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PHILOSOPHY AND PHYSICS OF PREDEMONSTRATION FUSION DEVICES*

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ABSTRACT

A PDFD will operate in the 1980's and must provide the plasma and plasma support technology information necessary to warrant design, construction, and operation of succeeding experimental power reactors and then the demonstration plant. The PDFD must be prototypical of economic fusion devices to justify its cost. Therefore, development of the fusion core will be the focus of the PDFD. The physics performance, power production objectives, and characteristics of the PDFD, and their relationship to the research and development needs to achieve them are outlined. The design criteria for a PDFD which satisfied these constraints will be established.

During the past seven years a number of tokamak fusion power reactor designs have been undertaken with the goal of identifying major technological obstacles to the realization of practical fusion power [1]. In addition to these long range studies a number of shorter range projects have attempted to identify the technological requirements for the construction of an experimental power reactor which would demonstrate the basic technology necessary to produce net fusion power [2,3,4]. These latter studies have proved useful in defining relative priorities within the ongoing tokamak R&D program. However,

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the devices themselves have proved to be large complex machines with a high cost benefit ratio. In fact, the cost benefit ratio is so high and the uncertainties in the present designs so large that one is forced to conclude that the EPR's as presently conceived are not the next logical step in the fusion program.

The original objective of the EPR program was to advance the science and technology required for commercial fusion power by providing on a timely basis: (1) system operating experience and testing of components and subsystems for a larger demonstration plant to follow; (2) an intermediate focal point for research and development programs; and (3) large scale testing of plasma physics scaling, including deuterium, tritium, and alpha particle effects. The attempt to satisfy all of these objectives in one device while at the same time generating significant amounts of electrical power resulted in the complex designs referred to above. The dilemma in defining the characteristics of the next logical step in the fusion program stems from the desire to eliminate as much of this complexity as possible, while at the same time providing for a major step forward in the fusion program.

If the US fusion program is to achieve its goal of a demonstration reactor by the year 2000, a number of critical scientific and technological problems must be addressed in the mid-1980's. Some of these questions will be addressed in the TFTR device, but many others will require the construction of an additional facility which we shall call a predemonstration fusion device. We shall attempt to define the nature of this device in this paper.

The primary objective of the TFTR experiment is the attainment of $Q \simeq 1$. Calculations have indicated that this objective can be reached in a device with a plasma radius on the order of 90 cm. The next step in the fusion program should be a reasonable extrapolation in performance and size beyond TFTR. On the basis of available scaling laws, to be discussed below, it follows that $Q \simeq 5$ operation can be attained with a reasonable step in size beyond TFTR. It can also be shown that with a Q of approximately 5, ignition can be achieved. Thus, it is reasonable that the PDFD should operate with a near ignition plasma. Operation of such a plasma in hydrogen would require a supplemental heating power of over 200 MW. This prohibitive requirement can be reduced to 50-75 MW when D-T is used and advantage is taken of alpha heating. Therefore, real ignition of the PDFD plasma seems necessary.

An ignition experiment will require sufficient pulse time to investigate the consequences of ignition. Again, simple considerations of fusion reactor rates lead one to conclude that the machine should have a pulse time on the order of tens of seconds. Designs of magnets for $Q = 1$ devices [5,6] indicate that on a purely economic basis superconducting coils would seem to be an essential part of the device. Long pulse operation also implies efficient control of impurity build-up if ignition is to be sustained. Furthermore, since the ignition implies high temperatures and densities, the device must be capable of withstanding large pulses of fusion power. Thus a logical extrapolation beyond the performance of TFTR leads us to a device possessing most of the characteristics of the EPR. The device need not possess the ability to breed tritium, recover the neutron energy, operate with

a high duty cycle, or convert heat to electricity. All of these functions are peripheral to operation of the fusion reactor core and can be developed separately from this core. Thus it seems that a PDFD, which is the minimum significant extrapolation beyond TFTR, can be identified by the characteristics of a fusion reactor core.

Since the PDFD is a fusion reactor core, its characteristics should be compatible with the generation of economic fusion power, if tokamaks are to qualify as power systems. In order to define the most relevant version of the PDFD, it would be well to consider some of the factors which determine the economics of fusion power. The first point to be made is that, unlike the fission process in which energy is generated and recovered in the same physical region, fusion energy is generated in a plasma and recovered in an external blanket. Since in building a reactor one pays for materials and construction, not the vacuum region where the plasma resides, the costs associated with fusion systems are those associated with the external structure surrounding the plasma. Let us consider a general idealized tokamak power system. To simplify calculations, the elliptical system shown in Fig. 1 is assumed to include the general features of noncircular tokamaks. It is easy to show that the average power density in the blanket region is

$$\frac{P_B}{V_B} = \frac{2P_W}{\Delta} \sqrt{\frac{1 + \sigma^2}{2}} \left\{ \frac{1}{1 + \sigma + \Delta/a} \right\} \qquad (1)$$

where the elongation, $\sigma = b/a$, the structure thickness, $\Delta = \Delta_S + \Delta_C$, includes the coil thickness, and P_W is the wall loading. For a fixed

wall loading, plasma elongation increases the structure power density by increasing the surface area; however, it also decreases the power density by increasing the volume of structural material. The thickness of the coil, Δ_C, is determined by the strength of the magnetic field. It is easy to show that

Fig. 1. The geometry of an idealized tokamak power reactor is shown. The elliptic shape is chosen to include the effects of elongation on reactor economics.

$$\Delta_C = a\sigma \left\{ \frac{B_M^2}{2\mu_0 S} \right\} \left\{ 1 - \frac{(1 + \Delta_s/a)}{A} \right\}^2 \qquad (2)$$

where B_M is the maximum value of the toroidal field on the coil as indicated in Fig. 1, S is the stress in the coil, and $A = R/a$. For equal stress in the toroidal field coil, elongation is accompanied by a thickening of the coil and consequently a lowering of the average power density in the structure.

Since the capital cost of constructing the fusion power reactor is proportional to the volume of material used, the unit cost of fusion power is simply proportional to the inverse of the average power density in the reactor structure. Thus

$$C_P \propto \frac{V_B}{P_B} = \frac{\Delta}{2P_W} \sqrt{\frac{2}{1 + \sigma^2}} \left\{ 1 + \sigma + \frac{\Delta}{a} \right\} \qquad (3)$$

It is clear that in order to minimize the unit cost of fusion power, one must operate with the highest possible wall loading, P_W, and the thinnest possible structure, Δ. In view of the above, any economic

reactor will operate with the highest practicable P_W. The practical limit on P_W is defined by the material damage of the wall material combined with the detailed economics of wall replacement. It is generally accepted that wall replacement times of less than five years would be economically unacceptable.

The scaling of unit power cost is independent of plasma performance if the plasma is capable of loading the wall to the material limit. From the plasma side, the wall loading depends on the plasma power density. This is conventionally written as $P_V \propto \beta^2 B^4 (\langle\sigma v\rangle_F / \overline{T}^2) E_F$ where $\beta = 4\mu_0 \overline{nT}/B^2$. Many reactor studies point out the power density advantage to be gained from high beta and magnetic field operation so that the wall loading, $P_W = V P_V / A_W$, can be increased.

Elongation of the system has an advantageous effect on the unit power cost because the increase in surface area admitting power to this structure outweighs the increased volume of the blanket structure. However, the increased coil thickness necessary to keep the coil stresses at a constant level adds to the volume of the structure. In terms of unit power cost, elongation of the plasma would be more advantageous if it were necessary to increase the plasma power output in order to raise the wall loading, P_W, to the limit imposed by the materials used in the construction of the first wall.

High magnetic fields affect the unit power cost in a deleterious way through Eq. 2 since the increased structure necessary to contain higher magnetic fields increases the structural volume. High magnetic fields would only be advantageous if they were necessary to raise the

level of wall loading to the material limit. Thus in terms of unit power cost, the ideal fusion reactor would be moderately elongated and would operate with the lowest possible magnetic field.

Aside from minimizing unit power cost, it is also desirable to minimize the total cost of a fusion reactor system. The total cost, C, is obtained by multiplying the unit cost by the total power output of the reactor.

$$C \propto A\Delta a^2 \left\{ 1 + \sigma + \frac{\Delta}{a} \right\} \qquad (4)$$

Equation 4 shows clearly that to minimize the total cost of a fusion system, one should choose the lowest possible aspect ratio, the smallest plasma radius, and the smallest elongation consistent with reactor operation. There are lower limits on each of these parameters.

One of the difficulties with the EPR designs is the fact that they all employ low aspect ratio construction. This creates problems with respect to the assembly of the reactor and its remote maintenance [2]. Thus, for ease of remote maintenance, there is a practical lower limit of $A \sim 4$.

The minimum size of the plasma radius is determined by the condition that the plasma, $n\tau$, satisfies the ignition condition. The plasma $n\tau$ is determined by the scaling law which applies to the reactor regime. This scaling law is typically a function of magnetic field, elongation, impurity content, and aspect ratio. Consequently, the precise dependence of the cost of a fusion reactor on these parameters depends on the operative scaling law determining the plasma radius.

There are presently two scaling laws which might be thought to apply to reactor operation. The first is the scaling law derived [7]

from the theory of trapped ion modes (TIM). When this theory is modified to apply to our elliptical plasma model, the plasma $n\tau$ becomes

$$(n\tau)_{TIM} = 3.1 \times 10^{13}\, a^4 \left(\frac{B_T}{5}\right)^6 B^2 Z \left(\frac{A}{3}\right)^{5/2} \frac{1}{T_e^{11/2}} \left(\frac{1+\sigma^2}{2}\right) \quad (5)^*$$

The linear instability theory on which Eq. 5 is based should apply if the plasma collisionality is sufficiently low. Collisionality is conveniently defined as the ratio of the effective plasma particle collision frequency to the so-called bounce frequency, or the frequency with which particles complete their orbits in tokamak magnetic fields. This is measured by the collisionality parameter, $\nu^* = 3.3 \times 10^{-18}\, q(A/3)^{3/2}(an/T^2)$. Thus reactors can have varying degrees of collisionality depending on their aspect ratio, plasma size, density, and temperature. Figure 2 shows the range of collisionality expected for the EIR and some other existing or planned experiments.

Fig. 2. The collisionality of some existing, planned and contemplated experiments are shown for comparison. ORMAK-Upgrade with 4 MW neutral heating, to be operational in 1978, should explore the range of collisionality appropriate to the devices operating in the 1980 time period.

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*The units in the practical equations in this paper are centimeters, teslas, and kiloelectron volts.

For each device a range of ν^* is shown since the collisionality is a function of radius in the plasma, reaching its minimum value at about half the plasma radius. The trapped particle modes are expected to appear clearly below $\nu^* \sim 0.1$. Thus they may not have been observed in existing experiments and will only be found in the new generation of tokamaks represented in the figure by ORMAK-Upgrade and TFTR. If instabilities do occur for collisionalities less than 0.1, they should appear in reactor plasmas. However, their effect on the transport is still not well understood and Eq. 5 represents only an approximate estimate of this effect. It will remain for experiments such as PLT, ORMAK-Upgrade, and TFTR to verify the effects of these particular modes as well as their existence.

Present day tokamak experiments obey an empirical scaling law [8], $n\tau \propto n^2a^2$. Plasmas obeying this scaling law have collisionalities ranging from a ν^* of 0.5 to 40.0. Reactors will operate in the range of $\nu^* \approx 0.001$ to .1. Consequently, there is a gap between the lowest collisionality observed in present day experiments and the highest collisionality which we can reasonably expect for a fusion reactor. If this gap in collisionality could be kept small by operating reactors at higher collisionality, there might be some hope [9] that the empirical scaling law observed on present day experiments might describe the behavior of fusion reactor plasmas. However, it is clear from Fig. 2 that it remains for machines like ORMAK-Upgrade to bridge this gap.

Operating reactor plasmas with collisionality comparable to present experiments in order to preserve the empirical scaling

requires high density or equivalently high beta operation. Written in terms of beta, the empirical scaling law becomes

$$(n\tau)_{emp} = 2.5 \times 10^{15}\, a^2 \left(\frac{B}{5}\right)^4 \frac{\beta^2}{T^2} \tag{6}$$

showing a strong dependence on magnetic field strength [10] and beta.

We can use Eqs. 5 and 6 to determine the size of an ignition experiment for collisionless ($\nu^* < .1$) or collisional ($\nu^* > .1$) reactor operation. From Eq. 5

$$a^2_{TIM} \propto \frac{1}{B^3\beta} \sqrt{\frac{2(n\tau)_{IGN}}{1+\sigma^2}} \tag{7}$$

and from Eq. 6

$$a^2_{EMP} \propto \frac{\sqrt{(n\tau)_{IGN}}}{B^4\beta^2} \tag{8}$$

In both cases, beta can be seen to be advantageous for lowering cost. The effect of elongation appears only in the case of the collisionless reactor and has a weaker effect on the plasma size. Returning to Eq. 4 we see that the total cost or size of the system is roughly independent of elongation for a collisionless reactor and rises with σ for a collisional reactor.

It is known that the minimum ignition $(n\tau)_{IGN}$ is a sensitive function of the plasma impurity content. The rapid increase of $(n\tau)_{IGN}$ with effective plasma charge Z and the direct dependence of a^2 on this increase dictates an extremely effective impurity control method in an economic reactor.

The advantage gained from high magnetic field is real, but limited. Extremely high magnetic fields can be defined as those

which cause the coil structure to dominate the blanket and shield structure. Equations 3, 4, 7, and 8 show that although the total cost can be minimized by extremely high field operation, the specific power cost will rise as B^2 for a fixed wall loading.

Let us now turn to an examination of an application of these considerations to the specification of a PDFD which satisfies the constraint of relevance to economic fusion power as well as the advancement of fusion science and technology. A consideration of the EPR designs reveals that these general rules do reflect the economic trends found in those studies.

Table I provides a comparison of the three EPR designs and a candidate for the PDFD. This candidate, the THS, has been developed by ORNL and Westinghouse to satisfy both the research and development needs of the US fusion program in the 1980's and the need to have a demonstration of the essential components of an economically attractive fusion reactor core. The device was sized using either empirical or trapped particle mode scaling as used in the ANL and ORNL EPR studies. High beta operation allows ignition for either scaling and provides high wall loading. The aspect ratio was enlarged relative to the EPR designs to allow for easier remote maintenance. Moderate D elongation was chosen to optimize trapped particle mode scaling and unit cost. This equilibrium also has a natural divertor property for impurity control. The device shown in Fig. 3 will be described further in the following paper.

Because of the present uncertainties associated with many features of the science and technology [illegible]S, which will be continually

TABLE I

	EPR			TNS
	ORNL*	ANL†	GA‡	ORNL/ W
Major Radius (M)	6.75	6.25	4.5	5
Minor Radius (M)	2.25	2.1	1.1	1.25
Structure Δ (M)	2.25	2.25	2.25	2.25
Elongation	1	1	3	1.6
Maximum Toroidal Field (T)	11	8.0	7.9	8.0
Plasma Toroidal Field (T)	5	3.5	3.9	4.1
Plasma Beta (%)	3	4.8	10	14
Wall Loading (MW/M^2)	.55	.35	.85	3.7
Thermal Power (MW)	357	261	303	1510
Fusion Core Cost (M$)	249‖	249	218	218#
Unit Power Cost§ ($/KW)	695‖	923	645	144#

*ORNL EPR study, ORNL/TM-5572-77, M. Roberts, Ed.

†ANL/CTR-76-3, August 1976, W. Stacey, Ed.

‡GA-A14043, July 1976, C. Baker.

§Thermal power decided by the cost of the fusion core.

‖For purpose of comparison we have used the cost of similar size ANL EPR.

#For purpose of comparison we have used the cost of similar size GA EPR rather than an independent cost estimate.

Fig. 3. The cross section of the initial TNS design is shown to illustrate the attempt at size reduction and economical structure utilization in a high performance tokamak reactor experiment.

resolved over the next four years, the design will undoubtedly evolve from its present form in that same time period. However, the reference parameters indicated illustrate the improvement over the performance of the EPR's which can be realized in tokamak systems by a focusing on the key design elements as revealed in Eqs. 3 and 4.

It should be emphasized here that the absolute dollar estimates quoted in the table are not to be taken seriously at this time. We are concerned only with the trends in total and specific power cost as a result of the selection of different design choices. For the sake of consistency, we have estimated the ORNL EPR cost and the TNS cost from the other two EPR's which should have relatively consistent costing since they were performed concurrently. We have also used the nominal structure thickness of 2.5 M for all the devices to simplify comparison. The model in Fig. 1 assumes a compact structure. Reference to a typical EPR cross section (Fig. 4) shows that the structure is greatly extended. By comparison, the TNS design (Fig. 3) attempts to economize on the volume of material to better accord with the prescriptions of Eq. 2 and 3.

As seen from Eq. 3 the dominant factor in determining the specific cost is the wall loading. The General Atomic EPR has the highest wall loading and the lowest specific cost. However, according to Eq. 3 the cost advantage would be 2.75 over the ANL design and 1.7 over the ORNL design. In fact, the actual advantage is 1.4 over the ANL design and the ORNL EPR achieves comparable cost. The reason is unclear. Compared to the ANL EPR, the GA design has larger S and B which should contribute to higher power density in the plasma at the same operating

Fig. 4. The cross section of the best performing EPR design, the GA EPR is shown. This design possesses many of the desirable characteristics of a PDFD and is a candidate for this function.

temperature. Thus, the average wall loading in the GA EPR, $\bar{P}_W \propto \beta^2 B^4 (V/A_W)$, should be about five times larger than in the ANL EPR. However, the wall loading advantage quoted is only 2.4. By comparison, the wall loadings of the ORNL EPR is larger than the ANL

EPR by the amount expected on the basis of the $\beta^2 B^4$ scaling. Thus, although Eq. 3 indicates a reduction in unit power cost with elongation in the elliptical model, it does not appear that this advantage is fully realized in the GA EPR. Therefore, the nominal performance of the GA EPR does not differ significantly from the others shown.

As mentioned above, the use of higher field on the ORNL EPR compensates for the low beta plasma and high wall loading is achieved. However, the field increase is modest and does not result in significant increased structure because of a novel design utilizing force cooled Nb_3Sn superconductor within stainless steel conduits [2] which support the increased forces. This results in roughly the same coil size as the ANL and GA designs. Larger fields would require increased structure and possibly new types of superconductor. Thus the range for further performance improvement through magnetic field is limited.

The performance of the TNS as indicated in Table 2 is greatly improved over all of the EPR designs. This improvement results from the operation of the device at a high beta and a moderate plasma elongation, in a D configuration which provides for an efficient utilization of available volume within the coils. This results in the wall loading in the TNS design being much larger than that in any of the EPR designs and the power output being five times greater than these devices.

The details of the TNS design will be described in the following paper [11]. However, it is important here to consider the reason for assuming that high beta can be achieved in such a device and that the resulting high wall loadings have practical application for fusion

TABLE II

REQUIREMENT FOR PDFD	CHARACTERISTICS OF TNS
High wall load	3.7 MW/M^2
High beta	14 %
Z control	Natural divertor
Moderate elongation	1.6
Moderate magnetic field	4.1 T
Minimum structure Δ	2.5 M
High performance	1500 MW_{TH}
Moderate size	a) Coils half EPR size b) $a_{TNS}/a_{TFTR} = 1.4$

power systems. The possibility of high beta operation is based on the flux conserving tokamak concept [12,13]. This concept utilizes the fact that heating of large reactor plasmas from their initial low beta state to the desired high beta ignition state must occur on time scales which are much faster than magnetic diffusion times. Consequently this heating will occur through a sequence of equilibria containing the same amount of magnetic flux. As a result the low beta q profile is preserved during the heating process and a unique final equilibrium is obtained. This final equilibrium has been shown to possess many interesting stability properties such as good shear and an absolute magnetic well [14]. The ORMAK-Upgrade experiment which will be operational in 1978 is [illegible]d at verifying the existence of such equilibria. The belt pinch [illegible] experiment seems to possess such an equilibrium at betas of 30 to 70% and to exhibit stable

operation for 20 MHD growth times.

Operation of tokamak plasmas at high beta with efficient use of the plasma volume inevitably results in high wall loading such as shown in Table II. Equation 3 indicates that this high wall loading has economic advantages with regard to reducing the unit cost of fusion power. However, if this high wall loading results in such severe wall damage that the reactor wall must be replaced on short time intervals, this advantage would be more than offset.

Recent results on the simulation of CTR radiation damage in stainless steel [16] has shown that wall lifetimes in excess of 20 megawatt years/m^2 could be expected from a reasonable materials development program. Consequently, the wall loading indicated for the TNS design would result in a wall lifetime in excess of five years.

An examination of the costs of TNS components resulting from our initial design shows that the fusion core of TNS has about the same cost per unit thermal output as the fission core of the Clinch River Breeder Reactor. Thus, we have some indication that a device with TNS parameters has characteristics of an economic power system. Therefore, the TNS parameters satisfy the major requirement of a PDFD. Elements of these requirements are indicated in Table II. We conclude that the plasma size is a reasonable step beyond the TFTR and the ignition condition seems to be attainable in a reactor core which is directly on the path leading to an economic fusion system. The key assumptions about the attainability of the beta and confinement necessary for the performance indicated must be verified by experiment over the next few years; however, the logic for TNS is clear. Results and plans

from the ongoing fusion program lead naturally to a DT fueled ignition device following the TFTR. The objective of ignition in turn sets definitive criteria for numerous of the key physics and technological systems. With these criteria set, the goals of the research and development program necessary to insure that the criteria can be met on a time scale which will support TNS construction can be established. In the following paper the criteria for the key physics and technological systems will be established. In the last paper of this series, the research and development programs for some of the necessary technology supportive of the TNS design will be described.

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