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ENGINEERING CONSIDERATIONS IN THE SELECTION OF THE TOKAMAK TO FOLLOW THE TOKAMAK FUSION TEST REACTOR (TFTR)*

T. E. Shannon
Oak Ridge National Laboratory
Fusion Engineering Design Center
P.O. Box Y
Oak Ridge, TN 37831

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Abstract: The tokamak to follow the Tokamak Fusion Test Reactor (TFTR) should satisfy two important objectives. First, it should be a significant step in physics and engineering goals in order to maintain the level of progress which the U.S. has established as the world leader in fusion energy development. The second objective should be to provide the information necessary to support the strategy and goals of the long-range Department of Energy (DOE) Fusion Program. In their Comprehensive Program Management Plan [1], the DOE identifies the need for a reactor technology program in the 1990s in which the major goal is to prove engineering feasibility. In this paper, the specific engineering needs are identified which have been developed through the tokamak design studies over the past decade. On the basis of these needs, it appears that several options are available for the next tokamak to follow TFTR. The final choice of the concept will involve consideration of the technical needs and the reality of the Fusion Program budget.

Introduction

Since the start of the TFTR Project in 1974, the Fusion Program has been searching for the definition of the "Next Step." Five different candidate options, ranging from an Experimental Power Reactor (EPR) to a Tokamak Fusion Core Experiment (TFCX), have been studied with an expenditure of more than 500 man-years. Almost a decade has passed, the TFTR is in operation, and the program has yet to commit to a new major construction project. Although excessive cost and technical uncertainty have been causes for rejection of the proposed options, a lack of general endorsement by the Fusion Community has been the predominant problem.

The EPR (1974-76) [2], [3], [4] was obviously an overly ambitious step to be proposed in 1975. These studies, however, were most useful in providing insight into the major engineering problems which existed at that time. The EPR designs provide a good reference to measure the progress that has been made. The tokamak concept has progressed from the rather impractical EPR design to a concept which now looks quite promising for possible power reactor applications.

The Next Step (TNS) series of studies (1977-78) [5], [6], [7] produced an innovative set of options, but there was major disagreement and lack of consensus among the tokamak labs over the definition of the concept. The Next Step studies were consolidated with the formation of the Fusion Engineering Design Center (FEDC) in 1979. The first concept proposed was an Engineering Test Facility (ETF) [8] with the idea that the program would focus on the construction of a facility and thereby take the emphasis off the device itself. This concept was relatively short-lived and was not endorsed by the scientific advisors to the Fusion Program. It was too early for engineering testing as the focus for the program.

The passage of the Fusion Engineering Act of 1980 [9] opened the door for the construction of a Fusion Engineering Device (FED) [10] and the formation of a Center for Magnetic Fusion Engineering. Unfortunately, the program was unable to define a project to simultaneously meet the performance and cost guidelines outlined in the Act, and, once again, the Program searched for a better option.

In an attempt to satisfy the recent federal budget limitations, the DOE has proposed a long-range program assuming no near-term budget increases. This plan identifies the next step as an Engineering Test Reactor (ETR) which would be constructed — starting in the late 1980s. This concept has not been favorably received by most members of the Fusion Community because of the concern over the delay in starting the next major program for another 4 to 5 years.

The most recent proposal, a concept called the Tokamak Fusion Core Experiment (TFCX) [11], has evolved through deliberations of a panel of the Magnetic Fusion Advisory Committee (MFAC). The basic concept has been endorsed by the full Committee [12]. The Princeton Plasma Physics Laboratory (PPPL) is leading a national effort to define the specific concept and to perform the conceptual design. Whether or not the TFCX will finally advance to a construction project will be determined on the basis of both technical and political considerations over the next several years.

Engineering issues have been the primary cause for disagreement and hence the lack of general endorsement of an option for the next step. In the following sections, the major engineering issues will be discussed. For this discussion, it is assumed that the next tokamak will be designed to operate with D-T. This does not rule out the possible need for additional, smaller-scale tokamak experiments for physics and technology development. It is assumed that experiments of this type will be carried out in parallel with the major tokamak project.

Engineering Issues

The discussion is organized around three comprehensive issues: 1) ignition and burn, 2) magnet technology, and 3) engineering development and testing. When factored into a tokamak design, the issues result in three classes of machines, each representing an incremental step when taken in the order given above. The three classes are compared on the basis of plasma size in Fig. 1. The TFTR and a commercial power reactor plasma (Starfire) are shown to illustrate the total range of development required.

The major parameters of the TFTR are given for reference in Table 1.

Ignition and Burn

Ignition and long-pulse operation are the most desirable advancements for the next tokamak project. In order to understand the operations and control

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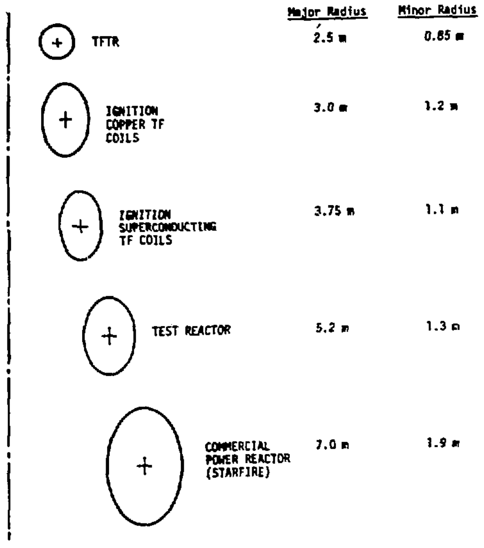

Fig. 1. Approximate plasma size comparison.

Table 1. Major parameters of the TFTR

Major radius, m	2.5
Minor radius, m	0.85
Field on-axis, T	5.2
Plasma current, MA	2.5
Beta, %	2.5
Fusion power, MW	30
Neutron wall load, MW/m^2	0.2
TF coil type	Copper
Ignition parameter	0.2
Pulse length, sec	1
Q	1
Impurity control type	None
Plasma heating, MW	33
Type	Neutral beam injection

aspects of a reactor-like plasma, it is necessary to have a pulse length of sufficient duration to maintain a steady-state equilibrium condition. Long-pulse operation, therefore, requires fueling, impurity control, and exhaust systems. The requirement for ignition has a major influence on the size and magnetic field requirements. Therefore, if ignition and equilibrium burn are to be fundamental requirements for the next step, these alone represent a rather significant step. The present mission statement for the TFCX design studies is essentially limited to this objective.

The application of rf waves for startup, heating, and current drive has been shown to significantly improve the overall tokamak concept [13], [14]. If the physics and technology data are available, it is almost certain that these features will be included in any future tokamak project.

Magnet Technology

From the point of view of power reactor technology development, the choice of toroidal field (TF) and poloidal field (PF) coil technology is the most fundamental issue. Superconducting magnets (SC) impose a different set of requirements on the tokamak configuration than copper magnets because of the need for thermal insulation. In addition, the superconducting magnets require more shielding than the copper magnets due to the neutron heat load on the conductors. The net result of these differences is an increase in size (major radius) of an all-superconducting machine of about 25%. The superconducting tokamak will therefore result in a project with increased capital cost; however, the operating cost of the copper coils will somewhat offset the capital cost difference due to resistive power loss of 300 to 400 MW.

Superconducting magnets are almost certainly a requirement for power reactor applications. There is, therefore, strong motivation to employ reactor-relevant magnet systems on an operating tokamak. Cost will be an important factor in the decision, and the FEDC Systems Code [15] will be a valuable tool to compare design tradeoffs. For the superconducting magnets, the Large Coil Project (LCP) [16] is providing a good cost data base. For copper magnets, actual procurement data are available.

One option under consideration for the TFCX consists of all-superconducting magnets. An elevation view of the preconceptual design (TFCX-S) is shown in Fig. 2. The major parameters for this option are shown in Table 2. These may be compared directly with the TFTR parameters given in Table 1.

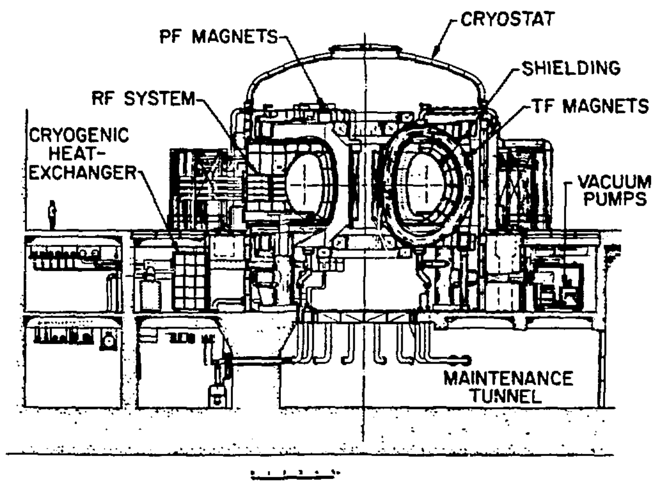

Fig. 2. TFCX-S elevation view.

Engineering Development and Testing

This third major issue results in the biggest step, but the specific differences are much more difficult to quantify. Engineering development and testing implies that the machine must operate for extended periods of time since information on machine maintenance and reliability is derived from operational experience. Statistical information on component failure rates is necessary in advance in order to design for high availability.

Table 2. Major parameters of the TFCX-S

Major radius, m	3.75
Minor radius, m	1.1
Field on-axis, T	4.3
Plasma current, MA	7.7
Beta, %	5.9
Fusion power, MW	230
Neutron wall load, MW/m^2	0.9
TF coil type	Superconducting
Ignition parameter	1.0
Pulse length, sec	300
Q	∞
Impurity control type	Pumped limiter
Plasma heating, MW	25
Type	ICRF

As a vehicle for testing, the machine will also accumulate high neutron fluence and therefore requires more shielding than that required for just ignition and burn testing. Nuclear issues relating to the design and development of tritium breeding blankets must obviously be addressed as one of the most important components requiring development in a fusion environment [17]. As illustrated in Fig. 1, the requirements for testing increase the major radius of the plasma from 3.75 m for the SC ignition plasma to 5.2 m, an increase of 35%. The quantifiable impact on the design is the increased shielding required for the higher fluence. Increased space is also assumed for blanket testing and access for overall maintenance and assembly operations. The time required for remote maintenance operations is strongly influenced by the working space available.

The best example of a tokamak design to satisfy requirements for engineering development and testing is the International Tokamak Reactor Design (INTOR) [14]. An elevation view of INTOR is shown in Fig. 3. The major parameters are presented for comparison to TFTR and TFCX-S (Table 3).

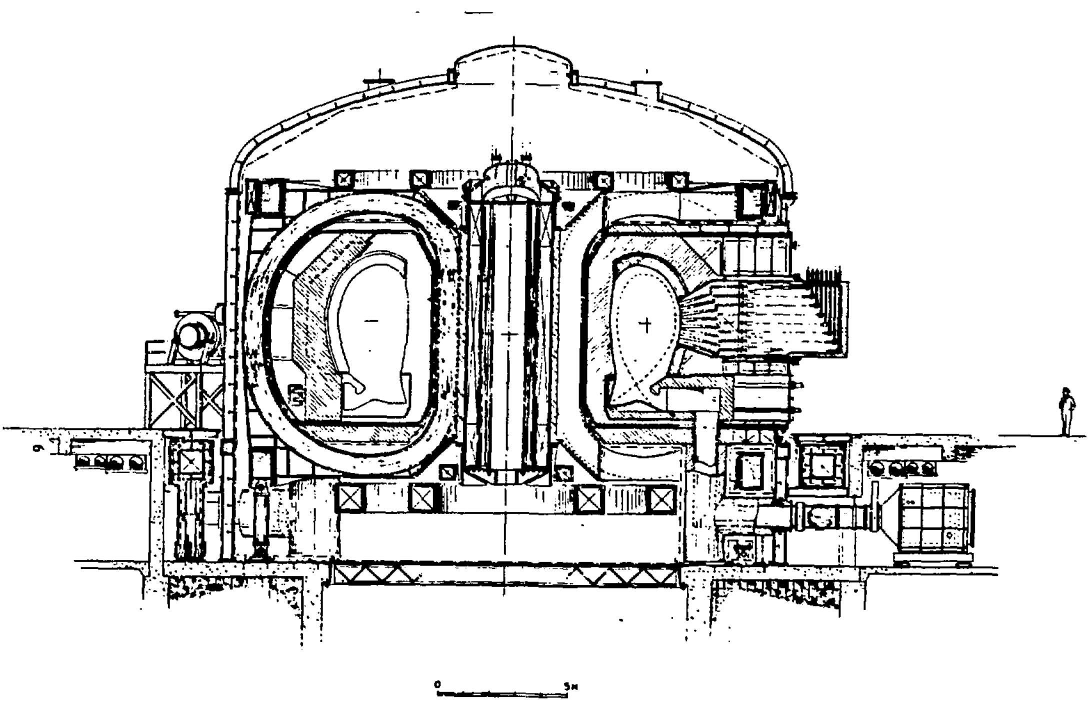

Fig. 3. INTOR elevation view.

Table 3. Major parameters of INTOR

Major radius, m	5.2
Minor radius, m	1.2
Field on-axis, T	5.5
Plasma current, MA	6.4
Beta, %	5.6
Fusion power, MW	620
Neutron wall load, MW/m^2	1.3
TF coil type	Superconducting
Ignition parameter	1
Pulse length, sec	200
Q	∞
Impurity control type	Poloidal divertor
Plasma heating, MW	25
Type	ICRF

Conclusions

The three classes of tokamak machine presented must each address a number of engineering issues that result from the major requirements. A more complete list of engineering needs that must be addressed to establish the engineering feasibility of fusion power is shown in Table 4. A significant percentage of the issues must be addressed for the ignition and burn class of machine. Whether or not a larger step, to include superconducting magnets, should be taken will depend on the thrust of the overall Fusion Program. If the objective of the program is directed toward fusion power development, it would seem that it is an essential step. If, on the other hand, it is determined that the uncertainty in the ignition and burn issues are so great that the superconducting magnets will jeopardize progress, then a copper TF magnet machine may be the best choice. The test reactor step, however, appears to be too big a step under almost all circumstances except for an international program in which the cost and risk would be shared by two or more countries.

For the near-term, the choice must be made between the copper and superconducting tokamak options. This could be the most important decision yet made in the Fusion Program.

Table 4. Engineering need for fusion power feasibility

1. Ignition and burn	Ignition Long-pulse/equilibrium burn RF heating Current drive Impurity control Remote maintenance Tritium handling
2. SC Magnet Technology	SC magnet technology Reactor-relevant configuration System integration with D-T
3. Engineering Development & Testing	Reliability/availability testing Blanket technology development T breeding Materials testing

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