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OAK RIDGE TNS PROGRAM 1976/1977

INTEGRATION OF ENGINEERING REALITY BRINGS US CLOSER TO REALIZABLE REACTOR

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ABSTRACT

Both the techniques and results of bringing engineering reality into the exploration of the possible design choices for The Next Step (TNS) in the Tokamak Fusion Program after TFTR are discussed in this report. Each of the elements of our interrelated, three-part approach --plasma engineering, engineering design, and program planning -- is highlighted. The constraints developed from an engineering viewpoint are seen to stimulate creative improvements in each area. Plasma engineering activities that reduce technological requirements for reactor core performance are described. The engineering design study comparing quantitatively various technical options for TF coils is outlined with summarized findings leading to a clearer view of the essential problems -- namely the setting of objectives and making of decisions. The findings of the draft program planning exercise are also presented.

1. INTRODUCTORY SUMMARY

The objective of our TNS efforts is to provide a focus within the U.S. fusion program for the development of a reactor core experiment in the next decade. 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 reference design (3). With this basis, the TNS activities were directed at 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 higher beta rather than larger systems at the lower beta has come from an engineering judgment that economical systems are necessary, not optional. The characterization of this 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 (Section 2), by developing consistent, feasible engineering models of systems of different size and magnetic field strength (Section 3) and by program planning studies of the steps required to implement the designs (Section 4).

In the first area, namely plasma engineering, early indications were that very stringent requirements were to be placed on physics achievements ($\beta \sim 10$-15%), beam technology ($\sim$ 500 keV), and system size including a divertor (up to $\sim$ 1/3 more in linear dimension). Rather than pursue these difficult requirements with even more difficult technology development programs, high risk 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 on achievable beta, neutral beam energy and fueling technology become. Under the constraint of a fixed, no-divertor TF coil shape, an innovative design concept for a compact poloidal divertor was developed that can have significant impact on the options available to plasma engineers (4).

*Operated by Union Carbide Corporation-Nuclear Division for the Department of Energy.

In the second area, system 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 (5), 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 cost alone; the relative costs for the Cu, Nb_3Sn, NbTi, and NbTi/Cu options were roughly 1:1.3:1.5:1.5. A closer examination of similar physical devices indicated that the balance of plant is the dominant factor and that the high technology questions are of great concern but have little economic impact.

In the third area, program planning, various elements of a preliminary program plan were initiated (6) that identified the central programmatic questions. In particular, an assessment of the R&D needs for TNS was made and recommendations for more emphasis on existing programs and for new initiatives were made and documented (7). Planning schedules for integration of the TNS project with the supporting R&D work and the subsequent reactor devices were developed (8) as well. From all this came the findings that plasma physics and decision-making are the true critical paths and that a route to engineering reliability must be laid out.

Based upon the findings in these three areas, the continued activities in the TNS program are being directed toward cost reduction and increased feasibility in the most critical areas, namely, divertor/poloidal magnetic design, mechanical assembly and maintenance and the interface with supporting R&D work (Section 5).

2. PLASMA ENGINEERING

The purpose of the plasma engineering studies within this program has been to establish credible ranges of physics parameters for an ignition test reactor as the next step (TNS) beyond TFTR. Our reactor concept is based on medium toroidal fields (9) (B_T = 4-7 Tesla), high plasma densities (10) ($\bar{n}$ = 0.6-2.5 x $10^{20}m^3$) and high tokamak betas ($\bar{\beta}$ = 5-10%).

Use of medium field strengths is compatible with the introduction of a large amount of neutral beam power which in turn is important to high density. With large neutral beam power, the plasma is expected to heat up in a time scale much shorter than the plasma skin time, resulting in a Flux Conserving Tokamak (FCT) (11). Calculations in D-shaped FCT (12) have produced equilibria at $\bar{\beta}$ above 20% with the safety factor up to 5. Although MHD instabilities may limit $\bar{\beta}$ to lower

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values, $\bar{\beta}$ values substantially above a few percent are expected to permit the use of medium field and/or to reduce the reactor size.

To insure consistency of our physics parameters, we have studied several important subjects in plasma engineering for synthesis with the design engineering and planning considerations, as summarized below.

The empirical energy confinement scaling derived from studies in ATC, ORMAK and Alcator has been used in a 0-D study (13) to choose a reference reactor with parameters shown in Table 1.

Table 1

Typical Parameters for a D-Shaped, Medium Field Ignition Test Reactor

	Unit	Parameters Based on the 0-D Model	Parameters refined with 1-D transport, MHD Equilibrium, and Stability
R_o	m	5	5
a	m	1.25	1.25
A	--	4	4
σ Elongation	--	1.6	1.6
B_T on axis	T	4.3	4.3
B_T at coil	T	8.0	8.0
I_p (low β)	MA	4.0	4.0
I_p (burn)	MA	6.0	4.5-5.5
q_a	--	4	4
$\bar{n}$ (low β)	m^{-3}	0.5×10^{20}	$0.3\text{-}0.5 \times 10^{20}$
$\bar{n}$ (ignition and burn)	m^{-3}	2.2×10^{20}	$0.6\text{-}2.5 \times 10^{20}$
$\bar{T}$ (low β)	keV	2	1.0-2.0
$\bar{T}$ (ignition)	keV	11	4.0-7.0
$\bar{T}$ (burn)	keV	13	5.0-10
$\bar{\beta}$ (ignition)	%	11	3.0-5.0
Injection Power	MW	75	50-75
$\bar{\beta}$ (burn)	%	15	3.5-10
Collisionality (low β)	--	0.5	0.14-0.96
Collisionality (burn)	--	0.02	0.01-0.15
$\bar{n}\tau$ (burn)	m^{-3}.sec	3×10^{20}	$0.6\text{-}3 \times 10^{20}$
Average fusion power density	MW/m^3	6	0.4-8.0
Plasma volume	m^3	250	250
Average neutron wall loading	MW/m^2	3.7	0.3-5.0
Total fusion power	MW	1500	100-2000

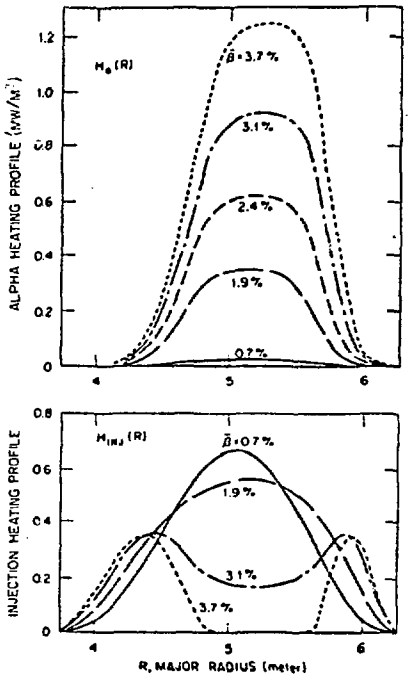
The effect of density profile on the effective global $\{D_{TIM}\}$ is studied with a 1-D multitifluid transport code incorporating particle and energy balances (14). It is found that $\{D_{TIM}\} \lesssim (D_{TIM}/10)$ is satisfied for reasonable density profiles, supporting the use of $(D_{TIM}/10)$ in the 0-D scaling studies. The 1-D study (see Table 1) also indicates that burn conditions can exist over a wide range of density and fusion power levels, in contrast with a single operating point in the 0-D model.

The evolution of equilibria by injection to ignition and burn is studied with the flux-surface averages of the particle and energy balance equations together with the axisymmetric FCT equilibria. It is found that the centrally localized α-particle heating density can exceed the injection heating density at relatively low values of $\bar{\beta} \gtrsim 2.5\%$. This fact, when combined with the constraint to use current positive ion source beam heating technology, has led to the following line of reasoning.

Because of the centralized α-particle heating, the need for full neutral beam penetration beyond $\bar{\beta} \sim 2.5\%$ is eliminated. An injection procedure (15) is found that starts with low density to facilitate penetration (Figure 1). The density is then increased with the accompanying, acceptable decrease in penetration. It is found that beam energy from 150 keV to 200 keV may be sufficient for perpendicular injection at $Z_{eff} \lesssim 1.5$. This is in sharp contrast to the 300-500 keV requirements developed from the initial 0-D model calculations.

Figure 1

CENTRALIZED ALPHA PARTICLE HEATING IN TNS HAS BEEN SHOWN TO EASE THE NEUTRAL BEAM PENETRATION REQUIREMENTS SO THAT 150 keV BEAMS SHOULD BE SUFFICIENT FOR $Z_{EFF} \lesssim 1.5$



MHD ballooning modes are expected to place limits on $\bar{\beta}$. Recent calculations (16) have shown a stable $\bar{\beta}$ near 5% for a D-shaped FCT equilibrium while improvements beyond these values seem possible. Current estimates for $\bar{\beta}$ are between 5% and 10% with shaping and profile modifications. This $\bar{\beta}$ range overlaps that calculated for steady state D-T burns.

A poloidal field system (17) in an FCT that maintains plasma D shape despite large and rapid changes in $\bar{\beta}$ has been obtained. In In TNS, coils more than 3 m away from the plasma edge can be properly located to produce D-shaped equilibria. However, the power supply required by these coils is around 10 times that required by coils 0.6 m away, requiring a systems analysis for overall balance.

Based on these considerations, self-consistent parameters are established and given in Table 1. Upcoming tokamak experiments will refine stability limits of $\bar{\beta}$ and plasma confinement scaling laws. Since B_T = 4.3 T is near the lower end of the medium field strength, a large margin of reliability can be achieved by using $B_T \simeq 6$ T. This field strength is within reach of present-day coil technologies and development programs.

SUMMARY

Imposition of technology/economics constraints resulted in creative improvements in plasma engineering models:

- o Detailed energy deposition calculations support use of existing 150 keV injection technology providing an alternative to pursuit of difficult, costly, risky, and time-consuming ∿ 500 keV technology (Figure 1).
- o Inclusion of profiles has reduced beta requirements (Table 1).
- o Compact poloidal divertor concept has been developed within nominal "D" TF coil geometry (4).

3. DESIGN ENGINEERING

A series of parametric trade studies was performed to evaluate consistently 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 have been investigated: water-cooled copper coils (called TNS-1), superconducting NbTi (TNS-3) and Nb_3Sn (TNS-4) coils, 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, which 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 radius from ∿0.75 m to 2.0 m, spanning the range from TFTR size plasmas to those chosen for recent Experimental Power Reactor (EPR) design studies. The device major radius was varied from ∿8-9 m down to some lower limit (∿4.4 m for a=.9 m to ∿6 m for a=2 m) which was consistent with the groundrules and still allowed a viable engineering design. 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.

The major tool used in performing these trade studies was a computer code designated COAST (5), written to permit COsting And Sizing of D-T burning Tokamak systems through detailed treatment of all major components of the total plant.

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_0, and B_{max} (Figure 2). The reasons for the slight cost difference between NbTi and Nb_3Sn 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 than the Nb_3Sn, as expected; however, the TF coil structure cost is larger for the NbTi 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 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 makes the technological differences between NbTi and Nb_3Sn insignificant from a cost point of view.

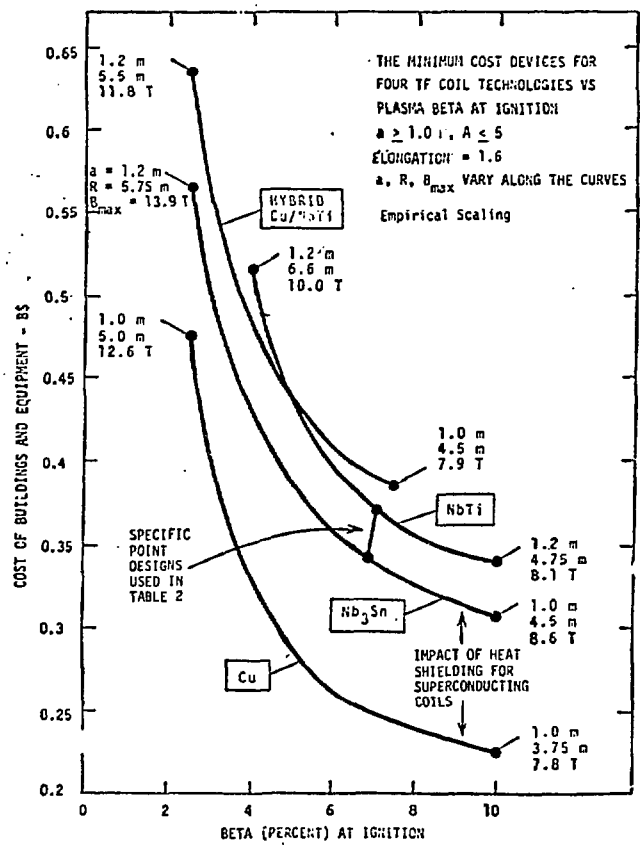


Figure 2

Table 2

COMPARISON OF COSTS FOR SIMILAR NbTi + Nb_3Sn DEVICES INDICATES OVERWHELMING ROLE OF BALANCE OF PLANT

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 Cost		50		23	27
"Balance of Plant"		235		233	2

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

Representative parameters and costs for four TNS point designs that achieve ignition at an average beta of 5% are given in Table 3. The maximum field at the TF coil for each design is about 10-11 T; this would require the NbTi superconductor to be designed to operate below 4 K and would permit 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 a larger and more costly size at a β of 5% or would require operation at an average beta of ~7.5% in devices of the size in Table 3.

Table 3
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	5.8	5.3
Toroidal Beta, β_t (%)	5.0	5.0	5.0	5.0
Plasma Current, I_p (MA)	4.1	3.8	4.1	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	13.3
Energy Confinement Time, τ_E (s)	1.5	1.8	1.8	1.5
$\bar{n}_e \tau_E$ (m^{-3} s)	2.4×10^{20}	2.4×10^{20}	2.4×10^{20}	2.4×10^{20}
Total Volt-Seconds	41.0	55.2	51.6	41.5
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	1.52
Total Fusion Power (MW)	558	795	698	628
Fusion Power Density (MW/m^3)	3.7	2.6	2.6	3.7
Neutral Beam Power (MW)	40.0	57.0	50.0	45.0
Steady State Burn Time (s)	16.0	16.0	16.0	16.3
Time Between Pulses (s)	300.0	300.0	300.0	300.0
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$)	288.7	434.4	388.3	435.3
Relative Cost	1.0	1.50	1.34	1.51
Annual Utility Cost (M$)	4.1	3.0	2.0	3.4

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 to demonstrate ignition 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 is, in addition to ignition, demonstration of the science and technology required for reactors -- i.e., sustained burn dynamics, and 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 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.

Clearly these capital cost comparisons have forced us to confront the real questions -- the choice of objectives (i.e., "ignition" or "reactor core") and resolution of the judgmental issues (Table 4).

Table 4
THE IMPORTANT COST FACTORS ARE MANY MORE THAN CAPITAL COST ALONE

QUANTIFIABLE[a]	SEMIQUANTIFIABLE[c]
CAPITAL COST[b]	MECHANICAL COMPLEXITY
OPERATION COST	TECHNICAL RISK
SIZE	ASSEMBLY/MAINTENANCE
PERFORMANCE	OPERATIONAL FLEXIBILITY
SCHEDULE	COST/SCHEDULE RISK
	REACTOR TECHNOLOGY
	EXTRAPOLATABILITY

(a) Quantified in present study.
(b) Principal target in present study.
(c) First attempts at quantification made in present study.

SUMMARY

Quantitative systems engineering emphasizes importance of overall program context.

- o Comparative costing illuminates impact of different technologies and highlights high cost impacts.
- o Comparative costing indicates dominant role of "balance of plant."
- o Costing exercises have illuminated the real program questions -- objectives plus judgments.

4. PROJECT PLANNING

Development of a practical means of synthesizing and building on the advances made in plasma engineering and design engineering is the focus of the TNS planning activity. In developing a draft TNS program plan, we came to three conclusions:

1. The physics and technology base does exist from which to start the TNS design as a central fusion program goal.
2. We have specific recommendations for new emphasis in certain physics and technology areas to minimize R&D program gaps.
3. TNS conceptual design must be started now, and a close look at organizing the fusion program around a TNS project is an essential need to support operation in the mid 1980's.

On the first point -- support base -- sufficient strides have been made in both fusion physics achievement (in plasma density, energy confinement, plasma temperature, and effective impurity level) and operational understanding to

encourage us to begin a serious planning effort. Even though we do not now have a working theoretical framework that allows us to extrapolate present-day plasma parameters into the low collisionality, high-density fusion plasma regime with confidence, we can examine many of the specific physics areas expected to be important in the TNS design process and begin to specify the kind of information required in that area during each major design period. Sound technology program bases from which to start exist in the three key areas for TNS -- i.e., toroidal field (TF) magnets for the Large Coil Program (LCP), 150keV beams for TFTR, and tritium handling for the Tritium Systems Test Assembly (TSTA).

On the second point -- principal gaps -- we find three principal areas in physics and between seven and fifteen areas in technologies requiring attention.

- A comprehensive impurity and particle control plan must be formulated and implemented on a timely basis to identify the best way to proceed in this most uncertain area.
- The need for experimental investigation of configuration maintenance (long pulse) and optimization in high-β, high temperature plasmas is not now being met in any existing or near-term facility.
- The applied theoretical program in impurity dynamics, plasma transport, and, most critically, coupled equilibrium, stability, transport, and heating simulation of ignition scenarios must be intensified in the existing plasma theory base program.
- Seven areas need initiation of programs or new emphasis in exploratory studies to ensure an acceptable technology base for TNS final design under any scenario.

Programs	Studies
Compound gas pump development	Limiter materials improvement
Neutral beam (NB) switch tube pulse lengthening	Plasma configuration sensing and control
Increased NB power and pulse length per source	Abnormal control operations
Poloidal field (PF) electrical systems (for cost reductions)	

- Six other programs related to Nb_3Sn TF coils, NbTi PF coils, active impurity controls, 300 keV beams, and > 2 km/s pellet fuel injectors might need increased emphasis depending upon TNS design decisions.
- The NbTi TF coil and pellet injector programs have critical timing questions in the generally compressed project schedule and must be closely examined further.

On the third point -- implementation -- development of a comprehensive work breakdown structure, a master schedule based on the work breakdown structure, and a first draft of the ingredients of the program plan has yielded six fundamental features:

- A ten-year schedule to operation from today requires an aggressive program.
- The principal, quantifiable critical path is construction of and machine assembly (basically the TF coils) within the main test cell (tokamak building).
- A phased approach, specifying main test cell first and tokamak device two years later, is essential to the achievement of the most rapid, logical schedule beginning in FY 1980.
- A reference design (i.e., an initial selection of principal design features, e.g., plasma size TF coil technology, etc.) with backup should be chosen now, and preparations for conceptual design of the facilities (main test cell, etc.) must be made in FY 1978 to match a FY 1980 schedule.
- A central project management is necessary to integrate all the program elements into a coordinated effort.
- The planning efforts have provided the preliminary schedules linking the project with R&D support with which to develop the necessary information supporting the reference design choice.

Underlying the discussion of adequacy and timeliness are two crucial factors. One is the requirement to tie the project schedule projections and project decisions to the institutional commitments, achievements, and level of effort in the support R&D program. The other is the fundamental importance to the design philosophy of basing all design on a firm criterion of reliable assembly and maintenance in a D-T environment. The assembly and maintenance program is based upon four parts: TFTR experience, models and mockups, an intermediate superconducting tokamak experiment and good design practice coupled with utility experience.

SUMMARY

Program planning is identifying critical programmatic questions:

- Project planning is based on detailed work breakdown structure.
- Systematic analysis highlights problem areas.
- Plasma physics and decision-making are probably true critical paths.
- Route to engineering reliability must be laid out.

5. FUTURE DIRECTIONS

On the basis of our studies thus far, the direction of future work is clear even though the pace is not. The first order of business is to

re-examine the key requirements that have led to high cost-high technology design solutions. The second step is then to initiate a conceptual design leading to the construction project. Proceeding with the first step involves reconsideration of the startup voltage and poloidal field system power requirements as well as further examination of the various divertor options, startup options and design trade-offs for reliable assembly and maintenance. As an example in the former category, the PFS, based upon an iron core magnetic circuit rather than an air core circuit, may well have considerably reduced power supply requirements. In the latter category, placement of the coils of the PFS outside the TF coils can significantly reduce the maintenance difficulties. In both cases, however, a systems analysis is required to balance the conflicting demands of mechanical, electrical, and plasma engineering.

In addition to pursuing these potential reductions in the design requirements, we will also be continuing the development of the baseline design and the program planning charts in selected systems as a systems focus for the study.

The TNS program continues to be an ORNL/industry effort focused on initiating pre-conceptual design for The Next Step in the tokamak program after TFTR.

6. CONCLUDING SUMMARY

Integration of engineering reality is bringing us closer to a realizable reactor:

- Imposition of technology/economics constraints has resulted in creative improvements in plasma engineering models.
- Quantitative systems engineering is emphasizing the importance of maintaining an awareness of the overall program context.
- Program planning is identifying critical programmatic questions.
- Based on this year's work, our current work tasks are confronting major "Go/Difficult Go" decision issues, and
- Industrial participation is being used to strengthen the early design process.

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