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AN ANALYSIS OF THE REQUIREMENTS FOR ECONOMIC MAGNETIC FUSION*

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A presentation by

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"Physics Requirements for An Attractive Magnetic Fusion Reactor," J. Sheffield, Nuclear Fusion, 25, 1773, 1985.

"Reference Reactor for Safety, Environment, Assessment Committee," DOE, J. G. Delene, R. A. Dory, and J. Sheffield, December 1985.

"An Economic Analysis of Fusion Breeders," J. G. Delene, 6th Topical Meeting on Fusion Energy, San Francisco, CA, March 1985.

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AN ANALYSIS OF THE REQUIREMENTS FOR ECONOMIC MAGNETIC FUSION

ABSTRACT

A generic reactor model is used to examine the economic viability of electricity generation by magnetic fusion. The simple model uses components which are representative of those used in previous reactor studies of deuterium-tritium burning tokamaks, stellarators, bumpy tori, reverse field pinches and tandem mirrors. Conservative costing assumptions are made. The generic reactor is not a tokamak but 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 a less good approximation to systems, such as the reversed field pinch 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. Sensitivity studies of varying the assumptions show that this result is not sensitively dependent on any given assumption. Of particular importance is the result that this scale of fusion reactor may be realized with only moderate advances in physics and technology capabilities.

For a fusion-fission hybrid with a high support ratio for fission reactors, the fusion island is not such a critical driver as for electricity production.

I. INTRODUCTION

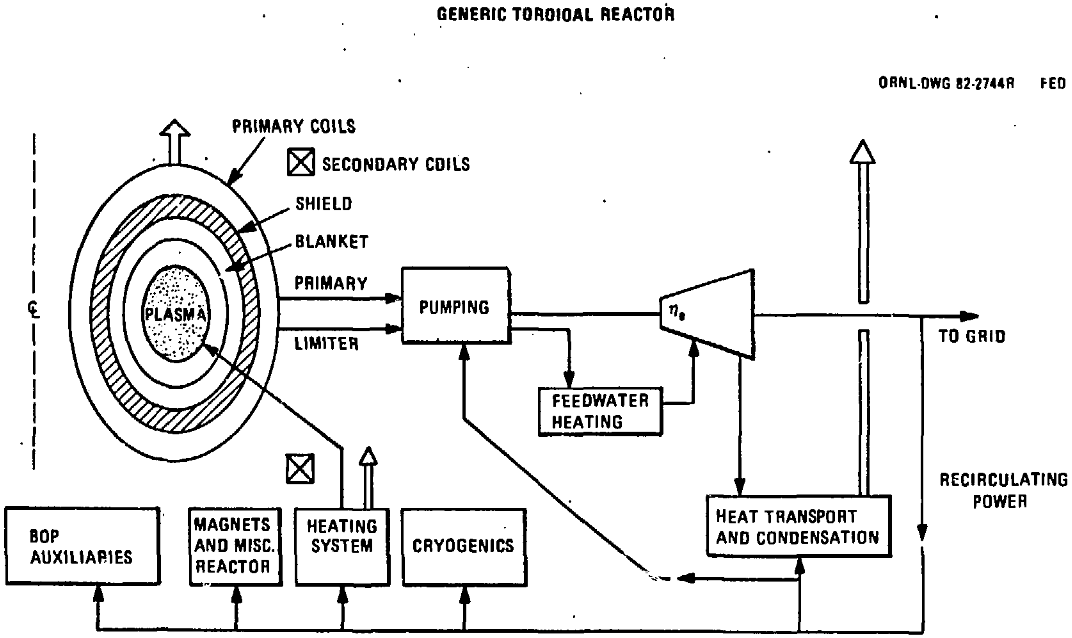
I.1. Introduction

Over the past decade several articles have been written which discuss the potential economics of magnetic fusion reactors[1, 2, 3, 4]. In these articles it is argued that, because fusion reactors may be larger than fission reactors, the cost of electricity from them 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 present 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 the neutron attenuation lengths in the shield materials and the tritium breeding and fusion cross sections 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?

I.2. Model

As a contribution towards resolving these questions a study has been undertaken at ORNL of what we call a "Generic Magnetic Fusion Reactor." This steady state, deuterium-tritium burning reactor includes all of the components which are common to various types of fusion reactors - superconducting coils, lithium breeding blanket for tritium production, plasma heating systems, power



I.1. Schematic diagram of generic fusion reactor.

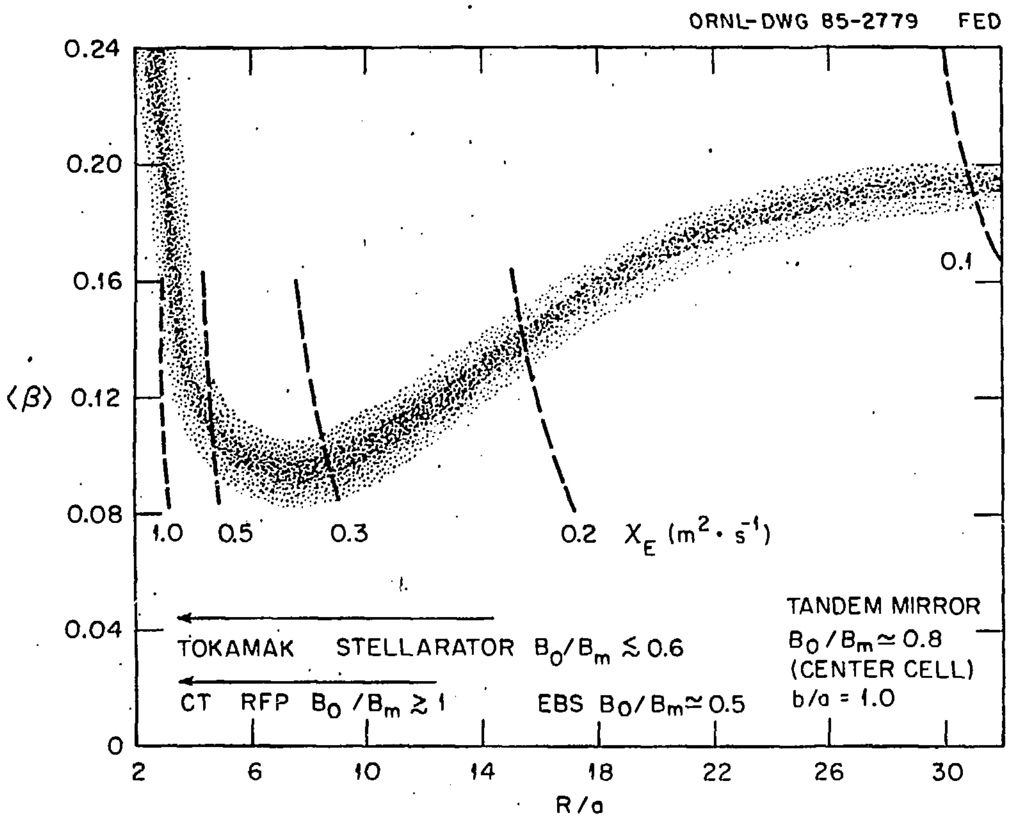
supplies, shielding, remote handling, buildings, generators, cooling towers, as illustrated in Fig. I.1. The characteristics of these components and their costs are based upon values developed in the previous studies of tokamaks, stellarators, bumpy tori, reversed field pinches and tandem mirror reactors. It is emphasized that 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 which are different. In a large aspect ratio version it approximates a tandem mirror, and in an intermediate aspect ratio it is a stellarator, as indicated in Fig. I.2. It is a slightly less accurate representation of systems, such as the reversed field pinch, in which the main field is produced by a plasma current. The technology assumptions are based upon a concensus of work in previous studies. Thus, superconducting coils are invoked which have characteristics close to those already developed. They have a cost based upon today's costs even though it is reasonable to expect substantial advances and cost reductions in this relatively young technology.

Construction lead time and plant availability are varied around the nominal values which are 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 meantime 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 costs of electricity - Nuclear Energy Cost Data Base, DOE/NE-0044/2, 1983[11]. The unit costs are taken, generally, from previous fusion studies. However, when more recent information is available from actual construction projects,

ATTRACTIVE REACTOR REGION

P_e = 1200 MW(e), P_a = 100 MW(e), B_m = 8-12 T, b/a = 1.0-2.0



I.2. Physics requirements ⟨β⟩, X_E for various types of configuration versus R/a for constant Cost of Electricity. CT = Compact Torus, RFP = Reversed Field Pinch, EBS = Elmo Bumpy Square.

these newer costs are used - e.g., for superconducting coils and cryogenic systems.

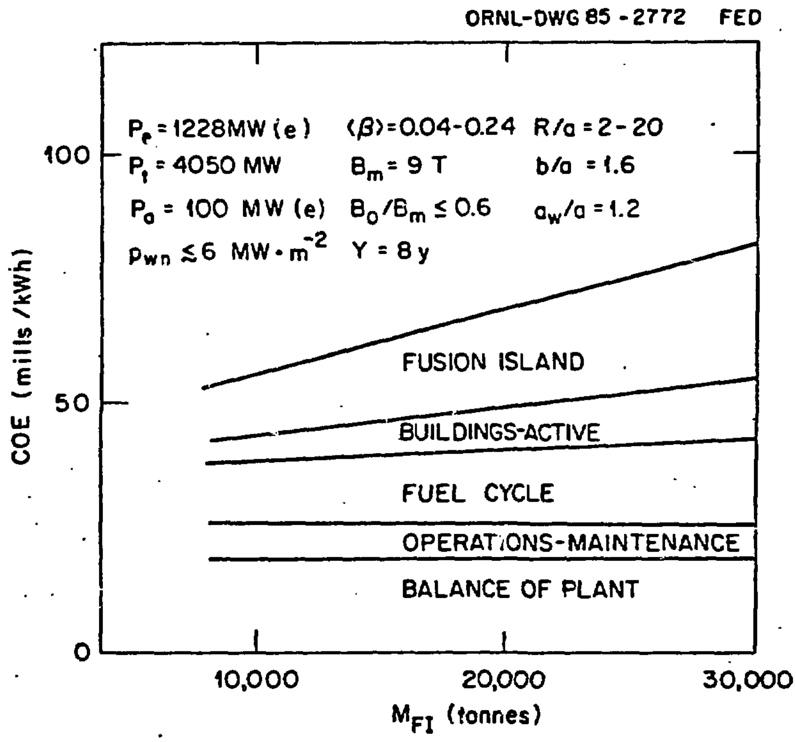
The model has been reviewed widely, in other fusion laboratories, in universities and of particular importance by industries and utilities, notably through the good offices of the Atomic Industrial Forum. The many valuable suggestions to improve the model and to improve the presentation of the results,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

II. CONCLUSIONS

II.1. Requirements and Comparison with Starfire

The model is used to identify the self-consistent requirements for the fusion reactor and its components which would make it competitive with fission systems in the 21st century. The financial requirement is taken to be that the cost of electricity (COE) to the utility reduced to 1986 \$, should be in the range of 50-67 mills/kW_e-hr. where 1 mill = 10^{-3} \$. This is to be compared with present fission and fossil costs, which costed on the same basis range from 39-56 mills/kW_e-hr. 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 factor in choice.

The results of the study are encouraging, indicating, as shown in Fig. I.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, implying too costly; typically for a 1200 MW_e plant, they had a weight of about 25,000



I.3. The Cost of Electricity (COE) decreases linearly with decrease in the mass of the fusion island.

tonnes. An interesting additional result from the model is that smaller fusion plants, down to 300 MW_e in output, could be competitive in multiple units. Similiar scaling assessments have been made for the more restrictive case of the tokamak[12, 13, 14, 15]. This study complements these other studies by confirming and extending the range of validity of their results.

We believe that such plant sizes are realizable. the physics and technology requirements both represent only a moderate advance over present day achievements, and fall within the projections of development programs. 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 reversed field pinches and field reversed theta pinches and is accessible, theoretically to a wide range of configurations, 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 a comparison of the parameters of Starfire[5] and an illustrative generic reactor are given in Table I.1. The reduction in size of the fusion core and the reduction in cost and cost of electricity 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
- lower recirculating power to the plasma

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

Table I.1. A Comparison of Starfire and an Optimized Generic Reactor.

	Starfire[5]	Generic Reactor
Fusion power[a] (MW_t)	4000	3750
Max. Auxiliary Power (MW_e)	150	50
Thermal-electric Efficiency	0.36	0.36
Net Electric Power (MW_e)	1200	1230
Neutron Flux ($MW.m^{-2}$)	3.6	5.1
Aspect Ratio (R/a)	3.6	6.0
Ellipticity (b/a)	1.6	2.0
Scrape-off Layer ($\frac{a_w}{a}$)	1.1	1.2
Beta, $\langle\beta\rangle$, ($\langle\beta_i\rangle$) (%)	6.7(2.3)	10.0(4.6)
Max. Coil Field (B_m) (T)	11.1	9.0
Thermal Diffusivity (χ_E) ($m^2.s^{-1}$)	0.55	0.48
Core Weight (M_{FI}) (tonnes)	24,000	10,200
(P_t/V_{FI})[b] ($MW_t.m^{-3}$)	0.78	1.8
(M/P_t) (tonnes.MW_t^{-1})	6.0	2.5
Cost of Electricity (mills/kW.hr)	~84[c]	54

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

(b) Volume (V_{FI}) includes plasma, scrape-off layer, blanket, shield, maintenance and services region, coils and structure.

(c) Calculated using the costing procedure of this report and given here in constant 1986 $.

Table I.2. Ranges of Key Parameters for Improved Fusion Power Plants $\left(1200\ MW_e\right)^{(a)}$

	Parameter	Standard	~± 10% COE Range	Comment
Fusion Power	$P_F\ \left(MW_t\right)$	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 wall to plasma radii	$\frac{a_w}{a}$	1.2	1.1-1.3	
Additional Plasma Heating Power	$P_a\ \left(MW_e\right)$	100	50-150	
Neutron Fluence Lifetime	$F_{wn}\ \left(MW.yr.m^{-2}\right)$	20	15-25	
Neutron Flux to Wall	$P_{wn}\ \left(MW.m^{-2}\right)$	5	3-6	
Minimum Blanket Thickness	Δb_1 (m)	0.45	0.45-0.60	One third of the blanket, maintenance gap and shield are at the minimum radial thickness.
Maximum Blanket Thickness	Δb_2 (m)	0.75	0.75-1.00	
Minimum, Blanket Gap, Shield	Δbgs_1 (m)	1.30	1.30-1.70	Two-thirds are at the maximum thickness.
Maximum Blanket Gap Shield	Δbgs_2 (m)	2.00	2.00-2.60	
Weight of Fusion[b] Island	M_{FI} (tonnes)	8600	8000-14000	
	$\frac{M_{FI}}{P_t}\ \left(\frac{tonnes}{MW_t}\right)$	2.3	2.0-3.0	
	$\frac{P_t}{V_{FI}}\ \left(\frac{MW_t}{m^3}\right)^{(c)}$	1.9	1.5-2.0	
Construction Time	Y (years)	8	6-10	
Availability	f_{av}	0.65	0.60-0.70	

Parameter	Standard	~± 1% COE Range	Comment
Unit Coil[d] Cost ($/kg)	90	14% change	
Unit Blanket[d] Cost ($/kg)	78	7% change	
P_a (MW_e)	100	7 MW at 2 $/W	

(a) It is assumed that the majority of parameters are close to their standard values when a given parameter is varied.

(b) Steam Generators not included.

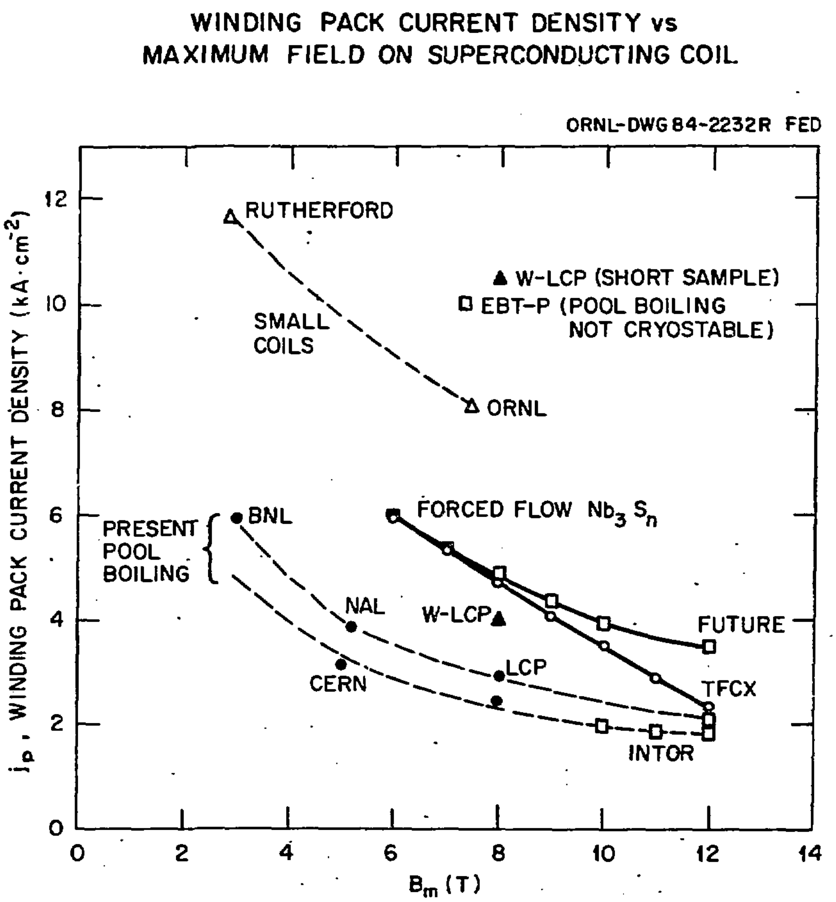
(c) V_{FI} is the Fusion Island Volume.

(d) Direct costs not including contingency.

The ranges of key parameters which lead to an improved 1200 MW_e fusion power plant are listed in Table I.2. The sensitivity of the cost of electricity to variations in these parameters is also given. In the sensitivity study it is assumed that the device has the nominal value of each parameter except the one being varied.

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. I.2. The minimum $\langle\beta\rangle$ requirement occurs for moderate aspect ratios with R/a ~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 the $\langle\beta\rangle$. The physics requirements are achievable theoretically by a variety of configurations as indicated in Fig. I.2. Good progress is being made experimentally towards their achievement[16].

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 lattitude to accommodate a range of blanket options[17]. The superconducting coils have characteristics close to those of coils which have been tested, as shown in Fig. I.4. 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 $F_{wn} \approx 20$ $MW.yr.m^{-2}$ 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 which could



I.4. Values of the maximum field B_m and winding pack current density j_p for existing and future superconducting coils.

recover spontaneously from loss of coolant accidents, providing an inherently safe system[19].

II.2. Cost Drivers

Important cost drivers are:

- The superconducting coil system or the copper coil system and its power supplies and recirculating power.
- The auxiliary power systems, particularly those required during the fusion burn, and the recirculating power.
- The blanket, first wall and limiter/target system.
- The availability, which involves the complexity of the configuration, component reliability and redundancy, and remote handling.
- The level of plasma performance. Fusion power is proportional to

Additional factors not considered in the generic reactor studies are: control systems and diagnostics.

An example of a generic reactor (in this case, tokamak-like) is given in Appendix 1.

II.2a. Superconducting Coil Systems

In the generic reactor studies, superconducting coils are assumed to have a performance close to that which has already been achieved. A 20% redundancy is used in each coil to improve the availability. The base cost of 80 $/kg (1986) (plus the indirect multiplier of 1.15 × 1.5 × 1.1) is consistent with present day experience. Cost of reference case Appendix 1 is 180 M$.

TABLE II.1. EXPERIMENTAL RESULTS NORMALIZED TO ATTRACTIVE REACTOR REQUIREMENTS

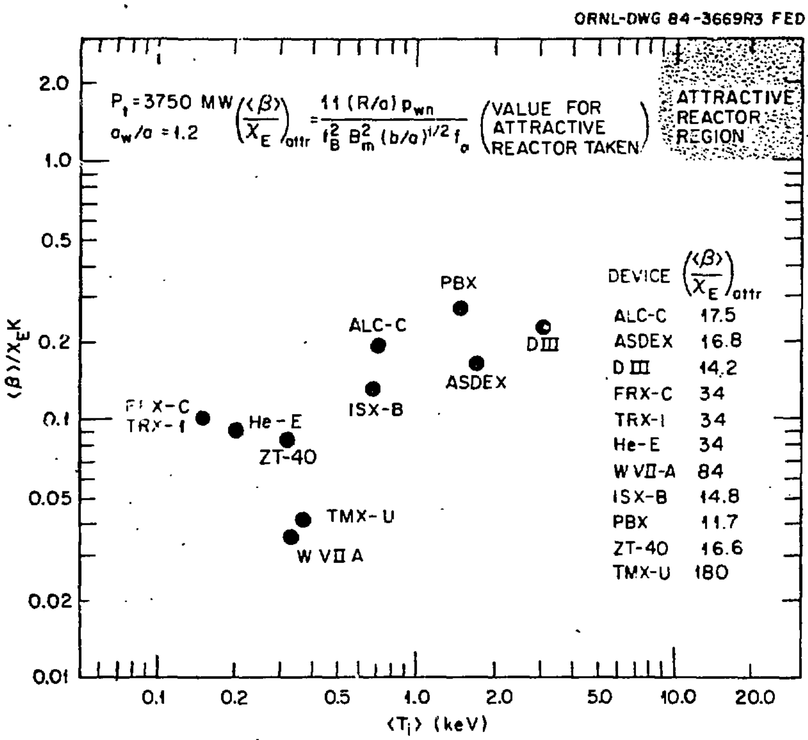
	Attractive reactor values						Experiment			
Experiment	R/a (b/a)	B_m (T)	f_B	P_{wn} ($MW \cdot m^{-2}$)	f_α	$\left(\frac{\langle\beta\rangle}{\chi_E}\right)_{attr}$ ($\%/m^2 \cdot s^{-1}$)	$\langle\beta\rangle$ (%)	χ_E ($m^2 \cdot s^{-1}$)	$\langle T_{ik}\rangle$ (keV)	$\left(\frac{\langle\beta\rangle}{\chi_E}\right)_{norm}$
Alcator-C [13]	3.9 (1.0)	9	0.44	4.2	0.8	13.0	0.4	0.16	0.7	0.19
Asdex [14]	4.7 (1.0)	9	0.50	4.3	0.8	12.5	1.3	0.63	1.7	0.17
D-III [15]	3.4 (1.38)	9	0.41	4.0	0.8	10.6	1.8	0.73	3.0	0.23
ISX-B [16]	3.6 (1.3)	9	0.42	4.0	0.8	11.0	2.3	1.61	0.68	0.13
PDX [17]	4.7 (2.0)	9	0.50	4.1	0.8	8.7	5.0	2.2	1.5	0.26
Heliotron-E [18]	15.0 (2.0)	9	0.60	4.8	0.8	25	2.0	0.8	0.2	0.10
WVII-A [19]	29.0 (2.0)	9	0.60	5.5	0.8	62	0.5	0.20	0.4	0.04
TMX-U [20]	(5.5 (1.0))[a]	8	0.80	8.5	0.80	134	6	1.13[b]	0.4	-
	30.0 (1.0)[c]									0.04
ZT-40 [21]	5.7 (1.0)	3	1.7	4.4	0.8	12.4	15	15[d]	0.3	0.08
FRX-C [22]	$\frac{L}{r_s}$ = 18[a]	3.1	1.0	$(2)_{av}$	0.8	35	88	32	0.15	0.11
TRX-1 [23]	$\frac{L}{r_s}$ = 8[c]									

[a] Experiment.

[b] For a perpendicular energy confinement time of 14 ms.

[c] Reactor; L = length, r_s = separatrix radius of FRC plasma.

[d] Poloidal value.



ORNL-DWG 84-3669R3 FED
P_t = 3750 MW
a_w/a = 1.2
$\left(\frac{\langle\beta\rangle}{X_E}\right)_{attr} = \frac{11\,(R/a)\,p_{wn}}{f_B^2\,B_m^2\,(b/a)^{1/2}\,f_\alpha}$
(VALUE FOR ATTRACTIVE REACTOR TAKEN)
ATTRACTIVE REACTOR REGION
$\langle\beta\rangle/X_E K$
$\langle T_i\rangle$ (keV)
PBX
ALC-C
DIII
ASDEX
ISX-B
FRX-C
TRX-1
He-E
ZT-40
TMX-U
W VII A
DEVICE $\left(\frac{\langle\beta\rangle}{X_E}\right)_{attr}$
ALC-C 17.5
ASDEX 16.8
D III 14.2
FRX-C 34
TRX-I 34
He-E 34
W VII-A 84
ISX-B 14.8
PBX 11.7
ZT-40 16.6
TMX-U 180

II.2b. Auxiliary Power Systems

These systems impact the cost in a number of ways; through their base cost; through their reliability; and through the recirculating power which they demand. The base cost of 2.25 $/Watt is consistent with present day experience for the simpler systems such as ion cyclotron heating. Clearly, because they act directly to reduct the net electric power, it is desirable to minimize their use during the burn. Cost of reference case Appendix 1 is 190 M$.

II.2c. Blanket, First Wall, Limiters and Divertor Targets

These systems enter into the initial capital cost and because they must be replaced regularly (first wall [blanket] every ~5 years for example) they are a major part of the operating costs. A key factor is the neutron fluence lifetime of the first wall, for an economic neutron wall loading of 5 MW/m^2, a fluence limit of $\geq$ 15 $MW.yr/m^2$ is required. The base unit cost is taken from the Starfire studies and is 78 $/kg. The initial cost is about 200 M$ in the reference case.

II.2d. Availability, Redundancy, Remote Handling

An availability model was used to assess the requirements for reliability and redundancy of the fusion components for a plant availability of 0.65. The upfront cost of including redundancy and spares approaches 200 M$ in the reference case. The most stringent reliability requirements are for the magnets, blanket and auxiliary power systems.

II.2e. Physics Requirements

The physics requirements to make an attractive reactor have been assessed for a variety of magnetic configurations[16], tokamak, stellarator, reversed field pinch, field reversed theta pinch, bumpy torus and tamdem mirror. Key parameters are beta (β), the ratio of plasma pressure to magnetic pressure, and the thermal diffusivity (conductivity) χ of the plasma. In fact, all of the above devices have the capability, classically of achieving the required parameters and are making good progress in that direction, see Fig. II.1.

II.2f. Implications for a Fusion-Fission Hybrid System

For a fusion-fission hybrid system, with a high support ratio for fission reactors, neither the fusion island nor the electrical production efficiency are as critical cost drivers as for electricity production alone. This permits some greater flexibility in choosing, for example, the level of neutron flux to the first wall; the needed physics performance; the level of redundancy; the level of recirculating power; and, if the system is primarily a fuel factory, its availability. Nevertheless, to provide adequate reliability and availability remains a major challenge as does developing a fusion-fission blanket and a 'simple' configuration.

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J. G. Delene
1/24/86

GENEROMAK
STANDARD PLANT COSTS

Prepared for
ESECOM Meeting

January 27, 1986

GENEROMAK CAPITAL COSTS[a]

Account number	Account title	Costs (1986, $M)		
20	Land and Land Rights	5.0		
21	Structures and Improvements	295.0		
21.01	Site Improvement and Facilities			14.8
21.02	Reactor Building			130.1
21.03	Turbine Building			47.8
21.04	Cooling System Structures			10.7
21.05	Electrical Equipment and Power Supply Building			12.2
21.06	Plant Auxiliary Systems Building			4.3
21.07	Hot Cell Building			44.3
21.08	Reactor Service Building			2.5
21.09	Service Water Building			0.9
21.10	Fuel Handling and Storage Building			11.6
21.11	Control Room Building			4.1
21.12	On-Site DC Power — Supply Building			2.7
21.13	Administration Building			1.1
21.14	Site Service Building			1.1
21.15	Cryogenics and Inert Gas Storage Building			1.2
21.16	Security Building			0.5
21.17	Ventilation Stack			2.5
21.18	Spare Parts Allowance			2.6
22	Reactor Plant Equipment	754.9		
22.1	Reactor Equipment		477.9	
22.1.1	Blanket and First Wall			179.2[b]
22.1.2	Shield			106.5
22.1.3	Magnets			178.9[c]
22.1.4	RF Heating and Current Drive			191.2[d]
22.1.5	Primary Structure and Support			19.3
22.1.6	Reactor Vacuum			6.2
22.1.7	Power Supply, Switching and Energy Storage			16.5
22.1.8	Impurity Control			3.3
22.1.9	ECRH Plasma Breakdown			3.8

GENEROMAK CAPITAL COSTS[a]

Account number		Account title	Costs (1986, $M)	
22.2		Main Heat Transfer and Transport System	93.0	
	22.2.1	Primary Coolant System		84.0
	22.2.2	Intermediate Coolant System		–
	22.2.3	Limiter Cooling System		8.2
	22.2.4	Residual Heat Removal System		0.8
22.3		Cryogenic Cooling System	21.4	
	22.3.1	Liquid Helium System		17.3
	22.3.2	Liquid Nitrogen System		4.1
22.4		Radioactive Waste Treatment of Disposal	6.3	
	22.4.1	Liquid Waste Processing and Equipment		2.2
	22.4.2	Gaseous Wastes and Off-Gas Processing System		2.4
	22.4.3	Solid Wastes Processing Equipment		1.7
22.5		Fuel Handling and Storage Systems	60.5	
	22.5.1	Fuel Purification Systems		11.7
	22.5.2	Liquefaction		–
	22.5.3	Fuel Preparation Systems		0.5
	22.5.4	Fuel Injection		10.9
	22.5.5	Fuel Storage		2.7
	22.5.6	Tritium Extraction and Recovery		7.1
	22.5.7	Atmospheric Tritium Recovery System		27.6
22.6		Other Reactor Plant Equipment	58.2	
	22.6.1	Maintenance Equipment		50.9
	22.6.2	Special Heating Systems		0.0
	22.6.3	Coolant Receiving, Storage and Make-Up Systems		0.3
	22.6.4	Gas Systems		0.1
	22.6.5	Inert Atmosphere System		0.0
	22.6.6	Fluid Leak Detection		2.7
	22.6.7	Closed Loop Coolant System		2.6
	22.6.8	Standby Cooling System		1.6

GENEROMAK CAPITAL COSTS[a]

Account number		Account title	Costs (1986, $M)	
22.7		Instrumentation and Control	31.0	
	22.7.1	Reactor I&C Equipment		10.0
	22.7.2	Monitoring Systems		2.3
	22.7.3	Instrumentation and Transducers		18.7
22.8		Spare Parts Allowance	6.6	
23		<u>Turbine Plant Equipment</u>	289.8	
23.1		Turbine-Generators	103.0	
23.2		Main Steam System	5.8	
23.3		Heat Rejection Systems	59.1	
23.4		Condensing Systems	25.5	
23.5		Feed Heating Systems	12.5	
23.6		Other Turbine Plant Equipment	67.7	
23.7		Instrumentation and Control (I&C) Equipment	11.6	
23.8		Spare Parts Allowance	4.6	
24		<u>Electric Plant Equipment</u>	121.2	
24.1		Switchgear	14.7	
24.2		Station Service Equipment	20.2	
24.3		Switchboards	9.3	
24.4		Protective Equipment	2.5	
24.5		Electrical Structures and Wiring Containers	20.6	
24.6		Power and Control Wiring	42.8	
24.7		Electrical Lighting	9.7	
24.8		Spare Parts Allowance	1.4	
25		<u>Miscellaneous Plant Equipment</u>	47.3	
25.1		Transportation and Lifting Equipment	20.9	
25.2		Air and Water Service Systems	16.4	
25.3		Communications Equipment	8.3	
25.4		Furnishing and Fixtures	1.0	
25.5		Spare Parts Allowance	0.7	
		<u>Total Direct Cost</u>	1513.2	

GENEROMAK CAPITAL COSTS[a]

Account number	Account title	Costs (1986, $M)
91	Construction Facilities, Equipment and Services (15%)	227.0
92	Engineering and Home Office Services (15%)	227.0
93	Field Office Services (7.5%)	113.5
	Total Indirect Cost	567.5
	Subtotal, Direct + Indirect Cost	2080.7
	Contingency	312.1
	Total Overnight Cost,	2393.0
	$/kWe	1990.0

[a]Reference Generomak for ESECOM studies.

[b]Treated as a fuel cost, shown for information purposes only, not included in totals, contains a 10% spares allowance.

[c]Contains 20% redundancy.

[d]25% of cost is treated as a fuel cost, $143.4 million included in capital.

STANDARD CASE

***** PHYSICS PARAMETERS *****

TOTAL PLASMA BETA(BETA)	0.100	
ASPECT RATIO OF TORUS(R/a)(ASPECT)	4.0	
PLASMA ELLIPTICITY(ELLIP)	2.500	
MAXIMUM FIELD IN COIL(BMAX)	10.0	
MAXIMUM ALLOWED BETA RATIO(BRMAX)	0.60	
BLANKET THICKNESS 1 AND 2(DELB1,DELB2)	0.45	0.90
GAP THICKNESS 1 AND 2(DELG1,DELG2)	0.10	0.30
SHIELD THICKNESS 1 AND 2(DELS1,DELS2)	0.75	0.80
AVERAGE CURRENT DENSITY IN COIL(DJBAR)	20446120.	
NUMBER OF ITERATIONS(NIT)	18	
THERMAL DIFFUSIVITY(CHIMAX)	0.736	
B4RAB	13596	
PLASMA RADIUS(AP)	1.393	
MAJOR RADIUS(RO)	5.572	
BO	4.737	
BETA RATIO(BRATIO)	0.474	
MEAN PLASMA RADIUS(ABAR)	2.203	
NEUTRON WALL LOADING(PWN)	4.509	
CURRENT DRIVE(CURRD)	16.502	
FUSION POWER,MWT(PFUS)	4000.0	
ELECTRIC POWER(PEL)	1203.4	
AUXILLIARY POWER,MWe(PAUX)	82.5	
Q	2.27	

STANDARD CASE

***** NUCLEAR ISLAND VOLUME, MASS, AND COST *****

	BLANKET	SHIELD	P. COIL	S. COIL	STRUCTURE	TOTAL
VOLUME	509.4	876.0	201.2	50.3	125.8	2408
WEIGHT	2088.5	5606.3	1589.7	397.4	754.6	10436
COST	179.2	106.5	143.1	35.8	19.3	

***** CAPITAL INVESTMENT, MILLIONS 1986 $ *****

LAND	5.0	
STRUCTURES AND IMPROVEMENTS	294.9	
REACTOR BLDG. AND HOT CELLS		174.4
OTHER STRUCTURES AND IMPROV.		120.6
REACTOR PLANT EQUIPMENT	750.5	
SHIELD		106.5
COILS		178.8
STRUCTURE		19.3
AUX. HEATER		139.2
TOTAL NUCLEAR ISLAND		443.9
STEAM GENERATOR		93.0
OTHER REACT. PLANT EQUIP		213.6
TURBINE PLANT EQUIPMENT	289.7	
ELECTRIC PLANT EQUIPMENT	121.2	
MISCELL. PLANT EQUIPMENT	47.3	
TOTAL DIRECT COST	1508.6	
INDIRECT COSTS	565.7	
TOTAL DIRECT+INDIRECT	2074.3	
CONTINGENCY	311.1	
TOTAL OVERNIGHT COST	2385.4	

***** ANNUAL COSTS, MILLIONS OF 1986 DOLLARS *****

OPERATION AND MAINT.	57.48
BLANKETS	42.01
LIMITERS	4.90
AUXILIARY HEAT	6.08
FUEL	2.45
WASTE DISPOSAL	6.85
TOTAL ANNUAL COST	119.77

***** POWER GENERATION COST *****

	MILLS/KWH
OPER AND MAINT	8.39
OTHER ANNUAL	9.09
CAPITAL INVESTMENT	32.35
TOTAL POWER COST	49.83