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Oak Ridge Tokamak Experimental Power Reactor Study—1976

Part 6

Research, Development, and Demonstration Needs

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

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RESEARCH, DEVELOPMENT, AND DEMONSTRATION NEEDS*

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The other reports in the *Oak Ridge Tokamak Experimental Power Reactor Study — 1976* are:

ORNL/TM-5572	EPR Summary
ORNL/TM-5573	Plasma Engineering
ORNL/TM-5574	Magnet Systems
ORNL/TM-5575	Nuclear Engineering
ORNL/TM-5576	Engineering

ABSTRACT

The major Research, Development, and Demonstration (R, D, & D) needs for EPR are developed from the technical evaluation of the September 1975 ORNL EPR Reference Design (ORNL/TM-5042) and are presented in a common format. Evaluation was concentrated on the key tokamak features, and only slight consideration was given to peripheral items. Although the list was developed specifically for EPR, it would apply to and be refined during the design of an intermediate system.

Each of the R, D, & D needs has been categorized by its program status/priority assignment and from this process, a number of observations can be made.

- There are many questions yet to be answered.
- The majority of those needs deemed either critical or important are the subject of ongoing programs.
- There are nineteen critical or important needs that could be addressed in programs for which adequate information exists.
- There are two critical areas — fueling and OH system energy handling, for which an inadequate technical base exists for prudent development of R, D, & D programs. Increased emphasis upon these two areas is sorely needed.

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INTRODUCTION

One of the principal objectives of the EPR Conceptual Studies is to provide a comprehensive list of major research, development, and demonstration needs to the fusion program planners. This listing of the major R, D, & D needs is based upon the technical evaluation of the September 1975 ORNL EPR Reference Design. Evaluation was concentrated on the key tokamak features, and only slight consideration was given to peripheral items. Table 6.1 presents a list of those topics covered in the context of the total systems identification for EPR. As the design progresses, it is expected that other, more detailed R, D, & D needs will be defined. Although the list was developed explicitly for EPR, it would apply to and be refined during the design of an intermediate system.

Format

- Brief statement of basic need
- More detailed statement of technical problem
- Classification by type of program development needed:
  - A - applied research and development required before program can be laid out
  - B - existing information sufficient to permit the development of the relevant program
  - C - a program exists now although not necessarily adequately supported to match the EPR schedule
- Priority:
  - 1 - a critical "go or no-go" issue for EPR
  - 2 - an important cost-schedule determinant
  - 3 - a necessary, though postponable task

The general references for the entire study are the following:

1. W. M. Stacey et al., Tokamak Experimental Power Reactor Studies, ANL/CTR-75-2, June 1975.
2. GAC Fusion Engineering Staff, Experimental Power Reactor Conceptual Design Study, GA-A13534, July 1975.
3. M. Roberts and E. S. Bettis, Oak Ridge Tokamak Experimental Power Reactor Study Reference Design, ORNL/TM-5042, November 1975.
4. M. Roberts, Oak Ridge Tokamak Experimental Power Reactor Study Scoping Report, ORNL/TM-5038, August 1975.
5. M. Murphy and J. Neff, Summary of the Proceedings of the Workshop on Conceptual Design Studies of Experimental Power Reactor-1, ERDA-89, November 1975.

SUMMARY OF THE R, D, & D NEEDS IDENTIFICATION

An overview of the identification work can be produced by categorizing each of the needs by its program status/priority assignment. This categorizing has been done and is shown in Table 6.2. From the table, there are a number of observations that can be made.

- There are many questions yet to be answered.
- The majority of those needs deemed either critical or important are the subject of ongoing programs.
- There are nineteen critical or important needs that could be addressed in programs for which adequate information exists.
- There are two critical areas — fueling and OH system energy handling for which an inadequate technical base exists for prudent development of R, D, & D programs. Increased emphasis upon these two areas is sorely needed.

Table 6.1. Index to the listing of major R, D, & D Needs[a]

A. PLASMA PHYSICS AND ENGINEERING
   1. Macroscopic Equilibrium
   2. Macroscopic Stability
   3. Plasma Transport
   4. Plasma Heating
   5. Impurity Control
   6. Plasma Edge
   7. Fueling
   8. Plasma Dynamics
   9. Diagnostics
   10. Atomic and Molecular Cross Sections

B. OVERALL PLANT (1.0)[b]
   1. Long-Pulse High-Duty-Factor System Integration
   2. System Modeling

C. BLANKET AND SHIELD SYSTEM (2.0)
   1. Nuclear Data Base
   2. Neutronics Methods
   3. Thermal Hydraulic and Heat Transfer Analysis
   4. Poloidal Field Effects
   5. Electrical Insulation
   6. Liquid Lithium Circulation
   7. Coolant/Containment Compatibility
   8. Qualification of Design
   9. Structural Materials
   10. Tritium Recovery

   (See also I and M for tritium-related areas.)

D. TOROIDAL MAGNETS SYSTEM (2.1)
   1. High-Field Conductor
   2. High-Current Cable
   3. Cryostabilizing Cooling
   4. Conductor Joint Technique
   5. AC Loss Analysis and Measurements
   6. Stress Analysis
   7. Radiation Damage
   8. Protection
   9. Large-Coil System Test

E. POLOIDAL FIELD SYSTEM (2.2)
   1. Mechanism of Carrying High Current in Rapidly Changing Fields
   2. Cryostabilizing Cooling
   3. Pulsed Coil Protection
   4. High-Voltage Capability
   5. Pulsed Conductor Fabrication
   6. Structural Materials
   7. Poloidal Field System Analysis
   8. Remotely Maintainable Shielding Coil Joints

F. STRUCTURAL SYSTEM (2.3)
   1. Structural Design Criteria
   2. Thermal Insulation

   IMPURITY CONTROL SYSTEM[c] (2.4)

   ELECTRICAL ENERGY STORAGE AND DISTRIBUTION SYSTEM[d] (3.0)

G. ELECTRICAL ENERGY STORAGE AND PULSE SYSTEMS (3.1)
   1. Ohmic Heating Energy Storage and Transfer
   2. Neutral Injection Power Supplies and Components

   INSTRUMENTATION AND CONTROL SYSTEMS[d] (4.0)

   DIAGNOSTIC SYSTEM[d] (4.1)

H. PLASMA HEATING SYSTEM (5.0)
   1. *In-situ* System Application
   2. High-Performance High-Energy Neutral Beams
   3. Mechanical Components
   4. High-Power High-Frequency Microwave Tubes

Table 6.1 (continued)

I. TRITIUM PROCESSING SYSTEM (6.0)	
1. Tritium Processing	
TRITIUM STORAGE SYSTEM- see M.1[d] (6.1)	
PLASMA FUELING SYSTEM[c] (6.2)	
J. VACUUM PUMPING SYSTEM (6.3)	
1. Vacuum Systems/Cryosorption Pumps	2. Large Valves
LITHIUM PROCESSING SYSTEM-see C.6, C.10 (6.4)	
PRIMARY COOLANT SYSTEM[d] (7.0)	
SECONDARY COOLANT SYSTEM[d] (7.1)	
HEAT CONVERSION/ELECTRICAL GENERATOR SYSTEM[d] (7.2)	
WASTE HEAT PROCESSING SYSTEM[d] (7.3)	
K. CRYOGENIC COOLING SYSTEM (7.4)	
1. Large 4 K Hardware	
REACTOR BUILDING COMPLEX[d] (8.0)	
L. MAINTENANCE AND ASSEMBLY SYSTEM (8.1)	
1. Adaptation of Remote Handling Techniques	
SAFETY AND FIRE PROTECTION SYSTEM[d] (8.2)	
LIQUID AND GAS STORAGE SYSTEM[d] (8.3)	
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SITE CRITERIA/IMPROVEMENT[d] (8.5)	
M. TRITIUM CONTAINMENT SYSTEM (9.0)	
1. Tritium Containment in Metals	2. Tritium Behavior in the Environment
RADIATION WASTE HANDLING SYSTEM (9.1)	

[a]In each area listed, considerable additional conceptual design effort is required to develop criteria and, from them, to determine the full extent of research and development necessary to support advanced design. This list represents only the major needs perceived at this early stage of the design process and will be updated as the design proceeds.

[b]Numbers in parentheses refer to the hardware-oriented Systems Design Breakdown dated 10/31/75 issued by ORNL EPR Program Office.

[c]Basic information inadequate for determination of hardware-related R & D needs.

[d]Design insufficient to determine any hardware-related R & D needs.

WORK YET TO BE DONE

Three principal tasks remain unfinished. These tasks, which should be carried on during the further stages of the advanced design work, are the following:

- Extension of the evaluation of the Reference Design to all the peripheral systems and the concomitant identification of R, D, & D needs therein.
- The continuing process of examining the findings of the design work as it becomes more and more specific for additions or modifications to the R, D, & D list.
- Development of specific recommendations concerning both the applicability of ongoing R, D, & D programs, and the structure of new R, D, & D programs that should and could now be undertaken. These recommendations should include basic direction, specific tasks and milestones, and necessary auxiliary facilities.

Table 6.2. Summary table of R, D, & D needs

	Program Status		
	A Requires more fundamental problem definition	B Could be developed	C Ongoing
1 Critical	A-7* G-1	A-4 A-5 A-6 A-8 A-9 B-1 C-8 D-9 J-1 M-2	A-1 D-3 A-2 D-6 A-3 D-8 A-4 E-1 A-5 E-2 C-7 E-3 C-9 E-6 C-10 E-7 D-1 H-1 I-1 M-1
2 Important		C-4 C-5 D-7 E-8 F-1 F-2 G-2 H-3 L-1	A-10 D-5 B-2 E-4 C-1 E-5 C-2 H-2 C-3 H-4 C-6 D-2 D-4
3 Necessary		J-2 K-1	

*These symbols identify subdivisions of each R, D, & D topic as listed in the Table of Contents.

A. INTRODUCTION TO THE PLASMA PHYSICS AND PLASMA ENGINEERING TOPICS

The validity of design criteria for every EPR system is dependent upon an ability to understand and predict the behavior of plasmas. Even though presently operating plasmas represent significant advances in achievement during past years and are better understood than previously, the need for research stems simply from the fact that information of the quality necessary to design an EPR is not at hand. In some cases the problem under study (e.g., heating) has been formulated and confronted through experiment, and it is the applicability and extrapolation of results to larger, hotter long-pulse systems that is in question. In other cases, the problem under study (e.g., fueling) has not been completely formulated nor adequately confronted through experiment. Research in plasma physics is required to lay a basis for understanding of the known as well as the dimly perceived problems. Continued effort in plasma engineering is required to couple plasma physics understanding with the design of hardware for EPR.

Investigation of these topics is essential for the support of the continuous process of definition and refinement of the scientific, technological, and engineering contributions to the eventual fusion product. Of the class of scientific "solutions" that apply to fusion, those that have perceived application to the economically attractive "practical" end points (e.g., high power density) should be most vigorously pursued. An effort has been made in this section to reflect the major experiments which pertain to each specific area, rather than to include every experiment which will contribute data. In fact, most devices starting with and beyond PLT will yield data which should provide valuable insight into most of the ten topics described in this section.

Basic References for Section A:

1. *The PLT Device*, Princeton University Special Report 71/5 (September 1971).
2. *Status and Objectives of Tokamak Systems for Fusion Research*, WASH-1295 (July 1974).
3. *Two Component Torus Joint Conceptual Design Study*, PPPL and Westinghouse Electric Co. (June 1974).

A-1. Macroscopic Equilibrium

Program: C

Priority: 1

Equilibrium configurations that are compatible with large plasma size must be determined. The sensitivity of these equilibria to changes in system parameters such as β_p, coil locations, neutral beam inputs, and feedback control characteristics must be understood. This information will provide a basis for the ultimate plasma shape.

Coil systems rather than conducting shells will provide the equilibria in large devices. Developments in this area must be advanced adequately to determine the feasibility of producing and operating high poloidal beta, noncircular plasmas, divertor systems, and magnetic limiters, with the overall aim of achieving configurational optimization.

This is a requirement for fundamental experimental and theoretical plasma physics investigations. The work must be accomplished on a time scale which supports the EPR conceptual design.

Devices including Doublet IIa, Doublet III, PDX, and ORMAK Upgrade will contribute in this regard. Necessary theoretical and numerical techniques compatible with the planned experimental program are being developed within the fusion community.

An equilibrium condition must be found which is compatible with the required beta, energy density, and long-pulse operation of a fusion reactor plasma core. The present Confinement Systems and Applied Plasma Physics Programs are addressing this problem. Experimental results or theoretical findings may suggest the need for other experiments. At present the planned experiments appear adequate.

A-2. Macroscopic Stability

Program: C

Priority: 1

Conventional requirements include "stable" plasma operation in the optimized equilibrium configuration selected. The operational range of plasma parameters consistent with this requirement must be established to determine the limits of design.

Determination of what level of stable or unstable activity is acceptable for the most efficient EPR operation, and what must be done to avoid the disruptive instability or to reduce its adverse effects, is basic to the design process. Various parameters have a strong impact on plasma stability or on the turbulence level. For example, high power density in a reactor plasma implies high β. As q is decreased, it becomes possible to achieve higher values of β. Theoretical and experimental efforts are required to determine and verify the practical limits on β and q, their relationship, and how they depend on the shape of the plasma cross section. The spatial distribution of q and its relationship to macroscopic stability and convection are not completely understood.

Conventional requirements require long-pulse stable plasma operation for fusion feasibility. Clear definition is needed of the performance limits of the reactor; these limits will dominate the cost of the nuclear island and related components.

To answer these questions, fundamental experimental and theoretical plasma physics investigations are required. Doublet IIa, PLT, Doublet III and PDX, and the ORMAK Upgrade will provide relevant information. The Confinement Systems and Applied Plasma Physics Programs are addressing this problem.

A-3. Plasma Transport

Program: C

Priority: 1

An understanding of fundamental energy transport processes and their relationship to plasma size and system parameters is essential in determining machine size and assessing plasma performance.

Characterization and scaling of fundamental energy transport processes are major uncertainties facing the development of fusion power. In addition to radiation, these processes include classical, neoclassical, pseudoclassical, and anomalous diffusion and transport. The anomalous processes are due to instabilities such as the internal disruption or "sawtooth" which, in turn, leads to anomalously fast transport within the q = 1 mode rational surface. This area is of major concern, since it relates directly to the present inability to calculate the plasma size required to achieve a particular operating objective. Machines with increased plasma size, and possibly profile shaping through neutral injection or other means, could provide control over some of these processes. Plasma modeling, using increasingly sophisticated simulation codes, supplements theoretical analyses in this area. The overall size of the system and energy flows, which could well be critical factors in determining fusion feasibility, will ultimately depend on the transport characteristics.

Fundamental experimental and theoretical plasma physics investigations in this area are needed. More intensive theory directed toward understanding present experimental behavior is required. PLT, ORMAK Upgrade, Doublet III, and the TFTR will provide important input from an experimental viewpoint. The Confinement Systems and Applied Plasma Physics Programs are addressing this problem. The theoretical effort in this area should be expanded.

A-4. Plasma Heating
Program: B, C (see below)
Priority: 1

The factors which influence the penetration and absorption of large amounts of heating power (beams and/or rf) into large, hot, and perhaps impure plasmas should be investigated to ascertain the feasibility of the presently accepted heating mechanisms.

Until now, most experiments have used only ohmic heating. In a large power-producing device, supplemental heating will be required to achieve the temperatures necessary for ignition. In the case of neutral beam injection, the injection power will be much greater than the ohmic power input during heating. Possible limitations under these circumstances must be explored. Also, fundamental questions remain with respect to impurity trapping effects which pertain to beam penetration. The acceptability of perpendicular injection is also an open question at present.

Rf heating is a second possibility. This includes electron cyclotron, lower hybrid, and ion cyclotron (fast and slow wave) heating. From the aspect of plasma physics, coupling to the center of the plasma is the principal problem yet to be solved using low-frequency power. Attainment of high-frequency waves at required power levels presents another challenge (see H-4).

Fundamental experimental and theoretical plasma physics investigations are needed in this area, since heating is one of the basic requirements which must be met to achieve reactor plasma conditions. Theoretical work is under way in the area of beam heating and PLT, ORMAK Upgrade, and TFTR will explore these questions experimentally. Experiments in the rf heating area are being planned for ISX, PLT, and PDX.

The Confinement Systems and Applied Plasma Physics and D & T Programs adequately address the beam heating problem. (C) The rf heating area, on the other hand, is not adequately addressed at this time. (B) Broader participation in theoretical analyses is needed, and priority must be given to experiments at power levels higher than those used in ATC and ALCATOR.

A-5. Impurity Control
Program: B, C (see below)
Priority: 1

Impurity production, transport, and effects must be understood so that techniques may be developed to control them. Major experimental and theoretical advances are required to establish both the feasibility of operating large hot plasmas and the impact of including an impurity control system in the design.

This is potentially one of the most serious problems facing tokamaks. The production of impurities due to the plasma-wall interaction, the transport of impurities within the plasma, and their effects on plasma operation, are not well understood. Long burn times associated with high-duty cycle operation could require impurity control. The usefulness to this end of systems such as divertors or gas blankets is not known. Theoretical understanding and modeling of impurities must be improved to establish criteria for these systems.

Data in this area will be provided primarily by ISX and PDX. In addition, serious theoretical effort should be devoted to developing models of the plasma edge in present and future plasmas. The Confinement Systems and Applied Plasma Physics Programs are addressing the existing short-pulse systems (C) in which time scales may be insufficient to permit observation of some effects. Problems in long-pulse devices (B) such as reactors must be addressed in experiments with large hot plasmas. The study of the proposed intermediate system being conducted by ORNL/Westinghouse does in fact address the problem of impurities in long-pulse devices. The results from this work should be analyzed and incorporated in the Program Plan.

A-6. Plasma Edge

Program: B

Priority: 1

A detailed understanding of plasma-wall interaction processes is needed to develop first-wall design criteria, to provide input to the impurity control problem, and to analyze the detailed plasma energy balance.

In present confinement devices, energy is transported from the central plasma zone primarily by conduction to the boundary zone where it is radiated to the first wall (or liner). The details of the processes dominant in the boundary zone or plasma edge are not well understood. For larger, hotter devices, questions of the uniformity of energy deposition and power handling in general become critical. For example, plasma edge physics and its dependence on particle recycling, structural walls (honeycomb), and divertors or magnetic limiters must be sufficiently well understood that design characteristics can be specified. In addition, sputtering, which relates directly to impurity production and material damage, will depend critically on the details of the conditions of the plasma edge. Achievement of the necessary high-vacuum conditions will depend upon pumping and vacuum techniques and, in particular, upon the condition of the boundary wall surfaces.

Basic experimental and theoretical plasma physics investigations are needed in this area. Surface physics questions must also be answered to provide input to the study of the plasma edge.

Theoretical techniques and codes in this area for the most part must be developed. Key experiments here include ISX and PDX and basic materials data studies which will determine sputtering and erosion rates for incident charged particles, including impurity ions, neutrals, and neutrons. The Surface Radiation Effects Program will contribute basic data. Studies of the response of surfaces to plasma and radiation bombardment can provide a basis for understanding impurity production mechanisms, and thence for controlling them. Surface physics investigations will provide information on surface characteristics relative to the design data needed for clean vacuum systems.

Included in this section is a suggested list of important processes, several of which have not been studied theoretically in any depth, together with an estimate of their priority and the time required for solution of problems.

This problem is important with respect to attaining ignition, overall energy balance, and material compatibility, and to preparing for the uncertain implications of plasma-edge phenomena.

Relative importance of problem:		Time required for solution:	
high	= 1	0-2 years	= a
medium	= 2	2-4 years	= b
low	= 3	>4 years	= c

Process	Importance	Required time
1. Sputtering:		
(a) Physical; liberation of material due to beam of particles	1	b
(b) Chemical; non-momentum transfer	1	b
2. Desorption; release of gas by:		
(a) Ions	1	b
(b) Electrons	3	a
(c) Photons	2	c
(d) Thermal effects	1	b
3. Blistering by:		
(a) Alphas	3	b
(b) Hydrogen isotopes	2	b
4. Backscattering	2	b
5. Trapping and release of implanted H and H_2	2	b
6. Pellet refueling; interaction of ions and electrons with solid H_2	2	c
7. Impurity control; gettering, baking, discharge cleaning	1	a
8. Chemical reactions; e.g., atomic hydrogen with low-Z materials	1	b
9. Combined effects; e.g., erosion rates of blistering plus large thermal effects	2	c

A-7. Fueling

Program: A

Priority: 1

A means for fueling the central zone of the plasma may be required to maintain the plasma density during long-pulse operation.

Pellets, gas blankets, particle clusters, and low-energy neutral injection are considered possible techniques for fueling the center of the plasma. Fueling may be required in a device which operates for pulse times several times greater than the particle containment time in the device. Uncertainties in the theoretical understanding of recycling in present devices obscure the severity of the fueling requirement. Pellet fueling, considered by many the most promising technique, is not well understood theoretically. Acceleration of the pellets to velocities sufficient to attain penetration to the plasma center presents a major technological challenge. Gas blanket or puffing analyses are presently unable to explain experimentally observed results on ALCATOR, PULSATOR, and ORMAK, where the central density responds to perturbations on the surface on a time scale shorter than that classically predicted.

Larger, hotter experiments are needed to determine the extent of the fueling problem. Experimental and theoretical plasma physics must investigate further both the nature of the problem and possible fueling technologies.

Support for this area is at a very low level. An expansion in all parts of the program is necessary. The program plan for fueling in the Fusion Systems Engineering Program Plan should be upgraded to include larger equipment funds in the near future to support experiments.

A-8. Plasma Dynamics

Program: B

Priority: 1

The allowable range of plasma operating parameters and the actual operating procedures (e.g., current risetimes, minimum and maximum field values, shutdown scenarios, etc.) are required to support the engineering design of chamber walls, magnet systems, electrical breaks, and energy handling systems.

Generally, this topic includes start-up, control of the plasma column during the burn phase, and shutdown. At present, uncertainties in each of these areas imply uncertainties in fusion reactor designs which affect many areas, including cost estimates. For example, the atomic physics and gas dynamics of the breakdown, ionization, and current initiation phases of start-up must be well understood. Poloidal field system criteria leading to engineering design work can be developed from this information. Control of the plasma column during the long-pulse burn phase of operation may require feedback or other systems to maintain a separation between the plasma and the wall. Finally, a controlled shutdown procedure will have to be developed and operated on a time scale consistent with a high-duty cycle. Basic work in each of the aspects of plasma transients can serve to clarify the needs for start-up drive capacity, control systems, and energy handling systems.

Experimental and theoretical plasma physics investigations in these areas are required, but by the nature of the problems must involve large hot plasma systems. PLT, PDX, TFTR, and other long-pulse experiments should provide important input to all of these areas. The role of plasma engineering, as recognized in the FSEPP, is to provide integration of the numerous disciplines involved in these areas.

Increased theoretical work is necessary with respect to the analyses associated with plasma dynamics. Next-generation confinement devices will provide experimental data which must be understood and reflected in the design of advanced devices. This process of continually absorbing new information must be supported by systems studies of reactor devices.

The aggregation of unknowns here is so great that a high priority is warranted. The maximum uncertainty is in the determination of the possible range of the parameters. Once this range is specified, the importance of the area would drop to a lower priority.

A-9. Diagnostics

Program: B

Priority: 1

Effective processes, reliable means, and the required equipment must be developed to monitor operation of a power-producing reactor plant; such operation renders some of the current techniques ineffective and introduces radiation damage considerations.

Certain key differences exist between present diagnostic schemes and the needs of a large, hot system. For example, even in present experiments, the plasma thickness requires development of a new technique for measuring central ion temperatures. Using charge-exchange neutral measurements to determine these temperatures was adequate in early experiments, but it will not be possible in large devices for two reasons. There will be, first, because of the higher temperatures, a decrease in the number of neutrals in the plasma center and second, shielding of the charge-exchange particles produced by the outer layers of the plasma. Basic consideration of the measurable quantities in large, hot, persistent plasmas and simultaneously of the feasible measurement techniques must begin by determining the diagnostic requirements and then proceed to developing the specific equipment to fill those needs.

This is a requirement for fundamental experimental and theoretical plasma physics investigations as well as for basic and applied instrumentation. Inadequate diagnostic measurements will hamper improvement in the understanding of physical processes and affect progress in a wide variety of ways.

TFTR will provide valuable experience in operating diagnostics in an intense radiation environment. PLT, PDX, and Doublet III will supply input applicable to larger devices and ISX will yield information useful for impurity diagnostics. A program to prepare diagnostics for EPR service should be devised.

A-10. Atomic and Molecular Cross Sections

Program: C

Priority: 2

Knowledge of atomic and molecular processes is required in the development of diagnostic techniques, the interpretation of the results of experiments, and the calculation of injection processes. It is a requirement for fundamental experimental and theoretical atomic physics investigations.

Cross-section data are inadequate in numerous areas affecting neutral beam injection, radiation losses, and the plasma-wall interface. In the injection heating area, data for high-energy ($\sim$150 keV) positive ion behavior are needed to understand plasma heating (and subsequent cooling). Data regarding conversion from positive ions to negative ions are needed in the development of new ion sources. Charge-exchange cross sections between multicharged ions found as contaminants in tokamak discharges and H_2, H, and H^+ are needed to interpret and understand line radiation of impurity ions. The problem of hydrogen recycling at the walls requires information on the behavior of reflected particles and distribution of hydrogenic species leaving the surface. To a large extent, atomic processes control plasma behavior in current experiments; in toroidal plasmas, the confinement is determined by collision rates which govern the electrical resistivity, particle transport rates, and energy losses by radiation.

The following list of needed data, involving the areas of impurities, plasma heating and cooling, and diagnostics, has been compiled from the fusion physics community:

a) electron excitation cross sections near threshold for multiple-charge light impurities (C and O);

b) charge-exchange reactions between H^+ and ions form diagnostic beams (Li^+, K^+, Tl^+) and light impurities (C and O);

c) cross section for negative ion production in the energy range 25 eV-1000 eV;

d) excitation cross section;

e) ionization cross section,

   e, H^+ and excited atoms,

   e and excited light (O, C) and heavy (W, Mo, Nb, Ta) wall impurities;

f) transition probabilities for highly ionized noble gases (Ne, Ar, Kr, Xe).

B. INTRODUCTION TO THE OVERALL PLANT TOPICS

The purpose of the systems requirement is to provide a confrontation with the total ensemble of tokamak and EPR-related issues as quickly as is practicable. Although it is very difficult to identify clearly beforehand each of the specific problems that will arise in the overall system integration, experience has shown (see ERDA-1) that a system test is essential for speedy success in a large project. These two topics cover both the theoretical and experimental aspects of the systems area.

Basic Reference for Section B:

M. Klein et al., *Report of LMFBR Program Review Group*, ERDA-1 (January 1975).

B-1. Long-Pulse High-Duty-Factor System Integration

Program: B

Priority: 1

Design, fabrication, and operation of a long-pulse high-duty-factor complete sub-EPR-size tokamak, using high beam power and with superconducting coils, is essential to the development of a secure basis upon which an EPR can be produced.

Given the great magnitude and complexity of the EPR project, it is imperative that as many as possible of the EPR-related problems should be confronted in earlier, smaller devices and then overcome. The EPR design will be based in part on the knowledge developed over the past decades, but will also require specific information about D-T fusion physics and related technology. Experiments in TFTR will address many of the physics-related and some of the technology-related questions of a fusing plasma, but only for the limited number of seconds that the pulsed toroidal field is on. Even though 1 to 10 seconds is long compared to present-day experiments, it is short compared to the expected 60 to 120 seconds for an EPR. Investigation of a steady state impurity control, neutral beam gas and power handling, fueling, superconducting magnet experience, and overall integrated system experience are the principal tasks which must be approached in a setting much simpler, earlier, and cheaper than a full-scale power-producing EPR.

The need for this step is now being recognized on the basis of evidence developed in the EPR studies. General consideration of such a step is included in many of the logic plans being prepared by DMFE and others. Specific consideration of the particular choices available is now being studied in the intermediate system study conducted at ORNL. Recommendation for a reference design is planned for October 1976.

Appropriate effort is now being exerted to understand the possible choices and consequences related to extension of currently planned facilities, such as Doublet III, PDX, and TFTR, and next logically postulated devices using varying amounts of D-T burning.

B-2. System Modeling

Program: C

Priority: 2

A comprehensive tokamak system model is required to provide a computational tool for overall plant performance and design trade-off studies. The availability of working plant models will certainly aid maximization of the benefit/cost ratio.

Sensitivity analysis to evaluate system parameters such as plasma size, coil shapes and field strength, blanket performance, and impurity buildup presently requires a time-consuming "trial and error" effort to arrive at a single design point. Quantitative analysis of those factors not related to physics which determine overall plant performance is sorely needed to develop a means of comparing the effects on benefit/cost of remote maintenance requirements for access and downtime, of size and field strength of magnets as related to difficulty of technology and risk of schedule slippage, and of power level on auxiliary systems such as tritium handling, safety, cost and handling, and balance of plant items. A system model would catalog the major device systems in terms of design parameters and interface relationships. Sensitivity studies and design options could be systematically evaluated in terms of performance and cost to arrive at an optimum EPR for the established goals. Presently available systems codes are too model-specific, requiring extensive reworking for application to our reference design.

Currently, comprehensive plasma models exist and are being expanded at each of the major tokamak locations. Plasma engineering models coupling plasma behavior to electromagnetic and nuclear systems are being developed at the EPR studies laboratories. Rudimentary plant models characterizing nonplasma components in very simple functional relationships are also of necessity being generated in these studies. At ANL, a more broadly inclusive code is being developed to address each system by a specific module for overall analysis. This code is specific to the EPR model and does not permit comparison with other designs.

The FSEPP calls for systems models to be available by September 1977. The models from this plan, along with earlier, less sophisticated working versions, appear to provide adequate systems-wide coverage. Careful evaluation of the content of each module will be necessary before this need can be considered satisfied.

C. INTRODUCTION TO THE BLANKET AND SHIELD SYSTEM TOPICS

The systems associated with blanket and shield fulfill several functions. The source of the output energy of the fusion reactor is derived from the energetic neutrons and from the non-neutron plasma energy deposited on the first wall. The EPR final design must be based on detailed analyses of the processes required to assure that the blanket and shield satisfactorily fulfill all of the necessary requirements. This implies the availability and capability of tools and methods to perform the necessary analyses in the following areas: neutronics, thermal/hydraulics, radiation damage, mechanical design including structural analyses, radiation shielding, and the use of tritium.

It is also necessary that the analyses be complemented by experimental programs designed to demonstrate the desired understanding in the applicable discipline areas including such areas as materials compatibility, thermal/hydraulics, radiation damage, tritium handling, and circulating liquid metals. Finally, the anticipated performance predicted by calculation must be supported by experimental test programs designed primarily to qualify the design and demonstrate the adequacy of the components in a controlled test environment. Because of the relatively short time in which conceptual design studies have focused on this problem, and especially because of the uncertainty in the actual configuration of a viable tokamak reactor, development of a detailed blanket/shield engineering program must await further information.

These needs are addressed in the ten areas considered to be of highest priority in the systems associated with the blanket and shield.

Basic References for Section C:

Fusion System, Engineering Program Plan, ERDA-DCTR-Draft (December 1975).
Technology Workshop on Blanket/Power Systems for Fusion Reactors, Brookhaven National Laboratory, March 29-April 2, 1976 (in press).

C-1. Nuclear Data Base
Program: C
Priority: 2

Establishment of a well-defined nuclear data base for all materials under consideration for EPR/Demo application is required to provide the means to obtain the desired accuracy in the associated analyses and to permit accurate optimization of the breeding and shielding design.

The nuclear data base presently available is incomplete and contains large uncertainties. As the evaluations of the designs and their performance mature, the analyses required to support the design will become substantially more sophisticated. The need to know and reduce the level of uncertainty in these analyses due to the nuclear data will increase.

The main problem concerns the accurate description of the nuclear heating and radiation damage in the blanket, shield, magnets, and structure of EPR. In particular, shielding of superconducting coils at penetrations in the reactor blanket will be a sensitive area requiring accurate data to avoid over-conservative and hence costly design. Other problems include the determination of tritium breeding capability in the experimental breeding modules, the description of induced activity in the various structural materials in the reactor, and the nuclear data requirement associated with the fuel cycle reaction process and the radiation shielding evaluations.

The need for a nuclear data base is recognized in the FSEPP. However, it is doubtful whether funds will be available at the right time to support development of this area.

Specific suggestions can be made to define the general program already laid out in the FSEEP. An ordered listing of nuclear data needs for EPR application follows.

AREA OF APPLICATION	ORDER OF IMPORTANCE	NEED
Nuclear Heating	1	Develop a complete data base for secondary gamma-ray production in the energy range 1 to 20 MeV.
Radiation Damage	1	Evaluate the (n,α) and (n,p) reaction cross section data for CTR application.
Tritium Breeding	2	Reevaluate $^7Li(n,\alpha n)T$ data for $E > 10$ MeV in an attempt to reduce uncertainties.
Induced Activity	2	Evaluate data on activation cross sections, half-lives, and decay schemes.
Fuel Cycle	3	Evaluate the $T(d,n)\ ^4He$ reaction cross-section. Evaluate charged particle reactions including both low-Z and high-Z fields.
Radiation Shielding	4	Evaluate nuclear and gamma cross sections.

The candidate materials now under consideration for EPR application include the following:

APPLICATION	MATERIALS
Breeding	Liquid Lithium
	Molten Salts (Li_2BeF_4, LiF_3, NaOH)
	Ceramic Compounds (Li_2O, Li_2C_2)
	Aluminum Compounds (LiAl, $Li_2Al_2O_4$)
Structural	Refractory-Based Alloys (Nb, V, Mo)
	Iron-Based Alloys
	Nickel-Based Alloys
	Aluminum-Based Materials
	Carbon-Based Materials
Coolant	Liquid Lithium and Potassium
	Molten Salts
	Helium
Moderator	The Breeding Materials
	Graphite
Neutron Multiplication	Beryllium

from Letter to B. Twining from M. Roberts, January 21, 1976

C-2. Neutronics Methods

Program: C

Priority: 2

Development of neutronics methods for accurate description of the nuclear performance of finite-sized, realistically configured blanket/shields is required to provide, along with bench scale tests, a demonstrated nuclear design capability.

Generalized numerical techniques exist to describe sophisticated space-time nuclear behavior; the Monte Carlo technique is one example. However, methods must be developed on the basis of such techniques, and then tested against bench scale experiments, to provide the calculational capability needed for detailed analyses of future designs. This includes developing a capability for describing the system under analysis in all dimensions including the effect of penetrations and the proper neutron source term for the toroidal fusing plasma geometry.

The FSEPP includes neutronics methods development as a recognized item, but at an inadequate support level.

C-3. Thermal Hydraulic and Heat Transfer Analysis

Program: C

Priority: 2

Development of computational methods to quantify the thermal fluid behavior of those coolants which appear promising for EPR/Demo application is required to provide the thermal hydraulic and heat transfer bases for the design.

The geometry of the coolant system, and the blanket it is cooling, is likely to be complicated, requiring sophisticated multi-dimensional calculational methods to describe accurately the thermal fluid and heat transfer behavior of the blanket for nominal pulsed operation and for postulated off-nominal and accident conditions. The impact of the thermal cycling on the design resulting from pulsed operation is recognized as a potentially severe problem. Accuracy in assessing the thermal stress conditions will be required to define materials development needs.

The funding allocated in the FSEPP adequately covers this requirement.

C-4. Poloidal Field Effects

Program: B

Priority: 2

Determination of how the design and performance of the poloidal field system are affected by the proposed mechanical aspects of the blanket and shield must be made to provide a basis for the electromagnetic aspects of the blanket/shield design.

The specific blanket and shield design selected for EPR application may use many materials of varying conductivities arranged in a complicated configuration. The problem of induced eddy currents (and resultant forces and fields) has been recognized and some work done in this area. However, electromagnetic field perturbation criteria must be generated, and methods must be developed to describe accurately the electromagnetic effects of non-sinusoidal time variations on the complex blanket and shield designs being considered for EPR/Demo application. Calculations of losses in the blanket are also needed to determine the effect of the blanket on the air core volt-second requirement.

The FSEPP does not explicitly include this task which was recently recognized in the EPR studies.

C-5. Electrical Insulation

Program: B

Priority: 2

Establishment of requirements for the electrical insulation of the blanket and shield is needed to provide the basis for the design of any electrical breaks in the blanket.

The blanket and shield are located in strong electromagnetic fields that undergo large, rapid changes presently uncertain in magnitude by much more than a factor of two. Accordingly, criteria for the electrical insulation of the EPR blanket and shield must be developed. Any special materials required to satisfy such criteria would have to be identified and approved, their behavior in a plasma radiation environment determined, and their performance under cyclic thermal loads established.

The FSEPP recognizes the general need to understand plasma start-up and dynamic behavior. The general insulation requirements are recognized in the materials plans. The potential for electrical insulation needs in the blanket and shield design should be included in the existing programs identified above. See also D-6 for magnet insulation requirements.

C-6. Liquid Lithium Circulation

Program: C

Priority: 2

Experimental demonstration of the acceptability of circulating liquid lithium in the EPR/Demo configuration environment is necessary to the qualification of the blanket design.

Liquid lithium is frequently identified for use in tokamak power reactors. An understanding needs to be developed of the performance of circulating liquid lithium in the magnetic field environment, so that acceptable performance can be realized.

The FSEPP recognizes this need in the Blanket Fabrication and Testing Activity. The existing program should be revised to recognize more specifically the large development effort associated with this need. Existing test facilities must be identified or new facilities built to accomplish this program need.

C-7. Coolant/Containment Compatibility

Program: C

Priority: 1

Determination of the materials compatibility between candidate coolants and containment materials is necessary to develop a basis for prediction of component lifetime.

Materials compatibility is essential to proper performance of fusion power reactors over the desired lifetime of the devices. Prior experience with complex technologies has demonstrated the critical importance of thorough understanding of materials behavior and especially the compatibility of materials. Unsuccessful materials compatibility in previous complex technologies has led to expensive failures. Investigation of corrosion behavior of blanket materials at high temperatures in the presence of fluids such as liquid lithium is required, as well as a study of the fabricability of corrosion-resistant materials.

The materials compatibility needs are recognized in the FSEPP.

C-8. Qualification of Design

Program: B

Priority: 1

Development of an experimental program to qualify the mechanical, thermal-hydraulic, heat transfer, and structural aspects of the blanket and shield design concept(s) is required to assure acceptable performance when the blanket is installed in EPR.

Once the more promising blanket and shield concepts are identified and the mechanical design aspects reasonably well established, it will be necessary to develop, and then implement, an experimental program to qualify the design(s) before incorporation into EPR. The test program will be designed to include testing of items such as:

- the adequacy of the coolant system,
- pumping power requirements,
- dimensional stability with temperature variations,
- corrosion compatibility,

- tritium recovery from the experimental breeding modules,
- fatigue lifetime under cyclic thermal load operating conditions, and
- other similar performance characteristics for the nominal range of operating parameters and for postulated accident conditions.

As one of the most costly items in the EPR, the blanket must have an adequate testing program. The FSEPP includes a general testing program but needs incorporation of specific requirements and approaches to satisfy these requirements; one specific program has been developed by the ORNL FRT program.

C-9. Structural Materials

Program: C

Priority: 1

Identification is needed of the structural material (including both the composition and metallurgical condition) which has optimum end-of-life properties for EPR application. This material will form the basis for design of the first wall and other blanket structure, and its selection is therefore a central "go or no-go" issue.

Knowledge of radiation effects in the various fusion reactor materials in the first wall and blanket is needed to avoid the dilemma of facing either over-conservative and hence costly design requirements, or foreshortened working life of the reactor components. The 14-MeV fusion neutrons generated by the thermonuclear reaction will produce significant radiation effects in the first vacuum wall and the structural walls of the blanket. Helium produced by the (n, α) reactions will embrittle most conventional structural materials, such as type 316 stainless steel, which is presently considered the best materials choice for the first experimental reactors. Moreover, radiation-induced damage increases with increasing wall temperature, with a drastic reduction in creep-rupture strength properties of 316 SS above 550°C. Large uncertainties exist in both irradiation conditions and requirements. Indications from reactor studies consistently support the economic necessity for neutron wall loadings high enough to portend significant metallurgical difficulties. The ability to generate plasmas producing these high wall loadings is uncertain but appears essential to the successful pursuit of tokamak fusion. To quantify these difficulties is a principal concern in the development of programs to meet this need.

Titanium-modified stainless steel, which has a reduced ductility sensitivity to irradiation, offers a promising approach to an acceptable and optimized material. Basic research in the radiation effects field must be pursued with the objective of identifying acceptable first-wall and structural materials. This includes establishing radiation effects related to atomic displacement levels, hydrogen and helium gas contents, cycling loading, and irradiation behavior of weldments. (See A-6 for materials-related questions affecting plasma behavior, e.g., sputtering.)

The CTR materials program is basically aimed at this issue. Thorough understanding of materials to be used in fusion reactor devices is integral to the eventual achievement of economic viability. The materials program should be accelerated, especially in the direction of providing facilities for irradiation testing of materials.

C-10. Tritium Recovery

Program: C

Priority: 1

A feasible scheme for recovery of tritium from the blanket must be identified and developed for EPR/Demo application to provide a basic design for this essential function in the breeding modules.

Significant tritium-related questions must be answered before full-scale societal debates can be held for EPR.

It will be necessary to recover and recycle tritium within the tokamak power reactor. The blanket recovery system is not well defined. By the time of commencement of EPR construction, the most promising schemes for blanket recovery, e.g., extraction, permeation, or absorption, must have been developed to the point where extensive testing (on a small scale) is completed. After testing, one or more must still appear promising. Since it is not envisioned that EPR-1 incorporate more than a few test breeding modules, the need for a fully qualified and workable scheme for tritium recovery from the blanket will not occur until the EPR-2 or Demo stage. However, it is crucial that a fully workable scheme which may be scaled up to Demo be available at the time. It is expected that EPR-1 will be the major testing stage for the subsequent scale-up to the EPR-2/Demo application.

Basic research into tritium chemistry processes would support the fusion needs directly. These studies should focus on schemes to remove tritium from lithium at temperatures of $\sim$500°C such as are expected in fusion reactors. Measurements of the solubility of H_2, D_2, and T_2 in lithium and of the effects of impurities on the solubility are needed, as well as measurements of tritium sorption from lithium. The properties of tritium-passing "windows" in the presence of possible "fogging" materials transported by lithium must be investigated in order to determine lifetimes of components.

The FSEPP recognizes the need for tritium recovery research, and has allocated what seems to be adequate support.

D. INTRODUCTION TO THE TOROIDAL MAGNETS SYSTEM TOPICS

Understanding the basic properties of high-field superconductors is essential to the successful production of reasonably-sized fusion reactors. All indications are that large, high-field, reliable superconducting magnets will be central components in fusion reactor design and operation. Large toroidal magnets (many meters in diameter) have not been used in fusion research. High-field magnets (maximum field strengths greater than 10 or 11 T) have not been used extensively in any area although small-bore (a few centimeters in diameter) coils wound with tape superconductor have reached 17 T. Questions of conductor metallurgy and production and cable behavior under severe mechanical, electrical, and thermal cycling must be answered before confident design of large-diameter high-field magnets can begin. The applicability of prior experience in large-scale solenoids is limited because of the introduction of non-simple fields. In solenoids, problems have developed with the end turns where vectorial fields were involved as in hybrid magnets. In the following pages, each of the separable R, D, and D needs, which together represent the support for large high-field magnets, is discussed in detail.

Investigation of the limits in each specific area of high-field operation could result in operating field values higher than now proposed in the light of present limited knowledge. Similarly, understanding of the thermal processes in the magnet could lead to more definitive, and possibly higher, limits on operation of the entire reactor. A clearer definition of the plasma-related phenomena affecting TF coil operation (namely, the effective rate of field change at the windings from the plasma current and from any local current elements, the importance of plasma aspect ratio and the importance of ripple fields on losses) would be of great value in delimiting the range of requirements to be imposed on the development program.

Basic Reference for Section D:

Program for Development of Toroidal Superconducting Magnets for Fusion Research, ORNL/TM-5401, Oak Ridge (April 1976).

D-1. High-Field Conductor

Program: C

Priority: 1

Work in the area of high-field superconductors less brittle than the presently available tape materials would result in an easing of the severe design restrictions now applied to high-field tape conductor.

The mechanical sensitivity of the well-established high-field (>10 T) conductor forms, such as Nb_3Sn tape, imposes very costly design restrictions required to maintain near-zero maximum strain values, i.e., well below 0.2%. Recent work in electrically stable multifilamentary forms of Nb_3Sn conductor promises one avenue of approach, to make the conductor more strain-tolerant by using small filaments in a matrix. Various conductor forms using this material are possible, namely, monolithic cables and hybrid cables in monolithic structure. Whether or not the present metallurgical compound is sufficiently strain-resistant is an open question. In the light of these uncertainties, a complementary program should be aimed at understanding the metallurgical processes of alloying, forming, and reacting composite multifilamentary superconductors. This understanding would then be used to support the fusion requirement for reliably-produced high magnetic fields with much less brittle conductors.

The basic need for less brittle superconductors is recognized in the DMFE programming, but the uncertainty in the benefit/cost ratio for high field itself is reflected in the low support level for this problem. Development work sponsored by the Department of Defense has resulted in the availability of Nb_3Sn multifilamentary conductor.[1] The cable development activities of the ORNL SCMDP now include plans to analyze systematically a wide range of geometric variations on a conductor made by a given metallurgical process. These tests would then determine the effects of twist pitch, filament size, number, transportation, etc. This work is being done in conjunction with the Harwell Laboratory in England. Additional tests of similar metallurgically processed materials would be made of comparative performances in cable and monolithic form. Tests of conductors of similar form but made by different metallurgical processes are also planned.

Research into more ductile materials should be intensified. The planned activities of the ORNL SCMDP recognize the importance of this problem. There is uncertainty both in the strength of the plasma physics incentive for high field and in the actual availability of high-field material. Simultaneously, many characteristics are shared by large high-field NbTi and Nb_3Sn magnets. Given these two factors, a careful accounting of all the work that is applicable to NbTi, Nb_3Sn, and other materials should be undertaken, to find out what level of incremental Nb_3Sn-specific support would be appropriate in the context of the overall high-field program. The available Nb_3Sn monolithic conductor should be characterized in the earliest test devices to ascertain the workability of this conductor, which has been already metallurgically developed. The existence of a workable high-field conductor might well determine the feasibility of the entire EPR system.

D-2. High-Current Cable

Program: C

Priority: 2

Development of high-current conductors in cable form using both multifilamentary Nb_3Sn and NbTi is required to improve substantially the TF coil performance in the areas of electrical and mechanical design. This would result in systems fabrication costs potentially lower than in systems using monolithic conductors.

High-current (i.e., $I > 10$ kA) superconductors have not been built. Extension of current technology to higher current cables, i.e., at tens and hundreds of kiloamperes, will require continued efforts directed toward solution of the fundamental problem of heat generation and heat removal. A balance between securing conductors tightly against motion to prevent eddy current heating, and providing space between conductors for adequate coolant flow to remove heat rapidly, must be struck at each higher current level with correspondingly tighter constraints. Greater knowledge is required of heat transfer coefficients in situations geometrically similar to the complex cable configurations. The need to maintain full transposition of the wires and strands must be balanced against the difficulty of manufacture. The heat transfer area must be balanced against the limiting current density set by the helium's heat capacity. No fundamentally unsolvable problems stand in the way of development of high-current cables, but a feasible method of balancing the conflicting requirements must be sought.

The large size of high-current conductor ensures better mechanical stability, reduces fabrication cost, and lowers coil inductance. The reduction in cost comes from the more effective use of material and decreased handling problems. The small number of turns permits a better match to the typically low-impedance energy storage devices. With this smaller inductance, smaller charging voltages will be used and a less severe insulation problem will exist. Cable rather than monolithic conductor is preferable, because it is simpler to supply the long conductor lengths required in small filament form, and because ac losses are lower in the cable form than in the monolithic form. Additionally, the use of many fine filaments renders harmless a break in any one filament. The possibility of developing hybrid forms of high-current cable, i.e., monolithic jackets over cables, requires investigation for steady field environments.

D-3. Cryostabilizing Cooling

Program: C

Priority: 1

Investigation and then demonstration of a method of cooling compatible with other design constraints are essential to provide a viable and cryogenically stable design concept for magnet operation.

Cryogenic stability* requires a thermal inertia in the form of a static mass (e.g., copper) intimately connected to the superconductor, a long cooling perimeter, and a high heat transfer to an external heat sink (e.g., forced-flow cooling).† Knowledge of the fundamental heat transfer phenomena is essential to the determination of the feasibility of this attractive cryostabilized cooling configuration. Until this technique is proven to be successful, however, active consideration of an alternative cooling method, the pool-boiling cable/braid design, would be prudent. In this method, where the cable is cooled by forced helium flow in a hollow conduit, the principal unknown is the effectiveness of local heat removal and size of pressure drops in the conduit which has both complicated geometry and walls with variable surface treatment. Extension of this design to large coil sizes where conductor motion is potentially deleterious is another major concern. The pump losses could become uneconomically high and the pulsed fatigue effects of conductor motion could become intolerable. At present, however, there is no feasible pool-boiling design which can assure adequate cooling and structural containment simultaneously.

These topics are being addressed by the ORNL—sponsored MIT-Francis Bitter National Magnet Laboratory program, and the basic component and large coil tests in the ORNL SCMDP.

D-4. Conductor Joint Technique

Program: C

Priority: 2

Development of a method of effecting reliable joints is necessary in order to optimize the use of particular superconductors in different regions of the coils. Without this direct technique, other more costly design techniques would have to be used.

At present, superconductor joint techniques are limited to monolithic conductor types or single strands. A metallurgical bond is made between the two normal metal pieces, while the superconducting filaments are usually just placed in proximity to each other. The joining techniques are labor-intensive, and if extended directly to cables would become even more so. The complication of remote maintenance makes this extension totally undesirable.

The recently reported explosive joining techniques are attractive and should be extended to cable application.

D-5. AC Loss Analysis and Measurement

Program: C

Priority: 2

Development and verification of the ac loss calculational technique are required to provide a means for determining the cryogenic heat loss in the magnets arising from pulsed fields.

Study in the area of pulsed losses and associated heat transport in the complicated conductor geometries would assist in determining limits of operation. The principal impediments to development

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*Cryogenic stability is defined as a condition in which a sudden heat input raises the coil temperature above ignition and then recovers to the original state through the inherent heat transfer mechanism.

†The hollow-conduit forced-flow design offers a high density current which is advantageous for space and cost saving.

of this technique are the complicated geometries of an actual conductor design and the vectorial nature (parallel and perpendicular) of the electromagnetic field imposed on the TF coil. This power loss is detrimental to the conductor design, cryogenic requirements, and the possible electromagnetic shielding scheme.

Clarification of the ac loss magnitude will be reflected principally in the verification of the load determination and hence give more accurate costs as well as design guides.

This task is at present a principal activity of the ORNL SCMDP.

D-6. Stress Analysis

Program: C

Priority: 1

Development of modeling information about the mechanical properties of composite and complex components is required to determine the structural design basis of coils.

Recent experience with PLT coils has verified earlier judgments that basic properties of composite structures are too inadequately known for accurate predictions to be made with stress models. Physical properties of the composite and realistic boundary conditions must be determined so as to make proper use of the existing analytical techniques. The structural factors bearing on the determination of the coil shape are significantly affected by the support conditions, an area insufficiently understood. Confident structural performance under normal and abnormal stress conditions is a fundamental requirement of the TF magnet system.

This task is at present a principal activity of the ORNL SCMDP.

D-7. Radiation Damage

Program: B

Priority: 2

Additional data on radiation damage to insulators and multifilamentary Nb_3Sn are needed to avoid the dilemma of facing either over-conservative design requirements or shortening of the coils' working life. Inability to find insulators capable of withstanding the total radiation environment could cause costly restrictions on design latitudes in the blanket and shield.

Presently available data on superconductors and normal materials are incomplete for both the insulating materials and multifilamentary Nb_3Sn at 4 K. With respect to the insulating materials in particular, radiation effects under the high electrical and mechanical stresses imposed at 4 K could result in electrical breakdown that could have most deleterious effects on the overall reactor operation. Improved data on individual magnet coil components at 4 K under some form of simulated load would assist in reactor design, particularly in design of the regions around blanket penetrations. The loading conditions should be chosen to develop information relevant to the possibility of synergistic effects in coil systems. This requirement for data on radiation effects at 4 K may lead to basic research into new insulating materials.

This task is recognized, but not at present supported, by the ORNL SCMDP.

D-8. Protection

Program: C

Priority: 1

Development and verification of coil protection schemes capable of handling effectively the tens of gigajoules of energy stored in the TF coils is necessary to ensure safe, reliable operation of this central component. Without assured protection of the costly coil system, it is doubtful that such a system will be built.

Extrapolation of present protection schemes to the EPR case of considerably greater stored energy is one part of the effort, while inclusion of the effects of the complex toroidal geometry of the present scheme is another. A flexible and reliable scheme should be developed for both the toroidal field and ohmic/equilbrium field coil systems to meet the potentially wide range of situations to be incurred. This system should prevent excessive terminal voltage and excessive temperature excursion in the coil in case of fault.

Investigation into protection schemes is recognized as an essential part of the ORNL SCMDP.

D-9. Large-Coil System Test

Program: B

Priority: 1

Design, fabrication, testing, and operation of large superconducting coils are essential steps required to prove candidate concepts of the EPR test coil.

In a large coil test, an intermediate step between laboratory demonstrations of solutions to the R & D problems presented above and the full-scale EPR should be taken using a setting similar to the EPR in as many important parameters as possible. The size must be large enough to ensure that fabrication and mechanical stability problems are similar; the field strength at the superconductor and the maximum strain in the conductor should be the same; the distribution of forces on the coils should be essentially the same as in a torus; and the pulsed fields and heat loads should simulate those in a tokamak. In this way, the magnet technology so critical to EPR success can be proven for use in an overall system test before the EPR design is implemented (see B-1).

A Large Coil Project program has been implemented by ORNL to meet this need.

E. INTRODUCTION TO THE POLOIDAL FIELD SYSTEM

The poloidal field system, defined as the conductors, supporting structure, and associated engineering concerns (materials, cryogenics, electrical, and mechanical) is intimately tied to the as yet uncertain plasma dynamics criteria (A-8) and to the potentially expensive energy storage and transfer systems (G-1). Because of this complexity and because of the relatively recent perception of this entire problem area, it is hard to assess the actual level of difficulty to be encountered in this work. Only after some substantial work has been done in many of these newly identified areas, can a realistic assessment be made of what trade-offs are feasible and necessary.

The needs are in two general categories: one, the conductors, and two, the structure. In the former, the requirement is for a conductor capable of generating and withstanding large, rapidly changing magnetic fields. In the latter, the requirement is for a structure capable of supporting the conductors in the low-temperature radiation environment with stability and acceptably low losses. The following detailed statements of needs address each of the separable parts of these two major R, D, & D requirements.

The last need — a system analysis — is essential because of the very complexity of the entire system and the perceived difficulties in each component.

At this stage in the underlying design process, most attention has been given to the central air-core superconducting coil and to the normal conductors forming the electromagnetic shielding coils. The R, D, & D needs developed here cover the air core only, since the problems in the shielding coil are principally design-related and insufficient work has been done on the other systems to illuminate problems specific to those systems.

Basic Reference for Section E:

Program for Development of Poloidal Superconducting Magnet for Fusion Research (Draft).

E-1. Mechanism of Carrying High Current in Rapidly Changing Fields

Program: C

Priority: 1

Knowledge of the behavior of superconductors immersed in and creating a large, rapidly changing magnetic field is essential to the successful design of a significant portion of the electromagnetic field confining and heating the plasma.

Understanding the mechanisms which limit the rate of field change and the current and voltage ratings is basic to conceiving means of dealing with and raising these limits and providing input to the interfaces with plasma operation and electrical power supplies and switchgear. Basically, it must be determined if heat can be extracted from a mixed-matrix (Cu and CuNi) NbTi superconductor with sufficient efficiency that the NbTi will remain superconducting under a set of severe requirements, including high maximum field, high rate of change, and high current density. It is simultaneously necessary to understand the relationship of different pulsed-field waveshapes to the heat deposition in the conductor. Out of this study comes a knowledge of the operating fields for various rates of field change and pulse length.

The limitation on conductor current and rate of field change is set by various phenomena.

One is the eddy current heating in the conductor structure. If the metallic tube now included in the hollow conduit design can be replaced with a leakproof fiber-reinforced plastic (see E-6), then this problem is reduced significantly.

Another is the potential for a reduction in the conduction of heat out of the superconductor which results from conductor motion and consequent cooling passage blockage (see also D-3).

A third is the set of superconducting phenomena which must be understood in order to design reliable high-current conductors. One of these, self-field effects, is the process of current transfer between outer filaments in a low-field region and all filaments in a high-field region. Losses in the normal matrix associated with the current transfer between these two regions could be uneconomically high in a pulsed situation. This same problem is faced at each level of conductor, i.e., filaments, wires, strands, etc. The problem can be reversed at the strand level by full transposition.

It is possible to manufacture a cable in which the current will be the same for all strands of the cable, namely, Roebel cable. This cable is manufactured out of copper routinely and used in high current transformers. Such a cable made with composite superconductor strand is also possible; some cable in fact has been made for the Los Alamos Scientific Laboratory-Magnetic Energy Transfer and Storage Program. However, this cable causes several problems. The insulation integrity is hard to maintain, and the packing is too dense for use in forced-flow conductors. It may, however, be useful in pool-boiling magnets. With some engineering this concept may be made suitable for use in a forced-flow conductor.

Among the other important factors is the self-field effect, which inductively couples each turn with the other turns in the magnet. This coupling may help overcome the inefficiencies associated with the wide distribution of maximum allowable currents throughout the various regions of the coil.

For a given charging power requirement the current and voltage factors are inversely proportional to each other. Their limitations give different requirements on the power supply and energy storage unit (see G-1). The coil voltage is limited because of the low dielectric strength of helium at 4 K and limited separation distance (see E-4). Further design is needed to determine the full implication of this fact along with the compacting of leads in the central core.

This problem is now clearly recognized in the ORNL SCMDP, is under active initial investigation in the LASL program and, in certain aspects, is addressed in the Lawrence Livermore Laboratory program. The recent sharp increase in attention given to this problem should be sustained. Efforts to perform the fundamental measurements of maximum stable B versus imposed $\dot{B}$ for different Δt's should be expanded. Successful PF coil performance is fundamentally necessary for EPR operation, and given the probable magnitude of the conductor development task, considerable effort is needed now to define better the actual scope of these problems.

E-2. Cryostabilizing Cooling

Program: C

Priority: 1

Investigation of the impacts of pulsed operation on the limits of cryogenic stability (see D-3) is necessary to define the operating range of the OH superconductor. Stable operation of the OH air core is necessary to the EPR.

In addition to those problems discussed in D-3, rapid pulsed operation imposes further stresses on the heat removal system. The principal trade-off is between the advantages and disadvantages of electrically stable mechanically mobile cabled configurations, and mechanically stable thermally isolated monolithic configurations in which the helium change must occur before the temperature rises above the critical value. The basic problem is to adjust the cooling system design to produce an acceptable temperature distribution in the coil for a given pulse rate.

This is a central element in the ORNL SCMDP.

E-3. Pulsed Coil Protection

Program: C

Priority: 1

Development of techniques to protect the OH coil against abnormal heat inputs or faults is an essential step to ensure the large investment in this central component. Because it is located centrally within the device, the OH system must operate reliably and continuously. Since the normal time scale for operation of this coil is fractions of a second, abnormalities can be difficult to detect before damage occurs.

A resistive region in a conductor may be detected with a set of voltage taps. This method is used in short sample tests to measure the critical current as a function of field and temperature. However, its use is frustrated by the fact that there are inductive voltages as well as resistive voltages. A method is needed whereby the voltages produced by $\frac{dI}{dt}$ can be subtracted from the signal voltages, and the voltage coming from resistive changes can be measured. The ORNL SCMDP is using a form of this alternative method now to measure pulse losses in small solenoids.

This is a requirement for fault detection and for control and energy transfer techniques in rapid pulsed operations.

This work is under way in the ORNL SCMDP.

Reference Document: ORNL/TM-5043

E-4. High-Voltage Capability

Program: C

Priority: 2

Determination of the limits on the voltage-handling capacity of the superconducting coil, and possibly development of means to increase this capacity, are necessary to define the operating limits or required protection with respect to startup, shutdown, and uncontrolled plasma changes.

Whenever there is a substantial change in the flux linking the air core, caused either by a change in current distribution or magnitude or both, high voltages are generated that are applied to the coil. With minimum peak voltages of hundreds of volts and minimum numbers of turns of many hundreds, voltages in the range of many tens to a few hundred thousand volts could be imposed on the coil. At present, the breakdown strength of the coil appears limited by the dielectric strength of helium, and further limited by severe space restrictions for insulators. Experiments in high-voltage superconducting transmission line work indicate that voltages at a few tens of kilovolts may be a practical limit in tokamak geometries, because of breakdowns coming from elongated bubbles in the helium.

At present, insufficient information exists to enable this problem to be dismissed as solvable or avoidable.

Work is in progress at the ERDA Division of Electrical Energy Systems (DEES) Cryoelectrics Program and at other laboratories.

E-5. Pulsed Conductor Fabrication

Program: C

Priority: 2

Development of an economical method of producing small-filament mixed-matrix NbTi pulsed superconductors is required to ensure that the design which is capable of withstanding the widest range of plasma parameters can be implemented. Better defined production procedures would improve both cost and schedule.

Reduction of hysteretic loss is accomplished by reduction of superconductor filament size. Reduction of eddy current coupling loss is accomplished by surrounding each filament with a layer of low-conductivity Cu-Ni material electrically isolating the filaments in the conductor. Production of economical superconductors combining both small filaments and Cu-Ni matrix materials is presently beyond the state of the metallurgical/fabrication art. At present, conductors of both large-filament Cu-Ni matrix material and small-filament plain Cu material are available, but not the small-filament mixed matrix combination. Even at this time, the production of the former is so complex and uncertain that yields are low and costs are high.

The role of certain raw material impurities is unclear both in the superconductors where they seem to limit the minimum filament size, and in the copper nickel where they apparently create fabrication problems.

This is a requirement for improved manufacturing, quality control, and quality assurance procedures in the pulsed conductor production process.

This is an element of the ORNL SCMDP.

E-6. Structural Materials

Program: C

Priority: 1

Collection or development of information on the structural properties of non-conducting materials (esp. reinforced plastics), and superconductors at 4 K under mechanical load and in a radiation field, is necessary to determine the feasibility of operating pulsed superconducting coils with tolerable heat loads.

Use of electrically conducting structures in the pulsed coils will incur large eddy-current losses resulting in very large refrigeration systems and restricted ranges of operation. Replacement of the conducting structure with non-conducting structure is presently hampered by the lack of data on the physical properties of these insulating materials at 4 K and under radiation field. Three specific questions must be answered about fiber-composites before they can be reliably used in superconducting magnets at 4 K.

a) What is their elastic response to load?
b) How is their failure mechanism related to the loading regime?
c) What is their response to dynamic fatigue?

These same three questions must be answered about the superconductors and especially about the composite structure including superconductor, normal material, and structure. A specific requirement is placed on the non-conducting structure related to eddy current losses in large pulsed conductors. If the structure can be made leakproof to pressurized helium, then the losses in the present metal liner containing the helium can be eliminated and larger current pulsed conductors made.

At present, there are no means of supporting pulsed superconducting coils with conducting materials without unacceptably high refrigeration costs. This task is being pursued in the ORNL SCMDP.

E-7. Poloidal Field System Analysis

Program: C

Priority: 1

Development of a model that includes each of the factors affecting the design of the poloidal field system is required to enable determination of the route of highest probability of success with least cost.

The present uncertainty in this central system could lead to misdirected work or absence of work, resulting in negative judgments based upon inadequate information about the difficulties of component problems in the EPR.

Since the poloidal field system is intimately related to the criteria, constraints, and requirements, usually only vaguely definable, of the plasma, magnetics, energy storage and transfer, cryogenics, and remote maintenance systems, a means of balancing quantitatively each of the factors involved would put the design effort on a much more systematic basis than at present. Each of these areas contains R, D, and D problems of significant, though uncertain, magnitude. An operating poloidal field systems model, fitting into a larger overall systems model, would provide the tool for choice.

LASL/UT has just been given the task of the development of a quantitative, parametric description of such a model. As the program plan and systems model is developed by LASL/UT, the output should be examined to ensure that a broadly based choice is available.

E-8. Remotely Maintainable Shielding Coil Joints

Program: B

Priority: 2

Demonstration of reliable joints for the normal conductors in the shielding coil using remote maintenance techniques is essential to a feasible mechanical design.

The basic function of the shielding coil requires that the amp-turns be located within the neutron shield. In this high-radiation environment, remote maintenance techniques are necessary for any work on the joints. In any variation of the assembly procedure now conceived, the joints on the OH shielding coil must be disassembled and later reassembled in order to change a blanket, vacuum chamber, or TF coil module. Various designs have been proposed for this joint, most of which do not require any further development work. Demonstration is what remains to be done.

In addition to the uncertainty about the need for poloidal field coils inside the TF coils, one of the principal questions about the electromagnetic shielding scheme is whether it can be extrapolated to an economic demonstration plant. Does extrapolation imply conversion from normal conductors to superconductors in the shielding coils? In any case, the ability to make and break many joints deep within the blanket/shield is a key to successful design.

F. STRUCTURAL SYSTEM

F-1. Structural Design Criteria

Program: B

Priority: 2

Development of criteria, adaptations of analytical codes, verification of analysis, and construction or modification of fabrication facilities form a set of tasks essential for design and implementation of EPR structure.

Considering the plant size and costs required for an EPR project, it is important to commence development as soon as possible of structural design criteria. Structural design criteria should consist of three major elements:

1. Definition of all pertinent conditions, environments and associated loadings to which the device might be subjected, e.g., seismic and tornado.

2. Definition of appropriate safety factors on loads or material strengths to ensure structural designs that provide acceptable risk to safety, environments, and economical operation.

3. Definition of analyses unique to the structural system which are required to translate the environments and loads into appropriate static and time-dependent structural response parameters (stresses, strains, displacements) in order to relate them to material strength parameters or other design criteria (e.g., maximum displacements).

Three major functions are served by structural design criteria:

1. They provide a "check list" to ensure that all pertinent loads and environments have been considered in the design and that they have been analyzed satisfactorily.

2. They establish appropriate safety factors or margins between the loads and material strength properties so that the risks associated with possible structural failure are commensurate with the consequences resulting from such a failure.

3. They provide a means for establishing a degree of uniformity between the many design organizations usually involved in a large project.

An interdisciplinary committee has been formed at ORNL to begin development of the criteria, and a joint proposal has been prepared by ORNL and Mechanics Research, Inc. (MRI) for a study to assess the present state of the art of tokamak reactor design, and further develop structural design criteria. This study is proposed as the first phase of a continuing program that will lead ultimately to industry-wide structural design criteria that will satisfy all pertinent licensing, safety, and reliability requirements.

F-2. Thermal Insulation

Program: B

Priority: 2

A fundamental problem in superconducting tokamaks is the design of thermal insulation for the TF coils and central support structure. The large thermal contraction of the TF coils from room temperature to 4 K requires that the support structure also be cooled to 4 K. To maintain thermal stability over long operating cycles, high-efficiency vacuum-type thermal insulators are a necessity.

The low aspect ratio and the necessity of supporting the coils uniformly along the inside of the torus seriously impede access. Various design alternatives have been considered, including 1) a single vacuum dewar enclosing both TF coils and structure, and 2) separate insulators with force transmission through the coil and structural insulation. There is a need for more detailed design and system trade-off studies to evaluate the economic advantages of various alternatives before specification of a material or hardware development program.

G. ELECTRICAL ENERGY STORAGE AND PULSE SYSTEMS

G-1. Ohmic Heating Energy Storage and Transfer

Program: A

Priority: 1

Development and/or extrapolation of OH circuit concepts and components, and demonstration of reliable operation at rated conditions, are required to provide the basic electrical engineering capability to create, maintain, and terminate the plasma current. Determination of the feasibility of handling the supply and transfer problems associated with a rapid change of ~ 2 GJ is essential to the EPR. At the gigajoule level now envisioned for the energy necessarily stored in the OH air core during operation, presently available methods and components for energy transfer, storage, and control in the overall OH circuit cannot be judged adequate. In various possible configurations of the OH circuit, heavy dependence is placed upon some subset of the following elements: homopolar generator, superconductive inductor, solid state device convertor, and mechanical switch, each one of which would be pushed beyond the state of the art in one or more of the configurations.

A LASL/UT program has just been initiated to make a systematic analysis of specific choices in the power supply, storage, and transfer areas. Further investigation of the relative merits of the possible circuits in combination with the plasma physics and superconductive technology considerations is required before a clear statement of the development problem is possible. Appropriate scoping studies are now under way to lay the basis for program development at ORNL.

G-2. Neutral Injection Power Supplies and Components

Program: B

Priority: 2

Development of high-voltage switch tubes, regulators, and power supplies is required to permit extrapolation of TFTR-type systems to EPR energy and power levels. This is a requirement for development of high-power electrical components and probably research into the basic science of switching. Adequate funding would allow extension of the present program to achieve EPR requirements.

The extension of electrical engineering technology previously used in TFTR beams, to achieve higher-voltage large power units, represents two steps beyond currently available equipment. Proposed switch tubes will have already been extended to the end of their range for TFTR beams at 60 A and 225 keV, while ratings of 120 A and 300 keV are needed for EPR. Unit power supply size and high-voltage regulator ratings will be increased by a factor of three from TFTR to EPR. Research in the area of electrical strengths in vacuum, gas, and plasma environments with high-current and high-voltage conditions should result in new switch techniques, or at least feasible extrapolations of existing techniques.

Lack of effective research in the area would require either excessively cumbersome and costly use of very many smaller components, or an imposition of restrictively low limits on operation.

H. INTRODUCTION TO THE PLASMA HEATING SYSTEM TOPICS

Basic work in the area of negative ion sources and the extraction and acceleration of negative ion beams is required to support the development of high-efficiency neutral beam systems. Research in this field could result in the perception of ways to produce the required beams or could demonstrate that the cost of heating continuously by beam rather than wave is excessively high. Since development programs in either beam or wave heating are, and will be, very expensive, early guidance on their relative technological merits, based on research into basic processes and possible techniques, would be especially helpful in making program choices. Information about neutral beam heating by positive ion source will come from the experiments associated with the next generation of hot plasma devices in the fusion program. The following sections detail the key problems in the plasma heating area.

Basic Reference for Section H:

Long Range Program Plan for Development of Neutral Injection Systems, ORNL (July 1975) Draft.

H-1. *In-situ* System Application

Program: C

Priority: 1

Demonstration of actual on-line plasma heating technology in situations that are within small scaling factors of all key parameters is required to minimize the risk of expensive failure in a full-size EPR.

Component development and test stand work must be coupled with on-machine testing to demonstrate the capability of plasma heaters. Experience in the increasingly successful plasma heating experiments to date has shown that strong feedback between laboratory preparation and field testing is essential to the overall progress.

The DMFE Plasma Heating program represents the largest single technology program, and all aspects of beam heating applicable to next-generation machines (PLT, ORMAK Upgrade, DIII, and TFTR) are being vigorously pursued.

Two major areas of research are needed for EPR in addition to those being pursued presently. New efforts in the areas of system testing for negative ion sources and long pulse length beam systems are now called for.

H-2. High-Performance High-Energy Neutral Beams

Program: C

Priority: 2

Development of the means to produce high-efficiency, high-intensity, and high-energy neutral beams is required, to permit the possibility of heating plasma to ignition temperatures in a fusion reactor.

Use of positive ion systems at the energy level required in near-term experimental reactors is believed to be technically feasible but requires both continued experiments with intermediate and final energy level neutral beams and, in actual use, the availability of a high level of pulsed power, $\sim$0.5-1 GW. Given the uncertain availability of this power, the difficulty of achieving a net energy output in the early reactors, and the requirement for efficient systems in the Demonstration Fusion Reactor, negative ion systems and direct convertors may be required. The efficiency of systems based on negative ions and direct convertors far exceeds that of systems based on positive ions. This improved efficiency leads to a significant reduction (by a factor of $\sim$3) in the power requirement for the grid operating the neutral beam system, when compared to positive ion systems.

Present negative ion sources are not yet directly extrapolatable to high-power, high-efficiency, and long-pulse operation. The LLL approach, which consists of double charge exchange in alkali metal vapor, is presently investigating the basic physics and technology of low-energy D^+ beam formation, double charge exchange, transport of the resulting low-energy D^- beam, and post-acceleration to high energy. Each of these areas has inherent difficult problems which remain to be resolved before extrapolation may be attempted. Similarly, the Brookhaven approach, of surface conversion of positive ions to negative ions in a magnetron discharge geometry coupled with direct extraction of the negative ions, is still investigating the basic physics and technology. ORNL is starting to investigate negative ion aspects of its positive ion beam program.

The direct recovery work of LLL is closer to being extrapolatable than the negative ion work. Direct recovery does require the full inefficient ion beam to be generated, however, with the attendant magnitude of beam hardware on the reactor.

H-3. Mechanical Components

Program: B

Priority: 2

Development of components compatible with radiation and large vacuum systems is needed to provide one part of the basis for design of the heating system.

With respect to the source, reliable operation in the intense radiation environment anticipated for EPR could dictate design requirements which should be considered at the outset. For example, providing high-voltage insulators for this application could be a problem. Gas handling, vacuum pumping, or cryopanel requirements and structural difficulties associated with a large complex vacuum facility, will require development and consideration, but all of these appear to be reasonable extrapolations from the TFTR system.

Specific consideration of the incremental beam line problems associated with EPR requirements awaits a clearer EPR design.

H-4. High-Power High-Frequency Microwave Tubes

Program: C

Priority: 2

Development of tubes with high specific power and high frequency is necessary to make the leading form of wave heating an economically and technically competitive heating option.

For frequencies up to ∿30 GHz, the power from a device (whether tube or solid state) scales inversely as the square of the frequency. Above 30 GHz the power scales as $f^{-5/2}$. This is a fundamental physical limitation due to transit time and space charge effects, and technological changes can only improve the constant of proportionality.

In the context of Electron Cyclotron Heating (ECH) and Upper Hybrid Heating (UHH), sources at ∿120 GHz will be needed for fields ∿4 T in an EPR. It may be possible to utilize lower-frequency sources for heating at subharmonics, but this has yet to be demonstrated.

At present, Varian Corporation is studying the possibility of developing the relatively new concept of the gyrotron (cyclotron radiation maser) into a steady state high power (∿200 kW) high frequency (∿25-28 GHz) amplifier. When used as an amplifier, it would be called a gyroklystron. This is the first stage in the development of a tube of much higher frequency needed for EBT development, viz., a gyroklystron operating continuously at 120 GHz and yielding 100 kW. This first stage should be ready in CY-1977 and the next stage in CY-1979 or later.

Electron Cyclotron Heating is a demonstrated plasma wave heating technique. Results from the Soviet TM-3 and TUMAN-2 tokamaks with gyrotrons developed in the U.S.S.R. show promise. The new tubes described above are vitally needed for the EBT program. The gyroklystron operating at 25-30 GHz with 200 kW could be used to great advantage on ISX and some other U.S. tokamaks such as Doublet IIa at General Atomic Company.

I. TRITIUM PROCESSING SYSTEM

I-1. Tritium Processing

Program: C

Priority: 1

Development and demonstration of tritium process steps is required for EPR breeding experiments. The tritium process steps of primary concern for EPR are:

- removing the D-T mixture from the plasma exhaust,
- purifying the D-T mixture for recycle to the fueling system, and
- developing isotope separation methods for supplying the plasma fueling system and the beam feed system.

It will be necessary to identify, develop, and test equipment to perform these functions for EPR application for normal operation conditions and for postulated abnormal and accident conditions.

J. VACUUM PUMPING SYSTEM

J-1. Vacuum Systems/Cryosorption Pumps

Program: B

Priority: 1

Significant extensions of current cryosorption pump technology are required to make possible the operation of the plasma and neutral beam vacuum chambers.

Main vacuum systems to remove plasma exhaust, impurities, and outgassing from the plasma chamber, and beam vacuum systems to remove gas cell exhaust, ion source neutral leakage, and gases resulting from unneutralized ions from the beam line, will be required. The main vacuum system will consist of a roughing system and cryosorption pumps, or a combination of cryopumps and cryosorption pumps. Between-pulse pumpdown time and background gas pressure requirements should be attainable. The plasma physics analyses and experiments must determine the requirements for pumping the plasma exhaust during long-pulse operation. Estimates of the required pumping speed during a pulse now include a wide range of uncertainty.

The beam vacuum system will consist of separate roughing systems, cryopanels, and cryosorption pumps for each beam line. The required speeds are enormous, and the geometry must be worked out carefully to allow sufficient conductance so that the required low pressures may be achieved.

Requirements in this area primarily involve criteria determination and, most likely, component development. Based on present estimates, larger cryosorption pumps than are presently available are needed to pump D-T in the main vacuum system. Increases in speed of a factor of 2 or more are required, as are still larger increases in storage capacity. Some development work will be required to assure the availability of proper-sized pumps. No major difficulties are foreseen in achieving this. On the other hand, bare metal cryopanels or cryopumps may be used to pump the hydrogen isotopes, while smaller cryosorption pumps are attached downstream to pump helium. Because the vacuum pumps or panels used will have to function in gamma and neutron radiation fields, any changes in the properties and performance of all materials used in candidate pumps, due to such exposure, should be determined. The possibilities for rapid low-temperature regeneration of cryosorption pumps operating under anticipated conditions must be examined. Information is needed on long-term reliability and maintainability, especially remote maintainability, and on performance of larger cryosorption pumps, especially after hundreds of regeneration cycles. Cryopanels should be tested under conditions similar to those which will exist in the beam lines including neutron, gamma, high-energy ion, and neutral fluxes and radiant heat loads. Some of these tests may be performed in the PLT and TFTR beam programs.

A program should be set up wherein components can be developed and tested under expected operating conditions. Assuming that conventionally envisaged vacuum techniques are applicable, this area would merit relatively low priority. If, on the other hand, plasma performance and recycling are such that ionized particle control (e.g., divertors) is necessary to meet vacuum requirements, this area would assume a high priority rating. Because of the uncertainty, the higher priority rating is assigned to emphasize the need for increased attention.

J-2. Large Valves

Program: B

Priority: 3

Development of large vacuum valves is necessary to provide the basic hardware components of the EPR vacuum system.

Large valves of two types will probably be needed for the EPR: the valves are not available at present. One type may be used for fast but not tight closure, to prevent pump-out of the initial fill before a discharge. A second type will be required to provide isolation of cryosorption pumps during regeneration.

K. CRYOGENIC COOLING SYSTEM

K-1. Large 4 K Hardware

Program: B

Priority: 3

Development of large-scale 4 K cryogenic hardware is required to provide component availability for use in EPR systems.

Presently available hardware is suitable either for small-scale application at 4 K or large-scale application at 77 K. Confrontation of the problems of design, fabrication, and operation of large-scale pumps, refrigerators, valves, etc. at 4 K is needed to demonstrate the availability of this cryogenic hardware for reliable EPR use.

L. MAINTENANCE AND ASSEMBLY SYSTEM

L-1. Adaptation of Remote Handling Techniques

Program: B

Priority: 2

Adaptation of existing remote handling techniques, tooling, equipment, procedures, and new developments, where necessary, are required to ascertain the feasibility and cost of remote operations on EPR. Remote maintenance is essential to a successful fusion power plant, and as far as is known should be attainable.

The thermonuclear reactions produced in EPR will induce high radioactivity in reactor components. Analysis is required to determine if any "hands-on" maintenance is permissible on the externals of the reactor. After a short period of operation, the components inside the shield will be so radioactive that maintenance operations will require remote means. Existing remote maintenance technology will be utilized as the basic equipment where possible. However, this must be augmented by specialized tools and equipment for specific tasks.

Design and development is necessary in the following categories:

- Massive precision handling devices for transporting, locating, and accurately positioning large subassemblies such as blanket segments, TF coils, shield segments, etc. These will be tailored to the design of the components.
- Fabrication and assembly tooling for welding and cutting a variety of shapes and thicknesses in locations with limited accessibility.
- Manipulators and special tools for bolting, clamping, and sealing or completing coolant lines and electrical and instrument leads.
- Viewing and inspection equipment involving three-dimensional television, fiber optics, and possibly ultrasonic and dye-penetrant equipment for orienting welding gear and checking integrity of weldments.
- Equipment for cutting and compacting, and transferring for disposal of radioactive components safely using a minimum of space and shielding requirements.

A general design program could be initiated at any time; however, specific designs of the actual equipment would have to wait until the reactor design has taken a more definite shape.

M. TRITIUM CONTAINMENT SYSTEM

M-1. Tritium Containment in Metals

Program: C

Priority: 1

Knowledge of tritium diffusion through metals is necessary to provide a basis for improved methods of containing tritium and removing it from the containment atmosphere.

Operation of tritium-breeding fusion reactors will require continuous handling and containment of large quantities of tritium. Most currently available permeation data is not for tritium and was not obtained at low pressures. Tritium permeation data must be obtained for the main piping and for the steam generator loops at pressures as low as 10^{-8} torr. These data are needed for realistic operating conditions such as those to be encountered in the steam generators. The atmosphere cleanup system requirements must be developed, and methods and equipment identified to satisfy the requirements.

Research upon tritium permeation of steam generator materials, clean metals, and refractory metals would provide a basis for understanding the containment problem. Permeation at low and high pressure and under thermal cycling should be investigated to make the data base secure enough for the fusion reactor application. Successful research in this area could result in straightforward accord with health and safety requirements on fusion reactor operations (see also C-10).

M-2. Tritium Behavior in the Environment

Program: B

Priority: 1

Because of the complex behavior of tritium in the environment, information on meteorologic, hydrologic, and biological factors will be required in order to assess the environmental impact of continuous, intermittent, or accidental releases of tritium from fusion reactors. Significant tritium-related questions must be answered before societal debates on the use of fusion energy can be intelligently concluded. Some information on behavior of tritium in the environment is available, particularly in the area of tritium metabolism and turnover by mammals including man, bioaccumulation factors of tritium in aquatic and terrestrial ecosystems, and retention times of tritium in some compartments of desert and tropical ecosystems. Specific questions which need to be addressed relate to the determination of

(1) rates of oxidation and of isotopic exchange of gaseous tritium (T_2) under a variety of environmental conditions,

(2) rates of dispersal of tritium in the hydrosphere from point source releases in temperate latitudes,

(3) transfer coefficients of tritium (e.g., rates of deposition and washout) in a variety of important ecosystems in temperate latitudes, including agricultural, forested, and aquatic systems,

(4) genetic effects in organisms from continuous long-term exposure to tritium in food and water over several generations, and

(5) transmitted genetic damage (both gene mutations and chromosome aberrations) from tritium in mammals under various conditions of exposure.

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