MARCH 1977

MASTER

**DRAFT PROGRAM PLAN FOR TNS -
THE NEXT STEP AFTER THE
TOKAMAK FUSION TEST REACTOR**

PART III - PROJECT SPECIFIC RD&D NEEDS

**fusion power
systems department**

Westinghouse Electric Corporation

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FOREWARD

The Division of Magnetic Fusion Energy (DMFE) within the Energy Research and Development Administration (ERDA) in mid-1976 initiated investigative studies intended to develop the basis for the next major tokamak device after the Tokamak Fusion Test Reactor (TFTR). This next device has been designated as The Next Step (TNS). The principal objectives identified for TNS are: 1) achievement of a fusion reactor core, i.e., deuterium-tritium ignition/burning, and, 2) act as a forcing function for reactor technology.

Westinghouse Fusion Power Systems has participated with the Oak Ridge National Laboratory in these on-going TNS studies. This report is one in a series of documents describing this work.

This assessment is Part III of a four part report which comprises the Draft Program Plan for TNS. The other parts of the report are:

ORNL/TM-5982 - Part I Summary

ORNL/TM-5983 - Part II R&D Needs Assessment

ORNL/TM-5984 - Part IV Program Planning

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1.0 INTRODUCTION

This compilation of Research, Development and Demonstration (RD&D) needs for The Next Step (TNS) represents one segment of a larger assessment requested of the ORNL/(W) design team by ERDA/DMFE. The objectives for the total assessment established by ERDA/DMFE included:

- Establishing the proper sequencing of design, R&D, and construction elements to support the orderly design and construction of a TNS.
- Identification of all critical RD&D tasks and programs necessary to support operation of a TNS.
- Identification of the necessary schedule to assure TNS operation in 1986.
- Identification of modifications in the schedule of activities as a function of changes in scheduled operation.
- Identification of the budget for each of the two preceding objectives and comparison with the current budget projection.

The compilation of RD&D needs for TNS in this document is characterized by the following:

- It concentrates on project and design related needs. The key question posed to the designers in creating this compilation has been
 - What must be done before you believe you can design the hardware in your area?

Some of the categories considered in addressing this question included the need for: 1) development of basic design data, 2) testing proof-of-principle, 3) assembly mock-ups/models, 4) manufacturing development, 5) performance qualification, 6) code development, and 7) hardware development.

In addition to concentrating on the project/design related needs, a limited number of critical RD&D tasks in the areas of reactor technology research and applied physics/plasma engineering are included. Basic physics and scientific issues which require resolution will be covered in more detail by ORNL. In this compilation we have considered a few of the most critical of the physics-related questions.

- It is the result of an intensive, short (several weeks) exercise. Accordingly, emphasis has been on identification of the problem requiring RD&D and what scope of work is required to develop a solution. Information has been included on what resources are required, where they exist, what ongoing programs may produce the solution and when, and what cost is estimated. However, technical judgement has been used where a firm quantitative basis could not readily be identified.
- It has been created prior to having a conceptual design for TNS. As a result, multiple RD&D paths continue to be necessary in many areas (e.g., toroidal field coil technology, impurity control, etc.). The list of needs is not complete and subsequent design iterations may indicate other areas where RD&D effort is required.
- It reflects many RD&D tasks needed not only for TNS, but also needed ultimately for the demonstration fusion reactors.
- It is a working draft. The information has not received the benefit of review and comment by cognizant individuals in ERDA, other National Laboratories, universities, and industry. This process is essential.

It is our judgement that this compilation provides a useful basis for developing assurance that the necessary programmatic steps exist to provide resolution to those RD&D needs essential to a TNS in the mid-1980's. Many of the current technology programs contain

elements specifically focused toward TNS; other programs have elements which can lend themselves to being supportive of TNS; finally, some new programs will be required. Due to the limited time available, the specific relationship between TNS needs and the focus and timing of on-going programs has not been fully addressed in this draft.

The remainder of this compilation is organized into three major sections. Section 2.0 presents a summary of this compilation. It provides an overview of the principal findings and conclusions. Section 3.0 presents individual RD&D needs by TNS hardware system. There are eight major chapters in this section. Included with each major section is an overview narrative for that system with commentary on the critical problem areas. Section 4.0 presents program recommendations. In addition, this section provides commentary on schedule and funding needs and provides a digest of RD&D need listings by cross-referencing with major device and technology programs.

2.0 CONTEXT AND OVERVIEW

This RD&D needs assessment is based in part on the experience and insight gained during prior months performing pre-conceptual design system studies for TNS. The recent Experimental Power Reactor studies by ORNL, GA, and ANL, as well as the TNS work performed to date, have highlighted a number of basic scientific uncertainties which significantly hamper the development of engineering requirements, specifications and concepts at this time. The favorable scaling laws observed in recent experiments and the emergence of several promising new theoretical concepts, such as flux conservation, does provide a strong incentive for continued emphasis on the tokamak approach. The important question at this time is, however, whether or not a firm scientific basis will exist for the TNS project by the time authorization will be requested for the expenditure of significant amounts of money for hardware. This occurs generally at the end of Title I (Preliminary Design) which is currently planned to occur at the end of FY '81.

Some of the major scientific uncertainties which have been identified include:

- confinement scaling
- ignition device parameters and associated margin
- non-circular plasma performance
- feasibility and consequences of high β operation
- plasma stability
- refueling requirements
- plasma-wall effects and impurity control
- plasma heating requirements
- magnetic field dynamics and topology requirements
- plasma dynamics

As we perceive the situation, therefore, the difficulty at this time is not so much that there are no engineering solutions as much as the lack of a well understood set of plasma physics-related requirements. Although the engineering problems may be formidable, it appears that a strong design effort with focused supporting engineering RD&D will permit achievement of project technical and schedular goals.

We conclude that a sufficiently firm basis and need exists for the initiation of TNS feasibility and conceptual design studies at this time and that the required RD&D can be performed in sufficient time to support the major financial decisions which must be made over the course of the project. The considerations and caveats associated with this conclusion are as follows:

- TNS will require extrapolation of current knowledge. In view of the goals set for TNS, it will not be possible to fully proof-test all of the TNS concepts and design approaches prior to operation. The required plasma conditions and operating environment for an ignition machine cannot be readily simulated. Program delay for this reason is not warranted since this situation will not improve with time. We can expect important advances in our theoretical understanding of plasma processes over the next few years, however, we must recognize the limited opportunities for full experimental confirmation regardless of the time and money invested in supporting physics programs. The goal should be to delineate the range of uncertainty and provide engineering designs which bracket those uncertainties. Our judgement is that this can be done with acceptable technical risk. The quantification of these risks requires design-oriented study.
- TNS design considerations are still very preliminary. In view of the limited funding available, a fully integrated design and analysis effort

has not been possible. Final judgement as to the viability of design concepts, associated technical risks, RD&D needs, and costs are premature at this time.

- Generic RD&D support exists, but is not sufficiently focused on TNS. Our assessment indicates that the framework for a TNS-oriented RD&D support program exists, with some notable exceptions; however, the support programs require the focus which can only be provided by a strong, end-product oriented, design effort. The current organization of these generic RD&D activities does not appear to be efficiently integrated and cannot be made fully responsive to the needs of TNS without management redirection. It is recognized that the TNS activity has been underway for a relatively brief period of time and has not progressed to the point where fully integrated management and technical coordination has been possible. Once a strong design effort is initiated and a baseline design defined, the necessary program coordination will be possible, provided the requisite management controls can be implemented.

Our recommendations for a plan of action are discussed in greater detail in Section 4. In addition to specific RD&D program activities, we recommend the following overall approach:

- Initiate a strong baseline design effort.
- Delineate physics uncertainties and their engineering design implications.
- Provide for strong RD&D management controls.
- Provide for design-oriented RD&D technical coordination and initiate high priority RD&D.
- Identify key technical decision milestones and provide for timely initiation, termination or redirection of these efforts based on continuous technical and management review.

2.1 RD&D ASSESSMENT ORGANIZATION AND GROUND RULES

For the purpose of this assessment, the definition of what constitutes RD&D as opposed to normal design activities associated with Plant and Capital Equipment (PACE) is consistent with ERDAM Appendix 1101, Part VI, to the extent possible. We have considered both generic and design-related RD&D requirements, however, the bulk of this assessment is concerned with specific design-related activities which are required during the course of, and in parallel with, conceptual and construction design phases. The specific definitions of RD&D used in the assessment are given in Table 2-1.

A form was developed for the definition of individual, specific RD&D tasks or activities. While this approach is somewhat confining, it assured the maximum possible coverage and uniformity in the information provided. Subsequent iterations during the course of the project will involve the development of activity plans with better definition of control milestones, costs and participants, as well as iteration with the associated 189 statements and the ERDA program plan.

A judgement has been made as to the priority and cost of the RD&D items. Priorities were established based on the definitions given in Table 2-2. Costs were estimated based on experience and judgement and must be considered very preliminary until the development of more detailed work scopes. A particularly gray area is the estimation of costs associated with the conduct of experiments in existing facilities, such as tokamaks, accelerators and fission reactors. These must be reviewed with other program participants and refined as the baseline TNS design is developed.

An important tool in the systematic identification of RD&D tasks from the point of view of TNS system design needs is the provisional TNS Work Breakdown Structure developed jointly by Westinghouse and ORNL. Table 2-3 indicates the current version of the WBS, which is cross-referenced in subsequent material with supporting RD&D tasks.

TABLE 2-1

TNS RD&D ACTIVITY CATEGORIES

DEVELOPMENT OF BASIC DESIGN DATA

Plasma physics research including code development, analysis and experiment associated with fundamental plasma processes; thermophysical property and radiation effects (on materials rather than components) measurement and evaluation; basic structural mechanics analysis and experiment; basic heat transfer analysis and experiment; neutronics analysis and experiment including cross section measurement and evaluation; and generic code development.

CONCEPT FEASIBILITY AND OPTION EVALUATION

The design, development, fabrication, and testing of systems and components leading to the selection of concepts, design approaches, systems, and components to be incorporated in the design of the project.

PROOF-OF-PRINCIPLE TEST

The design, development, fabrication, and testing of subscale hardware and breadboards; electrical, mechanical, thermal, fluid systems, radiation, and plasma systems simulation to obtain basic engineering data and to establish or confirm design requirements.

ASSEMBLY MOCK-UPS AND MODELS

The design, fabrication, and testing of hardware mock-ups and models required to prove feasibility and develop interface requirements, particularly in the area of remote handling and to support operator training.

MANUFACTURING MATERIALS AND PROCESS DEVELOPMENT

Tests to determine critical processing parameters for first-of-a-kind manufacturing activities where significant cost, performance, and quality assurance issues are involved.

DESIGN, MANUFACTURING, PERFORMANCE QUALIFICATION (PROTOTYPING)

Fabrication and testing of first-of-a-kind components and subsystems to assure design and performance and qualify vendors where significant cost, performance, and quality assurance issues are involved. The cost of any prototype hardware ultimately installed in the plant will be prorated and applied to the PACE account.

TABLE 2.1 (CONTINUED)

OPERATING SOFTWARE DEVELOPMENT

The development and documentation of software required for process control, data acquisition, and scientific computer systems which are part of the project.

EXPERIMENTAL HARDWARE DEVELOPMENT

The design, development, fabrication, and test of experimental hardware which is not part of the basic machine configuration but will be used for scientific and engineering experimentation after TNS is operational. Items in this category include plasma diagnostics and reactor technology test modules.

TABLE 2-2

TNS RD&D PRIORITY CATEGORIES

CRITICAL ITEMS (PRIORITY 1)

Information required to establish major design approach feasibility (go-no go) and reduce major item performance or cost uncertainty.

IMPORTANT ITEM (PRIORITY 2)

Information required for cost or performance optimization, selection between feasible alternatives, critical component performance and safety margin.

NECESSARY ITEM (PRIORITY 3)

Information required to establish final design and manufacturing parameters or to refine performance margin and cost estimates. Includes qualification of first-of-a-kind designs, components and assemblies.

GENERIC ITEM (PRIORITY 4)

Information not directly related to the basic TNS objectives, but which could, if successful, provide significant performance improvement or provide important fusion reactor science/technology data for follow-on reactors.

TABLE 2-3
TNS PROJECT PROVISIONAL WORK BREAKDOWN STRUCTURE

2/15/77

2.2 SUMMARY OF THE ASSESSMENT

A clear imperative in the development of the TNS concept is to incorporate as much programmatic and technical flexibility as possible to allow for the current uncertainties associated with the specification of engineering requirements for individual systems and the ultimate success of specific technologies and design approaches. As a result, it is necessary to plan on several parallel design tracks, each iterating with a baseline design during the feasibility and conceptual design phases. An example of this approach is currently employed in the impurity control area where both the wall treatment-plasma edge control and poloidal divertor concepts are being considered. It may be necessary to carry this dual-track approach well into conceptual design in order not to foreclose potentially viable options. As a consequence, in our RD&D needs assessment we have defined a number of important activities designed to permit the evaluation of a number of parallel-track options before final design decisions are made.

This approach must be carefully administered, however, to assure that the baseline effort is not diluted and timely decisions are made to concentrate effort on a specific option.

Table 2-4 contains an overall listing of the 139 RD&D items which have been identified in this assessment. The priority designation, estimated cost and associated WBS hardware elements are listed. The first six sections of the assessment deal primarily with design-related needs. Section 7, Reactor Technology Research, considers those tasks associated with the development of advanced testing capability which can be employed in TNS as well as generic environmental impact and safety research which can benefit the project.

Section 8, Applied Physics/Plasma Engineering, highlights the theoretical and experimental physics tasks which will be carried out at the major tokamak laboratories to support TNS.

TABLE 2-4
TNS RD&D ASSESSMENT

ITEM/SYSTEM		TOPIC	COST M \$	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	0.05	2	22f
1.1.1-2	Vacuum Vessel Structure	Vacuum Vessel Segmentation Joints	2.5	2	
1.1.1-3	Vacuum Vessel Structure	Verification of Vessel Cooling System Capability	2.4	3	
1.1.1-4	Vacuum Vessel Structure	Mechanical Stability Tests	2.3	3	
1.1.1-5	Vacuum Vessel Structure	Replaceable or Maintainable Electrical Insulators	2.9	3	
1.1.2-1	Plasma Limiter	Material Damage Studies	0.3	3	
1.1.2-2	Plasma Limiter	Thermal Performance of Limiter Bar	0.06	3	
1.1.3-1	Impurity Control	Verification of Poloidal Divertor Operation in a High Temperature Tokamak	25.0	1	
1.1.3-2	Impurity Control	Measure Properties of Scrape-Off Layer	1.0	1	
1.1.3-3	Impurity Control	Predict Scrape-Off Layer Properties	0.3	2	
1.1.3-4	Impurity Control	Measure and Evaluate Performance of Low Z Wall	0.6	2	
1.1.3-5	Impurity Control	Evaluate Performance of Honeycomb Wall	0.25	2	22f
1.1.3-6	Impurity Control	Impurity Reversal	0.5	2	
1.1.3-7	Impurity Control	Impurity Limiting Start-Up Scenarios	1.5	2	
1.1.3-8	Impurity Control	Surface Physics/Engineering Measurements	1.05	2	
1.1.3-9	Impurity Control	Experimental Evaluation of Burial Chamber Pumping	0.9	2	
1.1.3-10	Impurity Control	Bundle Divertor	0.15	2	
1.1.3-11	Impurity Control	Heat Removal Capabilities of Flowing Lithium	0.3	2	

TABLE 2-4
TNS RD&D ASSESSMENT

ITEM/SYSTEM		TOPIC	COST M \$	PRIORITY	WBS REFERENCE
1.1.3-12	Impurity Control	Particle Collection Capabilities of Lithium	0.65	2	22f
1.1.3-13	Impurity Control	Measure and Evaluate Getter Pumping in Divertor Burial Chamber	0.25	3	↓
1.2-1	TF Coil Assembly	NbTi Cable Fabrication Qualification	0.2	1	22c
1.2-2	TF Coil Assembly	Nb ₃ Sn Cable Fabrication Qualification	0.25	1	
1.2-3	TF Coil Assembly	Experimental Verification of TNS Conductor Cryostability	0.52	1	
1.2-4	TF Coil Assembly	S/C TF Coil Fabrication Qualification	7.0	1	
1.2-5	TF Coil Assembly	Determination of Thermophysical Properties of Nb ₃ Sn Superconductor for TNS	0.22	2	
1.2-6	TF Coil Assembly	Superconductor Cable Channel Heat Transfer and Pressure Drop Experiments	0.25	2	
1.2-7	TF Coil Assembly	Experimental Qualification of Superconducting Cable Insulation Performance	0.10	2	
1.2-8	TF Coil Assembly	Determination of Thermophysical Properties of NbTi Superconductor for TNS	0.19	2	
1.2-9	TF Coil Assembly	Qualification of the Dewar and Mechanical Support System	1.5	2	
1.2-10	TF Coil Assembly	Determination of Composite Material Properties	0.03	2	
1.2-11	TF Coil Assembly	Prototype S/C TF Coil Assembly Qualification for TNS	5.0	2	
1.2-12	TF Coil Assembly	Operation of Electrical Equipment in a Vacuum	0.15	3	
1.2-13	TF Coil Assembly	Experimental Evaluation of NbTi Winding Strain	0.11	3	
1.2-14	TF Coil Assembly	Experimental Evaluation of Nb ₃ Sn Winding Strain	0.13	3	
1.2-15	TF Coil Assembly	Liquid Helium Boiling Heat Transfer Data Acquisition and Correlation for TNS Superconducting Coil Design	0.74	3

TABLE 2-4
TNS RD&D ASSESSMENT

ITEM/SYSTEM		TOPIC	COST M \$	PRIORITY	WBS REFERENCE
1.2-16	TF Coil Assembly	Qualification of Electrical Connections for Superconducting TF Coils	0.20	3	22c
1.3-1	Poloidal Coil Assembly	Development and Qualification of Remotely Maintainable Poloidal Field Coil Connectors	1.00	1	22d
1.3-2	Poloidal Coil Assembly	Evaluation of Radiation Damage to Electrical Insulation for Copper Coils	0.20	2	↓
1.4-1	Auxiliary Coil Assembly	Diverter Coil Assembly Qualification	1.50	2	↓
1.5-1	Shield System	Code Development for Shield System Design	0.40	3	22e
1.5-2	Shield System	Nuclear Data Requirements	0.40	3	↓
1.5-3	Shield System	Integral Experiments for Shield Testing	1.00	3	↓
1.5-4	Shield System	Measurement of Eddy Current Effects in the Vacuum Vessel and Shield System	0.50	3	↓
1.5-5	Shield System	Shield Module Mock-up Heat Transfer and Hydraulic Experiments	0.44	3	↓
1.5-6	Shield System	Neutronic Measurements on TFTR	0.10	3	↓
1.6-1	Reactor Structurals	Toroidal Field Coil Deflection Measurements	0.10	2	↓
1.6-2	Reactor Structurals	Testing of Thermal and Electrical Insulating Materials	0.50	3	↓
1.6-3	Reactor Structurals	Remotely Maintainable Shear Fasteners	0.15	3	↓
1.6-4	Reactor Structurals	Basic Radiation Effects Data	2.00	3	↓
2.0	ELECTRICAL POWER SYSTEMS				↓
2.1-1	Primary Power System	AC Network Analysis	0.35	3	23b
2.1-2	Primary Power System	Development of Techniques for the Determination of TF/PF Rectifier Interaction with AC System	0.15	3	23b

TABLE 2-4
TNS RD&D ASSESSMENT

ITEM/SYSTEM		TOPIC	COST M \$	PRIORITY	WBS REFERENCE
2.2	ENERGY CONVERSION SYSTEM				23c
2.2.1-1	TF Power Conversion System	Experimental Qualification of Interrupting Switch System	0.25	3	↓
2.2.1-2	TF Power Conversion System	Development and Qualification of Fault Detection/Location System	0.30	3	
2.2.2-1	PF Power Conversion System	Testing of Ignitron Switches	0.20	3	
2.2.2-2	PF Power Conversion System	Experimental Demonstration of DC Current-Sharing	0.10	3	
2.2.2-3	PF Power Conversion System	Experimental Determination of Plasma Disruption Conditions	0.05	3	
2.2.2-4	PF Power Conversion System	Computer Simulation of the PF System Including the Plasma	0.30	3	
2.2.2-5	PF Power Conversion System	Development of Homopolar Generator	10.0	3	
2.2.2-6	PF Power Conversion System	Development of Mechanical DC Switches	1.0	2	
2.2.2-7	PF Power Conversion System	Experimental Evaluation of Thyristor Mean Time Between Failure (MTBF)	0.15	4	↓
3.0	PLASMA HEATING SYSTEM				24
3.1-1	Neutral Beam Injection	Experimental Verification of Effective Plasma Heating Scenarios	0.35	1	24a
3.1-2	Neutral Beam Injection	Experimental Verification of Ripple Injection	0.50	1	↓
3.1-3	Neutral Beam Injection	Experimental Test of Perpendicular Injection of NB's in Large Tokamaks	0.07	2	
3.1-4	Neutral Beam Injection	Negative Ion Source and Associated Beam Line Development	3.0	2	
3.1-5	Neutral Beam Injection	Development and Test of a 100 Ampere Ion Source	0.25	2	
3.1-6	Neutral Beam Injection	Control of Fractional Energy Components Produced by Ion Sources	0.18	2	↓

TABLE 2-4
TNS RD&D ASSESSMENT

ITEM/SYSTEM		TOPIC	COST M \$	PRIORITY	WBS REFERENCE
3.1-7	Neutral Beam Injection	Operation and Test of a Complete Neutral Beam Line	15.0	2	24a
3.1-8	Neutral Beam Injection	Ion Source Gas Efficiency Optimization	0.08	3	
3.1-9	Neutral Beam Injection	Design, Manufacture, and Test of Cryosorption Panel Assemblies	0.20	3	
3.1-10	Neutral Beam Injection	Basic Design Data for Beam Dump, Calorimeter, and Energy Conversion System	0.20	3	
3.1-11	Neutral Beam Injection	Test of Large Remotely Operated Vacuum Valves	0.20	3	
3.1-12	Neutral Beam Injection	Development and Test of Computer Control for Neutral Beam System	0.20	3	
3.1-13	Neutral Beam Injection	Design and Test of a Direct Energy Conversion System	0.35	4	
3.2-1	Rf Heating System	Determination of rf Source Frequency for TNS	0.50	2	24b
3.3-1	Plasma Heating Power Supply	Rf Amplifier Tube Development and Test	2.0	3	
3.3-2	Plasma Heating Power Supply	Development of Large NB Regulator Switch Tubes	0.25	2	24a
4.0	TOKAMAK SUPPORT SYSTEMS				
4.1-1	Remote Servicing System	Demonstration and Qualification of Remote Maintenance Operations	1.25	2	25a
4.1-2	Remote Servicing System	Design, Fabrication and Qualification of Remote Cutting and Welding Equipment for TNS	1.10	3	
4.1-3	Remote Servicing System	Design, Fabricate and Qualify Standardized Remotely Maintainable Joints for all Tokamak Systems	1.30	3	
4.1-4	Remote Servicing System	Demonstration and Qualification of the TNS Remote Maintenance System	1.73	3	
4.1-5	Remote Servicing System	Remote Leak Detection for Vacuum Systems	0.31	3	

TABLE 2-4
TNS RD&D ASSESSMENT

ITEM/SYSTEM		TOPIC	COST M \$	PRIORITY	WBS REFERENCE
4.2-1	Fuel Handling	Pellet Penetration Measurements	0.90	1	25g
4.2-2	Fuel Handling	Pellet Acceleration by Centrifuge	0.40	1	↓
4.2-3	Fuel Handling	Liquid Jet Injection Feasibility Tests	1.10	1	↓
4.2-4	Fuel Handling	Performance and Qualification Testing of Tritium Pumps	0.51	2	25a
4.2-5	Fuel Handling	Development of Transient Tritium Transport and Release Code	0.15	2	↓
4.2-6	Fuel Handling	Cryogenic Distillation Column Performance Measurements	1.10	2	↓
4.2-7	Fuel Handling	Measurement of Tritium Handling Component Performance Degradation	0.62	2	↓
4.2-8	Fuel Handling	T-Li-Y Transport Data and Demonstration of Extractor Performance	0.66	2	↓
4.2-9	Fuel Handling	Measurement of Tritium Transport Properties	0.66	3	↓
4.2-10	Fuel Handling	Development and Qualification of Valves for Tritium Service	0.27	3	↓
4.2-11	Fuel Handling	Hydrogen Isotope Phase Data Measurements	0.21	3	↓
4.3-1	Torus Vacuum Pumping System	Development of High Speed Foreline Pumps	0.25	3	25c
4.3-2	Torus Vacuum Pumping System	Performance Testing of Cryopumps	0.20	3	↓
4.3-3	Torus Vacuum Pumping System	Development of High Speed Helium Pumps	0.10	3	↓
4.4-1	Heat Dissipation Systems	Supercritical Helium Circulating Pumps	0.35	2	25d
4.4-2	Heat Dissipation Systems	Buffering of Peak Heat Loads	0.28	3	↓
4.5-1	Radiological Waste Systems	Tritium Retention Behavior	0.38	2	25f
4.5-2	Radiological Waste Systems	Detritiation of Reactor Vessel and Shielding Coolants	0.28	2	↓

TABLE 2-4
TNS RD&D ASSESSMENT

ITEM/SYSTEM		TOPIC	COST M \$	PRIORITY	WBS REFERENCE
5.0	INSTRUMENTATION CONTROL & DATA SYSTEMS				26
5.1	CENTRAL IC&D SYSTEM				26
5.1.1-1	Plasma Control System	Theoretical Modeling and Experimental Testing of Feedback Stabilization	1.70	1	26a
5.1.1-2	Plasma Control System	Plasma Density and Temperature Feedback Control	0.50	2	26a
5.1.2-1	Process Control System	Development and Test of Multipurpose Tritium Analyzer	0.41	3	26b
5.1.2-2	Process Control System	Development of System to Remotely Check and/or Calibrate Sensors	0.20	3	26b
5.1.2-3	Process Control System	Testing of Sensors Under Tokamak Environmental Conditions	0.20	3	26b
5.1.3	Safety/Protection System				
5.1.4-1	Data Handling System	Development of Data Compression Techniques	0.40	3	26a
5.2-1	Operational Instr. Systems	Qualification of Remotely-Replaceable Microwave Corner Reflector Array	0.11	2	26b
5.2-2	Operational Instr. Systems	Transparency Degradation of Microwave Windows	0.11	3	
5.2-3	Operational Instr. Systems	Development of X-ray Measuring Techniques for Determining the TNS Electron Temperatures	0.90	3	
5.2-4	Operational Instr. Systems	Development of Microwave Interferometer Designs for TNS	0.50	3	
5.2-5	Operational Instr. Systems	Qualification of Replaceable Rogowsky Loops	0.09	3	
5.2-6	Operational Instr. Systems	Qualification of Replaceable β_θ Coils	0.09	3	
5.2-7	Operational Instr. Systems	Qualification of Remote Disassembly of Voltage Loops	0.19	3	
5.2-8	Operational Instr. Systems	Hardware Development for Neutron Fluence Monitor	0.10	3	
5.3-1	Scientific Instrumentation	Development of Vessel Windows for Visible Light and Infrared Radiation	0.09	3	26c

↓

TABLE 2-4
TNS RD&D ASSESSMENT

ITEM/SYSTEM		TOPIC	COST M \$	PRIORITY	WBS REFERENCE
5.3-2	Scientific Instrumentation	Develop Instrument to Measure Ion Temperature	2.00	4	26 c
5.3-3	Scientific Instrumentation	Develop Instrument to Measure Z_{eff} Effective Ion Charge	3.00	4	↓
5.3-4	Scientific Instrumentation	Qualification of a Remotely-Replaceable Diamagnetic Loop	0.06	4	
5.3-5	Scientific Instrumentation	Development of a Short (< 1 mm) Wavelength Multichannel Laser Interferometer	2.00	4	
5.3-6	Scientific Instrumentation	Synchrotron Radiation As Diagnostic Tool	0.40	4	
6.0-1	Support Facilities	Development and Test of Passageway Sealing	0.14	3	25 e
6.0-2	Support Facilities	Development and Test of Utility Penetrations Seals	0.09	3	25 e
7.0	REACTOR TECHNOLOGY RESEARCH				
7.1-1	Blanket/Shield Test Cap.	Design and Development of Blanket/Shield Test Modules	0.15	3	22
7.2-1	Materials Test Capability	Design and Development of Materials Test Modules	2.90	4	22
7.2-2	Materials Test Capability	Fusion Reactor Radiation Effects Data	2.00	4	22
7.3-1	Remote Operations Test Capability	Design and Development of a Remote Handling Test Station	2.35	4	25 a
7.4-1	Impurity Control Test Capability	Design and Development of Impurity Control Test Capability	3.90	2	22 f
7.5-1	Tritium Handling Test Capability	Design and Development of Tritium Breeding Module	6.50	4	22
7.6-1	Plasma Dynamics Test Capability	Design and Development of Plasma Dynamics Test	1.25	4	22
7.7-1	Advanced Refueling Test Capability	Design and Development of Advanced Refueling Test Hardware	1.60	4	25 g
7.8-1	Electrical Power Generation Test Capability	Design, Development and Fabrication of an Electrical Power Generation Research Subsystem	1.75	4	22
7.9-1	Safety and Environmental Impact Research	Generic Fusion RD&D Environmental Statement	3.00	2	22

TABLE 2-4
TNS RD&D ASSESSMENT

ITEM/SYSTEM		TOPIC	COST M \$	PRIORITY	WBS REFERENCE
7.9-2	Safety and Environmental Impact Research	Generic PSAR/F5AR Criteria for Fusion Facilities	0.50	3	22
7.9-3	Safety and Environmental Impact Research	Development of Generic Engineering Codes and Standards	1.80	4	22
7.9-4	Safety and Environmental Impact Research	Generic Fusion Reactor Safety Research	9.00	4	22
8.0-1	Applied Physics/Plasma Engineering	Stability of Elongated High β Plasmas	2.00	1	22
8.0-2	Applied Physics/Plasma Engineering	High β Time Scale for FCT	2.00	1	22
8.0-3	Applied Physics/Plasma Engineering	Measurement of Plasma Scaling Relationships	3.00	1	22
8.0-4	Applied Physics/Plasma Engineering	Equilibrium and Transport During Start-up/Shutdown	2.00	2	22
8.0-5	Applied Physics/Plasma Engineering	Transport Property of Synchrotron Radiation	2.00	3	22

The most critical TNS RD&D needs may be grouped into eight problem areas which are, in general terms:

Plasma Physics and Engineering Design Basis

A general list of problems in this area was outlined at the start of this section. Focused code development and analysis is required along with major experiments performed on large tokamaks. Provision must be made for experimental studies on high beta tokamak plasmas, equilibria and stability, plasma dynamics, impurity control and plasma heating.

Superconducting Coil Technology

A decision on the baseline coil technology for the ORNL/(W) TNS design study is scheduled to be made by May, 1977. At this time it appears to be prudent to continue development of the NbTi option and accelerate the development of the Nb₃Sn option. Funding restraints may force an early decision in this area. If Nb₃Sn is selected as the reference material, a major redirection of the LCP program will be required. Conductor and structural qualification is required as well as sub-scale coil fabrication and test. A critical need in this area, which the LCP program must provide, is the development of a supportable cost data base for superconducting coil systems by the end of the TNS conceptual design phase.

Impurity and Gas Throughput Control

This topic will have a major impact on TNS design and cost. A final decision on the overall approach can be delayed until the end of conceptual design, but only if a dual-track design approach is used and R&D is strongly pursued to support each track. We believe that TNS must address the impurity control problem, the current issue is one of determining the appropriate design criteria. There is no overall experimental program in place, however, to provide the answers required for TNS. ISX and PDX are both necessary, however, they fall short of desired capability in terms of pulse duration, plasma temperature and experimental flexibility.

Poloidal Field System

The ORNL/(W) design team has tentatively selected water-cooled copper windings for this system; thus the need for the development of superconducting technology for this application has not been identified at this time. The advantages of superconducting or low temperature poloidal windings for the TNS application will be examined in the near future. There is a concern with the development of OH switching circuits and components which is complicated by a fundamental lack of knowledge of plasma dynamics (break-down, discharge initiation, termination and fault conditions). As far as the shaping or equilibrium field windings are concerned the major design issues presently are: locating the windings inside or outside of the TF coils, winding topology for effective plasma shaping, stability and control, and the need for high current, remotely actuated, electrical connectors.

Plasma Heating

The baseline approach for TNS in this area is near-perpendicular injection of positive ion-neutral beams which are scaled up from TFTR conceptual beam line designs. Considerable work must be done first to assure that TNS neutral beam design criteria are well established. Positive ion beam technology programs must investigate and implement design refinements to improve efficiency and cost. Advanced concepts and technologies must be pursued, such as: negative ion beams, ripple injection, control of fractional energy components and direct energy recovery of the unneutralized portion of the beam. A strong alternative to neutral beams which must be vigorously pursued is rf heating technology.

Fueling

The limited fueling research now underway must be broadened and accelerated, with particular emphasis on TNS requirements. Both pellet and liquid jet refueling must be examined on large tokamaks to provide a reasonable design basis.

Tritium Handling

The major issues in this area are the degree of tritium containment possible and necessary to assure accountability and safety, and the proof testing of various tritium removal and isotopic separation approaches. Considerable work must be performed to provide an unclassified tritium property data base.

Tokamak Assembly, Disassembly and Servicing

This critical area covers the investigation of a host of design questions related to machine segmentation, vacuum topology (individual versus common dewars for superconducting coils, versus secondary vacuum enclosures versus evacuation of the reactor cell), the development of interfaces compatible with remote handling tooling and the development of specialized remote techniques such as cutting, welding, inspection and leak detection.

2.3 TNS RD&D COSTS

The cost estimates which have been developed for the TNS RD&D needs assessment are quite preliminary at this time and can only be regarded as early, order-of-magnitude engineering judgements. Detailed evaluations of what is required to accomplish each task has not been possible in the time available. Such evaluation is essential to provide the basis necessary for better cost estimates. A large uncertainty is associated with those activities connected with on-going or generic MFE programs where an attempt has been made to allocate a portion of the overall operating cost of these activities to TNS.

A summary RD&D cost analysis is presented in Table 2-5 where cost estimates have been grouped by TNS system and priority classification. Contingency, escalation and RD&D management costs have not been included. The overall cost estimate is 179 M\$. This does not appear unreasonable, considering the total scope of the project, the time span involved (approximately nine years from initiation of conceptual design to start-up) and the fact that many of the required generic activities are already in place and accounted for, to some extent, in existing budget projections.

The tokamak system requires the greatest share of the effort (68 M\$ or 38% of the total). The total hardware system-related (system items 1 through 6) RD&D amounts to 131 M\$, while the reactor technology and plasma engineering research included in this compilation is estimated to cost 47.7 M\$. Most of the items in Category 7.0, Reactor Technology Research, have been given a generic priority which is subject to change as program objectives are solidified.

Another way to analyze the cost estimate is to consider the distinction between those activities which are generic to the entire MFE program, and consequently involve a number of organizations, and those which appear to interact strongly with the TNS design

and would be performed most efficiently under the direct control of the project. Table 2-6 summarizes the cost breakdown obtained by classifying items as generic or design-related. Again, this distinction is preliminary and requires considerable review as the cost and schedule requirements for the project are developed.

The cost estimate for design-related RD&D is 77 M\$ (or 43% of the total) and for generic related RD&D is 102 M\$ (or 57% of the total). Thus, over half of the cost of TNS RD&D is associated with generic work which is already in place in the MFE program (but without explicit TNS focus). A comparable analysis of the TFTR R&D budget (PPPL-1312, TFTR Reference Design Report) shows that they have provided for a total of 35 M\$ of design-related RD&D, with neutral beam line development (total cost not available at this time) the principal element of generic supporting RD&D.

TABLE 2-5
TNS RD&D COST SUMMARY (M\$)

<u>SYSTEM</u>	<u>PRIORITY 1 CRITICAL</u>	<u>PRIORITY 2 IMPORTANT</u>	<u>PRIORITY 3 NECESSARY</u>	<u>PRIORITY 4 GENERIC</u>	<u>SYSTEM TOTAL</u>
1. Tokamak	34.97	17.84	15.03	----	67.84
2. Electrical Power	----	1.00	11.70	0.15	12.85
3. Plasma Heating	0.85	19.25	2.88	0.35	23.33
4. Tokamak Support	2.91	4.28	6.92	----	14.11
5. IC&D	1.70	0.61	3.28	7.46	13.05
6. Support Facilities	<u>----</u>	<u>----</u>	<u>0.23</u>	<u>----</u>	<u>0.23</u>
SUBTOTAL (1-6)	<u>40.43</u>	<u>42.98</u>	<u>40.04</u>	<u>7.96</u>	<u>131.41</u>
7. Reactor Technology	----	6.90	0.65	29.15	36.00
8. Applied Physics/ Plasma Engineering	<u>7.00</u>	<u>2.00</u>	<u>2.00</u>	<u>----</u>	<u>11.00</u>
SUBTOTAL (7-8)	<u>7.00</u>	<u>8.90</u>	<u>2.65</u>	<u>29.15</u>	<u>47.70</u>
TOTAL (1-8)	47.43	51.88	42.69	37.11	179.11

TABLE 2-6
TNS RD&D COST BREAKDOWN BY GENERIC AND DESIGN-RELATED ACTIVITIES

<u>SYSTEM</u>	<u>DESIGN-RELATED RD&D (M\$)</u>	<u>GENERIC PROGRAM RD&D (M\$)</u>	<u>SYSTEM TOTAL (M\$)</u>
1. Tokamak	20.97	46.87	67.84
2. Electrical Power	2.65	10.20	12.85
3. Plasma Heating	15.20	8.13	23.33
4. Tokamak Support	6.12	7.99	14.11
5. IC&D	9.44	3.61	13.05
6. Support Facilities	<u>0.23</u>	<u>----</u>	<u>0.23</u>
SUBTOTAL (1-6)	<u>54.61</u>	<u>76.80</u>	<u>131.41</u>
7. Reactor Technology	20.40	16.30	36.70
8. Applied Physics/ Plasma Engineering	<u>2.00</u>	<u>9.00</u>	<u>11.00</u>
SUBTOTAL (7-8)	<u>22.40</u>	<u>25.30</u>	<u>47.70</u>
TOTAL 1-8)	77.01	102.10	179.11

3.0 RD&D NEEDS FOR TNS SYSTEMS

To expedite the identification and discussion of TNS RD&D needs, a common assessment form was developed containing a statement of the problem, data required, scope of the task, schedule requirements, resource requirements, estimated cost and a discussion of alternatives. Each of the 139 tasks is identified by an item number which is cross-referenced in Table 2-4 with a Work Breakdown Structure (WBS) designation indicating which hardware system or subsystem design is impacted by the RD&D item.

In the following compilation of RD&D assessments, the items belonging to each major system are preceded by a brief overview discussion.

3.1 TOKAMAK SYSTEM

3.1.1 Vacuum Vessel Assembly

The vacuum vessel assembly consists of three major components; these are the vacuum vessel structure, the plasma limiter, and the impurity control subsystems.

Five RD&D tasks are defined for the vacuum vessel structure. One is a research task necessary to establish the design basis of the vessel - determination of required toroidal electrical resistance. Two are development tasks necessary to show feasibility and permit comparisons between alternative design approaches - segmentation joints, and replaceable electrical insulators. The remaining two are demonstration tasks involving system capability, and shell stability.

Only two RD&D tasks are defined for the plasma limiter. The first is a research task - the search for new limiter materials and experimental evaluation of them to the extent possible in existing machines. The other task is a demonstration of the thermal performance

of a prototype limiter bar. Several additional development tasks may be necessary to measure material properties and to establish fabrication feasibility and procedures for potential limiter materials identified in the first task.

Thirteen RD&D tasks are defined for the impurity control subsystem, the large number is indicative of both the importance of impurity control and the very limited background of experience with impurity control phenomena and techniques. Five research tasks are intended to provide design basis information for impurity control subsystems: properties of the scrape-off layer, surface physics engineering measurements, and operational techniques to minimize the need for an impurity control subsystem. Six tasks are identified to permit evaluation and comparison of proposed subsystems: low Z-walls, honeycomb walls, gas blankets, and flowing lithium surfaces. Only two tasks are demonstrations, and these only in the sense of being proof-of-principle tests: verification of operation of a continuous poloidal divertor and a bundle divertor. Assuming that one or more approaches to impurity control gives promise of being successful, additional component development and demonstration tests will be necessary. Final demonstration of the complete subsystem can be made part of TNS operation.

TNS RD&D ASSESSMENT

DATE: 2/3/77
 BY: R. Flaherty
 ITEM: 1.1.1-1
 PRIORITY: 2

SYSTEM: Vessel Structure

COMPONENT: Vacuum Vessel Shell

TOPIC: Toroidal Electrical Resistance of Vacuum Vessel Shell

PROBLEM: During startup, at the beginning of ohmic heating, the initial plasma and the vessel are parallel loops linking the OH field. As the OH field is ramped, energy will be deposited in the vessel as well as in the plasma by resistive heating (I^2R). The energy deposited in the vessel contributes nothing to the heating of the plasma, but requires that additional capacity be provided in the OH power conversion equipment system, which is a major cost element of the tokamak system. To minimize the costs associated with this useless energy, the toroidal resistance of the vessel should be made very large, or even infinite by the inclusion of an electrical insulator in this path.

During an uncontrolled shutdown, caused perhaps by loss of vacuum, with the influx air quenching the plasma and replacing it with a nonconducting cold gas, the current flowing in the plasma will shift to the parallel conductor, the vessel. The resistance of the vessel will cause this current to decay and the change in current will induce a voltage around each turn of the poloidal coils; for a very rapid current decay in TNS the induced voltage could be several kilovolts per turn. To limit the induced voltage to a value that will not damage the electrical insulation of the poloidal coils, the toroidal resistance of the vessel should be made small so that the current decays slowly.

The problem is to find the maximum value for the toroidal resistance of the vessel which will provide for safe shutdown. This will be the target value for the resistance, because toroidal currents have no other beneficial effects. Currents flowing toroidally in the vacuum vessel have other possible deleterious effects: a) they tend to shield the plasma from the electric field and delay its appearance in the plasma; b) there is a vertical magnetic field associated with the current distribution in the vessel which can drive the plasma radially; c) the heating in the vacuum vessel is concentrated in the high resistance bellows, if bellows are used.

DATA REQUIRED: Plasma temperature vs time at start-up, for various realistic vessel resistances, plasma sizes, and OH power supplies. Induced turn-to-turn voltages in the poloidal field coils at shutdown, for various realistic vessel resistances and and plasma quench rates.

SCOPE OF TASK: Develop a computer model of the start-up and shutdown sequences that includes the ohmic heating process and the induced voltages in poloidal conductors at termination.

- Make experimental measurements on existing and planned large tokamaks (PLT, ORMAK-U, DIII, PDX, etc.).
- Compare the experimental values with those predicted by the computer model and fine-tune the computer model.
- Using the computer model, predict the effects of feasible changes in vacuum vessel resistance in existing large tokamaks.

- Verify the predictions experimentally, or refute them and modify the computer model accordingly.
- Using the computer model, determine the highest vessel resistance which will permit safe shutdown of TNS.
- Determine effect (chiefly cost difference) of this vessel resistance on the OH power conversion equipment system.
- Using the computer model, investigate the effects of design alternatives such as:
 - electrical gaps, lumped resistance (bellows), or insulators in the vessel (for start-up) in parallel with spark gaps (for shutdown).
 - spark gaps between poloidal field coil turns to limit voltage across insulation to that induced in a single turn.
 - a large cross section low resistance toroidal conductor with a toroidal gap, inside a high resistance vessel, to provide an alternative low resistance path for the plasma current.

SCHEDULE NEED/IMPACT: Start of Title II vessel design.

RESOURCE REQUIREMENTS: Computer, computer programs, and large tokamaks.

AVAILABLE RESOURCES/PROGRAMS: Computer programs are available which, with modifications, could be used for this purpose. Experimental measurements should be made on existing machines (PLT, ORMAK-U, etc.).

ESTIMATED COST: Computer programming and machine time, \$50,000 plus \$100,000 for operating time on existing tokamaks, minor modifications, and special instrumentation.

ALTERNATIVES: Extrapolate from experience with existing machines and design conditions of future machines. Design the TNS vessel with costly and complicated bellows sections, based on prior practice.

TNS RD&D ASSESSMENT

DATE: 2/4/77

BY: R. Flaherty

ITEM: 1.1.1-2

PRIORITY: 2

SYSTEM: Vessel Structure

COMPONENT: Vacuum Vessel Shell

TOPIC: Vacuum Vessel Segmentation Joints

PROBLEM: Final assembly of a vacuum vessel linking the TF coils requires at least two vacuum tight joints for final closure of the toroidal vessel. Disassembly after D-T operations requires that such joints be severed remotely. Continued use of the tokamak requires that such joints be resealed remotely.

DATA REQUIRED: Configuration of closure joints, including space requirements, access for remote separation and sealing, and design of remotely operated components and actuators. Experimental data on the performance of candidate concepts.

SCOPE OF TASK: Layout, design, and analysis of several conceptual joints, including welded joint, single gasket joint, staged vacuum joint (guard vacuum): Consider welding/cutting, electromechanical actuators, thermalmechanical actuators, etc.; Design and test critical components. Construct and demonstrate one full scale joint.

SCHEDULE NEED/IMPACT: Completion by end of FY 81 for Title II vessel design. Feasibility by start of Title I, and demonstration by the start of Title II.

RESOURCE REQUIREMENTS: Mechanical development laboratory for large equipment with design, fabrication/modification, assembly, and test capabilities.

AVAILABLE RESOURCES/PROGRAMS: Similar joints are required in TFTR, although TNS requires larger joints of more complex shape. The Grumman/Gamah joint development for PPPL may contribute to the TNS joint design.

ESTIMATED COST: Labor, \$450,000; welding/cutting machines, \$950,000; component test hardware, \$100,000; demonstration hardware, \$1,000,000. Total is \$2,500,000.

ALTERNATIVES: The alternative to development of such joints is the use of an evacuated test cell. With this, the joints between vessel components are required to be only a high impedance rather than a seal.

TNS RD&D ASSESSMENT:

DATE: 2/7/77
 BY: R. J. Budenholzer
 ITEM: 1.1.1-3
 PRIORITY: 3

SYSTEM: Vessel Structure

COMPONENT: Vacuum Vessel Cooling System

TOPIC: Verification of Vessel Cooling System Capability

PROBLEM: Despite detailed analysis of coolant flow distribution and heat transfer within the vacuum vessel walls (assuming that these are the first convectively cooled walls) it is necessary to demonstrate performance of a prototype before commitment to manufacture.

DATA REQUIRED: Flow distributions and temperature distributions (both coolant and outer skin) must be determined experimentally.

SCOPE OF TASK: A full wall segment, including representative penetrations, should be tested under simulated operating conditions, applying reduced heat flux but extended pulse length. Infrared photography may be used to find hot spots.

SCHEDULE NEED/IMPACT: Data required at start of Title II design

RESOURCE REQUIREMENTS: Flow simulation facilities, radiant or electron, ion beam heat sources.

AVAILABLE RESOURCES/PROGRAMS: Development programs on other devices may contribute to the design of the TNS vacuum vessel cooling system, but verification testing of the specific system of hardware by the TNS design team will still be required

ESTIMATED COST: Labor, \$150,000; test article, \$1,500,000; test rig, \$750,000;
 Total \$2,400,000.

ALTERNATIVES: Conservative design with a lingering probability of flow-starved areas leading to hot spots and premature cyclic fatigue failure.

TNS RD&D ASSESSMENT

DATE: 2/3/77
 BY: R. Flaherty
 ITEM: 1.1.1-4
 PRIORITY: 3

SYSTEM: Vessel Structure

COMPONENT: Vacuum Vessel Shell

TOPIC: Mechanical Stability Tests

PROBLEM: During design scoping and preliminary design of the vacuum vessel, stability is evaluated by means of equations having closed solutions. These are available only for idealized geometries such as circular cylinders, elliptical cylinders, a torus of circular cross section, etc. The final design of the vacuum vessel will be by iterative finite element analysis, which will include the effects of:

- Changes from a geometrically defined (probably elliptical) cross section to a similar but somewhat distorted cross section, i.e., the D-section vessel to provide a more desirable plasma space envelope.
- Deviations from the ideal doubly-curved vessel surfaces to permit use of feasible fabrication processes.
- Reduction of the toroidal span of vessel elements from the outboard equator to the inboard equator.
- Discontinuities in stress distribution resulting from penetrations, joints, mechanical and support loads, etc.

Finite element analysis has developed into a very effective and versatile design aid. Nevertheless, some experimental evidence is desirable to support the credibility of the representation of a novel structure with continuously varying structural properties as a network of elements with locally uniform properties. The most reliable support is strain measurements made on a prototype structure under actual load.

DATA REQUIRED: Stress level and stress distribution at all critical sections of the structure, as inferred from strain gage measurements made on a full-size prototypical portion of the vessel.

SCOPE OF TASK:

- Build a full size segment of the vacuum vessel using prototype materials and fabrication procedures; the segment must be representative of the entire vessel, either initially or by modifications.
- Design and build a test rig to apply test loading to the test article.
- Install strain gages on the test article and perform tests; testing to destruction (collapse) is not required.
- Analyze and present test data in a form suitable for comparison with design analysis.

SCHEDULE NEED/IMPACT: Need at end of Title II design.

RESOURCE REQUIREMENTS: Vacuum system, data acquisition system, data reduction system.

AVAILABLE RESOURCES/PROGRAMS: Structural testing laboratories experienced with spacecraft would be suitable for this test.

ESTIMATED COST:	Test Article	\$ 1, 200, 000
	Test Rig	600, 000
	Labor	450, 000
		<u>2, 250, 000</u>

ALTERNATIVES: Use service vessel as test article, accepting risk of delays for rework, retrofitting, etc.

TNS RD&D ASSESSMENT

DATE: 2/7/77
 BY: R. Flaherty
 ITEM: 1.1.1-5
 PRIORITY: 3

SYSTEM: Vessel Structure

COMPONENT: Vacuum Vessel

TOPIC: Replaceable or Maintainable Electrical Insulators

PROBLEM: The neutron fluence inside the shield of TNS is approximately five times the damage threshold of the best available electrical insulators. Provisions must be made therefore to replace all electrical insulators inside the shield; some of these will be seals around electrical penetrations of the vessel wall and others will be structural supports for conductors inside the vessel. Electrical breaks in the vessel wall or its support structure (intended to limit eddy currents) must also be replaceable. Thermocouples and strain gages must be replaceable if they must continue to function.

DATA REQUIRED: Configuration of remotely removable and replaceable electrically insulated vessel wall penetrations and supports, including space requirements, access requirements for remote tooling, and designs for remotely operated components, actuators, and extraction casks.

SCOPE OF TASK: Selection of realistic sizes of electrically insulated penetrations and supports, design, fabrication, and testing of the insulators, design, fabrication, and demonstration of the necessary remote extraction and installation tooling. A full size mock-up of a representative section of the machine is necessary.

SCHEDULE NEED/IMPACT: Needed by the beginning of Title I design to guide preliminary design of other systems and to prevent "re-invention" in systems undergoing parallel development.

RESOURCE REQUIREMENTS: Mechanical development laboratory for large equipment (aircraft, spacecraft, etc.) with design, fabrication/modification, assembly, and test capabilities.

AVAILABLE RESOURCES/PROGRAMS: PPPL has some work underway on mechanical aspects of seal problems in Grumman/Gamah seal development program; electrical insulator problem has not been addressed, and may not exist in TFTR.

ESTIMATED COST: Labor, \$922,000; Test Hardware, \$2,000,000; Total, \$2,922,000.

ALTERNATIVES: There is no real alternative to this program. If development does not proceed in an identified planned program, equivalent work will be done (and probably duplicated) in other programs.

TNS RD&D ASSESSMENT

DATE: 2/4/77
 BY: E. W. Sucov
 ITEM: 1.1.2-1
 PRIORITY: 3

SYSTEM: Plasma Limiter
 COMPONENT: Limiter Bar
 TOPIC: Material Damage Studies

PROBLEM: Contact of the plasma with the limiter either during the startup period or during the burn period will cause limiter material to be released into the plasma. These impurity ions cause energy losses from the plasma due to radiation and also degrade the plasma by reducing the density of fuel ions that can be supported by a given electron density. Materials other than tungsten may be able to satisfy the energy absorbing requirements of the limiter bar while at the same time have lower sputtering coefficient or be composed of lower atomic weight atoms or be less susceptible to damage. A program is needed that evaluates alternate materials under conditions similar to those found in a TNS type plasma.

DATA REQUIRED: Measurements on candidate materials of sputtering and damage rate caused by plasma attack. It will be desirable first to separately impact the materials with fuel ions, electrons, alphas and neutrons of the appropriate energy so as to identify promising candidates. However, final evaluation must be in an actual plasma and evaluation criteria will be in terms of plasma effects such as change in resistivity, radiation losses, or Z_{eff} .

SCOPE OF TASK: Approximate models of material behavior should be applied to existing information on limiter effects in order to suggest candidate materials. Sputtering and damage measurements under impact by ions, electrons and neutrons could be performed in radiation damage laboratories which have appropriate sources. However, the final evaluation must be done in an operating tokamak.

SCHEDULE NEED/IMPACT: This information should be available by 1982 in order for it to be included in the design and to provide proper lead time for fabrication of the bars. However, delay in developing this information would not be critical since the limiter bar decision can be postponed till 1984.

RESOURCE REQUIREMENTS: Sources of 0.1 to 2 keV ions and electrons and 14 MeV neutrons with flux density about 1 MW/m². Ultra high vacuum chambers with provision for measuring sputtering coefficient. Tokamak plasma with provision for measuring Z_{eff} , radiated losses, etc.

AVAILABLE RESOURCES/PROGRAMS: Radiation damage on materials studies labs at ANL, BNL, or ORNL, tokamaks such as PLT are presently operating. ISX will be operating by 1979 and is designed to test materials in a plasma environment; however, its plasma temperature and pulse length are lower than that in TNS, so PLT or ORMAK-U should be considered for the final proof tests.

ESTIMATED COST: \$200,000 to perform the materials evaluation; about \$100,000 to check candidate limiter bars in a tokamak plasma.

ALTERNATIVES: Continue to use tungsten limiter bars.

TNS RD&D ASSESSMENT

DATE: 2/7/77
 BY: R. J. Budenholzer
 ITEM: 1.1.2-2
 PRIORITY: 3

SYSTEM: Plasma Limiter

COMPONENT: Limiter Bar

TOPIC: Thermal Performance of Limiter Bar

PROBLEM: Demonstration of adequate thermal performance of the limiter bar would be desirable, but is not feasible because a heat source equivalent to the TNS plasma is not available. Therefore qualification of the limiter bar will be by comparison of the thermal characteristics of a prototype limiter bar with the characteristics used in its design. This type of qualification will be necessary without question if, as expected, the limiter bar is a laminated diffusion bonded or isostatically compressed powder structure.

DATA REQUIRED: Thermal conductivity in appropriate directions through prototype, thermal diffusivity, emissivity of surfaces at effective temperatures, stability of emissivity (or emissivity coatings, if used).

SCOPE OF TASK: From a review of the thermal design of the limiter bar, determine the critical thermal paths through the limiter bar. Arrange heat sources to approximate thermal inputs from plasma and monitor temperatures along the critical paths. Testing must be done in vacuum and through a wide range of temperatures.

SCHEDULE NEED/IMPACT: Data required prior to start of Title II design.

RESOURCE REQUIREMENTS: Vacuum system, heat sources, instrumentation, shop facilities adequate to install instrumentation.

AVAILABLE RESOURCES/PROGRAMS: PLT and TFTR tests of limiters may provide adequate design information given proper focus.

ESTIMATED COST:	Test article	\$20,000 minimum
	Testing	42,000
		<u>\$62,000</u>

ALTERNATIVES: Acceptance of risk associated with limiter design based on extrapolated data from other machines, without verification.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: E. W. Sucov/T. F. Yang
 ITEM: 1.1.3-1
 PRIORITY: 1

SYSTEM: Impurity Control

COMPONENT: Poloidal Divertor

TOPIC: Verification of Poloidal Divertor Operation in a High Temperature Tokamak

PROBLEM: Current DMFE plans call for the PDX (Poloidal Divertor Experiment) to demonstrate the effectiveness of and limitations to the poloidal divertor concept. Even if PDX is totally successful in its design goals, it will not provide an adequate basis for the design of a poloidal divertor for TNS because the plasma temperature is too low (~ 1.5 keV) and the pulse duration is too short (~ 0.5 sec). Recent analyses of the effect of poloidal divertors on transport properties of the plasma show different effects at different plasma temperature so operation at TNS temperature could not be predicted from PDX experience. Furthermore, the particle collection system in the burial chamber in PDX is designed to handle short pulses of low throughput gas loads. It is incapable of handling long pulse duration, high throughput gas loads which would be characteristic of TNS plasma operation. A viable system of long pulse quasi-continuous particle collection must be conceived, developed, and tested. The divertor removes leaked fuel ions from the plasma region; continued burn under long pulse (several times particle confinement time) operation requires that the fuel be replenished continuously. An upgrade of PDX must be designed and built to address these problems and provide a test bed for evaluating candidate schemes for solving these problems.

DATA REQUIRED: Rates of particle and energy leakage from the plasma must be available, either by direct measurement on a high temperature PDX or extrapolation from other machines. In addition, demonstration of capability of schemes for collecting high throughput, long duration gas loads and demonstration of capability of schemes to refuel the plasma during long pulse burn are needed.

SCOPE OF TASK: Design and construction of an upgraded PDX so as to provide higher temperature plasmas for several seconds. Measurements of particle and energy flux from a high temperature plasma with a poloidal divertor in operation. Conception, development, installation, and proof of operation in PDX-U of particle collection and refueling schemes.

SCHEDULE NEED/IMPACT: This information is needed by the start of Title II, preferably by the end of the conceptual design.

RESOURCE REQUIREMENTS: An upgraded PDX with associated diagnostics and scientific and engineering staff is essential to prove the various collection and refueling schemes. To conceive, develop, and make feasibility tests on collection and refueling schemes will require laboratories with capabilities in vacuum handling, ion beam generation and control, cryogenic liquid handling and control.

ITEM: 1.1.3-1 (Continued)

AVAILABLE RESOURCES/PROGRAMS: PDX is presently under construction at PPPL; this site would be the logical location for the upgrade. For the other work, government, industrial, and university laboratories have adequate facilities.

ESTIMATED COST: To upgrade PDX will require larger TF and PF coils and power supplies, additional neutral beam lines, and provision for installing candidate collection and refueling schemes. This is estimated to cost about \$25,000,000.

ALTERNATIVES: If PDX-U is not available, TNS itself would have to become the test bed for proving poloidal divertor operation, or TNS could be constructed without active impurity control systems.

TNS RD&D ASSESSMENT

DATE: 1/26/77
 BY: E. W. Sucov
 ITEM: 1.1.3-2
 PRIORITY: 1

SYSTEM: Impurity Control

COMPONENT: Poloidal Divertor

TOPIC: Measure Properties of Scrape-Off Layer
 (see also Predict Scrape-off Layer Properties, Item 1.1.3-3)

PROBLEM: The poloidal divertor is being proposed as a means whereby fuel ions leaking from the plasma and impurity ions sputtered off the wall can be captured in a scrape-off layer, located between the plasma and the wall, and removed from the plasma chamber. However, there exists no experimental verification that the scrape-off layer will indeed perform the above functions as effectively as is necessary. Theoretical predictions of scrape-off layer performance dependence on such parameters as radial distributions of the ion and neutral densities and temperatures also need to be verified. Because the scrape-off layer interaction with the plasma cannot be simulated it requires a full scale tokamak plasma as a test bed.

DATA REQUIRED: Measurements of n_e (electron density), n_i (ion density), and T in at least one point in the scrape-off layer as functions of plasma Z_{eff} , n and T distributions, wall material, gas pressure in the burial chamber, etc., will be needed. The flux of fuel ions emerging from the plasma, which theory states will be influenced by the scrape-off layer performance, needs to be measured.

SCOPE OF TASK: A special tokamak with poloidal divertor and provision for measuring scrape-off layer and plasma parameters must be available. Preliminary measurements of capture coefficients could be performed in crossed beam experiments.

SCHEDULE NEED/IMPACT: Decision on whether to incorporate a poloidal divertor in the TNS design must be made by end of Title I. Delay in receiving positive information would likely cause the poloidal divertor to be removed from the TNS design or would result in a design based solely on theoretical predictions.

RESOURCE REQUIREMENTS: Tokamak plasma with poloidal divertor and means to influence plasma divertor properties as well as to measure these properties. To prove the concept for TNS the plasma should have current ~ 2.5 MA, temperature ~ 5 keV, pulse length ~ 5 sec, and electron density $\sim 10^{20} \text{ m}^{-3}$.

AVAILABLE RESOURCES/PROGRAMS: PDX is the only tokamak in the US which incorporates a poloidal divertor. However, its present design goals are much more modest than indicated above as necessary, and as a consequence will provide limited answers in terms of scrape-off layer properties. An upgraded PDX, with properties as indicated above, must be built in order to prove the concept.

ESTIMATED COST: Assuming PDX and PDX-U are available, \$1,000,000.

ALTERNATIVES: Other impurity control schemes such as cold gas blanket, low Z wall, bundle divertor, etc., might be considered. However, these would have to be funded and test bed tokamaks with appropriate plasma properties made available. A scheme involving injection of protons to cause "impurity flow reversal" is to be tested in the ISX, however there is no provision to incorporate it in the TFTR so it will not have the chance to be proven in a plasma with properties approaching that of TNS. The only alternative to divertors which is in a position to be proven for TNS is low Z walls.

TNS RD&D ASSESSMENT

DATE: 1/26/77
 BY: E. W. Sucov
 ITEM: 1.1.3-3
 PRIORITY: 2

SYSTEM: Impurity Control

COMPONENT: Poloidal Divertor

TOPIC: Predict Scrape-Off Layer Properties
 (See also Measure Scrape-off Layer Properties, Item 1.1.3-2)

PROBLEM: The poloidal divertor is being proposed as a means whereby fuel ions leaking from the plasma and impurity atoms sputtered off the wall can be captured in a scrape-off layer, located between the plasma and the wall, and removed from the plasma chamber. Theoretical models exist which predict scrape-off layer capture capabilities. However, incorporation of a scrape-off layer seriously changes the transport properties of the plasma from that predicted for a plasma without it. It becomes essential therefore to improve the existing self consistent particle transport and energy balance code for the plasma which takes into account the new boundary conditions, namely the scrape-off layer, by adding an impurity transport code.

DATA REQUIRED: Additional models must be developed for sputtering off walls by fuel ions and charge exchange neutrals and diffusion of impurity atoms through the scrape-off layer and into the plasma.

SCOPE OF TASK: Models described above must be developed and substantiated by experimental or theoretical evidence, and incorporated into the plasma transport code. The enlarged code must be made operational.

SCHEDULE NEED/IMPACT: Code should be ready by the end of 1978 in order to be verified by PDX measurements.

RESOURCE NEEDS: Access to DMFE/CTR computer; particle transport and energy balance code.

AVAILABLE RESOURCES/PROGRAMS: Programs are underway at ORNL, PPPL, and University of Wisconsin to develop these enlarged codes. Work should be done by 1978-1979.

ESTIMATED COST: \$300,000

ALTERNATIVES: Perform measurements of scrape-off layer properties and construct model from these.

TNS RD&D ASSESSMENT

DATE: 1/26/77

BY: E. W. Sucov

ITEM: 1.1.3-4

PRIORITY: 2

SYSTEM: Impurity Control

COMPONENT: Low Z Wall - Carbon, B₄C, etc.

TOPIC: Measure and Evaluate Performance of Low Z Walls

PROBLEM: During the plasma burn period, ions and charge exchange neutrals from the plasma bombard the wall and sputter off impurity atoms which enter the plasma. Because the deleterious effects of these impurity ions, namely radiation losses and decrease in density of fuel ions, are proportional to the number of electrons in the atom, low Z walls may be less harmful to the plasma than walls made of high Z materials like steel or molybdenum. However, low Z walls have other properties which might disqualify them for consideration either as a load bearing wall or as a liner. Specifically low Z materials usually have lower melting point, lower physical strength, greater chemical reactivity, etc., than do high Z materials. Thus it is necessary to carefully measure and evaluate the advantages and disadvantages of low Z wall materials under plasma conditions.

DATA REQUIRED: Physical and chemical sputtering coefficients under bombardment by ions and neutrals of energies from 0.1 to 2 keV. Damage or chemical reaction rates under discharge cleaning and plasma burn conditions. Physical stability and mechanical integrity limits under cyclic thermal stress conditions characteristic of a plasma.

SCOPE OF TASK: These measurements need not be performed in a tokamak plasma, although final proof testing in such a plasma will be necessary. Simulation chambers can be used for generating discharge and thermal stress conditions; ion and neutral beam sources can be used to study the sputtering reactions. Samples and test equipment need to be fabricated.

SCHEDULE NEED/IMPACT: This information should be available by the end of Title I in order to permit the final design of the vacuum vessel to proceed in a timely manner.

RESOURCE REQUIREMENTS: Ion and neutral beam sources that can deliver 0.1-2 keV at 1 MW/m²; ultra high vacuum systems; high and low pressure discharge chambers; thermal stress chambers; or a test bed tokamak.

AVAILABLE RESOURCES/PROGRAMS: Radiation damage laboratories are at ANL, BNL, ORNL. ISX at ORNL will study various materials under cool plasma conditions. An ISX upgraded to higher temperature and longer pulse length would provide more relevant conditions.

ESTIMATED COST: Disregarding the cost of facilities, the task would cost ~\$500,000 for manpower and ~\$100,000 for equipment.

ALTERNATIVES: Continue to use stainless steel walls plus impurity control schemes.

TNS RD&D ASSESSMENT

DATE: 1/26/77
 BY: E. W. Sucov
 ITEM: 1.1.3-5
 PRIORITY: 2

SYSTEM: Impurity Control

COMPONENT: Honeycomb Wall

TOPIC: Evaluate Performance of Honeycomb Wall

PROBLEM: During the plasma burn period, ions and charge exchange neutrals from the plasma bombard the wall and sputter off impurity ions which enter and degrade the plasma. The honeycomb wall concept would reduce the entry rate of these impurities by forcing them to suffer multiple bounces off the honeycomb cell walls. This concept has been studied analytically but it has not yet been verified experimentally. The honeycomb wall, to be useful to the TNS, must demonstrate this reduction in impurity contamination after exposure to many 30 second pulses. Two effects that are likely to occur are preferential damage and erosion of cell walls causing the honeycomb structure to disappear and cyclic thermal stresses causing mechanical failure. Measurements must be made under plasma conditions to establish the long term value of the honeycomb wall.

DATA REQUIRED: Experimental measurements of change (decrease) in Z_{eff} in a plasma when honeycomb wall is present; these observations should be followed over many 30 second pulses. Erosion rate of wall under plasma conditions. Limits to physical stability and mechanical integrity under cyclic thermal stress conditions.

SCOPE OF TASK: Materials for the wall have to be chosen and sample walls fabricated. Normal measurements of Z_{eff} would continue to be taken.

SCHEDULE NEED/IMPACT: Needed by start of Title II design.

RESOURCE REQUIREMENTS: Hot, TNS-like, plasma with capability for subjecting many test panels to ion and neutron irradiation is essential. Ion and neutron beam sources to simulate plasma conditions. Honeycomb material fabrication capability.

AVAILABLE RESOURCES/PROGRAMS: ISX at ORNL is planning to test the honeycomb wall. However, ISX must be upgraded to provide hotter plasma (~ 5 keV) and longer pulse length (~ 10 s).

ESTIMATED COST: If ISX-U is available, the additional cost should be about \$200,000 for labor costs plus \$50,000 for fabrication and materials.

ALTERNATIVES: If ISX-U is unavailable, but ISX results were encouraging, honeycomb walls could be inserted into TFTR for further testing. If qualifying data is unavailable, designers will not include it in the design, or will include it at high cost with uncertain benefits.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: E. W. Sucov
 ITEM: 1.1.3-6
 PRIORITY: 2

SYSTEM: Impurity Control

COMPONENT: -----

TOPIC: Impurity Reversal

PROBLEM: The currently accepted models which describe diffusion of heavy impurity ions in a plasma predict that impurities will diffuse toward the point of maximum hydrogen density. Measurements of fuel ion density in various tokamaks show that it has a parabolic like distribution with peak value occurring on axis; the temperature distribution is also found to be parabolic with its peak value on axis. Thus, impurities are expected to diffuse into the central, hot region of the plasma where they will be most effective in lowering the temperature of the plasma. Inward diffusion of impurities could be stopped if the gradient of the density of fuel ions were reversed in the outer region of the plasma. Schemes which have been proposed for generating the reversed density gradient include cold gas blanket, injection of low energy neutral beams, and flowing of hydrogen gas down and around the plasma. A cold gas blanket has been used with good results in the Alcator machine, but it is not clear whether this is a feasible process for TNS-like plasmas. The last two schemes have been studied analytically but no experimental support for these concepts exists. The flowing hydrogen concept is to be tested in the ISX. Recent experimental data from TFR suggests that impurities do not diffuse inward but rather recycle in an outer region of the plasma. Thus, the foundation for all the impurity reversal schemes is suspect and must be verified.

DATA REQUIRED: Measurements will be needed of spatial and temporal distribution of tokamak plasma parameters (n_e , n_i , T_e , T_i , I_p) and line radiation from highly ionized states of the impurity, when impurities of different Z are introduced into the plasma and when various density reversal schemes are employed.

SCOPE OF TASK: A special tokamak with provision for radial and temporal measurement of the above plasma and radiation parameters must be constructed. In addition, it should have provision for implementing the above schemes for density reversal.

SCHEDULE NEED/IMPACT: Decision on which impurity control scheme to use in TNS must be made by the end of Title I (preferably by the end of conceptual design) since it is a major system affecting many other systems. ISX is designed to study the hydrogen flow scheme and is scheduled to be operational in 1978 so information on this scheme should be available in time. In order to test the cold gas blanket concept, the hydrogen flow system could be easily modified, so information on this scheme should be available in time. However, to examine the low energy neutral beam concept would require major modification of ISX; modification of neutral beam lines on other tokamaks like PLT would probably be a more desirable option.

RESOURCE REQUIREMENTS: Tokamak plasma with gas flow and neutral beam systems as well as diagnostics to measure plasma and radiation parameters as a function of radial position and time. To prove the concept for TNS, the plasma should have temperature ~ 5 keV, pulse length ~ 5 sec and electron density $\sim 10^{20} \text{ m}^{-3}$.

AVAILABLE RESOURCES/PROGRAMS: ISX is the only tokamak specifically designed to study nondivertor impurity generation and control. However, its present design goals are much more modest than indicated above as necessary. Thus, even if any of the systems work well it can only be considered as encouraging. An upgraded ISX with hotter plasma would have to be built in order to prove the concepts. The cold gas blanket means of controlling impurities could be tested in PLT and perhaps on PDX where measurements with and without divertor operation could be made.

ESTIMATED COST: Assuming a proper ISX-U or PLT is available, the additional cost to evaluate the density gradient reversal concepts would be about \$500,000.

ALTERNATIVES: If ISX provides encouraging results for the cold gas or flowing gas concept, but no ISX-U or PLT is available, designers could optimistically assume that the same results will be obtained for a much hotter plasma. To evaluate the low energy neutral beam concept existing neutral beam lines on other tokamaks, like PLT, could be modified.

TNS RD&D ASSESSMENT

DATE: 2/11/77
 BY: E. W. Sucov
 ITEM: 1.1.3-7
 PRIORITY: 2

SYSTEM: Impurity Control

COMPONENT: ---

TOPIC: Impurity Limiting Start-Up Scenarios

PROBLEM: At present, plasmas are initiated at the wall or limiter of the tokamak and generate large amounts of impurities which can make Z_{eff} (and losses) larger than desired for the most efficient operation of the plasma. While wall treatment or poloidal divertors may ultimately bring Z_{eff} down to desired values, the time constant for this process is not known. A feasible scheme is required which would avoid the initial surge of impurities and would make each pulse clean and reproducible. The most promising approach is that of the magnetic limiter, in which the plasma is constrained by an octupole field, such that it is initiated away from the walls. Another approach is to irradiate the cold gas with rf of wavelength such that maximum absorption occurs in the center of the volume. Neither of these schemes has been experimentally verified.

DATA REQUIRED: Time to form stable octupole null as function of cold gas pressure, vacuum vessel radius and volume, location and distribution of PF coils. Demonstration of stability and repeatability of formation of plasma away from the wall (for either or both schemes) and controlled growth to full size within required time intervals. Amount of change in Z_{eff} of a working plasma resulting from use of impurity limiting start-up scenario.

SCOPE OF TASK: Design, construct, and make operative the start-up system. Develop, construct and install diagnostics in an analog plasma container. Demonstrate feasibility in simulated tokamak conditions. Install in actual tokamak and demonstrate performance.

SCHEDULE NEED/IMPACT: If the TNS concept were to include a poloidal divertor or shaping coils, the octupole magnetic limiter would be easily compatible with it and a decision on its inclusion could be postponed until the end of Title II. However, if the TNS does not include special shaping coils or if the start-up scheme is rf excitation, feasibility information will be needed by the end of conceptual design. The PDX, as presently planned, should be able to demonstrate the feasibility of the magnetic limiter concept by 1980. However, the scheme will need to be demonstrated further in a hotter, denser, longer lived plasma such as a PDX Upgrade or TFTR.

ITEM: 1.1.3-7 (Continued)

RESOURCE REQUIREMENTS: Codes that describe equilibrium and shaping field and that describe absorption of rf as a function of time, density, size, and temperature of the plasma capability to design and construct (1) Plasma diagnostic systems, (2) rf generation, transmission and injection systems, (3) shaping field coils power supplies, and control systems. Analog and real tokamak plasmas.

AVAILABLE RESOURCES/PROGRAMS: PDX is specifically designed to check out magnetic limiter action. The other facilities are available in many government, industrial and university labs. Programs to study rf heating are underway at several locations; these could be easily modified to include plasma start-up studies. Information from the initial operation of TFTR with hydrogen may be available in the 1981-1982 period to provide additional confidence in the approach.

ESTIMATED COST: Hardware (assuming PDX-U is available) ~\$500,000; Manpower ~\$1,000,000.

ALTERNATIVES: Allow plasma to start at wall and use impurity removal schemes to bring Z_{eff} down to its required value.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: E. W. Sucov
 ITEM: 1.1.3-8
 PRIORITY: 2

SYSTEM: Impurity Control

COMPONENT:

TOPIC: Surface Physics/Engineering Measurements

PROBLEM: Sputtering and outgassing of a wall, liner, or limiter introduce damaging impurities into the plasma. Based on our present understanding, low Z impurities will cause less damage to the plasma than would higher Z impurities. However, low Z materials generally have higher sputtering coefficients and lower mechanical strength than do the high Z materials so it is not clear which type of material will be best suited for use as a wall or liner inside the vacuum vessel. If limiters are used in TNS, they will be chosen from a small set of highly refractory, strong materials such as tungsten or molybdenum. Here too, some refractories have lower sputtering and damage coefficients than others. Some information on sputtering, damage, thermal fatigue limit, etc. is available but it is not complete, nor does it span the anticipated conditions inside the vacuum vessel.

DATA REQUIRED: Physical and chemical (hydrogen atmosphere) sputtering coefficients for candidate wall, liner, and limiter materials under impact by 0.1 to 2 keV fuel ions and 14 MeV neutrons at temperatures up to 600° C. Thermal fatigue limit of candidate materials used as structural (wall) or nonstructural (liner, limiter) members under impact of 0.1 to 2 keV fuel ions, 14 MeV neutrons, and temperature up to 600° C cycling 30 sec in every 5 minutes.

SCOPE OF TASK: Experimental measurements on sample materials in situations ranging from laboratory ($\sim 5 \text{ cm}^2$) to fractional full size ($\sim 5 \text{ m}^2$).

SCHEDULE NEED/IMPACT: This information should be available by the end of Title I to be in time for incorporation into final engineering design.

RESOURCE REQUIREMENTS: Materials fabrication shop; vacuum systems; ion and neutron sources; large chamber with controllable atmosphere and temperature; diagnostic and monitoring instruments.

AVAILABLE RESOURCES/PROGRAMS: Many government, industrial, and university labs have capabilities in vacuum, atmosphere and temperature control, instrumentation and materials fabrication. Several facilities are under construction now as intense neutron sources; ANL is developing capability for generating low energy (0.1 to 2 keV) ion beams.

ESTIMATED COST: Hardware $\sim$ \$50,000; manpower $\sim$ \$1,000,000.

ALTERNATIVES: Use existing but incomplete data and run the risk of not meeting performance objectives through the choice of inappropriate materials.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: E. W. Sucoy/T. F. Yang
 ITEM: 1.1.3-9
 PRIORITY: 2

SYSTEM: Impurity Control

COMPONENT: Poloidal Divertor

TOPIC: Experimental Evaluation of Burial Chamber Pumping

PROBLEM: The poloidal divertor is used to bring fuel and helium ions that leak out of the plasma and impurity atoms that sputter off the walls to a burial chamber where they strike a collector plate, give up their energy, become neutral and must be pumped away by a vacuum system. For TNS operation, this requires that about 10^{23} particles/sec or ~ 1500 torr liter/second be removed during a 30 second pulse. To maintain the vapor pressure in the burial chamber at 10^{-5} torr requires that the vacuum pump system develop a speed of 1.5×10^8 liter/second. Because this is such a large value, the concept of using a hydrogen getter in the burial chamber has been proposed as a means of reducing the gas load on the pumps by several orders of magnitude. If this concept is used, required pump speeds could be reduced to 5×10^5 liter/second. This is still a very large requirement: at present only cryosorption or condensation panels offer the possibility of achieving it. Helium is generated in the TNS plasma at the rate of 5.2×10^{20} alpha particles/second or 8 torr liter/sec. Since lithium (assuming a lithium particle collection approach) does not getter helium, there will be no reduction in the helium gas load and the pump speed required to keep the helium vapor pressure at 10^{-5} torr is 8×10^5 liter/second. Cryosorption panels, operating at around 4 K, appear to be the only feasible means for developing this high pump speed. However, arrays of panels capable of generating this high speed have never been operated at high gas loads, in a hostile, high temperature environment, and at high duty cycle. Cryosorption and cryocondensation panel vacuum pump systems need to be developed, evaluated and qualified for TNS operation.

DATA REQUIRED: Data on pumping speed of the panels as a function of gas load, protective chevron temperature and configuration, panel temperature, ambient temperature and total panel area are required to establish the basic design parameters. Further data are needed on gas load that saturates the panels, time to regenerate the panels, efficiency of tritium evaporation, lifetime of cryosorption material in presence of various thermal cycles and particle and radiation fields in order to establish operating parameters.

SCOPE OF TASK: Panels, panel assemblies and simulation chamber must be fabricated. Cryogenic control, delivery, and measurement system must be installed.

SCHEDULE NEED/IMPACT: This information is needed by the start of Title I. Delay causes uncertainty in design of burial chamber.

RESOURCE REQUIREMENTS: Large gas throughput source, large area cryopanel with provision for changing configuration, cryogenic source and monitoring system, large volume vacuum building.

ITEM: 1.1.3-9 (Continued)

AVAILABLE RESOURCES/PROGRAMS: Present DMFE program calls for solving this problem by June 1979, however no effort is being given to the helium buildup problem.

ESTIMATED COST: Labor, \$600,000 plus hardware, \$300,000.

ALTERNATIVES: Limit burn time of the plasma; locate burial chamber outside the vacuum vessel to enlarge potential cryopanel pumping area.

TNS RD&D ASSESSMENT

DATE: 2/11/77
 BY: E. W. Sucov
 ITEM: 1.1.3-10
 PRIORITY: 2

SYSTEM: Impurity Control

COMPONENT: Bundle Divertor

TOPIC: Bundle Divertor

PROBLEM: A poloidal divertor burial chamber is typically located above and below the plasma and inside the vacuum chamber. This tends to increase the inner bore of the TF coils, thereby increasing the cost of the tokamak. In addition, this design places a high conductance path between the burial chamber and the plasma, thereby increasing the likelihood of neutral backflow into the plasma. Finally, the space available in a burial chamber inside the vacuum vessel is limited. This, in turn, puts an upper limit on the vacuum pumping speed that is attainable. The bundle divertor promises to solve all these problems because it causes the plasma scrape-off layer to pass through a duct in the vacuum vessel in a small bundle into a burial chamber outside the vacuum vessel. The current in a TNS bundle divertor coil would be quite large, ~ 8.5 MA, since it must buck out the toroidal field at a distance of over 1 meter. This generates very large torques, of the order of 2×10^7 Nm, which must be restrained by some physical structure. It is not clear that space will be available between TF coils for this structure. It is estimated that 250 MW will be deposited on the particle collector; if the bundle cross section is as large as 1 m^2 (it will more likely be less than 1 m^2) the power density on the collector is 250 MW/m^2 , about 150 times greater than can be handled by known surfaces with known cooling systems.

DATA REQUIRED: Divertor coil current necessary to create separatrix, resultant torque and bundle area. Strength to size ratios for various coil support designs. Data on efficiency of capture of leaked fuel ions and capture of sputtered (or injected) impurity atoms in a bundle divertor on a hot plasma.

SCOPE OF TASK: Analysis of forces on divertor coils; conceptual design and fabrication of structure that can withstand the forces within available space. Design and construction of coils. Experimental measurement of divertor effectiveness on actual hot plasmas.

SCHEDULE NEED/IMPACT: This task should be done by the end of Title I. Delay in developing this information would likely eliminate the bundle divertor from active consideration as a design option.

RESOURCE REQUIREMENTS: Tokamak with plasma temperature ~ 5 keV and $B_t \gtrsim 5$ T. Toroidal and equilibrium field design codes.

AVAILABLE RESOURCES/PROGRAMS: The only tokamak in existence which incorporates a bundle divertor is the DITE, in Culham. However, this has a very small plasma ($a = 25$ cm) with low temperature ($T_e \sim 0.5$ keV, $T_i \sim 0.2$ keV) low ion density ($n_i \sim 2 \times 10^{19} \text{ m}^{-3}$), and low toroidal field ($B_t \sim 1.5$ T), not at all capable of examining the problems identified above. Computational tools exist in many governmental, university, and industrial laboratories. If this approach is

considered an alternate for TNS it will be necessary for the TNS design team to complement the generic R & D with focussed design and analysis.

ESTIMATED COST: Assuming a large, hot tokamak with bundle divertor is available, the cost of measurements should be ~\$100,000. Calculations and analyses should cost ~\$50,000.

ALTERNATIVES: Utilize one of the other candidate schemes for impurity control.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: E. W. Sucov
 ITEM: 1.1.3-11
 PRIORITY: 2

SYSTEM: Impurity Control

COMPONENT: Poloidal Divertor

TOPIC: Heat Removal Capabilities of Flowing Lithium
 (Also see: Particle Collection Capabilities of Lithium, Item 1.1.3-12)

PROBLEM: The poloidal divertor scheme uses the scrape off layer to bring particles and heat to a burial chamber. For TNS operation, this requires that ~ 250 MW be removed during a 30 second pulse. Solid targets with internal flowing coolant can be designed to handle this heat load. However, solid targets would sputter impurities that would add to the already huge problem of removing the particle flux. If solid getters were used to capture the incident particles, the heat load may be too severe. A flowing liquid getter, such as lithium, appears to be able to simultaneously handle the requirements for particle and heat removal. Preliminary measurements have shown that lithium, free flowing down a screen can absorb ~ 10 W/cm² with $\Delta T \sim 10$ K. This is about 1/10 the anticipated loading of 100 W/cm² (1 MW/m²) so further experiments are needed to verify the heat removal capabilities of flowing lithium. In an actual tokamak the lithium in the burial chamber will be flowing across a strong magnetic field which will slow down the flow velocity. This effect needs to be quantified and its impact on heat removal determined. Finally, the actual heat load delivered to the flowing lithium will not be evenly distributed, but rather will likely be exponentially decaying away from a peak value. This can cause hot regions in which viscosity and sputtering change drastically.

DATA REQUIRED: Flow velocity of liquid lithium in presence of magnetic field. Temperature rise as a function of heat load and flow velocity. Effect of screen substrate on stability of laminar flow. Effect of energy distribution on flow properties and temperature change.

SCOPE OF TASK: These measurements will require construction of a test chamber with ion beam heating capability. Provision of a magnetic field of sufficient strength over large enough area will require construction of a magnet.

SCHEDULE NEED/IMPACT: This task should be done by end of Title I. If the target date is not met, it is likely that the design of the burial chamber will be delayed or alternate designs will be pursued.

RESOURCE REQUIREMENTS: Facilities to handle liquid lithium: ion source with output energy 0.1 - 2 keV at 1 MW/m²; magnetic field of ~ 5 T.

AVAILABLE RESOURCES/PROGRAMS: Liquid metal facilities are at industry and government labs. Ion source at ANL may be able to reach the design goals, if upgraded. Magnet can be constructed anywhere.

ESTIMATED COST: Labor, \$250,000; hardware, \$50,000; Total, \$300,000.

ALTERNATIVES: Use solid gettering or nongettering targets with flowing coolant. Enlarge surface area of chamber and use shaped divertor field to spread the energy on the large surface.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: E. W. Sucov
 ITEM: 1.1.3-12
 PRIORITY: 2

SYSTEM: Impurity Control

COMPONENT: Poloidal Divertor

TOPIC: Particle Collection Capabilities of Lithium
 (Also see, Heat Removal Capabilities of Flowing Lithium, see Item: 1.1.3-11)

PROBLEM: The poloidal divertor scheme uses the scrape off layer to bring particles and heat to a burial chamber. For TNS operation, this requires that ~250 MW be removed during a 30 second pulse. Solid targets with internal flowing coolant can be designed to handle this heat load. However, solid targets would sputter impurities that would add to the already huge problem of removing the particle flux. If solid getters were used to capture the incident particles, the heat load may be too severe. A flowing liquid getter, such as lithium appears to be able to simultaneously handle the requirements for particle and heat removal. Preliminary measurements at Culham and more recently at ANL have found that the capture coefficient is about 90%. However, the anticipated particle load to the burial chamber is of the order of 1500 Torr liter/second of neutral hydrogenic gas to be removed by standard vacuum systems. For a design pressure of 10^{-5} Torr, this requires the vacuum pump system to have a speed of 1.5×10^7 liter/second; this is far beyond the capacity of the available surface area, even if cryopanel could be placed in the burial chamber. The concept of a lithium labyrinth has been proposed; analysis shows that multiple scattering causes the capture coefficient to increase to 99.9%. If this concept works, the demand on the vacuum system is reduced 100 fold, down to a reasonable value of 1.5×10^5 liter/second. The labyrinth concept must be tested and evaluated under realistic conditions.

DATA REQUIRED: The capture coefficient for single impact @ ~1 keV has already been measured. Similar measurements have to be made on a flowing lithium labyrinth. In addition the sputtering coefficient of lithium under 1 keV ion impact should be measured.

SCOPE OF TASK: Given the existence of an appropriate ion source (ANL upgraded), various candidate geometries have to be investigated analytically, physical models of the labyrinth have to be fabricated and inserted into the test chamber, and measurements of capture coefficient taken. Finally, the concept should be tested in a working Tokamak.

SCHEDULE NEED/IMPACT: This task should be done by end of Title I. If this date is not met either the design of the burial chamber will be delayed or alternate non-divertor designs will be pursued under present plans.

RESOURCE REQUIREMENTS: Upgraded ion source that can deliver 1 MW/m^2 at ~1 keV energy, facilities for handling and controlling liquid lithium; ultra high vacuum chamber; burial chamber in a tokamak with divertor. The effort would require about 6 m/yr and \$ 100,000 for equipment.

AVAILABLE RESOURCES/PROGRAMS: Ion source at ANL must be upgraded. Liquid metal and high vacuum facilities are at industry and government labs. Most reasonable place to perform final proof testing is in PDX. This effort is not included in any programs. It should be part of a PDX Upgrade experiment.

ESTIMATED COST: Preliminary experiments ~\$ 500,000. Proof testing experiment in PDX-U ~\$ 150,000.

ALTERNATIVES: Extrapolate from single surface measurements now being performed at ANL. Use solid target and enlarge burial chamber so sufficient pump speed can be generated.

TNS RD&D ASSESSMENT

DATE: 2/11/77
 BY: D.A. Sink/T.F. Yang
 ITEM: 1.1.3-13
 PRIORITY: 3

SYSTEM: Impurity Control

COMPONENT: Divertor Particle Collector System

TOPIC: Measure and Evaluate Getter Pumping in Divertor Burial Chamber

PROBLEM: The particle collection system associated with a divertor must operate under conditions in which the collecting surfaces are exposed to high fluxes of particles and heat. These surfaces will undergo severe thermal loads ($\sim 1 \text{ MW m}^{-2}$) and will be required to have excellent radiation damage properties in addition to removing the particles from the divertor stream. Gettering materials such as zirconium-aluminum are possible candidates for such an application, but basic data on the performance of such materials under the expected conditions must be determined before the design of such a collector system can be made.

DATA REQUIRED: The pumping of ion streams in the energy range of 50 - 2000 eV, particle fluxes in the order of $10^{20} \text{ m}^{-2} \text{ s}^{-1}$, and energy fluxes of approximately 1 MW m^{-2} are required. The pumps which are made of getter material, e.g., zirconium-aluminum, should be studied for many regenerations of the surfaces and for varying heat removal rates to establish pump lifetimes and optimum operating temperatures. The effects of the surface interactions of the ions with the pumps for direct impact of beams, as well as for ion streams scattered off solid targets and then removed by the getters must be studied. Sputtering coefficients and capture probabilities must also be measured.

SCOPE OF TASK: Approximately one year of effort is required to select the getting materials, design the testing system and procedure, and to collect the required data. This work involves several disciplines including surface physics, vacuum technology, thermal design and ion beam technology.

SCHEDULE NEED/IMPACT: The results are needed by the end of Title I to impact the particle collecting method in burial chamber.

RESOURCE REQUIREMENTS: A testing facility with hardware fabrication, vacuum, and ion beam production capabilities is required.

AVAILABLE RESOURCES/PROGRAMS: Several low energy ion sources at the various national labs. and elsewhere may be applicable for this task.

ESTIMATED COST: Assuming an ion source is available, approximately 2 man-years of effort are required and the total cost, including manpower and hardware, is estimated at \$250 k.

ALTERNATIVES: If divertors are necessary for TNS, and if an ion removal system using solid surfaces such as getter surfaces or flowing liquid lithium surfaces (see 1.1.3-12) is not feasible passive impurity control is necessary.

3.1.2 Toroidal Field Coil Assembly

A decision on the baseline coil technology for the ORNL/(W) TNS design study is scheduled to be made by May, 1977. In order to develop high toroidal magnetic fields most efficiently for TNS and next generation fusion reactors, it is necessary to consider superconducting TF coils. A number of RD&D tasks have been identified to support design activities in this area, assuming the viability of each of the major options. These tasks will be redefined at a later date consistent with the coil technology decision to be made in May.

Although several superconducting magnets have been built, none are in the large size category required by TNS (approximately 5 x 7 meters) nor have they been designed for tokamak geometry and operating conditions. The bulk of experience to date has been with NbTi conductor. However, the potentially higher field capability of Nb₃Sn over NbTi dictates that the superconductor selection be carefully studied from a systems point of view. Once the superconductor is selected it will then be imperative that a superconducting cable be developed and qualified. With the high loads induced by magnetic fields and the low strain limits associated with the superconductor it is necessary to provide a significant amount of structural support to keep the superconductor strain to a low value. Finally, since the inherent coil size is prohibitively large from a shipping standpoint, it will be necessary to develop a coil design which can be assembled in the field, in conjunction with the large surrounding dewar. In summary, the best superconducting material must be selected, a conductor qualified, a coil winding concept selected and its fabrication technique qualified.

Superconducting Material

A choice must be made between the two prime candidate superconducting materials: NbTi or Nb₃Sn. Although Nb₃Sn has higher field capability than NbTi (12 vs. 8 Tesla, respectively) and greater temperature margin from the standpoint of loss of superconductivity, Nb₃Sn has a lower strain limit at which superconductivity is degraded.

A significant amount of basic data needs to be generated to support the development of coil designs regardless of which material is chosen.

- Cryostability Data

Cryostability can be lost by direct application of heat, by rapidly varying external magnetic fields, or by applying too large a magnetic field. The results of these effects need to be quantified to aid in the selection of the proper superconductor.

- Thermophysical Data

Although Nb_3Sn appears to be a more attractive choice for superconductor there is little data and experience available compared to that for NbTi.

To develop adequate confidence in resulting coil designs (using either material), adequate thermophysical measurements (thermal conductivity, specific heat, density) as a function of S/C composition, magnetic field, temperature, and radiation dose must be completed.

- Strain Data

A strain of .2% has been considered as practical working limit of NbTi before appreciable degradation of superconductivity occurs, however, the strain limit for Nb_3Sn is less. Data needs to be generated so that the materials can be properly evaluated. Strain sensitivity should also be evaluated in the conductor/cable design.

Superconductor Cable

- Cable Conductor Strain

The conductor design employs stranded cables to reduce the amount of strain as a result of winding and operational mechanical loads. Since strain cannot be predicted in the cable design because of the unknown

amount of slip that occurs between strands, it is necessary to test a stranded configuration to determine the effect of bending or mechanical loads on the conductor design chosen.

- Conductor Cooling

Irregular flow channels in the candidate winding geometries make pressure drop and heat transfer correlations difficult to predict. A test program should be incorporated into LCP to develop the correlations to support and confirm the ultimate selection of cable/conductor configuration. In addition, data should be generated for helium forced critical flow as well as pool boiling and forced flow boiling heat transfer to justify the selection of the most advantageous cooling mode.

Coil Assembly

Some coil assemblies are too large for conventional shipping and handling. A design must be developed such that the components can be fabricated and assembled or finish fabricated at the plant. Or, if field fabrication is the only alternative, special manufacturing techniques must be developed and fabricated to assure quality results. The following are some of the pertinent problems which must be addressed:

- Support Structure

Since the mechanical load capability of superconducting materials is limited, the structure required to minimize conductor strain becomes a significant portion of the coil cost. The coil support concept needs to be developed and a decision developed in the LCP as to whether the coil should be a one-piece welded bobbin pancake winding, bolted laminated pancake, spiral wound or some other configuration. A coil must be built in full size or to an extrapolable size to demonstrate that the selected design can be assembled on site.

- Coil Winding

A coil winding station will need to be developed and adequately tested to show that the conductor can be wound at the site with a high degree of confidence that strains are not exceeded, cable integrity is maintained and insulation is not degraded. Conductors need to be developed in adequate lengths with minimum number of joints to produce electrical resistance satisfactory for the concept selected, whether pancake or spirally wound.

- Dewar Structure

It must be demonstrated that a large size dewar can in fact be produced and a support system devised to minimize heat leakage through the LN₂ outer dewar thermal shield.

- Insulation Integrity

Since electrical breakdown characteristics in vacuum are unpredictable, gap sizes will need to be evaluated for insulated conductors in the vacuum dewars and elsewhere if it is decided to operate the reactor in a large vacuum chamber.

Full Size Assembly Prototype

A complete full size coil including dewar should be fabricated and assembled under realistic conditions and tested to develop the confidence that the components can be assembled when delivered to the site. In the process of developing the full size coil it can be determined whether the coil is required to have capability for being repaired during the assembly process.

TNS RD&D ASSESSMENT

DATE: 2/7/77

BY: J. Karbowski/R. Gold

ITEM: 1.2-1

PRIORITY: 1

SYSTEM: TF Coil Assembly

COMPONENT: Conductor/Cable

TOPIC: NbTi Cable Fabrication Qualification

PROBLEM: There is a need to develop an off-the-shelf NbTi superconductor or cable to use as a building block for winding coils, whether the coils are pancake or spirally wound. Cable must be of adequate length to minimize or eliminate joints within the cable which would introduce excessive electrical resistance.

DATA REQUIRED: Qualification of cable fabrication process (repeatability, quality, etc.). Resistance measurement data to indicate sound joints and tensile data to verify sufficient strength to demonstrate further processing capability (winding, installation of sheath or conduit). Cost of finished cable will be determined. Supplier qualification by virtue of producing finished cable.

SCOPE OF TASK: Determine basic size of cable, fabricate cable in reasonable lengths (at least 150 m) for pancake windings (TBD length for spirally wound design). Perform electrical resistance tests to verify acceptable resistance. Conduct flow impedance tests to demonstrate acceptability and repeatability of coolant flow through the cable.

SCHEDULE NEED/IMPACT: Start of conceptual design. Absence of a qualified cable could delay conceptual design of TF coils with attendant risk of meeting downstream schedules (preliminary and final design). Lack of data could delay coil winding development program.

RESOURCE REQUIREMENTS: Facility which can take raw material billets, fabricate, and wind and assemble cables. Materials testing capability to examine variations in cable dimensions, composition, electrical properties and strength.

AVAILABLE RESOURCES/PROGRAMS: The effort is currently part of the LCP for NbTi.

ESTIMATED COST: \$150,000 to \$200,000 to develop a cable.

ALTERNATIVES: Replace S/C design with a copper design instead of NbTi or continue with available data only, at high risk.

TNS RD&D ASSESSMENT

DATE: 2/8/77
 BY: J. Karbowski/R. Gold
 ITEM: 1.2-2
 PRIORITY: 1

SYSTEM: TF Coil Assembly

COMPONENT: Conductor/Cable

TOPIC: Nb₃Sn Cable Fabrication Qualification

PROBLEM: There is a need to develop an off the shelf Nb₃Sn superconductor or cable to use as a building block for winding coils, whether they are pancake or spirally wound. Cable must be of adequate length to minimize or eliminate joints within the cable which would introduce excessive electrical resistance.

DATA REQUIRED: Qualification of cable fabrication process (repeatability, quality, etc.). Resistance measurement data to indicate sound joints and tensile data to verify sufficient strength to demonstrate further processing capability (winding, installation of sheath or conduit). Cost of finished cable will be determined. Supplier qualification by virtue of producing finished cable.

SCOPE OF TASK: Determine basic size of cable and fabricate cable in reasonable lengths (at least 150 meters) for pancake windings (TBD length for spirally wound design). Perform electrical resistance tests to verify acceptable resistance. Conduct flow impedance tests to demonstrate acceptability and repeatability of coolant flow through the cable.

SCHEDULE NEED/IMPACT: Beginning of conceptual design. Absence of a qualified cable could delay conceptual design of TF coils with attendant risk of meeting downstream schedule for preliminary design. Lack of data could delay the coil winding development program.

RESOURCE REQUIREMENTS: Facility which can take raw material billets, fabricate, wind and assemble cables. Materials testing capability to examine variations in cable in cable dimensions, composition, electrical properties and strength.

AVAILABLE RESOURCES/PROGRAMS: This effort is not specifically defined to be part of the LCP however, it could be integrated with this program.

ESTIMATED COST \$ 200,000 to \$ 250,000 to develop a cable

ALTERNATIVES: Use NbTi conductor if available or replace S/C design with a copper design. Continue with available data only at extremely higher risk compared to NbTi or copper

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: A. Y. Lee
 ITEM: 1.2-3
 PRIORITY: 1

SYSTEM: TF Coil Assembly

COMPONENT: Superconductors

TOPIC: Experimental verification of TNS conductor cryostability

PROBLEM: Sudden localized heat generation in a superconductor can occur due to some abnormal conditions. Stability can be lost by direct introduction of heat, by rapidly varying the external magnetic field, or by applying too large a magnetic field. If the coolant is not sufficient to recover the conductor to a fully superconducting state, the entire winding may quench, resulting in disruption of the service of the TF coils. The coils are therefore, designed for cryogenic, intrinsic and dynamic stability. Laboratory model stability tests must be conducted to verify the conductor design. Additionally, because of the compaction, bending and twisting of the strands inside the cable, accurate modeling of the strands is difficult. Heat transfer area, void fraction, etc. are at best estimates. The test data can provide information to improve the analytical model and the analysis methods.

DATA REQUIRED: Recovery capability of the TNS NbTi and Nb₃Sn superconductors with heat input up to 300 MJ/cc of conductor volume at various flow rate and current density. Induced losses and any quenching which occurs in a magnetic field changing at rates up to 5 T/s. Measurement of supercritical helium coolant flow rate, temperature and pressure drop so that friction and heat transfer data may be correlated.

SCOPE OF TASK: (1) Fabricate conductor and coils. The length of the winding should be comparable to one turn in a TNS coil. (2) Perform cryogenic static steady flow tests, so that the hydraulic characteristics of the cable channel can be obtained and compared with predictions. (3) Perform recovery capability tests with simulated heat input and compare results with analyses. (4) Improve analytical model and computational methods, then optimize design.

SCHEDULE NEED/IMPACT: Start of Title I design. The concept of forced flow supercritical helium cooled, pancake-wound, cabled conductor depends on its integrity under mechanical and thermal loads. An early verification of the concept is necessary to large coil technology prior to committing to Title I design.

RESOURCE REQUIREMENTS: Conductor manufacturers, mechanical and heat transfer laboratory with small background coils for inducing and varying magnetic fields.

AVAILABLE RESOURCES/PROGRAMS: Industry, University, Government Laboratories. These present short sample test program of ORNL/MIT. The LCP program can be focussed for this activity.

ESTIMATED COST: Labor \$240,000; test cables and coils \$100,000; test equipment \$125,000; data reduction and analysis \$50,000; total estimated cost \$515,000.

ALTERNATIVES: Use water cooled copper coils or design TNS superconducting coils using available data and analytical capability with high risk and uncertainty and provide conservative thermal margin (over-sized refrigeration capacity.)

TNS RD&D ASSESSMENT

DATE: 2/10/77

BY: J. S. Karbowski

ITEM: 1.2-4

PRIORITY: 1

SYSTEM: TF Coil Assembly

COMPONENT: TF Coil

TOPIC: S/C TF Coil Fabrication Qualification

(See also Item 1.2-11, Prototype TF Coil Qualification)

PROBLEM: In order to achieve low resistance in the superconductors under consideration for TNS TF magnets, the strain limits imposed on the superconductor must be kept very low (less than 0.2%) to prevent degradation of conductivity. With these low strain limits, and the high induced magnetic loads on the superconductor, it is not possible for the conductor itself to carry a substantial portion of the mechanical load as is the case with copper conductor windings. It is therefore necessary to design additional structure to carry the load and limit the conductor strain. Since the cost of the structure is a significant portion of the coil cost it is imperative that the ratio of structure to conductor on the coil cross section be minimized. Different techniques such as spiral wound coils, pinned laminated pancake design, single piece pancake, etc. need to be investigated. Consideration should be given to the necessity for assembling at the site because of the large component size, necessity for repair during assembly, and development of winding station(s) at the site.

DATA REQUIRED: Qualification of a viable fabrication technique. Electrical methods to verify integrity of windings, including acceptable performance of S/C joints and insulation. Verification that dewar is adequate to maintain the S.C at low enough ($4 - 5^{\circ}$ K) operating temperature. Determination of coil costs with less uncertainty.

SCOPE OF TASK: Evaluate potential techniques and designs to achieve a design which is structurally adequate. Construct mockups and evaluate potential fabrication techniques. Select the best candidate considering trade offs between minimum structural weight, ease of fabricating and associated reliability, and accessibility of windings for possible repair during assembly. Fabricate coil/dewar assembly. Test the coil to verify fabrication and performance.

SCHEDULE NEED/IMPACT: Prior to Title II Design. Lack of data will induce risk since design will have to be committed to minimize schedular delay.

RESOURCE REQUIREMENTS: National Labs., Industries with expertise in machining of large pieces, plus high quality welding. Facility with a winding station for assembly and testing capability would reduce cost.

AVAILABLE RESOURCES: Industry in conjunction with National Labs. This should be incorporated into LCP.

ESTIMATED COST: Engineering studies \$800, 000; Design and build test coil \$5, 700, 000; testing \$500, 000.

ALTERNATIVES: Use copper coil design which would not be as efficient. Use a fabricated bolted in lieu of welded construction which would lead to a larger, more expensive device. Commit to a design with attendant high risk downstream.

TNS RD&D ASSESSMENT

DATE: 2/10/77

BY: A. Y. Lee

ITEM: 1.2-5

PRIORITY: 2

SYSTEM: TF Coil Assembly

COMPONENT: Superconductor Nb₃Sn

TOPIC: Determination of thermophysical properties of Nb₃Sn superconductor for TNS

PROBLEM: For high magnetic field applications (over 10 tesla) using Nb₃Sn superconductor in TNS, thermophysical properties with and without irradiation are needed for design and performance analyses. Fragmentary data are available from published literature and private sources. There is a need to compile and assess the available data and perform additional experiments to obtain those data not presently available

DATA REQUIRED: Thermal conductivity, specific heat and density as function of composition; magnetic fields from 0 to 12 tesla; temperatures from 2 to 25 K and irradiation doses from 0 to 10¹⁸ n/cm².

SCOPE OF TASK: (1) Compile, classify and assess existing data. (2) Identify experiments for additional data. (3) Fabricate samples and perform experiments. (4) Issue data in a comprehensive material properties handbook or manual for Industry-wide usage

SCHEDULE NEED/IMPACT: Start of Title I design; data necessary to provide high level of confidence in predicting thermal response/performance of the superconductor needed for TF coil design.

RESOURCE REQUIREMENTS: Superconductor manufacturers; heat transfer laboratories with cryogenic fluid handling capability and experience; irradiation facility to prepare samples before properties measurements; data acquisition and instrumentation systems; data reduction system.

AVAILABLE RESOURCES/PROGRAMS: Industry, National Labs, Universities.

ESTIMATED COST: Labor \$90,000; test samples and equipment \$130,000; total estimated cost \$220,000.

ALTERNATIVES: Use water cooled copper design or use available Nb₃Sn data with extrapolation or interpolation when necessary and accept high performance risk and uncertainty. Use NbTi superconductor on which more data is available but which might not be the best candidate material.

TNS RD&D ASSESSMENT

DATE: 2/7/77
 BY: A. Y. Lee
 ITEM: 1.2-6
 PRIORITY: 2

SYSTEM: TF Coil Assembly

COMPONENT: Superconductors

TOPIC: Superconductor Cable Channel Heat Transfer and Pressure Drop Experiments

PROBLEM: The twisting of the filaments in superconductor cables for TNS provides irregular flow channels and increases frictional pressure loss in forced cooled flow channels to above that predicted by smooth tube data. The "roughness" also enhances heat transfer. No heat transfer or pressure drop correlations for such rough channels are available. They are needed for thermal design of superconductor and its cooling system, especially in cryostability analysis.

DATA REQUIRED: Friction factor pressure drop coefficient and heat transfer correlations as function of Reynolds number at various operating conditions and geometries encountered in present and future superconductor designs with supercritical helium forced flow cooling in large magnets. Data needs to be generated as a function of cable stretch and bend radii from 1.5 m to 3 - 4 meters. Data required to correlate LH_e flow at $\sim .2 - 1$ m/sec at 4 K.

SCOPE OF TASK: Measure frictional pressure loss and heat transfer and generate pressure drop data. Construct prototype cable and test sections before and after forming on mandrels or fixtures to simulate a section of coil. Test cable will be $\approx 2 \times 2$ cm cross section with 40% void.

SCHEDULE NEED/IMPACT: Required by end of conceptual design. Necessary to help determine the proper void fraction of conductor since the conductor will need to be defined for other R & D tests.

RESOURCE REQUIREMENTS: A heat transfer laboratory equipped to handle liquid helium.

AVAILABLE RESOURCES/PROGRAMS: Industry, Universities and National Labs. Should be part of LCP.

ESTIMATED COST: $\sim$ \$250, 000 (labor and materials)

ALTERNATIVES: Wait until coil winding set up is available and test a full size winding with risk of not having selected the proper void fraction which might increase pumping power necessitating additional refrigeration.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: J. Karbowski/R. Gold
 ITEM: 1.2-7
 PRIORITY: 2

SYSTEM: TF Coil Assembly

COMPONENT: Insulation

TOPIC: Experimental Qualification of Superconducting Cable
Insulation Performance

PROBLEM: TF coil conductor outer insulation may be installed at the construction site during the coil winding. As currently envisioned, the insulation consisting of overlapping layers of resin rich mica tape would be applied by a taping head. A final layer of heat shrinkable material would then be applied over the mica. The conductors will then be forced into close fitting spiral grooves. It is not known what effect the compressing and bending will have on the integrity of the insulation. A final electrical short circuit test will be performed prior to bonding and sealing to the grooves. It is important to know that the winding operation will not damage the insulation. Additionally, it is desirable to verify that windings can be removed from the grooves prior to sealing to replace defective cables.

DATA REQUIRED: Voltage breakdown data between coil turns and insulation integrity or durability as a function of mechanical deformation or compression during assembly. Insulation durability as a function of repeated assembly/disassembly trials.

SCOPE OF TEST: Determine insulation to be used. Construct bench model of a portion of the winding. Subject insulation/cable assembly to deformations and strains to be encountered in actual winding plus simulated operating pressures/forces imposed during operation (for example, additional strain induced by differences in thermal expansion or structure strain). Subject sections of coil to repeat tests after replacing part of the coils to simulate repair during assembly of windings. Irradiation testing to determine these should damage levels in the complete cable configuration

SCHEDULE NEED/IMPACT: Needed by end of conceptual design to support development of winding station on schedule.

RESOURCE REQUIREMENT: Model shop, conductor electrical test lab, radiation facility.

AVAILABLE RESOURCES/PROGRAMS: Industry, Universities, National Labs; fits into LCP.

ESTIMATED COST: \$100,000.

ALTERNATIVES: Assume schedular risk in the development of a qualified winding station and cable performance risk.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: A. Y. Lee
 ITEM: 1.2-8
 PRIORITY: 2

SYSTEM: TF Coil Assembly

COMPONENT: Superconductor NbTi

TOPIC: Determination of Thermophysical Properties of NbTi Superconductor
 For TNS

PROBLEM: NbTi superconductors have been used and tested in various small and low field magnets. In order to utilize this superconductor in a large scale magnet for TNS at fields up to 10 Tesla and in a radiation environment, accurate thermophysical properties are needed for detailed design and performance analyses. Fragmentary data are available from various published literature and private sources. There is a need to compile and assess the available data and perform additional experiments to obtain those not presently available.

DATA REQUIRED: Thermal conductivity, specific heat and density as function of composition, magnetic field from 0 to 10 Tesla, temperature from 2 to 25°K, and radiation doses from 0 to 10^{18} n/cm².

SCOPE OF TASK:

- 1) Compile, classify and assess existing data on NbTi.
- 2) Identify experiments for additional data.
- 3) Fabricate samples and perform experiments.
- 4) Issue data in a comprehensive material properties handbook or manual for industry-wide usage.

SCHEDULE/IMPACT: Start of Title I design. Data necessary to provide high level of confidence in predicting thermal response/performance of the superconductor.

RESOURCE REQUIREMENT: Superconductor manufacturers; heat transfer laboratories with cryogenic fluid handling capability and experience; irradiation facility to prepare samples before properties measurements; data acquisition and instrumentation systems, data reduction system.

AVAILABLE RESOURCES/PROGRAM: Industry, National Labs, Universities.

ESTIMATED COST: Labor \$90,000; Test samples & equipment &100,000;
 Total \$190,000

ALTERNATIVES: Use water cooled copper TF coil design, or use available NbTi data with extrapolation or interpolation when necessary and accept high performance risk and uncertainty.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: R. Gromada
 ITEM: 1.2-9
 PRIORITY: 2

SYSTEM: TF Coil Assembly

COMPONENT: Dewar

TOPIC: Qualification of the Dewar and Mechanical Support System

PROBLEM: Although there is a substantial effort in the large coil program (LCP) to build a large superconducting TF coil, no existing program has been directed to qualify a dewar system (cryogenic shield and support structure) for the coils. Due to the large size of the coils and dewar, the development of a suitable dewar system will introduce significant engineering problems unknown in present magnetic systems. To insure the reliable operation of the TF coils in TNS, a large dewar system must be designed, built and tested in sufficient detail to develop and resolve the more troublesome design problems. These include 1) a reliable vacuum system capable of maintaining the coil at liquid helium temperatures, 2) a structural support to withstand the gravitational, magnetic and thermal forces, 3) the minimization of heat loads on the coolant system from structural conduction and thermal radiation 4) the selection of materials capable of performing satisfactorily at cryogenic temperatures and finally 5) the selection of a design that is capable of segmentation and remote disassembly. In short, a large dewar program is required to demonstrate technological feasibility of the superconducting concept for TNS.

DATA REQUIRED: Qualification of the dewar concept will include both computational and test results. Simulating actual operating conditions will be difficult (example, magnetic centering forces on the dewar walls), and require extensive computational analysis of the loads, temperatures and materials in question. Similarly, test results on structural stresses, deflections, heat loads, and fabrication techniques at both room temperature and cryogenic temperatures will help determine if the chosen concept is reliable for TNS.

SCOPE OF TASK: Choose a concept, based on the current state of technology most appropriate for TNS. Design and fabricate a full size mock-up capable of testing at expected operating loads and temperatures. Perform tests on mock-up, simulating TF coil operation. Measure stresses, deflections, loads and temperatures on the mock-up. Perform maintenance operations on mock-up using remote disassembly techniques.

SCHEDULE NEED/IMPACT: Testing should be completed prior to start of Title II design.

RESOURCE REQUIREMENTS: Engineering design capability, fabrication shop and test facilities capable of simulating coil performance.

AVAILABLE RESOURCES/PROGRAMS: Industrial contractor or government laboratory.

ESTIMATED COST: \$1,500,000

ALTERNATIVES: Select the copper TF coil concept for TNS. Design dewars in conjunction with TNS design. This implies considerable uncertainty and high performance and cost risk.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: R. Gromada
 ITEM: 1.2-10
 PRIORITY: 2

SYSTEM: TF Coil Assembly

COMPONENT: Copper Field Coils

TOPIC: Determination of composite material properties

PROBLEM: Precise material properties used in the analysis of copper field coils does not exist for the composite coil structure. The composite structure would consist of various ratios of copper conductor, water channel, electrical insulation and support structure. Although the properties of each material is well known, the effect of insulation bond strength on the composite structure can only be determined by conducting tests on typical coil cross-sections.

DATA REQUIRED: Material properties on selected composite structures including stress-strain and fatigue at the expected coil temperatures.

SCOPE OF TASK: Select the various composite structures that could be used on TNS. Prepare test specimens and perform detailed experiments to determine the material properties required.

SCHEDULE NEED/IMPACT: Testing should be completed prior to start of Title II design.

RESOURCE REQUIREMENTS: Fabrication facility, engineering mechanics test facility.

AVAILABLE RESOURCES/PROGRAMS: Industrial contractor or government laboratory.

ESTIMATED COST: \$25,000

ALTERNATIVES: Without the test data, coil design would have to depend on judgement in selecting correct material properties.

TNS RD&D ASSESSMENT

DATE: 2/9/77
BY: J. S. Karbowski
ITEM: 1.2-11
PRIORITY: 3

SYSTEM: TF Coil Assembly

COMPONENT: TF Coil

TOPIC: Prototype S/C Coil Assembly Qualification for TNS

PROBLEM: Toroidal field coils for TNS are expected to be too large ($\approx 5 \times 7$ m) for transporting, necessitating that they be wound and assembled in the field. Reasonable confidence must be developed to assure that the components can be satisfactorily assembled when they arrive at the site. In addition, it is extremely desirable to demonstrate that coils can be repaired during assembly to minimize losses which might be incurred if a large assembly had to be scrapped.

DATA REQUIRED: Qualification of an assembly technique (including coil winding, assembly by bolting or welding, dewar assembly) that will yield a reliable assembly. This will also represent an opportunity to get cost verification data.

SCOPE OF TASK:

- Based on TNS conceptual studies and LCP subscale testing select a design to be fabricated.
- Fabricate a full size coil assembly using S/C windings, proper electrical, hydraulic connections and surrounding dewar. Selection of assembly site should favor an industrial site or national lab which has winding stations to minimize cost. Fabrication sequence should contain enough in process checks to maximize success of final assembly integrity.
- After completion of the assembly, perform all electrical, thermal checks to qualify finished coil.

SCHEDULE NEED/IMPACT: During early Title II phase. Without test, there is a risk of encountering assembly problems downstream in the program.

RESOURCE REQUIREMENTS: Facility with expertise in machining and fabricating large close toleranced assemblies, plus high quality welding. Facility with winding station desired. Capability for high field testing with cryogenic (LH_2 , LN_2) testing capability.

AVAILABLE RESOURCES: Industry and/or National Labs.

ESTIMATED COST: $\$5 \times 10^6$

ALTERNATIVES: Use a more conventional Cu coil design which would not be as efficient. Commit to design without RD&D program with risk of assembly problems later in the program.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: G. S. Smeltzer
 ITEM: 1.2-12
 PRIORITY: 3

SYSTEM: TF Coil Assembly

COMPONENT: High Voltage Coils, Bus, Etc.

TOPIC: Operation of Electrical Equipment in a Vacuum

PROBLEM: One option being considered for TNS is enclosing the entire tokamak device in a common vacuum space. Two electrical systems problems go with this approach. First, if a vacuum leak occurs which the pump cannot control, then the vacuum pressure will go through a region (which depends upon spacings) in which the arc-over voltage is 300 to 500 volts. If the equipment is not designed for this, and if the voltages are not turned off before this occurs, or if the voltages cannot be turned off without losing control of the plasma, then serious damage could occur. The second problem is that many normal insulations, such as those which might be used in drive motors, electric lighting, etc., tend to fail under extended vacuum conditions because their flexibility is provided by organic fluids which can be pumped out by a vacuum rendering the insulation brittle.

DATA REQUIRED: A study should be made to prove the capability of the coil assemblies etc., to withstand the anticipated voltages in a vacuum. If conclusive results cannot be obtained, then tests must be performed on mock-ups to verify the capability to withstand expected voltages for specific item shapes, gaps, insulation and vacuum pressures which duplicate final designs for all practical purposes. Where necessary, determine electrical shielding and/or insulation required to prevent a voltage breakdown. Simulate vacuum leaks by raising the pressure, measure changes in breakdown voltages, and make recommendations to protect equipment from reduced voltage breakdown when a leak occurs.

SCOPE OF TASK: Perform breakdown tests in a vacuum chamber for simulated conditions. Investigate and evaluate breakdowns which occur as vacuum pressure rises thereby simulating a vacuum leak. For the case of a vacuum leak determine if a system can be shutdown before a destructive voltage breakdown would occur.

SCHEDULE NEED/IMPACT: By end of Title I

RESOURCE REQUIREMENTS: Large vacuum chamber, mock-up of coils, bus, etc. The vacuum chamber must have electrical feeds capable of handling the peak voltages of the TF, OH and poloidal Coils.

AVAILABLE RESOURCES/PROGRAMS: Industry, National Labs, TNS design team

ESTIMATED COST: \$150 K

ALTERNATIVES: Mount coils, etc., in inert atmosphere or accept high design risk for the evacuated cell approach.

TNS RD&D ASSESSMENT

DATE: 2/10/77

BY: J. S. Karbowski

ITEM: 1.2-13

PRIORITY: 3

SYSTEM: TF Coil Assembly

COMPONENT: Conductor/Cable

TOPIC: Experimental Evaluation of NbTi Winding Strain

PROBLEM: TF coil assemblies, particularly D shaped coils, induce winding strains on the superconducting strands. The conductor concepts under consideration for TNS are stranded cables to minimize conductor strain and provide reasonable flexibility for winding. Since superconducting materials are very strain sensitive, it is necessary to know the strain to which the conductor is subjected as a result of the coil winding operation. A monolithic conductor 2 cm thick would exceed 0.2% strain if the bend radius were less than ≈ 5.5 meters. D shape coils for TNS could have minimum bend radii about 1.5 to 2 meters. Since the stranded cables permit slipping between strands to minimize the strain, the amount of slipping and consequent strain are difficult to predict.

DATA REQUIRED: Strain or strain effect data incurred when the "qualified" conductor is subjected to bend radius of 1.5 meters minimum to 3-4 meters maximum. Strain effect due to applied axial load on conductor.

SCOPE OF TASK: Procure several lengths of prototype superconducting cable. Instrument cable to detect strain imposed by bending or tensile loading. (May require a cable configuration with simulated superconducting strands to obtain strain data). Design a test arrangement to induce bending strains by wrapping around a simulated portion of a coil bobbin or a suitable mandrel of the same radius, and an arrangement for producing tensile loads in the conductor. Instrument to detect changes in conductor resistance as strains are imposed. Arrangement should have capability to test under cryogenic (LH_e) environment to make resistivity checks.

Acquire data relating strand strain to bend radius and cable strain.

Acquire data of electrical resistance as function of bend radius and axial cable strain. Verify the acceptable maximum strain limits before cable performance degrades electrically.

SCHEDULE NEED/IMPACT: Prior to initiation of Phase 1 Preliminary Design. Data needed to confirm that it is logical to proceed with conductor concept. Data required to support other coil RD&D items.

RESOURCE REQUIREMENTS: Engineering Lab. capability to design test arrangement. Electrical resistance and strain measuring capability of low resistance materials under cryogenic conditions.

ITEM: 1.2-13 (Continued)

AVAILABLE RESOURCES/PROGRAMS: National Labs., Industry, Universities; Could be incorporated into LCP.

ESTIMATED COST: \$110,000

ALTERNATIVES: Ignore and assume risk of coils not performing adequately. Change to Cu design with less risk, but not necessarily as efficient.

TNS RD&D ASSESSMENT

DATE: 2/7/77
 BY: J. S. Karbowski
 ITEM: 1.2-14
 PRIORITY: 3

SYSTEM: TF Coil Assembly

COMPONENT: Conductor/Cable

TOPIC: Experimental Evaluation of Nb₃Sn Winding Strain

PROBLEM: TF Coil Assemblies particularly D shaped coils, impose winding strains on the superconductors. The conductor concepts under consideration are stranded cables to minimize conductor strain and provide reasonable flexibility for winding. Since S/C materials are strain sensitive (particularly Nb₃Sn) it is necessary to know the strain to which the superconductor is subjected during winding. A monolithic conductor 2 cm. thick would exceed 0.1 % strain if the bend radius were less than 11 meters. D shaped coils for TNS could have minimum bend radii of 1.5 to 2 meters. Since the stranded coils permit slipping between strands to minimize the strain, the amount of slipping and consequent strain are difficult to predict.

DATA REQUIRED: Strain or strain effect data incurred when the "qualified" conductor is subjected to a bend radius of 1.5 meters minimum to 3-4 meters maximum.

SCOPE OF TASK: Procure several lengths of prototype superconducting cable. Instrument cable to detect strain imposed by bending or tensile loading. Design a test arrangement to induce bending strains by wrapping around a simulated portion of a coil bobbin or a suitable mandrel of the same radius, and an arrangement for producing tensile loads in the conductor. Instrument to detect changes in conductor resistance as strains are imposed. Arrangement should have capability to test under cryogenic (LHe) environment. Acquire data relating strand strain to bend radius and cable strain. Acquire data of electrical resistance as function of bend radius and axial cable strain. Verify the acceptable maximum strain limits before cable performance degrades electrically.

SCHEDULE NEED/IMPACT: Prior to initiation of Phase II Conceptual Design. Data needed to confirm that it is logical to complete conceptual design prior to committing to preliminary design. Data required to support other coil development RD&D items.

RESOURCE REQUIREMENTS: Engineering capability to design test arrangement. Electrical and strain measuring capability under cryogenic conditions.

AVAILABLE RESOURCES/PROGRAMS: National Labs, Industry, Universities; could be incorporated into LCP:

ESTIMATED COST: \$ 125,000

ALTERNATIVES: Ignore and assume risk of coils not performing adequately. Change to Cu design with less risk, but not as efficient.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: A. Y. Lee
 ITEM: 1.2-15
 PRIORITY: 3

SYSTEM: TF Coil Assembly

COMPONENT: Conductor

TOPIC: Liquid Helium Boiling Heat Transfer Data Acquisition and Correlation for TNS Superconducting Coil Design.

PROBLEM: Forced flow supercritical helium cooling of the superconductors requires a considerable amount of pump work to circulate the coolant. The pump work is a major portion of the cryogenic refrigeration load. Other potential modes of cooling are by either liquid helium pool boiling or by forced flow boiling heat transfer. To design a coil using the pool boiling method of cooling, experimental heat flux data from a heated metal (Cu or Al) surface to the liquid helium in nucleate and film boiling regimes are required. To design a coil using forced flow boiling method of cooling, the problem is slightly more complicated, since two phase fluid flow is involved. Experimental data and correlations for forced convection boiling heat transfer coefficients and friction loss are required. There are currently few existing data which are applicable to TNS. Additional experiments are needed.

DATA REQUIRED: For pool boiling; the boiling heat fluxes vs $\Delta T (T_{wall} - T_{He})$ from 0.1 to 25° K at different channel geometries, plate or rod sizes, surface orientations and conditions. For forced flow boiling; the nucleate and film boiling heat transfer coefficients and friction correlations. Predictions of critical heat flux and the minimum film boiling heat flux. Effect of channel geometry, pressure and flow rate.

SCOPE OF TASK: (1) Fabricate metal (Cu and Al) plates, rods and blocks (with grooves simulating flow channels) for pool boiling tests. Fabricate straight and curved tubes for flow boiling tests. (2) Perform pool boiling heat transfer experiments using heated plates, rods and blocks with heated surface positioned at different directions to obtain boiling heat fluxes as a function of temperature difference. (3) Perform forced flow boiling in heated tubes during chilldown or heat-up so that a two phase flow is developed and develop heat transfer coefficient data. (4) Data acquisition, reduction and analysis. (5) Correlation development.

SCHEDULE NEED/IMPACT: Start of Title I design. Without boiling heat transfer data, single phase supercritical helium heat transfer will have to be used in the TF coils design to minimize risk.

RESOURCE REQUIREMENTS: Heat transfer laboratory with liquid helium handling capability and experience.

ITEM:

1.2-15 (Continued)

AVAILABLE RESOURCE/PROGRAMS: Industry, National Lab. University. In the LCP program, the two coils to be designed using pool boiling method of cooling can only be used to verify design adequacy, they will not generate generic, basic heat transfer data. The program objective and scope could be extended to include this R&D using a coil properly instrumented coil.

ESTIMATED COST: Labor \$ 440, 000; Test samples and equipment \$300, 000;
Total \$740, 000

ALTERNATIVES: Design TNS superconducting coils using available data on supercritical helium technology. This approach will not result in optimized design as to performance and overall cost, or over-design boiling cooled coils with limited confidence that performance will be satisfactory.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: R. Gromada
 ITEM: 1.2-16
 PRIORITY: 3

SYSTEM: TF Coil Assembly

COMPONENT: Electrical Connections for Superconducting TF Coils

TOPIC: Qualification of Electrical Connections for Superconducting TF Coils

PROBLEM: Several of the TNS concepts currently being considered use superconducting TF coils. Although a lot of attention has been directed to developing these coils, very little effort has been directed to develop a reliable electrical connection to penetrate the dewar and provide electrical power to the coils. The connection must be designed to withstand extreme temperature changes during cooling, and to insulate and seal the electrical leads during reactor operation at temperatures approaching absolute zero. A large number of these connections would be required to permit disassembly of the device for periodic maintenance and repair. Electrical connections would be required between coils and between power supplies and coils. A reliable electrical connection must be developed to insure the effective performance of the coils and the reliability of the device.

DATA REQUIRED: Confirmation that the electrical connection is a highly reliable design capable of withstanding the cryogenic temperatures without loss of insulation properties or sealing capabilities.

SCOPE OF TASK: Design connections and fabricate test hardware. Conduct performance tests to demonstrate reliability of connections.

SCHEDULE NEED/IMPACT: Required prior to end of Title I design.

RESOURCE REQUIREMENTS: Design capability, fabrication shop, electro-mechanical test facility with cryogenic capabilities.

AVAILABLE RESOURCES/PROGRAMS: Industrial contractor or government lab.

ESTIMATED COST: \$200,000

ALTERNATIVES: Will not be required if the copper TF coil option is selected. Design without qualification at high risk.

3.1.3 Poloidal and Auxiliary Field Coil Assemblies

The design of the poloidal field windings for TNS requires the solution to several important design questions. Areas requiring development include:

Remotely Maintainable Connectors

Segmentation methods proposed for performing maintenance operations on TNS include the separation of the PF coils along vertical parting lines. There are no connectors currently available that are capable of performing this operation throughout the life-time of the device. Therefore, a remotely maintainable connector must be designed, built and tested that satisfies the maintenance requirements of TNS.

Radiation Resistant Insulation

Location of the shaping field coils within the bore of the TF coils subjects them to high radiation fluxes. Some of the more promising but untested radiation-resistant insulation materials should be tested to insure their suitability for use in TNS.

Divertor Coil Assembly

A weakness of the poloidal divertor concept is that it requires poloidal windings in close proximity to, and even within, the toroidal vacuum vessel. The experimental evaluation of candidate coil assembly concepts is required to finally select a concept and demonstrate viability.

TNS RD&D ASSESSMENT

DATE: 2/7/77

BY: B. Fedor/R. Gromada

ITEM: 1.3-1

PRIORITY: 1

SYSTEM: Poloidal Coil Assembly

COMPONENT: Shaping Field Coils

TOPIC: Development and qualification of remotely maintainable poloidal field coil connectors

PROBLEM: The location of the copper shaping field coils within the bore of the TF coil array requires that these coils be remotely disconnected during maintenance operation or repairs. The removal of a TF coil would be one such operation where all of the SF coils would have to be disconnected. Remotely operated coil connectors, which are currently not available, are required to insure the timely and efficient disassembly and re-assembly of the copper shaping field coils.

DATA REQUIRED: The copper connectors would be an integral part of the copper coils requiring similar thermal, electrical and mechanical properties. Test data should include yield strength, fatigue strength, leak rates, thermal conductivity and joint resistance measurements.

SCOPE OF TASK: ● Design and develop remotely operable connectors for the shaping field coils
 ● Make test mock-ups and conduct performance tests to demonstrate remote connector design acceptability
 ● Perform tests to measure the thermal, electrical and mechanical properties of the connectors.

SCHEDULE NEED/IMPACT: Prior to end of conceptual design

RESOURCE REQUIREMENTS: Design capability, fabrication shop, electro-mechanical test facility.

AVAILABLE RESOURCES/PROGRAMS: Industrial contractor or government lab.

ESTIMATED COST: Labor \$500,000; Equipment \$150,000; Materials and Services \$350,000
 Total cost \$1,000,000

ALTERNATIVES: 1) Proceed with design and high dependency on reliability 2) locate SF coils outside the TF coils if feasible

TNS RD&D ASSESSMENTDATE: 2/8/77BY: R. J. GromadaITEM: 1.3-2PRIORITY: 2SYSTEM: Poloidal Coil AssemblyCOMPONENT: InsulationTOPIC: Evaluation of Radiation Damage to Electrical Insulation for
Copper Coils

PROBLEM: The copper shaping field (SF) coils for TNS are located within the bore of the TF coil array, an area subjected to high radiation fluxes. The location of each coil, relative to the plasma center, will ultimately be determined by magnetic field studies. The maximum neutron dose on the coils nearest the plasma is expected to reach 2.0×10^{11} rads.

The electrical insulation on the coils will have to withstand the radiation without substantial loss of mechanical or electrical properties. The highest radiation resistance insulations (epoxy resins) currently available are able to withstand a dose of only 10^{10} rads without damage and may not be suitable for use in TNS. Any repair or replacement of the coils due to radiation damage would be difficult, expensive, and interrupt the normal operation of the machine. It is, therefore, essential that a number of the more promising coil insulations be tested to insure their suitability (radiation resistance) for use in TNS.

DATA REQUIRED: Tests performed should determine the mechanical properties (bond strength, impact strength, and tensile strength) as a function of absorbed radiation, and the electrical properties (resistivity and dielectric strength) as a function of absorbed radiation dose. Candidate insulating materials tested should include glass fiber reinforced, mica-filled epoxies, blended epoxies, and fine-grained (0.5-1 micron) epoxy fillers.

SCOPE OF TASK:

- Design and fabricate test hardware capable of performing radiation tests on candidate insulating materials.
- Prepare test samples from coil materials using manufacturing techniques typical of coil installation.
- Perform tests at a suitable irradiation facility.
- Determine the electrical and mechanical properties of the test materials for various radiation doses.

SCHEDULE NEED/IMPACT: Prior to end of Title I design.

RESOURCE REQUIREMENTS: Sophisticated radiation test facility, engineering mechanics test laboratory.

AVAILABLE RESOURCES/PROGRAMS: National laboratory (FFTR, RTNS, INS, HFIR) facility.

ESTIMATED COST: \$200,000

ALTERNATIVES: Without the material test data, coil design would have to depend on the extrapolation of existing insulation properties after irradiation. This implies considerable uncertainty in effective machine lifetime and uncertainty as to EPR "stretch" capability.

TNS RD&D ASSESSMENT

DATE: 2/7/77

BY: R. Gromada

ITEM: 1.4-1

PRIORITY: 2

SYSTEM: Auxiliary Coil Assembly

COMPONENT: Divertor Coil

TOPIC: Divertor Coil Assembly Qualification

PROBLEM: TNS may utilize a poloidal divertor system for impurity control within the vacuum vessel. Copper field coils would be placed inside the divertor chamber to establish the magnetic field lines necessary for impurity capture. These coils would be exposed to energetic neutrons and charged particle bombardment. Development of a divertor coil assembly is mandatory to insure the feasibility of the divertor concept. Coil development would have to resolve design problems related to; electrical insulation, vacuum enclosures, coil supports, shielding, coolant attachment, electrical attachment, and remote disassembly.

DATA REQUIRED:

- Computational results on coil cooling, radiation damage and coil stress levels.
- Test results establishing design feasibility

SCOPE OF TASK:

- Develop several copper field coil designs, evaluate and select the most feasible concept.
- Make mock-up of coil and conduct performance tests to demonstrate design feasibility and the remote disassembly features.

SCHEDULE NEED/IMPACT: Prior to end of Title I design.

RESOURCE REQUIREMENTS: Engineering design capability, fabrication shop and test facilities capable of simulating performance requirements.

AVAILABLE RESOURCE/PROGRAMS: Industrial contractor or government Labs.

ESTIMATED COST: \$ 1,500,000

ALTERNATIVES: Select divertor concept with field coils outside the vacuum chamber, use existing data to design divertor coils with large uncertainty and risk.

3.1.5 Reactor Shield System

The design tools (computer codes and cross-section libraries) that have been developed for carrying out neutron and gamma ray analyses and shield and blanket designs for fission reactors are applicable to fusion devices also. However, R&D tasks are required in the following three areas before these tools can be qualified and utilized:

- Because of the lack of 14 MeV neutron sources nuclear cross-sections are needed for many materials used in fusion devices, and improved cross-section data is required for various energy intervals for many materials.
- Because of the complex geometries found in fusion devices, modifications are required to existing codes to improve their accuracy and make them more useful.
- There have been no "bench-mark" experiments carried out which can be used for testing the nuclear methods and cross-section data for fusion devices. The results from such experiments are necessary for qualifying the calculational methods.

When TFTR commences D-T operation, it will mark the first time that measurements on bulk shielding effectiveness, streaming effects, dose rates, activation rates and nuclear heating rates can be carried out in a meaningful way on an operating tokamak. An R&D task has been defined for collecting data during TFTR operation to be used for qualifying the nuclear analysis methods.

Finally, there are unknowns concerning the shield itself which must be investigated by R&D programs prior to design. For example, it is important to know the magnitude of induced eddy currents and the magnetic field diffusion time constant when the shield is exposed to a changing magnetic field. This information is important since the shaping

field windings lie outside the shield, and the shield geometry is much too complicated (presently steel spheres in borated water) to allow analyses without experimental data obtained from tests made on a sample module.

TNS RD&D ASSESSMENT

DATE: 2/8/77

BY: D. Chapin

ITEM: 1.5-1

PRIORITY: 3

SYSTEM: Shield System

COMPONENT: Shield Modules

TOPIC: Code Development for Shield System Design

PROBLEM: New computer codes need to be developed and existing ones modified in order to provide better tools for the nuclear analysis of the shield design. Without these more advanced codes, the shield design may be unoptimized and may also have large uncertainties in its predicted performance.

DATA REQUIRED: New or improved nuclear analysis codes to handle such areas as: a) neutron and gamma radiation transport in toroidal geometry; b) neutron streaming through ducts and penetrations; c) shield optimization using perturbation theory; d) activation, radioactivity, and afterheat, and e) nuclear data handling and preparation.

SCOPE OF TASK: Modify existing codes or develop new ones so as to be able to calculate these areas of interest in shield design more accurately. Test the resulting codes, document them; and make them available for fusion community use (perhaps on the DMFE-CTR computer).

SCHEDULE NEED/IMPACT: Codes would be needed before the start of Title II design. If new codes are unavailable, larger TF coils could result since the uncertainty must be compensated for by additional shielding.

RESOURCE REQUIREMENTS: Computer facility, TNS Design Team.

AVAILABLE RESOURCES/PROGRAMS: The DMFE-CTR computer would be a likely place to develop and install the codes. Several codes exist which could be modified for these areas, both by Government Labs and industry.

ESTIMATED COST: \$400,000

ALTERNATIVES: Use existing codes with "fudge" factors to account for toroidal geometry, etc., with a resulting uncertainty in the shield design.

TNS RD&D ASSESSMENT

DATE: 2/8/77
 BY: D. Chapin
 ITEM: 1.5-2
 PRIORITY: 3

SYSTEM: Shield System

COMPONENT: Shield Modules

TOPIC: Nuclear Data Requirements

PROBLEM: More accurate nuclear cross section measurements are required, especially for 14 MeV neutrons, in order to accurately calculate neutron and gamma radiation transport in the shield. Associated data, such as activation cross sections and radioactive decay chains, should also be measured more accurately.

DATA REQUIRED: a) Neutron emission spectra at a number of angles and secondary neutron energies for elements Fe, Cr, Ni, Mn, Mo, C, B¹¹, Li⁷, Pb, Li⁶, Al, Be, Cu, Ti, Nb, Sn. b) Gas production (charged particle) reaction cross sections for B¹¹, C, Fe, Mo, Ni, Cr, Cu, Ti, Nb, O. c) Neutron multiplication (n, 2n) reaction cross sections for Fe, Cr, Ni, Mo, Be, N. d) Decay chain half-life measurements for isotopes of Fe, Cr, Ni, Mo, Cu, N, O. e) Energy released per reaction (for use in kerma factors) for elements Fe, Cr, Ni, Mn, Mo, C, B¹¹, Pb, Cu, Ti, Nb, Sn.

SCOPE OF TASK: Perform basic nuclear data measurements at high neutron energies (e.g., 500 keV - 14 MeV) for the reactions identified above. Compile the results and make available for general use by incorporating them into the ENDF/B library.

SCHEDULE NEED/IMPACT: Most data should be measured before Title I, so that they can be made available for use in nuclear analysis codes by the start of Title II. More accurate data will improve the shield design and also the safety analysis and environmental impact statements (through activation calculations).

RESOURCE REQUIREMENTS: High energy neutron source (up to 14 MeV), assumed to be presently available.

AVAILABLE RESOURCES/PROGRAMS: Cross section measurements are presently done at places such as Brookhaven, ORNL, and BNWL; need to direct their emphasis at those data needs of the fusion program.

ESTIMATED COST: \$ 400,000

ALTERNATIVES: Use presently available data, of uncertain accuracy, for the shield design, with resultant uncertainty in the shielding design calculations. This uncertainty results in additional shielding which increases the size and cost of the TNS device.

TNS RD&D ASSESSMENT

DATE: 2/7/77

BY: D. Chapin

ITEM: 1.5-3

PRIORITY: 3

SYSTEM: Shield System

COMPONENT: Shield Modules

TOPIC: Integral Experiments for Shield Testing

PROBLEM: Results from "bench-mark" experiments are not available for testing the nuclear calculational methods and cross section data that will be used in the design of the TNS shield. Such an experiment should be done for 14 MeV neutrons interacting with different shield materials and geometries that might be used in TNS, in order to verify the accuracy of the nuclear methods and data.

DATA REQUIRED: Nuclear heating, radiation damage, and bulk shielding attenuation properties for a number of different proposed shield designs.

SCOPE OF TASK: Design and fabricate experimental mock-ups of different shield designs. Perform shield integral experiments using a 14 MeV neutron source to measure the attenuation properties of the shield configurations.

SCHEDULE NEED/IMPACT: The experimental data would be needed before Title II design. The results will impact the shield design and nuclear analyses methods used in the detailed design phase of TNS.

RESOURCE REQUIREMENTS: Experimental facility with a 14 MeV neutron source and mock-ups of various proposed shield designs.

AVAILABLE RESOURCES/PROGRAMS: Available facilities and neutron sources exist at such places as ORNL (SAMES) and LLL (RTNS); however, they may require upgrading to increase the flux levels for these measurements.

ESTIMATED COST: Approximately \$1,000,000

ALTERNATIVES: Perform detailed shield design without actual testing of materials performance and nuclear analyses methods; hence, would risk large uncertainties in the shield performance of TNS.

TNS RD&D ASSESSMENT

DATE: 2/7/77
 BY: G. W. Ruck
 ITEM: 1.5-4
 PRIORITY: 3

SYSTEM: Shield System

COMPONENT: Shield Modules and Vacuum Vessel Shell

TOPIC: Measurement of Eddy Current Effects in the Vacuum Vessel and Shield System.

PROBLEM: Eddy currents induced into the components surrounding the plasma such as the vacuum vessel and shield by changes in the externally applied fields (SF and OH) result in an undesirable delay of the desired electric and magnetic fields appearing at the plasma. These eddy currents also result in ohmic heating of the components and a loss of power. The magnitude of these effects are unknown because of the complex geometry of the components and the design of the shield and vacuum vessel will be impeded until measurements are made. Eddy currents arising from changes in the SF only are considered in this RD&D task.

DATA REQUIRED: Magnitude of eddy currents, power depositions, magnetic field diffusion rates in the vacuum vessel and shield as a function of the rate of rise of an applied magnetic field which passes through the components.

SCOPE OF TASK: Mock-ups of various sections of the vacuum vessel and shield will be subjected to changing magnetic fields (1 T s^{-1} to 20 T s^{-1}). Measurements of the required data will be made.

SCHEDULE NEED/IMPACT: Needed before Title II, Evaluation of the eddy current effects on the vacuum vessel and shield systems will influence the final design of the reactor components.

RESOURCE REQUIREMENTS: Electrical test facility with capabilities of supplying pulsed magnetic fields (1 T s^{-1} to 20 T s^{-1}) are required.

AVAILABLE RESOURCES/PROGRAMS: Industry or Government Labs.

ESTIMATED COST: \$500,000

ALTERNATIVES: Use best engineering judgment available and design systems for estimated worst case conditions.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: D. Chapin/A. Lee
 ITEM: 1.5-5
 PRIORITY: 3

SYSTEM: Shield System

COMPONENT: Shield Modules

TOPIC: Shield Module Mock-up Heat Transfer and Hydraulic Experiments

PROBLEM: Heat transfer and hydraulic analysis are within the state-of-the-art, however model testing will have to be performed to confirm and/or improve analytical predictions especially if the coolant is not contained in closed cooling channels. The design concepts of the shielding with open channel cooling would also require confirmation by mock-up testing.

DATA REQUIRED: Shield system material temperature and coolant pressure distributions are needed. Other data requirements include heat generation rates, pumping power required to circulate water over shield modules, flow rates and coolant temperature rise. The design adequacy of the shielding as related to flow maldistributions, blockage of fluid channels and spills are also required.

SCOPE OF TASK: Design and fabricate a shield module for prototype testing. The module should have capability of simulation of heat generation for various operating conditions. Set up test loop with required instrumentation, collect data and analyze system.

SCHEDULE NEED/IMPACT: Needed prior to Title II. Shield design has significant impact on TF coils, diagnostics and heat removal systems design and space allocation.

RESOURCE REQUIREMENTS: Test facilities with technical personnel capable of conducting heat transfer and hydraulic flow tests. The facility should have test cooling systems available for removing 1 to 5 MW/m² of heat from the mock-up.

AVAILABLE RESOURCES/PROGRAMS: Industry, National Labs or University.

ESTIMATED COST: Labor \$240,000; Mock-up and Test Equipment \$200,000. Total \$440,000.

ALTERNATIVES: Proceed with available design data and technology. Accept risk of poor performance and costly refitting.

TNS RD&D ASSESSMENT

DATE: 2/8/77

BY: D. Chapin

ITEM: 1.5-6

PRIORITY: 3

SYSTEM: Shield System

COMPONENT: Shield Modules

TOPIC: Neutronic Measurements on TFTR

PROBLEM: Prior to TFTR operation, there will be no 14 MeV fusion neutron source sufficiently large to make measurements of various neutron and gamma radiation induced quantities in the components and test cell of a fusion device. Such measurements would be needed to confirm the accuracy of the nuclear codes and data in predicting these quantities for the TNS device.

DATA REQUIRED: Various neutronic measurements on TFTR, such as (a) Neutron and gamma fluxes along major penetrations and ducts; (b) Activation and afterheat in the structural components; and (c) Dose rates delivered at several locations in the test cell and surrounding areas.

SCOPE OF TASK: Utilize about 6 months of TFTR time to make measurements on the above mentioned radiation induced quantities. Compare these with predictions from neutronics codes, and attempt to resolve any differences or specific deficiencies in the data or codes.

SCHEDULE NEED/IMPACT: Done during TFTR D-T operation; data should be made available before TNS Title II design so that it can be useful in the detailed neutronic design. Will impact on shielding design details of TNS and on the data and techniques used in the TNS nuclear analysis.

RESOURCE REQUIREMENTS: Assuming the necessary detectors and experimental techniques are installed on TFTR, then it would be about a 1 man-year effort to analyze the measurements and compare them to calculational results.

AVAILABLE RESOURCES/PROGRAMS: The TFTR would be the most readily available device on which to perform these measurements. Could perhaps also make such measurements as a joint US-USSR activity on T-20, however, the status of T-20 is uncertain at the present.

ESTIMATED COST: Assuming availability of TFTR, operating crew, and instrumentation, additional cost of about \$100,000.

ALTERNATIVES: Perform the nuclear analysis for the TNS design using presently available methods and data which have not been verified through measurements on a fusion device. Hence, there would be an associated uncertainty in the shield system design.

3.1.6 Reactor Structurals

The technology required to design and build the TNS reactor structural components is basically available with a few exceptions; R&D programs have been identified that should provide the technology that is lacking. These tasks are summarized below.

Certain tokamak structures, such as shear panels between the TF coils, can provide low resistance paths through which large eddy currents may flow when the poloidal fields are pulsed. To avoid this problem an insulating gap must be introduced into the structure. A high strength insulating material capable of withstanding wear and irradiation must be found.

There is insufficient reliable data concerning the effects of 14 MeV neutrons on the properties of materials that could be used in the TNS device. Poor selections of materials such as insulators could result unless this data is obtained.

Remotely maintainable shear fasteners must be developed. This R&D task is required because close tolerances are necessary for these fasteners which greatly complicates the remote disassembly. Remote servicing techniques are addressed in other R&D assessments presented in Section 3.7.

Structural requirements could conceivably be relaxed by developing quantitative design criteria. Measurements must be made utilizing existing tokamaks to develop these criteria. For example, the structural requirements for the TF coils are sensitive to the amount of overturning deflection that is tolerable. The TF coils tend to overturn because of the forces exerted on the TF coil currents arising from the vertical magnetic field. Overturning of the coils results in a possibly undesirable vertical component of the magnetic field.

TNS RD&D ASSESSMENT

DATE: 2/7/77

BY: R. A. Smith

ITEM: 1.6-1

PRIORITY: 2

SYSTEM: Reactor Structural

COMPONENT: Toroidal Field Coil Support Structures

TOPIC: Toroidal Field Coil Deflection Measurements

PROBLEM: The interacting magnetic field forces of the toroidal field coils (TFC) and the poloidal field coils are such that they will tend to rotate the TFC about a horizontal center-line through the TFC support structure. This rotation produces an undesirable vertical magnetic force component on the plasma with a magnitude relative to the degree of tipping of the TFC. An allowable magnitude for a vertical magnetic force component which does not seriously impair the performance of the plasma should be determined since total eliminations of all deflections of the TFC by stiffening the structural restraints results in very massive designs.

DATA REQUIRED: By actual test determining the amount of deflection (vertical tipping) of the toroidal field coils that produces a vertical field component on the plasma which is acceptable in the operation of the tokamak. In practice obtain TF coil vertical deflections relating to vertical field component changes on the plasma.

SCOPE OF TASK: By experiment, determine the allowable permissible vertical field component permitted on the plasma. This experiment would require a physical tipping of the TF coil and measurement of the vertical field component on the plasma as a function of the degree of TF coil tipping.

SCHEDULE NEED/IMPACT: Complete by the start of Title II. A definite value for the allowable deflection will permit a more realistic design of the reactor structurals.

RESOURCE REQUIREMENTS: A tokamak that could, with minor modifications, physically tip the TF coils so that the effects of the vertical field component on the plasma could be studied.

AVAILABLE RESOURCES/PROGRAMS: Tests could be performed on the PLT, PDX, ORMAK-Upgrade or the Doublet III using the existing toroidal coils.

ESTIMATED COST: \$100,000.

ALTERNATIVES: Allow no vertical field components at the expense of massive structural restraints.

TNS RD&D ASSESSMENT

DATE: 2/7/77
 BY: A. Y. Lee
 ITEM: 1.6-2
 PRIORITY: 3

SYSTEM: Reactor Structural

COMPONENT: Thermal and Electrical Insulation

TOPIC: Testing of thermal and electrical insulating materials

PROBLEM: Thermal and electrical insulating materials are needed to 1) isolate the cold structures (cryopanel, dewars, etc.) from the structures that are heated during the operation of the reactor, and 2) to interrupt electrical circuits through the reactor structures to limit the effect of eddy currents.

DATA REQUIRED: Determine the chemical and physical properties, dielectric strength and thermal conductivity of insulating materials as a function of irradiation and wear. Candidates for testing would be oxide films, plasma-sprayed coatings, refractory coatings and paints that could be used at interconnecting joints of the reactor structurals, i.e. shear panels, dewar joints and supports, shield joints etc.

SCOPE OF TASK: Conduct a survey to identify materials and/or coatings for various applications in the reactor structures. Set up and perform a test program to test the coatings and materials.

SCHEDULE NEED/IMPACT: Complete by start of Title II design. Development of or identification of a satisfactory insulator will enhance and simplify the design of the reactor structurals.

RESOURCE REQUIREMENTS: A refractories laboratory with the added capability of testing oxide films, plasma-sprayed coatings and paints.

AVAILABLE RESOURCES/PROGRAMS: Industry and government labs.

ESTIMATED COST: \$500,000

ALTERNATIVES: Use existing technical data available on insulating materials and run the risk of thermal/electrical failure.

TNS RD&D ASSESSMENT

DATE: 2/3/77
 BY: G. W. Ruck
 ITEM: 1.6-3
 PRIORITY: 3

SYSTEM: Reactor Structural

COMPONENT: Shear Fasteners

TOPIC: Remotely maintainable Shear Fasteners

PROBLEM: Body bound bolts, dowel pins and keys are typical fasteners used to maintain alignment and restrain components in shear. Because of the close tolerance requirements of these type fasteners they do not lend themselves well in areas where they must be removed and reinstalled by remote handling equipment. For this reason a development study of remotely maintainable shear fasteners for general use is required.

DATA REQUIRED: Experiments are to be developed for testing remotely maintainable shear fasteners. The test is to include fasteners already on the market and any new concepts resulting from this development study. The fasteners should be tested for reliability, strength, holding power after several uses and ease of installation and removal by remote handling equipment etc.

SCOPE OF TASK: Develop, design and fabricate all conceptual designs for remotely maintainable shear fasteners and test the performance of the new designs as well as any fastener already on the market.

SCHEDULE NEED/IMPACT: Complete by start of Title II; Development of remotely maintainable shear fasteners will effect the final design of the structural components of the machine.

RESOURCE REQUIREMENTS: Development and testing lab with background in remote handling equipment design.

AVAILABLE RESOURCES/PROGRAMS: Industry or Government Laboratories.

ESTIMATED COST: ~ \$150,000

ALTERNATIVES: Design a specific fastener for each joint design and develop special remote maintenance tooling for each specific fastener.

TNS RD&D ASSESSMENT

DATE: 2/11/77

BY: R. E. Gold, D. Chapin

ITEM: 1.6-4

PRIORITY: 3

SYSTEM: Reactor Structurals

COMPONENT: TNS Device

TOPIC: Basic radiation effects data

PROBLEM: There is insufficient reliable data on the effects of 14 MeV neutrons on the properties of many materials that could be used in the TNS device. Poor selections of materials and components for TNS may be made as a result of this lack of information. Excessive replacement of components may result.

DATA REQUIRED: Effect of radiation on materials such as insulators, solid state devices, stabilizing conductors for superconducting coils, and related components/devices critical to TNS design.

SCOPE OF TASK: Irradiation testing program to look at bulk neutron radiation damage of materials that may be used in TNS (the information will be useful for all subsequent fusion devices also).

SCHEDULE NEED/IMPACT: The information is required prior to the initiation of Title II.

RESOURCE REQUIREMENTS: A shielded test facility having a 14 MeV source of neutrons is required. Diagnostic apparatus to measure the deterioration of material properties will be utilized.

AVAILABLE RESOURCES/PROGRAMS: The SAMES accelerator at ORNL (can be used to produce low fluxes), the RTNS facility at LLL (available 1978) and the INS facility at LASL (will be available ~1981). The ORNL HFIR and ORR test/research reactors can be used to provide a lower neutron energy spectrum; theoretical extrapolation to higher energies is required.

ESTIMATED COST: 2.0 M\$. This assumes an available facility.

ALTERNATIVES: Provide excessive shielding at high cost. Select alternate, but less desirable materials and components. Design and operation of important components can be carried out based on questionable data, design for quick replacement.

3.2 ELECTRICAL POWER SYSTEMS

Most of the main electrical systems can be constructed with available components. However, in the cases of OH switching and NB regulation and switching, serious deficiencies exist. In some cases the number of individual components in an assembly is beyond the state-of-the-art, and is expected to result in extremely high costs. Less expensive items could be developed in place of more conventional equipment. The RD&D requirements for the main electrical systems are of three kinds: 1) qualification of equipment assemblies; 2) development of alternative equipment; 3) development of computational tools necessary to determine component requirements.

The ac power supply system can be assembled completely from commercially available components. The analysis of the system is complicated by the presence of large phase controlled rectifier loads which effectively apply phase-to-phase short circuits to the ac system lasting one to three milliseconds, repeated every 8.3 milliseconds on each two phases. Different rectifiers will do this at different times. The result is a flutter in the effective voltage, and potentially severe interference between different rectifiers, controls, and instrumentation. The principles for analyzing these problems and determining the required filters are understood, but it is necessary to develop a computer program to perform the required analysis.

The TF power conversion system for superconducting coils requires a power supply within the state-of-the-art. For reliability the coil dumping resistors will be permanently connected across the coils. The power supply voltage will be substantially lower than the coil dump voltage which means that the power supply requires an isolation switch for coil dumping. Since this switch should not require frequent use and carries only 10 kA, it can be a commercial three phase ac circuit breaker with the poles paralleled. This is not the operation for which such a switch was designed, therefore, it should be tested with its commutating circuit to qualify it for the service. The resulting switch should be substantially less expensive than an all solid state switch.

The TF coil will have ~ 6 GJ of stored energy which can do substantial damage in the event of coil or system faults. The other coil systems are lower in energy but still capable of producing significant damage in the event of a fault condition. Therefore, a fast responding fault detection system is required. Since fault sites will often be covered by structure or other equipment and may temporarily clear when the high voltage is removed, it is important to have a fault location capability to avoid lengthy down time for searching out the coil segment which faulted.

The PF systems plus the plasma are an interactive set which must be analyzed simultaneously in order to correctly define the requirements for the circuit components. Therefore, a simulation model in the form of a computer code for the specific configuration is essential to rational design. Since the design process must iterate on the configuration, the code must have the flexibility to change the configuration without a major programming effort. This suggests the use of a circuit simulation code such as SCEPTRE or the use of a hybrid computer with most of the circuit elements connected via the analog patch bay.

The PF systems require dc switches for currents of 100 to 200 kA in order to have coils inside the TF coils with remote disconnects. The paralleling of many more thyristor switch elements than has been achieved to date must be verified experimentally for critical subsystems.

The PF systems require circuits that must control levels of voltage and current beyond the state-of-the-art. An approach with conventional equipment can be applied with a reasonable level, but the cost of such an assembly would exceed \$100 M. As a low cost alternative to several valid state switches in the PF systems, development of high reliability mechanical switches is recommended. It has also been projected that a reliable homopolar generator may allow a significant reduction in the PF system cost. This must be verified analytically for TNS and, if true, homopolar generator development should be accelerated.

TNS RD&D ASSESSMENT

DATE: 2/8/77

BY: F. M. Heck

ITEM: 2.1-1

PRIORITY: 3

SYSTEM: Primary Power Systems

COMPONENT: System/Components

TOPIC: AC Network Analysis

PROBLEM: The facility will be a pulsating load on the 60 hz ac supply system and will generate harmonic frequencies which will be fed back. These effects need to be quantitatively analyzed to determine the resulting influence on other loads within the facility and on the main ac system and any required changes identified.

DATA REQUIRED: 1. Voltage swings at facility and on ac system.
2. Harmonic voltages present.
3. Changes required.

SCOPE OF TASK: System analysis, simulation.

SCHEDULE NEED/IMPACT: Need by end of conceptual design. Delay may result in costly retrofit of changes in ac system.

RESOURCE REQUIREMENTS: AC Network Analysis Computer Program.

AVAILABLE RESOURCES/PROGRAMS: Must be a part of TNS Conceptual Design.

ESTIMATED COST: Manpower \$300 K. Computer time \$50 K. Total \$350,000.

ALTERNATIVES: Build system based on estimates, measure fixes required, and rebuild as needed

TNS RD&D ASSESSMENT

DATE: 2/10/77

BY: G. S. Smeltzer

ITEM: 2.1-2

PRIORITY: 3

SYSTEM: Primary Power Systems

COMPONENT: TF/PF Rectifiers

TOPIC: Development of Techniques for the Determination of TF/PF Rectifier
Interaction with AC System

PROBLEM: Large phase-controlled-rectifiers introduce perturbations on the AC side voltages which can interfere with the operation of other rectifiers, reduce the effective voltage to other equipment, and interfere with rectifier control systems.

DATA REQUIRED: Organized method and computer simulation to allow calculation of:

- Voltage fluctuations and the effects on equipment size such as transformers due to phase-control-rectifier perturbations.
- The requirements for filters and other protection

SCOPE OF TASK: Study how rectifier commutation affects the interaction of the TF rectifiers, the PF rectifiers, and other pulsed loads on the ac system. Determine the effects on voltage regulation and on equipment size.

SCHEDULE NEED/IMPACT: Completion by beginning of Title I.

RESOURCE REQUIREMENTS: Digital-Hybrid computer. Must be a part of the TNS conceptual design.

AVAILABLE RESOURCES/PROGRAMS: TFTR simulation activities will produce valuable input. Industry and government laboratories can also provide support.

ESTIMATED COST: \$150 K

ALTERNATIVES: An alternative to the study would be to have a very conservative (costly) design that would ensure adequate voltages and outputs coupled with the risk of a retrofit program for such things as interference with rectifier control systems.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: G. S. Smeltzer
 ITEM: 2.2.1-1
 PRIORITY: 3

SYSTEM: TF Power Conversion System

COMPONENT: DC Interrupting Switch System for Superconducting TF Coil Circuit

TOPIC: Experimental Qualification of Interrupting Switch System

PROBLEM: For protective purposes, the superconducting TF coil must be disconnected from the TF power conversion system by means of a dc switch system which includes a commutating circuit and a mechanical switch. There is no standard switch available for this service.

DATA REQUIRED: Operational performance of the switch with commutating circuit under simulated conditions.

SCOPE OF TASK: Procure, test and qualify prototype switch system under simulated conditions.

SCHEDULE NEED/IMPACT: End of Title I

RESOURCE REQUIREMENTS: Manufacturer for switch, fabrication facilities for commutation circuit. Facilities to test switch system at operating currents and voltages.

AVAILABLE RESOURCES/PROGRAMS: Industrial Manufacturing Laboratories

ESTIMATED COST: \$250 K

ALTERNATIVES: Solid State Switch

TNS RD&D ASSESSMENT

DATE: 2/11/77
 BY: G. S. Smeltzer
 ITEM: 2.2.1-2
 PRIORITY: 3

SYSTEM: TF Power Conversion System

COMPONENT: TF Power Conversion System

TOPIC: Development and Qualification of Fault Detection/Location System

PROBLEM: Faults, such as a superconductor going normal, grounds, and/or shorted turns can potentially damage the coils and/or other system components. A protective system is needed to detect these faults, grounds, and shorted turns and initiate protective action to minimize damage. The values of the fault voltages and fault currents are required for the design of the equipment for the coil systems.

DATA REQUIRED: Magnitudes of fault currents and fault voltages for each component of the system. Location of test points required for detection of faults. Determine required inputs to fault detection system. Determine requirements to analyze faults, locate faults, locate grounds, and locate shorted turns. Qualification of prototype system.

SCOPE OF TASK: Computer study to determine maximum fault currents and voltages for each part of the system. Requirements for system to detect and locate faults, grounds and shorted turns. Prototype and test system.

SCHEDULE NEED/IMPACT: End of Title I

RESOURCE REQUIREMENTS: Computer program such as SCEPTRE, TNS design group, manufacturer, test laboratory. PF Power Conversion System Simulator (See "Computer Simulation of the PF System Including the Plasma" 2.2.2-4).

AVAILABLE RESOURCES/PROGRAMS: TFTR

ESTIMATED COST: \$300 K

ALTERNATIVES: Accept higher risk in design.

TNS RD&D ASSESSMENTDATE: 2/3/77BY: G. SmeltzerITEM: 2.2.2-1PRIORITY: 3SYSTEM: PF Power Conversion SystemCOMPONENT: Ignitron SwitchesTOPIC: Testing of Ignitron Switches

PROBLEM: The OH system requires series/parallel operation of ignitron switches. The ignitrons may be used in commutating circuits and crowbar circuits where the data sheets will not provide the necessary information to properly apply the ignitrons.

DATA REQUIRED: Current Capability, Voltage Capability (after conduction), Recovery Time (after conduction), Maximum dv/dt (after conduction), Information to properly operate ignitrons in series and parallel.

SCOPE OF TASK: Test design under operating conditions

SCHEDULE NEED/IMPACT: End of Title I

RESOURCE REQUIREMENTS: Ignitron Manufacturer, Test Laboratory to Evaluate Design

AVAILABLE RESOURCES/PROGRAMS: TFTR may provide this.

ESTIMATED COST: \$200 K

ALTERNATIVES: Solid State Switches

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: J. H. Schultz
 ITEM: 2.2.2-2
 PRIORITY: 3

SYSTEM: PF Power Conversion System

COMPONENT: DC Switch, Shunt Switch

TOPIC: Experimental Demonstration of DC Current-Sharing

PROBLEM: Current-sharing among many (~100 for TNS) parallel solid-state switching devices for low-frequency currents has not been demonstrated. Current distribution needs to be balanced to allow full utilization of each device. Bussing problem is complicated by requirement that each parallel module be easily serviceable. Cannot be satisfactorily done by analysis alone.

DATA REQUIRED: Knowledge of current distributions in paralleled devices for different bus layouts/different values of current-sharing resistors over the expected range of static device impedances.

SCOPE OF TASK: Design, fabrication and test of paralleled thyristor modules.

SCHEDULE NEED/IMPACT: End of Title I

RESOURCE REQUIREMENTS: Manufacturing test laboratory

AVAILABLE RESOURCES/PROGRAMS: Manufacturers' design laboratories

ESTIMATED COST: \$100,000

ALTERNATIVES: Conservative design using more devices.

TNS RD&D ASSESSMENT

DATE: 2/11/77
BY: F. M. Heck
ITEM: 2.2.2-3
PRIORITY: 3

SYSTEM: PF Power Conversion System

COMPONENT: Fault Protection Equipment

TOPIC: Experimental Determination of Plasma Disruption Conditions

PROBLEM: In case of plasma disruption (due to instability or loss of control) large fault voltages (~ 2000 Volts/turn)/currents will be induced in the poloidal field coils and affect the electrical system. The fault design conditions must be designed for in advance. Data, which is not now available, is required for the analysis of this condition.

DATA REQUIRED: Probable speed of plasma disruption. Time rate of decay of plasma current. Resistance and inductance of vacuum vessels used for experiment.

SCOPE OF TASK: Deliberately disrupt plasma by gas injection and by dropping current in vertical field coils. Measure total current versus time. Measure vessel current separately, if feasible.

SCHEDULE NEED/IMPACT: End of Conceptual Design

RESOURCE REQUIREMENTS: Large Tokamak Experiments.

AVAILABLE RESOURCES/PROGRAMS: PLT, ORMAK-U, PDX, ISX, D-III.

ESTIMATED COST: $\sim \$50,000$ Labor.

ALTERNATIVES: Design electrical system for estimated values with risk of damage to PF systems.

TNS RD&D ASSESSMENT

DATE: 2/10/77

BY: J. H. Schultz

ITEM: 2.2.2-4

PRIORITY: 3

SYSTEM: PF Power Conversion System

COMPONENT: Simulator

TOPIC: Computer Simulation of the PF System Including the Plasma
(See "Toroidal Electrical Resistance of Vacuum Vessel Shell 1.1.1-1)

PROBLEM: Available plasma codes are not in a form useful for evaluating the necessary electrical components specifications for the PF PCS. The voltage spike during initiation and plasma losses during plasma current buildup cannot yet be calculated for a TNS-type scenario. The combined interactions of the machine's electrical characteristics and the plasma are required to define the electrical components specifications.

DATA REQUIRED: Capability to compute the electrical components specifications

SCOPE TO TASK: Development of computer simulation of entire PF electrical system with zero dimensional model. Even better would be first order model to determine effects of PF currents briefly not tracking plasma current along with zero order model of r.f. preionization. Correlation of code results with actual machine data and one dimensional calculations.

SCHEDULE NEED/IMPACT: Prior to completion of Conceptual Design

RESOURCE REQUIREMENTS: Computer system capable of handling SCEPTRE, W COPE and LASLOD

AVAILABLE RESOURCES/PROGRAMS: Zero dimensional plasma codes from various National and Industrial Laboratories.

ESTIMATED COST: \$300,000.

ALTERNATIVES: Conservative design at considerable additional cost.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: J. H. Schultz
 ITEM: 2.2.2-5
 PRIORITY: 3

SYSTEM: PF Power Conversion System

COMPONENT: Homopolar Generator

TOPIC: Development of Homopolar Generator

PROBLEM: SCR controlled voltage sources for driving coil currents during start-up and shutdown are very expensive (~\$80 M for TNS). If energy storage at about \$0.01/J were available, ~\$20 M could be saved by the use of passive temporary energy storage, at the expense of losing active control of plasma position during start-up and shutdown. At storage costs of >\$0.07/J, no money can be saved.

DATA REQUIRED: Demonstration of a low-cost homopolar generator with energy storage of at least 300 MJ and ability to reverse current in one second with voltage/current requirements suitable for TNS coil system.

SCOPE OF TASK: Design and fabrication and test of homopolar generator

SCHEDULE NEED/IMPACT: Before start of Title I design.

RESOURCE REQUIREMENTS: Generator Manufacturer with test facility.

AVAILABLE RESOURCES/PROGRAMS: Electrical generator manufacturers, HETS Program.

ESTIMATED COST: \$10M

ALTERNATIVES: SCR controlled voltage supplies with ac line or AC/MG feeds

TNS RD&D ASSESSMENT

DATE: 2/10/77

BY: J. H. Schultz

ITEM: 2.2.2-6

PRIORITY: 2

SYSTEM: PF Power Conversion System

COMPONENT: DC Switches

TOPIC: Development of Mechanical DC Switches

PROBLEM: Plasma initiation requires dc switches with power-handling capabilities in excess of any yet built. Solid state dc switches at TNS power levels may have a total cost of ~\$50 M.

DATA REQUIRED: Reliability and cost of applicable mechanical dc switches.

SCOPE OF TASK: A prototype switch would have to be fabricated with performance characteristics to match the needs of the TNS PF coils with a minimum steady state dc rating of 25 kA, with the ability to block 50 kV 500 microseconds after current zero. Actuator reliability for $10^5 - 10^6$ operations is necessary, assuming routine maintenance, including periodic contact replacement. Design, fabricate and test to 10^6 operations.

SCHEDULE NEED/IMPACT: Need by end of conceptual design — 1 year reliability testing and 1 year for production prototype. Otherwise, would have to order solid-state switches, with a large cost impact.

RESOURCE REQUIREMENTS: An electrical manufacturing laboratory

AVAILABLE RESOURCES/PROGRAMS: Industrial laboratories.

ESTIMATED COST: \$1 M

ALTERNATIVES: Solid-state switches or existing state-of-the-art mechanical switches with frequent maintenance.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: J. H. Schultz
 ITEM: 2.2.2-7
 PRIORITY: 4

SYSTEM: PF Power Conversion System

COMPONENT: All Active Devices (Thyristors)

TOPIC: Experimental Evaluation of Thyristor Mean Time Between Failure (MTBF)

PROBLEM: The design requires $10^4 - 10^5$ active devices whereas present day systems generally have $10^2 - 10^3$. According to existing inadequate reliability data, device MTBF substantially greater than one week cannot be achieved. Existing data is not adequate to design a system to a specific system MTBF with a high confidence level.

DATA REQUIRED: Failure rate data. Experimental study with series and parallel modules operating at TNS-type conditions at higher than 1 per 5 minute rate. Also, systems study on reducing/coping with high failure rate of many-thyristor devices.

SCOPE OF TASK: Design and build test module. Carry out experimental testing. Statistically evaluate data.

SCHEDULE NEED/IMPACT: End of preliminary design (Title I).

RESOURCE REQUIREMENTS: Electrical Test Laboratory.

AVAILABLE RESOURCES/PROGRAMS: Semiconductor manufacturers. EPRI/PSI reliability study.

ESTIMATED COST: \$150 K

ALTERNATIVES: A conservative and expensive approach would use several redundant parallel lines

3.3 PLASMA HEATING SYSTEMS

Tokamak plasmas are heated ohmically to 1 or 2 keV. Higher temperatures are achieved by auxiliary heating provided by the injection of energetic neutral beams. Other heating methods include adiabatic magnetic field compression and the application of radio-frequency power. None of the presently known methods have reached a state of development such that they appear to be capable of providing the auxiliary heating necessary for TNS with assurance. Therefore, this is a problem whose solution must be given the highest priority.

Neutral beams are regarded as the most likely method for auxiliary tokamak plasma heating. However, an aggressive RD&D program is needed to determine how the injection is to be carried out, and what neutral beam energy is required. The fundamental goal of the neutral beam RD&D program is the design, fabrication, assembly, and qualification of a complete neutral beam injection arm; i.e., the development of a prototype with the requisite performance capability.

If all heating options are to be retained, the logic given below can be applied. Some of the RD&D tasks which are discussed are of a plasma physics nature and are of generic value, whereas others require the development of new hardware specifically for TNS, and perhaps future reactors.

- There must be a determination of the energy required for the neutral beam particles for injection into the high- β , large plasmas of TNS. To determine whether low (TFTR type) energy beams can be used, three tests can be made:
 - 1) Will a TFTR type beam be adequate if a programmed plasma build-up beam injection scheme is employed? To answer this question, there initially must be analytical evaluations such as are currently being carried out at ORNL and PPPL. Following this, experimental verification will be required on operating devices such as PLT and subsequently on devices such as ORMAK-U, Doublet III, and TFTR.

- 2) Will ripple injection work? Experimental verification is needed on tokamak devices such as PLT, ORMAK-U, and TFTR.
 - 3) The beam losses that occur when radial injection is employed must be determined experimentally on ORMAK-U, PLT, Doublet III, and TFTR.
- If the approaches discussed above are unsuccessful, high energy neutral beams will be required and there are two alternatives:
 - 1) High energy, positive ion sources must be developed, and for future viability, energy recovery from the unneutralized portion of the beam must be demonstrated. This work would be carried out within the existing ion source programs at ORNL and LBL/LLL.
 - 2) Negative ion sources must be developed that can produce the large accelerated ion currents that are required. The high neutralization efficiencies of these beams are attractive for future applications (ORNL, LBL/LLL).

Regardless of the approach that is selected for TNS, there must be a development program to assure ion sources will operate for the long pulses required in TNS and future reactors.

If neutral beams should prove to be a nonviable approach, rf heating would represent a strong alternative. A high priority program should be supported that is aimed at experimentally demonstrating that efficient rf heating can be achieved in operating tokamaks. The frequency of radiation to be utilized should be determined experimentally during this program. Strong coupling of the rf with the plasma should be demonstrated, and a high-power, high-efficiency source must be developed.

It should be emphasized that when TNS is better defined a more focussed RD&D program may prove more economical with regard to cost and schedule.

TNS RD&D ASSESSMENT

DATE: 2/8/77
 BY: D. A. Sink
 ITEM: 3.1-1
 PRIORITY: 1

SYSTEM: Neutral Beam Injection

COMPONENT: 150 keV Injectors

TOPIC: Experimental verification of effective plasma heating scenarios

PROBLEM: Because the requirements for neutral beam injection heating of TNS plasmas are not presently established, the design features of the injectors, the hardware requirements, and the manufacturing processes for components cannot be established. If 150 keV neutral beam injection is found to be an effective means to heat the plasmas, the hardware requirements and the cost of the injection system can be determined and could result in the incorporation of existing (as of TFTR) hardware and a reduction in the cost of the system for TNS over that for a more advanced system.

DATA REQUIRED: Neutral beam deposition profiles in tokamak plasmas as a function of the beam energy and the plasma parameters (temperatures, densities, spacial profiles, etc.) which can test theoretical predictions are required. Data on injection during a programmed build-up of the plasma is necessary. Since the effects of the alpha-heating of the central region of the plasma cannot be tested prior to TFTR, supportive theoretical work in this area is also required.

SCOPE OF TASK: Theoretical modeling and calculations, approximately six months of users' time on an existing tokamak, and approximately six months of effort following the experimental work to analyze the results. The task will result in a number of design changes in the tokamak device to be used. These design changes will lead to down-time to incorporate diagnostic equipment, plasma control hardware, and the interfacing of the neutral beam system if the existing system requires modification.

SCHEDULE NEED/IMPACT: The results are needed during the conceptual design phase.

RESOURCE REQUIREMENTS: Work requires users' time at a neutral beam injected tokamak facility. Hardware development and computer time are required to support the experimental and theoretical effort.

AVAILABLE RESOURCES/PROGRAMS: Present studies on neutral beam injected tokamaks at PPPL, ORNL, and GA are in various stages of development. These studies may require rescheduling if the present work is to be incorporated in time to impact TNS.

ESTIMATED COST: Assuming the work can be carried out at an existing facility, approximately 4 man-years of effort by an experimental team is required. On the order of \$50 k in hardware would also be required and computer costs must be included. Total cost ~ \$350 k.

ALTERNATIVES: If programmed injection of 150 keV neutral beams are found to be ineffective, several alternatives are possible and include: ripple injection of 150 keV neutral beams, higher energy neutral beam systems using positive ion sources or negative ion sources, or RF heating of the plasma.

TNS RD&D ASSESSMENT

DATE: 2/8/77
 BY: D. A. Sink
 ITEM: 3.1-2
 PRIORITY: 1

SYSTEM: Neutral Beam Injection

COMPONENT: Ripple Injection System

TOPIC: Experimental verification of ripple injection

PROBLEM: In addition to the injection of 150 keV neutrals into a TNS plasma during programmed build-up of the plasma column, the ripple injection of 150 keV neutrals must be experimentally evaluated. Ripple injection uses the toroidal field ripple at the outer edge of the plasma to trap the neutrals and to enhance the radial deposition profile of the resulting ions. In a similar argument as indicated in ITEM 3.1-1, if the ripple injection of 150 keV neutrals can be utilized, establishing a plasma heating method with its associated technology, hardware, and costs can be identified, and the dependence of TNS on a more advanced system greatly reduced.

DATA REQUIRED: Neutral beam deposition profiles in tokamak plasmas as a function of the beam energy, plasma parameters, and toroidal field ripple are required. The data would also include deleterious effects on particle confinement as a function of toroidal field ripple. Data on the ratio of trapped to lost beam particles would be required.

SCOPE OF TASK: The task will involve approximately six months of users' time on an existing tokamak, and approximately six months of analysis following the experiments. The task will definitely result in a number of design changes in the neutral beam system and the TF coil field system of the device selected. Several months of down-time would result following many months of hardware development.

SCHEDULE NEED/IMPACT: The results are needed at the start of Title I.

RESOURCE REQUIREMENTS: Resource requirements would be users' time on a large tokamak incorporating high-energy neutral beam heating. Hardware development of the various interfaces (NB's and TF coils) are required.

AVAILABLE RESOURCES/PROGRAMS: Present studies on neutral beam injected tokamaks do not include experiments on ripple injection, but could be added to the studies at either PPPL, ORNL, or GA.

ESTIMATED COST: Assuming the work can be carried out at an existing facility, approximately 4 man-years of effort by an experimental team is required. With roughly \$100 k in hardware and computer costs, the total cost would be approximately \$500 k.

ALTERNATIVES: If 150 keV neutral beams cannot be effectively utilized on TNS, alternatives are: higher energy neutral beam systems using either positive or negative ion sources, or RF heating methods.

TNS RD&D ASSESSMENT

DATE: 2/8/77

BY: D. A. Sink

ITEM: 3.1-3

PRIORITY: 2

SYSTEM: Neutral Beam Injection

COMPONENT: Perpendicularly Injected Neutral Beams

TOPIC: Experimental test of perpendicular injection of NB's in large tokamaks

PROBLEM: Because of nuclear shielding and machine access limitations between TF coils, tangential injection is not reasonable for TNS. In addition, beam energy requirements favor radially (perpendicularly) injected beams. The problem to be examined is that associated with the beam particle loss rate during perpendicular or near perpendicular injection.

DATA REQUIRED: Data on the ratio of beam particles lost to these particles trapped in the plasma are required. Data as a function of injection near to perpendicular is required to study the effects of ripple trapping in the plasma. Power deposition profiles are also required.

SCOPE OF TASK: Approximately six months of users' time on an existing tokamak, and approximately six months of effort following the experimental work to analyze the results. The task will result in a number of design changes in the tokamak device to be used. These design changes will lead to down-time to incorporate diagnostic equipment, plasma control hardware, and the interfacing of the neutral beam system if the existing system requires modification.

SCHEDULE NEED/IMPACT: The results are needed during the conceptual design phase.

RESOURCE REQUIREMENTS: Available time on a tokamak facility having neutral beam injection capabilities is required. Hardware development and computer time are also required.

AVAILABLE RESOURCES/PROGRAMS: Present programs on the neutral beam injection of tokamaks exist at PPPL, ORNL, and GA but do not presently include plans for radially-injected beam systems. Such existing programs could be broadened to include this type of injection without great difficulty, and would provide important input to any injection scheme utilized on TNS.

ESTIMATED COST: Assuming the work can be carried out at existing tokamak facilities, and that sufficiently versatile designs have been incorporated into those facilities, roughly one man-year of effort to coordinate the experimental work into existing problems would be required. The cost would be roughly \$50 k to \$75 k depending on hardware costs.

ALTERNATIVES: Alternatives would include schemes for injecting in at nonradial angles or the use of RF heating. As the angle of injection differs from perpendicular, the machine size and beam energy must increase resulting in a higher risk for success.

TNS RD&D ASSESSMENT

DATE: 2/8/77

BY: D. A. Sink

ITEM: 3.1-4

PRIORITY: 2

SYSTEM: Neutral Beam Injection

COMPONENT: Negative Ion Sources

TOPIC: Negative ion source and associated beam line development

PROBLEM: If high-energy (≥ 200 keV) neutral beams are required for TNS, the efficiency of converting electrical power into neutral beam power delivered to the plasma from the beams neutralized after leaving positive ion sources is extremely low ($\sim 10\%$). If a system based on negative ion sources can be developed, neutral beams can be produced with a greater efficiency. The problem is to develop such a system based on high-current sources which can effectively convert a deuterium gas to high-energy D ions.

DATA REQUIRED: Data is required on the performance of a beam line utilizing high-current, high-energy negative ion sources. The data would include currents, current densities, neutralization efficiencies, gas utilization efficiencies, vacuum system requirements, power conversion efficiencies, beam characteristics, and costs.

SCOPE OF TASK: This task would require extensive theoretical, calculational, experimental, and hardware development. A test stand able to handle 100 A sources of 200-300 keV ions in beams having a current density in the order of 0.1 A cm^{-2} is required. The stand must provide controls, diagnostics, vacuum system and heat dissipation systems.

SCHEDULE NEED/IMPACT: The results are needed at the end of conceptual design, otherwise at a time three years prior to the completion of the fabrication of such lines.

RESOURCE REQUIREMENTS: A high-voltage, high-current test facility having capabilities in the areas of hardware development, engineering design, and computer utilization is required.

AVAILABLE RESOURCES/PROGRAMS: Presently, programs at BNL and LLL exist. The efforts at these labs are not at adequate levels to have desired impact on TNS and must be upgraded.

ESTIMATED COST: A facility with an engineering/scientific team of ten working over a two year period would be required. The total cost including manpower and hardware is approximately \$3 M.

ALTERNATIVES: If negative ions cannot be utilized on TNS and if energies > 200 keV are required, low efficiency systems based on positive ions would have to be used, or an RF heating system would be required to heat the plasmas.

TNS RD&D ASSESSMENT

DATE: 2/8/77
 BY: D. A. Sink
 ITEM: 3.1-5
 PRIORITY: 2

SYSTEM: Neutral Beam Injection

COMPONENT: Ion Source

TOPIC: Development and test of a 100 ampere ion source.

PROBLEM: Both the control and maintenance systems of the neutral beam injectors for TNS will be large and complex. The size of each ion source and the total number of these sources will directly effect the complexity of these systems as well as have an impact on the engineering of the overall size of the device and facility.

DATA REQUIRED: The design and development of a source with the greatest current output at the required energy for TNS is required. Data on the performance characteristics and engineering design characteristics are required beam properties, source efficiencies, maximum currents, pulse duration, etc. are required. As the current per source is increased the total number of sources will decrease. Sources producing currents of 100 A or greater are required.

SCOPE OF TASK: The task requires the design, fabrication, and operation of a high-current deuterium test stand. The stand which must be enclosed in nuclear shielding will be used to measure ion source characteristics.

SCHEDULE NEED/IMPACT: The availability of large, high-current sources should be known before the initiation of Title 1.

RESOURCE REQUIREMENTS: A high-current, high-energy deuterium beam test stand is required. The test stand must be properly shielded. Computer and fabrication facilities are also required.

AVAILABLE RESOURCES/PROGRAMS: Ion source development is being pursued at ORNL and LBL/LLL. Such resources could be upgraded to include nuclear shielding for the operation and maintenance of deuterium beams and the radiation and activation of components which will result.

ESTIMATED COST: Assuming that an existing facility can be upgraded, approximately \$250 k in hardware to provide proper shielding and maintenance would be required.

ALTERNATIVES: Since "50 A" sources will be available for TFTR, a system based on approximately double the number of sources could be utilized. The system would be more complex, more difficult to maintain, and could have a major effect on the increase in the size of TNS over that associated with a 100 A source.

TNS RD&D ASSESSMENT

DATE: 2/8/77

BY: D. A. Sink

ITEM: 3.1-6

PRIORITY: 2

SYSTEM: Neutral Beam Injection

COMPONENT: Ion Source

TOPIC: Control of fractional energy components produced by ion sources

PROBLEM: The half-energy and one-third energy components associated with the acceleration of molecular species have a deposition profile which is highly peaked toward the outside of the plasma. The problem is that these fractional energy components will cause the plasma density to build-up on the edge and then reduce the probability that the full energy atoms of the beam can penetrate into the plasma enough to produce the proper temperature profile.

DATA REQUIRED: Data is required on the ratio of the molecular components to the atomic component of the beams produced by a source as a function of the source geometry and operating parameters. The design of the source electrodes, and their operating voltages should be studied and evaluated for their effect on minimizing the molecular species produced.

SCOPE OF TASK: Approximately one year of effort by an engineering/scientific team to design, test, and evaluate various schemes of source design and operation is required. The task will require the usage of a high-voltage neutral beam test stand and facility.

SCHEDULE NEED/IMPACT: The results are needed by the end of the conceptual design phase.

RESOURCE REQUIREMENTS: Time on a neutral beam test stand, a hardware fabrication facility, and computer facilities are required.

AVAILABLE RESOURCES/PROGRAMS: Neutral beam test stands at LBL/LLL and ORNL exist and could be utilized.

ESTIMATED COST: Assuming a test stand is available, approximately 2 man-years of effort are required and the total cost, including hardware development, is approximately \$175 k.

ALTERNATIVES: If ion sources produce a substantial component of molecular beams, either an analyzing magnet to separate the undesirable components out or beams of a much higher energy will be required.

TNS RD&D ASSESSMENT

DATE: 2/8/77
 BY: D. A. Sink
 ITEM: 3.1-7
 PRIORITY: 2

SYSTEM: Neutral Beam Injection

COMPONENT: Neutral Beam Line Prototype

TOPIC: Operation and test of a complete neutral beam line

PROBLEM: A completed assembly of a neutral beam line must be tested and performance checked. A total prototypical system as well as a shielded test facility are necessary. The problem is to guarantee the proper interfacing of the various components and to guarantee that the entire system provides all the essential functions such as vacuum valving and nuclear shielding between the plasma target and the beam line components.

DATA REQUIRED: Data on the performance and design of the completed beam line prototype are required. Detailed drawings and performance specifications are required so that the complete TNS neutral beam system can be costed, fabricated, and tested.

SCOPE OF TASK: An engineering team is required to operate a shielded test facility and to complete a set of tests and, if necessary, design changes necessary to bring the prototype into proper operation after the test facility becomes operational, approximately 6 months to a year will be required to complete the tests.

SCHEDULE NEED/IMPACT: The prototype should be operating by the end of Title I.

RESOURCE REQUIREMENTS: A neutral beam test facility with computer and fabrication capabilities is required.

AVAILABLE RESOURCES/PROGRAMS: The required test facility could be constructed at the TNS site. It would necessarily be one of the first facilities to be operational and could also serve at the test and maintenance facility for the actual operation of TNS.

ESTIMATED COST: Assuming that the test facility is part of the TNS facility, the cost, including manpower, the prototype, and the testing, is estimated at \$15 M. If the prototype is used in TNS and the cost is charged to PACE, the R&D costs can eventually be reduced by ~ \$12M.

ALTERNATIVES: If the testing of a completed prototypical line is not made, the complete line will require testing on the TNS tokamak. This will necessarily involve more risk and could lead to the delay of the full operation of TNS.

TNS RD&D ASSESSMENT

DATE: 2/8/77
 BY: D. A. Sink
 ITEM: 3.1-8
 PRIORITY: 3

SYSTEM: Neutral Beam Injection

COMPONENT: Ion Source

TOPIC: Ion source gas efficiency optimization

PROBLEM: The efficiency for converting the working gas supplied to an ion source to beam particles is presently low (~50%) putting severe requirements on the vacuum pumping system to maintain a desired operating pressure during a shot. In addition to vacuum pumping problems, the control of the gas pressure in the neutralizer cell is also affected by this gas conversion efficiency.

DATA REQUIRED: Data is required on the gas conversion efficiencies as a function of various source parameters and geometries. Data on the optimum conversion efficiency is required for various filament geometries, filament voltages, gas feed geometries, electrode voltages, gas temperatures, etc. The affects of voltage breakdown as a function of gas pressure is also required.

SCOPE OF TASK: The task requires approximately one man-year of scientific investigation and experimentation. The use of a test stand is required.

SCHEDULE NEED/IMPACT: Gas conversion efficiencies are needed by the end of Title I.

RESOURCE REQUIREMENTS: A test stand and its associated hardware fabrication facility are required.

AVAILABLE RESOURCES/PROGRAMS: Programs exist at LBL/LLL and ORNL on ion source development and the above work could become an important aspect of such programs if such a task has not yet been identified.

ESTIMATED COST: Assuming the work is incorporated into an ongoing program, 1 man-year of effort at an existing test facility is required. The total cost including hardware fabrication is estimated at approximately \$75 k.

ALTERNATIVES: If gas efficiencies are low, the vacuum pumping systems and the neutralizers will require designs which may be substantially different from those presently under study. The pumping system required may necessarily be large and substantially increase the overall size of the beam lines.

TNS RD&D ASSESSMENTDATE: 2/8/77BY: G. W. Ruck, D. A. SinkITEM: 3.1-9PRIORITY: 3SYSTEM: Neutral Beam InjectionCOMPONENT: CryopanelTOPIC: Design, manufacture, and test of cryosorption panel assemblies
(also see ITEM 4.3-2 on the performance testing of cryopumps)

PROBLEM: Since the utilization of large cryosorption panels made of a molecular sieve material and properly shielded from thermal radiation and nuclear radiation are not commercially available, their design, manufacturing processes, and testing under appropriate conditions must be demonstrated. The design must account for pumping under conditions expected during neutron production by the tokamak plasma and changing magnetic fields which can produce eddy current heating of panel surfaces.

DATA REQUIRED: Design details on one or more panel assemblies which have been tested and found to be satisfactorily operated over a wide range of operating conditions is required. Data is required on the operation of the units and would include pumping speeds, pumping capacities, sticking probabilities for different gases as a function of neutron fluxes and of changing magnetic fields. Data on the processes for fabricating and bonding the panels to form flow paths for the helium and nitrogen coolant are also required. In addition, data on the operation of the panels are needed and include helium consumption, panel regeneration processing, and effects of transient effects such as a temperature excursion.

SCOPE OF TASK: The task requires approximately a year to develop designs, fabricate panel units, develop manufacturing procedures, and test panels.

SCHEDULE NEED/IMPACT: Results of the study are required by the end of Title I.

RESOURCE REQUIREMENTS: A facility or facilities which will provide a wide range of neutron fluxes and a wide range of changing magnetic fields are required. In addition, an engineering and fabrication facility for the production of panel design is required.

AVAILABLE RESOURCES/PROGRAMS: Programs at ORNL and LBL/LLL on the development of cryopumps exist. These programs would require changes if the above considerations were added. Various accelerator facilities could serve as a neutron source, and a facility utilizing large magnets (a tokamak facility) could be used.

ESTIMATED COST: If the work is carried out at existing facilities, the cost will be that associated with supporting a team of two engineers over a year as well as hardware fabrication costs for an estimated \$200 k total cost.

ALTERNATIVES: If a cryosorption panel of the type required is not available, cryocondensation panels can be used. Condensation panels performance in neutron fluxes and changing magnetic field have not yet been studied either.

TNS RD&D ASSESSMENT

DATE: 2/8/77
 BY: A. Y. Lee, D. A. Sink
 ITEM: 3.1-10
 PRIORITY: 3

SYSTEM: Neutral Beam Injection

COMPONENT: Beam Dump, Calorimeter, and Energy Conversion System

TOPIC: Basic design data for beam dump, calorimeter, and energy conversion system

PROBLEM: The unneutralized fraction of the beams leaving the neutralizers will be collected in beam dumps or in an energy conversion system, while both neutralized and unneutralized beams will be frequently collected in a calorimeter. The corresponding surface geometry and cooling system must be designed to handle atomic beams which generate energy fluxes in the order of 5 kW cm^{-2} . The basic data required to arrive at such designs is not available.

DATA REQUIRED: Surface interaction data for 150-300 keV deuterium atoms on various surfaces and materials held at a number of temperatures is required. Surface properties under various heat fluxes over a number of different pulse lengths are required. The surfaces should be examined for a number of designs for the removal of heat and for a number of coolants. Designs of beam dumps using either a bending magnet and a solenoidal coil (to enhance space charge blow up) to divert the beams must be examined.

SCOPE OF TASK: The task will include the development of component designs, their fabrication, and testing. The work involves many disciplines including thermal engineering, surface physics, and mechanical design. A research team working for an estimated one-year is required.

SCHEDULE NEED/IMPACT: The results and data are needed before Title I.

RESOURCE REQUIREMENTS: A facility for the design and fabrication of components is required. To acquire the data hydrogen and deuterium beams at 150-300 keV energy are required.

AVAILABLE RESOURCES/PROGRAMS: Component designs for neutral beams are under present study at ORNL and LBL/LLL and the above task could be included in either program.

ESTIMATED COST: Assuming the work can be carried out at an existing facility, approximately 2 man-years of effort is required. Including equipment and hardware fabrication, the total cost of completing the task is roughly \$200 k.

ALTERNATIVES: Since both beam dumps and calorimeters are required on neutral beam lines, some combination of a beam dispersion system and a beam dump/calorimeter design must be arrived at before neutral beams can be utilized with confidence on TNS.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: D. A. Sink
 ITEM: 3.1-11
 PRIORITY: 3

SYSTEM: Neutral Beam Injection

COMPONENT: Isolation Valve at Duct to Device

TOPIC: Test of large remotely operated vacuum valves

PROBLEM: Very large (≥ 50 cm diameter) all-metal remotely operated isolation valves will be required to separate an NBI arm from the device. These valves must have a low leak rate (UHV standards) and be remotely maintainable. Since such valves are not commercially available, they must be designed, developed, and tested.

DATA REQUIRED: Test data on the performance of a large pneumatically operated all-metal gate valve. Leak rates, number of open/close cycles per seal are required.

SCOPE OF TASK: The task will involve the design, fabrication, and testing of a number of valve designs and will require an estimated one-year to complete.

SCHEDULE NEED/IMPACT: The results are needed by the end of Title I.

RESOURCE REQUIREMENTS: Test facility with ultra-high vacuum equipment and fabrication capabilities is required. Data, consultation, and cooperation with vacuum valve manufacturers is required.

AVAILABLE RESOURCES/PROGRAMS: The TFTR program includes efforts toward the development of a large valve, but this task will more than likely require a separate development effort.

ESTIMATED COST: The total cost includes manpower and hardware development and is estimated at \$200 k.

ALTERNATIVES: If a valve is not available, the system must be designed without a means of providing vacuum isolation between the main toroidal vessel and each neutral beam line.

TNS RD&D ASSESSMENT

DATE: 2/9/77

BY: D. A. Sink

ITEM: 3.1-12

PRIORITY: 3

SYSTEM: Neutral Beam Injection

COMPONENT: Computer Control System

TOPIC: Development and test of computer control for neutral beam system

PROBLEM: For the long pulse, multi-source, multi-injector system required on TNS, a computer control system at least as complex as that for TFTR will be required. The system must control the beams for varying pulse length and possibly for usage during refueling and during periods when the plasma requires additional driving. The problem is to develop and test such a system prior to its incorporation on TNS.

DATA REQUIRED: Data on TFTR and MX neutral beam systems controls is required. Additional data on various computer control systems and techniques is required. The specification of the hardware for TNS is required and the development of the software must be completed and tested.

SCOPE OF TASK: Review previous work (PLT, TFTR, MX, etc.), develop computer control operating software.

SCHEDULE NEED/IMPACT: The task must be completed by the end of Title I.

RESOURCE REQUIREMENTS: The requirements include a computer facility for software development, consultation with computer manufacturers, and consultation with those people who have developed and operated such systems.

AVAILABLE RESOURCES/PROGRAMS: Available resources include all the computer manufacturers, TFTR, MX, and the TNS design team.

ESTIMATED COST: Including manpower and computer access, the estimated cost is \$200 k.

ALTERNATIVES: Computer control of NBI system is essential.

TNS RD&D ASSESSMENT

DATE: 2/10/77
BY: D. A. Sink
ITEM: 3.1-13
PRIORITY: 4

SYSTEM: Neutral Beam Injection

COMPONENT: Neutral Beam Dump Direct Energy Conversion System

TOPIC: Design and test of a direct energy conversion system

PROBLEM: All neutral beam injector systems have power losses due to the inefficiency of converting charged ions into neutral atoms. These losses increase rapidly with the energy of injection for D^+ beams and is $\sim 80\%$ for 200 keV D^+ beams. Injectors using high energy D^- beams are more efficient but the losses are still $\sim 35\%$. Ideas for the recovery of this power, which is in the form of ion beams, back into electrical power are being studied, but need to be developed in more detail. The development necessary to have a practical system includes the design, fabrication, and testing of the hardware associated with a conversion scheme.

DATA REQUIRED: The design requirements are needed for the various electrical systems associated with the conversion system. These include voltage requirements, insulation requirements, the design considerations of the circuitry associated with the ion collector plates and power conversion equipment, and the interfacing requirements between such a system and the other components of the neutral beam line. Based on these requirements, the detailed design and construction of the system is required. Sub-scale elements of this system must be tested and various operating parameters determined.

SCOPE OF TASK: The task will require several man-years of research by an engineering/scientific team, hardware development and fabrication, and extensive testing of resulting systems.

SCHEDULE NEED/IMPACT: If a design is found feasible, it must be available and tested during Title II in order to be implemented on TNS.

RESOURCE REQUIREMENTS: A facility for the design, fabrication, and testing of the electrical aspects of the conversion system is required. A full test of the system will require a source of high energy (~ 150 – 300 keV) hydrogen beam.

AVAILABLE RESOURCES/PROGRAMS: Work is presently being carried out at ORNL and LBL/LLL on the development of direct conversion systems. At this time, this work is at the scoping level and must be broadened to include development of hardware.

ESTIMATED COST: Assuming the work can be carried out at an existing facility, approximately 3 man-years of effort is required. The total cost, including manpower and hardware costs, is estimated at \$350 k.

ALTERNATIVES: A direct energy conversion scheme for TNS is not necessary, but if high energy (>200 keV) positive ions are utilized, such a scheme could substantially reduce the power supply costs as well as operating costs.

TNS RD&D ASSESSMENT

DATE: 2/9/77

BY: D. A. Sink

ITEM: 3,2-1

PRIORITY: 2

SYSTEM: Rf Heating System

COMPONENT: Rf Source

TOPIC: Determination of rf source frequency for TNS

PROBLEM: Since a range (1 MHz to 100 GHz) of rf frequencies may have applications in heating plasmas theoretical and experimental considerations are required to allow for "best" choice for TNS.

DATA REQUIRED: Theoretical data is required. Experimental results on PLT, PDX, D III, and/or TFTR are required for the full range of rf frequencies. Data on coupling efficiencies between the rf and the plasma, and data on the various constraints imposed on the rf system before it is coupled to a tokamak are required.

SCOPE OF TASK: The task will require approximately a year of users' time on an existing tokamak. Theoretical calculation will provide guidance on the frequency(ies) selected, and the fabrication of an rf system will be required. Design changes on the device selected will be required resulting in machine down-time.

SCHEDULE NEED/IMPACT: The results are needed by the end of the conceptual design phase.

RESOURCE REQUIREMENTS: Resources include a large tokamak and its associated facilities. Hardware development and computer time are also required.

AVAILABLE RESOURCES/PROGRAMS: Programs at PPPL and GA are underway, but TNS criteria should be determined and then allowed to influence the program. Data on rf heating could be obtained using the D III device.

ESTIMATED COST: Assuming a tokamak facility is available, roughly 5 man-years of effort will be required. A total cost of \$500 k is estimated.

ALTERNATIVES: Alternatives to rf heating include the various methods for neutral beam heating of plasmas.

TNS RD&D ASSESSMENT

DATE: 2/9/77

BY: J. H. Schultz

ITEM: 3.3-1

PRIORITY: 3

SYSTEM: Plasma Heating Power Supplies

COMPONENT: Rf Power Supply

TOPIC: Rf Amplifier Tube Development and Test

PROBLEM: Following a determination of the best one or two frequency ranges for rf heating, the rf supplies must be upgraded from their present low power and low efficiency operating levels. The lower the frequency chosen, the less development work will have to be done on the amplifier tube. For 1986 operation electron cyclotron resonance heating can probably be eliminated, because of the very low power per tube and the inability to parallel tubes.

DATA REQUIRED: Characteristics and costs of prototype rf tubes. Rf supply performance driving into a plasma.

SCOPE OF TASK: Design, fabrication and testing of prototypes.

SCHEDULE NEED/IMPACT: End of Title I

RESOURCE REQUIREMENTS: Manufacturing design laboratory. Existing tokamak fusion devices for testing.

AVAILABLE RESOURCES/PROGRAMS: Tube manufacturers, on-going rf power supply programs.

ESTIMATED COST: 2 M\$

ALTERNATIVES: Neutral beams. TNS rf heating experiments will be planned, with neutral beams selected as the primary source of auxiliary heating.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: J. H. Schultz
 ITEM: 3.3.-2
 PRIORITY: 2

SYSTEM: Plasma Heating Power Supplies

COMPONENT: Series Regulator/Switch

TOPIC: Development of Large NB Regulator Switch Tubes

PROBLEM: Operation of large NB sources will require regulation and switching on the order of 100 A at 200 kV and above. Tubes capable of this level of power handling don't exist as single units.

DATA REQUIRED: Either development of tubes capable of passing 100 A and blocking 200 kV or knowledge of how to series smaller units, such as the tubes being developed for TFTR by RCA and Varian.

SCOPE OF TASK: Development of industrial prototype or experiments with existing tubes requiring construction of high-power supply.

SCHEDULE NEED/IMPACT: Start of Title I

RESOURCE REQUIREMENTS: Tube manufacturing facility or laboratory with facilities for very-high-power brassboarding.

AVAILABLE RESOURCES/PROGRAMS: RCA/Varian tube development for TFTR neutral beam program. LLNL & ORNL neutral beam test facilities.

ESTIMATED COST: \$250 K.

ALTERNATIVES: Delay development, attempt to procure tubes without development with uncertainty in cost and performance.

3.4 TOKAMAK SUPPORT SYSTEMS

3.4.1 Remote Servicing Systems

The TNS device will become highly radioactive due to neutron reactions in materials during D-T operations. The radiation levels anticipated will require that remote handling techniques be applied during virtually all maintenance operations on the reactor. These remote operations are anticipated to be extremely difficult and complex, primarily because of the complex configuration, large size of individual components, need for accurate positioning and reliable joining techniques, and limited space for assembly/disassembly operations. Many of the remote operations and equipment envisioned for TNS have no prior precedent. Although considerable experience exists from the fission reactor program, the specific methods and equipment for remote maintenance of fusion devices remain to be identified. It has been recognized that the remote maintenance requirements will have a great influence on the design of TNS and future fusion reactors and will play a critical role in determining plant availability and thereby overall economics. It is in this regard that the RD&D tasks described in this section are directed. Briefly, the proposed tasks are based on the following considerations:

The feasibility of component designs and planned maintenance operations must be confirmed. Mock-ups and models of device components and remote maintenance equipment are proposed for these confirmation tests.

Remote cutting and welding tools must be designed to accommodate cutting and welding of all welded joints. Qualification tests of the equipment must be performed to confirm acceptability.

Standardized, remotely operable joint designs must be developed to minimize the number of dissimilar types of joints requiring different methods of remote servicing and to simplify remote operations.

A method must be developed to systematically detect and repair leaks in the ultra high vacuum systems.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: B. J. Fedor
 ITEM: 4.1-1
 PRIORITY: 2

SYSTEM: Remote Servicing System

COMPONENT: Mock-ups of Device Components

TOPIC: Demonstration and Qualification of Remote Maintenance Operations

PROBLEM: Remote maintenance operations in TNS are anticipated to be extremely difficult and complex. The feasibility of many of the operations has not been demonstrated. In this regard models of device components must be designed and fabricated to confirm the feasibility of planned operations, assure design compatibility with remote handling tooling, refine handling techniques and train personnel.

DATA REQUIRED: Experimental confirmation of maintenance concepts for key components of the TNS device

SCOPE OF TASK: Design and fabricate low cost models of device components to confirm the feasibility of designs and planned maintenance operations. Feasibility will be confirmed by the ability to perform maintenance functions reliably within the specified time constraints. The operations to be simulated by models include the following:

1. Replacement of the vacuum vessel
2. Replacement of TF coils
3. Replacement of Poloidal coils
4. Replacement of other major structurals
5. Servicing of all major components including those identified in 1 through 4 above.

Following the demonstration of the acceptability of the remote operations, the mock-ups will be qualified and used to train operating personnel.

SCHEDULE NEED/IMPACT:

- Prove feasibility by end of Title I design
- Demonstrate the acceptability of TNS remote operations by the end of Title II design
- Qualify equipment and train operators by the end of Title III design.

RESOURCE REQUIREMENTS:

- An engineering design and testing facility with remote handling equipment for early feasibility tests
- TNS mock-up facility for demonstration and qualification tests

AVAILABLE RESOURCES/PROGRAMS: Industrial Laboratories and Government Laboratories; TNS design and operating team.

ESTIMATED COST: Labor, \$ 500,000; Equipment, \$ 250,000; Materials & Services, \$ 500,000; Total \$ 1,250,000

ALTERNATIVES: Design, fabricate and perform remote maintenance operations without demonstration and qualification tests using currently available information at high performance and cost risk.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: B. J. Fedor
 ITEM: 4.1-2
 PRIORITY: 3

SYSTEM: Remote Servicing Systems

COMPONENT: Cutting and Welding tools

TOPIC: Design, Fabrication and Qualification of Remote Cutting and Welding Equipment for TNS.

PROBLEM: The maintenance of TNS will require the application of remote cutting and welding techniques during disconnecting and repairing various component systems. Remote cutting and welding equipment does not currently exist in a usable form and must be designed or adapted to TNS systems.

DATA REQUIRED: Experimental confirmation that the remote cutting and welding equipment performs as required.

SCOPE OF TASK: Design, fabricate, and test remotely operable cutting and welding equipment for specific TNS joint configurations and potential repair operations. The equipment will be designed to accommodate cutting and welding of all welded joints other than the primary vacuum vessel joint. These include, diagnostic tubes, instrumentation tubes, vacuum piping, etc., that may have to be serviced or repaired during maintenance operation. Included in this task is the design and qualification of cutting and welding equipment for the repair of components including the vacuum vessel while in place.

SCHEDULE NEED/IMPACT: Required for start of Title II design.

RESOURCE REQUIREMENTS: An engineering design and testing facility. TNS mock-up facility for demonstration and qualification tests.

AVAILABLE RESOURCES/PROGRAMS Industrial Laboratories and Government Laboratories

ESTIMATED COST: Materials & Services, \$ 500, 000; Equipment, \$ 200, 000; Labor, \$ 400, 000; Total \$ 1, 100, 000

ALTERNATIVES: Adapt currently available equipment and information at high performance and cost risk.

TNS RD&D ASSESSMENTDATE: 2/8/77BY: B. J. FedorITEM: 4.1-3PRIORITY: 3SYSTEM: Remote Servicing SystemsCOMPONENT: Standardized JointsTOPIC: Design, Fabricate and Qualify Standardized Remotely Maintainable Joints for all Tokamak Systems (coil, vacuum electric, cooling, etc.)

PROBLEM: Standardized joint designs do not exist for TNS components to be serviced by remotely operable maintenance equipment. Unless standardized joints are developed this could result in an extremely large number of dissimilar types of joints requiring different methods of remote servicing.

DATA REQUIRED: Experimental confirmation that joints perform as required.

SCOPE OF TASK: Design, fabricate, and test standardized remotely maintainable joints for all tokamak systems. The objectives are to minimize the number of different types of joints; simplify remote operation by reducing the number of degrees of motion required for actuation, and finally to qualify the joints by testing. Standardized joints will be designed for the following major tokamak systems: Vacuum; Electrical; Cooling, other (diagnostics etc.).

SCHEDULE NEED/IMPACT: Required prior to the end of Title II design.

RESOURCE REQUIREMENTS: An engineering design and testing facility. TNS mock-up facility for demonstration and qualification tests.

AVAILABLE RESOURCES/PROGRAMS: TFTR, Industrial Laboratories, Government Laboratories.

ESTIMATED COST: Total \$1,300,000. Materials and Services \$500,000; Equipment \$200,000; Labor \$600,000.

ALTERNATIVES: If joints designs are not standardized where possible, excessive time and cost will be experienced for routine maintenance operations.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: B. J. Fedor
 ITEM: 4.1-4
 PRIORITY: 3

SYSTEM: Remote Servicing Systems

COMPONENT: Remote Maintenance Equipment

TOPIC: Demonstration and Qualification of the TNS Remote Maintenance System.

PROBLEM: The radiation levels anticipated during TNS operation will require that remote handling equipment and techniques be applied during virtually all maintenance operations on the device. These operations are expected to be extremely difficult and complex due in part to the complex configuration and size of the components. Many of the operations have no prior precedence and have not been demonstrated. In this regard full-size prototypical maintenance equipment must be designed, fabricated and tested in order to demonstrate and qualify the proposed TNS maintenance systems.

DATA REQUIRED: Experimental confirmation that the remote maintenance systems for TNS perform satisfactorily. Calibration data for the individual handling equipment.

SCOPE OF TASK: Design, fabricate and test full-size prototypical maintenance equipment that is capable of demonstrating and qualifying the maintenance method selected for TNS. The prototype equipment will be designed such that it is compatible with the individual component mock-ups and designs. The demonstration and qualification tests will include the following major operations.

1. Servicing the vacuum vessel including replacement.
2. Servicing the TF coils including replacement.
3. Servicing the poloidal coils including replacement.
4. Servicing the major structural components including N.B. lines, vacuum, electrical and cooling systems etc.

Following the demonstration of the acceptability of the remote equipment and operations the equipment will be qualified and used to train operating personnel.

SCHEDULE NEED/IMPACT: Prove feasibility by end of Title I design; Demonstrate acceptability of TNS remote operations by the end of Title II; Qualify equipment and train operators by the end of Title III.

RESOURCE REQUIREMENTS: An engineering design and testing facility with component mock-ups for early feasibility tests; TNS mock-up facility for demonstration and qualification tests.

AVAILABLE RESOURCES/PROGRAMS Industrial Laboratories and Government Laboratories. TFTR can provide some of this information.

ESTIMATED COST: Labor \$730,000, Equipment \$200,000, Material and Services \$800,000
Total \$1,730,000.

ALTERNATIVES: Design, fabricate and perform remote maintenance operations without demonstration and qualification tests using currently available information at high performance and cost risk.

TNS RD&D ASSESSMENT

DATE: 2/8/77
 BY: B. J. Fedor
 ITEM: 4.1-5
 PRIORITY: 3

SYSTEM: Remote Servicing Systems

COMPONENT: Leak Detection Equipment

TOPIC: Remote Leak Detection for Vacuum Systems

PROBLEM: TNS will have a large number of joints in the ultra high vacuum systems which must be capable of being maintained remotely.

DATA REQUIRED: Define necessary modifications to closure joints to make them compatible with leak detection system. Define system configuration, detection gas, sensors and special probes. Calibrate known leaks against sensors to determine the sensitivity of the leak detection equipment.

SCOPE OF TASK: Design, fabricate, and test a remotely operable leak detection and repair system that is adaptable to all TNS vacuum systems.

SCHEDULE NEED/IMPACT: Required prior to the end of Title II design.

RESOURCE REQUIREMENTS: An engineering design and testing facility.

AVAILABLE RESOURCES/PROGRAMS: Industrial and Government Laboratories, TFTR, and the TNS design team.

ESTIMATED COST: Labor: \$160,000; Materials and Services \$100,000; Equipment \$50,000; Total: \$310,000.

ALTERNATIVES: Use currently available, conventional leak detection and repair methods and accept the potential delay and uncertainty. The evacuation of the entire test cell would change the nature of the leak rate problem.

3.4.2 Fuel Handling Systems

Because of the relatively short (~ 1 s) pulse length capability of operating tokamaks, very little experience has been gained in fuel injection. Fuel injection becomes a serious problem for dense plasmas having a large cross-section, and an RD&D program is required to demonstrate that a satisfactory method is possible for the long pulse lengths anticipated in TNS. Energetic neutral injection is not expected to be feasible economically as a method of fuel injection. The basic questions to be answered by the RD&D program are: 1) what are the requirements for fueling, and 2) how can fuel be introduced into the center of the plasma?

Will fuel introduced at the surface of the plasma diffuse into the center of the plasma? Experimental confirmation is required in existing and planned tokamaks such as PLT, ORMAK-U, DOUBLET II, TFTR. There is some evidence in present devices that the central hot column density does increase as cold neutral gas is added at the plasma boundary. Knowledge of this phenomenon is required to determine the rate of refueling required, and to determine whether fuel refluxing from the walls will occur.

If fuel must be introduced directly into the center of the plasma, a mechanism for accelerating pellets to a velocity of $>10^5$ cm/sec and for rapid injection ~ 100 pellets/sec (depending on the amount of fuel refluxing) must be experimentally developed. Successful injection into existing tokamaks must be demonstrated.

As an alternate method, the development of a liquid jet injector should also be experimentally evaluated.

There has been very little experience to date with the use of tritium in fusion devices. Limited experience will be gained from TFTR, but because of the larger quantities that will be required for TNS there will be RD&D needs, particularly in two areas:

- In order to satisfy tritium accountability, knowledge of the values of solubility, permeability, and diffusivity of tritium in materials and the efficacy of equipment cleanup by bakeout will be required.
- There will be a need for cryogenic distillation capabilities to produce high purity T, D, and D-T product streams in order to recycle spent plasma. Qualification of apparatus will be required.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: E. W. Sucov
 ITEM: 4.2-1
 PRIORITY: 1

SYSTEM: Fuel Handling

COMPONENT: Fuel Delivery System

TOPIC: Pellet penetration measurements

PROBLEM: Plasmas which have a burn duration several times longer than the confinement time will lose fuel ions by transport and removal by a divertor system; or, if recycling of fuel ions turns out to be feasible, fuel ions will be lost by the fusion reactions. In the first case, refueling will be needed at the rate of the total plasma content per second; in the second case, refueling will be needed at about 1/10 the above rate. The most promising scheme available for refueling is to inject high velocity pellets into the plasma. Theories predicting the velocities required for penetration have not been experimentally confirmed not have verified theoretical models been developed and qualified to predict what degree penetration may be required for fueling TNS. Those theories and models must be developed and then experimentally confirmed.

DATA REQUIRED: Maximum penetration of various sized pellets as a function of pellet velocity and plasma size, density and temperature.

SCOPE OF TASK: Assuming that appropriate plasmas are available in other tokamaks, two major efforts must be successful. 1. Development of systems that can, at low repetition rates, accelerate pellets up to technologically feasible limits. 2. Development of diagnostics to follow particles as they penetrate the plasma.

SCHEDULE NEED/IMPACT: This information should be available by the end of the conceptual design phase.

RESOURCE REQUIREMENTS: Cryogenic handling and controlling apparatus, acceleration scheme, high vacuum capability, diagnostics to measure velocity and penetration, tokamak with plasma of appropriate density and temperature.

AVAILABLE RESOURCES/PROGRAMS: Several tokamaks are or could be available: ORMAK, PLT, ORMAK-U, PDX, PDX-U, TFTR. Government, industry, and university labs have adequate facilities for developing the acceleration and diagnostic systems.

ESTIMATED COST: Assuming the availability of tokamak plasmas, the cost should be about \$800,000 for labor and \$100,000 for hardware.

ALTERNATIVES: Assume current theories are correct and base design goals on these theories; design TNS without refueling capability; rely on other injection approaches.

TNS RD&D ASSESSMENT

DATE: 2/8/77
 BY: E. W. Sucov
 ITEM: 4.2-2
 PRIORITY: 1

SYSTEM: Fuel Handling

COMPONENT: Fuel Delivery System

TOPIC: Pellet Acceleration by Centrifuge

PROBLEM: Refueling rates for the TNS plasma will vary depending on whether the loss in fuel is due only to fusion reactions ($\sim 1\%/second$) or whether it is due also to fast removal by a divertor scrape-off layer ($\sim 100\%/second$). In either case, the fuel must be replenished in the hot core of the plasma. Analysis of requirements for pellet injection of fuel into a plasma of ~ 1 m radius shows that the required pellet velocity will be quite high (potentially greater than 10^5 cm/sec). This may be very difficult to achieve. The current approach, followed by ORNL, is to accelerate pellets initially to $\sim 10^5$ cm/sec by means of an ultra-centrifuge. At this time, the ultra-centrifuge method may not be able to provide the required repetition rate. Subsequent development will be needed to increase the rate to the highest technically achievable.

DATA REQUIRED: Maximum attainable velocity and repetition rate for the ultra-centrifuge method. Thermophysical properties and phase relationships of frozen D and T, especially energy absorbed in the pellet during acceleration.

SCOPE OF TASK: Identification of novel materials having promising strength to mass ratios and fabrication of centrifuge rotors from these materials. Analyses of dynamics of DT pellets during acceleration.

SCHEDULE NEED/IMPACT: This information must be available by the end of the conceptual design phase.

RESOURCE REQUIREMENTS: Cryogenic liquid-solid storage and control; pellet forming and acceleration systems; velocity measuring systems, plasma simulation mockup.

AVAILABLE RESOURCES/PROGRAMS: ORNL is developing a rotating mechanical accelerator which is capable of accelerating pellets to the order of 10^5 cm/sec. Subsequent development will attempt to increase this velocity to as high a value as technically feasible by using a high strength composite material rotor.

ESTIMATED COST: $\sim$ \$300,000 for labor and \$100,000 for hardware.

ALTERNATIVES: Assume other schemes such as liquid jet or gas blanket can fuel the plasma. Limit the burn time to ~ 10 seconds in a non-divertor TNS.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: E. W. Sucov
 ITEM: 4.2-3
 PRIORITY: 1

SYSTEM: Fuel Handling

COMPONENT: Fuel Delivery System

TOPIC: Liquid Jet Injection Feasibility Tests

PROBLEM: Analysis of requirements for pellet injection of fuel into a plasma of ~ 1 m radius shows that the pellet velocity will be quite high (potentially greater than 10^5 cm/sec). This may be very difficult to achieve. The current approach is to develop an ultra-centrifuge to reach velocities $\sim 5 \times 10^5$ cm/sec but extrapolation to much greater values may prove very difficult. An alternate scheme, using a water jet, should be evaluated for its ability to generate a liquid tritium jet at high velocities.

DATA REQUIRED: Volumetric flow rate of liquid tritium or deuterium as a function of over-pressure, temperature, and nozzle diameter. Analysis of thermophysical processes occurring in the jet stream and their relative magnitudes during flight. Maximum allowable stress on materials and configurations used to store, pump, and accelerate the liquid tritium.

SCOPE OF TASK: Analytic studies should be performed on the following questions: material limits to achieving the required velocity (e.g., stresses on containers and nozzles, evaporation or freezing of liquid under acceleration, etc.), engineering feasibility of cryogenic operation of pumps, containers, seals, etc. Development of system to control, store, pump, and eject cryogenic liquids. Perform injection experiments into simulated plasmas and then into tokamak plasmas.

SCHEDULE NEED/IMPACT: Information as to the feasibility of this concept should be available by the end of the conceptual design phase.

RESOURCE REQUIREMENTS: Cryogenic storage and handling capabilities; capability to perform engineering design and fabrication of cryogenic pumps, transducers, seals, nozzles, etc.; high vacuum and gas discharge plasma equipment; diagnostics.

AVAILABLE RESOURCES/PROGRAMS: Many government, industrial, and university laboratories have capability in cryogenics, engineering, vacuum, and gas discharge plasmas. Several industrial organizations have experience and capability in high velocity water jets.

ESTIMATED COST: Equipment $\sim$ \$500,000; Manpower $\sim$ \$600,000.

ALTERNATIVES: Use ultra-centrifuge acceleration method. Develop other means of refueling now being pursued by the Europeans.

TNS RD&D ASSESSMENT

DATE: 2/3/77

BY: H. J. Garber

ITEM: 4.2-4

PRIORITY: 2

SYSTEM: Fuel Handling

COMPONENT: Transfer Pumps, Compressors, Roughing Pumps for Tritium Service

TOPIC: Performance and Qualification Testing of Tritium Pumps

PROBLEM: The severe requirements for tritium pumping devices (zero leak, all metal, high reliability, non-reacting, no rotating seals, wide temperature range, freedom from organics, stability to radiation) limits the potential candidates. Also, the suitability and long term reliability of these in tritium service have not been conclusively demonstrated. There is a need to test the equipment now available to circumscribe their adaptability, limitations, areas where best applied, service life, etc.

DATA REQUIRED: Performance qualification of candidate commercially available pumps and compressors. This includes compressions to ~200 psi, transfer pumping of gaseous and liquid H-D-T-He mixtures, and roughing pumps for vacuum systems and regenerations of cryosorption panels and ZrAl getters.

SCOPE OF TASK: Test of each candidate pump/compressor for its performance characteristics, reliability, durability, operational malfunctions and frequency, flexibility, stretch capacity and the like under tritium service conditions.

SCHEDULE NEED/IMPACT: Testing program should be completed about 2 months in advance of Title II inception.

RESOURCE REQUIREMENTS: Loop in test stand; specimen pumps and piping (estimate 5-10 devices), facility equipped to do tritium test work.

AVAILABLE RESOURCES/PROGRAMS: This effort is included in LASL's TSTA program.

ESTIMATED COST: Personnel ~\$150,000; Equipment ~\$280,000; Services ~\$80,000.

ALTERNATIVES: - None, cannot design or operate tritium handling system properly without conduct of this task.

TNS RD&D ASSESSMENT

DATE: 2/2/77
 BY: H. J. Garber
 ITEM: 4.2-5
 PRIORITY: 2

SYSTEM: Fuel Handling

COMPONENT: _____

TOPIC: Development of Transient Tritium Transport and Release Code

PROBLEM: In connection with such matters as satisfying tritium accountability requirements, planning and judging the efficacy of equipment cleanup by bakeout, scoping problems of maintenance of contaminated equipment, determination of tritium releases during normal operation, and specifying the design standards to be applied to primary loop hardware items so as to comply with safety requirements, it is essential to have on hand a computer code that keeps a running account of the amounts of tritium in the entire plant and where it is located in detail. Such a code is not now in existence.

DATA REQUIRED: Requires prior knowledge of transport properties of all materials "seen" by the fuel, relationships that accurately describe the transport mechanisms involved, closed form solutions for the applicable differential equations, transform algorithms that very substantially reduce the number of terms required in the series solutions for cumulative tritium contents and releases. For the cooling loops the concentration of tritium and other radioactive products transported into the coolant must be predicted, based on analysis of long term operation applicable to the proposed scenario.

SCOPE OF TASK: Development and implementation of a versatile computer code, to be used both for design of plant components and systems, and for tritium accountability during plant operations.

SCHEDULE NEED/IMPACT: The code is required for Title I design, hence this task should be completed with the code operational by start of FY '80. This impacts on the design of the vacuum vessel, vacuum system, fuel handling systems, tritium cleanup systems, remote maintenance, radiological waste system, heat dissipation systems.

RESOURCE REQUIREMENTS: Transport information for temperature and pressure dependence of tritium solubility, diffusivity, and permeability for proposed materials must be on hand to implement the code. Requires services of skilled numerical analyst to develop and verify general purpose code, mathematical physicist to develop required algorithms transforms, and chemical engineer skilled in transport kinetics.

AVAILABLE RESOURCES/PROGRAMS: Could be performed in Industry or Government Labs, using a combination of disciplines and high precision computer as indicated in Resource Requirements. Due to geometry dependence, should be coupled to TNS design effort.

ESTIMATED COST: \$150,000

ALTERNATIVES: Resort to hand calculations as conducted on limited basis in previous conceptual and scoping work for TFTR and TNS. These are very tedious, time consuming, and much too clumsy for both design and accountability purposes. Additionally, excessive conservatism would be incorporated at higher cost, with safety hazards inaccurately defined.

TNS RD&D ASSESSMENT

DATE: 2/3/77

BY: H. J. Garber

ITEM: 4.2-6

PRIORITY: 2

SYSTEM: Fuel Handling

COMPONENT: Cryogenic Distillation System

TOPIC: Cryogenic Distillation Column Performance Measurements

PROBLEM: Successful operation of TNS and subsequent CTR machines will require cryogenic distillation capabilities to produce high purity T, D, DT product streams from spent plasma feeds. with substantially complete elimination of H and other impurities. Guidance needed for the design of such systems requires information on the performance characteristics derived from operating system. Such information, to the degree required, does not currently exist. Demonstration that the close separations required can actually be achieved are mandatory.

DATA REQUIRED: Design parameters and details for array of columns and other accessories. Tabulation of relevant operating data noted during pertinent experimental runs that demonstrate capability for essentially complete separations. Performance characteristics derived from experimental programs as HTU or HETP, Murphree efficiency, column holdup, allowable mass velocities, actual refluxing requirements, temperatures and mass velocities required for isotope equilibrators, degradations if any of equilibrators.

SCOPE OF TASK: Design cryogenic distillation array based on actual H-D-T phase data or assumed ideal system behavior, construct equipment and conduct operation tests, assemble and tabulate test results. While the objective is to demonstrate that the complete separation required can be achieved, the generation of performance data is of equal importance.

SCHEDULE NEED/IMPACT: Can get by without the information for Title I considerations, but very essential for Title II efforts.

RESOURCE REQUIREMENTS: Work performance requires a laboratory fully equipped for tritium handling with enclosures (~18 ft. tall). Involves cryogenic distillation equipment and support accessories (liquid He, isotope analysis equipment).

AVAILABLE RESOURCES/PROGRAMS: Work can be done at LASL as part of TSTA program. Might also be conducted at qualified industrial laboratories.

ESTIMATED COST: Equipment ~ \$600,000; Personnel ~ \$500,000, Total \$1,100,000

ALTERNATIVES: In the absence of availability of demonstration of achievability of desired separations and performance information the alternatives are: 1) design of cryogenic system would be based on a highly conservative approach, without certainty that desired separations can be achieved; 2) despite the higher costs associated with assumed ultraconservative base, actual performance may fall short of goal and this will impact on the TNS fuelings. May have to modify the systems and compromise on composition control or may have to draw more heavily on ERDA T supplies to cover system shortcomings.

TNS RD&D ASSESSMENT

DATE: 2/3/77

BY: H. J. Garber

ITEM: 4.2-7

PRIORITY: 2

SYSTEM: Fuel Handling

COMPONENT: Cryopanel, Diffusers, Isotropic Equilibrators,
Catalytic Oxidizers, ZrAl Getters

TOPIC: Measurement of Tritium Handling Component Performance
Degradation

PROBLEM: Various impurities will be generated by the plasma discharges which may have deleterious effects on system performance due to "poisoning". Additionally, radioactive decay of trapped T along with the release of He-3 may deteriorate the performance and integrity of vital elements of the processing equipment. The extent to which such deterioration may or may not occur is not known and should be determined.

DATA REQUIRED: Long term (over 2-3 year service) performance and mechanical integrity characteristics of key items when operating with tritium bearing streams containing impurities.

SCOPE OF TASK: Experimental determination of mechanical integrity and performance degradation on representative specimens (of cryopanel, Pd alloy diffusers, isotopic equilibrators, catalytic oxidizers, ZrAl getters), when subjected to long term repeated service (or regeneration) in tritium environments containing representative amounts of spent plasma impurities.

SCHEDULE NEED/IMPACT: By end of conceptual design.

RESOURCE REQUIREMENTS: Performed at an ERDA Lab outfitted to handle tritium programs. Requires test beds for long term tests and performance determination setups.

AVAILABLE RESOURCES/PROGRAMS: Studies can be done at LASL in conjunction with conduct of TSTA program. Examinations might be accomplished on small unit operated in parallel with larger systems of LASL integrated loop.

ESTIMATED COST: Equipment ~ \$150,000; Personnel \$470,000.

ALTERNATIVES: Assume arbitrary values for mechanical property deterioration and performance degradation, incorporating these into the design, and accept consequences if adequate conservatism has not been provided. This may lead to more frequent shutdowns for replacement of degraded items than anticipated and possibly substandard performance in vacuum, fuel handling, and tritium cleanup systems.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: H. J. Garber
 ITEM: 4.2-8
 PRIORITY: 2

SYSTEM: Fuel Handling

COMPONENT: Tritium-Lithium Extraction System

TOPIC: T-Li-Y Transport data and demonstration of extractor performance

PROBLEM: There is a finite probability that a poloidal divertor will be required by TNS and future CTR devices. A candidate approach involves spent plasma trapping on flowing Li followed by extraction in Y and subsequent recovery/recycle of the D-T. Design of the extraction-recovery system requires availability of T-D-H-Li-Y phase and transport properties and operating experience with prototype equipment and an integrated trapping/recovery system. Currently, this does not exist.

DATA REQUIRED: Phase relationships for the system T-D-H-Li-T in the range 520-1100 K; transport kinetics of T-D-H extraction from Li into Y in the range 520-650 K; drainage characteristics of Li from Y chip beds; release kinetics of T-D-H from Y in range 520-1100 K.

SCOPE OF TASK: Experimental determinations of aforementioned phase and transport kinetics; design, fabrication, and testing of extraction equipment and hydrogen isotope recovery equipment; assembly of pilot integrated assembly of trapping-extraction-recovery equipment and demonstration testing of system, with development of performance characteristics.

SCHEDULE NEED/IMPACT: This task must be completed by the end of Title I in order to determine whether this approach can be applied in resolving the crucial problem of purity control.

RESOURCE REQUIREMENTS: Equipment array consisting of spent plasma trapping module, extractor, heat exchangers, vacuum equipment, circulating and transfer pumps, instrumentation and controls, analytical equipment, enclosures, monitors.

AVAILABLE RESOURCES/PROGRAMS: Can be done at National Laboratories.

ESTIMATED COST: Equipment ~\$300,000; manpower ~\$360,000; total of ~\$660,000.

ALTERNATIVES: Alternatives include: (a) proceed with the trapping/recovery design on the basis of the current paucity of applicable data but incorporating large margins for performance uncertainties, with risk that this approach may not be workable; (b) abandon this approach in favor of other modes of purity control by special surface treatments or installing extremely large vacuum systems (orders of magnitude larger than would be required otherwise).

TNS RD&D ASSESSMENT

DATE: 1/13/77
 BY: H. J. Garber
 ITEM: 4.2-9
 PRIORITY: 3

SYSTEM: Fuel Handling

COMPONENT: _____

TOPIC: Measurement of Tritium Transport Properties

PROBLEM: Determination of such matters as wall thicknesses of equipment, sizing of spent fuel handling systems and their containments, and realistic estimates of tritium releases hinges on having trustworthy values of tritium transport properties on hand during the early hardware design phases. Such trustworthy data to the extent required does not currently exist.

DATA REQUIRED: Experimentally determined values of the solubility, permeability, and diffusivity of tritium in those metals that are candidate materials of construction for the vacuum vessel, limiter, neutral beam catcher, first wall, and spent plasma processing equipment (e.g., austenitic stainless steels, tungsten, molybdenum, TZM copper, inconels) over the 10^{-8} to 10^{-2} torr and 100 to 900 K temperature range, with mathematical formulations of the variations.

SCOPE OF TASK: Design of experimental test equipment, fabrication and assembly, conduct of experiments, evaluation and analysis of results, formulation of expressions that describe the pressure and temperature dependency for each material and property.

SCHEDULE NEED/IMPACT: Results of investigations must be completed by or before the end of conceptual design in order that information may be applied during Title I design phase for vacuum vessel and fuel handling equipment.

RESOURCE REQUIREMENTS: Requires physical measurements (high vacuum) laboratory, diffusion permeability cell setups (3 units), high precision machining and analytical facilities.

AVAILABLE RESOURCES/PROGRAMS: Could be conducted at ERDA facilities (KAPL, ORNL, ANL, SRO, LASL, Mound) in tritium facilities. By using stand-ins of H and D for T could perform at Industrial R&D Laboratories.

ESTIMATED COST: Hardware \$200,000; Labor \$460,000.

ALTERNATIVES: Problem cannot be worked around due to high uncertainties of presently available very limited data. Temperature extrapolations are too great to be trustworthy and pressure dependence is highly in doubt (may scale more like αP rather than $\beta P^{1/2}$ for actual pressures). Alternative is to design based on limited available data and possibly over-design considerably to be on safe-side.

TNS RD&D ASSESSMENT

DATE: 2/8/77
 BY: H. J. Garber
 ITEM: 4.2-10
 PRIORITY: 3

SYSTEM: Fuel Handling

COMPONENT: High Integrity Valves (For Tritium Service)

TOPIC: Development and Qualification of Valves for Tritium Service

PROBLEM: The availability of "zero-leakage", high reliability, quick acting, remotely operated, longlife, 100% metallic, small and medium size valves (1/4 to 1") for tritium processing and handling operations in the range 10 - 800 K must be assured. This kind of equipment does not currently exist, hence, must be developed, prototyped, and proof-tested.

DATA REQUIRED: Performance characteristics of valves developed as to: leakage rates and variation with use; opening and closing times; wear on seats; function capability in flow control operation; freedom from difficulty temperature range; cycles possible prior to bellows damage; requirements of valve operator; response to open and close signals; other.

SCOPE OF TASK: Design of valves and operators (if necessary); fabricate and test prototype alternates; fabricate and performance test; qualify for tritium service at specified working conditions.

SCHEDULE NEED/IMPACT: Results of development and preliminary testing must be on hand before end of FY 79. Detailed testing could be done in FY 79 through 81 within Tritium Test Facility program at LASL.

RESOURCE REQUIREMENTS: Design by engineers of valve specialty manufacturer should be guided by fusion group. Tests can be done first with H or D as stand-in. Final testing and qualification should be conducted in a tritium environment at use conditions. Requires ME's for design, prototype fabrication, preliminary testing at valve manufacturers plant, followed by detailed testing of final version in a tritium facility.

AVAILABLE RESOURCES/PPOGRAMS: NASA and related space programs valve development efforts. Possibly, information/experience from Savannah River. Final testing qualification in strenuous service conditions should be included in TSTA programs at LASL.

ESTIMATED COST: Labor and Materials: \$270,000. Testing of candidate valves done over a 2 - 3 year period (include in TSTA operations cost).

ALTERNATIVES: 1) accept higher cost and delays if crash program is required to do the necessary development and testing, 2) recognize risks involved with utilizing currently available hardware and be ready to accept operational malfunctions-delays, 3) install excessive redundant items to be able to limp through operations when malfunctions occur.

TNS RD&D ASSESSMENT

DATE: 1/18/77
 BY: H. J. Garber
 ITEM: 4.2-11
 PRIORITY: 3

SYSTEM: Fuel Handling

COMPONENT: Cryogenic Distillation System

TOPIC: Hydrogen Isotope Phase Data Measurements

PROBLEM: For design of the cryogenic distillation system and devising operations procedures to extend system flexibility regarding composition of product steams, the liquid-vapor equilibria for the system T, D, H, TD, TH, HD are required. This information currently does not exist. There are some limited information on binary system behavior (vapor pressures, relative volatilities), but these are very inadequate.

DATA REQUIRED: Liquid-vapor equilibria for the ternary system T-D-H (phase relationships covering variation in compositions of the vapor phase in equilibrium with specified liquid phase to 2 atmospheres. This requires delineation of liquid-vapor thermodynamic surfaces molar heats of evaporation of H, D, T, and heats of formation-dissociation of HD, HT, DT.

SCOPE OF TASK: Design and construct equilibrium testing apparatus. Perform measurements. Evaluate, analyze, and document data in form of liquid-vapor isotherms, relative volatilities tabulations and sections through phase data. Make thermochemical measurements of heats of evaporation of H, D, T, HD, HT, DT and heats of formation and dissociation of HD, HT, DT, and document these.

SCHEDULE NEED/IMPACT: By start of Title II design.

RESOURCE REQUIREMENTS: Requires availability of a high quality laboratory (enclosures) equipped for tritium handling operations (as Mound, LLL, Sandia, ORNL, LASL) and highest capability analytical techniques. Requires special design low temperature equilibrium still and services of highly skilled physical chemists.

AVAILABLE RESOURCES/PROGRAMS: Candidate locations for work are Mound, LASL, LLL, or PNL. Related programs may exist. Hickman, et al., at LLL has been treating this problem via theoretical approaches for "ideal behavior".

ESTIMATED COST: Equipment ~\$50,000; Labor \$163,000, total \$213,000

ALTERNATIVES: Design on basis of limited data available (guesstimating), over-designing system to cope with uncertainties, and manipulate with final installation to see what operation routines are required to yield the desired product streams. Achievement of the desired goals may then be non-realizable.

3.4.3 Torus Vacuum Pumping System

The pumping system required for the TNS torus tends to be conventional, provided that it is not directly coupled with a divertor system, and as such requires some modest R&D because of the presence of tritium in the fuel and helium originating during the burn. The R&D required if the torus pumping system is located in the burial chamber of a divertor system is addressed in Section 3.1.1.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: D. A. Sink
 ITEM: 4.3-1
 PRIORITY: 3

SYSTEM: Torus Vacuum Pumping System

COMPONENT: Oil-Less and Leak-Less Foreline Pumps

TOPIC: Development of high speed foreline pumps

PROBLEM: Two basic requirements of any component of the vacuum pumping system are: 1) the component cannot contribute any impurities to the plasma, and 2) the gases handled by the component cannot escape from the component to the surrounding atmosphere since such gases will contain radioactive gases. In order that the various foreline pumps meet these requirements they must operate without contaminating the forelines with oil as well as operate without leaking any gases to the atmosphere. Since such pumps at the pumping speeds required (>30 liter/s) are not commercially available, they must be designed, fabricated, and tested.

DATA REQUIRED: Data on various foreline pumps presently available is required to determine the approach to developing the required pump(s). Mechanical pumps, turbomolecular pumps, sorption pumps, ion pumps, and getter pumps should be considered. The design changes necessary to meet requirements are needed, as well as the results of the tests on the new design. Helium leak-rates are of particular importance.

SCOPE OF TASK: Approximately one year of effort by a design team is required to first examine all existing possibilities, to prepare designs, to consult with manufacturers, and to fabricate and test various solutions.

SCHEDULE NEED/IMPACT: The results are needed by the end of Title I.

RESOURCE REQUIREMENTS: Resources would include a hardware fabrication and test facility having UHV capabilities and the expertise of a number of vacuum pump manufacturers.

AVAILABLE RESOURCES/PROGRAMS: Research and development programs within the TFTR project exist but the present task involves considerably more restrictive requirements. As for the vendors of vacuum pumps, a large number of manufacturers of high quality pumps exist.

ESTIMATED COST: Assuming that the work will require a team of two engineer/scientists at an existing facility with hardware fabrication, and UHV capabilities, a total cost of \$250 k is estimated.

ALTERNATIVES: If oil lubricated pumps must be used, a system of redundant oil filters are required to isolate the pumps. These filters will reduce the effective pumping speed of the pump. If the leakage rate of gases from a pump are too high, such pumps can be housed in a leak-tight container or room.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: D. A. Sink
 ITEM: 4.3-2
 PRIORITY: 3

SYSTEM: Torus Vacuum Pumping System

COMPONENT: Cryopumps

TOPIC: Performance testing of cryopumps (also see ITEM 3.1-9 on
 The design, manufacture, and test of cryosorption panel assemblies)

PROBLEM: In addition to the removal of He, D₂, T₂, and H₂ gas mixtures, impurities sputtered off the vessel walls will be removed by the cryopanel. The performance of cryosorption pumps under the conditions imposed by such impurities must be examined to determine if they will continue to operate following a large number of regenerations.

DATA REQUIRED: Data on the pumping of hydrogenous gases in the presence of impurities expected in TNS is required as a function of impurity level and following many pump regenerations. Impurities, in varying amounts, of iron, carbon, oxygen, methane, tungsten, molybdenum, nickel, chromium, silicon, manganese, etc. as well as various hydrogenous compounds must be studied. The data on a variety of molecule sieve materials is required.

SCOPE OF TASK: The task will involve a year of study and experimentation and will require the employment of very sensitive residual gas analysis and gas feed systems.

SCHEDULE NEED/IMPACT: Results are needed by the end of Title I.

RESOURCE REQUIREMENTS: Resources would include a UHV test facility and a number of cryosorption panels supplied by a few vendors.

AVAILABLE RESOURCES/PROGRAMS: Cryopanel development work is being conducted at PPPL, ORNL, and LBL/LLL.

ESTIMATED COST: Assuming a test facility is available, the total cost for a team of two researchers working for a year and for hardware acquisition and fabrication is estimated at \$200 k.

ALTERNATIVES: If impurities accumulate in cryosorption surfaces over a number of regenerations to the point where pumping speed is impaired, panel replacement is required, or the employment of all-metal cryopumps of the cryocondensation type are required.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: D. A. Sink
 ITEM: 4.3-3
 PRIORITY: 3

SYSTEM: Torus Vacuum Pumping System

COMPONENT: Helium Pumps

TOPIC: Development of high speed helium pumps (also see ITEM 1.1.3-9
Experimental evaluation of burial chamber pumping)

PROBLEM: Since He is a by-product of fusion, pumping of helium-hydrogen-isotope mixtures is required. Presently, there are no high speed pumps which can effectively remove the helium, and a development effort is needed to provide such a pump for TNS.

DATA REQUIRED: He pumping rates for various pumps, particularly for 4 K cryosorption panel, and He pumping rates in the presence of hydrogenous gases are required. The design and costs of these pumps providing the highest pumping speeds are required. The results of performance tests and the operating parameters are required.

SCOPE OF TASK: The task will require approximately six months of designing and testing of pumps.

SCHEDULE NEED/IMPACT: The results are needed by the end of Title I.

RESOURCE REQUIREMENTS: Resources would include a hardware fabrication and UHV test facility. The expertise of those people manufacturing cryosorption pumps are required.

AVAILABLE RESOURCES/PROGRAMS: Manufacturer of cryosorption pumps and other types of pumps have considered helium pumps, but the requirements for TNS are orders of magnitude higher than previously needed.

ESTIMATED COST: Assuming that a UHV facility is available, the task will require approximately one man-year of effort plus hardware for an estimated cost of \$ 150 K.

ALTERNATIVES: Helium pumps are essential for TNS if pulse lengths on the order of 30 seconds are expected. If the helium is not affectively removed, the gas will dilute the plasma and cause it to cool below ignition temperatures, and thus shorten the effective pulse length of the burn.

3.4.4 Heat Dissipation Systems

The heat dissipation systems for the TNS facility include systems for cooling of the toroidal vacuum vessel, the vacuum vessel shield, plasma limiters, neutral beam systems, normal copper field coils, power conversion apparatus, air conditioning systems, and the general plant circulating water system and cooling tower. Also included are the cryogenic refrigeration and coolant distribution systems for supply of 4.0 K supercritical helium to the superconducting toroidal field coils and vacuum cryopumps, and 77 K liquid nitrogen for the cooling of TF coil dewars and other thermal barriers.

Aside from the cryogenic systems, and possibly the divertor burial chamber cooling system, all major plant heat loads will be absorbed by water coolants. The vacuum vessel and shield cooling systems will use water at temperatures below 400 K and pressures below 1 MPa. Plasma limiters, and neutral beam calorimeters and beam dump will require high pressure water systems, but not in excess of conventional practice. Therefore, no basic heat transfer or fluid flow research is required for these systems.

Prototype development of vacuum vessel wall segments, plasma limiters, calorimeters, and beam dumps will include thermo-hydraulic tests for design qualification. These tests are discussed in the context of the individual component RD&D programs in other parts of this document.

There are significant questions in regard to the nuclear safety aspects of cooling system design, especially in the vacuum vessel, shield, and limiter systems. Programs for the prediction of coolant contamination by tritium are discussed in Section 3.4.2, Fuel Handling Systems. Water chemistry and treatment problems are within the range of experience from fission reactor programs and should require no basic research. The establishment of design standards for heat exchangers, piping, valves, pumps, and other components remains to be done, but this is considered to be within the normal design function. Hence, no specific RD&D programs are proposed in this section for any of the water cooling systems.

Proper plasma impurity control may require use of a magnetic divertor which will direct a sizable fraction of plasma power to a burial chamber. The RD&D requirements related to burial chamber cooling are addressed in Section 3.1.1 under Impurity Control Subsystems.

The cryogenics industry has matured to the point where a 5000 liter/hr helium liquifier, equivalent to approximately 20 kW refrigeration at 4.2 K, will be shipped to Fermilab in the fall of 1977. The manufacturers have indicated that construction of this unit required no extraordinary development, and that systems of 100 kW capacity at 3.5 K are within the state-of-the-art. Such systems can satisfy the basic refrigeration requirements for TNS.

A development program is required for the design, manufacture, and prototype testing of pumping systems to circulate 4.0 K supercritical helium for the TF coil conductor and bobbin cooling loops. A second involves analysis to determine the most effective means of leveling peak heat loads imposed on the helium refrigerator, so that the capacity and cost of refrigeration systems can be minimized.

In summary, the objectives of the TNS device in the heat dissipation area can be satisfied by using advanced state-of-the-art thermo-hydraulic design technology with rather modest basic research requirements. Several components should be subjected to prototype tests for design qualification as noted. However, the lack of any current requirement for thermal/electric power conversion allows considerable freedom in coolant selection and the selection of operating temperatures and pressures.

In Section 3.7 consideration is given to RD&D associated with the definition of capability to perform advanced blanket/shield and fusion energy conversion experiments in TNS subsequent to its initial operation. These activities may ultimately impact the baseline design of the heat dissipation systems and require additional supporting RD&D.

TNS RD&D ASSESSMENT

DATE: 2/4/77
 BY: R. J. Budenholzer
 ITEM: 4.4-1
 PRIORITY: 2

SYSTEM: Heat Dissipation Systems

COMPONENT: Helium Refrigeration System

TOPIC: Supercritical Helium Circulating Pumps

PROBLEM: Supercritical helium coolant for TF coil conductor and bobbin cooling is to be circulated in isolated primary loops. Large, highly efficient circulating pumps will be required to provide heads as high as 6 atmospheres. Pumps built to date have been of laboratory scale and their overall efficiency has been on the order of 35%. Pump and motor efficiencies will improve in larger sizes, but operation of pumps in the neighborhood of the helium critical point will complicate design. Experience must be gained in the design and operation of larger scale helium circulating pumps so that issues of efficiency, range of application, and reliability can be settled.

DATA REQUIRED: Design, manufacturing, and performance qualification of prototype circulating pumps for TF coil conductor and bobbin cooling applications. Performance characteristics required include pressure (or pressure ratio) and efficiency versus flow rate for design as well as off-design inlet conditions and rotating speeds. Surge and cavitation limits must be determined. Sufficient life testing to assess reliability and required maintenance is required.

SCOPE OF TASK: Technology forcing program to develop and test prototype helium circulation pumps and pump motors for operation at 4.0 K. Different pump designs will be required for conductor and bobbin coolant.

SCHEDULE NEED/IMPACT: Design requirements for prototypes must be determined in early Title I conceptual design. Manufacturing and testing prior to Title II design.

RESOURCE REQUIREMENTS:
 design experience. Cryogenic flow laboratory.

AVAILABLE RESOURCES/PROGRAMS: Cryogenic equipment manufacturers, University Labs. Useful design data should be available from rocket engine pump development programs. Large coil program will require reduced scale equipment.

ESTIMATED COST: (For two pump designs) \$350,000. Labor: \$225,000. Prototype Manufacturing: \$100,000; Special Test Equipment \$25,000.

ALTERNATIVES: Design of refrigerators to supply the specific inlet and outlet state points required for each helium loop, with circulating pump power supplied at room temperature, or some intermediate level.

TNS RD&D ASSESSMENT

DATE: 1/27/77
 BY: R. J. Budenholzer
 ITEM: 4.4-2
 PRIORITY: 3

SYSTEM: Heat Dissipation Systems

COMPONENT: Helium Refrigeration System

TOPIC: Buffering of Peak Heat Loads

PROBLEM: Pulsed neutron and gamma heating, as well as intermittent ac electrical losses will result in unsteady heat input to the 4.0 K superconducting toroidal field coils. The rate at which these pulsed heat loads are conveyed to the helium refrigeration system will depend on the detailed design of the TF coil coolant loops, but it is clear that the resulting refrigeration load will not be constant. In order to minimize the cost of helium refrigeration apparatus, it is desirable to level these refrigeration loads in a way that introduces minimum irreversibility.

DATA REQUIRED: Design configurations, operating characteristics, and estimated cost of alternative systems to level (buffer) pulsed refrigeration loads. Proof of principle and reliability testing may be required if first-of-a-kind equipment proves desirable.

SCOPE OF TASK: Analysis of alternative schemes for thermal buffering, including an assessment of the effect of using no buffer system. Possible prototype design, and qualification testing.

SCHEDULE NEED/IMPACT: Analysis of alternatives required prior to Title II design.

RESOURCE REQUIREMENTS: Transient refrigeration load characteristics, based on TF coil analysis. Computer code for transient analysis of refrigeration system with alternative buffer arrangements.

AVAILABLE RESOURCES/PROGRAMS: University and Industrial Research Labs., Cryogenic Equipment Manufacturers.

ESTIMATED COST: \$75,000 for engineering analysis and computer time. Possible expenditures for development and testing of prototype equipment of up to \$200,000.

ALTERNATIVES: Design of oversized refrigeration systems which more closely approach the peak incident load. A ten percent increase in refrigerator capacity may cost approximately \$2,000,000.

3.4.5 Radiological Waste Systems

No serious radiological waste problems arising from the operation of TNS are anticipated, and conventional disposal methods will be employed, with the exception of the tritiated water associated with cooling the reactor vessel and the device shield. At present, there is no method available for the detritiation of large volumes of water. An R&D task has been defined to develop a solution for this problem, and also one designed to yield information concerning the affinity of tritium to other elements and compounds.

TNS RD&D ASSESSMENT

DATE: 2/3/77
 BY: H. J. Garber
 ITEM: 4.5-1
 PRIORITY: 2

SYSTEM: Radiological Waste Systems
 COMPONENT: Reactor Cell Cleanup System
 TOPIC: Tritium Retention Behavior

PROBLEM: The behavior of released tritium in combining with other elements -compounds and its isotopic kin is not well known, nor is its oxidation rate and interchange rate with water in the gas phase or on surfaces well established. Additionally, the kinetics of tritium attachment to surfaces and the subsequent release as the contiguous environment is depleted with respect to tritium is not known. This information is required to analyze and assess operational performance for such activities as decontamination, radiation monitoring, safety and environmental analysis, facility cleanup system operation.

DATA REQUIRED: Kinetics of tritium oxidation ($T + O \rightarrow$, $T + H_2O \rightarrow$) and the catalysis of these by surfaces; specific surface adsorption of T on anticipated surfaces exposed to released T; rate of pickup and subsequent release of T from surfaces; threshold values of surface adsorbed T.

SCOPE OF TASK: Collect and evaluate any pertinent information available in technical literature; devise, construct, assemble equipment required to carry out the exchange, kinetics, surface adsorption, and depletion measurements; carry out the experimental investigations, treat the results, and issue summary reports that quantify the findings.

SCHEDULE NEED/IMPACT: Information is needed very early in the program, no later than mid Title I period.

RESOURCE REQUIREMENTS: Requires glove box tritium facilities and special experimental equipment.

AVAILABLE RESOURCES/PROGRAMS: Best conducted at ERDA Lab equipped to do T work as Mound, LASL, ORNL, Sandia Livermore. Could be included as part of LASL TSTA program support.

ESTIMATED COST: Equipment ~ \$90,000, Labor and Support Services: \$290,000.
 Totals \$380,000

ALTERNATIVES: Failure to develop the indicated information will force assumptions that may be unrealistic even if in the supposedly conservative direction. This could lead to over-optimism regarding ability to cleanup-decontaminate the facility both for normal and emergency situations. The inability to predict tritium behavior adequately may tend to compromise safety and environmental aspects of TNS and future CTR devices.

TNS RD&D ASSESSMENT

DATE: 2/11/77
 BY: H. J. Garber
 ITEM: 4.5-2
 PRIORITY: 3

SYSTEM: Radiological Waste Systems

COMPONENT: Aqueous Coolants Detritiation

TOPIC: Detritiation of Reactor Vessel and Shielding Coolants

PROBLEM: Large volumes of liquids are involved for cooling the reactor vessel (demineralized water) and its shield (borated-lithiated water). Due to tritium diffusion into the former and breeding in the latter, these closed cycle fluids become contaminated, posing an ultimate disposal problem because there is currently no effective way to detritiate such streams. Fission reactor practice with such streams is to release them diluted to acceptable limits to streams, or hold them up.

DATA REQUIRED: Technology applicable to detritiation of large volume aqueous coolant streams.

SCOPE OF TASK: Restudy of previously proposed detritium schemes and development of new concepts, followed by selection of several "best" approaches, and experimental testing of these, eventually hopefully culminating in an attractive new detritiation technology.

SCHEDULE NEED/IMPACT: For Title I design

RESOURCE REQUIREMENTS: Bench scale experimental equipment requiring tritium handling capabilities.

AVAILABLE RESOURCES/PROGRAMS: Work could be performed at an ERDA facility as ORNL, Mound, LASL, Savannah River, Sandia Livermore or qualified industrial laboratories.

ESTIMATED COST: Manpower ~\$130,000, Equipment and Supplies ~\$150,000

ALTERNATIVES: Proceed on the basis of providing long term hold-up tankage or lagoons (~1,000,000 gal) for TNS, and controlled discharge eventually into streams in compliance with regulatory requirements.

3.5 INSTRUMENTATION, CONTROL AND DATA SYSTEMS

The control and data systems can be built of commercially available components. It is necessary to develop improved data handling techniques to reduce equipment size and cost, and to develop methods to define the control requirements. Operational and scientific sensors are basically similar to those used in previous tokamaks but a great deal of further development is required of those items located in or adjacent to the very high neutron flux expected from a long burn ignition machine. In many cases the large plasma size in TNS will require the development of new measurement and diagnostics techniques. A major new requirement imposed on all instruments located within the reactor cell will be the need to remotely calibrate sensors periodically and verify that they are operational.

In order to design a plasma control system it is necessary to first establish precisely the requirements through simulation and analysis of the expected behavior of the plasma and definition of the requirements on the control elements (coils). This will be part of the PF power conversion system development (see "Computer Simulation of PF System Including the Plasma, ITEM 2.2.1-2). The control element requirements may define development of extremely large dc amplifiers to drive the coils.

The total number of instrumentation channels will be large, many will require relatively high frequency (~ 1 k hz), and most will need to be monitored for 30 seconds. Development of an integrated hardware/software system and data compression techniques should be undertaken to minimize cost, complexity, and failure rate.

TNS RD&D ASSESSMENT

DATE: 2/5/77
 BY: T. F. Yang, J. Schultz,
H. R. Howland
 ITEM: 5.1.1-1
 PRIORITY: 1

SYSTEM: Plasma Control System

COMPONENT: Plasma Position Control

TOPIC: Theoretical Modeling and Experimental Testing of Feedback
Stabilization

PROBLEM: High β elongated plasmas have not been achieved in the laboratory and are theoretically known not to be stable with respect to the axisymmetric MHD modes (vertical and horizontal displacement). The time scale of these instabilities are not known and experimental verification does not exist for the plasma position feedback control design of TNS.

DATA REQUIRED: Rise time of the axisymmetric MHD instabilities. Response characteristics of sensors. Time response of experimental plasmas to control currents.

SCOPE OF TASK: Completion of detailed 2D instability calculations to estimate the rise time of the axisymmetric instabilities. Modeling feedback stabilization methods and carrying out 2D time dependent MHD simulation. Performance of feedback position control experiments on the major tokamak facilities by creating unstable high β and elongated plasma.

SCHEDULE NEED/IMPACT: Develop analytical and experimental basis by the end of Title I design.

RESOURCE REQUIREMENTS: Tokamaks with capability of changing plasma configurations, on line computer, high response power supply, diagnostics.

AVAILABLE RESOURCES/PROGRAMS: 1) Experimental programs: ORMAK-U, PDX, ALCATOR, DOUBLET; 2) Princeton 2D, ΔW MHD stability code, PEST; 3) Princeton 2D time dependent MHD code (in development); 4) ORNL, PPPL, SAI, GA time dependent transport code; 5) EPRI-DRAPER tokamak control simulator.

ESTIMATED COST: Code development, \$1M; Numerical simulations on major tokamaks, \$200 K; Experimental study, \$500 K.

ALTERNATIVES: Rely on existing calculations and experimental data and conservatively design an axisymmetric stable tokamak.

TNS RD&D ASSESSMENT

DATE: 2/4/77
 BY: T. F. Yang
 ITEM: 5.1.1-2
 PRIORITY: 2

SYSTEM: Plasma Control System

COMPONENT: Plasma

TOPIC: Plasma Density and Temperature Feedback Control

PROBLEM: In an ignition tokamak, the D-T will burn and the plasma density will decrease. The temperature will also decrease via radiation and particle transport. The fueling rate and heating rate have to be monitored and adjusted to maintain a constant plasma density. Instabilities in density and temperature can arise if the fueling and heating rates are not feedback controlled. Information on related phenomena is needed for designing the pertinent components for achieving the steady state operation of TNS.

DATA REQUIRED: Information on transport phenomena associated with fueling and heating during burning. Time scale of the density and temperature fluctuations and the rates of fueling and heating required to prevent quenching or runaway.

SCOPE OF TASK: To carry out the detailed time dependent transport analysis of ignition tokamaks by incorporating fueling and heating mechanisms. Modeling various feedback control methods to stabilize the density and temperature. Carrying out simulation experiments on TFTR.

SCHEDULE NEED/IMPACT: Analytical information required by end of conceptual design. Experimental data required by the end of Title II. TFTR generated data required by 1984.

RESOURCE REQUIREMENTS: D-T tokamak (TFTR). Time dependent transport code with fueling and heating models. Diagnostics. Neutral beam and/or pellet injector.

AVAILABLE RESOURCES/PROGRAMS:

1. Experimental programs: TFTR device.
2. ORNL pellet fueling, theoretical and experimental work.
3. ORNL and Wisconsin time dependent transport codes.

ESTIMATED COST: Simulated Experiments, \$300 K; Numerical Simulation, \$200 K.

ALTERNATIVES: Experimenting with various fueling and heating feedback control methods during initial TNS operation with the risk of not having provided sufficient device capability in this area.

TNS RD&D ASSESSMENT

DATE: 2/9/77

BY: H. J. Garber

ITEM: 5.1.2-1

PRIORITY: 3

SYSTEM: Process Control System

COMPONENT: Multipurpose Tritium Analyzer

TOPIC: Development and Test of Multipurpose Tritium Analyzer

PROBLEM: For both process control in the fuel handling system and working area monitoring there is a requirement for a high precision, fast response, memory-free, tritium-form-discriminating, rugged, continuous readout, tritium monitor-analyzer with capability of being incorporated into an instrumentation network to control and regulate/modulate operation of fuel processing equipment (on gas and liquid streams). Such a versatile piece of equipment is not on hand as a commercially available or experimental item.

DATA REQUIRED: The instrument must be capable of determining the tritium content of a flowing stream covering a high concentration range (10^{-6} to 1 atom ratio), and discriminating between the tritium forms (e.g., T₂, HT, HD, TD, HTO, T₂O), and be essentially non-affected by the presence of a radiation or magnetic field. Additionally, the signal generated must be amenable to incorporation into a feedback loop for control instrumentation.

SCOPE OF TASK: Involves sorting of potential approaches, testing and selecting the best of these by bread-boarding type of approaches, design and preliminary proof testing of prototype instruments, construction of several prototype instrument packages, followed by performance reliability - compliance testing - acceptance testing at near-service conditions in a tritium demonstration loop at TSTA (LASL).

SCHEDULE NEED/IMPACT: Instrument feasibility verification - beginning of Title II.
Prototype test - end of Title II.

RESOURCE REQUIREMENTS: Requires services of an instrument development team with experience in tritium monitoring problems, and various spectra analysis techniques (magnetic and radiation).

AVAILABLE RESOURCES/PROGRAMS: Several instrument specialties labs (as ORNL, Sandia, LLL) or commercial firms could perform final testing; can be accomplished at LASL in conjunction with Tritium Test Lab Program or Mound (to control cryodistillation system).

ESTIMATED COST: For equipment ~\$ 60,000; Labor: \$350,000.

ALTERNATIVES: In absence of availability will have to utilize best current, but inadequate, devices and accept consequences of inadequacies of these. This means that the fueling of the system may be coarse rather than "fine-tuned"

TNS RD&D ASSESSMENT

DATE: 2/10/77

BY: G. S. Smeltzer

ITEM: 5.1.2-2

PRIORITY: 3

SYSTEM: Process Control System

COMPONENT: Sensors

TOPIC: Development of System to Remotely Check and/or Calibrate Sensors

PROBLEM: Some sensors will be in areas where they cannot be directly calibrated or checked because of high radiation levels. Therefore, there must be a way to remotely check and calibrate these sensors. Examples of these sensors are ionization gauges, Rogowski Coils and B_0 Loops, Charge Particle Probes, and Diapmagnetic Loops.

DATA REQUIRED: Methods, procedures and/or devices and circuits which will permit calibration and checking in situ.

SCOPE OF TASK: Develop system to remotely check and/or calibrate each type of sensor. Verify each design by building and testing a prototype unit.

SCHEDULE NEED/IMPACT: End of Title II

RESOURCE REQUIREMENTS: Industrial manufacturing laboratory, government laboratories.

AVAILABLE RESOURCES/PROGRAMS: ERDA Laboratories, industrial firms with aerospace and fission reactor experience, TNS design team.

ESTIMATE COST: \$200 K

ALTERNATIVES: Use duplicate sensors. Remove sensor for calibration by remote manipulators.

TNS RD&D ASSESSMENT

DATE: 2/11/77

BY: G. S. Smeltzer

ITEM: 5.1.2-3

PRIORITY: 3

SYSTEM: Process Control System

COMPONENT: Sensors

TOPIC: Testing of Sensors Under Tokamak Environmental Conditions

PROBLEM: The sensors near the tokamak will be subjected to heat, cold, magnetic flux, radiation, vacuum, etc. These conditions can damage the sensors and/or affect their accuracy. The environmental conditions will vary with sensor location which will have to be taken into account when testing the sensors.

Examples of these sensors are ionization gauges, Rogowski Coils and B_0 Loops, Charge Particle Probes, and Diamagnetic Loops.

DATA REQUIRED: Sensor output accuracy as a function of environmental parameters such as magnetic flux, radiation, vacuum, etc. Where necessary determine required magnetic shields, heat shields, etc.

SCOPE OF TASK: Environmental tests should be performed on the sensor to determine: (1) What will damage the sensor? (2) How the sensor can be protected? (3) What affects the accuracy of the sensor? Where a sensor is being developed, this should be part of that program. (See separate sensor items)

SCHEDULE NEED/IMPACT: End of Title I

RESOURCE REQUIREMENTS: Laboratory which can test sensors under environmental conditions.

AVAILABLE RESOURCES/PROGRAMS: TFTR sensor systems, Industry and ERDA laboratories.

ESTIMATED COST: \$200 K

ALTERNATIVES: Have retrofit program where inaccuracy of sensors is not acceptable. Periodically replace sensor, that are gradually degraded.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: Heck/Schultz
 ITEM: 5.1.4-1
 PRIORITY: 3

SYSTEM: Data Handling System

COMPONENT: Software

TOPIC: Development of Data Compression Techniques

PROBLEM: The number of instrumentation devices required for TNS will be at least as great as the number required for TFTR. Since the planned length of each experiment is 30 times as great, the total mass of data values per experiment will be at least 30 times as great as for TFTR. Hence, using techniques which may be developed to compress the data for TFTR will still require much more high speed computer memory and much more sophisticated permanent record files. In order to minimize the capital cost impact and to minimize the loss in reliability associated with a larger computer system, further development of data compression techniques should be undertaken.

DATA REQUIRED: Improved methods of high speed on-line data compression, and improved methods of off-line (between experiments) compression, editing, and conversion for immediate use and permanent storage. Verified set of tests of these methods on prototypical hardware.

SCOPE OF TASK: Method and software development and testing on currently available hardware.

SCHEDULE NEED/IMPACT: Need preliminary results by the end of Title I with final verification by the end of Title II.

RESOURCE REQUIREMENTS: 5 scientist/programmer years, large computer facility

AVAILABLE RESOURCES/PROGRAMS: TFTR design experience relevant. Industrial software vendors. National Laboratories with major software development capability.

ESTIMATED COST: \$400,000

ALTERNATIVES: Much more expensive data-handling system.

TNS RD&D ASSESSMENT

DATE: 2/10/77
BY: John E. Faulkner
ITEM: 5.2-1
PRIORITY: 2

SYSTEM: Operational Instrumentation Systems

COMPONENT: Microwave Corner Reflector Array

TOPIC: Qualification of remotely-replaceable microwave corner reflector array

PROBLEM: Microwave beams are transmitted across plasmas to measure the line integral of electron density. Such information is needed prior to initiating the OH pulse so as to assure good energy transfer to the plasma. Microwave beams that traverse the TNS plasma near the equatorial plane will be refracted if the plasma is not symmetrical about this plane. Such refraction may cause the microwave beam to miss a receiving antenna on the far side of the plasma. A corner reflector array will intercept the beam, regardless of refraction, and send it back to the transmitting antenna. The problem is to develop a corner reflector array that is suitable for TNS and that can be replaced remotely, if it is damaged by the plasma. Nuclear heating may be a problem with the corner reflector.

DATA REQUIRED: This development effort is required to assure that there will be a working method for measuring electron density prior to firing the OH coil. Verification and qualification of the corner reflector array is required.

SCOPE OF TASK: Design hardware, fabricate a prototype, and test. Hardware design will account for nuclear heating and potential damaging effects of the plasma. Hardware design will include hardware required to replace the corner reflector array using remote maintenance equipment.

SCHEDULE NEED/IMPACT: A tested design is needed for the corner reflector array prior to the start of Title II. Failure to meet this date could cause substantial rework of TNS design.

RESOURCE REQUIREMENTS: A microwave laboratory, a machine shop, TNS remote maintenance equipment, and a large mock-up space are needed for this program.

AVAILABLE RESOURCES/PROGRAMS: Industry and government laboratories have the resources required with the exception of the TNS remote maintenance equipment. Remote maintenance equipment must be provided, but is not funded by this program. TFTR may use a microwave corner reflector array. If so, that design will be upgraded to account for the higher D-T power density expected in TNS.

ESTIMATED COST: Labor ~ \$80,000, Materials: \$30,000, Total: \$110,000.

ALTERNATIVES: If the corner reflector array cannot be used, it may be possible to use an array of receiving antennas. These will require development work to protect them from nuclear and plasma heating and to provide replaceable waveguides to the receiving antennas. This alternative will have an impact on TNS vessel and shield design.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: John E. Faulkner
 ITEM: 5.2-2
 PRIORITY: 3

SYSTEM: Operational Instrumentation Systems

COMPONENT: Microwave Windows

TOPIC: Transparency degradation of microwave windows

PROBLEM: Microwave beams are transmitted across plasmas to measure the line integral of electron density. Such information is needed to monitor the initiation and build-up of the plasma. Ceramic windows that are used to transmit the microwaves through the vacuum vessel wall are not expected to remain transparent at the expected neutron fluence (about $8 \times 10^{19} \text{ n cm}^{-2}$). Metallic atoms deposited from the plasma will also reduce the transparency of the windows.

DATA REQUIRED: Development, verification, and qualification of microwave windows are required in terms of design and remote handling capability. This effort is required to assure that there will be a method for measuring electron density throughout the life of TNS.

SCOPE OF TASK: Design hardware which will shield window from the plasma when the window is not in use (a remotely activated shutter). Design window and antenna port which is replaceable remotely. Design hardware to interface between port hardware and remote maintenance equipment. Fabricate a prototype and test, using remote maintenance equipment.

SCHEDULE NEED/IMPACT: A tested design is needed prior to the beginning of Title II work. Failure to meet this schedule may cause rework of design drawings for TNS.

RESOURCE REQUIREMENTS: A machine shop, TNS remote maintenance equipment, and a large mock-up space are required.

AVAILABLE RESOURCES/PROGRAMS: Industry and government laboratories have the resources required with the exception of the TNS remote maintenance equipment. Remote maintenance equipment must be provided but is not funded by this program. If remotely replaceable microwave windows are developed for TFTR, that design will be upgraded to meet the more severe environment anticipated in TNS.

ESTIMATED COST: Labor: \$85,000, Equipment: \$20,000, Total: \$105,000.

ALTERNATIVES: Electron density measurements are vital in the operation of tokamaks because they indicate when the preignition ionization level is high enough to permit good coupling of the OH pulse to the plasma. Alternatives would be (1) to omit microwave interferometry which would leave the operator flying blind or (2) to go with an untested, unqualified design at high risk.

TNS RD&D ASSESSMENT

DATE: 2/10/77

BY: John E. Faulkner

ITEM: 5.2-3

PRIORITY: 3

SYSTEM: Operational Instrumentation Systems

COMPONENT: X-Ray Diagnostics

TOPIC: Development of x-ray measuring techniques for determining the TNS electron temperatures

PROBLEM: X-ray measurement systems will be used on TNS to obtain information on electron temperature and plasma motions. These systems will be extrapolations of technology existing at the time of design. The problems will be associated with adapting the technology to the TNS geometry and environment. Nuclear and magnetic shielding will be required. Remote maintenance will be required.

DATA REQUIRED: Development, verification, and qualification of the x-ray systems are required in terms of design and remote handling capability. This effort is required to assume that there will be a capability for measuring electron temperature and plasma position, throughout the life of TNS.

SCOPE OF TASK: Design hardware, fabricate prototypes, and test. Hardware design must include tools to interface between x-ray system components and remote maintenance manipulators. Vertical and horizontal scan capability shall be included in the designs. Design shall include consideration of radiation leakage problems, radiation shielding, and magnetic shielding.

SCHEDULE NEED/IMPACT: Tested design of interfaces with TNS shield and vacuum vessel needed by the beginning of Title II work. Design of actual x-ray measurement systems needed at the beginning of Title III work. Failure to meet this schedule could result in redesign of TNS.

RESOURCE REQUIREMENTS: An x-ray instrument development laboratory, a machine shop, and a large mock-up space are required.

AVAILABLE RESOURCES/PROGRAMS: Industry and government laboratories have the required resources. X-ray diagnostic tools are being used and are being improved at major plasma physics laboratories. If TFTR is designed for D-T operation, then the designs of their x-ray systems can be upgraded to the more severe TNS conditions.

ESTIMATED COST: Labor, equipment and services: \$900,000.

ALTERNATIVES: Electron temperature measurements are vital to monitoring the operation of TNS. An alternative would be Thompson scattering measurements, but such measurements are believed to be more difficult than x-ray measurements of temperature at the TNS power level. Plasma motion can be monitored with B_θ coils; the x-ray measurement will give an independent source of information. If this program is not done, then instruments of untested design would be used. The designs might be incompatible with TNS and cause design and construction modifications.

TNS RD&D ASSESSMENT

DATE: 2/10/77
BY: John E. Faulkner
ITEM: 5.2-4
PRIORITY: 3

SYSTEM: Operational Instrumentation Systems

COMPONENT: Horizontal Microwave Interferometers

TOPIC: Development of microwave interferometer designs for TNS

PROBLEM: These diagnostic tools measure the integral of the product of plasma density and path length. They are necessary for determining plasma density prior to firing the OH system and prior to injecting neutral beams. The microwave interferometers must be tailored to the geometry of TNS. Testing will be required before TNS operations begin to be sure that the interferometer designs will work. Remote maintenance will be required. Nuclear heating of microwave antennas may be a problem.

DATA REQUIRED: Performance parameter measurements, hardware design verification, and qualification for remote handling.

SCOPE OF TASK: Design hardware, fabricate prototypes and test. Hardware design will include provisions for remote maintenance including replacement of parts. Tools required for interfacing between interferometer components and remote maintenance manipulators are included in this task.

SCHEDULE NEED/IMPACT: Design verification is required during Title II by the time when detailed designs are completed for the vacuum vessel and the device shield. The interferometers must be integrated into the vessel and shield designs.

RESOURCE REQUIREMENTS: A microwave laboratory, a machine shop, TNS remote maintenance equipment, and a large mock-up space are needed.

AVAILABLE RESOURCES/PROGRAMS: Major plasma physics laboratories have the required resources with the exception of the TNS maintenance manipulators. Manipulators are not funded by this task. Designs of interferometers used on TFTR will provide a basis for the TNS interferometers which must be designed for a higher electron line densities and for a more intense nuclear environment.

ESTIMATED COST: Labor, equipment and services: \$500,000.

ALTERNATIVES: One alternative would be to not do this task and go with an untested design. This could result in rework of the interferometer design and delay of TNS operations. No technological alternatives are available.

TNS RD&D ASSESSMENT

DATE: 2/10/77

BY: John E. Faulkner

ITEM: 5.2-5

PRIORITY: 3

SYSTEM: Operational Instrumentation Systems

COMPONENT: Rogowsky Loops

TOPIC: Qualification of replaceable Rogowsky loops

PROBLEM: Rogowsky loops measure the change in the poloidal magnetic field caused by changes in the current flowing in the plasma. Such measurements are important in monitoring the operation of tokamaks. Insulators used on the coil wire, in the coil form, and in the coil support structure are not expected to function satisfactorily for the full TNS neutron fluence (about $8 \times 10^{19} \text{ n cm}^{-2}$). Consequently, the loops should be replaceable.

DATA REQUIRED: Verification and qualification of remotely replaceable hardware for Rogowsky loops.

SCOPE OF TASK: Design hardware for the Rogowsky loops so that they may be replaced remotely. Fabricate a prototype and test using remote maintenance manipulators. Hardware design must include tools for interfacing between the remote maintenance manipulator and the Rogowsky loop.

SCHEDULE NEED/IMPACT: A tested design is needed by the end of Title I, when detailed design starts on tokamak systems. Delay may cause rework of TNS drawings.

RESOURCE REQUIREMENTS: A large mock-up space, a partial mock-up of TNS, and a TNS remote maintenance manipulator are needed. The latter two items are not funded under this task.

AVAILABLE RESOURCES/PROGRAMS: Industry and government laboratories can provide the required resources.

ESTIMATED COST: Labor, equipment and services: \$85,000.

ALTERNATIVES: An alternative would be to find an insulating material that can withstand the anticipated radiation dose without degrading the mechanical or electrical performance below acceptable levels. Some insulators, e.g., silicate impregnated mica or glass fiber, are satisfactory from a mechanical point of view. RD & D ITEM 1.6-2 (testing of thermal and electrical insulating materials) is directed toward finding suitable insulating materials.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: John E. Faulkner
 ITEM: 5.2-6
 PRIORITY: 3

SYSTEM: Operational Instrumentation Systems

COMPONENT: B_θ Coils

TOPIC: Qualification of replaceable B_θ coils

PROBLEM: B_θ coils are small electrical coils that are distributed around the minor circumference of the vacuum vessel; they are sensitive to changes in the local poloidal magnetic field created by the plasma current. Comparison of the integrated output of the coils provides information on the center of current flow in the plasma. Insulation used on the coil wires and in the coil support structure is not expected to function satisfactorily for the full TNS neutron fluence (about 8×10^{19} n cm⁻²). Consequently the coils should be replaceable.

DATA REQUIRED: Verification and qualification of remotely replaceable hardware for B_θ coils.

SCOPE OF TASK: Design hardware for B_θ coils so that they may be replaced remotely. Fabricate a prototype and test using a TNS remote maintenance manipulator. Hardware design must include tools for interfacing between the B_θ coil structure and the remote maintenance manipulator.

SCHEDULE NEED/IMPACT: A tested design is needed by the end of Title I, when detailed design begins on tokamak systems. Delay may cause rework of TNS drawings.

RESOURCE REQUIREMENTS: A large mock-up space, a partial mock-up of TNS, and a TNS remote maintenance manipulator are needed. The latter two items are not funded by this task.

AVAILABLE RESOURCES/PROGRAMS: Industry and government laboratories can provide the required resources.

ESTIMATED COST: Labor, equipment and services: \$85,000.

ALTERNATIVES: One alternative is to use x-ray scans of the plasma to provide information on the plasma position; this technique does not work well at low electron temperatures such as are encountered in plasma build-up. A second alternative is to find an insulating material that can withstand the anticipated radiation dose; some insulators, e.g., silicate impregnated mica or glass fiber will withstand the dose without mechanical damage. RD & D ITEM 1.6-2 (testing of thermal and electrical insulating materials) is directed toward finding suitable insulating materials.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: John E. Faulkner
 ITEM: 5.2-7
 PRIORITY: 3

SYSTEM: Operational Instrumentation Systems

COMPONENT: Single Turn Voltage Loops

TOPIC: Qualification of remote disassembly of voltage loops

PROBLEM: Single turn voltage loops encircle the vacuum vessel in the toroidal direction. They monitor the changes in magnetic flux through the surface that is bounded by the plasma. Thus, the operation of the OH system can be monitored. Disassembly of TNS (removal of a sector) will require disengagement of the voltage loops; this is one problem. A second problem is that the insulators that support the voltage loops are not expected to survive the anticipated neutron fluence ($8 \times 10^{19} \text{ n cm}^{-2}$). Consequently, voltage loops are required that can be disconnected and replaced remotely.

DATA REQUIRED: Verification and qualification of single-turn-voltage-loop hardware that permits disassembly of TNS and that is remotely replaceable.

SCOPE OF TASK: Design voltage loop hardware which is consistent with remote disassembly of TNS and which can be replaced remotely prior to the onset of radiation damage effects. Fabricate a prototype and test using remote maintenance manipulator. Hardware design must include tools for interfacing between the loop structure and the remote maintenance manipulator.

SCHEDULE NEED/IMPACT: A tested design is needed by the end of Title I, when detailed design begins on tokamak systems. Delay may cause significant rework of TNS design drawings.

RESOURCE REQUIREMENTS: A large mock-up space, a partial mock-up of TNS, and TNS remote maintenance equipment are needed. The latter two items are not funded by this task.

AVAILABLE RESOURCES/PROGRAMS: Industry and government laboratories can provide the required resources.

ESTIMATED COST: Labor, equipment and services: \$190,000.

ALTERNATIVES: (1) One could consider eliminating the voltage loops; the result would be loss of information on the voltage that is being impressed on the plasma. (2) Remote replacement of the loops might be avoided if an insulating material can be found that can withstand the anticipated radiation dose. However, this would only solve the second problem; the first problem, the requirement for a tested design that is consistent with disassembly of TNS remains. RD & D ITEM 1.6-2 (testing of thermal and electrical insulating materials) is directed toward insulating materials.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: John E. Faulkner
 ITEM: 5.2-8
 PRIORITY: 3

SYSTEM: Operational Instrumentation Systems

COMPONENT: Neutron Fluence Monitor

TOPIC: Hardware development for neutron fluence monitor

PROBLEM: A neutron fluence monitor is needed just outside the vacuum vessel for two reasons: first, to monitor the fluence of 14 MeV neutrons out of the plasma and thus provide an absolute measurement of the integrated energy developed by D-T processes in the plasma; and second, to monitor the integrated radiation dose that has been delivered to TNS components in this region of maximum dose. The problem is to develop a monitor that provides this information for TNS.

DATA REQUIRED: Verification and qualification of hardware that provides information on neutron fluence for single pulses and for all pulses over the surface of the vacuum vessel.

SCOPE OF TASK: Design hardware which placed and retrieved remotely considering neutron activated foils and/or wires. The positions for irradiation shall be such as to give information on the toroidal and poloidal distribution of neutron fluence over the surface of the vacuum vessel. Fabricate a prototype and test. Hardware must be maintainable remotely.

SCHEDULE NEED/IMPACT: A tested design is needed by the end of Title I when detailed design begins on tokamak systems. Delay could cause rework of design drawings.

RESOURCE REQUIREMENTS: A large mock-up space, a partial mock-up of TNS and TNS remote maintenance equipment are needed. The latter two items are not funded by this task.

AVAILABLE RESOURCES/PROGRAMS: Industry and government laboratories can provide the required resources. If TFTR is designed for significant D-T operation, and if a neutron fluence monitor is developed which monitors the fluence at the vacuum vessel, then that design can be upgraded to the more severe TNS conditions.

ESTIMATED COST: Labor, equipment and services: \$100,000.

ALTERNATIVES: Don't monitor neutron fluence and dose at the outside of the vacuum vessel. This eliminates a direct measurement of the D-T fusion energy developed in the plasma. Under this alternative, components that are expected to suffer radiation damage would be replaced either when they show signs of damage or when a theoretical estimate indicates that it is time for replacement.

TNS RD&D ASSESSMENT

DATE: 2/10/77

BY: John E. Faulkner

ITEM: 5.3-1

PRIORITY: 3

SYSTEM: Scientific Instrumentation

COMPONENT: Vessel Windows For Visible Light And Infrared Radiation

TOPIC: Development of vessel windows for visible light and infrared radiation

PROBLEM: Many instruments used in plasma diagnostics require a viewing window in the wall of the TNS vacuum vessel. These windows have two problems: first, they lose transparency because of vapor deposition from the plasma; and second, they are darkened by nuclear radiation. TNS window designs must be developed which provide moveable shutters and which allow remote replacement of windows that have lost their transparency.

DATA REQUIRED: Verification and qualification of designs for TNS window/shutter assemblies are required. Designs must allow for remote maintenance and remote replacement.

SCOPE OF TASK: Design hardware, fabricate and test a prototype of each size window. Hardware design includes tools for remote maintenance and remote replacement; these tools interface between the windows and the remote maintenance equipment.

SCHEDULE NEED/IMPACT: Tested designs are needed by the end of Title I, when detailed design will begin on tokamak systems. Delay could cause rework of design drawings.

RESOURCE REQUIREMENTS: A large mock-up space, a partial mock-up of TNS, and TNS remote maintenance equipment are needed. The latter two items are not funded by this task.

AVAILABLE RESOURCES/PROGRAMS: Industry and government laboratories can provide the required resources. If TFTR windows are designed for remote replacement, those designs can serve as the foundation for this task.

ESTIMATED COST: Labor: \$60,000, Equipment: \$30,000, Total: \$90,000.

ALTERNATIVES: Some windows are required and these windows must be remotely replaceable. Therefore, it is not obvious that there are any alternatives to this task.

TNS RD&D ASSESSMENTDATE: 2/10/77BY: John E. FaulknerITEM: 5.3-2PRIORITY: 4SYSTEM: Scientific InstrumentationCOMPONENT: Ion Temperature Diagnostic ApparatusTOPIC: Develop instrument to measure ion temperature

PROBLEM: Ion temperature is one of the most important parameters involved in nuclear fusion in a plasma. Hence, there is great interest in being able to measure ion temperature. The techniques currently in use, charge exchange particle spectrometers, work with plasmas with small minor diameters. When used with large plasmas, the ion temperatures that are measured will be heavily weighted toward the surface of the plasma. A technique is needed which will give ion temperature as a function of minor radius in the plasma.

DATA REQUIRED: Development, verification, and qualification of a technique for measuring ion temperature as a function of radial position in TNS.

SCOPE OF TASK: Develop a new technique for measuring ion temperature as a function of radial position. Design, fabricate, and test hardware involved in this technique.

SCHEDULE NEED/IMPACT: This instrument is not required for design of This is a plasma research tool, and if it can be developed, then the working instrument package must be available by the time of final assembly of TNS, i.e., by the end of Title III.

RESOURCE REQUIREMENTS: A fully equipped plasma physics laboratory.

AVAILABLE RESOURCES/PROGRAMS: Major plasma physics laboratories are aware of this problem. Some effort will go into the problem for TFTR. If an ion temperature measuring instrument is developed for TFTR it may be possible to adapt it to the larger TNS.

ESTIMATED COST: Labor, equipment and services: \$2,000,000.

ALTERNATIVES: An alternative is to delete direct measurements of ion temperatures. In this case, neutron production could be used as a measure of the combined effects of ion density and ion temperature averaged over the plasma. This would not be helpful for hydrogen plasmas.

TNS RD&D ASSESSMENT

DATE: 2/10/77

BY: John E. Faulkner

ITEM: 5.3-3

PRIORITY: 4

SYSTEM: Scientific Instrumentation

COMPONENT: Diagnostic Apparatus For Measuring Z_{eff}

TOPIC: Develop instrument to measure Z_{eff} , effective ion charge

PROBLEM: Impurities increase the effective charge, Z_{eff} , in a plasma, and cause unwanted energy losses from the plasma. Consequently, measurements of Z_{eff} as a function of position in the plasma are wanted. Techniques do not exist for such measurements in a TNS size plasma.

DATA REQUIRED: Development, verification, and qualification of a technique for directly measuring Z_{eff} as a function of radial position in a plasma.

SCOPE OF TASK: Develop a technique for measuring Z_{eff} as a function of position in TNS size plasmas. This is a research and development program. Design, fabricate, and test hardware needed for measurement.

SCHEDULE NEED/IMPACT: This instrument is not required for the design or operation of TNS. However, it is potentially important as a research tool. If an instrument can be developed, then the working instrument package must be available by the time of final assembly of TNS, i.e., by the end of Title III.

RESOURCE REQUIREMENTS: A fully equipped plasma physics laboratory.

AVAILABLE RESOURCES/PROGRAMS: Major plasma physics laboratories, which are supported by government funds, are available. Instruments being developed for TFTR may solve this problem; if so, the instruments may be extrapolated to TNS operating conditions.

ESTIMATED COST: Labor, equipment and services: \$3,000,000.

ALTERNATIVES: Delete measurements of Z_{eff} .

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: John E. Faulkner
 ITEM: 5.3-4
 PRIORITY: 4

SYSTEM: Scientific Instrumentation

COMPONENT: Support and Insulation for Diamagnetic Loop

TOPIC: Qualification of a remotely-replaceable diamagnetic loop

PROBLEM: Diamagnetic loops are used to measure plasma pressure. The measurement is difficult because the instrument is sensitive to relative motions between the loop and the tokamak structure. The loop goes around the minor circumference of the vacuum vessel and thus is in a high radiation field. Consequently, radiation damage may affect the operation of the loop ($8 \times 10^{19} \text{ n.cm}^{-2}$ expected). A well-supported, remotely-replaceable diamagnetic loop is needed to solve these two problems.

DATA REQUIRED: Verification and qualification of replaceable hardware for a diamagnetic loop.

SCOPE OF TASK: Design hardware for a replaceable diamagnetic loop. Fabricate a prototype and test. Hardware design shall include components needed to interface between diamagnetic loop and remote maintenance machine.

SCHEDULE NEED/IMPACT: This is a plasma research tool that is not required for operation of TNS. If a diamagnetic loop is to be used, the tested design is needed at the beginning of Title II work, detailed design of tokamak components. Delay could cause some revision of design drawings.

RESOURCE REQUIREMENTS: A large mock-up space, a partial mock-up of TNS, and TNS remote maintenance equipment are needed. The latter two items are not funded by this task.

AVAILABLE RESOURCES/PROGRAMS: Industry and government laboratories can provide the required resources.

ESTIMATED COST: Labor, equipment and services: \$60,000.

ALTERNATIVES: An alternative is to delete diamagnetic loops as diagnostic tools for TNS. A second alternative would be to find an insulating material that can withstand the expected neutron fluence. Then the loop would not have to be replaceable. RD & D ITEM 1.6-2 (testing of thermal and electrical insulating materials) is directed toward finding radiation resistant insulating materials.

TNS RD&D ASSESSMENTDATE: 2/10/77BY: John E. FaulknerITEM: 5.3-5PRIORITY: 4SYSTEM: Scientific InstrumentationCOMPONENT: Multichannel Laser Interferometer For Electron Density MeasurementsTOPIC: Development of a short (<1 mm) wavelength multichannel laser interferometer

PROBLEM: Multichannel interferometers are used to measure electron line density as a function of position in a plasma. Microwave interferometers will not be useful for these off-axis measurements in TNS because of severe refraction effects. A much shorter wavelength than that available from microwave generators (down to 1 mm), is needed. A multichannel laser interferometer (wavelength much less than 1 mm) must be developed to solve this problem.

DATA REQUIRED: Development, verification, and qualification of a short wavelength, multichannel interferometer.

SCOPE OF TASK: Research and development work are required on short wavelength (compared to 1 mm) high intensity radiation sources, transmission paths, windows, and detectors. Following such R & D work, a multichannel interferometer must be designed, fabricated, and tested.

SCHEDULE NEED/IMPACT: This is a plasma research tool and is not required for operation of TNS. However, it would provide valuable information on the plasma. If such a tool is to be used, it should be available by the end of Title III, completion of final assembly of TNS.

RESOURCE REQUIREMENTS: A laboratory equipped for both laser instrument development and plasma research is required initially. Ultimately a partial mock-up of TNS will be required.

AVAILABLE RESOURCES/PROGRAMS: Major plasma physics laboratories have the required resources. PPPL is working on development of an HCN laser (337 μm) and interferometer.

ESTIMATED COST: Labor, equipment and services: \$2,000,000.

ALTERNATIVES: Delete measurements of electron line density as a function of distance from the plasma centerline.

TNS RD&D ASSESSMENT

DATE: 2/4/77
BY: T. F. Yang
ITEM: 5.3-6
PRIORITY: 4

SYSTEM: Scientific Instrumentation

COMPONENT:

TOPIC: Synchrotron radiation as diagnostic tool

PROBLEM: Latest experimental results from PLT, ORMAK, TFR have demonstrated that the measurement of synchrotron radiation is a useful tool. It can be developed, and will be needed as an additional diagnostic tool and even as a sensor for a plasma control system for TNS operation where internal magnetic loops may be found to be inapplicable.

DATA REQUIRED: High resolution and reliability synchrotron radiation detecting and analyzing instruments.

SCOPE OF TASK: Design high resolution synchrotron analyzer or interferometer. Measure synchrotron radiation from high temperature and density plasmas on an operating tokamak. Observe plasma motion.

SCHEDULE/IMPACT: By the end of TNS conceptual design. Will affect the TNS control system design and consolidate TNS diagnostic capability.

RESOURCE REQUIREMENTS: Large tokamaks, interferometers or analyzers.

AVAILABLE RESOURCES/PROGRAMS: 1) ORMAK-U, PLT, TFTR. 2) Synchrotron radiation experimental group of the University of Maryland, ORNL, PPPL.

ESTIMATED COST: Personnel and equipments for carrying out the experiments - 400 K.

ALTERNATIVES: Use of Thompson scattering, X-ray measurement, magnetic loops if they can be made operable.

3.6 SUPPORT FACILITIES

The support facilities required for TNS can be constructed based on known technologies developed primarily for the fission reactor plants. Tritium containment will present some new problems related to sealing of penetrations and openings. None of these are expected to present insurmountable problems and should be resolved with relatively simple development programs.

Other systems which are likely to have a significant impact on the configuration of the test cell are the remote maintenance system and the various device support systems. It will be necessary to make an early selection of an overall approach to the maintenance system. For instance, if the device is segmented additional space would be required to allow the segments to be retracted to a work position. A different approach, such as splitting the device in half, could completely change the layout of the test cell.

The remote maintenance handling equipment becomes an integral part of the test cell. Overhead cranes, side wall cranes, manipulators, transfer-systems, hot cells and viewing systems must be integrated into the planning and layout of the test cell. Early determination of capacity, interface requirements and location of the equipment will eliminate expensive rework and delays later in the program. The remote maintenance RD&D problems are discussed in Section 3.4.1.

Many of the support systems for the device must be strategically located to reduce losses and in many cases make it possible for the system to function properly. Examples would be neutral beam power supplies, control and diagnostic, instrumentation, vacuum pumping systems, the tritium handling system and the various coolant systems. Each of these systems has several interfaces with the test cell which are very often competing for the same space. In order to allow for proper design of the test cell and the support systems space allocations must be made during the facility conceptual design phase. The Tokamak support system RD&D efforts are discussed in Section 3.4.

Several options relative to the vacuum topology are also being considered. They include

individual dewars for the superconducting coils, secondary vacuum enclosures and evacuation of the entire reactor cell. Each of these options has significant impact on the design and possibly the size of the test cell. Again an early decision is needed if the facilities design is going to proceed on schedule.

TNS RD&D ASSESSMENT

DATE: 2/7/77
 BY: M. Sniderman
 ITEM: 6.0-1
 PRIORITY: 3

SYSTEM: Support Facilities

COMPONENT: Reactor Cell

TOPIC: Development and Test of Passageway Sealing

PROBLEM: To provide a method of sealing large openings (such as sliding doors, hatches and rail track passages under movable doors) so that any tritium leakage from the reactor cell is minimized. If the design specifies that the complete reactor cell is to be evacuated, then the requirement of maintaining a relatively hard vacuum would be added.

DATA REQUIRED: Proof that either some existing sealing method or material will function satisfactorily or develop a new seal design for wall and floor passageways. Method of attachment and activation of seal. Expected lifetime of seal. Positive means to check and continuously assure that the seal is functioning properly.

SCOPE OF TASK: Conduct search of operating facilities and commercial vendors to determine the adaptability of existing sealing materials and methods. If no satisfactory seal is found, contact with commercial vendors for development of a satisfactory sealing method. After seal is developed, conduct mock-up test to prove seal is satisfactory.

SCHEDULE NEED/IMPACT: Need acceptable sealing means at start of reactor cell Title II design.

RESOURCE REQUIREMENTS: Industrial Test Facility with vacuum equipment.

AVAILABLE RESOURCES/PROGRAMS: Could be tested in existing ERDA facilities or industrial test facilities (Plum Brook NASA Facility). No known existing program.

ESTIMATED COST: Hardware \$35,000, Manpower \$100,000, Total \$135,000.

ALTERNATIVES: If acceptable sealing method cannot be established in time, a curtailment or limitation of the tokamak D T operations might be required or expensive multiple building containment would be needed.

TNS RD&D ASSESSMENT

DATE: 1/25/77
 BY: M. Sniderman
 ITEM: 6.0-2
 PRIORITY: 3

SYSTEM: Support Facilities

COMPONENT: Reactor Cell

TOPIC: Development and Test of Utility Penetrations Seals

PROBLEM: To provide a reliable method of sealing the numerous utility services (water, electric, etc.) which penetrate the reactor cell so that a potential leakage paths for tritium and radiation will be minimized. If the design specifies that the complete reactor cell is to be evacuated, then the requirement for maintaining a relatively hard vacuum would be added.

DATA REQUIRED: Proof that either some existing sealing compound or method is adaptable to TNS needs or develop a new design specifically for these applications. Limiting size of seal. Method of attaching seal to wall being penetrated. Construction material and operating lifetime of seal. Means to assure that seal is functioning properly.

SCOPE OF TASK: Conduct search of operating facilities and commercial vendors to determine the adaptability of existing sealing materials and methods. If no satisfactory seal is found, contract with commercial vendors for development of a satisfactory sealing method. Test resultant seal.

SCHEDULE NEED/IMPACT: Need acceptable sealing means by start of Title II design for the test cell.

RESOURCE REQUIREMENTS: Industrial Test Facility with vacuum capability.

AVAILABLE RESOURCES/PROGRAMS: Could be tested in existing ERD A facilities or industrial test facilities, (Plum Brook NASA Facility). No known existing program.

ESTIMATED COST: Hardware \$15,000, Manpower \$77,000, Total \$92,000.

ALTERNATIVES: If leakage is excessive, there would be a possible curtailment or limitation of tokamak D-T operations.

3.7 REACTOR TECHNOLOGY RESEARCH

Operation of TNS in the mid-1980's will provide the fusion program with its first opportunity for the examination of the performance of materials, design approaches, and components totally in the environment of an ignited fusion reactor. Planning and implementation of an integrated reactor technology research operating program for TNS must occur in parallel with the construction project to assure that the design of TNS is sufficiently flexible to accommodate these activities and that the requisite test results and hardware are available for incorporation in TNS.

Assuming a nine-year period for design and construction of TNS and a minimum useful operating life of ten years indicates that the TNS program will span almost twenty years and several technology generations. During this period the design of follow-on machines will be initiated. It is therefore necessary to anticipate in the planning of TNS its vital role as a test bed for the examination of reactor technology questions over this span of time.

This section represents a preliminary identification of those reactor technology research activities which appear to be compatible with the currently envisioned objectives and capabilities of TNS. This work is outside of the financial scope of the basic construction project. However, it is envisioned that this work will be performed in large part by members of the TNS design team to assure coordination of interfaces. This particularly applies to those tasks involving the design of test hardware to be installed in TNS during the operating program. Areas which are covered include blanket and shield test modules, materials test modules, remote operation test capability, tritium handling test capability, plasma dynamics test capability and power generation test capability.

A number of generic support activities have also been identified which provide important input to TNS and could result in cost and schedule improvement or reduction in technical

uncertainty. These include ongoing materials, blanket and shield, and impurity control efforts. The final category considered in this section is environmental impact and safety research. While we do not expect significant problems for TNS in these areas, the generic activities identified provide for early consideration of the proper format, content and data base for environmental impact and safety reports. These activities, if implemented, would minimize delay in preparation and approval of such documentation for TNS.

TNS RD&D ASSESSMENT

DATE: 2/7/77

BY: D. L. Chapin

ITEM: 7.1-1

PRIORITY: 3

SYSTEM: Blanket/Shield Test Capability

COMPONENT: Blanket/Shield Test Module

TOPIC: Design and Development of Blanket/Shield Test Modules

PROBLEM: Design, develop and test modules for use in TNS to answer various questions regarding blanket/shield design in future machines such as EPR/DEMO. The modules should provide information on such areas of interest as tritium breeding, shield attenuation properties, power conversion, and coolant thermal and hydraulic properties under cyclic D-T operation in TNS.

DATA REQUIRED: Various experimental measurements in the modules, such as radiation fluxes and nuclear heating rates; tritium production and diffusion rates for a number of different Li bearing materials (both solid and fluid); temperature and pressure distribution for different coolants.

SCOPE OF TASK: Design and fabricate a few test modules and the required mechanical structure and remote handling equipment for installation and maintenance of the modules in the TNS device.

SCHEDULE NEED/IMPACT: Design specifications of the modules should be completed by the end of Title II, with the hardware finished by the end of Title III. The module design will be influenced by the overall TNS shield design in consideration of space, maintenance, etc.

RESOURCE REQUIREMENTS: Facilities and equipment to perform the work would be available during TNS design and construction. Design, fabrication, and testing of the modules would require about a 2-3 man year effort involving engineers, draftsmen, and technicians.

AVAILABLE RESOURCES/PROGRAMS: Preliminary work has been done on module design by the EPR study groups and for a joint US-USSR activity on T-20; however, the status of T-20 is uncertain. Brookhaven has done work on module designs for fusion devices.

ESTIMATED COST: \$150,000 for labor and materials.

ALTERNATIVES: Don't use such modules on TNS, and instead defer the questions of advanced blanket/shield design to future devices such as EPR/DEMO. Hence, there would be some uncertainty in the blanket design of the EPR/DEMO.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: D. Chapin/R. E. Gold
 ITEM: 7.2-1
 PRIORITY: 4

SYSTEM: Materials Test Capability

COMPONENT: Test Modules

TOPIC: Design and Development of Materials Test Modules

PROBLEM: We currently expect TNS to provide a relatively low neutron fluence ($\sim 10^{20}$ n/cm²) by reactor standards, however, we will have an opportunity (for the first time) for large bulk sample 14 MeV neutron irradiations and the early detection of synergistic effects (if they exist at TNS conditions). The thrust of this task is to design, develop and test materials modules and test sections to examine various basic materials performance questions, in the TNS operating environment, which are of interest for the design of future devices such as EPR. The principal area of investigation at this time is envisioned to involve surface radiation effects on liner, limiter and first wall which can cause blistering and exfoliation damage and threaten the operational integrity of these components. Also, these damage phenomena can pose threats to plasma purity and sustained operation. Low fluence radiation effects could also be examined in materials such as solid state components and insulators, and an attempt made to determine threshold limits for certain levels of damage.

DATA REQUIRED: Measurements of radiation dose (particularly from 14 MeV neutrons) correlated with material damage levels for such fusion device components as optical equipment, insulators, seals, solid state elements, etc. which are placed in the test modules. Surface radiation damage effects on first wall structural materials in a radiation environment (charged particles and neutrons) having a reactor-like distribution of both particles and energy spectra.

SCOPE OF TASK: Design and fabricate materials test modules and the required mechanical structure and remote handling equipment for installation and maintenance of the modules in TNS. Proof-testing of these modules is also required in a remote handling mock-up facility and in TNS during non-D-T operation.

SCHEDULE NEED/IMPACT: Complete design specifications by end of Title II, module fabrication by end of Title III.

RESOURCE REQUIREMENTS: Government Labs, Industry. Particular emphasis should be made with respect to fission reactor materials and remote handling experience.

AVAILABLE RESOURCES/PROGRAMS: Facilities and equipment to perform the work will be available during TNS design and construction in the context of the project. A related on-going activity which can provide valuable input is the module design effort which is part of the joint USA-USSR blanket/shield task on T-20. Brookhaven has also done work on module designs for fusion reactors.

ESTIMATED COST: \$720,000 Labor, \$2,200,000 Equipment.

ALTERNATIVES: Don't use the modules on TNS, and rely on materials performance information from irradiation by D-T neutron sources such as RTNS, HIFER, and INS for the design of next generation devices.

TNS RD&D ASSESSMENT

DATE: 2/11/77
 BY: R. E. Gold, D. Chapin
 ITEM: 7.2-2
 PRIORITY: 4

SYSTEM: Materials Test Capability

COMPONENT: TNS Device (Test Modules)

TOPIC: Fusion Reactor Radiation Effects Data

PROBLEM: Reactor-scale materials performance will be verified in the DEMO, but earlier ongoing radiation environment tests from EPR, TNS, and irradiation facilities which utilize high intensity 14 MeV neutron sources will have specified materials and performance expectations. Lack of the information to be generated in these programs would result in poor material selections, and this in turn would result in excessive shielding requirements or failure of components and rapid replacement. This RD&D task is supportive of the irradiation facilities which will generate radiation damage data important for EPR and future fusion reactors, but will also provide information that will be important in the design of the material test modules for TNS.

DATA REQUIRED: Degradation of fusion device material and component properties as a result of 14 MeV neutron irradiation; the effect of radiation on insulators, solid state devices, stabilizing conductors for superconducting coils, and related components/devices critical to fusion reactor design and the swelling, sputtering, and embrittlement of materials.

SCOPE OF TASK: To develop the materials and components required to permit economical generation of energy from the fusion process. The emphasis will be on the development of radiation resistant first wall, blanket, and shield materials and hot and cryogenic insulators. Radiation effects on electronic apparatus associated with diagnostics gear will also be investigated.

SCHEDULE NEED/IMPACT: There will be a continuous need for this information until the demo plant is operational. However, in order to impact on the design of modules for TNS the information will have to be available prior to or during the early phase of Title III.

RESOURCE REQUIREMENTS: A shielded test facility having a 14 MeV source of neutrons is required. Diagnostic apparatus to measure the deterioration of properties of material samples will be utilized.

AVAILABLE RESOURCES/PROGRAMS: The SAMES accelerator at ORNL (low fluxes), the RTNS facility at LLL (available 1978), and the INS facility at LASL (available 1981). The ORNL HFIR and ORR test/research reactors can be used to provide a lower neutron energy spectrum; theoretical extrapolation to higher energies is required.

ESTIMATED COST: 2 M\$ (This assumes an available facility; it is in addition to the cost of this effort described in 1.6-4 (basic radiation effects data) and covers the time to the end of Title III.)

ALTERNATIVES: Design the test modules for TNS with the best information available, and obtain some of the irradiation information at that time with TNS. This could extend the TNS experimental program, and delay information necessary for EPR and the DEMO. Proceed with the fusion program without this information with all the attendant risks, e.g., excessive shielding, component failure, rapid replacement of components, etc.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: B. J. Fedor
 ITEM: 7.3 - 1
 PRIORITY: 4

SYSTEM: Remote Operations Test Capability

COMPONENT: Remote Servicing Test Station

TOPIC: Design and Development of a Remote Handling Test Station

PROBLEM: Remote servicing of TNS and future fusion reactors will require that maintenance operations be performed in relatively high radiation fields. The equipment and techniques have not yet been developed for many of the maintenance operations envisioned. It is also expected that following the development of the remote maintenance equipment, extensive testing under actual reactor environmental conditions will be required in order to confirm the operation of the equipment and to refine the sophisticated techniques required. It is in this regard that this task is aimed, that is, to design and develop a remote handling test station for TNS which would be used for qualification of handling equipment, development of remote servicing techniques, and training of operators.

DATA REQUIRED: Design and performance qualification of remote handling interfaces, equipment and techniques under actual reactor operating conditions.

SCOPE OF TASK: Design, develop and fabricate a remote handling test station to be installed in TNS. The proposed test station will be designed to provide test facilities to accommodate the various types of remote handling equipment and operations envisioned for TNS.

SCHEDULE NEED/IMPACT: Complete Design Specifications by the end of Title II design. Complete hardware by the end of Title III construction.

RESOURCE REQUIREMENTS: A fusion reactor test facility (TNS)

AVAILABLE RESOURCES/PROGRAMS: The test station must be designed for TNS by the TNS design team. TFTR experience could potentially provide valuable input, provided pre-operational testing with TFTR mock-ups is completed by the end of TNS Title II.

ESTIMATED COST: Materials and Services, \$750,000; Equipment, \$250,000; Labor \$175,000; Total \$1,175,000.

ALTERNATIVES: Test advanced remote handling equipment under non-reactor conditions and accept the operational delays in the schedule for design and operation of next generation reactors resulting from the learning curve.

TNS RD&D ASSESSMENT

DATE: 2/10/77

BY: E. Sucov

ITEM: 7.4-1

PRIORITY: 2

SYSTEM: Impurity Control Test Capability

COMPONENT: Impurity Control Test Module

TOPIC: Design and Development of Impurity Control Test Capability

PROBLEM: The present goal of TNS is operation in the ignited mode for about 20 seconds. While this will be long enough to demonstrate the feasibility of the impurity control system provided in the initial design of TNS, it is not necessarily long enough to verify that the system is compatible with EPR operation which will have a high duty cycle, perhaps 90%, along with longer pulse length, perhaps 100 seconds. Present calculations suggest that the wall treatment impurity control system (low Z liner, discharge cleaned walls, recycling of fuel and helium ions) will work for 20 or 30 seconds. Improved systems will have to be conceived, developed, and ultimately tested under TNS plasma conditions. Furthermore, the divertor plus burial chamber impurity control system, as presently conceived for the TNS, utilizes flowing lithium as a particle collector. In order for it to be verified for use in an EPR it must be evaluated for operation with longer pulses and higher duty cycles. The TNS provides a convenient and logical test bed for evaluating these systems. However, test modules must be developed that can test the various upgraded impurity control schemes during the TNS operating program.

DATA REQUIRED: Magnitude of wall treatment system influences on plasma to determine minimum size of module which can produce measurable and identifiable effects on TNS plasma. Development of method to apply a desired wall treatment system to modules designed for other purposes (shield studies, heat removal studies, etc.). Development of method to change design details of liquid lithium particle collection system and rapidly install it into the vacuum vessel.

SCOPE OF TASK: Measurement, analysis and quantitative prediction of plasma - wall interaction. Mechanical design of modules and vacuum vessel to facilitate rapid change-over.

SCHEDULE NEED/IMPACT: The design and analysis activities must parallel TNS Title I and Title II design since coordination of design interfaces is critical. Fabricated modules must be available for fit-up testing prior to D-T operations in TNS.

RESOURCE REQUIREMENTS: Experience with TNS systems, especially in plasma engineering and mechanical engineering. Experience with problems of remote handling in a hot environment. Analytic, computational, mechanical design, and drafting facilities. Shops to fabricate preliminary versions of module design.

AVAILABLE RESOURCES: Must be accomplished by the TNS design team.

ESTIMATED COST: Materials ~\$3,000,000; Manpower ~\$900,000.

ALTERNATIVES: Assume TNS impurity control systems can extrapolate to EPR conditions.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: H. J. Garber
 ITEM: 7.5-1
 PRIORITY: 4

SYSTEM: Tritium Handling Test Capability

COMPONENT: Tritium Test Module

TOPIC: Design and Development of Tritium Breeding Module

PROBLEM: Tritium breeding is not included in the shorter range TNS goals. However, long term utilization of TNS to test breeding blanket module concepts and demonstrate T breeding and recovery under power reactor-like conditions is a strong possibility. Attainment of this capability requires inclusion of special features in the TNS design to accommodate future emplacement of candidate breeding modules and the associated T handling-recovery equipment and the associated remote maintenance gear for servicing the added apparatus.

DATA REQUIRED: Conceptual and preliminary designs of candidate breeding modules (e.g., flowing Li, lithium aluminate, T removal by He sweep or permeation through Nb windows, T extraction from Li by Y beds, etc.). Principal data requirements are space and geometry needed to replace selected shield modules by breeding modules, neutronics computations to optimize module design and emplacement, space requirements for associated T handling equipment, installation and remote maintenance gear, modification required in cooling systems.

SCOPE OF TASK: Conduct neutronics computations. Design and construct breeding modules and associated T handling-recovery systems along with relevant instrumentation and controls. Remove selected shield modules and replace by breeding blanket modules. Conduct testing programs and evaluate results.

SCHEDULE NEED/IMPACT: Planning should be done during Title I TNS to provide capability to make the necessary future changes. Detail design of the breeding modules can be deferred, pending development of basic data on T release-recovery from laboratory tests. Installation and conducting of breeding test programs can be started subsequent to initial D-T operation of TNS.

RESOURCE REQUIREMENTS: Physical chemistry laboratory for process scoping tests. Chemical engineering process laboratory for basic process development and equipment pilot testing with standin of H or D for T. Tritium laboratory setups for process verification with T. Neutronics checkout and computer runs to select system parameters. TNS design group to prepare designs, select materials, plan revisions to TNS, plan remote installation, design I&C setups, and plan testing campaigns.

AVAILABLE RESOURCES/PROGRAMS: Basic test work can be accomplished at National Labs such as ORNL, ANL, LASL. Some data may be extractable from Savannah River experience. Design work must be accomplished by TNS design team.

ESTIMATED COST: Labor: \$2,150,000; Materials and Equipment: \$4,150,000;
Total: \$6,300,000.

ALTERNATIVES: Conduct breeding testing in other devices as EPR, without having prior proof testing in an earlier time frame.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: Yang/Schultz/Heck
 ITEM: 7.6-1
 PRIORITY: 4

SYSTEM: Plasma Dynamics Test Capability

COMPONENT: Plasma Dynamics Test Program and Equipment

TOPIC: Design and Development of Plasma Dynamics Tests

PROBLEM: The dynamic characteristics of fully developed "ignited" plasmas are unknown at this time. To design with confidence on Experimental Fusion Power Reactor and/or a Demonstration Fusion Power Plant, it is essential to have experimental data on the dynamic characteristics of the ignited plasma to confirm theoretical predictions.

DATA REQUIRED: The response of the plasma to internal disturbances such as micro-instabilities, fluctuations in partial densities and changes in composition. The response of the plasma to external disturbances such as fluctuations in magnetic fields, vacuum pumping and fueling rate. The limits on plasma elongation and β . The scaling laws for $n\tau$ including the effects of varying composition and fueling rate. The limitations on the length of the burn period.

SCOPE OF TASK: Develop test methods and procedures based on available theory. Perform tests and interpret results in light of the available theory. Development of sensors, means of introducing disturbances, and interpretive systems may be required.

SCHEDULE NEED/IMPACT: End of Title III

RESOURCE REQUIREMENTS: TNS, TNS Design Team

AVAILABLE RESOURCES/PROGRAMS: The measurement programs on existing machines for non-ignited plasmas provide vital input information and testing of some measurement techniques. This effort must be performed primarily by the TNS design team.

ESTIMATED COST: 450 K\$ Labor Total: \$1,250,000
 800 K\$ Hardware

ALTERNATIVES: High risk in performance of EPR/Demo

TNS RD&D ASSESSMENT

DATE: 2/9/77
BY: E. W. Sucov
ITEM: 7.7-1
PRIORITY: 4

SYSTEM: Advanced Refueling Test Capability

COMPONENT: Refueling Hardware

TOPIC: Design and development of advanced refueling test hardware

PROBLEM: This task is concerned with an ongoing refueling RD&D effort which will permit the development of new ideas which can be tested in TNS subsequent to its initial operation. While the TNS will require a refueling system that can deliver variable amounts and proportions of D&T for about 30 seconds, the EPR will require refueling at about the same rate but over longer times and higher duty cycles. Schemes for accelerating and injecting the pellets, such as ultracentrifuge or liquid jet, need to be proven in operation for pulses at least 100 seconds long and with 50% duty cycles over many cycles.

DATA REQUIRED: Fatigue limit of special composition and bearings used for ultracentrifuge rotors operating at cryogenic temperatures and high stresses. Location and reason for system breakdown after many cycles of operation. Fatigue limits of materials and systems used in liquid jet scheme. Performance and design characteristics of advanced high velocity, high duty cycle refueling hardware.

SCOPE OF TASK: Experimental determination of failure modes under prolonged cyclic operation. Analysis of the failure both experimentally and analytically to determine source of failure. Development of ways to prevent failure and proof of feasibility. The principal end product will be the design and fabrication of advanced fueling equipment which can replace or complement the refueling hardware provided as part of the original TNS construction project.

SCHEDULE NEED/IMPACT: Proven designs of refueling equipment should be available by the time of final design of the EPR. The specific test equipment to be developed as part of this task should be ready two years after initial operation of TNS.

RESOURCE REQUIREMENTS: Cryogenic storage and handling; vacuum and mechanical facilities; model shop to fabricate improved systems; materials and solid state analysis laboratories.

AVAILABLE RESOURCES/PROGRAMS: Many government, industrial and university laboratories have these facilities.

COST: Hardware ~\$1,100,000; Manpower ~\$500,000. Total: \$1,600,000.

ALTERNATIVES: Assume TNS refueling systems are so well designed that they will perform adequately under more demanding EPR conditions. Provide redundant systems for quick replacement of failed system.

TNS RD&D ASSESSMENT

DATE: 2/9/77
 BY: T. C. Varljen
 ITEM: 7.8-1
 PRIORITY: 4

SYSTEM: Electrical Power Generation Test Capability

COMPONENT: Electrical Power Generation Equipment

TOPIC: Design, Development and Fabrication of an Electrical Power Generation Research Subsystem

PROBLEM: TNS does not now incorporate provisions for the conversion of fusion energy into electrical energy. An early examination and demonstration of this capability in TNS, even on a limited basis, would be a historic event in its own right. However, this activity is required as a forcing function in this technology area. The evaluation of specific technologies and design approaches is required, as well as the experimental examination of key design issues such as: 1) choice of working fluid; 2) blanket/shield and coolant loop design integration; 3) design criteria for intermediate heat exchangers; 4) thermal or electrical load buffering; 5) electrical interfacing between pulsed station loads and the output generators; 6) turbine generator system design criteria 7) means for removal of hydrogen isotopes from the coolant (arising from metal water reactions and diffusion into the coolant).

DATA REQUIRED: Results of power conversion systems trade studies and the specified experimental activities will yield design and performance data necessary for the design of next generation fusion reactor electrical power generation subsystems.

SCOPE OF TASK: Trade studies, design, fabrication and test of components and subsystems, installation of a modular system on TNS which would permit demonstration of conversion of fusion energy to electrical energy on a limited basis and in-situ hardware testing.

SCHEDULE NEED/IMPACT: Development and design work should proceed in parallel with the TNS design effort to assure interface control. Hardware to be tested in TNS should be available for installation and checkout prior to the beginning of D-T test operations.

RESOURCE REQUIREMENTS: Thermal and materials test laboratory, precision fabrication facility, TNS reactor and design team.

AVAILABLE RESOURCES/PROGRAMS: TNS design team.

ESTIMATED COST: \$250,000 Labor; 1.5 M\$ Equipment.

ALTERNATIVES: Do not provide for the testing and demonstration of electrical power generation capability in TNS.

TNS RD&D ASSESSMENT

DATE: 2/8/77
BY: T. C. Varljen
ITEM: 7.9-1
PRIORITY: 2

SYSTEM: Safety and Environmental Impact Research

COMPONENT: -

TOPIC: Generic Fusion R&D Environmental Statement

PROBLEM: The fusion R&D program will require the preparation and approval of a generic Environmental Statement. At this time the proper timing for this effort has not been established. However, in view of the expected cost and tritium inventory for TNS it is possible that delay in the issuance of the generic statement could delay TNS.

DATA REQUIRED: The development of generic information relating fusion to alternate technologies, total program costs and impact, projected impact and cost/benefit analysis for full scale fusion power plants as well as research facilities, and anticipated overall resource commitments..

SCOPE OF TASK: 1) Development of environmental impact data base for fusion, 2) Evaluation of fusion and alternate technologies, 3) Completion of cost benefit analyses, 4) Completion of resource requirements, 4) Completion and issuance of generic environmental statement.

SCHEDULE NEED/IMPACT: Ongoing effort, need provisional version by end of FY-79 to coincide with TNS environmental statement.

RESOURCE REQUIREMENTS: Gov't lab personnel with strong input from utilities (owner-operators of fission plants), fission reactor vendors and A/E's.

AVAILABLE RESOURCES/PROGRAMS: Pacific Northwest Labs, LMFBF generic statement, CRBRP Contractors

ESTIMATED COST: 3M\$

ALTERNATIVES: Do not prepare or complete generic statement and risk TNS program delay pending completion.

TNS RD&D ASSESSMENT

DATE: 2/7/77
 BY: T. C. Varljen
 ITEM: 7.9-2
 PRIORITY: 3

SYSTEM: Safety and Environmental Impact Research

COMPONENT: _____

TOPIC: Generic PSAR/FSAR Criteria for Fusion Facilities

PROBLEM: TFTR will provide early experience in the development and acceptability of a specific PSAR/FSAR approach. However, the larger scope of TNS and subsequent reactor projects and the long lead time involved in effectively planning for these safety documentation efforts requires the development of generic criteria and the early identification of problem areas.

DATA REQUIRED: The development of generic PSAR/FSAR criteria for fusion facilities covering such areas as design basis definitions, accident scenarios, acceptable analytical tools and techniques, safety data base including failure rate data, documentation of analyses and computational tools, and safety-related quality assurance.

SCOPE OF TASK: 1) Literature search and evaluation 2) Development of required data base 3) Appointment of a joint Government, ERDA Lab. and industry task force 4) Task force review, evaluation and recommendations at quarterly intervals 5) Development and issuance of working guidelines and criteria.

SCHEDULE NEED/IMPACT: Ongoing effort, provisional criteria should be developed by the start of TNS Title I.

RESOURCE REQUIREMENTS: Government Lab. and ERDA personnel with strong input from utilities (owner-operators of fission plants), fission reactor vendors and A/E's.

AVAILABLE RESOURCES/PROGRAMS: Close liaison with the TFTR PSAR/FSAR effort, fission reactor programs.

ESTIMATED COST: 100k\$/yr., FY'78 - FY'82. Total: \$500,000.

ALTERNATIVES: Do not prepare generic criteria. TNS Project will develop ad hoc criteria and implementation with significant delay in completion and approval. This approach will not assure that overall program perspectives are considered and factored into the TNS safety effort.

TNS RD&D ASSESSMENT

DATE: 2/8/77
 BY: T.C.Varljen
 ITEM: 7.9-3
 PRIORITY: 4

SYSTEM: Safety and Environmental Impact Reseach

COMPONENT: -

TOPIC: Development of Generic Engineering Codes and Standards

PROBLEM: A key ingredient in the sequence of events leading to fusion power reactor commercialization will be the development of engineering codes and standards. Early development of these codes and standards (many of which may be based on existing practice) will guide the orderly development of hardware and expedite environmental impact and safety acceptance of near-term fusion systems.

DATA REQUIRED: Formulation of a code/standard framework and development and issuance of these criteria for the design, fabrication, testing and operation of fusion plant facilities and equipment.

SCOPE OF TASK: 1) Appointment of a joint National Society-Government-Laboratory-Industry code and standard committee to meet regularly and guide development 2) Identification of working subcommittees in the context of existing code/standard groups 3) funding of generic analysis, manufacturing and test efforts to qualify techniques 4) Issuance of codes and standards.

SCHEDULE NEED/IMPACT: Ongoing effort, preliminary versions of these codes and standards must be ready by the start of TNS Title I if they are to be implemented in the design.

RESOURCE REQUIREMENTS: Government, Laboratory, Industry personnel with fission reactor experience.

AVAILABLE RESOURCES/PROGRAMS: Existing ERDA RDT program, National Professional Society Code groups, Industrial Standards Organizations.

ESTIMATED COST: ~100 k \$/Yr, FY'78-FY'80; ~250 k \$/Yr, FY'81-FY'86
 Total: \$1,800,000.

ALTERNATIVES: Use ad hoc standards for TNS and defer generic standards development until next generation systems are in design.

TNS RD&D ASSESSMENT

DATE: 2/8/77
 BY: T. C. Varljen
 ITEM: 7.9-4
 PRIORITY: 4

SYSTEM: Safety and Environmental Impact Research

COMPONENT: _____

TOPIC: Generic Fusion Reactor Safety Research

PROBLEM: The experience of the fission reactor program has demonstrated the need for ongoing safety research activities to identify and characterize the accident risks of fusion power reactors and research facilities and to guide the development of the methodology and engineered safeguards necessary to provide for the safe construction and operation of these facilities.

DATA REQUIRED: 1) Component and system failure rate and accident histories
 2) Characterization of potential risks (e.g., loss of coolant, plasma instability, loss of vacuum, fires, explosion, tritium release, electrical faults and failures, etc.)
 3) Analytical and experimental confirmation of safeguards and safety systems.

SCOPE OF TASK: 1) Develop and maintain component and system failure rate accident/data base
 2) Analysis and characterization of potential risks
 3) Analytical and experimental proof-testing involving mock-ups and prototype hardware

SCHEDULE NEED/IMPACT: Ongoing effort, preliminary results must be available by the start of Title I to be factored into TNS design criteria.

RESOURCE REQUIREMENTS: Government Labs and Industry (Reactor vendors and A/E's with fission reactor backgrounds).

AVAILABLE RESOURCES/PROGRAMS: Government Labs and Fission reactor vendors and A/E's.

ESTIMATED COST: 9 M \$, FY'78-FY'82

ALTERNATIVES: Develop TNS safety design criteria based on available data and ad hoc analysis. This will not assure that overall program perspectives are factored into TNS criteria and will defer generic safety R&D until next generation systems are in design.

3.8 APPLIED PHYSICS/PLASMA ENGINEERING

The RD&D tasks highlighted in this section form the backbone of the plasma physics research programs being carried out at the national tokamak facilities. The results from the ongoing experimental and theoretical work are vital to the planning and design of any future tokamak device including TNS. In fact, the design of every component of TNS will be sensitive to the available knowledge on the plasma behavior that is described in the RD&D needs presented in this section.

Some of the RD&D tasks are supportive of the programs as they are currently conceived. In other instances the tasks will require redirection of the programs in order to focus on the specific needs of TNS. The plasma physics areas are addressed generally and include: plasma transport and scaling, plasma shape optimization, rapid heating and β limitations, plasma stability, and impurity control. Some ways in which this information impacts on the engineering of TNS are discussed below.

In order to size TNS, and determine the operating parameters such as plasma current, plasma temperature, and toroidal magnetic field, the scaling law for the plasma density-energy confinement time product, $n\tau_E$, for a plasma heated by auxiliary means must be determined. The values of the energy confinement time and particle confinement time are required separately for the engineering of the cooling systems and the gas throughput control system. All operating or planned tokamaks which have auxiliary heating will provide information in this area (PLT, PDX, TFTR, ORMAK, ORMAK-U, Doublet III).

The limiting β in tokamaks is an important element in their economics as power reactors. One of the goals of TNS is to show that high β 's are achievable; β 's of 5-10% are expected to be required for an economic system. To determine whether or not a modest sized TNS can be designed to achieve high β , tests are required of plasmas having noncircular cross sections and of rapidly heated tokamaks in general. Doublet II and III, PLT, ORMAK-U, and TFTR

can contribute to our understanding of these limitations. In addition, there are specific tests relative to TNS that can be carried out with some modifications to the design of these devices. For example, with modification to the shaping field systems it could be determined whether or not high β achieved through flux conservation can be maintained for a sufficiently long period of time for reactor operation.

Information on the start-up and shutdown techniques that will be required for large plasmas, such as for TNS, can be obtained on operating tokamaks over the next four years. This information will be required for the proper engineering of mechanical and/or magnetic limiters, magnetic plasma control systems, first wall design, etc., for TNS. The following examples illustrate new information that must be available for TNS. Current tokamaks tend to allow the plasma to terminate unstably, however, with the large energies that are associated with the TNS plasma and poloidal field, unstable termination cannot be tolerated. For plasma start-up, methods must be developed that allow the plasma to be initiated at a prescribed location within a large vacuum vessel and for the plasma current to grow without excessive skin effects. Otherwise instabilities can occur and/or excessive impurities can be introduced with large requirements set on the power supplies for the poloidal winding because of large volt-second requirements. The PDX, PLT, TFTR, ORMAK-U, and Doublet programs can provide data in these areas.

There are other major areas of the tokamak physics program such as heating, fueling, impurity control and boundary effects which are not represented in this section but are included in the other sections of this RD&D assessment compilation.

The importance of the tokamak physics program to TNS cannot be measured simply by the data it will provide for problems now identified for TNS, but also by the still unknown phenomena that will be uncovered by this research. These phenomena may affect the TNS design and hopefully provide guidance in the direction of reactor performance improvement.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: T.F. Yang, H.R. Howland
 ITEM: 8.0-1
 PRIORITY: 1

SYSTEM: Applied Physics/Plasma Engineering

COMPONENT: Plasma

TOPIC: Stability of elongated high β plasmas

PROBLEM: The stability problems that might occur for high- β and elongated plasmas are not yet known. Detailed theoretical analyses of the important MHD modes, such as axisymmetric modes, kink modes, ballooning modes, tearing modes, sawtooth modes, and so forth should be performed. In order to properly design TNS, the experimental measurements of these modes should be made to establish upper limits on β and elongation.

DATA REQUIRED: The magnitude of each MHD instability and its effect on confinement and limit on β and elongation.

SCOPE OF TASK: Detailed theoretical and numerical analyses of the MHD axisymmetric, kink instabilities and so forth for high- β TNS will be carried out. Experiments on the major tokamak facilities will be carried out to check the numerical results which are obtained for these devices. A range of β and elongation will be studied to establish the limits.

SCHEDULE NEED/IMPACT: Needed before the Title I. Results will affect ignition parameters. Tokamak reactors can be more compact and economically designed at higher possible β and elongation.

RESOURCE REQUIREMENTS: Tokamak devices, neutral beam injectors, auxiliary heating, plasma diagnostics, simulation codes.

AVAILABLE RESOURCES/PROGRAMS: (1) Experimental programs: ORMAK-U, PLT, PDX, DOUBLET, TFTR. (2) Theoretical programs: ORNL, FCT, MHD computer code; Princeton ΔW stability code PEST.

ESTIMATED COST: (1) Personnel and operating cost for experimental program \$1 M.
 (2) Personnel and computer time for code development and theoretical analyses \$1 M.
 Total: \$2 M

ALTERNATIVES: Low β large device, high field toroidal magnet.

TNS RD&D ASSESSMENT

DATE: 2/4/77
 BY: T. F. Yang, H. R. Howland
 ITEM: 8.0-2
 PRIORITY: 1

SYSTEM: Applied Physics/Plasma Engineering

COMPONENT: Plasma

TOPIC: High β Time Scale for FCT

PROBLEM: Whether or not high- β plasmas achieved in FCT's will persist for a useful time has not been demonstrated experimentally. The design of TNS may be adversely affected by the assumption of this effect without confirmation and it is highly desirable to provide an experimental basis.

DATA REQUIRED: The time sequence of FCT heating, the persistence of high - β plasmas over a useful time scale, upper limit of β .

SCOPE OF TASK: Perform an experiment on an auxiliary heated tokamak to obtain high β and related confinement time. Observe known instabilities. Develop advanced theory to interpret the experimental results so as to determine a scaling law.

SCHEDULE NEED/IMPACT: Before the start of Title I. Results will affect the major parameters of TNS. Tokamak reactors can be more compact and economical if high β plasmas achieved by flux conservation (FCT) can persist over a significant time.

RESOURCE REQUIREMENTS: Tokamaks, Neutral beam injector, plasma diagnostics, Auxiliary heating, computer.

AVAILABLE RESOURCES/PROBLEMS:

1. Experimental programs:	ORMAK-U, PLT, TFTR
2. Theoretical programs:	ORNL, PPPL, and Industries
3. Computer facilities:	LLL CTR computer

ESTIMATED COST: 1. Operating cost and personnel to perform experiments and data analysis \$1M.
 2. Personnel and computer time for code development and studies \$1M. 3. Total cost: \$2M.

ALTERNATIVES: Low β larger device, develop high field toroidal magnet.

TNS RD&D ASSESSMENT

DATE: 2/5/77

BY: E. W. Sucov/T. F. Yang

ITEM: 8.0-3

PRIORITY: 1

SYSTEM: Applied Physics/Plasma Engineering

COMPONENT: Plasma

TOPIC: Measurement of Plasma Scaling Relationships

PROBLEM: The scaling laws for $n \tau_E$ are not known for high temperature plasmas that are heated by auxiliary means. The design for ignition conditions, the impurity control methods and pulse length will be affected by the scaling laws used.

DATA REQUIRED: An empirical law for $n \tau_E$ for high β . Determine scaling for τ_E , τ_p for tokamaks with divertor or other impurity control means.

SCOPE OF TASK: Extensive experimental work will be carried out on the major tokamak facilities to measure $n \tau_E$ for a wide range of plasma parameters. Detailed analyses will be made of the data to obtain a reliable empirical formula. The quantities τ_p , τ_E will be extracted for various plasma and machine parameters and configurations.

SCHEDULE NEED/IMPACT: Before the start of Title I design. Results will affect the size of an ignition machine and the impurity control method.

RESOURCE REQUIREMENTS: Tokamaks with or without divertor configurations, neutral beam injector, auxiliary heating, plasma diagnostics, computer facility.

AVAILABLE RESOURCES/PROGRAMS: Experimental programs, ORMAK-U, PLT, Doublet, PDX, TFTR, ALCATOR.

ESTIMATED COST: Personnel and operating cost for performing experiment and analysis \$3 M.

ALTERNATIVES: Design in a conservative manner based on judgement.

TNS RD&D ASSESSMENT

DATE: 2/10/77
 BY: Yang/Howland
 ITEM: 8.0-4
 PRIORITY: 2

SYSTEM: Applied Physics/Plasma Engineering

COMPONENT: Plasma

TOPIC: Equilibrium and Transport During Start-up/Shutdown

PROBLEM: Because of low β operation and the relatively low energy content associated with the plasmas, information obtained from currently operating devices about plasma start-up and shutdown is not applicable to TNS. More complex start-up and shutdown procedures such as the use of magnetic and/or moving mechanical limiters, programmed plasma buildup and neutral beam injection, etc., will be required and experimentally verified analytical methods are not available for carrying out the design of the pertinent components.

DATA REQUIRED: Range of equilibria during start-up and shutdown. Particle transport (confinement during start-up and shutdown). Plasma current and resistivity during start-up and shutdown. The effect of runaway electrons on start-up and shutdown.

SCOPE OF TASK: Develop time dependent coupled equilibrium and transport code. Carry out the detail study of the start-up and shutdown method, such as using the magnetic or mechanical limiters. Perform start-up and shutdown experiments on one of the major tokamak facilities.

SCHEDULE NEED/IMPACT: Needed by end of TNS conceptual design. It would affect TNS PF and OH coil and power supply design which has direct impact on the cost of TNS.

RESOURCE REQUIREMENTS: Tokamaks, neutral beam, auxillary heating, high response power supply, high speed pumping equipment. Plasma diagnostics.

AVAILABLE RESOURCES/PROGRAMS: (1) Experimental Program: ORMAK-U, PLT, TFTR.
 (2) Theoretical Programs: ORNL, PPL, SAI, GA, time dependent MHD and Transport Code Development Programs.

ESTIMATED COST: (1) Personnel and computer time for code developing \$1 M.
 (2) Personnel and operating cost for performing experiments \$1 M. Total: \$2 M.

ALTERNATIVES: Design the system by assuming plasma would start linearly and no problem with shutdown. Over-design the electrical power system and neutral beam injector and experiment start-up during initial stage of operation.

TNS RD&D ASSESSMENT

DATE: 2/4/77

BY: T. F. Yang

ITEM: 8.0-5

PRIORITY: 3

SYSTEM: Applied Physics/Plasma Engineering

COMPONENT: Plasma

TOPIC: Transport property of synchrotron radiation

PROBLEM: Latest experimental results from PLT indicate that synchrotron radiation has a cooling effect on the center of plasma and heats up the plasma edge. This indicates that the transport property of synchrotron radiation is important and is not yet known. This property is expected to be more prominent for high β tokamaks such as TNS. The ultimate temperature profile will influence the TNS design.

DATA REQUIRED: A theoretical model of synchrotron radiation transport and temperature profile obtained by synchrotron radiation measurement.

SCOPE OF TASK: Theoretical model of synchrotron radiation transport will be developed. Measurements of temperature profiles will be made on operating tokamaks by using synchrotron radiation for various temperatures and densities. The data will be analyzed and comparison will be made with the theoretical model.

SCHEDULE NEED/IMPACT: Needed after Title I. Will affect the energy balance of the particle transport and MHD equilibrium and stability calculations.

RESOURCE REQUIREMENTS: Large tokamaks, synchrotron radiation analyzers or interferometers.

AVAILABLE RESOURCES/PROGRAMS: 1) Experimental tokamaks ORMAK-U, PLT, TFTR
2) Synchrotron radiation experimental program of University of Maryland, ORNL, PPPL.
3) Theoretical programs, PPPL, Industries.

ESTIMATED COST: 1) Personnel, capital cost for equipment, operating cost - \$500 K.
2) Theoretical work - \$500 K. Total Cost: 2 M\$.

ALTERNATIVES: To design TNS conservatively to account for the fact that this method of plasma cooling is not yet understood.

4.0 PROGRAM RECOMMENDATIONS

We have concluded that the basis exists for the initiation of TNS conceptual design, and furthermore, a sufficiently firm scientific basis can be developed for TNS by the time authorization is requested for the expenditure of construction funds to support facility operation by FY '86. The schedule is tight, however, and an end-product oriented, highly focused effort will be required to plan and implement the required activities. A plan of action to assure that TNS will proceed on schedule will include the following elements.

INITIATE CONCEPTUAL DESIGN

A strong, integrated, baseline design effort must be initiated. This will also serve as a forcing function for the RD&D program. Component and subsystem design requirements, developed from an integrated systems point of view, are necessary to focus RD&D activities on specific design issues and to provide the framework for evaluating results and the applicability of new ideas and techniques.

DEVELOP A TECHNICAL CONTINGENCY PLAN

The design for TNS and the associated program of supporting RD&D must be optimistic, but realistic. Otherwise the planned operation in 1986 and program cost estimates to achieve this goal will not be credible. The recommended approach in this area is the development of a design risk tree (analogous to a fault tree), initiation of a multi-track design and research effort, and the quantification of physics and engineering uncertainties. In this way the design process, and the associated end-products, can be made to bracket uncertainties in either requirements or solutions. This activity should be an integral part of the conceptual design effort.

PROVIDE FOR RD&D MANAGEMENT CONTROLS

When the technical and financial progress of a project of the magnitude of TNS depends heavily on supporting RD&D, project management must have the means to assure that the work performed is fully responsive in terms of cost, schedule and technical end product. This poses difficulties where the work is clearly generic and is part of a larger, on-going R&D program. Regardless of where the work is performed, and the specific lines of control involved, each RD&D activity supporting TNS must develop appropriate task descriptions, budgets and progress measurement or decision milestones. The TNS project should have the means to provide for timely initiation, termination or redirection of these efforts, based on continuous technical and management review.

PROVIDE FOR TECHNICAL COORDINATION AND TNS FOCUS

The tight schedule for both design and supporting RD&D requires strong technical coupling in planning and implementation. Many activities will be performed in parallel, rather than in series. In-progress reviews and reports will be required to assure that technical data is quickly disseminated. A centralized TNS project documentation activity (particularly during conceptual design) is a logical way to assure that overall project technical status information is made available to all participants on a timely basis.

PROVIDE FOR EARLY RD&D INITIATION

A lesson should be learned from TFTR where very limited design-related RD&D was accomplished during the 28-month conceptual design period. As a result, the majority of the RD&D must be accomplished in parallel with Titles I and II. This situation has delayed several important design decisions and prevents the examination of potentially significant design options. The focusing of generic RD&D programs toward TNS can begin at once along with planning for the early initiation of design-related RD&D.

RECOMMENDATIONS FOR SUPPORT BY EXISTING PROGRAMS

A considerable number of specific supporting RD&D tasks have been identified which could potentially be accommodated by existing or on-going major MFE programs. However, it has not been possible during the present RD&D assessment to identify and evaluate the suitability of all of the MFE programs nor make specific judgements as to which MFE program would be most appropriate for specific RD&D tasks.

Table 4-1 cross-references the major MFE device and technology programs with appropriate TNS RD&D topics. In many cases several facilities have been identified as possibilities for performing the same task or the same measurement. Additional review is necessary to establish where each task can and should be performed and the schedule for such performance.

It must be strongly emphasized that few of the tasks listed in this compilation are explicitly planned or have a TNS focus. Timely and systematic interaction between MFE, the performing organizations, and the TNS design teams, will be required in the coming months to provide the required focus.

TABLE 4-1

RECOMMENDATIONS FOR TNS-RELATED EXPERIMENTAL WORK AT EXISTING FACILITIES

ITEM	FACILITY	ACTION
1.1.1-1	PLT	Measure Vacuum Vessel Electrical Resistance Effects
1.1.2-1		Measure Plasma Limiter Radiation Damage
1.1.2-2		Measure Thermal Performance Of Limiter
1.1.3-7		Study Impurity-Limiting Start-Up Scenarios
1.6-1		Measure TF Coil Deflections
2.2.2-3		Measure Plasma Disruption Conditions
3.1-1		Verification of Plasma Heating Scenarios
3.1-2		Verification of Ripple Injection
3.1-3		Test of Perpendicular Injection
3.2-1		Evaluate rf Source Frequencies
4.2-1		Measure Pellet Injection Penetration
5.3-6		Use Synchrotron Radiation As A Plasma Diagnostic Tool
8.0-2		Study High β Characteristics of FCT
8.0-3		Study Plasma Scaling Relationships
8.0-4		Study Plasma Start-Up Characteristics
8.0-5		Measure Synchrotron Radiation Properties
1.1.3-1	PDX	Study Poloidal Divertor Operation
1.1.3-2		Measure Scrape-Off Layer Properties
1.1.3-7		Study Impurity-Limiting Start-Up Scenarios
1.1.3-12		Particle Collection Capabilities of Lithium
1.6-1		Measure TF Coil Deflection

TABLE 4-1

RECOMMENDATIONS FOR TNS-RELATED EXPERIMENTAL WORK AT EXISTING FACILITIES

ITEM	FACILITY	ACTION
2.2.2-3	PDX (Continued)	Measure Plasma Disruption Conditions
3.1-1		Verification Of Plasma Heating Scenarios
3.1-2		Verification Of Ripple Injection
3.1-3		Test Of Perpendicular Injection
8.0-1		Study Stability Of Elongated High β Plasmas
1.1.1-1	ORMAK-U	Measure Vacuum Vessel Electrical Resistance Effects
1.1.2-1		Measure Plasma Limiter Radiation Damage
1.1.2-2		Measure Thermal Performance Of Limiter
1.1.3-7		Study Impurity-Limiting Start-Up Scenarios
1.6-1		Measure TF Coil Deflections
2.2.2-3		Measure Plasma Disruption Conditions
3.1-1		Verification Of Plasma Heating Scenarios
3.1-2		Verification Of Ripple Injection
3.1-3		Test Of Perpendicular Injection
3.2-1		Evaluate rf Source Frequencies
4.2-1		Measure Pellet Injection Penetrations
5.1.1-1		Test Feedback Stabilization Of Plasmas
5.3-6		Use Synchrotron Radiation As A Plasma Diagnostic Tool
8.0-2		Study High β Characteristics Of FCT
8.0-3		Study Plasma Scaling Relationships
8.0-4		Study Plasma Start-Up Characteristics
8.0-5		Measure Synchrotron Radiation Properties

4-5

TABLE 4-1

RECOMMENDATIONS FOR TNS-RELATED EXPERIMENTAL WORK AT EXISTING FACILITIES

ITEM	FACILITY	ACTION
1.1.3-7	DOUBLET III	Study Impurity-Limiting Start-Up Scenarios
1.6-1		Measure TF Coil Deflection
3.1-1		Verification Of Plasma Heating Scenarios
3.1-2		Verification Of Ripple Injection
3.1-3		Test Of Perpendicular Injection
3.2-1		Evaluate rf Source Frequencies
5.1.1-1		Test Feedback Stabilization Of Plasmas
8.0-1		Study Stability Of Elongated High β Plasmas
8.0-2		Study High β Characteristics Of FCT
8.0-3		Study Plasma Scaling Relationships
8.0-4		Study Plasma Start-Up Characteristics
1.1.3-4	ISX	Measure Performance Of Low Z Walls
1.1.3-5		Evaluate Performance Of Honeycomb Walls
1.1.3-6		Study Impurity Reversal
1.1.3-7		Study Impurity-Limiting Start-Up Scenarios
1.1.1-1	TFTR	Measure Vacuum Vessel Electrical Resistance Effects
1.1-6		Measure TF Coil Reflections
1.1.2-1		Measure Plasma Limiter Radiation Damage
1.1.2-2		Measure Thermal Performance Of Limiter
1.1.3-7		Study Impurity-Limiting Start-Up Scenarios
1.5-6		Neutronic Measurements on TFTR

TABLE 4-1

RECOMMENDATIONS FOR TNS-RELATED EXPERIMENTAL WORK AT EXISTING FACILITIES

ITEM	FACILITY	ACTION
2.2.2-3	TFTR (Continued)	Measure Plasma Disruption Voltages
3.1-1		Verification Of Plasma Heating Scenarios
3.1-2		Verification Of Ripple Injection
3.1-3		Test Of Perpendicular Injection
3.2-1		Evaluate rf Source Frequencies
4.2-1		Measure Pellet Injection Penetrations
5.1.1-1		Test Feedback Stabilization Of Plasmas
5.1.1-2		Measure Plasma Density And Temperature Dynamics
5.1.2-3		D-T Tokamak Sensor Tests
5.3-6		Synchrotron Radiation As Diagnostic Tool
8.0-2		Study High β Characteristics Of FCT
8.0-3		Study Plasma Scaling Relationships
8.0-4		Study Plasma Start-Up Characteristics
8.0-5		Measure Synchrotron Radiation Properties
1.3-2	FFTF	Electrical Insulation Radiation Damage
1.6-4		Measure Material Radiation Damage
7.2-2		Fusion Reactor Radiation Effects Data
1.3-2	RTNS	Electrical Insulation Radiation Damage
1.6-4		Measure Material Radiation Damage
7.2-2		Fusion Reactor Radiation Effects Data

RECOMMENDATIONS FOR TNS-RELATED EXPERIMENTAL WORK AT EXISTING FACILITIES

ITEM	FACILITY	ACTION
1.3-2	INS (Neutron Source)	Electrical Insulation Radiation Damage
1.6-4		Measure Material Radiation Damage
7.2-2		Fusion Reactor Radiation Effects Data
1.3-2	HFIR	Electrical Insulation Radiation Damage
1.6-4		Measure Material Radiation Damage
7.2-2		Fusion Reactor Radiation Effects Data
4.2-2	TSTA	Test Performance Of Tritium Pumps
4.2-6		Measure Cryogenic Distillation Column Performance
4.2-7		Measure Tritium Handling Component Performance Degradation
4.2-8		Measure T-Li-Y Transport Data
4.2-9		Measure Tritium Transport Properties
4.2-10		Qualify Valve Performance For Tritium Service
4.2-11		Measure Hydrogen Isotope Phase Data
4.5-1		Measure Tritium Retention Behavior
5.1-2		Develop Multipurpose Tritium Analyzer
1.2-1	LCP	Qualify NbTi Cable Fabrication Process
1.2-2		Qualify Nb ₃ Sn Cable Fabrication Process
1.2-3		Verify Conductor Cryostability
1.2-4		Verify Superconducting TF Coil Fabrication Process
1.2-5		Measure Nb ₃ Sn Thermophysical Properties

TABLE 4-1

RECOMMENDATIONS FOR TNS-RELATED EXPERIMENTAL WORK AT EXISTING FACILITIES

ITEM	FACILITY	ACTION
1.2-6		Superconducting Cable Heat Transfer Properties
1.2-7		Qualify Superconducting Cable Insulation Performance
1.2-8		Measure NbTi Thermophysical Properties
1.2-13		Measure NbTi Winding Strain
1.2-14		Measure NbSn Winding Strain
1.2-15		Measure Liquid Helium Boiling Heat Transfer
4.4-1		Test Supercritical Helium Circulating Pumps

DATE: March, 1977

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