Sh. 147

ORNL/TM-6201

MASTER

Oak Ridge TNS Program: Context, Scope, and Baseline Design of the FY 1978 Activities

D. Steiner
T. G. Brown
T-K. M. Peng
R. L. Reid
M. Roberts
T. E. Shannon
P. T. Spampinato

OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION · FOR THE DEPARTMENT OF ENERGY

ORNL/TM-6201
Dist. Category UC-20d

Contract No. W-7405-eng-26

FUSION ENERGY DIVISION

OAK RIDGE TNS PROGRAM: CONTEXT, SCOPE, AND BASELINE DESIGN OF THE FY 1978 ACTIVITIES

D. Steiner
T. G. Brown
Y-K. M. Peng
R. L. Reid
M. Roberts
T. E. Shannon
P. T. Spampinato

Date Published: May 1978

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

CONTENTS

LIST OF FIGURES

Figure

LIST OF TABLES

ABSTRACT

A status report on the Oak Ridge TNS Program has been prepared with three basic parts — a summary of the FY 1977 activities, a discussion of the current baseline design, and a statement of work tasks for FY 1978. Within the FY 1977 activities, the plasma engineering efforts were directed toward improving the economical performance of tokamak reactors and toward easing the requirements placed upon the supporting technology development programs. The FY 1977 systems modeling efforts were used to develop comprehensive systems models for cost comparison of different toroidal field (TF) coil technology options. The FY 1977 program planning tasks provided a draft program plan with both an R&D assessment and schedule considerations. On the basis of these activities, the FY 1978 effort is being directed toward initiation of preconceptual design.

The current baseline design, characterized by key parameters and overall layout drawings, is being developed from the FY 1977 activities as a starting point for the FY 1978 preconceptual design study tasks. The projected performance of the baseline design as an ignited and burning primitive fusion reactor facility is being developed through self-consistent plasma engineering calculations using 0-D, 1-D, and 1-1/2-D models. A set of pertinent work tasks for the FY 1978 effort has been developed from a systematic analysis of the status of each subsystem.

ACKNOWLEDGMENTS

The technical and engineering studies that underlie the conclusions and work tasks outlined in this document were performed by the Oak Ridge TNS Program Staff including members of the ORNL technical staff, UCC-ND Engineering Organization, Westinghouse Electric Corporation, and other key industrial participants. In particular, the trade studies reported in Sect. 3 were performed with the strong support of the Westinghouse Fusion Power Systems Department (WFPS). The baseline design work in Sect. 4 based upon the WFPS modeling was performed by the UCC-ND Fusion Reactor Engineering Department. The work breakdown structure in Sect. 4 was developed by W. B. Wood. The projected operating parameters of the baseline design, Sect. 5, were based on work performed by the Plasma Engineering Group of the Plasma Theory Section.

1. INTRODUCTION

The purpose of this document is to summarize the context and scope of the Oak Ridge TNS program for FY 1978. The Next Step (TNS) program established by DOE's Division of Magnetic Fusion Energy at ORNL in early 1976 has two principal objectives:

(1) to implement in the next decade a facility with a fusion reactor core that can be extrapolated to an economically viable fusion reactor, and
(2) to provide a near-term means of focussing the efforts of the national fusion program toward achievement of the first objective.

During the FY 1977 period, the Oak Ridge TNS program pursued these objectives through efforts in three broad areas:

(1) plasma engineering,
(2) systems modeling, and
(3) program planning.

The major results of the FY 1977 activities are summarized in Sect. 2.

Based upon the findings of the FY 1977 efforts, it has been judged that continued activities in the Oak Ridge TNS program should be directed toward preconceptual design with particular emphasis placed on engineering feasibility. As a point of departure for the FY 1978 activities, we have selected a baseline design based on the efforts of last year. The rationale for the design selection is discussed in Sect. 3, an engineering description of this design is presented in Sect. 4, and the projected operating parameters are reported in Sect. 5.

As noted above, in FY 1978 the emphasis of the Oak Ridge TNS program will shift from systems modeling to an integrated preconceptual design effort including the ongoing activities in the areas of plasma engineering and program planning. The baseline design represents both the culmination of the FY 1977 activity and the starting point for the FY 1978 preconceptual design activity. A principal objective of the FY 1978 Oak Ridge TNS effort will be to begin the development of a preconceptual design from the baseline design. This objective is reflected in the work tasks which have been developed for consideration in FY 1978. These work tasks are described in Sect. 6.

2. SUMMARY OF THE FY 1977 PROGRAM

The purpose of this section is to summarize the major features and results of our FY 1977 TNS activities. In order to place our TNS program in perspective, it is useful to consider the evolution of our advanced systems studies. Our prior advanced systems studies started with point designs (F/BX I and II),[1] explored the design issues of the tokamak EPR (scoping studies),[2] and culminated in an evaluated EPR reference design.[3] With this basis, the TNS activities were directed toward characterizing the design space between TFTR and EPR with a fundamental emphasis on higher beta plasma systems than previously projected, i.e., $\bar{\beta} \sim$ 5-10% as compared to 1-3%. The orientation toward smaller sized, higher beta systems rather than larger systems at the lower beta has come from an engineering judgment that the larger systems are both mechanically and economically impractical. This judgment was quantified in our Fusion Power Demonstration Study.[4] The characterization of this TFTR-EPR design space has proceeded by plasma engineering investigations of the dynamics of the higher beta plasmas and the requirements on technology of heating and fueling,[5] by developing consistent, feasible engineering models of systems of different size and magnetic field strength,[6] and by program planning studies of the steps required to implement the designs.[7]

In the first area, plasma engineering, early indications were that very stringent requirements were to be placed on physics achievements (i.e., $\bar{\beta} \sim$ 10-15%), on beam technology (i.e., ~500 keV), on fueling technology (i.e., ~10,000 m/s pellet velocities to reach the plasma center), and on a large system size.* Rather than pursue these difficult requirements with even more difficult technology development programs, high risk

---

*A "conventional" poloidal divertor was found to distort the nominal TF coil dimension by at least one-third causing a strong psychological, if not real, handicap in considering the scale-up from LCP to this overlarge coil.

physics or high cost solutions, we reexamined the basis for the requirements. We found that as more realistic models of the higher beta plasma are used, specifically going from 0-D to 1-D models with spatial profiles, the lower the requirements became on achievable beta, neutral beam energy, and fueling technology. Under the constraint of a fixed, no-divertor TF coil shape, an innovative design concept for a compact poloidal divertor was developed. The design of the divertor can have significant impact on the options available to plasma engineers.[8]

In the second area, systems modeling, the principal questions asked were, "What is the cost variation with size?" and "How does cost depend upon the TF coil technology used?" Based upon fairly comprehensive engineering models as opposed to optimized point designs, curves of relative cost vs the principal geometric and operating characteristics have been produced. With the costing and sizing model,[9] the cost sensitivity to any of the assumptions can be investigated and modifications made. With respect to the second question, impact of TF coil type, the result was that the principal differences between the use of superconducting and copper coils were those of objectives and risks, and not of cost alone. These differences and the relative costs for the Cu, Nb_3Sn, NbTi, and a concentric hybrid arrangement of NbTi/Cu options were roughly as shown in Table 2.1.

Table 2.1 Approximate, relative, total plant costs of four systems with different TF coil options

Coil type	Cu	Nb_3Sn	NbTi	NbTi/Cu (hybrid)
Approximate relative cost	1	1.3	1.5	1.5
Most suitable objective	Ignition alone	Reactor prototype	Reactor prototype for $\beta > 5\%$	Reactor prototype not dependent upon Nb_3Sn

With respect to the longstanding question concerning the differences between a NbTi and a Nb_3Sn system, a closer examination of similar physical devices indicated that the balance of plant is the dominant factor and that the high technology questions of the tokamak device are of great concern but have little quantified economic impact.

In the third area, program planning, various elements of a preliminary program plan were initiated[7] that identified the central programmatic questions. An assessment of both the generic and design-specific R&D needs for TNS was made. Recommendations for more emphasis on existing programs and for new initiatives were made and documented.[10] Planning schedules for integration of the TNS project with the supporting R&D work and the subsequent reactor devices were also developed.[11] It was concluded that plasma physics and decision making are probably the true critical paths, and that a route to achievement of improved engineering reliability must be laid out and implemented for a successful program.

Based upon the findings in these three areas, it is judged that continued activities in the Oak Ridge TNS program be directed toward preconceptual design with particular emphasis placed on reducing the plasma engineering requirements through innovations and refinements in the calculations, on making cost reductions, and on achieving increased engineering feasibility. This represents a shift in emphasis from systems modeling to preconceptual design with improved integration of the plasma engineering and program planning activities.

3. RATIONALE FOR THE SELECTION OF THE BASELINE DESIGN

In order to initiate the preconceptual design effort, a baseline design has been selected on the basis of the FY 1977 efforts. The purpose of this section is to examine the rationale of the selection process.

3.1 PARAMETRIC TRADE STUDIES

A series of parametric studies was performed by Westinghouse Fusion Power Systems Department as part of the ORNL/W TNS team to evaluate consistently the relative costs and performance parameters of D-T burning tokamaks over a range of plasma sizes and TF coil technologies. Four different types of TF coil technologies have been investigated:* water-cooled copper coils (TNS-1), superconducting NbTi coils (TNS-3), Nb_3Sn coils (TNS-4), and a "hybrid" coil arrangement (TNS-5) consisting of a normal conducting Cu coil nested within a superconducting NbTi coil. To limit the set of distinctly different options satisfying the TNS objectives to a reasonable size, it was concluded that plasma size (a measure of cost and flexibility) and TF coil technology (representing the widest range of key technology options) were the most important characteristics to investigate in the initial trade studies.

In performing these trade studies for TNS tokamaks in a consistent way to develop data suitable for a comparison of respective costs, complexity, risk, and availability, certain engineering groundrules were established. These included constant-tension D-shaped coils, water-cooled copper poloidal field (PF) coils located within the TF coil bore, and auxiliary plasma heating by neutral beams.

The device sizes considered in these trade studies covered a range in the plasma minor horizontal radius, a, from $\sim$0.75 m to 2.0 m, spanning the range of TFTR size plasmas to those chosen for recent EPR design studies. The device major radius, R, was varied from $\sim$8-9 m down to some lower limit ($R \sim 4.4$ m for $a = 0.9$ m, to $R \sim 6$ m for $a = 2$ m) which was consistent with the groundrules and still allowed a viable engineering design. The average 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 of $\sim$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.

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 through detailed treatment of all major components of the total plant.

---

*An early option called TNS-2 was defined as a hydrogen fueled, NbTi TF coil device to be used as a comparison with TNS-3, the D-T fueled NbTi TF coil device. After a clarification of program objectives, TNS-2 was not pursued further.

3.2 TECHNICAL RESULTS

In these studies, we determined that for each coil technology and plasma beta at ignition, there is some minimum cost device at a specific a, R, and B_m (maximum magnetic field strength at the coil) (Fig. 3.1). Beyond the particular numerical values of the cost estimates generated, which should be used more as comparative values than absolute values, there are two striking features. The first is that an increase in average beta from a value of about 3% to a value of about 10% results in a reduction in overall plant cost of about a factor of two in each case. The second is that the requirement of a heat shield in the three designs including superconducting coils results in an increase in an overall cost of about 50% above the comparable copper coil case at a fixed plant cost.

Beyond these principal differences, one can address the reasons for the slight cost difference between NbTi and Nb_3Sn devices (Table 3.1) for a typical machine with a = 1.2 m, R = 5.0 m, and B_m = 9.0 T. Note that the TF coil conductor cost is larger for the Nb_3Sn device than the NbTi device, as expected; however, the TF coil structure cost is larger for the NbTi device because its radial build is larger due to its lower current density limitation. The main cost item difference is in the liquid He refrigeration costs, which are about twice as high for the NbTi device due to its lower thermal operating margin. The most important finding of this particular cost comparison, however, is that the balance of plant overwhelmingly dominates the total cost, and risk aside, it makes the technological differences between NbTi and Nb_3Sn devices insignificant from a cost point of view.

Representative parameters and costs for four TNS point designs that achieve ignition at an average beta of 5% are given in Table 3.2. The maximum field at the TF coil for each design is about 10-11 T; this requires the NbTi superconductor to be designed to operate below 4 K and permits a Nb_3Sn design at a modest maximum field value. A NbTi superconducting design which would operate with a maximum field at the TF coil of 8 T would require either a larger size at the same $\bar{\beta}$ = 5% with an attendant cost increase of ∿25%, or would require operation at the increased average beta value of ∿7.5% in devices of the size in Table 3.2.

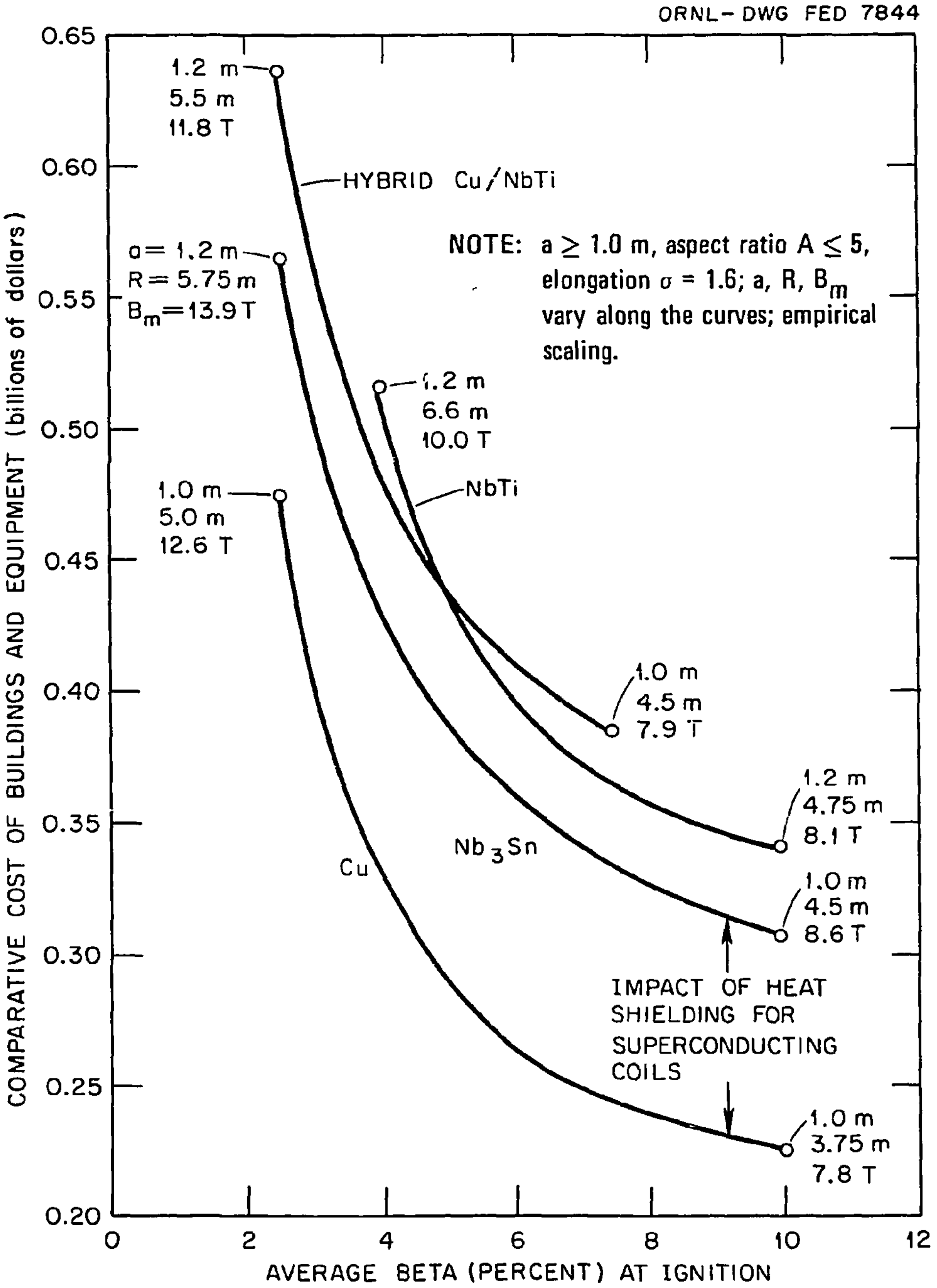


Fig. 3.1. The minimum cost devices for four TF coil technologies vs average plasma beta at ignition.

Table 3.1 Comparison of costs for similar NbTi and Nb_3Sn TF coil based devices indicating overwhelming role of balance of plant

	Costs in millions of dollars		
	NbTi TF coil option	Nb_3Sn TF coil option	Difference of NbTi less Nb_3Sn costs
• Selected TF coil related costs			
Conductor*	24	37	-13
Structure & dewar	61	55	6
Refrigeration	50	23	27
Subtotal	135	115	20
• Balance of plant	235	233	2
Total cost	370	348	22

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

3.3 SELECTION OF Nb_3Sn BASED SYSTEM FOR REACTOR APPLICATION

For a chosen plasma beta operating value, two main conclusions seem possible as the best choice for a tokamak TNS depending upon the perceived objective. If the main goal of TNS is to demonstrate ignition with a minimum of technology development in the shortest time, then water-cooled copper coils at moderate field strengths (10-11 T) and with moderate physics demand seem the best choice, assuming $\bar{\beta} \sim 5\%$. In addition to ignition, the goal of TNS is demonstration of the sciences and technology required for reactors, i.e., sustained burn dynamics, beam power handling, and systems integrated superconducting coils which would extrapolate to a power reactor; then, the Nb_3Sn TF coil devices seem the best choice at a cost about 30% higher than for the copper device. The lower field NbTi devices generally result in larger and more expensive devices, as do the more complex hybrid NbTi/copper options, and hence are not as attractive as the copper or Nb_3Sn. The choice of Nb_3Sn would imply an associated technological risk, although the benefits of its higher field capability and larger

Table 3.2 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	5.3
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	55	52	44
Plasma volume, V_p (m^3)	126.3	259.2	227.6	142.1
Neutron wall load (MW/m^2)	1.5	1.3	1.3	1.5
Total fusion power (MW)	560	800	700	630
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
PACE cost ($M)†	290	435	390	435
Relative cost	1.0	1.5	1.34	1.5
Annual utility cost ($M)	4.1	3.0	2.0	3.4

*A parameter of considerable interest for demonstration of positive energy balance (see Sect. 3.3).

†Plant and capital equipment.

issues, no one of which has yet been dealt with satisfactorily. An attempt to quantify[12] these judgmental issues has resulted in support for the qualitative conclusions discussed in this work.

Table 3.3 The important cost factors are many more than capital cost alone

Quantifiable	Semiquantifiable[b]
Capital cost[a]	Mechanical complexity
Operation cost	Technical risk
Size	Assembly/maintenance
Performance	Operational flexibility
Schedule	Cost/schedule risk
	Reactor technology
	Extrapolatability

[a] Principal target in FY 1977 ORNL/W TNS study.[6]

[b] First attempts at quantification made in FY 1977 ORNL/W TNS Study.[12]

4. ENGINEERING DESCRIPTION OF THE BASELINE DESIGN

4.1 SYSTEMS DESCRIPTION

The purpose of this section is to provide an engineering description of the baseline design based upon the TNS-4 model. Layouts of the overall tokamak mechanical configuration have been developed and are discussed below. Some of the system parameters generated by the COAST computer code are listed in Table 4.1.

Using the TNS Project Work Breakdown Structure[13] (Fig. 4.1), the major project hardware systems have been organized into a matrix to summarize the baseline technology. The baseline design summary description is given in this matrix format in Table 4.2. The major tokamak systems are

Table 4.1 Some system parameters of the baseline design

Number of TF coils	20
TF coil conductor	Nb_3Sn
TF coil vertical bore (m)	7.6
TF coil horizontal bore (m)	4.9
Plasma minor radius, a (m)	1.2
Plasma major radius, R (m)	5.0
Plasma elongation, δ (-)	1.6
Aspect ratio, A (-)	4.2
Field at TF coil, B_m (T)	10.9
Field on axis, B_t (T)	5.3
Plasma current, I_p (MA)	4.9-5.6*
Total volt-seconds	52
Plasma volume, V_p (m^3)	230
Neutron wall load (MW/m^2)	1.3
Total fusion power (MW)	700
Fusion power density (MW/m^3)	2.6
Neutral beam power (MW)	50-75
Steady-state burn time (s)	16
Time between pulses (s)	300
Shielding	Stainless steel balls with borated water
Divertor	Westinghouse compact poloidal design†
Neutral beam injectors	5 @ 150-200 keV
HV pumping	Cryopumps
Fueling	1 pellet injector

*I_p determined through MHD equilibrium calculations of D-shaped FCT plasmas.

†Ref. 8.

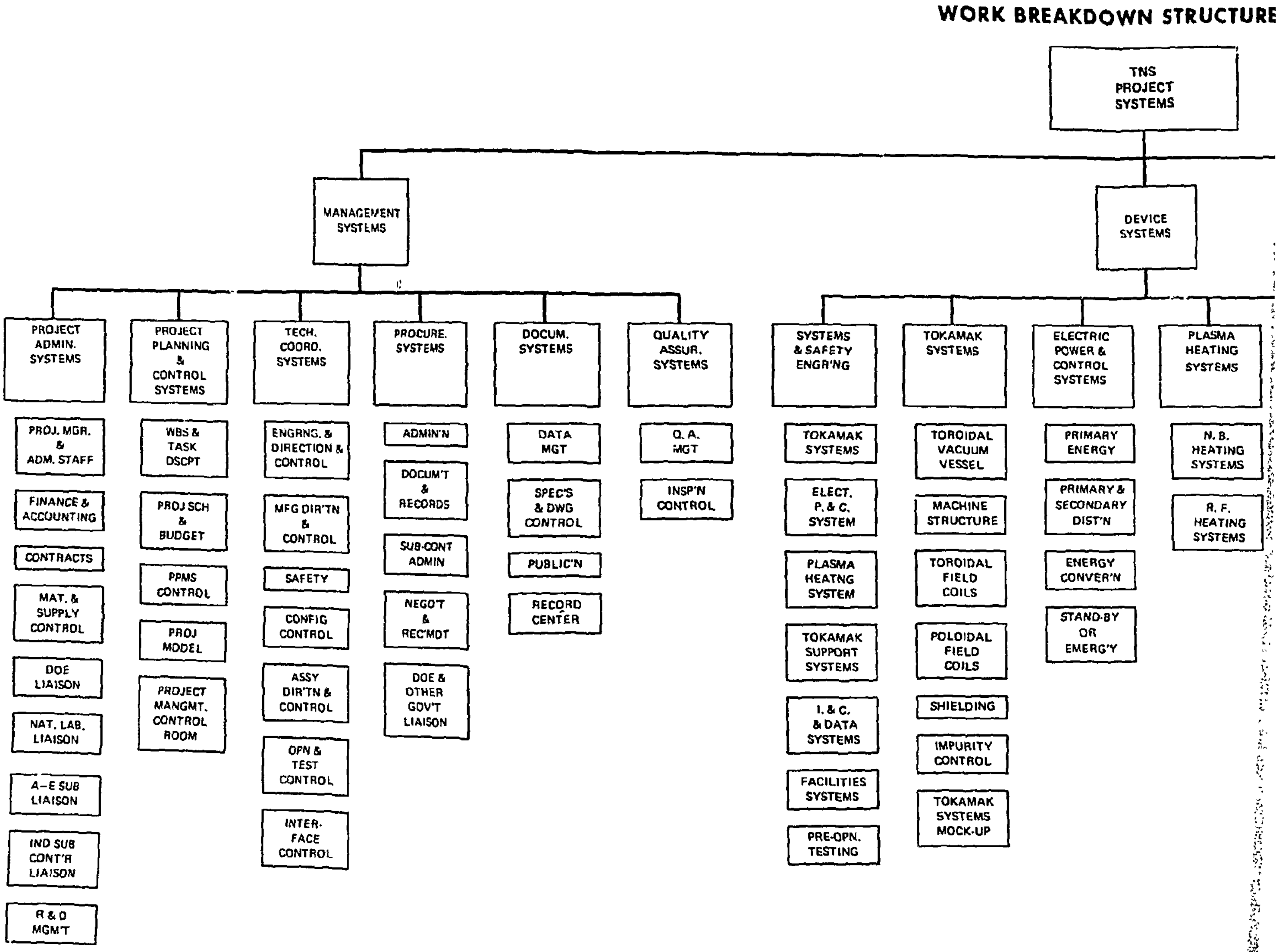
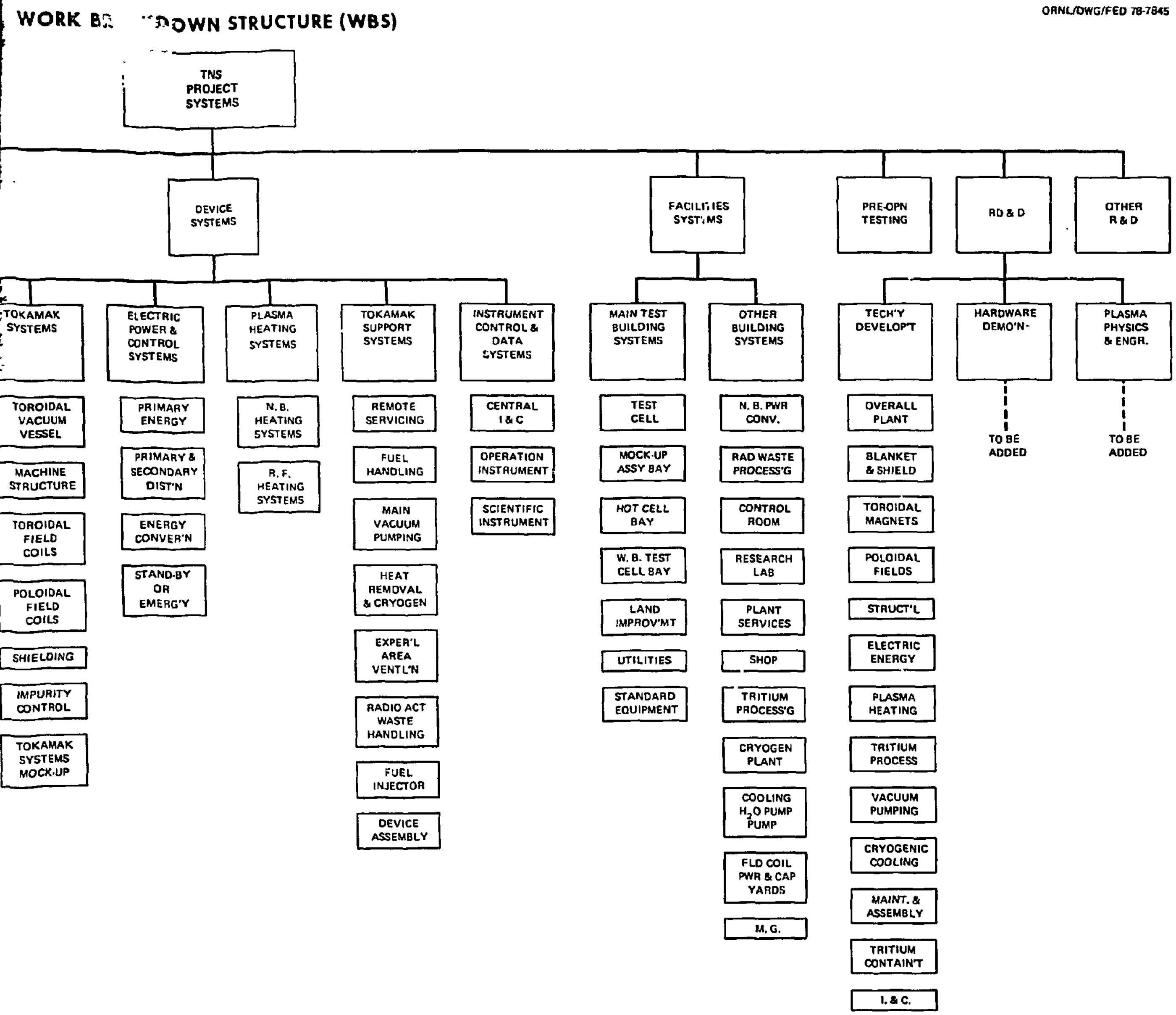


Fig. 4.1. Work breakdown

BLANK PAGE



ig. 4.1. Work breakdown structure.

Table 4.2 Systems matrix for the TNS baseline configuration

WBS No.	System (or Subsystem)	Baseline technology	Comments
21	Systems engineering	Existing codes (COAST et al.)	Existing code is tailored to the FY 1977 design configuration
22a	Toroidal vacuum vessel	*D-shaped structure with integral divertor chambers and integral shield modules*	Structural discontinuity at divertor and insufficient shielding around chamber
22b i	Machine structure	Stainless steel welded construction	Material activation and structural determinacy are forcing functions
ii	TF coil support	Supports are integral with segmentation concept	Supports must be cryogenically cooled
iii	Intercoil panels	Designed for single-coil fault condition	Panels must be cryogenically cooled
iv	Central TF coil support	Reacts centering forces with no coil wedging	Cylinder required relocation of several PF coils
v	Central dewar	Common dewar interfaces with individual coil dewars	Dewar interface is extremely difficult to disassemble
22c i	TF coils	Twenty Nb_3Sn coils; forced flow maximum field 10.9 T; similar to Westinghouse LCP design	Maximizing access between coils benefits shielding of major penetrations
ii	TF coil dewars	Individual dewars interface with common central dewar	Intercoil attachments require major dewar penetrations

Table 4.2 (continued)

WBS No.	System (or Subsystem)	Baseline technology	Comments
22d	PF coils	Air core concept using water-cooled copper coils	Disassembly of lower OH coils and EF coils in shield is extremely difficult
22e	Shielding	Stainless steel modules with borated water	Shield is integral with toroidal vacuum vessel
22f i	Liner-limiter	Separately cooled TZM liner; no limiter	No need for limiters is assumed with divertors
ii	Divertor	Compact poloidal concept	Vertical bore of TF coil does not provide sufficient divertor shielding
23a	Primary energy storage	Motor-generator flywheel is the buffer to the grid source	Energy requirements may be reduced with the iron core and new start-up concepts
23b	Primary & secondary distribution	Available commercial switching equipment is assumed	Experience gained from TFTR will be incorporated
23c	Energy conversion	This equipment is assumed to exist for the PF & TF systems	May not be available as commercial equipment
23d	Emergency standby	Assumed to be commercially available	The details of this system are dependent on WBS No. 23b
24a	Neutral beam injection	Five injectors; 50 ∿ 75 MW; 150 ∿ 200 keV	Injector units contain three sources
24b	RF heating	Not included in baseline	May relax N.B. requirements

Table 4.2 (continued)

WBS No.	System (or Subsystem)	Baseline technology	Comments
25a	Remote servicing	Components within the device envelope will be remotely handled	Remote disassembly/assembly is the basis for the mechanical configuration
25b	Fuel handling	On-site tritium processing for plasma exhaust	Current technology satisfies baseline criteria
25c	Main vacuum pumping	Cryopumps operated from divertor chamber	Wherever possible, pump ducts are common to beam line ducts
25d	Heat removal and cryogenics	The PF coils and the vacuum vessel/shield are water cooled; cooling towers are the ultimate heat sink; the TF coils and the HV pumping require LH_e with LN_2 barriers	LCP development of refrigeration systems will be the basis for TNS
25e	Experimental area ventilation	Standard reactor cell ventilation	Use of a vacuum building concept would impose additional requirements
25f	Radioactive waste handling	Specific waste handling systems have not been specified	Current handling technology will not impose any design restrictions on TNS
25g	Fuel injector	One unit for pellet fueling; similar to ORNL prototype, 900 m/s	Centrifugal fuelers may be limited to <3000 m/s (ORNL/TM-6026)
25h	Device assembly	The continuing work will emphasize assembly/disassembly problems	Disassembly of the vacuum vessel/shield, dewars, PF coil joints, and the central TF keyway support have not been addressed yet

Table 4.2 (continued)

WBS No.	System (or Subsystem)	Baseline technology	Comments
26	Instrumentation control and data acquisition	Conventional tokamak instrumentation and control is assumed	Instrumentation and control and diagnostics may impose additional requirements on the remote servicing systems
31 & 32	Buildings and facilities	Conventional reactor test facility is assumed	A vacuum building approach would represent significant departure from conventional reactor test facilities

described at the fourth level (Equipment Systems) and the facility systems are defined at the third level (Building Systems).

As would be expected, the computer generated design parameters do not provide a fully consistent design considering the constraints of mechanical/structural design, assembly, and maintenance. There were no significant modifications made to the reference parameters to improve the mechanical design. Major unresolved design issues are listed in the comments of Table 4.2.

The baseline design will be used as the point of departure for the FY 1978 preconceptual design effort. The design will be modified, as required, to reflect the results of the engineering/plasma physics studies. Alternate design concepts to be considered in the FY 1978 tasks are described in Sect. 6.

4.2 DESIGN DRAWINGS

The baseline design is presented in three layout drawings as follows.

4.2.1 TNS Baseline Configuration — Typical Section (Fig. 4.2)

In this elevation view of a typical cross section, details of the radial build and overall toroidal chamber are shown. The overall TF and PF coil system geometry is illustrated in this drawing. Details of the compact poloidal divertor, shielding, and major penetrations are shown.

4.2.2 TNS Baseline Configuration — Plan (Fig. 4.3)

The TNS plan view best illustrates the overall structural configuration and the arrangement of the neutral beam injectors, vacuum pumps, and fuel injector. A typical one-tenth segment is also shown in the process of removal or assembly.

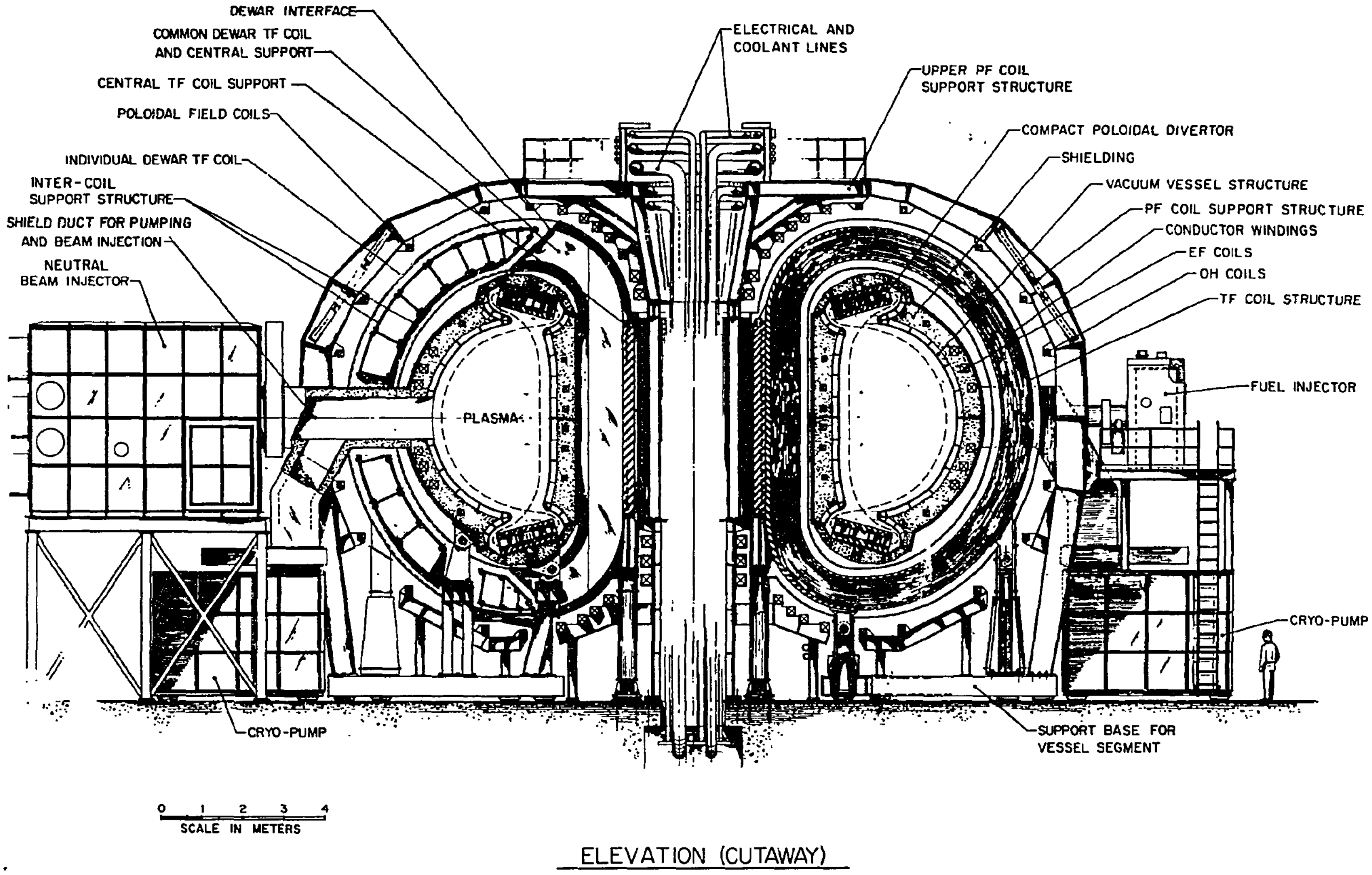


Fig. 4.2. TNS baseline configuration — typical section.

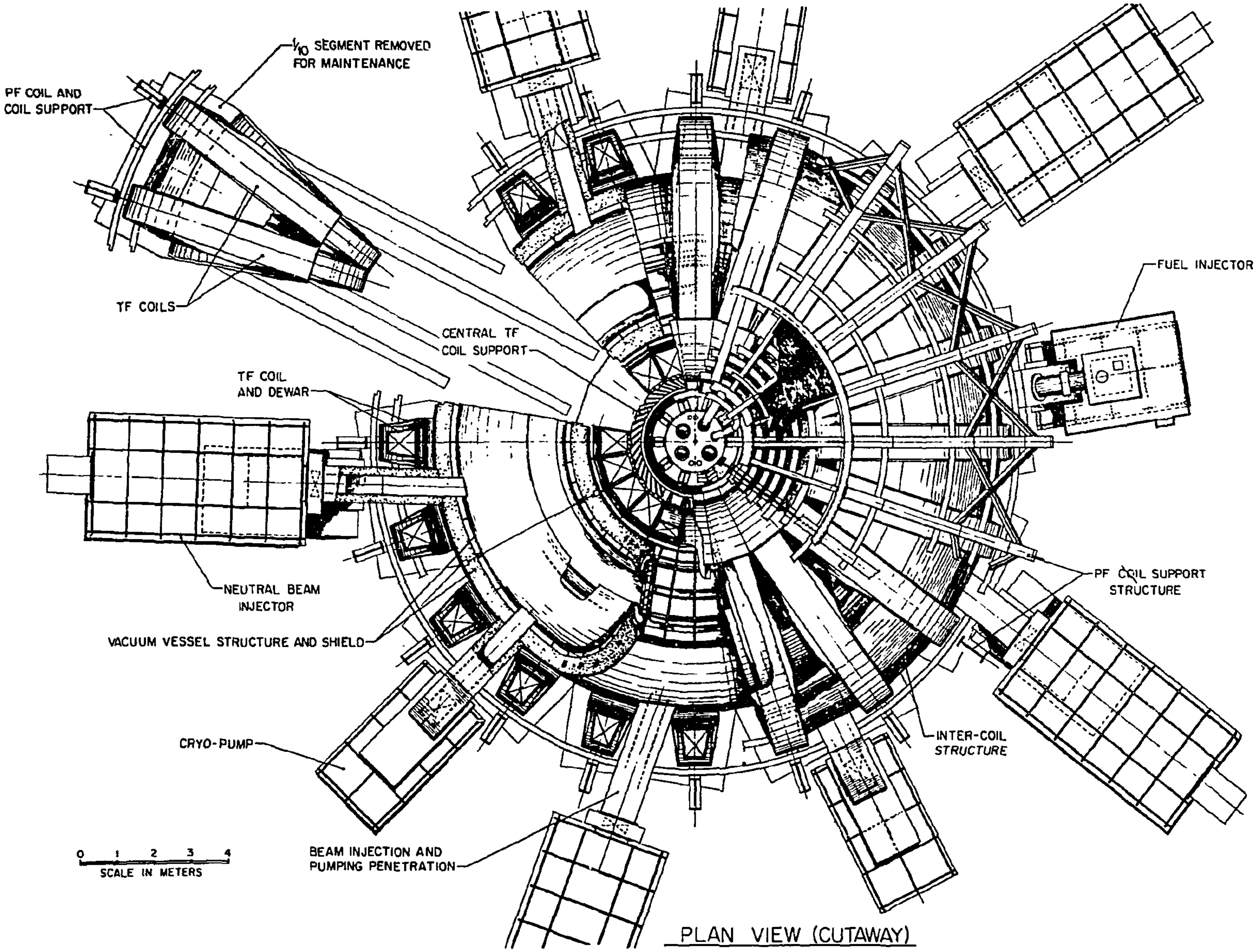


Fig. 4.3. TNS baseline configuration — plan.

4.2.3 TNS Baseline Configuration — Building Section (Fig. 4.4)

In this overall facility layout, the TNS device is illustrated in the reactor containment cell. Overall building size includes space for translation and movement of all major components.

5. PROJECTED OPERATING PARAMETERS OF THE BASELINE DESIGN

The purpose of this section is to examine the projected plasma performance of the baseline design. The projected plasma performance of the baseline design is strongly influenced by trade-offs between the assumed plasma confinement physics and the assumed technological capabilities. Since understanding in the areas of physics and technology is expected to improve continually, our assumptions in these areas must be reevaluated continually. In spite of this evolutionary process, in any serious design study it is necessary to ensure consistency in the physics assumptions used. Moreover, it is essential that we identify physics assumptions and operating scenarios that have potentials for reducing the implied technological requirements. In this fashion, we can enhance the probability of arriving at an economic tokamak reactor with minimized cost and complexity.

5.1 ZERO-DIMENSIONAL ESTIMATES

The parameters for TNS-4 shown in Table 3.2 (Sect. 3) are based on zero-dimensional calculations assuming scaling laws of empirical energy confinement or one-tenth the trapped ion mode loss rate ($D_{TIM}/10$).[14] As indicated in Sect. 3, these parameters provide for a nearly minimum cost device after evaluations in a domain of medium toroidal fields on axis (B_t = 4-7 T), high plasma density ($\overline{n} > 1.0 \times 10^{20}$ m^{-3}), and high average tokamak betas ($\overline{\beta} > 5\%$).

Use of medium fields is expected to allow sufficient access for large neutral beam powers. High density is based on the Murakami scaling,[15] which indicates that the achievable plasma density can be increased by increasing the heating power density. High $\overline{\beta}$ is based on the assumptions of flux-conserving tokamak (FCT) operation[16,17] with large neutral injection power. These assumptions are expected to result in increased fusion power density and reduced size and cost of the TNS reactor.

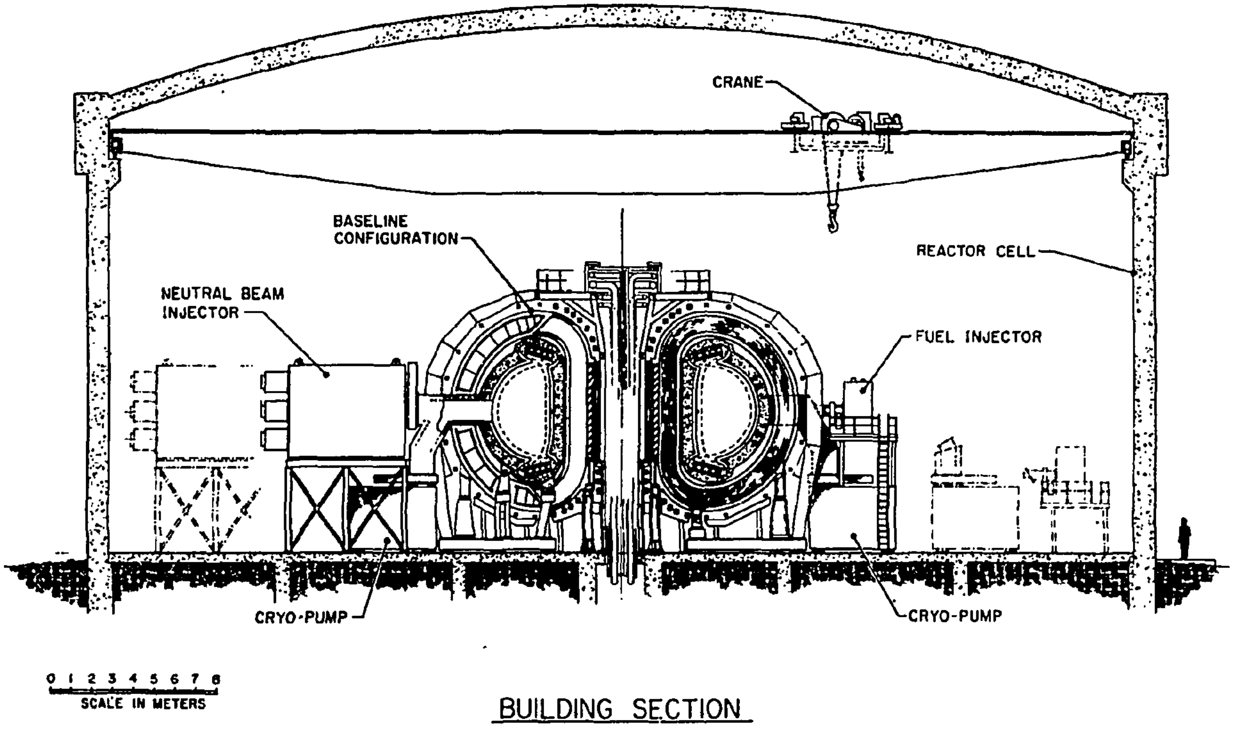


Fig. 4.4. TNS baseline configuration — building section.

While the FY 1977 cost trade studies were being carried out, plasma engineering considerations and theory studies produced results that refined the physics concepts and plasma parameters for the TNS reactor. These refinements are summarized as follows.

5.2 1-D MULTIFLUID TRANSPORT ESTIMATES

Although the use of a full D_{TIM} loss rate may result in pessimistic estimates of the plasma performance in TNS, the use of $D_{TIM}/10$ in the 0-D calculations needs justification. Such a justification can be found in a recent study using a 1-D analytic model that describes the energy and particle transport in a tokamak reactor dominated by the TIM instability.[18] It was shown that the density profile solution of the transport equations leads to an equivalent global loss rate, $\langle D_{TIM} \rangle$, no larger than $D_{TIM}/10$.

The effects of the density profile on $\langle D_{TIM} \rangle$ was also investigated using 1-D multifluid transport codes with pellet fueling. It was shown that fueling profiles peaked toward the plasma edge tend to flatten the density profile, which in turn reduces the trapped ion loss rate.[19]

5.3 HIGH $\overline{\beta}$ SHELL-LIKE EF COILS

The characteristic configurations of the proper equilibrium field (EF) coils have been determined. It has been shown that the proper coil arrangements can either be interior[20] or exterior[21] to the TF coils. Either the interior or the exterior coils are divided into three groups; the coils in each group are connected in series and require a single power supply. It has also been demonstrated[21] that either position option of the coils can maintain the plasma position and D-shape over a wide range of $\overline{\beta}$ values.

5.4 LIMITS ON $\overline{\beta}$ BY MHD BALLOONING MODES

Although calculated magnetohydrodynamic (MHD) equilibrium $\overline{\beta}$ values above 20% with $q_a < 5$ in TNS have been obtained (based on the FCT approach), pressure-driven MHD instabilities are expected to limit $\overline{\beta}$ to lower values. Recent calculations[22] have revealed D-shaped equilibria which are stable with respect to the internal ballooning modes at $\overline{\beta}$ values of $\sim$5% for TNS-like tokamaks. For a tokamak with aspect ratio equal to 2.4, stable $\bar{\beta}$ values up to 12% have been found.[23] With shaping and profile optimizations, current estimates of the stable $\bar{\beta}$ limit are between 5% and 10% for TNS.

5.5 1-1/2-D* EVOLUTION OF D-T PLASMA IN FLUX-CONSERVING TNS TOKAMAK

Since the D-T fusion power density is proportional to $n_D n_T \propto n^2$ and is significant only when the local temperature $T > 6$ keV, one finds that $\int dV n_D n_T \langle \sigma v(T) \rangle >> V \bar{n}_D \bar{n}_T \langle \sigma v(\bar{T}) \rangle$ near ignition. The 0-D model is thus inadequate in estimating the ignition and burn requirements of the TNS plasma.

The evolution of the TNS plasma heated by neutral injection to ignition and burn is studied with the flux-surface averages of the particle and energy balance equations together with the FCT MHD equilibria.[24] It is found that the centrally peaked n and T profiles result in centrally localized α-particle heating which can exceed the injection heating when a relatively low value of $\bar{\beta}$ ($\sim$2.0% for $B_t = 5.3$ T) is reached. When $\bar{\beta} >$ 2.3%, the plasma can be considered ignited near the center to bring about an overall steady-state burn. The steady-state burn can occur (assuming the empirical confinement relation) with $2.6\% < \bar{\beta} < 10\%$ and yields 100 MW $< P_{D-T} <$ 3000 MW by controlling the density over the range of 0.6×10^{20} m^{-3} $< \bar{n} < 3 \times 10^{20}$ m^{-3}. The upper $\bar{\beta}$ limit is set by the MHD stability requirement of ballooning modes. Thus, it is seen that the ignition and burn processes in TNS can be controlled over a wide range of $\bar{\beta}$ and P_{D-T} values by adjusting $\bar{n}$.

5.6 NEUTRAL BEAM INJECTION HEATING SCENARIOS

Because of the centralized α-particle heating, the need for full neutral beam penetration beyond $\bar{\beta} \sim 2.0\%$ is eliminated. An attractive injection procedure[25] emerges that starts with low density, ohmically heated plasma to facilitate initial penetration. Plasma density is increased in conjunction with the increased $\bar{\beta}$ to reduce beam penetration away from the plasma center where significant α-particle heating occurs.

---

*2-D MHD equilibrium calculation coupled to 1-D transport calculation.

It is found that beam energy from 150 keV to 200 keV may be sufficient for perpendicular injection at $Z_{eff} < 1.5$ in TNS.

5.7 SELF-CONSISTENT TNS PLASMA PARAMETERS FOR THE BASELINE DESIGN

Based on the physics concepts discussed above, we can arrive at a set of self-consistent plasma parameters for the TNS reactor with B_t = 5.3 T, medium to high density ($0.6 \times 10^{20}\ \mathrm{m}^{-3} < \bar{n} < 3.0 \times 10^{20}\ \mathrm{m}^{-3}$), and high tokamak beta ($\bar{\beta}$ up to 10%) (see Table 5.1). Upcoming tokamak experiments will refine stability limits of $\bar{\beta}$ and plasma confinement scaling relations. Since B_t = 5.3 T is in the middle of the medium-field strength, a large margin of flexibility can be achieved in TNS by using B_t = 6-7 T with a similar device size. If the experiments indicate $\bar{\beta}$ limits and confinement scalings comparable to or more favorable than those used in this discussion, smaller TNS sizes can be considered in the future. Plasma engineering innovations will be pursued to reduce the technological requirements, and thereby reduce the cost and complexity of the TNS reactor.[26]

6. THE CONTEXT AND SCOPE OF THE FY 1978 TASKS

After summarizing the activities of the prior year and then basing the selection of the current baseline design upon those findings, we can plan the appropriate work tasks for FY 1978. The purpose of this section is to set out the specific context of the FY 1978 activities and to define the specific work tasks to be undertaken.

6.1 SYSTEMS MATRIX

In developing the work tasks that must cover the crucial areas of the entire systems with tightly constrained resources, we have used the comprehensive work breakdown structure (WBS) (Fig. 4.1) to systematize our planning. Table 6.1 contains a system matrix ordered by the components of the hardware portions of the WBS containing an identification of the baseline technology used, an indication of whether follow-on work is being done by us this year and, if so, the nature of that work. The

Table 5.1 Baseline design parameters

Baseline parameters	0-D estimates (used in TNS-4)	Ranges of self-consistent values
I_p, ohmic (MA)	4.9*	4.9
I_p, burn (MA)	5.6*	5.2-6.5
$\overline{n}$, ohmic (m^{-3})	0.5×10^{20}	$0.3\text{-}0.5 \times 10^{20}$
$\overline{n}$, burn (m^{-3})	1.3×10^{20}	$0.6\text{-}3.0 \times 10^{20}$
$\overline{T}$, ohmic (keV)	2	1.0-2.0
$\overline{T}$, burn (keV)	13	5.0-12
$\overline{\beta}$, burn (%)	5	2.6-10
Collisionality (ohmic)	0.5	0.4-1.0
Collisionality (burn)	0.02	0.01-0.20
$\overline{n\tau}$, burn (m^{-3} sec)	2.4×10^{20}	$0.6\text{-}3.6 \times 10^{20}$
P_{D-T}/V (MW/m^3)	2.6	0.4-12.0
W_L (MW/m^2)	1.3	0.3-7.5
P_{D-T} (MW)	700	100-3000
R (m)	5	
a (m)	1.2	
b/a (σ)	1.6	
B_m (T)	10.9	
B_t (T)	5.3	
q_a (-)	3.5	

---

*I_p determined through MHD equilibrium calculations of D-shaped FCT plasmas.

Table 6.1 System matrix for the FY 1978 work tasks

WBS No.	System (or Subsystem)	Baseline technology	Study in FY 1978*		Comments or continuing work
			Yes (Task No.)†	No	
21	Systems Engineering	Existing codes (COAST et al.)	X (1)		Evolve reference design from baseline configuration. Develop systems Design Manual. Add iron core capability to codes.
22a	Toroidal vacuum vessel	D-shaped structure with integral divertor chambers and integral shield modules		X (2)	Modify cross sectional shape and torus support for overall structural integrity
22b i	Machine structure	Stainless steel welded construction	X (2)		Evaluate aluminum and titanium bolted construction
ii	TF coil support	Supports are self-contained within each segment; coils removable — two per segment		X (2)	Increased TF ripple may allow stationary coil installation with removable shield
iii	Intercoil panels	Designed for single-coil fault condition	X (2)		Details of panel disassembly to be developed
iv	Central TF coil support	Reacts centering forces with no coil wedging		X (2)	May be eliminated with iron core concept

Table 6.1 (continued)

WBS No.	System (or Subsystem)	Baseline technology	Study in FY 1978*		Comments or continuing work
			Yes (Task No.)†	No	
v	Central dewar	Common dewar interfaces with individual coil dewars	X (2)		Evaluate possible elimination of dewars within vacuum building concept; if not, examine key interface problems from central dewar viewpoint
22c i	TF coils	Twenty Nb_3Sn coils; forced flow maximum field 10.9 T; similar	X (2)		Examine the impact of a relaxed TF ripple criterion on the number and design of the TF coils; investigate the General Dynamics and General Electric LCP coil designs
ii	TF coil dewars	Individual dewars interface with common central dewar	X (2)		Evaluate possible elimination of dewars within vacuum building concept; if not, examine key interface problems from TF coil dewar viewpoint

Table 6.1 (continued)

WBS No.	System (or Subsystem)	Baseline technology	Study in FY 1978*		Comments or continuing work
			Yes (Task No.)†	No	
22d	PF coils	Air core concept using water-cooled copper coils	X (3)		High beta, shell-like coil concept will reduce the number of coils; comparative study of iron and air cores will impact further number of of coils and power requirement; study possibility of using superconducting coils outside TF coils
22e	Shielding	Stainless steel modules with borated water		X (2)	Need to evaluate shield configuration (geometry and materials) from remote maintenance point of view
22f i	Liner-limiter	Separately cooled TZM liner with no limiter-initial concept		X (2)	Evaluate need for liner
ii	Divertor	Compact poloidal concept	X (5)		Details of current and alternate (bundle ripple divertor) design to be developed

Table 6.1 (continued)

WBS No.	System (or Subsystem)	Baseline technology	Study in FY 1978*		Comments or continuing work
			Yes (Task No.)†	No	
23a	Primary energy storage	Motor-generator flywheel is the buffer to the grid source	X (3)		Site development work will consider the availability of primary energy
23b	Primary & secondary distribution	Available commercial equipment		X (3)	Experience of TFTR will be incorporated; homopolar generator and superconducting energy storage will be considered
23c	Energy conversion	Conventional solid state equipment is assumed	X (3)		Innovative startup scenarios to ease demands on energy conversion. Poloidal field system R&D needs assessment will be made
23d	Emergency standby	Assumed to be commercially available		X (3)	This system is dependent on WBS No. 23b above
24a	Neutral beam	Five injectors; 50 MW; 150 keV	X (4)		The beam heating scenario will be matched to startup schemes with relieved energy & design constraints. R&D needs assessment to be updated

Table 6.1 (continued)

WBS No.	System (or Subsystem)	Baseline technology	Study in FY 1978* Yes (Task No.)	†No	Comments or continuing work
24b	RF heating	Not included in baseline	X (4)		RF assisted startup study results will support bulk heating system considerations. R&D needs assessment to be updated
25a	Remote servicing	Device segmentation and welded joints are currently employed; all components within the device envelope will be remotely handled.	X (2)		Zones of maintenance will be established; modifications in either allowable TF ripple, PF coil location or vacuum topology may relax requirements for remote servicing equipment
25b	Fuel handling	On-site tritium processing for plasma exhaust		X (5)	TSTA concepts will be incorporated in baseline
25c	Main vacuum pumping	Cryopumps operated from main chamber	X (2)		In light of the vacuum building concept, evaluation of the pumping speeds will be assessed and alternate techniques will be evaluated; relocation of the pumping ports to the divertor chamber will be considered

Table 6.1 (continued)

WBS No.	System (or Subsystem)	Baseline technology	Study in FY 1978*		Comments or continuing work
			Yes (Task No.)†	No	
25d	Heat removal and cryogenics	The PF coils and the vacuum vessel/shield are water cooled; cooling towers are the ultimate heat sink; the TF coils and the HV pumping require LHe and LN_2 barriers		X (2)	These parameters will remain unchanged for FY 1978 work
25e	Experimental area ventilation	Standard reactor cell ventilation		X (5)	TSTA program developments will be incorporated; impacts will result from vacuum building consideration
25f	Radioactive waste handling	Specific waste handling systems have not been specified		X (5)	Currently available waste handling will be assumed; will be considered in Committed Fusion Site evaluation
25g	Fuel injector	One unit for pellet fueling; similar to ORNL prototype, 900 m/s	X (5)		Developments in pellet fueling will be incorporated in baseline
25h	Device assembly	The systems studies did not emphasize explicitly assembly/disassembly problems	X (2)		Major emphasis will be machine assembly/disassembly integrated with plasma engineering requirements

Table 6.1 (continued)

WBS No.	System (or Subsystem)	Baseline technology	Study in FY 1978[*]		Comments or continuing work
			Yes (Task No.)[†]	No	
26	Instrumentation control & data acquisition	Conventional tokamak instrumentation and control is assumed	X (4)		An iron core option will be modeled in the TFTR Control Synthesis Program for comparison of control system requirements for iron and air core systems
31 & 32	Buildings and facilities	Conventional reactor test facility is assumed		X** (1)	Development of site requirements and characteristics will incorporate buildings and facilities as well as tritium safety considerations

---

[*] "Study" here means an effort is being directed specifically toward improving the state of knowledge or evaluating a new concept in the particular WBS area. A "no" entry here means either a minor change will be made or no work is anticipated; work may well result from the impact of one of the directed tasks. As an example, work may have to be done on the central TF coil support if an iron core system is adopted although no work is planned directly for the support area.

[†] Indicated task number (1 through 5) relates work plan task to relevant WBS system.

[**] This effort will be conducted under the aegis of the ORNL Committed Fusion Site Feasibility Study.

follow-on work can be either pursuit of alternate concepts or the conduct of additional studies in the original area. Where there is no follow-on work indicated, we have judged that within the current budgetary limitations the existing information will have to be adequate for this year's activities.

6.2 WORK TASKS

The individual investigations that would result from pursuit of the questions raised by the FY 1977 work and brought up in outlining the systems matrix have been synthesized into five major task areas. These areas represent the major concerns of both the overall systems reference design and the specific technical issues critical to progress in the overall designs. Each of these latter tasks has an associated component of planning and coordination with the relevant research and development support and interaction with the overall design schedule.

TASK NO. 1 SYSTEMS ENGINEERING

The scope of the Systems Engineering Task is to provide systems analysis and trade studies required for the completion of other FY 1978 TNS Study Tasks. In particular, systems studies will be provided to identify the TF coil cost and configuration, sensitivity to magnetic field ripple, Task 2, and the impact of variation in the poloidal field design on tokamak configuration and cost, Task 3. The systems studies will be accomplished through the use of a modified version of the code COAST developed by Westinghouse for the costing and sizing of D-T burning tokamak systems. The code will be expanded to include the provision for an iron core option in the poloidal field coil system. A document containing a description of each major system of the TNS, including design criteria and performance parameters, will be developed and maintained.

TASKS

(1) Develop and maintain a systems description for the TNS air core design.

(2) Develop and maintain a systems description for the TNS iron core design.

(3) Document design criteria.

(4) Update Plasma Physics portion of COAST code.

(5) Add an iron core option to the COAST code.

(6) Compare results from the COAST code with those from the JET cost and sizing code.

(7) Implement guidelines developed by DOE regarding fusion reactor cost accounting.

(8) Determine the impact of the variation in TF coil size resulting from differing fabrication techniques.

TASK NO. 2 MECHANICAL DESIGN

2.1 MECHANICAL FEASIBILITY

Mechanical feasibility will assess the overall integrity of the baseline configuration within the context of mechanical/structural design criteria. Emphasis will be on establishing design criteria and on device assembly/disassembly from a remote maintenance point of view. Engineering drawings will be developed to establish the mechanical feasibility of the baseline.

TASKS

(1) Develop mechanical/structural design criteria.

(2) Establish an activation topology from our current 1-D neutronic analyses; identify remote maintenance requirements for major tokamak systems and define the remote servicing logistics as they apply to the zones of maintenance.

(3) Develop a mechanical configuration of TNS which incorporates ripple injection. Structural feasibility as well as device assembly/disassembly will be evaluated for baseline inclusion.

(4) Establish the mechanical feasibility of microwave-assisted start-up as a baseline candidate by generating layout drawings.

(5) Develop a mechanical design of the pellet fueling system including requirements for materials, shielding, pumping, and safety.

(6) Generate sets of engineering drawings (plan, elevation, details) during the evolution of the TNS baseline. Ensure mechanical/structural feasibility, including assembly/disassembly, and remote servicing requirements.

2.2 TF COIL RIPPLE

The scope of this activity is to perform engineering trade studies in conjunction with plasma physics investigations to select an optimum TF coil system based on plasma losses, cost, and accessibility for tokamak assembly and maintenance. The engineering trade study will be accomplished by the use of the COAST code formulated by Westinghouse as part of the FY 1977 TNS effort to size and cost tokamaks as a function of ripple variations. The plasma physics investigation of ripple effects on plasma dynamics will be accomplished by the use of 1-D transport codes and the "ripple" code.

TASKS

(1) Determine the TF coil cost sensitivity to ripple. Evaluate the trade between the number of coils and the coil size at fixed values of field ripple.

(2) Determine the effect of the number and size of TF coils on tokamak assembly and maintenance.

(3) Using the ripple code, determine the effects of ripple (probably >1%) on plasma confinement.

(4) Select a TF coil configuration based on both physics and engineering considerations.

(5) Combine the 1-D transport code with the ripple code in order to evaluate self-consistent, time-dependent ripple effects.

2.3 VACUUM TOPOLOGY FEASIBILITY STUDY

The vacuum topology study will determine feasibility of utilizing a secondary vacuum enclosure (SVE) for containment of the TNS plasma. The task covers definition of current TNS vacuum requirements for the plasma chamber, neutral beam injector, and TF coil dewars. These requirements will be the basis of comparison for an SVE-TNS design.

TASKS

(1) Specify the vacuum pumping system for the baseline TNS.

(2) Determine the impact of a vacuum environment on the major TNS subsystems (superconducting coils, neutral beam injectors, and in-cell rms equipment).

(3) Determine the operating pressure and pumpdown time for the SVE as a function of TNS outgassing rates.

(4) Perform a conceptual design study of an SVE-TNS configuration including, as a minimum, the vacuum building, belljar, and dual seal parting plane concept. Using results of Tasks 2 and 3, select the preferred SVE configuration.

(5) Determine the criterion for comparing the current TNS design with the SVE-TNS design.

(6) Perform a trade-off study of current vs SVE-TNS.

(7) Write final report.

TASK NO. 3 POLOIDAL SYSTEM

The scope of this statement of work shall encompass performing the necessary electrical, mechanical, and plasma engineering evaluations of the poloidal system of both an air and iron core TNS reactor. Additional tasks are added to generate a baseline iron core design to compare the design to an updated reference air core machine (to be produced in separate TNS tasks).

TASKS

(1) Perform parametric studies on the configuration and cost of an iron core system for TNS considering the location of the PF coils and the impact on the electrical and mechanical requirements.

(2) Perform plasma physics calculations to substantiate the elimination of the OH coils through the use of high β, shell-like coils. Consider the possibility of using superconducting coils outside the TF coils.

(3) Generate an iron core baseline design comprised of the critical machine components and determine the impact of microwave start-up on this design.

(4) Assess the impact of assembly and maintenance of a TNS machine operating with an iron core.

(5) Update the poloidal system of the reference air core machine and determine the impact of microwave start-up on the PF coil system.

(6) Define the power supply, circuitry, and switching requirements for the iron and air core poloidal systems.

(7) Determine the implication of reducing the stray fields that may impact the operation of other machine elements, e.g., diagnostics and neutral beams.

(8) Determine the impact of the iron core on the plasma control requirements when operating in a saturated and unsaturated mode.

TASK NO. 4 PLASMA DYNAMICS

This task involves three areas: 4.1 Plasma Start-up and Shutdown, 4.2 Neutral Beam Heating, and 4.3 β Maintenance. The main thrust of this task is to develop and analyze innovative approaches to ease the technological requirements anticipated during a plasma discharge. Favorable plasma engineering findings may be included in the TNS engineering design studies at appropriate times.

4.1 START-UP AND SHUTDOWN

This subtask aims to develop and evaluate effective start-up (initiation of the plasma current and subsequent build-up to full size plasma) and shutdown scenarios in tokamak reactors. Preliminary physics analysis points to some desirable schemes whose engineering and cost advantages and disadvantages can be estimated by the accompanying engineering analysis.

TASKS

(1) Produce a preliminary list of physics parameters for the three-phase start-up scenario.
(2) Complete plasma engineering studies of the three-phase start-up scenario.
(3) Identify workable methods for controlling plasma position during regular shutdown or during abort.

4.2 PLASMA HEATING SCENARIOS

This subtask covers preliminary plasma engineering and engineering evaluations necessary to quantify the relative advantages and disadvantages of two neutral beam plasma heating scenarios. These include:

- Full bore plasma heating with controlled density build-up, which may permit the use of 150-200 keV deuteron beams.
- Ripple injection heating, which may permit the use of ∿100 keV deuteron beams.

TASKS

(1) Produce internal memo describing parameters for ripple injection in TNS.
(2) Complete plasma engineering investigation of full bore plasma heating with controlled density.

4.3 β MAINTENANCE

High β maintenance in a tokamak reactor deals with the maintenance of the plasma cross section and the control of plasma position during the heating and burn phases of the discharge. MHD equilibrium and stability form the bases of the physics input. The engineering implications of the requirements of plasma shaping and feedback control will be evaluated to assess the feasibility and costs.

TASKS

(1) Specify equilibrium field coils for iron core and air core TNS.

(2) Specify plasma model for position control.

(3) Calculate the inductances needed for control study (after the poloidal field system parameters become available).

(4) TNS air core position control calculations.

(5) Comparison and completion of TNS iron core control calculations.

TASK NO. 5 PARTICLE CONTROL

The scope of this task covers the investigation of systems for purity control and fueling. Physics criteria will be identified for both divertors and pellet fuelers. A bundle divertor design concept will be developed to investigate its potential for both experimental and power producing reactors.

TASKS

(1) Specify pellet fueling requirements (speed, size, and rate) for the baseline design and document plasma physics basis.

(2) Specify physics assumptions for the bundle divertor design.
   (a) Scrape-off zone thickness and width.
   (b) Particle and energy fluences.

(3) Evaluate nuclear requirements (heating and damage) for shielding.

(4) Develop electromagnetic design configuration.

(5) Develop mechanical design configuration including structural loading and support (including TF coils).

(6) Establish the particle and energy collection potential of the final design.

REFERENCES

1. P. N. Haubenreich and M. Roberts, "ORMAK F/BX, A Tokamak Fusion Test Reactor," ORNL/TM-4634, Oak Ridge National Laboratory, Oak Ridge, Tennessee (June 1974).
2. M. Roberts, "Oak Ridge Tokamak Experimental Power Reactor Study Scoping Report," ORNL/TM-5038, Oak Ridge National Laboratory, Oak Ridge, Tennessee (March 1977).
3. "Oak Ridge Tokamak Experimental Power Reactor Study — 1976. Parts 1-6":

   Part 1. M. Roberts et al., "EPR Summary" (April 1977).
   Part 2. D. G. McAlees et al., "Plasma Engineering in a Deuterium-Tritium Fueled Tokamak" (October 1976).
   Part 3. J. W. Lue et al., "Magnet Systems" (February 1977).
   Part 4. C. A. Flanagan et al., "Nuclear Engineering" (December 1976).
   Part 5. T. E. Shannon et al., "Engineering" (February 1977).
   Part 6. M. Roberts et al., "Research, Development, and Demonstration Needs" (January 1977).

4. Don Steiner et al., "ORNL Fusion Power Demonstration Study: Interim Report," ORNL/TM-5813, Oak Ridge National Laboratory, Oak Ridge, Tennessee (March 1977).
5. Y-K. M. Peng et al., "Plasma Engineering Innovations in the ORNL/Westinghouse TNS Tokamaks," paper presented at IEEE 7th Symposium on Engineering Problems of Fusion Research, Knoxville, Tennessee, October 25-28, 1977.
6. "TNS Engineering Trade Study Analysis," WFPS-TME-069, Westinghouse Electric Corporation (October 1977).
7. M. Roberts, "Draft Program Plan for TNS — The Next Step After the Tokamak Fusion Test Reactor, Part I — Summary," ORNL/TM-5982, Oak Ridge National Laboratory, Oak Ridge, Tennessee (October 1977).
8. T. F. Yang et al., "Westinghouse Compact Poloidal Divertor Reference Design for TNS," WFPS-TME-042, Westinghouse Electric Corporation (August 1977).

9. D. A. Sink and E. M. Iwinski, "A Computer Code for the Costing and Sizing of TNS Tokamaks," WFPS-TME-062, Westinghouse Electric Corporation (September 1977).

10. M. Roberts et al., "Draft Program Plan for TNS — The Next Step After the Tokamak Fusion Test Reactor, Part II — R&D Needs Assessment," ORNL/TM-5983, Oak Ridge National Laboratory, Oak Ridge, Tennessee (December 1977); "Draft Program Plan for TNS — The Next Step After the Tokamak Fusion Test Reactor, Part III — Project Specific R&D Needs," WFPS-TME-044, Westinghouse Electric Corporation (March 1977).

11. M. Roberts et al., "Draft Program Plan for TNS — The Next Step After the Tokamak Fusion Test Reactor, Part IV — Program Planning," in preparation.

12. H. R. Howland and T. C. Varljen, "An Approach to Decision Modeling for an Ignition Test Reactor," WFPS-TME-066, Westinghouse Electric Corporation (September 1977).

13. W. B. Wood, "Draft Program Plan for TNS — The Next Step After the Tokamak Fusion Test Reactor, Part IV — Program Planning," ORNL/TM-5984, Oak Ridge National Laboratory, Oak Ridge, Tennessee, to be published.

14. S. O. Dean et al., "Status and Objectives of Tokamak Systems for Fusion Research," USAEC Report, WASH-1295 Washington, D.C. (July 1974).

15. M. Murakami, J. D. Callen, and L. A. Berry, Nucl. Fusion 16, 347 (1977).

16. J. F. Clarke and D. J. Sigmar, Phys. Rev. Lett. 38, 70 (1977).

17. R. A. Dory and Y-K. M. Peng, Nucl. Fusion 17, 21 (1977).

18. J. F. Clarke, "An Improved Estimate of Trapped Ion Mode Energy Loss from Tokamak Reactors," ORNL/TM-5860, Oak Ridge National Laboratory, Oak Ridge, Tennessee (May 1977).

19. A. T. Mense, W. A. Houlberg, S. E. Attenberger, and S. L. Milora, "Effects of Fueling Profiles on Plasma Transport," ORNL/TM-6026, Oak Ridge National Laboratory, Oak Ridge, Tennessee, to be published.

20. J. D. Callen et al., "Tokamak Plasma Magnetics," in Plasma Physics and Controlled Nuclear Fusion Research, Vol. II, p. 369 (IAEA, Vienna, 1977).

21. Y-K. M. Peng, R. A. Dory, and D. J. Strickler, "Poloidal Field Considerations for D-shaped Tokamaks," ORNL/TM-5648, Oak Ridge National Laboratory, Oak Ridge, Tennessee, to be published.
22. G. Bateman and Y-K. M. Peng, Phys. Rev. Lett. 38, 829 (1977).
23. A. Sykes, J. A. Nessen, and S. J. Cox, Phys. Rev. Lett. 38, 757 (1977).
24. J. A. Holmes and Y-K. M. Peng, "Time-dependent Equilibrium Evolution in a Flux-conserving D-T Tokamak Reactor," Bull. Am. Phys. Soc. 22, 1135 (1977).
25. J. A. Rome, Y-K. M. Peng, and J. A. Holmes, "Injection Heating Scenarios for TNS," ORNL/TM-5931, Oak Ridge National Laboratory, Oak Ridge, Tennessee (July 1977).
26. Y-K. M. Peng et al., "The ORNL TNS Program: Plasma Engineering Considerations and Innovations for a Medium-Field Tokamak Reactor," ORNL/TM-6510, Oak Ridge National Laboratory, Oak Ridge, Tennessee (November 1977).

GLOSSARY

TNS	The Next Step
DOE	Department of Energy
ORNL	Oak Ridge National Laboratory
EPR	Experimental Power Reactor
TFTR	Tokamak Fusion Test Reactor
FPDS	Fusion Power Demonstration Study
0-D	Zero-dimensional
1-D	One-dimensional
1-1/2-D	One-and-a-half-dimensional
TF	Toroidal field
R&D	Research and Development
ORNL/_W_	Oak Ridge National Laboratory/Westinghouse
D-T	Deuterium-tritium
PF	Poloidal field
WBS	Work Breakdown Structure
FCT	Flux Conserving Tokamak
MHD	Magnetohydrodynamic
OH	Ohmic heating
FED	Fusion Energy Division
GD	General Dynamics Corporation
GE	General Electric Company
EF	Equilibrium field
I&C	Instrumentation and control
HV	High vacuum
TZM	Molybdenum alloy
RF	Radio frequency
LH_e	Liquid helium
LN_2	Liquid nitrogen
D_{TIM}	Differential coefficient for trapped ion mode loss
TSTA	Tritium Systems Test Assembly