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**Conclusions from the Oak Ridge EPR
Studies and Initiation of the
TNS Program—A Brief Summary**

M. Roberts

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FUSION ENERGY DIVISION

CONCLUSIONS FROM THE OAK RIDGE EPR
STUDIES AND INITIATION OF THE
TNS PROGRAM - A BRIEF
SUMMARY

M. Roberts

for the

Oak Ridge EPR/TNS Program Team

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ABSTRACT

This ORNL Study has resulted in an evaluated Reference Design that does satisfy the technical objectives set out for a Tokamak Experimental Power Reactor (EPR). Because of this design's large size, high cost, and poor extrapolation to a demonstration reactor, the basic physics and range of technical objectives have been reconsidered. This has led to an intermediate step and new design, The Next Step (TNS) after TFTR, having a higher benefit/cost than EPR. The TNS program, now in the early design phases, is focused on a device with smaller size and considerably higher power output than the EPR design. This device's improved performance is made possible by a projection of operation at higher plasma density than that assumed for EPR. This more optimistic plasma performance projection is based on a reexamination of basic physics assumptions and of current plasma physics experiments; a focused experimental and theoretical effort will be required in the near future to validate this projection. With this improved performance, the TNS designs can be extrapolated to an economically viable fusion reactor.

1. SUMMARY OF EPR STUDY

1.1 INTRODUCTION

In terms of the overall fusion design process, the FY 75-76 EPR study¹⁻³ represents the most extensive effort to date in advanced studies of early power reactors, though it is still only the present point on the evolutionary scale of design for the first fusion "reactor." The results of this study have been twofold in nature. On the detailed technical level many issues have been investigated and more clearly appreciated; work is now under way to address the problems identified. On the broader programmatic level, the need for an achievable, high power density fusion plasma device which would be extrapolatable to an economically viable reactor has been keenly made clear.^{1,2} The present EPR design does not satisfy the economic viability criterion, although it does fulfill the technical requirements (as determined by a preliminary design). The recognition of the pressing need for operation at higher power density has led to the development of the TNS program;¹¹ The Next Step after TFTR is being pursued as an ignition device whose characteristics do extrapolate to an economically viable fusion reactor.^{1,2}

1.2 PRINCIPAL CONSIDERATIONS AT THE OUTSET OF THE EPR STUDY

1. EPR is a major step in the U.S. fusion program.

As such, it is necessary for rational fusion program planning that a clear picture of the EPR's nature, magnitude, requirements, and options be generated as input to the overall plan.

2. This study is a forcing function for science and technology.

From the iterative process of defining objectives, projecting current scientific and technological understanding to reactor application, undertaking engineering design, and then comparing costs and schedules with objectives, two critical benefits emerge:

- the technical issues are better addressed, because the implications that emerge from the extrapolation of current ideas are made clear to the community, and
- the key research, development, and demonstration needs become better defined and the ongoing programs more able to contribute effectively.

3. The effort is conceptual in nature and is not intended to result in a project proposal.

At this early stage, the emphasis is placed on defining what is technically necessary and feasible and not on preparing to build the device. The study aims at the identification of problem areas and the development of possible solutions using an engineering-oriented reference design. With the resources available, the study has been further limited to the examination and technical evaluation of the key reactor systems (plasma, magnets, blanket, beams). A secondary emphasis has been placed on the balance of the plant systems.

4. This study was conducted using a project orientation.

Given the manifold problems so closely linked to ongoing research and development, and the perhaps surprisingly tight schedule for the execution of a major project even ten to fifteen years in the future, the study was organized into a project environment. This approach was used for effective coupling of the systems-oriented technical personnel with the research and development specialists and with the engineering design team. The latest information is thus available for use in making technical judgments necessary to meet program requirements.

1.3 RELATIONSHIP TO OTHER STUDIES^{1,3}

The EPR is envisaged as a step leading to the successful operation of the Demonstration Reactor Plant (Demo) and the succeeding Commercial Power Plants (CPP). In view of this role, the EPR study has been conducted in parallel with a Demonstration Reactor Plant study^{1,2} in which the principal concepts for EPR

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are extrapolated to the Demo and CPP and designs acceptable for all three applications were sought.

The nature of EPR as an early fusion reactor requires that the study be closely connected to all other relevant fusion work. This is the case at ORNL. Through the work of the plasma engineering personnel, the best information available from the experimental and theoretical plasma effort here and elsewhere is included in the EPR study. The ongoing development work in large superconducting tokamak magnets; in high power, long pulse neutral beams; and in nuclear technology areas is reflected in the EPR study.

1.4 OBJECTIVES OF THE EPR STUDY

A clear view of the EPR is essential to the effective performance of the EPR study. The EPR objectives were outlined by ERDA-DIFE^{1,2} and are summarized here from the results of the first task in the ORNL study. They form the base for the remainder of this paper.

The EPR itself is viewed as the first facility to generate significant amounts of high temperature fusion-derived energy with continuous high duty cycle operation.

The objective of the EPR program is to advance the science and technology required for commercial fusion power by providing on a timely basis:

- system operating experience and testing of components and subsystems for a larger demonstration plant,
- a focal point for research and development programs, and
- large-scale testing of plasma physics scaling including the effects of an ignited deuterium-tritium plasma.

This general objective requires that the EPR program qualify for subsequent demonstration (in the Demo) all essential features of a safe, reliable, working fusion power plant.

As a critical control, the EPR must

- be able to accomplish the technical

objectives in a timely and economical manner.

"Timely" means that design, construction, and operation of the EPR fit smoothly with the preceding experiments and expedite successful Demo operation. "Economical" means that the actual total program costs be a reasonable step up from the preceding experiment and, as importantly, that the extrapolation of the EPR costs both to larger power output and to the economics associated with scale be reasonable.

1.5 SUMMARY OF ACTIVITIES

The principal activities in the EPR Program thus far fall into three major phases: a scoping study,³ development of a reference design,⁴ and evaluation of the reference design.⁵⁻⁷

Based on the findings of the broad scoping study which identified problem areas and potential solutions, a reference design was established as the design focus for the EPR studies in FY 76. Choices in the reference design were based on the following considerations:

- high probability of providing a successful scientific experiment based on extrapolation of current plasma physics, and
- high probability of technological and engineering feasibility in the 1980's, derived from research, development, and demonstration programs in the late 1970's.

1.5.1 Description of the September 1975 Reference Design

A set of basic machine parameters was chosen for the EPR Reference Design. These parameters, which would produce a reactor-grade plasma with significant neutron flux, included the following: minor radius of 2.25 m, major radius of 6.75 m, magnetic field on axis of 4.8 T (requiring use of Nb₃Sn conductor with 11 T at the winding), and plasma current of 7.2 MA.

Despite uncertainties in plasma scaling, it was possible to predict that the neutron flux would be produced under both beam-driven and ignition conditions. The neutral beam power needed was 100 MW, with an accelerating voltage of 200 keV. The safety factor, $q(a)$, was 2.5. Burn time was 100 sec, with a duty cycle equal to 50%. The overall diameter was 22 m. The output power was 400 MW(t) for a driven system and 200 MW(t) for a system under ignition conditions for the specific operating modes examined.

1.5.2 Improvement of the Reference Design

The bases on which the reference design was established varied widely from explicit calculations to management judgments. Consequently, the major thrust of the work in FY 76 was to perform a technical evaluation of the reference design and to upgrade it where necessary. A number of technical issues were addressed, and where possible "solutions" were developed. That is to say, in a number of critical areas, those ideas which upon serious consideration appeared to be feasible design concepts have been proposed and examined. In the current reference design, for example, the following items have been added to the original reference design:

- A fuller description of an ignited plasma.⁵
- A new TF magnet design more credible in terms of fabrication.⁶ Additional analytic tools have been developed and used to define more closely the stability margin and the ac losses.
- In-depth study of the ohmic heating and electromagnetic shielding systems driving the plasma current, protecting the TF coils, and reducing the energy requirements.^{5,6} Critical questions have been identified.⁹
- A new modular, maintainable, workable blanket design.⁷
- Establishment of the basis for the overall structural system.⁸
- A first pass at the balance of plant.⁸

1.5.3 Evaluation of the Reference Design

In addition to reemphasizing the importance of resolving the key technical issues, the conceptual development of some of the technical problems has identified some very difficult judgmental issues.

- The benefit/cost for a low power, high cost design must be assessed.
- The mechanical system is extremely complex. Even though a new model has been developed, the successful execution of the design, the successful execution of all subassembly tests is doubtful.
- Of the required extrapolations in plasma physics parameters, it is the extrapolation with pulse time that is the greatest and hence the most uncertain.
- Each of the component technologies is being pushed and extended significantly beyond present capabilities.

In each of these four issues, the risks, though clearly visible to each participant, are not quantifiable. Considerable work is needed if these issues are to be made more quantitatively balanced between gain and risk.

1.5.4 Principal Findings

On the basis of the technical evaluation, a number of key findings became clear; these findings are considered in this section. This consideration and an appreciation of the difficult judgmental issues raised in Sect. 1.5.3 lead to an examination of the fundamental assumptions used in the study; this examination is made in Sect. 1.5.5. The principal findings impacting the technical program can be divided into three convenient categories:

Scientific

- In the area of scaling, continually improved models are available for performance prediction, but significant additions to the experimental data base and improvements to the analysis are needed before confidence can be generated that, for example, the scaling relations are

appropriate and that profile effects have been properly considered.

- in the area of dynamics, detailed experiments are needed to provide hard information on start-up/burn (fueling)/shutdown for engineering criteria.
- Similarly, in impurity effects and plasma electromagnetics, experimental information is sorely needed for guidance of design efforts.

Technological

- Demonstrations, at the appropriate scale, are required for each of the key technological components required in the EPR design: TF and PF coils, tritium handling, heating techniques and hardware, etc.
- Nb₃Sn superconductor development must be emphasized and expanded if the critical technological flexibility of higher magnetic field is to be available for any next step.
- A dedicated poloidal field coil design and development effort is required to address this crucial and newly appreciated area.
- Development of a nonconducting structural material capable of meeting the stringent thermal, mechanical, electrical, and nuclear requirements of the OH coil support structure is essential to the feasibility of a superconducting PF system.
- Energy storage, transfer, and control associated with the PF system require a dedicated, intensive effort to make this aspect feasible; cost reduction is a secondary objective here.
- Plasma heating requirements demand an uncertain combination of ingenious plasma operating scenarios to make use of the available positive ion beam technology and creative negative ion source development for flexibility in the design.
- Exploitation of the indications of extended material lifetimes under irradiation is a fundamental necessity in the drive for economical systems in which replacement

costs are a dominant factor in the plant economics.

Engineering

Given that a number of significant engineering issues have been addressed, and addressed successfully (e.g., workable design solutions in the blanket, TF coil, and remote maintenance areas), the net result is still an extraordinarily complex device.

This complexity can be appreciated by considering the following four areas of design requirements:

- mechanical complexity of nested tori, wide temperature ranges, large structural loads on large elements, and intertwined coil sets
- many operating pulses
- high auxiliary power demands
- remote handling combined with high tritium inventory.

The key finding here is not this list of complexities but rather the appreciation of means of reducing the complexity.

- Increasing the aspect ratio relieves the first problem considerably.
- Lengthening the burn time relieves the second.
- Increasing the thermal power output reduces the impact of the third.
- Ingenuity and serious design can relieve the fourth.

The finding here, then, is a set of requirements for both engineering and plasma physics that can lead to an economically viable power plant.

1.5.5 Technical Considerations

Taking into account the key findings and judgmental issues, it is instructive to reexamine the underlying scientific and technological considerations that have led to the present situation.

Size and cost

The size of the EPR plasma and its blanket and shield determine the size of the superconducting coil which, in turn, is closely related to the overall cost. The plasma size is determined by the scaling laws used to specify the energy containment of the plasma. All of the EPR designs have used the so-called trapped-ion mode scaling at densities of $10.7 \times 10^{21} \text{ m}^{-3}$ to specify the energy containment time. This has led to large plasma sizes, which are necessary in order to attain an $n_e T_e$ near the ignition condition. This large plasma size, combined with the necessity for a blanket and shield between the plasma and the superconducting coils, has resulted in EPR superconducting coils roughly 7 m (horizontal) by 10 m (vertical) with a weight of several hundred tons each.

Low aspect ratio

The EPR designs are of low aspect ratio machines. Once an aspect ratio has been chosen, and low aspect ratios are favored in the present regimes of the models, the magnetic field in the plasma is determined by the maximum allowable field at the conductor. There is thus strong motivation to utilize the more expensive high field superconductors. However, the use of high field superconducting magnets in a low aspect ratio torus results in extreme asymmetric forces on the coils; these forces must be minimized by the fabrication of asymmetric coils. Unfortunately, the fabrication of such asymmetric coils is complicated by the fact that they must be of large size, in accord with the EPR designs. Simultaneously, the general design and assembly problems are made most difficult by the cramped nature of a low aspect ratio device.

High fusion power density

The fusion power density produced in a magnetic confinement system varies as $\beta^2 B^4$; therefore, the attainment of high beta and high magnetic field has been emphasized in the EPR studies.

In the ORNL EPR studies, β_p has been limited to .5. As a result, the attainable total beta in the EPR designs is .37.

Elongation of the plasma may permit an increase in the attainable value of beta, but uncertainties exist in the equilibrium and stability behavior to be expected in such cases, and economic and engineering difficulties are associated with producing a high degree of elongation. The incentive for elongated plasmas is clear, but the actual advantage remains to be determined.

Although the fusion power varies as the fourth power of the magnetic field, the importance of achieving the highest possible value of beta follows from the difficulty of obtaining high magnetic fields. The strength of the magnetic field (B) which can be utilized in a magnetic confinement device is constrained by technology. There is a limit on magnetic field for the two types of superconductor, NbTi and Nb₃Sn, which are available in commercial quantities. In addition, practical engineering considerations and economic constraints may prevent the use of fields much in excess of 12 T at the surface of the superconducting coil.

Many of the difficulties perceived to exist in the technology and engineering areas result from the plasma physics scaling laws and beta relationships discussed above. If the power density and the aspect ratio could be increased, many of these problems would be less severe. The concept of flux conservation through intense neutral beam heating appears to have potential as a way to comply with both requirements.^{10,11} The exploration of the implementation of this more attractive set of conditions forms the basis for the positive tone of the conclusions presented below.

1.6 CONCLUSIONS

- EPR should produce a significant amount of power.

The step in the fusion program that encompasses thermonuclear power production at a high duty cycle will be large, difficult, and costly.

Since this step appears to be inherently very expensive, it should be accompanied or characterized by production of an amount of power that represents a significant fraction of the output of a commercial power plant.

- The assumption and requirements used in the EPR study have resulted in a large device and the need for major technology extrapolations.

The inherent difficulty and associated cost follow directly from the need for a large device. The size is dictated by the plasma scaling assumptions used in the study and by the need for the blanket/shield to satisfy the requirement for continuous, high duty cycle operation at hundreds of thermal megawatts. The toroidal field magnet size compatible with this system is itself very large and is a major extrapolation from present experience. Similarly, the neutral beam power requirements and ohmic heating system characteristics far exceed those of present devices.

- The current EPR device is uncomfortably large and the power output is uncomfortably small.

For a device of the size and complexity of the current EPR design, the cost appears to be in the range of \$1-2 billion. The fusion power density depends on a number of variables and can potentially be improved by technical advances. Therefore, effort must first be directed toward developing improved performance in a device of reduced size.

- EPR, as presently conceived, is not the next logical step.

Since the magnitude of the EPR task is such a large increment beyond the present state of the art and since the benefit is uncertain, the EPR is not the next logical step to take in the fusion program. Following the line of argument above, efforts are needed to conceive, develop, and demonstrate means of improving the fusion power density before an EPR is undertaken. These efforts are discussed in Sect. 3.

2. THE UPDATED EPR REFERENCE DESIGN

2.1 DESCRIPTION

As a result of intensive evaluation of the blanket and magnet systems of the September 1975 Reference Design, along with a continuing examination of the plasma engineering basis, an updated reference design has been generated. Although significant improvements have been made in the key systems, this updated design does not represent a full iteration of the design; in particular, there is no change in plasma shape or impurity control, both of which would be changed in a new reference design. Full and summary descriptions of the reference design are contained in Refs. 8 and 16.

The updated EPR is an ignited, D-T burning, power-producing, air core tokamak with superconducting toroidal field (TF) and superconducting and normal poloidal field (PF) coils. The duty cycle is 87%, with a burn time of 100 sec. The machine has a major radius of 6.75 m and a circular plasma radius of 2.25 m (aspect ratio of 3.0). A blanket is provided to transfer a nominal 410 MW(t) from the burning plasma to a steam power cycle. For design purposes, the nuclear aspects of the EPR are based on a neutron wall loading of $\sim 1 \text{ MW/m}^2$, which is equivalent to a power output of 600 MW(t). Operation at this power level is considered an optimistic upper limit. A neutral beam system is provided to inject 50 MW of power into the plasma to achieve ignition. Figure 1 illustrates the elevation view. Figure 2 presents a composite chart of each of the key preparatory steps before operation and the key events during an operating cycle.

A tabulation of overall system parameters and their values for the EPR is shown in Table 1.

2.2 EVALUATION OF A SELECTED EXAMPLE

As an example of the system-oriented work performed in this part of the study, the various aspects of the poloidal field system (PFS) design will be highlighted here. Table 2

Fig. 1. Oak Ridge EPR design - elevation view.

Fig. 2. EPR operating chart.

defines the research, development, and demonstration needs of the PFS.

2.2.1 Purpose

The poloidal field system with magnetic shielding is consistent with a long pulse, high B_p tokamak with superconducting TF coils. It is nearly an optimal system, in the sense that it minimizes the volt-seconds required to set up the plasma current, permits an increase in pulse length and duty cycle, and shields the TF coils. In Fig. 3a, the magnetic flux lines are shown for the EPR for a plasma equilibrium with MHD parameters $B_J = 1.33$ ($B_J \approx B_p$). In Fig. 3b, the flux plot which results from a more conventional

poloidal field system is shown under similar conditions. The EPR system minimizes the pulsed field at the superconducting TF coils (reduces it by a factor of 6) in order to permit the highest toroidal field to be attained with the least risk of superconduction quenching. It has equilibrium field coils coupled closely to the plasma so that they will respond rapidly to large increases in plasma beta. An intrinsic advantage of such a system is a substantial reduction of power supplies (by 41%) and stored energies (by 34%) as compared to the designs without magnetic shielding. In view of the uncertainties in the development of large, superconducting, high field coils (TF) and

Table 1. Overall system parameters for the EPR

A. General characteristics1. Requirements

	<u>Symbol</u>	<u>Value</u>
Device lifetime	t_L	10 years
Duty cycle	dc	87%
Availability - normal		80%
Thermonuclear power (ignition)	$P_o(th)$	410 MW
Net electric power	$P_o(e)$	~10 MW

2. Other features

Plasma radius	a	2.25 m
Major radius	R_o	6.75 m
Aspect ratio	A	3.0
Plasma edge to winding distance	Δ	1.40 m
Plasma volume	V	675 m ³
Overall height	H	15 m
Overall diameter	D	23.3 m

B. Plasma parameters

Burn time	t_B	100 sec
Current	I_p	7.2 MA
Confinement measure	$N_e \tau_E$	2.7×10^{20} sec m ⁻³
Plasma temperature		
Ion temperature	T_i	12.2 keV
Electron temperature	T_e	13 keV
Beta poloidal	β_p	1.9
Beta (total)	β	0.03
Safety factor	q	2.5
Electron density	N_e	7.4×10^{19} m ⁻³
Fuel ion density	N_i	7.0×10^{19} m ⁻³
Impurity level	Z_{eff}	1.34
Injection deuteron energy	P_b	50 MW
Injected deuteron energy	E_b	200 keV
Particle confinement time	τ_p	9.6 sec
Energy confinement time	τ_E	3.7 sec

C. Electromagnetic parameters

Maximum toroidal field	B_{max}	11 T
Toroidal field on axis	B_T	4.8 T
Number of toroidal coils	N_c	20
Magnetic field ripple at plasma edge	ΔB	2.2%
Conductor configuration		composite cable in a square aluminum conduit

Table 1. (continued)

	<u>Symbol</u>	<u>Value</u>
Superconductor		
in the high field region		Nb ₃ Sn in Cu-Sn matrix conductor
in the moderate and low field region		NbTi in Cu matrix conductor
Average poloidal field at plasma edge	B_p	0.64 T
Poloidal field coil core type		air
Poloidal coil volt-seconds	VS	165 Mb
D. <u>Thermal</u>		
Maximum power rating of blanket	P_R	800 MW
Blanket coolant		helium
Outlet temperature of blanket coolant	T_{out}	370°C
Blanket coolant pressure	P_{He}	70 atm
Shield coolant		borated water
Coil coolant (superconducting)		helium
E. <u>Nuclear parameters</u>		
Neutron flux on first wall (operating point)	P_w	0.55 MW/m ²
Neutron wall loading (design point)	P_w	1.07 MW/m ²
Neutron flux on first wall (operating point)	ϕ_w	$2.4 \times 10^{19} n/m^2/sec$
Neutron flux on first wall (design point)	ϕ_w	$4.7 \times 10^{19} n/m^2/sec$
Tritium breeding ratio (in one experimental module)	BR	1.15

Table 2. Research, development, and demonstration needs in the poloidal field system

- 1. Plasma**
 - Plasma dynamics (start-up/burn/shutdown cycle) for β , V, V-sec, and ampere-turn distribution requirements
- 2. Conductor**
 - Basic properties of high current, small filament wire
 - Reliable manufacture of mixed-matrix conductor
 - Behavior of cable in conduit at 4 K
- 3. Material**
 - Mechanical properties of plastic at 4 K for nonconducting structure
 - Insulator, structure, and conductor radiation damage effects
 - Fatigue properties of structure
 - Construction of a helium-tight conduit liner which does not conduct electricity
- 4. Cryogenics**
 - Forced-flow system characteristics
 - Impact of multiple coolant leads
- 5. Electrical**
 - High voltage strength of helium
 - Economical power systems
- 6. Mechanical**
 - Demonstration of remotely maintainable joints

Fig. 3. "Snapshots" of field due to currents ($\beta_j = 1.33$) (a) with shielding coils and (b) without shielding coils.

pulsed high field coils (Oh-primary), the fact that the magnetic field shielding system makes available the options of using simpler superconductor coil designs makes it a likely candidate for future tokamak reactors.

2.2.2 Plasma Input Considerations

The plasma start-up problem has been considered on the basis of several effects. For very low preionization, the breakdown of the plasma proceeds as an exponential increase in plasma density and is described in terms of the gas discharge parameters E/p , α/p , V_D , and T_e .

The volt-second consumption depends critically upon the preionization level. At 50 V and $p = 4.4 \times 10^{-4}$ torr in EPR, a density increase by a factor of 10^{12} requires 10.5 V-sec, whereas an increase by a factor of 10^2 requires only 1.75 V-sec. Such uncertainties have a strong impact on the PFS criteria. Similarly, since small radius or low density start-up procedures (see Fig. 4 for examples of time-dependent start-up characteristics) may be required in the EPR and future power devices, additional time-dependent control may well have to be incorporated in the PFS. Another important time-dependent aspect of plasma behavior that impacts the

Fig. 4. EPR start-up. Time-dependent density of H_1^0 , H_2^0 , H_1^+ , H_2^+ , e , and current. T_{10} and T_{20} are variable. $N_{20} = 0.3 \times 10^{19} \text{ m}^{-3}$.

PFS strongly is impurity control. By considering the long pulse values of the ion temperature, performance criteria for the impurity control mechanisms (assuming present models are properly indicative) can be generated, as shown in Fig. 5.

2.2.3 Design Considerations for the PF System

The function of the PF coil system is to create, preheat, and develop the plasma current and to maintain and stabilize the plasma column. Usually the system consists of two different sets of coils: the ohmic heating (OH) coils, which provide the necessary flux swing, and the equilibrium vertical field (VF) coils, which serve a stabilizing function (although the

latter usually also supply significant volt-seconds).

An important design consideration is the position of the VF coils: inside or outside of the TF coils. Placing the VF coils outside the TF coils is the engineer's choice, as it makes assembly and maintenance jobs simpler. On the other hand, placing the VF coils inside could lower the ampere-turn and energy storage requirements of the PF coil system; with proper design, this alternative could also reduce pulse fields on the TF coils and provide an option of shaping the plasma. The physics advantages were judged to be strong enough to take the latter approach. With this scheme, a set of shield-vertical field (S-VF) coils is placed inside the

Fig. 5. Time-dependent ion temperature for several conditions of impurity control.

TF coils, a counterwrap winding of decoupled coils is placed at the same location as the OH winding, and a set of trim-vertical field (T-VF) coils is used for the fine-tuning of the vertical fields. Figure 6 shows the locations of the different sets of PF coils. Because of the engineering difficulties anticipated in the construction, the S-VF coils are room-temperature, normal conductor windings. The rest of the vertical field coils and the OH coils are superconducting, as the power and refrigeration requirements for these coils are found to be prohibitively high if they are not superconducting.

Fig. 6. Poloidal field system with magnetic shielding.

2.2.4 Remote Maintenance Implications

Key assembly questions have been examined for feasibility of the design concepts. The basic approach to the reference design has been to assume that the center compression hub and the large TF coils would be semipermanent installations and that all other components could be removed and replaced without moving them. Modular construction of the vacuum vessel, blanket, and shield units has been proposed to facilitate the design and development of remote handling equipment (see Fig. 7).

The design of the connecting joints of the shield-vertical field windings must therefore be meshed with the overall design. Sixteen conductors recessed into the inner shield surface form this coil, which lies in a toroidal direction around the plasma. These coil segments are made up of 2- X 2-in. copper extrusions, and they have a 1/4-in. hole in the center for water-cooling. Nine of these conductors are potted in a square to make up the conductors of the coil segments. These segments are bolted into the shield segments before the shield segments are installed in the reactor. When the shield segments are put in place, each of the 16 coil segments extends beyond the edge of the shield on each side. The coil segments in one shield match the corresponding coil segments in the adjacent shield. A square bus with a special terminal fixture is situated on each end of the segments (see Fig. 8), and a special clamping clevis engages adjacent coil terminals, completing a mechanical and electrical joint between coil segments. This detailed study was conducted because the reference OH system forms a fundamental constraint on machine assembly, which in turn dictates strongly the overall cost effectiveness of EPR.

2.2.5 Summary

Running across the various areas of plasma phenomena is the set of electromagnetic effects linking the plasma to the outside environment. These areas, most aptly described as plasma magnetics, have been the scene of much innovation and progress, resulting in large part from focus on EPR. Careful, detailed distributions of ampere-turns providing and matching appropriate plasma conditions have been calculated. Conception and development of the TF coil shielding idea find their basis in an understanding of plasma magnetics. Investigation of this scheme leads to a comprehensive calculation of volt-second demands, but even here experimental evidence is sorely needed to verify or to guide choices in volt-second requirements in the transient states. A remaining undetermined

Fig. 7. Schematic of blanket construction.

factor is the actual magnitude of the changing magnetic fields at the TF coils, which may lead to significant hardware demands on both refrigeration and ohmic heating supplies.

On the technological side, three issues stand out, namely, conductor design, structure, and energy storage and transfer. Each of these three issues is now the subject of a development program, and many important design bases are yet to be determined.

3. THE NEXT STEP

As the EPR study progressed and the findings at each of the EPR study laboratories became more definite (while remaining similar), attention was focused on assessing the implications of the study. The following sections discuss the Oak Ridge judgments concerning this assessment and the actions to be taken.

The outcome of the EPR study indicates that intermediate steps will be required to support development of an EPR.^{10,17}

Fig. 8. Shield winding mechanical joints.

3.1 CLARIFICATION OF THE EPR OBJECTIVES

Examination of the EPR objectives indicates that many of the objectives subordinate to the ultimate EPR goal of net electric power can be achieved in earlier, lesser facilities. Those objectives that can only be achieved in an EPR are related to the high duty cycle and availability of the plant and to the full energy conversion and tritium breeding in the blanket. With the renewed assignment of these most advanced goals to the EPR, satisfaction of the subordinate objectives can be achieved at a benefit/cost ratio and cost level seen to be acceptable.

3.2 RETHINKING THE BASIC PHYSICS EXTRAPOLATION

The basic plasma engineering assumptions concerning minimum size and field for ignition play a dominant role in setting the overall size and difficulty of the EPR. Recent advances, both experimental and conceptual, have led to a rethinking of these basic assumptions.^{10,15} These advances indicate that (1) it may be possible to achieve higher beta values than previously supposed and (2) operation at high density should provide improved performance. The key to improved benefit/cost for the next major fusion step is the assumed value of plasma density. Using a value of $n < 10^{20} \text{ m}^{-3}$ resulted

in both a plasma radius of ~ 2 m (high cost) and a wall loading of ~ 1 MW/m² (low benefit). In setting up the basis for the next tokamak step, use will be made of the benefits of high density plasma operation and close attention will be given to a better understanding of its achievement. "Making" $n > 10^{20}$ m⁻³ does improve the benefit/cost both for the next step and for reactors. Achieving this higher density of $n \sim 2 \times 10^{20}$ m⁻³ clearly requires additional information on plasma stability at high beta equilibria and on materials properties at higher wall loadings ($\sim 2-4$ MW/m²). More data on the scientific and technological basis for the postulated high density, high beta operation will be forthcoming from the next generation of large experiments and continued materials research.

3.3 PLANS FOR THE NEXT STEP

The Next Step Program (TNS) at ORNL has been initiated to develop the basis for a major experiment in the mid-1980's having two principal objectives: 1) achievement of a

fusion reactor core, i.e., D-T ignition and burning, and 2) forcing function for reactor technology. The ORNL-TNS program is based upon the operation of high density, hot plasma using technologies being developed in the ORFE plan. Long pulse length operation permitting burn dynamics to be studied is planned, whereas continuous, high duty cycle operation is deferred until the EPR phase of the fusion program. Preliminary calculations indicate a thermal power output greater than 1500 MW in an $n = 2 \times 10^{20}$ m⁻³ plasma whose minor radii are 1.25 m (horizontal) by 2.0 m (vertical). Judging by these preliminary indications, TNS will have a benefit/cost considerably greater than the EPR design discussed here (four times output power in one-half size); furthermore, the extrapolation from TNS is to an economically viable fusion reactor. The technical basis for TNS appears verifiable in the next three to five years in the experimental and theoretical programs now underway: high beta in ORMAK Upgrade,¹⁸ superconducting coil performance in the Large Coil Program,¹⁹ and high power beams in the TFTR beam programs.¹⁰

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