A BRIEF HISTORY

of

FUSION POWER PLANTS

DON STEINER
RPI

SYMPOSIUM on FUSION POWER PLANTS
MIT

JANUARY 22,2001

THIS PRESENTATION WILL CONSIDER THREE DECADES IN THE EVOLUTION OF FUSION POWER PLANT DESIGN

- .1954-1965

  THE AGE OF INNOCENCE

- .1965-1975

  THE AGE OF ENLIGHTENMENT

- .1975-1985

  THE AGE OF UNWARRANTED EXUBERANCE

FUSION POWER PLANT STUDIES

1954-1965

Spitzer, Grove, Johnson, Tonks, Westendorp, *Problems of the Stellarator as a Useful Power Source*, NYO-6047, Aug.1954.

Lawson, *Some Criteria for a Useful Thermonuclear Reactor*, AEREGPIR-1807, Dec.1955, and Proc. Phys. Soc. London, B, 70, *46 (1957)*.

Christofilos, *General Parameters for a 500-MWAstron Power Reactor,* UCRL-5095, Jan.22, 1958.

Mills, *Fusion Power from Magnetically Confined Plasma*, MATT-34, Mar.1960.

FUSION POWER PLANT STUDIES *(continued)*

Post, *Some Aspects of the Economics of Fusion Reactors*, UCRL6077, August 1960.

Rose, *Basic Concepts for a Steady-State Fusion Reactor*, Trans. Am. Nuclear Society, 4 No.1, page 98, (1962).

Ribe, et al, *Feasibility Study of a Pulsed Thermonuclear Reactor*, LA3294-MS, (1965).

UNCLASSIFIED

NYO-6047

Photostat Price $47.90
Microfilm Price $11.10

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D.C.

PROBLEMS OF THE STELLARATOR AS A USESFUL POWER SOURCE

August 1, 1954

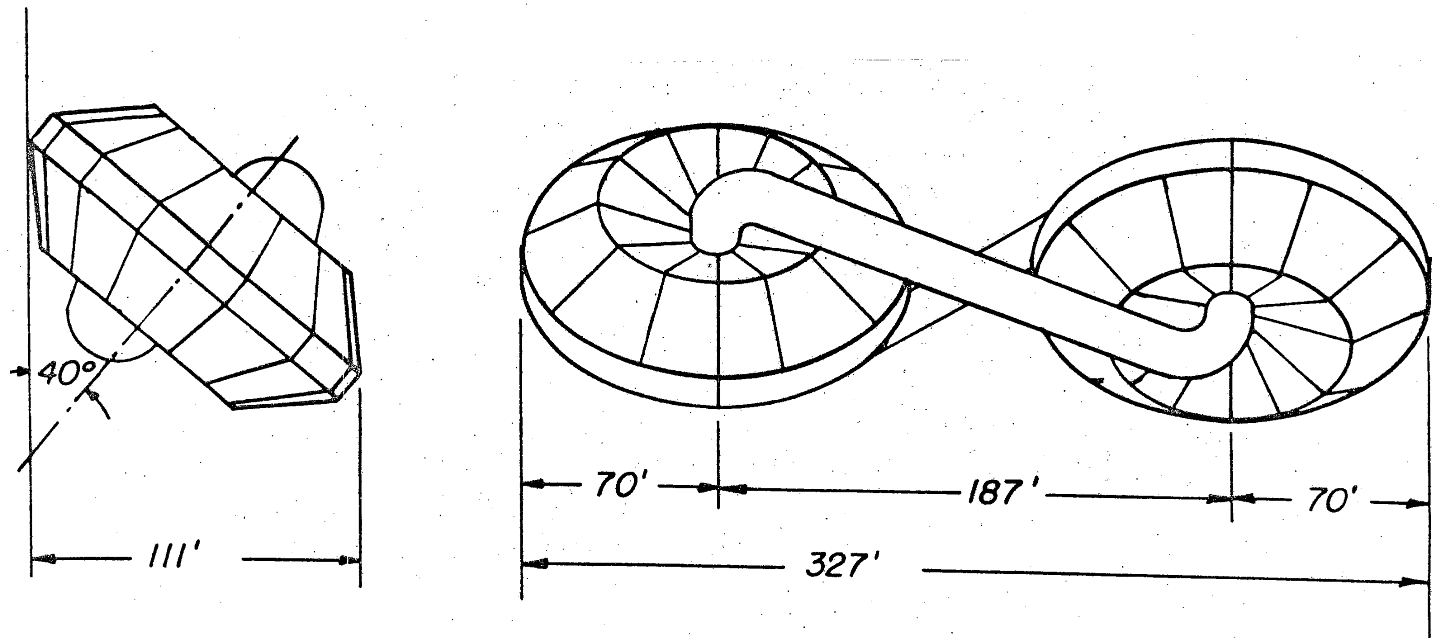
Report written by:
Lyman Spitzer, Jr.
Donald J. Grove
Woodrow E. Johnson
Lewi Tonks
Willem F.Westendorp

Contract No. AT(30-1)-1238

UNCLASSIFIED

SECRET

TABLE OF CONTENTS



TOP VIEW and END VIEW of STELLARATOR

Fig. I-4

SUMMARY OF THREE CASES STUDIED

MAXIMUM MAGNETIC FIELD (gauss)	50,000	75,000	100,000
POWER AS HEAT AT TURBINE THROTTLE (kw)	3.41×10^6	$17.3 \text{x} 10^6$	$54.5 \text{x} 10^6$
ELECTRICAL POWER FOR MAGNET AND SALE (kw)	1.19	6.0	19.0
MAGNET POWER REQUIRED (kw)	0.60	1.34	2.38
NET SALEABLE POWER (kw)	0.59.	4.68	16.6
INVESTMENT COST (dollars per kw)	669	209	149

75,000 gauss

1.	External Heat Exchangers	$64.7 x 106
2.	Magnet	78.4
3.	Rectification	80.3
4.	Reaction Tube	27.6
5.	Li and H_2O Pumps	27.0
6.	Building and Structures	30.0
7.	Lithium Metal	2.7
	Sub- Total	310.7
	Over-head at 17%	52.8
8.	Turbo-Electric	363.5
		555.4
	Total	918.9
9.	Magnetic Pumping	30.0
10.	Injection and Recovery	30.0
	Grand Total	978.9 x 10^6

Investment cost in dollars per kilowatt of capability	209

SECRET

PROBLEMS FOR FUTURE RESEARCH

1. Confinement and heating of a plasma in a magnetic field.

2. Effect of reverse curvature on a plasma.

3. Magnetic field produced by a system of coils.

4. Relevant neutron cross sections.

5. Neutron diffusion in heterogeneous blankets.

Problems for Future Research *(continued)*

6. Lithium corrosion in heat exchanger.

7. Tritium recovery methods.

8. Efficient hydrogen liquefaction.

9. Injection.

10. Magnetic Pumping.

Material for the McKinney Report

Prepared by Arthur E. Ruark, December 31, 1959

Progress Toward Fusion-Power

"It is important to state clearly the nature of this effort to release the power of the hydrogen isotopes in controlled fashion. In the early days of the development of fission power, there were many over-optimistic statements about the date of its general availability at competitive prices. Responsible individuals working in the field avoided this error. Similarly, responsible people in the Sherwood field continually point out that current efforts are devoted to the creation of thermonuclear plasma, in order that we may determine the possibility or the impossibility of fusion machines producing net power."

McKinney Report *(continued)*

"The successive goals are as follows:

1. To heat and confine a plasma, at a particle-energy equal or superior to the so-called ignition energy.
2. To study such thermonuclear plasma, and, if it be thought possible, to design and build a pilot plant yielding net power.
3. To assess, by experience, the possibility of economic generation of power."

"It is not likely that there will be any sudden breakthrough. While it is hoped that the ignition energy may be reached in a relatively short time, perhaps one or two years, we have had this hope before, and have been sternly corrected by the appearance of technical difficulties which came to light only when some of the more obvious ones had been overcome. Therefore, it is safer to say that the time for attainment of Goal 1 may be five years."

McKinney Report *(continued)*

"The possibility of hybrid reactors, making use of both fusion and fission, has been considered. Natural uranium (or thorium) in the blanket could be used to produce plutonium (or U 233), and also to increase the breeding of tritium. (We notice, of course, that use of these expedients would introduce once more the problem of fission products). Fusion reactors and breeding fission reactors are the extreme members of a whole series of hybrid reactors. From this point of view, the efforts on Sherwood and on fission breeders should be considered complementary, rather than competitive."

Fusion Power Plant Studies

1965-1975

R.G. Mills, "Some Engineering Problems of Thermonuclear Reactors, MATT- 548, Princeton University (1967).

R. C. Carruthers, P.A. Davenport, and J.T.D. Mitchell, "The Economic Generation of Power from Thermonuclear Fusion," CLM-R85, Culham Laboratory, Abingdon, England (1967).

D.J. Rose, *Nuci. Fusion, 9*, 183 (1969).

R.W. Werner, G.A. Carlson, J. Hovingh, J.D. Lee, and M.A. Peterson, "Progress Report No.2 on the Design Considerations for a Low Power Experimental Mirror Fusion Reactor," UCRL-74054-2, Lawrence Livermore Laboratory (1974).

Fusion Power Plant Studies *(continued)*

"An Engineering Design Study of a Reference Theta-Pinch Reactor (RTPR)," LA-5336 or ANL-8019, A Joint Report by Argonne National Laboratory and Los Alamos Scientific Laboratory (1974).

G.L. Kulcinski and R.W. Conn, "The Conceptual Design of a Tokamak Fusion Power Reactor, UMWAK-I," *Proc. jst Topi. Mtg. Technology of Controlled Nuclear Fusion*, San Diego, C ONF -740402, Vol.1, p.38, U.S. Atomic Energy Commission and the American Nuclear Society (1974).

J. Williams, T. Merson, F. Finch, P. Schilling, and T. Frank, Conceptual Laser Controlled Thermonuclear Reactor Power Plant," *Proc. 1st Topi. Mtg. Technology ofControlled Nuclear Fusion*, San Diego, CONF-740402, Vol.1, p.70, U.S. Atomic Energy Commission and American Nuclear Society (1974).

CLM – R85

United Kingdom Atomic Energy Authority

RESEARCH GROUP

Report

THE ECONOMIC GENERATION OF POWER FROM THERMONUCLEAR FUSION

R. CARRUTHERS
P.A. DAVENPORT
J.T.D. MITCHELL

Culham Laboratory
Abingdon Berkshire

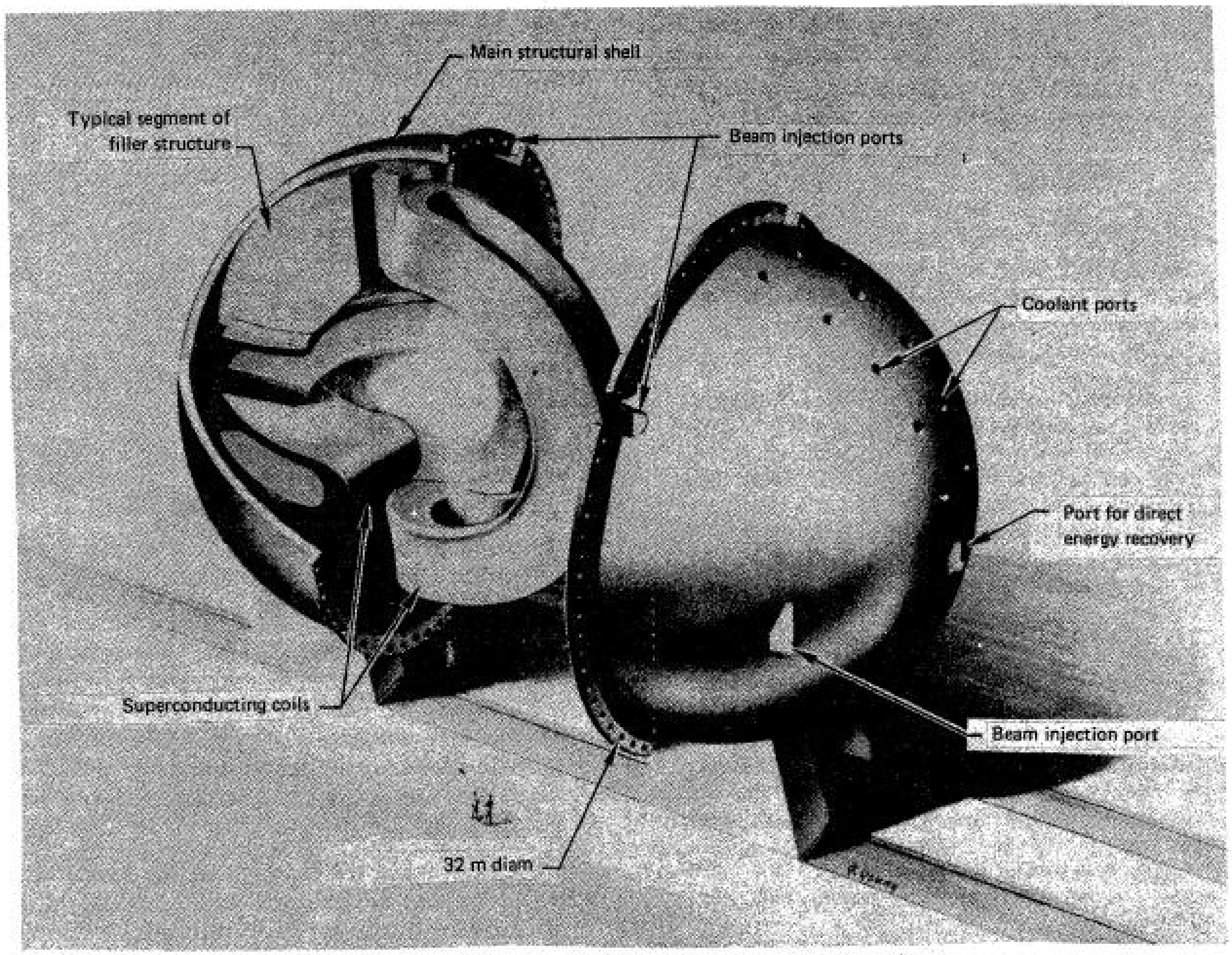
1967

Available from H. M. Stationery Office
FOUR SHILLINGS AND SIXPENCE NET

CONTENTS

TECHNOLOGICAL PROBLEMS

- THE VACUUM WALL
- FUEL INJECTION
- EXHAUST EXTRACTION
- STARTING THE REACTOR
- TRITIUM CYCLING AND BREEDING
- MAGNETIC FIELD PRODUCTION
- RADIATION DAMAGE
- DIRECT CONVERSION
- SODIUM BLANKETS

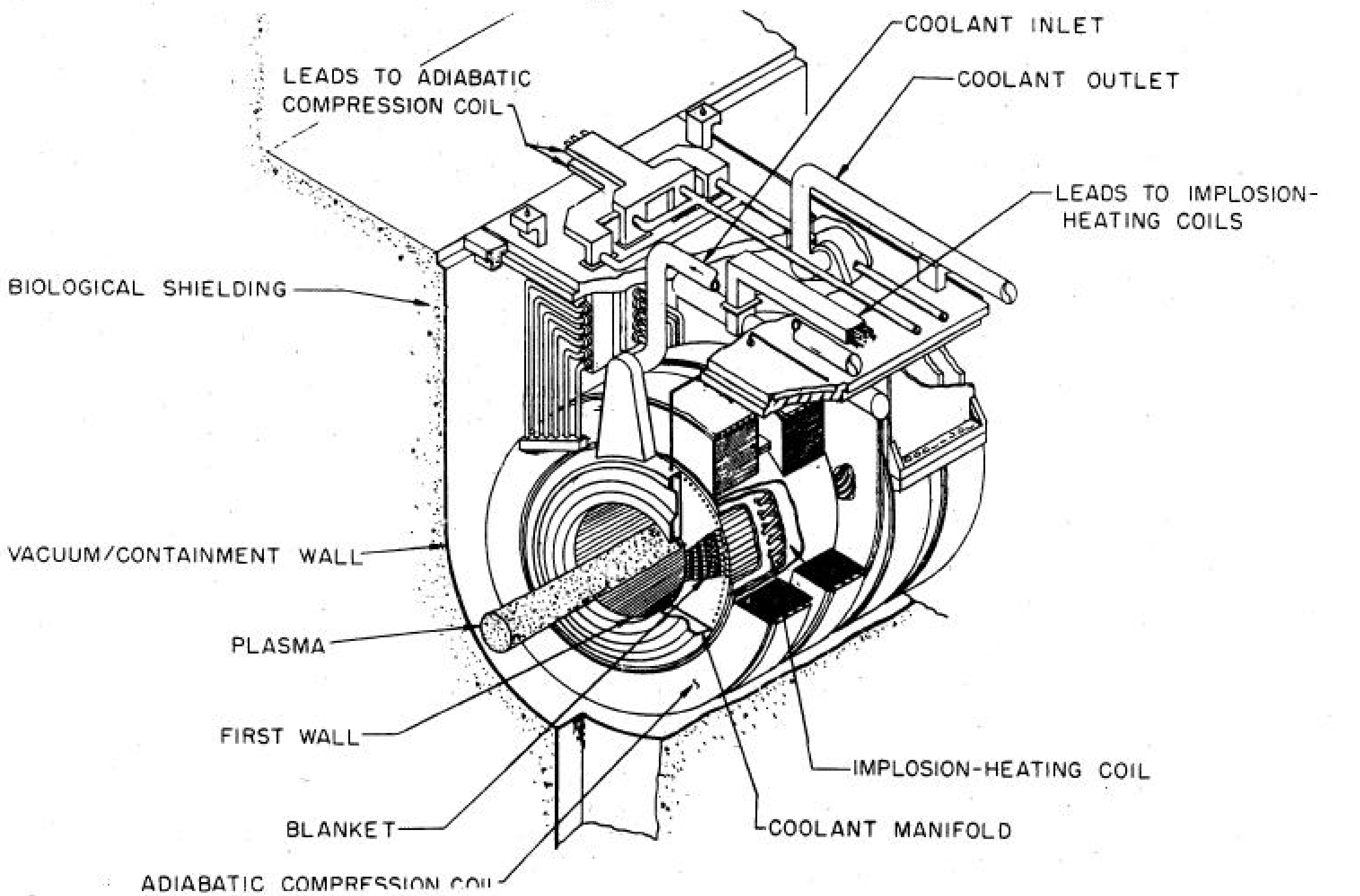


Main structural shell
Typical segment of filler structure
Beam injection ports
Coolant ports
Port for direct energy recovery
Superconducting coils
Beam injection port
32 m diam

Operating Characteristics of the Mirror Reactor
Considered by Werner et al.

Parameter	Value
Plasma volume[a]	130 m^3
Plasma β	0.85
Ion density[b]	$1.2 \times 10^{14}/cm^3$
Mean ion energy[c]	610 keV
Mean electron energy	80 keV
Central field	50 kG
Mirror field	150 kG
Fusion power density	4.5 MW/m^3
Fusion power output	590 MW
Fractional burnup[d]	8%
Confinement time	3.1 sec
Neutron wall-loading	1.6 MW/m^2
Average injection energy	550 keV
Injected power	490 MW
Fuel feed rate[e]	5.6×10^{21}/sec

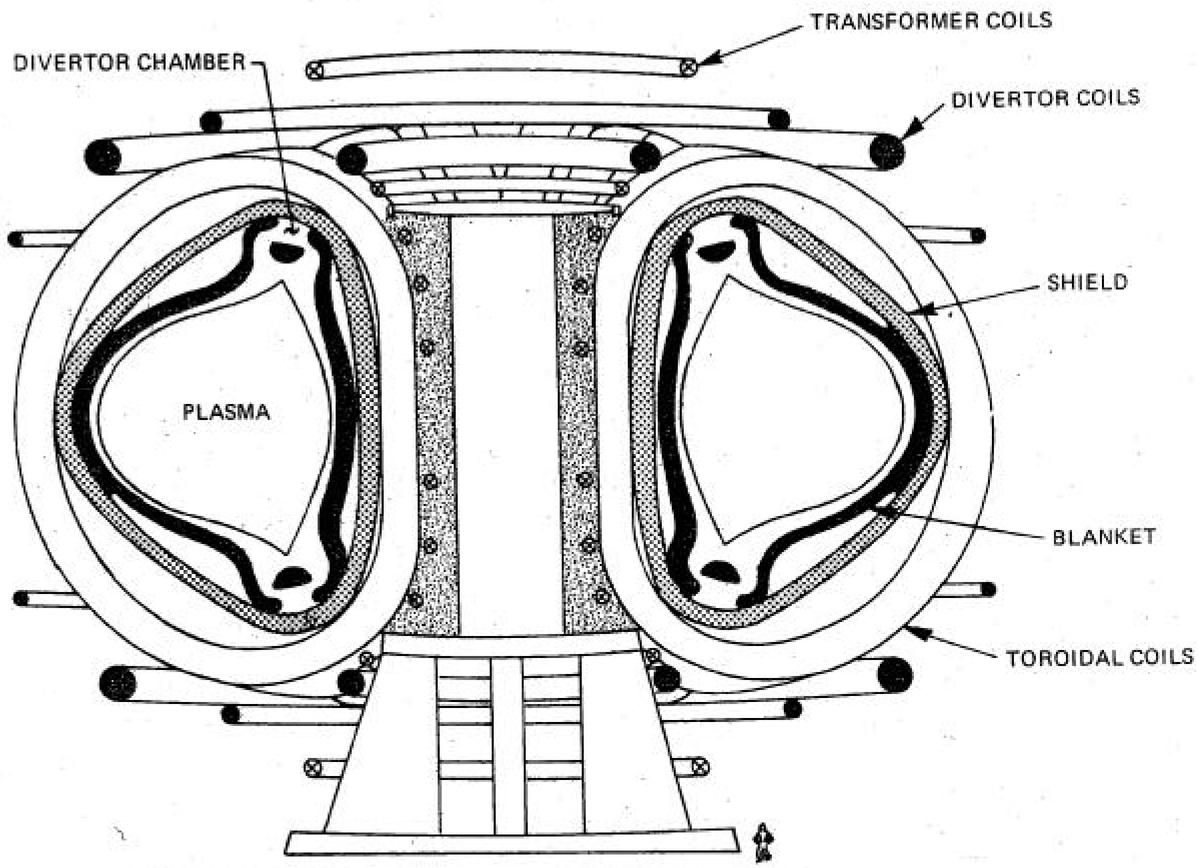
The Reference Theta-Pinch Reactor (RTPR): Cutaway View of a 2-m-Long RTPR Module



Operating Characteristics of the Reference
Theta-Pinch Reactor

Parameter	Value
Radius of first wall	50 cm
Plasma radius at start of burn	11.3 cm
Plasma radius at end of burn	20.0 cm
Major radius of torus	56 m
Plasma volume at start of burn	14.1 m^3
Plasma β	~1
Density at start of burn[a]	$2.5 \times 10^{16}/cm^3$
Fractional burnup	4.8%
Fusion power density[b]	200 MW/m^3
Fusion power output[b]	2820 MW
Neutron wall-loading[c]	2 MW/m^2

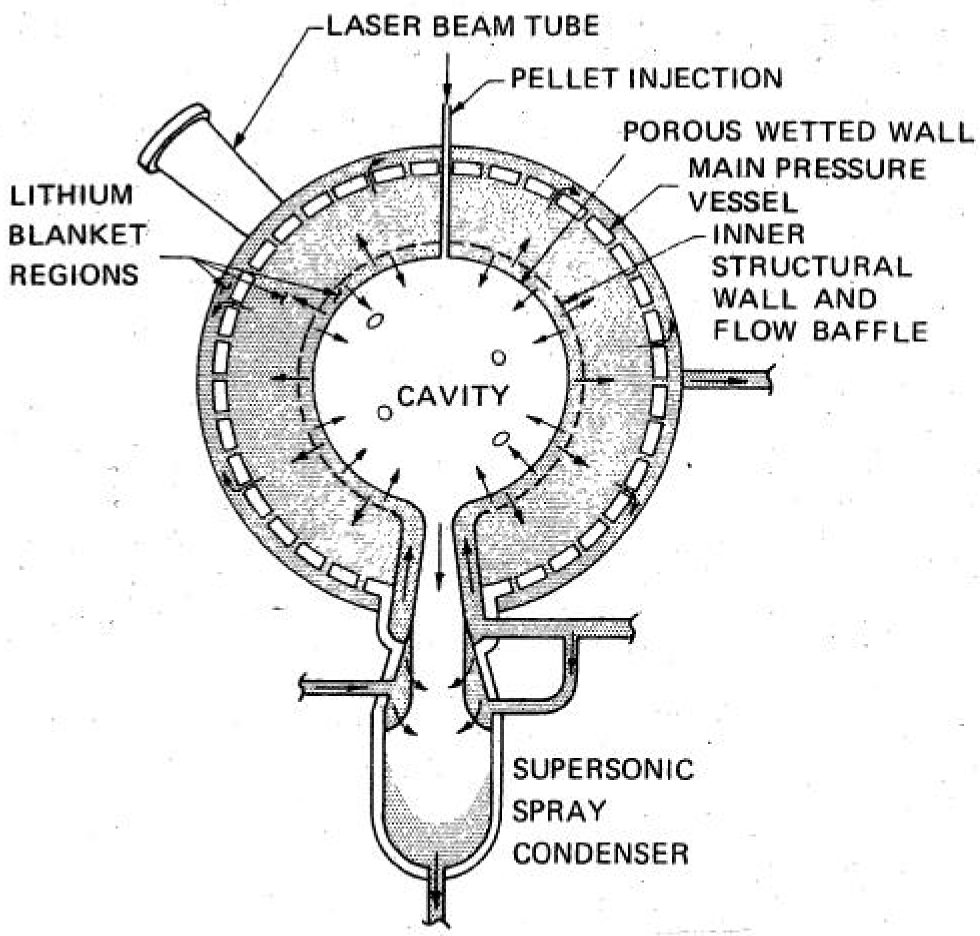
The Tokamak Reactor Model, Cross-Section View



Operating Characteristics of the Tokamak Reactor Described by Kulcinski and Conn

Parameter	Value
Plasma radius	5 m
Major radius of torus	13 m
Plasma volume	6400 m^3
Plasma β	5%
Ion density[a]	$0.8 \times 10^{14}/cm^3$
Ion temperature[b]	11 keV
Maximum toroidal field[c]	87 kG
Axial current	21 MA
Fusion power density	0.7 MW/m^3
Fusion power output	4480 MW
Fractional burnup	7.2%
Confinement time	14 sec
Burn time	5400 sec
Current rise (reversal) time	100 sec
Cycle time	5800 sec
Injected power[d]	15 MW
Injection energy[d]	500 keV
Fuel feed rate	$4 \times 10^{22}/sec$
Neutron wall-loading	1.25 MW/m^2

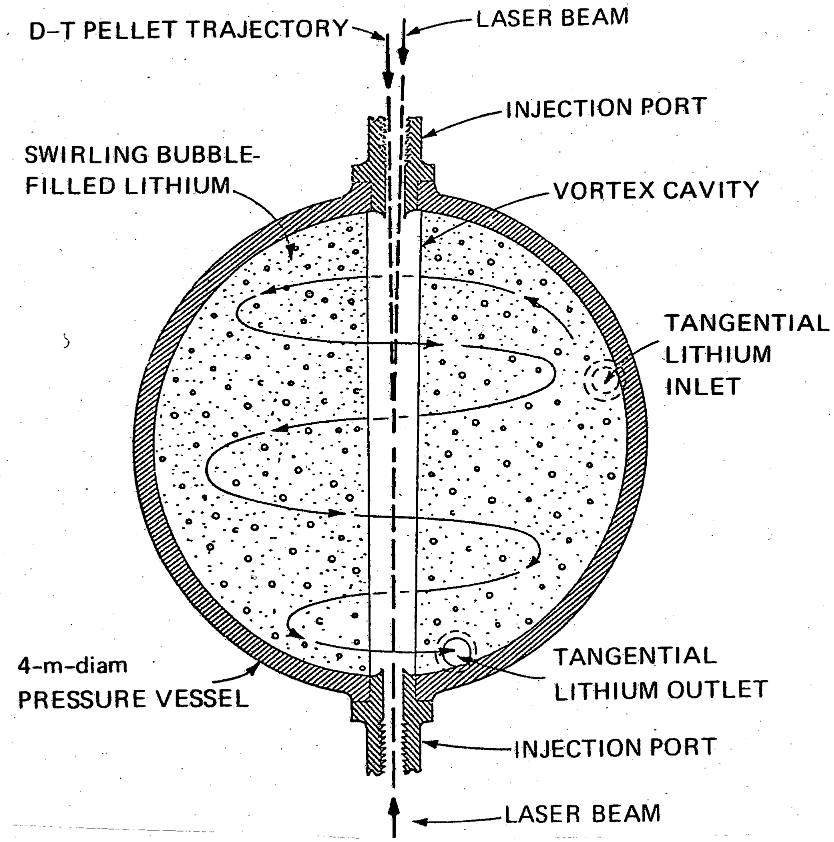
The Wetted-Wall Laser-Pellet Concept



Operating Characteristics of a "Wetted-Wall"
Laser-Pellet Reactor

Parameter	Value
Cavity radius[a]	1.7 m
Laser energy[b]	1 MJ
Fusion energy release	100 MJ/microexplosion
Cavity pulse rate	1.2/sec per cavity
Neutron wall-loading[c]	2.6 MW/m^2
Number of cavities[d]	24
Fusion power output	2880 MW

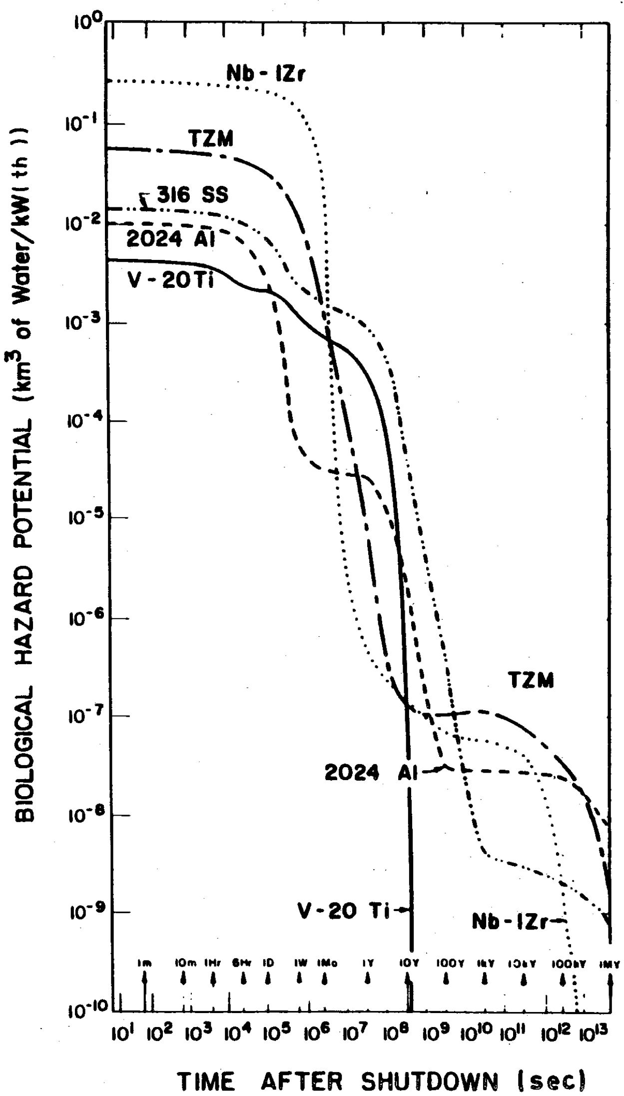
The Swirling-Lithium Vortex Laser-Pellet Concept

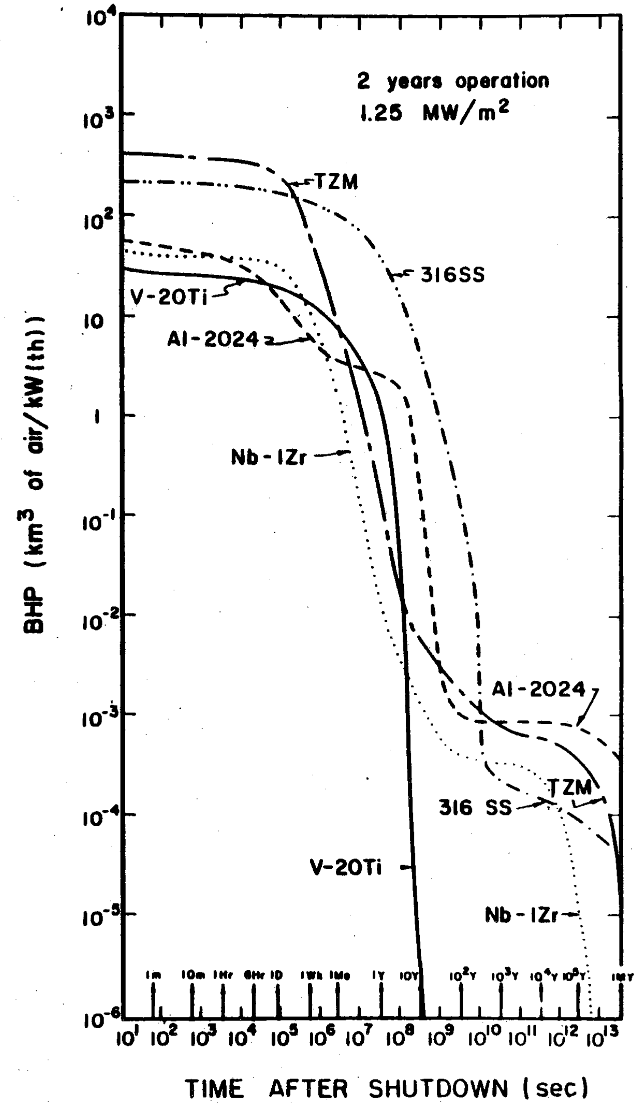


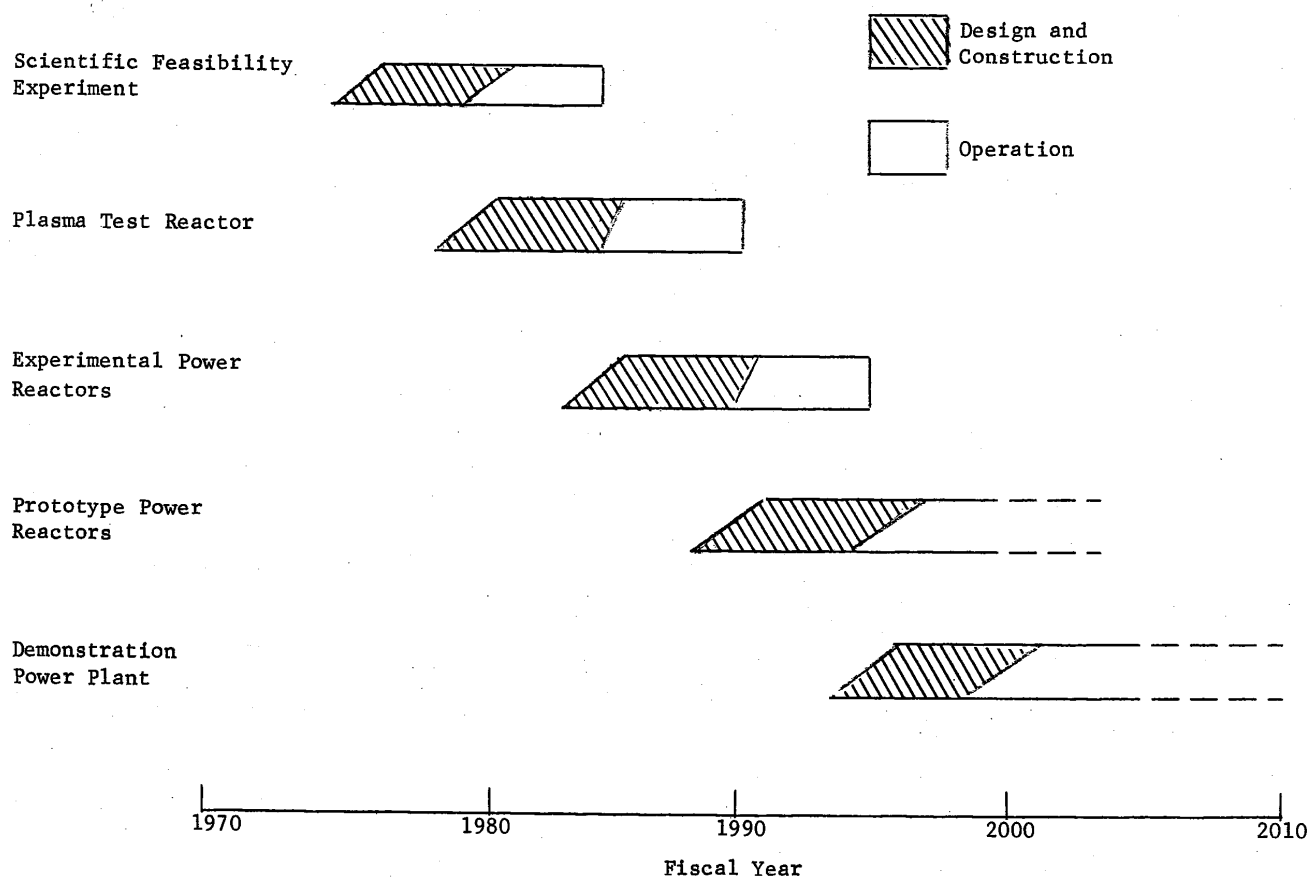
Characteristics and Breeding Performance of Several Blanket Designs

	Design 1 (Ref. 58)	Design 2 (Ref. 59)	Design 3 (Ref. 60)	Design 4 (Ref. 61)
Thickness of breeding region (cm)	82	80	101	38
Breeding material (^6Li enrichment)	LiAl (90%)	Li_2BeF_4 (natural)	Li (natural)	Li[a] (95%)
Volume % beryllium additions	16	none	none	6.6
Structural material	SAP[b]	PE-16[c]	vanadium	niobium
Volume % structural material	21	5	1.6	3.4
Coolant	helium	helium	lithium	lithium
Additional moderator	graphite	none	graphite	graphite
Breeding ratio	1.49	1.07	1.56	1.12

[a]Both enriched and natural lithium are employed in this design.
[b]Sintered Aluminum Product consisting of 90% aluminum and 10% Al_2O_3.
[c]NIMONIC alloy consisting of 43% nickel, 39% iron, and 18% chromium.

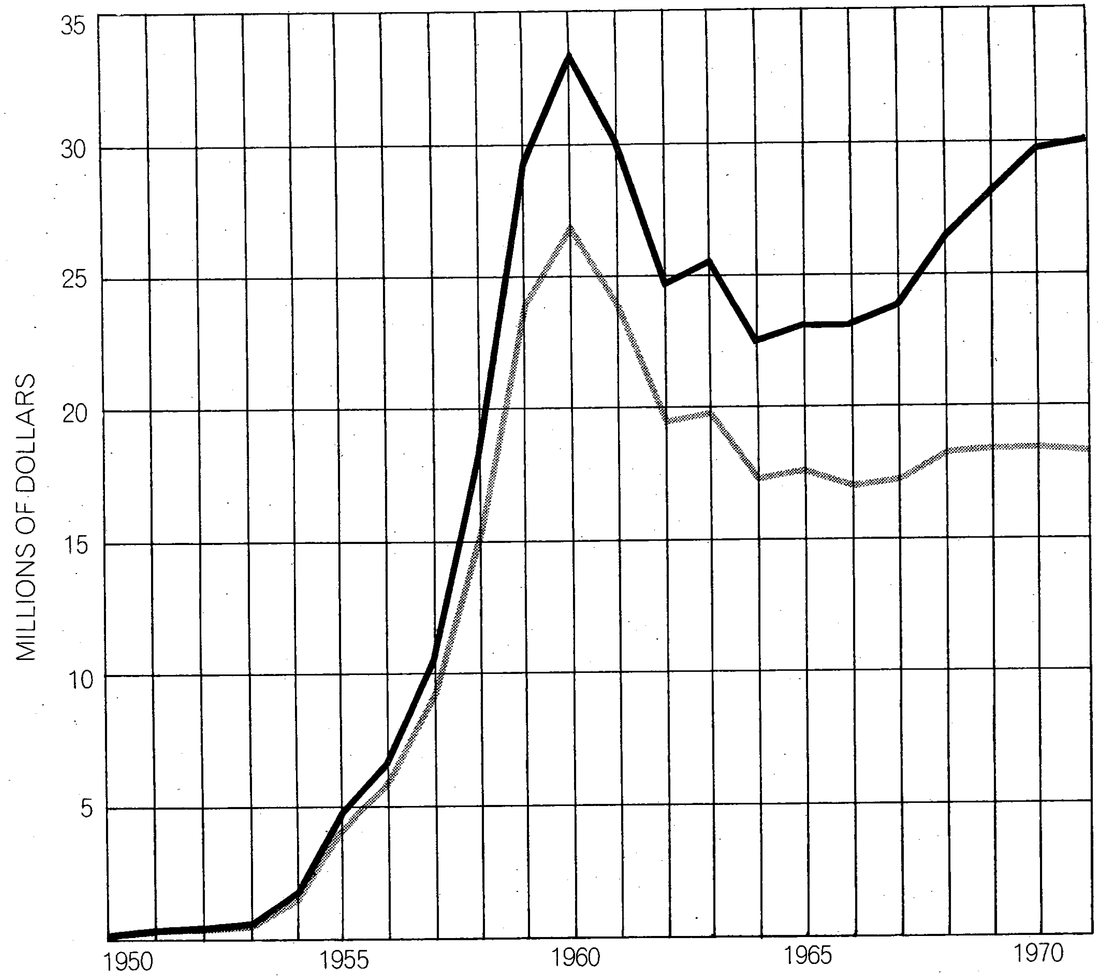

BIOLOGICAL HAZARD POTENTIAL (km^3 of Water/kW(th))
Nb-1Zr
TZM
316 SS
2024 Al
V-20Ti
V-20 Ti
Nb-1Zr
TIME AFTER SHUTDOWN (sec)


2 years operation
1.25 MW/m^2
BHP (km^3 of air/kW(th))
TZM
316SS
V-20Ti
Al-2024
Nb-1Zr
Al-2024
316 SS
TZM
V-20Ti
Nb-1Zr
TIME AFTER SHUTDOWN (sec)



Projected Fusion-Reactor Development Program
Wash-1267, July 1973

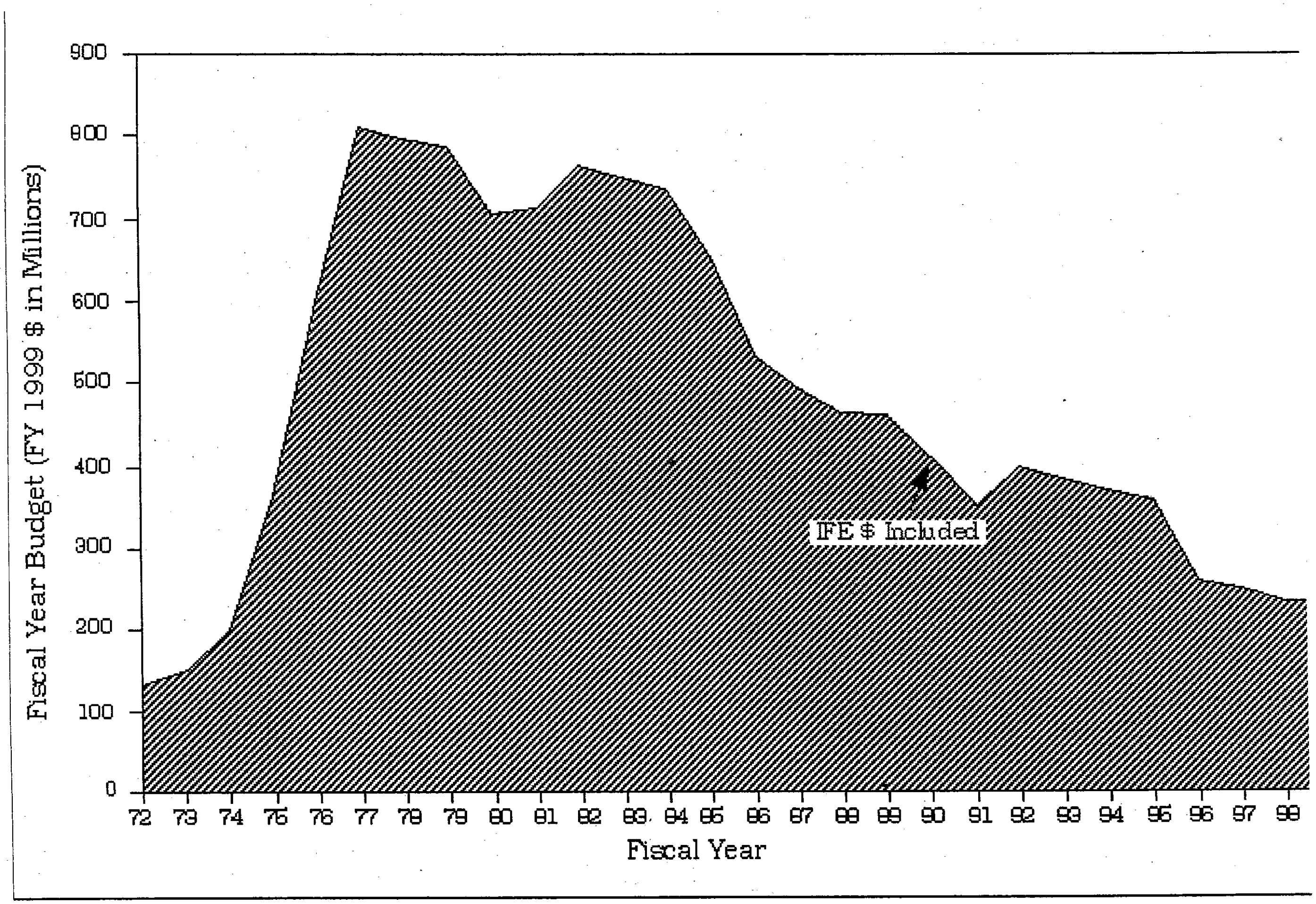
U.S. Fusion Program Support



CHARACTERISTICS OF THE 1975-1985 TIME PERIOD

- SIGNIFICANTLY ENHANCED BUDGETS
- NATIONAL AND INTERNATIONAL EFFORT ON NEXT STEP TOKAMAK DEVICES
- MAJOR POWER PLANT STUDIES
- EMPHASIS ON COMPACT DESIGN

U.S. Fusion Energy Sciences Budget History



Design Parameters for Near-Term Tokamak Reactors

Design Parameter	T-20 (U.S.S.R., 1977)	EPR (U.S., 1977)	TNS (U.S., 1978)	ETF (U.S., 1980)	FED (U.S., 1981)	FER-1 (Japan, 1981)	FER-2 (Japan 1981)	INTOR (IAEA, 1981)	INTOR (IAEA 1982[a]
Major radius (m)	4.5	4.7	5.0	5.4	5.0	5.5	5.5	5.2	5.1
Plasma radius (m)	1.0	1.3	1.2	1.3	1.3	1.1	1.1	1.3	1.3
Plasma elongation	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.6	1.6
Fusion power, thermal (MW)	450	600	1140	570	450	440	440	620	620
Neutron wall load (MW/m^2)	1.0	1.3	2.4	1.5	1.0	1.0	1.0	1.3	1.3
Plasma current (MA)	3.6	7.3	5.0	6.1	6.5	5.3	5.3	6.4	6.4
Average β^b(%)	3.7	7.0	7.0	6.0	5.2	4.0	4.0	5.6	5.6
Number of pulses	4×10^5	1×10^6	5×10^5	5×10^5	3×10^5	4×10^5	4×10^5	7×10^5	$> 4 \times 10^5$
Pulse length (sec)	300	60	500	100	100/50	100	100	200	200
Heating method[c]	NBI	NBI	NBI	NBI	rf	NBI + rf	NBI + rf	NBI	rf
Beam energy (keV)/ frequency (MHz)	400/	180/	150/	150/	/68	150–170/	150–170/	150/	/85
Heating power (MW)	60	40	50	60	50	60	60	75	60
Toroidal field (T)	12	10	11	> 11	10	12	12	11	11
Toroidal coil bore (m)	3.0×7.0	5.6×8.7	6.2×9.8	7.5×10.8	7.5×10.9	6.1×9.1	5.8×8.0	7.7×10.7	6.6×9.3
Impurity control method[d]	—	—	—	PD	PL/PD	PD/PL	PD/PL	PD	PD/PL
Structural material	SS	SS	SS	SS	SS	SS	SS	SS	SS
Coolant	H_2O/He	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O
Breeding material	None	None	None	None	None	Li_2O	Li_2O	Li_2SiO_3	$Li_2O/Li_{17}P_{83}$

Key Parameters for the FED Baseline

	8 T	Common Value	10 T
Major radius (m)		5.0	
Plasma radius (m)		1.3	
Plasma elongation		1.6	
Fusion power (MW)	180		450
Neutron wall loading (MW/m^2)	0.4		1.0
Heating power (MW)			
Initial		50	
Burn	36		0
Amplification factor, Q	5		Ignited
Burn time (s)	$\geqslant$100		~50
Duty factor[a]	0.65		0.5
Average D-T density (m^{-3})	0.8×10^{20}		1.2×10^{20}
Average total beta (%)		5.2	
Plasma current (MA)	5.4		6.5
TF coil clear bore, width $\times$ height (m)		7.4×10.9	
Field on axis (T)	3.6		4.6
Number of full-field pulses	2.5×10^5		2.5×10^4
Availability[b] (%)	10 to 20		10 to 20

[a]Defined as ratio of burn time to cycle time.
[b]Defined as ratio of operating time to operating time plus downtime.

Design Parameters for Commercial Tokamak Reactors

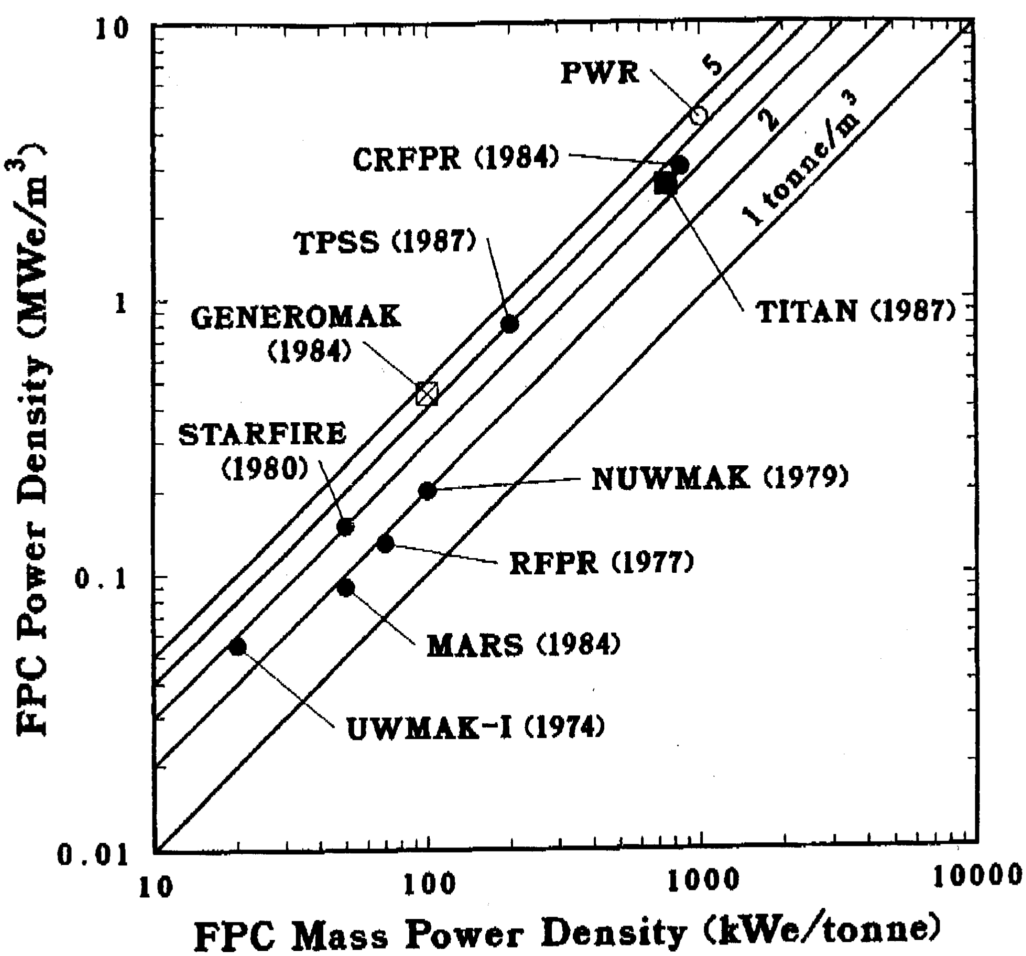
Design Parameter	NUWMAK (U.S., 1979)	Culham IIC (U.K., 1979)	STARFIRE (U.S., 1980)	SPTR-P (Japan, 1981)
Major plasma radius (m)	5.1	7.8	7.0	6.8
Minor plasma radius (m)	1.13	2.0	1.94	2.0
Plasma elongation	1.64	1.68	1.6	1.6
Gross thermal power (MW)	2100	1825	4000	3700
Neutron wall loading (MW/m^2)	4.0	1.5	3.6	3.3
Plasma current (MA)	7.2	11.0	10.1	16.4
Average toroidal β (%)	6.5	7.7	6.7	7.0
Burn pulse length (sec)	225	27	"Continuous"	"Continuous"
Plasma current drive[a]	None	None	rf	rf
	—	—	90 MW, 1.7 GHz	80 MW
Plasma heating[a]	rf	NBI	rf	rf
	80 MW, 92 MHz	86 MW	90 MW, 1.7 GHz	
Toroidal field (T)	12	>8	11	12
Impurity control method	Gas blanket	None	Pumped limiter	Pumped limiter
Structural material/coolant	Ti-Al-V/H_2O	SS/He	SS/H_2O	SS/H_2O
Blanket breeding material	$Li_{62}Pb_{38}$	Li compound	$LiAlO_2$	Li_2O

Design Parameters for Tandem Mirror Reactors

Design Parameter	Near-Term Test Facilities: TASKA[a] (U.S./F.R.G., 1981)	TDF[a] (U.S., 1982)	Commercial Facilities: LLNL[a] (U.S., 1977)	LLNL[a] (U.S., 1979)	WITAMIR (U.S., 1980)	LLNL (U.S., 1981)	MARS[b] (U.S., 1982)
Plasma energy multiplication Q	—	—	5	10	28	22	17
Central cell length (m)	21	8	100	320	165	150	150
Fusion power, thermal (MW)	80	20	2540	3000	3000	3500	3500
Neutron wall load (MW/m^2)	1.5	1.4	2.0	1.3	2.4	2.3	5.0
NBI[c] energy (keV)	250	80	1200	400	500	250	475
Magnetic field							
Large minimum-B coils (T)	6	3	17	13	6	4	8
Small circular coils (T)	20	15	—	—	14	20	24
Structural material	FS[d]	SS	Inconel	Inconel	FS	Inconel	FS
Coolant	$Li_{17}Pb_{83}$	H_2O	He	He	$Li_{17}Pb_{83}$	He	$Li_{17}Pb_{83}$/He
Breeding material	$Li_{17}Pb_{83}$	—	Li	Li	$Li_{17}Pb_{83}$	Li_2O	$Li_{17}Pb_{83}/Li_2O$

The Evolution of Compact Design

	UWMAK I 1973	UWMAK III 1976	ORNL DEMO 1977	HFCTR 1979	AFTR2 1981	Riggatron 1978
Plasma radius (m)	5	2.5	1.5	1.2	1.3	0.34
Major radius (m)	13	8.1	6	6	4.9	0.85
Plasma volume (m^3)	6400	2370	430	317	304	1.9
Wall loading[a] (MW/m^2)	1.25	2.5	3.0	3.4	5.2	68.0
First-wall material	Stainless steel	TZM	Stainless steel	TZM	Not specified	Copper
Power density (MW/m^3)	0.8	2.3	5.3	7.7	10.9	460
Average beta (%)	5	9	15	4	7	20
Maximum field in TF coil (T)	8.7	8.7	7.1	13.1	9.3	24
Position of TF coil	Outside shield	Outside shield	Outside shield	Outside shield	Outside shield	Inside shield
TF coil conductor	NbTi	NbTi	NbTi	Nb_3Sn	Copper	Copper
Ratio of resistive losses to fusion power	NA[b]	NA	NA	NA	0.12	0.20
Plasma heating	NB[c]	RF[d]	NB	NB	RF	Ohmic


10
1
0.1
0.01
10
100
1000
10000
FPC Power Density (MWe/m³)
FPC Mass Power Density (kWe/tonne)
PWR
5
2
1 tonne/m³
CRFPR (1984)
TPSS (1987)
GENEROMAK
(1984)
TITAN (1987)
STARFIRE
(1980)
NUWMAK (1979)
RFPR (1977)
MARS (1984)
UWMAK-I (1974)

POWER PLANT DESGNS HAVE PLAYED AND WILL CONTINUE TO PLAY AN IMPORTANT ROLE IN THE FUSION PROGRAM

- THEY ARE A VEHICLE FOR INTEGRATING AND ASSESSING OUR KNOWLEDGE BASE
- THEY HELP GUIDE OUR SCIENCE AND TECHNOLOGY PROGRAMS
- THEY PROVIDE SPECIFIC, THOUGH SPECULATIVE, VISIONS OF OUR END PRODUCT