**TNS QUARTERLY PROGRESS REPORT
FOR THE PERIOD
JANUARY, FEBRUARY, MARCH
(1977)**

MASTER

**fusion power
systems department**

Westinghouse Electric Corporation

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TNS QUARTERLY ENGINEERING PROGRESS REPORT
(JANUARY-FEBRUARY-MARCH, 1977)

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FOREWORD

The Division of Magnetic Fusion Energy within the U. S. Energy Research and Development Administration has initiated within the fusion development program for tokamak power reactors a series of systems studies aimed at the definition of subsequent generations of tokamak devices leading to a commercial prototype reactor. Since April, 1976, a design team composed of representatives from the ORNL Fusion Energy Division and the Westinghouse Fusion Power Systems Department has been engaged in scoping studies associated with the definition of The Next Step (TNS) in the tokamak program after the TFTR. Provisional goals established for TNS include:

- Achievement of Ignition
- Demonstration of Burning Dynamics
- Evaluation of Design Requirements and Solutions for Long Pulse Operation
- Features which Extrapolate to a Viable Power Reactor
- Availability in the Mid-to-Late 1980's

It is in this context that the work reported herein was performed.

TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
1.0	INTRODUCTION AND SUMMARY	1-1
1.1	KEY PROJECT MEETINGS	1-1
1.2	TNS RESEARCH, DEVELOPMENT AND DEMONSTRATION NEEDS ASSESSMENT (SECTION 3)	1-1
1.3	TRADE STUDY LOGIC AND GROUND RULES (SECTION 4)	1-2
1.4	TOKAMAK CONFIGURATIONAL TRADE STUDIES (SECTION 5)	1-4
1.5	SYSTEMS DESIGN AND ANALYSIS (SECTION 6)	1-4
2.0	QUARTERLY REVIEW FOR ERDA-DMFE	2-1
3.0	TNS RESEARCH, DEVELOPMENT AND DEMONSTRATION NEEDS ASSESSMENT	3-1
4.0	TRADE STUDY LOGIC AND GROUND RULES	4-1
4.1	GROUND RULE STATUS	4-1
4.1.1	Changes in Ground Rules	4-1
4.1.2	Ground Rules not Incorporated in Present Trade Studies	4-4
4.2	COAST CODE STATUS	4-5
4.2.1	The Completion of COAST, Edition 1	4-5
4.2.2	A Summary Description of COAST	4-7
4.3	TNS DECISION MODEL DEVELOPMENT	4-16
5.0	TOKAMAK CONFIGURATIONAL TRADE STUDIES	5-1

TABLE OF CONTENTS (Continued)

<u>Section</u>		<u>Page</u>
6.0	SYSTEM DESIGN AND ANALYSIS	6-1
6.1	ELECTRICAL POWER SYSTEMS	6-1
6.2	POLOIDAL WINDING SYSTEM	6-8
6.2.1	Coil Description	6-8
6.2.2	Coil Failure Criteria	6-11
6.2.3	Coil Reliability and Redundancy	6-13
6.2.4	Design Recommendations	6-15
6.3	Nb ₃ Sn SUPERCONDUCTOR COOLING STUDIES	6-17
6.4	HEAT DISSIPATION SYSTEMS	6-25
6.4.1	Copper Field Coil Cooling Systems	6-26
6.4.2	Helium Refrigeration System	6-36
6.5	NUCLEAR ANALYSIS	6-46
6.6	VACUUM VESSEL SYSTEM	6-51
6.7	COMPACT POLOIDAL DIVERTOR DESIGN STUDY	6-54
7.0	REFERENCES	7-1
APPENDIX A	- POSTERS PREPARED FOR THE TNS QUARTERLY REVIEW MEETING AT ERDA ON JANUARY 28, 1977	AA-1
APPENDIX B	- TNS RD&D ASSESSMENT	AB - 1

LIST OF TABLES

<u>Table</u>		<u>Page</u>
3-1	TNS RD&D Activity Categories	3-3
3-2	TNS RD&D Priority Categories	3-5
4.3-1	TNS Selection Criteria	4-18
4.3-2	TNS Selection Criteria - 2nd Level Criteria	4-19
5-1	TNS-1, 3, 4, and 5 Machine Sizes and Costs Using Empirical Scaling with $\beta = 10\%$	5-3
5-2	TNS-1 Devices with 20 Coils Sized with TIM Scaling	5-8
5-3	TNS-4 Devices with 20 Coils Sized with TIM Scaling	5-9
5-4	TNS-3 Devices with 20 Coils Sized with TIM Scaling	5-10
5-5	TNS-5 Devices with 20 Coils Sized with TIM Scaling	5-12
5-6	Parameters of Selected TNS Configurations	5-14
6.2-1	Preliminary Machine Parameters for TNS-4	6-10
6.3-1	Design Parameters of the TF Coils of TNS-4 Analyzed	6-20
6.3-2	Preliminary Specifications of the Nb ₃ Sn Superconductors for the TF Coils of TNS-4	6-21
6.4-1	Effective Current Flat Top Time, T_{eff} , and Adiabatic Temperature Rise, $\Delta \theta_a$, for Typical TNS Copper Field Coils	6-28
6.4-2	Copper Coil Thermal Parameters Predicted by First Order Calorimetric Cool Down Model	6-35
6.4-3	Helium Refrigeration Load Typical TNS-3 Device	6-44
6.5-1	Geometry and Material Composition of a Typical TNS Shield and Coil Configuration	6-47

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
4-1	COAST Logic	4-8
4-2	Schematic of the arrangement of device components along the midplane of the tokamak	4-13
6.1-1	Early Copper TF Coil power-conditioning circuit as described in WFPS-TN-039	6-4
6.1-2	Revised Copper TF Coil power-conditioning circuit in COAST Editions 1 and 2	6-4
6.1-3	Preliminary configuration of the toroidal field coil electrical supply for superconducting windings	6-5
6.1-4	OH Coil power-conditioning circuit in COAST Edition 1	6-6
6.1-5	OH Coil power-conditioning circuit in COAST Edition 2	6-6
6.1-6	EF Coil power-conditioning circuits in COAST Edition 1	6-7
6.1-7	EF Coil power-conditioning circuits in COAST Edition 2	6-7
6.2-1	Preliminary schematic arrangement of TNS-4 (16 Nb ₃ Sn TF Coils)	6-9
6.3-1	J _c -H-T diagram of Nb ₃ Sn superconductor	6-18
6.3-2	Axial distribution of conductor critical temperature and threshold temperature for current sharing	6-23
6.3-3	Pressure drop and ideal pump work at normal operations	6-24
6.4-1	Lumped parameter transient coil cooling model	6-31
6.5-1	Comparison of nuclear heating rates in a typically TNS shield and coil from S ₈ -P ₃ and S ₆ -P ₁ ANISN runs	6-49

LIST OF FIGURES (Continued)

<u>Figure</u>		<u>Page</u>
6.7-1	Proposed divertor design, flux in the chamber is compressed by two sets of coils	6-55
6.7-2	Plan and side view of poloidal divertor structure	6-56
6.7-3	Collector horn with liquid lithium wetted screens	6-59
6.7-4	Simplified magnetohydrodynamic channel flow for $\vec{E} \times \vec{B}$ pump	6-63
6.7-5	Lithium falls particles collecting surfaces	6-66
6.7-6	Particle collection method using solid getters	6-67
6.7-7	Expanded particle collection section ABCD of Figure 6.7-6. The scattered and sputtered neutrals are retrapped by baffles and ZrAl panels,	6-68
6.7-8	Solid getters	6-70
6.7-9	Temperatures of collector plate	6-71

1.0 INTRODUCTION AND SUMMARY

The TNS effort during the January-February-March, 1977 period included the completion of the first iteration of an assessment of the Research, Development and Demonstration needs for TNS and further development of system size and cost models to support TF coil technology and plasma size trade studies. The following material highlights key accomplishments during the quarter which are discussed in greater detail in subsequent sections.

1.1 REVIEW MEETING

Quarterly Review for ERDA-DMFE. A quarterly review of TNS progress was held with ERDA-DMFE in Germantown on Friday, January 28, 1977. At this meeting the integrated ORNL/(w) program status was presented. An hour presentation highlighting the Westinghouse effort during the past quarter was prepared. In addition, twelve posters (Appendix A) were prepared providing additional technical detail.

1.2 TNS RESEARCH, DEVELOPMENT AND DEMONSTRATION NEEDS ASSESSMENT (Section 3)

The ORNL/(w) and GA/ANL design teams were asked in January, 1977, by ERDA-DMFE to prepare an assessment of the RD&D activities necessary to assure that TNS can be operational in FY '86. The focus of the Westinghouse assessment was on specific design-related needs, which are reported in TME-044, March, 1977. A set of 139 RD&D task assessments was prepared along with estimates of priority and very preliminary estimate of cost. We conclude that a sufficiently firm basis exists for the initiation of TNS feasibility and conceptual design studies and that required RD&D can be performed in sufficient time to support the major financial decisions which must be made during the course of the project. A plan of action was proposed to support this contention.

1.3 TRADE STUDY LOGIC AND GROUND RULES (Section 4)

Despite the fact that some high priority tasks such as the RD&D assessment requested by ERDA were required during this quarter, a great deal of progress was made in our numerical capability for carrying out the trade studies. Version I of the COAST code was completed, including programming for cost models for all of the device components and facility, and placed into operation. The cost models were linked with the physical models programmed earlier.

The trade study logic and ground rules for these studies were presented in detail in the previous quarterly report⁽¹⁾. However, there have been some changes in the ground rules, and some of the analyses for determining component parameters were upgraded. These changes are discussed in Section 4.

Examples of some of the changes that were incorporated into Version I of COAST are: a) the early model for determining the radiation shielding requirements was generalized to allow for variations in pulse length and duty factor; b) the allowed ripple (peak-to-average) was increased from 0.5% to 1.0%; c) a model was introduced for determining the structure-to-conductor ratio for Cu TF coils rather than using a single value for all cases; d) the required power conversion component ratings for the copper and hybrid TF coil systems were upgraded to include the resistive losses as well as the stored energy; e) the heat dissipation system that had been conservatively based on peak levels previously, now more realistically, accounts for the transient behavior of the heat load; and, f) the pump efficiency for the He cooling system was increased from 25% to 50%.

In order to get the automated trade studies underway, Version I of COAST was considered closed, detailed checks were made of the models, and the code was placed in production usage. Documentation of the technical and cost models was initiated and reports will be distributed during the next quarter. As a result of the preliminary calculations with COAST-I, plans are crystallizing for the manner in which the studies will proceed and appropriate formats for the presentation of results.

Refinements and generalization of the models are still being carried out. In addition, as analyses of the results of COAST-I are carried out, improvements in the models are emerging. All of these changes will be incorporated into COAST-I to generate COAST-II which should be available before the end of April. Most of the differences between COAST-I and COAST-II will be in the costing models and base costs.

The trade study techniques will have been established with the scoping analyses carried out with COAST-I by the time COAST-II becomes operational. COAST-II will be used to confirm the findings obtained with COAST-I and to carry out sensitivity analyses.

In addition to obtaining the tools for carrying out numerical analyses of the trade studies considerable effort was spent this quarter on establishing methods for evaluating the less quantifiable aspects of the various options such as degree of risk, reliability, ease of maintenance, etc. A systematic technique is being developed for rating the options under study relative to their non-quantifiable aspects. Two decision models are currently being studied.

One decision model is based on establishing a comparison matrix of selection criteria. Every one of the options under study is given a relative rating for each criteria. The sum of the ratings can then be compared to establish a favored option. The first and second level criteria and some of the weighting factors of the comparison matrix are presented in Section 4.3.

The second decision model attaches a cost to each and every selection criteria. In this case the selection would be made on the overall costs of the various options. However, it is more difficult to assign absolute dollars to a particular aspect of a candidate than to assign a relative rank. On the other hand, a comparison of options should be more easily carried out when simply based on cost.

1.4 TOKAMAK CONFIGURATIONAL TRADE STUDIES (Section 5)

The first operational version of the COAST code has been used to generate preliminary results for the four TNS coil technology options. Two types of plasma scaling, empirical and trapped ion mode (TIM), were used to study size and cost trends of the various machines. The results presented in Section 5 are very preliminary and will probably be revised as the cost models in COAST are improved.

From this set of preliminary results from COAST for the four TNS coil technology options, several observations can be made, including:

- For the same size (a , R) device, TNS-1 (Cu-TF) is more expensive than TNS-4 (Nb_3Sn -TF) due to power conversion costs, but the field margin is larger for TNS-1.
- TNS-3 (NbTi-TF) devices which achieve ignition with $R < 7$ m will require operation with $\beta > 10\%$.
- For the same size device, TNS-3 is less expensive than either TNS-1 or TNS-4. However, the field margin with β of 10% is much smaller for TNS-3.
- TNS-5 (Cu-NbTi-Hybrid TF) costs are $\sim 50\%$ larger than the costs for the other coil technologies.

1.5 SYSTEMS DESIGN AND ANALYSIS (Section 6)

The circuit concepts and the costing base for the poloidal coil systems were revised this quarter. The OH system was modified to eliminate a separate power supply during burn by providing the plasma current buildup capability in the form of separate series supplies which can be operated aiding or bucking to get the necessary voltage, without all the

current going through the generator. This change eliminated the need for the shunt switch across the power supply. The EF fields were changed in the same way as the OH and the power supply sizes were reduced by providing the initial drive from a charged capacitor. The copper coil TF supply was altered by replacing the phase-controlled power supply with a straight rectifier and providing the voltage control from the generator. Cost modifications were made in COAST to reflect these changes. In addition, cost provision was made to permit pricing either solid state or mechanical switches.

The preliminary version of the COAST code was completed, and initial calculations made to verify the modeling. A report is being prepared which documents the ground rules, assumptions, cost modeling basis, and the analyses developed in preparing the code. The unit cost information is being upgraded as new information becomes available.

Cooling studies for the Nb_3Sn superconducting TF coils have been initiated and preliminary results obtained for a TNS-4 coil configuration. The current density limit in the peak field area was determined to be 2445 A/cm^2 of winding area. In order to raise the average current density in the coil and reduce the coil size the winding is graded in three zones. A graph has been prepared, from the analysis based on 30 seconds operating out of 300 seconds, from which the pumping power can be determined.

Nuclear shield analysis has been performed to evaluate the best approximation to use in the ANISN computer code. Much of the previous work has been done using the S_6-P_1 approximation. Significantly improved results were achieved with the S_8-P_3 approximation, with the expected result that the nuclear heating rates deep within the shield and in the coils is calculated to be substantially higher; for example, 67% higher in the TF coils. Work has been initiated to convert the ORNL VITAMIN-C fusion library to operation in the CDC-7600 machine. A program has been implemented which provides for integration and collapsing of the ANISN output.

A review of the vacuum vessel shape in COAST has been performed. Several alternate shapes might be better fits for the proposed plasma shape. For the purpose of relative cost determination, it is felt that no bias results for any of the designs by using the elliptical cross section currently in COAST.

A preliminary conceptual mechanical and thermal design has been prepared for evaluation of the engineering feasibility of the compact poloidal divertor. A workable mechanical design which fits into the available space and the modified magnetic field map is available. The thermal and MHD calculations for the lithium getter indicate that the design is feasible. The plumbing and the electrical auxiliaries for the lithium system are significant in size. As an alternative, a solid getter system backed by ZrAl auxiliary pumping system is being evaluated.

2.0 QUARTERLY REVIEW FOR ERDA-DMFE

A Quarterly Review Meeting was held in Germantown on Friday, January 28, 1977. At this meeting the integrated ORNL/Ⓢ program status was presented. An hour presentation highlighting the Westinghouse effort during the past quarter was prepared. In addition, twelve posters were prepared providing additional technical detail in the following areas:

Hybrid Toroidal Field Coil Electrical Considerations. This work reviewed the problem of electromagnetic interactions between the two TF coil segments (outer windings of superconducting NbTi and inner windings of water-cooled copper) and presented circuit configurations, current and voltage profiles, power requirements for both coil segments, and scenarios for the operation of the copper windings in the pulsed mode.

OH Winding Modeling Considerations. The development of an OH winding design and analysis procedure was described. The technique permits consideration of hoop stress limits, current density and space constraints to arrive at the design parameters and cost of a technically feasible coil configuration.

Power Conversion Systems. Typical circuit configurations for the TF and PF power conversion systems were presented, illustrating how these functions are accomplished for each of the TNS options. A summary of the OH bias optimization study was also included.

Facility Heat Dissipation Systems. Equipment arrangements and flow schematics developed for the trade studies were presented.

Tritium Systems. Modeling ground rules, design criteria and system flow schematics were presented to indicate how the tritium systems are represented in the trade studies was presented.

Segmentation and Remote Handling. The results of preliminary studies related to TNS assembly and disassembly concepts were described.

Typical TNS Device Arrangements. Four posters were used to display a point design for each version of TNS. These designs show the major physical features and component arrangements associated with a specific set of ignition device parameters.

Typical TNS Parameters and Scenarios. The major design parameters associated with an early TNS-3 (with superconducting NbTi TF coils) reference design were summarized. Of particular interest was the development of a standard time-line or operating scenario for a typical experiment which is used as the reference scenario for the trade studies.

Compact Poloidal Divertor Design. The essential features of an innovative poloidal divertor concept were presented. Should a divertor be found to be necessary for the attainment of TNS goals, this concept appears to minimize the penalty in TF coil size usually associated with poloidal divertors.

These posters are reproduced in Appendix A of this report.

3.0 TNS RESEARCH, DEVELOPMENT, AND DEMONSTRATION NEEDS ASSESSMENT

The ORNL/Ⓜ and GA/ANL design teams were asked in January, 1977 by ERDA-DMFE to prepare an assessment of the RD&D activities necessary to assure that TNS can be operational in FY '86. The focus of the Westinghouse assessment was on specific design-related needs, and are reported in TME-044, March, 1977. This compilation was made Volume 3 of the total assessment prepared by ORNL, which included:

Volume 1 - Executive Summary

Volume 2 - R&D Needs Assessment

Volume 3 - Project-Specific RD&D Assessment

Volume 4 - Program Planning

The specific objectives for the total assessment which were 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 for 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.

On the basis of a review of draft material completed in January, and comments received from ORNL personnel, a final set of 139 specific RD&D task assessments was prepared along

with estimates of priority and a very preliminary estimate of cost. We conclude that a sufficiently firm basis exists for the initiation of TNS feasibility and conceptual design studies and that required RD&D can be performed in sufficient time to support the major financial decisions which must be made during the course of the project. A plan of action was proposed to support this contention.

In this assessment the definition of what constitutes RD&D as opposed to normal design activities associated with Plant and Capital Equipment (PACE) was consistent with ERDAM Appendix 1101, Part VI, to the extent possible. Both generic and design-related RD&D requirements were considered, however, the bulk of the material prepared by Westinghouse in this assessment was concerned with specific design-related activities which are required during the course of, and in parallel with, conceptual and construction design phases. ORNL developed complementary information, primarily associated with generic and supporting technology programs. The specific definitions of RD&D used in the Westinghouse assessment are given in Table 3-1.

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 was made as to the priority and cost of the RD&D items. Priorities for each item were established based on the definitions given in Table 3-2. The categories defined were: 1) critical, 2) important, 3) necessary, and 4) generic. Costs were estimated based on experience and engineering judgement and must be considered very preliminary until the development of a baseline TNS design and the preparation of more detailed work scopes for the RD&D tasks. 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.

TABLE 3-1

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.

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 3-2

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.

Appendix B contains an overall listing of the RD&D items which were identified in the 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 and safety research which can benefit the project. Section 8, Applied Physics/Plasma Engineering, highlights some of the theoretical and plasma physics tasks which need to be carried out at the major tokamak laboratories to support 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.

The recommended plan of action to assure that TNS will proceed on schedule included the following elements:

- Initiation of a strong baseline design effort.
- Delineation of physics uncertainties and their engineering design implications.

- Provision for strong RD&D management controls.
- Provision for design-oriented RD&D technical coordination and initiation of high priority RD&D during conceptual design.
- Identification of key technical decision milestones and provision for timely initiation, termination or redirection of these efforts based on continuous technical and management review.

4.0 TRADE STUDY LOGIC AND GROUND RULES

4.1 GROUND RULE STATUS

In evaluating the four TNS options, a set of ground rules was established to enable comparisons to be made on an equal basis. Two types of ground rules have evolved depending on whether the application is a general one covering all four options or the application is specific to a particular option. An example of the first type is the following: all the PF coils have water-cooled copper conductors. As an example of the second type, a specified ground rule which applies to TNS-4 only is one which sets the structure-to-conductor area (A_s/A_c) at 1.75. The numerical value of A_s/A_c is different for the other options. The detailed ground rules for all the various components and subsystems were reported in a document, dated November 30, 1976, and entitled "Development of the TNS Reference Design Choice - Representative Data for Trade Study Modeling", (ORNL/CF-76/379). Since the issuing of that report, the COAST code was developed and the ground rules were updated for various reasons. In this section, changes in the ground rules which have occurred since November, 1976 are discussed. A discussion of those ground rules which have no impact on the trade studies using the COAST code is also presented in Section 4.1.2.

4.1.1 Changes in Ground Rules

The following is a summary of those changes in the ground rules which most directly impact the trade studies and the COAST code:

Radiation Shielding. The models for the scaling of the thickness of both the device shielding and the reactor cell shielding have been refined such that they are now explicit functions of the TNS time scenario and radiation limits. The actual volumes of shielding materials are now computed from geometric considerations and the costing based on those values. Previously it was assumed that the device shielding volume was proportional to aR_o .

Toroidal Field Coils - All Types. The ripple in the toroidal field at the outer edge of the plasma has been increased from 0.5% to 1.0% (peak to average value).

Toroidal Field Coils - Copper Only. The structure-to-conductor area (A_s/A_c) is calculated as a function of hoop stresses rather than set at constant value of 0.45. The packing factor was originally 0.70, and has been increased to 0.75.

Toroidal Field Coils - Superconducting Only. The cooling requirements of 50 kW maximum for the time-averaged refrigeration power at helium temperatures has been re-examined and the present COAST code calculates the required cooling based on losses due to conduction, convection, pumping power, on losses at mechanical joints, and on nuclear heating. The velocity of the coolant is no longer assumed to be a constant of 0.3 m s^{-1} , but is allowed to vary in magnitude. A packing factor of 0.6 is now used in COAST calculations. A packing factor was not specified in the original ground rules.

Tritium Systems. The plasma D^+ (or T^+) density during burn was assumed to be a constant, 10^{20} m^{-3} . This density is a parameter which is calculated according to the physics constraints. The tritium processing losses during recovery-recycle operations were estimated at 0.15%.

Heat Dissipation Systems. The de-ionized water cooling system, as well as the pressurized water cooling system for the neutral beam arms were included as part of the heat dissipation systems, but the recent COAST considerations have included them as part of the neutral beam system itself. This change is consistent with the ORNL TFTR neutral beam system. This change has not had any effect on the general plant cooling since the overall heat loads continue to include those from the beam arms.

The primary cooling system was originally sized such that the coolant flow would be determined as the sum of the flows required to cool peak equipment heat loads. Presently, this system is assumed to be similar to a turbine-generator cooling system such that it is sized to meet a peak cooling demand for adiabatic heating followed by exponential cooling having a 73-second time constant.

The pumps used in the supercritical helium primary coolant loop for the TF coils has an efficiency which was increased from 25% to 50%. The refrigerator costs for the helium cooling was changed from a method based on Strohbridge (NBS Technical Note 655) to one in which a unit cost per watt is an input in COAST. The compressor power is now assumed to be a fixed value times the calculated refrigeration load, whereas it was originally based on a Carnot efficiency.

Electric Energy Storage and Conversion Systems. The TF coil power systems are specified in different manners, depending on whether the coils are copper, superconducting, or hybrid. For the copper coil power, the dump is through the power supply and no crowbar is included in the system. In the hybrid design the superconducting windings operate at steady-state current.

The neutral beam power conversion system is presently considered in COAST calculations as part of the total neutral beam system and is not specifically rated or costed as part of the power conversion systems as considered under the heading of Electric Energy Storage and Conversion.

The poloidal coil power systems have ground rules which have changed very little over the period, but the incorporation of these ground rules in arriving at the various ratings and cost scalings has been under careful study throughout the quarter.

4.1.2 Ground Rules Not Incorporated in Present Trade Studies

For a number of reasons, certain ground rules established in November, 1976 are not presently used in the trade studies and thus not in COAST. The main reasons are: 1) the ground rule is of a general nature with no direct effect on the sizing and costing of TNS, 2) the ground rule addresses an aspect of a component in more detail than can be modeled in the trade studies and have only a second order effect on the sizing and costing, and, 3) the ground rule has sufficient overlap with other ground rules that it is not necessary to incorporate it. Summarizing as in Section 4.1.1, the ground rules not incorporated include:

Radiation Shielding. The quarterly permissible radiation doses of 600 mrem to personnel in restricted on site areas and the annual permissible radiation doses of 1000 mrem to personnel in restricted areas on site have not been incorporated into the studies. These dose limits can be applied as the details of the buildings and facilities are worked out.

Toroidal Vacuum Vessel. A number of rules with regard to the vessel are not used and include: the limiter supports will be TZM, the maximum bulk temperature of the vessel will be 400°C , and the circulation rate will be sufficient to provide a heat transfer coefficient, h , of $20 \text{ kW m}^{-2} \text{ K}^{-1}$.

Toroidal Field Coils. Since the number of turns is not required in COAST, the conductor current, e.g., 20 kA for TNS-1, is not used throughout most of the code. The only exception is in sizing the liquid helium refrigeration system where each cooling channel is assumed to cool a specific number of current turns. The temperature limits for the copper coil cooling and the pressure limits for all the coil cooling systems have not been utilized since such requirements are details and not anticipated to have an impact on the trade studies. The rule on the number of conductors per slot for the S/C coils has not been invoked in COAST since the value of A_s/A_c is sufficient to size the coils given a value for current density.

A number of ground rules specific to the TF coil electrical insulation have been given in the November, 1976 report, but with few exceptions those rules have not been included in the trade studies since they provide detail for an engineering design rather than for a scoping design study as presently undertaken.

Heat Dissipation Systems. An average circulating water temperature rise of 10 K has not been incorporated. Various water cooling subsystems for the rotating machinery for the OH coil energy storage and miscellaneous electrical apparatus has not been addressed in COAST.

Electrical Energy Storage and Conversion System. Most of the ground rules on these systems are of a general nature and even though they apply, many have only second-order effects and have not been directly incorporated in the trade studies.

4.2 COAST CODE STATUS

During the quarter the first edition of COAST was completed and was immediately incorporated into the trade studies. As the code was being developed it was providing results for the trade studies, but a well-defined survey procedure was not used until the edition was finalized. In the following two subsections brief descriptions of the work which was carried out this quarter to complete the COAST code (edition 1), and of the main features of the code itself are given.

4.2.1 The Completion of COAST, Edition 1

At the beginning of the quarter, the programming for the sizing of TNS-1, TNS-3, and TNS-4 was essentially complete. The sizing of TNS-5 and the cost modeling were the main additions in COAST required to complete all the calculational steps. Since the two-coil hybrid design of TNS-5 is considerably more complex than the design of the other three devices, a number of special parameters and equations are required. For example, the required number of ampere-turns is divided between two coil sets such that the field on axis, the field at the inner copper coil and the field at the outer S/C coil are all consistent with the requirements

for each. In addition, the incorporation of two coil sets requires special attention to access requirements for neutral beam ducts as well as to the tabulation of machine space requirements within the bore of each coil set. The TNS-5 option is a combination of TNS-1 and TNS-3 and where possible calculations which apply to these two options are also applied to TNS-5.

The entire set of cost models, most of which were developed to a degree last quarter, were incorporated in the COAST code during this three-month period. The cost models are directly coupled to the sizing models and use of the results of the sizing calculations as a data base. In addition to the sizing data, a set of unit cost coefficients, obtained through vendor quotes, manufacturing information, engineering judgement, etc., and read into the COAST code, complete the required information to carry out the trade studies.

Other additions and updates to the COAST code include the following items. The completion of the empirical scaling ($na = \text{const}$, and $a^2 B_t^4 = \text{const}$ when β and T are constant) logic for all options, and for cases where margin, i.e., more field on axis than required for ignition according to the scaling laws, is calculated assuming a consistent set of engineering ground rules. A generalized model for the radiation shielding system was added. The new shielding models are explicitly dependent on plasma pulse length and repetition rates as well as anticipated annual and total full-power D-T pulses. A third change which should be mentioned is in the logic for the selection of the radius of the outer leg of the TF coils. Taking TF ripple at the plasma edge, neutral beam access requirements, and machine space requirements to fit all the components necessary within the TF coil bore into account, a step of COAST selects this radius and an indication in the output is made as to which requirement is dominant. In a fourth change, the heat loads on the heat removal system were updated. The copper TF coil power conversion system was remodeled to take proper account of resistive losses as well as ratings on individual components such as the flywheel and the rectifier. Finally, the output listing of device geometry, component-by-component, was expanded and now includes tables for both vertical and horizontal directions.

4.2.2 A Summary Description of COAST

A detailed description which documents the logic, the sizing and cost calculations (including those mentioned in the previous section), and a set of user's instructions for COAST will be completed as a separate report. The last section of that report is a summary and the following paragraphs are taken from that summary.

The code is in FORTRAN and consists of a single routine which can best be described as a large set of three calculational loops (DO-loops) nested one within a second, which in turn is nested inside the first two. The first loop is over device options (TNS-1, TNS-3, TNS-4, and TNS-5), the second over the scaling data read in, and the third over the choices for the number of discrete coils per TF coil assembly. The logic in COAST is shown in Figure 4-1 and consists of twenty-six calculational STEPS. The logic allows physics data to be incorporated in COAST in two distinctly different manners. The first is one in which the major radius is minimized for given values of minor radius and field on axis, while in the second, these three parameters--minor radius, major radius, and field on axis--are specified and any resulting tokamak which meets the ground rules will provide at least as much field on axis as required for ignition.

The first fifteen STEPS in COAST involve the calculation of the main sizing features of the device and of all the device parameters required for the costing calculations. The sizing includes the dimensions, volumes, masses, and ratings of components along the midplane (the definitions of the symbols are given in the COAST report). Figure 4-2 indicates schematically the arrangement of components along the midplane of the tokamak.

In the costing portion of COAST, STEPS XVI through XXIV, there are a total of 38 items which are costed based on the physical sizes and electrical, thermal, and mechanical ratings arrived at in the first half of the code. These items have been grouped into five main systems where the first system, the Tokamak System, is the one most frequently encountered in costing

Figure 4-1. COAST Logic

Figure 4-1. COAST Logic (Continued)

Figure 4-1. COAST Logic (Continued)

Figure 4-1. COAST Logic (Continued)

Figure 4-1. COAST Logic (Continued)

and sizing studies. The four other systems are often considered in less detail and include the electrical systems, the support systems, the facility, and the neutral beam systems. For example, the support systems, as presented in COAST, consists of considerable detail for the makeup of the fuel handling system, the tritium cleanup systems, and the radioactive waste systems. Such systems are generally considered important, but are not quantified. The costing also includes the calculation of EDIA, installation, shipping and handling, and contingency costs.

The last two STEPS, XXV and XXVI, along with parts of other STEPS provide the user with considerable output data from each COAST calculation. This data is printed in a well-planned set of tables. The tables and user's instructions are discussed in the COAST report.

A primary emphasis throughout the COAST calculation and logic has been in arriving at details on the various TF coil assembly options in the code. The four options include: 1) TNS-1, water-cooled copper coils; 2) TNS-3, superconducting NbTi coils; 3) TNS-4, superconducting Nb₃Sn coils, and 4) TNS-5, hybrid coils made of copper coils within NbTi coils. The number, N_{TF} , of discrete coils is an input variable within the values of $N_{TF} = 16, 20, 24, \text{ and } 28$, so that the size and cost differences associated with a change in N_{TF} can be studied. In all cases the TF coils are assumed to be constant-tension D-shaped coils, and the high field side of the coil inner legs have an upper limit for the magnetic field at the conductor, and this value is an input parameter arrived at from independent engineering considerations. The coils are also constrained by the requirements on TF ripple at the inner leg, and neutral beam access requirements and ripple conditions at the plasma for the outer legs of the TF coils. The ratio of the structure-to-conductor cross-sectional areas are required as input so that the user can apply engineering judgement in the structural aspects of the coil design. In addition to detail on the TF assemblies there is also a set of detailed calculations for arriving at the ratings for the power supplies required to operate the coils. Each of the four coil systems is handled on an individual basis to allow these ratings to reflect the differences in the electrical powers and energies required.

In addition to the TF coils, COAST handles a number of other device systems in considerable detail, and a few outstanding examples are the following. The poloidal field coils which include a copper OH coil assembly occupying the device inner bore and an EF assembly contained within the TF bore, are sized on the basis of the COAST calculated volt-seconds requirements as well as on the assumption that the total EF current is equal to the plasma current. The device and reactor cell nuclear shield systems have been modeled to take into account the radiation damage of magnetic field coil insulation, the heating rates in the superconducting coils, and in the dose limitations at the TNS site boundary. The heat dissipation systems have been modeled to include individual ratings for cooling the TF coils, the vacuum vessel, the nuclear shield, the neutral beam injection, and the poloidal field coils. The last examples which should be mentioned (keeping in mind others could also be included in this list), are the fuel and tritium systems. The cost models for the various gas handling systems which include the cleanup systems and radioactive waste handling system have been developed with special attention toward the representation of the effect of the plasma size, the pulsing rate and duration, the helium production rates in the plasma, and the neutral beam injection requirements.

The COAST code does take into account the entire facility. The reactor cell is sized for the device components and neutral beam injectors, and the facility is modeled to include remote handling, offices, work shops, etc. This first edition of COAST does not address the employment of divertors on TNS. This aspect of TNS is being considered by studies independent of the COAST analyses, and will be added to the trade studies considerations in the near future.

As for the application of COAST in future studies including the divertor question, the code will undergo a number of updates. In particular, one of the near-term applications of COAST will be in the sensitivity studies of the engineering ground rules presently applied to TNS. To this end, the code is being generalized to take into account the explicit dependence of component sizes and costs on plasma pulse length, pulse repetition rate, neutron production rate, plasma elongation, etc. It is believed that almost all the explicit dependences are now incorporated but a study will be conducted to firmly establish this. In addition, there

will also be an update on the models for the ratings and costs of the poloidal field coil assembly power supplies. The present power conversion models are considered as reasonable ones for the initiation of COAST, while more detailed ones are being developed.

4.3 TNS DECISION MODEL DEVELOPMENT

The trade studies performed to date have generated tentative performance parameters and costs for four TNS options distinguished primarily by TF coil technology. Though the COAST code allows the size and capital cost of each candidate TNS to be determined, the candidates also differ in less easily quantifiable ways, such as risk, reliability, and development requirements. These other factors will have an important influence on the final recommendation as to plasma size and TF coil technology.

Many everyday examples could be cited to show the difficulties inherent in making decisions taking relatively subjective factors into account. Decision models of various kinds are being studied to;

- Provide an organized framework for discussion.
- Determine the most relevant factors related to the decisions.
- Assess the relative importance of the various factors.
- Quantify the evaluation process.
- Explain the methods and results to other interested parties.

In this section, the decision models considered to date will be described, their advantages and disadvantages pointed out, and the preliminary results displayed.

Two decision models are being considered currently: a comparison matrix, and an evaluated cost model. The comparison matrix decision model will be described first. A comparison matrix consists of a hierarchy of selection criteria, a set of weights, and a rating process

which can be applied to each candidate. Primary, or first level, selection criteria are the most general (favorable) properties to be considered; they overlap as little as possible logically. Weights from 0 to 1 indicate the relative importance of each criterion; the weights sum to unity. The degree to which each candidate fulfills the criterion is its rating for that criterion. The first level criteria may be in turn divided into second level criteria in order to make the rating process more specific. The hierarchy can be extended to any sensible degree. The result of applying the rating process results in a ranking of the candidates.

The advantage of a comparison matrix decision model are:

- It explicitly arranges and weights the factors.
- Diverse factors can be included in the decision making process.
- Sensitivity analyses with respect to weights can be performed.

Potential disadvantages of this method are:

- The influence of a particular selection criterion far down in the hierarchy may be obscured in the overall figure of merit.
- The comparison matrix may fail to discriminate adequately between candidates.
- Quantitative ratings for the more subjective selection criteria may be questioned.

The advantages and disadvantages of the comparison matrix will become clearer as its application to the TNS candidates continues.

A hierarchy of first and second level weights has already been subjected to one iteration of internal discussion. Table 4.3-1 shows the first level selection criteria and weights to date. The weights are only indicative. Table 4.3-2 shows the second level selection criteria to date. Weights for them have not yet been assigned. The selection criteria and weights clearly are subject to further discussion and refinement.

TABLE 4.3-1
TNS SELECTION CRITERIA

<u>FIRST LEVEL CRITERIA</u>	<u>WEIGHTING FACTOR</u>
- COST	0.45
- SCHEDULAR/DEVELOPMENT RISK	0.20
- OPERATIONAL RISK	0.15
- OPERATIONAL FLEXIBILITY	0.10
- RELEVANCE TO REACTOR TECHNOLOGY	0.10
	<hr/>
	1.00

TABLE 4.3-2

TNS SELECTION CRITERIA - 2ND LEVEL CRITERIA

<u>Cost</u>	<u>Schedular/Development Risk</u>	<u>Operational Risk</u>
<ul style="list-style-type: none"> - Capital Cost - Operating Cost - Development Cost 	<ul style="list-style-type: none"> - Materials Dev. Risk - Component Dev. Risk - Remote Handling Techniques Dev. Risk - Ease of Assembly 	<ul style="list-style-type: none"> - Plasma Physics Risk - Reliability - Ease of Maintenance - Sensitivity to Design Uncertainties
<u>Operational Flexibility</u>	<u>Relevance to Reactor Technology</u>	
<ul style="list-style-type: none"> - Dead-Startup Preparation - Poloidal Field System Flexibility - Blanket/Shield Experimentation - Thermal/Neutron Yield Handling Capability 	<ul style="list-style-type: none"> - Features/Components like DEMO - Performance Parameters like DEMO - Components Size like DEMO - Upgrade Capability 	

The other decision model currently under consideration is an evaluated cost model. In this model, a dollar cost (or value) is attached explicitly to each set of non-overlapping selection criteria. Risk can be treated parametrically by trading off expenditures in development against the probability of failure. This approach has proved useful to electric utilities, who must consider the impact upon revenue of delays in construction or timing in addition to power plant capacity.

An advantage of an evaluated cost model is that presentation in terms of dollars makes comparisons of options easier than relative merit.

A disadvantage of an evaluated cost model is that it is more difficult to assign absolute dollars to a particular aspect of a candidate than to assign a relative rank.

These two approaches to decision modeling are not very different conceptually. If cost is one of the first level selection criteria of a comparison matrix, then an implicit or shadow cost can be calculated for the other first level criteria. Also, as a general rule, the same information about each candidate is used for either model. To a large degree the differences are in presentation rather than substance. It is planned to continue with the evaluated cost approach as a cross-check on the comparison matrix.

5.0 TOKAMAK CONFIGURATIONAL TRADE STUDIES

The COAST code described in Section 4.2 has been used to generate preliminary results for the four TNS coil technology options. Both types of scaling, empirical and trapped ion mode (TIM), were used to study size and cost trends of the various machines. It must be stressed that the results presented here are very preliminary and will be revised as the cost models in COAST are updated.

Recall that for empirical scaling with COAST, the minor radius a and aspect ratio A are input. The code then solves for the toroidal field on axis B_t needed for ignition for a given value of β . The actual field on axis, B_{tt} , may be larger than B_t for the specified (a, A) machine size, and hence empirical scaling usually results in a margin $\Delta B = B_{tt} - B_t$ in the field for the given β value.

For TIM scaling, a and B_t are input and COAST solves for the minimum major radius R which will yield a field B_t on axis. This field is assumed to be exactly that value required for ignition and thus there is never a field margin with TIM scaling. At present, all sets of (a, B_t) values assume $A = 4$. However, recent ORNL results⁽²⁾ indicate that the (a, B_t) values used are fairly insensitive to aspect ratio for a range of $A = 3$ to 7 .

The results presented here assume a plasma elongation of 1.6, Z_{eff} of 1.14, and plasma temperature (electron and ion) of 13 keV.

Empirical Scaling Results. For a first test of empirical scaling, a set of machines were generated for TNS-1, 3, 4, and 5 with 16 and 20 TF coils. Two sets of (a, A) values were used:

- $a = 1.2$ m, $A = 4, 5, 6$.
- $a = 0.8, 0.9, 1.0, 1.1, 1.2$ m, $R = 5.0$ m.

In addition, TNS-3 was run with $R = 6.0$ m and $a = 0.8 - 1.2$ m. The plasma beta for these cases was held at a constant value of 10%.

The results for these machines that were consistent are shown in Table 5-1. Some of the machines from these sets of (a, A) were not consistent, due either to insufficient mechanical clearance or too low a field on axis to achieve ignition.

Since TNS-1 (Cu) and TNS-4 (Nb_3Sn) have the same field (12 T) at the coil, they result in basically the same size machine, and are shown in the top portion of Table 5-1. The most important difference between the two is the margin in the toroidal field above that needed for ignition at the given beta value. TNS-1 has a larger ΔB than TNS-4 for the same a and R , because of the larger space required for shielding and dewars with the superconducting TNS-4 machine. This is equivalent to saying either that TNS-1 could operate at a lower β than TNS-4 for the same plasma density and temperature, or that TNS-1 could operate at a higher density (hence larger $n \tau$) for the same β .

It is also seen from Table 5-1 that 20 TF coil machines are less costly than 16 coil machines. This is because the coil size actually decreases for 20 coils because the constraint on percent ripple at the plasma edge is more easily satisfied. The 20 coil devices are limited by neutral beam access space, which restricts the coil size from decreasing farther. The next version of COAST will permit examination of a larger range of coil numbers and sizes. In addition, the relationship of manufacturing cost to coil number is being reformulated.

The table also shows that for the same size (a, R) device, TNS-4 with Nb_3Sn coils is less expensive than TNS-1 with Cu coils. The reason is that while the TF coil assembly cost and support systems cost for refrigeration, etc., in TNS-4 are larger than TNS-1, the TF power conversion equipment cost is much greater for TNS-1 than TNS-4. For most of the TNS-1 cases the TF power conversion cost is at least 20 % of the total device cost. Hence, while TNS-1 is slightly more expensive, it also operates with a larger field margin which provides

TABLE 5-1

TNS-1, 3, 4, AND 5 MACHINE SIZES AND COSTS USING EMPIRICAL SCALING WITH $\beta = 10\%$

R (m)	a (m)	A	On Axis B _z (T)	TF Margin ΔB (T)		TF Coils	Relative Cost		Case No.
				SC	Cu		SC	Cu	
TNS-1 and 4:									
5.0	0.8	6.25	5.63	0.8	2.5	16	0.544	0.620	1
5.0	0.8	6.25	5.63	0.8	2.5	20	0.539	0.575	1
5.0	0.9	5.55	5.30	0.9	2.5	16	0.582	0.668	2
5.0	0.9	5.55	5.30	0.9	2.5	20	0.564	0.617	2
5.0	1.0	5.00	5.03	0.9	2.5	16	0.626	0.722	3
5.0	1.0	5.00	5.03	0.9	2.5	20	0.605	0.665	3
5.0	1.1	4.55	4.80	0.9	2.5	16	0.675	0.789	4
5.0	1.1	4.55	4.80	0.9	2.5	20	0.650	0.718	4
5.0	1.2	4.17	4.59	0.9	2.5	16	0.746	0.895	5
5.0	1.2	4.17	4.59	0.9	2.5	20	0.709	0.782	5
4.8	1.2	4.0	4.59	0.7	2.3	16	0.802*	1.013*	6
4.8	1.2	4.0	4.59	0.7	2.3	20	0.775*	0.890*	6
6.0	1.2	5.0	4.59	1.8	3.3	16	0.738	0.921	7
6.0	1.2	5.0	4.59	1.8	3.3	20	0.704	0.849	7
7.2	1.2	6.0	4.59	2.6	4.0	16	0.866	1.137	8
7.2	1.2	6.0	4.59	2.6	4.0	20	0.820	1.038	8

* Current density in OH coils larger than value assumed in ground rules (15MA/m^2).

TABLE 5-1 (CONTINUED)

R (m)	a (m)	A	On Axis B _t (T)	TF Margin ΔB (T)		TF Coils	Relative Cost		Case No.
				SC	Cu		SC	Cu	
<u>TNS-3:</u>									
7.2	1.2	6.0	4.59	0.2		16	0.743	-----	9
7.2	1.2	6.0	4.59	0.2		20	0.706	-----	9
<u>TNS-5:</u>									
6.0	1.2	5.0	4.59	3.2		16	1.181	-----	10
6.0	1.2	5.0	4.59	3.2		20	1.092	-----	10
7.2	1.2	6.0	4.59	3.9		16	1.331	-----	11
7.2	1.2	6.0	4.59	3.9		20	1.233	-----	11

for operation at a lower beta or higher density. It must be stressed that these results are preliminary; in particular, the power conversion costs used in COAST are being reviewed to determine their validity and the possibility of cost reduction through the rearrangement of functions and circuit configurations.

Another way to compare TNS-1 and TNS-4 with empirical scaling is for machines with the same TF margin above ignition. Two such machines with the same minor radius of 1.2 m and field margin (~ 2.5 T) are given by cases 5 and 8 in Table 5-1. By comparing TNS-1 and TNS-4 with the same field margin and same plasma radius, one can make the following observations:

- The relative cost will be about the same (0.782 vs. 0.820).
- TNS-4 will have a larger major radius (7.2 m vs. 5.0 m).
- TNS-1 will have a larger TF power conversion cost, which is just about exactly off-set by the higher TF coil assembly cost for TNS-4.
- TNS-1 will have a larger OH power conversion cost due to the smaller machine size.
- TNS-4 will have a larger cost for the tokamak support systems.
- TNS-4 will have a larger neutral beam cost due to the larger plasma volume.
- TNS-4 will have a larger fusion power although the wall loading is the same as TNS-1.

The only TNS-3 machines that resulted from this set of runs with empirical scaling were for $R = 7.2$ m and $a = 1.2$ m, as shown in Table 5-1. There were no cases at all for $R = 5.0$ m or $R = 6.0$ m with a plasma radius of 1.2 m or less and a plasma beta of 10 %, which is due to the lower field limit for the NbTi coils of 8 T. However, this does not mean that TNS-3

cannot be built for R smaller than ~ 7 m. Instead, the beta value must be increased above 10% so that the required field for ignition decreases. This, however, implies a risk in the plasma physics basis for TNS-3 with $a \lesssim 1.2$ m and $R \lesssim 7.0$ m. This will be discussed further in the following section on TNS-3 with TIM scaling.

By comparing cases 8 and 9 in Table 5-1, one sees that for the same size device TNS-3 is less expensive than either TNS-1 or TNS-4. However, the field margin with β of 10 % is much smaller for TNS-3.

Only a few TNS-5 machines with the hybrid NbTi/Cu coils were found from this set of empirical scaling runs, due mostly to machine space limitations. Note that the TNS-5 costs are at least 50 % higher than for similar sized devices of the other options, reflecting the inherent complexity of TNS-5.

TIM Scaling Results. The four TNS coil technology options were also studied using TIM scaling to supply sets of (a, B_f) values. As noted earlier, the fields assumed here are those required for ignition with no margin for an aspect ratio of 4 and plasma density of $2.2 \times 10^{20} \text{ m}^{-3}$. The results for the four devices with 20 coils are shown in Table 5-2 thru 5-4.

A series of TNS-1 machines with $a \leq 0.9$ m is shown in Table 5-2. With the present TIM scaling, no TNS-1 device can be modeled by COAST with a minor radius larger than 0.9 m. This is because then the field requirement becomes too low and the machine size decreases to impractically low values ($R < 4.3$ m). This is a direct result of the "no margin" (a, B_f) scaling, and can be corrected by using a higher value of B_f in COAST, which forces a field margin. Such cases will be the subject of future studies with COAST. Note, however, that it is difficult to accurately determine the field margin for other aspect ratios since the (a, B_f) values have been calculated only for devices with an aspect ratio of 4.

From the TNS-1 devices shown in Table 5-2, it is seen that the relative cost passes thru a minimum for $a = 0.86$ m. For larger plasma radii the OH power conversion equipment costs dominate as the machine bore space decreases, until the point is reached at $a = 0.89$ m where the required current density in the OH coils is larger than the ground rule value of 15 MA/m^2 . For smaller plasma radii the larger machine size and TF coil size dominate the cost. Note that the plasma β for this set of TNS-1 machines ranges from 4% to less than 3%.

A series of TNS-4 devices with $0.85 \text{ m} \leq a \leq 1.1 \text{ m}$ is shown in Table 5-3. For the cases investigated, there is a minimum in the cost for $a \simeq 0.98$ m for the same reasons previously mentioned, i.e., large OH power conversion costs for the lower aspect ratio machines and larger overall size costs at larger values of R . The same effect of the no-margin scaling produces a maximum minor radius of 1.1 m, which violates the trade study ground rule* on the OH coil current density. To produce TNS-4 machines with COAST with aspect ratios less than 4.2 will require using some margin in B_t as discussed previously. Note that the device with $a = 1.04$ m and $R = 4.94$ m is essentially the TNS-4 point design case discussed in the previous quarter (1). The range in β for this set of machines varies from a high 7.1% at $a = 1.1$ m to 3.1% at $a = 0.85$ m.

By comparing TNS-1 and TNS-4 from Tables 5-2 and 5-3, one sees that the minimum cost for each is about the same. However, as was observed for the empirical scaling cases with the same field margin, TNS-4 is a slightly larger machine which would perhaps facilitate construction and maintenance of the device.

Seven TNS-3 machines are shown in Table 5-4 for a between 1.1 m and 1.43 m. Below $a = 1.1$ m the major radius becomes very large due to the higher field requirements for ignition. Note again there is a rather shallow minimum in the cost for $a \simeq 1.38$ m. The minimum TNS-3 cost appears to be about 10% larger than the TNS-1 and TNS-4 costs. The

* This particular ground rule is somewhat arbitrary and may be reviewed in future sensitivity studies.

TABLE 5-2
TNS-1 DEVICES WITH 20 COILS SIZED WITH TIM SCALING

<u>a (m)</u>	<u>R (m)</u>	<u>A</u>	<u>B_t (T)</u>	<u>β</u>	<u>Relative Cost</u>
0.90	4.30	4.78	7.26	4.0%	0.682*
0.89	4.50	5.06	7.50	3.7%	0.626*
0.88	4.73	5.38	7.75	3.5%	0.576
0.86	4.96	5.77	8.00	3.3%	0.571
0.85	5.25	6.18	8.25	3.1%	0.584
0.83	5.55	6.68	8.50	2.9%	0.605
0.81	6.38	7.87	9.00	2.6%	0.693

* OH coil current density larger than 15 MA/m².

TABLE 5-3

TNS-4 DEVICES WITH 20 COILS SIZED WITH TIM SCALING

<u>a (m)</u>	<u>R (m)</u>	<u>A</u>	<u>B_t (T)</u>	<u>β</u>	<u>Relative Cost</u>
1.10	4.63	4.20	5.5	7.1%	0.703*
1.07	4.78	4.46	5.75	6.5%	0.657*
1.04	4.94	4.75	6.0	6.0%	0.594
1.00	5.12	5.12	6.28	5.4%	0.566
0.98	5.32	5.43	6.5	5.1%	0.561
0.93	5.82	6.26	7.0	4.4%	0.569
0.90	6.12	6.80	7.26	4.1%	0.579
0.89	6.51	7.30	7.50	3.8%	0.603
0.85	8.09	9.52	8.25	3.1%	0.722

* OH coil current density larger than 15 MA/m².

TABLE 5-4
TNS-3 DEVICES WITH 20 COILS SIZED WITH TIM SCALING

<u>a (m)</u>	<u>R (m)</u>	<u>A</u>	<u>B_t (T)</u>	<u>β</u>	<u>Relative Cost</u>
1.10	9.30	8.45	5.5	6.8%	0.854
1.20	7.07	5.89	4.8	8.9%	0.688
1.25	6.47	5.17	4.5	10.1%	0.658
1.29	6.05	4.69	4.25	11.4%	0.640
1.32	5.90	4.47	4.13	12.0%	0.638
1.34	5.72	4.27	4.0	12.8%	0.633
1.38	5.42	3.92	3.75	14.6%	0.630
1.43	5.17	3.62	3.5	16.8%	0.651

TNS-3 case with $a = 1.34$ m and $R = 5.7$ m is particularly interesting since the aspect ratio is close to the value of 4 assumed in the TIM scaling. This machine is essentially the point design case for TNS-3 which was previously discussed⁽²⁾.

From this table of TNS-3 devices it is evident that to keep $R < 7$ m will require operation with β of $>10\%$. This is a direct result of the low field limit for the NbTi coils of 8 T. The only way to avoid this is to go to lower plasma density ($\sim 6 \times 10^{19} \text{ m}^{-3}$) and larger plasma radius (~ 2.0 m) and operate with a field on axis of ~ 3.5 T. This would result in a more conservative beta value of $\sim 5\%$. However, this size machine is basically in the EPR range and hence must probably be rejected for a TNS choice due to its larger cost. Thus, if a NbTi coil machine is to be built as a TNS, it will have to operate with higher beta values, with a resultant uncertainty in the plasma physics basis for the device.

Table 5-5 shows the COAST results for seven TNS-5 cases with $a = 0.81$ m - 0.90 m. Again because of the no margin scaling, the plasma radius must be less than 0.9 m. The TNS-5 costs pass through a minimum at $a \approx 0.83$ m, with the cost being about 30% to 50% higher than the other TNS options. Note that the beta values for these devices are in the relatively conservative range of less than 4%. The device with $a = 0.86$ m and $R = 5.1$ m is essentially the point design case for TNS-5 which was previously discussed⁽¹⁾.

Summary of Preliminary COAST Results. From this set of preliminary results from COAST for the four TNS coil technology options, several observations can be made, including:

- For the same field margin, TNS-1 (Cu-TF) and TNS-4 (Nb₃Sn-TF) have about the same relative cost, although TNS-4 is a larger device.
- For the same size (a , R) device, TNS-1 is more expensive than TNS-4 due to power conversion costs, but the field margin is larger for TNS-1.
- Devices with 20 TF coils cost less than devices with 16 TF coils.

TABLE 5-5
TNS-5 DEVICES WITH 20 COILS SIZED WITH TIM SCALING

<u>a (m)</u>	<u>R (m)</u>	<u>A</u>	<u>B_t (T)</u>	<u>β</u>	<u>Relative Cost</u>
0.90	4.43	4.92	7.26	4.2%	2.653*
0.88	4.87	5.54	7.75	3.7%	1.123*
0.86	5.11	5.94	8.0	3.5%	0.984*
0.85	5.41	6.37	8.25	3.3%	0.873
0.83	5.72	6.89	8.5	3.1%	0.827
0.82	6.11	7.46	8.75	2.9%	0.830
0.81	6.58	8.12	9.0	2.7%	0.858

* OH coil current density larger than 15 MA/m².

- TNS-3 (NbTi -TF) devices which achieve ignition with $R < 7$ m will require operation with $\beta > 10\%$.
- TNS-3 costs are $\sim 10\%$ larger than TNS-1 and TNS-4 costs.
- TNS-5 (Cu-NbTi-Hybrid TF) costs are $\sim 50\%$ larger than the costs for the other coil technologies.
- All of the TNS options show a minimum in the cost, with overall machine size costs dominating at small plasma radii and OH power conversion costs dominating at larger minor radii.

It must be stressed that these observations are all very preliminary, and will be subject to revision as further investigations of machine cost trends are performed with COAST.

As a basis of further study for each of the coil technology options, the devices with the minimum cost from the TIM scaling results have been selected from Tables 5-2 to 5-5. These machines are shown collectively in Table 5-6. The various component costs and mechanical considerations for each of these machines are discussed in more detail in the following sections. These machines have been selected only for illustrative purposes, and should not be considered as point designs.

TABLE 5-6
PARAMETERS OF SELECTED TNS CONFIGURATIONS*

	<u>TNS-1</u>	<u>TNS-3</u>	<u>TNS-4</u>	<u>TNS-5</u>
R_o , major radius (m)	4.96	5.72	5.32	5.72
a , minor radius (m)	0.86	1.34	0.98	0.83
A , aspect ratio (-)	5.77	4.27	5.43	6.89
B_z , field on axis (T)	8.0	4.0	6.5	8.5
B_m , peak field at TF coil (T)	12.0	8.0	12.0	12.0
β , total beta	3.3%	12.8%	5.1%	3.1%
I_p , plasma current (mA)	3.4	3.5	3.3	2.9
$V-S$, total volt seconds	119.8	84.8	108.8	140.4
V_p , plasma volume (m^3)	115.9	324.6	161.3	124.4
P_f , total fusion power (MW)	799.2	2239.0	1112.5	858.3
L_n , wall loading (MW/m^2)	1.96	3.26	2.28	1.88
N_{TF} , No. of TF Coils	20	20	20	20
Toroidal Field Coil Type	Cu	NbTi	Nb ₃ Sn	NbTi/Cu
Relative Cost	0.571	0.633	0.561	0.827

* Common parameters are: $\bar{n}_e = 2.2 \times 10^{20} m^{-3}$, $\bar{T}_e = 13$ keV, Elongation = 1.6,
 $q = 3$, $Z_{eff} = 1.14$.

6.0 SYSTEM DESIGN AND ANALYSIS

6.1 ELECTRICAL POWER SYSTEMS

The design and costing of the field coil power conditioning systems were altered in the past quarter. Projected costs for the copper coil toroidal field system were lowered by replacing the thyristor-controlled voltage supply with a diode supply and generator exciter control. Projected costs for the poloidal systems were lowered by a single circuit configuration change in each of the poloidal field power conditioning systems and by the use of temporary, passive energy storage in the EF systems during plasma initiation. The costing algorithms were also expanded to include individual costing of each subsystem functional block and to allow each block to be scaled as a function of pulse time, pulse rise time and plasma dimensions, including elongation. The geometrical scaling laws were also modified.

The toroidal field power conditioning system for copper coils was changed from the configuration shown in Figure 6.1-1 to that shown in Figure 6.1-2. An exciter control circuit is necessary in either case, but is used in Figure 6.1-2 to provide the 30-50% voltage swing needed during the toroidal field charging and flat-top pulse period. Between pulses, the energy in the TF coils is dumped passively, and any energy left in the coils at the beginning of a succeeding pulse is used to reduce the charging requirements for that pulse.

A preliminary circuit configuration was prepared for superconducting TF coil systems. Representative parameter values are defined for TNS-3. Figure 6.1-3 is the circuit diagram for this case. Using this as a basis, an initial failure modes and effects analysis was performed on the TF circuit for superconducting TF coils. No major changes are required in the design as a result of the study. Future effort should be devoted to evaluation of the reliability of the mechanical switch in isolating the power supply to allow a coil energy dump.

The ohmic heating power conditioning system was changed from the configuration shown in Figure 6.1-4 to that shown in Figure 6.1-5. The circuit shown in Figure 6.1-4 uses a high-voltage supply for charging and a low-voltage supply during the burn period, in order to avoid the low power-factor that would be generated at low d.c. bus voltages by a single controlled-voltage supply. This undesirable effect at low-voltage can also be eliminated by using two back-to-back controlled voltage sources, as shown in Figure 6.1-5. For example, when the d.c. bus voltage is zero, one supply is nearly full on as a rectifier and the other is operating as an inverter, so that they have opposite voltage polarities. This circuit is slightly more lossy than the circuit shown in Figure 6.1-4, but has a considerably lower capital cost.

The change from a low voltage supply with a shunt switch to back-to-back voltage supplies is also made in the equilibrium field systems (see Figures 6.1-6 and 6.1-7). A high-voltage capacitive energy storage system, consisting either of capacitors or homopolar generators, is used in the new design to provide the high voltage needed during the initial period of electrical breakdown in the plasma, as shown in Figure 6.1-7. The energy storage requirements of this system are not severe, because the high voltage is supplied for a short time only (typically 30 ms) and at low coil currents. The benefit is that the controlled voltage supply, which is the highest cost module in the equilibrium field system, is protected from the high voltage across the EF coils during the initiation period. The disadvantage is that some degree of control over the current waveshape is lost during the initiation period, in comparison with using a controlled voltage source. The amplitude and starting time of the initiation pulse can still be controlled, using the circuit shown in Figure 6.1-7.

Each block in the circuit block diagrams (Figures 6.1-2,5,7) is costed separately. Energy switching elements are costed as a function of the peak voltage across the block and the peak current through the block. Energy storage elements are costed as functions of peak power and peak energy storage. "Switches" are incorporated into the COAST code to change the circuit configuration. The "switches" incorporated into the code during this quarter provide the ability to compare capacitive vs. homopolar generator energy storage, solid-state vs.

mechanical d.c. switching and motor-generator-flywheel sets vs. running directly from a utility line. "Macro switches" which would allow the comparison of two different circuit topologies can also be inserted easily into the code.

The cost-determining currents and voltages are obtained for a reference case, by using a consistent set of specified currents and calculated voltages, using the per turn inductance-resistance matrix generated for the reference design. The inductances and resistances in the matrix are functions of size and elongation, the induced voltages are functions of "charging" times, and energy dissipation is a function of total pulse time. The OH current is not specified as the EF currents are, but is calculated as a function of the leakage between the EF coils and the plasma. The copper toroidal field system costs are specified as functions of maximum stored energy, pulse flat-top time, shaft speed variation and the ratio of charging voltage to flat-top voltage (which determines the charging time).

The geometrical scaling can be stated in terms of the inductance-resistance matrix. The plasma self-inductance is scaled as

$$R_o \left(\ln \frac{8 R_o}{a \sqrt{\delta}} - C \right)$$

The EF-EF mutual and EF self-inductances are scaled as R_o . The OH mutual and self-inductances are scaled as the self-inductance, using Smythe's formula for a thick-walled equivalent short solenoid. The OH mutual inductances are taken to scale as the OH self-inductance, by the assumption of complete coupling of the OH flux to the EF coils and plasma. The EF resistances are scaled as $1/R_o$, while the OH resistance is scaled inversely as the OH bore. The voltage and OH current scaling are then determined by the explicit solution of the Kirchoff voltage law for all 5 equivalent PF circuits at all time points of interest.

Note: Circuit permits TF Coil to be charged and dumped in 30 seconds every cycle through power supply. Crowbar only used in case of power supply failure.

Figure 6.1-1. Early Copper TF Coil power-conditioning circuit as described in WFPS-TN-039.

Figure 6.1-2. Revised Copper TF Coil power-conditioning circuit in COAST Editions 1 and 2.

Figure 6.1-3. Preliminary configuration of the toroidal field coil electrical supply for superconducting windings.

Note: Circuit provides full control start-up and full control shutdown at any time.

Figure 6.1-4. OH Coil power conditioning circuit in COAST Edition 1.

Figure 6.1-5. OH Coil power-conditioning circuit in COAST Edition 2.

Note: Circuits provide EF currents proportional to plasma current, proportional multiplier varies with time.

Figure 6.1-6. EF Coil power conditioning circuits in COAST Edition 1.

Figure 6.1-7. EF Coil power conditioning circuits in COAST Edition 2.

6.2 POLOIDAL WINDING SYSTEM

Studies of repair and maintenance of tokamak reactors are at a very early stage, but it is already obvious that a clear understanding of the maintenance requirements is essential in the design of reactor components. The effects of radiation and temperature from the plasma following shut-down will make it near impossible to service the structure using normal maintenance procedures.

In the current concept of the shaping field coils, the feasibility of the repair procedure is dependent on the development of reliable conductor joints and well proven remote maintenance techniques. However, the design of the shaping field coils should proceed, following sound engineering criteria in preparing a repairable system.

6.2.1 Coil Description

The shaping field coils are an important consideration for a flux-conserving tokamak such as TNS. Their purpose is to maintain plasma equilibrium during the heating phase of the cycle, at which time the plasma expands and becomes noncircular. The location of the coils relative to the plasma significantly influences plasma stability and power consumption in the coils. Both factors heavily favor placing the coils as close to the plasma as physically possible.

The TNS studies in FY '77 have included four classes of devices involving copper, NbTi, Nb₃Sn and hybrid TF coils over a range of machine sizes. Each machine variant used water cooled copper poloidal field coils insulated with radiation resistant resins. The shaping field coils are located within the bore of the TF coil array, as near to the plasma as design constraints would allow. The conceptual TNS-4 design shown in Figure 6.2-1 was selected from the studies to identify various components and to evaluate possible maintenance techniques. Table 6.2-1 summarizes the major parameters of the device.

Figure 6.2-1. Preliminary schematic arrangement of TNS-4
(16 Nb₃Sn TF coils)

TABLE 6.2-1

PRELIMINARY MACHINE PARAMETERS FOR TNS-4

Major Radius (m)	4.94
Minor Radius (m)	1.06
Elongation	1.6
Field on Axis (T)	6.0
Field at Conductor $B_{\max}$ (T)	12.0
TF Coils	16 - Nb ₃ Sn Superconducting
Coil Shape	Constant Tension "D"
Horizontal TF Bore (m)	4.3
Vertical TF Bore (m)	6.5
Poloidal Field Coils	OFHC Copper
Conductor Current Density	1.5 kA/cm ²
Conductor Coolant	Forced Flow Water

6.2.2 Coil Failure Criteria

The problem of coil maintenance can best be understood by stating the failure criteria the design must satisfy if the coils are to be serviceable. There are two classes of failures leading to the repair and maintenance of the shaping field coils; the first is primary failures resulting from coil damage and joint failure, and the second is secondary failures resulting from damage to other components in the device.

- **Primary Failures**

Primary failures to the coil result from radiation damage to the copper and random failures from non-nuclear causes. The total radiation dose could increase the resistivity of the copper and the power consumption of the coils, and damage the electrical insulation protecting the conductors, without adequate nuclear shielding. In TNS, this type of failure is minimized through the placement of nuclear shielding between the vacuum vessel and shaping field coils. The probability of random failures from non-nuclear causes is the significant maintenance problem. These include electrical insulation failures, structural failures and conductor joint failures. Servicing a multi-turn coil ($0 \leq T \leq 50$) to repair a random failure limited to several conductor turns is one of the maintenance problems a designer must solve if the system is to continue to perform its function.

- **Joint Failures**

All of the tokamak devices require that the SF coils be separable for the purpose of maintenance and repair. Also, their location within the bore of the TF coils necessitates that this be done in-place. Therefore it is critical to the success of any coil design to select a reliable conductor joint capable of sectioning the

conductor and joining the disconnection. Two concepts currently under investigation include coil brazing and mechanical connectors.

Welded or brazed connections have been used very successfully in the fabrication of coils in-place. A technique developed for silver-brazing field coils is described in detail in Reference ⁽³⁾. This method of conductor joining has produced a water-tight joint with a very low contact resistance. Although joint alignment and fixturing could be difficult for remote procedures, the technique can be performed in confined areas and is considered suitable for TNS.

Whereas the brazed connection is a proven joining technique, the connector concept is not. Connector designs for equilibrium field coils have undergone limited testing including flat type connectors, laminated type connectors and plug type connectors. The results of connector tests, as reported in Reference ⁽⁴⁾ have shown that joint resistance and temperature increase with conductor current and pulse length. Also, the alignment and attachment of the connectors could be difficult, especially for remote techniques. And finally, sufficient coolant must be maintained in the contact area to reduce heating and connectors must remain leak tight for the device to function properly.

- **Secondary Failures**

Secondary maintenance operations are the most serious problems of repair and maintenance associated with the shaping field coils. Segmentation, to remove a TF coil, is recognized as the single most difficult maintenance operation, requiring the sectioning and joining of every conductor turn in the coils. Maintenance procedures

would be identical for both the primary and secondary failure criteria. Only the magnitude of the repair operation and the time required for completion would differentiate between the two failure criteria.

6.2.3 Coil Reliability and Redundancy

The important criteria relative to maintenance requirements have been identified for the shaping field coils and viable repair techniques may now be developed. However, one should also develop a clear understanding of the probable frequency of repair and the probable design and operating requirements, at a very early stage in the design process through the application of component reliability and design redundancy.

- **Component Reliability**

Reliability refers to the performance of a design over a period of time. One of the major aspects of reliability in a tokamak reactor is the total failure of a component such as a shaping field coil. As an example, in the mechanical aspects of the coil design, reliability could be increased by selecting the appropriate factor of safety employed in sizing the support structure. If absolutely no structural failure occurrences can be tolerated, the load capability of the coil must be greater than or equal to all possible loads to which the coil might be subjected to in usage. The selection of the appropriate factor of safety will assure the design of having absolutely no possible failure occurrences. Another example for improving the reliability of the coils would be in the selection of the appropriate conductor joint. Brazed conductors would maintain a high degree of reliability and require a longer maintenance period, whereas a connector would have

a lower degree of reliability and certainly require more frequent maintenance operations, resulting in a lower performance level for the device. The connectors are judged to have a lower reliability because of possible material degradation from local heating at the contact area, possible insulation damage from coolant leaks and changing power requirements from increasing contact resistance.

It is understood that a sufficient data base will exist from past studies and past experience to insure that reasonable limits are incorporated in the selection of a factor of safety. If the data base is not available, design conservatism based on good engineering practices would ultimately be the basis for selecting the design limits. Similar reliability procedures, applied to other components would result in minimization of the occurrence of failures and minimization of the consequences.

Systems made up of several independent components in series would be less reliable than any of its parts. Failure of the system would essentially be due to the most severe flaw among a large number of flaws in the system. This means that in order for the shaping field coils to function with a high degree of reliability, all of its sub-systems must function with a high degree of reliability.

- **Design Redundancy**

In a tokamak reactor, redundant or parallel systems would be available from the start of the operation and would be used in the event of another similar part failing in service. Operation of the device would continue at a satisfactory performance level. The feasibility of redundancies in the shaping field coils would depend on whether a failed section of the coil (failure from electrical short or coolant leak) could be isolated

from the rest of the system and not impede the continued performance of the coil. The combination of component redundancy and design reliability will reduce the frequency of repair operations and improve the performance of the device.

6.2.4 Design Recommendations

Provisions must be made in TNS for access to all parts which will be subject to failure so that they may be repaired. To facilitate the repair and maintenance of the shaping field coils, the following design proposals should all be reviewed and relevant features incorporated into the design.

- (1) Simplification and uniformity in the design must be adopted early in the study to enhance maintenance capabilities. Qualification of a single maintenance technique should suffice for each component in the system.
- (2) Provisions for detection and location of possible failures should be included in the design of all systems. Delays in locating and isolating failed components could significantly increased the time needed to perform the repair operation.
- (3) Accessibility is the most important feature of each design relative to maintenance requirements. The accessibility of each component must be as good as can be arranged subject to design constraints. (Coils located behind the vacuum vessel and shielding would be raised or lowered to permit repair, see Figure 1.) Inaccessible components would require the disassembly of adjacent structures, resulting in unnecessary delays in the time needed to complete the repairs.

A variety of methods have been proposed to permit the maintenance and repair of the SF coils in a tokamak device, and the range of possibilities is clearly not exhausted. The validity of these methods should be pursued to establish a clear understanding and solutions to the maintenance requirements. However, the problem of coil design and service will not be advanced until a reliable joint design and remote maintenance technique have been successfully demonstrated.

6.3 Nb₃Sn SUPERCONDUCTOR COOLING STUDIES

The Nb₃Sn superconductors for the toroidal field coils of the TNS-4 are to be designed to consist of multifilamentary and cabled conductors with copper as the substrate and are to be cooled by forced flow supercritical helium. The conceptual thermal design of the conductors has been initiated and the results of analysis obtained in this quarter are summarized in this section.

The TNS-4 device studied has the following dimensions: major radius (R) = 4.94 m; minor radius (a) = 1.06 m and field on axis (B_p) = 6.0 tesla. This is the current reference case for TNS-4. Many other sizes of TF coils have been examined by the COAST code to estimate the costs of the devices with various dimensions. The reference thermal performance of the Nb₃Sn superconductors should apply, however, to many of the TNS-4 devices examined, if the size of the TF coils is not significantly different from that of the reference case.

The physical parameters of the TF coils being analyzed are shown in Table 6.3-1. The superconductor current density-magnetic field-temperature (J_c-H-T) characteristic diagram used in the analysis is shown in Figure 6.3-1⁽⁵⁾. For this study, the conductor cooling channel inlet temperature was selected to be 5 K. From the figure it is determined that the superconductor critical current at 5 K and at the peak field of 12 tesla is $1.3 \times 10^5 \text{ A/cm}^2$. The superconductor operating current density was selected to be about one half of the critical value, or $6.52 \times 10^4 \text{ A/cm}^2$. The threshold temperature (T_{CS}) for current sharing at this operating current density and 12 tesla is then 6.5 K and the superconductor critical temperature (T_{CR}) at zero current and 12 tesla is 7.5 K.

The Nb₃Sn filaments were assumed to be manufactured from the Nb-bronze reaction. The resulting bronze-to-superconductor ratio was assumed to be 3:1. To be dynamically stable, the copper-to-Nb₃Sn ratio was selected to be 12:1 at the peak field region of 12 tesla. To be cryogenically stable the helium volume was selected to be 40% of the winding cross-sectional

Figure 6.3-1. J_c -H-T diagram of Nb_3Sn superconductor

area at the peak field region. With the above selections, the winding overall average current density at the peak field region is:

$$J_{avg} = \frac{J_{SC, operating} (1 - VF)}{(R_{cu} + R_{Br} + 1)} \quad (1)$$

where $J_{SC, operating}$ = superconductor operating current density = $6.52 \times 10^4 \text{ A/cm}^2$
 VF = void fraction = 0.4
 R_{cu} = Cu/Nb₃Sn ratio = 12
 R_{Br} = Bronze/Nb₃Sn ratio = 3

Substituting the above values in Equation (1), one obtains

$$J_{avg} = 2445 \text{ A/cm}^2$$

This overall current density is much less than the nominal desired current density of 3750 A/cm^2 shown in Table 6.3-1. Grading of the winding is then necessary, so that the current density at the peak field region can be low and that the low field region can be high with an average density value approximately 3750 A/cm^2 . Three zone and five zone gradings were studied. A three zone grading is better hydraulically and less complex from a manufacturing standpoint. It is hence selected for the present study. The preliminary superconductor specifications are given in Table 6.3-2. The axial distributions of the critical temperature and the threshold temperature for current sharing along the conductor channel are shown in Figure 6.3-2.

Thermal analyses for normal operations considering a 10% duty cycle (30 seconds of power pulse in a 300 second cycle) were performed with various channel inlet flow rates to establish an operating map for normal operations. The same thermal modeling procedure and computer code which were used for the NbTi (TNS-3) superconductors thermal analyses were used for the

TABLE 6.3-1

DESIGN PARAMETERS OF THE TF COILS OF TNS-4 ANALYZED

Major radius (R), m	4.94
Minor radius (a), m	1.06
Field on axis (B_z), T	6.0
Peak field at winding, T	12.0
Outer radius of vertical leg, m	2.672
Coil cross-section area, m ²	10.885
Total amp-turns, A-T	1.48×10^8
Conductor current, Amp	15000
Nominal overall current density, A/cm ²	3750
Structure-to-conductor area ratio	1.75
Coil radial build, m	2.672

TABLE 6.3-2

PRELIMINARY SPECIFICATIONS OF THE Nb_3Sn SUPERCONDUCTORS
FOR THE TF COILS OF TNS-4

<u>Zone</u>	<u>1</u>	<u>2</u>	<u>3</u>
Magnetic Field Grading, Tesla	12	10	7.2
No of Turns in Bobbin	6	6	12
Bronze Plus Nb_3Sn Area, cm^2	0.92	0.48	0.25
Copper/Sc + Bronze Ratio	3.0	3.2	4.0
Conductor Plus He Area, cm^2	6.14	4.00	2.97
Void Fraction	0.40	0.50	0.58
Strand Diameter, cm	0.108	.080	.063
Current, A	15,000	15,000	15,000
SC Operating Current Density, A/cm^2	6.52×10^4	12.5×10^4	24.0×10^4
Overall Average Current Density, A/cm^2	2,445	3,750	5,055
No. of Strands		3 x 7 x 19	
Cooling Arrangement		3-in-hand	
Cooling Mode		supercritical helium	
Channel Inlet Pressure, atm		variable, depending on flow rate	
Channel Inlet Temperature, K		5	
Channel Outlet Pressure, atm		3.0	
Channel Length, m		196	
Total No. of Channels in Array (Approximate)		1235	

present analyses. The total heating during the duty cycle was taken to be $1.72 \times 10^{-3} \text{ W cm}^{-3}$ as used in the NbTi superconductor analyses. This value includes the nuclear and ac heating, and other heat leakages. The calculated channel pressure drop and the ideal pumping power requirement at channel inlet flow rates from 4.0 to 14.0 g/s are shown in Figure 6.3-3. The pressure drop curve is used to determine channel inlet pressure, when exit pressure is fixed at 3 atm. It is seen from this figure that the pumping power requirement is reasonable, mainly because of the increasing void fractions selected for the three zones of the channel and the large heat transfer area of the conductor. A normal operating flow rate is to be selected based on the stability requirement. Once the operating flow rate is known, the pumping power requirement can be obtained from this figure. The stability analysis for this Nb_3Sn superconductor will continue along these lines during the next quarter.

Figure 6.3-2. Axial distribution of conductor critical temperature and threshold temperature for current sharing

Figure 6.3-3. Pressure drop and ideal pump work at normal operations

6.4 HEAT DISSIPATION SYSTEMS

Work in the reporting quarter included the refinement of several heat dissipation system cost models in COAST Version 1 and development of improved cost data and ground rules for an update of all system models in COAST Version 2. Only work culminating in changes to the COAST Version 1 heat dissipation system models will be reviewed in this section. A consolidated report of all heat dissipation system ground rules, unit costs, and overall system cost data, incorporating revisions made in COAST Version 2 will be issued in the near future. This should minimize confusion in regard to the status of updates.

Recent modifications of heat dissipation system models in COAST Version 1 are summarized as follows:

<u>System</u>	<u>Modifications</u>
Vacuum Vessel Cooling	None
Shield Cooling	None
Copper Field Coil Cooling	The peak heat removal rate for which the primary deionized water cooling loop is sized is now based upon a simple first order lumped parameter cool down model
Neutral Beam System Cooling	All cooling equipment other than a water connection to the general plant circulating water system is now considered part of the neutral beam systems.
Helium Refrigeration Systems	A fixed cooling system heat load has been replaced by a heat load model sensitive to coil size, duty cycle, and pumping requirements. Separate models are developed for TNS-3, TNS-4, and TNS-5.
Nitrogen Refrigeration System	None
Experimental Area Ventilation Systems	None

General Plant Circulating
Water System

Heat rejection from helium and nitrogen
refrigeration systems is added to the total
system load.

In the remainder of this section, the basis for the revisions to the copper field coil and helium refrigeration system models are described.

6.4.1 Copper Field Coil Cooling Systems

The geometry of the copper field coil systems has not been identified to the extent required for a detailed transient thermal analysis. On the other hand, reasonable assumptions can be made to allow a first approximation of the relation between heat generation in the coils and its transfer to the primary and secondary loop coolant. This can be done by an investigation of some of the very simple thermal/hydraulic characteristics of the coil system, and exercising judgement in regard to which effects will be of controlling importance.

The first parameter of interest in determining transient coil thermal behavior is the adiabatic temperature rise rate, $\frac{d\theta_a}{dt}$, $\frac{K}{s}$. This rise rate is a simple function of the conductor material, operating temperature, and current density. The relation determining $\frac{d\theta_a}{dt}$ is given by the equation

$$\frac{d\theta_a}{dt} = \frac{q'''}{\gamma C_p} = \frac{J^2 \rho}{\gamma C_p}$$

where q''' is the volumetric heat generation rate due to Joule heating (W/cm^3).

J is the conductor current density (A/cm^2)

ρ is the conductor resistivity (Ωcm)

γ is the conductor density (g/cm^3)

C_p is the conductor specific heat ($J/g K$)

The peak value of J assumed for copper coil design in the COAST code is 1500 A/cm^2 . By assuming a copper resistivity at 52°C of $1.94 (10^{-6}) \Omega\text{cm}$, γ of 8.94 g/cm^3 and C_p of 0.381 J/g K we arrive at

$$\frac{d\theta_a}{dt} = 1.28 \frac{\text{K}}{\text{s}}.$$

This parameter, together with a limitation on coil cyclic temperature rise, limits the effective current flat top time (T_{eff}) allowable in the absence of cooling. Assuming a temperature rise limit of 60°C , it is clear that the allowable effective current flat top time is about 47 sec, which is comparable to the total pulse length of the TNS reference cycle. Hence, each of the copper coil cooling systems may be designed to remove the pulsed J_p^2 heating throughout the full operating cycle, and need not remove a major fraction of heat generation within the pulse period. This also indicates that the coils may be capable of sustaining a full pulse without coolant flow under fault conditions.

Actually, based on the current TNS reference pulse scenario, all but the copper TF coils for TNS-1 will have an effective current flat top time, T_{eff} , shorter than 47 seconds. For an arbitrary variation of current density through a pulse, $J(t)$, T_{eff} will be defined by the relation

$$T_{\text{eff}} = \int \left[\frac{J(t)}{J_p} \right]^2 dt$$

where J_p is the peak design value of current density, currently set at 1500 A/cm^2 .

For a typical TNS-1 configuration, T_{eff} and the adiabatic temperature rise $\Delta\theta_a \left(= T_{\text{eff}} \frac{d\theta_a}{dt} \right)$ for the various coil systems is shown in Table 6.4-1.

Heat transfer from the copper coils to water coolant does not represent a major concern. This can be demonstrated by means of a steady state calculation of conductive and convective heat transfer for a conductor of circular cross-section, with outside radius r_o , and a circular coolant hole of radius r_i .

TABLE 6.4-1
EFFECTIVE CURRENT FLAT TOP TIME, T_{eff} , AND
ADIABATIC TEMPERATURE RISE, $\Delta\theta_a$, FOR
TYPICAL TNS COPPER FIELD COILS

Peak Current Density = 1500 A/cm^2

Coil System	T_{eff} (S)	$\Delta\theta_a$ (K)
Toroidal Field	54.0	69.1
Ohmic Heating	28.9	37.0
Equilibrium Field - O	21.5	27.5
Equilibrium Field - I	17.5	22.4
Equilibrium Field - D	21.5	27.5

It can be shown that the conduction of $J^2 \rho$ losses through the copper to the inner wetted surface results in a temperature differential

$$\theta_o - \theta_i = \frac{J^2 \rho r_o^2}{2k} \left[\ln \left(\frac{r_o}{r_i} \right) - \frac{1}{2} \left(1 - \left(\frac{r_i}{r_o} \right)^2 \right) \right]$$

For a conductor with $r_o = 1.581$ cm, $r_i = 0.500$ cm, and hence a ratio of coolant cross-section to overall cross-section of 0.100, this results in a temperature differential of only 0.99 K. (The thermal conductivity of copper, k , is assumed to be 3.86 W/cm K).

The convective heat transfer coefficient, h , for the internal coolant channel can be calculated from the Dittus-Boelter equation. Assuming pure water coolant at 52°C and 0.34 MPa, and a velocity of 3 m/s, the convective coefficient for the above conductor is 1.5 W/cm² K. The resulting steady state temperature differential is

$$\theta_i - \theta_b = \frac{J^2 \rho (r_o^2 - r_i^2)}{2 r_i h} = 6.65 \text{ K}$$

A first order time constant (τ_h) for a system composed of a short length of conductor cooled by an infinite source of water at constant temperature may be described by the relation

$$\tau_h = \frac{\gamma C_p S}{h P} = \frac{\gamma C_p (r_o^2 - r_i^2)}{2 h r_i}$$

where S is the conductor (copper) cross-sectional area, and
 P is the wetted perimeter

For the reference conductor geometry, the value of τ_h is 5.11 seconds. This value is small compared to the time required for coolant to traverse a channel (i.e., 10 seconds for flow

through a 30 m channel at 3 m/s), indicating that it will not be a major factor in determining the transient cooling behavior of the coil system.

It turns out that the rate of heat removal from the copper coils will be governed essentially by calorimetric considerations. This is a result of two features common to all attractive coil geometries. First, the heat capacity of the water coolant in the coil is small in comparison to the copper heat capacity. Second, the number of coolant turnovers through the conductor during a pulse or cycle is limited due to a desire for long channels and reasonable coolant velocities and pressure drops.

The ratio of water to conductor heat capacity (C_w/C_{cu}) is calculated simply by the relation

$$\frac{C_w}{C_{cu}} = \frac{\gamma_w C_{pw} r_i^2}{\gamma_{cu} C_{pcu} (r_o^2 - r_i^2)}$$

For the reference conductor geometry this ratio is 0.135. Since it takes 10 seconds for a coolant turnover assuming a 30 m channel length and 3 m/s velocity, it will take 74.1 seconds to pass a quantity of water through the conductor having a total heat capacity equal to the conductor. It will be shown that this value is the time constant for a first order coil cool down model based on a lumped parameter model as will be described below.

Figure 6.4-1 depicts an idealized copper conductor at a uniform temperature θ . Its overall heat capacity C is described by the relation

$$C = \gamma_{cu} C_{pcu} \pi (r_o^2 - r_i^2) L$$

where L is the length of conductor from coolant inlet to discharge. Each unit of water mass flow dm_w entering the conductor brings in an amount of heat $dq_i = \theta_i C_{pw} dm_w$, while an

Heat input by water

$$dq_i = \theta_i C_{Pw} dm_w$$

Heat removed by water

$$dq_o = \theta_o C_{Pw} dm_w$$

Heat stored in copper

$$dQ = C d\theta$$

$$\text{Heat Stored} = \text{Heat Input} - \text{Heat Removed}$$

$$dQ = dq_i - dq_o$$

$$Cd\theta = (\theta_i - \theta_o) C_{Pw} dm_w$$

Assuming $\theta_i = 0$, $\theta_o = \theta$

$$Cd\theta = -\theta C_{Pw} dm_w$$

$$\frac{d\theta}{\theta} = -\frac{C_{Pw}}{C} dm_w$$

Figure 6.4-1. Lumped parameter transient coil cooling model

equal mass of water leaving removes an amount of heat $dq_o = \theta_o C_{pw} dm_w$. Defining the heat stored in the conductor as $dQ = Cd\theta$, one may write a heat balance for the conductor as

$$dQ = dq_i - dq_o.$$

$$Cd\theta = (\theta_i - \theta_o) C_{pw} dm_w$$

By setting θ_i equal to zero, and assuming that water leaves the conductor at the conductor bulk temperature θ ,

$$Cd\theta = -\theta C_{pw} dm_w$$

and,

$$\frac{d\theta}{\theta} = -\frac{C_{pw}}{C} dm_w$$

This is the familiar differential equation for a simple first order system. It is convenient to rewrite this equation in terms of the physical parameters of the system. This is done by substitution for C using its definition, and by expressing dm_w in terms of the water coolant velocity, V_w , as follows:

$$dm_w = \gamma_w V_w \pi r_i^2 dt$$

Making these substitutions,

$$\frac{d\theta}{\theta} = \left(\frac{\gamma_w C_{pw}}{\gamma_{cu} C_{pcu}} \right) \left(\frac{r_i^2}{r_o^2 - r_i^2} \right) \frac{V_w dt}{L}$$

Finally, recognizing that the above equation is of the form

$$\frac{d\theta}{\theta} = -\frac{dt}{\tau_c}$$

it is clear that the first order time constant τ_c is expressed as

$$\tau_c = \frac{\gamma_{cu} C_{Pcu} (r_o^2 - r_i^2) L}{\gamma_w C_{Pw} r_i^2 V_w}$$

τ_c equals 74.1 seconds for the reference conductor design, with a 30 m length and 3 m/s water velocity. The friction pressure drop for this case is 300 k Pa (44 psi).

The above differential equation is easily solved with the assumption of impulse heating at the beginning of each operational cycle. Denoting the cycle length by T , the solution is

$$\theta(t) = \frac{\Delta\theta_a}{\left(1 - e^{-\frac{T}{\tau_c}}\right)} e^{-\frac{t}{\tau_c}} \quad 0 \leq t < T$$

From this equation, the ratio of peak to average conductor temperature is

$$\frac{\theta_{Peak}}{\theta_{Ave}} = \frac{T}{\tau_c} \left[1 - e^{-\frac{T}{\tau_c}} \right]^{-1}$$

Since the coolant temperature rise is equal to θ , and the coolant mass flow rate is constant, the rate of heat removal is proportional to θ . Hence

$$\frac{\dot{Q}_{peak}}{\dot{Q}_{ave}} = \frac{T}{\tau_c} \left[1 - e^{-\frac{T}{\tau_c}} \right]^{-1}$$

This is the equation used in the COAST code to determine the peak heat load on the copper coil deionized water cooling systems. For all of the poloidal field coils, as well as the copper TF coils, τ_c is chosen as 73.13 seconds, and T is variable. This value was based on the reference conductor geometry reported here, and coolant physical constants differing slightly from those reported. For the reference 300s pulse, $\dot{Q}_{peak}/\dot{Q}_{ave}$ is equal to 4.03.

Table 6.4-2 lists the maximum, minimum and average coil temperatures predicted by this simple model, assuming an inlet coolant temperature of 40°C, a time constant of 73.13 s, and the typical value of $\Delta\theta_a$ listed previously. Also listed are typical values of the peak and average heat rejection of each coil system, and the peak rate of heat generation within each coil.

This lumped parameter first order coil cooling model provides significant insight into the effects of the major coil design parameters on thermal performance. Its accuracy is judged to be satisfactory for the selection of coil geometries for more detailed thermal analysis by means of transient thermal analysis codes such as TAP-B. Care must be exercised in judging its range of applicability and shortcomings.

Use of the above model by the COAST computer code requires calculation of the total heat generation in the toroidal and poloidal field coil systems during each pulse. For the poloidal coils, a simple scaling law was developed which assumes that the coil heat generation (Q_{PF} , MJ) is proportional to the product of plasma current (I_p , MA) and the device major radius (R_O , m). The scaling law also assumes that the heat generation will increase linearly with pulse duration (ΔT , s) from a base value representative of the start-up and shut-down periods. The resulting model is

$$Q_{PF} = I_p \times R_O \times (42.0 + 3.31 \times \Delta T)$$

The average and peak heat rejection rates are then calculated by the equations

$$\dot{Q}_{ave} = Q_{PF} / T$$

and

$$\dot{Q}_{Peak} = \frac{Q_{PF}}{73.13 \left(1 - e^{-T/73.13}\right)}$$

TABLE 6.4-2

COPPER COIL THERMAL PARAMETERS PREDICTED BY FIRST ORDER
CALORIMETRIC COOL DOWN MODEL

$$\tau_c = 73.13 \text{ s}$$

Coil System	TF	OH	EF-O	EF-I	EF-D
Adiabatic Temperature Rise (°C)	69.1	37.0	27.5	22.4	27.5
Peak Coil Temperature (°C)	110.3	77.6	68.0	62.8	68.0
Min Coil Temperature (°C)	41.2	40.6	40.5	40.4	40.5
Average Coil Temperature (°C)	56.9	49.0	46.7	45.5	46.7
Peak Heat Rejection (Mw)	576.4	5.7	35.3	3.3	1.5
Average Heat Rejection (Mw)	138.3	1.4	8.9	0.8	0.4
Peak Heat Generation (Mw)	768.3	11.3	94.5	10.9	4.0

The heat generation for the copper toroidal field coils is calculated by more detailed models in COAST, but heat rejection rates are then calculated using the same relationships as for the PF coils.

6.4.2 Helium Refrigeration System

A model for determining the helium refrigeration requirement has been developed based on estimates of structural conduction, residual gas conduction, thermal radiation, nuclear heating, ac current losses, joint losses, and helium pumping power. Many of the basic assumptions contained in the model are due to Dr. A. Y. Lee. Following is a description of the model plus an evaluation of the various contributions to refrigerative load for a typical version of TNS-3, with Nb-Ti superconductors.

Structural Conduction. It is assumed that each toroidal field coil will be supported within a dewar structure maintained by liquid nitrogen at 77 K. Support will be by means of an array of spokes arranged to accept gravitational and out of plane coil loads in tension. It is assumed that the average spoke length (L , m) will be 0.75 m and that the total spoke cross-sectional area will be 0.01 times the surface area of the toroidal field coil (S_{TF} , m²). Since the thermal conductivity (k , w/m K) of the spoke material will decline rapidly from 77 K at the dewar to 4 K at the coil, an effective value of conductivity k^* must be used which is determined by the relation

$$k^* = \frac{1}{(T_2 - T_1)} \int_{T_1}^{T_2} k(T) dT$$

A value of k^* equal to 5.0 W/m K is chosen as being representative of stainless steels and Inconels in the range of 4 K to 77 K. The resulting equation for structural conduction

$(\dot{Q}_{SC}, W)$ is therefore

$$\dot{Q}_{SC} = \frac{0.01 S_{TF}}{L} k^* (T_{\text{dewar}} - T_{\text{coil}})$$

or

$$\dot{Q}_{SC} = 4.87 S_{TF}$$

Gas Conduction. The conduction of heat from the dewar to the toroidal field coil through the residual gas ($\dot{Q}_{GC}, W$) is governed by the free molecular conduction equation

$$\dot{Q}_{GC} = \left(\frac{\gamma+1}{\gamma-1} \right) \alpha \left(\frac{R}{8\pi MT} \right)^{1/2} P (T_2 - T_1) A$$

where γ is the ratio of specific heats C_p/C_v

α is the overall accommodation coefficient

R is the universal gas constant

M is the residual gas molecular weight

T is the absolute temperature of the conducting gas

P is the absolute pressure corresponding to the temperature T ($P/\sqrt{T}$ is constant within a given molecular flow region)

A is the surface area of each of two parallel plates at T_1 and T_2 .

Assuming that the residual gas is helium at a pressure of 10^{-4} torr relative to a temperature of 300 K, and that the overall accommodation coefficient α is 1.0, this equation reduces for

the present purpose to

$$\dot{Q}_{GC} = 2.04 S_{TF} \quad \begin{matrix} (\dot{Q}_{GC}, W) \\ (S_{TF}, m^2) \end{matrix}$$

Thermal Radiation. Thermal radiation from the dewar to the coil bobbin is determined by the equation

$$\dot{Q}_{TR} = E \sigma A_1 (T_2^4 - T_1^4)$$

where E is the effective emissivity factor for two concentric cylinders

σ is the Stefan-Boltzmann constant

A_1 is the surface area of the inner (cold) cylinder (coil bobbin)

A_2 is the surface area of the outer (warm) cylinder (dewar)

T_1, T_2 are the respective surface absolute temperatures

The value of E is further defined for the case of diffuse radiation as

$$E = \frac{e_1 e_2}{e_2 + \frac{A_1}{A_2} (1 - e_2) e_1}$$

where e_1, e_2 are the respective emissivities of the inner and outer surfaces.

By assuming that both emissivities equal 0.08, representative of polished stainless steel at room temperature, and the ratio of coil bobbin to dewar surface area is 0.8, the resulting model for thermal radiation to the coil bobbins is

$$\dot{Q}_{TR} = 0.093 S_{TF} \quad (\dot{Q}_{TR}, W)$$

The sum of structural conduction, residual gas conduction, and thermal radiation can be expressed as the total heat leak, $\dot{Q}_{HL}$ as

$$\begin{aligned}\dot{Q}_{HL} &= (4.87 + 2.04 + 0.09) S_{TF} \\ &= 7.00 S_{TF} \quad (\dot{Q}_{HL}, \text{ W})\end{aligned}$$

This model is felt to be conservative, especially in the assumption that the total spoke cross-sectional area is 0.01 times the bobbin surface area. Calculations to date indicate that approximately half of this area may be required.

For a typical version of TNS-3, with R_o equal to 5.7 m, S_{TF} is approximately 1524 m^2 . Hence the total heat leak to the coil bobbins will be

$$\dot{Q}_{HL} = 10,700 \text{ W}$$

This loss is continuous during both operational and non-operational periods.

Nuclear Heating. The shielding within the toroidal field coils is sized by an algorithm in the COAST code to limit nuclear heating to a time averaged value chosen as input. This same value is used in the calculation of helium refrigeration requirement. The currently chosen value is 20,000 W.

AC Losses. These losses are only a concern during the plasma initiation and plasma heating period, when significant eddy currents will be induced by rapid flux swings in the OH coil system. Their contribution to the total refrigeration requirement is small, and is ignored.

Joint Losses. The pancake winding design proposed for TNS-3 involves winding of four parallel conductors through five turns per pancake. It is assumed that each conductor will be constructed in a continuous length suitable for five turns, and that a non-superconducting joint will be used for the electrical connection of the conductor to its successor in the next pancake. It is assumed that each of these joints will have a heat generation of 1 watt.

The total number of such joints can be calculated simply by dividing the total ampere-turn requirement for the TF coil set, NI_{TF} , by the ampere-turn contribution of each conductor, NI_C . This contribution is assumed to be 50,000 At for each 2 cm x 2 cm Nb-Ti conductor (10,000 amperes times 5 turns) and 75,000 At for each Nb₃Sn conductor (15,000 amperes times 5 turns). Hence, the joint loss heat generation ($\dot{Q}_{JL}$, W) is

$$\dot{Q}_{JL} = 1.0 \left(\frac{NI_{TF}}{NI_C} \right)$$

For the typical TNS-3 design referenced previously, $NI_{TF} = 115 (10^6)$ At, so

$$\dot{Q}_{JL} = 1.0 \left(\frac{115 (10^6)}{50 (10^3)} \right) = 2300 \text{ W}$$

Pumping Power. Helium coolant is assumed to be circulated through the superconductors in a closed primary loop, with circulating work input by a submerged pump/motor system. The total circulating work required is determined from a scaling model whose basis is the

calculated circulating work ($\dot{w}$, W) required to maintain cryostability in a reference 120 m length of conductor. The scaling law includes a linear dependence upon both the number of conductors and the conductor length.

The linear dependence of pumping power on the number of conductors is obvious since all conductors will be in parallel in the hydraulic circuit. The linear dependence upon conductor length is more idealized. If one were to assume that the coolant massflow rate per conductor must increase linearly with the conductor length, perhaps to maintain the same average coolant temperature rise, the pumping power would increase with the fourth power of conductor length. Obviously, at some value of conductor length one must rearrange the bobbin layout so that more parallel conductors are used, with fewer turns per conductor. This results in only a linear increase in pumping power with increased coil circumference. With this in mind, as well as other means for optimizing the conductor hydraulic design, it appears unreasonable to penalize large coil designs with a pump power dependent on the fourth power of coil circumference, and the more optimistic linear dependence is assumed.

Detailed cryostability analysis of the 120 m reference Nb-Ti conductor have been performed using the TAP-B computer code. This analysis has established a requirement for a coolant mass flow per conductor of 11 g/s with a resulting pump work of 12.6 W. A similar analysis for Nb₃Sn conductors is in progress and indicates that pump work requirements may be much lower than those for Nb-Ti. Pending completion of this analysis, version 1 of COAST assumes the same pump work per conductor for both Nb-Ti and Nb₃Sn, i.e., 12.6 W.

The pumping of liquid helium has received attention in the cryogenics literature, and several small scale pumps have been built and tested. Their efficiencies have generally been low, in the neighborhood of 25 to 35 percent. Discussions with Mr. Robert Hamm of Sundstrand corporation, a major supplier of cryogenic pumps, indicate that pump systems of

the size required for TNS can have efficiencies in excess of 50 percent. This is primarily because pump hydraulic efficiencies will improve as sizes increase, just as is the case with most other turbomachinery. A significant problem lies in the design of pump drive systems. Here, a choice must be made between use of a close coupled electric motor cooled by the pumped fluid (4 K liquid helium), or an external drive system incorporating rotating high vacuum seals on a drive shaft connecting a room temperature (or perhaps liquid nitrogen temperature) motor and the 4.0 K pump.

Use of immersed, close coupled pump motors appears to be the more straightforward and reliable solution. With such a motor all losses would go to the helium refrigerator bath, assumed at 3.5 K for TNS-3. In comparison to a room temperature motor, the iron losses would be nearly the same, I^2R losses would be considerably reduced, bearing losses would probably increase due to a desire for light bearing loads and higher than optimum bearing diameters (assuming use of rolling element bearings), and motor windage losses might either decrease or increase depending on whether the fluid in the motor air gap were gaseous or liquid helium. Detailed studies are necessary to develop desirable design configurations and to indicate attainable efficiencies, but there seem to be no problems which would preclude attainment of a design goal in excess of 50 percent efficiency for the combined pump/motor system.

The algorithm to calculate the refrigerative load chargeable to the pumping system is

$$\dot{Q}_P = \frac{\dot{W}_P}{\eta_P} \left(\frac{NI_{TF}}{NI_C} \right) \left(\frac{C_{TF}}{24} \right) \quad (1.1)$$

where $\dot{W}_P$ equals the required ideal pump work per conductor, an input value currently set at 12.6 W for both Nb-Ti and Nb₃Sn conductors

η_P is the overall pump-drive efficiency currently set at 0.50

and C_{TF} is the TF coil mean circumference, m

In this algorithm, the factor 1.1 provides for pumping power for a separate coil bobbin cooling loop equal to 10% of the superconductor pump power. For the previously referenced version of TNS-3, the TF coil circumference is 28.2 m, and the resulting refrigerative load due to pumping is

$$\dot{Q}_p = 74,900 \text{ W}$$

Total Helium Refrigeration Load. For the reference TNS-3 version, a breakdown of the total helium refrigeration load is shown in Table 6.4-3. The dominance of helium pumping power is apparent, and indicates that significant design effort should be directed toward minimizing the required flow rate or pressure drop dictated by cryostability requirements, maximizing pump efficiency, or developing a refrigeration cycle which supplies the head required for coolant circulation by means of the room temperature helium compressors.

Helium System Unit Cost Algorithm. A minor modification has been made to the unit cost model for helium refrigeration systems. The systems for providing coolant at 5.0 K for Nb_3Sn conductors are now assessed at \$350/W versus \$400/W for the 4.0 K systems required for Nb-Ti conductors. The difference accounts for a reduction of approximately 25% in the refrigerator cost, but no reduction in the cost of distribution systems and other helium management facilities.

Based on the previously calculated helium refrigeration load of 107.9 kW, for a version of TNS-3 with a 5.7 m major radius, the system cost is estimated to be \$43,160,000.

The thermal load imposed by the helium refrigeration system on the general plant circulating water system is assumed to be 350 watts per watt of refrigerative load. This value is based

TABLE 6.4-3
HELIUM REFRIGERATION LOAD
TYPICAL TNS-3 DEVICE

<u>Component</u>	<u>Refrigerative Load</u> KW	<u>Percent of</u> <u>Total</u>
Structural Conduction	7.4	6.9
Residual Gas Conduction	3.1	2.9
Thermal Radiation	<u>.1</u>	<u>.1</u>
Total Heat Leak	10.6	9.9
Nuclear Heating	20.0	18.5
AC Losses	*	*
Joint Losses	2.3	2.1
Pump Power		
Direct	37.5	34.8
Inefficiency	37.5	34.8
Total Refrigerative Load	107.9	100.0

* Small in comparison to other losses

on the compressor power required to provide refrigeration for a helium bath at 3.5 K (0.5 K below the primary loop temperature) with a 310 K heat rejection temperature and a cycle operating at 25 percent of Carnot efficiency. This cycle heat rejection is not differentiated between the Nb-Ti and Nb₃Sn superconductors. For the reference unit this amounts to 37.8 MW.

6.5 NUCLEAR ANALYSIS

The effort in the nuclear analysis of the TNS shield design has concentrated on two areas of general interest which will become important when a detailed analysis of the reference design shield is undertaken. The first area was a sensitivity study of the nuclear heating rate to changes in the discretization of the angular variable used in radiation transport calculation. The second area involved the implementation of a recently released nuclear data library which was generated especially for fusion reactor analysis.

Angle Discretization Sensitivity Study. Most of the previous effort ⁽⁶⁾ in the nuclear analysis of the TNS shield has been based on one-dimensional (radial) calculations of the neutron and gamma radiation transport using the ANISN ⁽⁷⁾ code. A 121 group (100 neutron, 21 gamma) cross section set ⁽⁸⁾ was used with an $S_6 - P_1$ treatment of the angular variables. However, the very high energy (14.1 MeV) D-T fusion neutrons will undergo highly anisotropic scattering reactions as they interact with the shield, and thus the calculated nuclear heating rates in the TF coils may be sensitive to the S and P order assumed.

In order to assess the effect of different S and P orders, a set of ANISN calculations was made for a typical TNS shield design. The geometry and material composition by zone of the shield and coil which was used for the study are given in Table 6.5-1. Cylindrical geometry was used with a uniform, isotropic fusion neutron source of radius 1.25 m. A 48 group (30 neutron, 18 gamma) cross section set was collapsed from the 121 group set for use in the study. Three different angular variable treatments were analyzed: $S_4 - P_1$, $S_6 - P_1$, and $S_8 - P_3$. Various quantities of interest, such as the nuclear heating rate in the TF coils and the high energy neutron flux at various mesh intervals, were compared for each case.

A comparison of the fluxes and nuclear heating rates in the $S_4 - P_1$ and $S_6 - P_1$ cases revealed differences of less than 5%, which indicates that the calculation is relatively insensitive to the S order for the same P order. This corresponds to the general rule that the S order should be

TABLE 6.5-1

GEOMETRY AND MATERIAL COMPOSITION OF A
TYPICAL TNS SHIELD AND COIL CONFIGURATION

<u>Zone No.</u>	<u>Outer Radius (m)</u>	<u>Thickness (m)</u>	<u>Material Composition</u>
1	1.25	1.25	Plasma Source
2	1.35	0.10	Void
3	1.55	0.20	SS-316 (27.6 %) *
4	2.10	0.55	Shield
5	2.15	0.05	Lead
6	2.30	0.15	Insulation
7	2.90	0.60	TF Coil
8	3.05	0.15	Insulation

Shield: 65% SS-316, 35% borated water.

Insulation: 40% foam (C-H), 15% SS-316.

TF Coil: 20% Cu, 1.3 % Nb, 0.7% Ti, 5% Void, 73% SS-316.

* All percents are by volume.

slightly greater than twice the P order for maximum cost effectiveness with ANISN. For larger S orders the accuracy is not greatly improved since the P order restricts the possible scattering angles.

However, there is a much larger difference when the S and P orders are increased, as shown in Figure 6.5-1. Here the total (neutron plus gamma) nuclear heating rate is shown vs. position in the shield and coil for the $S_6 - P_1$ and $S_8 - P_3$ cases. As can be seen, the $S_8 - P_3$ analysis predicts significantly higher heat deposition, especially for those regions beyond the shield. For example, the heating rate is 67% larger in the TF coils with $S_8 - P_3$ relative to $S_6 - P_1$.

This result is somewhat expected, since the higher P order allows a better representation of the anisotropic forward scattering of the high energy neutrons. Hence, the neutrons penetrate deeper into the shield and coil region before being greatly attenuated, and thus the heat deposition is larger in these zones. However, the heating rate is about the same or even a little less in the front region of the shield.

The neutron and gamma fluxes exhibit this same behavior for the two cases. For example, the total neutron flux with energies above 1 MeV at the front of the TF coil is 74% larger with $S_8 - P_3$ than $S_6 - P_1$. Likewise, the 14.1 MeV neutron flux is 125% larger and the total gamma flux is 63% higher. However, at the front of the shield the neutron flux with energy above 1 MeV is 2% smaller for the $S_8 - P_3$ case.

Thus, the nuclear analysis of the TNS shield will be relatively sensitive to the S and P order used in the transport calculation. A good value, based on accuracy and cost effectiveness, is an $S_8 - P_3$ treatment of the angular variables.

Figure 6.5-1. Comparison of nuclear heating rates in a typical TNS shield and coil from $S_8 - P_3$ and $S_6 - P_1$ ANISN runs.

CTR Processed Nuclear Data Library. The results presented in the previous section used the nuclear data set known as the EPR library. This is a 121 group (100 neutron, 21 gamma) cross section set generated from ENDF/B-IV data. A more flexible nuclear data set has since been generated by ORNL-RSIC for specific use in fusion reactor design.

This cross section library⁽⁹⁾ designated VITAMIN-C (Versatile Integrated Techniques for Using AMPX and MINX Interfaces for Neutronics Studies with Coupled Libraries), has recently been released by ORNL-RSIC. It is a 171 neutron, 36 gamma-ray group library with associated retrieval codes which allow the user to merge, edit, check, couple, and collapse the data to his specific needs. It also has the capability to self-shield and temperature correct the cross sections, as well as to retain all partial cross sections of interest.

The code package is available in an IBM version at present. Work has now begun to convert the codes to a form compatible with a CDC-7600 computer so they can be used for the TNS shield design. Once the CDC conversion is complete, some sample problems will be run to verify the system is functioning correctly.

ANISN Activity Program AAP. A computer code designated AAP (ANISN Activity Program) has been implemented for use as a peripheral program with ANISN. AAP reads the flux output tape from an ANISN run and calculates total activities by zone, activity densities by interval, and flux weighted average cross sections by zone. It allows user specification of the energy group limits in the integration, so that reaction rate contributions from different segments of the energy spectrum may be analyzed and neutron or gamma only integrals can be extracted from coupled neutron-gamma problems.

AAP will be of great use with ANISN for the TNS shield design. A user's guide and program description is given in WFPS-TN-050.

6.6 VACUUM VESSEL SYSTEM

There are three major components in the vacuum vessel system which are closely related but which have unique and separable functions. These are the vacuum vessel, the liner, and the impurity control system (which is presently expected to be a material limiter rather than a magnetic divertor).

Vacuum Vessel. The vacuum vessel in the TNS trade studies is a toroidal shell surrounding a toroidal plasma. The plasma is not circular in cross-section but is elongated vertically and, because of the variation in the magnetic field across it, tends to assume a D-shape with the curved portion of the D in the region of lower magnetic field. The degree of distortion of a circular or elliptical cross-section increases as β increases. Nevertheless, in the COAST computer program which is used in the trade studies, the vacuum vessel cross-section is treated as if it were elliptical although this shape is obviously not the best envelope around a D-shaped plasma. It has been suggested that some other cross-section would be a better representation of a close-fitting vessel (for example, a straight cylindrical inner wall, a half-elliptical outer wall, and quarter-circle or quarter-elliptical transitions between them). Such a refinement has not been incorporated in the code for the following reasons:

- The proportions of the D-shape of the limiting size plasma have not been established.
- There is no method of performing a stress analysis of a vessel having a cross-section composed of arbitrarily selected geometrically defined elements, other than finite-element analysis.
- Finite-element analysis at this stage of design is inappropriate; it would need to be repeated in greater detail to include specific dimensions, effects of curvature in the toroidal direction, effects of penetrations, and support forces and mechanical loads.

- The code assumes that the vessel is shaped to fit around the plasma, i.e., it does not test for reduced clearance or interference between the plasma and the vessel, nor does it provide clearances to alleviate these conditions.

Liner. The liner is a component having two functions. The first is a negative function, that it not introduce impurities into the plasma. This may require that the liner be a separate structure or adherent coating of the vacuum vessel having high melting temperature, low sputtering rate, low Z , and low vapor pressure, or some optimum combination of these properties. Refractory metals, pyrographite, and silicon carbide are potential liner materials. The other function of the liner is that it protects the vessel from short-term damage by the processes going on inside it.

Structural components on or near the first wall of an ignited tokamak must be designed to survive long-term damage resulting from thermal cycling, neutron irradiation, and plasma leakage; there seems to be no way to protect them from these influences. They can however be protected from the two short-term damage mechanisms, localized plasma termination and neutral beam strikes. These events are of roughly the same magnitude; an unattenuated neutral beam strike deposits 56.5 MJ on approximately 1 m^2 of the wall, and the plasma energy of 90 MJ could conceivably be deposited in an equal area. Furthermore, the TNS neutral beams are directed approximately radially inward (so they strike the inner wall of the vessel), and most of the plasma terminations on PLT have been observed in the same area. Therefore protection will be provided tentatively for 25% of the vessel inner surface (about 100 m^2) continuously around the throat of the torus. To provide a reference point (not a design) for the liner, 90 MJ will heat 327 kg of tungsten from 250 C to 2187 C (2/3 of its melting temperature); if this material is distributed over 1 m^2 , it will be a plate 0.0166 m thick.

Limiter. An evaluation was made of the radial space required around a TNS-size plasma for a magnetic divertor. Consideration of particle behavior in the absence of the divertor magnetic field lead to the design requirements for a material limiter. A design approach for a single full-aperture limiter was outlined, but a realistic limiter design has not yet been developed. It appears, however, that the 0.25 m radial space provided for the limiter in the COAST code is adequate, but not excessive. This space is also adequate for a magnetic divertor, except that additional space would be required locally for the burial chambers.

6.7 COMPACT POLOIDAL DIVERTOR DESIGN STUDY

Overview. A preliminary conceptual mechanical and thermal design has been completed for evaluating the engineering feasibility of the compact poloidal divertor. The physical concept has been described in the previous quarterly and technical reports^(10,11). For the convenience of discussion the divertor picture is reintroduced here and is shown by Figure 6.7-1. The particle burial chamber is a dish-shaped washer-like gap between a pair of divertor coils. There was no difficulty in providing the restraint to overcome the repulsive force between the pair of coils which was the primary concern. The flowing lithium fluid getter system is, however, very much complicated by the lithium piping and electric network. This led us to take a hard look at solid getters. A brief evaluation has shown that a molybdenum getter with ZrAl auxiliary pumping will provide a highly efficient particle collection system. A qualitative discussion of the status of this work will be given here; detailed results will be documented during the next quarter.

A preliminary MHD equilibrium calculation has been performed for this compact divertor configuration. The magnetic flux pattern confirms the proposed concept. More numerical calculations have to be carried out to optimize the flux pattern.

In the following we will discuss briefly the mechanical design, the thermal design, lithium recirculation design, the solid getters and vacuum problems.

Mechanical Design for Divertor Coil Support. A workable design for the mechanical structure of the compact poloidal divertor and burial chamber concept for TNS is shown in Figure 6.7-2. The dimensions discussed here and shown on the associated figures are based on TNS-3 as the reactor model.

The main structure consists of two stainless steel dish-shaped washer-like structures with an I.D. of 6.7 m and O.D. of 9.9 m. The dish-shaped structures are each approximately 19 cm thick and are separated by tubular spaces to form a gap of approximately 35.5 cm. This gap

Figure 6.7-1. Proposed divertor design, flux in the chamber is compressed by two sets of coils.

Figure 6.7-2. Plan and side view of poloidal divertor structure

provides the burial chamber which houses the lithium wetted screen lined collector horns, the lithium piping and pumps. The dish-shaped structure is sloped 20 degrees to the center of the reactor torus and is divided into 16 pie-cut segments to facilitate construction and assembly operations. Each segment has overlapping edges to provide circular continuity and add structural strength at the intersecting joints. Cut into the inner face surface of each dish-shaped structure are six circumferentially oriented grooves for nesting the divertor coils. The three coil grooves on either side of the structure centerline are separated by a 20.3 cm wide rib while the adjacent coil grooves are separated by 5.1 cm wide ribs. The 20.3 cm rib at the center contains passageways for connecting the lithium piping network on the bottom structure to the top structure. The smaller adjacent ribs provide lithium passageways to the screens located inside the collector horns. In addition to the piping, the center rib and the three adjacent ribs on either side of the center rib contain the holes for the structural bolts which tie the upper and lower structure together. The top dish-shaped structure is spaced relative to the bottom dish-shaped structure by tubular spaces threaded over the structural bolts. These spacers provide the proper spacing (burial chamber) between the upper and lower set of coils while the structural bolts provide the restraint to overcome the total repulsive forces between the two sets of coils. This force is approximately 10^6 newton/m.

The structural bolts are located in groups along the circumference of each rib such that they pass between the lithium wetted screen lined collector horns. The outer and inner edges of the dish-shaped structure, as defined by the I.D. and O.D. of the structures, are held together by means of thin tension plates (1.6 cm) which are keyed and bolted to the top and bottom structures. These plates are notched into the circumference of the structure at such an angle as to align the thin edge of the tension plate with the collector horns. This provides the maximum entrance throat to the collector horns and minimizes the leading edge of the collector screen.

The Flowing Lithium System. The concept and rationale for the use of flowing lithium as a particle collection medium has been described previously⁽¹²⁾. In the following subsection, we discuss the mechanical and thermal designs for this system.

Mechanical Design. A piping manifold is attached to the top surface of the upper dish-shaped structure to provide distribution of the liquid lithium to the surfaces of the screens mounted inside the collector horns. To help reduce the heat load on the lithium as it passes over the screens the lithium is introduced onto the screen at three places along the length of the horn. Each liquid lithium inlet is located approximately 1/3 distance along the path of the lithium as it flows over the screen. If the liquid lithium were to enter one end of the collector horn at T_i and exit the other end at T_o , it would increase in temperature by some ΔT , however, with liquid lithium being introduced at two more points along the path as proposed in this design, the temperature rise of the liquid lithium is reduced by the intermixing of liquid lithium at a temperature T_o from the additional inlets.

The assembled dish-shaped structure is mounted inside, near the top of the vacuum vessel and supported by tension members which transfer the load through the vacuum vessel to the external reactor structures. A similar assembly is installed inside, near the bottom of the vacuum vessel and is supported from the floor of the reactor base by compression members that transmit the loads through the vacuum vessel.

The getter system for this concept consists of liquid lithium wetted screen lined collector horns, 96 inside and 96 outside types, as shown in Figure 6.7-3. The collector horns mounted on the inside and the outside circumference of the dish-shaped structure are 35.5 cm high, the only difference being in the throat opening of the horns (43.9 cm and 65.1 cm, respectively).

The collector horns are constructed of heavy gage stainless steel (0.5 cm) and the inner surfaces are lined with metal screening. The screening on the top and sides of the horns are designed to have a clearance between the screen and the internal surface of the horn such that the screens can be totally engulfed with liquid lithium. The clearance between the bottom screens and the bottom of the horn is achieved by having the screen rest on several ribs attached to the inner surface of the horn bottom plate. The top plate of the horn is

Figure 6.7-3. Collector horn with liquid lithium wetted screens.

recessed and contains many small holes to provide distribution of the liquid lithium on the top and side screens. The small holes are eliminated in the horn top plate just below the three liquid lithium inlet ports to prevent the lithium from passing on through the screen. The lithium that travels down the side screens, is collected on the bottom plate of the collector horn. Coverage of the bottom screen with liquid lithium is assured by the small metal ribs or divider plates which are constructed across the bottom plate of the horn. As the liquid lithium spills over the divider plates, it will come in contact with the bottom screen, and because of the good wetting characteristics of the liquid lithium, will travel along the surface of the bottom screen.

Once the lithium has traveled to the narrow end of the outside collector horn, it will drain off into a reservoir where it will be pumped out of the horn by electromagnetic ($\vec{E} \times \vec{B}$) pumps and out of the vacuum vessel by supplementary pumping systems to a point where the lithium will be cooled and reconditioned for a return cycle. The inside collector horns are similar in construction but in this case the liquid lithium is introduced into the collector horn from the small end and allowed to run down the screen to the large end where it is also removed by the $\vec{E} \times \vec{B}$ pumps and recycled in the same manner as the liquid lithium from the outside collecting horns.

Thermal Design for Flowing Lithium. The total collecting surface area of the design described in the last section is about 320 m^2 . For a total power deposition of 300 MW the surface heat flux is therefore 0.94 MW/m^2 . A design value of 1.0 MW/m^2 was used in the analysis. The design temperature rise of the liquid lithium was selected to be 100° C which is about 70% of the allowable temperature change of lithium from its melting point of 186° C and its boiling point of 325° C at the plasma vessel pressure of about 10^{-5} torr. With the above given heat flux and temperature rise, the total liquid lithium flow rate is

$$w = Q/C_p \Delta T = 1.0 \times 320/4.188 \times 100 = 764 \text{ kg/sec}$$

where Q = total heat input = 1.0×320 MW

C_p = specific heat of lithium = 4.188 J/g $^{\circ}\text{C}$

ΔT = lithium temperature rise = 100°C

With this flowrate and the surface area, the film thickness of the lithium fall was estimated to be about 0.2 cm which appears to be reasonable. A design value of 800 kg/sec is used for the pumping requirement calculations.

Since there are 192 wedge-shaped collectors in the design, the flowrate per collector is $764/192 = 4.0$ kg/sec. Assuming one pipe is used to circulate the lithium flow per collector and the cross sectional area of the pipe is $0.3 \times .0333 = 0.01$ m², the lithium flow velocity in the pipe is

$$V = \frac{w}{A\rho} = \frac{4.0}{.01 \times 497} = 0.8 \text{ m/sec} \quad (1)$$

where A = pipe flow area = $.01$ m²

ρ = lithium density = 496.96 kg/m³

The Hartmann number for the lithium flow is then

$$H_1 = aB_1 \sqrt{\frac{\sigma}{\eta}} \quad (2)$$

where H_1 = Hartmann number

a = one-half of the width of the channel area = $.01666$ m

B_1 = transverse poloidal magnetic field = 4.5 Tesla

σ = lithium conductivity = 2.22×10^6 mhos/m

η = lithium viscosity = 5.8×10^{-4} kg/sec-m

Substituting the above values in H_1 , one obtains

$$H_1 = .0166 \times 4.5 \sqrt{\frac{2.22 \times 10^6}{5.8 \times 10^{-4}}} = 4638 \quad (3)$$

and the transition Reynold's number is

$$Re_t = 500 H_{\perp} = 2.319 \times 10^6 \quad (4)$$

whereas the Reynold's number of the flow is

$$R_e = \frac{\rho V D}{\eta} = \frac{496.96 \times 0.8 \times 0.06}{5.8 \times 10^{-4}} = 4.113 \times 10^4 \quad (5)$$

which is smaller than the transition Reynold's number given previously, therefore, the MHD Hartmann flow regime applies. The calculations for the electromagnetic pump to circulate the lithium are described in Reference⁽¹³⁾. The results of calculations are summarized in the following subsection.

The Lithium Recirculation System. The free surface lithium in the vacuum has to be re-circulated by $\vec{E} \times \vec{B}$ pumps. The simplified geometry of the pump is shown in Figure 6.7-4. The dimensions are $2w = 0.3$ m, $2a = 0.0333$ m and $L = 1$ m. The flow is along the Z-axis direction and the transverse magnetic field is along the X-axis direction. As shown in the last section, the Hartmann number of the flow is 4638, so that the flow is Hartmann and the flow velocity is given by the $\vec{E} \times \vec{B}$ drift or $U_0 = 0.8$ m/sec.

The pressure gradient of Hartmann flow is given by the following equation:

$$\frac{\partial P}{\partial Z} = \left\{ \frac{H_a^2}{R_e} \left[K - \frac{H_a}{H_a - \tanh H_a} \right] \pm \rho g L \right\} \vec{Z} \quad (6)$$

where R_e is the Reynold's number and H_a the Hartmann number. In equation (6)

$K = Ey/\bar{u} B_0$ where Ey is the electric field in y - direction, $\bar{u}$ is the average flow velocity and B_0 the magnetic induction. The second term of Eq. (6) is the pressure drop due to the magnetic viscosity. The third term is the gravitational pressure drop. The average velocity of the channel flow is given in the following expression.

Figure 6.7-4. Simplified magnetohydrodynamic channel flow for the $\vec{E} \times \vec{B}$ pump

$$\bar{u} = \frac{E_y}{KB_o} \quad (7)$$

The gravitational pressure drop is negligible in comparison with magnetic pressure drop. The factor $H_a / (H_a - \tanh H_a)$ is approximately 1 for large Hartmann numbers, H_a . Then K is chosen to be 1.1 to account for the pressure drop due to end effects, Hall effect and nonuniformity of the magnetic field, which are neglected in the Eq. (6). Making $\bar{u} = U_o$, the lithium mass flow velocity, and taking $B_o = 4.5$ T, the electric field required is

$$E = K\bar{u} B_o = 3.96 \text{ volts/m} \quad (8)$$

The current per channel is

$$I = 2(K-1) \sigma B_o \bar{u} (2a \cdot L) = 54 \text{ kA.} \quad (9)$$

The total power requirement is

$$W = 196 (I \cdot E \cdot 2w) = 12.5 \text{ MW} \quad (10)$$

which is reasonable.

If we use a current density in the leads to be 1500 A/cm^2 for each pump, the cross-sectional area of the lead for each pump is 36 cm^2 . The Joule heating of the conductor is

$$Q''' = J^2 \rho_{cu} = (1500)^2 (1.67 \times 10^{-6}) = 3.76 \text{ MW/m}^3 \quad (11)$$

Therefore the cooling of the conductor is necessary and the conductor size is quite significant.

The Solid Getter Systems. As is discussed previously, the lithium circulating system requires complicated design solutions. The corrosion, vaporization and sputtering associated with lithium may impose a problem. The physical properties of a flowing thin lithium film in a magnetic field are not yet known. Therefore, the solid getter method has been evaluated for this application. Because of the fact that the thermal load can for this divertor be designed at as low as 0.5 MW/m^2 , the solid getters do become competitive. The collection method, the thermal problem and vacuum problem are discussed qualitatively as follows.

The Method of Particle Collection. As a comparison, the particle collection with the flowing lithium scheme is shown by Figure 6.7-5. A possible particle collection approach with solid getters is shown by Figure 6.7-6. These figures show a bundle of flux going through a burial chamber. At the lower half of Figure 6.7-6, the molybdenum particle collection panels supported by the ribs on their back are shown by heavy solid lines. The dashed curves are the lines of force. The panels are tilted away from the field lines to intercept particles whereas the ribs are shadowed by the panel so that they will not see the direct incident charged particles. The ribs will also serve as traps for scattered or sputtered neutrals which is illustrated by the enlargement of the section ABCD shown in Figure 6.7-7. The escaped neutrals will be gettered by ZrAl panels. The gettering efficiency of molybdenum is about 60%. The multiple scattering and trapping of neutrals will increase the overall trapping efficiency to 90%. The neutrals escaped from the opening will also be gettered by the auxiliary ZrAl pumps. The backstream to the plasma can be as low as 1%. In the following we will discuss the advantages and disadvantages of using solid getters.

A key property of the solid getters under consideration is the sticking coefficient for ions which is higher than that for neutrals. The sticking coefficient is high even when the getters are operated at high temperatures. Satisfactory operating temperatures of 500°C can be maintained by thermal radiation cooling. Therefore, there is no complicated cooling network. The collected hydrogen isotopes can be released by heating the getter to a very high temperature ($\sim 1000^\circ\text{C}$) so that tritium recovery is simpler than reprocessing the spent lithium. The

Figure 6.7-5. Lithium falls particles collecting surfaces

Figure 6.7-6. Particle collection method using solid getters

Figure 6.7-7. Expanded particle collection section ABCD of Figure 6.7-6. The scattered and sputtered neutrals are re trapped by baffles and ZrAl panels.

disadvantages of the solid getters are: 1) that the getter surface is not renewable after being sputtered, therefore, service lifetime is a concern, and, 2) that the getters can be poisoned by oxygen and carbon. This problem could be minimized by flushing the system with Argon during the down time. All these problems will be considered in our study when the important information has been collected.

Mechanical Design Considerations. The design of the structural members of the compact poloidal divertor is such that the liquid lithium wetted screens enclosed in the collector horns can be replaced with a solid collecting target as shown in Figure 6.7-8. The physical dimensions of the collector horn and the method of attaching the collector horn remain unchanged. Since the solid getter is not liquid cooled, more surface area is required to reduce the heat load. This is accomplished by designing six 0.9 cm thick solid collector panels in the collector horn. These collector panels are made of molybdenum. The back side of these panels contain ribs or fins. These fins, in addition to serving as traps for scattered or sputtered neutrals, provide stiffeners for the thin collector panels.

Thermal Considerations. Molybdenum was selected for the solid particle collecting plates, based on the thermal stresses and melting temperature considerations and for the excellent particle absorption characteristics of the material. Since space is available, the total collecting surface area can be doubled from 320 m^2 to 640 m^2 in order to reduce the heat load on the plate by one-half: from 1 MW/m^2 to 0.5 MW/m^2 . It is desirable to reduce the heat load on the plates so that the thermal stresses and service life of the plates can be improved significantly. The thickness of the plate was selected to be 0.9 cm.

Transient temperature responses of the plate during a 10 second power pulse in a 300 seconds cycle were calculated. The plate was assumed to be cooled by thermal radiation to its surroundings only. The peak temperatures at the end of a pulse and the temperatures at the end of a 300 second cycle for 10 consecutive cycles are shown in Figure 6.7-9. Since thermal radiation cooling depends on the temperature difference between the hot and the cold surfaces,

Figure 6.7-8. Solid getters

Figure 6.7-9. Temperatures of collector plate

the 290 seconds time between two power pulses is not long enough for the plate to be cooled back down to the temperature level at the beginning of a cycle during the early cycles. The plate temperature continues to increase until an equilibrium condition is reached, such that the heat deposited during the 10 seconds of cool down time of a cycle. As shown in the figure, it took about 10 cycles for the plate to reach the equilibrium condition. The steady operating temperature of the plate is therefore between 670°C and 480°C . In this calculation two surrounding environment temperatures were assumed: -196°C and 27°C . The difference on the calculated plate temperatures using these two surrounding temperatures is small. The results using 27°C as the environment temperature are shown in the figure. This indicates that the surroundings do not have to be cooled to a low temperature for the collector plates to operate.

Summary. The MHD equilibrium magnetic flux pattern for the compact poloidal divertor has been confirmed by numerical solution. The preliminary mechanical and thermal designs for liquid lithium systems have been completed. The system is feasible except that the lithium circulating network is quite complicated. Analysis for a solid getter approach has been initiated. The use of solid getters appears to be very competitive qualitatively.

The divertor system under study appears to be very promising as a means for impurity control and particle removal and in addition appears to have less of an impact on total system design and cost than alternative magnetic divertor designs. The divertor itself has the dual functions of collecting energy and charged particles and pumping neutrals.

While the detailed requirements for a magnetic divertor as a means of impurity control have not been substantiated by analysis or experiment, it does appear that if such an approach is required, reasonable engineering solutions can be found to accomplish this function.

7.0 REFERENCES

1. WFPS-TME-050, "TNS Quarterly Progress Report (October-November-December, 1976)," January, 1977.
2. Marcus, F. B., ORNL, private communication.
3. Bahr, M.W.G., P. J. Heitzenroeder, Jr., and H. G. Johnson, "Silver Brazing Methods for Joining the OH and SF Field Coil Turns for the PLT Machine," Proceedings of the Sixth Symposium on Engineering Problems of Fusion Research, November 19, 1975.
4. Giesen, B., D. Boring, W. Kohlhaas, and C. Stickelmann, "Behavior of Copper Contacts at High Direct Currents," Proceedings of the Sixth Symposium on Engineering Problems of Fusion Research, November 20, 1975.
5. Rosner, C. H., "Niobium - Tin Technology," IEEE Publication No. 72, Proceedings of the Applied Superconductivity Conference, 1972.
6. WFPS-TME-049, "TNS Quarterly Progress Report (July-August-September, 1976)," October, 1976.
7. Engle, W. W., Jr., "A User's Manual for ANISN," Oak Ridge Gaseous Diffusion Plant Report, K-1693 (1967).
8. Ford, W. E., R. T. Santoro, R. W. Roussin, and D. M. Plaster, ORNL/TM-5249 (March, 1976).
9. Roussin, R. W., et al., Trans. Am Nucl. Soc., 23, 14 (1976).
10. Yang, T. F., A. Y. Lee, and G. W. Ruck, "A Compact Poloidal Divertor Reference Design for TNS," WFPS-TME-055, October, 1977.
11. WFPS-TME-051, "TNS Quarterly Progress Report for the Period January-February-March, 1977," April, 1977.
12. Sucov, E. W., D. K. McClain, and J. W. H. Chi, "Efficient Particle Removal from Tokamak Reactors," ANS Transactions, November, 1976.
13. Schivell, J. F., and D. J. Grove, "Thermal Stress Under High-Power Surface Heating," PPPL, MAT-1010 (1973).

APPENDIX A

**POSTERS PREPARED FOR THE TNS QUARTERLY REVIEW MEETING
AT ERDA ON JANUARY 28, 1977**

SAMPLE ARRANGEMENT OF TNS-1

ORNL/ THE NEXT STEP (TNS)KEY FEATURES OF THE TNS-1
OPTION ARE THE FOLLOWING:

- TF COIL SYSTEM -Copper
- COOLING OF ALL COIL SYSTEMS -Water
- CENTERING FORCE RESTRAINT -Wedging At Coil Nose
- MAXIMUM CURRENT DENSITY -1500 A/cm²
- PEAK FIELD AT CONDUCTOR -12T
- STRUCTURE TO CONDUCTOR AREA -Varies

SAMPLE ARRANGEMENT OF TNS-3

ORNL/ THE NEXT STEP (TNS)

KEY FEATURES OF THE TNS-3
OPTION ARE THE FOLLOWING:

- TF COIL SYSTEM NbTi Multifilimentary, Pancake Wound
- COOLING-S/C Liquid Helium, Super Critical, Forced Flow
- CENTERING FORCE RESTRAINT Bucking Cylinder (Common Nose Dewar)
- PEAK CURRENT DENSITY OVER WINDING SLOT 2500 A/cm²
- PEAK FIELD AT CONDUCTOR 8 T
- STRUCTURE TO CONDUCTOR AREA RATIO 1.5

SAMPLE ARRANGEMENT OF TNS-4

ORNL/ THE NEXT STEP (TNS)

THE MAIN CHARACTERISTIC OF TNS-4
IS THE HIGH FIELD
SUPERCONDUCTING TF COILS

OTHER KEY FEATURES ARE:

- TF COIL SYSTEM Nb_3Sn
Multifilimentary,
Pancake Wound
- COOLING-S/C Liquid Helium,
Super Critical,
Forced Flow
- CENTERING FORCE RESTRAINT Bucking Cylinder
With Wedging
(Common Nose
Dewar)
- PEAK CURRENT DENSITY
OVER WINDING SLOT 3750 A/cm^2
- PEAK FIELD AT CONDUCTOR 12 T
- STRUCTURE TO CONDUCTOR
AREA RATIO 1.75

TF/OH COIL CROSS SECTION

THE TNS-5 OPTION ATTAINS HIGH TOROIDAL
FIELD CAPABILITY THROUGH THE USE OF BOTH
COPPER AND NbTi WINDINGS -
OTHER KEY FEATURES ARE :

	Superconducting	Copper
TF COIL SYSTEM	NbTi With Cu Pancake, D	OFHC
COOLING	Liquid Helium Super Critical Forced Flow	Water
CENTERING FORCE RESTRAINT	Bucking Cylinder	Wedging Faces At Coil Nose
MAXIMUM CURRENT DENSITY	2500 A/cm ²	1500 A/cm ²
PEAK FIELD AT CONDUCTOR	8T	12T
STRUCTURE TO CONDUCTOR AREA	1.5	Varies

SAMPLE ARRANGEMENT OF TNS-5

ORNL / THE NEXT STEP (TNS)

TYPICAL TNS PARAMETERS AND SCENARIO
TNS-3 OPTION

ORNL/ THE NEXT STEP (TNS)

THIS CHART PRESENTS A SELF-CONSISTENT SET OF PARAMETERS FOR THE TNS-3 OPTION (NBTI). THE CONTINUING TRADE STUDIES WILL INVOLVE ITERATION ON THE ENGINEERING DESIGN GROUND RULES AND THE RESULTING MACHINE PARAMETERS. DESIGN OPTIMIZATION (SIZE AND COST) WILL FOLLOW.

THE TNS SYSTEM

TF COILS - SUPERCONDUCTING NBTI ($B_{max} = 8\text{ T}$)

POLOIDAL COILS - COPPER

$R_0 = 5.7\text{ m}$

$a = 1.34\text{ m}$

$B_t = 4.0\text{ T}$

D-T PLASMA

NEUTRAL BEAM INJECTION

MAGNETIC COIL ASSEMBLIES

$B_{OH} = 1.8\text{ T}$

TOTAL NUMBER OF EF COILS (ALL INBOARD FROM TF COILS) = 18

TOTAL NUMBER OF CONSTANT TENSION D-SHAPED TF COILS = 20

PEAK TF FIELD AT WINDINGS = 8.0 T

PEAK-TO-PEAK HIGH FIELD RIPLE AT TF COIL WINDING = 8%

RADIUS OF HIGH FIELD SIDE OF TF COILS = 3.1 m

TOTAL AMPERE TURNS IN TF COIL SET = 114 MA TURNS

AVERAGE CURRENT DENSITIES

- COPPER OH COILS = 15 MA m^{-2}
- COPPER EF COILS = 15 MA m^{-2}
- NBTI S/C TF COILS = 25 MA m^{-2}

TF COIL ASSEMBLY DIMENSIONS

- INNER RADIUS TO NEUTRAL AXIS = 2.76 m
- OUTER RADIUS TO NEUTRAL AXIS = 9.19 m
- MAX. HALF-HEIGHT TO NEUTRAL AXIS = 4.52 m
- FREE VERTICAL BORE = 7.95 m
- FREE HORIZONTAL BORE = 5.33 m

TOTAL NUMBER OF PULSES (DESIGN BASE) = 10^6

COPPER ELECTRICAL INSULATION DOSE LIMIT = 10^{10} rad

PLASMA PARAMETERS

MAJOR RADIUS = 5.7 m

MINOR RADIUS = 1.34 m

ELONGATION = 1.6

ASPECT RATIO = 4.3

VOLUME = 328 m^3

LOW-BETA Q-VALUE = 3

TOROIDAL FIELD ON AXIS = 4.0 T

LOW-BETA PLASMA CURRENT = 3.5 MA

PLASMA INDUCTANCE x PLASMA CURRENT = 39.3 Vs

MAX TF RIPLE AT PLASMA (P-TO-P) = 2%

ION DENSITY = $2 \times 10^{20}\text{ m}^{-3}$

TEMPERATURE = 13 keV

AVERAGE TOROIDAL BETA = 0.12

TOTAL FUSION POWER GENERATED (17.6 MeV PER REACTION) = 1860 MW

AVERAGE NEUTRON WALL LOADING = 3.26 MW m^{-2}

TOTAL FUSION-ALPHA POWER GENERATED = 370 MW

NEUTRAL BEAM INJECTION SYSTEM

TOTAL NEUTRAL BEAM POWER TO PLASMA = 100 MW

NEUTRAL BEAM ENERGY = $\geq 200\text{ keV}$

CHARGE STATE OF SOURCE IONS = +1

INJECTION ANGLE (FROM $\perp$) = 16°

NUMBER OF SOURCES = 30

NUMBER OF NBI ARMS = 10

CURRENT/SOURCE = 100 A

SOURCE GAS EFFICIENCY = 50%

NEUTRALIZATION EFFICIENCY (D^0) = 20%

NBI ARM DUCT DIMENSIONS = 0.4 m x 0.9 m

TOROIDAL MACHINE SPACE BETWEEN DEVICE CENTER AND PLASMA CENTER

	THICKNESS (m)	OUTSIDE RADIUS (m)
INNER BORE	1.58	1.58
OH COILS	0.30	1.88
DEWAR-TF COILS	0.20	2.08
BUCKING CYLINDER	0.30	2.39
TF COIL-RADIAL BUILD	0.70	3.09
DEWAR-TF COILS	0.20	3.29
ASSEMBLY GAP	0.05	3.34
LEAD SHIELD	0.05	3.39
OUTER SHIELD	0.15	3.53
EF COILS	0.18	3.71
INNER SHIELD	0.23	3.94
VESSEL WALL	0.18	4.12
LIMITER/LINER SPACE	0.25	4.37
PLASMA CENTER	1.34	5.71

TORUS VACUUM VESSEL AND PUMPING SYSTEM

VESSEL VOLUME = 430 m^3

VESSEL SMOOTH SURFACE AREA = 450 m^2

RATIO OF EFFECTIVE TO SMOOTH AREA = 10

PUMPING SPEED OF VACUUM PUMPS = $\sim 10^5\text{ liter/s}$

OPERATING PRESSURE BETWEEN PULSES = $\sim 1 \times 10^{-8}\text{ torr}$

NUMBER OF CRYOADSORPTION PUMPS = 10

AREA OF PUMPING PANEL PER PUMP = 2 m^2

GAS LOAD CAPACITY PER REGENERATION = 10^6 torr liter

VACUUM VESSEL IS OF I-BEAM CONSTRUCTION WITH A D-SHAPED MINOR CROSS SECTION. THE CRYOPUMPS ARE BACKED BY A SYSTEM CLOSED WITH RESPECT TO THE ATMOSPHERE AND CONSISTING OF OIL-LESS MECHANICAL PUMPS, ZIRCONIUM-ALUMINUM GETTER PUMPS, AND REGIONAL GAS ANALYZERS (FOR MONITORING AND LEAK TESTING).

TNS-3 OPERATING CHART

THE PRESENT SET OF PARAMETERS IS BASED ON THE OPERATING SCENARIO AS SHOWN ABOVE

SEGMENTATION AND REMOTE HANDLING

ORNL / THE NEXT STEP (TNS)

THIS CHART PORTRAYS A METHOD OF SEGMENTATION FOR REMOTE MAINTENANCE OF TNS AND EXAMPLES OF REMOTE HANDLING CONCEPTS

- FIGURE 1 - IS A PLAN VIEW DEPICTING A 45° SEGMENT OF TNS DISENGAGED AND TRANSLATED TO A MAINTENANCE POSITION.
- FIGURE 2 - SHOWS AN ELEVATION OF THE SEGMENTED DEVICE ILLUSTRATING THE VARIOUS COMPONENT JOINTS AND INTERFACES. A METHOD OF TRANSLATING THE SEGMENT BY TRACKED VEHICLE IS DEPICTED.
- FIGURE 3 - DEPICTS A REMOTE MANNED MANIPULATOR, SUSPENDED FROM AN OVERHEAD CRANE, BEING USED TO DISCONNECT THE EXTERNAL OH COIL JOINTS.
- FIGURE 4 - ILLUSTRATES A SHIELDED MAINTENANCE MODULE BEING USED IN CONJUNCTION WITH A REMOTE CUTTING/WELDING TOOL DURING CUTTING (OR WELDING) OF THE VACUUM VESSEL BY OPERATING THROUGH AN ACCESS PORT IN THE VESSEL.

Figure 1 TNS - Segmentation For Maintenance (16 Coil Array)

Figure 2 Typical TNS Cross Section Depicting Segment Being Separated From Device

Figure 3 Disconnecting Coil Joints

Figure 4 Remote Cutting (Or Welding) Of The Vacuum Vessel

TRITIUM SYSTEMS

ORNL/ THE NEXT STEP (TNS)

A PRELIMINARY DESIGN FOR TNS FUEL SUPPLY AND TREATMENT SYSTEMS HAS BEEN DEVELOPED. THIS CHART DISPLAYS THE FLOW SCHEMATIC AND HIGHLIGHTS KEY FEATURES. THIS SYSTEM FORMS THE BASIS FOR THE TRITIUM SYSTEM MODELS (SIZE AND COST) IN THE COAST CODE.

PRELIMINARY TNS FUEL SUPPLY AND TREATMENT FLOW SCHEMATIC

SYSTEM CAPABILITIES

FUEL INJECTIONS

1. H₂, D, T, 1:1 D-T, He — gases for vacuum vessel prefill (tritium tests) or
2. Non-tritium experiments
3. T, D, 1:1 D-T pellets for refueling during ignited state testing
4. D as high energy neutral beams (up to 150 MW and 250 keV)

SEPARATION OF HYDROGEN ISOTOPES FROM IMPURITIES

1. Particulate filters
2. Pd-alloy diffusers
3. Depleted U and Zr-Al getters
4. Vacuum stripping

SEPARATION OF HYDROGEN ISOTOPES

1. Cryogenic distillation to yield H, D, T, 1:1 D-T product streams

STORAGE OF TRITIUM

1. Bulk inventory storage in solidified form as UT_{2.8} (depleted U)
2. Temporary holdup (H, D, T) on Zr-Al getters
3. In-process storage for refueling streams as liquid D, T, 1:1 D-T

DETITRATION OF STREAMS AND ATMOSPHERES

1. Gaseous impurity stream treatment includes catalytic thermal cracking of tritiated hydrocarbons, oxidation promoted by suspended precious metal catalysts, adsorption on regenerable (and non regenerable) desiccants, followed by recovery-recycle (electrolysis) or burial disposal.
2. Treatment of He sweep streams of secondary containment systems and process piping jackets includes removal of hydrogen isotopes by Pd-alloy diffusers and cleanup of He stream by catalytic oxidation and desiccation.
3. Reactor Cell atmosphere detritiation system is based on catalytic oxidation and desiccation. Operation is intended primarily for emergency situations.
4. No suitable technology currently exists for detritiation of vacuum vessel and shield aqueous coolants. Lagoon storage is provided for long-term holdup.

CURRENT GROUND RULES REGARDING SYSTEM CONFIGURATION

FUELING

1. Prefill is gaseous 1:1 D-T, 100% excess over that required to attain $10^{20}/m^3$ of D⁺ or T⁺ in plasma.
2. Refueling as pellets of 1:1 D-T and T in amounts necessary to maintain $10^{20}/m^3$ of D⁺ or T⁺ in plasma up to onset of quench.
3. Neutral beam D injection (up to 150 MW and 250 keV) for time (~6 s) adequate to initiate plasma ignited state.

TRITIUM STAND-BY STORAGE

1. As solidified tritide on depleted U chips in three separate compartmented isolated generator-storage units.
2. Storage-generator design based on UT_{2.8} with storage capability equivalent to 360 full power reference D-T pulses, with a 2 g/cm³ bulk density:
 - o Internal volume 10 times that of U
 - o Configuration based on 2:1 height to diameter ratio
 - o U charge excess of 30% based on UT_{2.8}
3. On-site stand-by T inventory (not including in-process T) equivalent to two months supply, augmented by a 30% contingency, amounting to 260 full power 42 s duration D-T pulses.

SPENT PLASMA TRAPPING AND PROCESSING

1. Trapping currently is via cryoadsorbent panel (pumping and immobilization). Alternative is via flowing lithium in divertor burial chamber if poloidal divertor approach is utilized.
2. H entry into plasma based on an outgassing rate of 10^{-10} torr liter/s cm² and a surface 10 times that of computed smooth internal area of elliptical toroid vacuum vessel.
3. T processing loss (excluding radioactive decay) during recovery-recycle of 0.015% of the initial T content of the spent plasma products.
4. Processing-purification accomplished by combinations of mechanical filtration selective permeation-diffusion, cryogenic distillation, catalytic cracking-oxidation, adsorption-desiccation, thermal-electrolytic dissociation.
5. Cryogenic distillation capability to produce adequately pure H, D, T, 1:1 D-T product streams.
6. Nominal operation at 650 K and 1.5 M Pa (~230 psia) on upstream side for Pd-alloy selective diffusers.
7. Maximum pressure of 0.4 M Pa (~60 psia) in gas holdup storage tanks.
8. Alternative trapping system utilizes Y to extract hydrogen isotopes from U carrier-coolant of poloidal divertor burial chamber.

TRITIUM CONTAINMENT AND CLEANUP

1. Each T storage-generator unit is to be provided with its own dedicated heaters, coolers, controllers, inert gas blanketing, vault, emergency system.
2. Pumps for tritium processing operations shall not have rotating seals - If this criterion cannot be met, complete containment is required.
3. Redundancy is required for gas holdup tanks, in-process transfer lines, isolation/control valves, surge tanks, transfer pumps.
4. All tritium processing equipment is to be doubly enclosed. The volumes enclosed by these jackets are to be continuously flushed by a circulating inert cover-gas which is processed by a cleanup system to maintain a low cover-gas tritium level.
5. Tritium cleanup systems provided for off-gas holding tanks, vacuum vessel, reactor cell, and interconnected volumes.
 - o Sizing of the reactor cell system to be based on cleanup accomplishment within 120 hours of operation for a major release.
6. Ample storage capacity provided for separate holdup of all the closed-circuit vacuum vessel and shielding coolants.

FACILITY HEAT DISSIPATION SYSTEMS

ORNL / THE NEXT STEP (TNS)

- DESIGN FEATURES
- VACUUM VESSEL COOLING SYSTEM
- LOW TEMPERATURE, LOW PRESSURE WATER COOLING SYSTEM.
 - COOLANT CHANNELS MAY BE THIN WALLED AND RESISTANT TO CYCLIC THERMAL FATIGUE DAMAGE.
 - BUFFER SYSTEM PROVIDES SECONDARY CONTAINMENT OF RADIOACTIVE PRIMARY COOLANT.
 - THERMAL LOAD TRANSFERRED TO CIRCULATING WATER IS NOMINALLY CONSTANT.
 - VOLUME OF PRIMARY LOOP IS MINIMIZED BY LOCATION OF IHX1 IN TEST CELL BASEMENT AND INCORPORATING BUFFER FUNCTION IN SECONDARY LOOP.
 - COMPLEX COLD LEG BUFFER PUMP AND VALVE SYSTEM COULD BE SIMPLIFIED BY USE OF ELEVATED COLD WATER STORAGE TANK.

- NEUTRON SHIELD COOLING SYSTEM
- CONFIGURATION IDENTICAL TO VACUUM VESSEL SYSTEM.
 - BORATED WATER (1 B ATOM PER 64 H₂O) USED IN PRIMARY COOLANT LOOPS.
 - PARALLEL SYSTEMS SERVE EACH HALF OF THE SHIELDING.

- DEIONIZED WATER SYSTEMS
- SERVE: COPPER TF COILS (TNS-1, TNS-5)
OH COILS
EF COILS
ELECTRICAL POWER CONVERSION EQUIPMENT
PLASMA INITIATION RESISTORS
NEUTRAL BEAM ION SOURCE ACCELERATORS
 - 313 K DEIONIZED WATER COOLANT PROVIDED BY DIRECT USE OF PLANT CIRCULATING WATER IN THERMAL BUFFER SYSTEM.
 - COMMON THERMAL BUFFER SYSTEM SERVES ISOLATED PRIMARY LOOP FOR EACH MAJOR ELECTRICAL SYSTEM.

- PRESSURIZED WATER COOLING SYSTEM
- SERVES NEUTRAL BEAM DUMPS AND CALORIMETERS.
 - PRIMARY LOOP PRESSURIZED TO 7 M Pa.
 - MAXIMUM COOLANT TEMPERATURE OF 550 K.
 - SHARES THERMAL BUFFER SYSTEM OF DEIONIZED WATER SYSTEMS.

- HELIUM REFRIGERATION SYSTEM
- CLAUDE CYCLE HELIUM REFRIGERATOR MAINTAINS LIQUID HELIUM BATH AT 3.5 K.
 - SUPERCRITICAL HELIUM SUPPLIED AT 4.0 K TO COOL SUPERCONDUCTORS AND COIL BOBBINS.
 - FLOW RATES AND OPERATING PRESSURES OF CONDUCTOR AND BOBBIN COOLING LOOPS ARE INDEPENDENT OF EACH OTHER AND REFRIGERATOR.
 - EFFICIENT LOW TEMPERATURE HELIUM CIRCULATING PUMPS REQUIRE DEVELOPMENT.
 - CONSTANT PRESSURE, VOLUME COMPENSATION DEVICE ABSORBS EXCESS BOIL OFF FROM THE BATH DURING PEAK THERMAL LOADS, ALLOWING REFRIGERATOR TO OPERATE AT CONSTANT FLOW.
 - CRYO-PUMP PANELS TO BE COOLED AT VARYING TEMPERATURES.

- NITROGEN REFRIGERATION SYSTEM
- PROVIDES LIQUID NITROGEN AT 77 K FOR COOLING OF TF COIL DEWARs AND OTHER THERMAL SHIELDS.
 - MAY BE USED FOR PRECOOLING IN HELIUM REFRIGERATION SYSTEM.

- AIR CONDITIONING SYSTEMS
- COOL AND DEHUMIDIFY AIR ON A ONCE-THROUGH BASIS.

POWER CONVERSION SYSTEMS

ORNL/ THE NEXT STEP (TNS)

DEPICTED HERE ARE SOME OF THE KEY CONSIDERATIONS ASSOCIATED WITH DEVELOPING THE ELECTRICAL POWER CONVERSION SYSTEMS

- DESIGN APPROACH FOR THE ELECTRICAL POWER CONVERSION SYSTEMS
- (1) IN ORDER TO DESIGN THE PF PCS, THE TOTAL CURRENT SWINGS MUST BE KNOWN. THESE CAN BE CALCULATED FOR A REFERENCE DESIGN FROM THE VOLT-SECONDS REQUIRED BY THE PLASMA.
 - (2) THE COST OF THE OH PCS IS A FUNCTION OF INITIAL OH BIAS, EXPRESSED AS A FRACTION OF TOTAL OH CURRENT SWING. FOR A GIVEN SCENARIO, THE RATINGS OF KEY COMPONENTS CAN BE DETERMINED AS FUNCTIONS OF THE BIAS.
 - (3) PER-UNIT COST MODELS OF ELECTRICAL SUBSYSTEMS WERE DERIVED FROM A SURVEY OF DELIVERED AND QUOTED PRICES OF HIGH-POWER EQUIPMENT.
 - (4) A SEPARATE CALCULATION OF COIL VOLTAGE REQUIREMENTS GAVE A COMPLETE SPECIFICATION OF THE LOAD, PERMITTING DIFFERENT CIRCUIT CONFIGURATIONS TO BE COMPARED ON THE BASIS OF COST.
 - (5) IF POWER CONVERSION REQUIREMENTS TREATED SEPARATELY.

TOTAL VOLT-SECONDS CONTRIBUTED BY THE PF COILS FOR A 7.5 MA PLASMA BURN CURRENT

Coil System	Inductive	Relative	Total
EF-O	55.4 V-S	0 V-S	55.4 V-S
EF-I	6.1 V-S	0 V-S	6.1 V-S
EF-D	1.61 V-S	0 V-S	1.6 V-S
EF _{Total}	63.1 V-S	0 V-S	63.1 V-S
OH	19.5 V-S	32.9 V-S	72.4 V-S
TOTAL	82.5 V-S	32.9 V-S

Parameter	Value	Component	Cost
Lenax Energy Storage	312.00 MJ	Energy	\$ 1.82 M
Lenax Energy Storage	714.00 MJ	Coil	\$ 24.00 M
I _{peak} V _{peak}	2.71 GVA	Power Supply	\$ 33.9 M
		Switch	\$ 43.0 M
		TOTAL	\$101.7 M
Lenax Energy Storage	328.00 MJ	Energy	\$ 1.88 M
Lenax Energy Storage	487.00 MJ	Coil	\$ 16.9 M
I _{peak} V _{peak}	2.26 GVA	Power Supply	\$ 29.1 M
		Switch	\$ 33.8 M
		TOTAL	\$81.7 M
Lenax Energy Storage	572.5 MJ	Energy	\$ 3.34 M
Lenax Energy Storage	304.00 MJ	Coil	\$ 13.0 M
I _{peak} V _{peak}	1.79 GVA	Power Supply	\$ 24.0 M
		Switch	\$ 29.1 M
		TOTAL	\$66.4 M
Lenax Energy Storage	1,587.0 MJ	Energy	\$ 9.25 M
Lenax Energy Storage	453.0 MJ	Coil	\$ 23.7 M
I _{peak} V _{peak}	3.65 GVA	Power Supply	\$ 36.6 M
		Switch	\$ 41.2 M
		TOTAL	\$109.8 M

VARIATIONS OF ELECTRICAL PARAMETERS AND THE COST OF MAJOR COMPONENTS OF THE OH POWER CONDITIONING SYSTEM AS FUNCTIONS OF THE BIAS OF OH COIL CURRENT

- RESULTS FOR THE REFERENCE DESIGN
- (1) OVER 130 V- ϕ WERE REQUIRED FROM THE PF PCS FOR THE ENTIRE CYCLE, WITH EQUAL CONTRIBUTIONS FROM THE OH AND EF SYSTEMS.
 - (2) THE LOWEST OH SYSTEM COST RESULTED FROM A BIAS SLIGHTLY ABOVE .5.
 - (3) THE COSTS OF TEMPORARY ENERGY STORAGE ELEMENTS, SUCH AS AC GENERATORS, AND OF DC SWITCHES ARE HIGH ENOUGH TO PRECLUDE LARGE COST SAVINGS OVER DIRECTLY DRIVING COILS WITH CONTROLLED RECTIFIER SOURCES.
 - (4) DIRECT DRIVE BY ACTIVE SUPPLIES DURING START-UP AND SHUTDOWN WAS ALSO CHOSEN TO MEET THESE GROUND RULES.
 - EF CURRENTS PROPORTIONAL TO PLASMA CURRENT AT ALL TIMES
 - OH CIRCUIT CAN EXTINGUISH PLASMA AT ANY TIME.
 - (5) THE POWER CONVERSION SYSTEM FOR SUPERCONDUCTING TF COILS IS RELATIVELY INEXPENSIVE. THE SYSTEM FOR COPPER COILS MUST HANDLE HIGH POWER, BUT IS AN EXTENSION OF AVAILABLE TECHNOLOGY.

OH WINDING MODELING CONSIDERATIONS

THE DEVELOPMENT OF A MODEL TO REPRESENT THE OH WINDING IS DEPICTED ON THIS CHART

PROBLEM STATEMENT

- THE FLUX PRODUCING CAPABILITY OF AN OH COIL IS SEVERELY LIMITED BY THE ALLOWABLE WORKING LEVEL OF THE CURRENT DENSITY AND THE ALLOWABLE MECHANICAL STRESS LIMIT OF THE WINDING MATERIALS IN TENSION.

MODEL DEVELOPMENT

- FIGURES 1, 2, and 3 SHOW THE FUNDAMENTAL GEOMETRY, FLUX DENSITY AND BODY FORCES.
- THE STRESS GENERATING FORCES ARE ALL RADIAL, TENDING TO EXPAND THE COILS TO A NEW OR LARGER RADIUS WITH AN ACCOMPANYING INCREASE IN CIRCUMFERENCE (SEE FIGURE 4).
- BECAUSE OF A CIRCUMFERENTIAL EXPANSION, THERE IS A RADIAL CONTRACTION OF THE COIL (SEE FIGURE 5).
- BECAUSE THE COIL BECOMES THINNER AS IT IS EXTENDED, A POINT ON THE OUTER RADIUS HAS LESS RADIAL AND CIRCUMFERENTIAL GROWTH THAN THE MEAN COIL GROWTH. BY THE SAME REASONING THE CONDUCTOR WITH THE LEAST RADIUS HAS A GROWTH GREATER THAN THE MEAN GROWTH (SEE FIGURE 6).
- SINCE PER UNIT STRAIN (AND LOCAL MATERIAL STRESS) VARIES AS THE ABSOLUTE STRAIN DIVIDED BY ABSOLUTE LENGTH, STRESS IS PROPORTIONAL TO STRAIN/RADIUS. FIGURE 7 SHOWS THE RELATIVE STRESS AS A FUNCTION OF RADIUS FOR THE STRETCHED COIL.
- MANY COILS WITH MANY INNER AND OUTER RADIi WOULD PRODUCE THE REQUIRED FLUX, BUT THEY MAY REQUIRE EXCESSIVE CURRENT DENSITIES OR PROVE SELF-DESTRUCTIVE DUE TO EXCESSIVE STRESS.
- THE MODELING LOGIC IS ILLUSTRATED BY THE FLOW DIAGRAM - FIGURE 8.
 - A GEOMETRY IS SELECTED
 - A REQUIRED FLUX IS SPECIFIED
 - THE NECESSARY CURRENT DENSITY IS CALCULATED
 - THE MECHANICAL STRESS IS CALCULATED
 - TESTS ARE MADE TO CHECK SUITABILITY OR SAFE OPERATION
 - GEOMETRY IS MODIFIED IF MARGIN EXISTS TO MOVE IN DIRECTION TO REDUCE COST
 - LAST SUCCESSFUL GEOMETRY IS REPORTED

LEAST OUTER RADIUS VS WEBERS REQUIRED

- THE PLOT (FIGURE 9) PROVIDES INFORMATION RELATIVE TO THE RADIUS REQUIRED FOR A SPECIFIED FLUX.
- THE CURVE (FIGURE 9) GIVES A FEEL FOR COIL SIZE OR AVAILABLE FLUX FOR A GIVEN GEOMETRY, AND FOR A PARTICULAR SET OF DESIGN LIMITS.
- THE EQUATIONS FROM WHICH FIGURE 9 WAS DEVELOPED ARE PROGRAMMED INTO COAST.

COAST CODE UTILITY

- CODE REVEALS WHETHER OR NOT ANY DESIGN IS POSSIBLE AND WILL HOME IN ON THE LEAST COSTLY POSSIBLE DESIGN.
- CODE WILL FUNCTION FOR ANY SELECTED INPUT VALUES OF: CURRENT DENSITY - STRESS LIMITS - SPACE UTILIZATION FACTOR - POISSON'S RATIO - AND REQUIRED FLUX.

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

FIGURE 7

FIGURE 8

NOTE: ANY UNIT NOT REJECTED MAY BE A CANDIDATE. THE LAST UNIT REPORTED OUT WOULD BE THE LEAST COSTLY TO MANUFACTURE. TRADE STUDIES MAY DICTATE USE OF MORE COSTLY CANDIDATE WITH LESS LOSSES AND LESS COSTLY POWER SUPPLIES.

ORNL / THE NEXT STEP (TNS)

FIGURE 9

HYBRID TF COIL ELECTRICAL DESIGN CONSIDERATIONS

ORNL / THE NEXT STEP (TNS)

THIS CHART SUMMARIZES THE KEY ELECTRICAL DESIGN CONSIDERATIONS IN OUR HYBRID (NbTi/Cu) TF COIL OPTION

THE PROBLEM

- A NbTi SUPERCONDUCTING WINDING CANNOT FUNCTION WITH PEAK FLUX DENSITIES AS GREAT AS WOULD BE REQUIRED TO MEET THE DESIRED FLUX DENSITY ON THE PLASMA AXIS.

A SOLUTION

- A NORMAL COPPER WINDING NESTED WITHIN THE SUPERCONDUCTING WINDING CAN SUPPLY THE ADDITIONAL FLUX ON AXIS TO SATISFY THE DESIGN REQUIREMENTS.

PERTINENT LIMITATIONS

- THE NORMAL WINDING CANNOT OPERATE CONTINUOUSLY BECAUSE OF THE LOSS LIMITATIONS.
- THE NORMAL WINDING MUST BE EXCITED BY A CURRENT PULSE -- A RAMP IS CONSIDERED HERE -- AND THE FLUX FROM THE NORMAL WINDING IS PULSED AS A CONSEQUENCE.

PRINCIPAL PENALTY

- BECAUSE OF THE PULSING NATURE OF THE FLUX IN EXCESS OF THE SUPERCONDUCTING WINDING FLUX, A VOLTAGE IS INDUCED IN THE SUPERCONDUCTING WINDING WHICH MUST BE MATCHED BY THE SUPERCONDUCTING POWER SUPPLY.

CONCLUSIONS

- A HYBRID DESIGN PROVIDES A MEANS TO ACHIEVING FLUX ON AXIS NOT ATTAINABLE WITH A NbTi SUPERCONDUCTING WINDING ALONE.
- THE ENERGY PULSED INTO THE HYBRID DESIGN DURING EACH CYCLE IS LESS THAN WOULD BE REQUIRED OF A PURELY NORMAL WINDING.
- THE SUPERCONDUCTING POWER SUPPLY IS NOT A SMALL STEADY STATE LOW LEVEL POWER DEVICE AS IN AN ALL SUPERCONDUCTING APPLICATION. PULSING THE NORMAL WINDING CAUSES THE TOTAL STORED ENERGY TO CHANGE RADICALLY AND THE NORMAL WINDING SUPPLIES ONLY PART OF THE ADDED STORED ENERGY. DEPENDING ON THE FLUX LEVELS CONTRIBUTED BY EACH WINDING, THE SUPERCONDUCTING POWER SUPPLY CAN EXCEED THE NORMAL WINDING SUPPLY.

SUPPORTING MATERIALS

THE ACCOMPANYING TEXT AND DIAGRAMS PROVIDE ADDITIONAL REINFORCEMENT OF THE GENERAL STATEMENT OF THE PROBLEM AND CONCLUSIONS.

FIGURE 1

RELATIVE CONFIGURATION OF HYBRID WINDING

OUTER COIL SUPERCONDUCTING (Figure 1)

- COIL SENSES NORMAL COIL FLUX LINKAGE CHANGES
- ACTUAL CONDUCTORS NEVER SENSE NORMAL FLUX LOCALLY
- SUPERCONDUCTING WINDING MUST REMAIN EXTERNAL TO NORMAL WINDING

INNER COIL WITH NORMAL CONDUCTORS (Figure 1)

- COIL WOULD SENSE SUPERCONDUCTING FLUX LINKAGE CHANGES IF ANY
- ENTIRE WINDING LIES WITHIN THE B FIELD OF THE SUPERCONDUCTING WINDING
- NORMAL WINDING MUST LIE WITHIN SUPERCONDUCTING WINDING

FLUX CONSIDERATIONS DURING A FLUX PULSE

- SUPERCONDUCTING CURRENT SHOULD REMAIN CONSTANT (See Figure 2)
FLUX FROM SUPERCONDUCTING COIL SHOULD REMAIN CONSTANT
- NORMAL WINDING IS PULSED (See Figure 2)
FLUX FROM NORMAL WINDING VARIES WITH PULSED CURRENT

INDUCED VOLTAGE CONSIDERATIONS (See Figure 3)

- SUPERCONDUCTOR HAS NO SELF-INDUCED VOLTAGES
- SUPERCONDUCTOR SENSES CHANGES IN NORMAL WINDING FLUX WHICH TOTALLY LINK EACH SUPERCONDUCTING WINDING TURN
- $(E_{SC})_{INDUCED} = N_{SC} \frac{d}{dt} \Phi_{NORMAL}$
- NORMAL WINDING HAS A SELF-INDUCED VOLTAGE
- THERE ARE NO CHANGES IN FLUX LINKAGES DUE TO SUPERCONDUCTING FLUX
- $(E_{NORMAL})_{INDUCED} = N_{NORMAL} \frac{d}{dt} \Phi_{AV-NORMAL}$

$\Phi_{AV-NORMAL}$ IS THE AVERAGE FLUX LINKING A NORMAL TURN, TAKING INTO ACCOUNT THE FACT THAT ONLY A FEW TURNS LINK ALL THE FLUX AND MOST TURNS LINK VARYING FRACTIONS OF THE FLUX.

RESISTANCE VOLTAGE CONSIDERATIONS (See I-R Drop Profiles - Figure 4)

- SUPERCONDUCTING WINDING HAS "0" RESISTANCE AND NO I-R DROP
- NORMAL WINDING HAS A PROMINENT I-R DROP

CONSEQUENCES OF RAMPING NORMAL WINDING CURRENT

- GIVEN LSC = SUPERCONDUCTING COIL INDUCTANCE HENRIES
LNORM = NORMAL COIL INDUCTANCE HENRIES
LSCN = MUTUAL INDUCTANCE HENRIES
SLOPE = RAMPING RATE OF NORMAL CURRENT AMPERE/SECONDS
- DURING THE RAMP
NORMAL CURRENT RISES TO SLOPE x RISE TIME (Figure 2)
NORMAL COIL INDUCED VOLTS = LNORM x SLOPE (Figure 3)
NORMAL COIL I-R DROP RISES FROM "0" TO PEAK I-R DROP LINEARLY (Fig. 4)
NORMAL COIL TERMINAL VOLTS SUM OF INDUCED AND I-R VOLTAGES (Figure 5)
SUPERCONDUCTING CURRENT HOLDS CONSTANT (Figure 2)
SUPERCONDUCTING INDUCED VOLTAGES = LSCN x SLOPE (Figure 3)
SUPERCONDUCTING COIL I-R DROP = 0 (Figure 4)
SUPERCONDUCTING COIL TERMINAL VOLTS = INDUCED VOLTAGE ONLY (Figure 5)
- FOR THE HOLD PERIOD FOLLOWING THE RAMP
NORMAL AND SUPERCONDUCTING CURRENTS CONTINUE AT CONSTANT VALUES (Fig. 2)
NORMAL AND SUPERCONDUCTING COIL INDUCED VOLTAGES DROP TO "0" (Fig. 3)
NORMAL COIL I-R DROP REMAINS AT PEAK I-R DROP VALUE (Figures 4 & 5)
NORMAL COIL TERMINAL VOLTS CONSISTS OF I-R DROP ONLY (Figure 5)
SUPERCONDUCTING COIL TERMINAL VOLTS RETURNS TO "0" (Figure 5)
- POWER CONSIDERATIONS (Figure 7)
NORMAL COIL
DURING RAMP STORED ENERGY DEMANDS INCREASING POWER RAMP
DURING RAMP JOULE HEATING ($I^2 R$) INCREASES
DURING HOLD TIME THE JOULE HEATING PERSISTS
SUPERCONDUCTING COIL
DURING RAMP THE CURRENT AND INDUCED VOLTAGE PRODUCT REMAINS CONSTANT AND HIGH AS ENERGY IS STORED IN THE SYSTEM
DURING HOLD TIME NO INPUT REQUIRED WHILE CURRENT HOLDS CONSTANT

THIS CHART DESCRIBES A COMPACT POLOIDAL DIVERTOR DESIGN NOW BEING DEVELOPED. IT REPRESENTS ONE OF THE ALTERNATIVES UNDER CONSIDERATION FOR ACTIVE IMPURITY CONTROL

PROBLEMS ASSOCIATED WITH POLOIDAL DIVERTOR

- (1) LEAKAGE PARTICLE FLUX VERY LARGE - 320 MW.
- (2) POWER DISSIPATION ON THE COLLECTING SURFACE IN THE BURIAL CHAMBER IS AS HIGH AS 20 MW/m² BECAUSE THE PEAKING OF POWER DISTRIBUTION NEAR THE SEPARATRIX.
- (3) BURIAL CHAMBER HEIGHT WILL EXCEED 1 m TO OBTAIN 2 MW/m² AVERAGE POWER DISSIPATION.
- (4) BACKFLOW TO THE PLASMA IS LARGE.
- (5) COLLECTING SURFACE THERMAL DESIGN IS DIFFICULT.

PROPOSED FEASIBLE SCHEME

- (1) COMPRESS THE MAGNETIC FLUX VERTICALLY IN THE BURIAL CHAMBER INSTEAD OF EXPANDING THE FLUX CONVENTIONALLY. THIS WOULD REDUCE THE VERTICAL HEIGHT BUT INCREASE THE HORIZONTAL WIDTH OF THE CHAMBER.
- (2) 300 m² OR LARGER COLLECTING SURFACE CAN BE OBTAINED. SO THE POWER DISSIPATION WILL BE LESS THAN ~2 MW/m².
- (3) BOTH LIQUID METAL OR SOLID METAL COLLECTING SURFACE CAN BE CONSIDERED.
- (4) BACKFLOW TO THE PLASMA IS REDUCED CONSIDERABLY.

COMPACT POLOIDAL DIVERTOR DESIGN

ORNL / THE NEXT STEP (TNS)

FIGURE 2. FIELD LINE AROUND THE DIVERTOR COIL. THE PITCH ANGLE IS VERY SMALL.

FIGURE 8. CUT-OFF VIEW OF THE BURIAL CHAMBER AS VIEWED FROM INSIDE CIRCUMFERENCE.

FIGURE 9. CUT-OFF VIEW OF THE BURIAL CHAMBER AS VIEWED FROM THE OUTSIDE CIRCUMFERENCE.

- PARAMETERS ASSOCIATED WITH COMPACT DIVERTOR CONCEPT
- (1) SIX PAIRS OF COILS, EACH COIL CARRIES .5 MA
 - (2) ESTIMATED FORCE ON EACH COIL IS $\sim 3 \times 10^6$ NEWTON/m
 - (3) NET UPWARD MAGNETIC FORCE IS $\sim 10^6$ NEWTON/m WHICH WILL BE BALANCED BY THE DOWNWARD WEIGHT
 - (4) CHAMBER HEIGHT = 0.3 m
CHAMBER WIDTH = 1.5 m
 - (5) ESTIMATED LITHIUM FLOW - 1700 kg/sec
DIMENSION OF PUMP - 10 m x 10 m x .3 m
ELECTRICAL FIELD NEEDED FOR EACH PUMP - ~ 40 V/m
TOTAL NUMBER OF PUMPS - 160
 - (6) DIMENSION OF EACH HORN
OPENING WIDTH OF THE OUTSIDE HORN - 0.8 m
OPENING WIDTH OF THE INSIDE HORN - 0.55 m
OPENING HEIGHT OF EACH HORN - 0.3 m
TOTAL LENGTH OF THE SIDE WALL - 5 m
TOTAL SIDE WALL SURFACE AREA - 240 m²
TOTAL TOP AND BOTTOM SURFACE AREA - 80 m²
TOTAL COLLECTING AREA - 320 m²
 - (7) POWER DEPOSITION ≈ 1 MW/m²
 - (8) THE BACKFLOW AND POWER DEPOSITION CAN BE FURTHER REDUCED BY INCORPORATING THE CHEVRON STRUCTURE IN EACH HORN. THEN SOLID COLLECTING PLATE WOULD BE FEASIBLE
 - (9) TOTAL HEIGHT IS $\sim 7.0 - 8.0$ m (CONVENTIONAL DESIGN REQUIRES AT LEAST 9 m)

APPENDIX B 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	
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	22f
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	
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	

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	↓

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 Structural	Toroidal Field Coil Deflection Measurements	0.10	2	↓
1.6-2	Reactor Structural	Testing of Thermal and Electrical Insulating Materials	0.50	3	↓
1.6-3	Reactor Structural	Remotely Maintainable Shear Fasteners	0.15	3	↓
1.6-4	Reactor Structural	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

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	↓

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	

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 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	↓

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 Stablization	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

ITEM/SYSTEM		TOPIC	COST M \$	PRIORITY	WBS REFERENCE
5.3-2	Scientific Instrumentation	Develop Instrument to Measure Ion Temperature	2.00	4	26c
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	25e
6.0-2	Support Facilities	Development and Test of Utility Penetrations Seals	0.09	3	25e
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	25a
7.4-1	Impurity Control Test Capability	Design and Development of Impurity Control Test Capability	3.90	2	22f
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	25g
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

ITEM/SYSTEM		TOPIC	COST M \$	PRIORITY	WBS REFERENCE
7.9-2	Safety and Environmental Impact Research	Generic PSAR/FSAR 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

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