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ENGINEERING PARAMETERS FOR FOUR IGNITION TNS TOKAMAK REACTOR SYSTEMS

MASTER

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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.

ENGINEERING PARAMETERS FOR FOUR IGNITION TNS TOKAMAK REACTOR SYSTEMS

Summary

The ORNL/Westinghouse program for The Next Step (TNS) tokamak beyond TFTR has examined a large number of potential configurations for D-T burning ignition tokamak systems. An objective of this work has been to quantify the trade-offs associated with the assumption of certain plasma physics criteria and toroidal field coil technologies. Four tokamak system point designs are described, each representative of the TF coil technologies considered, to illustrate the engineering features associated with each concept. Point designs, such as the ones discussed herein, have been used to develop component size, performance and cost scaling relationships which have been incorporated in a digital computer code to facilitate an examination of the total design and cost impact of candidate design approaches. The point designs which are described are typical, however, they have not been individually optimized. The options are distinguished by the TF coil technology chosen and include: 1) a high field water-cooled copper TF system, 2) a moderate field NbTi superconducting TF system, 3) a high field Nb_3Sn superconducting TF system, and 4) a high field hybrid TF system with outer NbTi superconducting windings and inner water-cooled copper windings. Descriptions are provided for the major device components and all major support systems including power supplies, vacuum systems, fuel systems, heat transport and facility systems.

Introduction

An ORNL/Westinghouse design team has been engaged in the study of alternative strategies for a near-term (after TFTR) ignition test reactor, provisionally designated The Next Step (TNS), which could provide answers to the most

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pressing technical feasibility questions associated with ignition. Principal TNS objectives assumed included: 1) demonstration of ignition and burning dynamics, and 2) reactor technology forcing. The selection of an overall design approach for TNS required an early quantitative assessment of the most important design issues, namely, choice of ignition plasma design conditions (principally size and confining field on axis) and choice of toroidal field coil technology (resistive or superconducting windings). The process which led to the selection of the four reference designs included the following elements:

- formulation of a set of study ground rules which would focus on the relative differences in system performance, size, and cost associated with the major design alternatives (as well as provide absolute cost estimates)
- development of system and component point designs and size and cost scaling relationships
- development of a digital computer code, called COAST[1], to integrate subsystem models and generate self-consistent tokamak point design descriptions and cost estimates
- performance of trade and sensitivity studies[2] using COAST
- determination of selection criteria and selection of four reference points

A final step, described in Reference 3, involved a further comparison of the four reference concepts using decision modeling techniques to choose a preferred design approach for the TNS mission.

Basis for Reference Design Point Selection

The process of choosing four "typical" point designs, each representing a candidate TF magnet technology, was complicated by the desire to use these designs for a consistent comparison of the implications of TF technology selection. Simply choosing the minimum cost devices on a global basis was not practical since these devices would tend to have uncomfortably high values of toroidal beta or uncomfortably small plasma column dimensions. The criteria developed were the following:

- ignition via empirical scaling. No margin in $n\tau$ or magnetic field would be provided for in the selection, though, of course, they would be considered in a final design
- plasma minor radius $\geq$ 1 m. While the assumed scaling laws predicted smaller ignition devices at relatively high magnetic fields, some improvement over TFTR plasma dimensions (a = 0.85) was felt to be necessary.
- aspect ratio < 5 - from gross stability considerations
- minimum cost at a fixed toroidal beta of 5%.

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. The achievement of high values of beta will permit the development of relatively compact and potentially less expensive machines, however, current estimates based on linear, ideal MHD stability calculations indicate that the largest achievable β's will be in the range of 5-10%. On this basis it was felt reasonable to use a fixed β of 5% as a common measure of plasma performance, along with the other stated criteria. Each of the devices selected would then be capable of testing high β operation, but successful demonstation of ignition would be predicated on achieving β = 5%.

Reference System Parameters

Table 1 provides an overall summary of the key parameters of the four reference TNS designs selected according to the above criteria. The designs have not been optimized on a total system basis (from either the cost or performance point of view). However, each design is self-consistent and fully delineated in terms of the arrangement, size and/or rating of major components in both the tokamak and the required overall facility. The building and equipment cost shown does not include engineering, design, inspection and administration (EDIA), contingency or escalation. Annual utility cost includes the cost of electricity and tritium fuel. Electricity costs are determined on the basis of total plant energy consumption, which includes all electrical energy conversion losses, resistive and inductive losses and prime movers (pumps, motors, etc.).

Key parameters which are fixed for all options include plasma elongation (1.6) toroidal beta (5%), mean ion temperature (13 keV), Lawson parameter ($\bar{n}_e\tau_E$ = 2.4 x 10^{20} m^{-3} s), number of TF coils (20) and operating scenarios. Figure 1 illustrates the standard operating scenarios assumed in the studies. A plasma burn time of 16 s and a pulse repetition interval of 300 s was fixed for the present comparison, however, these quantities were varied in the associated trade study to establish cost sensitivity.

The total fusion power (based on 21 MeV per reaction) developed by the reference designs ranges from 558 to 795 MW, which seems quite reasonable from the point of view of heat transport and rejection without production of electrical power. Electrical power to operate the experiment is assumed to be provided by a modest link with a utility grid with a motor-generator-flywheel energy storage system to buffer the pulsed electrical loads. Note that the device with Nb_3Sn TF coils is a net energy producer and could provide an early demonstration (with some blanket/shield modification) of electrical power generation.

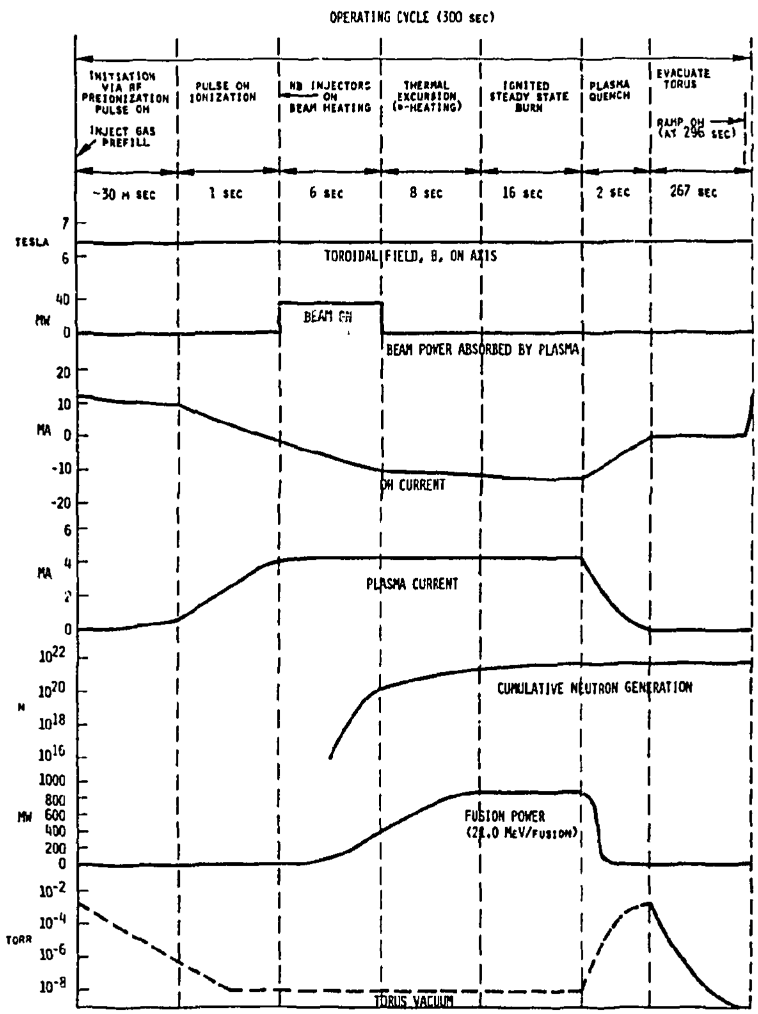

FIGURE 1. THE REFERENCE OPERATING SCENARIO FOR THE TNS OPTION WITH Nb_3Sn TF COILS IS TYPICAL OF THAT ASSOCIATED WITH OTHER OPTIONS.

TABLE 1

COMPARISON OF REPRESENTATIVE PARAMETERS
FOR FOUR TNS POINT DESIGNS

	TNS-1	TNS-3	TNS-4	TNS-5
TF Coil Conductor	Cu	NbTi	Nb_3Sn	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, $\overline{n}_e$ (m^{-3})	1.6×10^{20}	1.3×10^{20}	1.3×10^{20}	1.6×10^{20}
Mean Ion Temperature, $\overline{T}_i$ (keV)	13	13	13	13
Energy Confinement Time, τ_E (s)	1.5	1.8	1.8	1.5
$\overline{n}_e \tau_E$ (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)	126.3	259.2	227.6	142.1
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	57	50	45
Steady State Burn Time (s)	16	16	16	16
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

The TNS with water-cooled copper TF coils is the smallest and cheapest system and is not a very large step up from TFTR in terms of magnet technology. The TNS with Nb_3Sn TF coils is 34% more expensive; however, this design would represent an important step toward the demonstration of reactor technology. The peak field required at the Nb_3Sn winding is only 10.9 T, providing a comfortable engineering margin. We find, in contrast, that the device with NbTi TF coils requires a peak field of 9.9 T, which represents a significant technological and operational risk with little potential design margin. A reduction of the design peak field to 8 T in NbTi would involve a reliance upon operation at a toroidal beta of at least 7.5% and a relatively low toroidal field on axis (4.3 T).

A hybrid TF coil using a water-cooled copper segment in the inner, high field region and an NbTi segment in the outer, low field region was considered since it could provide an opportunity to use and demonstrate a nearer-term superconducting material technology with high field design flexibility provided by the copper insert. As expected, the high field performance flexibility and compactness associated with the all-copper TNS system was attained by the hybrid. However, considerable engineering complexity is associated with the hybrid approach, particularly in the mechanical and electrical design areas.

Reference System Design Features

Cross-sectional views of the four reference TNS devices are shown in Figures 2, 3, 4 and 5 where details associated with the treatment of the toroidal field coils, vacuum vessel and nuclear shielding are indicated. Many of the design features of the four reference systems are similar, therefore, it has been possible to pursue them in some detail.

Vacuum Systems. The vacuum vessels in each design were assumed to be made of 316 stainless steel and formed from beam-stiffened shells with an overall "D"-shaped cross-section. The overall electrical resistance of the structure was felt to be sufficient to obviate the need for high resistance segments such as bellows or ceramic breaks. Vessel cooling is accomplished by a low

REFERENCE TNS WITH COPPER TF COILS

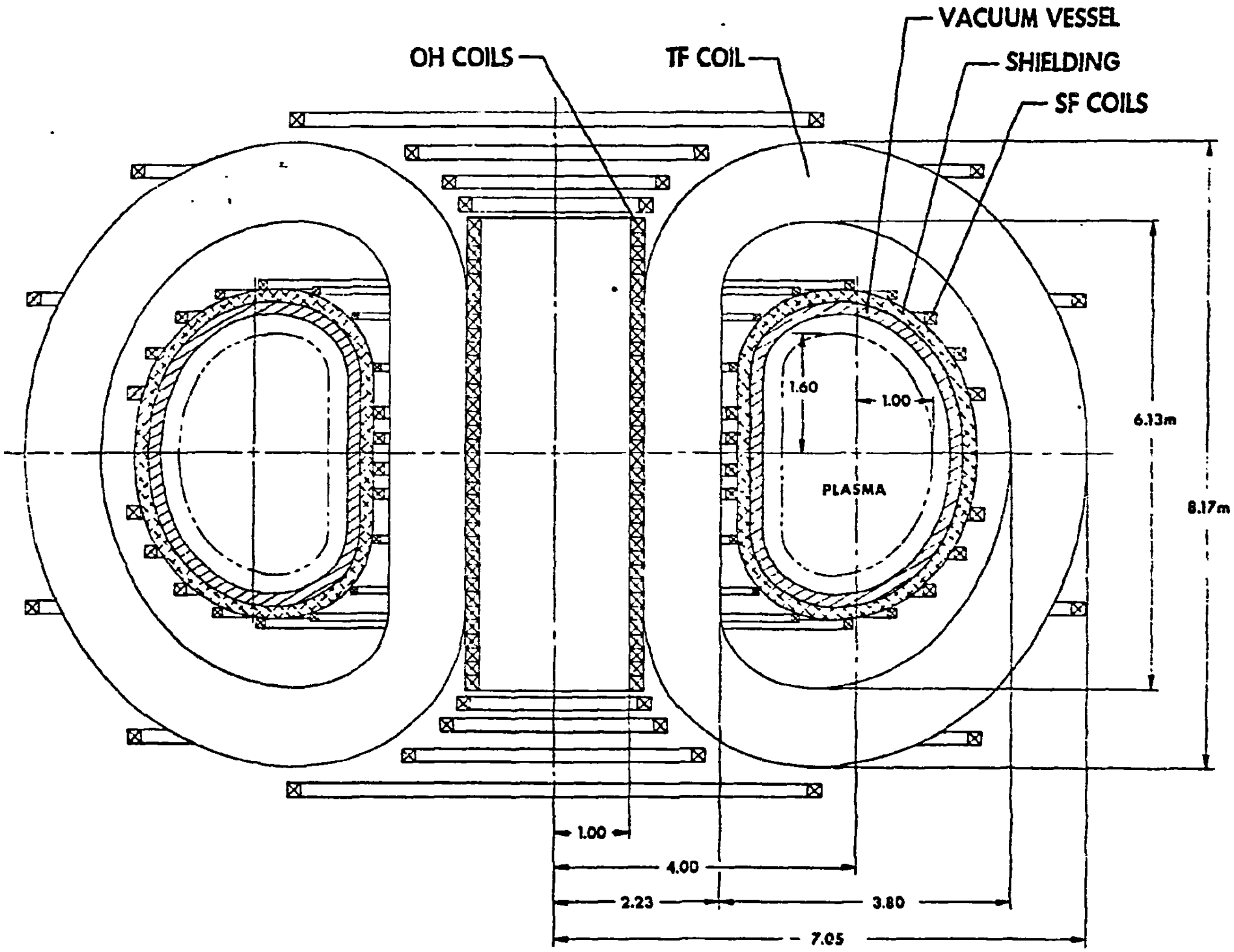

FIGURE 2. REFERENCE TNS WITH COPPER TF COILS

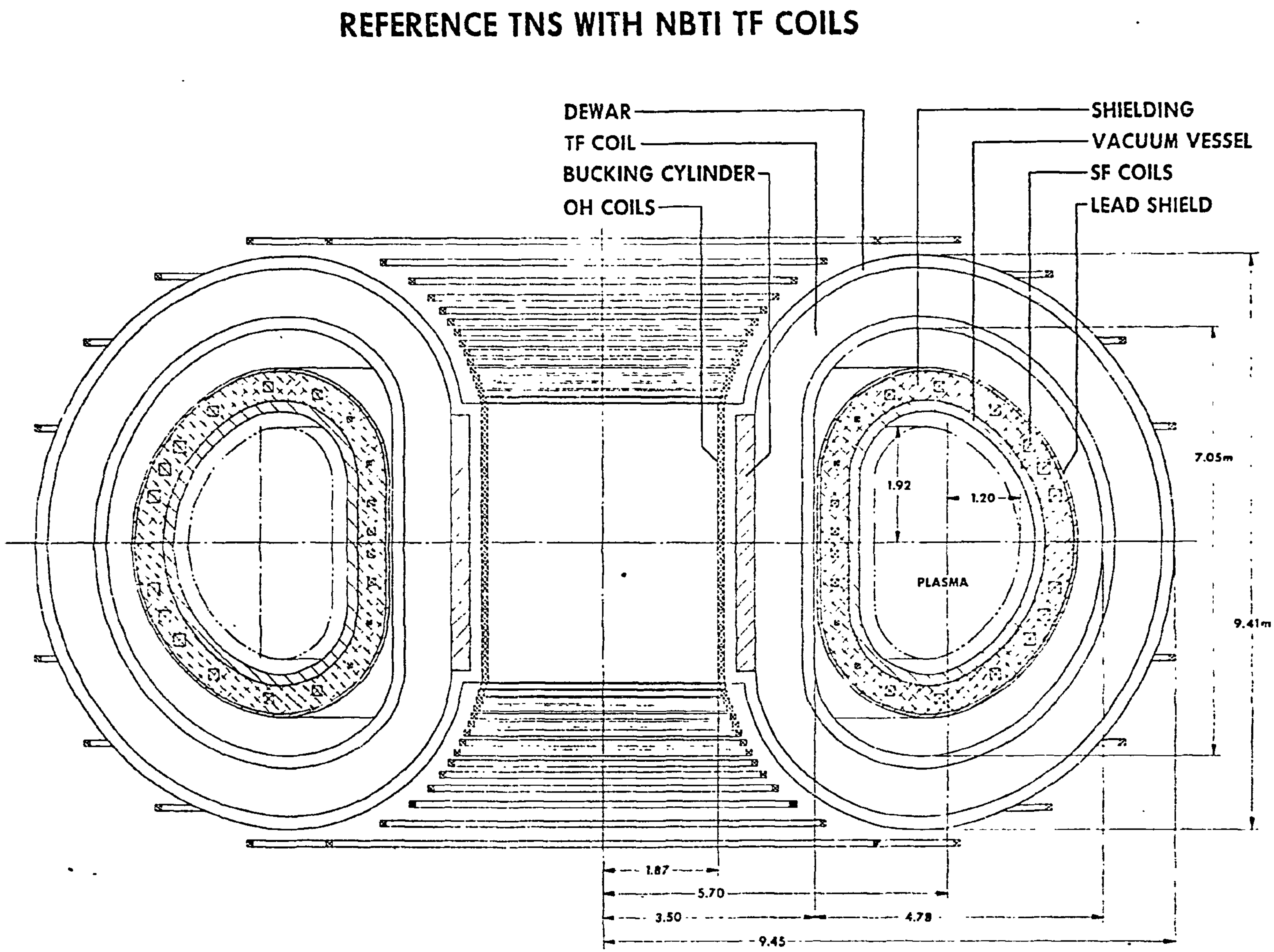

FIGURE 3. REFERENCE TNS WITH NbTi TF COILS

REFERENCE TNS WITH NB_3SN TF COILS

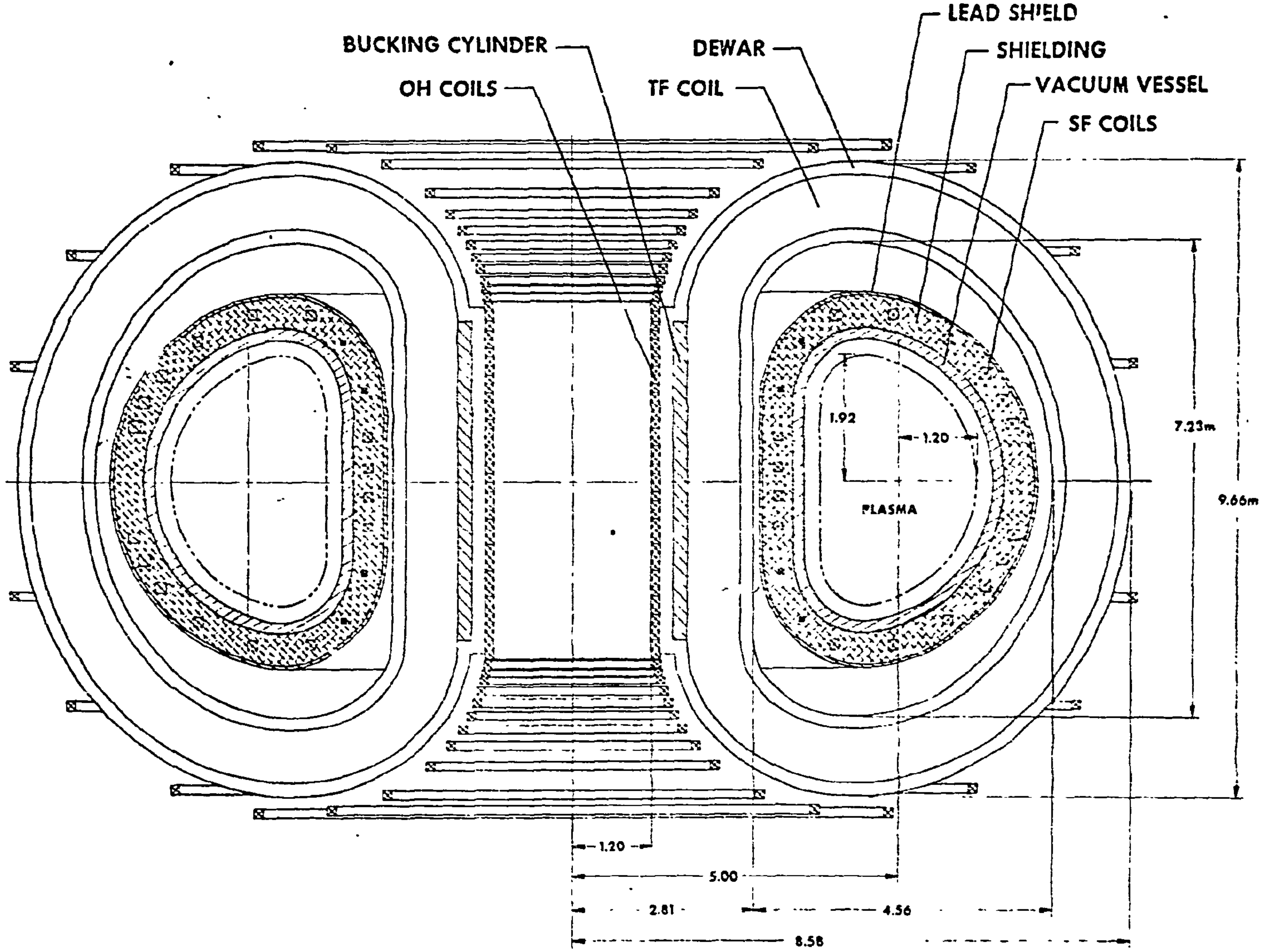

FIGURE 4. REFERENCE TNS WITH Nb_3Sn TF COILS

REFERENCE TNS WITH COPPER/NBTI TF COILS

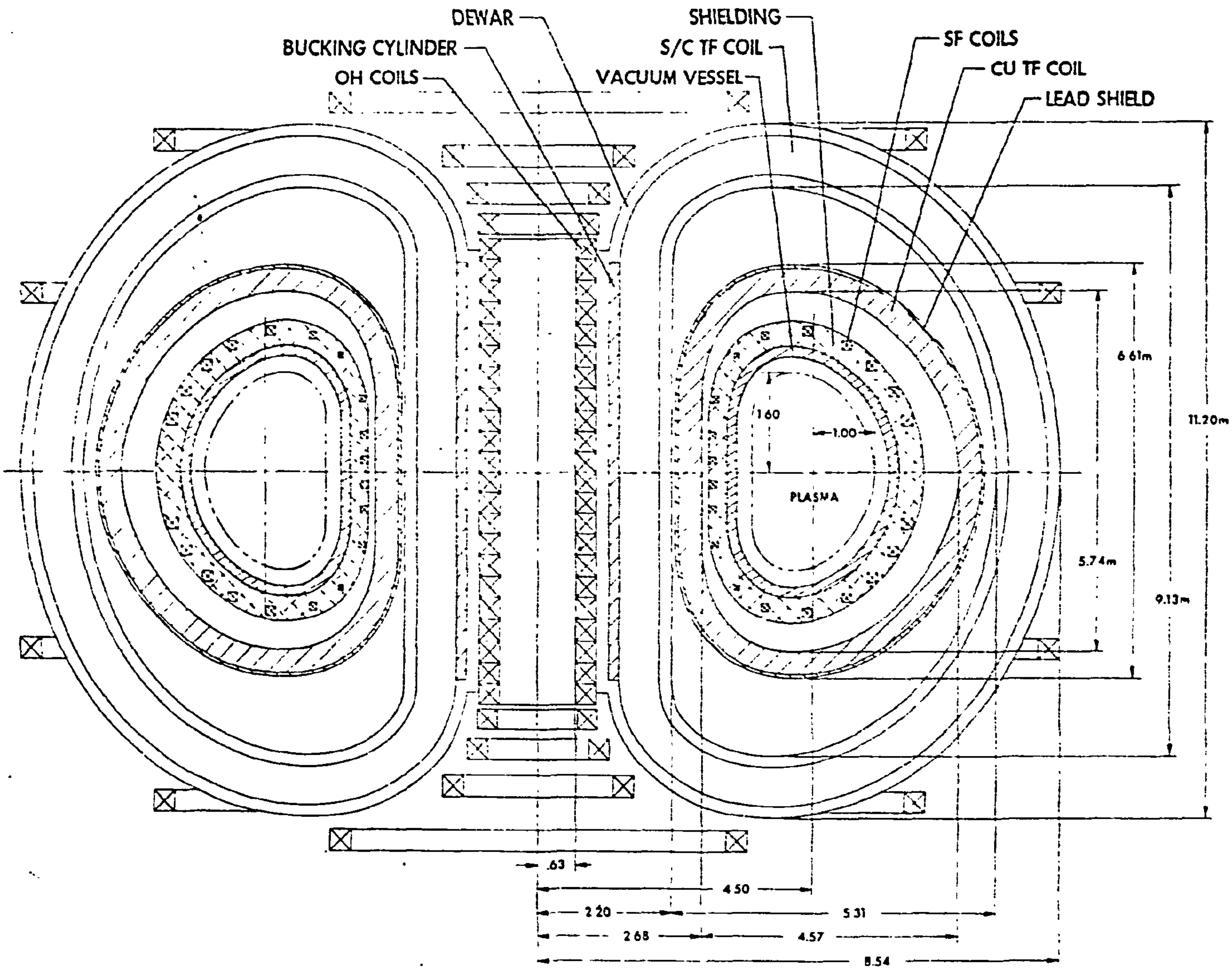

FIGURE 5. REFERENCE TNS WITH COPPER/NbTi TF COILS

pressure water heat transport system designed to limit the peak bulk vessel wall temperature to 400°C. Conventional radiation-cooled tungsten limiters are employed. A cryopumping high vacuum system is specified in each case to provide a torus base pressure of 1×10^{-8} torr.

Impurity Control. Impurity control is assumed to be accomplished by wall treatment and plasma edge control. Associated studies[4] have developed a compact magnetic poloidal divertor concept which could be accommodated, if required, within the available TF bore of each of the reference designs. It is estimated that implementation of the divertor concept would increase the cost of each of the machines by no more than 10%.

Poloidal Field Magnet Systems. The poloidal windings were assumed to be water-cooled copper, with the air core OH solenoid located outside of the TF bore and the equilibrium field (EF) or shaping field (SF) windings located within the bore to facilitate plasma shaping and control. The potential of cost and performance improvement through the use of superconducting windings for the OH solenoid is recognized and should be pursued in subsequent design iterations. Similarly, alternate locations for the EF and SF windings must be examined.

Toroidal Field Magnet Systems. The centering force restraint for the water-cooled copper TF system is implemented by nose-wedging, with the pancake-wound OFHC conductors encased in a steel support structure. Shear panels are employed to react over-turning moments and out-of-plane forces. The superconducting TF system utilizes a low temperature bucking cylinder structure located in a central dewar common to the coil noses. The outer leg of each coil is encased in individual dewars. Forced flow liquid helium cooling is specified for the superconductors. Each coil is designed in the shape of a constant tension "D", regardless of conductor type.

Nuclear Shielding. The limiting shielding constraint in all designs was the requirement to limit the lifetime neutron dose to the electrical insulation on the inner-most poloidal field windings to 10^{10} rads. This shielding was augmented in devices employing superconducting TF coils to limit the total time averaged nuclear heating rate in the conductors to $\leq$ 20 kW. The primary shielding media are lead sheet and borated water-cooled stainless steel balls. Additional concrete shielding is provided in the containment structure associated with each design to limit the annual dose to personnel just outside of the reactor cell to 100 mrem.

Tritium Systems.[5] Tritium is stored in uranium chip beds, coupled to the device for initial fill of gaseous tritium and to a solid-pellet forming and delivery system for refueling. Tritium reprocessing is accomplished by a cryogenic distillation plant operating in a batch feed mode. Helium separation is accomplished by permeation-diffusion.

Electrical Power Systems.[6] Power for superconducting TF coils is provided by a line-driven three-phase controlled rectifier on a continuous basis. Copper TF coils are supplied by a pulsed ac motor-generator-flywheel system and a three-phase rectifier. The hybrid TF system requires two independent power supplies to maintain fixed current superconducting coil operation while the copper coil is pulsed. The poloidal field coils and neutral beam systems are powered by motor-generator-flywheel sets and appropriate pulsed power rectification and switching systems. A common instrumentation, control and diagnostics system is assumed for all designs.

Heat Transport Systems. A single evaporative cooling tower, consisting of multiple mechanical draft cells sized according to the requirements of each reference design is provided to reject all plant heat loads to the atmosphere. A common approach is taken in all designs for the vacuum vessel, shield and poloidal field coil water cooling systems. Where superconducting TF coils are involved, liquid helium and liquid nitrogen refrigeration and heat exchange systems are defined.

Plasma Heating. Positive ion-neutral beam injection systems are defined with a fixed peak energy requirement of 150 keV and power adjusted to the needs of each design. Space has been provided in terms of vessel apertures and installation and maintenance areas in the reactor cell. A shielded duct space of 40 cm x 90 cm high has been provided for each neutral beam arm. Near-perpendicular injection has been assumed.

Plant Facilities. Each reference design consists of a complete stand-alone facility with equipment and structures provided for assembly, remote maintenance, radioactive waste storage and disposal, electrical power distribution and control, neutral beam maintanance, central control, shops, and support laboratories.

Comparison of Reference System Cost Estimates

A breakdown of the overall cost estimates for buildings and equipment for each of the four point designs is shown in Table 2. As a consequence of the common facility and support systems ground rules assumed the principal differences in the cost estimates are due to TF coil technology requirements. The cost of the Tokamaks with NbTi and Nb_3Sn conductors is balanced by the increased cost of structure associated with the lower current density NbTi windings. As expected, the two systems employing copper TF coils exhibit high electrical power systems costs due to the need to provide large amounts of stored energy. The three systems with superconducting windings have considerably higher tokamak support systems costs compared to the copper system due to the large cryogenic refrigeration systems required. The Nb_3Sn system fares much better than the systems employing NbTi superconductors due to its favorable thermal margin at the design point chosen.

Conclusions and Recommendations

The TNS trade studies and the development of four reference TNS designs have provided an important framework for the extension of this work toward the definition of a practical ignition test reactor. The design embodiments described in this paper have not been optimized, however, they are representative

TABLE 2

COST ESTIMATE COMPARISON FOR FOUR TNS POINT DESIGNS

SYSTEM	COPPER TF	NbTi TF	Nb_3Sn TF	COPPER/NbTi TF
Tokamak System	79.3M$	202.1M$	199.1M$	163.0M$
Electrical Power Systems	94.6	29.8	35.9	99.4
Tokamak Support Systems	48.8	118.2	76.1	100.1
Structures and Site Services	31.5	35.2	34.1	34.7
Neutral Beam Systems	34.5	49.1	43.1	38.8
TOTAL	288.7 M$	434.4M$	388.3M$	436.0M$

of what can be expected for the TNS mission in terms of system size and cost given our present understanding of plasma physics and the state of toroidal field coil technology. A detailed assessment(3) of the generic implications of TF coil technology selection leads us to conclude that the reference tokamak system design with Nb_3Sn TF coils is the preferred configuration for TNS.

During the process of developing the four reference TNS designs which have been discussed, future design priorities have been identified, particularly for the recommended TNS Nb_3Sn baseline device. Some of the most important design issues are:

- integration of the compact poloidal divertor assembly design into the total system
- examination of the benefits/risks associated with the incorporation of superconducting poloidal field coils
- development of a plasma refueling subsystem design concept
- further development of design details associated with the TF coil-dewar-device interface

While there is room in the reference design approach for engineering improvement the potential for significant reduction in cost is not considered great unless 1) operation at high β or very high toroidal field is shown to be feasible, and 2) the mission objectives for TNS are relaxed. If the principal goal of TNS is to achieve ignition in the shortest possible time frame, variants of the copper TF TNS design discussed herein offer the greatest chance of success. A preliminary examination of this possibility leads us to estimate that total hardware costs in the vicinity of 200M$ appear to be attainable for a TNS with the following features:

- liquid nitrogen cooled copper TF system
- short ($\sim$ 5 s ignited burn)
- moderately high field ($B_T \sim 10$ T)
- no on-site tritium processing

Acknowledgement

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References

1. D. A. Sink and E. M. Iwinski, "A Computer Code for the Costing and Sizing of TNS Tokamaks", Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research, October, 1977.

2. D. L. Chapin, et al, "Trade Study Analysis for TNS Tokamsks", Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research, October, 1977.

3. H. R. Howland and T. C. Varljen, "An Approach to Decision Modeling for an Ingition Test Reactor", Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research, October, 1977.

4. T. F. Yang, et al, "A Compact Poloidal Divertor Reference Design for TNS", Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research, October, 1977.

5. H. J. Garber and J. S. Watson, "Tritium Systems Preliminary Design for TNS," Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research, October, 1977.

6. F. M. Heck, et al, "TNS Electrical System Design Considerations," Proceedings of the Seventh Symposium on Engineering Problems of Fusion Research, October, 1977.