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ADVANCED COMMERCIAL TOKAMAK STUDY

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ABSTRACT

Advanced commercial tokamak studies were performed by the Fusion Engineering Design Center (FEDC) as a participant in the Tokamak Power Systems Studies (TPSS) project coordinated by the Office of Fusion Energy. The FEDC studies addressed the issues of tokamak reactor cost, size, and complexity. A scoping study model was developed to determine the effect of beta on tokamak economics, and it was found that a competitive cost of electricity could be achieved at a beta of 10 to 15%. The implications of operating at a beta of up to 25% were also addressed. It was found that the economics of fusion, like those of fission, improve as unit size increases. However, small units were found to be competitive as elements of a multiplex plant, provided that unit cost and maintenance time reductions are realized for the small units. The modular tokamak configuration combined several new approaches to develop a less complex and lower cost reactor. The modular design combines the toroidal field coil with the reactor structure, locates the primary vacuum boundary at the reactor cell wall, and uses a vertical assembly and maintenance approach.

1. INTRODUCTION AND SUMMARY

1.1 BACKGROUND

The TPSS project was organized by the Office of Fusion Energy (OFE) in FY 1985 to investigate the basis for a significantly more attractive tokamak power reactor. The present reference point for commercial tokamaks is the 1980 STARFIRE¹ study that characterized a 1200-MW(e) fusion plant. Although STARFIRE was projected to be economically competitive with other energy sources at the time of the study, it is not now generally perceived to be a commercial power plant option. The particular feature of STARFIRE that is most questioned is the large financial investment in the fusion core of the plant. The scope of work at the FEDC was directed at finding ways to reduce that investment. The TPSS project consisted of independent studies by several participants. The studies were coordinated by OFE, and quarterly workshops were used to exchange and evaluate proposed tokamak improvements. This report describes the work performed by the FEDC as a participant in the TPSS project in FY 1985.

1.2 SCOPE

The FEDC work on the TPSS project concentrated on the three general criticisms of tokamaks: that they are too expensive, too large, and too complex. The first criticism was approached directly by evaluating the economic benefit of increasing the plasma stability limit. Higher, stable plasma beta can be used to increase the plasma power density, resulting in smaller, but more highly stressed, reactor components. Alternatively, the magnetic field can be reduced as beta is increased, maintaining a constant plasma power density, but reducing the magnet costs. The results of these scoping studies are reported in Sect. 2.

The issue of reactor size was addressed by evaluating the economic potential of tokamaks with a lower power rating. The physics of stability and confinement do not require that tokamaks have net power ratings of 1200 MW(e), but economic analysis shows an advantage to increasing unit size. Following trends in the fission industry, the FEDC investigated the economics of multiplex power plants. This type of plant combines the thermal output of several small units [approximately 200 MW(e)] to serve the common energy conversion system of a large power plant. The economic analysis of multiplex fusion plants is reported in Sect. 3.

The complexity of tokamaks is characterized by the need to have perpendicular sets of superconducting magnets, resulting in a "rings-within-rings" design. The magnets are designed to last the lifetime of the plant and require considerable mechanical support, so that there is an incentive to design the magnet systems as permanent installations. This type of design adds to the complexity by requiring that the life-limited components, closer to the reacting plasma, be removed and replaced through windows between the magnets. A new tokamak configuration developed at the FEDC is based on a modular assembly and maintenance approach. The tokamak is composed of independent modules that include the magnets, first wall, blanket, and shield. The modules are removable without relocating other reactor components. In addition to simplifying maintenance, the modular approach has several economic advantages, described in Sect. 4.

1.3 CONCLUSIONS

The economic scoping studies show that a commercially attractive tokamak power plant can be realized at a beta of 10-15%, provided that an efficient, noninductive current drive is developed. Tokamak economics continue to improve, but at a slower rate, as beta is increased to 25%. More detailed analysis is required to assess the engineering benefit and the physics uncertainty of increasing beta from 15 to 25%. Tokamak fusion power plants, like fission plants, will

achieve the lowest unit power cost at the maximum practical size. However, smaller reactors may achieve unit cost and maintainability advantages that will allow a multiplex power plant composed of smaller units to compete with the single-unit plant. Detailed analysis is required to determine the characteristics and assess the advantages of minimum-size tokamaks. Much of the benefit of smaller units may be realized by the modular tokamak design, which simplifies fabrication and maintenance.

Compared with other sources of energy, tokamak reactors are perceived to be expensive, large, and complex because of a set of physics and engineering requirements that are consistent with the presently available database. The extrapolation of the database to the advanced commercial tokamak, which is economically competitive with other energy sources, is within the domain of plausible fusion physics and engineering advances. For example, the required increase in beta is within that projected for tokamak plasma operation in the second stability region. The projections of attractive economics by these systems studies therefore serve as an impetus to verifications of these more aggressive assumptions, such as second stability operation and plasma profile control by efficient current drive.

2. THE EFFECT OF BETA LIMITS ON TOKAMAK ECONOMICS

It is evident that confining a plasma at higher pressure for a given magnetic field improves tokamak economics. The need to obtain higher beta than can be directly extrapolated from present experiments is caused by the perception that tokamaks cannot compete economically with other energy sources. The objective of the work reported in this section is to determine the sensitivity of costs to beta and, in particular, to determine what beta is required to identify a competitive tokamak in the present economic climate.

The means of achieving higher beta are not addressed. The reference cases for study assume a high-aspect-ratio tokamak, since this reduces plasma current requirements and simplifies mechanical design. The studies are therefore predicated on advanced techniques of plasma shaping and profile control to obtain higher beta, rather than the low-aspect-ratio and high-elongation approaches. In so doing, we would also forego the conventional density limit (proportional to B/R) to assess the full benefit of very high beta in tokamak reactor economy.

The scoping study model developed specifically for this project is described in Sect. 2.1. The general sensitivity studies reported in Sect. 2.2 conclude that an economically attractive tokamak can be designed with a beta of 10-15%. The design impact of operating at a higher beta is studied by point design comparisons of tokamaks with betas of 12.5% and 25% in Sect. 2.3.

2.1 SCOPING STUDY MODEL

A systems code using a personal computer was developed at the FEDC to perform scoping studies of commercial tokamak reactor options. The key feature of this code is the flexibility to analyze a wide range of options over a wide parameter space. The fundamental study parameter, beta, is typically varied from 5 to 25%. The device options include the selection of copper or superconducting coils, confinement scaling laws, current drive mechanisms, and plant arrangements. The code is designed

for simplicity and speed of operation and modification. To obtain flexibility, the code necessarily does not contain the design detail or constraints of the existing large systems codes, such as the Tokamak Systems Code² at the FEDC. However, it is well suited to a generic analysis approach,³ which is intended to determine a broad range of tokamak reactor parameters without specifying detailed design constraints.

The plasma parameters are calculated using the standard zero-dimensional equations, with the inputs being power (fusion or net electric), average plasma temperature, maximum magnetic field, plasma elongation, safety factor at the edge, impurity levels, plasma temperature and density profiles, and two of the following parameters: average neutron wall loading, beta, aspect ratio, or field on axis. The plasma current is approximated by⁴

$$I = 2.5(1 + \kappa^2) \frac{aB}{q} \epsilon \frac{(1.22 - 0.68\epsilon)}{(1 - \epsilon^2)^2} \text{ MA} , \quad (1)$$

where

- κ = elongation,
- a = minor radius (m),
- B = field on axis (T),
- q = safety factor at edge,
- ϵ = inverse of aspect ratio.

Although this equation was derived for aspect ratios up to about 4, it is a good approximation for higher aspect-ratio devices.⁵ The power required to drive the plasma current can be calculated by the lower hybrid, slow wave model used in STARFIRE¹ or by the fast wave model. Using the best theoretical efficiency in the fast wave model results in the ideal current drive, with a minimum power requirement, P , estimated⁶ to be

$$P = \frac{n_e R I}{1.4 \times 10^{20}} \text{ MW} , \quad (2)$$

where

n_e = electron density (m^{-3}),

R = major radius (m),

I = plasma current (MA).

The ignition margin is calculated by the definition

$$M = \frac{f_{\alpha} P_{\alpha} + P}{P_L + P_R}, \quad (3)$$

where

f_{α} = fraction of α particles trapped ,

P_{α} = fusion α power ,

P_L = energy transport losses,

P_R = total radiation losses.

The confinement is depicted by the energy confinement time, τ_E , by

$$\tau_E = \frac{W_p}{P_L} \quad (4)$$

where W_p is the plasma energy. Since the applications of the empirical scaling laws to the cases considered here are uncertain, four scaling options are included in the code: neoclassical, neo-Alcator, H-mode, and Mirnov scalings for electrons, and neoclassical scaling for ions.

The first wall, blanket, and shield conform to the elliptical plasma shape with minimal gaps. The code does not perform any geometrical checks for access clearances or torus penetration requirements, since this is generally satisfiable at large aspect ratios. The outboard blanket and shield are assumed to be 0.6 m and 0.4 m thick, respectively. The inboard shield (no inboard blanket is assumed) is sized to limit the nuclear heating in the toroidal field (TF) coil, the neutron damage to the coil insulator, or the time period between winding pack annealings. For the cost model, the shield is assumed to be water-cooled FE-1422, and the blanket is assumed to be self-cooled lithium lead with a neutron energy multiplication of 1.15 and a thermal-to-electric efficiency of 0.40.

The current density in the superconducting TF coils is approximated by

$$J = (6.5 - 0.25 B_m) 10^7 \text{ A/m}^2, \quad (5)$$

where B_m is the maximum field in the winding in tesla. The magnet case thickness and the winding pack copper fraction are specified as input and are typically assumed to be 0.1 m and 0.80, respectively. The code calculates the stresses in the TF coils and in the bucking cylinder. The poloidal field (PF) coil system is assumed to be composed of four coils: two located close to the inboard side of the plasma and the other two located close to the outboard side of the TF coil. The current in each PF coil is assumed to be equal to the plasma current, as suggested by magnetohydrodynamic (MHD) calculations of plasma equilibria for representative cases.

The plant power balance accounts for: the current drive power required, generally assuming an electrical efficiency of 0.7; the cryogenics required due to the nuclear heating in the TF coil; and the auxiliary heating power, which is taken to be 6% of the gross electric power.

The direct cost of the reactor and associated equipment is calculated based on algorithms developed at the FEDC or scaled from STARFIRE values. The direct cost of the balance-of-plant equipment is based on the Energy Economic Data Base⁷ data and STARFIRE. Indirect costs are assumed to be 35% of direct costs, and a 15% contingency is included. Interest during construction is calculated based on an inflation-free, effective cost of money of 4.2%. The levelized-revenue-requirements method is used to calculate the cost of electricity^{8,9} with a fixed charge rate of 8.3%.

The overall plant availability is taken to be 75% up to a neutron wall loading of about 13 MW/m². This is based on assumptions that half of a torus can be replaced during a scheduled annual plant maintenance period of 30 days, that the unscheduled maintenance period is 61 days,

and that the wall life is $20 \text{ MW} \cdot \text{year}/\text{m}^2$. If the wall loading divided by the wall life exceeds $2/3 \text{ year}^{-1}$, then the availability is reduced to accommodate more frequent torus replacement in the following:

$$\text{Availability} = 0.83/[1 + 0.164 \text{ wall load } (\text{MW}/\text{m}^2)/\text{wall life } (\text{MW} \cdot \text{year}/\text{m}^2)].$$

2.2 PARAMETRIC STUDIES

The scoping study code was used to assess the impact of arbitrary beta on reactor design parameters and economics. No explicit model for beta is used; it is assumed that plasma stability at arbitrarily high beta can be achieved at arbitrary aspect ratio. A possible scenario for achieving this performance is to gain access to the second stability region through plasma indentation (bean shaping).¹⁰ The scoping studies reported here generally assumed an aspect ratio of 6, an edge safety factor of 2.4, a plasma elongation of 1.6, and a plasma temperature of 20 keV.

Figure 1 shows the general trend of decreasing cost of electricity (COE) with increasing beta for the ideal current drive case. Based on the economic methods used in this study, the estimated COE of future large fission plants is 40 mills/kWh.⁸ It is seen that the fusion cost in this case achieves this target at a beta of 10-15% and that the COE is weakly dependent on betas above 15%. Also shown in Fig. 1 is the limiting line at which the ignition margin, assuming neoclassical scaling, becomes unity. This is an indication that the operating space at higher beta may be restricted by confinement requirements. As beta is increased in this fashion, the plasma size and current decrease for constant reactor performance, eventually reducing the ignition margin to below one. Neoclassical scaling for both ions and electrons is used here as the representative case; Mirnov scaling is slightly more restrictive, and H-mode and neo-Alcator scalings extend the operating space. For the 6-T case, operation at a beta of 20% is permitted by Mirnov, 22.5% by neoclassical, and 25% by H-mode.

Fig. 1. Effect of arbitrary beta on cost of electricity.

If the lower hybrid current drive model is used, the COE of the fusion plant reaches a minimum at a beta near 10% and does not enter the competitive range of 40 mills/kWh (Fig. 2). The higher cost of the lower hybrid case is accounted for by the increased size of current drive equipment and by the increased recirculating power. The unit cost and electrical efficiency of the current drive equipment were assumed to be the same for either type of current drive.

The effect of the ability to achieve second stability operation relative to present stability limits is shown in Fig. 3. The conservative beta limit used for next-generation-device studies is represented by $0.03 I/aB$, where I is the plasma current, a is the minor radius, and B is the field on axis. The model predicts that the COE of a tokamak following this scaling would be 50% greater than the target. If it is assumed that this scaling law is a factor of 2 low, then the COE is reduced to 20% greater than the target. A similar result is obtained by the scaling law used in the STARFIRE study, with a stability limit of $0.24 a/R$, where R is the major radius. It is also clear from Fig. 3 that the ability to achieve high beta at large aspect ratios (the arbitrary beta case of the figure uses an aspect ratio of 6) improves the COE.

The results of the general scoping studies show that an attractive commercial tokamak design can be developed at 10-15% beta, if second stability operation and fast wave current drive are assumed. It is found that present first stability beta limits or lower hybrid current drive models increase the COE, resulting in devices that are less economically attractive than fission plants. The estimated COE of the ideal tokamak reactor continues to decrease as beta increases beyond 15%, provided that confinement constraints do not restrict the operating space.

2.3 POINT DESIGN COMPARISONS

The engineering requirements of maximum magnetic field and neutron wall load influence the selection of an operating point at high beta.

Fig. 2. Effect of current drive model on COE.

Fig. 3. Effect of first stability beta limits on COE.

As shown by the second stability operating space of Fig. 4, higher beta can be used to increase power density (and therefore wall load) or to reduce magnet requirements. Neither of these effects can be very accurately modeled by a scoping code of the level of detail used in these studies. It is nevertheless expected that a reduced magnetic field will simplify tokamak structural design, simplify magnet fabrication, and simplify liquid metal blanket design. Increasing neutron wall load, on the other hand, will complicate first wall and blanket design and require alternative first wall materials. It is also clear that a more frequent first wall replacement requirement is undesirable. For a given COE and an arbitrary beta, the left portion of the operating map of Fig. 4 is therefore preferred, since this results in lower magnetic fields and wall loads.

The argument presented above for the lower wall load (and power density) does not hold for the compact reactor approach to fusion, which is based on very high power density and short reactor life. Considerable benefits are predicted if the device can be so compact that the entire core can be factory-fabricated and simply replaced as a unit. The compact approach is more suitable for tokamaks using normal copper magnets than for the superconducting magnet tokamaks considered here. The limits to the maximum field in superconducting coils and the reduced confinement at arbitrarily high beta (for constant reactor performance) tend to limit the plasma power density so that the wall loading is usually limited to less than about 10 MW/m^2 .

It is noted that the results of this section assume parabolic density and temperature profiles across the plasma radius. The general study results of the previous section use the assumption of a flat density profile. The parabolic profile is used to reflect the second stability requirements of carefully tailored and highly peaked plasma profiles. This has little effect on the COE for the fast wave, current drive case but does extend the operating space allowed by confinement.

Two reference points were selected to characterize device options: a "nominal" case at 12.5% beta and a "high-performance" case at 25%

Fig. 4. Second stability tokamak operating space.

beta. The design and economic parameters of these cases are compared with those that would be derived using the STARFIRE assumptions in Table 1. The COE of the tokamak with 12.5% beta is 12% less than that using the STARFIRE design point, and that of the 25% beta tokamak is 18% less than the STARFIRE model. Both cases operate at a moderate wall loading near 5 MW/m^2 and at a much lower magnetic field than STARFIRE.

If beta were truly arbitrary, that is, if the 25% beta case could be achieved with no more difficulty or expense than the 12.5% beta case, then the 25% beta case is clearly preferable. The "high-performance" designation reflects the fact that this case operates more closely to fundamental constraints than the nominal case. Figure 5 reflects this by showing the effect of changes in the arbitrary model assumptions (safety factor, elongation, and aspect ratio) on the results. There is essentially no effect on COE but a strong effect on confinement as a result of changes in these assumptions. It is found that increasing safety factor, decreasing elongation, or increasing aspect ratio decreases the ignition margin when reactor performance is held constant. The models for energy confinement, as well as for plasma current, are of course not known to be applicable in this region, so the case cannot be excluded from consideration.

Figure 6 shows that the COE of the reference cases is not sensitive to the current drive mechanism, provided the current drive efficiency is at least half of the ideal case. The maximum increase in COE due to current drive effects is approximately 20%, as represented by the lower hybrid model points on Fig. 6. The fact that Fig. 6 shows a more favorable COE for the lower hybrid case relative to the fast wave case than does Fig. 2 is due to the assumed density profile. For the parabolic profile, the lower hybrid COE is reduced 15-20% relative to the flat profile, while the fast wave COE is reduced 3-5%.

The results of the point design comparison show that, from an engineering point of view, the tokamak with 25% beta and a 6-T maximum field is preferable. A consistent set of plasma parameters that satisfies both stability and confinement for this case is required, as is the development of an efficient current drive mechanism that can control the plasma profiles.

Table 1. Reference tokamak parameters

Parameter	STARFIRE	Nominal	High performance
Net electric power, MW	800	800	800
Beta, %	6.7	12.5	25.0
Maximum field, T	11.1	8.4	6.0
Wall load, MW/m ²	2.9	5.1	5.1
Aspect ratio	3.6	6.0	6.0
Elongation	1.6	1.6	1.6
Safety factor	5.1	2.4	2.4
Density profile	1.1	1.0	1.0
Temperature profile	0.3	1.0	1.0
Plasma temperature, keV	20	20	20
Major radius, m	5.9	5.7	5.7
Minor radius, m	1.6	0.95	0.95
Plasma current, MA	5.2	3.5	2.5
Current drive power, MA	25	22	15
Neoclassical ignition margin	2.7	2.6	1.2
Fusion power core (FPC) volume, m ³	870	580	550
FPC mass, tonne	4970	3360	3100
FPC power density, MW(t)/m ³	2.6	3.9	4.1
FPC mass utilization, t/MW(t)	2.2	1.5	1.4
Magnet cost, \$ million	260	150	90
Reactor plant cost, \$ million	580	390	320
Total direct cost, \$ million	260	1070	990
COE, mills/kWh	45.7	40.2	37.6

Fig. 5. Sensitivity of results to model assumptions.

Fig. 6. Sensitivity of results to current drive model.

3. REACTOR SIZE AND MULTIPLEXING

Commercial fusion power plant design studies assume that the design and construction of the plant (other than the reactor itself) can be correlated with nuclear fission power plant experience. The current re-evaluation of the fission industry requires changes in fusion plant assumptions and a more precise assessment of the relationship between fusion and fission plants. A key issue is how strongly the COE decreases as the plant electrical capacity increases and, in particular, at what capacity this economy of scale is lost. A related question is whether fusion has acquired a fission economy of scale by the use of cost algorithms derived from fission experience. The fission industry is evaluating new reactor designs of low unit power. These studies may show that the predicted loss of economy of scale is more than compensated for by the benefits of small units, when the units are used as elements of a multiplex power plant.

The objective of the work reported in this section is to assess the potential for reducing the financial liability of tokamaks by reducing the unit power rating of the reactor. The economy of scale for fusion (Sect. 3.1) is found to be comparable to that for fission and to be controlled by reactor design constraints. Single-unit plants are expected to follow the economic trends of fission and to optimize in the range of 800 to 1200 MW(e). The multiplex plant study (Sect. 3.2) shows that the concept is economically competitive with single-unit plants under the appropriate assumptions for unit cost and availability. A key issue is the identification of the minimum unit size allowed by physics constraints and whether this size is suitable for factory fabrication. It is recommended that both the single-unit plant and the minimum-capital-cost tokamak be studied. The latter represents the first commercial demonstration reactor and may be suitable for future multiplex plants.

3.1 ECONOMY OF SCALE

The decrease in unit cost with increased output is defined by the elasticity, e , where for constant e

$$\frac{c_2}{c_1} = \left(\frac{Q_1}{Q_2} \right)^e,$$

where

c = cost per unit output

Q = output.

The elasticity will be positive, so unit costs will decrease with output, up to a maximum economic capacity.

Table 2 shows the elasticity that is used in the economic models for nuclear and coal plants.⁸ These models show that there is no difference between nuclear and coal plants in overall direct cost scaling.

However, indirect costs are more elastic for nuclear plants than for coal plants (the difference has been even greater in recent experience, but the data of Table 2 are used to model future plants). This indirect cost difference is primarily due to the quality assurance and control requirements associated with the safety and licensing of nuclear plants. The reduction of these requirements by the design of inherently safe units, preferably factory-fabricated, is a major goal of fusion, since this would result in absolute cost reductions and reduce the cost elasticity to improve the economics of small units relative to large units. Finally, the COE is seen to be even less elastic for coal than for nuclear plants, but this effect is due to the inelasticity of fuel costs, which are a major contributor to the coal COE.

The scaling of COE with plant size as determined by the scoping study code (Fig. 7) shows that cost scaling depends on design assumptions for the tokamak model. If beta can be arbitrarily increased, holding the wall load constant, then the COE is less elastic than if beta must be held constant and the wall load varied. The model used in the scoping studies assumes that the direct cost of most of the plant (other than the reactor and reactor building) scales according to

Table 2. Nuclear vs coal economy of scale

Account	Elasticity, e	
	Nuclear	Coal
Land	1.00	1.00
Structures	0.50	0.45
Reactor/boiler	0.40	0.40
Turbine	0.20	0.25
Electric	0.60	0.50
Miscellaneous	0.70	0.75
Heat rejection	<u>0.20</u>	<u>0.05</u>
Total direct cost	0.40	0.39
Construction services	0.55	0.40
Office engineering	0.80	0.40
Field engineering	0.60	0.30
Owner	<u>0.50</u>	<u>0.40</u>
Total indirect cost	0.63	0.38
Capital cost	0.48	0.39
Operating cost	0.50	0.40
Fuel cost	0.00	0.00
COE	0.40	0.29

Fig. 7. Effect of plant capacity on COE [fast wave, current drive case (aspect ratio 6, maximum field 8 T)].

the nuclear plant elasticity and assumes that indirect costs scale the same as direct costs (a constant factor being used). However, Fig. 8 shows that the plant scaling assumptions do not change the result -- that the economy of scale is dominated by the reactor assumptions. Figure 8 shows the scaling as determined by the code for the constant wall load and constant beta cases, as well as the scaling that would occur if either the nuclear or coal elasticities for direct and indirect costs (from Table 2) were applied.

3.2 MULTIPLEX PLANT STUDY

A multiplex plant was defined by the TPSS to be composed of several independent reactors connected to a common steam system and turbine generator. The advantages of multiplexing are the economy-of-scale benefit for the common systems, the potential for sharing of systems that are not required continuously by all reactors, and possible availability improvement through interconnections of parallel components. The work at the FEDC was not to assess the benefits of multiplexing, but rather to assess whether these benefits would allow small reactors to be economically competitive. The attractiveness of smaller reactors is the lower financial risk (which is most important for the first-generation devices), the ability to add capacity in smaller increments, and the expected availability advantage of smaller units. If the reactors can be made small enough, then the simplicity of a remove-and-replace maintenance approach and the benefits of factory fabrication can be achieved. Factory fabrication of the tokamak should substantially reduce unit costs through the controlled environment and learning effects, and it should simplify licensing procedures by allowing easier standardization and inspection of units. In addition, if inherently safe, complete units can be fabricated in the factory, the balance-of-plant costs may be reduced by elimination of safety functions.

Unit sizes of 200 and 300 MW(e) were considered in the evaluation of a multiplex plant with a total net output of 1200 MW(e). The design and

Fig. 8. Fusion economy of scale for different elasticity models.

economic parameters of these small units are compared with those of a single 1200-MW(e) unit in Table 3. The three units have the same wall loading of 3.6 MW/m^2 and the same beta of 13%. The safety factor at the edge is taken to be 2.4, and a parabolic density profile is assumed. The fact that confinement is harder to achieve in the smaller tokamaks is reflected by the greater elongation used in these comparisons.

As expected, the power cost of the small units is much greater than that of the large unit, even when a shorter construction time is assumed. However, it is also noted that small-unit capital investment is much less, which is of importance for first-generation plants. In particular, the fusion power core cost (reactor blanket, shield, and TF coils) is near \$100 million. The size and mass of the fusion power core would allow barge transport for the smaller units, but it is unlikely that factory fabrication or a remove-and-replace maintenance approach would be suitable.

If the 200- and 300-MW(e) units are multiplexed in a 1200-MW(e) power plant, the power costs will be reduced by the economy of scale for common systems and by equipment sharing. This effect is estimated by the scoping code to reduce the power cost by about 40%, as shown in Table 4. Also shown is the 10% further reduction that is achieved by learning effects. The learning effect was calculated separately for reactor components that were assumed to be factory-assembled, with a net reduction in reactor plant equipment cost of about 20%. With these assumptions, the multiplex plant direct cost using 300-MW(e) units is within 10% of that of the single-unit plant.

The availability of power plants is known to increase as plant size is reduced. It is also expected that the cross-connections of a multiplexed plant will increase complexity. Independent of these effects, the availability of the multiplex plant was calculated to determine whether there are significant availability advantages in the multiplex concept that could lower the COE. The model assumes that the reactors in the multiplex plant are configured to feed any combination of turbines. The annual scheduled outage for the reference reactor was

Table 3. Small reactor parameters

Unit net power, MW(e)	200	300	1200
Beta	0.13	0.13	0.13
Neutron wall load, MW/m ²	3.6	3.6	3.6
Maximum field, T	12	10	6.2
Aspect ratio	6	6	6
Major radius, m	3.1	3.7	8.3
Elongation	2.2	2.2	1.6
Plasma current, MA	3.2	3.7	4.1
TF coil radial build, m	5.9	6.4	11.7
Recirculating power fraction	0.18	0.16	0.11
Fusion core mass, tonne	1700	2000	5300
Fusion core cost, \$ million	110	120	280
Reactor plant cost, \$ million	210	240	560
Direct cost, \$ million	570	670	1470
Relative direct cost, \$/kW(e)	2850	2230	1220
Construction time, years	4	4	8
Relative capital cost, \$/kW(e)	4760	3720	2170

Table 4. Multiplex plant economics

Unit net power, MW(e)	200	300	1200
Number of units	6	4	1
Relative direct cost, \$/kW(e)			
Separate plants	2850	2230	1220
Multiplex plant	1690	1480	1220
Multiplex with learning	1510	1350	1220

assumed to be 30 days, and the unscheduled outage was assumed to be either 41 or 84 days. A second case was considered in which these outage times were reduced by 20% to reflect more rapid maintenance of smaller units. The annual unscheduled outage time for the turbine was taken to be 23 days, and it was assumed that scheduled turbine maintenance could be performed during the scheduled reactor outage. The UNIRAM¹¹ availability model was used to evaluate the various options, and the results are shown in Table 5. Also tabulated are the relative COE, assuming that the capital costs are based on the multiplex plants with learning effects. It is seen that if the 300-MW(e) units can be maintained in 20% less time than the 1200-MW(e) units, and if the learning effect savings are achieved, then the multiplex plant is competitive with the single-unit plant.

It is also noted that the choice of a single-unit or multiplex plant will be strongly dependent on the owner's load management choices. For the 75%-availability case, the six-unit plant will provide 50% of the plant capacity 90% of the time and will provide full capacity about 34% of the time.

The importance of the multiplex plant study is that it shows that fusion need not be restricted to large reactors, with their associated large financial liability and development expense. If the advanced small reactors can be developed, and if the smaller size results in lower unit fabrication costs and easier maintenance, then a multiplex plant using such reactors can be competitive with the large, single-unit plants.

Table 5. Availability and relative COE of 1200-MW(e) plants

No. of reactors	No. of turbines	41-day unscheduled outage		84-day unscheduled outage	
		Availability	COE	Availability	COE
1	1	75.0	1	64.0	1 ^a
4	2	75.7	1.10	65.4	1.08
4 at 80% ^b	2	81.7	1.02	73.3	0.97
6	3	76.3	1.22	66.3	1.20
6 at 80%	3	82.0	1.13	74	1.07

^a COE base is different for 41- and 84-day cases.

^b Reactor maintenance time is 80% of base.

4. MODULAR TOKAMAK CONFIGURATION

4.1 DESIGN BASIS

A tokamak configuration using a modular assembly and maintenance approach has been developed at the FEDC. This approach incorporates the following fundamental changes from previous superconducting tokamak designs.

- (1) Modular design. The tokamak is designed in independent, toroidal sectors, which include the TF coil, shield, blanket, first wall, and a saddle-PF coil. The maintenance approach is to remove and replace an entire module rather than to perform repairs on the reactor. Figure 9 shows one tokamak power module in place, and Fig. 10 shows the completely assembled reactor.
- (2) Combined reactor building and biological shield. The radiation shielding that does not specifically protect reactor components is provided by the wall of the building, or cell, that contains the reactor. There are no provisions for personnel access to the reactor in the cell.
- (3) No intercoil access. In keeping with the modular maintenance approach, no provisions are made for withdrawing internal reactor components (such as blanket segments) between the toroidal field coils. The reactor first wall, blanket, shield, and toroidal field coils are located as tightly as possible around the plasma, with no access clearances.
- (4) External vacuum boundary. The reactor cell forms the primary vacuum boundary. A secondary vacuum boundary between the cell and the plasma is maintained by mechanical seals between modules.
- (5) Vertical assembly. The reactor is located in a cylindrical cell with a removable cover that also forms part of the floor of a maintenance cell above the reactor. When a cover section is removed, a reactor module can be lifted from the reactor cell to the maintenance area by direct use of the maintenance cell crane.

Fig. 9. Tokamak power module installation.

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Fig. 10. Advanced commercial tokamak configuration.

4.2 MODULAR TOKAMAK DESIGN DESCRIPTION

The modular tokamak configuration was developed for a device with a major radius of 6 m, a minor radius of 1 m, and a vertical elongation of 2. The plasma is indented by 20%, and the tokamak is assumed to operate in the second stability region. For a maximum toroidal field of 6 T and an assumed beta of 25%, the net electric power is estimated to be 1000 MW(e).

The locations and currents of the PF coils were determined by FEDC MHD equilibrium code calculations (Fig. 11). The plasma indentation is achieved by the inboard set of copper magnets; the outboard magnets are superconducting. Equilibrium was calculated without using magnets above or below the reactor, so that reactor modules can be vertically removed without disturbing the coils.

The TF coils and reactor shield of each module are tied together to form a monolithic structure (Fig. 12). Each coil is independently encased and supported so that maintenance operations do not require downtime for warming or cooling the magnets. The electromagnetic forces are transmitted through alumina polyimide chocks. The contact area between the coil inner leg and the bucking post was determined to be 10% of the interface area, and the centering force is transmitted through a 25-cm thermal insulator with a nitrogen cold shield. The peak heat flux in the winding facing the bucking post is 0.5 MW/cm^2 . The total heat load into the TF coils is estimated to be 750 W, and the cold shield heat load at liquid nitrogen temperature is 2 kW. The inner legs of the TF coils are not butted but are framed by extensions of the bucking post to support the out-of-plane loads. The TF coil in each module is split to allow a greater space in the center of the module for service connections. The forces between these legs in the outer region are carried by cold-cold supports, and the insulators are used between the coils and the module structure. The entire module is encased, so that forces between modules are all carried at room temperature.

The inboard PF coils are realized as two saddle copper coils mounted in each module (Fig. 13). The equilibrium calculations determined a

Fig. 11. MHD equilibrium coil locations.

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Fig. 12. Tokamak power module.

Fig. 13. Power module disassembly.

coil current of 1.3 MA for a plasma current of 7 MA.¹² Using a conductor current density of 3000 A/cm^2 and 12 modules in the 6-m major radius geometry results in a resistive power loss of 6 MW per coil, or 140 MW for the reactor. Design studies to reduce this requirement by changing coil current density and location have not been undertaken as yet, because it is expected that the reference reactor design will be physically smaller and will require a lower plasma current. It is expected that periodic replacement of the pusher coils, as well as of the first wall and blanket, will be required. These maintenance operations will be performed as shown in Fig. 13 after the module is removed from the reactor.

The outboard PF coils are superconducting and are mounted to the reactor cell wall (Figs. 14 and 15). The installation of these coils and of the bucking post is the first step in reactor assembly. The tokamak modules are lowered into the frame formed by the bucking post and outboard keys in the cell wall. The modules are then wedged together to carry the forces between modules. The connection to the vacuum system beneath the reactor and the connections between modules are simplified by maintaining the reactor cell at rough vacuum during operation. Other service connections are made at the top of the reactor, as shown, and the cell is sealed by installing the removable shield sections that form the roof.

The modular configuration results in significantly smaller facilities required for tokamak operations and maintenance. The total volume required for the reactor, the primary heat transport system, and the maintenance area is $87,000 \text{ m}^3$, which is one-quarter of that required in the STARFIRE design. The dimensions of the main operating floor, shown in Fig. 16, are 31 m by 42 m. After a reactor cell shield cover is removed, a sector is vertically removed and placed in one of the sector maintenance bays. Sectors are removed from the reactor building by lowering them through an opening in the maintenance bay row to a rail-mounted transport carriage on the mezzanine level (Fig. 17). The sector is then transferred to the auxiliary building and raised by a

Fig. 14. Modular tokamak elevation.

Fig. 15. Modular tokamak plan.

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Fig. 16. Operating floor of reactor building.

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Fig. 17. Lower level of reactor building.

separate overhead crane for placement in the storage pool or in the preparation area for shipment out of the plant. A longitudinal section of the reactor building is shown in Fig. 18 and a partial plot plan of the plant in Fig. 19.

4.3 DESIGN ANALYSIS

The apparent advantages of the modular configuration are reductions in the tokamak plant cost and maintenance complexity. The cost reductions are gained by the use of smaller facilities for the reactor and its maintenance operations, the elimination of biological shielding on the reactor, and the elimination of requirements for maintenance access between coils. Maintenance is simplified by the elimination of welds on the tokamak, by the ability to remove and replace modules using only an overhead crane, and by the possibility of total reactor disassembly using normal maintenance procedures. The innovative design approach necessarily violates some generally accepted conventions. Among these violations are the required removal of an expected lifetime component (the TF coil) to replace a life-limited component (the first wall); the absence of any provisions for personnel access to the reactor cell; and the elimination of the common cryostat, which is generally used to simplify magnet structural design.

Further analysis of the modular design is required to determine the feasibility of further opportunities for tokamak improvement. An additional advantage can be achieved if the modules can be designed to be transportable from the factory to the plant site. Factory fabrication would result in lower unit costs because of learning effects and simplified inspection and licensing. The 800-MW(e) reactors described in Sect. 2.3 would require modules with approximate dimensions of 5 x 6 x 7 m and weights of 250 tonnes. The values are near the general guidelines for rail shipment. An even greater benefit would result if the reactor module were so small that the module and its associated primary cooling system, including an intermediate heat

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Fig. 18. Reactor building longitudinal section.

Fig. 19. Advanced commercial tokamak partial plot plan.

exchanger, could be considered as a unit. An extremely compact heat transport system could be designed if the bore of the tokamak were large enough to accommodate the heat exchanger. The unit shipped from the factory could then be designed to be truly inherently safe, containing both the reactor and its primary coolant.

The modular configuration was developed for a commercial power plant, but its advantages also make it a candidate for near-term reactors. This application would require the adoption of the commercial maintenance philosophy by the near-term project. In the modular design, all maintenance operations must be performed remotely with controls outside of the reactor cell. In addition, the reliability requirements for components must consider that all components are equally accessible.

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