156
8/15/86

W.B.

(2)

(25)

I-27561

1879-1

ORNL/FEDC-86/3

MULTIPLEX TOKAMAK POWER PLANT

A. E. Dabiri

FUSION ENGINEERING DESIGN CENTER

OAK RIDGE NATIONAL LABORATORY

Operated by MARTIN MARIETTA ENERGY SYSTEMS, INC.

REPRODUCTION OF THIS DOCUMENT IS UNLIMITED

~~DISCLAIMER~~

MASTER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ORNL/FEDC-86/3

Dist. Category UC-20 c,d

FUSION ENERGY DIVISION

ORNL/FEDC--86/3

DE86 014400

MULTI-LEX TOKAMAK POWER PLANT

A. E. Dabiri

Fusion Engineering Design Center/
Science Applications International Corporation

Date Published - July 1986

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

EB
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

CONTENTS

LIST OF FIGURES.....	v
LIST OF TAELES.....	vi
ABSTRACT.....	vii
I. INTRODUCTION.....	1
II. METHOD OF ANALYSIS.....	3
III. RESULTS.....	8
IV. MULTIPLEX POWER PLANT AVAILABILITY.....	15
V. DISCUSSION OF RESULTS AND CONCLUSIONS.	19
ACKNOWLEDGMENTS.....	24
REFERENCES.....	25

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	COE vs number of tokamaks multiplexed for a superconducting magnet tokamak.....	12
2	COE vs number of tokamaks multiplexed for a spherical torus.....	14
3	COE vs number of tokamaks multiplexed for an elongated tokamak...	16
4	Relative COE vs number of tokamaks multiplexed for a superconducting magnet tokamak (TRW results).....	21

LIST OF TABLES

<u>Table</u>	<u>Page</u>
1 Direct Cost Algorithm for Multiplex Reactor (millions of dollars).	4
2 Plant Unit Cost Factors for Various Reactor Components.....	7
3 Multiplex Plant Parameters (S/C Magnet).....	9
4 Multiplex Plant Parameters (ST).....	10
5 Multiplex Plant Parameters (ET).....	11
6 Availability and Effective COE of 1200-MW(e) Plants.....	18
7 Availability and Effective COE of 2400-MW(e) Plants.....	20
8 Ignition Margin for Various Confinement Scalings for Small Tokamak Reactors.....	23

I. INTRODUCTION

There have recently been some innovative design approaches in the fission industry to address the problems of safety and long construction time (1,2,3). In all of the design studies, smaller units [100-300 MW(e)] have been adopted. Such sizes could lead to the use of factory fabrication, which should reduce construction time. Factory fabrication should reduce unit cost through learning effects and should expedite licensing procedures by allowing easier standardization and inspection of units, all of which reduce the indirect cost of the power plant. The other common feature of these design studies is inherent safety. (A reactor is inherently safe if there is a passive means for sufficient afterheat removal in the event of an accident. This would prevent significant structural damage or radioactivity release.)

The lower-power reactors could make it possible for utilities to commit generating capacities in relatively small increments in order to meet low-load growth that has recently been experienced by the utilities. This could translate into reducing capital outlay for load increments and avoiding a penalty for overcapacity. Another expected benefit would be a higher plant availability. An improvement in plant availability could occur if the small units could be repaired more rapidly than the large units, particularly if complete modules could be replaced.

The STARFIRE (4) class of devices may not at present represent the best option to characterize either the potential of fusion or the feasibility of tokamaks. The particular feature of STARFIRE that is most questioned is the large financial investment in the fusion core of the plant. Without improvements, this translates into a higher cost of electricity (COE), which could perhaps be 50% higher than the COE of the light-water reactors.

The purpose of this paper is to study the feasibility of small tokamak reactors that could take advantage of the expected benefits discussed above for small fission reactors, that is, indirect cost reduction and inherent safety. Depending on the choices of fusion materials, passive-afterheat removal in loss-of-coolant or loss-of-flow

accidents could be aided by substantially lower afterheat-generation rates, compared with fission (5). Therefore, it seems feasible to design a small fusion reactor with moderate wall loading (approximately 5 MW/m^2) that would be inherently safe. We also explore the conditions under which these small, low-power tokamaks can be economically combined into a 1200- to 2400-MW(e) multiplex power plant. Although the economy of scale for the reactors may penalize the multiplex plant relative to the large, single-unit plant, the expected benefits mentioned above for small reactors might compensate for the scale effect. (A power plant composed of more than one complete power-generating unit, operated in parallel, is defined to be a modular plant. A multiplex plant is a modular plant, except that one or more of the systems are shared, so that the units are not totally independent. This would take advantage of the economy of scale for some systems to reduce power cost.)

The attractiveness of a multiplex power plant depends largely on the variety of utility-related characteristics. These include, among others, utility system size and generation mix, as well as load growth and load characteristics. For example, smaller plants might be more attractive to a utility with low-load growth, high uncertainty in the growth rate, and small initial-generating system (6). Since it is impractical at the present time to quantify the impact of all of these parameters on the multiplex power plant, only the most important issues have been addressed. These include capital cost, cost of electricity, and the plant availability as preliminary tools to compare the multiplex power plant with that of a single unit.

Three tokamak options were selected from among nine options that were considered as commercial reactors (7). They are Spherical Torus (ST) (8), Elongated Tokamak (ET) (9), and superconducting magnet tokamaks operating in the second stability regime with fast-wave current drive (10). These options are more favorable for multiplexing relative to others, based on the COE of the multiplex plant as a selection criteria. ST and ET tokamaks are described elsewhere (8,9).

Unit sizes from 200 to 600 MW(e) were considered in the evaluation of a multiplex plant with a total net output of 600-2400 MW(e). In this

paper attention is focused only on exploring the concept of multiplexing, and by no means are the reactors optimally sized.

II. METHOD OF ANALYSIS

Methodology used in this analysis has required that a number of assumptions be made. Where possible, the assumptions have a well-defined basis and logic so that numerical values are well conceived. These are identified and described in the following description of the analysis method. In some instances, however, it has been necessary to make choices that are less easily justifiable. In these instances, engineering judgment has been used, and the numerical values have been selected to ensure an optimistic assumption with respect to multiplexing. A systems code, developed for scoping studies of commercial tokamak reactor options, is described in Ref. 7. The direct cost of the reactor and associated equipment is calculated based on algorithms developed at the Fusion Engineering Design Center (FEDC) or scaled from STARFIRE (4) values. The direct cost of the balance-of-plant equipment is based on the Energy Economic Data base (11) and STARFIRE. These are shown in Tables I and II. Some of the algorithms in Table I could have been based on thermal power rather than gross electric power; however, since the thermal efficiency of power plants is within a narrow range, all the algorithms were based on gross electric power. Indirect costs are assumed to be 35% of direct costs. This indirect cost is lower than the short-time projection for fission reactors but is higher than what is projected for coal-fired plants (12). Interest during construction is calculated based on an inflation-free, effective cost of money of 4.2% (13). The levelized-revenue-requirements method is used to calculate the cost of electricity (12,13), with a fixed charge rate of 8.3%. These cost algorithms were developed specifically for this study. A more general cost data base is in preparation as an extension to the FEDC cost accounting system.(13)

Based on the number of components to be built in a fusion economy, increased use of factory fabrication, and easier standardization and inspection of units, learning-curve factors have been assumed for the

Table I

Direct Cost Algorithm for Multiplex Reactor (millions of dollars)

Cost Account	Single Plant	Multiplex Units (N units)
Land and land rights	5	5
Site improvement and facilities	20	20
Reactor building	$180 \left(\frac{P_G^*}{1200} \right)^{.5}$	$240 \left(\frac{P_G}{1200} \right)^{.5} \text{ (a)}$
Turbine building	$\left\{ \begin{array}{l} 32 \left(\frac{P_G}{1200} \right)^{.5(b)} \\ 48 \left(\frac{P_G}{1200} \right)^{.5} \end{array} \right.$	$\left\{ \begin{array}{l} 48 \left(\frac{P_G}{1200} \right)^{.5(c)} \\ 72 \left(\frac{P_G}{1200} \right)^{.5} \end{array} \right.$
Reactor maintenance building	$70 \left(\frac{P_G}{1200} \right)^{.5}$	$70 \left(\frac{P_G}{1200} \right)^{.5}$
Tritium building	$10 \left(\frac{P_G}{1200} \right)^{.5}$	$10 \left(\frac{P_G}{1200} \right)^{.5}$
Heat transport	$70 \left(\frac{P_G}{1200} \right)^{.6}$	$\frac{70 N}{2} \left(\frac{2P_G/N}{1200} \right)^{.6(d)}$
Fuel handling	$40 \left(\frac{P_G}{1200} \right)^{.6}$	$40 \left(\frac{P_G}{1200} \right)^{.6(e)}$
Maintenance equipment	$40 \left(\frac{P_G}{1200} \right)^{.6}$	$40 \left(\frac{P_G}{1200} \right)^{.6(e)}$
Instrument and control	23	46

Table 1 (continued)

Cost Account	Single Plant	Multiplex Units (N units)
Turbine plant equipment	$\begin{cases} 250 \left(\frac{P_G}{1200} \right)^{.8} \\ 500 \left(\frac{P_G}{2400} \right)^{.8} \end{cases}$	$\frac{250 N}{2} \left(\frac{2 P_G / N}{1200} \right)^{.8(d)}$
Heat rejection system	$30 \left(\frac{P_G}{1200} \right)^{.8}$	$30 \left(\frac{P_G}{1200} \right)^{.8(e)}$
Electric plant equipment	$100 \left(\frac{P_G}{1200} \right)^{.8}$	$100 \left(\frac{P_G}{1200} \right)^{.8}$
Miscellaneous plant equipment	$35 \left(\frac{P_G}{1200} \right)^{.3}$	$35 \left(\frac{P_G}{1200} \right)^{.3}$
Electrical equipment building	$13 \left(\frac{P_G}{1200} \right)^{.5}$	$13 \left(\frac{P_G}{1200} \right)^{.5}$
Miscellaneous buildings	$25 \left(\frac{P_G}{1200} \right)^{.5}$	$25 \left(\frac{P_G}{1200} \right)^{.5}$

* P_G is the total gross electrical power of the plant.

(a)

In a multiplex plant, the cost of a reactor is assumed to be 1.5 times the cost of a building housing one reactor with the same total net electric power.

(b)

It is assumed that there will be two turbines if P_G is greater than 1200 MW(e), but only one turbine building. The cost of the building housing two turbines is assumed to be 1.5 times the cost of one housing one turbine.

Table 1 (continued)

(c)

In a multiplex plant, the number of turbines is either two or three, depending on the number of fusion power cores, to increase the plant availability. Therefore, the building cost is higher relative to a building housing one unit. It is assumed that the building cost for a multiplex plant is 1.5 times the building cost for a single plant.

(d)

It is based on one turbine serving two reactors.

(e)

It is assumed that the multiplexing will not increase fuel handling, maintenance equipment, and heat rejection system costs, which are considered optimistic.

Table II
Plant Unit Cost Factors for Various
Reactor Components (1985 dollar)

First wall, \$/kg	70
Blanket, \$/kg	70
Reflector, \$/kg	16
Stainless steel shield, \$/kg	20
Magnet conductor, \$/kA-m-T	2.5
TF magnet winding, \$/kg	80
PF and OH magnet winding, \$/kg	175
Magnet case, \$/kg	40
Copper magnet, \$/kg	85
ICRF power, \$/W	1.1
Power supply, \$/W	0.1

NbTi conductor.

Pool-boiling-type winding.

Forced-flow-type winding.

Minimally machined welded stainless steel case.

Single-in-hand, single-pancake winding of internally cooled copper conductor.

first wall/blanket, superconducting magnet case, superconducting magnet winding, copper coil, and RF system. These are 0.75, 0.585, 0.585, 0.65, and 0.65, respectively. This reduces the cost of the reactor plant equipment by 10 to 15%. The construction period for multiplex plants is assumed to be four years, compared to eight years for a single-unit plant, due to increased use of factory fabrication. This reduces the interest during construction by about a factor of 2. Although these factors may be on the optimistic side, they are chosen to explore the maximum potential benefits of a multiplex power plant. In the cost analysis, it was assumed that all the units would be built at the same time.

III. RESULTS

Three different tokamak concepts were considered: ST, ET, and the superconducting magnet operating in the second stability regime with fast-wave current drive. Unit sizes from 200 to 600 MW(e) were considered in the evaluation of a multiplex plant, with a total net output of 600 to 2400 MW(e). Steady-state operation was assumed for the reactors (except ET, which is inductively driven), in which long pulses (approximately 0.5 h) were considered. The input as well as output parameters and economics of plants using the three concepts are shown in Tables III-V.

The cases presented for the superconducting magnet tokamak all use average and peak temperatures of 20 and 40 keV, respectively, an elongation of 1.6, a safety factor of 2.4, and an aspect ratio of 6. An average temperature of 20 keV was selected to reduce the current drive power requirement. The maximum field was varied from 12 to 7 T to keep beta approximately constant, and wall load was kept in the range of 4-5 MW/m² to keep physics and technology requirements the same for all the reactors, assuming they are qualitatively represented by beta and wall load. The COE for a single power plant drops from 90 mills/kWh for a 200-MW(e) net power plant to 29 mills/kWh for a 2400-MW(e) net power plant. Figure 1 shows the COE of superconducting magnet tokamaks vs the number of tokamaks multiplexed. The three dashed lines represent three

Table III
Multiplex Plant Parameters (S/C Magnet)

	Unit Net Power, MW(e)				
	200	300	600	1200	2400
<u>Input</u>					
Temperature, keV	20	20	20	20	20
Elongation	1.6	1.6	1.6	1.6	1.6
Safety factor	2.4	2.4	2.4	2.4	2.4
Aspect ratio	6	6	6	6	6
Neutron wall load, MW/m ²	4	5	5	5	5
Maximum field, T	12	12	10	8	7
Availability	0.75	0.75	0.75	0.75	0.75
<u>Output</u>					
Major radius, m	3.3	3.6	5.04	7.05	9.9
Beta, %	0.105	0.105	0.10	0.11	0.107
Plasma current, MA	2.5	2.8	3.7	4.6	5.9
Plasma density, 10 ²⁰ /m ³	2.6	2.8	2.4	2	1.7
Recirculating power fraction, %	0.18	0.17	0.14	0.12	0.105
Engineering Q	5.5	6.1	7.2	8.5	9.5
Mass power density, kW/tonne	130	170	210	260	290
Unit direct cost, \$10 ³ /kW	2.8	2.3	1.6	1.2	1.0
COE, mills/kWh(e)	90.3	70.7	49.2	36.4	29
(Constant dollar)					

Table IV
Multiplex Plant Parameters (ST)

	Unit Net Power, MW(e)				
	200	300	600	1200	2400
<u>Input</u>					
Temperature, keV	15	15	15	15	15
Elongation	3	3	3	3	3
Safety factor	2.7	2.7	2.7	2.7	2.7
Field on axis, T	3.5	3.5	3.5	3	3
Paramagnetism	1.57	1.57	1.57	1.57	1.57
TF coil current density, A/m ² × 10 ⁷	2	2	2	2	2
Availability	0.75	0.75	0.75	0.75	0.75
<u>Output</u>					
Major radius, m	2.1	2.19	2.39	2.76	3.7
Aspect ratio	2.56	2.5	2.38	2.07	2
Beta, %	25	26	28	35	39
Wall load, MW/m ²	4.6	5.3	7.0	8.1	11.4
Plasma current, MA	13.8	15.4	18.9	27.3	35
Plasma density, 10 ²⁰ /m ³	2.6	2.7	2.9	2.7	2.9
Recirculating power fraction, %	0.53	0.46	0.35	0.26	0.20
Engineering Q	1.9	2.2	2.9	3.8	5
Mass power density, kW/tonne	170	225	370	560	870
Unit direct cost, \$10 ³ /kW	3.4	2.1	1.7	1.2	0.9
COE, mills/kWh(e)	104	78	50	35.5	26.4
(Constant dollar)					

Table V

Multiplex Plant Parameters (ET)

Unit Net Power, MW(e)	200	300	600	1200	2400
<u>Input</u>					
Temperature, keV	10	10	10	10	10
Elongation	9	9	9	9	9
Safety factor	2.4	2.4	2.4	2.4	2.4
Field on axis, T	4.0	4.0	4.0	4.0	3.5
TF coil current density, $A/m^2 \times 10^7$	1	1	1	1	1
OH coil current density, $A/m^2 \times 10^7$	1	1	1	1	1
Troyon coefficient	1	1	1	1	1
Availability	0.75	0.75	0.75	0.75	0.75
<u>Output</u>					
Major radius, m	2.46	2.6	2.84	3.12	3.54
Aspect ratio	10.8	10.3	9.7	8.9	7.31
Beta, %	31	32	34	37	45
Wall load, MW/m ²	4.1	4.8	6.5	9.0	10.9
Plasma current, MA	8.5	9.7	12.2	15.7	23.2
Plasma density, $10^{20}/m^3$	6.3	6.5	7	7.6	7.2
Recirculating power fraction, %	44	38	29	22	17
Engineering Q	2.3	2.6	3.4	4.5	5.9
Mass power density, kW/tonne	130	175	275	425	610
Unit direct cost, $\$10^3/kW$	3.3	2.6	1.7	1.2	0.9
COE, mills/kWh(e)	102	77.7	50.5	36	27.3
(Constant dollar)

Fig. 1. COE vs number of tokamaks multiplexed for a superconducting magnet tokamak.

power plants with capacities ranging from 600 to 2400 MW(e). Each power plant is composed of either a single unit or several smaller units. As this figure shows, multiplexing will increase COE, except for the 2400-MW(e) power plant case. In this case, a multiplex plant composed of two 1200-MW(e) units has a COE that is 5% lower than that of a single power plant with a 2400-MW(e) capacity. The results presented here are based on 75% plant availability for all the reactors. The effect of multiplexing on availability is discussed in Sect. IV.

Table IV tabulates the parameters for spherical torus reactors. All use average and peak temperatures of 15 and 30 keV, respectively, an elongation of 3, a safety factor of 2.7, and a paramagnetism of 1.57. Due to its large natural elongation feature (8), an elongation of 3 was not considered excessive and is consistent with the magnetohydrodynamic (MHD) calculation. The value of paramagnetism was derived from the equilibria calculation. The magnetic field on axis was varied from 3.5 to 3, to result in an optimum reactor: (1) avoiding excessive wall loads, (2) obtaining lower plasma current, which would make the current drive easier, and (3) approaching minimum COE. The result shows that the wall load increases from 4.5 MW/m² for 200 MW(e) to 11.4 MW/m² for a 2400-MW(e) net power plant. The COE for a single power plant drops from 107 mills/kWh for a 200-MW(e) plant to 27.0 mills/kWh for a 2400-MW(e) net power plant.

Figure 2 presents the COE of a spherical torus vs the number of units multiplexed. It is clear that multiplexing in general will increase the cost of electricity for ST. The COE for a 2400-MW(e), single plant is approximately equal to the COE of a plant composed of two units, each 1200 MW(e).

Table V shows the parameters for elongated tokamak reactors. All use average and peak temperatures of 10 and 20 keV, respectively, an elongation of 9, and a safety factor of 2.4. These parameters are very close to those chosen by other investigators (9). The magnetic field on axis was varied in a way to satisfy some of the requirements mentioned for ST. Variations of wall load, beta, and COE with respect to the reactor output is the same as ST, but the plasma currents are about 65%

Fig. 2. COE vs number of tokamaks multiplexed for a spherical torus.

of the ST for all sizes. Figure 3 shows the COE of ET vs the number of units multiplexed. The result is similar to ST.

IV. MULTIPLEX POWER PLANT AVAILABILITY

The purpose of this section is to compare the availability of a multiplex tokamak fusion plant to that of a single-unit tokamak plant to determine if there are significant availability advantages in the multiplex concept that could lower the COE. This comparison will not be a trivial task, since it would be a function of a number of factors that are difficult to quantify. The most important ones are briefly discussed below.

Smaller units may require less maintenance time than larger units because of the relative ease of handling smaller equipment and the effect of the learning curve for maintenance of several identical units on one site.

Shared equipment has a complex effect on plant availability. On one hand, shared equipment increases availability; on the other hand, cross-connection between the units will add to the complexity of the plant, which may reduce the availability.

Smaller units tend to have lower optimum wall loading. This could make them more reliable, which, in turn, could increase the plant availability.

An effort was made to quantify the above-mentioned issues. Four types of analyses were performed to determine the availability of a multiplex plant as opposed to that of a single unit:

1. In the first analysis, it was assumed that the unavailability of fusion reactor equipment or turbine equipment has the same value, whether the equipment is arranged as a one-unit plant or as a multiplex plant.
2. In the second analysis, it was assumed that the maintenance time required for a multiplex plant is 80% of that required for a single unit.
3. Third, one additional reactor core was included in the multiplex plant.

Fig. 3. COE vs number of tokamaks multiplexed for an elongated tokamak.

4. Finally, one additional turbine was included in the multiplex plant.

Other assumptions used in the analysis are:

- For the multiplex plant, all fusion reactors are configured so that they can feed any combination of turbines. This will improve availability because the equipment will be shared between units.
- An average of 30 days per year scheduled outage was assumed for a fusion reactor. This is based on assumptions that half of a torus can be replaced during a scheduled annual plant maintenance period. This assumption is consistent with STARFIRE (4) and INTOR (14).
- A turbine and its associated equipment can be maintained during the same 30-day, scheduled outage.
- Annual unscheduled outage time for turbine equipment is 23 days.
- Annual unscheduled outage time for fusion reactor equipment is assigned two different values: 41 days for an overall single-unit plant availability of 75% and 84 days for a single-unit plant availability of 64%. (The unscheduled outage duration for the turbine and reactor equipment cannot be directly added, since some of the forced outages overlap.)
- Cross-connections in heat exchangers and turbines in a multiplex plant will add to the complexity of the plant, which may reduce the plant availability. This effect has been neglected in the analysis.

The UNIRAM (15) availability model was used to determine the availability of various fusion plant configurations, based on the assumptions listed above. Results are tabulated in Table VI. Conclusions from this analysis are that there is little advantage, relative to availability, in the multiplex concept over a single-unit plant, unless an additional fusion reactor or an additional turbine is provided, or unless maintenance time can be reduced for the smaller units. In these cases, there is a significant availability advantage, particularly if the fusion reactor portion of the plant has a lower-than-anticipated availability. The assumption of less maintenance time for smaller units could be justified by the study of the National Electric Reliability Council (16). Over a ten-year period from 1971 to 1980, the average equivalent availability of fossil plants with a capacity of 300-400 MW(e) is five

Table VI

Availability and Effective COE of 1200-MW(e) Plants

No. of Reactors	No. of Turbines	41-Day Unscheduled Outage				81-Day Unscheduled Outage			
		Availability (%)	Relative COE			Availability (%)	Relative COE		
			S/C	ST	ET		S/C	ST	ET
1	1	75.0	1	1	1	64.0	1 ^a	1	1
4	2	75.7	1.13	1.32	1.28	65.4	1.12	1.31	1.26
4 at 80% ^b	2	81.7	1.04	1.23	1.18	73.3	1	1.17	1.13
6	3	76.3	1.24	1.53	1.46	66.3	1.22	1.50	1.44
6 at 80%	3	82.0	1.15	1.40	1.36	74	1.09	1.35	1.29
7 ^c	3	80.4	1.27	--	--	72.6	1.20	--	--
6	4 ^d	79.4	1.26	--	--	68.2	1.25	--	--

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

^bReactor maintenance time is 80% of base.

^cIncludes one additional reactor core.

^dIncludes one additional turbine.

points greater than that of plants with capacities greater than 800 MW(e).

The combined effects of availability and plant capital cost on the relative COE for a 1200-MW(e) multiplex plant are also shown in Table VI for the three tokamak concepts. There is no net advantage for the multiplex plant using 200-MW(e) units. However, if the maintenance time required for the 300-MW(e) unit is 80% of that required for a 1200-MW(e) unit, then the multiplex plant may be competitive with the single-unit plant only for superconducting tokamak reactors.

The analysis was also performed on the combined effects of availability and plant capital cost on the relative COE for a 2400-MW(e) multiplex plant. The result, Table VII, indicates that the multiplex plant is slightly preferred if the maintenance time required for the 600-MW(e) unit is 80% of that required for a 2400-MW(e) unit. As mentioned in Sect. III and shown in Fig. 1, the COE for a multiplex plant for each 1200 MW(e) is 5% lower than a single 2400-MW(e) unit, using the same plant availability.

V. DISCUSSION OF RESULTS AND CONCLUSIONS

The study shows the multiplex plants with superconducting magnets operating in the second stability regime with fast-wave current drive could be competitive with the single-unit plant in some unit sizes, as shown in Tables VI and VII. This is based on the assumption that lower maintenance time is possible for the smaller units. Since the size and mass of the fusion power core, which includes the first wall, blanket, shield, reactor structure, and magnets, are substantial, even for the 200-MW(e) plant, achieving lower maintenance time compared with a single unit may be an optimistic goal. It is even unlikely that a simple remove-and-replace scenario for these small units could be accomplished.

Multiplexing was also studied by TRW (17) for superconducting magnet tokamaks for 600- to 2400-MW(e) plants composed of 300- to 1200-MW(e) units. Figure 4 presents their results. These results are based on a number of assumptions, some of which are different from this author's. Although a direct comparison is not justified, some conclusions can be reached by a comparison of Figs. 1 and 4.

Table VII

Availability and Effective COE of 2400-MW(e) Plants

No. of Reactors	No. of Turbines	41-Day Unscheduled Outage		81-Day Unscheduled Outage	
		Availability (%)	Relative COE	Availability (%)	Relative COE
1	1	75.0	1	64.0	1 ^b
4	2	75.7	1.07	65.4	1.06
4 at 80% ^a	2	81.7	0.99	73.3	0.94

^aReactor maintenance time is 80% of base.

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

Fig. 4. Relative COE vs number of tokamaks multiplexed for a superconducting magnet tokamak (TRW results).

- Both figures indicate that the COE of a multiplex plant with a 600-MW(e) capacity is greater than that of a single plant.
- Both figures show a decrease in COE going from a single, 2400-MW(e) plant to two plants, each 1200 MW(e). This trend reverses if the number of multiplex plants increases from two to four units.
- TRW results indicate that a multiplex plant composed of two 600-MW(e) units would have a lower COE than that of a 1200-MW(e) single unit. This is in contrast to our result that shows a slight increase in COE. However, both figures indicate that the COE of a multiplex plant composed of four 300-MW(e) units would have a higher COE than that of a 1200-MW(e), single unit.

Small and low-power units should be investigated further as first-generation, commercial plants because the financial risk of the new technology would be limited. Although the COE from a small, single-unit plant of 200-300 MW(e) is estimated to be about twice that of a 1200-MW(e) multiplex plant using the same units (Table III), the total investment is expected to be two to three times less.

A key issue in the multiplex-plant study is the minimum-size reactor allowed by confinement. A confinement study has been made for superconducting magnet tokamaks because the plasma currents are low in the second stability regime. Table VIII shows the ignition margins calculated for four confinement scalings for electrons (neoclassical scaling was assumed for ions) and three density profiles. Equations for energy confinement scaling models, in addition to the definition of temperature and density profile coefficients, are reported elsewhere (10). It is seen that the 300-MW(e) device has almost adequate confinement, even with a flat-density profile. Ignition of the 200-MW(e) case will require at least a parabolic-density profile.

The choice of a multiplex or single-unit plant will be strongly dependent on the utilities' load management. For example, smaller units would be more attractive to utilities with low growth rates, high uncertainty in the growth rate, and small initial generating systems (6).

Multiplexing tends to lower the wall load, which could improve the feasibility of achieving an inherently safe reactor. On the other hand,

Table VIII

Ignition Margin for Various Confinement Scalings for Small Tokamak Reactors

Confinement Scaling	$\alpha_n = 0, \alpha_T = 1$		$\alpha_n = 1, \alpha_T = 1$		$\alpha_n = 2, \alpha_T = 1$	
	200 MW(e)	300 MW(e)	200 MW(e)	300 MW(e)	200 MW(e)	300 MW(e)
Neo-Alcator	1.1	1.6	1.4	2.0	1.5	2.3
Neoclassical	0.81	1.1	1.2	1.7	1.7	2.4
H-mode	0.84	1.2	1.1	1.5	1.3	1.9
Mirnov	0.63	1.9	0.77	1.1	0.92	1.3

multiplexing would increase the mass of fusion power cores compared with a single unit for a fixed power rating. This is a drawback for multiplexing due to disposal of the waste materials.

The key issues of multiplexing--factory fabrication, economy of scale, the extent of equipment sharing, inherent safety, maintainability, and utility load management--must be investigated further to quantify the expected benefits.

ACKNOWLEDGMENTS

The author would like to thank D. C. Keeton for performing the availability analysis. C. A. Flanagan is also acknowledged for his valuable comments during the manuscript review.

REFERENCES

1. K. Hannerz, "Toward Intrinsically Safe Light Water Reactors," Research Memorandum ORAU/IEA-83-2(M)-Rev. Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee (1983).
2. L. D. Mears et al., "Evaluation of Small Modular High Temperature Gas-Cooled Reactors Applied to Electricity Generation," Gas-Cooled Reactor Associated Report GCRA 84-002, issued by Bechtel Group, Inc. (May 1984).
3. B. Blumberg et al., "Modular Reactor Plant Concept Design and Feasibility Report," XL 897-830130-2, General Electric Co., Sunnyvale, California, Report to DOE (September 30, 1983).
4. C. C. Baker et al., "STARFIRE--A Commercial Tokamak Fusion Power Plant Study," ANL/FPP-80-1, Argonne National Laboratory (September 1980).
5. B. G. Logan, "A Rationale for Fusion Economics Based on Inherent Safety," UCRL-91761, Lawrence Livermore National Laboratory (November 1984).
6. R. D. Endicott, "Modular-Multiplex or Single Large Power Plants--Advantages and Disadvantages for Utility Systems," presented at the 11th Symposium on Fusion Engineering, Austin, Texas, November 18-22, 1985.
7. A. E. Dabiri, "Economic Considerations of Commercial Tokamak Reactors," to be submitted for publication.
8. Y-K. M. Peng, "Spherical Torus, Compact Fusion at Low Field," ORNL/FEDC-84/7, Oak Ridge National Laboratory (January 1985) and Y-K. M. Peng and D. J. Strickler, "Features of Spherical Torus Plasmas," ORNL/FEDC-85/6, submitted to Nucl. Fusion.
9. K. R. Schultz et al., "The Elongated Tokamak Commercial Reactor Study," presented at the American Nuclear Society meeting, Boston, Massachusetts (June 1985).
10. A. E. Dabiri et al., "Options for Commercial Tokamaks," Fusion Technol., to be published.

11. U.S. Department of Energy, "Phase V Update (1982) Report for the Energy Economic Data Base Program," DOE/NE-0051 U.S. Department of Energy (1983).
12. J. G. Delene et al., "Nuclear Energy Cost Data Base," DOE/NE-004412, U.S. Department of Energy (1984).
13. W. R. Hamilton, D. C. Keeton, and S. L. Thomson, "Cost Accounting System for Fusion Studies," Oak Ridge National Laboratory, to be published.
14. U.S. Contribution to the INTOR Phase-Two-A Workshop, Chapter VI, Rep. FED-INTOR/82-1, Georgia Institute of Technology, Atlanta, Georgia (1982).
15. "User's Guide for the UNIRAM Availability Assessment Methodology," NP-3305-CCM, Electric Power Research Institute (1983).
16. "Analyses and Report of Generating Availability Data System," National Electric Reliability Council (1980).
17. R. Whitley and J. Gordon, TRW Inc., private communication (August 1985).

INTERNAL DISTRIBUTION

1. L. A. Berry	14. T. Uckan
2-6. A. E. Dabiri	15-16. Laboratory Records Department
7. J. C. Glowicka	17. Laboratory Records, ORNL-RC
8. K. E. Rothe	18. Central Research Library
9. M. J. Saltmarsh	19. Document Reference Section
10. T. E. Shannon	20. Fusion Energy Division Library
11. J. Sheffield	21. Fusion Energy Division Publications
Office
12. P. T. Spampinato	22. ORNL Patent Office
13. N. A. Uckan	

EXTERNAL DISTRIBUTION

23. M. A. Abdou, Boelter Hall, University of California, Los Angeles, CA 90024
24. C. A. Anderson, Westinghouse Electric Corporation, Advanced Energy Systems Division, P.O. Box 158, Madison, PA 15663
25. J. L. Anderson, CMB-3, Mail Stop 348, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
26. C. C. Baker, FPP/208, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
27. D. S. Beard, Office of Fusion Energy, Office of Energy Research, ER-531 Germantown, U.S. Department of Energy, Washington, DC 20545
28. K. L. Black, Department E452, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
29. R. Botwin, C47-05, Grumman Aerospace Corporation, P.O. Box 31, Bethpage, NY 11714
30. W. B. Briggs, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
31. J. N. Brooks, FPP/207, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
32. S. C. Burnett, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
33. J. D. Callen, Department of Nuclear Engineering, University of Wisconsin, Madison, WI 53706
34. R. N. Cherdack, Burns and Roe, Inc., 800 Kinderkamack Road, Oradell, NJ 07649
35. D. R. Cohn, MIT Plasma Fusion Center, 167 Albany Street, Cambridge, MA 02139
36. J. W. Courten, C36-05, Grumman Aerospace Corporation, P.O. Box 31, Bethpage, NY 11714
37. R. W. Conn, School of Chemical, Nuclear, and Thermal Engineering, Boelter Hall, University of California, Los Angeles, CA 90024
38. J. G. Crocker, EG&G Idaho, P.O. Box 1625, Idaho Falls, ID 83401
39. G. R. Dalton, Department of Nuclear Engineering Science, Nuclear Science Center, University of Florida, Gainesville, FL 32611
40. R. C. Davidson, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139

41. N. A. Davies, Office of Fusion Energy, Office of Energy Research, ER-51 Germantown, U.S. Department of Energy, Washington, DC 20545
42. S. O. Dean, Director, Fusion Energy Development, Science Applications International Corporation, 2 Professional Drive, Suite 249, Gaithersburg, MD 20760
43. D. DeFrece, E451, Building 81/1/B7, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
44. J. N. Doggett, L-441, Lawrence Livermore National Laboratory, P.O. Box 5511, Livermore, CA 94550
45. H. Dreicer, Division Leader, CRT, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
46. D. Ebst, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
47. F. Farfaletti-Casali, Engineering Division, Joint Research Center, Ispra Establishment, 21020 Ispra (Varese), Italy
48. P. A. Finn, Fusion Power Program, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
49. H. K. Forsen, Bechtel Group, Inc., Research & Engineering, P.O. Box 3965, San Francisco, CA 94119
50. J. S. Foster, Jr., Building R4-2004, TRW Defense and Space Systems, 1 Space Park, Redondo Beach, CA 90278
51. T. K. Fowler, Associate Director for Magnetic Fusion Energy, L-436, Lawrence Livermore National Laboratory, P.O. Box 5511, Livermore, CA 94550
52. J. W. French, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
53. H. P. Furth, Director, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
54. J. G. Gavin, Jr., President, A01-11, Grumman Aerospace Corporation, P.O. Box 31, Bethpage, NY 11714
55. G. Gibson, Westinghouse Electric Company, Research and Development Center, Churchill Site, 1310 Beulah Road, Pittsburgh, PA 15235
56. J. R. Gilleland, GA Technologies, Inc., Fusion and Advanced Technology, P.O. Box 81608, San Diego, CA 92138
57. M. Y. Gohar, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
58. R. W. Gould, Department of Applied Physics, California Institute of Technology, Pasadena, CA 91109
59. R. A. Gross, Plasma Research Laboratory, Columbia University, New York, NY 10027
60. J. R. Haines, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
61. C. D. Henning, Lawrence Livermore National Laboratory, P.O. Box 5511, Livermore, CA 94550
62. J. J. Holmes, Westinghouse-Hanford Engineering Development Laboratory, P.O. Box 1970, Richland, WA 99352
63. J. B. Joyce, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
64. R. A. Krakowski, CTR-12, Mail Stop 641, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
65. G. L. Kulcinski, University of Wisconsin, Department of Nuclear Engineering, Engineering Research Building, Room 439, 1500 Johnson Drive, Madison, WI 53706
66. D. L. Kummer, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
67. W. Marton, Office of Fusion Energy, Office of Energy Research, ER-55 Germantown, U.S. Department of Energy, Washington, DC 20545
68. L. G. Masson, EG&G Idaho, Idaho National Engineering Laboratory, P.O. Box 1625, Idaho Falls, ID 83401

69. D. M. Meade, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
70. A. T. Mense, Building 107, Post 82, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO 63166
71. R. W. Moir, Lawrence Livermore National Laboratory, P.O. Box 5511, Livermore, CA 94550
72. D. B. Montgomery, MIT Plasma Fusion Center, 167 Albany Street, Cambridge, MA 02139
73. A. E. Munier, Grumman Aerospace Corporation, P.O. Box 31, Bethpage, NY 11714
74. R. E. Nygren, FPP/207, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
75. T. Ohkawa, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
76. J. A. O'Toole, Plasma Physics Laboratory, James Forrestal Campus, Building I-P, Room 8A, P.O. Box 451, Princeton, NJ 08544
77. R. R. Parker, Francis Bitter National Magnet Laboratory, 170 Albany Street, Cambridge, MA 02139
78. B. Pease, Culham Laboratory, Abingdon, Oxfordshire OX14 3DB, United Kingdom
79. M. Pelovitz, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
80. F. W. Perkins, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
81. M. Porkolab, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139
82. D. E. Post, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
83. R. E. Price, Office of Fusion Energy, Office of Energy Research, ER-55 Germantown, U.S. Department of Energy, Washington, DC 20545
84. F. A. Puhn, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
85. J. Purcell, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
86. R. V. Pyle, University of California, Lawrence Berkeley Laboratory, Berkeley, CA 94720
87. J. M. Rawls, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
88. M. Roberts, Office of Fusion Energy, ER-52 Germantown, U.S. Department of Energy, Washington, DC 20545
89. J. D. Rogers, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
90. M. L. Rogers, Monsanto Research Corporation, Mound Laboratory Facility, P.O. Box 32, Miamisburg, OH 45342
91. M. N. Rosenbluth, RLM 11.218, Institute for Fusion Studies, University of Texas, Austin, TX 78712
92. P. H. Rutherford, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
93. J. A. Schmidt, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
94. J. Schultz, MIT Plasma Fusion Center, 167 Albany Street, Cambridge, MA 02139
95. F. R. Scott, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94304
96. G. Sheffield, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
97. D. Smith, Materials Science Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
98. W. M. Stacey, Jr., School of Nuclear Engineering and Health Physics, Georgia Institute of Technology, Atlanta, GA 30332
99. D. Steiner, Rensselaer Polytechnic Institute, Nuclear Engineering Department, NES Building, Tibbets Avenue, Troy, NY 12181
100. E. Stern, Grumman Aerospace Corporation, CN-59, Forrestal Campus, Princeton, NJ 08544

101. P. M. Stone, Office of Fusion Energy, Office of Energy Research, ER-532
Germantown, U.S. Department of Energy, Washington, DC 20545
102. I. N. Sviatoslavsky, Room 33, Engineering Research Building, 1500 Johnson Drive,
University of Wisconsin, Madison, WI 53706
103. R. E. Tatro, Manager, Energy Systems, M.Z. 16-1070, General Dynamics-Convair
Division, P.O. Box 80847, San Diego, CA 92138
104. F. Thomas, B-20-5, Grumman Aerospace Corporation, Bethpage, NY 11714
105. K. I. Thomassen, Lawrence Livermore National Laboratory, P.O. Box 5511, Livermore,
CA 94550
106. R. J. Thome, Francis Bitter National Magnet Laboratory, 170 Albany Street,
Cambridge, MA 02139
107. C. Trachsel, McDonnell Douglas Astronautics Company, P.O. Box 516, St. Louis, MO
63166
108. A. W. Trivelpiece, Office of Energy Research, U.S. Department of Energy, Washington,
DC 20545
109. L. R. Turner, Fusion Power Program, Argonne National Laboratory, 9700 South Cass
Avenue, Argonne, IL 60439
110. E. H. Valeo, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
111. R. Varma, Physical Research Laboratory, Navrangpura, Ahmedabad 380009, India
112. J. C. Wesley, GA Technologies, Inc., P.O. Box 81608, San Diego, CA 92138
113. J. E. C. Williams, Francis Bitter National Magnet Laboratory, 170 Albany Street,
Cambridge, MA 02139
114. H. H. Yoshikawa, W/A-62, Hanford Engineering Development Laboratory, P.O. Box
1970, Richland, WA 99352
115. K. M. Young, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ
08544
116. N. E. Young, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08544
117. Bibliothek, Max-Planck Institut für Plasmaphysik, D-8046 Garching, Federal Republic
of Germany
118. Bibliothek, Institut für Plasmaphysik, KFA, Postfach 1913, D-5170 Jülich, Federal
Republic of Germany
119. Bibliotheque, CEN/Cadarache, Department de Recherches sur la Fusion Controlee,
13108 Saint-Paul-lez-Durance, France
120. Documentation S.I.G.N., Department de la Physique du Plasma et de la Fusion
Controlee, Association EURATOM-CEA, Centre d'Etudes Nucleaires, B.P. 85, Centre
du Tri, 38041 Grenoble, Cedex, France
121. Library, Centre de Recherches en Physique des Plasmas, 21 Avenue des Bains, 1007
Lausanne, Switzerland
122. Library, Culham Laboratory, UKAEA, Abingdon, Oxfordshire, OX14 3DB, England
123. Library, FOM Instituut voor Plasma-Fysica, Rijnhuizen, Edisonbaan 14, 3439 MN
Nieuwegein, Netherlands
124. Library, Institute of Physics, Academia Sinica, Beijing, Peoples' Republic of China
125. Library, Institute for Plasma Physics, Nagoya University, Nagoya 464, Japan
126. Library, International Centre for Theoretical Physics, Trieste, Italy
127. Library, JET Joint Undertaking, Abingdon, Oxfordshire, OX14 3DB, England
128. Library, Laboratorio Gas Ionizzati, CP 56, I-00044 Frascati, Rome, Italy
129. Plasma Research Laboratory, Australian National Laboratory, P.O. Box 4, Canberra,
ACT 2000, Australia
130. Thermonuclear Library, Japan Atomic Energy Research Institute, Tokai, Naka, Ibaraki,
Japan
131. Library, Plasma Physics Laboratory, Kyoto University, Gokasho, Uji, Kyoto, Japan

132. Office of the Assistant Manager for Energy Research and Development, U.S.
Department of Energy, Oak Ridge Operations, P.O. Box E, Oak Ridge, TN 37831
- 133-307. Given distribution as shown in TIC-4500, Magnetic Fusion Energy (Distribution
Category UC-20 c,d: Reactor Materials and Fusion Systems)

ABSTRACT

The concept of multiplexing for a fusion power core as an option for producing power is explored. Superconducting, as well as normal magnet, coils in either first or second stability regimes are considered. The results show that multiplex plants with superconducting magnets operating in the second stability regime could be competitive with the single-unit plants in some unit sizes. The key issues that impact the expected benefits of multiplexing must be investigated further. These are factory fabrication, economy of scale, the extent of equipment sharing, inherent safety, maintainability, and utility load management.