**Draft Program Plan for TNS—
The Next Step After the Tokamak
Fusion Test Reactor**

Part I—Summary

M. Roberts

MASTER

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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Fusion Energy Division

DRAFT PROGRAM PLAN FOR INS
THE NEXT STEP AFTER THE TOKAMAK
FUSION TEST REACTOR.
PART I — SUMMARY

Date Published - October 1977

M. Roberts, Program Manager

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Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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This summary is Part I of a four-part report which comprises the
Draft Program Plan for TNS. The other parts of the report are

ORNL/TM-5983	Part II R&D Needs Assessment
WFPS/TME-044	Part III Project Specific R&D Needs
ORNL/TM-5984	Part IV Program Planning

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FOREWORD

The Next Step (TNS) Program, established by ERDA's Division of Magnetic Fusion Energy at ORNL in early 1976, has two principal objectives:

1. To demonstrate in a timely fashion a fusion reactor core that can be extrapolated to an economically viable fusion reactor.
2. To provide a near-term means of focusing the efforts of the National Fusion Program to achieve the first objective.

This first draft of an attempt to outline a TNS program plan addresses the second objective. The draft program plan is presented in four parts:

- PART I Summary
- PART II R&D Needs Assessment
- PART III Project Specific R&D Needs
- PART IV Program Planning

This assessment was developed initially in an intense few-week period, based upon the understanding and information which has been built up at ORNL and Westinghouse over the preceding years by participation in the Fusion Program in general and in the Tokamak Fusion Test Reactor (TFTR) [both the Feasibility/Burning Experiment (F/BX) and the Two Component Torus (TCT)], the Experimental Power Reactor (EPR), and prior TNS studies, in particular.

In attempting to develop a program plan, two kinds of information were included in the assessment, namely, current status and extrapolation. With rapid technical progress being made in many laboratories, elements of the current technical status should be reevaluated on perhaps a semiyearly or yearly basis. Since the fusion program is tied strongly to the nation's energy program in general, the extrapolation can change and does change on a much more rapid time scale. In particular, this "snapshot" of the TNS support program taken in January-February 1977 does not take into account budget changes discussed in the same period and does not reflect the evolution of schedular planning that occurred

in the March-April 1977 period. As a result, some of the implications for action based upon the targeted FY-1980 line item are no longer meaningful, whereas the basic arguments still apply but to a line item some years later.

ACKNOWLEDGMENTS

Development of the information contained in this Draft Program Plan has resulted from the efforts of many people in the fusion community. The principal contributors are members of the Oak Ridge TNS Program team, both at ORNL and Westinghouse, who have devoted their full efforts to this task for many weeks. Bringing specific technical expertise to the development for varying lengths of time have been individuals from the ORNL Fusion Program and from various institutions around the country. The participation of teams from the LASL-UT OH Study, the NBS Low Temperature Materials Program, the C. S. Draper C&I Program, as well as specific critical comments of individuals from PPPL, University of Wisconsin, and Science Applications, Inc., is much appreciated. From ERDA-DMFE, J. O. Neff and his colleagues have provided valuable guidance and comments; S. Waddle and G. Benedict have participated in the review process from ERDA-ORO. This document has benefited considerably from critical reviews by L. A. Berry, J. D. Callen, D. D. Cannon, J. F. Clarke, G. G. Kelley, G. A. Krist, M. S. Lubell, A. T. Mense, J. A. Rome, and G. Schilling.

Throughout this exercise, J. F. Clarke has provided valuable direction and strong support. The high level of timely, professional support from the secretarial and Technical Publications staffs has made rapid dissemination of this information possible.

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ABSTRACT

A draft program plan for TNS has been prepared which consists of two basic parts — an R&D Needs Assessment and a Project Plan with schedules and necessary implementation steps. In this brief but intensive effort, questions concerning (1) the present basis for the TNS program, (2) the principal gaps in the supporting program, and (3) the necessary actions to be taken to implement the TNS program were examined. The study supported the thesis that the physics and technology bases do exist from which to start the TNS design as a central fusion program goal. Specific recommendations are made to emphasize those physics, technology, and engineering areas in which there are program gaps. In the project engineering study, a basic schedule with close support from the R&D program is developed from which recommendations on administrative actions and areas for further elucidation are made. This document presents in summary form the findings of the study, the development of the principal theses, and the recommendation to ERDA-DMFE.

1. INTRODUCTORY SUMMARY

1.1 Content, Scope, and Purpose of the Document

1.1.1 Content

This summary document is intended to

1. set the rationale for this study (Section 2 — Why start TNS now?),
2. present the findings of our preliminary study (Section 3 — What do we have in place now, what will be coming in place, and is it timely?),
3. present the recommendations (Section 4 — What specific actions should be initiated?),
4. make clear a recommended path to take to improve this work (Section 5 — Questions yet to be addressed), and
5. reiterate the necessity for initiation of the reference design activity (Section 6 — TNS is needed now).

1.1.2 Scope

Three principal areas of investigation and preparation comprise the TNS Program activities.

- development of the technical basis for direction and decision
- identification and assessment of the supporting research, development, and demonstration programs
- program planning

The latter two areas are the topics for discussion here. The first area — that of technical work — is being reported on a regular basis by frequent reviews and reports.

1.1.3 Purpose

Earlier assessments of the Research Development and Demonstration* (RD&D) needs^{1,2,3} and program plans^{4,5} have been made for advanced, EPR

* Research Development and Demonstration (RD&D) and Research and Development (R&D) are used interchangeably in many places throughout this document.

tokamak systems. What, then, is the difference between the earlier work and this present effort? The principal difference, aside from improved knowledge of plasma physics and technology, is the specific project nature now central to these studies. Earlier studies addressed the fusion condition, and more recently the generic fusion reactor; but this present study takes the evolutionary process another step toward a conceptual design and considers specific device objectives in a specific time frame with a specific schedule based upon specific programs.

This assessment and planning work is being carried out for at least five reasons:

- The need to establish a written, coherent, and comprehensive plan for this vast national undertaking that will become the focal point of the fusion program.
- The need to answer valid and pointed questions that are being asked about the existence of a relevant R&D base for a near-term, high-cost fusion enterprise after TFTR.
- The need to make clear what design-specific R&D will be required in addition to the generic base programs now under way.
- The need to face the extraordinarily difficult task of interfacing the fusion physics research program, accustomed to an output of continually evolving judgments, with the construction project, characterized by specific decisions on specific dates.
- The need to initiate discussions now to provide the basis for moving forward to the earliest fusion reactor demonstration.

1.2 Summary of the Study Findings

The information contained in this document represents the brief but intensive efforts of the Oak Ridge TNS Program Team^{*} to answer the following questions:

^{*}The Oak Ridge TNS Program Team is made up of individuals from ORNL and UCC-ND Engineering, Westinghouse Fusion Power Systems Department, and key industrial participants. ORNL's Fusion Energy Division provides technical management and plasma physics, plasma engineering, and fusion technology with support in fusion reactor technology from ORNL's Neutron Physics, Chemical Technology, and Metals and Ceramics divisions; UCC-ND's Engineering organization provides design engineering direction and review and project engineering. Westinghouse provides the engineering design team, and individuals from General Electric Co., Grumman Aerospace Co., Westinghouse Electric Co., and Burns & Roe, Inc., provide special technical expertise.

1. Is there an adequate basis of R&D support for the TNS program as a central, ambitious goal for the fusion program?
2. What are the principal gaps in the current and projected R&D program?
3. What must be done to permit operation of TNS in the mid 1980s?

The findings of our preliminary study provide these answers to the questions:

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 1980s.

On the first point — support base — significant strides have been made in both fusion physics achievement (in plasma density, energy confinement, plasma temperature, and effective impurity level) and operational understanding. 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. Some areas (e.g., impurity control) require more study before a clear picture of the problem itself can be developed, and other areas (e.g., ash removal) might first be properly addressed in TNS. 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), 150-keV beams for TFTR, and tritium handling for the Tritium Systems Test Assembly (TSTA). Adequate power electronics capability exists in industry for the poloidal field (PF) system requirements, although preliminary estimates indicate at high cost.

On the second point — principal gaps — those areas known to require more knowledge and increased emphasis are the subject of current and planned investigation, with three principal exceptions in physics and

between seven and fifteen exceptions in technologies. These exceptions form the principal gaps.

- A comprehensive plan covering both impurity and particle control and fueling must be formulated on a timely basis to identify the best way to proceed in this most uncertain area, which has been made even more critical by recent cross-section data calculations;⁶ rapid implementation of the plan must follow if gap is to be filled.
- The need for experimental investigation of configuration maintenance and optimization in high- β , high temperature plasmas is not now being met in any existing or near-term facility; in the near-term (i.e., about 3 years) the two facilities closest in capability, namely Doublet III and PDX, will be addressing specifically Doublet shapes and divertor operation respectively. Present capability does include the ability to develop but not to maintain the configuration of interest. Therefore, either a revision of current objectives for the relevant, existing devices or consideration of a new device is called for.
- 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. These applications-oriented efforts, addressing the most uncertain problem areas in TNS plasma physics, are essential to make transport code predictions reliable and complete.
- 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 might need increased emphasis depending upon TNS design decisions. (For this study aimed at the earliest schedule, it was judged necessary and sufficient to assume existing technologies.)

Nb₃Sn TF coils (if required)

Nonconducting structural materials for superconducting (s/c) PFC (if s/c is used)

Active impurity control technology (if passive techniques are inadequate)

High power negative ion source }
300-keV NB switch tube } (if >200-keV beams are needed)

High velocity pellet injection (if pellet fueling is necessary and 2000 meters per sec is inadequate)

- Two programs have critical timing questions in the generally compressed project schedule and must be closely examined further.

NbTi TF coils (questions of prototyping, manufacturing, and assembly contingent upon technology development and engineering)

Pellet fuel injector (need is principally contingent upon physics information; given that, questions of developing backup techniques are contingent upon both physics and technology)

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:

- Development of a schedule aimed at 1986 to 1988 (the beginning of FY 1987 was used as a specific target) has resulted in a preliminary judgment that a 1988 completion requires an aggressive program, that 1990 is likely, and that 1986, though highly improbable, is not impossible; starting immediately was assumed throughout.
- The principal, quantifiable critical path is construction of and machine assembly within the main test cell (tokamak building), i.e., basically the path associated with preparations for and manufacturing and assembly of TF coils.
- 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 must be chosen in mid FY 1977, 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 to achieve the TNS goals most expeditiously.
- The planning efforts have provided the preliminary schedules linking the project with R&D support with which to develop the necessary information supporting the mid FY 1977 reference design choice.

Underlying the discussion of adequacy and timeliness 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.

Four tasks remain to be undertaken in a serious way in addition to any refinement or updating of the current information.

1. Careful considerations of support program costs are necessary.
2. An analysis of the schedule's sensitivity to the outcome of the ongoing R&D program and budget considerations remains to be done.
3. A determination of the implications of early design choices is needed to avoid serious difficulties later.
4. Effective involvement of the entire fusion community in this process is a necessary condition for meaningful planning.

REFERENCES FOR SECTION 1

1. S. O. Dean et al., *Status and Objectives of Tokamak Systems for Fusion Research*, WASH-1295; W. M. Stacey, Jr., et al., *Tokamak Experimental Power Reactor Studies*, ANL/CTR-75-2 (June 1975).
2. M. Roberts et al., *Oak Ridge Experimental Power Reactor Study. Part 6: RD&D Needs*, ORNL/TM-5577 (January 1977).
3. Letter from Z. M. Shapiro to E. E. Kintner, Critique of EPR, September 1975.
4. *Fusion Power by Magnetic Confinement Program Plan. Vol. II: Long-Range Planning Projections*, ERDA-76/110/2 (July 1976).
5. T. E. Shannon, R. L. Reid, et al., *Oak Ridge Experimental Power Reactor Study. Part 5: Engineering*, ORNL/TM-5575 (February 1977).
6. R. V. Jenson, D. E. Post, et al., *Calculations of Impurity Radiation and Its Effects on Tokamak Experiments*, PPPL-1334 (March 1977).

2. MOTIVATION TO PROCEED NOW

The last statement in Sect. 1.1.3 postulates that now is the time to proceed toward active preparation for a fusion reactor core demonstration. Is this really necessary, and is it possible?

The answer to the first question is a straightforward yes and comes directly from an examination of the fusion program requirements and elementary construction schedules.

The answer to the second question requires a much more thorough examination, such as this study initiates, and is judgmental in any case. We believe the answer is yes, with the clear statement that preparation for initial TNS design is necessary and possible now, not commitments to final design or construction.

2.1 The Necessity of Proceeding Now with the Preparation for TNS

"Preparation now for TNS" means specifically choosing a set of reference design parameters with a backup and planning to develop a cost estimate for the facilities portion of TNS by April 1978.

Starting from the view that commercially available fusion power is a highly desirable national goal, then a sequence of five arguments make the case for beginning TNS now.

1. At present, and subject to continual reexamination, the tokamak approach is most likely to meet the principal TNS objective of a fusion reactor core demonstration.
2. The present understanding leads one to conclude that there is a clear need in the mid to late 1980s for a new experimental device for fusion work, one that is more reactor-like than the TFTR device presently under construction.
3. Postulating about four years of new state-of-the-art work in TFTR [one year of hydrogen plasma characterization, about one year of conversion to and experience with full deuterium-tritium (D-T) operation, and two years of work to reach and understand the full potential of the device], TNS would be most effective if initial operation occurred in about 1986 to 1987.
4. Current construction experience on large reactor projects indicates at least 60 to 70 months elapsed time between initiation and completion; this interval requires a 1980 to 1981 start as

corroborated by elementary schedule development (see Fig. 1 for an outline of the schedule, Sect. 3 for a more complete exposition of the schedule, and Part IV for a detailed discussion).

5. Initiation of a facilities construction line item in 1980 requires a budget submission in April 1978, which in turn requires a conceptual design in the preceding year. This schedule means starting nominally in April 1977 for facilities projects of significant size and complexity, and TNS is certainly one. In fact, engineering judgments based upon nonfusion program experience would probably estimate a two-year design period before a cost estimate of a large facility with uncertain interfaces. Therefore, regardless of uncertainty in the end date, conceptual design should be started as soon as possible.

The arguments above present the program for a "roll forward" approach, in which one develops future needs on the basis of current experience; the technical aspects of this approach form the basis of Sect. 3. An equally valid argument for starting now comes from the "roll backward" approach, in which one develops future needs on the basis of end-point requirements. This argument is fully developed in the *Fusion Power Demonstration Reactor Plant Study - Interim Report*.¹ An essential part of the argument in the Demonstration Report is the following:

- For commercial feasibility in this century, the number of new technologies and facilities for fusion demonstration must be minimized.
- Economic trends for fusion plants based upon the present studies using trapped-particle or empirical transport scaling indicate unit capital costs decrease with decreasing plant size for given plasma beta, thereby favoring power modules of minimum size that ensures ignition.
- Plasma characteristics for a commercial module are essentially the same as those for an ignition demonstration; thus the extrapolation from TNS (ignition demonstration) to demonstration (commercial feasibility) is in engineering function, not in plasma beta, size, or regime.
- Sharing the large, costly pulsed power systems among three to five power-producing tokamak modules would significantly ease the economic burden.

Necessary for a successful demonstration of this sort in the decade of the 1990s is a TNS in the 1980s which would provide the necessary

Fig. 1. A simplified version of the overall schedule by major elements of the Work Breakdown Structure (WBS). See Part IV for a full explanation. (Heavy line represents principal, quantifiable critical path.)

* The WBS 1 consideration here does not include site and contractor selection — a step, discussed in April and May, which may add two-to-three years to the overall process.

fusion physics capability, namely ignition with average beta in the economic range of 5 to 15% and the essential technology and engineering information.

The Demonstration Report does present these economic, technical, and engineering considerations in full. Let it suffice to say here that a TNS using minimum extrapolations of current and near-term technology can be the first step toward a facility which can be upgraded to power conversion, tritium breeding, and high duty cycle, and later to a commercial prototype by adding additional reactor modules to a common pulsed electrical system.

2.2 The Ability to Proceed Now Toward TNS

The following points are frequently raised that question the fusion program's ability to proceed now with a reference design and initiation of a facility conceptual design:

1. Physics base is uncertain
2. Technology base is shallow
3. Cost estimates are high
4. Funds are better spent elsewhere

Each of these cautions is worthy of careful consideration. In our judgment, presented in the following paragraphs, this consideration does show that preparation is both possible and necessary:

1. The physics base is uncertain, as it usually is at the beginning of a fusion venture. The requirement then is to match a flexible design program to the uncertainties in the physics program.

The "physics base" can be defined in two complementary terms: (a) the pragmatic base of achievements in both parameter values and operational understanding and of experience, and (b) the fundamental base of development and validation of predictive tools. An extended discussion of the base is presented in Sect. 3.1.1.1.

From the practical view of past experience, Figs. 2a and 2b show the state of the art in the United States tokamak experience as it applies to this question.

ORNL-DWG 77-5022

**PHYSICS BASE IS UNCERTAIN –
AS USUAL AT BEGINNING OF FUSION VENTURE**

ORNL-DWG 77-5023

**AS PLASMA SIZES INCREASE, SO DOES TIME BETWEEN
COMMITMENT TO PREPARE AND COMMITMENT TO BUILD**

Fig. 2. Historical argument about initiation of fusion projects.

- In Fig. 2a, one can see that each succeeding large tokamak step has been initiated on preliminary information before the physics base was "certain"; here, "certainty" would be useful operation of those devices then under construction but not complete. In Fig. 2b, a second feature emerges, namely the lengthening of the time between "start of preparation" and "start of construction." In the Oak Ridge Tokamak (ORMAK), that time difference was weeks; in TFTR, the interval was many months; and, in TNS, the interval appears to be years.

The design program must include a growth of knowledge in addition to a specific machine design schedule.

- We are principally concerned about the ability to understand the outcomes of the near-term experiments. If this ability is not continuously increased, then the risk of generating incorrect design information will be increasingly greater as we move further from the range of application of the present operational understanding. The beginnings of a plan to match the design program to the physics program are discussed in Sect. 3.

2. The technology base is indeed too shallow for an optimized reactor, but it is sufficient to begin preparation for TNS.

- There is a superconducting toroidal field coil development and demonstration program in place producing NbTi coils on a schedule integratable with TNS schedule.
- There is a 150-keV Neutral Beam Program base in place, and TNS beams can be made available. In this area, there is a committed program for 120-keV TFTR beams at LBL and the capability to extend voltage, power level, and pulse lengths at ORNL.
- There is a tritium-handling demonstration facility coming into place on a compatible schedule.
- There exists the necessary technology for the electrical systems and hardware.

There is real economic need for advancing technology as it applies to reactor optimization, but in most crucial areas, current technologies can be made to work. The balance of cost, reliability, and availability for current vs advanced technologies must be made on an individual basis.

3. Presently projected costs are too high for a 1977 hardware commitment, but not for starting the design process for 1982.

- Conceptual design is a necessary prerequisite for a cost estimate — there has been no conceptual design done yet for TNS. Any actual hardware commitment will come after evaluation of the next few years' experience with physics and technology experiments — ORMAK Upgrade (O-U), Poloidal Divertor Experiment (PDX), Doublet-III (D-III), Impurity Study Experiment (ISX), LCP, and TSTA.
- If TNS design is confirmed, work continues; if not, work is redirected or stopped — with a sharp program focus and system experience gained, at minimum cost.

4. These project funds are needed elsewhere to advance any one specific area, certainly, but to advance the integrated fusion program further along the path to commercialization, they are best used in supporting a strong system focus.

Only three percent of the tokamak budget is being used to provide system guidance to the whole tokamak program (Fig. 3). This small fraction for TNS will serve to maintain the option in 1980 of proceeding to an ignition demonstration in the mid 1980s without a two-year delay.

ORNL-DWG 77-4250

PROJECT FUNDS NEEDED ELSEWHERE —

**ADVANCING ONE SPECIFIC AREA
BUT FUSION PROGRAM**

**YES
NO**

FY 78 + FY 79 FUNDS ~300-500M

**IS THERE A BETTER
2 YR, 3% INVESTMENT?**

Fig. 3. Relationship of TNS project funds to whole tokamak budget.

2.3 Conclusion about Proceeding Now

On the basis of these arguments of need and ability and on the basis of the RD&D needs assessment and program planning discussed in Sect. 3 and in Parts II, III, and IV, our judgment is that a TNS program can be and should be started, matching current expenditures to the increasing probability of success.

REFERENCE FOR SECTION 2

1. D. Steiner, *Fusion Power Demonstration Reactor Plant Study - Interim Report*, ORNL/TM-5813 (March 1977).

3. FINDINGS OF THE STUDY

3.1 R&D Needs Assessment

Three different facets of the research, development, and demonstration needs comprise the whole, namely:

- Generic and specific fusion physics questions such as:
 - How will plasma transport scale with collisionality?
 - How many volts and voltseconds will TNS need?
- Generic technology questions such as:
 - Will fabrication of large-scale superconducting TF coils be demonstrated by the time of TNS device cost estimate?
- Specific engineering questions such as:
 - What is a viable technique for repair or replacement of the innermost PF windings?

In the three sections that follow, each of these facets is treated in turn.

3.1.1 Fusion physics situation as applied to TNS

Supporting information for this summary is found in Part II, Sect. 3. Three tangible outputs are presented there.

- Development of the questions that should and can be answered in each major area at the various phases of the design process.
- An evolutionary development (listing) of the physics issues requiring further study and an indication of facility availability.
- A discussion of the specific TNS physics needs.

Our analysis of (1) the base from which to ask the questions, (2) the ability to address the questions, and (3) the projected timeliness of the answers is presented in the following paragraphs.

3.1.1.1 Base from which to ask questions. The adequacy of a base in this fundamental and complex area — fusion physics — can be measured in two complementary ways.

- Pragmatic achievement (plasma parameter values attained)
- Fundamental understanding (ability to predict extrapolations with confidence)

With respect to achievement, four numbers are usually quoted:

1. plasma density N ,
2. energy confinement time τ ,
3. plasma temperature T , and
4. effective impurity level Z_{eff} .

Even though these parameters are a simplification of the real situation characterized more by plasma regimes, profiles, transients, etc., they still represent quantifiable and recognizable measures of success.

Taken in the usual combination, the average values needed for an ignition demonstration in the TNS plasma are

$$\left. \begin{array}{l} N\tau \sim 2 \times 10^{20} \text{ sec/m}^3 , \\ T \sim 10 \text{ keV} , \\ Z_{\text{eff}} \sim \leq 1.5 . \end{array} \right\} \text{TNS}$$

(The Z_{eff} measure does not yet reflect the serious impact of very small amounts of high Z impurity). At the initiation of the tokamak studies — late 1960s — the values were

$$\left. \begin{array}{l} N\tau \sim 10^{17} \text{ sec/m}^3 , \\ T \sim 0.5 \text{ keV} , \\ Z_{\text{eff}} \sim 3-10 \gg 1 . \end{array} \right\} \text{T-3 (USSR)}$$

By the early 1970s, these values had been improved to

$$\begin{array}{ll} N\tau \sim 10^{18} \text{ sec/m}^3 , & \text{ORMAK (ORNL)} \\ T \sim 1 \text{ keV} , & \text{ST (PPPL)} \\ Z_{\text{eff}} > 1 . & \text{TFR (France)} \end{array}$$

Within the last couple of years, significant improvements have resulted in

$$\begin{array}{ll} N\tau \sim 2 \times 10^{19} \text{ sec/m}^3 , & \text{Alcator (MIT)} \\ T \sim 1.8 \text{ keV} , & \text{ORMAK (ORNL), TFR (France)} \\ Z_{\text{eff}} \sim 1 . & \text{Alcator (MIT)} \end{array}$$

Although the experimental regimes in ORMAK and Alcator are characterized by many parameters in addition to the four quoted above, there are some important points in common ($Z_{\text{eff}} \sim 1/N_e$ and $\tau_E \sim N_e/Z_{\text{eff}}^{1/2}$ in specific situations). If it becomes possible through improved, detailed understanding to consider the two experiments as complementary parts of a generic tokamak, then even greater improvements can be inferred.

In the commonly used measure of remaining distance to success,

$$\frac{(N\tau T) \text{ TNS}}{(N\tau T) \text{ at any given time}} ,$$

progress is clear and satisfying as seen by the change in this quotient over the years:

$$\begin{array}{l} \sim 10^6 \text{ in early 1960s (mirrors and theta pinches) ,} \\ \sim 2 \times 10^4 \text{ in late 1960s ,} \\ \sim 2 \times 10^3 \text{ in early 1970s ,} \\ \sim 4 \times 10^2 \text{ today in Alcator , and} \end{array}$$

using the generic tokamak concept, $\sim 10^2$ in Alcator and ORMAK taken together.

With respect to understanding or the ability to predict extrapolation with confidence, Table 1 can serve to focus the discussion.

The end point of the "understanding" process is the ability to provide definite criteria for reactor designers. A convenient starting point is the physics assessment made in WASH-1295 in 1973. At that time, plasma confinement and heating were the dominant issues treated in

Table 1. Evolution of physics problems from abstract to specific design inputs

Early development				Present development			
Basic physics approach (in the abstract) WASH-1295 1973		Detailed basic physics approach (in the abstract) EPR RD&D ^a 1976		TNS-oriented framework (applied to specific design requirement) TNS RD&D ^b 1977			
Goals (G), Problems (P), Topics (T)	EPR Problem areas			Discharge-cycle oriented	Design-oriented		
	EPR RD&D No.	Title	TNS RD&D No.	TNS No.	Primary design inputs A-D from TNS No.	Secondary design inputs WBS No.	
I. Confinement and heating in plasma physics regime (G)				1. Establishing the current (1.2 Wall-plasma interaction) ^c			
A. Configurational stability (P)				2. Heating to ignition	PFS - magnetics and plasma shaping (A) 1,3	Electrical 23, 24 (A-D)	
1. MHD ^d equilibrium (T) →	A-1	Macroscopic equilibrium	→ 3				
2. MHD stability (T) →	A-2	Macroscopic stability	→ 3				
B. Plasma transport and scaling (P)				(2.4 Heating profiles, wall loadings in n ^c plasmas)			
1. Microscopic plasma transport (T) →	A-3	Plasma transport	→ 3				
2. Scaling laws (T) →							
C. Heating (P)				3. Maintenance of discharge during burn phase	Heating (B) 1.2, 2		
1. Heating (T) →	A-4	Plasma heating	→ 2				
D. Boundary effects (P)						Mechanical 22, 24 (A-D)	
1. Impurity control (T) →	A-5	Impurity control	→ 7				
2. Plasma material interactions (T) →	A-6	Plasma edge	→ 7				
II. Burn for net energy gain (G)	A-7	Fueling	→ 6	4. Removal of heat	TF (C) 2, 3, 4, 7	Support 25 (A-D)	
	A-8	Plasma dynamics		5. Ash removal			
		Start-up	→ 1				
		Burn control	→ 3-6				
		Shutdown	→ 8				
III. Other (G)	A-9	Diagnostics		6. Particle replacement	Particle control (D) 1.2, 2.4, 5, 6, 7, 8	IC&D 26 (A-D)	
	A-10	Atomic and molecular cross sections		7. Prevention of impurity buildup			
				8. Shutdown procedure			

^aM. Roberts et al., Oak Ridge Experimental Power Reactor Study. Part 3: RD&D Needs, ORNL/TM-5577 (January 1967).

^bThis document.

^cSee Table 3 in Part II for complete listing of detailed areas (1.1-1.3, 2.1-2.5, etc.).

^dMagnetohydrodynamic.

a list of four major headings subdivided into seven generic problems. The entries in column one, headed WASH-1295, represented the first step toward the end point referred to above; this first step was a basic physics approach to the fusion reactor considered in the abstract.

As the program began to focus on a class of reactors, EPR, another step was taken. This second step, EPR RD&D shown in column 2, represents a more detailed and comprehensive approach to the problem, but one still oriented from a basic physics viewpoint. In this column, the "new" issues listed involve getting to ignition and to burning after ignition is achieved.

In the present and third step in this process, the questions that must be answered for a specific device, TNS, become the framework for discussion of the physics issues. In this view (column 3), eight discharge-cycle-oriented design areas are identified, and within them about 30 specific areas in which more knowledge is necessary are separately dealt with in Part II, Sect. 3.

In the fourth and next step in the process, the discharge-cycle-oriented physics problems become reordered to match the design-oriented arrangement. Shown in the column headed "primary design inputs" are the four principal design areas (A-D) requiring intimate involvement with the basic physics issues. Under each design area are shown the essential contributing discharge-cycle-oriented issues from column 3. In the column headed "secondary design inputs," the major elements of the device portion of the WBS are displayed. Each of these four elements receives its input from each of the four primary-design input areas (A-D).

Through the transitions between each of the columns going from left to right, from abstract to specific, the basic physics issues can be coupled into the design requirements for each specific WBS system.

In addition to the basic fact that we can now begin to define specific design-oriented experimental questions that need to be addressed, the following brief discussion presents an attempt to establish a measure of understanding.

Each of the eight design-oriented issues is being addressed to some degree on a theoretical level. The component parts vary in their status: some such as "transport" are topics of long-standing investigations; others such as "start-up" and "rapid heating to high β " are newly under way; and others such as "impurity control," which are characterized by a paucity of real understanding, are topics of common interest everywhere.

On the experimental level, the situation differs somewhat. Each issue is being faced by necessity but in different ways. "Start-up" and "shutdown" are characterized more by empirical procedure than by systematic understanding, but heating and transport are being systematically studied (Table 2).

SUMMARY: Each topic is being investigated theoretically at some level. Some crucial experimental studies are not yet under way. The real impact of the theoretical and experimental program uncertainties comes in dealing with the second problem, the ability to address the necessary issues in the near-term future.

3.1.1.2 Ability to address these questions. Will the fusion program continue the activities now being systematically investigated so that they apply to regimes of direct TNS relevance? In general, the answer is yes, with one significant question. Given the names of the fusion physics problems as in Table 1, we can now consider the requirements for solutions. A strong theoretical and computational framework is a basic ingredient for solutions. There is, however, a clear lack of fundamental understanding in the area of the TNS operating regime. There are no experiments in the low collisionality regime ($\nu^* \sim 0.01$) that can serve as guides for selection of this theory. Experiments (PLT, PDX, ISX) in the near future will be addressing these questions so that a complementary theory and diagnostics program must be assured to make use of this experimental information.

Higher temperature and larger sizes can be obtained in even more applicable regimes in the Princeton Large Torus (PLT) and TFTR.

Does the fusion program plan to initiate those activities in Table 2 listed as being now lacking? The answer here is mixed, as shown in Table 3. The many "yes" entries in Table 3 testify to the fact that

Table 2. A measure of physics understanding — current work in progress

Essential design topics (discharge-cycle orientation from Table 1)	Theoretical studies		Experimental work	
	Longstanding	Newly under way	Empirically based	Systematically investigated
1. Establishing the current (start-up)		V ^a	V	X ^b
2. Heating to ignition		V	V	V
3. Maintenance of discharge during burn phase				
• configuration	V		V	X
• beta		V	V	X
• poloidal field systems		V	V	X
• scaling	V		V	V
4. Removal of heat	V		V	X
5. Ash removal				
6. Particle replacement				
7. Prevention of impurity buildup	V		V	X
8. Shutdown procedure		V	V	X

^aV indicates specific topic being investigated.

^bX indicates current lack of experimental or theoretical work.

Table 3. A measure of the ability to address the TNS questions in the planned experimental program

Essential design topics	Systematically being studied now?	Possible in next generation of experiments ^{a,b?} (1977-1978)	Possible in succeeding generations ^{a,b?} (1979-1980)	Possible in final experiments ^{a,b,c?} (1981-1982)
Start-up	Started	Yes— ^d	Yes—	Yes—
Heating	Yes	Yes	Yes	Yes
Maintenance of discharge				
Configuration (ohmically heated)				
Circular	Done to 0.5 sec			
Elliptical (+D)	Started ^e	Yes	Yes	Yes
Doublet	Started ^e	Yes	Yes	Yes
Beta (beam heated)	Started ^f	Yes	Yes	Yes
		but need configuration maintenance (many seconds), optimization, and collisionless studies		
Scaling	Yes	Yes	Yes	Yes
Fueling	Started	Yes	Yes	Yes
		(if pellet development is successful)		
Impurity control	Started	Yes	Yes	Yes
Shutdown	Equipment available, but no plans			

^a Assumes capability exists with minor modifications and without regard to experimental schedules, i.e., how many simultaneous experiments can be conducted.

^b Assumes about one year from time of initiation of operation to first meaningful results.

^c Assumes this is last input to basic TNS design, which is at this time in the detailed drawing-construction phase. Continuing information will affect operational procedure and, of course, if necessary alter even completed detailed design or fabrication.

^d Yes = hardware + plans. Yes- = hardware but no plans. "Plans" is not equivalent automatically to a funded, committed program with milestones incorporated as a format element in the DMFE program.

^e Have 15% of flux outside separatrix for 15 msec; need 40% for ~1 msec.

^f Through 1%; need 5 to 10%.

the hardware exists in most instances to do the job and that plans also exist in most cases. There is an important distinction that must be made, however, between "plans" and "program commitment." Until each area is the object of an actual program commitment with assigned budgets and milestones representing an institutional commitment, then the "yeses" are incomplete. An evaluation of the actual commitments was not done here systematically.

SUMMARY: The fusion program in its near-term plan does have the ability to address the necessary questions with an ever increasing capability with two principal groups of exceptions.

1. There is no facility presently planned that is able to investigate configuration maintenance and then optimization at high β and temperature with a real-time active feedback, poloidal field system. Configuration development and MHD stability can be studied in planned facilities, as can the maintenance of circular, beam heated plasmas. Configuration maintenance or the evolution of beam heated, high- β , noncircular cross section plasma equilibria is not now covered in the plan.
2. There must be a stronger applied effort in impurity dynamics, plasma transport, and, most critically, in coupled equilibrium, stability transport, and heating simulation of ignition scenarios.

Associated with the fulfillment of these specific theory efforts is the probable need for additional computing facilities.

3.1.1.3 Timeliness of the answers. Whether or not the planned physics program is "timely" depends upon the schedule against which "timeliness" is being measured and upon what kinds of outputs are expected. A detailed development of both sides of this question now is not meaningful because of uncertainties in both areas. What can be done, however, lends credence to the thesis that the physics program can provide timely input.

The design process for TNS goes in stages from considerable uncertainty to minimum uncertainty. So does the physics understanding process. Do the two match in large measure? As outlined in Table 4, yes, they do.

3.1.1.4 Summary of physics findings. A physics basis composed of achievements in plasma parameters, considerable operational understanding,

Table 4. Elementary integration of design and physics understanding time scales^a

Fiscal year	1976	1977	1978	1979	1980	1981	1982
<u>Design stages</u>							
Facility		PCD & CD ^b	Advanced eng.	Prelim.	Detailed eng. & Construction		
Scoping studies				eng.			
Device		Device envelope PCD feasibility study	Conceptual design	Advanced eng.	Prelim. eng.	Detailed eng.	
<u>Levels of information</u>		<u>Initial (Ranges)</u>		<u>Preliminary (Techniques)</u>		<u>Final (Detailed data)</u>	
<u>Physics stages</u>							
Basic achievements and identification of issues	First focused studies on special topics - preliminary choices of heating energies, start-up scenarios, etc.		Investigation of basic assumptions at high- β , low Z; specify techniques with confidence		Verification and quantification of expectations in large size and low Z, high T		
	PLT-beams, ISX		PDX, ISX-U, D-III		TFTR(H), PDX-U		

^a Potential impacts on schedules of the February 1977 budget reductions are not yet considered here.

^b Preliminary conceptual design and conceptual design.

and a broadly based and applied program of theoretical support does exist from which to begin the first steps of the TNS design process. These first steps require the ability to define ranges of expected design parameter values; subsequent steps in later years require more specific inputs.

The ability to address the relevant, essential questions in the near-term does exist with two significant exceptions.

- There must be a configuration maintenance, high- β and high temperature, actively controlled plasma facility capable of providing answers in this central plasma regime expected for TNS operation.
- There must be a stronger applied theoretical program in impurity dynamics, plasma transport, and, most critically, in coupled equilibrium, stability, transport, and heating simulation of ignition scenarios. With such a program our present, incomplete knowledge of magnetized plasma (and impurity) transport and heating can be sufficiently improved to support fusion development over the next decade.

The physics program outputs, both experimental and theoretical, can be timely as well as can be understood now with the uncertainties that exist in both the TNS scheduling and the physics program.

3.1.2 Fusion technology situation as applied to TNS

The starting point for the technology discussion is the hardware-oriented Work Breakdown Structure (WBS). The device hardware portion is shown in Fig. 4. The full WBS is discussed in Sect. 3.2 and more completely in Part IV.

Table 5 outlines the relevant base program for each system, whether planned programs will address necessary questions, and whether this is done on a timely basis.

Each of the technology areas is addressed specifically with a prose summary and a schedule comparing development to design schedule in Part II, Sect. 4; an example of the schedule charts is shown in Fig. 5. The schedule chart contains six principal pieces of information:

1. the particular pieces of physics information needed at each design review to guide specific technology choices in this WBS system;

2. the principal R&D support program schedule;
3. the principal design and construction schedule elements leading to preoperational testing;
4. the design-specific tasks that are associated with the system;
5. a summary event line on which each key requirement or milestone is indicated along with two key distinctions:
 - a. ∇ — action by others, review by TNS,
 Δ — action by TNS, review by others,
 - b. Δ^+ — event presently programmed by DMFE,
 Δ^- — event not currently programmed by DMFE;
6. a judgment of probability of achieving the projected time increments is made for each individual element of the schedule:

likely — with business as usual atmosphere,
 possible — with aggressive atmosphere,
 conceivable — with totally optimistic program.

On the basis of information developed from schedule charts such as shown in Fig. 5, a summary assessment about all the WBS systems and their related technologies can be made.

SUMMARY: With a few exceptions, base programs exist in each area, planned programs are addressing the issues, and these planned programs, to the degree that such a judgment can be made at this time, do appear to be timely. The exceptions are in the toroidal field coils, impurity and particle control, energy conversion, main vacuum pumping, and central C&I systems as discussed in the footnotes to Table 5 and summarized in Table 6.

Fig. 4. The device hardware portion of the WBS with identifying numbers.

Table 5a. Tokamak systems: technology assessment

WBS No.	System	Existing adequate base program	Planned relevant program	Timely	Source
22a	Toroidal vacuum vessel	V ^a	V	V	TFTR, industry
22b	Machine structure	V	V	V	TFTR, industry
22c	Toroidal field coils	V ^b	V ^b	? ^{b,c}	ORNL/LCP ^d /SCMDP, ^e industry
22d	Poloidal field coils	V ^f	V ^f	V ^f	PDX, ^g TFTR
22e	Shielding	V	V	V	ORNL/Integral Expt.
22f	Impurity control	X ^h			
22g	Tokamak systems mockup	V	V	V	TFTR, JET, ⁱ industry

^aThroughout Table 5, V indicates specific topic being investigated, and X indicates current lack of experimental work.

^bAssumes NbTi s/c is required and adequate. If Nb₃Sn s/c coils are required, then a minimum of one additional year is added.

^cThe role of a full-size prototype and the method of integrating coil tests with design schedule in this critical path item are not yet fully clear.

^dLarge Coil Program.

^eSuperconducting Magnet Development Program.

^fAssumes normal PF coils. If s/c coils are required, then a nonconducting structural material must be used, perhaps incurring delays.

^gPoloidal Divertor Experiment.

^hIf more extrapolation of Alcator experience can be made to TNS plasma regime, then no vastly new technology base is required. If this is not possible, then some new technology such as that associated with divertors will be required. In any case, a study of limiter material technology requirements is necessary.

ⁱJoint European Tokamak.

Table 5b. Electric power and control systems: technology assessment

WBS No.	System	Existing adequate base program	Planned relevant program	Timely	Source
23a	Primary energy	V ^a			Industry, TFTR
23b	Primary and secondary distribution	V ^a			Industry
23c	Energy conversion	V	X ^b		Beam Prog., TFTR industry
23d	Standby or emergency	V ^a			Industry

^a Cursory examination of these areas indicates no development requirements; further investigation is deferred at this time.

^b Existing motor generator flywheel (M-G-F) sets along with solid-state devices and mechanical switches can satisfy the TNS needs, but potentially at prohibitively high costs. Associated with the cost issue is the development question of multiple ganging of solid-state devices. If circuit analyses indicate substantial cost savings in the solid-state switches (the dominant cost item) through use of homopolar machines, then the homopolar generator development program should be pursued vigorously for economic reasons.

Table 5c. Plasma heating systems: technology assessment

WBS No.	System	Existing adequate base program	Planned relevant program	Timely	Source
24a	Neutral beam heating system	V	X ^{a,b}		TFTR-ORNL
24b	RF heating systems	V	X ^c		PLT, ISX, EBT, ^d industry

^aTwo TNS requirements beyond TFTR beams must be addressed:

1. increasing ion source and switch tube pulse length capacity to about 10 sec from the present value of about 1 sec;
2. increasing the power per unit beam line to permit about 75 MW(e) to be physically accessed in the TNS device.

^bIf the decision is made to require neutral beams in the 300 keV range, then two additional requirements must be met:

1. development of a high power negative ion source;
2. development of switch tubes capable of 300 keV — present tubes are already put in series to reach 150 keV.

^cRF heating experiments at electron cyclotron resonant heating (ECRH) regimes provide a confident base of extrapolation in physics but not in technology. Present judgment is that it is not possible to develop high power ECRH tubes suitable for bulk heating by TNS schedule. Supplementary or complementary heating does seem reasonable, and an adequate supply of modest power, high frequency tubes could be available if microwave tube programs are supported at the present levels. At lower frequencies, there is less certainty over the effectiveness of ion cyclotron resonant heating (ICRH) or lower hybrid heating (LHH), but experiments are planned for PLT in the next two years. Preparation should be made to accelerate the RF program to such a level that if negative impurity control information comes from PDX (thereby making it more difficult to heat with beams), large-scale RF heating at frequencies below ECRH can be made possible.

^dElmo Bumpy Torus.

Table 5d. Tokamak support systems: technology assessment

WBS No.	System	Existing adequate base program	Planned relevant program	Timely	Source
25a	Remote servicing	V	V	V	TFTR, JET industry
25b	Fuel handling	V	V	V	TSTA
25c	Main vacuum pumping	X ^a			
25d	Heat removal and cryogenics	V	V	V	LCP, Fermi Lab.
25e	Experimental area ventilation	V			Industry, TFTR
25f	Radioactive waste handling	V			Fission
25g	Fuel injector	V	V	? ^b	ORNL, Univ. of Illinois

^aCompound gas pumping of helium and hydrogen isotopes has been identified and demonstrated by ORNL as a problem with commercially available cryo panels. Development work is needed here to support full-scale demonstration in TSTA.

^bThe timeliness of the fuel injector is questionable because of the uncertainty in physics requirements. If pellets are required and velocities of <3000 meters per sec are adequate, then the program is timely. If >3000 meters per sec velocities are required or other, high technology solutions are required, then timeliness is in doubt.

Table 5e. Instrument, control and data systems: technology assessment

WBS No.	System	Existing adequate base program	Planned relevant program	Timely	Source
26a	Central C&I	V	X ^{a,b}		All expts. CSD Lab. ^c
26b	Operations instrumentation	V	X ^{a,b}		
26c	Scientific instrumentation	V	X ^{a,b}		

^a A principal gap is plasma configuration sensing and control. As plasma pulse times become longer, active real-time feedback will be necessary. As importantly, the controlled plasma is expected to be a high- β , shaped plasma, which is not yet in hand. An important need, therefore, is experimental work with an actively controlled, shaped, rapidly heated plasma.

^b A second principal gap is control of abnormal discharges, which becomes important as the energy content of the plasma increases and the repair time lengthens. Specific attention directed to this area along with shutdown experiments is called for.

^c C. S. Draper Laboratory.

Fig. 5. An example of the program schedule chart prepared for each WBS system. The circled numbers 1-7 are keyed to the discussion in Sect. 3.1.2.

Table 6. Main gaps in the fusion technology program for TNS

Topic	New program commitment needed ^a		Focused study required	Uncertain criteria could require new or increased program	Timing unclear ^b
	Technically	Economically			
NbTi TF coils					V ^c
Nb ₃ Sn TF coils				V	
S/c PFC structural material				V	
Impurity control technology				V	
Limiter materials			V		
PF electrical systems		V			
NB switch tube and ion source pulse lengthening	V				
NB power per unit source	V				
High power negative ion source				V	
300-keV NB switch tube				V	
Compound gas pumps	V				
High velocity pellet injection				V	V
Plasma configuration sensing and control	V		V		
Abnormal operations control	V		V		

^aIn each case, the capability to proceed toward solution exists: the gap is in commitment, not capability.

^bApplies to those technologies assumed to be leading candidates for TNS (e.g., NbTi, positive ion beams, etc.). If design decisions require any of the six advanced technology programs shown in the column to the left, then those programs will show as "timing unclear" also.

^cV indicates specific topic being investigated.

3.1.3 Specific engineering questions as applied to TNS

An extensive examination of the specific RD&D needs of a set of particular TNS designs has resulted in four principal outputs.

1. The basis exists for significantly increased comprehension of the RD&D needs of a specific device.

In the EPR RD&D Needs document, about 45 technological problems were identified, described, and assigned a priority. In this present study (presented in Part III), each problem area has been investigated in more detail, and areas untouched or barely touched in the EPR study (primary power, remote servicing, operational instrumentation) were investigated for the first time in a consistent manner. In addition to ending up with a list more than tripled in number, the individual assessments are more complete and useful through the inclusion of "required data," "scope of test," and "alternatives."

2. The most critical issues identified were all being dealt with in the base program aimed at TNS (e.g., impurity control criteria, superconductor qualification, etc.). This independent check, i.e., beginning from the specific design (TNS) rather than from the generic reactor (EPR), corroborates the program plan decisions made thus far.

3. It is in this area that the absence of a reference design is most keenly felt. Carrying various TF coil options, impurity control options, and PF coil options results in a greater level of uncertainty than is desirable with given resources. Focusing on a reference design would permit this activity to be most effective.

4. As in the other two areas, a fundamental finding is that the capacity to investigate these problems exists. But is it usable? Unless focused, the programs that provide the resources will not provide the results in an integrated, timely manner.

It should be clear from the definition of this area that most of the work lies ahead, after the specific design path is chosen. Thus the value of this detailed investigation is to point out what must be done under the aegis of the project rather than to point out "gaps" to be filled by the base R&D program. That no different "gaps" were found in the course of the investigation is reason for satisfaction with the scope of the current program.

Table 7 contains a summary of the systems considered, the specific issue discussed, a judgment of priority, references to Part III, and WBS system number.

Table 7. Design-specific RD&D needs

No.	Item or system	Topic	Priority*	WBS reference
1.0	Tokamak			
1.1	Vacuum vessel assembly			22a
1.1.1-1	Vacuum vessel structure	Toroidal electrical resistance of vacuum vessel shell	2
1.1.1-2	Vacuum vessel structure	Vacuum vessel segmentation joints	2	
1.1.1-3	Vacuum vessel structure	Verification of vessel cooling system capability	3	
1.1.1-4	Vacuum vessel structure	Mechanical stability tests	3	
1.1.1-5	Vacuum vessel structure	Replaceable or maintainable electrical insulators	3	
1.1.2-1	Plasma limiter	Material damage studies	3	
1.1.2-2	Plasma limiter	Thermal performance of limiter bar	3	
1.1.3-1	Impurity control	Verification of poloidal divertor operation in a high temperature tokamak	1	
1.1.3-2	Impurity control	Measure properties of scrape- off layer	1	
1.1.3-3	Impurity control	Predict scrape-off layer properties	2	
1.1.3-4	Impurity control	Measure and evaluate perfor- mance of low Z wall	2	
1.1.3-5	Impurity control	Evaluate performance of honey- comb wall	2	
1.1.3-6	Impurity control	Impurity reversal	2	
1.1.3-7	Impurity control	Impurity limiting start-up scenarios	2	
1.1.3-8	Impurity control	Surface physics-engineering measurements	2	

Table 7 (continued)

No.	Item or system	Topic	Priority *	WBS reference
1.1.3-9	Impurity control	Experimental evaluation of burial chamber pumping	2	22f
1.1.3-10	Impurity control	Bundle divertor	2	↓
1.1.3-11	Impurity control	Heat removal capabilities of flowing lithium	2	
1.1.3-12	Impurity control	Particle collection capabilities of lithium	2	
1.1.3-13	Impurity control	Measure and evaluate getter pumping in divertor burial chamber	3	
1.2-1	TF coil assembly	NbTi cable fabrication qualification	1	22c
1.2-2	TF coil assembly	Nb ₃ Sn cable fabrication qualification	1	↓
1.2-3	TF coil assembly	Experimental verification of TNS conductor cryostability	1	
1.2-4	TF coil assembly	S/c TF coil fabrication qualification	1	
1.2-5	TF coil assembly	Determination of thermophysical properties of Nb ₃ Sn superconductor for TNS	2	
1.2-6	TF coil assembly	Superconductor cable channel heat transfer and pressure drop experiments	2	
1.2-7	TF coil assembly	Experimental qualification of superconducting cable insulation performance	2	
1.2-8	TF coil assembly	Determination of thermophysical properties of NbTi superconductor for TNS	2	
1.2-9	TF coil assembly	Qualification of the dewar and mechanical support system	2	

Table 7 (continued)

No.	Item or system	Topic	Priority *	WBS reference
1.2-10	TF coil assembly	Determination of composite material properties	2	22c
1.2-11	TF coil assembly	Prototype s/c TF coil assembly qualification for TNS	2	
1.2-12	TF coil assembly	Operation of electrical equipment in a vacuum	3	
1.2-13	TF coil assembly	Experimental evaluation of NbTi winding strain	3	
1.2-14	TF coil assembly	Experimental evaluation of Nb ₃ Sn winding strain	3	
1.2-15	TF coil assembly	Liquid helium boiling heat transfer data acquisition and correlation for TNS superconducting coil design	3	
1.2-16	TF coil assembly	Qualification of electrical connections for superconducting TF coils	3	
1.3-1	Poloidal coil assembly	Development and qualification of remotely maintainable poloidal field coil connectors	1	22d
1.3-2	Poloidal coil assembly	Evaluation of radiation damage to electrical insulation for copper coils	2	
1.4-1	Auxiliary coil assembly	Divertor coil assembly qualification	2	
1.5-1	Shield system	Code development for shield system design	3	22e
1.5-2	Shield system	Nuclear data requirements	3	
1.5-3	Shield system	Integral experiments for shield testing	3	

Table 7 (continued)

No.	Item or system	Topic	Priority*	WBS reference
1.5-4	Shield system	Measurement of eddy current effects in the vacuum vessel and shield system	3	22e
1.5-5	Shield system	Shield module mock-up heat transfer and hydraulic experiments	3	
1.5-6	Shield system	Neutronic measurements on TFTR	3	
1.6-1	Reactor structurals	Toroidal field coil deflection measurements	2	
1.6-2	Reactor structurals	Testing of thermal and electrical insulating materials	3	
1.6-3	Reactor structurals	Remotely maintainable shear fasteners	3	
1.6-4	Reactor structurals	Basic radiation effects data	3	
2.0	Electrical power systems			
2.1-1	Primary power system	AC network analysis	3	23b
2.1-2	Primary power system	Development of techniques for the determination of TF-PF rectifier interaction with AC system	3	23b
2.2	Energy conversion system			
2.2.1-1	TF power conversion system	Experimental qualification of interrupting switch system	3	23c
2.2.1-2	TF power conversion system	Development and qualification of fault detection-location system	3	
2.2.2-1	PF power conversion system	Testing of ignition switches	3	
2.2.2-2	PF power conversion system	Experimental demonstration of DC current-sharing	3	
2.2.2-3	PF power conversion system	Experimental determination of plasma disruption conditions	3	

Table 7 (continued)

No.	Item or system	Topic	Priority *	WBS reference
2.2.2-4	PF power conversion system	Computer simulation of the PF system including the plasma	3	23c
2.2.2-5	PF power conversion system	Development of homopolar generator	3	
2.2.2-6	PF power conversion system	Development of mechanical DC switches	2	
2.2.2-7	PF power conversion system	Experimental evaluation of thyristor mean time between failure (MTBF)	4	
3.0	Plasma heating system			24
3.1-1	Neutral beam injection	Experimental verification of effective plasma heating scenarios	1	24a
3.1-2	Neutral beam injection	Experimental verification of ripple injection	1	
3.1-3	Neutral beam injection	Experimental test of perpendicular injection of NBs in large tokamaks	2	
3.1-4	Neutral beam injection	Negative ion source and associated beam line development	2	
3.1-5	Neutral beam injection	Development and test of a 100-ampere ion source	2	
3.1-6	Neutral beam injection	Control of fractional energy components produced by ion sources	2	
3.1-7	Neutral beam injection	Operation and test of complete neutral beam line	3	
3.1-8	Neutral beam injection	Ion source gas efficiency optimization	3	

Table 7 (continued)

No.	Item or system	Topic	Priority*	WBS reference
3.1-9	Neutral beam injection	Design, manufacture, and test of cryosorption panel assemblies	3	24a
3.1-10	Neutral beam injection	Basic design data for beam dump, calorimeter, and energy conversion system	3	
3.1-11	Neutral beam injection	Test of large remotely operated vacuum valves	3	
3.1-12	Neutral beam injection	Development and test of computer control for neutral beam system	3	
3.1-13	Neutral beam injection	Design and test of a direct energy conversion system	4	
3.2-1	RF heating system	Determination of RF source frequency for TNS	2	24b
3.3-1	Plasma heating power supply	RF amplifier tube development and test	3	
3.3-2	Plasma heating power supply	Development of large NB regulator switch tubes	2	24c
4.0	Tokamak support systems			
4.1-1	Remote servicing system	Demonstration and qualification of remote maintenance operations	2	25a
4.1-2	Remote servicing system	Design, fabrication, and qualification of remote cutting and welding equipment for TNS	3	
4.1-3	Remote servicing system	Design, fabricate, and qualify standardized remotely maintainable joints for all tokamak systems	3	

Table 7 (continued)

No.	Item or system	Topic	Priority*	WBS reference
4.1-4	Remote servicing system	Demonstration and qualification of remote maintenance system	3	25a
4.1-5	Remote servicing system	Remote leak detection for vacuum systems	3	↓
4.2-1	Fuel handling	Pellet penetration measurements	1	25g
4.2-2	Fuel handling	Pellet acceleration by centrifuge	1	↓
4.2-3	Fuel handling	Liquid jet injection feasibility tests	1	↓
4.2-4	Fuel handling	Performance and qualification testing of tritium pumps	2	25a
4.2-5	Fuel handling	Development of transient tritium transport and release code	2	↓
4.2-6	Fuel handling	Cryogenic distillation column performance measurements	2	↓
4.2-7	Fuel handling	Measurement of tritium-handling component performance degradation	2	↓
4.2-8	Fuel handling	Tritium-lithium-yttrium transport data and demonstration of extractor performance	2	↓
4.2-9	Fuel handling	Measurement of tritium transport properties	3	↓
4.2-10	Fuel handling	Development and qualification of valves for tritium service	3	↓
4.2-11	Fuel handling	Hydrogen isotope phase data measurements	3	↓

Table 7 (continued)

No.	Item or system	Topic	Priority*	WBS reference
4.3-1	Torus vacuum pumping system	Development of high speed foreline pumps	3	25c
4.3-2	Torus vacuum pumping system	Performance testing of cryo-pumps	3	
4.3-3	Torus vacuum pumping system	Development of high speed helium pumps	3	
4.4-1	Heat dissipation systems	Supercritical helium circulating pumps	2	25d
4.4-2	Heat dissipation systems	Buffering of peak heat loads	3	
4.5-1	Radiological waste systems	Tritium retention behavior	2	25f
4.5-2	Radiological waste systems	Detritiation of reactor vessel and shielding coolants	2	
5.0	Instrumentation control and data systems			
5.1	Central IC&D system			26
5.1.1-1	Plasma control system	Theoretical modeling and experimental testing of feedback stabilization	1	26a
5.1.1-2	Plasma control system	Plasma density and temperature feedback control	2	26a
5.1.2-1	Process control system	Development and test of multi-purpose tritium analyzer	3	26b
5.1.2-2	Process control system	Development of system to remotely check and/or calibrate sensors	3	26b
5.1.2-3	Process control system	Testing of sensors under tokamak environmental conditions	3	26b
5.1.3	Safety-protection system			
5.1.4-1	Data handling system	Development of data compression techniques	3	26a

Table 7 (continued)

No.	Item or system	Topic	Priority *	WBS reference
5.2-1	Operational instrumentation systems	Qualification of remotely replaceable microwave corner reflector array	2	26b
5.2-2	Operational instrumentation systems	Transparency degradation of microwave windows	3	↓
5.2-3	Operational instrumentation systems	Development of x-ray measuring techniques for determining the TNS electron temperatures	3	
5.2-4	Operational instrumentation systems	Development of microwave interferometer designs for TNS	3	
5.2-5	Operational instrumentation systems	Qualification of replaceable rogowsky loops	3	
5.2-6	Operational instrumentation systems	Qualification of replaceable B_0 coils	3	
5.2-7	Operational instrumentation systems	Qualification of remote disassembly of voltage loops	3	
5.2-8	Operational instrumentation systems	Hardware development for neutron fluence monitor	3	
5.3-1	Scientific instrumentation	Development of vessel windows for visible light and infrared radiation	3	26c
5.3-2	Scientific instrumentation	Develop instrument to measure ion temperature	4	↓
5.3-3	Scientific instrumentation	Develop instrument to measure Z_{eff} , effective ion charge	4	
5.3-4	Scientific instrumentation	Qualification of a remotely replaceable diamagnetic loop	4	
5.3-5	Scientific instrumentation	Development of a short (<1 mm) wavelength multichannel laser interferometer	4	

Table 7 (continued)

No.	Item or system	Topic	Priority *	WBS reference
5.3-6	Scientific instrumentation	Synchrotron radiation as diagnostic tool	4	26c ↓
6.0-1	Support facilities	Development and test of passageway sealing	3	25e
6.0-2	Support facilities	Development and test of utility penetrations seals	3	25e
7.0	Reactor technology research			
7.1-1	Blanket-shield test capability	Design and development of blanket-shield test modules	3	22
7.2-1	Materials test capability	Design and development of materials test modules	4	22
7.2-2	Materials test capability	Fusion reactor radiation effects data	4	22
7.3-1	Remote operations test capability	Design and development of a remote handling test station	4	25a
7.4-1	Impurity control test capability	Design and development of impurity control test capability	2	22f
7.5-1	Tritium-handling test capability	Design and development of tritium-breeding module	4	22
7.6-1	Plasma dynamics test capability	Design and development of plasma dynamics test	4	22
7.7-1	Advanced refueling test capability	Design and development of advanced refueling test hardware	4	25g
7.8-1	Electrical power generation test capability	Design, development, and fabrication of an electrical power generation research subsystem	4	22

Table 7 (continued)

No.	Item or system	Topic	Priority *	WBS reference
7.9-1	Safety and environmental impact research	Generic fusion RD&D environmental statement	2	22
7.9-2	Safety and environmental impact research	Generic PSAR-FSAR ^a criteria for fusion facilities	3	22
7.9-3	Safety and environmental impact research	Development of generic engineering codes and standards	4	22
7.9-4	Safety and Environmental impact research	Generic fusion reactor safety research	4	22
8.0-1	Applied physics-plasma engineering	Stability of elongated high- β plasmas	1	22
8.0-2	Applied physics-plasma engineering	High- β time scale for FCT ^b	1	22
8.0-3	Applied physics-plasma engineering	Measurement of plasma scaling relationships	1	22
8.0-4	Applied physics-plasma engineering	Equilibrium and transport during start-up or shutdown	2	22
8.0-5	Applied physics-plasma engineering	Transport property of synchrotron radiation	3	22

* Priority: 1 = Critical — go, no-go issue;
 2 = Important — significant cost-schedule impact;
 3 = Necessary — required during design process;
 4 = General — design optimization.

^a Preliminary Safety Analysis Report and Final Safety Analysis Report.

^b Flux-Conserving Tokamak.

3.2 Program Planning

The key objective in this major area is to bring a coherence to the overall Oak Ridge TNS Program, to make clear through schedule development the urgency of proceeding, and to make clear to all members of the community affected by TNS what is being planned. The program planning work done thus far, represented here and in greater depth in Part IV, does satisfy this objective.

The tangible outputs of this study are a comprehensive work breakdown structure, an overall schedule based on the elements of the WBS, specific administrative schedules for each phase of the project, and first estimates of participation and funding information.

3.2.1 Central planning elements

Two central plans, the Work Breakdown Structure and the overall project schedule, form the backbone of the planning process. The WBS forms a logically arranged and totally inclusive framework of all functions and hardware associated with the project. An abbreviated form is shown in Table 8; the full, presently four-level WBS is shown in Part IV.

The schedule is developed on the basis of the relevant WBS items, programming assumptions, and administrative constraints listed in Table 9.

On the basis of this input data, a schedule was generated that met all the criteria and has an end date for start-up of regular operations at the beginning of FY 1987. The outline of the schedule was presented as Fig. 1, is shown in full detail in Part IV, and also is discussed in Sect. 3.2.2 below.

Table 8. Work Breakdown Structure (WBS) for TNS through third level

TNS project system 0

Management systems 1	Device systems 2	Facilities systems 3	Preoperational testing 4	Project specific RD&D 5	Base program RD&D 6
Project administration 11	Systems and safety eng. 21	Main test bldg. 31		Technology dev. 51	
Project planning and control 12	Tokamak 22	Other bldgs. 32		Hardware dem. 52	
	Electrical power and control 23			Plasma physics and engineering 53	
Technical coordination 13	Plasma heating 24				
Procurement 14	Tokamak support 25				
Documentation 15	Instrumentation, control, and data 26				
Quality assurance 16					

Table 9. Basic premises for development of the TNS schedule

WBS items ^a (37) ^b	Programmatic assumptions	Administrative constraint
1. Management systems (1)	1. FY 1980 initiation of facilities phase	1. Cost estimate required 18 months before beginning of BY
22a.-26. Device systems (21)	2. Device cost estimate made after operation of large expts. in late 1970s	
31-32. Facilities systems (2)		
4. Preoperational testing (1)		
51a-51m. Technology development (13)	3. Device construction starts after operation of TFTR (hydrogen)	
	4. Construction times similar to those of fission program	

^aFor each item, a sequence is developed, an assembly method is used to blend items, and an indication of the supporting RD&D is given.

^bNumber of items individually treated in the schedule development.

3.2.2 Principal findings from the development of WBS and schedule

1. It is possible to consider a FY 1987 completion date. Development of a schedule aimed at 1986 to 1988 has resulted in a preliminary judgment that a 1988 completion requires an aggressive program, 1990 is likely, and 1986, though highly improbable, is not impossible.

2. The principal, quantifiable critical path is main building construction and fabrication and assembly of TF coils. Clearly, other presently unquantifiable critical paths can exist such as impurity and particle control, particle transport scaling, etc. Of those that can be quantified, the TF coil system is the critical path.

3. To fit within the requirements of the earliest completion date based upon research and development constraints, facility construction must begin at the same time the device conceptual design is completed. This requirement translates into a split line item in which the facilities portion is authorized two years before the device portion.

4. To maintain the earliest schedule compatible with the R&D constraints, two actions must be taken in mid FY 1977.

- Choose a set of reference design parameters and a backup.
- Prepare for conceptual design of the facilities portion starting in FY 1978.

The former action is, in fact, the object of the TNS program activities in the first half of FY 1977. The latter action requires the technical work of preparing the facilities preconceptual design with the aid of a device design envelope and the administrative work of preparing to engage an industrial participant to support ORNL in performing the conceptual design.

5. The schedule is so tight in so many places — that is, it has multiple critical paths through each major system — that a clearly defined, central project management is necessary to accomplish this task.

The evolution of the fusion program organization from totally independent research units ten years ago to increasingly interdependent and mutually supportive RD&D elements today must continue until it is a clearly defined, integrated, centrally managed whole.

6. To come to the decisions required in No. 4 above, E. E. Kintner, Director of ERDA-DMFE, has requested a plan that makes clear a means to develop the TNS design while minimizing risk.

This planning effort has provided the framework in which the three following necessary elements fit.

- Pertinent R&D input
- Technical and administrative requirements of the design and construction schedule
- Clearly defined, workable mechanism that links the two together

In schematic form, the outline of this plan is presented in Fig. 6.

This exposition serves to clarify the distinction between preparation (initiation of the conceptual design process) and construction (initiation of line-item Title I design) by setting out the various steps in the design process. It graphically illustrates the intimate connection of the TNS schedule with the ongoing R&D program. The principal intent of the plan layout is to show how the coupling can be made between the design and R&D programs at minimum risk. The basic concept of design-analysis integration was shown in Table 4 above. In Fig. 6, the integration is made more definite by addressing specifically the design review checkpoints. It has provided a framework for discussions between physicists, engineers, technologists, administrators, and managers.

3.2.3 Findings in the area of administrative factors

Another essential part of the whole project is development of the proposed method and requirements for implementation. Four elements of this implementation are under study now as requested in J. T. Milloway's letter (See Part IV, Appendix).

1. Type of institutional participation at each stage
2. Organization of the participants
3. Type of funding at each stage
4. Amount of funding at each stage

FY	1977	1978	1979	1980	1981	1982	
<u>Design and construction</u>							
Level of detail (increases →)	<u>Start reference design</u>	<u>End facility CD</u>	<u>Start device CD</u>	<u>Start facility detailed design</u>	<u>Start device design</u>	<u>Device fabrication</u>	
	Start facility PCD w/device envelope	Start adv. eng. and device PCD		Start device advanced eng.			
<u>Design reviews</u>							
(redirects design on basis of continuing R&D input)	Project initiation	Phase I CD	Phase II CD	Phase II #1	Phase II #1	Phase II #3	Phase II #4
	(Agree on ref. des. and plan)	(Approve device envelope)	(Review early expts. before start CD — e.g., ISX, PLT-B)	(Before ground- breaking, review mid expts.)	(Mid Title I)	[Review TFTR (H)]	(Begin fab.)
				D-III, PDX LCP, TSTA			
<u>Levels of information</u>	Initial (Ranges)			Preliminary (Techniques)		Final (Detailed data)	
<u>R&D program</u>							
Level of uncer- tainty (decreases →)	Early expts., coupled codes, ISX, PLT-B, LCS, TSTA, design, 150-keV, short pulse beams			Mid expts., low Z, high-β methods, PDX, D-III, TSTA, LCP, 150-keV, long pulse beams		Late expts., verification and quantification of design data	

Fig. 6. Outline of a preliminary version of an overall TNS plan

Although this effort has just begun, first cuts at each of these elements have been made and are contained in Part IV.

The principal findings or premises in each area can be simply stated:

1. Type of participation

- The design and construction process will be based heavily on the support of industrial participants under the direction of the TNS team.
- Because of the high level of interface between physics, technology, and engineering, and because of split phasing, it appears crucial to have a single, fusion-knowledgable, prime contractor.

2. Organization

- For the same reasons of complexity and interface ties, it appears essential to have the TNS team managed as one coherent entity rather than to have separate elements reporting formally to a higher official.

3. Type of funding

- Expense funding for the feasibility, preconceptual, and conceptual designs as well as for project specific R&D will be needed.
- Construction Planning and Design (CP&D) funds will be required to improve certain costly and complex item designs.
- Line item funds will be needed for the Plant and Capital Equipment (PACE) items.

4. Amount of funding

- Preliminary numbers are being put together for each activity.

4. RECOMMENDATIONS

On the basis of the investigations whose findings are summarized in Sect. 3, a set of recommendations in both the technical and administrative areas clearly emerges.

4.1 Technical Areas

In these areas, the recommendations are conveniently divided into impacts on the physics, technology, and engineering programs.

4.1.1 Physics

1. Formulate and then implement a plan for proceeding in the closely linked areas of impurity and particle control and fueling. This sorely needed formulation should incorporate the understanding developed by each experimental group yet seldom published. This formulation should be community-wide but clearly focused on relevance to TNS design questions and timing so that the usefulness to TNS of the pertinent experiments and theory of the next two to three years can be maximized.

2. Assess the means to achieve in one device or in others jointly in the next two-to-three years an investigation and demonstration of a number of related physics and plasma technology issues such as the following: (a) configuration development, maintenance, and then optimization in a high- β , rapidly heated, high temperature plasma operation; (b) long pulse operation as the only direct support for an ~ 30 sec burning plasma experiment in TNS; (c) RF heating as a backup to neutral beams; (d) high velocity pellet injection coupled to a long pulse plasma.

3. Make a commitment to a more intensive, supportive applied research program in impurity dynamics, plasma transport, and, most critically, coupled equilibrium, stability, transport, and heating simulation of ignition scenarios along with requisite computational facilities to ensure the required growth in predictive abilities.

4. Expand the development of an integrated plan beyond the TNS teams to include each of the principal experimental and theoretical groups in the national program. The task of moving toward an integrated science-technology-engineering program is so difficult that restriction of the information input to that from the TNS teams alone can result in an inferior product of little use. Close working relationships between the TNS team and each principal group will be necessary to encourage cooperation.

4.1.2 Technology

1. Increase emphasis on those development areas which are essential under any design scenario; specifically, direct program commitments are needed in

- Compound (He,D,T) gas pumps,
- Higher specific power output, longer pulse neutral beam systems,
- Longer pulse neutral beam switch tubes, and
- PF electrical systems,

whereas specific studies should be directed toward

- Abnormal operations control,
- Limiter materials, and
- Plasma configuration sensing and control.

In these areas, program plans and funding should be developed to meet known TNS needs.

2. Act in the six technology areas in which new programs or increased emphasis on existing programs might be needed if certain TNS design decisions are made. Specifically in this category are the following.

- High power negative ion source
- High velocity pellet injection
- Impurity control technology
- Nb₃Sn conductor qualification

Superconducting poloidal field coil structural
materials

300-keV neutral beam switch tube

If the TNS reference design decision includes any of these items, then increased emphasis will be necessary. If it does not, then little additional emphasis is necessary for TNS application. In the absence of a decision, however, the basis for these development programs should be laid so that there would be little delay in a future decision to proceed or little cost penalty in a future decision to stop. In these areas, plans should be developed to assess the optimum strategy under different funding and decision-making scenarios.

3. Expand the development of an integrated plan to include each of the principal technology groups on the working level. The efforts begun with LCS-LCP, TSTA, Beam Program, etc., must continue and become more integrated. As an example, the detailed timing of the TF coil development, demonstration, fabrication, and machine assembly process (probably best known of all the important paths) is as yet not sufficiently clear and requires continued attention.

4.1.3 Engineering

1. Select a reference design and a backup that permit serious attention to be put on a design, recognizing that the design is not yet at hand.

The development of a clear design process schedule with physics and technology checkpoints resulting in minimum risk is under way.

2. Improve the engineering reliability level of fusion experiments — a second and more difficult action. It is inconceivable that TNS will be built in the manner of the early tokamaks. There is and has been a continuous improvement in fusion engineering that must accelerate.

A plan should be developed to demonstrate the fusion community's capability to progress to the required engineering quality level on TNS. This can be done by examining the recent fusion experiences with engineering success and failure, by giving the TFTR engineering process continuing high visibility, and by seeking the experience of other

knowledgeable groups. This information must then be fed back into the fusion program plans and funding estimates. A specific task here is the comparison of the TNS costing models with existing experiments. A principal difference should be the quality level built into the different objectives.

3. Strengthen specific TNS systems activity — a necessary ingredient in the integration process. The systems engineering activity provides the central focus for the TNS Program, and as the various elements begin to find a common direction, additional staff will be needed to provide the coupling.

4.2 Administrative Areas

Three closely related recommendations comprise this topic.

1. Look hard at the DMFE organizational structure as it supports the central objective of an aggressive, timely TNS project. For TNS to be able to rely on supporting R&D programs and conversely for R&D programs to rely on TNS as a goal, there must be some form of central project management. Without this central direction, individual components are unable to discern what is really needed, cannot be held accountable directly, and face conflicting directives from various quarters.

The action required here is to develop and carry out a workable scheme that provides a clear project atmosphere within which the various DMFE program elements can work together.

2. Establish a TNS R&D plan essential to orderly planning by all concerned. This document forms the basis for a first draft of the plan. The initiating request from J. M. Williams ends with the milestone dated 24 February 1977 entitled "Establish Schedule for Formal TNS R&D Plan."

The action here is to follow through on the existing plan.

3. Establish a program plan essential to orderly planning by all concerned. This document also forms the basis for a first draft of the plan. The program plan encompasses the R&D plan and covers the administrative and programmatic aspects of the direct TNS Project activities as well.

J. O. Neff's letter of 10 December 1976 (see Appendix to Part IV) calls for an initiation of the conceptual design plan. The action here is to follow through on the existing plans.

5. QUESTIONS YET TO BE ADDRESSED

The present embodiment of this work is not an end in itself but rather a useful vehicle for discussion and development of the TNS Program Plan. In addition to the improvement of that which is already included, four principal tasks have yet to be addressed in any serious manner.

5.1 Cost Estimates

What does the TNS RD&D support program cost? That question cannot be answered on the basis of what has been done thus far. The clarification of the integration of the required base programs and costs with the required design-specific R&D has to be done. A wide agreement on the projected costs of individual items also has yet to be reached.

5.2 Schedule Sensitivity

A basic success-oriented schedule has been developed. The sensitivity of this schedule to changes either in projected funding or anticipated results has yet to be analyzed on more than a superficial level. The impact of the site and contractor selection process on the starting date and the method of starting must also be fully considered.

5.3 Implications of Early Design Decisions

As each of the supporting RD&D Programs is initiated and specific parameter values or ranges are provided by the TNS teams, what long range directions are being set or restricted? The question cannot yet be answered. An essential part of the continuing TNS system work is an understanding of the implications of the numbers being provided.

5.4 Community Involvement

This document was developed by the Oak Ridge TNS team with help from the many sectors of the ORNL Fusion Program and through meetings

with representatives from Princeton Plasma Physics Laboratory, Los Alamos Scientific Laboratory — University of Texas, C. S. Draper Laboratory, and National Bureau of Standards as well as ERDA-DMFE staff. It has not yet been assessed by the majority of people at these and other laboratories and institutions. A vitally important task is the inclusion of a wider range of input both for its inherent technical merit and for its value in developing support and community understanding.

These four tasks, along with refinement and necessary reevaluations of the existing information, form the directions of the ongoing work.

6. WHY TNS NOW? - A RECAPITULATION

An adequate basis for initiation of TNS reference design studies exists. It is necessary to begin this work now as supported in the following arguments.

1. A forward moving TNS project will provide a sharply defined goal for the fusion program.

The project will

- Identify missing programs so that they can be initiated,
- Provide a framework for experimentalists to aim for so that a sense of timing and clear responsibility can be achieved,
- Provide a framework for technology program to establish priorities and backups on a known schedule.

2. The strong engineering component of TNS provides a central, credible schedule.

The project will

- Integrate the program by understanding its timeliness and its interfaces, and
- Inform fusion, governmental, and industrial communities so that they can react knowledgeably to fusion program needs.

3. The realistic approach to TNS will provide substance to the crucial educational process required to achieve TNS objectives.

The project will

- Focus creative energies on economical fusion power plant concepts; this need must be recognized to be at the very base of national support for fusion; TNS represents and advocates that view,
- Assess the means to achieve the implementation of TNS; designing for power plant level reliability has not been the requirement in fusion previously; TNS provides the driving force in that evolutionary process,
- Understand the learning curve in fusion so that we can prepare for a large, costly undertaking with uncertainty in present design criteria, and
- Understand how information yet to be developed colors our thinking about proceeding now.

4. A strong emphasis on program planning in TNS will illuminate organizational issues that can seriously affect accomplishment of TNS in the desired time frame. This one area appears to present the greatest "gap" in the fusion program aimed at TNS objectives in the mid to late 1980s.

ERDA-DMFE can

- Use TNS planning to bring to the front those questions of field and headquarters organization and liaison that affect and are affected by TNS as a project.

5. A strong TNS physics effort will clarify the real meaning of the ignition, fusion reactor core objective.

The project can with the support of plasma theory and experiment

- Clarify the issue of ignition. Current definitions of ignition are usually of a threshold nature, "ignited or not ignited," implying averaged values of the plasma characteristics. A more accurate and useful definition considers ignition of a certain fraction of the plasma — the ignited core. Consideration of the radial profiles of density and temperature indicates that ignition on axis is relatively easily achieved when compared with the requirements for average values.

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