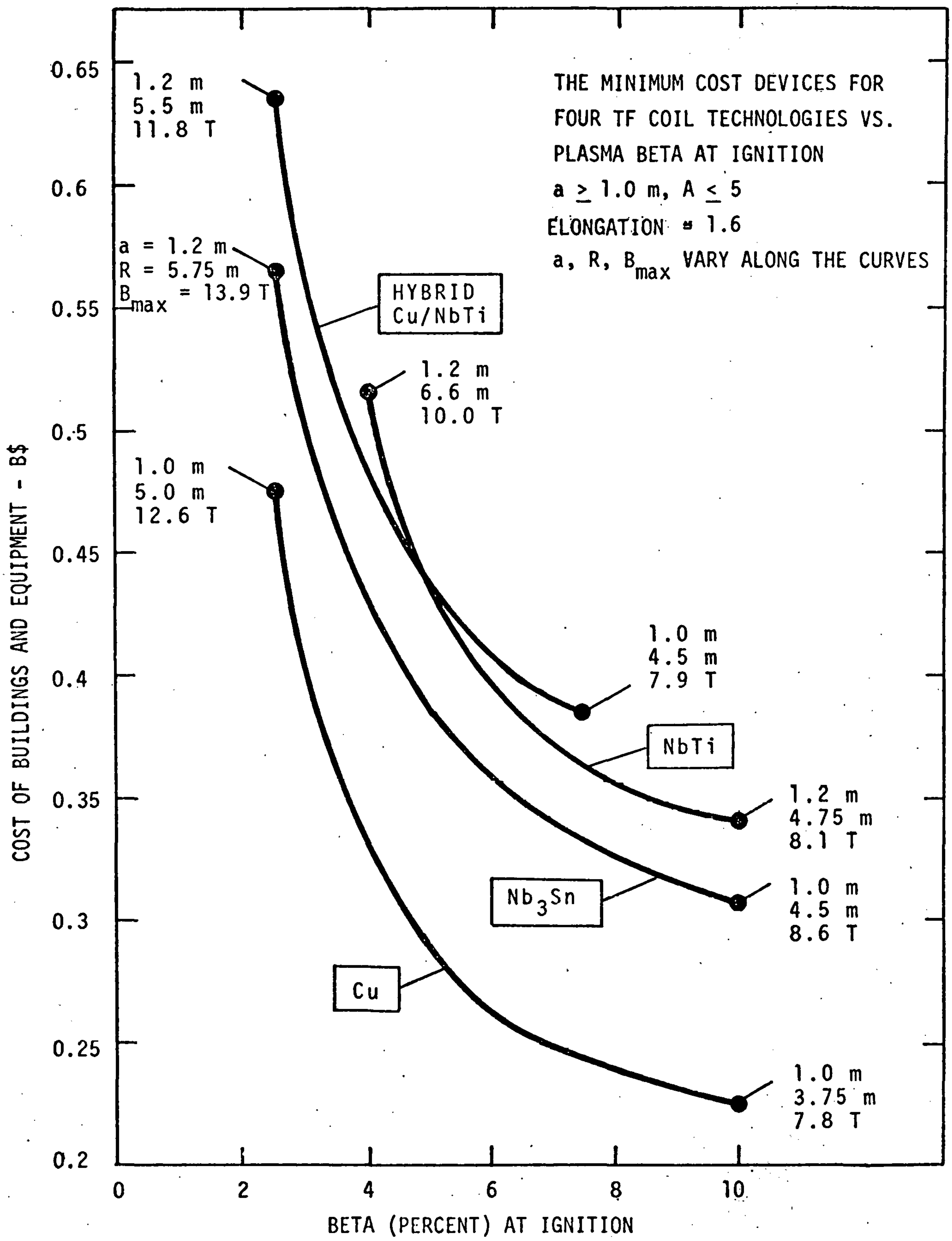

Figure 4. Minimum Cost Devices vs Percent Beta.

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. The least cost device parameters of the four TF coil technology options for four beta values of 2.5%, 5.0%, 7.5% and 10.0% are presented in Table 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 β = 5.0%. The devices shown in Table 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 β = 2.5% to β = 10.0%. In fact, a rough estimate which is evident from Table 1 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 Nb_3Sn is about 30% more costly and the NbTi and Cu/NbTi are about 50% more costly. The β = 2.5% cases, which provide for a margin in the plasma physics, require high fields at the coil and achieve high fields on the axis. The NbTi devices are very undesirable at this low β due to the low limits on the coil field. A more intermediate value of β = 5% would seem to be relizable 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 β = 5% appears to offer a good compromise between these two considerations.

It is interesting to note from Table 1 or Figure 4 that for the same values of a, R_o, and B_{max} the Nb_3Sn TF coil devices are about 5% - 10% cheaper than the NbTi TF coil devices. The reasons for these cost differences between NbTi and Nb_3Sn

TABLE 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)
β = 2.5%						
Cu	12.6	476	1.65	1.0	5.0	8.2
NbTi	10.0	>800	>3.0	>1.6	>8.0	-
Nb_3Sn	13.9	566	1.96	1.2	5.75	7.5
Hybrid	11.8	636	2.20	1.2	5.5	7.5
β = 5.0%						
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_3Sn	10.9	388	1.34	1.2	5.0	5.3
Hybrid	9.7	436	1.51	1.0	4.5	5.8
β = 7.5%						
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_3Sn	9.9	332	1.15	1.0	4.5	4.7
Hybrid	7.9	386	1.34	1.0	4.5	4.7
β = 10.0%						
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_3Sn	8.6	307	1.06	1.0	4.5	4.1
Hybrid	NOT NEEDED AT 10% β					

devices are shown in Table 2 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 Nb_3Sn, 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 cables, based on recent vendor quotes, were $100/kg for Nb_3Sn 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 in the NbTi device.

Conclusions

These results on the analysis of various plasma sizes and TF coil technology options for D-T burning tokamaks have revealed several interesting trends which are useful in the choice of an ignition device as the basis of the ORNL/Westinghouse TNS tokamak design studies. A related paper[4] in this conference describes the engineering parameters of four TNS tokamak reactor systems which were selected based in part on these trade studies.

For a chosen plasma beta operating value, there seem to be two main conclusions possible on the best choice for a TNS tokamak, depending upon the perceived objective of TNS. If the main goal of TNS is simply to demonstrate ignition and burn dynamics with a minimum of technology development in the shortest time, then water-cooled Cu coils at moderate field strengths (10 - 11 T) seem the best choice. If, on the other hand, the goal of TNS, besides demonstrating ignition and burn dynamics, is also to demonstrate advanced engineering technology such as superconducting coils which could extrapolate to a power reactor, then Nb_3Sn TF coil devices seem the best choice, at a cost about 30% higher than for the Cu device. The lower field NbTi devices generally result in larger and more expensive devices, as do the more complex hybrid NbTi/Cu options, and hence are not as attractive as the Cu or Nb_3Sn. The choice of Nb_3Sn would imply an associated technological risk, although the benefits of its higher field capability and larger thermal margin make it very desirable for fusion power reactor applications.

TABLE 2

COMPARISON OF THE COSTS OF DEVICES WITH SUPERCONDUCTING NbTi AND Nb_3Sn 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

ITEM	NbTi	Nb_3Sn	NbTi - Nb_3Sn
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

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*Based on \$100/kg for Nb_3Sn and \$50/kg for NbTi.

Another interesting result from these trade studies is that for the same sized device and same peak field at the coil, devices with Nb_3Sn coils are about 5% less expensive than those with NbTi coils. This is due to recent vendor quotes which have lowered the cost of Nb_3Sn conductor cable, as well as larger refrigeration costs for the NbTi coils due to their lower thermal margin.

Acknowledgement

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