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COST ASSESSMENT OF A GENERIC MAGNETIC FUSION REACTOR

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CONTENTS

LIST OF ABBREVIATIONS

ANL	Argonne National Laboratory
BOP	balance of plant
COE	cost of electricity
CRF	capital recovery factor
CT	compact torus
D	deuterium
D-D	deuterium-deuterium
D-T	deuterium-tritium
EBS	ELMO Bumpy Square
EBT	ELMO Bumpy Torus
EBT-R	EBT Reactor
ECH	electron cyclotron heating
ICRF	ion cyclotron range of frequencies
ICRH	ion cyclotron resonance heating
IDC	interest during construction
INTOR	International Tokamak Reactor
ITC	investment tax credit
LANL	Los Alamos National Laboratory
LMFBR	liquid-metal fast breeder reactor
LHRH	lower hybrid resonance heating
MARS	Mirror Advanced Reactor Study
MSR	modular stellarator reactor
MSR-IIB	upgrade of MSR
NUWMAK	University of Wisconsin tokamak design
ORNL	Oak Ridge National Laboratory
PNL	Pacific Northwest Laboratories
PWR	pressurized-water reactor
rf	radio frequency
RFP	reversed-field pinch
RFPR	RFP reactor
TFCX	Tokamak Fusion Core Experiment

LIST OF SYMBOLS

SYMBOL	DEFINITION
a (m)	plasma minor radius, small dimension
$\bar{a}$ (m)	average plasma minor radius
a_w (m)	wall minor radius, small dimension
A_w (m^2)	first-wall area
A_{tt} (m^2)	total divertor target area
b (m)	plasma minor radius, large dimension
b/a	plasma ellipticity
B	number of financial periods in construction lead time
B_0 (T)	primary magnetic field in the plasma
B_m (T)	maximum field on the primary coil set
C_a (\$)	initial cost of regularly replaced auxiliary heating components
C_a^u [\$/W(e)]	unit cost of auxiliary heating system
C_{aa} (\$)	annual cost of auxiliary heating components
C_b (\$)	first blanket cost
C_b^u (\$/kg)	unit cost of blanket
C_{ba} (\$)	annual blanket cost
C_{bt} (\$)	total blanket cost over plant lifetime
C_c^u (\$ $\times$ 10^6/kg)	unit cost of coils
C_C (\$)	total capitalized cost up to reactor operation (current dollars)
C_{C0} (\$)	total capitalized cost (constant dollars)
C_D (\$ $\times$ 10^6)	total direct capital cost
C_F (\$)	annual fuel cycle costs
C_{fa} (\$)	annual fuel and miscellaneous costs
C_{FI} (\$ $\times$ 10^6)	fusion island direct capital cost
C_s^u (\$ $\times$ 10^6/kg)	unit cost of shield
C_{st}^u (\$ $\times$ 10^6/kg)	unit cost of structure
C_{ta} (\$)	annual cost of target and limiters
C_{tt} (\$)	initial cost of target and limiters
C_{OBG} (mill/kWh)	cost of reactor buildings as a component of COE
C_{OBP} (mill/kWh)	cost of balance of plant as a component of COE
C_{OF} (mill/kWh)	cost of fuel cycle as a component of COE
C_{OFI} (mill/kWh)	cost of fusion island as a component of COE
C_{om} (mill/kWh)	cost of operations and maintenance as a component of COE

D_n^{T} ($)	tax-deductible depreciation, year n
D_n^{B} ($)	book depreciation over plant life, year n
f_α	fraction of alpha power available to support radial conduction losses
f_{av}	power plant availability at full power (equivalent)
f_{b}	debt (bond) fraction
f_B	field utilization factor
f_{CAP} ($)	current-dollar capitalization factor
f_{CAP0} ($)	constant-dollar capitalization factor
f_{con}	contingency factor on total direct capital cost
f_{IND}	indirect cost multiplier
f_{p}	preferred stock fraction
f_{rc}	fraction of electric power recirculated to power plant (excluding auxiliary heating)
f_{s}	equity (stock) fraction
f_{sc}	ratio of mass (volume) of secondary to primary coils
F_{a} ($\mathrm{MW \cdot m^{-2}}$)	neutron fluence limit for the auxiliary heating launchers
F_{CR}	fixed charge rate—current dollars
F_{CR0}	fixed charge rate—constant dollars
F_{m}	fraction of component breakdowns that are major
$F_{\mathrm{ra}}(l)$ ($\mathrm{h^{-1}}$)	failure rate, component l
F_{tt} ($\mathrm{MW \cdot m^{-2}}$)	target/limiter thermal fluence lifetime
F_{wn} ($\mathrm{MW \cdot year \cdot m^{-2}}$)	first-wall neutron fluence lifetime
g_{n}	exothermic neutron energy gain in blanket
I (MA)	plasma current in a tokamak
$(\mathrm{ITC})_0$ ($)	investment tax credit on the initial capital investment
j_m ($\mathrm{kA \cdot cm^{-2}}$)	coil average current density
j_{p} ($\mathrm{kA \cdot cm^{-2}}$)	winding pack current density
L (year)	plant lifetime
M_{b} (tonne)	blanket weight
M_{cp} ('onne)	primary coil weight
M_{FI} (tonne)	fusion island weight
M_{s} (tonne)	shield weight
M_{r0} (h)	mean time to repair for a major breakdown
M_{r1} (h)	mean time to repair for a minor breakdown
n_{e} ($\mathrm{m^{-3}}$)	electron density
n_{i} ($\mathrm{m^{-3}}$)	ion density
n_{i0} ($\mathrm{m^{-3}}$)	peak ion density

n_D (m^{-3})	deuterium density
n_T (m^{-3})	tritium density
n_Z (m^{-3})	nonhydrogenic impurity density
N (year)	levelization period
O_n (\$)	property taxes and interim replacement cost of general plant, year n
O_p (\$)	annualized property taxes
p_α ($MW \cdot m^{-3}$)	alpha power density
p_b ($MW \cdot m^{-3}$)	bremsstrahlung power density
p_s ($MW \cdot m^{-3}$)	synchrotron radiation power density
p_{tt} ($MW \cdot m^{-2}$)	thermal power flux to targets and limiters
p_{wn} ($MW \cdot m^{-2}$)	neutron flux to first wall
$p(t_j)$ (\$)	constant-dollar direct and indirect investment costs paid in period from t_{j-1} to t_j
P_a [MW(e)]	auxiliary power for plasma heating
P_b (MW)	bremsstrahlung power
P_{dt}	average fractional downtime during operation
P_e [MW(e)]	net electric power
P_{eg} [MW(e)]	total electric power
P_F (MW)	fusion power produced by plasma
P_s (MW)	synchrotron radiation power
$P_{se(t)}$	probability that a component is in full service at time t
P_t (MW)	total thermal power
P_α (MW)	alpha power
r_b	debt (bond) interest rate
r_{Dn}	percentage depreciation recovery expenses
r_p	preferred stock interest rate
r_s	equity (stock) return rate
R (m)	plasma major radius
R_e	wall reflectivity
R_n (\$)	revenue during year n
$\hat{R}$	ratio of constant- to current-dollar fixed charge rate
S_{maint}	fraction of time scheduled for maintenance
t (s)	time
T (eV)	plasma temperature
T_e (eV)	electron temperature
T_{e0} (eV)	peak electron temperature
T_i (eV)	ion temperature
T_{i0} (eV)	peak ion temperature

T_k (keV)	plasma temperature
$T_f(l)$ (h)	time to failure of component l
T_{fs} (h)	mean time to failure of a system
T_n ($)	taxes, year n
V_b (m^3)	blanket volume
V_{cp} (m^3)	primary coil volume
V_{ct} (m^3)	total coil volume
V_{FI} (m^3)	fusion island volume
V_n ($)	capital outstanding, year n
V_s (m^3)	shield volume
V_{st} (m^3)	structure volume
x	tax-adjusted cost of money
x_B	effective tax-adjusted cost of money for financial period B
y	inflation rate
y_B	effective inflation rate for financial period B
Y (year)	construction lead time
Z	charge state of an ion
Z_{eff}	effective charge state of a plasma
$\langle\beta\rangle$	volume-average plasma beta
$\langle\beta_e\rangle$	volume-average electron beta
$\langle\beta_i\rangle$	volume-average ion beta
$\langle\beta\rangle_{max}$	maximum permitted beta
$\langle\beta\rangle_Z$	volume-average impurity ion beta
Δb_1, Δb_2 (m)	radial thickness of blanket, regions 1 and 2
Δbgs_1, Δbgs_2 (m)	overall radial thickness of blanket, gap, and shield, regions 1 and 2
Δd (m)	radial thickness of superconducting coil dewar
Δg_1, Δg_2 (m)	radial thickness of maintenance/services gap, regions 1 and 2
Δs_1, Δs_2 (m)	radial thickness of shield, regions 1 and 2
η_e	thermal-to-electric conversion efficiency
ρ_b ($kg \cdot m^{-3}$)	blanket density
ρ_c ($kg \cdot m^{-3}$)	coil density
ρ_s ($kg \cdot m^{-3}$)	shield density
ρ_{st} ($kg \cdot m^{-3}$)	structure density

τ	effective tax rate
τ_F	federal income tax rate
τ_s	state income tax rate
$\chi_E\,(m^2 \cdot s^{-1})$	plasma thermal diffusivity

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ABSTRACT

A generic reactor model is used to examine the economic viability of generating electricity by magnetic fusion. The simple model uses components that are representative of those used in previous reactor studies of deuterium-tritium–burning tokamaks, stellarators, bumpy tori, reversed-field pinches (RFPs), and tandem mirrors. Conservative costing assumptions are made. The generic reactor is *not* a tokamak; rather, it is intended to emphasize what is common to all magnetic fusion reactors. The reactor uses a superconducting toroidal coil set to produce the dominant magnetic field. To this extent, it is not as good an approximation to systems such as the RFP in which the main field is produced by a plasma current.

The main output of the study is the cost of electricity as a function of the weight and size of the fusion core—blanket, shield, structure, and coils. The model shows that a 1200-MW(e) power plant with a fusion core weight of about 10,000 tonnes should be competitive in the future with fission and fossil plants. Studies of the sensitivity of the model to variations in the assumptions show that this result is not sensitively dependent on any given assumption. Of particular importance is the result that a fusion reactor of this scale may be realized with only moderate advances in physics and technology capabilities.

1. INTRODUCTION

Over the past decade, several articles have been written that discuss the potential economics of magnetic fusion reactors [1–4]. In these articles it is argued that, because fusion reactors may be larger than fission reactors, the cost of electricity (COE) from the fusion reactors will be prohibitively high. Such observations are based upon more or less detailed comparisons between existing fission reactors and conceptual fusion reactors such as STARFIRE [5], NUWMAK [6], MARS [7], EBT-R [8], RFPR [9], and MSR [10].* However, the deployment of fusion is some years away, and it is important to decouple the limitations set by generic considerations from those deriving from the state of the art. On the one hand, advances can be expected that will enhance the attractiveness of fusion; on the other hand, generic constraints, such as neutron attenuation lengths in shield materials and cross sections for tritium breeding and fusion, set ultimate limits on advances. Key questions are:

- What are the requirements for competitiveness?
- What scale of fusion reactor would be competitive?
- Are the requirements achievable?

1.1 MODEL

As a contribution towards resolving these questions, a study has been undertaken at ORNL of a generic magnetic fusion reactor. This steady-state reactor with deuterium-tritium (D-T) fuel includes all of the components that are common to various types of fusion reactors—superconducting coils, a lithium breeding blanket for tritium production, plasma heating systems, power supplies, shielding, remote handling, buildings, generators, and cooling towers, as illustrated in Fig. 1.1. The characteristics of these components and their costs are based upon values developed in the previous studies of tokamaks, stellarators, bumpy tori, reversed-field pinches (RFPs), and tandem mirror reactors. While the generic reactor is toroidal and uses a superconducting toroidal coil set to produce the main magnetic field, it is *not* a tokamak. It is intended to approximate any configuration because those features common to all configurations are more numerous than those that are different. In a large-aspect-ratio version it approximates a tandem mirror, and with an intermediate aspect ratio it is a stellarator, as indicated in Fig. 1.2. It is a slightly less accurate representation of systems such as the RFP in which the main field is produced by a plasma current. The technology assumptions are based upon a consensus of work in previous studies. Thus, the superconducting coils invoked have characteristics close to those already developed. Their costs are based upon today's costs, even though it is reasonable to expect substantial advances and cost reductions in this relatively young technology.

*See p. v for definitions of the abbreviations used in this report.

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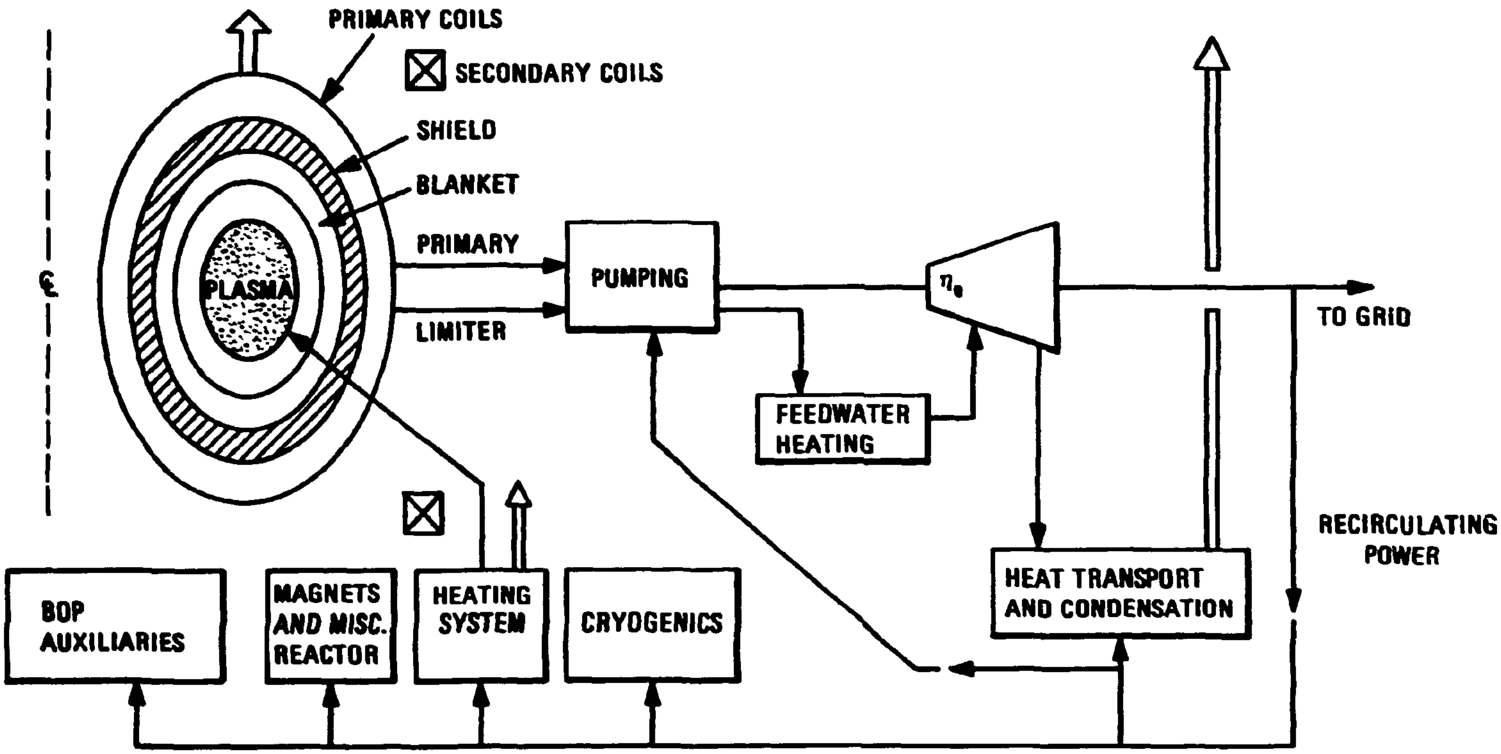

Fig. 1.1. Schematic diagram of generic fusion reactor.

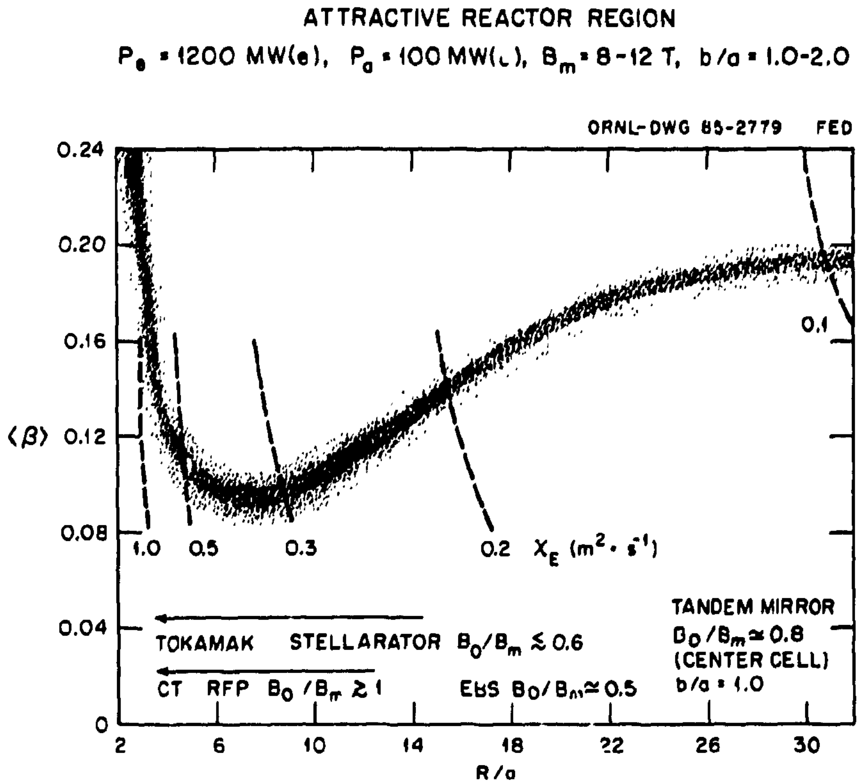

Fig. 1.2. Physics requirements ⟨β⟩, χ_E for various configurations vs R/a for constant COE. CT = compact torus, RFP = reversed-field pinch, EBS = ELMO Bumpy Square.

Construction lead time and plant availability are varied around nominal values comparable to those experienced with the better fission reactors. A separate model is used to calculate the availability for a reference case; this model indicates the minimum reliability and maximum mean time to repair for the fusion components if the reference availability is to be attained.

The costing procedure is that used in assessments of fission and fossil COEs [11]. The unit costs are generally taken from previous fusion studies. However, when more recent information is available from actual construction projects (e.g., for superconducting coils and cryogenic systems), these newer costs are used.

The model has been reviewed widely in other fusion laboratories, in universities, and—of particular importance—by industries and utilities, notably through the good offices of the Atomic Industrial Forum. The many valuable suggestions to improve the model and to improve the presentation of the results have been incorporated in this report.

1.2 CONCLUSIONS

The model is used to identify the self-consistent requirements for the fusion reactor and the components that would make it competitive with fission systems in the 21st century. The financial requirement assumed is that the COE to the utility, reduced to 1983 dollars, should be in the range of 45–60 mills/kWh(e), where 1 mill = $0.001. This is to be compared with present fission and fossil costs, which when costed on the same basis range from 35 to 50 mills/kWh(e). We contend that at this stage of fusion development it is necessary only to show that fusion costs could be comparable. The potential environmental advantages of fusion, coupled with the eventual increasing cost of fissile and fossil fuels, would then be the deciding factors in choice.

The results of the study are encouraging, indicating, as shown in Fig. 1.3, that a 1200-MW(e) fusion reactor would be competitive if the fusion core island weight (first wall, blanket, shield, coils, and support structure) were reduced to about 10,000 tonnes. This result is consistent with the view that many of the earlier conceptual fusion reactors were too heavy and therefore too costly; typically, a 1200-MW(e) plant weighed about 25,000 tonnes. Another interesting result from the model is that smaller fusion plants, down to 300 MW(e) in output, could be competitive in multiple units. Similar scaling

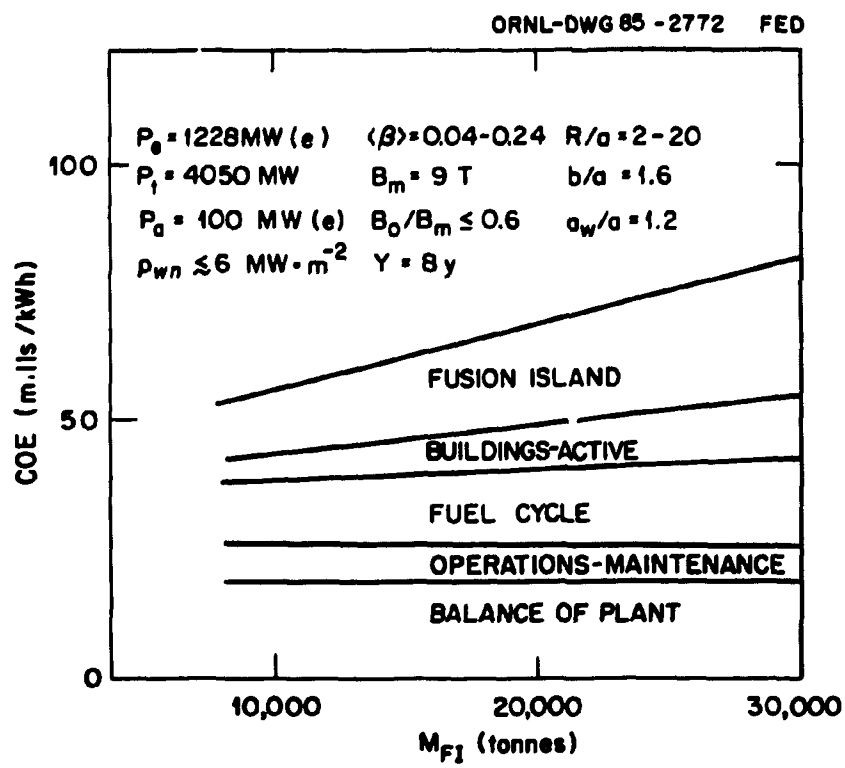

Fig. 1.3. The COE decreases linearly with decrease in the mass of the fusion island.

assessments have been made for the more restrictive case of the tokamak [12–15]. This study complements the previous studies by confirming and extending the range of validity of their results.

We believe that the indicated plant sizes are realizable. As discussed in the body of this report, both the physics and technology requirements represent only a moderate advance over present-day achievements and fall within the projections of development programs [16]. For example, one key parameter is beta, the ratio of plasma pressure to magnetic pressure. Values for beta of 0.08 or greater are required, depending on configuration and superconducting coil performance. Such a level has been attained in RFPs and field-reversed theta pinches and is accessible, theoretically, to a wide range of configurations, including tokamaks, stellarators, bumpy tori, and tandem mirrors. Similarly, the level of thermal insulation required to maintain the hot reacting plasma may be achieved, theoretically, in these configurations. Good progress is being made towards the reactor goals in the experimental programs. Superconducting coils have been built and operated with parameters close to those required, and further advances may be expected. Substantial progress has been made in the development of the required materials and heating and fueling systems.

To illustrate the improvements required over previous conceptual reactors, the parameters of STARFIRE [5] and an illustrative generic reactor are compared in Table 1.1. The generic reactor's reduction in size of the fusion core, in cost, and in COE resulted from the following improvements:

- increased beta,
- a higher ratio of fuel-ion beta to total beta,
- slightly improved thermal diffusivity,
- lower-field, but higher current density, coils,
- larger aspect ratio and higher field utilization factor,
- magnetic configuration requiring (allowing) closer-fitting coils,
- lower auxiliary heating requirements, and
- lower recirculating power to the plasma.

The reduction in COE is made even though (1) the coils include 20% redundancy and have a substantially higher (2.7×) unit cost, (2) the indirect costs are higher (50% in contrast to 23%), and (3) the operations costs are higher.

A comparison of the COEs for fission and optimized fusion is given in Table 1.2. The fission range encompasses the reference fission reactor and optimized fission reactor discussed in ref. 11, with the price of U_3O_8 taken to be 60–120 $/lb (the present price is about 20 $/lb), as discussed in Chap. 4. The price of U_3O_8 is expected to rise to this range in the future.

The ranges of key parameters that lead to an improved 1200-MW(e) fusion power plant are listed in Table 1.3. The sensitivity of the COE to variations in these parameters is also given. In the sensitivity study, it is assumed that all device parameters except the one being varied have their nominal (standard) values.

Table 1.1. Comparison of STARFIRE and an optimized generic reactor

	STARFIRE	Generic reactor
Fusion power,[a] MW(t)	4,000	3,750
Maximum auxiliary power, MW(e)	150	50
Thermal-electric efficiency	0.36	0.36
Net electric power, MW(e)	1,200	1,230
Neutron flux, $MW \cdot m^{-2}$	3.6	5.1
Aspect ratio R/a	3.6	6.0
Ellipticity b/a	1.6	2.0
Scrapeoff layer a_w/a	1.1	1.2
Beta $\langle\beta\rangle$ ($\langle\beta_i\rangle$), %	6.7 (2.3)	10.0 (4.6)
Maximum coil field B_m, T	11.1	9.0
Thermal diffusivity χ_E, $m^2 \cdot s^{-1}$	0.55	0.48
Fusion island weight M_{FI}, tonnes	24,000	10,200
(P_t/V_{FI}),[b] $MW(t) \cdot m^{-3}$	0.78	1.8
(M_{FI}/P_t), tonnes$\cdot MW(t)^{-1}$	6.0	2.5
COE, mill/kWh	~75[c]	49

[a]Fusion power including exothermic blanket gain [see Eqs. (2.1), (2.2), and (2.3)].

[b]Volume (V_{FI}) includes plasma, scrapeoff layer, blanket, shield, maintenance and services region, coils, and structure.

[c]Calculated using the costing procedure of this report and given here in constant 1983 dollars.

The requirements for beta ($\langle\beta\rangle$) and thermal diffusivity (χ_E) depend upon the geometry of the plasma and the field utilization factor. These requirements are illustrated for a reference case in Fig. 1.2. The minimum $\langle\beta\rangle$ requirement occurs for moderate aspect ratios with $R/a \sim 5$, where in a toroidal device the field utilization is high (~0.6) and the plasma radius is comparable to the blanket and shield thickness. Since the field utilization factor does not increase much for larger aspect ratios, cylindrical effects lead to relatively larger core components and to increased costs. This may be compensated for by increasing $\langle\beta\rangle$. The physics requirements can theoretically be met by a variety of configurations, as indicated in Fig. 1.2. Good progress is being made experimentally towards their achievement [16].

Table 1.2. Comparison of the COE (constant 1983 dollars) for 1200-MW(e) fission and improved fusion power plants[a,b]

Account	COE [mill/kWh(e)]		
	Fission[c]		
	Optimized	Average	Improved fusion range[d]
Reactor plant	6.9	9.3	9.7–16.4
Reactor buildings	2.8	4.5	4.0–5.1
Balance of plant	11.7	17.2	16.2–18.2
Fuel cycle	9.4	14.3[e]	9.7–11.6
Operations and maintenance	7.4	7.4	7.6
Total	38	53	47–59

[a]The 1200-MW(e) plant size was chosen to allow comparison with STARFIRE, other fusion reactors, and modern PWRs.

[b]Plant availability at maximum power f_{av} = 0.65.

[c]Fission costs are taken from *Nuclear Energy Cost Data Base*, DOE/NE-0044, U.S. Department of Energy, 1982 (updated 1983), and are given in Table A.2.1.

[d]The range in costs allows for the following variations: B_m = 8–10 T, P_a = 50–100 MW(e), (a_w/a) = 1.1–1.2, $\langle\beta\rangle$ = 0.08–0.24, R/a = 2–30, Y = 6–10 years.

[e]The fuel cycle COE for fission assumes that U_3O_8 costs 60–120 $/lb.

The technology requirements of the improved reactors also fall within the projected achievements of the development program. The blanket and shielding thicknesses are consistent with previous designs, and there is sufficient latitude to accommodate a range of blanket options [17]. The superconducting coils have characteristics close to those of coils that have been tested, as shown in Fig. 2.1. The power density requirements of a 14-MeV neutron flux to the first wall of $p_{wn} \approx 5$ MW·m^{-2} and a neutron fluence lifetime $F_{wn} \approx$ 20 MW·year·m^{-2} are viewed as reasonable goals in the development program, and good progress has been made towards developing suitable materials [18]. It is interesting that 5 MW·m^{-2} is within the range of power densities for which it should be possible to design a blanket and shield system that could recover spontaneously from loss-of-coolant accidents, providing an inherently safe system [19].

Having stated these conclusions, we should recognize the tremendous challenge of combining all of these elements into a single attractive reactor. However, the history of technology development is one in which what was "inconceivable" in one decade has become commonplace in another—television, space travel, air travel with its myriad of complicated components, computers, pocket calculators, and much more.

Table 1.3. Ranges of key parameters for improved 1200-MW(e) fusion power plants[a]

Parameter	Standard	Change to vary COE
		COE variation ~ ±10%
Fusion power P_F, MW(t)	4000	3650–4350
Maximum field on coil B_m, T	9	8–10
Aspect ratio R/a	6	2–30
Ellipticity b/a	1.6	1.0–2.0
Ratio of wall radius to plasma radius a_w/a	1.2	1.1–1.3
Auxiliary plasma heating power P_a, MW(e)	100	50–150
Neutron fluence lifetime F_{wn}, MW·year·m^{-2}	20	15–25
Neutron flux to wall p_{wn}, MW·m^{-2}	5	3–6
Minimum blanket thickness[b] Δb_1, m	0.45	0.45–0.60
Maximum blanket thickness[b] Δb_2, m	0.75	0.75–1.00
Minimum blanket-gap-shield thickness Δbgs_1, m	1.30	1.30–1.70
Maximum blanket-gap-shield thickness Δbgs_2, m	2.00	2.00–2.60
Weight of fusion island M_{FI},[c] tonnes	8,600	8,000–14,000
M_{FI}/P_t, tonnes/MW(t)	2.3	2.0–3.0
P_t/V_{FI},[d] MW(t)/m^3	1.9	1.5–2.0
Construction time Y, years	8	6–10
Availability f_{av}	0.65	0.60–0.70
		COE variation ~ ±1%
Unit coil cost C_c^u,[e] \$/kg	80	14% change
Unit blanket cost C_b^u,[e] \$/kg	70	7% change
Auxiliary power P_a, MW(e)	100	7 MW at 2 \$/W

[a]It is assumed that when a given parameter is varied, the majority of the other parameters are at or near their standard values.

[b]One-third of the blanket, gap, and shield is at the minimum radial thickness; two-thirds, at the maximum radial thickness.

[c]Not including steam generators.

[d]V_{FI} = fusion island volume.

[e]Direct cost, not including contingency.

We are convinced that magnetic fusion can be a viable source of energy for the future. The time scale for the deployment of any energy system is so great (tens of years) that it is important to push development now, even though deployment will not occur until the 21st century, so that it will be possible to have a choice.

2. FUSION POWER PLANT MODEL

2.1 INTRODUCTION

Previous detailed studies of fusion power costs have generally involved a specific type of magnetic fusion device—for example, a tokamak in the STARFIRE study [5] and a tandem mirror in the MARS study [7]. These studies are valuable in identifying the virtues and vices of a particular configuration. However, they do not indicate clearly the ultimate generic limitations of magnetic fusion that are set by such factors as first wall neutron fluence, tritium breeding, neutron shielding, and coil current density. Scaling studies using simpler models of the reactor have been used at Argonne National Laboratory (ANL) [12], GA Technologies [13], and Culham Laboratory [14, 15] to assess such limitations for tokamaks. The fusion reactor study group at Los Alamos National Laboratory has analyzed some of the generic issues by comparing the results of various reactor studies [8–10]. In particular, this group has derived relationships between the capital cost, the COE, and the weight of the nuclear island [20]. We have generalized these models by removing their restriction to tokamaks and extending them to other configurations in order to improve the understanding of the generic issues. The characteristics of many of the reactor features are based upon the earlier studies, as discussed in Sect. 2.3.

2.2 GOALS

- The first goal of the generic fusion reactor study is to calculate the COE as a function of the weight of the fusion island M_{FI}. In particular, the goal is to determine the weight at which a 1200-MW(e) fusion plant could be competitive in the future with 1200-MW(e) fission and fossil plants. The fusion island is defined in this report as the first wall and tritium-breeding blanket, the shield, the superconducting coils, and the support structure for these components.
- The second goal is to identify the self-consistent physics and technology requirements for such competitive reactors, namely, volume-average beta $\langle\beta\rangle$ and thermal diffusivity χ_E, maximum coil field B_m and current density j_m, and neutron flux to the first wall p_{wn}.
- The third goal is to determine the sensitivity of the results to the built-in assumptions of the analysis: blanket and shield thickness Δbgs, secondary coil fraction f_{sc}, neutron fluence lifetime of the first wall (and blanket) F_{wn}, auxiliary power to the plasma P_a, plasma geometry R/a and b/a, field utilization factor $f_B = B_0/B_m$, construction lead time Y, and interest charges.

2.3 REPRESENTATIVE PARAMETERS FOR D-T REACTORS

The input data for the D-T reactor design and cost analysis presented here derive from previous reactor studies and from experience in the construction of present fusion facilities. The main components of the fusion reactor are indicated schematically in

Fig. 1.1. Table 2.1 gives representative parameters of some fusion reactor studies. Since these studies were done, conceptual advances have been made in design; in the tokamak area, lower-weight shields are proposed [21] and improved plasma configurations may be possible [22]; in the stellarator area, recent advances [23] lead to reduced plasma aspect ratio and improved plasma performance; in the RFP area, the possibility of steady-state operation now exists [24]; in the EBT area, there are now improved configurations [25]; and in the tandem-mirror area, there are improved end-cell and barrier systems [26]. All of these improvements are reflected in the generic parameters listed in Appendix 1 (Table A.1.1); these parameters imply the development of configurations that combine the better features of the earlier designs.

2.4 DEVELOPMENT OF THE FUSION DEVICE PARAMETERS

The procedure for developing a self-consistent fusion configuration is indicated in Table 2.2, which lists the physics and technology input and output parameters. The assumptions and the algorithms used to relate the parameters are given below. Definitions are given at the front of the report.

2.4.1 Plasma Characteristics

The plasma cross section may be varied using the ellipticity parameter b/a. Surrounding the plasma is a scrapeoff layer for handling the thermal output from the plasma and for controlling particle and impurity flow. It is characterized by the ratio of the first wall radius to the plasma radius a_w/a.

The impurity beta, including the constant level of helium produced by the fusion reactions, is taken to be $\langle\beta_Z\rangle = 0.2\langle\beta_e\rangle$, where $\langle\beta_e\rangle$ is the electron beta, which is taken to be equal to the ion beta, $\langle\beta_e\rangle = \langle\beta_i\rangle$.

The plasma characteristics are discussed in more detail in Appendix 1.

2.4.2 Auxiliary Plasma Heating

A wide variety of plasma heating systems are used by the different types of fusion devices, and it is not possible to approximate each one accurately with a simple generic system. It is assumed here that a single system is used both for the initial heating and raising the temperature to ignition (startup) and for plasma (configuration) maintenance during the steady-state burn. It is assumed further that only 50% of the available power is required for maintenance of the plasma and that the excess power required during startup may be used to provide backup (redundancy) during plasma operation. The efficiency of the transfer of power to the plasma during the burn is taken to be 70%.

Table 2.1. Representative parameters from D-T reactor studies

Parameter	STARFIRE [5]		MSR-IIB [10]		EBT-R [8]		MARS [7]		Generic reference	
P_F, MW	4,000		4,000		4,030		4,060[a]		4,000	
P_e(net), MW(e)	1,200		1,300		1,200		1,360 (1,570)		[See Eq. (2.2)]	
$(P_{eg} - P_e)/P_{eg}$	0.167		0.07		0.16		0.29 (0.20)		[See Eq. (2.2)]	
η_e, %	0.357		0.350		0.355		0.386 (0.436)		0.36	
R, m	7.0		23.0		36.0		24.0			
$\bar{a}$, m	2.45		0.81		1.0		0.43			
$R/\bar{a}$	2.86		28.4		36.0		55.8			
B_0, T	5.8		6.56		3.64		4.7			
B_0/B_m	0.523		0.566		0.375		0.635		≤0.60[b]	
$\bar{a}_w/a$	1.10		1.41		1.10		1.40		1.10	
P_a (dc), MW(e)	153				105		354		100	
P_a (pulse), MW(e)	12				100					
g_n	1.14		1.10		1.50		1.16		1.14	
Δb,[c] m	0.37	0.90	0.41	1.07	0.37	0.55	0.38	1.13	0.45	0.90
Δg, m	0.04	1.00	0	0	0.02	0.07	0.14	0.38	0.10	0.30
Δs, m	0.64	1.10	0.60	1.00	0.67	0.63	0.84	0.45	0.75	0.80
Δbgs, m	1.05	3.00	1.01	2.07	1.06	1.25	1.36	1.96	1.30	2.00
M_b, tonnes	1,550		2,060		4,120		3,220			
M_s, tonnes	13,400		10,280		13,110		5,930[d]			
M_{cp}, tonnes	5,310		12,860		20,230		9,600[d]			
V_{ct}, m^3	950									
f_{cs}[e]	0.41		0.10		0.26		0.27		0.25	
V_{st}/V_{ct}, m^3	0.5								0.5	
M_{FI}, tonnes	25,280		26,490		43,360		21,340			

[a]The numbers in parentheses are for an improved barrier system that requires less power. The high efficiency (η_e) results from the use of a direct recovery system for the plasma thermal power.

[b]It is assumed for the generic toroidal system that B_0/B_m has the value of a simple toroidal coil set. The constraint to $B_0/B_m \leq 0.60$ reflects the fact that large aspect ratio is generally associated with configurations without a continuous toroidal magnet at the inner bore of the torus. For the tandem mirror, the ratio is limited by access requirements, and values as high as 0.8 have been used in reactor designs. For configurations such as the RFP, where the main field is produced by a plasma current $B_0/B_m > 1$, the model is not such a good approximation.

[c]The two sets of numbers for the radial build of blanket and shield refer generally to values under and between coils. For the generic studies, the coil radius will be determined by the smaller value. The volume of blanket and shield is based upon assuming that one-third of the blanket and shield have the smaller radial build and two-thirds the larger build.

[d]Solid breeder blanket; includes central-cell support structure.

[e]f_{cs} represents the mass (volume) of coils normalized to those coils (or parts of coils) that give the toroidal field. In the case of MARS, it is the ratio of end-cell to central-cell magnets.

Table 2.2. Physics and technology input and output for the generic fusion reactor analysis

Input	Output
Reactor power balance	
Reactor thermal power P_t	Net electric power P_e
Auxiliary plasma power P_a	Plasma fusion power P_F
Exothermic blanket gain g	
Thermal-electric efficiency η_e	
Plasma parameters	
Volume-average beta $\langle\beta\rangle$	Field in plasma B_p
Maximum coil field B_m	Dimensions R, a, b, a_w
Plasma aspect ratio $R/a + P_F$	Thermal diffusivity χ_E
Plasma ellipticity b/a	
Engineering parameters	
Wall-plasma ratio a_w/a	First wall neutron flux p_{wn}
Minimum blanket, gap, and shield radial build under coils[a] Δbgs_1	
Coil dewar width Δd	
Neutron fluence limit F_{wn}, p_{wn}	First wall (blanket) lifetime
Coil structure fraction	
Relation of current density j_m to B_m	
Secondary coil/primary coil ratio f_{sc}	Primary (toroidal coil) weight, volume
Coil and structure density	Secondary coil weight, volume
Maximum blanket, gap, and shield radial build[a] Δbgs_2	Blanket weight and volume
	Shield weight and volume
Relative weight of island structure	Structure weight and volume
Structure density	
	Fusion island weight M_{FI} and volume V_{FI}

[a]It is assumed that one-third of the blanket, shield, and gap are at the minimum radial build and are between the plasma and the coils; the other two-thirds are between the coils.

2.4.3 Power

The thermal fusion power (in megawatts) out of the reactor is given by

$$\begin{aligned} P_t &= 25.6[1 + 4(1 + g)]\langle\beta_i\rangle^2 B_0^4 Rab + 0.5P_a \\ &= P_F + 0.5P_\alpha \ , \end{aligned} \tag{2.1}$$

where $0.5P_a$ is the fraction of total auxiliary power that is applied during steady-state operation, P_F is the fusion power produced by the plasma plus the blanket gain, and the neutron energy gain in the blanket is taken to be $g = 0.14$, following STARFIRE.

The volume-average D-T ion beta is denoted by $\langle\beta_i\rangle$. For the plasma conditions discussed above, $\langle\beta_i\rangle = 0.455\langle\beta\rangle$. The power available for conversion to electricity is less than P_t because some of the thermal power leaving the plasma edge is low-grade heat. It is assumed here that 30% of this thermal power is wasted, and the power is given by

$$P_{eg} = \left\{25.6[0.7 + 4(1 + g)]\langle\beta_i\rangle^2 B_0^4 Rab + 0.35P_a\right\}\eta_e \quad [\mathrm{MW(e)}] \ , \tag{2.2}$$

where η_e is the thermal-to-electric conversion efficiency. The net electric power is given by

$$P_e \ [\mathrm{MW(e)}] = P_{eg}\left[1 - f_{re}\left(\frac{4150}{P_t}\right)^{0.2}\right] - 0.5P_a \ , \tag{2.3}$$

where f_{re} is the fraction of power recirculated to the system, excluding the auxiliary power systems, and 4150 is the total thermal power deposited in the fusion island of STARFIRE. For the calculations that follow, $f_{re} = 0.07$ [10].

2.4.4 Fusion Parameters

The alpha power is given by

$$P_\alpha = 25.6\langle\beta_i\rangle^2 B_0^4 Rab \quad (\mathrm{MW}) \ . \tag{2.4}$$

If we denote the fraction of alpha power lost via conduction by f_α, then the thermal diffusivity required is given by

$$\chi_E = \frac{(1.6 \times 10^{-2}) f_\alpha P_\alpha}{\langle\beta\rangle B_0^2 R} \quad (\mathrm{m^2 \cdot s^{-1}}) \ . \tag{2.5}$$

For the calculations that follow it is assumed that 80% of the power is available to support radial conduction losses and $f_a = 0.8$; the remainder is lost by electromagnetic radiation and direct particle losses. The average neutron flux to the first wall is

$$p_{wn} = \frac{102\langle\beta_i\rangle^2 B_0^4 Rab}{A_w} \quad (\mathrm{MW{\cdot}m^{-2}}) \ , \tag{2.6}$$

where the first wall area is

$$A_w = 2\pi^2 Ra\,[2 + 2(b/a)^2]^{1/2}\left(\frac{a_w}{a}\right) \approx 4\pi^2 R/a(b/a)^{1/2}\left(\frac{a_w}{a}\right)a^2 \ .$$

See Appendix 1 for additional details.

2.4.5 Power Handling

A key problem for fusion reactors is erosion of components by plasma bombardment. For a reactor to be viable, erosion must be minimized, which requires that the plasma edge be cold. Good progress is being made in the development of techniques for maintaining low edge temperatures [27]. When erosion cannot be avoided, it must occur only on easily replaceable components. Therefore, it is assumed here that the first wall, which is replaced with the blanket (typically every few years), receives predominantly heat as electromagnetic radiation from the plasma. The limit on first wall lifetime is then set by neutron damage, not erosion. On the other hand, the lifetime of targets and limiters, which handle the remaining thermal power, is set by erosion damage rather than neutron damage. In principle, these components may be replaced while the system is under vacuum, thus minimizing the replacement time.

The fluence limit for the targets and limiters is denoted by F_{tt} ($\mathrm{MW{\cdot}year{\cdot}m^{-2}}$). Their lifetime is set by the average thermal power on the surface p_{tt} ($\mathrm{MW{\cdot}m^{-2}}$).

The fluence limit of the first wall and blanket and of the components of the auxiliary heating systems that are bombarded by neutrons is denoted by F_{wn} ($\mathrm{MW{\cdot}year{\cdot}m^{-2}}$). Their lifetime is set by the average neutron wall loading p_{wn} ($\mathrm{MW{\cdot}m^{-2}}$).

2.4.6 Fusion Island Components

Blanket, gap, and shield

Surrounding the plasma are a first wall and blanket. Outside the blanket is a region called the gap, where services and maintenance are carried out. Outside the maintenance gap is the neutron and gamma radiation shield. For costing purposes, the blanket and shield are treated as if they cover the whole surface of the torus. In reality, they will contain gaps for particle and impurity control, heating, diagnostics, and maintenance. To cover these gaps, additional shielding will be required. The shielding volume is increased by 25% to allow for this factor.

It is assumed that one-third of the blanket, gap, and shield fall under the coils and have the minimum thickness, which is sufficient to shield the coils from radiation. The value used (see Table 2.1) is representative of that used in earlier fusion studies [5, 7, 8, 10]. The other two-thirds fit between the coils and have the maximum thickness. This is typical of many reactor designs (e.g., stellarators, bumpy tori, tandem mirrors).

The minimum values of the radial build for the blanket, gap, and shield are denoted respectively by Δb_1, Δg_1, and Δs_1. The maximum values of the radial build are denoted by Δb_2, Δg_2, and Δs_2; in the model $\Delta bgs_1 = \Delta b_1 + \Delta g_1 + \Delta s_1$ and $\Delta bgs_2 = \Delta b_2 + \Delta g_2 + \Delta s_2$.

Coils

The coils are treated as if they had two components: a primary coil set, which is toroidal and is separated from the plasma by the minimum blanket, gap, and shield thickness, and a secondary coil set, which represents all other coils. The ratio of secondary coil volume to primary coil volume is denoted by f_{cs}, and $f_{cs} = 0.25$ is typically used in this study (see Table 2.1).

In a tokamak, the primary set represents the toroidal coils, and the secondary set represents the poloidal and divertor coils. In a stellarator, the primary set represents the toroidal component of the helical coils. In a tandem mirror, the primary set represents the central-cell coils, and the secondary set represents the mirror and end-cell coils.

The coils are superconducting. The primary coil set has 20 coils, and calculations are made to ensure that the coils do not interfere in the bore of the torus and that the local field on a coil is less than the prescribed maximum field. Around each coil is a dewar of width Δd. The maximum field on each coil is B_m (T). Differences in the maximum field on various coils are beyond the scope of this study.

The field in the plasma is related to the field on the coils and to the geometry by

$$B_0 = [(R - a_w - \Delta bgs_1 - \Delta d)/R]B_m \ , \tag{2.7}$$

where generally $B_0/B_m \leqslant 0.6$, and a_w is the minimum wall radius. The restriction on B_0/B_m is a good approximation for most systems except those in which the field (B_0) is provided mainly by a plasma current (e.g., the RFP). For the tandem-mirror central cell, $B_0/B_m \simeq 0.8$ is appropriate.

In Fig. 2.1, present experience in superconducting coil technology is illustrated with a plot of current density over the winding pack (j_p) as a function of the maximum field on the coil [28]. Existing reactor designs have magnets based upon pool-boiling liquid helium cooling, where, for example, at 8 T a current density of 2.8 kA/cm^2 is a typical value. The dependence of winding pack current density on B_m for such magnets is

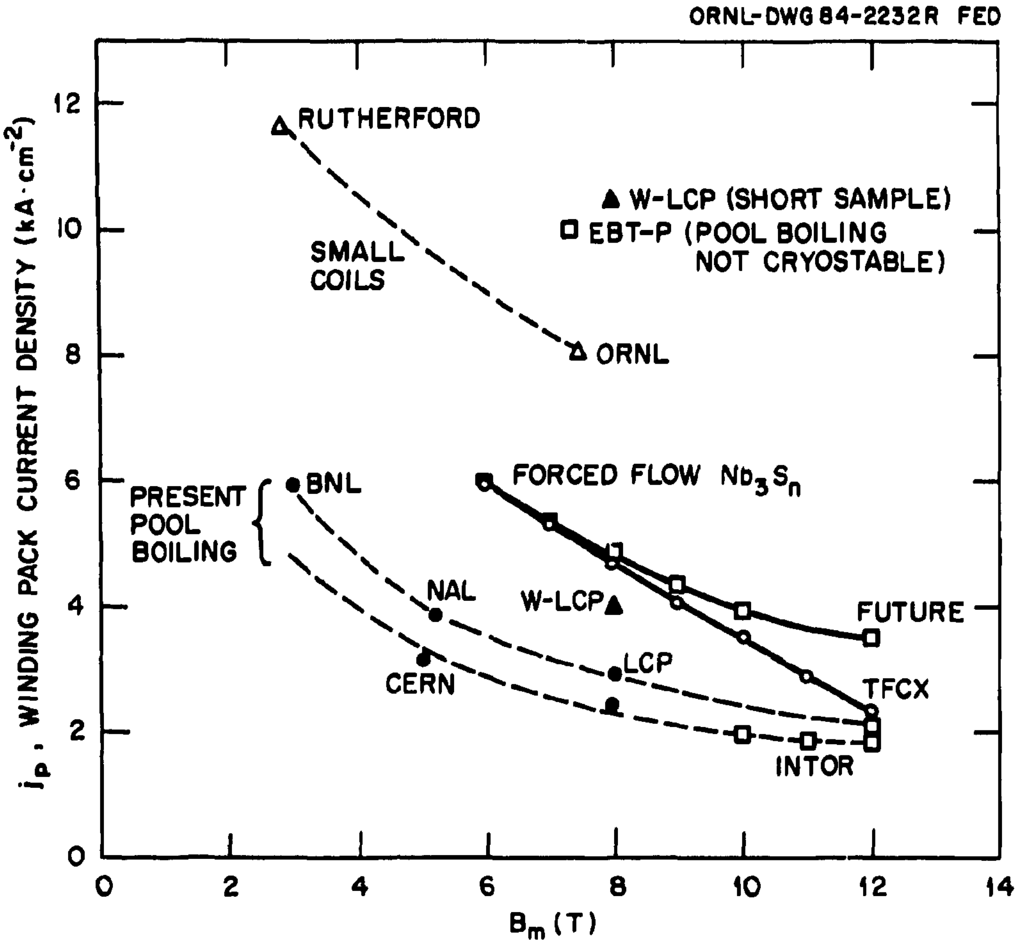

Fig. 2.1. Values of the maximum field B_m and winding pack current density j_p for existing and future superconducting coils.

$$j_p \simeq 2\left(\frac{12}{B_m}\right)^{0.8} \quad (\text{kA/cm}^2) \ . \tag{2.8}$$

Recent developments indicate that higher current densities may be used, particularly with Nb_3Sn conductor and forced-flow helium cooling. Recent studies made for the INTOR and TFCX [29] programs support the use of a higher current density. An algorithm based upon these studies is used in these calculations. For $B_m \leq 12$ T,

$$j_p = 9.6 - 0.6B_m \quad (\text{kA/cm}^2) \ . \tag{2.9}$$

The coils include some structure; based upon the INTOR studies, this is assumed to scale in volume as $1 + (B_m/12)^{1.5}$. Thus at $B_m = 12$ T, the structure volume equals the winding pack volume. The coil current density is then given by

$$j_m = (9.6 - 0.6B_m)/[1 + (B_m/12)^{1.5}] \quad (\text{kA/cm}^2) \ . \tag{2.10}$$

For the future, higher current densities should be possible at $B_m \geqslant 8$ T, and use of Eq. (2.8) with a further multiplier as high as 1.5–2.0 may be possible.

A key question for the availability of fusion reactors is the reliability of the magnets, particularly for the superconducting coil cases where the mean time to replace may be long. In this study, 20% redundancy is used in both winding pack and structure. It is assumed further that there will be good access to winding pack connections in each coil so that damaged turns can be shorted out, if that type of failure occurs. Thus the mean time to repair may be kept small, and the probability of total coil failure will be low. A brief study of availability is presented in Appendix 6.

Structure

The intercoil structure and the gravity support structure are taken to be 50% of the total coil volume V_{ct}. The structure volume $V_{st} = 0.5V_{ct} = 1.2/2(1 + f_{cs})V_{cp}$, where the factor 1.2 allows for redundancy and V_{cp} is the primary coil volume.

2.4.7 Balance of Plant

The balance-of-plant (BOP) components are based upon the STARFIRE [5] and MARS [7] studies and upon fission and fossil power plant experience [11]. They are discussed in Appendix 4.

3. COSTING MODEL

3.1 PROCEDURE

The economic analysis uses the procedure discussed in ref. 11 for the capital cost; it is summarized in Appendices 2 and 3. The procedure differs slightly in two areas from that proposed for fusion power plants in refs. 30 and 31. The indirect charges for construction are raised from 35% to 50% to better represent present-day power plant experience, and the lithium blanket costs are levelized over the operating lifetime of the power plant and are included in the fuel cycle costs. The latter procedure is useful because it shows the effects of power density on the blanket costs.

The COE is calculated in two ways. In the current-dollar approach, inflation is explicitly included, the purchasing price of the dollar changes with time, and the COE is quoted in dollars of a future year; the capital costs are levelized [11] and the fuel and operations cost are quoted in dollars of the first year of operation. This makes it difficult for the reader to compare costs with present-day costs. Therefore, in most of this report the costs are quoted in constant 1983 dollars. Where current dollars are used, it is so indicated (Sect. 3.5). The capital investment costs are first calculated in current dollars, and the constant-dollar COE is obtained from the current-dollar value by deflating the current-dollar COE to the 1983 level. This takes into account the effect of inflation on the depreciation of capital costs.

For the constant-dollar case, the operating costs are calculated in 1983 dollars. A levelized cost over the plant operating lifetime is obtained, including both the up-front costs for items such as the initial blanket and the cost of replacement and spare blankets. Inflation and escalation are not included in this calculation. In our view, their use would imply a greater knowledge of fusion plant operation than exists. Nevertheless, we believe that the assumptions about operating costs are conservative in terms of personnel numbers and the levels of spares and replacements.

In the comparison with fission and fossil plants, the same procedures [11] are applied except that the operating costs of these plants are known and levelized values including inflation and escalation are used.

For the current-dollar case, the constant-dollar operating costs are inflated to the first year of operation.

3.2 CURRENT-DOLLAR COE

The current-dollar COE, at the first year of operation, is given by

$$\mathrm{COE}_{\mathrm{current}} = \frac{C_C F_{CR} + (C_F + C_{om})(1 + \iota)^Y}{(P_e \times 8760 \times f_{av})} \quad \mathrm{mill/kWh} \ , \qquad (3.1)$$

where 1 mill = \$0.001, P_e is taken to be the maximum net electric power [MW(e)] (i.e., the plant capacity), 8760 is the number of hours in a year, and f_{av} is the plant availability normalized to the maximum power. In this analysis, the plant capacity factor is assumed to be the same as the availability factor. The level $f_{av} = 0.65$, which is used in much of this report, is somewhat higher than recent industry averages for nuclear and coal-fired plants but is somewhat lower than has been achieved by better plants. The requirements to achieve this level are discussed in Appendix 6.

In Eq. (3.1), C_F is the equivalent of the annual fuel costs for fission and fossil plants. In those systems it includes the cost of the uranium and coal. In past fusion studies such as STARFIRE [5] and in the Pacific Northwest Laboratories (PNL) costing guidelines [30, 31], items such as the initial blanket have been classified as direct costs. This makes it harder to assess the effects of varying, say, power density, since it is the replaceable items that are affected, and hiding part of their cost in initial capital cost confuses the picture. The system used here is to assig. all items that involve continuing replacement and relate to the "fuel" or "energy gain" cycles to the fuel cost account. The items included are the first wall and blanket, limiters/targets, and the expendable components of auxiliary heating used in the power production phases (see Appendix 5.1).

The annual running costs beyond those included in C_F are represented by C_{om} (see Appendix 5.2). The number of operating staff has been increased from the STARFIRE [5] value of 163 persons to 457 persons following a study of personnel needs for fission plants [32].

The construction lead time in years Y is used with the annual inflation rate ι in the factor $(1 + \iota)^Y$ to raise the constant-dollar values of C_F and C_{om} to the values appropriate to the first year of operation.

The fixed charge rate F_{CR} is set so that $C_C F_{CR}$ is the equivalent annual charge necessary to meet revenue requirements during a set period; the charge is similar to a mortgage payment. Although plants are operated for 30- to 50-year lifetimes, utilities usually use periods less than the full life for cost comparison purposes. This report assumes a 30-year life and a 20-year levelization period. Assuming the cost of money and inflation rates used in ref. 11 (see Appendix 3), the value of F_{CR} is 0.165 for the current-dollar calculation (see Table A.3.2).

The total estimated capitalized cost up to operation of the reactor, including inflation and interest charges during construction, is

$$C_C = \sum_{j=1}^{B} p(t_j)(1 + y_B)^{j-1}(1 + x_B)^{B+1-j} \quad (\$) \ , \tag{3.2}$$

where B is the number of financial periods (3 months, or 0.25 year, in this report) between the start of facility design, at the year of the constant-dollar price estimate, and the start of full operation. The subscript B is used to identify the appropriate escalation and interest rates for this shorter period. The effective escalation rate y_B is taken here to be the inflation rate ι_B; x_B is the effective tax-adjusted cost of money for the chosen period [see Eq. (A.2.7)]; and $p(t_j)$ is the constant-dollar direct and indirect capital investment costs paid in the period from t_{j-1} to t_j.

A typical form for the accumulative spending rate is

$$C_D f_{IND} = \sum_{j=1}^{B} p(t_j) \ , \tag{3.3}$$

where C_D ($) is the direct capital cost and f_{IND} is the indirect cost multiplier, which is taken to be typical of better fission plant experience [11], since we hope that fusion will be less affected by changing regulations. For the nominal 8-year total lead time ($Y = 8$) assumed in this report, the indirect charges $f_{IND} = 150$, where construction facilities, equipment, and services constitute 15%; engineering management services, 25%; and owners' costs, 10%. For fossil plants the indirect charges and construction lead times are generally less [11]. To relate indirect charges and lead time, we assume that

$$f_{IND} \simeq 1 + 0.5(Y/8) \ , \qquad 6 \leq Y \leq 12 \ . \tag{3.4}$$

This relation is consistent with the coupled values of indirect charges and lead times given in ref. 11. The purpose of this assumption is to set a penalty or gain for varying lead time that goes beyond that obtained with a fixed spending profile as lead time is varied, which affects the interest charges.

3.3 CONSTANT-DOLLAR COE

The constant-dollar COE is given by

$$\mathrm{COE} = \frac{C_{C0}F_{CR0} + C_F + C_{om}}{P_e \times 8760 \times f_{av}} \quad (\mathrm{mill/kWh}) \ , \tag{3.5}$$

where C_{C0} is the constant-dollar capital investment cost,

$$C_{C0} = \sum_{j=1}^{B} p(t_j) \left[\frac{1 + y_B}{1 + \iota_B}\right]^{j-1} \left[\frac{1 + x_B}{1 + \iota_B}\right]^{B+1-j} \quad (\$) \ ,$$

and F_{CR0} is the constant-dollar fixed charged rate derived in Appendix 3, where, for a levelization period of 20 years and the interest and inflation rates assumed in ref. 11, $F_{CR0} = 0.10$. For zero inflation, $F_{CR0} = F_{CR}$.

3.4 THE DIRECT CAPITAL COST

In FY 1983 dollars, the direct capital cost (in millions of dollars) is given by (see Appendix 4)

$$C_D = 1.15\left(\text{BOP} + \text{reactor buildings} + \text{fusion island}\right)$$

$$= 1.15\left[685\left(\frac{P_t}{4150}\right)^{0.6} + 319\left(\frac{V_{FI}}{5100}\right)^{0.67} + C_{FI}\right] . \qquad (3.6)$$

An overall contingency factor of f_{con} 1.15 is used [5].

This simple costing model is intended mainly for studying 1200-MW(e) fusion reactors and comparing them with earlier 1200-MW(e) designs as the physical size is changed. Simple scaling formulae are used to allow for variation in the power output and in the size. The thermal power P_t and the fusion island volume V_{FI} are normalized to STARFIRE [5] values. The scaling powers are based upon typical values for power stations [32, 33] and the assumption that with a fixed wall thickness the reactor building cost scales as the square of the reactor dimensions.

The cost of the fusion island (in millions of dollars) is the sum of the costs of the steam generators, the coils, the structure, the shields, and the auxiliary power,

$$C_{FI} = \left[84\left(\frac{P_t}{4150}\right)^{0.6} + 1.2(1.25V_{cp}\rho_c C_c^u)\right.$$

$$\left. + V_{st}\rho_{st}C_{st}^u + 1.25V_s\rho_s C_s^u + 0.75\, C_a^u P_a\right] . \qquad (3.7)$$

The steam generators are assumed to be similar to those proposed for STARFIRE [5].

The primary coil volume V_{cp} is obtained from the maximum field B_m, the coil current density algorithm [Eq. (2.10)], and the minor radial dimensions of the fusion island. The coil density $\rho_c = 7.9 \times 10^3$ kg/m^{-3}, and the unit cost of the coils $C_c^u = 8.0 \times 10^{-5}$ ($\$\times 10^6$)/kg. The factor 1.2 allows for redundancy in each coil. The structure volume $V_{st} = 0.75V_{cp}$, the density $\rho_{st} = 6.0 \times 10^3$ kg/m^3, and the unit cost $C_{st}^u = 2.3 \times 10^{-5}$ ($\$\times 10^6$)/kg.

The shield volume V_s is calculated from the plasma dimensions, the wall dimensions, and the given blanket, gap, and shield thickness. A 30% contingency is added to handle the shielding of ducts and other apertures in the base shield. The shield density $\rho_s = 6.4 \times 10^3$ kg/m^3, and the unit cost $C_s^u = 1.7 \times 10^{-5}$ ($\$\times 10^6$)/kg.

As noted in Sect. 3.2, the auxiliary power costs are divided between direct and indirect costs; 75% of the costs are included here. The unit cost $C_a^u = 2.0$ \$/W(e).

Comparisons of STARFIRE and generic reactor costs and unit costs are given in Tables 3.1 and 3.2.

3.5 EXAMPLE

The costing model was used to determine the COE for a fusion reactor with the following parameters:

$R = 6.73$ m	$\langle\beta\rangle = 0.10$	$B_0 = 5.3$ T
$a = 1.12$ m	$B_m = 9$ T	$P_a = 50$ MW(e)
$R/a = 6.0$	$\Delta bgs_1 = 1.3$ m	$p_{wn} = 5.1\ \mathrm{MW\cdot m^{-2}}$
$b/a = 2.0$	$\Delta bgs_2 = 2.0$ m	$\chi_E = 0.48\ \mathrm{m^2\cdot s^{-1}}$
$a_w/a = 1.2$	$j_m = 2.55 \times 10^7\ \mathrm{A\cdot m^{-2}}$	$M_{FI} = 10{,}300$ tonnes
	$P_e = 1250$ MW(e)	

The following costs and factors were included:

$C_{D0} = \$1470$ million	$F_{CR0} = 0.1$	$f_{IND} = 1.50$
$C_F = \$72$ million per year	$F_{CR} = 0.165$	$f_{CAP} = 1.10$
	$f_{con} = 1.15$	$Y = 8$
	$f_{av} = 0.65$	

The results are shown in Table 3.3.

Table 3.1. Cost comparison for STARFIRE and 1200-MW(e) generic fusion reactor

Account number	Title	Direct cost (millions of 1983 dollars)	
		STARFIRE[a]	Generic reactor
	Balance of plant [Costs to be scaled as $(P_t/4150)^{0.6}$][b]		
20	Land	4	4
21	Buildings (except main reactor, hot cells)	109	109
22.4	Radioactive waste processing	6	6
22.5	Fuel handling[c]	47	55
22.6	Other reactor plant equipment	53	53
22.7	Instrumentation and controls	28	28
22.8	Spare parts allowance[d]	80	6
23, 26	Turbine plant, main heat rejection	263	263
24	Electrical plant equipment	123	110
25	Miscellaneous equipment	43	43
		756	677
	[Costs to be scaled as $(V_{FI}/5100)^{0.7}$][e]		
21	Main reactor building + hot cells	255	255
22.016	Vacuum[f]	6	9
22.017	Power supplies, coils, peripherals[g]	69	24
22.3	Cryogenics[h]	20	31
		350	319

Table 3.1. (continued)

Account number	Title	Direct cost (millions of 1983 dollars) STARFIRE[a]	Generic reactor
	Fusion island		
		Unit cost	
22.012	Shield	17 $/kg	17 $/kg
22.013	Coils	28 $/kg	80 $/kg
22.015	Structure	23 $/kg	23 $/kg
22.014 } 22.019 }	Auxiliary heating[i]	0.38 $/W(e)	2.0 $/W(e)
22.2	Main heat transfer system	84	$84\left(\frac{P_t}{4150}\right)^{0.6}$

[a]Costs adjusted to 1983 dollars assuming an inflation factor of 1.094 for 1980–81, 1.063 for 1981–82, and 1.038 for 1982–83. Factors taken from *Business Conditions Digest*, Bureau of Economic Analysis, U.S. Department of Commerce, September 1984.

[b]The exponent for the scaling with power is based upon fission reactor experience (M. L. Myers et al., *Nonfuel Operations and Maintenance Costs for Large Steam-Electric Power Plants*, ORNL/TM-8324, Oak Ridge National Laboratory, 1982; G. R. Smolen et al., *Regional Projections of Nuclear and Fossil Electric Power Generation Costs*, ORNL/TM-8958, Oak Ridge National Laboratory, 1983).

[c]The increase reflects the addition of two pellet injectors (unit cost $5 million). One fueler is sufficient for operation.

[d]In the generic reactor costing, most spares are carried in other accounts (e.g., blanket, auxiliary heating, limiters/targets, coil redundancy). The cost in this account is 20% of $30 million; the remaining 80% is carried under fuel cycle costs.

[e]The remaining 80% of the $30 million cost is carried in the fuel cycle costs. The fusion island volume V_{FI} is the volume of plasma, scrapeoff layer, blanket, first wall, shield, structure, and magnets.

[f]Increased for generic reactor to include redundancy.

[g]Reduced for generic reactor because auxiliary heating power supply costs are carried in account 22.014. Coil supply costs are representative of those used in a number of reactor designs (C. C. Baker et al., *STARFIRE—A Commercial Tokamak Fusion Power Plant Study*, ANL/FPP-80-1, Argonne National Laboratory, Argonne, Ill., 1980; *MARS, Mirror Advanced Reactor Studies*, UCRL-53333, Lawrence Livermore National Laboratory, Livermore, Calif., 1983; C. G. Bathke et al., *ELMO Bumpy Torus Reactor and Power Plant*, LA-8882-MS, Los Alamos National Laboratory, Los Alamos, N.M., 1981; R. L. Miller et al., *A Modular Stellarator Reactor*, LA-9737-MS, Los Alamos National Laboratory, Los Alamos, N.M., 1983).

[h]A study of the cryogenics costs for STARFIRE and MARS (see note *g*) shows that the liquid helium (LHe) refrigeration capability amounts to approximately 20 W per cubic meter of superconducting magnet. The liquid nitrogen (LN_2) capability is approximately 400 W per cubic meter of magnet. Taking the MARS recommendations of 1330 $/W for LHe refrigeration and 16 $/W for LN_2 refrigeration leads to a capital cost of $31 million for STARFIRE, for which the total coil volume is 950 m^3. To allow for variations with the fusion reactor size it is assumed that this cost is given by $31(V_{FI}/5100)^{0.67}$, where V_{FI} is the volume of the nuclear island, normalized to the equivalent STARFIRE volume.

[i]75% of cost; the remaining 25% is carried in the fuel cycle costs. The direct cost per unit electric power including power supplies reflects present experience in devices with high-power, long-pulse heating systems. Lower costs may be achieved as the heating systems are developed further.

Table 3.2. Fuel cycle costs

Account number	Title	Cost[a] STARFIRE[b]	Cost[a] Generic reactor
22.011	Blanket and first wall[c]	64 \$/kg	70 \$/kg
22.018	Targets/limiters[c]	?	5×10^4 \$/m^2
22.014 22.019	Auxiliary heating (25% of total)[c,d,e]	0.45 \$/W	2 \$/W
	Fuel costs (per year)	4.4×10^5 \$	4.4×10^5 \$
22.8	Spare parts allowance (80% of total), initial cost[c]		\$24 million
	Waste disposal	?	1 mill/kWh
	Work force for operations and maintenance	163 persons	457 persons

[a]These costs are used to calculate the average annual cost over *N* years of plant operation, as described in Appendix 2.4.

[b]Inflated assuming a rate of 1.094 for 1980–81, 1.063 for 1981–82, and 1.038 for 1982–83 (factors taken from *Business Conditions Digest*, Bureau of Economic Analysis, U.S. Department of Commerce, September 1984.

[c]The initial cost of these items is capitalized. The equivalent annual cost is calculated using the annual fixed charge rate.

[d]These costs represent 25% of the auxiliary heating costs and are to cover annual replacement of components such as launching structures, klystrons, etc.

[e]Including power supplies. In the generic reactor study, costs are varied to test the sensitivity of the COE to this item. The standard direct cost is representative of present-day costs for lower-cost systems (neutral beam injection or ion cyclotron heating).

Table 3.3. COE for an example reactor

Cost component	Cost in current dollars[a] (mill/kWh)	Cost in constant dollars[b] (mill/kWh)
Fusion island C_{OFI}	29.7	11.3
Fuel cycle[c] C_{OF}	17.6	11.1
Operations and maintenance[c] C_{om}	12.0	7.6
Reactor buildings C_{OBG}	13.0	4.9
Balance of plant C_{OBP}	47.3	18.0
Total COE	119.6	52.9

[a]Cost in current dollars for operation in 1991.

[b]Cost in constant (1983) dollars.

[c]Cost in first year of operation.

4. GENERIC REACTOR COSTS

4.1 COST SCALING STUDIES SUMMARY

The model described in this report was used to compute the COE of a wide range of toroidal configurations. A standard case (see Table 1.3) was used for determining the dependence of the COE on the following parameters:

- R/a, the aspect ratio,
- $\langle\beta\rangle$, the volume-average beta,
- χ_E, the average thermal diffusivity,
- p_{wn}, the neutron flux on the first wall,
- M_{FI}, the mass of the fusion island, and
- P_t/V_{FI}, the ratio of average power and volume of the fusion island.

The effects of changing the conditions, which were taken for the standard case, were tested by varying:

- B_m, the maximum field on the primary coils,
- P_a, the auxiliary power to the plasma,
- b/a, the plasma ellipticity,
- a_w/a, which determines the plasma-wall gap,
- F_{wn}, the neutron fluence lifetime,
- Δbgs, the thickness of the blanket, gap, and shield,
- Y, the construction time,
- P_e, the net electric power,
- η_e, the thermal-electric efficiency, and
- f_{re}, the fraction of power recirculated (excluding auxiliary heating).

The ranges of these variables are also shown in Table 1.3. The sensitivity to the costing assumptions was tested by varying:

- the coil unit cost C_c^u,
- the blanket unit cost C_b^u,
- the shield unit cost C_s^u,
- the auxiliary heating unit cost C_a^u, and
- the tax-adjusted interest rate and the fixed charge rate.

Finally, to illustrate the use of redundancy in improving availability and lowering the COE, the redundancy in the toroidal coils was varied (see Appendix 6). Other studies of the use of redundancy have been made for STARFIRE [5] and MARS [34].

4.2 DEPENDENCE OF COE ON ASPECT RATIO AND BETA

Figure 4.1 shows the variation of the COE with changing aspect ratio R/a and volume-average beta $\langle\beta\rangle$. For a given $\langle\beta\rangle$, the minimum cost lies in the range $R/a \sim 4$–8.

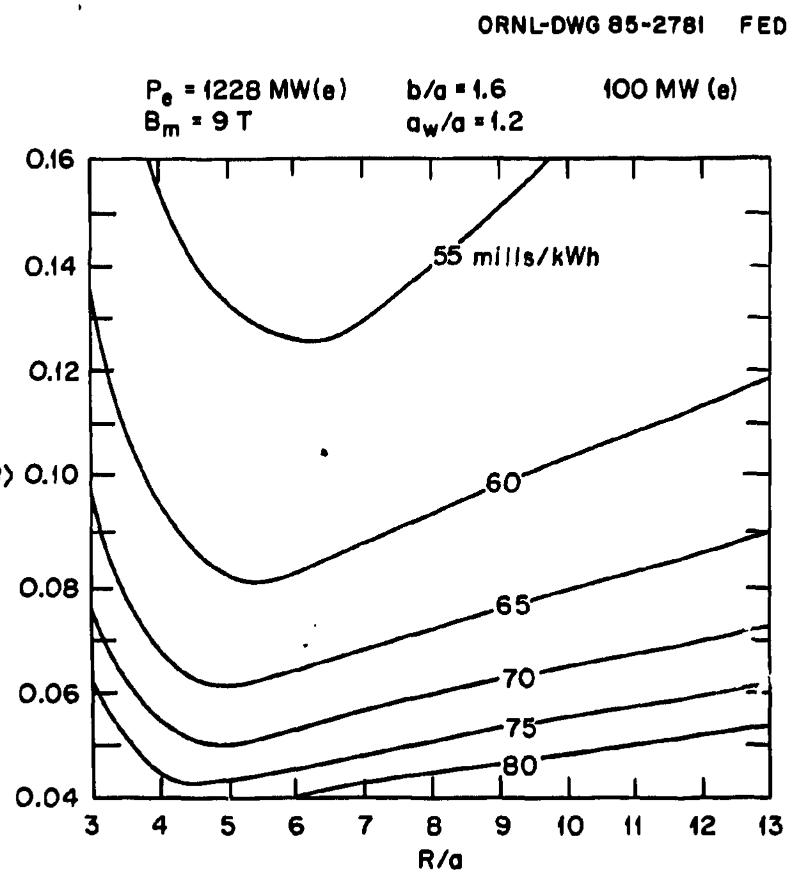

Fig. 4.1. Variation of COE with volume-average beta $\langle\beta\rangle$ and aspect ratio R/a.

The COE is relatively insensitive to changes in R/a for an even wider range. The increase in cost at low R/a occurs because the overall scale of the plasma must be increased in order to attain the maximum field B_m on the inner leg of the primary coil. The tokamak and the compact torus can have low R/a. For the tokamak, theoretical projections [35] and recent experimental data [16] suggest that the beta limit is given by $\langle\beta\rangle \lesssim (0.03\text{–}0.04)I/aB_0$. For standard noncircular plasmas this allows the tokamak to achieve the attractive reactor region for $R/a \lesssim 3$ with $B_m \simeq 10$ T. The beta may be raised at larger R/a by using more subtle shaping of the plasma (bean shape) [22]. The field in compact tori is produced mainly by currents flowing in the plasma. They are therefore less restricted in B_0/B_m than the formula [Eq. (2.7)] implies. Further, the field-reversed theta pinches have achieved $\langle\beta\rangle \sim 0.9$ [36, 37]. At large aspect ratio the increase in the ratio of plasma surface area to volume leads to a larger nuclear island and increased costs. The limitation $B_0/B_m \leqslant 0.6$ eliminates the factor that ameliorates the increase in size as aspect ratio is increased. The larger-aspect-ratio ($R/a \lesssim 15$) configurations, such as the stellarator and bumpy torus, are restricted to $B_0/B_m \leq 0.6$. The tandem-mirror central cell, however, is not so restricted, and $B_0/B_m \simeq 0.8$ is possible, limited mainly by access requirements [38].

The plot of COE vs $\langle\beta\rangle$ in Fig. 4.2 illustrates the importance of achieving $\langle\beta\rangle \sim 0.10$ (rather than ~ 0.05) as far as cost is concerned. (Note that, as discussed below, fission costs are expected to rise from present costs of ~40 mill/kWh to ~50 mill/kWh in the

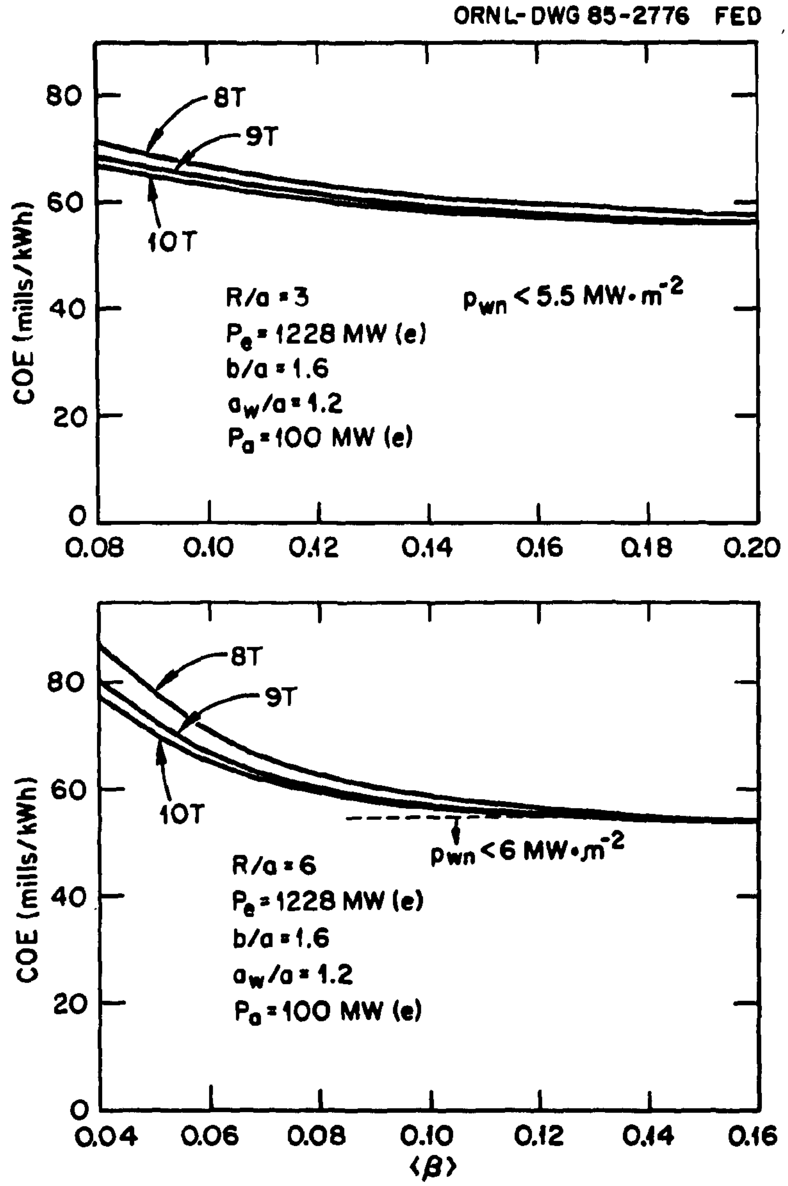

Fig. 4.2. The COE decreases with increasing $\langle\beta\rangle$ at a fixed maximum field B_m on the coil.

future.) Going beyond $\langle\beta\rangle \sim 0.10$ for D-T systems at the reference level mum field ($B_m = 9$ T) leads to only a small decrease in COE, and this comes at use of increased neutron wall loading. As found in previous studies, the main advantage of higher beta is that lower fields may be used for the same size device, thereby lowering the COE. However, as indicated below, the limits on beta and field may then be set by thermal diffusivity requirements.

4.3 THERMAL DIFFUSIVITY REQUIREMENTS

Figure 4.3 illustrates the point that at a fixed COE, the larger-aspect-ratio devices require a lower thermal diffusivity χ_E. It is important to remember that for a real reactor there will be a connection between $\langle\beta\rangle$, χ_E, B_0, and R/a, so that not all portions of the $\langle\beta\rangle$, R/a space will be accessible for a given magnetic configuration. This is illustrated for a tokamak with axisymmetric, neoclassical ion thermal diffusivity χ_{inc} [39] as the limiting

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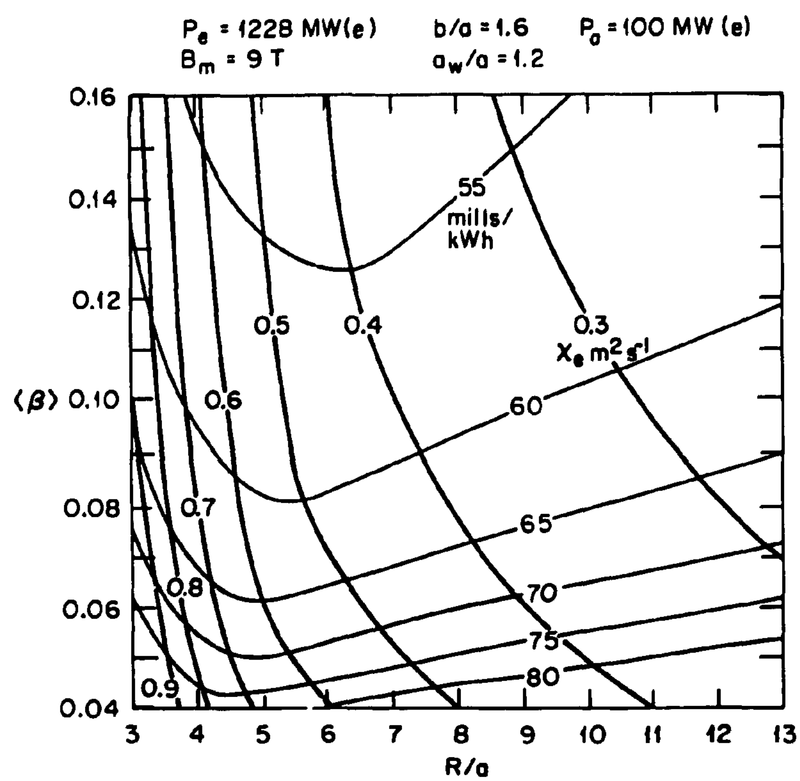

Fig. 4.3. At fixed COE, larger-aspect-ratio devices require a lower thermal diffusivity χ_E.

transport mechanism. For a relatively flat density profile, a parabolic temperature profile, and an average safety factor $q \simeq 1.5$, the thermal diffusivity is given by

$$\chi_E = \chi_{\rm inc} \simeq \frac{17.0\langle\beta\rangle(R/a)^{3/2}}{\langle T_{\rm k}\rangle^{3/2}(b/a)^{3/4}} \quad ({\rm m^2 \cdot s^{-1}}) \ , \tag{4.1}$$

where $\langle T_{\rm k}\rangle$ is the volume-average temperature in kiloelectron volts.

From Appendix 1.1, the alpha power is given by

$$P_\alpha \simeq 5.8\langle\beta\rangle^2 B_0^4 Rab \quad ({\rm MW}) \ , \tag{4.2}$$

and the required thermal diffusivity is

$$\chi_E \leqslant \frac{(1.6 \times 10^{-2}) f_\alpha P_\alpha}{\langle\beta\rangle B_0^2 R} \ . \tag{4.3}$$

Equating Eqs. (4.1) and (4.3), using Eqs. (2.6) and (4.2) with $f_\alpha = 0.8$, and rearranging leads to

$$\langle\beta\rangle_{\rm max} \leqslant \frac{(1.0 \times 10^{-3})(b/a)^{9/8} P_\alpha^{3/4} \langle T_{\rm k}\rangle^{3/2}}{(R/a)^{9/4}[p_{\rm wn}(a_{\rm w}/a)]^{1/4}} \tag{4.4}$$

or alternatively

$$B_0 \leqslant \frac{49(R/a)^{5/4}[p_{\rm wn}(a_{\rm w}/a)]^{1/2}}{(b/a)^{5/8} P_\alpha^{1/2} \langle T_{\rm k}\rangle^{3/4}} \quad ({\rm T}) \ , \tag{4.5}$$

at the maximum beta and $B_0 \propto 1/\langle\beta\rangle$.

As an example, we take the following set of parameters:

$b/a = 2.0$, $P_\alpha = 668$ MW, $P_e \simeq 1200$ MW(e),
$\langle T_{\rm k}\rangle = 14$ keV, $p_{\rm wn} = 4$ ${\rm MW \cdot m^{-2}}$, $a_{\rm w}/a = 1.1$,
$\langle\beta\rangle_{\rm max} \leqslant 10/(R/a)^{9/4}$,
$B_0 \leqslant 0.35(R/a)^{5/4}$ at $\langle\beta\rangle_{\rm max}$.

Then we can show the effects of increasing R/a on $\langle\beta\rangle$, B_0, and χ_e (numbers in parentheses assume operation at $\langle\beta\rangle = 0.25$):

R/a	$\langle\beta\rangle_{max}$	B_0 (T)	χ_E ($m^2 \cdot s^{-1}$)
3	0.84 (0.25)	1.4 (4.6)	0.82 (0.24)
5	0.27 (0.25)	2.6 (2.8)	0.56 (0.52)
7	0.13	4.0	0.45
9	0.07	5.5	0.35

For a standard noncircular tokamak the beta is limited, theoretically [35], to $\langle\beta\rangle \leqslant (0.03–0.04)I/aB_0$. To achieve the beta values listed here requires a more subtle shaping of the plasma [22].

It is important to note that these numbers depend strongly on the assumptions about plasma profiles, temperature levels, and the safety factor q. Nevertheless, the trend of this scaling for any particular fixed configuration is a decreasing window of $\langle\beta\rangle$ as R/a increases (see Fig. 4.4).

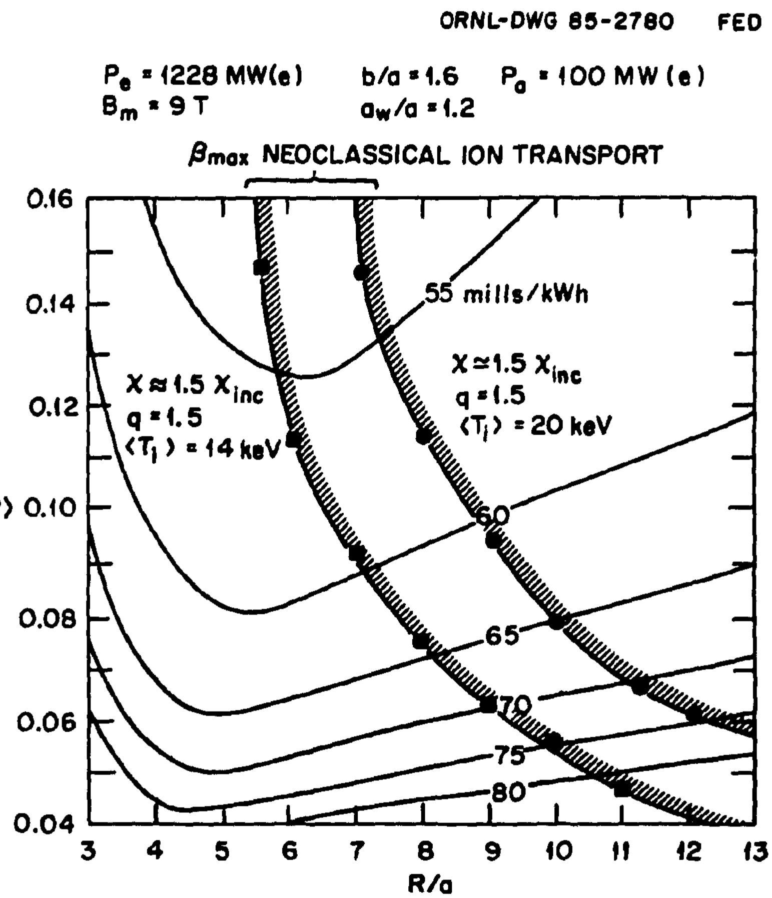

Fig. 4.4. In an axisymmetric toroidal reactor with nested flux surfaces, the neoclassical ion thermal diffusivity χ_{inc} limits the accessible $\langle\beta\rangle$, R/a space, with other conditions fixed.

If high beta and low thermal diffusivity are in fact achieved, it may be possible to use water-cooled copper coils, which require less neutron shielding. This route has been proposed both for tokamaks [40] with blankets outside the coils as well as inside [41] and for RFPs [42].

4.4 RELATIONSHIP OF COE TO NEUTRON FLUX

Figure 4.5 shows the increase in the neutron flux to the first wall, at fixed COE, as R/a is increased. This increase is counter to the simple logic that at fixed volume the surface area increases with aspect ratio and, therefore, that at constant neutron production p_{wn} should decrease with increasing R/a. At low aspect ratio, the decrease in B_0 for fixed B_m [Eq. (2.7)] requires an increase in plasma volume and consequently an increase in the surface area, which lowers p_{wn}; at large aspect ratio, where B_0 is fixed at $0.6B_m$, the volume of the nuclear island increases with R/a. Consequently, higher beta and smaller volume are required to maintain a constant COE, and the decrease in surface area leads to an increase in p_{wn}.

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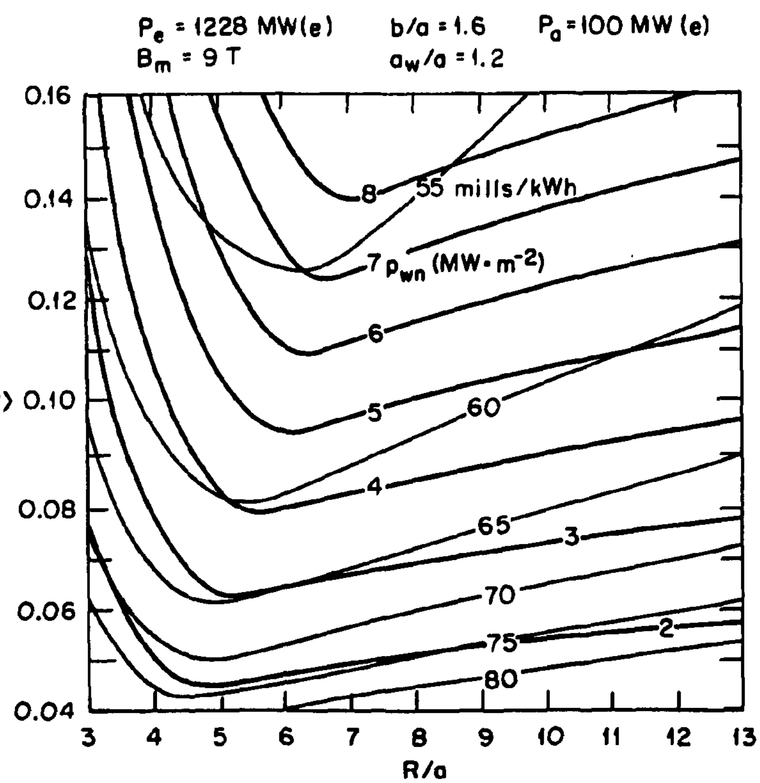

Fig. 4.5. As the aspect ratio is increased, the neutron flux to the wall p_{wn} increases with large aspect ratio at a fixed COE.

4.5 DEPENDENCE OF COE ON MAXIMUM FIELD

The algorithm that relates the coil current density to the maximum field on the coil (B_m) and specifies the volume of the coil structure [Eq. (2.10)] is discussed in Sect. 2.4. For this algorithm, as shown in Fig. 4.6, the COE is a relatively insensitive function of B_m for $\langle\beta\rangle$ in the range 0.06–0.12. However, there is a slight COE minimum for $B_m \sim$ 8–10 T. Also shown in Fig. 4.6 is p_{wn}, which increases steadily with B_m. For a given beta, the lower-field versions can tolerate a higher χ_E because of their greater plasma minor

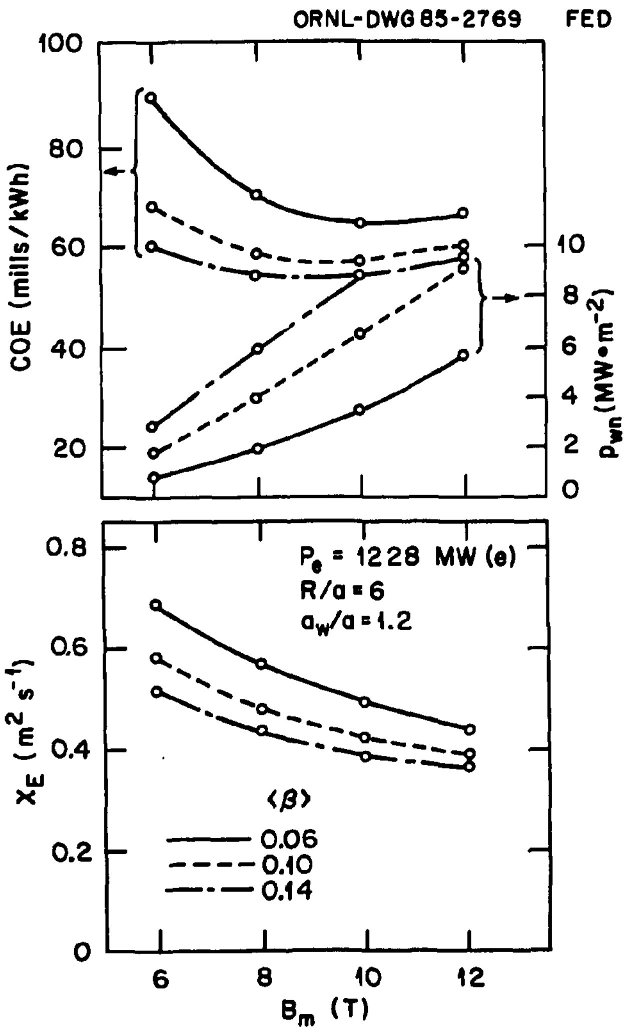

Fig. 4.6. Variation of COE, p_{wn}, and χ_E with B_m at fixed $\langle\beta\rangle$. (a) COE is a relatively insensitive function of B_m, but p_{wn} increases with B_m. (b) A lower χ_E is required as B_m increases.

radius; therefore, for this model, it is advantageous to work at the lower-field side of the minimum of COE, which is why the standard case uses $B_m = 9$ T. Similar cost dependences for superconducting coils have been demonstrated before [12, 13, 43].

The effect of small changes in the unit cost of the coils in the standard case for $R/a = 6$ and $\langle\beta\rangle = 0.04$–$0.14$ is given approximately by

$$\Delta\mathrm{COE} = 0.34(\mathrm{COE}_{\mathrm{standard}} - 44.3)\left(\frac{C_c^u - 80}{80}\right) \text{ mill/kWh} . \tag{4.6}$$

Thus, a 10% change in the unit cost of the coils (72–88 \$/kg) at a COE of 55 mill/kWh gives an incremental change of ±0.4 mill/kWh (~ ±1%).

4.6 DEPENDENCE OF THE COE ON THE FUSION ISLAND WEIGHT

The variation of the COE and its subelements with the fusion island weight M_{FI} is shown in Fig. 4.7. The plot illustrates two important points. First, the fusion island contributes less than half of the COE, even in large reactors; second, the fuel cycle costs, including all of the blanket elements, are a relatively insensitive function of M_{FI} (p_{wn}). The reason is simply that the total number of first wall and blanket components, limiters, and targets cycled through the plant during its lifetime depends primarily upon the neutron and thermal fluences. For a fixed output power, these fluences are constant for a fixed plant lifetime. The large, low-flux devices have a slightly higher COE for this item, because they have a greater up-front cost.

A factor not taken into account here is the dependence of availability on power density. For moderate power fluxes (e.g., $p_{wn} \sim 2$–6 MW·m^{-2}, $F_{wn} = 20$ MW·year·m^{-2}, and $f_{av} = 0.65$), the blanket will need replacing at a maximum every 5 years. In principle, this may be accomplished during scheduled downtimes. For higher fluxes, however, the replacements may begin to affect availability. In addition, the reliability may decrease as the power flux is increased and thereby increase the unscheduled downtime. A brief discussion of these points is given in Appendix 6.

The studies presented here show trends similar to those of earlier studies [20], carried out at Los Alamos National Laboratory, in which a variety of reference fusion reactors were compared. A plot of the direct capital cost (in millions of 1983 dollars) vs the weight of the fusion island normalized to the thermal power is shown in Fig. 4.8; it is given by

$$C_{D0} \simeq 1100 + 178\,\frac{M_{\mathrm{FI}}}{P_t} . \tag{4.7}$$

Note that as the power density is increased (M_{FI}/P_t decreased) beyond some level (e.g., $\gtrsim 6$ MW·m^{-2}) the types of material and structure will change, and the unit costs may

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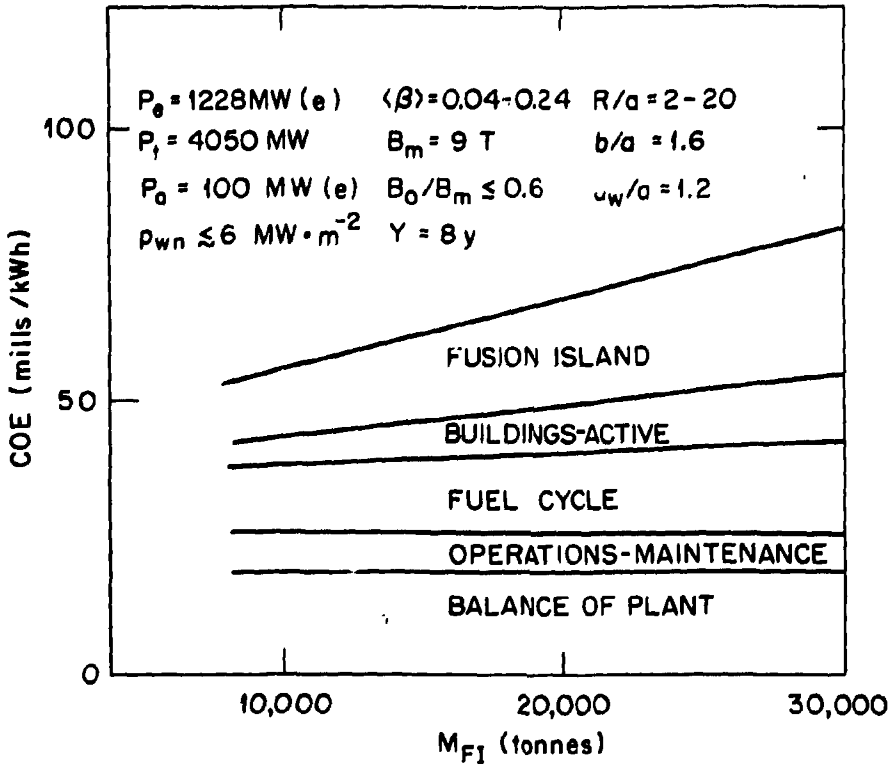

Fig. 4.7. The COE decreases as the mass of the fusion island M_{FI} decreases.

become a function of power density. For $p_{wn} \lesssim 5$ MW·m^{-2}, for which inherently safe systems may be made [19], it is assumed that the form of the construction and the unit costs are independent of power density.

Another parameter used to characterize fusion reactors [4, 20] is the fusion island power density (P_t/V_{FI}), where V_{FI} is the volume of plasma, blanket, gap, shield, coils, and structure. The argument has been made that for fusion to be competitive with fission, P_t/V_{FI} and M_{FI}/P_t should be comparable with values for a fission reactor (see Table 4.1).

The weight of the fusion island has even been compared to the weight of the pressure vessel for a boiling-water reactor (BWR) or pressurized-water reactor (PWR), which is typically ~500–1000 tonnes. This is a poor comparison, because the weight of the nuclear island for fission reactors is many thousands of tonnes, and, as shown in Table A.4.2, the cost of the pressure vessel is a minor part of the cost of the reactor plant equipment. Further, as demonstrated below, the argument is weak because the COE depends also on the fuel cycle costs for fission, and expected increases in this area will compensate for a

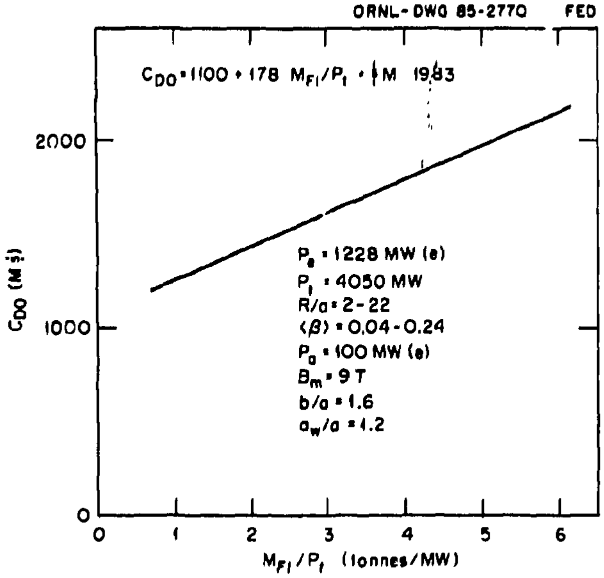

Fig. 4.8. There is a simple relationship between the direct capital cost C_{D0} and the mass per unit thermal power M_{FI}/P_t of the fusion island.

Table 4.1. Typical power densities inside the primary pressure vessel for economical fission power plants

	Power density ($MW \cdot m^{-3}$)
Gas-cooled reactor	
Hinkley Point A[a]	0.8
Advanced gas-cooled reactor	
Hinkley Point B[a]	1.2
Boiling-water reactors	
Dresden 2[b]	3.2[c]
Mk 3[b]	4.7[c]
Pressurized-water reactors	
Point Beach[a]	10.8
Indian Point 2[b]	11.6

[a]M. M. El-Wakil, *Nuclear Energy Conversion*, Intext Educational Publishers, Scranton, Pa., 1971.

[b]M. Myers, Oak Ridge National Laboratory, private communication, 1984.

[c]Inside the secondary containment (wet well), the power density is ~1.0 $MW \cdot m^{-3}$.

slightly higher fusion capital cost. Note that, for the same power output, the core of a fossil plant with stringent emission control can cost more than the nuclear island of a fission plant [11] and, though the power density is substantially lower, the COE is comparable (Table A.4.3).

The issue for fusion is that P_t/V_{FI} should be high enough (M_{FI}/P_t low enough) so that the COE is competitive. The plots of COE vs P_t/V_{FI} in Fig. 4.9 and vs P_e/M_{FI} in Fig. 4.10 show that for the generic reactors with superconducting coils it is cost-effective to use $P_t/V_{FI} \sim$ 1–2 $MW \cdot m^{-3}$ and $P_e/M_{FI} \gtrsim$ 100 kW(e)/tonne. There is little cost advantage in going higher than this level, and at higher power densities p_{wn} is higher, requiring lower χ_E, as shown in Fig. 4.11. The generic reactor model indicates that in this power density range, which entails $M_{FI} \simeq$ 10,000 tonnes, fusion reactors should be competitive in the future.

The comparison with a PWR has been used [9] to make the case for a smaller water-cooled copper reactor. In principle, as mentioned above, such a low-weight device may be achieved if high beta, coupled with low thermal diffusivity, and moderate to high B_0 are realized. Suggested alternatives are the high-field tokamak [40, 41] and the compact RFP [42], for which $B_0/B_m \geqslant 1$. These are intriguing concepts and should be studied further. However, as discussed in Appendix 6, their viability depends strongly on the achievement of high availability in the face of the need for frequent blanket replacements and high power fluxes. This study suggests that while this route may be interesting, it is not the only

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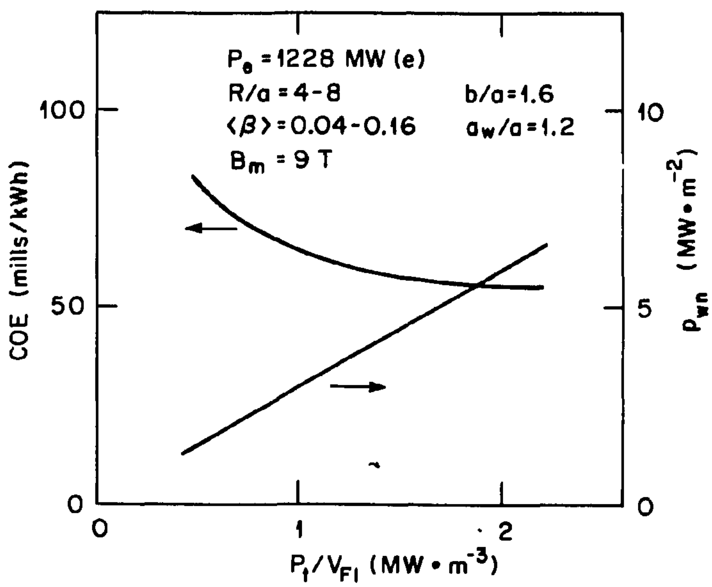

Fig. 4.9. The COE decreases with the power density P_t/V_{FI} of the fusion island, but p_{wn} increases. For superconducting coil reactors, an optimum region appears at around 2 $MW \cdot m^{-3}$ for a plant producing ~1200 MW(e).

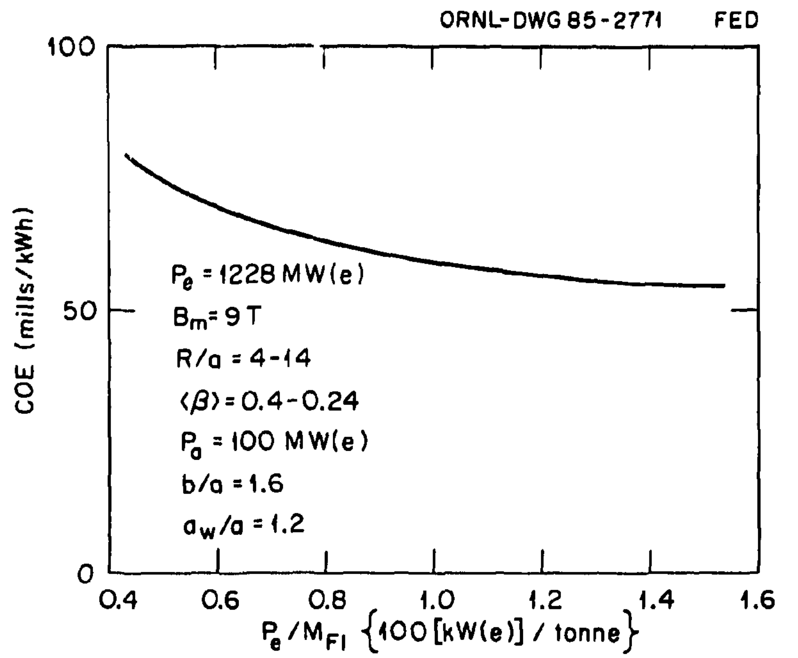

Fig. 4.10. The decrease in COE with increasing P_e/M_{FI} levels off above a value of about 100 kW(e)/tonne for systems with superconducting coils.

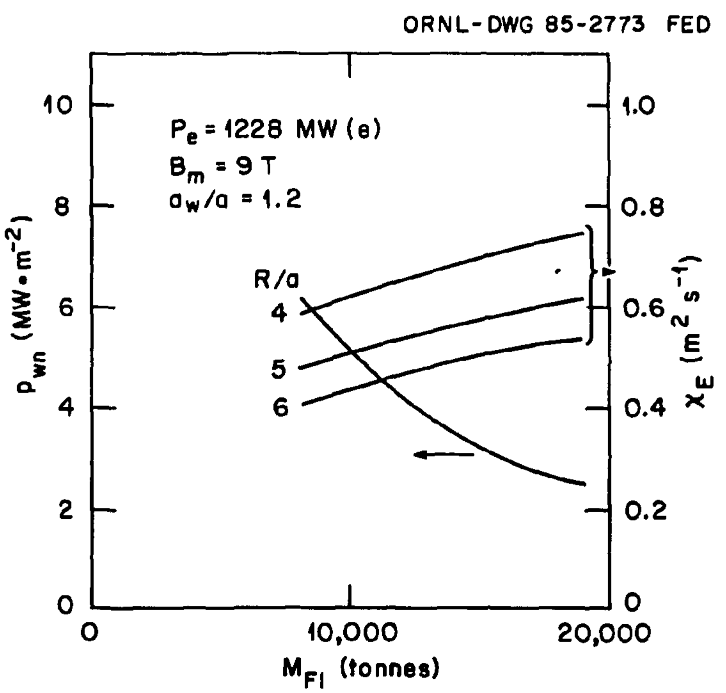

Fig. 4.11. As the reactor is made smaller at constant power output (smaller mass), p_{wn} increases and the required χ_E decreases.

route to economically viable fusion. In fact, if a higher beta (>10%) and good confinement can be achieved, then a more profitable route for fusion may be catalyzed D-D operation [44].

4.7 VARIATION OF COE WITH KEY PARAMETERS

4.7.1 Auxiliary Power

For the reference case the auxiliary power P_a was varied from 50 to 200 MW(e) (the power refers to the electrical power input to the auxiliary heating system). A plot of COE vs M_{FI} is given in Fig. 4.12 for P_a = 50, 100, and 150 MW(e). For a base unit cost C_a^u of 2 \$/W, the incremental change in the COE is ΔCOE $\simeq$ 0.08 (mill/kWh)/MW. This incremental cost comes in part from the change in the direct capital cost (~0.05), in part from the reduction in P_e as P_a is increased (~0.02), and in part from the increased cost of operations. Changing the unit base cost acts only upon ~0.06 (mill/kWh)/MW. Thus,

$$\Delta \text{COE} \simeq 0.02 + 0.06(C_a^u/2)\ \text{(mill/kWh)/MW} \ . \tag{4.8}$$

4.7.2 Blanket-Gap-Shield Thickness

The effect of varying the thickness of the blanket, gap, and shield Δbgs was tested for the reference case by multiplying the radial thicknesses by the factor 1.15, so that Δbgs_1 increased from 1.30 m to 1.50 m and Δbgs_2 increased from 2.0 m to 2.30 m. The average

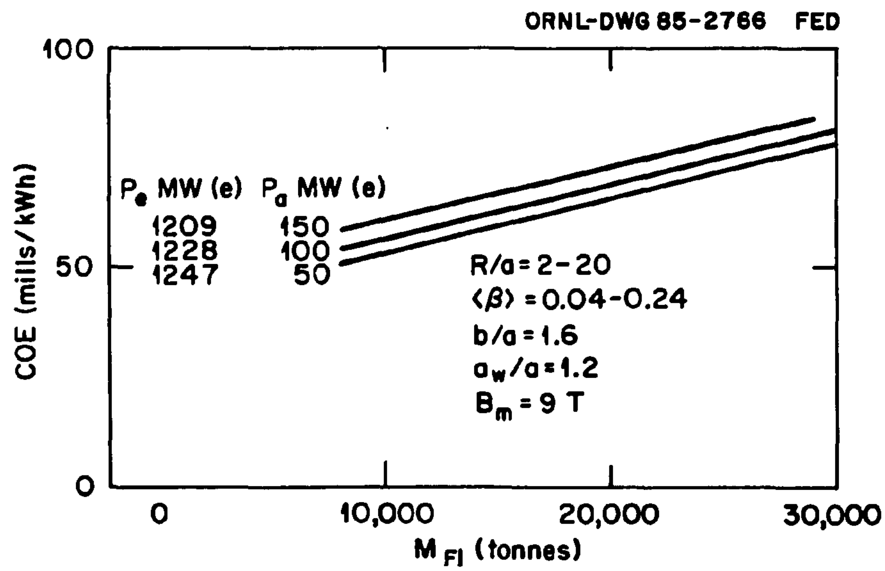

Fig. 4.12. Dependence of the COE on auxiliary power P_a as a function of fusion island mass M_{FI}.

percentage change in the COE for $R/a = 6$ and $\langle\beta\rangle = 0.04$–$0.12$ was $\Delta COE/COE \simeq 0.36 \pm 0.03\%$ for each 1% increase in thickness.

For example, at $R/a = 6$ and $\langle\beta\rangle = 0.10$, the COE with the standard values for Δbgs is $COE_1 = 57.1$ mill/kWh. When Δbgs is multiplied by 1.15, the COE becomes $COE_{1.15} = 60.3$ mill/kWh. Thus, ΔCOE is 3.2 mill/kWh, and $\Delta COE/COE_1 = 0.37\%$ foı each 1% increase in thickness.

The effect of changing the unit cost of the blanket C_b^u for the standard case with $R/a = 6$ and $\langle\beta\rangle = 0.04$–$0.12$ is given approximately for small changes in the unit cost by

$$COE = COE_{standard}\left[1 + 0.15\left(\frac{C_b^u - 70}{70}\right)\right] \text{ mill/kWh} \ . \qquad (4.9)$$

Thus, a 10% change in the blanket unit cost (63–77 $/kg) at COE = 57 mill/kWh gives an incremental change of ±0.9 mill/kWh.

4.7.3 Ellipticity

The effect on the COE of varying the ellipticity b/a is shown in Fig. 4.13(a) for the standard case with $\langle\beta\rangle = 0.10$ and R/a varied from 3 to 13. Increasing ellipticity reduces the COE mainly because of a reduction in the coil and structure volume. There is no significant change in p_{wn}, but the required χ_E increases slightly as b/a is increased. Whether this gain from ellipticity can be realized in practice will depend upon the dependence of $\langle\beta\rangle$ and χ_E on ellipticity.

4.7.4 Plasma-Wall Separation

Increasing the plasma-wall gap a_w/a increases the COE because it increases the volume of the coils, structure, blanket, and shield. However, it also leads to a lower neutron flux on the wall, as shown in Fig. 4.13(b). For $R/a \geq 6$, there is only a small increase in the COE.

4.7.5 Neutron Fluence Limit

The variation of COE and blanket replacement time with a changing neutron fluence limit F_{wn} is shown in Fig. 4.14. The figure illustrates the need to achieve $F_{wn} \geq 20$ MW·year·m^{-2}, not only because of the rapid increase of COE as F_{wn} is lowered (as the result of increased blanket costs), but also because the blanket replacement time becomes uncomfortably small; this point is discussed in Appendix 6. The main point is that the best time to replace the blanket elements is during the scheduled maintenance period for the turbines, which occurs every two years, as discussed in the STARFIRE report [5]. For a 4-year lifetime, half the blanket may be replaced every two years. For the standard case shown in Fig. 4.14, the wall loading may be reduced from 6.2 to 5.1 MW/m^2 by

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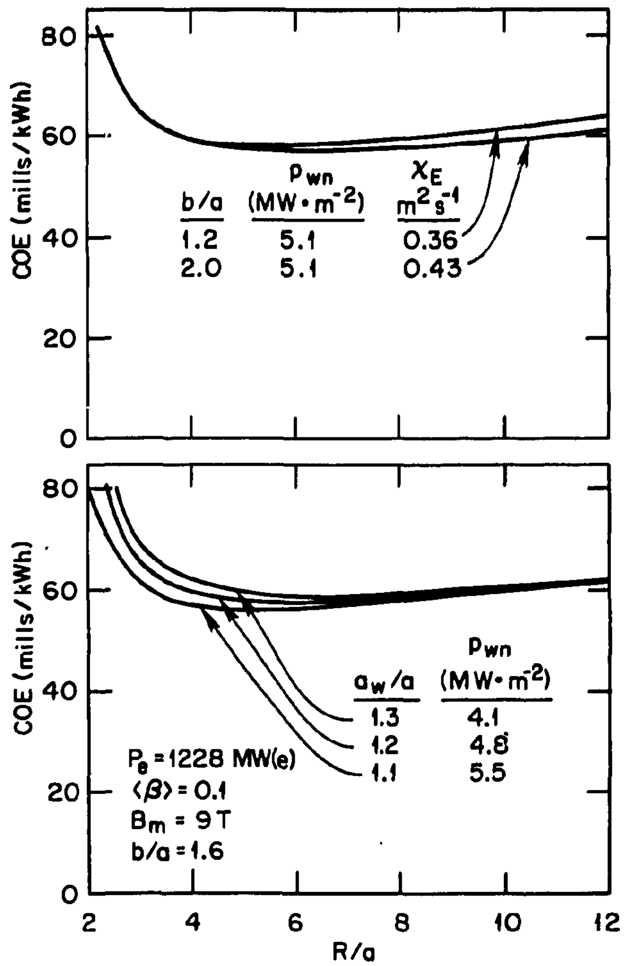

Fig. 4.13. Dependence of the COE on (a) plasma ellipticity b/a and (b) the relative scrapeoff layer thickness a_w/a, both as a function of R/a.

increasing a_w/a from 1.1 to 1.2, with a minor increase in cost from 55.3 to 55.8 mill/kWh. In the latter case, the blanket may be replaced every 6 years. The neutron flux level of ~5 MW/m^2, which is required for competitive fusion reactors, is within the range of power density that can be inherently safe [19].

4.7.6 Tax-Adjusted Cost of Money

The fixed charge rate increases with the tax-adjusted cost of money x, as discussed in Appendix 3. The dependence of the COE on the cost of money is shown in Fig. 4.15. Every increase of 0.1 in x adds about 6 mill/kWh to the COE.

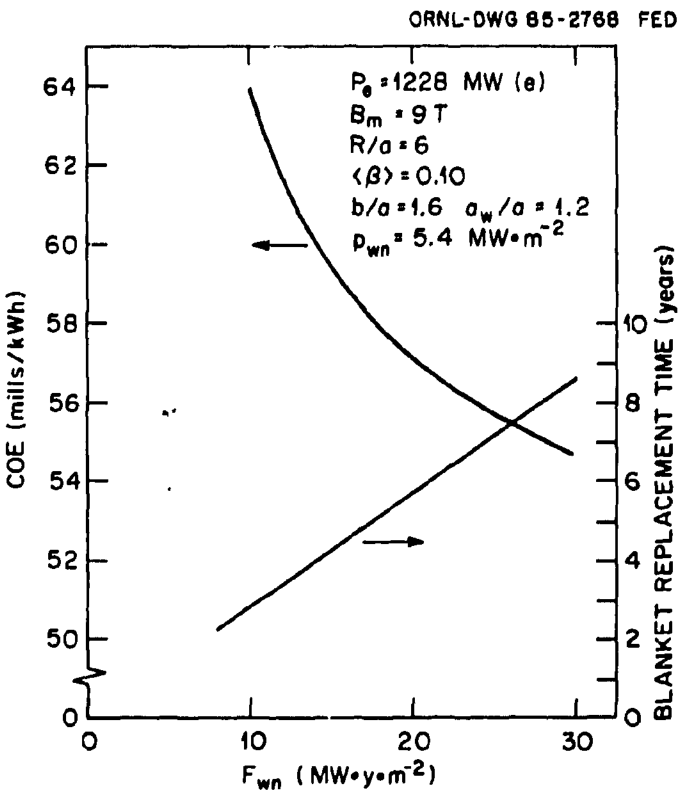

Fig. 4.14. Variation of the COE and blanket replacement time on the first-wall neutron fluence lifetime F_{wn}.

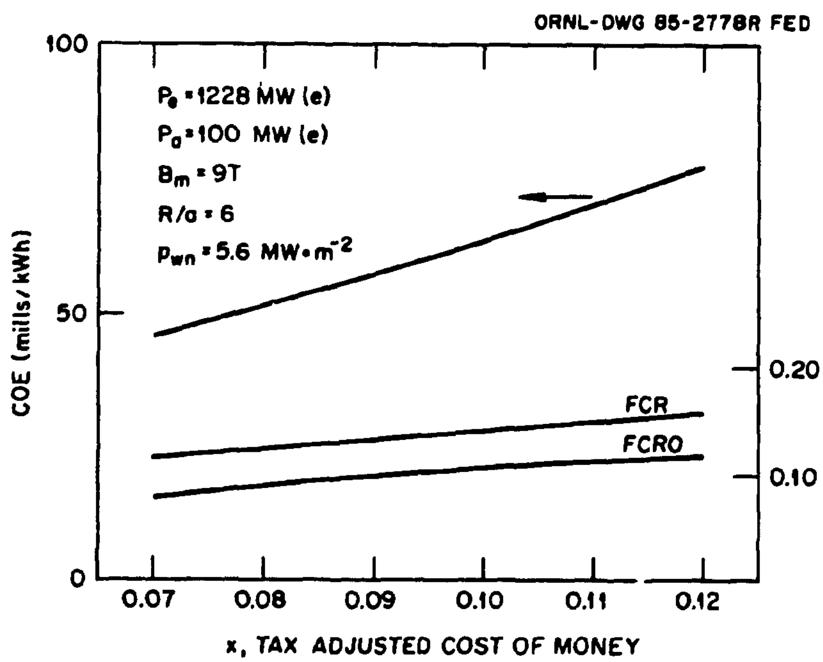

Fig. 4.15. The COE increases rapidly with increasing tax-adjusted cost of money x.

4.7.7 Lead Time

The design and construction lead time Y affects the COE in two ways. First, the interest charges increase as Y increases; for example, in the constant-dollar case,

$$f_{\mathrm{CAP0}} = (1.011)^{Y+0.61}$$

(see Appendix 2). Second, increased construction lead time increases the time during which construction personnel must be supported. These effects have been accounted for by varying the indirect charges as

$$f_{\mathrm{IND}} = \left(1 + 0.5\frac{Y}{8}\right) ,$$

as discussed in Sect. 3.2. A plot of the COE for $Y = 6$, 8, and 10 years as a function of the mass of the fusion island is shown in Fig. 4.16. The values of f_{CAP0} are, respectively, 1.075, 1.099, and 1.123; the values of f_{IND} are 1.43, 1.50, and 1.56. The percentage change in the COE for a one-year change in the construction time is $(\Delta\mathrm{COE}/\mathrm{COE}) \times 100 \simeq 4.0\%$ for this model.

4.7.8 Electric Power

The COE decreases as the power output from the plant P_e is increased. Figure 4.17 shows this trend for the case of $R/a = 6$, $B_m = 9$ T, and $\langle\beta\rangle = 0.10$, with $P_e \propto P_F$. A similar trend occurs for other values of these parameters. For B_m in the range 6–9 T, the lowest COE was for $B_m = 9$ T. The associated values of M_{FI}, p_{wn}, and χ_E are also shown. Low-power plants have a lower neutron wall flux than high-power plants, but they also require a smaller value of χ_E. If higher $\langle\beta\rangle$ is possible, then the COE for the smaller plants may be decreased; however, as mentioned, this will be realizable only if χ_E is commensurately small.

4.8 MULTIPLE-UNIT REACTORS

The increase in COE with decreasing unit power, shown in Fig. 4.17, occurs for two reasons: first, the fixed blanket and shield thickness leads to a lower power density as the power is reduced at fixed B_m and $\langle\beta\rangle$; second, it has been assumed that the costs of operations and maintenance and of the BOP scale nonlinearly with power, $\mathrm{COE}_{\mathrm{om}} \propto (1200/P_e)^{0.5}$ [32] and $C_{\mathrm{DBOP}} \propto (P_t/4150)^{0.6}$ [11]. While higher $\langle\beta\rangle$ is a route to higher power density and lower cost, it requires even lower values for the thermal diffusivity (χ_E) and might be hard to achieve; on the other hand, the lower power density (p_{wn}) may lead to a more reliable unit.

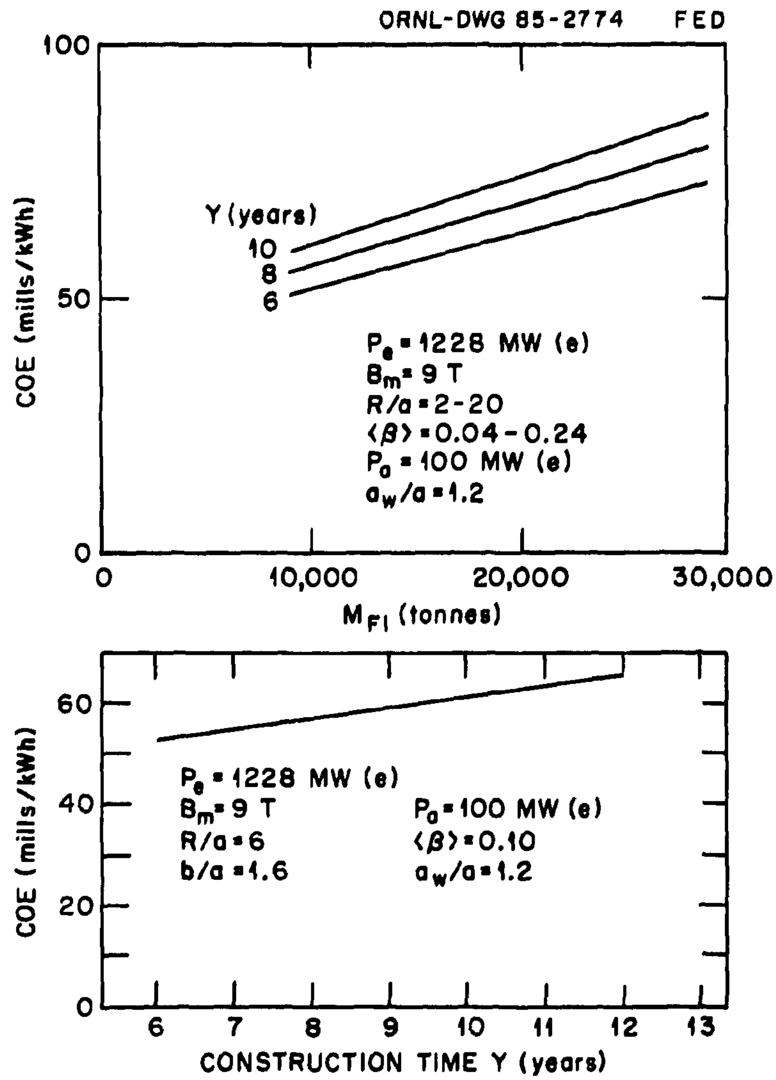

Fig. 4.16. Dependence of the COE on (a) the construction time Y as a function of M_{FI} and (b) Y at fixed $\langle\beta\rangle$.

The disadvantages of the smaller unit may be overcome, in part, by using multiple reactor units on one site. Thus rather than having, for example, one 1200-MW(e) unit, it may be advantageous to have two 600-MW(e), three 400-MW(e), or even four 300-MW(e) units.

The main advantages attributed to the use of multiple reactors are [45, 46]

- improved load-following capability,
- lower cost because greater numbers of each component are produced,

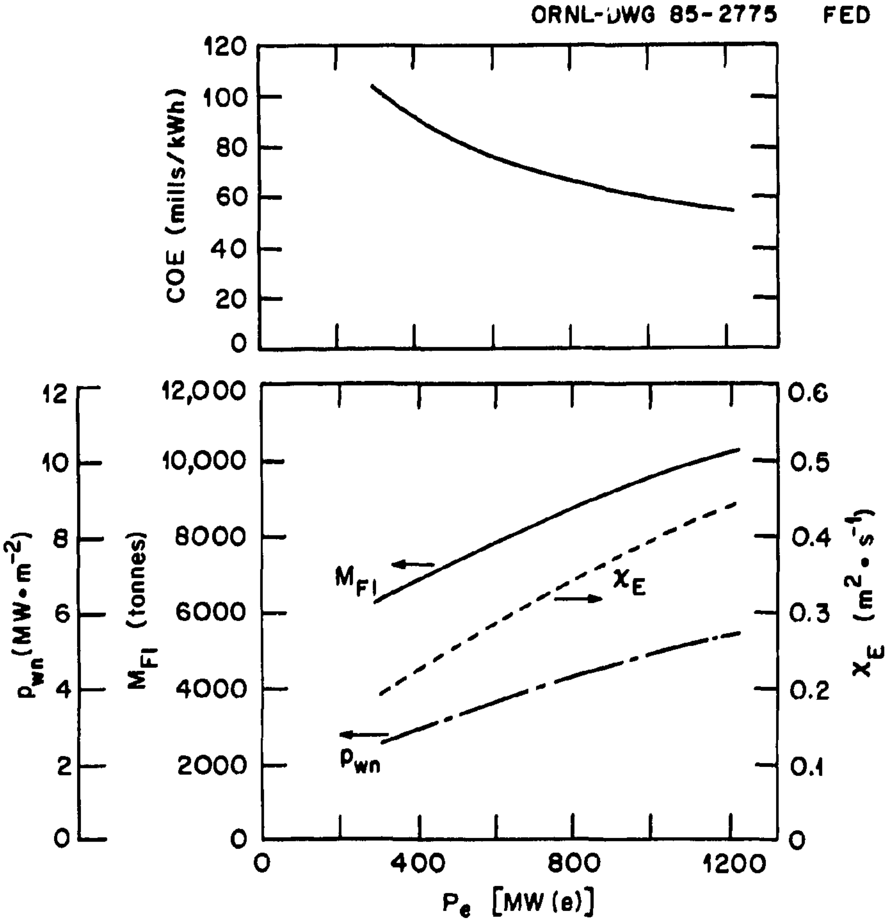

Fig. 4.17. Dependence on the net electric power P_e of (a) COE and (b) M_{FI}, p_{wn}, and χ_E.

- a relative reduction in spares compared to a single small unit,
- effectively shorter construction time, and
- redundancy of shared components, which may lead to higher availability.

Disadvantages are

- a larger work force than that needed for a single large unit,
- larger land area, and
- increased complexity owing to interconnections.

A simple procedure described in Appendix 6 indicates the possible gains of using multiple units.

4.9 IMPROVED GENERIC FUSION REACTOR

A progression towards an improved fusion reactor with $R/a = 6$ and $b/a = 1.6$ is shown in Fig. 4.18. Parameters of these and a number of other generic reactors are given in Table 4.2. Figure 4.18(a) shows the variation of COE and p_{wn} with changing B_m. On the basis of this plot, $B_m = 9$ T is chosen to minimize the COE and p_{wn}, and $\langle\beta\rangle$ is then varied [Fig. 4.18(b)]. As a compromise between decreasing COE and increasing p_{wn}, the value $\langle\beta\rangle = 0.10$ is chosen, and P_a is varied [Fig. 4.18(c)]. With $P_a = 50$ MW(e) the plasma-wall ratio a_w/a is increased to lower p_{wn} [Fig. 4.18(d)]. Finally, after making allowance for variation in construction time and for the possibility of more detailed optimization in the other parameters, a range of the COE for an improved generic reactor is obtained [Fig. 4.18(e)], namely, 47–59 mill/kWh. The effect of variations in the unit costs of fusion components is discussed in Sect. 3.4; such variations will broaden the range of COE.

For comparison, the range of costs expected for fission reactors is plotted as a function of the cost of U_3O_8 in Fig. 4.18(f). The contributions of the various accounts that make up the COE for fusion and fission are compared in Table 4.3 for a 1200-MW(e) plant. For the fission systems, the reference and optimized reactors are taken from ref. 11. In this study the price of U_3O_8 is 34 $/lb and is assumed to be escalating at 7.9% per year, which includes a general 6% inflation rate. The contribution of the cost of U_3O_8 to the fuel cycle COE is 4.2 mill/kWh (1983 dollars) for a plant starting operation in 1995. If the price of U_3O_8 is not escalating above the general inflation rate, the U_3O_8 component of fuel cost is 0.082 (mill/kWh)/($/lb) or 2.8 mill/kWh at 34 $/lb. As the price of uranium rises in real terms, it should tend to stabilize, albeit at higher and higher prices. Such a stabilization may be caused by the deployment of fission breeder reactors or high-conversion-ratio fission reactors [47] using reprocessing to recycle unspent fuel and fuel bred in the reactors.

A system based upon liquid-metal fast breeder reactors is expected to have a total COE about 20% higher than present costs [47], and a recent analysis shows that fission breeders should be competitive with light-water reactors when the cost of uranium rises into the range 60–180 $/lb [48]. A fusion-fission hybrid breeder system should also be capable of operating in this range [48, 49]. Studies of the extraction of uranium from seawater [50] show more optimistic results as time progresses; nevertheless, the optimistic projections are on the high-cost side of the alternatives. To put in perspective the difficulties of this route, it should be understood that it is necessary to process continuously a flow of water comparable to that in the Mississippi River in order to support a 1-GW(e) fission plant.

The foregoing calculations suggest that fusion reactors could be directly competitive with fission reactors when the price of U_3O_8 rises to around 60–180 $/lb. Since other factors (public perception, safety, environmental impact, regulations, etc.) enter into the choice and cost of a particular system, fusion appears to offer a potentially attractive alternative for central power generation.

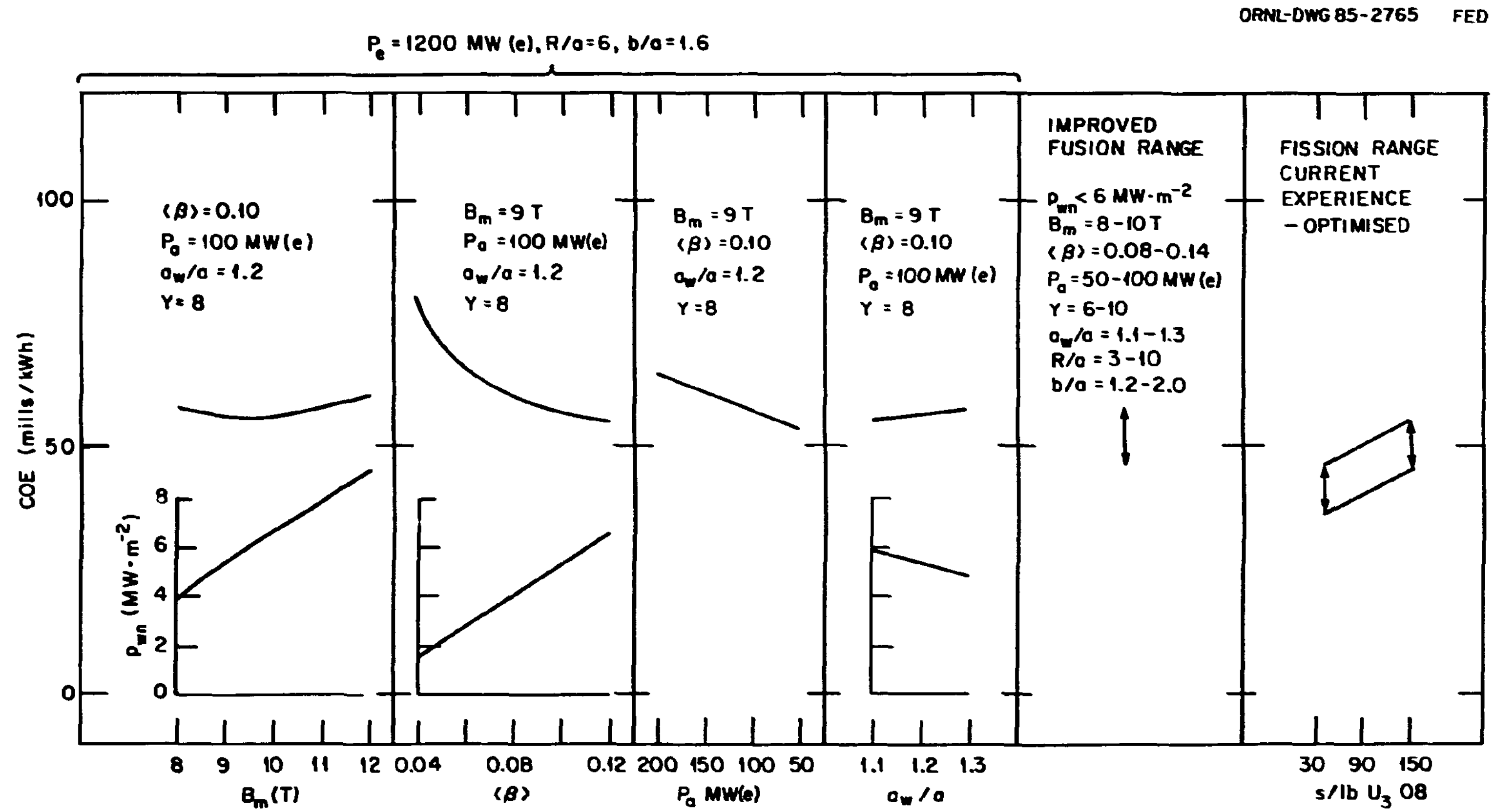

Fig. 4.18. Progression toward an improved fusion reactor and range of COE for a fission reactor. (a) Dependence of COE and p_{wn} on B_m at fixed $\langle\beta\rangle$, a_w/a, P_a. (b) Dependence of COE on $\langle\beta\rangle$ and p_{wn} at fixed B_m, a_w/a, P_a. (c) Dependence of COE on P_a at fixed $\langle\beta\rangle$, p_{wn}, B_m, a_w/a. (d) Dependence of COE and p_{wn} on a_w/a at fixed $\langle\beta\rangle$, B_m, P_a. (e) Range of COE for ranges of B_m, $\langle\beta\rangle$, p_{wn}, P_a, a_w/a, Y, and R/a. (f) Range of COE for a fission reactor, including current experience to future optimized, as a function of the price of U_3O_8.

Table 4.2. **Improved fusion reactors with $P_F = 4000$ MW**

P_e, MW(e)	1,247	1,228	1,247	1,228	1,228	1,247	1,228	1,247	1,228
P_a, MW(e)	50	100	50	100	100	50	100	50	100
B_m, T	9	9	9	9	9	9	10	8	6
$\langle\beta\rangle$	0.16	0.16	0.12	0.10	0.10	0.08	0.09	0.15	0.22
R/a	4	4	6	6	6	6	6	12	25
R, m	5.73	5.73	6.20	7.11	7.11	7.66	6.92	9.36	14.9
a, m	1.43	1.43	1.03	1.19	1.19	1.28	1.15	0.78	0.60
b/a	1.6	1.6	2.0	1.6	1.6	2.0	1.6	2.0	1.0
a_w/a	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.2	1.4
M_{FI}, tonnes	8,790	8,790	8,930	10,380	10,380	12,770	11,410	10,780	12,560
V_{FI}, m^3	2,020	2,020	1,920	2,250	2,250	2,880	2,380	2,120	2,380
M_{FI}/P_t, tonne/MW	2.2	2.2	2.2	2.6	2.6	3.2	2.8	2.7	3.1
P_t/V_{FI}, MW(t)/m^3	2.0	2.0	2.1	1.8	1.8	1.4	1.7	1.9	1.7
χ_E, m$^2 \cdot$s^{-1}	0.60	0.60	0.46	0.44	0.44	0.52	0.44	0.28	0.12
P_{wn}, MW$\cdot$m^{-2}	5.6	5.6	6.0	5.4	5.4	3.9	5.3	5.3	5.9
F_{wn}, MW$\cdot$year$\cdot$m^{-2}	20	20	20	20	30	30	20	20	20
Y, years	8	10	6	8	8	6	8	6	8
C_D, millions of dollars	1,390	1,480	1,400	1,570	1,570	1,590	1,650	1,460	1,580
COE, mill/kWh	50.9	59.0	47.2	57.1	54.7	51.6	59.4	48.9	59.3

Table 4.3. Comparison of COE (constant 1983 dollars) for 1200-MW(e) fusion and fission plants

P_e = 1200 MW(e), f_{av} = 0.65, F_{CR} = 0.10COE

Account	COE (mill/kWh)		
	Fission[a]		
	Reference (Indirect charges = 85.5%)	Optimized (Indirect charges = 50%)	Improved fusion[b] (Indirect charges = 50%)
Reactor plant	9.3	6.9	9.7–16.4
Reactor buildings	4.5	2.8	4.0–5.1
Balance of plant	17.2	11.7	16.2–18.4[c]
Fuel cycle	9.4–19.3[d]	9.4–19.3[d]	9.7–11.6
Operations and maintenance	7.4	7.4	7.6
Total	48–58	38–48	47–59

[a]Fission costs are given in Table A.2.1

[b]The range in costs allows for the following variations: B_m = 8–10 T, P_a = 50–100 MW(e), a_w/a = 1.1–1.2, $\langle\beta\rangle$ = 0.08–0.12, R/a = 4–8, Y = 6–10 years.

[c]BOP for the fusion reactors includes items with costs scaling as P_t, which are included in reactor plant for fission (see Appendix 4).

[d]U_3O_8 at 60–180 $/lb.

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APPENDIXES

Appendix 1

PLASMA POWER BALANCE

A simple power balance is obtained for a D-T plasma by equating conduction losses and radiation losses to the net alpha power input,

$$-\frac{2}{r}\frac{\partial}{\partial r} rne\chi_E \frac{\partial T}{\partial r} + p_b + p_s = P_\alpha \ , \qquad \text{(A.1.1)}$$

where χ_E is the thermal diffusivity and, for this calculation, $T = T_e = T_i$ and $n = n_e = n_i$. The bremsstrahlung radiation power density is given by

$$p_b \simeq (1.9 \times 10^{-38}) n_e^2 T_e^{1/2} Z_{eff} \quad (\mathrm{W \cdot m^{-3}}) \ , \qquad \text{(A.1.2)}$$

where $Z_{eff} = (\sum_Z Z^2 \ n_Z + n_i)/n_e$, and n_Z and Z are the density and charge state of nonhydrogenic impurities. The synchrotron radiation power density is given by

$$p_s \simeq (6.2 \times 10^{-20}) n_e T_e B_0^2 \phi \quad (\mathrm{W \cdot m^{-3}}) \ , \qquad \text{(A.1.3)}$$

where

$$\phi = (7.8 \times 10^3) T_e^{1.1} \left(\frac{B_0}{n_e \bar{a}}\right)^{1/2} (1 - R_e)^{1/2}$$

and the wall reflectivity is assumed to be $R_e = 0.95$.

Integrating Eq. (A.1.1) over the plasma volume leads to

$$-\ 8\pi^2 R\bar{a}n\chi_E e \frac{\partial T}{\partial r} = f_\alpha P_\alpha \quad (\mathrm{W}) \ , \qquad \text{(A.1.4)}$$

where f_α allows for modest losses of energetic alpha particles and for electromagnetic radiation and $\bar{a} = \sqrt{ab}$. Now

$$\langle\beta\rangle = \frac{(0.8 \times 10^{-24})\langle nT \rangle}{B_0^2} \qquad \text{(A.1.5)}$$

(not in percent), and

$$\langle\beta_i\rangle = 0.4 \times 10^{-24}\frac{\langle n_i T_i\rangle}{B_0^2} \ .$$

The deuterium and tritium density will be less than the electron density because of the presence of helium from the fusion reactions and other impurities, and

$$\langle\beta_i\rangle = \langle\beta\rangle/[1 + (1 + \langle\beta_Z\rangle/\langle\beta_e\rangle)/(\langle\beta_i\rangle/\langle\beta_e\rangle)] \ . \qquad (A.1.6)$$

We assume that $\langle\beta_Z\rangle/\langle\beta_e\rangle = 0.2$ and that T_i exceeds T_e sufficiently to compensate for the surplus electron density so that $\langle\beta_i\rangle = \langle\beta_e\rangle$. In this case $\langle\beta_i\rangle = 0.455\langle\beta\rangle$, and with $\partial T/\partial r \rightarrow -(4T/\bar{a})$, we have

$$\chi_E \simeq \frac{(1.6 \times 10^{-2}) f_\alpha P_\alpha \quad (\mathrm{MW})}{\langle\beta\rangle\, B_0^2 R} \quad \mathrm{m^2{\cdot}s^{-1}} \ . \qquad (A.1.7)$$

For a D-T plasma the dominant reaction when $n_D \sim n_T$ is

$$\mathrm{D + T \rightarrow {}^4He\ (3.5\ MeV) + n\ (14.1\ MeV)} \ .$$

The power per unit volume is

$$p_f = n_D n_T \overline{\sigma v_{DT}} E_f \ ,$$

where $E_f = 2.82 \times 10^{-12}$ J. To a good approximation for $T_i \sim 10$ keV, the reaction rate is given by

$$\overline{\sigma v_{DT}} \simeq (1.1 \times 10^{-30}) T_i^2 \quad (\mathrm{m^3{\cdot}s^{-1}}) \ ,$$

and

$$p_f = (3.1 \times 10^{-42}) n_D n_T T_i^2 \quad (\mathrm{W{\cdot}m^{-3}}) \ , \qquad (A.1.8)$$

$$p_\alpha = (6.2 \times 10^{-43}) n_D n_T T_i^2 \quad (\mathrm{W{\cdot}m^{-3}}) \ .$$

For the whole plasma, assuming a parabolic pressure profile (see Fig. A.1.1),

$$p_i = n_{i0}T_{i0}(1 - r^2/\bar{a}^2) \ , \qquad \langle n_i T_i \rangle = \frac{n_{i0}T_{i0}}{2} \ ,$$

and

$$P_F = (2.04 \times 10^{-41})\langle n_i T_i \rangle^2 Rab \quad \text{(W)}$$

or

$$P_F = 128\langle \beta_i \rangle^2 B_0^4 Rab \quad \text{(MW)} \ , \qquad \text{(A.1.9)}$$

where $n_D = n_T = 0.5n_i$, and

$$P_\alpha = (0.41 \times 10^{-41})\langle n_i T_i \rangle^2 Rab \quad \text{(W)} \ , \qquad \text{(A.1.10)}$$

$$P_b = (3.5 \times 10^{-37})\bar{n}_e^2(\overline{T}_e)^{1/2} Z_{eff} Rab \quad \text{(W)} \ , \qquad \text{(A.1.11)}$$

and

$$P_s = (2.5 \times 10^{-18})\bar{n}_e \overline{T}_e B_0^2 Rab\phi \quad \text{(W)} \ , \qquad \text{(A.1.12)}$$

where $\phi \simeq (7.8 \times 10^3)\,(\overline{T}_e)^{1.1}\,(B_0/n_e\bar{a})^{1/2}(1 - R_e)^{1/2}$, with $R_e = 0.95$.

As an example, we may use the following values:

$B_0 = 5$ T	$\bar{n}_e = 2.0 \times 10^{20}$ m^{-3}
$\langle \beta \rangle = 0.08$	$\bar{n}_i = 1.7 \times 10^{20}$ m^{-3}
$R = 8$ m	$\bar{n}_\alpha$ (slow) $\simeq 0.12 \times 10^{20}$ m^{-3}
$a = 1.6$ m	$\bar{n}_Z$ (carbon) $\simeq 0.014 \times 10^{20}$ m^{-3}
$b/a = 1.6$	$\overline{T}_e = 11.9$ keV
$Z_{eff} = 1.6$	$\overline{T}_i = 13.9$ keV

From these values, we obtain $P_F = 3470$ MW; $P_\alpha = 695$ MW; $P_b = 80$ MW and $P_s = 29$ MW, which, with allowance for about 5% losses of alphas, leads to $f_\alpha \simeq 0.8$; and $\chi_E \simeq 0.61$ m$^2 \cdot$s^{-1}.

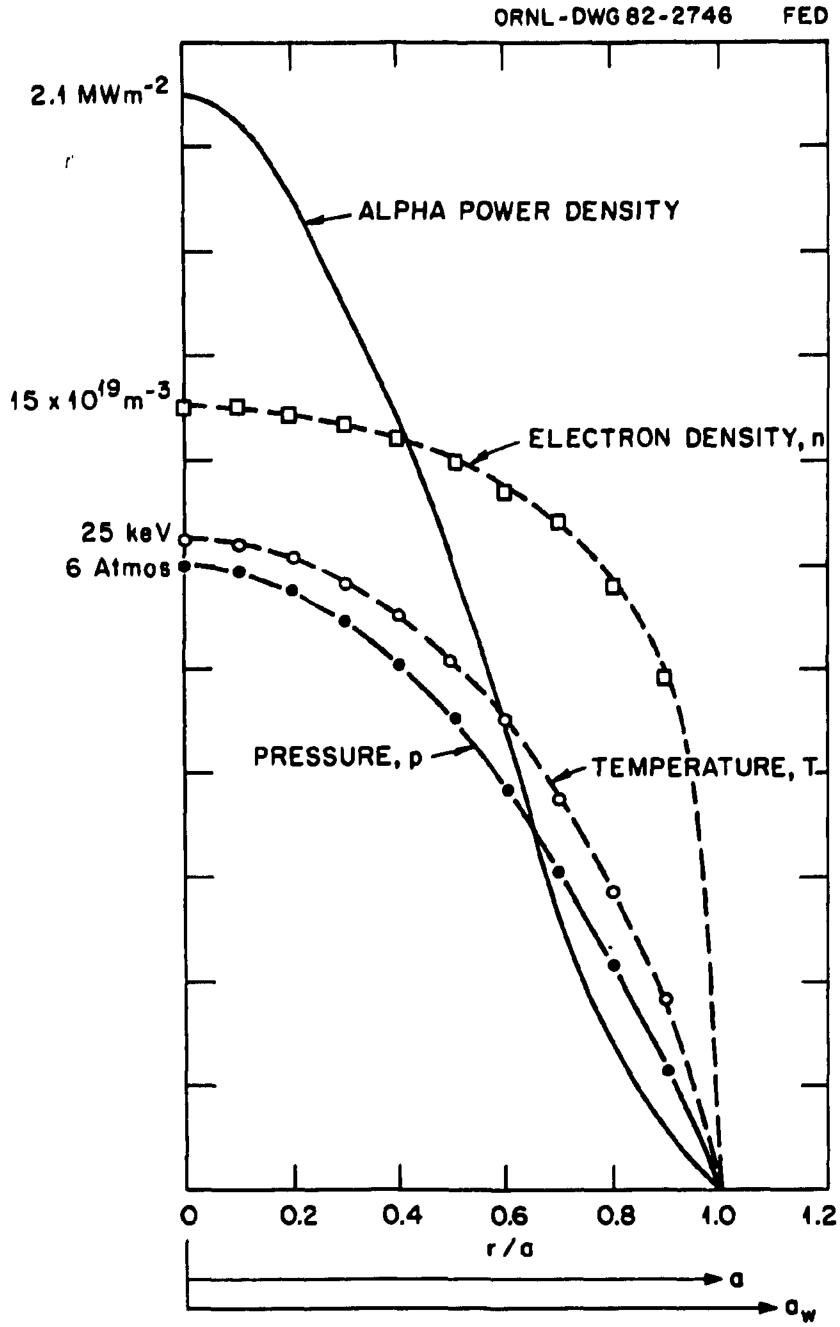

Fig. A.1.1. Representative profiles for the plasma density, temperature, and pressure.

Appendix 2

CALCULATING THE COST OF ELECTRICITY

A.2.1 The Cost of Electricity

The economic analysis uses the procedure discussed in the Nuclear Energy Cost Data Base [1] for the capital cost. The procedure differs slightly in two areas from that proposed for fusion power plants in studies done at Pacific Northwest Laboratories (PNL) [2,3]. The indirect charges for construction are raised from 35% to 50% to better represent present-day power plant experience, and the lithium blanket costs are levelized over the operating lifetime of the power plant and included in the fuel cycle costs. The latter procedure is useful because it shows the effects of power density on the blanket costs.

The cost of electricity (COE) is calculated in two ways. In the current-dollar approach, inflation is explicitly included, the purchasing price of the dollar changes with time, and the COE is quoted in dollars of a future year; the capital costs are levelized [1], and the fuel and operations costs are quoted in dollars of the first year of operation. This makes it difficult for the reader to compare costs with present-day costs. Therefore, in most of this report the costs are quoted in constant 1983 dollars. Where current dollars are used, it is so indicated. The capital investment costs are first calculated in current dollars, and the constant-dollar COE is obtained from the current-dollar value by deflating the current-dollar COE to the 1983 level. This takes into account the effect of inflation on the depreciation of capital costs.

For the constant-dollar case, the operating costs are calculated in 1983 dollars. A levelized cost over the plant operating lifetime is obtained, including both the up-front costs for items such as the initial blanket and the cost of replacement and spare blankets. Inflation and escalation are not included in this calculation. In our view their use would imply a greater knowledge of fusion plant operation than exists. Nevertheless, we believe that the assumptions about operating costs are conservative in terms of the number of personnel and the levels of spares and replacements.

In the comparison of fusion plants with fission and fossil plants, the same procedures [1] are applied, except that the operating costs for the existing plants are better known and levelized values including inflation and escalation are used.

For the current-dollar case, the constant-dollar operating costs are inflated to the first year of operation.

A.2.2 Current-Dollar COE

The current-dollar COE at the first year of operation is given by

$$COE_{current} = \frac{C_I F_{cr} + (C_F + C_{om})(1 + i)^Y}{P_e \times 8760 \times f_{av}} \text{ mill/kWh} , \qquad (A.2.1)$$

where 1 mill = \$0.001, P_e is taken to be the maximum net electric power [MW(e)] (i.e., the plant capacity), 8760 is the number of hours in a year, and f_{av} is the plant availability normalized to the maximum power. In this analysis, the plant capacity factor is assumed to be the same as the availability factor. The level $f_{av} = 0.65$, which is used as the standard in this report, is somewhat higher than recent industry averages for nuclear and coal-fired plants but is somewhat lower than has been achieved by better plants. The requirements to achieve this level are discussed in Appendix 6.

In Eq. (A.2.1), C_F is the equivalent of the annual fuel costs for fission and fossil plants. In those systems it includes the cost of the uranium and coal. In past fusion studies such as STARFIRE [4] and in the PNL costing guidelines [2,3], items such as the initial blanket have been classified as direct costs. This makes it harder to assess the effects of varying, say, power density, since it is the replaceable items that are affected; further, fuel is not generally included in the initial capital cost of nuclear and coal plants. The system used here is to assign to this account all items peculiar to fusion that involve continuing replacement and that relate to the "fuel" or "energy gain" cycles. The items included are the first wall and blanket, limiters/targets, and the expendable components of auxiliary heating used in the power production phases (see Appendix 5.1).

The annual operation costs beyond those included in C_F are represented by C_{om} (see Appendix 5.2). The number of operating staff has been increased from the STARFIRE [4] value of 163 persons to 457 persons following a study of personnel needs for fission plants [5].

The construction lead time in years Y includes design, licensing, construction, and startup and is used with the annual inflation rate ι in the factor $(1 + \iota)^Y$ to raise the constant-dollar (1983) values of C_F and C_{om} to the values appropriate for the first year of operation.

The fixed charge rate F_{CR} is t so that $C_C F_{CR}$ is the equivalent annual charge necessary to meet revenue requirements during a given period; the charge is similar to an annual mortgage payment. Although plants are operated for 30- to 50-year lifetimes, utilities usually use periods less than the full life for cost comparison purposes. This report assumes a 30-year life and a 20-year levelization period. For the interest and inflation rates used in ref. 1 (see Appendix 3), the value is $F_{CR} = 0.165$ for the current-dollar calculation (see Table A.3.2).

The estimated total capitalized cost up to operation of the reactor, including time-related costs (interest and escalation), is

$$C_C = \sum_{j=1}^{B} p(t_j)(1 + y_B)^{j-1}(1 + x_B)^{B+1-j} \quad (\$) , \tag{A.2.2}$$

where B is the number of financial periods (3 months, or 0.25 years, in this report) between the start of facility design, at the year of the constant-dollar price estimate, and the start of full operation. The subscript B is used to denote the appropriate escalation and interest rates for this shorter period.

The effective escalation rate y_B is taken here to be the inflation rate ι_B; x_B is the effective tax-adjusted cost of money for the chosen period [see Eq. (A.2.7)]; and $p(t_j)$ is the constant-dollar direct and indirect capital investment costs paid in the period from t_{j-1} to t_j.

A typical form for the accumulative spending rate, given in Fig. A.2.1, is

$$C_D f_{IND} = \sum_{j=1}^{B} p(t_j) \;, \qquad \text{(A.2.3)}$$

where C_D (in dollars) is the direct capital cost and f_{IND} is the indirect cost multiplier, which is taken to be typical of better fission plant experience [1], since we hope that fusion will be less affected by changing regulations. For the nominal 8-year total lead time (Y = 8) assumed in this report, the indirect charges f_{IND} = 1.50, where construction facilities, equipment, and services constitute 15%; engineering management services, 25%; and owners' costs, 10%. The total indirect charges are similar to those recommended in the PNL studies [2,3] when a 6-year lead time is assumed; they are substantially larger than those used for STARFIRE [4], which assumes factory fabrication and modular construction,

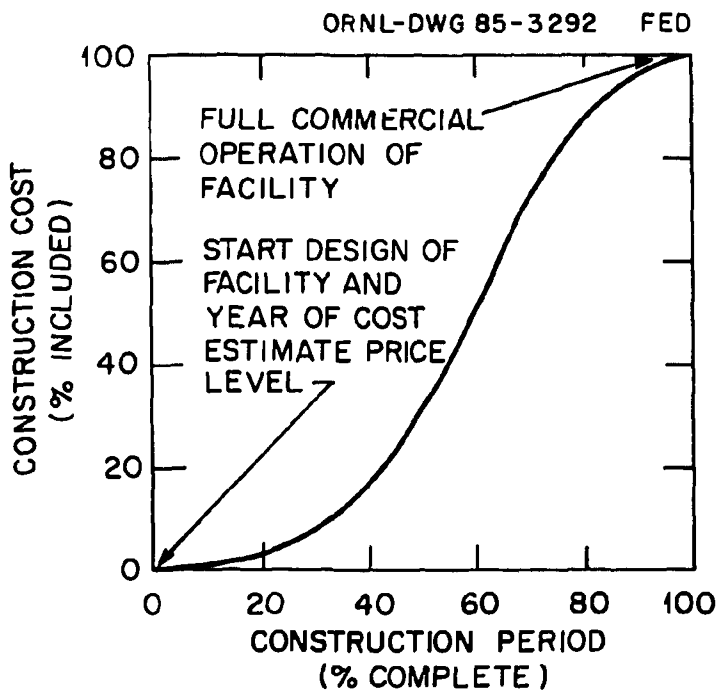

Fig. A.2.1. Reference cumulative expenditure pattern for a conventional power plant (S. C. Schulte et al., *Fusion Reactor Design Studies--Standard Accounts for Cost Estimates*, PNL-2648, Pacific Northwest Laboratories, 1978).

because in principle the same procedure could be used for fission systems and we are attempting to compare with present-day fission systems. For fossil plants, the indirect charges and construction lead times are generally less [1]. To relate indirect charges and lead time, we assume that

$$f_{IND} \simeq \left(1 + 0.5\,\frac{Y}{8}\right) , \qquad 6 \leq Y \leq 12 \; . \tag{A.2.4}$$

This relation is consistent with the coupled values of indirect charges and lead times given in ref. 1. The purpose of this assumption is to set a penalty or gain for varying lead time that goes beyond that obtained with a fixed spending profile as lead time is varied, which increases the time-related charges.

A.2.3 Constant-Dollar COE

The constant-dollar COE is given by

$$\mathrm{COE} = \frac{C_{C0}F_{CR0} + C_F + C_{om}}{P_e \times 8760 \times f_{av}} \quad (\mathrm{mill/kWh}) \; , \tag{A.2.5}$$

where C_{C0} is the constant-dollar capital investment cost,

$$C_{C0} = \sum_{j=1}^{B} p(t_j)\left(\frac{1 + y_B}{1 + \iota_B}\right)_{j-1}\left(\frac{1 + x_B}{1 + \iota_B}\right)_{B+1-j} \quad (\$) \; , \tag{A.2.6}$$

and F_{CR0} is the constant-dollar fixed charge rate derived in Appendix 3, where a value of $F_{CR0} = 0.10$ is calculated. For zero inflation, $F_{CR0} = F_{CR}$.

A.2.4 Time-Related Costs

After the indirect charges have been added to the direct costs [Eq. (A.2.3)], the time-related costs must be included to obtain the total capitalized cost C_C. It is assumed here that the cumulative expenditure pattern has the same form as that for a conventional power plant [2], shown in Fig. A.2.1. The time-related costs consist of the cost of interest during construction and the cost of escalation during construction (EDC).

The effective tax-adjusted cost of money (COM) is given by

$$x = (1 - \tau)r_b f_b + r_s f_s + r_p f_p \; , \tag{A.2.7}$$

where τ is the effective income tax rate on net corporate income, f_b is the debt (bond) fraction and r_b is the debt (bond) interest rate, f_s is the equity (stock) fraction and r_s is the equity (stock) return rate, and f_p is the preferred stock fraction and r_p is the interest rate on preferred stock.

In this report is is assumed, following ref. 1, that

the federal income tax rate $\tau_F = 0.46$,
the state income tax rate $\tau_s = 0.04$,
the effective tax rate $\tau = \tau_s + (1 - \tau_s)\tau_F = 0.4816$,
the capitalization debt $f_b = 0.50$ with an interest rate $r_b = 0.10$,
the preferred stock fraction $f_p = 0.12$ with an interest rate $r_p = 0.09$, and
the equity (stock) fraction $f_s = 0.38$ with an interest rate $r_s = 0.14$;

consequently, the effective COM is $x = 0.09$.

Further, it is assumed that escalation and general inflation are the same,

$$y = \iota = 0.06 \ .$$

The formulation of Eq. (A.2.2) assumes that money is borrowed at the beginning of a financial period to pay for all charges during that period. Alternative forms are sometimes used; for example, Phung [6] assumes that money is borrowed at the end of a financial period. These alternative forms give similar answers if the chosen financial period is short. We use a 3-month financial period with the COM and escalation given by $1 + x_B = (1 + x)^{1/4}$ and $1 + y_B = (1 + y)^{1/4}$. An alternative approach might be to set $(1 + x_B) = (1 + x/4)$. For $x \lesssim 0.1$, the two forms give similar answers. Clearly, this is a matter to be worked out between lender and borrower.

The current-dollar capitalization factor (f_{CAP}) is the ratio of the current-dollar capitalized cost to the nonescalated or inflated construction cost (overnight cost),

$$f_{CAP} = \frac{C_C}{C_D f_{IND}} = \frac{\sum_{j=1}^{B} \left\{ \left[(1 + y)^{1/4}\right]^{j-1} \left[(1 + x)^{1/4}\right]^{B+1-j} p(t_j) \right\}}{\sum p(t_j)} \ . \qquad \text{(A.2.8a)}$$

A simple formula derived for f_{CAP} is a good approximation for $\iota = y$ in the range 0.06–0.12, x in the range 0.06–0.12, and Y in the range 6–12 years; it is

$$f_{CAP} = [1.0840 + 0.55(\iota - 0.09) + 0.38(x - 0.09)]^{Y+0.61} \ . \qquad \text{(A.2.8b)}$$

Similarly, the constant-dollar capitalization factor (f_{CAP0}) is the ratio of this constant-dollar capitalized cost to the nonescalated or inflated construction cost (overnight cost), as if there were zero construction time,

$$f_{CAP0} = \frac{C_{C0}}{C_D/f_{IND}} = \frac{\sum_{j=1}^{B} \left[\left(\frac{1+y}{1+\iota}\right)^{1/4}\right]^{j-1} \left[\left(\frac{1+x}{1+\iota}\right)^{1/4}\right]^{B+1-j} p(t_j)}{\sum p(t_j)} \qquad \text{(A.2.9a)}$$

or, when $\iota = y$,

$$f_{CAP0} = \frac{f_{CAP}}{(1+\iota)^Y} \ . \qquad \text{(A.2.9b)}$$

The ratio of the total capitalized cost, including inflation, to the total escalated cost paid for construction is also important because the IDC is not a deductible item for income tax purposes. This ratio is given by

$$f_{IDC} = \frac{\sum_{j=1}^{B} \left\{\left[(1+y)^{1/4}\right]^{j-1} \left[(1+x)^{1/4}\right]^{B+1-j} p(t_j)\right\}}{\sum_{j=1}^{B} \left\{p(t_j)\left[(1+y)^{1/4}\right]^{j-1}\right\}} \ , \qquad \text{(A.2.10)}$$

where the construction time $Y = B/4$.

For simplicity in evaluating these functions, we use a simple functional form for $p(t_j)$,

$$p(\psi) = A[\sin(\psi - 90°) + 1.0] \ , \quad 0 \leq \psi \leq 180° \ , \qquad \text{(A.2.11)}$$

$$A[0.95 \sin(1.7\psi + 144°) + 1.05] \ , \quad 180° \leq \psi \leq 257.1° \ ,$$

where $\psi = j(257.1/B)°$ and

$$A = \sum_{j=1}^{B} p(\psi) \ .$$

In Table A.2.1, values of f_{IDC}, f_{CAP}, and f_{CAP0} are given for different construction times Y.

Table A.2.1. Interest charges as a function of construction time for $\iota = y = 0.06$ and $x = 0.09$[a]

Lead time	Capitalization factor		Interest factor
	Current dollars	Constant dollars	
Y (years)	f_{CAP}	f_{CAPO}	f_{IDC}
4	1.327	1.051	1.165
5	1.422	1.063	1.204
6	1.524	1.075	1.244
7	1.634	1.087	1.286
8	1.751	1.099	1.328
9	1.877	1.111	1.372
10	2.012	1.123	1.418
11	2.156	1.136	1.464
12	2.311	1.149	1.512
13	2.478	1.162	1.561
14	2.656	1.175	1.612

[a]These calculations assume the expenditure pattern given by $p(t)$ in Eq. (A.2.11). If $Y = 8$ but operation is delayed, say, an additional 6 years, so that interest is paid for 6 years on the full capitalized cost, then charges will be substantially higher. This is another problem altogether and is not addressed in this report.

REFERENCES FOR APPENDIX 2

[1] *Nuclear Energy Cost Data Base—A Reference Data Base for Nuclear and Coal-Fired Powerplant Power Generation Cost Analysis*, DOE/NE-0044, U.S. Department of Energy, 1982 and subsequent updates.

[2] S. C. Schulte et al., *Fusion Reactor Design Studies—Standard Accounts for Cost Estimates*, PNL-2648, Pacific Northwest Laboratories, 1978.

[3] S. C. Schulte et al., *Fusion Reactor Design Studies—Standard Unit Costs and Cost Scaling Rules*, PNL-2987, Pacific Northwest Laboratories, 1979.

[4] C. C. Baker et al., *STARFIRE—A Commercial Tokamak Fusion Power Plant Study*, ANL/FPP-80-1, Argonne National Laboratory, Argonne, Ill., 1980.

[5] M. L. Myers et al., *Nonfuel Operations and Maintenance Costs for Large Steam-Electric Power Plants*, ORNL/TM-8324, Oak Ridge National Laboratory, 1982.

[6] D. C. Phung, *A Method for Estimating Escalation and Interest During Construction (EDC and IDC)*, ORAU/IEA-78-7, Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tenn., 1978.

Appendix 3

CALCULATION OF THE FIXED CHARGE RATE

A.3.1 Equivalent Annual Charge on Capital Investment Cost

During the operating life of the plant, a quantity $C_C F_{CR}$ may be calculated, which is the equivalent fixed annual cost of charges that can be related directly to the initial capital investment. The fixed charge rate factor F_{CR} may be determined as follows [1]. The capital at the start of the first period is $V_1 = C_C$. The taxes T to be paid at the end of the first period will be on the revenue minus the total deductions,

$$T_1 = \tau\left[R_1 - O_1 - D_1^T - C_C r_b f_b\right] - (\mathrm{ITC})_0 \ , \tag{A.3.1}$$

where T_1 indicates the taxes for year 1 and

τ = effective tax rate,
R_1 = revenue during year 1,
O_1 = property taxes and interim replacement of general plant,
D_1^T = tax-deductible depreciation,
f_b = fraction of capitalization from debt,
r_b = interest rate paid on debt, and
$(\mathrm{ITC})_0$ = investment tax credit on the initial capital investment.

All operating costs are accounted for separately. Interim replacement is taken as 0.5% per year of the initial capital investment.

At the end of the first period, the funds available C_1 to pay back the outstanding capital will be

$$C_1 = R_1 - O_1 - C_C(r_b f_b + r_s f_s) - T_1 \tag{A.3.2}$$

$$= (1 - \tau)(R_1 - O_1) - C_C[r_s f_s + (1 - \tau) r_b f_b] + \tau D_1^T + (\mathrm{ITC})_0 \ ,$$

where f_s is the fraction of capitalization from equity and r_s is the interest rate paid on equity. Note that the COE and the revenue R will be set by the need to pay back the capital at the agreed rate over the agreed number of years.

At the beginning of the second year, the outstanding capital is

$$V_2 = C_C - C_1 \ . \tag{A.3.3}$$

In the analysis of ref. 1, any additional capital investment made during the first year is added to Eq. (A.5.10). In this analysis, however, such charges are put in the fuel cycle account, so

$$V_2 = C_C - (1 - \tau)(R_1 - O_1) + C_C[r_s f_s + (1 - \tau) r_b f_b] - \tau D_1^T - (ITC)_0$$

or

$$V_2 = C_C[1 + r_s f_s + (1 - \tau) r_b f_b] + (1 - \tau) O_1 - \tau D_1^T - (1 - \tau) R_1 - (ITC)_0 \ . \quad \text{(A.3.4)}$$

The tax-adjusted discount rate, or cost of money (COM), is defined in Eq. (A.5.2) as

$$x = r_s f_s + (1 - \tau) r_b f_b + r_p f_p \ ,$$

so

$$V_2 = (1 + x) C_C + (1 - \tau) O_1 - \tau D_1^T - (1 - \tau) R_1 - (ITC)_0 \ .$$

Taxes to be paid at the end of the second period are

$$T_2 = \tau (R_2 - O_2 - D_2^T - V_2 r_b f_b) \ ,$$

so the funds available to pay back the outstanding capital will be

$$C_2 = R_2 - O_2 - V_2(r_b f_b + r_s f_s) - \tau (R_2 - O_2 - V_2 r_b f_b - D_2^T) \ . \quad \text{(A.3.5)}$$

The capital outstanding at the beginning of the third period is

$$V_3 = V_2 - C_2$$
$$= (1 + x) V_2 + I_2 + (1 - \tau) O_2 - \tau D_2^T - (1 - \tau) R_2 \ , \quad \text{(A.3.6)}$$

or, substituting for V_2,

$$V_3 = C_C(1 + x)^2 + (1 - \tau)[(1 + x) O_1 + O_2] - (1 - \tau)[(1 + x) R_1 + R_2] - (1 + x)\tau[D_1^T + (ITC)_0] + \tau D_2^T \ .$$

If we continue this procedure through the $(N-1)$th period, then

$$V_N = C_C(1+x)^{N-1} + (1-\tau)\sum_{n=1}^{N-1} O_n(1+x)^{N-1-n}$$

$$- (1-\tau)\sum_{n=1}^{N-1} R_n(1+x)^{N-1-n} - \tau\sum_{n=1}^{N-1} D_1^T(1+x)^{N-1-n}$$

$$- (ITC)_0(1+x)^{N-2} \; . \qquad \text{(A.3.7)}$$

At the end of the Nth period, the repayments should be such that the outstanding capital is equal to a salvage value or unrecovered book value S; therefore, $V_{n+1} = S$ or

$$(1-\tau)\sum_{n=1}^{N} R_n(1+x)^{N-n} = C_C(1+x)^N - S + (1-\tau)\sum_{n=1}^{N} O_n(1+x)^{N-n}$$

$$- \tau\sum_{n=1}^{N} D_1^T(1+x)^{N-n} - (ITC)_0(1+x)^{N-1} \; . \qquad \text{(A.3.8)}$$

It is now assumed that the annual revenues R_n used to service the capital-investment-related costs are held constant, as for a mortgage, such that

$$R_n = C_C F_{CR} \; . \qquad \text{(A.3.9)}$$

Equation (A.3.9) is now divided by $(1-\tau)(1+x)^N$, and use is made of the equality

$$\sum_{n=1}^{N} \frac{1}{(1+x)^n} = \frac{1-(1+x)^{-N}}{x} \; . \qquad \text{(A.3.10)}$$

The inverse of this quantity is the commonly used capital recovery factor (CRF),

$$\mathrm{CRF}(x,N) = \frac{x}{1-(1+x)^{-N}} \; ,$$

and assuming constant annual operational charges $O_n = O_p$,

$$F_{CR} = \mathrm{CRF}(x,N)\left\{\frac{[1 - s(1 + x)^{-N}]}{(1 - \tau)} - \frac{(\mathrm{ITC})_0}{(1 - \tau)(1 + x)C_C}\right.$$

$$\left.\times \frac{\tau}{(1 - \tau)} \sum_{n=1}^{N} \frac{D_n^T(1 + x)^{-n}}{C_C}\right\} + O_p \ . \qquad (A.3.11)$$

With $(\mathrm{ITC})_0$ a fixed percentage r_{ITC} of the capitalized investment cost [excluding the interest during construction (IDC)],

$$(\mathrm{ITC})_0 = \frac{r_{ITC}C_C}{f_{IDC}} \ .$$

Equally, the tax depreciation (D_n^T) is a given percentage r_{Dn} of the capitalized investment cost excluding the IDC,

$$D_n^T = \frac{r_{Dn}C_C}{f_{IDC}} \ .$$

The percentages r_{Dn} are given in Table A.3.1 for tax depreciation over ten years.

The salvage value S, or undepreciated book value, is some fraction s of the initial investment cost $S = sC_C$. The fixed charge rate is given by

$$F_{CR} = \left\{\frac{x}{[1 - (1 + x)^{-N}]}\right\} \left\{\frac{[1 - s(1 + x)^{-N}]}{(1 - \tau)} - \frac{1}{(1 - \tau)(1 + x)} \frac{r_{ITC}}{f_{IDC}}\right.$$

$$\left. - \frac{\tau}{(1 - \tau)} \sum_{n=1}^{N} \frac{r_{Dn}}{f_{IDC}} (1 + x)^{-n}\right\} + O_p \ . \qquad (A.3.12)$$

This rate is based upon current COMs, which include a general inflation rate i. This is applied to the total capitalized cost, including inflation. To obtain the constant-dollar fixed charge rate, it is necessary to renormalize Eq. (A.3.12) to the constant-dollar cost of

Table A.3.1. Depreciation recovery expenses

Year (n)	Percentage (r_{Dn})
1	8
2	14
3	12
4	10
5	10
6	10
7	9
8	9
9	9
10	9

Source: Nuclear Energy Cost Data Base—A Reference Data Base for Nuclear and Coal-Fired Powerplant Power Generation Cost Analysis, DOE/NE-0044, U.S. Department of Energy, 1983 and subsequent updates.

money, which is given by $x_0 = (x - y)/(1 + y)$. This is achieved by multiplying by the ratio of constant to current dollars,

$$\hat{R} = \frac{x_0/[1 - (1 + x_0)^{-N}]}{x/[1 - (1 + x)^{-N}]}$$

or

$$\hat{R} = \frac{\mathrm{CRF}(x,N)}{\mathrm{CRF}(x_0,N)} \ ,$$

as discussed in ref. 1. Thus,

$$F_{\mathrm{CR0}} = \hat{R}F_{\mathrm{CR}} \ . \tag{A.3.13}$$

This constant-dollar fixed charge rate is applied to the constant-dollar capitalized cost.

Although the fixed charge rate derivation shown here was obtained using a discounted cash-flow approach, the same results may be found using utility revenue requirements methodology with flowthrough tax accounting. The method is discussed in detail in ref. 1. With this approach, the year-by-year revenues needed by the utility to pay operating costs, taxes, return on undepreciated capital investment, and depreciation are calculated. The basic equation for the necessary revenue in period n is

$$R_n = (r_s f_s + r_p f_p + r_b f_b)V_n + D_n^B + O_n + T_n \ .$$

The income taxes for that period are

$$T_n = \tau(R_n - O_n - D_n^T - V_n r_b f_b) - \mathrm{ITC}_n \ ,$$

where

$$\mathrm{ITC}_n = \frac{r_{\mathrm{ITC}} C_C}{f_{\mathrm{IDC}}} \ , \quad n = 1$$

$$= 0 \ , \quad n \neq 1 \ .$$

The plant is depreciated for book purposes over the life of the plant L,

$$D_n^B = \frac{C_C}{L} \ .$$

The rate base term V_n is the undepreciated capital investment,

$$V_n = C_C - \sum_{j=1}^{n-1} D_n^B \ .$$

If only those costs that are directly related to the initial investment are considered, then the levelized fixed charge rate over the first N years of the project may be found as

$$F_{CR} = \frac{\mathrm{CRF}(x,N)}{C_C} \sum_{n=1}^{N} \frac{R_n}{(1 + x)^n} \ ;$$

here the revenues R_n are in current dollars, including inflation. Inflation may be removed from R_n, adjusting it to dollars of the buying power of the beginning of the startup year, by the equation

$$R_{0,n} = \frac{R_n}{(1+y)^n} \ .$$

The constant-dollar fixed charge rate is then determined by the expression

$$F_{CR0} = \frac{CRF(x_0,N)}{C_C} \sum_{n=1}^{N} \frac{R_0 n}{(1+x_0)^n} \ .$$

Note that

$$\sum_{n=1}^{N} \frac{R_n}{(1+x)^n} = \sum_{n=1}^{N} \frac{R_{0,n}}{(1+x_0)^n}$$

and

$$F_{CR0} = \hat{R}F_{CR} \ ,$$

as shown previously.

A.3.2 Fixed Charge Rate for Other Costs of Money

The results of the calculation of the fixed charge rate using the revenue requirements equations are shown in Table A.3.2. The levelized fixed charge rates over the first 20 years of a 30-year plant life are shown. The same results would have been obtained using Eqs. (A.3.12) and (A.3.13) if the quantity s is the unrecovered book value fraction or 0.333 for a 30-year plant life and 20-year levelization period.

The parameters used in the calculation are as follows:

Levelization period $N = 20$ years
Plant life $L = 30$ years
Federal income tax rate $\tau_f = 0.46$
State income tax rate $\tau_s = 0.04$
Effective tax rate $\tau = \tau_s + (1 - \tau_s)\tau_f = 0.4816$
Capitalization
  Debt fraction and rate $f_b = 0.50$, $r_b = 0.10$
  Preferred stock fraction and rate $f_p = 0.12$, $r_p = 0.09$
  Equity fraction and rate $f_s = 0.38$, $r_s = 0.14$
General inflation rate $\iota = 0.06$
Tax-adjusted cost of money $x = 0.09$
Constant-dollar cost of money $x_0 = 0.0283$

Table A.3.2. Fixed charge rate using revenue requirements methods[a]

Initial investment = $1000; IDC factor = 1.3280

								Revenue requirements		Cumulative F_{CR}	
Year	Rate base	Return on capital	Book depreciation	Tax depreciation	Income taxes	Property taxes	Interim replacement	Current dollars	Constant dollars	Current dollars	Constant dollars
1	1000.00	114.0	33.3	60.2	−81.7	20.0	5.3	90.9	85.7	0.0909	0.0857
2	966.7	110.2	33.3	105.4	−9.5	20.0	5.6	159.7	142.1	0.1238	0.1135
3	933.3	106.4	33.3	90.4	2.5	20.0	6.0	168.2	141.2	0.1373	0.1225
4	900.0	102.6	33.3	75.3	14.5	20.0	6.3	176.8	140.0	0.1460	0.1267
5	866.7	98.8	33.3	75.3	12.5	20.0	6.7	171.4	128.1	0.1502	0.1270
6	833.3	95.0	33.3	75.3	10.6	20.0	7.1	166.0	117.0	0.1523	0.1254
7	800.0	91.2	33.3	67.8	15.6	20.0	7.5	167.6	111.5	0.1540	0.1236
8	766.7	87.4	33.3	67.8	13.6	20.0	8.0	162.3	101.8	0.1547	0.1211
9	733.3	83.6	33.3	67.8	11.6	20.0	8.4	157.0	92.9	0.1549	0.1183
10	700.0	79.8	33.3	67.8	9.6	20.0	9.0	151.7	84.7	0.1547	0.1154
11	666.7	76.0	33.3	0.0	70.6	20.0	9.5	209.4	110.3	0.1578	0.1150
12	633.3	72.2	33.3	0.0	68.6	20.0	10.1	204.2	101.5	0.1601	0.1140
13	600.0	68.4	33.3	0.0	66.6	20.0	10.7	199.0	93.3	0.1618	0.1127
14	566.7	64.6	33.3	0.0	64.7	20.0	11.3	193.9	85.8	0.1630	0.1111
15	533.3	60.8	33.3	0.0	62.7	20.0	12.0	188.8	78.8	0.1639	0.1093
16	500.0	57.0	33.3	0.0	60.7	20.0	12.7	183.7	72.3	0.1645	0.1075
17	466.7	53.2	33.3	0.0	58.7	20.0	13.5	178.7	66.4	0.1649	0.1055
18	433.3	49.4	33.3	0.0	56.7	20.0	14.3	173.7	60.0	0.1651	0.1036
19	400.0	45.6	33.3	0.0	54.7	20.0	15.1	168.8	55.8	0.1652	0.1017
20	366.7	41.8	33.3	0.0	52.8	20.0	16.0	163.9	51.1	0.1652	0.0998

[a] Fixed charge rate: current-dollar rate = 0.1652; constant-dollar rate = 0.0998.

Investment tax credit fraction $r_{ITC} = 0.08$
Depreciation recovery expenses r_{Dn} given in Table A.5.2
Interest factor $f_{IDC} = 1.328$
Ratio of constant to current dollars $\hat{R} = 0.604$
Operating costs
Property taxes = 0.02
Interim replacement = 0.008, which allows for 6% inflation on annual replacement cost of 0.5% of initial capital investment
$O_p = 0.028$

The results shown assume flowthrough tax accounting. Normalized tax accounting procedures will result in slightly higher fixed charge rates.

The current-dollar fixed charge rate was taken as 0.165 and the constant-dollar fixed charge rate as 0.10 for this analysis. The actual fixed charge rate for a utility project will depend on many factors. One important factor is a utility's cost of money. Fixed charge rates for alternative COMs are shown in Table A.3.3. A 6% inflation rate is assumed. The 12% COM could occur if recent trends in utility finance were to continue. A utility with the reference capital structure and tax rate would have to have a 17% equity return, a 14% preferred stock return, and a 14.9% cost of borrowed money to achieve an effective COM of 12%.

Table A.3.3. Fixed charge rates for alternative costs of money

Cost of money (%)	Fixed charge rates[a] Current-dollar rate F_{CR}	Constant-dollar rate F_{CR0}
7	0.134	0.078
8	0.149	0.089
9	0.165	0.100
10	0.182	0.112
11	0.198	0.124
12	0.215	0.136

[a]6% inflation/escalation rate.

REFERENCE
FOR APPENDIX 3

[1] *Nuclear Energy Cost Data Base—A Reference Data Base for Nuclear and Coal-Fired Powerplant Power Generation Cost Analysis*, DOE/NE-0044, U.S. Department of Energy, 1982 and subsequent updates.

Appendix 4

CAPITAL COSTS

A.4.1 Comparison of Fusion and Fission Costs

Fusion plant component costs are based mainly upon STARFIRE costs [1], with adjustments made to reflect inflation from 1980 to 1983 and improved information on some of the unit costs. The fission reactor costs are based upon the study in ref. 2, adjusted to a 1200-MW(e) plant size. The direct and indirect costs of a representative 1200-MW(e) pressurized water reactor (PWR) and STARFIRE are given in Table A.4.1. A standard accounts arrangement, used in the STARFIRE report, is followed. For the fission reactor, the first column gives medium costs for recently constructed reactors; the second column reflects savings that might result from regulatory reform, which would lead to more rapid construction with fewer changes. These costs also reflect the best of current experience. The main differences between fission and fusion are in account 21 (structures), where the reactor building and hot cells raise fusion costs, and in account 22 (reactor plant equipment). The cost increases for fusion reflect the size and weight of the STARFIRE reactor plant, which are considerably greater than those of a PWR. It should be noted that in account 22 for STARFIRE the blanket is included, while customarily the fuel for a fusion reactor is carried in a fuel account. The assumptions made by different authors about indirect charges vary widely; for the comparison in this report, the indirect charges are set at 50% for all reactors, and the contingency is taken to be 15%. For the fission reactor, today's medium costs (column 1) are used. Thus, the total costs taken are intermediate between the medium and the best of present experience.

A detailed breakdown of account 22 is given in Table A.4.2. In Table A.4.3 fission and fossil costs are compared.

A.4.2 Cost Breakdown

The costing procedure follows that of STARFIRE, except that the blanket and first wall, limiters, targets, 25% of the auxiliary heating costs, and 80% of the miscellaneous replacement costs are placed under fuel cycle costs. This procedure is used to clarify the comparison with fission and fossil systems. The fuel cycle costs, which include accounts 22.011, 22.014, 22.018, 22.019 and 22.8 (80%), are discussed in Appendix 5.

The remaining capital costs are included under three categories. For this generic model, simple scaling relationships are used.

1. Balance of plant: Items with costs that scale with the plant thermal power P_t.
2. Reactor building: Items with costs that scale with the volume of the fusion island (plasma, scrapeoff layer, first wall and blanket, shield, coils, and support structure).
3. Fusion island: Items for which costs are calculated using the required component volume and a unit cost [density × ($/kg)].

Table A.4.1. Comparison of costs for a PWR and STARFIRE

Account number	Title	Cost[a] (millions of 1983 dollars) 1200-MW(e) PWR[b] Medium	Best	1200-MW(e) STARFIRE
20	Land	5	5	4
21	Structures	238	182	364[c]
22	Reactor plant equipment	287	264	1027
23, 26	Turbine plant, heat rejection	273	249	263
24	Electric plant	105	83	123
25	Miscellaneous	34	28	43
Subtotal (direct)		943	811	1824
Contingency (15%)		141	120	274
Indirect charges		820 (75.6%)	465 (50%)	483 (23%)
Total[d]		1904	1396	2581
Initial fuel costs		~100	~100	

[a]The costs were adjusted to 1983 dollars assuming an inflation factor of 1.094 for 1980–81, 1.063 for 1981–82, and 1.038 for 1982–83 (factors taken from *Business Conditions Digest*, Bureau of Economic Analysis, U.S. Department of Commerce, September 1984).

[b]Costs adjusted from 1100-MW(e) size in *Nuclear Energy Cost Data Base—A Reference Data Base for Nuclear and Coal-Fired Powerplant Power Generation Cost Analysis*, DOE/NE-0044/2, U.S. Department of Energy, 1982; updated 1983.

[c]Reactor buildings and hot cells $255 million, other buildings $109 million.

[d]Overnight costs, excluding escalation and interest during construction.

Table A.4.2. Comparison of reactor plant equipment (account 22) costs of a PWR and STARFIRE

Account number	PWR Title	PWR Cost (millions of 1983 dollars)	STARFIRE Title	STARFIRE Cost (millions of 1983 dollars)
22.011	Vessel	20	Blanket, first wall	99
22.012	Internals	11	Shield	225
22.013	Control rods	13	Magnets	207
22.014			Auxiliary heating	40
22.015			Structure	65
22.016	Undistributed costs	37	Vacuum	6
22.017			Power supplies	65
22.018			Impurity control	3
22.019			ECH breakdown	4
22.1	Reactor equipment	6		
22.2	Main heat transfer	83	Main heat transfer	84
22.3	Safeguards	26	Cryogenics	19
22.4	Radioactive waste processing	20	Radioactive waste processing	6
22.5	Fuel handling and storage	7	Fuel handling and storage	47
22.6	Other reactor plant equipment	42	Other reactor plant equipment	53
22.7	Instrumentation and controls	16	Instrumentation and controls	28
22.8	Spare parts allowance	6	Spare parts allowance	80
Total		287	Total	1027

Table A.4.3. Cost comparison for STARFIRE and 1200-MW(e) generic fusion reactor

Account number	Title	Direct cost (millions of 1983 dollars) STARFIRE[a]	Generic reactor
	Balance of plant [Costs to be scaled as $(P_t/4150)^{0.6}$][b]		
20	Land	4	4
21	Buildings (except main reactor, hot cells)	109	109
22.4	Radioactive waste processing	6	6
22.5	Fuel handling[c]	47	55
22.6	Other reactor plant equipment	53	53
22.7	Instrumentation and controls	28	28
22.8	Spare parts allowance[d]	80	6
23, 26	Turbine plant, main heat rejection	263	263
24	Electrical plant equipment	123	110
25	Miscellaneous equipment	43	43
		756	677
	[Costs to be scaled as $(V_{FI}/5100)^{0.7}$][e]		
21	Main reactor building, hot cells	255	255
22.016	Vacuum[f]	6	9
22.017	Power supplies, coils, peripherals[g]	69	24
22.3	Cryogenics[h]	20	31
		350	319

Table A.4.3. (continued)

Account number	Title	Direct cost (millions of 1983 dollars)	
		STARFIRE[a]	Generic reactor
	Fusion island		
		Unit cost	
22.012	Shield unit cost	17 $/kg	17 $/kg
22.013	Coils unit cost	28 $/kg	80 $/kg
22.015	Structure unit cost	23 $/kg	23 $/kg
22.014 22.019	Auxiliary heating[i] unit cost	0.38 $/kW	2.0 $/kW
22.2	Main heat transfer system	84	$84(P_t/4150)^{0.6}$

[a]Costs adjusted to 1983 dollars assuming an inflation factor of 1.094 for 1980–81, 1.063 for 1981–82, and 1.038 for 1982–83. Factors taken from *Business Conditions Digest*, Bureau of Economic Analysis, U.S. Department of Commerce, September 1984.

[b]The exponent for the scaling with power is based upon fission reactor experience (M. L. Myers et al., *Nonfuel Operations and Maintenance Costs for Large Steam-Electric Power Plants*, ORNL/TM-8324, Oak Ridge National Laboratory, 1982; G. R. Smolen et al., *Regional Projections of Nuclear and Fossil Electric Power Generation Costs*, ORNL/TM-8958, Oak Ridge National Laboratory, 1983).

[c]The increase reflects the addition of two pellet injectors (unit cost $5 million). One fueler is sufficient for operation.

[d]In the generic reactor costing, most spares are carried in other accounts (e.g., blanket, auxiliary heating, limiters/targets, coil redundancy). The cost in this account is 20% of $30 million; the remaining 80% is carried under fuel cycle costs.

[e]The remaining 80% of the $30 million cost is carried in the fuel cycle costs. The fusion island volume V_{FI} is the volume of plasma, scrapeoff layer, blanket, first wall, shield, structure, and magnets.

[f]Increased for generic reactor to include redundancy.

[g]Reduced for generic reactor because auxiliary heating power supply costs are carried in account 22.014. Coil supply costs are representative of those used in a number of reactor designs (C. C. Baker et al., *STARFIRE—A Commercial Tokamak Fusion Power Plant Study*, ANL/FPP-80-1, Argonne National Laboratory, Argonne, Ill., 1980; *MARS, Mirror Advanced Reactor Studies*, UCRL-53333, Lawrence Livermore National Laboratory, Livermore, Calif., 1983; C. G. Bathke et al., *ELMO Bumpy Torus Reactor and Power Plant*, LA-8882-MS, Los Alamos National Laboratory, Los Alamos, N.M., 1981; R. L. Miller et al., *A Modular Stellarator Reactor*, LA-9737-MS, Los Alamos National Laboratory, Los Alamos, N M., 1983).

[h]A study of the cryogenics costs for STARFIRE and MARS (see note *g*) shows that the liquid helium (LHe) refrigeration capability amounts to approximately 20 W per cubic meter of superconducting magnet. The liquid nitrogen (LN_2) capability is approximately 400 W per cubic meter of magnet. Taking the MARS recommendations of 1330 $/W for LHe refrigeration and 16 $/W for LN_2 refrigeration leads to a capital cost of $31 million for STARFIRE, for which the total coil volume is 950 m^3. To allow for variations with the fusion reactor size it is assumed that this cost is given by $31(V_{FI}/5100)^{0.67}$, where V_{FI} is the volume of the nuclear island, normalized to the equivalent STARFIRE volume.

[i]75% of cost; the remaining 25% is carried in the fuel cycle costs. The direct cost per unit electric power including power supplies reflects present experience in devices with high-power, long-pulse heating systems. Lower costs may be achieved as the heating systems are developed further.

This is a simple model, but it should be adequate for achieving the main purposes of this study, which are (1) to determine the scale of a 1200-MW(e) fusion reactor that would be competitive with a fission plant of comparable output; (2) to determine the physics and technology requirements for such a reactor; and (3) to determine the sensitivity of the results to the assumptions and requirements. The model is less adequate for describing the cost variation with power output P_e. The costs are listed in Table A.4.3.

With these scaling relationships, the total direct cost of a fusion reactor may be written as

$$C_D = 1.15(\text{BOP} + \text{reactor buildings} + \text{cost of fusion island})$$

$$= 1.15\left[685\left(\frac{P_t}{4150}\right)^{0.6} + 319\left(\frac{V_{FI}}{5100}\right)^{0.67} + C_{FI}\right] \quad (\$) \ , \qquad \text{(A.4.1)}$$

where the overall contingency factor of 1.15 is used [1]. The thermal power (fusion power + auxiliary power) P_t (MW) and the fusion island volume V_{FI} (m^3) are normalized to the STARFIRE values. The scaling powers are based respectively upon typical values for power stations [3] and upon the assumption that the reactor buildings, cryogenics, vacuum system, and coil power supplies will scale as the square of the reactor dimensions.

A.4.3 Fusion Island Costs

The fusion island cost encompasses the following accounts:

22.012	Shield
22.013	Coils
22.014, 22.019	Auxiliary heating system (75%)
22.015	Structure
22.2	Main heat transfer system (steam generators, etc.)

The cost of the fusion island is the sum of the costs of the steam generators, the coils, the structure, the shield, and the auxiliary power,

$$C_{FI} = \left[84\left(\frac{P_t}{4150}\right)^{0.6} + 1.2(1.25V_{cp}\rho_c C_C^u) + V_{st}\rho_{st}C_{st}^u + V_s\rho_s \sum^{C_s^u} + 0.75C_a^u P_a\right] \ . \qquad \text{(A.4.2)}$$

The steam generators are assumed to be of the type proposed for STARFIRE [1]. This category includes 75% of the auxiliary power costs; the unit cost C_a^u = 2.0 \$/W(e). The factor 1.2 is a redundancy in each coil (see Appendix 6). The factor 1.25 allows for the secondary coil set (see Table 2.1). The average coil density $\rho_c = 7.9 \times 10^3$ kg/m^3.

The structure volume V_{st} is taken to be $0.75V_{cp}$ (Table 2.1). The density $\rho_{st} = 6.0 \times 10^3$ kg/m^3.

The shield volume is given by

$$V_s = 1.25 \sum_s C_s 2\pi^2 R \left[\left(\bar{a}_w + \Delta b_s + \Delta g_s + \Delta s_s\right)^2 - \left(\bar{a}_w + \Delta b_s + \Delta g_s\right)^2 \right] \ (\mathrm{m}^3) \ , \tag{A.4.3}$$

where there are two regions (see Table 2.1): under the coil, where $C_1 = 1/3$ and Δb_1, Δg_1, and Δs_1 have their smallest values, and between the coils, where $C_2 = 2/3$ and Δb_2, Δg_2, and Δs_2 have their largest values. The density $\rho_s = 6.4 \times 10^3$ kg/m^3. The factor 1.25 allows for additional shielding required for penetrations. The blanket costs are included in the fuel cycle costs.

Representative unit costs from the STARFIRE [1] and ELMO Bumpy Torus Reactor [4] designs are given in Table A.4.4 with the reference costs for the generic reactor study. The unit costs for the coils and structure are somewhat higher than those in ref. 5. A major difference lies in the superconducting coil costs; these are taken to be much larger and reflect recent superconducting coil experience as described in a study made for TFCX and INTOR [6]. An optimistic view is taken of future developments in that present costs reflect limited production of a relatively new technology. In addition, it is assumed that much of the cost represents labor; therefore, cost per unit weight of the total coil (winding pack plus structure) is used. A second difference is in the auxiliary heating costs. The total STARFIRE direct cost in accounts 22.014, 22.017, and 22.019 is some $60 million. In the generic reactor study a 100-MW auxiliary heating system, which includes startup systems, has a direct cost of $200 million. The coil power supply costs are generic and are a compromise developed from the costs for a tokamak [1], bumpy torus [4], mirror [7], and stellarator [8].

Table A.4.4. Unit direct costs[a] of components

Component	STARFIRE Volume (m^3)	STARFIRE Weight (tonnes)	STARFIRE Cost (millions of dollars)	STARFIRE Density ($tonnes/m^3$)	STARFIRE Unit cost	EBT-R unit cost	Generic reactor unit cost[b]
Blanket, first wall	380	1,550	99	4.1	64 $/kg	56 $/kg	70 $/kg
Coils[c]	950	7,500	207	7.9	28 $/kg	28 $/kg	80 $/kg
Structure[d]	470	2,823	64	6.0	23 $/kg	26 $/kg	23 $/kg
Shield[d]	2,100	13,400	175	6.4	17 $/kg	19 $/kg	17 $/kg
Auxiliary heating[e] (lower-hybrid heating, 142 MW(e) for $40 million)						0.38 $/W(e)	2 $/W(e)

[a]Costs adjusted to 1983 dollars assuming an inflation factor of 1.094 for 1980–81, 1.063 for 1981–82, and 1.038 for 1982–83 (factors taken from *Business Conditions Digest*, Bureau of Economic Analysis, U.S. Department of Commerce, September 1984).

[b]Note that these costs do *not* contain the 15% contingency.

[c]Recent analyses of the cost of present superconducting coils (S. S. Kalsi and R. J. Hooper, *Superconducting Toroidal Field Current Densities for the TFCX*, ORNL/FEDC-84/11, Oak Ridge, Tennessee, 1985) indicate a capital cost of about 120 $/kg for the winding pack and 75 $/kg for the coil structure (in FY 1984 dollars). For simplicity we assume that structure and winding pack are equal [Eq. (A.1.2)], and in 1983 dollars without contingency the cost reduces to 80 $/kg.

[d]The intercoil and support structure and shield are assumed to involve simpler construction techniques than the internal coil structure—hence the much lower unit costs. These costs are consistent with present experience.

[e]While it is to be hoped that the cost of auxiliary plasma power supplies will decrease in the future, present direct costs for the lower-cost system are around 2 $/W(e).

REFERENCES FOR APPENDIX 4

[1] C. C. Baker et al., *STARFIRE— A Commercial Tokamak Fusion Power Plant Study*, ANL/FPP-80-1, Argonne National Laboratory, Argonne, Ill., 1980.

[2] *Nuclear Energy Cost Data Base—A Reference Data Base for Nuclear and Coal-Fired Powerplant Power Generation Cost Analysis*, DOE/NE-0044, U.S. Department of Energy, 1982 and subsequent updates.

[3] G. R. Smolen et al., *Regional Projections of Nuclear and Fossil Electric Power Generation Costs*, ORNL/TM-8958, Oak Ridge National Laboratory, 1983.

[4] C. G. Bathte et al., *ELMO Bumpy Torus Reactor and Power Plant*, LA-8882-MS, Los Alamos National Laboratory, Los Alamos, N.M., August 1981.

[5] S. C. Schulte et al., *Fusion Reactor Design Studies—Standard Accounts for Cost Estimates*, PNL-2648, Pacific Northwest Laboratories, 1978.

[6] S. S. Kalsi and R. J. Hooper, *Superconducting Toroidal Field Coil Current Densities for the TFCX*, ORNL/FEDC-84/11, Fusion Engineering Design Center, Oak Ridge National Laboratory, 1985.

[7] *MARS, Mirror Advanced Reactor Studies*, UCRL-53333, Lawrence Livermore National Laboratory, Livermore, Calif., 1983.

[8] R. L. Miller et al., *A Modular Stellarator Reactor*, LA-9737-MS, Los Alamos National Laboratory, Los Alamos, N.M., 1983.

Appendix 5
OPERATING COSTS

A.5.1 Fuel Cycle Costs

The fuel cycle account includes the blanket cost and the costs of other replaceable components that are, in effect, a part of the energy gain system; this classification does not alter the final cost of electricity (COE), but it does facilitate the comparison of costs in the various accounts for fusion and fission. The account includes the initial blanket, first wall, limiters, and targets and their replacements, plus components of the auxiliary heating systems that require regular replacement (e.g., rf launchers). The bulk of miscellaneous replacements (account 22.8) is covered by these items.

The fuel cycle cost C_F represents the annual repayment necessary to cover all of these costs over the normal plant lifetime of N years. For simplicity, inflation is not included in this calculation. Consequently, if there is a stream of running costs, with essentially regular replacement of components such as, for example, divertor targets every year or a complete blanket every five years, then the levelized annual repayment is simply the average yearly cost. It is assumed that there is no escalation of costs in the constant-dollar case and that escalation is equal to inflation in the current-dollar case. Thus,

$$C_F = (C_{ba} + C_{ta} + C_{aa} + C_{fa}) + \text{waste disposal costs} \ , \qquad (A.5.1)$$

where

C_{ba} is the average annual blanket and first wall cost,
C_{ta} is the average target and limiter cost,
C_{aa} is the average cost of replacement of auxiliary heating components, and
C_{fa} is the annual fuel cost plus miscellaneous replacements (~80% of total).

Blanket and first wall costs

The capital cost per unit weight of a blanket is denoted by C_b^u = 70 \$/kg (see Table A.4.4). The volume of the blanket is given by

$$V_b = \frac{2\pi}{3} R\pi\left[\left(\bar{a}_w + \Delta b_1\right)^2 - \bar{a}_w^2\right] + \frac{4\pi}{3} R\pi\left[\left(\bar{a}_w + \Delta b_2\right)^2 - \bar{a}_w^2\right] \quad (m^3) \ , \qquad (A.5.2)$$

where R is the toroidal major radius and $\bar{a}_w$ is the average wall radius.

As discussed in Chap. 2, the blanket and shield are divided into two regions. About one-third of the blanket and shield are under the coils, and the blanket is made as thin as possible (Δb_1) consistent with adequate tritium breeding and shielding. Over the remaining two-thirds, which is the region between the primary coils, the blanket and shield are thicker (Δb_2) to provide slightly better tritium breeding and shielding. The average blanket density is $\rho_b = 4.1 \times 10^3$ kg/m^3 (see Table A.4.4). The cost of the first blanket is given, conservatively (see below), by

$$C_b = \sum_{l=1}^{M} s_b(t_l)(1 + x)^{M - t_l + 1}(1.50) \ , \tag{A.5.3}$$

where

$$\sum_{l=1}^{M} s_b = V_b C_b^u \rho_b \ ;$$

$\sum_{l=1}^{M} s_b(t_l)$ is the direct cost, with t_l the accounting period; $(1 + x)^{M-t_l+1}$ is the interest factor, where x is the effective interest rate and Mt_l is the construction time (e.g., if t_l is 3 months, $M = 16$ for a 4-year construction time); and 1.50 is the indirect cost factor.

If the reactor is tenth of a kind, the construction time of the blanket should be less than the total plant construction time. It seems reasonable to allow for spares, so the initial cost is taken as $1.1C_b$. In addition, a further 10% for spares of all blanket elements used during the plant lifetime is included to allow for failures (see Appendix 6). Over the lifetime of the plant, the blanket elements will be replaced a number of times. Let p_{wn} (in MW·m^{-2}) be the neutron wall loading, and let F_{wn} (in MW·year·m^{-2}) be the lifetime fluence before replacement. The fluence limit may be set by radiation damage or by depletion of lithium in a solid blanket [1]. Let N be the plant lifetime (in years) and f_{av} be the availability at full power. The total blanket cost over the plant lifetime is then

$$C_{bt} = 1.1\left[1.1C_b + \left(\frac{f_{av}Np_{wn}}{F_{wn}} - 1\right)C_b\right] \ .$$

Then the annual cost C_{ba} is obtained by using a cost recovery factor on the initial blanket and dividing the cost of the remaining elements over the plant lifetime. For operating costs, a constant-dollar value is obtained. For a current-dollar calculation this is inflated to the first year of operation,

$$C_{ba} = 1.1C_b F_{CRO} + \left(\frac{f_{av}Np_{wn}}{F_{wn}} - 1\right)\frac{C_b}{N} \ . \tag{A.5.4}$$

For the reference case, the lifetime is set by $F_{wn} = 20$ MW·year·m^{-2}. (The second term is rounded up to the nearest 0.1 units.) There are some areas of uncertainty in this procedure. For example, although the initial blanket is costed in the conventional way, replacement blankets may be cheaper. If money is taken from revenue to purchase them, then should interest be paid? Also, if the blanket is designed, will the indirect costs be less? We need to resolve these questions.

Target and limiter costs

The procedure for costing targets and limiters is similar to that for the blanket elements. It is assumed that a constant fraction F_{tt} of the thermal power is taken on the targets (limiters) at a given average thermal loading of p_{tt} ($MW \cdot m^{-2}$). To allow for failures an additional 20% of spares is included.

The annual cost is given by

$$C_{ta} = 1.2\left[1.1 C_{tt} F_{CR} + \left(\frac{f_{av} N p_{tt}}{F_{tt}} - 1\right)\frac{C_{tt}}{N}\right] . \qquad (A.5.5)$$

For the reference case, it is assumed that $p_{tt} = 10\ MW \cdot m^{-2}$ and that the lifetime is set by the fluence limit, $F_{tt} = 10\ MW \cdot year \cdot m^{-2}$. (The second term is rounded up to the nearest 0.1 units.) The same issues of costing apply here as for the blanket; the total cost is

$$C_{tt} = \sum_{l=1}^{K} s_{tt}(t_l)(1 + x)^{K - t_l + 1}(1.5) , \qquad (A.5.6)$$

where

$$\sum_{l=1}^{K} s_{tt} = A_{tt} C_{tt}^{u} ,$$

$A_{tt} = P_{\alpha}/p_{tt}$ is the total target area, and $C_{tt}^{u} = 5 \times 10^4\ \$/m^2$ is the cost per unit area. For the reference case all the thermal power from the plasma is deposited on the limiters/targets. For a toroidal system, A_{tt} will typically be ≈10% of the first wall area.

Auxiliary heating costs

It is difficult to know exactly how to share the costs for auxiliary heating systems between the initial capital costs and the fuel cycle costs because there are so many possibilities. Nevertheless, for this cost assessment it is assumed that (1) 75% of the direct capital costs are for components and labor, which should properly be in the initial capital cost, and (2) 25% of the costs are for components requiring regular replacement, including vacuum windows, launching structures for ion cyclotron resonance heating (ICRH), launching structures and klystrons for lower hybrid resonance heating (LHRH), launching structures and gyrotrons for electron cyclotron heating (ECH) sources, dumps and ion source components for neutral beam heating systems, and safety and switching circuits for all systems. In addition, a parameter C_a^u, the cost in dollars per watt, is assigned to the system, where the watts refer to electric power input to the auxiliary heating system. Again, it seems sensible to set costs in terms of a power density and a lifetime fluence limit; this is certainly valid for most launching structures and sources. The neutron fluence limit is as appropriate as any other limit. The cost is therefore

$$C_{sa} = 1.1 C_a F_{CR} + \left(\frac{f_{ava} N p_a}{F_a} - 1\right) \frac{C_a}{N} , \qquad (A.5.7)$$

where $p_a = p_{wn}$; $F_a = F_{wn}$; $f_{ava} = 0.325$ (the availability is different from f_{av} since it is assumed that 50% of the systems may be used only for startup); p_a (MW·m^{-2}) is the average power density; F_a (MW·year·m^{-2}) is the fluence limit;

$$C_a = \sum_{i=1}^{J} 1.5 s_a(t_i)(1 + x)^{J - t_i + 1} , \qquad (A.5.8)$$

with $\sum_{i=1}^{J} s_a = (C_a^u/4)P_a$ and P_a the auxiliary power to the plasma; as noted, $C_a^u =$ 2 \$/W(e).

Miscellaneous scheduled replaceable items

In the STARFIRE estimates [1], there are many scheduled replaceable items, which are either included elsewhere in this report or are items that should be repairable. Therefore, this category is costed at the lower level of \$30 million, and 80% of this cost is included here. The annual cost is then $24F_{CR0}$ (in millions of dollars).

Fuel costs

For STARFIRE, with $P_F \sim 3600$ MW, the annual fuel costs (in millions of 1983 dollars) amount to \$0.4 million, giving a total for fuel and miscellaneous charges of

$$C_{fa} = (0.4 + 24F_{CR0}) \times 10^6 \quad (\$) .$$

Waste disposal

For fission plants [2,3] the waste disposal charge is 1.0 mill/kWh. For fusion the charge should be less; however, we have taken conservatively the same level. In total, then,

$$C_{OF} = \frac{C_{ba} + C_{ta} + C_{aa} + C_{fa}}{P_e \times 8760 \times f_{av}} + 1.0 \text{ (mill/kWh)} , \qquad (A.5.9)$$

where P_e (MW) is the maximum net electric power, 8760 is the number of hours in a year, and f_{av} is the plant availability at maximum power.

Interestingly, the fuel cycle costs depend mainly upon the total energy output of the system and not so much on the system power density (Fig. 4.7). This occurs because components are replaced after exposure to a fixed thermal or neutron fluence. Thus, if the power density is higher on a smaller surface area, components must be replaced more often, but they have a smaller volume. Cylindrical effects lead to a moderate variation in cost, and at low power densities with infrequent replacement of the whole blanket the up-front interest charges raise the cost.

A.5.2 Operations and Maintenance Costs

In the STARFIRE report it is estimated that 153 personnel could operate a 1200-MW(e) fusion reactor. In the light of recent increases in personnel requirements for a fission reactor, this level seems too low. Recommended figures for a fusion reactor are given in Table A.5.1. These figures are based upon a fission reactor analysis [3]. Increases above the level for fission reactors take account of the increased effort in operations and maintenance resulting from the greater complexity of a fusion reactor, which uses today's technology and demands additional skills in areas such as superconducting coils, rf heating, pellet fueling, etc. The number of security personnel has been reduced for the fusion plant because it does not use fissile material. The following accounts contribute to the operations and maintenance cost C_{om}:

Account 40, staff costs. The annual cost from Table A.5.1 is $30.9 million (in 1983 dollars).

Account 41, annual miscellaneous (consumable) supplies and equipment. The ORNL procedure [4] is used; this account is assessed at 45% of staff costs ($13.9 million).

Account 42, annual outside support services. Following STARFIRE, this is taken as $1.1 million (in 1983 dollars).

Account 43, annual general and administrative costs. These are included in Account 40.

Account 44, annual coolant makeup. Following STARFIRE, this is taken as zero.

Table A.5.1. Recommended staffing for a fusion reactor producing 800 to 1200 MW(e)

	Number of persons[a]	Annual cost[b] (thousands of dollars)	Total cost (millions of 1983 dollars)
Plant manager's office			
Manager	1	105	0.105
Assistant	1	100	0.100
Quality assurance	8 (6)	75	0.600
Environmental control	1	75	0.075
Public relations	1	75	0.075
Training	20 (12)	75	1.500
Safety and fire protection	1	75	0.075
Administrative services	55 (49)	55	3.025
Health services	2	80	0.160
Security	50 (94)	65	3.250
	120 (168)		8.965
Operations			
Supervision	12 (9)	80	0.960
Shifts[c]	72 (52)	70	5.040
	84 (61)		6.000
Maintenance			
Supervision	16 (12)	75	1.200
Crafts	73 (55)	65	4.745
Peak maintenance, annualized	73 (55)	65	4.745
	162 (122)		10.690
Technical and engineering			
Reactor	10 (5)	90	0.900
Radiochemical	6 (8)	90	0.540
Engineering	24 (16)	85	1.800
Performance, reports, technicians	30 (21)	60	1.800
	71 (50)		5.280
	457 (401)		30.9

[a]Figures in parentheses are from M. L. Myers et al., *Nonfuel Operations and Maintenance Costs for Large Steam-Electric Power Plants*, ORNL/TM-8324, Oak Ridge National Laboratory, 1982.

[b]Approximate 1980 figures from STARFIRE, multiplied by 1.3 to bring to 1983 dollars.

[c]This staffing level assumes six-shift capability, at four per day, with one shift in training and as a reserve and one on surveillance testing.

Account 45, annual process material. This would include water treatment or tritium processing. Following STARFIRE, this is taken as $1.3 million.

Account 46, annual fuel handling costs. Following STARFIRE, this is taken as zero.

Account 47, annual miscellaneous costs. This includes training, requalification of operators, equipment rental, travel, etc. Following STARFIRE (although some of these costs appear under account 40), this is taken as $1.9 million.

Decommissioning. Following fission experience [2], we take 0.5 mill/kWh for decommissioning.

In total, the sum of accounts 40–47 (inclusive) is C_{om} = $49.1 million per year (in 1983 dollars). To determine the contribution to the cost of electricity (COE), we divide by $P_e \times 8760 \times f_{av}$, where 8760 is the number of hours in a year; for example, for $P_e = 1.2 \times 10^6$ kW and $f_{av} = 0.65$,

$$C_{om} = \frac{4.91 \times 10^7 \times 10^3}{(1.2 \times 10^6) \times 8760 \times 0.65} + 0.5$$

$$= 7.7 \text{ mill/kWh} .$$

More generally, to allow for changing the size of the power plant, we set [3]

$$C_{om} = 7.7 \left(\frac{1200}{P_e} \right)^{0.5} . \tag{A.5.10}$$

The operations and maintenance costs for multiple reactor units producing a given amount of power will be higher than those for a single unit producing the same power. The main contributors to increased cost will be the increases required in operations and maintenance staff and the concomitant increase in annual miscellaneous costs (45% of staff costs). Some increase may also be expected in decommissioning costs. To illustrate how the COE might vary with the number of units, it is assumed that these increases will scale as $(U)^{0.5}$, where U is the number of units. Then for the case of a complex producing 1200 MW(e) with $f_{av} = 0.65$, the COE will be:

Number of units	Power produced by each unit [MW(e)]	COE (mill/kWh)
1	1200	7.7
2	600	9.4
3	400	10.6
4	300	11.7

REFERENCES
FOR APPENDIX 5

[1] C. C. Baker et al., *STARFIRE—A Commercial Tokamak Fusion Power Plant Study*, ANL/FPP-80-1, Argonne National Laboratory, Argonne, Ill., September 1980.

[2] *Nuclear Energy Cost Data Base—A Reference Data Base for Nuclear and Coal-Fired Powerplant Power Generation Cost Analysis*, DOE/NE-0044, U.S. Department of Energy, 1982 and subsequent updates.

[3] M. L. Myers et al., *Nonfuel Operations and Maintenance Costs for Large Steam-Electric Power Plants*, ORNL/TM-8324, Oak Ridge National Laboratory, 1982.

[4] Oak Ridge National Laboratory, *Procedure for Estimating Nonfuel Operating and Maintenance Costs for a Large Steam-Electric Power Plant*, ERDA-76-35, Energy Research and Development Administration, Washington, D.C., 1975.

Appendix 6

AVAILABILITY ANALYSIS

A.6.1 Introduction

An availability analysis procedure has been applied to calculate the potential availability of a generic fusion power plant. In calculating the availability, a probability of failure (F_{ra}) and a mean time to repair (M_r) are assigned to each component. For well-established components, such as those (generators, pumps, etc.) in the balance of plant (BOP), the input data come from existing experience [1]; for the fusion components, however, there is no such data base. Therefore, the program calculates what is necessary for the achievement of a given system availability. The program also helps to identify areas in which redundancy can improve reliability. Similar calculations have been made for the MARS reference fusion reactor [2] by Muzicki and Maynard [3]. The calculations are also similar to those used in the DOE/MRI methodology for studying the productivity and reliability of power plants [4, 5].

A.6.2 Model

A computer program has been written to predict the availability of a power plant by simulating its operating history. This program was used in the development of a simpler procedure for assessing the impact on availability of such factors as redundancy. The power plant is described by a hierarchical structure in which level 1 represents the entire plant, level 2 represents the major systems, and successively higher levels are included to describe in detail the components of each system. This hierarchy is illustrated in Fig. A.6.1.

Systems may operate either in series, in which case failure of any member fails the entire system, or in parallel, in which case M out of N members ($M < N$) are required for successful operation.

For each component i the following characteristics are assigned:

- a failure rate $F_{ra}(i)$ (h^{-1}),
- mean times to repair, M_{r0} (h) for major breakdowns and M_{r1} (h) for minor breakdowns,
- the fraction of major breakdowns F_m, and
- a dormancy factor d_f, which is the reduction in failure rate when the plant is not in service (conditions for many components are less stressful when the plant is not operating).

Values of these characteristics are given for the major systems in Table A.6.1. The probability that a component is in full service at a given time t is given by

$$P_{se} = \exp(-F_{ra} \cdot t) \ . \qquad \text{(A.6.1)}$$

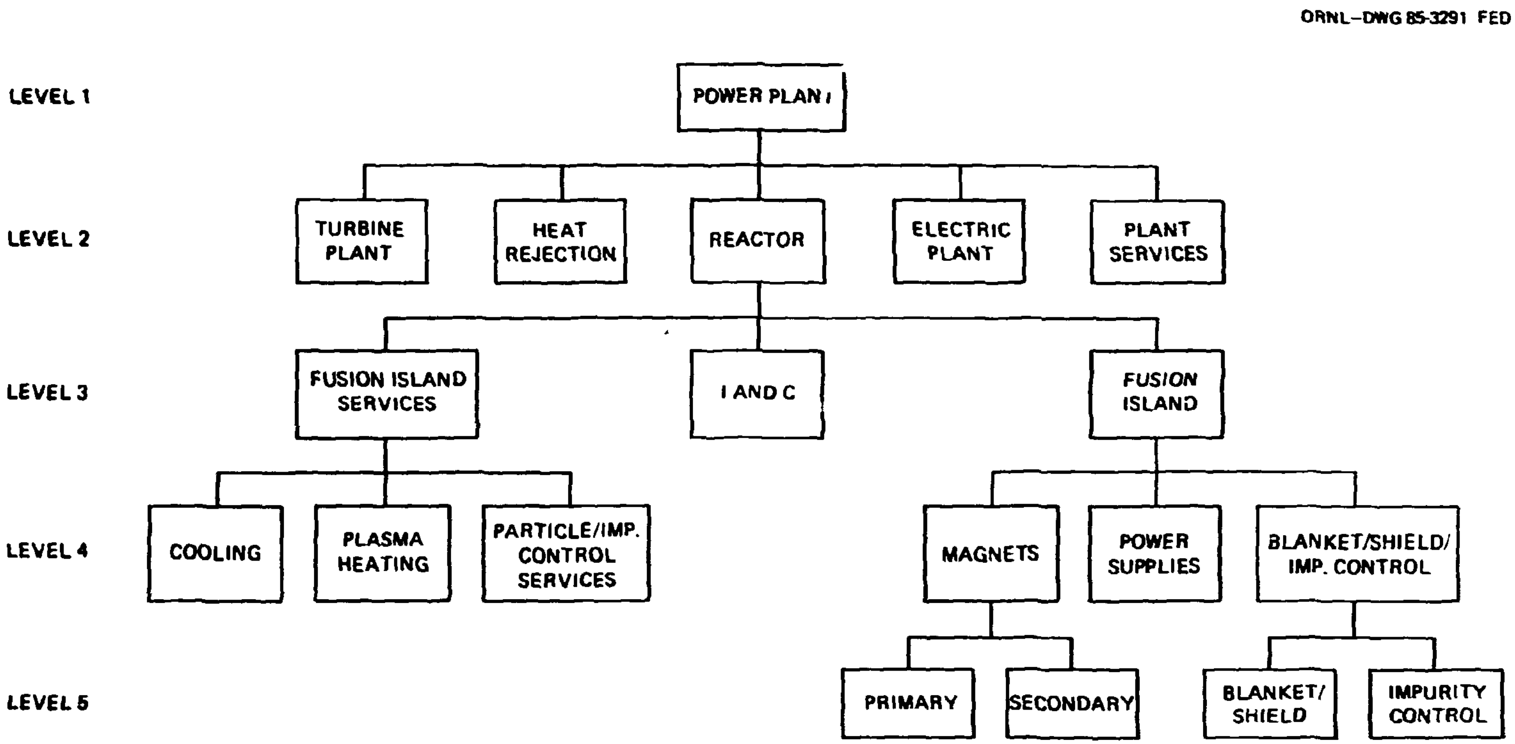

Fig. A.6.1. Hierarchy of levels for the availability of a generic fusion reactor.

Table A.6.1. Component characteristics

Component	Number [n (r)]		Level	F_{ra} (h^{-1})	d_f	M_{r0} (h)	M_{r1} (h)	F_m	Comment
Primary coils and auxiliaries	10		5	6.0×10^{-6}	0.01	10^4	240	0.1[a]	*b*
Secondary coils and auxiliaries	4		5	6.0×10^{-6}	0.01	10^4	240	0.1[a]	*b*
Magnet supplies	2		4	2.0×10^{-4}	0.01	100	10	0.1	*b*
Cryogenic system	1		4	2.0×10^{-4}	0.1	500	24	0.1	*b*
Blanket/shield	20		5	3.6×10^{-6}	0.01	440	320	0.5	
Impurity/particle control components	10	(8)	5	3.0×10^{-5}	0.01	250	10	0.1	*b*
Fueling	2	(1)	5	2.3×10^{-4}	0.01	72		1.0	*c*
Vacuum systems	3		5	1.0×10^{-5}	1.0	72	6	0.1	*b*
Plasma heating	3	(2)	4	5.0×10^{-4}	0.01	350	20	0.3	*c*
Cooling	3		4	1.0×10^{-4}	1.0	100	5	0.1	*b*
Instrumentation	1		3	1.0×10^{-3}	0.01	100	3	0.1	*b*
Turbine plant	1		2	6.6×10^{-4}	0.01	172			*d*
Electric plant	1		2	1.0×10^{-4}	1.0	90			*b*
Plant services	1		2	6.0×10^{-6}	0.01	170			
Heat rejection	1		2	9.8×10^{-7}	1.0	13			

[a]For coils with no redundant turns, $F_m = 0.1$. For coils with redundancy, see Eq. (A.6.10).
[b]Redundancy is included in arriving at these characteristics.
[c]The redundancy shown reduces unavailability.
[d]The input data on equipment such as the turbine plant come from existing experience [*Component Failures at Pressurized Water Reactors*, ALO-74, Combustion Engineering, Inc., 1980; *Proc. Inst. Mech. Eng.* **184**, 21 (1969)].

The other parameters specified are:

- the plant lifetime in years,
- the duration of the operating cycle, and
- the scheduled maintenance downtime in the operating cycle.

The plant is started with all components operational. The time to failure $T_f(l)$ of each component l is then estimated at each time step using the relationship

$$T_f(l) = \frac{-\ln(r)}{F_{rs}(l)} , \quad (A.6.2)$$

where r is a random number between 0 and 1.

The program operates by searching, at each time step, for the shortest time to the next event that affects plant operation. This event may be a component failure, a component repair, a scheduled shutdown, a scheduled startup, or the end of the plant's lifetime. In some cases the event can be handled by redundancy; in other cases, it will lead to plant shutdown. The shortest time is chosen, and the appropriate action is taken.

Failures that occur during a scheduled downtime are incorporated into that time. The scheduled shutdown may be extended as necessary to complete repairs. If a repair or scheduled shutdown would extend past the end of life, the operating lifetime is ended immediately.

The output of the code lists (1) the overall availability of the plant during its lifetime, including scheduled and unscheduled maintenance; (2) the contributions to unavailability of the various subsystems; and (3) the number of failed components for each subsystem. For example, in a system with 20 blanket elements, each of which would be replaced every 5 years (120 elements over 30 years of operation), the number of failures led to the need for an additional 18 elements. To allow for replacement of failed elements, the generic reactor has a 10% allowance of spares initially plus a 10% spares allowance for all blanket elements used in the 30-year operating time.

A.6.3 Simplified Model

The computer code has been run including components down to level 6. On the basis of the output from these runs, the code has been simplified to emphasize the contributions of the key subsystems at level 5 and above (see Table A.6.1). As discussed below, the essential results may be obtained in an even simpler manner, analytically, using simple formulae, when an ensemble of power plants is considered [4, 5].

Availability of an ensemble of systems

For an ensemble of systems, the average time to failure is given by

$$T_f(t) = \frac{-\int_0^1 \ln(r)\, dr}{F_{ra}(t) \int_0^1 dr} = \frac{1}{F_{ra}(t)} \, . \tag{A.6.3}$$

Thus, the average fractional downtime during operation is simply

$$P_{dt}(t) = M_r(t)\, F_{ra}(t) = \frac{M_r(t)}{T_f(t)}$$

or, more generally,

$$P_{dt}(t) = \frac{M_{r0}(t) F_m(t) + M_{r1}(t)[1 - F_m(t)]}{T_f(t)} \, . \tag{A.6.4}$$

If a dormancy factor is assigned so that the probability of component failure is very small during either scheduled or unscheduled downtime, then

$$P_{dt}(t) = \frac{M_r(t)(1 - S_{maint})}{T_f(t)} \tag{A.6.5}$$

where S_{maint} is the fraction of time scheduled for maintenance. It is assumed that scheduled maintenance is 6 weeks of every year with a 10-week maintenance period every 10 years to completely refurbish the turbine plant.

Effect of incorporating redundancy

If redundancy is incorporated, then the availability for a system is improved. We consider the change in the mean time to failure of a system T_{fs} with n components, of which only r components are required for operation. As discussed in ref. 5, if failure of a component does *not* lead to plant outage, then

$$T_{fs} = \frac{\sum_{j=r}^{n} \binom{n}{j} T_{f1}^{j} M_r^{n-j}}{n \binom{n-1}{r-1} T_{f1}^{(r-1)} M_r^{n-r}} \tag{A.6.6}$$

where T_{f1} and M_r are the mean time to failure and mean time to repair of one component,

$$\binom{n}{j} = \frac{n!}{j!(n-j)!} ,$$

and the value of T_{f1} depends on the values of r and n:

$$r = n , \quad T_{fs} = \frac{T_{f1}}{n} ; \tag{A.6.7}$$

$$n = 2 , r = 1 , \quad T_{fs} = T_{f1} + \frac{T_{f1}^2}{2M_r} ;$$

$$n = 3 , r = 1 , \quad T_{fs} = T_{f1} + \frac{T_{f1}^2}{M_r} + \frac{T_{f1}^3}{3M_r^2} ;$$

$$n = 3 , r = 2 , \quad T_{fs} = \frac{T_{f1}}{2} + \frac{T_{f1}^2}{6M_r} ;$$

and so on. When system repairs require a plant outage,

$$T_{fs} = T_{f1} \sum_{j=r}^{n} \frac{1}{j} . \tag{A.6.8}$$

Simple formula for availability

A simple formula for the availability may be written using these equations:

$$f_{av} \simeq (1 - S_{maint}) 1 - \sum_{i} \frac{N(i)M_{r0}(i)F_m(i) + M_{r1}(i)[1 - F_m(i)]}{T_{fs}(i)} , \tag{A.6.9}$$

where $T_{fs}(i)$ is the mean time to failure of each subsystem, account has been taken of redundancy, and $N(i)$ is the number of identical independent nonredundant components.

Description of redundant systems

Systems with redundancy include the fueling, magnet coil, impurity/particle control, and plasma heating systems.

It is assumed that there are two pellet injectors, each of which can provide all fueling. An injector may be removed and repaired while the plant is operating. For these fuelers, $T_{fi} = 4350$ h, $M_r = 72$. Using Eq. (A.6.7), $T_{fs} = 1.36 \times 10^5$ h and $P_{dt} = 0.005$.

It is assumed that each coil has n windings, of which only r are required for operation. In the base case, there is 20% redundancy, so $n = 12$ and $r = 10$. For this example, the mean time to failure of a coil is in effect 3.65 times longer than if $n = r = 10$. For a major failure, when a coil must be replaced, the mean time to repair is $M_{r0} = 10^4$ h. For a minor failure, when either a winding fails and redundancy permits it to be taken out of service, or a subcomponent (such as a dump resistor) fails, the mean time to repair $M_{r1} = 250$ h. The effect of redundancy is taken into account by varying the fraction of major failures such that

$$F_m = F_{m0} \Big/ \left[r \sum_{j=r}^{n} \left(\frac{1}{j} \right) \right] . \tag{A.6.10}$$

For the impurity/particle control system, the worst failure is probably damage to a target or limiter, leading to a water leak or at least making such an event probable. If the erosion of a target/limiter surface can be detected by doping the surface layer at the permitted maximum erosion depth, it might be possible to avoid the catastrophic failure. If, in addition, only a fraction of targets/limiters is required for operation (e.g., eight out of ten), then the probability of major failure may be kept low ($F_m = 0.1$).

A.6.4 Results

The contributions of the system components to the unavailability of the reference reactor are given in Table A.6.2. For this case, each coil has 20% redundancy. The redundancy and characteristics of fusion components have been chosen to give the required reference availability of $f_{av} = 0.65$, with the fraction of scheduled downtime $S_{maint} = 0.115$. The standard deviation of the availability about the mean value for an ensemble of 40 reactors is 95–105% of the mean value. The sensitivity of the COE to availability was tested for three cases: varying the coil turn redundancy and varying the blanket failure rate and the scheduled maintenance time. The generic model varies slightly from that given in the body of the report, but this has little effect on the results.

The effect of varying the number of redundant turns is shown in Fig. A.6.2. The minimum COE is a result of a trade-off between increased cost and increased availability as the redundancy is increased. For this model, 20% redundancy of turns yields the minimum COE and is used in the standard generic reactor case.

For the blanket, the use of a constant failure rate implies that there is no penalty associated with higher power density that necessitates more frequent replacement of the blanket for a fixed fluence lifetime.

Table A.6.2. Availability of reference reactor

Component	Number	F_{ra} (h^{-1})	M_{r0} (h)	M_{r1} (h)	F_m	Unavailability P_{dt}
Primary coils	10	6.0×10^{-6}	10^4	240	0.0365[a]	0.0358
Secondary coils	4	6.0×10^{-6}	10^4	240	0.0365[a]	0.0143
Magnet supplies	2	2.0×10^{-4}	100	10	0.1	0.0080
Cryogenic system	1	2.0×10^{-4}	500	24	0.1	0.0148
Blanket/shield	20	3.6×10^{-6}	440	320	0.5	0.0274
Impurity/particle control	10	3.0×10^{-5}	250	10	0.1[a]	0.0105
Fueling	1	7.4×10^{-6}[a]	72		1.0	0.0005
Vacuum system	3	1.0×10^{-5}	72	6	0.1	0.0004
Plasma heating	1	1.5×10^{-4}[a]	350	20	0.3	0.0174
Cooling	3	1.0×10^{-4}	100	5	0.1	0.0045
Instrumentation	1	1.0×10^{-3}	100	3	0.1	0.0130
Turbine plant	1	6.6×10^{-4}	172		1.0	0.1135
Electric plant	1	1.0×10^{-4}	90		1.0	0.0090
Plant services	1	6.0×10^{-6}	170		1.0	0.0010
Heat rejection	1	9.8×10^{-7}	13		1.0	0.0000
Total						0.270[b]

[a]These numbers reflect the use of redundancy.

[b]The full computer code gives $f_{av} = 0.71$ with a standard deviation of 0.06. The probability of achieving $f_{av} \geq 0.65$ is 92%, and $f_{av} = 0.65$ may be obtained using the approximate formula of Eq. (A.6.13).

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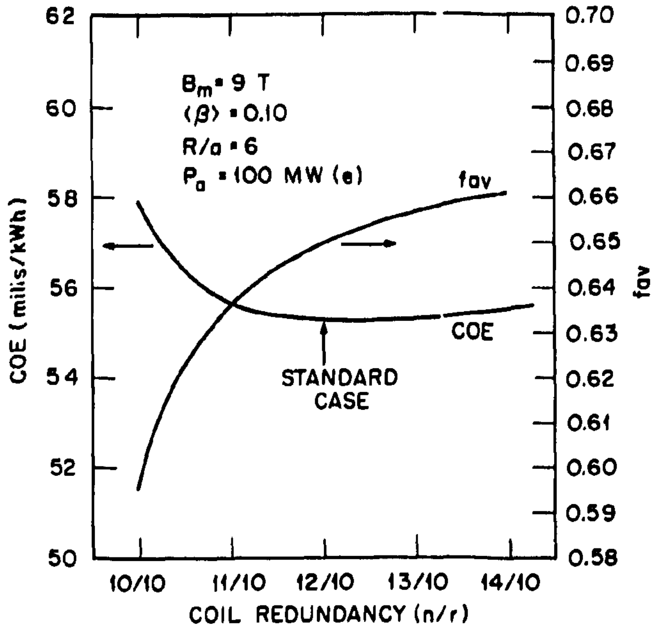

Fig. A.6.2. Effect on availability of varying the number of redundant turns in a superconducting coil.

Solely for the purpose of illustrating that a power-dependent failure rate could have a significant impact on the COE and optimum reactor configuration, a simple model dependence of F_{ra} on p_{wn} has been tested:

$$F_{ra} = F_{ra0}\left(\frac{p_{wn}}{2}\right)^{\alpha-1} . \quad \text{(A.6.11)}$$

The standard case has $\alpha = 1$. It is assumed that at $p_{wn} = 2\ \mathrm{MW \cdot m^{-2}}$ the power density is low enough for the main problem to be the damage caused by neutron fluence. However, as p_{wn} is raised, the additional thermal load from the plasma will rise.

It is assumed that the thermal load is a fixed fraction of p_{wn}, typically $p_{wt} \leq 0.10 p_{wn}$ (i.e., ~50% of the thermal power goes to the limiters and targets). As p_{wn} and p_{wt} increase, the first wall must be made thinner to handle the heat transfer, which makes it progressively more vulnerable to damage by charge-exchange erosion or plasma disruption. To allow for this, the availability has been written as

$$f_{av} = 0.885\left[0.762 - 0.0274\left(\frac{p_{wn}}{2}\right)^{\alpha-1}\right] , \quad \text{(A.6.12)}$$

which is a modification of the formula in Table A.6.2.

The variation of COE with fusion island weight M_{FI} is shown in Fig. A.6.3 for $\alpha = 1$, 1.5, 2.0, and 2.5. The strong dependence of COE on α suggests that a study of this effect is required to determine the likely dependence of F_{ra} on p_{wn}. Figure 4.13 illustrates a second issue for the blanket and first wall, which is the required frequency of replacement. For the standard and improved reactors considered in the bulk of this report, F_{wn} = 20–30 MW·year·m^{-2} and $p_{wn} < 6$ MW·m^{-2}, so that the blanket replacement time (with f_{av} = 0.65) is ≥5 years. In this situation, scheduled replacement may be fit within the scheduled downtime for turbine maintenance. However, if higher power densities are used, then more frequent replacement will be required, and eventually this will have an impact on availability. This effect will show up when the replacement time $F_{wn}/f_{av}p_{wn} < 2$ years. For this reason, in high-power-density systems [6, 7] the whole reactor design is geared to minimize the first wall/blanket replacement time.

A.6.5 Availability of Multiple Reactor Units

As discussed in Sect. 4.8, there may be advantages in operating multiple reactor units to produce a given power rather than operating a single reactor. If it is assumed that the BOP components and such equipment as power supplies and cryogenic systems may be shared between the multiple units, then this redundancy may be used to increase the availability over that of a single unit.

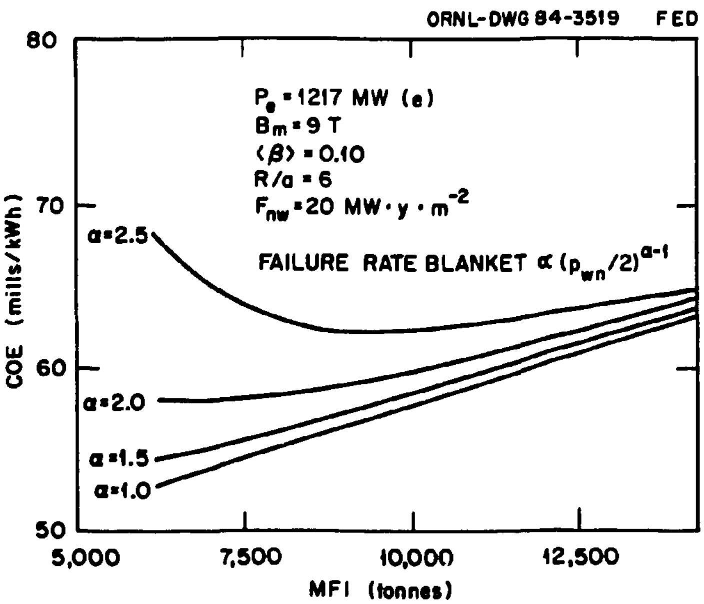

Fig. A.6.3. Dependence of COE on the blanket failure probability as a function of M_{FI} (p_{wn}).

A simple formula for availability is

$$f_{av} \simeq (1 - 0.115)(1 - 0.12 - 0.15) = 0.65 \ , \qquad \text{(A.6.13)}$$

where 0.1? .he value for the fusion island and 0.15 is that for shared equipment. The contributions to the unavailability are

- 0.115 for scheduled maintenance,
- 0.106 for the fusion island, and
- 0.133 for shared equipment.

For two units, the unavailability due to scheduled maintenance and failures in each fusion island remains the same for each unit. However, if one unit is shut down the other may use the shared equipment to provide redundancy. If the possibility that the same components would fail in both units is ignored, then the system is repairable on line and Eq. (A.6.6) is appropriate to show the improvement in mean time to failure. For the second unit, the unavailability of most shared components, with doubled redundancy, becomes negligible. The main exception is the turbine plant, for which Eq. (A.6.6) indicates that the single-unit unavailability of 0.1135 would change to 0.021.

Using this unavailability for the shared equipment, the overall availability is given approximately by

$$f_{av} \simeq \frac{0.646 + 0.758}{2} \simeq 0.702$$

for two units. Similarly, for three units the shared equipment unavailability for a second plant when the first has failed will be $\simeq$0.058 and for the third plant when the other two fail will be $\simeq$0.003. In total, the availability $f_{av} \simeq 0.714$ for three units, and for a four-unit system $f_{av} \simeq 0.717$.

A simple procedure is described to indicate the possible gains of using multiple units. For simplicity it is assumed that the lower unit costs and relatively smaller number of spares offset the costs of the larger land area and increased complexity. It is assumed also that the BOP cost and construction time are the same as for a large single unit, though the alternative of spreading out the construction and costs of the BOP may be a better choice. The COE is reduced, however, for the multiple units by the improved availability.

The total auxiliary power to the plasma is fixed at $P_a = 100$ MW(e). It is assumed that the construction time, other than the BOP, for multiple units is effectively 6 years, rather than the 8 years used for the large single unit; this reduces the indirect cost factor from 1.5 to 1.375 [see Eq. (3.4)].

It is assumed that BOP components, power supplies, and cryogenic systems are shared so that when one fusion island is inoperative the other units may use this shared equipment to provide redundancy. A simple model for the availability has been discussed previously.

The operations and maintenance costs for multiple reactor unit systems are discussed in Appendix 5.2. The numbers given there for 1-, 2-, 3-, and 4-unit systems are modified here to take account of the changing availability.

The parameters of a 1200-MW(e) plant using 1, 2, 3, and 4 units are given in Table A.6.3. The model used here, which differs slightly from that used in the body of the report, indicates only a modest cost penalty in going to multiple units; this penalty may well be outweighed by the advantages of lower wall loading, staged construction, and increased load-following capability compared to a single unit.

Table A.6.3. Parameters and COE for multiple reactor units producing 1200 MW(e)

$R/a = 6$, $B_m = 9$ T, $\langle\beta\rangle = 0.10$, $b/a = 1.6$, $a_w/a = 1.1$

	Number of units				Single 300-MW(e) unit
	1	2	3	4	
f_{av}	0.646	0.702	0.714	0.714	0.646
P_e (MW)	1217	602	398	297	297
χ_E ($m^2 \cdot s^{-1}$)	0.44	0.29	0.22	0.19	0.19
R (m)	6.76	5.72	5.26	4.97	4.97
a (m)	1.13	0.95	0.88	0.83	0.83
p_{wn} ($MW \cdot m^{-2}$)	6.2	4.3	3.4	2.9	2.9
C_{OFI} (mill/kWh)	11.6	11.2	11.9	12.7	14.1
C_{OF} (mill/kWh)	7.6	8.7	9.7	10.6	15.5
C_{OM} (mill/kWh)	13.3	15.0	17.8	20.6	24.9
C_{OBG} (mill/kWh)	4.3	6.2	8.3	10.4	12.6
C_{OBP} (mill/kWh)	18.4	16.9	16.6	16.6	32.8
COE (mills/kWh)	55.2	58.0	64.3	70.9	99.9

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