MASTER

Suggestions for an Updated Fusion Power Program

J. F. Clarke

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SUGGESTIONS FOR AN UPDATED FUSION POWER PROGRAM

J. F. Clarke

Abstract

The present fusion RD&D plan culminating in an EPR reactor by 1985 must be revised because of scheduling difficulties and lower than expected funding of the CTR Program. This document contains suggestions for a revised CTR Program strategy which should allow us to achieve equivalent goals while operating within the above constraints. The revised program is designed around three major facilities. The first is an upgrading of the present TFTR facility which will provide a demonstration of the generation of tens of megawatts electric equivalent originally envisioned for the 1985 EPR. The second device is the TTAP which will allow the integration and optimization of the plasma physics results obtained from the next generation of plasma physics experiments. The improvement in tokamak reactor operation resulting from this optimization of fusion plasma performance will enable an EPR to be designed which will produce several hundred megawatts of electric power by 1990. This will move the fusion program much closer to its goal of commercial fusion power by the turn of the century. In addition to this function the TTAP will serve as a prototype of the 1990 EPR system, thus making more certain the successful operation of this device. The third element of this revised program is an intense radiation damage facility which will provide the radiation damage information necessary for the EPR and subsequent fusion reactor facilities. The sum total of experience gained from reacting plasma experiments on TFTR, reactor grade plasma optimization and technological prototyping on TTAP, and end of life radiation damage results from the intense neutron facility will solve all of the presently foreseen problems associated with a tokamak fusion power reactor except those associated with the external nuclear systems. These external system problems such as tritium breeding and optimal power recovery can be developed in parallel on the 1990 EPR. Thus the goal of a fusion demonstration plant by the late 1990's can still be achieved. The above considerations constitute a fusion power development program consistent with level three logic.

SUGGESTIONS FOR
AN UPDATED FUSION POWER PROGRAM
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Background

In 1969 the US Fusion Program began devoting major attention to tokamak magnetic confinement as a major approach to fusion power and experimental programs were started at General Atomic (GA), Massachusetts Institute of Technology (MIT), Oak Ridge National Laboratory (ORNL), Princeton Plasma Physics Laboratory (PPPL), and the University of Texas. By 1972, at the suggestion of Robert Hirsch, a group at ORNL had begun considering the requirements for a tokamak device which would for the first time burn significant amounts of deuterium and tritium. This device, called F/BX, was conceived of as a large superconducting tokamak which would be operated in its first stage as a large hydrogen physics experiment to verify the plasma physics conditions necessary for sustaining a controlled thermonuclear burn. In a second stage this same experiment would have allowed the initiation of such a burn. By 1974 the progress of tokamak experiments was such that serious consideration was being given to implementing these plans. At the same time it was demonstrated by a group at PPPL that some of the goals of this device could be realized in a smaller facility, called the two component torus (TCT), by optimizing the device to maximize fusion reactions between epithermal injected ions and the bulk plasma. Because of the greater assurance in achieving some measure of success in such a device, it was decided in early 1974 to begin work on a device utilizing the TCT concept and known as the Tokamak Fusion Test Reactor (TFTR) at Princeton University.² The goal of this device was the production of an amount of thermal fusion power equivalent to the power used to heat the plasma.

The scheduling and hence the scope of the TFTR machine was constrained by the desire to achieve a working experimental power reactor (EPR) by 1985. This EPR was conceived of as a facility which unlike the TFTR would necessarily possess features similar to those recognized to be characteristic of a tokamak fusion power reactor. Paramount among these features was the production of tens of megawatts of electric power. Additional features were the utilization of superconducting toroidal field coils, high duty factor and long pulse operation, fueling, high beta plasma operation, and impurity control. In order to better define these requirements, three EPR design studies were initiated in 1974 at ORNL, Argonne National Laboratory (ANL), and GA. The purpose of these design studies was to specify the nature of the EPR in greater detail so that the necessary R&D programs could be initiated to lay the technological foundation for a decision to proceed with an EPR.

As a result of these EPR design studies, completed at the end of 1975, it has become apparent that an EPR device which would produce a few tens of megawatts of electric power is of necessity a large, expensive and complicated device. However because of the rapid increase of the power output with size in such a device, a small increase in size would result in the production of several hundred megawatts of electric power. Thus it has become apparent that the return on the EPR investment increases rapidly with an increase in the scope of the EPR project. Naturally an increased scope of the project will require an extension of the schedule, both because of the increased tasks involved and because of the greater development necessary in the component technologies of the project.

From these same EPR design studies it also became apparent that the schedule which would have had to be followed if one decided to attempt a minimal EPR by 1985 was itself uncomfortably tight because of the short time available for development of these component technologies. In addition one would have to initiate the project before the operation of the TFTR device and in fact before results have been attained from the next generation of plasma physics experiments now being constructed. This is illustrated in Figure 1 which shows in a schematic way the relationship of the TFTR schedule, a typical 1985 EPR schedule, the group of next generation plasma physics experiments, and two of the major component technologies, high energy neutral beams and superconducting magnets.

The beginning of the square bars in each area indicates the earliest date that one can expect results and in fact in most cases an additional year beyond the time shown should be allowed for contingency. Clearly the undertaking of the large experimental power reactor project indicated by the EPR design studies would be very risky on the time scale shown.

It is hoped that plasma physics and technological advances achieved in the array of programs indicated in the figure would result in a significant improvement in the performance of the EPR. However, if one were to proceed on the schedule indicated there would be no time for incorporating these advances into the EPR project. This would guarantee less than optimum performance in the EPR. This is especially true because the CTR budget has lagged behind projections and consequently many of the development programs are not proceeding at the pace anticipated when the 1985 EPR schedule was first established.

In view of the above circumstances it has become necessary to reconsider the CTR program strategy for the next decade in order to adhere to our larger goal of practical fusion power by the turn of the century. This restructured fusion program attempts to remove the difficulties of the 1985 EPR program while at the same time attempting to achieve as many of the objectives of this program as possible. We believe that this is possible, in fact, by a judicious combination and use of our available resources and with the addition of some experimental facilities in the early 80s.

A Revised CTR RD&D Strategy

The revised CTR strategy which will be described has evolved from a detailed consideration by ORNL of the many functions which the 1985 EPR was to have served.³ A list of problem areas which would have been encountered for the first time on the 1985 EPR facility is given in Table 1. These problems can be naturally divided into three groups. The first consists of those problems which are characteristic of the EPR itself and which cannot be addressed in any smaller device. The second consists of those problems which have to do with the handling and burning of deuterium and tritium and which can be addressed on the TFTR device. The third group of problems are those which cannot be addressed on the TFTR device and yet which are not necessarily restricted to a device of the full EPR size. It is this latter list of problems which defines the nature of an additional facility for the early 80s which would serve many of the purposes of the 1985 EPR. In fact a consideration of the problems listed in Table 1 shows that the combination of the TFTR facility

FIGURE 1

Table 1. Features that must be Incorporated in a
Tokamak Experimental Power Reactor

Feature	Problems addressed in		
	TFTR	TTAP	EPR
<u>Fusion Reactor Technologies</u>			
Tritium feed and recovery	Yes	No	Yes
Tritium enrichment and recycle	No	No	Yes
Radiation shielding	Yes	No	Yes
Maintenance of radioactive systems	Yes	No	Yes
Confinement of radioactive gases	Yes	No	Yes
Control of fusion reaction near ignition	No	No	Yes
Recovery of neutron energy in high-temperature coolant	No	No	Yes
End of life radiation damage experiments	No	No	No
<u>Long Pulse, High Duty Cycle Operation</u>			
Superconducting magnet systems (toroidal and poloidal)	No	Yes	Yes
Steady state cooling of first wall	No	Yes	Yes
Fueling	No	Yes	Yes
Control of impurity buildup	No	Yes	Yes
Steady state gas handling (vacuum pumping)	No	Yes	Yes
Steady state operation of neutral beam injectors	No	Yes	Yes
<u>Confinement Improvements</u>			
Utilize results of Doublet III, PDX, and ORMAK Upgrade	No	Yes	Yes

and this additional facility which we call Technology Test Assembly with Plasma (TTAP)⁴ does in fact accomplish many of the purposes of the original EPR. An essentially complete overlap can be achieved if one considers what can be accomplished with a second stage modification of the TFTR facility on the 1985 time scale. Thus, a combination of the TFTR and TTAP facility would not only accomplish the purposes of the original limited EPR program but would provide an extremely sound technological base for the construction of a larger and more cost effective EPR at a slightly later date. The addition of an intense end of life radiation damage facility would fill the one remaining gap in the technological base necessary to make fusion power a reality.

Figure 2 shows the interrelation of the basic components which we consider necessary to a comprehensive fusion program in the 1980s. The figure shows three facilities during the 80s, the TFTR facility which is already under construction, the TTAP facility which has been under conceptual design at ORNL for the last year, and a high intensity radiation damage facility of the D-Li stripping type such as that proposed by ORNL.⁵

In the following we will attempt to show that a modification of the basic TFTR facility together with the TTA facility and the radiation damage facility can provide all of the information necessary for the successful design and construction of an EPR in 1990 which will produce several hundred megawatts of electric power. We feel that, because of the optimization of plasma design which will be possible from the research conducted on TFTR and TTAP, this advanced EPR can be no larger nor more expensive than the presently conceived EPR designs and yet will be a much greater advance for the fusion power program. This facility together with the end of life radiation damage data obtained from the high intensity radiation damage facility should provide an extremely solid base for the development of a successful demonstration fusion power reactor in the 1990s.

Ultimate Consequences of a Revised Strategy

Before pursuing the details of the facilities shown in Figure 2, we need to address the basic objection to any delay in any feature of the fusion program, namely that it would delay commercial availability of fusion power. This is a real concern since delay in a projected application date tends to have characteristics of a self-fulfilling prophecy; the further off the application the less attention is given to the program. In this regard it is important to note a significant difference between fusion and fission which has been overlooked to some extent in the planning of the fusion program. In laying out a program for the development of fusion power, great use has been made of the valuable experience gained in the development of the fission power industry. In particular, a sequence of devices of increasing complexity and commercial relevance has been projected for the fusion program in a manner similar to the evolution of the fission program. However the basic difference in the operation of these two power systems must at some point cause the fusion program to deviate from the historical precedent set by the fission power development. In particular we may have planned for too many intermediate steps in the evolution of fusion power.

The most basic difference between fission and fusion has often been cited as a disadvantage of fusion. This is the fact that fusion power is produced in a reacting plasma and this power must be transported through a material surface into a surrounding heat recovery medium in order to

FIGURE 2

produce practical power. Fission energy is produced in intimate contact with the thermal power recovery medium. This factor allows much higher power densities to be achieved in fission reactors than can be contemplated in fusion reactors. On the other hand, it must be recognized that because the power recovery structure is inextricably mixed with the fissioning reactor core, optimization of the power recovery system has required the complete redesign of the fission system. Thus a different set of fission problems must be solved for different types of fusion burners such as light water reactors and HTGR systems and yet more diverse problems for the burner and breeder systems themselves.

In a fusion reactor on the other hand, once the fusing plasma has been established and the first wall problem resolved all of the power recovery system development is done external to the plasma region. This will result in a rapid optimization of the fusion power system once the fusion reactor core has been developed. This underscores the importance of designing a fusion R&D program which allows early optimization of the fusion plasma and its container. For example as outlined in Figure 3, one can conceive of the 1990 EPR serving as a test bed for the development of a variety of different nuclear systems which will lead to a rapid optimization of tritium breeding and power recovery techniques. As is evident in the figure, different nuclear systems problems such as liquid metal blanket development, liquid metal tritium breeding, gas cooled blanket development, and solid blanket tritium breeding can all be explored either in parallel or in rapid sequence so that the Demo design could take advantage of real operating experience with the optimum combination of nuclear subsystems. This combined with five to six years of operating experience with the fusion core plasma and the information to be produced from twelve years of operation with the high intensity radiation damage facility will result in the realization of a sophisticated demonstration facility. As indicated in the figure, the TTAP facility can be used in a second phase as a development and demonstration test bed for improved fusion plasma development for the Demo in response to information flowing from the operation of the EPR. The combination of information flowing from the above facilities should lead to a more rapid development of reliable commercial power plants than has been possible in the analogous fission development program. Therefore, it is conceivable that the combination of facilities outlined in Figure 2 will, in fact, lead to commercial fusion power on a more rapid time scale than the previously considered 1985 EPR Program.

Optimized Fusion RD&D Facilities

A. The Second Stage TFTR

Let us now return to a consideration of some of the details of the facilities which are necessary to implement this strategy. First we will consider a potential modification of the TFTR facility which will provide fusing plasma information similar to that expected from the original 1985 EPR. Figure 4 shows the first stage TFTR experiment as originally conceived; that is, a two component torus (TCT) experiment which would produce approximate energy break-even by the use of 40 megawatts of high energy neutral beams injected into a sub-ignition plasma with an $n\tau$ product of roughly $5 \times 10^{13} \text{ cm}^{-3} \text{ sec}$. This experiment will give us initial information on the interaction of high energy neutral beams with fusion grade plasma and provide practical experience

FIGURE 3

FIGURE 4

with handling fusion tritium systems. In order to assure that this experiment attained these goals with the greatest safety margin against engineering and physics problems, the experimental device is designed to utilize only part of the machine cross section for experiments of less than one second duration.

The above arrangement provides the greatest experimental flexibility and maximizes the probability that the device will be able to attain its goals. Once these goals have been attained however it should be possible to utilize the full bore of the device, upgrade the power supply to allow pulses of up to five seconds, and to increase the neutral injection power to 100 megawatts. By the time of this conversion shown in Figure 4 the beam development program will have had five years to optimize the operation of high energy positive ion beams and nearly four years to develop the theoretically more efficient negative ion beams required for the EPR. Thus the operation of the second stage of the TFTR would provide prototypical beam testing for the EPR and as is clear from the figure, this would occur early enough in the EPR design process to allow fully confident design of the neutral beam heaters for this device. Recent calculations at ORNL have shown that the addition of 100 megawatts of beams to the full bore TFTR plasma should under reasonably optimistic conditions allow this device to approach the ignition condition and the net power produced by such operation should be much greater than the input power of the beams. Consequently this device would approach electrical power break-even and thus accomplish one of the goals of the original 1985 EPR. Of course the 1985 EPR would possess a number of characteristics, summarized in Table 1, which would not be duplicated by a second stage TFTR. Fortunately a number of these characteristics can be duplicated in the TTAP device as indicated in Figure 6.

B. The TTAP

The most fundamental characteristic of the TTAP device is that it utilizes a superconducting magnet system which is prototypical of the experimental power reactor. Thus from this device we gain integrated systems experience in operating a tokamak device with this new technology. In order to be prototypical of the EPR magnets, studies at ORNL have shown that these coils must be noncircular and possess a cross section of roughly three by five meters. Since the second stage TFTR would be dealing with prototypical operation of deuterium-tritium burning tokamaks there is no need to provide for tritium burning in the TTAP. This allows the full bore of the superconducting magnets to be utilized for plasma experimentation. The resulting flexibility of the device will allow the optimization of plasma behavior for the EPR utilizing the results of the next generation series of plasma physics experiments shown in Figure 6. These experiments, PLT, ISX, ORMAK Upgrade, Doublet-III, and PDX, are designed to pursue solutions to specific aspects of the plasma physics problem. The solution of these problems would make the plasma behavior in the EPR approach more closely the characteristics of a commercial tokamak fusion reactor. Consequently the incorporation of these advances in the EPR is an important goal for the CTR program.

In the previous plan for a 1985 EPR there was no opportunity to incorporate the advances resulting from this experimental program in the EPR. The size of the project and the complexity introduced by solving all the plasma physics and nuclear technology problems on one machine precluded a flexible approach in the plasma system design. Whereas TTAP could

FIGURE 5

FIGURE 6

accomplish its goals with a large uncertainty in the $n\tau$ product achieved with the first plasma system design, the 1985 EPR would be forced to the most conservative and thus the least flexible design by the need to guarantee an $n\tau$ large enough to produce power. *In the present plan, the scheduling of the EPR is such that not only can the advances of this experimental program be incorporated in the EPR but the same advances can be incorporated in the TTAP in a prototypical manner and thus gain advanced operating experience with an integrated EPR plasma system before title two design of the EPR commences.* This is possible because the large size of the TTAP superconducting magnet system and the lack of neutron shielding requirements in the system provide space to accommodate a variety of plasma configurations representative of the full range of the next generations research program. Thus the facility can be constructed in two phases. The earliest phase called TTA is the construction of the basic superconducting magnet system and power supplies for major experiment components. This can begin as early as 1978 and constitutes the largest fraction of the project. Because of the large variation in plasma size which is compatible with the achievement of TTAP goals, those features of the facility which are associated with the optimization of the plasma behavior can be started as late as 1980. This will allow time for the digestion and integration of the results of the experimental program shown in Figure 6. Thus by July 1982 the TTAP facility should be able to produce results on long pulse experiments with a prototypical EPR plasma system incorporating the fueling system developed in the plasma fueling program, the high beta operation techniques resulting from ORMAK Upgrade experiments, the noncircular plasma advances resulting from the Doublet program, the impurity control techniques developed on ISX, and the divertor results obtained from the PDX experiment. All of this information will be available to feed into the Title one and Title two design phases of the EPR.

In addition to its function as a facility which integrates our advanced knowledge of plasma physics behavior the TTAP serves as a prototypical systems test for all of the technological components of the EPR not specifically associated with the use of tritium. Since it is a superconducting system it has the capability of duplicating the high duty factor operation required in the EPR, and, by the use of the high energy ion beams which will be available at the time of its operation, the first wall loading of the EPR due to both plasma and high energy particles can be quite closely simulated in the TTAP.

C. The Radiation Damage Facility

Of course the neutron flux in the EPR can be simulated neither in the TFTR nor the TTAP. Consequently there is a great need for the development of a high intensity neutron facility. Recent proposals from Brookhaven and ORNL suggest that a facility based on the D-Li stripping reaction could be constructed by 1983 as shown in Figure 2 and provide a sufficiently large volume of neutrons with a flux in the vicinity of 10^{15} neutrons per square centimeter per second such that even these neutron wall interaction problems should be subject to some investigation before the operation of the EPR. Consequently the EPR program should be able to concentrate its efforts on those unique characteristics of EPR operation, high temperature tritium handling and breeding, and blanket and shield optimization.

FIGURE 7

The Superconducting Magnet Development Program

A basic requirement for the operation of the EPR is the development of large reliable superconducting magnet coils. The TTAP shares this requirement since it is intended to be a prototypical model of the EPR. Figure 7 shows the relationship of the presently envisioned superconducting magnet development program at ORNL in relationship to the TTAP and the EPR. The basic requirement of this superconducting magnet development program is the fabrication and testing of large superconducting toroidal coils. In order that these coils incorporate the technology which will be required for the EPR coils the minimum size is in the vicinity of 3 x 5 meters.

Thus the major task in the superconducting magnet program is the fabrication of such coils. This fabrication will be done in industry and will require the cooperation of those segments of industry with experience in superconducting coil fabrication and, because of the large size of the coils, those elements of industry with experience in the fabrication of large items of sophisticated technology. There are presently several different design options for the construction of these coils and it is much too early in the superconducting magnet development program to narrow our options. Thus, we envision the construction of several coils combining different design options.

These coils must be tested and evaluated in a simulated toroidal environment and this is the function of the large coil test. This test will require the assembly of six of the earliest coils in an extremely low aspect ratio toroidal array. This will allow each coil to experience the full asymmetric stresses which could be expected in TTAP and EPR operation. This facility will provide the first operational experience with large toroidal superconducting magnet sets and additionally will allow the development of shielding techniques and the pulsed superconducting coils required for the poloidal magnetic field in the EPR and TTAP.

The final step in the superconducting magnet program is the fabrication and testing of a full size EPR coil. The design of this coil must be based on the outcome of the large coil test. Its fabrication must be undertaken in industry and because of its size, approximately 7 x 11 meters, its testing will most likely be done close to its point of manufacture.

Industrial Involvement in the Revised Fusion Power Program

Points of industrial involvement in the fusion power program have already been indicated in the preceding discussion. However, it is important to emphasize that the fusion power development strategy suggested above lends itself in a very fruitful way to the systematic and effective incorporation of industrial talents in the fusion power program. This can be summarized as shown in Figure 8. The TFTR project at PPPL is already underway and will shortly select a firm to participate as the major contractor in its fabrication. The superconducting magnet development program at ORNL is preparing to let contracts for the fabrication of several large 3 x 5 meter superconducting coils. Since this activity involves both design and fabrication activities of large objects, it will require not only the participation of existing firms but the formation of new groupings of companies to accomplish the task.

FIGURE 8

Since these coils will be prototypical TTAP coils and subsize prototypes of the EPR reactor coil, involvement in their production constitutes a fundamental involvement in the early stages of preparation for the TTAP and EPR. This same involvement continues through the fabrication and testing of EPR coils which because of their much larger size will perhaps involve a different combination of companies. Certainly the TTAP project which is of the same order of magnitude as the TFTR project will involve the participation of a major industrial contractor who will bear the same responsibilities as the industrial subcontractor involved in the TFTR device.

Thus we have the possibility for industrial involvement in four separate activities in the fusion program over the next five years on the times indicated in Figure 8. This broad range of industrial involvement at early stages in the fusion development program will provide a broad base of expertise so that by 1982 when the EPR project begins in earnest there will be a broad range of industrial skills available for participation in this project.

Conclusions

The present fusion RD&D plan culminating in an EPR reactor by 1985 should be revised because of scheduling difficulties, lower than expected funding of the CTR program and also our ability to accomplish equivalent goals with less risk by utilization of an alternate strategy. This alternate strategy is summarized by Figure 2 which shows the major facilities required for an updated fusion RD&D program during the next ten years and Figure 3 which outlines the subsequent CTR facilities culminating in a Demonstration Plant by the year 2000. This program essentially consists of three major facilities. The first is an upgrading of the TFTR facility which will provide a demonstration of the generation of tens of megawatts electric equivalent originally envisioned for the 1985 EPR. The second device is the TTAP which will allow the integration and optimization of the plasma physics results obtained from the next generation of plasma physics experiments. The successful operation of this device will enable an EPR to be designed which will produce several hundred megawatts of electric power by 1990 and serve as a nuclear system development facility for the Demonstration Reactor. In addition to this function the TTAP will serve as a prototype of the 1990 EPR system, thus making more certain the successful operation of this device and in a later phase as a non-nuclear technology development facility for the Demonstration Reactor. The third element of this program is an intense radiation damage facility which will provide the radiation damage information necessary for the EPR and subsequent fusion reactor facilities.

The plan outlined in Figure 2 is a synthesis of the opinions of the senior staff of the ORNL Fusion Program. As such it represents the views of experienced and knowledgeable experts in all aspects of tokamak RD&D. We believe that the adoption of such a strategy represents little change in fact in present or planned program activities. Rather it requires a shifting in emphasis and scope among existing programs. By clarifying the goals of the fusion program it will allow greater cost effectiveness in utilizing CTR facilities over the next ten years. It also allows early and realistic incorporation of industrial expertise in critical elements of the program.

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