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GENERIC MAGNETIC FUSION REACTOR

COST ASSESSMENT*

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SYMPOSIUM ON FUSION POWER DEVELOPMENT

AT

LAWRENCE LIVERMORE NATIONAL LABORATORY

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A GENERIC D-T BURNING MAGNETIC FUSION REACTOR MODEL SHOWS THAT WITHIN THE CONSTRAINTS SET BY GENERIC LIMITATIONS IT IS POSSIBLE FOR MAGNETIC FUSION TO BE A COMPETITIVE SOURCE OF ELECTRICITY IN THE 21st CENTURY.

IN ASSESSING THE VIABILITY OF MAGNETIC FUSION AS AN ECONOMIC SOURCE OF ELECTRICITY IT IS IMPORTANT TO SEPARATE THE LIMITATIONS SET BY

- THE STATE-OF-THE-ART TODAY
 - REACTOR DESIGNS
 - TECHNOLOGY
 - RELIABILITY
- THE GENERIC LIMITATIONS
 - CROSS SECTIONS
 - MATERIALS PROPERTIES

THE GENERIC MAGNETIC FUSION REACTOR ACHIEVES THIS GOAL BY USING

- GENERIC LIMITATIONS AS THE MAIN CONSTRAINTS
- TECHNOLOGY WHICH EXISTS OR IS A MODEST IMPROVEMENT OVER THE PRESENT STATE
- CONSERVATIVE COSTING

WHILE ALLOWING FOR MODERATE IMPROVEMENTS IN REACTOR DESIGN.

Table A.4.1 Representative Parameters from D-T Reactor Studies

Parameter	Units	Starfire	MSR-IIB	EBT-R	MARS	Generic
P_{th}	MS	4000	4000	4030	4060 ^(d)	3880
$P_{e(net)}$	MW _e	1200	1300	1200	1360(1570)	1200
P_{er}/P_{eg}	-	0.167	0.07	0.13	0.29(0.20)	0.14
η_e	%	35.7	35.0	35.5	38.6(43.6)	36.0
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	-
E_o	T	5.8	6.56	3.64	4.7	-
$D_o/\bar{D}_m$	-	0.523	0.566	0.375	0.635	$\leq 0.60^{(e)}$
$\bar{a}_w/a$	-	1.10	1.41	1.10	1.40	1.10
P_{aux} DC	MW	153	-	105	354	100
P_{aux} Pulse	MW	12	-	100	-	-
ξ_n	-	1.14	1.10	1.50	1.16	1.14
$\Delta b^{(a)}$	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	0.02 0.07	0.14 0.38	0.10 0.30
Δs	m	<u>0.64</u> <u>1.10</u>	<u>0.60</u> <u>1.00</u>	<u>0.67</u> <u>0.63</u>	<u>0.84</u> <u>0.45</u>	<u>0.75</u> <u>0.80</u>
$\int \Delta$	m	1.05 3.10	1.01 2.07	1.06 1.25	1.36 1.96	1.30 2.00
W_b	tonnes	1550	2060	4120	4110	-
W_s	tonnes	13400	10280	13110	9020	-
W_{cp}	tonnes	5310	12860	20230	9070	-
$V_{ct}^{(b)}$	m ³	950	-	-	-	-
$f_{cs}^{(c)}$	-	0.41	0.10	0.26	0.72	0.40
V_{st}/V_{ct}	m ³	0.5	-	-	-	0.5
$\int W$	tonnes	25,280	26,490	43,360	29,810	-

DEVELOPMENT OF GENERIC REACTOR MODEL

- PRESENT REACTOR DESIGNS, STARFIRE, MARS, EBT-R, MSR-IIB ARE USED

- TO SET GENERAL CHARACTERISTICS
 - ELECTRICAL EFFICIENCY 36%
 - MAXIMUM FIELD RATIO FOR PRIMARY COIL SET

$$\frac{B_{\text{PLASMA}}}{B_{\text{COIL}}} \leq 0.60$$
 - WALL TO PLASMA RADIUS

$$\frac{\bar{a}_w}{\bar{a}} = 1.10$$
 - ADDITIONAL HEATING POWER $\sim 100 \text{ MW}_e$
(HALF FOR START UP ONLY),
 - BLANKET GAIN 1.14
 - BLANKET AND SHIELD THICKNESS

1/3	MINIMUM REGION	1.30 m
2/3	MAXIMUM REGION	2.00 m
 - RATIO SECONDARY TO PRIMARY COIL SET WEIGHT 0.4
 - RATIO ADDITIONAL STRUCTURE VOLUME TO TOTAL COIL VOLUME 0.5
 - STEADY STATE

- TO ESTABLISH BALANCE OF PLANT REQUIREMENTS.

THE GENERIC REACTOR IS TOROIDAL

- THE PRIMARY COIL SET IS TOROIDAL THIS LEADS TO A SIMPLE RELATIONSHIP FOR $\frac{B_p}{B_m}$ SUBJECT TO A LIMITATION ≤ 0.60 .
- THE SECONDARY COIL SET IS TAKEN TO REPRESENT POLOIDAL COIL COMPONENTS AND DIVERTOR COILS OR THE MIRROR AND END CELLS IN A TANDEM MIRROR (THE MODEL DOES NOT REPRESENT ADEQUATELY A REVERSE FIELD PINCH).
- IT IS ASSUMED THAT THE TOROIDAL COILS FIT CLOSE TO THE PLASMA SEPARATED BY THE MINIMUM BLANKET AND SHIELD THICKNESS.
(AS IN A TANDEM MIRROR CENTER CELL, STELLARATOR, EBT).
- 20% REDUNDANCY IS INCLUDED IN ALL COILS.

GENERIC TOROIDAL REACTOR

ORNL-DWG 82-2744R FED

Figure 1

Figure 3. Representative Plasma Profiles.

WINDING PACK CURRENT DENSITY vs MAXIMUM FIELD ON SUPERCONDUCTING COIL

ORNL-DWG 84-2232 FED

COST OF ELECTRICITY (COE)

$$\text{COE} = \frac{(C_C \times F_{cr} + C_F + C_{OM}) \text{ M\$}}{(P_e \text{ GW}_e) \times 8760(\text{hr}) \times f_{av} \times 10^{-3}} \quad \text{mills/kW.hr}$$

$$C_C = C_{DO} \times 1.15 \times 1.50 \times 1.10$$

DIRECT CAPITAL INDIRECT INTEREST IN CONSTANT DOLLARS
COST CONTINGENCY (8 YEARS CONSTRUCTION)

- INDIRECT CHARGES 8 YEARS CONSTRUCTION (SCALED WITH YEARS).
- CONSTRUCTION FACILITIES SERVICES (15%)
- ENGINEERING, MANAGEMENT (25%)
- OWNERS COST (10%)
- INTEREST OVER CONSTRUCTION TIME 9% TAX ADJUSTED RATE
- 6% INFLATION

$$F_{CR} = 0.1 \quad \text{FIXED CHARGE RATE (MORTGAGE) IN CONSTANT DOLLARS}$$

$$C_F = \text{ANNUALIZED FUEL COSTS INCLUDING BLANKET, LIMITERS, TARGETS, ADDITIONAL HEATING REPLACEMENTS,}$$

C_{OM} = OPERATIONS AND MAINTENANCE

$$f_{av} = 0.65, \text{ PLANT AVAILABILITY AT FULL NET POWER } P_F.$$

EXAMPLE

$$C_{DO} = 1300 \text{ M\$}$$

$$C_C = 2490 \text{ M\$}$$

$$C_F = 68 \text{ M\$}$$

C_{OM} = 46 M\$

$$P_E = 1.22 \text{ GW}_e$$

COE = 51.9 mills/kW.h

COSTING FOR GENERIC REACTOR

- BLANKET + FIRST WALL 70 \$/kg (87 \$/kg)
- SHIELD 22 \$/kg
- STRUCTURE 25 \$/kg
- MAGNET 67 \$/kg (84 \$/kg)
- ADDITIONAL POWER 2 \$/W_e

- $$C_{DO} = 1.15 \left\{ \underset{\text{BOP}}{766 \left(\frac{P_t}{P_{ts}} \right)^{0.6}} + \underset{\text{REACTOR BUILDINGS}}{277 \left(\frac{V_{ni}}{V_{nis}} \right)^{0.67}} + \underset{\text{NUCLEAR ISLAND}}{C_{ni}} \right\} \text{ M\$}$$

P_t = TOTAL THERMAL POWER, V_{ni} = NUCLEAR ISLAND VOLUME

C_{ni} = DETAILED NUCLEAR ISLAND COST, SUBSCRIPT (s) for STARFIRE

- FUEL CYCLE COSTS - BLANKET + FIRST WALL, 20 MW.y/m² NEUTRON
FLUENCE LIMIT
 - 25% OF ADDITIONAL HEATING REPLACED REGULARLY
 - LIMITERS/TARGETS
- PERSONNEL FOR 1200 MW_e PLANT 437

TABLE A.2.1. COMPARISON OF PWR AND STARFIRE DIRECT COSTS. FY 82 M\$

Starfire (FY 80 costs) multiplied by 1.10 x 1.085
(15% contingency taken out)

Account Number	Title	PWR	Starfire	
20.	Land	2.8	3.4	
21.	Structures	219.7	359.7	
22.	Reactor Plant Equipment	275.9	1015.1	
23&26	Turbine Plant Equipment Main Heat Rejection Sys.	250.5	259.7	
24.	Electric Plant Equipment	81.2	121.9	
25.	Miscellaneous Equipment	<u>25.4</u>	<u>42.4</u>	
		855.5	1802.0	
	Contingency 10%	<u>85.6</u>	<u>257.3</u>	14.3%
		941.1	2059.3	
	Initial Fuel Costs	~100.0	—	

This Table is based upon existing costing procedures.

PWR from Nuclear Energy Cost Data Base DOE/NE-0044-1 1982.

COST OF ELECTRICITY CONTOURS (mills/kWh)

ORNL-DWG 84-2235 FED

$P_e = 1.22 \text{ GW(e)}$ $b/a = 1.6$

$B_c / B_m \leq 0.6$ $B_m = 10 \text{ T}$ $P_{add} = 100 \text{ MW(e)}$

CULHAM mkII-B

$B_m = 8 \text{ T}$

$\langle \beta \rangle = 9.2 \%$

2500+ tonnes

$P_{wn} = 3.6 \text{ MW} \cdot \text{m}^{-2}$

$P_e = 1200 \text{ MW (e)}$

GENERIC

$B_m = 8 \text{ T}$

$\langle \beta \rangle = 8.0 \%$

10,000 tonnes

$P_{wn} = 3.6 \text{ MW} \cdot \text{m}^{-2}$

$P_e = 1200 \text{ MW (e)}$

VARIATION OF COE FOR REFERENCE REACTOR WITH CHANGING CONSTRUCTION TIME AND ADDITIONAL POWER

ORNL-DWG 84-2233 FED

COST OF ELECTRICITY CONTOURS (mills/kWh)

ORNL-DWG 84-2234

FED

$$\langle \beta \rangle = 0.03$$

$$b/a = 1.6$$

$$B_o/B_m \leq 0.6$$

$$R/a = 5.0$$

$$P_{add} \propto P_{fus}$$

VARIATION OF COE WITH $\langle \beta \rangle$ FOR SINGLE 600 MW(e) AND 1200 MW(e) FUSION REACTORS

ORNL-DWG 84-2240 FED

COMPARISON OF COST OF ELECTRICITY AT THE POWER PLANT FOR FISSION AND
GENERIC FUSION. "APPROXIMATE NUMBERS" FOR 150 \$/lb U_3O_8

- COMMON ASSUMPTIONS
 - * 8 YEAR CONSTRUCTION
 - * 0.10 - FIXED CHARGE RATE
 - * 0.50 - INDIRECT CHARGES
 - * 0.10 - TAX ADJUSTED INTEREST
 - * 0.15 - CONTINGENCY
 - * CONSTANT DOLLARS 1983
 - * 0.65 AVAILABILITY

	1 x 1200 MW _e FISSION	1 x 1200 MW _e FUSION	2 x 600 MW FISSION	2 x 600 MW _e FUSION
DIRECT COST M\$	900	1300	1150	1550
TOTAL COST (M\$)	1700	2450	2200	2950
<u>COE</u> mills/kw.h				
O and M	6	7	7	8
FUEL	21	10	21	11
BOP	17	18	22	22
BLDGS.	3	4	3	6
NUCL. ISL.	5	13	7	15
TOTAL	52	52	60	62

$$\langle \beta \rangle = 8\%$$

$$B_m = 9 \text{ T}$$

$$\langle \beta \rangle = 12\%$$

$$B_m = 9 \text{ T}$$

GENERIC TOROIDAL REACTOR STUDIES WERE STARTED AT ORNL, INITIALLY BECAUSE OF CONCERN ABOUT SOME ASSESSMENTS OF MAGNETIC FUSION VIABILITY.

- THEY HAVE EVOLVED TO MEET THE GOALS OF DEFINING A SATISFACTORY PRODUCT AND TO DETERMINE THE SELF-CONSISTENT COMPONENT REQUIREMENTS OF THE SYSTEM
- AN AVAILABILITY CODE IS NOW OPERATING AND IT WILL BE USED TO DEFINE COMPONENT REQUIREMENTS AND TO STUDY THE AFFECT OF POWER DENSITY ON COST OF ELECTRICITY
- THE STUDIES INDICATE THAT A MODERATE SCALE 10,000-15,000 tonne s/c COIL TOROIDAL REACTOR $\langle B \rangle \simeq 8\%$ OF 1200 MW_e SHOULD BE COMPETITIVE IN THE FUTURE
- COMPONENT REQUIREMENTS FOR SUCH A DEVICE ARE IN THE RANGE CONSIDERED IN PRESENT STUDIES WITH s/c COILS.
 $B_m \simeq 10T$ FIRST WALLS ($P_{wa} \simeq 4 \text{ MW.m}^{-2}$) ADDITIONAL POWER, (2\$/W_e)
- INTERESTINGLY THE STUDIES INDICATE THAT A 2 x 600 MW_e STATION RATHER THAN A 1 x 1200 MW_e STATION WOULD INVOLVE A COST PENALTY NO DIFFERENT FROM THAT EXPERIENCED IN PRESENT DAY POWER STATIONS