

APPENDIX A

Contents

A.1.	TABLE OF TITAN-I REACTOR PARAMETERS	A-1
A.2.	SYSTEMS CODE PARAMETERS OF TITAN-I	A-24
A.3.	COST SUMMARY OF TITAN-I REACTOR	A-27
A.4.	COST DATA BASE FOR TITAN-I REACTOR	A-35
	REFERENCES	A-43

APPENDIX A

A.1. TABLE OF TITAN-I REACTOR PARAMETERS

1. CHARACTERISTIC MACHINE DIMENSIONS

1.1. Reactor Envelope ⁽¹⁻¹⁾

1.1.1. Height	5.67 m
1.1.2. Outside diameter	13.69 m
1.1.3. Circumference	43.01 m
1.1.4. Volume	834.78 m ³

1.2. Plasma Chamber

1.2.1. Major toroidal radius, R_T	3.90 m
1.2.2. Plasma minor radius, r_p	0.60 m
1.2.3. First wall minor radius, r_{FW}	0.66 m
1.2.4. Plasma volume, V_p	27.71 m ³
1.2.5. Plasma chamber volume	33.53 m ³
1.2.6. First wall surface area ⁽¹⁻²⁾	169.62 m ²
1.2.7. Number of sectors ⁽¹⁻³⁾	3

1.3. Vacuum Tank ⁽¹⁻¹⁾

1.3.1. Average height	12 m
1.3.2. Outside diameter	15 m
1.3.3. Wall thickness	0.05 m
1.3.4. Circumference	47 m
1.3.5. Volume	2120 m ³

2. PLASMA PARAMETERS

2.1. Fuel Cycle

DT/Li

2.2. Plasma Dimensions

2.2.1. Major radius, R_T	3.90 m
2.2.2. Minor radius, r_p	0.60 m
2.2.3. Plasma cross section	circular

2.3. Electron Density, n_e ⁽²⁻¹⁾	
2.3.1. Average electron density	$9.5 \times 10^{20} \text{ m}^{-3}$
2.3.2. Central electron density	$1.4 \times 10^{21} \text{ m}^{-3}$
2.4. Ion Density, n_i ⁽²⁻¹⁾	
2.4.1. Average ion density	$8.9 \times 10^{20} \text{ m}^{-3}$
2.4.2. Central ion density	$1.3 \times 10^{21} \text{ m}^{-3}$
2.5. Average Alpha-Particle Density, n_α ⁽²⁻²⁾	$4.5 \times 10^{19} \text{ m}^{-3}$
2.6. Ion Temperature, T_i ⁽²⁻¹⁾	
2.6.1. Average ion temperature	10 keV
2.6.2. Central ion temperature	15 keV
2.7. Electron Temperature, T_e ⁽²⁻¹⁾	
2.7.1. Average electron temperature	10 keV
2.7.2. Central electron temperature	15 keV
2.8. Average Alpha-Particle Energy, E_α ⁽²⁻²⁾	68 keV
2.9. Effective Plasma Ion Charge, Z_{eff} ⁽²⁻⁸⁾	1.690
2.10. Global Energy-Confinement Time, τ_E ⁽²⁻⁴⁾	0.22 s
2.11. Effective Global Thermal Diffusivity, $\chi_E = (3/16)r_p^2/\tau_E$ ⁽²⁻⁴⁾	0.31 m ² /s
2.12. Electron Energy-Confinement Time, τ_{Ee} ⁽²⁻⁴⁾	0.28 s
2.13. Particle Confinement Time at Burn, τ_p	
2.13.1. Without recycling ⁽²⁻⁵⁾	1.10 s
2.13.2. With recycling ⁽²⁻⁶⁾	
2.13.2.1. Fuel ions (average)	3.68 s
2.13.2.2. Helium	1.52 s
2.14. Lawson Parameter, $n_i \tau_E$ ⁽²⁻⁴⁾	$1.92 \times 10^{19} \text{ s/m}^3$
2.15. Plasma Toroidal Current, I_ϕ ⁽²⁻⁷⁾	17.8 MA
2.16. Average Toroidal Current Density, j_ϕ ⁽²⁻⁷⁾	15.7 MA/m ²

2.17. Toroidal Field, B_ϕ ⁽²⁻¹⁾		
2.17.1. Average	3.90	T
2.17.2. At plasma edge	0.38	T
2.17.3. At plasma axis	11.85	T
2.17.4. Peak field on the coil ⁽²⁻⁸⁾	4.90	T
2.18. Poloidal Field, B_θ ⁽²⁻¹⁾		
2.18.1. Average	6.21	T
2.18.2. At plasma edge	5.93	T
2.19. Vertical Field,		
2.19.1. At plasma axis	1.56	T
2.19.2. Decay index, n	0.16	
2.19.3. Stray field at startup	0.43	mT
2.20. Poloidal Beta, $\beta_\theta = 2\mu_0 p / B_\theta^2(r_p)$	0.22	
2.21. Toroidal Beta $\beta = 2\mu_0 p / \langle B_\phi \rangle^2$	0.52	
2.22. Engineering Beta ⁽²⁻⁹⁾	7.75	
2.23. Reversal Parameter, F ^{(2-7),(2-10)}		
2.23.1. Mean value at burn	-0.1	
2.23.2. During OFCD oscillation	-0.03 to -0.17	
2.24. Pinch Parameter, Θ ^{(2-7),(2-10)}		
2.24.1. Mean value at burn	1.56	
2.24.2. During OFCD oscillation	1.50 to 1.62	
2.25. Safety Factor, $q = rB_\phi / RB_\theta$		
2.25.1. On axis	0.11	
2.25.2. At plasma edge	-0.01	
2.25.3. Radius of reversal surface ($q = 0$)	0.55	m
2.26. Streaming Parameter, j_ϕ / n		
2.26.1. During startup (maximum value)	6.5×10^{-14}	A-m
2.26.2. At burn	1.8×10^{-14}	A-m
2.27. Electron Streaming Parameter, $\xi = v_D / v_{th}$		
2.27.1. During startup (maximum value)	2.0×10^{-2}	
2.27.2. At burn	1.9×10^{-3}	

2.28. Radiation Fraction ⁽²⁻⁸⁾	
2.28.1. Core plasma	0.70
2.28.2. Scrape-off layer	0.23
2.28.3. Divertor plasma	0.04
2.28.4. Total radiation fraction	0.97
2.28.5. Radiation fraction to first wall, f_{RAD}	0.95
2.28.6. Radiation fraction to divertor plate	0.02
2.29. Current Drive ⁽²⁻¹¹⁾	
2.29.1. Method	OFCD
2.29.2. Frequency, f	25 Hz
2.29.3. Toroidal-flux swing, $\delta\phi/\phi_0$	0.035
2.29.4. Θ variation	1.50 to 1.62
2.29.5. F variation	-0.03 to -0.17
2.29.6. Input power (toroidal/poloidal circuits)	
2.29.6.1. Real (supplied) power	44.86/2.08 MW
2.29.6.2. Reactive power	503.88/188.36 MVA
2.29.7. Power-supply dissipation ⁽²⁻¹²⁾	6.92 MW
2.29.8. Current-drive power	56.83 MW
2.29.9. Efficiency, I_ϕ/P_{CD} ⁽²⁻¹³⁾	0.31 A/W
2.30. Plasma Heating Method	Ohmic
2.31. Plasma Ohmic Dissipation	28.5 MW
2.32. Plasma Energy Gain, $Q_p = P_f/P_\Omega$ ⁽²⁻¹⁴⁾	80.2
3. POWER OUTPUT	
3.1. Plasma Fusion Power, P_f	2300.6 MW
3.1.1. Neutron power, P_n	1840.5 MW
3.1.2. Alpha-particle power, P_α	460.1 MW
3.2. Blanket Energy Multiplication, M ⁽³⁻¹⁾	1.2
3.3. Nuclear Power ($MP_n + P_\alpha$)	2668.7 MW
3.4. Ohmic Heating Power, P_Ω ⁽³⁻²⁾	28.5 MW

3.5. Power to First Wall		
3.5.1. Surface heating, $f_{RAD}(P_{\alpha} + P_{\Omega})$	464.2	MW
3.5.2. Nuclear heating		
3.5.2.1. Structure	115.9	MW
3.5.2.2. Coolant	118.1	MW
3.5.3. OFCD heating (eddy currents) ⁽³⁻³⁾	0.01	MW
3.5.4. Coolant-pumping power ⁽³⁻⁴⁾	37.7	MW
3.5.5. Total thermal power, P_{FW}	735.9	MW
3.6. Power to Integrated Blanket Coil (IBC)		
3.6.1. Nuclear heating		
3.6.1.1. Structure	373.3	MW
3.6.1.2. Coolant	870.1	MW
3.6.2. OFCD heating (eddy currents) ⁽³⁻³⁾	1.0	MW
3.6.3. OFCD joule heating ⁽³⁻⁵⁾	16.0	MW
3.6.4. TF-IBC joule heating	25.6	MW
3.6.5. Coolant-pumping power ⁽³⁻⁴⁾	6.0	MW
3.6.6. Total thermal power, P_{IBC}	1292.0	MW
3.7. Power to Hot Shield ⁽³⁻⁶⁾		
3.7.1. Nuclear heating		
3.7.1.1. Structure	458.9	MW
3.7.1.2. Coolant	247.3	MW
3.7.2. Coolant-pumping power ⁽³⁻⁴⁾	3.0	MW
3.7.3. Total thermal power, P_{HS}	709.2	MW
3.8. Power to Divertor Plate		
3.8.1. Surface heating, $(1 - f_{RAD})(P_{\alpha} + P_{\Omega})$	24.4	MW
3.8.2. Nuclear heating		
3.8.2.1. Structure	2.8	MW
3.8.2.2. Coolant	1.2	MW
3.8.3. Coolant-pumping power ⁽³⁻⁴⁾	0.9	MW
3.8.4. Total thermal power, P_{DP}	29.3	MW
3.9. Power to Divertor IBC ⁽³⁻⁷⁾		
3.9.1. Nuclear heating		
3.9.1.1. Structure	17.0	MW
3.9.1.2. Coolant	4.0	MW
3.9.2. Divertor-IBC OFCD joule heating	26.8	MW
3.9.3. Divertor-IBC joule heating	120.5	MW
3.9.4. Coolant-pumping power ⁽³⁻⁴⁾	0.5	MW
3.9.5. Total thermal power, P_{DIBC}	168.8	MW

3.10. Total Reactor Thermal Power, P_{th} ⁽³⁻⁸⁾	2935.2 MW
3.10.1. Power Cycle I	
3.10.1.1. First wall thermal power	735.9 MW
3.10.1.2. Divertor plate thermal power	29.3 MW
3.10.1.3. Total	765.2 MW
3.10.2. Power Cycle II	
3.10.2.1. IBC thermal power	1292.0 MW
3.10.2.2. Hot shield thermal power	709.2 MW
3.10.2.3. Divertor-IBC thermal power	168.8 MW
3.10.2.4. Total	2170.0 MW
3.11. Thermal-Cycle Efficiencies, η_{th} ⁽³⁻⁸⁾	
3.11.1. Cycle I	0.370
3.11.2. Cycle II	0.465
3.11.3. Overall thermal efficiency	0.440
3.12. Gross Electric Power, P_{ET}	1291.5 MWe
3.13. Recirculating Power	
3.13.1. TF-IBC joule losses	25.6 MWe
3.13.2. Divertor-IBC joule losses	120.5 MWe
3.13.3. OFCD system ⁽³⁻⁹⁾	84.4 MWe
3.13.4. Coolant-pumping power	48.1 MWe
3.13.5. Auxiliary power ⁽³⁻¹⁰⁾	42.9 MWe
3.13.6. Total	321.5 MWe
3.14. Recirculating-Power Fraction, ϵ	0.249
3.15. Engineering Q ($= 1/\epsilon$)	4.016
3.16. Net Electric Power	970.0 MWe
3.17. Net Plant Efficiency, $\eta_p = \eta_{th}(1 - \epsilon)$	0.330
3.18. Mass Power Density, MPD ⁽³⁻¹¹⁾	757 kWe/tonne
3.19. Plasma Power Density, P_f/V_p	83 MW/m ³

4. REACTOR COOLANT SYSTEM

4.1. First Wall System ⁽⁴⁻¹⁾

	A bank of circular tubes with single-pass, poloidal coolant flow	
	Lithium (30% ⁶ Li)	
	V-3Ti-1Si	
4.1.1. Coolant	10.5	mm
4.1.2. Structural material	8.0	mm
4.1.3. Tube outer diameter ⁽⁴⁻¹⁾	0.25	mm
4.1.4. Tube inner diameter ⁽⁴⁻¹⁾	2730	
4.1.5. Erosion allowance	0.400	
4.1.6. Number of tubes ⁽⁴⁻²⁾	0.375	
4.1.7. Structure volume fraction	0.225	
4.1.8. Coolant volume fraction	713	K
4.1.9. Void volume fraction	593	K
4.1.10. Outlet temperature	~ 0.1	MPa
4.1.11. Inlet temperature	12	MPa
4.1.12. Outlet pressure	50	MPa
4.1.13. Inlet pressure ⁽⁴⁻³⁾	288	MPa
4.1.14. Maximum primary stress	1020	K
4.1.15. Maximum secondary stress	1464	kg/s
4.1.16. Maximum wall temperature	21.6	m/s
4.1.17. Coolant flow rate (total)	1.90×10^5	
4.1.18. Coolant flow velocity	0.48	
4.1.19. Reynolds number, Re	2.01×10^2	
4.1.20. Magnetic Reynolds number, Re_m	3.04×10^8	
4.1.21. Hartmann number, Ha		
4.1.21.1. Perpendicular, $Ha_{\perp}$	0.21	
4.1.21.2. Parallel, $Ha_{\parallel}$	48.60	
4.1.22. Interaction parameter, $N = Ha^2/Re$	10.35	
4.1.22.1. Perpendicular, $N = Ha_{\perp}^2/Re$	0.04	
4.1.22.2. Parallel, $N = Ha_{\parallel}^2/Re$	7.76×10^8	
4.1.23. Nusselt number, Nu ⁽⁴⁻⁴⁾		
4.1.24. Prandtl number, Pr		
4.1.25. Peclet number, Pe		

4.2. Integrated-Blanket-Coil (IBC) System ⁽⁴⁻⁵⁾

4.2.1. Coolant	6 rows of circular tubes with single-pass, poloidal coolant flow Lithium (30% ⁶ Li)
4.2.2. Structural material	V-3Ti-1Si
4.2.3. Tube outer diameter ⁽⁴⁻⁶⁾	52.5 mm
4.2.4. Tube inner diameter ⁽⁴⁻⁶⁾	47.5 mm
4.2.5. Tube wall thickness	2.5 mm
4.2.6. Number of tubes ⁽⁴⁻⁷⁾	3075
4.2.7. Structure volume fraction ⁽⁴⁻⁸⁾	0.18
4.2.8. Coolant volume fraction ⁽⁴⁻⁸⁾	0.72
4.2.9. Void volume fraction ⁽⁴⁻⁸⁾	0.10
4.2.10. Outlet temperature	973 K
4.2.11. Inlet temperature	593 K
4.2.12. Outlet pressure	~ 0.1 MPa
4.2.13. Inlet pressure ⁽⁴⁻⁹⁾	2.8 MPa
4.2.14. Maximum primary stress	30.0 MPa
4.2.15. Maximum secondary stress	5.0 MPa
4.2.16. Maximum wall temperature	1020 K
4.2.17. Coolant flow rate (total)	918 kg/s
4.2.18. Coolant flow velocity ⁽⁴⁻¹⁰⁾	0.5 m/s
4.2.19. Reynolds number, Re ⁽⁴⁻¹⁰⁾	2.75×10^4
4.2.20. Magnetic Reynolds number, Re_m ⁽⁴⁻¹⁰⁾	0.066
4.2.21. Hartmann number, Ha ⁽⁴⁻¹⁰⁾	
4.2.21.1. Perpendicular, $Ha_{\perp}$	1.30×10^3
4.2.21.2. Parallel, $Ha_{\parallel}$	1.90×10^4
4.2.22. Interaction parameter, $N = Ha^2/Re$ ⁽⁴⁻¹⁰⁾	
4.2.22.1. Perpendicular, $N = Ha_{\perp}^2/Re$	6.15×10^1
4.2.22.2. Parallel, $N = Ha_{\parallel}^2/Re$	1.33×10^4
4.2.23. Nusselt number, Nu ^{(4-10),(4-11)}	5.6

4.3. Hot Shield System ⁽⁴⁻¹²⁾

	Double-pass, poloidal circuit consisting of two zones:
Zone 1:	5 rows of square channels
Zone 2:	4 rows of rectangular channels
4.3.1. Coolant	Lithium (30% ⁶ Li)
4.3.2. Structural material	V-3Ti-1Si
4.3.3. Channel outer dimensions ⁽⁴⁻⁶⁾	
4.3.3.1. 1st zone	60.0 × 60.0 mm
4.3.3.2. 2nd zone	112.5 × 37.5 mm
4.3.4. Channel inner dimensions ⁽⁴⁻⁶⁾	
4.3.4.1. 1st zone	50.0 × 50.0 mm
4.3.4.2. 2nd zone	80.0 × 5.0 mm

4.3.5. Channel hydraulic diameter, d_h ^{(4-13),(4-6)}	
4.3.5.1. 1st zone	50.0 mm
4.3.5.2. 2nd zone	9.4 mm
4.3.6. Number of channels	
4.3.6.1. 1st zone	2640
4.3.6.2. 2nd zone	1126
4.3.7. Structure volume fraction ⁽⁴⁻⁸⁾	
4.3.7.1. 1st zone	0.3
4.3.7.2. 2nd zone	0.9
4.3.8. Coolant volume fraction ⁽⁴⁻⁸⁾	
4.3.8.1. 1st zone	0.7
4.3.8.2. 2nd zone	0.1
4.3.9. Void volume fraction ⁽⁴⁻⁸⁾	
4.3.9.1. 1st zone	0.0
4.3.9.2. 2nd zone	0.0
4.3.10. Outlet temperature	973 K
4.3.11. Inlet temperature	593 K
4.3.12. Outlet pressure	~ 0.1 MPa
4.3.13. Inlet pressure ⁽⁴⁻⁹⁾	2.8 MPa
4.3.14. Maximum primary stress	0.5 MPa
4.3.15. Maximum secondary stress	5.0 MPa
4.3.16. Maximum wall temperature	1020 K
4.3.17. Coolant flow rate (total)	445 kg/s
4.3.18. Coolant flow velocity ⁽⁴⁻⁸⁾	0.17 m/s
4.3.19. Reynolds number, Re ⁽⁴⁻¹⁰⁾	
4.3.19.1. 1st zone	9.79×10^3
4.3.19.2. 2nd zone	1.84×10^3
4.3.20. Magnetic Reynolds number, Re_m ⁽⁴⁻¹⁰⁾	
4.3.20.1. 1st zone	2.40×10^{-2}
4.3.20.2. 2nd zone	4.52×10^{-3}
4.3.21. Hartmann number, Ha ⁽⁴⁻¹⁰⁾	
4.3.21.1. Perpendicular, $Ha_{\perp}$	0.
4.3.21.2. Parallel, $Ha_{\parallel}$ ⁽⁴⁻¹⁰⁾	
4.3.21.2.1. 1st zone	7.00×10^3
4.3.21.2.2. 2nd zone	1.30×10^3
4.3.22. Interaction parameter, $N = Ha^2/Re$ ⁽⁴⁻¹⁰⁾	
4.3.22.1. Perpendicular, $N = Ha_{\perp}^2/Re$	0.
4.3.22.2. Parallel, $N = Ha_{\parallel}^2/Re$	
4.3.22.2.1. 1st zone	2.24×10^3
4.3.22.2.2. 2nd zone	4.10×10^3
4.3.23. Nusselt number, Nu ⁽⁴⁻¹¹⁾	
4.3.23.1. 1st zone	3.6
4.3.23.2. 2nd zone	8.2

4.4. Divertor Plate System ⁽⁴⁻¹⁴⁾

The armor is brazed to
a bank of circular tubes with
single-pass, poloidal coolant flow
Lithium (30% ⁶Li)

4.4.1. Coolant	
4.4.2. Structural material	
4.4.2.1. Armor	W-26Re
4.4.2.2. Coolant tube	V-3Ti-1Si
4.4.2.3. Insulator	Spinel (MgAl ₂ O ₄)
4.4.3. Coolant-tube outer diameter	6.0 mm
4.4.4. Coolant-tube inner diameter	5.0 mm
4.4.5. Armor thickness	2.0 mm
4.4.6. Outlet temperature	813 K
4.4.7. Inlet temperature	593 K
4.4.8. Outlet pressure	~ 0.1 MPa
4.4.9. Inlet pressure ⁽⁴⁻¹⁵⁾	12 MPa
4.4.10. Maximum primary stress	
4.4.10.1. Armor	~ 30 MPa
4.4.10.2. Coolant tube	67 MPa
4.4.11. Maximum secondary stress	
4.4.11.1. Armor	480 MPa
4.4.11.2. Coolant tube	160 MPa
4.4.12. Maximum wall temperature	
4.4.12.1. Armor	1193 K
4.4.12.2. Coolant tube	1033 K
4.4.13. Coolant flow rate (total)	31 kg/s
4.4.14. Maximum coolant flow velocity ⁽⁴⁻¹⁶⁾	25 m/s

4.5. Coolant-Circulator Type

4.5.1. First wall and divertor plate	Two-stage centrifugal pump
4.5.2. IBC, hot shield, and divertor IBC	Single-stage centrifugal pump

4.6. Power Input to Each Circulator ⁽⁴⁻¹⁷⁾

4.6.1. First wall and divertor plate	38.6 MWe
4.6.2. IBC, hot shield, and divertor IBC	9.5 MWe

4.7. Thermal-Energy Storage

Not Required

4.8. Peak Temperature During a Loss-of-Flow Accident (LOFA)

4.8.1. First wall	1328 K
4.8.2. IBC	1320 K
4.8.3. Hot shield	1120 K
4.8.4. Coolant	1328 K

4.9. Peak Temperature During a Loss-of-Coolant Accident (LOCA)

4.9.1. First wall	1819 K
4.9.2. IBC	1816 K
4.9.3. Hot shield	1650 K
4.9.4. Coolant ⁽⁴⁻¹⁸⁾	762 K

5. INTERMEDIATE COOLANT SYSTEM ⁽⁵⁻¹⁾

	<u>Cycle 1</u>	<u>Cycle 2</u>	
5.1. Secondary Coolant	Lithium	Lithium	(natural)
5.2. Total Thermal Power	765	2170	MW
5.3. Number of Intermediate Heat Exchangers, IHX ⁽⁵⁻²⁾	3	6	
5.4. Primary-Coolant Inlet Temperature	715	973	K
5.5. Primary-Coolant Outlet Temperature	593	593	K
5.6. Primary-Coolant Flow Rate	1495	1363	kg/s
5.7. Secondary-Coolant Inlet Temperature	573	573	K
5.8. Secondary-Coolant Outlet Temperature	695	953	K
5.9. Secondary-Coolant Flow Rate	1495	1363	kg/s

6. STEAM GENERATION SYSTEM

	<u>Cycle 1</u>	<u>Cycle 2</u>	
6.1. Steam Outlet Temperature	669	839	K
6.2. Steam Outlet Pressure	10.7	21.4	MPa
6.3. Total Steam Flow Rate	326	703	kg/s
6.4. Feedwater Inlet Temperature	442	531	K
6.5. Number of Steam Generators per Sector	1	1	
6.6. Gross Thermal-Power Efficiency	0.370	0.465	
6.7. Gross Electric Output	283.1	1009.4	MWe

7. SHIELD COOLANT SYSTEM ⁽⁷⁻¹⁾**7.1. EFC-Shield Coolant ⁽⁷⁻²⁾**

Gaseous helium

7.2. B₄C Radiation-Shield Coolant ⁽⁷⁻³⁾

Argon

8. REACTOR AUXILIARY SYSTEM**8.1. Vacuum Pumping System ⁽⁸⁻¹⁾****8.1.1. Vacuum and plasma chamber pressure****8.1.1.1. Base plasma chamber pressure** 10^{-5} mtorr**8.1.1.2. Divertor duct pressure ⁽⁸⁻²⁾**

20 – 100 mtorr

8.1.1.3. Vacuum tank pressure

20 mtorr

8.1.2. Temperature of neutral gas

700 K

8.1.3. Plasma chamber volume33.6 m³**8.1.4. Vacuum chamber volume**2120 m³**8.1.5. Particle throughput ⁽⁸⁻³⁾****8.1.5.1. DT** 6.7×10^{21} s⁻¹**8.1.5.2. Helium** 8.2×10^{20} s⁻¹**8.1.6. Conductance of the divertor duct****8.1.6.1. For DT**215 m³/s**8.1.6.2. For He**224 m³/s**8.1.7. Type of pumps ⁽⁸⁻⁴⁾**

Turbo-molecular

8.1.8. Number of vacuum pumps ^{(8-4),(8-5)}

16

8.1.9. Helium pumping speed (per pump) ⁽⁸⁻⁶⁾20 m³/s**8.2. Magnet Cooling System****8.2.1. Toroidal-field coils ^{(8-7),(8-8)}****8.2.1.1. Coolant**Lithium (30% ⁶Li)**8.2.1.2. Cooling load**

41.6 MW

8.2.2. Divertor-field coils ⁽⁸⁻⁷⁾**8.2.2.1. Coolant**Lithium (30% ⁶Li)**8.2.2.2. Cooling load**

147.3 MW

8.2.3. Ohmic-heating coils ^{(8-8),(8-9)}**8.2.3.1. Coolant**

Gaseous helium

8.2.3.2. Peak Cooling load during startup

200 to 300 MW

8.2.3.3. Cooling load during normal operation

14 MW

8.2.4. Equilibrium-field coils ⁽⁸⁻¹⁰⁾**8.2.4.1. Coolant**

Liquid helium

8.2.4.2. Cooling load ⁽⁸⁻¹¹⁾

8.3. Plasma-Fueling System ⁽⁸⁻¹²⁾

8.3.1. Type	DT pellet
8.3.2. Fuel composition	50% D, 50% T
8.3.3. Fueling rates	0.035 g/s
8.3.4. Pellet diameter	3.4 mm
8.3.5. Pellet speed	2.1 km/s
8.3.6. Pellet injection frequency	6.25 s ⁻¹

8.4. Tritium-Processing and Recovery System

8.4.1. Type	Molten-salt extraction
8.4.2. Total tritium inventory	1.65 kg
8.4.3. Tritium handling rate ⁽⁸⁻¹³⁾	0.52 kg/d
8.4.4. Lithium processing rate	2.11×10^6 kg/d
8.4.5. Primary-coolant tritium concentration	1 wppm
8.4.6. Tritium recovery efficiency	0.90
8.4.7. Number of extractor units	28
8.4.8. Required electrical power	104 kW

9. REACTOR COMPONENTS

9.1. First Wall and Integrated Blanket Coil

9.1.1. Structural material	V-3Ti-1Si
9.1.2. Breeding material	Lithium (30% ⁶ Li)
9.1.3. Neutron multiplier material	none
9.1.4. Tritium breeding ratio (TBR) ⁽⁹⁻¹⁾	1.184
9.1.5. Number of modules ⁽⁹⁻²⁾	1
9.1.6. Weight of modules	45 tonnes
9.1.7. Largest single component	
9.1.7.1. Weight	45 tonnes
9.1.7.2. Dimensions (diameter×height)	9.7×1.9 m
9.1.9. Lifetime ⁽⁹⁻³⁾	1 y

9.2. Hot Shield

9.2.1. Structural material	V-3Ti-1Si
9.2.2. Number of modules ⁽⁹⁻⁴⁾	2
9.2.3. Weight of upper module	146 tonnes
9.2.4. Weight of lower module	73 tonnes
9.2.5. Largest single component	
9.2.5.1. Weight	146 tonnes
9.2.5.2. Dimensions (diameter×height)	10.6×2.0 m
9.2.6. Lifetime ⁽⁹⁻³⁾	5 y

9.3. Divertor

9.3.1. Type	Toroidal-field divertors
9.3.2. Number of divertors	3
9.3.3. Neutralizer plate	
9.3.3.1 Armor	W-26Re
9.3.3.2 Coolant tube	V-3Ti-1Si
9.3.3.3 Coolant	Lithium
9.3.4. Weight of each divertor	11 tonnes
9.3.5. Dimensions (diameter×height)	3 × 3 m
9.3.6. Lifetime ⁽⁹⁻²⁾	1 y

9.4. Magnets

9.4.1. Ohmic-heating coils ^{(9-5),(9-6)}	
9.4.1.1. Type	Normal
9.4.1.2. Number	16
9.4.1.3. Conductor	Copper
9.4.1.4. Structure	Steel
9.4.1.5. Insulator	Spinel (MgAl ₂ O ₄)
9.4.1.6. Coolant	Gaseous helium
9.4.1.7. Operating temperature	20 – 80 °C
9.4.1.8. Maximum stress in coil	83 MPa
9.4.1.9. Mean coil radius	2.15 – 6.0 m
9.4.2. Equilibrium-field coils ⁽⁹⁻⁷⁾	
9.4.2.1. Type	Superconducting
9.4.2.2. Number	2
9.4.2.3. Conductor	Nb-Ti
9.4.2.4. Structure	Steel
9.4.2.5. Stabilizer	Copper
9.4.2.6. Coolant	Liquid helium
9.4.2.7. Operating temperature	4 K
9.4.2.8. Mean stress in coil ⁽⁹⁻⁷⁾	
9.4.2.9. Mean coil radius	6.50 m
9.4.3. Toroidal-field coils ⁽⁹⁻⁵⁾	
9.4.3.1. Type	Normal (IBC)
9.4.3.2. Number	12
9.4.3.3. Conductor	Lithium (30% ⁶ Li)
9.4.3.4. Structure	V-3Ti-1Si
9.4.3.5. Insulator	Spinel (MgAl ₂ O ₄)
9.4.3.6. Coolant	Lithium (30% ⁶ Li)
9.4.3.7. Operating temperature	783 K
9.4.3.8. Mean stress in coil ⁽⁹⁻⁸⁾	30 MPa
9.4.3.9. Mean coil radius	0.8 m

9.4.4. Divertor-field coils	
9.4.4.1. Type	Normal (IBC)
9.4.4.2. Number	12
9.4.4.3. Conductor	Lithium (30% ^6Li)
9.4.4.4. Structure	V-3Ti-1Si
9.4.4.5. Insulator	Spinel (MgAl_2O_4)
9.4.4.6. Coolant	Lithium (30% ^6Li)
9.4.4.7. Operating temperature	783 K
9.4.4.8. Mean stress in coil ⁽⁹⁻⁸⁾	30 MPa
9.4.4.9. Mean coil radius	0.8 m
9.4.5. Maximum force transmitted to building ⁽⁹⁻⁹⁾	
9.4.6. Maximum toroidal field	
9.4.6.1. At plasma axis	11.85 T
9.4.6.2. At plasma edge	0.38 T
9.4.6.3. At TF coil	0.38 T
9.4.7. Total stored energy ⁽⁹⁻¹⁰⁾	
9.4.7.1. Poloidal field	3.9 GJ
9.4.7.2. Toroidal field	0.7 GJ
9.4.8. Largest single component ⁽⁹⁻¹¹⁾	
9.4.8.1. Weight	250 tonnes
9.4.8.2. Dimensions (diameter×height)	8.5×1.7 m
9.5 Energy Transfer and Storage	None
9.6. Plasma Heating	
9.6.1. Type	Ohmic
9.6.2. Frequency	—
9.6.3. Power to plasma ⁽⁹⁻¹²⁾	35 MW
9.6.4. Transmission method	Induction
9.6.5. Power reflected from plasma	— MW
9.6.6. Power loss in transmission	— MW
9.6.7. Power loss in amplifiers	—
9.6.8. Power loss in power supplies ⁽⁹⁻¹³⁾	5 MW
9.6.9. System input power ⁽⁹⁻¹²⁾	500 MW
9.6.10. Heating time ⁽⁹⁻¹⁴⁾	11 s

10. ELECTRICAL-POWER REQUIREMENTS

10.1. Cold-Plasma Startup Power from Grid ⁽¹⁰⁻¹⁾	500 MWe
10.2. Auxiliary Power Requirements (Normal Operation)	
10.2.1. Electrical energy storage	None
10.2.2. Toroidal-field coils (IBC)	25.6 MWe
10.2.3. Divertor-field coils (IBC)	120.5 MWe
10.2.4. OFCD ⁽¹⁰⁻²⁾	84.4 MWe
10.2.5. First wall and divertor coolant circulators	38.6 MWe
10.2.6. IBC and hot-shield coolant circulators	9.5 MWe
10.2.7. Other auxiliary systems ⁽¹⁰⁻³⁾	42.9 MWe
10.2.8. Total	321.5 MWe

11. BUILDINGS

11.1. Reactor Building ⁽¹¹⁻²⁾	
11.1.1. Characteristic dimensions	
11.1.1.1. Length	80 m
11.1.1.2. Width	30 m
11.1.1.3. Height	30 m
11.1.2. Enclosed volume	
11.1.2.1. Free volume ⁽¹¹⁻²⁾	69800 m ³
11.1.2.2. Total volume	72000 m ³
11.1.3. Minimum wall thickness ⁽¹¹⁻³⁾ for shielding	1 m
11.1.4. Internal pressure	1 atm
11.1.5. Containment atmosphere	Argon
11.2. Turbine Building ⁽¹¹⁻⁴⁾	
11.2.1. Characteristic dimensions for Cycle 1	
11.2.1.1. Length	86 m
11.2.1.2. Width	40 m
11.2.1.3. Height	32 m
11.2.2. Characteristic dimensions for Cycle 2	
11.2.2.1. Length	113 m
11.2.2.2. Width	40 m
11.2.2.3. Height	34 m
11.2.3. Total enclosed volume	2.64×10^5 m ³
11.3. Reactor Service Building	
11.3.1. Characteristic dimensions ⁽¹¹⁻⁵⁾	

12. REACTOR MAINTENANCE**12.1. First Wall, IBC, and Divertor**

12.1.1. Lifetime

1 y

12.1.2. Weight

45 tonnes

12.2. Hot Shield

12.2.1. Lifetime

5 y

12.2.2. Weight

219 tonnes

12.3. OH and EF Magnet12.3.1. Lifetime ⁽¹²⁻¹⁾

40 y

12.3.2. Weight

568 tonnes

12.4. Radioactive Material Storage for Life of Plant ⁽¹²⁻¹⁾12.4.1. Total Class C ⁽¹²⁻²⁾

12.4.1.1. Weight

1363 tonnes

12.4.1.2. Volume

199 m³12.4.2. Total non-Class C ⁽¹²⁻³⁾

12.4.2.1. Weight

14 tonnes

12.4.2.2. Volume

1 m³**12.5. Overall Plant Availability**

0.76

FOOTNOTES TO TABLE A.1

- 1-1) The reactor envelope is defined by the cylinder enclosed by the upper and lower EF coils.
- 1-2) The first wall is corrugated, therefore, the total plasma-facing area is $\frac{\pi}{2} (2\pi R_T) (2\pi r_{FW})$.
- 1-3) Sectors are used only for factory manufacturing and shipment to the site. These sectors, together with divertor modules, are assembled on-site into a single torus and tested to full operational condition prior to installation into the reactor vault.

- 2-1) During the startup, plasma profiles are assumed to be

$$\begin{aligned} n(r)/n_o &= (1 - r/r_p)^{2.5} \\ T(r)/T_o &= (1 - r/r_p)^4 \\ \mu(r)/\mu_o &= (1 - r/r_p)^8 . \end{aligned}$$

During the steady-state burn, TITAN-I operates with a highly radiative plasma (through injection of xenon impurities). The plasma profiles at burn are computed in Section 5.3 and are:

$$\begin{aligned} n(r)/n_o &= 1.00 - 0.86(r/r_p)^{3.44} \\ T(r)/T_o &= \begin{cases} 1.00 - 3.26(r/r_p)^{2.85} & \text{for } 0.00 < r/r_p < 0.25 \\ 1.12 - 0.71(r/r_p) & \text{for } 0.25 < r/r_p < 0.83 \\ 0.56 - 0.55(r/r_p)^{14.02} & \text{for } 0.83 < r/r_p < 1 \end{cases} \\ \mu(r)/\mu_o &= 1.00 - 0.44(r/r_p)^8 - 0.56(r/r_p)^8 . \end{aligned}$$

- 2-2) Averaged value over both fast and thermal components.
- 2-3) The TITAN-I design operates with a highly radiative plasma by deliberately doping the plasma with xenon impurities.
- 2-4) Assuming a beta-limited confinement time of the form $\tau_E = c_\nu I_\phi^2 r_p^2 f(\beta_\theta)$.
- 2-5) Assumed to be $\tau_p \simeq 4\tau_{Ee}$.
- 2-6) Based on self-consistent core-plasma, edge-plasma, and neutral-particle transport calculations.
- 2-7) Represents the mean value during the OFCD cycle (see item 2.29).
- 2-8) Including the poloidal field. The field produced by the coil is about 0.4 T.
- 2-9) The engineering beta is defined as the ratio of the average plasma pressure to the maximum field strength on the toroidal-field coils.
- 2-10) The reversal parameter is held constant during the startup (by adjusting the toroidal-field strength), and the values of the pinch parameter are from equilibrium calculations.

- 2-11) Results of detailed calculations assuming full-coverage TF coils (Section 7). Current-drive parameters quoted in the rest of this table are found by scaling the results of Section 7 to include the effects of the currents in the divertor coils which should also be oscillated to keep the separatrix in its position. For this case, the supplied real power in the toroidal circuit is 72.4 MW including 28.55 to the plasma, 16.0 MW to TF coils, 26.8 MW to the divertor coils, and 1.04 MW eddy-current heating in the blanket. The power to TF and divertor coils represent the AC component of the currents in these coils and include additional heating in the hot and cold legs of coolant by IBC power supplies connections.
- 2-12) Assuming a power supply efficiency, $Q = 100$.
- 2-13) A "wall-plug" efficiency including power-supply losses.
- 2-14) All of the current-drive power deposited in the plasma appears as ohmic heating power.
- 3-1) Including nuclear heating in non-current-carrying divertor IBC and divertor shield.
- 3-2) All of the current-drive power deposited in the plasma appears as ohmic heating power.
- 3-3) Heating by eddy currents induced in the first wall and blanket by OFCD cycles.
- 3-4) Assuming an efficiency of 90% for coolant-circulation pumps.
- 3-5) Joule heating in the IBC which also acts as the driver coil of the toroidal circuit of the OFCD system.
- 3-6) Values are summed over the two zones of the hot shield.
- 3-7) Values for current-carrying divertor IBC. Values for non-current-carrying part is included in item 3.6.
- 3-8) TITAN-I design has two power cycles. The first power cycle handles the thermal power from the first wall and the divertor plate. The thermal power from the IBC, hot shield, and the divertor IBC are converted by the second power cycle.
- 3-9) Including the losses in the divertor coils (see footnote 2-10).
- 3-10) Allocated for housekeeping and auxiliary functions.
- 3-11) Mass power density is defined as the ratio of the net electric output to the mass of the FPC which includes the first wall, blanket, shield, divertor modules, coils, and related structure.
- 4-1) The first wall tubes have constant cross section. They are staggered slightly on the inboard side to account for the smaller length in the toroidal direction there. Manifolds and headers are not included. The parallel (poloidal) and perpendicular (toroidal) magnetic field strengths are, respectively, 5.4 and 0.36 T.
- 4-2) Assuming 100% coverage of the first wall and does not account for the divertor modules.
- 4-3) Inlet pressure of the first wall and divertor plate coolant circuit. The pressure at the inlet of the first wall tubes is reduced to 10 MPa by orifices.

- 4-4) The coolant flow is turbulent.
- 4-5) The IBC tubes have a circular cross section on the outboard midplane location. The tubes are deformed and have elliptical cross section (but with a constant cross-sectional area) at other places to account for varying toroidal lengths. Manifolds and headers are not included. The parallel (poloidal) and perpendicular (toroidal) magnetic field strengths at the first row of IBC tubes are, respectively, 4.5 and 0.36 T.
- 4-6) Dimensions at the outboard midplane location.
- 4-7) Including the divertor IBC tubes.
- 4-8) Averaged over the entire system.
- 4-9) Inlet pressure of the blanket and shield circuit. Orifices are used to reduce the pressure from 2.8 MPa to the required value for each row of channels.
- 4-10) Values for the first row of coolant channels.
- 4-11) The coolant flow is laminar.
- 4-12) The TITAN-I hot shield is made of two pieces. The upper shield is removed during the annual maintenance to allow access to the torus assembly and is re-installed after the replacement of the reactor torus. The coolant enters upper- or lower-shield sections through the first four square channels, make a 180° turn, and exits through the last square channels and the five rectangular channels. Manifolds and headers are not included. The parallel (poloidal) and perpendicular (toroidal) magnetic field strengths at the first row of channels are, respectively, 2 and 0 T (hot shield channels are outside of the TF-IBCs).
- 4-13) The hydraulic diameter of the channel is defined as $d_h = 4 \times \frac{\text{area}}{\text{perimeter}}$.
- 4-14) The TITAN-I divertor plate is made of an armor which is brazed to (and insulated from) a bank of circular, constant cross section tubes. Manifolds and headers are not included. The parallel (poloidal) and perpendicular (toroidal) magnetic field strengths vary at each coolant-tube location. The coolant flow is laminar in certain tubes and turbulent in others.
- 4-15) Inlet pressure of the first wall and divertor plate coolant circuit which is set by the maximum pressure drops in divertor-coolant tubes. The pressure at the inlet of most of the divertor-coolant tubes is lower than 12 MPa and orifices are used to reduce the pressure to the desired value at the inlet of these tubes.
- 4-16) The maximum coolant-flow velocity, imposed as a constraint on the thermal-hydraulic design of the divertor plate. The coolant-flow velocity in most of tubes is lower than this value.
- 4-17) The efficiency of circulating pumps is assumed to be 90%.
- 4-18) Peak lithium temperature in the event of a combined LOCA and air influx to the reactor vault. A drain-time of 30 s is assumed for the burn-time of the spilled lithium.
- 5-1) TITAN-I design has two power cycles. Power cycle 1 includes first wall and divertor plate coolant circuits. Power cycle 2 includes the IBC, hot shield, and divertor-IBC coolant circuits.

- 5-2) Total number of IHXs for all three sectors. There are two IHXs per sector for blanket and hot shield circuit based on electrical engineering requirements of the IBC system.
- 7-1) Power is recovered from the hot shield (see item 4.3.)
- 7-2) Shield for superconducting EF coils. This shield is cooled by the ohmic-heating-coil cooling circuit.
- 7-3) Radiation shield to reduce activation of the argon cover gas. This shield is cooled by the natural circulation.
- 8-1) The TITAN-I reactor is located inside a vacuum tank.
- 8-2) The pressure in the vacuum duct varies in the poloidal direction.
- 8-3) Based on neutral transport calculations (Section 5.5). Particle throughput is enriched by about a factor 3 in He (with respect to DT throughput) and also by a factor of about 3 in D (with respect to T).
- 8-4) The turbo-molecular pumps are backed by 12 scroll pumps with pumping speed of $600 \text{ m}^3/\text{hr}$, operating between 50 mtorr and atmospheric pressure.
- 8-5) Based on the required total pumping speed of $260 \text{ m}^3/\text{s}$, only 13 pumps are needed. The additional 3 pumps are in reserve.
- 8-6) Assuming out-gassing rate of 10^{-11} to 10^{-12} torr-l/s, the required pumping speed to maintain the base pressure in the plasma chamber is in the range 3 to $35 \text{ m}^3/\text{s}$, much lower than the required pumping speed of $260 \text{ m}^3/\text{s}$ for removal of the He ash.
- 8-7) Both toroidal and divertor-field coils are based on the IBC concept. The cooling loads for these coils are deposited directly into the primary coolant.
- 8-8) Includes both steady state and OFCD contributions.
- 8-9) Peak heating load during startup.
- 8-10) A pair of normal-conducting, EF trim coils are used during startup and OFCD cycles. Cooling loads for these coils are included in item 8.2.3.
- 8-11) The EF coils are based on present day technology with Nb-Ti conductor. Detailed design for these coils, therefore, was not performed.
- 8-12) The neutral-transport calculation of plasma exhaust shows some enrichment in D in the exhaust (Section 5). The effect of this enrichment is not included in this item. Also, plasma-driven permeation of D and T ions through the first wall is ignored.
- 8-13) Based on a tritium-breeding ratio of 1.2 and assuming 100 g/d of plasma-driven permeation of tritium through the first wall.
- 9-1) Based on 3D neutronics calculations of the final design.

- 9-2) The reactor torus is assembled on-site from 3 prefabricated sectors interlinked by the 3 divertors. The reactor torus is installed and removed as one single piece.
- 9-3) Based on a lifetime of 15 MW-y/m².
- 9-4) The TITAN-I hot shield is made of two pieces. The upper shield is removed during the annual maintenance to allow access to the torus assembly and is re-installed after the replacement of the reactor torus.
- 9-5) Also act as the driver coils for the OFCD system.
- 9-6) Includes a pair of normal-conducting, EF trim coils which are used during startup and OFCD cycles.
- 9-7) The EF coils are based on present day technology with Nb-Ti conductor. Detailed design for these coils, therefore, was not performed.
- 9-8) Primarily caused by the coolant pressure in the IBC.
- 9-9) Primarily caused by the weight of the FPC.
- 9-10) Including the plasma stored energy. The poloidal magnetic energies stored in the system are 0.3 GJ internal to the plasma and 3.6 GJ external to the plasma, noting that the plasma current and the EFC current are flowing in opposite directions. The toroidal magnetic energy internal to the plasma is 0.4 GJ and external to the plasma is 0.02 GJ.
- 9-11) The largest component is the EF coil, including EFC shield.
- 9-12) Maximum value during startup.
- 9-13) Assuming an efficiency of 99% for power supplies.
- 9-14) Time from cold startup to ignition.
- 10-1) Maximum value during startup.
- 10-2) Including the losses in the divertor coils (see footnote 2-10).
- 10-2) Includes the refrigeration systems, vacuum systems, tritium-extraction systems, feed-water pumps, heat-rejection systems, and other miscellaneous reactor auxiliary systems.
- 11-1) Reactor building volume includes: reactor vault, lay-down area (for vacuum tank lid, OH coils, and upper shield), and storage area (for new, pretested torus).
- 11-2) Free volume consists of total volume minus the vacuum tank volume.
- 11-3) Required wall thickness is based on activation issues for argon atmosphere surrounding the vacuum tank.
- 11-4) Turbine-building dimensions were scaled from those of the MARS reactor design (B. G. Logan *et al.*, Lawrence Livermore National Laboratory report, UCRL-53480, 1984).
- 11-5) Not calculated.

- 12-1) Assuming 30 full-power-year operation with 76% availability.
- 12-2) Including first wall, blanket, shield, and magnets.
- 12-3) The divertor target plates, if they have to be disposed of separately.

A.2. SYSTEMS CODE PARAMETERS OF TITAN-I

1 TITAN Reversed-Field Pinch Reactor calculations (ver. 9.q)
 1 1 0 0 1 1 0 1 0 11/24/87

plasma parameters

plasma aspect ratio, A	6.500
plasma minor radius (m)	0.600
plasma toroidal major radius (m)	3.900
plasma volume (m ³)	27.714
plasma/first-wall radius ratio, x	0.909
plasma current (MA)	17.818
toroidal current density (MA/m ²)	15.754
plasma ion temperature (keV)	10.000
plasma electron temperature (keV)	9.500
plasma fus. prod. temperature (keV)	65.000
plasma impurity temperature (keV)	10.000
Lawson parameter * t2 (1.0e22 s keV ⁻² /m ³)	1.917
Lawson parameter (1.0e20 s/m ³)	1.917
plasma (total) ion density (1.0e20/m ³)	8.934
plasma electron density (1.0e20/m ³)	9.331
ion (D,T,He3,He4,Xe) density fractions:	
0.48484 0.48484 0.00000 0.03000 0.00033	
effective plasma charge, Zeff	1.690
energy confinement time (s)	0.215
alpha ion particle confinement time (steady state) (s)	0.855
thermal diffusivity (m ² /s)	0.315
dt fusion power density (MW/m ³)	83.014
fusion power, Pf (MW)	2300.650
alpha power (MW)	460.653
bremsstrahlung power (MW)	251.297
poloidal beta (incl. fus. prods. and imps., Zeff>1.0)	0.220
poloidal beta (only fuel ions and electrons, Zeff=1.0)	0.200
pinch parameter, theta	1.556
reversal parameter, F	0.100
streaming parameter (1.0e-14 A m)	1.763
streaming function (1.0e-3)	1.856
plasma ohmic dissipation during burn (MW)	28.527
plasma loop voltage (V)	1.601
gdt, gohm, gbr = 1.403 2.924 1.172	
OFCD plasma Poynting power (tor/pol) (MW)	3956.711 247.110
OFCD FW dissipated power (tor/pol) (MW)	0.000 0.011
OFCD blanket dissipated power (tor/pol) (MW)	1.038 0.000
OFCD coil dissipated power (OHC/TFC/PEFC/SEFC) (MW)	
0.131 50.621 0.000 1.948	
OFCD total dissipated power (tor/pol) (MW)	51.660 2.091
OFCD terminal real(lost) power (OHC/TFC/PEFC/SEFC) (MW)	
1.617 79.062 0.000 3.438	
OFCD power-supply dissipated power, pcdps (MW)	7.266
OFCD total dissipated power, pcdd (MW)	61.915
OFCD terminal reactive power (OHC/TFC/PEFC/SEFC) (MW)	
74.861 538.345 0.000 113.350	
OFCD total reactive power, pcdr (MW)	726.555
OFCD power-supply q-value, Q(PS)	100.000
OFCD circuit q-value, Q(C)	11.735
OFCD q-value, Q(CD)	2.170
OFCD efficiency figure of merit (A/W)	0.288

1 poloidal field quantities

OH-coil thickness (m)	0.270
average minor radius of coil (m)	1.565
OH coil center offset	0.439
vertical field (T)	1.562
magnetic field level at the coil (T)	2.277
magnetic field level at the plasma surface (T)	5.939
OH coil back-bias power ratio, $f_{gridp} = (I_{OH+}/I_{OH-})^2$	1.000
OH coil factor for resistive flux dissipated in startup	0.109
OH coil factor	0.390
OH-coil current swing (MA)	50.422
OH- coil current (MA)	25.211
OH- coil current density (MA/m ²)	13.148
coil stress (MPa)	106.262
OH+ coil current (MA)	25.211
OH+ coil current density (MA/m ²)	13.148
OH coil power supply requirement (MVA)	445.271
mass of OH coil set (tonne)	343.002
ohmic dissipation during back-bias (MW)	120.916
volumetric heating during back-bias (MW/m ³)	2.573
EF coil current (MA)	20.556
EF coil current density (MA/m ²)	19.159
EF coil power supply requirement (MVA)	477.396
mass of EF coil set (tonne)	304.927
magnetic energy stored in coil (MJ)	5194.986
ohmic dissipation during burn (MW)	0.000
volumetric heating during burn (MW/m ³)	0.000
plasma startup risetime (s)	8.000
Ref,zef,delef (m) =	6.1962e+00 2.6663e+00 7.3243e-01

0 toroidal field quantities

TF-coil thickness (m)	0.280
average minor radius of coil (m)	0.680
mass of coil (tonne)	0.000
initial toroidal bias field (T)	3.410
reversed-toroidal field during the burn (T)	0.382
magnetic energy stored in the coil (MJ)	164.739
TF-coil current (MA)	6.603
TF coil current density (MA/m ²)	1.644
ohmic dissipation during burn (MW)	27.629
volumetric heating during burn (MW/m ³)	1.335

0 impurity control

first-wall surface area (m ²)	101.617
total divertor plate surface area (m ²)	6.998
first-wall/divertor surface heat flux (MW/m ²)	4.573
radiation fraction, frad	0.950
scrape-off thickness (m)	0.060
DF-coil current (MA)	2.845
DF coil current density (MA/m ²)	19.840
mass of coil (tonne)	0.554
ohmic dissipation during burn (MW)	141.541

1

engineering summary

thermal conversion efficiency	0.440
auxiliary site power fraction of P_g , f_{aux}	0.030
primary loop pumping power fraction of P_g , f_{pmp}	0.040
engineering q-value, QE	4.017
recirculating power fraction, $\epsilon = 1/QE$	0.249
net plant efficiency	0.330
ohmic q-value, Q_t	12.702
plasma q-value, Q_p	80.648
total thermal power, P_{th} (MW)	2935.187
fusion power, P_f (MW)	2300.650
tritium burnup (kg/day)	0.353
fractional burnup	0.057
tritium thru-put (no recycle) (kg/day)	6.221
blanket LM 6Li enrichment	0.300
14.06-MeV neutron load, I_w (MW/m ²)	18.107
14.06-MeV neutron energy multiplication in blanket, M	1.200
2.45-MeV neutron load (MW/m ²)	0.000
2.45-MeV neutron energy multiplication in blanket, M	0.000
first-wall radius (m)	0.660
FW/SW/blanket/gap/reflector/gap/shield thickness (m)	0.760
shield/coil gap thickness (m)	0.010
OH-coil thickness (m)	0.270
minor radius of system (m)	1.700
blanket volume (m ³)	31.356
reflector volume (m ³)	51.733
shield volume (m ³)	27.553
EF-coil shield volume (m ³)	54.194
TF-coil volume (m ³)	0.000
OH-coil volume (m ³)	46.987
EF-coil volume (m ³)	41.771
DF-coil volume (m ³)	0.721
mass of FW/SW/blanket (tonne)	40.582
mass of reflector (tonne)	116.066
mass of OHC shield (tonne)	151.263
mass of EFC shield (tonne)	325.166
mass of TF coil set (tonne)	0.000
mass of OH coil set (tonne)	343.002
mass of EF coil set (tonne)	304.927
mass of DF coil set (tonne)	0.554
total coil-set mass (tonne)	648.482
PPC (FW/SW/B/R/S/C) mass (tonne)	1281.972
mass power density, MPD (kWe/tonne)	756.643
system power density (MWt/m ³)	13.193
mass utilization (tonne/MWt)	0.437
mass of PPC structure (tonne)	313.897
blanket power density (MW/m ³)	24.119
magnetic energy recovery time (s)	1.826

A.3. COST SUMMARY OF TITAN-I REACTOR

fusion reactor economic evaluation (ver. 4.5)

d 11/24/87

acc. no.	account title	million dollars (1986)
20. 1.	land & privilege acquisition	4.500
20. 2.	relocation of buildings, utilities, highways, etc.	0.500
20.	land & land rights	5.000
21. 1. 1.	general yard improvements	
21. 1. 2.	waterfront improvements	
21. 1. 3.	transportation access (off site)	
21. 1.	site improvements & facilities	15.208
21. 2. 1.	basic building structures	69.729
21. 2. 2.	building services	2.696
21. 2. 3.	containment structures	40.446
21. 2. 4.	architectural	10.111
21. 2.	reactor building	122.983
21. 3. 1.	basic building structures	40.446
21. 3. 2.	building services	2.696
21. 3. 3.	architectural	2.022
21. 3.	turbine building	45.165
21. 4. 1.	intake structures	
21. 4. 2.	discharge structures	
21. 4. 3.	unpressurized intake & discharge conduits	
21. 4. 4.	recirculating structures	
21. 4. 5.	cooling tower systems	
21. 4.	cooling system structures	10.386
21. 5. 1.	basic building structures	10.826
21. 5. 2.	building services	0.715
21. 5. 3.	architectural	0.809
21. 5.	power supply & energy storage building	12.350
21. 6. 1.	reactor auxiliaries building(incl. switchgear bay)	4.395
21. 6. 2.	hot cell building	72.749
21. 6. 3.	fuel storage building	11.635
21. 6. 4.	control room building	4.179
21. 6. 5.	diesel generator building	2.764
21. 6. 6.	administration building	1.173
21. 6. 7.	service building	2.535
21. 6. 8.	cryogenics building	1.227
21. 6. 9.	miscellaneous structures & building work	2.481
21. 6.	miscellaneous buildings	103.137
21. 7.	ventilation stack	2.440
21.98.	spare parts allowance	
21.99.	contingency allowance	
21.	structures & site facilities	311.669

22. 1. 1. 1.	breeding material(incl. tritium breeding)	12.833	
22. 1. 1. 2.	first wall & structural material	10.149	
22. 1. 1. 3.	attenuators, reflectors, & multipliers		
22. 1. 1. 4.	wall modifiers(coatings, liners, limiters, etc.)		
22. 1. 1. 5.	reflector	29.036	
22. 1. 1. 6.	other		
22. 1. 1.	FW/SW/blanket/reflector		52.017
22. 1. 2. 1.	primary	37.839	
22. 1. 2. 2.	secondary	6.870	
22. 1. 2.	shield		44.709
22. 1. 3. 1.	toroidal field coils	0.000	
22. 1. 3. 2.	ohmic-heating coils	30.058	
22. 1. 3. 3.	equilibrium field coils	53.439	
22. 1. 3. 4.	divertor field coils	0.097	
22. 1. 3. 5.	other coils		
22. 1. 3.	magnets		83.594
22. 1. 4. 1.	beam heating(neutral, ion or electron)		
22. 1. 4. 2.	rf heating	0.000	
22. 1. 4. 3.	laser heating		
22. 1. 4. 4.	other heating systems		
22. 1. 4.	supplemental heating systems		
22. 1. 5. 1.	reactor structure		
22. 1. 5. 2.	equipment support structure		
22. 1. 5.	primary structure & support		7.936
22. 1. 6. 1.	plasma chamber vacuum(incl. pumps/comp./pipe)	6.562	
22. 1. 6. 2.	magnet dewar vacuum(incl. pumps/comp./pipe)		
22. 1. 6. 3.	suppl. heating vacuum(incl. pumps/comp./pipe)		
22. 1. 6. 4.	direct convertor vacuum(incl. pumps/comp./pipe)		
22. 1. 6. 5.	reactor vacuum system(low grade)		
22. 1. 6. 6.	reactor vacuum wall	10.236	
22. 1. 6.	reactor vacuum systems(unless integral elsewhere)		16.799
22. 1. 7. 1.	EF-coil power supplies	13.986	
22. 1. 7. 2.	OH-coil power supplies	11.137	
22. 1. 7. 3.	TF-coil power supplies	32.822	
22. 1. 7. 4.	DF-coil power supplies	45.041	
22. 1. 7. 5.	other power supplies	1.348	
22. 1. 7. 6.	current drive power supplies	36.333	
22. 1. 7. 7.	control system		
22. 1. 7. 8.	central energy storage		
22. 1. 7. 9.	other incl. busbars	6.281	
22. 1. 7.	power supply, switching & energy storage		146.948
22. 1. 8.	impurity control		6.227
22. 1. 9. 1.	vacuum tank		
22. 1. 9. 2.	direct convertor modules		
22. 1. 9. 3.	thermal panels		
22. 1. 9. 4.	power conditioning equipment		
22. 1. 9.	direct energy conversion system		
22. 1.10.	ecrh breakdown system	2.142	
22. 1.	reactor equipment		360.371

22. 2. 1. 1.	pumps & motor drives(modular & nonmodular)	
22. 2. 1. 2.	piping	
22. 2. 1. 3.	heat exchangers	
22. 2. 1. 4.	tanks(dump,make-up,clean-up,trit.,hot storage)	
22. 2. 1. 5.	clean-up system	
22. 2. 1. 6.	thermal insulation, piping & equipment	
22. 2. 1. 7.	tritium extraction	
22. 2. 1. 8.	pressurizer	
22. 2. 1. 9.	other	
22. 2. 1.	primary coolant system	161.286
22. 2. 2. 1.	pumps & motor drives(modular & nonmodular)	
22. 2. 2. 2.	piping	
22. 2. 2. 3.	heat exchangers	
22. 2. 2. 4.	tanks(dump,make-up,clean-up,trit.,hot storage)	
22. 2. 2. 5.	clean-up system	
22. 2. 2. 6.	thermal insulation, piping & equipment	
22. 2. 2. 7.	tritium extraction	
22. 2. 2. 8.	pressurizer	
22. 2. 2. 9.	other	
22. 2. 2.	intermediate coolant system	
22. 2. 3. 1.	pumps & motor drives(modular & nonmodular)	
22. 2. 3. 2.	piping	
22. 2. 3. 3.	heat exchangers	
22. 2. 3. 4.	tanks(dump,make-up,clean-up,trit.,hot storage)	
22. 2. 3. 5.	clean-up system	
22. 2. 3. 6.	thermal insulation, piping & equipment	
22. 2. 3. 7.	tritium extraction	
22. 2. 3. 8.	pressurizer	
22. 2. 3. 9.	other	
22. 2. 3.	secondary coolant system	0.000
22. 2.	main heat transfer & transport systems	161.286
22. 3. 1. 1.	refrigeration	
22. 3. 1. 2.	piping	
22. 3. 1. 3.	fluid circulation driving system	
22. 3. 1. 4.	tanks	
22. 3. 1. 5.	purification	
22. 3. 1.	magnet cooling system	
22. 3. 2. 1.	refrigeration	
22. 3. 2. 2.	piping	
22. 3. 2. 3.	fluid circulation driving system	
22. 3. 2. 4.	tanks	
22. 3. 2. 5.	purification	
22. 3. 2.	shield & structure cooling system	2.651
22. 3. 3. 1.	refrigeration	
22. 3. 3. 2.	piping	
22. 3. 3. 3.	fluid circulation driving system	
22. 3. 3. 4.	tanks	
22. 3. 3. 5.	purification	
22. 3. 3.	supplemental heating system cooling system	
22. 3. 4. 1.	refrigeration	
22. 3. 4. 2.	piping	
22. 3. 4. 3.	fluid circulation driving system	
22. 3. 4. 4.	tanks	
22. 3. 4. 5.	purification	
22. 3. 4.	power supply cooling system	
22. 3. 5.	other cooling systems (ECCS)	
22. 3.	auxiliary cooling systems	2.651

22. 4. 1.	liquid waste processing & equipment	
22. 4. 2.	gaseous wastes & off-gas processing system	
22. 4. 3.	solid waste processing equipment	
22. 4.	radioactive waste treatment & disposal	4.748
22. 5. 1.	fuel injection systems	10.001
22. 5. 2.	fuel processing systems	13.701
22. 5. 3.	fuel storage	5.000
22. 5. 4.	atmospheric tritium recovery	2.131
22. 5. 5.	water tritium recovery systems	5.000
22. 5. 6.	blanket tritium recovery systems	5.000
22. 5. 7.	other	
22. 5.	fuel handling & storage systems	40.834
22. 6. 1. 1.	blanket & coil maintenance equipment	
22. 6. 1. 2.	components rotated into service to allow maint.	
22. 6. 1. 3.	other maintenance equipment	
22. 6. 1.	maintenance equipment	
22. 6. 2.	special heating systems(start-up,trace, etc.)	
22. 6. 3.	coolant receiving, storage & make-up systems	
22. 6. 4.	gas systems	
22. 6. 5.	building vacuum systems	
22. 6.	other reactor plant equipment	43.289
22. 7. 1.	reactor i&c equip.(burn control, diagnostics, etc.	
22. 7. 2.	radiation monitoring systems	
22. 7. 3.	isolated indicating & recording gauges, etc.	
22. 7.	instrumentation & control(i&c)	31.561
22.98.	spare parts allowance	
22.99.	contingency allowance	
22.	reactor plant equipment	644.742

23. 1. 1.	turbine-generators & accessories	
23. 1. 2.	foundations	
23. 1. 3.	standby exciters	
23. 1. 4.	lubricating system	
23. 1. 5.	gas systems	
23. 1. 6.	reheaters	
23. 1. 7.	shielding	
23. 1. 8.	weather-proof housing	
23. 1.	turbine-generators	96.606
23. 2.	main steam (or other fluid) system	6.640
23. 3. 1.	water intake common facilities	
23. 3. 2.	circulating water systems	
23. 3. 3.	cooling towers	
23. 3. 4.	other systems which reject heat to the atmosphere	
23. 3.	heat rejection systems	31.845
23. 4. 1.	condensers	
23. 4. 2.	condensate system	
23. 4. 3.	gas removal system	
23. 4. 4.	turbine by-pass systems(excl. piping)	
23. 4.	condensing systems	23.416
23. 5. 1.	regenerators & recuperators	
23. 5. 2.	pumps	
23. 5. 3.	tanks	
23. 5.	feed heating system	10.446
23. 6. 1.	turbine auxiliaries	
23. 6. 2.	auxiliaries cooling system(excl. piping)	
23. 6. 3.	make-up treat. system(excl. piping)	
23. 6. 4.	chemical treat. & condensate purification systems	
23. 6. 5.	central lubrication service system(excl. piping)	
23. 6.	other turbine plant equipment	64.284
23. 7.	instrumentation & control(i&c) equipment	11.355
23.98.	spare parts allowance	
23.99.	contingency allowance	
23.	turbine plant equipment	244.593

24. 1. 1.	generator circuits	
24. 1. 2.	station service	
24. 1.	switchgear	14.969
24. 2. 1.	station service & startup transformers	
24. 2. 2.	low voltage unit substation & lighting transformer	
24. 2. 3.	battery system	
24. 2. 4.	diesel engine generators	
24. 2. 5.	gas turbine generators	
24. 2. 6.	motor generator sets	
24. 2.	station service equipment	24.715
24. 3. 1.	main control board for electric system	
24. 3. 2.	auxiliary power & signal boards	
24. 3.	switchboards (incl. heat tracing)	9.399
24. 4. 1.	gen. station grounding sys. & cathodic protection	
24. 4.	protective equipment	2.845
24. 5. 1.	concrete cable tunnels, trenches & envelopes	
24. 5. 2.	cable trays & support	
24. 5. 3.	conduit	
24. 5. 4.	other structures	
24. 5.	electrical structures & wiring containers	22.582
24. 6. 1.	generator circuits wiring	
24. 6. 2.	station service power wiring	
24. 6. 3.	control wiring	
24. 6. 4.	instrument wiring	
24. 6. 5.	containment penetrations	
24. 6.	power & control wiring	46.729
24. 7. 1.	reactor building lighting	
24. 7. 2.	turbine building lighting	
24. 7. 3.	reactor auxiliaries building lighting	
24. 7. 4.	radioactive waste building lighting	
24. 7. 5.	fuel storage building lighting	
24. 7. 6.	miscellaneous buildings lighting	
24. 7. 7.	yard lighting	
24. 7.	electrical lighting	11.055
24.98.	spare parts allowance	
24.99.	contingency allowance	
24.	electric plant equipment	132.294

25. 1. 1.	cranes, hoists, monorails, & conveyors	
25. 1. 2.	railway	
25. 1. 3.	roadway equipment	
25. 1. 4.	watercraft	
25. 1. 5.	vehicle maintenance equipment	
25. 1.	transportation & lifting equipment	21.140
25. 2. 1.	air systems(excl. piping)	
25. 2. 2.	water systems(excl. piping)	
25. 2. 3.	auxiliary heating boilers(excl. piping)	
25. 2.	air & water service systems	16.650
25. 3. 1.	local communications systems	
25. 3. 2.	signal systems	
25. 3.	communications equipment	8.386
25. 4. 1.	safety equipment	
25. 4. 2.	shop, laboratory, & test equipment	
25. 4. 3.	office equipment & furnishings	
25. 4. 4.	change room equipment	
25. 4. 5.	environmental monitoring equipment	
25. 4. 6.	dining facilities	
25. 4.	furnishings & fixtures	1.618
25.98.	spare parts allowance	
25.99.	contingency allowance	
25.	miscellaneous plant equipment	47.794
26. 1.	reactor coolant	98.655
26. 2.	intermediate coolant	
26. 3.	turbine cycle working fluids	
26. 4.	other materials	0.337
26. 5.	Ar reactor-building cover gas	0.174
26.98.	spare parts allowance	
26.99.	contingency allowance	
26.	special materials	99.166

Los Alamos fusion reactor economic evaluation (ver. 4.5)

d 11/24/87

acc. no.	account title	million dollars (1986)
20.	land & land rights	5.000
21.	structures & site facilities	311.669
22.	reactor plant equipment	644.742
22. 1. 1.	PW/SW/blanket/reflector	52.017
22. 1. 2.	shield	44.709
22. 1. 3.	magnets	83.594
22. 1. 4.	supplemental heating systems	0.000
22. 1. 5.	primary structure & support	7.936
22. 1. 6.	reactor vacuum systems(unless integral elsewhere)	16.799
22. 1. 7.	power supply, switching & energy storage	146.948
22. 1. 8.	impurity control	6.227
22. 1. 9.	direct energy conversion system	0.000
22. 1.10.	ecrh breakdown system	2.142
22. 1.	reactor equipment	360.371
23.	turbine plant equipment	244.593
24.	electric plant equipment	132.294
25.	miscellaneous plant equipment	47.794
26.	special materials	99.166
90.	direct cost (not incl. spares and contingency)	1485.258
91.	construction services & equipment	148.526
92.	home office engineering & services	148.526
93.	field office engineering & services	148.526
94.	owner's cost	74.263
96.	project contingency	148.526
97.	interest during construction (IDC)	242.067
99.	total cost	2395.691

thermal power (MWth)	= 2935.19	unit direct cost (\$/kWe) [90]= 1531.20 1531.20
gross electric power (MWe)	= 1291.48	unit base cost (\$/kWe) [94]= 2220.24 2220.24
net electric power (MWe)	= 969.99	unit total cost (\$/kWe) [99]= 2469.87 3384.60
1/recirculating power fraction QE=	4.017	capital return (mill/kWeh) = 29.72 69.24
plant availability factor =	0.759	O&M(2.00%) (mill/kWeh) [40-47,51]= 6.68 9.47
construction= 6 yr: constant then-current		W/B/R replace. (mill/kWeh) [50]= 3.26 4.62
FCR=	0.0800 0.1360	decommissioning allowance = 0.00 0.00
fIDC=	0.1124 0.2444	deuterium fuel (mill/kWeh) [02]= 0.04 0.04
fEDC=	0.0000 0.2800	COE (mill/kWeh) = 39.69 83.38

A.4. COST DATA BASE FOR TITAN-I REACTOR

cost data base (ver. 4.5)

date:11/24/87

acc. no.	account title UC(1986) = 1.348 x UC(1980)	unit cost(1980)	no. of units	refs.
20. 1. 0. 0	land & privilege acquisition	3.338e+03 \$/acre	1.000e+03 10	
20. 2. 0. 0	relocation of buildings, utilities, highways, etc.	3.710e+02 \$/acre	1.000e+03 10	
20. 0. 0. 0	land & land rights	0.	1.000e+00	
21. 1. 1. 0	general yard improvements	0.	1.000e+00	
21. 1. 2. 0	waterfront improvements	0.	1.000e+00	
21. 1. 3. 0	transportation access (off site)	0.	1.000e+00	
21. 1. 0. 0	site improvements & facilities	1.128e+07 \$	1.000e+00 10	
21. 2. 1. 0	basic building structures	3.000e+02 \$/m ³	1.724e+05 13,18	
21. 2. 2. 0	building services	2.000e+06 \$	1.000e+00 13,14,+	
21. 2. 3. 0	containment structures	3.000e+07 \$	1.000e+00 13,14,+	
21. 2. 4. 0	architectural	7.500e+06 \$	1.000e+00 13,14,+	
21. 2. 0. 0	reactor building	0.	1.000e+00	
21. 3. 1. 0	basic building structures	3.000e+07 \$	1.000e+00 13,14,18	
21. 3. 2. 0	building services	2.000e+06 \$	1.000e+00 13,14,+	
21. 3. 3. 0	architectural	1.500e+06 \$	1.000e+00 13	
21. 3. 0. 0	turbine building	0.	1.000e+00	
21. 4. 1. 0	intake structures	0.	1.000e+00	
21. 4. 2. 0	discharge structures	0.	1.000e+00	
21. 4. 3. 0	unpressurized intake & discharge conduits	0.	1.000e+00	
21. 4. 4. 0	recirculating structures	0.	1.000e+00	
21. 4. 5. 0	cooling tower systems	0.	1.000e+00	
21. 4. 0. 0	cooling system structures	8.982e+05 \$/unit	8.577e+00 2,13,14	
21. 5. 1. 0	basic building structures	8.030e+06 \$	1.000e+00 13,14	
21. 5. 2. 0	building services	5.300e+05 \$	1.000e+00 13,14	
21. 5. 3. 0	architectural	6.000e+05 \$	1.000e+00 13	
21. 5. 0. 0	power supply & energy storage building	0.	1.000e+00	
21. 6. 1. 0	reactor auxiliaries building(incl. switchgear bay)	3.260e+06 \$	1.000e+00 13,14	
21. 6. 2. 0	hot cell building	5.396e+07 \$	1.000e+00 13,14	
21. 6. 3. 0	fuel storage building	8.630e+06 \$	1.000e+00 13,14	
21. 6. 4. 0	control room building	3.100e+06 \$	1.000e+00 13,14	
21. 6. 5. 0	diesel generator building	2.050e+06 \$	1.000e+00 13,14	
21. 6. 6. 0	administration building	8.700e+05 \$	1.000e+00 13,14	
21. 6. 7. 0	service building	1.880e+06 \$	1.000e+00 13,14	
21. 6. 8. 0	cryogenics building	9.100e+05 \$	1.000e+00 13,14	
21. 6. 9. 0	miscellaneous structures & building work	1.840e+06 \$	1.000e+00 13,14	
21. 6. 0. 0	miscellaneous buildings	0.	1.000e+00	
21. 7. 0. 0	ventilation stack	1.810e+06 \$	1.000e+00 13,14	
21.98. 0. 0	spare parts allowance	0. fraction	-1.000e+00 2,13,14	
21.99. 0. 0	contingency allowance	0. fraction	-1.000e+00 2,13,14	
21. 0. 0. 0	structures & site facilities	0.	1.000e+00	

22. 1. 1. 1	breeding material(incl. tritium breeding)	2.927e+02 \$/kg	3.252e+04 15.18
22. 1. 1. 2	first wall & structural material	1.855e+02 \$/kg	4.058e+04 10
22. 1. 1. 3	attenuators, reflectors, & multipliers	0.	1.000e+00
22. 1. 1. 4	wall modifiers(coatings, liners, limiters, etc.)	0.	1.000e+00
22. 1. 1. 5	reflector	1.855e+02 \$/kg	1.161e+05 6
22. 1. 1. 6	other	0.	1.000e+00
22. 1. 1. 0	FW/SW/blanket/reflector	0.	1.000e+00
22. 1. 2. 1	primary	1.855e+02 \$/kg	1.513e+05 10
22. 1. 2. 2	secondary	1.567e+01 \$/kg	3.252e+05 10
22. 1. 2. 0	shield	0.	1.000e+00
22. 1. 3. 1	toroidal field coils	6.500e+01 \$/kg	0. 10
22. 1. 3. 2	ohmic-heating coils	6.500e+01 \$/kg	3.430e+05 10
22. 1. 3. 3	equilibrium field coils	1.300e+02 \$/kg	3.049e+05 10
22. 1. 3. 4	divertor field coils	1.300e+02 \$/kg	5.541e+02 10
22. 1. 3. 5	other coils	0.	1.000e+00
22. 1. 3. 0	magnets	0.	1.000e+00
22. 1. 4. 1	beam heating(neutral, ion or electron)	0.	1.000e+00
22. 1. 4. 2	rf heating	1.654e+00 \$/W	0. 16.17
22. 1. 4. 3	laser heating	0.	1.000e+00
22. 1. 4. 4	other heating systems	0.	1.000e+00
22. 1. 4. 0	supplemental heating systems	0.	1.000e+00
22. 1. 5. 1	reactor structure	0.	1.000e+00
22. 1. 5. 2	equipment support structure	0.	1.000e+00
22. 1. 5. 0	primary structure & support	1.125e+05 \$/m ³	5.232e+01 13.14
22. 1. 6. 1	plasma chamber vacuum(incl. pumps/comp./pipe)	1.500e+01 \$/kg	3.245e+05 9
22. 1. 6. 2	magnet devar vacuum(incl. pumps/comp./pipe)	0.	1.000e+00
22. 1. 6. 3	suppl. heating vacuum(incl. pumps/comp./pipe)	0.	1.000e+00
22. 1. 6. 4	direct convertor vacuum(incl. pumps/comp./pipe)	0.	1.000e+00
22. 1. 6. 5	reactor vacuum system(low grade)	0.	1.000e+00
22. 1. 6. 6	reactor vacuum wall	2.500e+06 \$/unit	3.037e+00 9
22. 1. 6. 0	reactor vacuum systems(unless integral elsewhere)	0.	1.000e+00
22. 1. 7. 1	EF-coil power supplies	2.173e+01 \$/kVA	4.774e+05 10
22. 1. 7. 2	OH-coil power supplies	1.855e+01 \$/kVA	4.453e+05 10
22. 1. 7. 3	TF-coil power supplies	8.811e+02 \$/kVA	2.763e+04 22
22. 1. 7. 4	DF-coil power supplies	2.361e+02 \$/kVA	1.415e+05 22
22. 1. 7. 5	other power supplies	1.000e+06	1.000e+00
22. 1. 7. 6	current drive power supplies	3.709e+01 \$/kVA _{cr}	7.266e+05 10
22. 1. 7. 7	control system	0.	1.000e+00
22. 1. 7. 8	central energy storage	0.	1.000e+00
22. 1. 7. 9	other incl. busbars	4.659e+06 \$	1.000e+00
22. 1. 7. 0	power supply, switching & energy storage	0.	1.000e+00
22. 1. 8. 0	impurity control	6.600e+05 \$/m ²	6.998e+00 10
22. 1. 9. 1	vacuum tank	0.	1.000e+00
22. 1. 9. 2	direct convertor modules	0.	1.000e+00
22. 1. 9. 3	thermal panels	0.	1.000e+00
22. 1. 9. 4	power conditioning equipment	0.	1.000e+00
22. 1. 9. 0	direct energy conversion system	0.	1.000e+00
22. 1.10. 0	ecrh breakdown system	1.589e+06 \$	1.000e+00 13
22. 1. 0. 0	reactor equipment	0.	1.000e+00

22. 2. 1. 1	pumps & motor drives(modular & nonmodular)	0.	1.000e+00
22. 2. 1. 2	piping	0.	1.000e+00
22. 2. 1. 3	heat exchangers	0.	1.000e+00
22. 2. 1. 4	tanks(dump,make-up,clean-up,trit.,hot storage)	0.	1.000e+00
22. 2. 1. 5	clean-up system	0.	1.000e+00
22. 2. 1. 6	thermal insulation, piping & equipment	0.	1.000e+00
22. 2. 1. 7	tritium extraction	0.	1.000e+00
22. 2. 1. 8	pressurizer	0.	1.000e+00
22. 2. 1. 9	other	0.	1.000e+00
22. 2. 1. 0	primary coolant system	4.076e+04 \$/MWth	2.935e+03 10
22. 2. 2. 1	pumps & motor drives(modular & nonmodular)	0.	1.000e+00
22. 2. 2. 2	piping	0.	1.000e+00
22. 2. 2. 3	heat exchangers	0.	1.000e+00
22. 2. 2. 4	tanks(dump,make-up,clean-up,trit.,hot storage)	0.	1.000e+00
22. 2. 2. 5	clean-up system	0.	1.000e+00
22. 2. 2. 6	thermal insulation, piping & equipment	0.	1.000e+00
22. 2. 2. 7	tritium extraction	0.	1.000e+00
22. 2. 2. 8	pressurizer	0.	1.000e+00
22. 2. 2. 9	other	0.	1.000e+00
22. 2. 2. 0	intermediate coolant system	0.	1.000e+00
22. 2. 3. 1	pumps & motor drives(modular & nonmodular)	0.	1.000e+00
22. 2. 3. 2	piping	0.	1.000e+00
22. 2. 3. 3	heat exchangers	0.	1.000e+00
22. 2. 3. 4	tanks(dump,make-up,clean-up,trit.,hot storage)	0.	1.000e+00
22. 2. 3. 5	clean-up system	0.	1.000e+00
22. 2. 3. 6	thermal insulation, piping & equipment	0.	1.000e+00
22. 2. 3. 7	tritium extraction	0.	1.000e+00
22. 2. 3. 8	pressurizer	0.	1.000e+00
22. 2. 3. 9	other	0.	1.000e+00
22. 2. 3. 0	secondary coolant system	5.238e+05 \$/MWth	2.935e-04 10
22. 2. 0. 0	main heat transfer & transport systems	0.	1.000e+00
22. 3. 1. 1	refrigeration	7.546e+01 \$/unit	3.473e-03 23
22. 3. 1. 2	piping	0.	1.000e+00
22. 3. 1. 3	fluid circulation driving system	0.	1.000e+00
22. 3. 1. 4	tanks	0.	1.000e+00
22. 3. 1. 5	purification	0.	1.000e+00
22. 3. 1. 0	magnet cooling system	0.	1.000e+00
22. 3. 2. 1	refrigeration	0.	1.000e+00
22. 3. 2. 2	piping	0.	1.000e+00
22. 3. 2. 3	fluid circulation driving system	0.	1.000e+00
22. 3. 2. 4	tanks	0.	1.000e+00
22. 3. 2. 5	purification	0.	1.000e+00
22. 3. 2. 0	shield & structure cooling system	6.700e+02 \$/MWth	2.935e+03 13
22. 3. 3. 1	refrigeration	0.	1.000e+00
22. 3. 3. 2	piping	0.	1.000e+00
22. 3. 3. 3	fluid circulation driving system	0.	1.000e+00
22. 3. 3. 4	tanks	0.	1.000e+00
22. 3. 3. 5	purification	0.	1.000e+00
22. 3. 3. 0	supplemental heating system cooling system	0.	1.000e+00
22. 3. 4. 1	refrigeration	0.	1.000e+00
22. 3. 4. 2	piping	0.	1.000e+00
22. 3. 4. 3	fluid circulation driving system	0.	1.000e+00
22. 3. 4. 4	tanks	0.	1.000e+00
22. 3. 4. 5	purification	0.	1.000e+00
22. 3. 4. 0	power supply cooling system	0.	1.000e+00
22. 3. 5. 0	other cooling systems (ECCS)	0.	1.000e+00
22. 3. 0. 0	auxiliary cooling systems	0.	1.000e+00

22. 4. 1. 0	liquid waste processing & equipment	0.	1.000e+00	
22. 4. 2. 0	gaseous wastes & off-gas processing system	0.	1.000e+00	
22. 4. 3. 0	solid waste processing equipment	0.	1.000e+00	
22. 4. 0. 0	radioactive waste treatment & disposal	1.200e+03 \$/MWth	2.935e+03	13,14
22. 5. 1. 0	fuel injection systems	3.709e+06 \$	2.000e+00	10
22. 5. 2. 0	fuel processing systems	3.709e+04 \$/unit	2.740e+02	10
22. 5. 3. 0	fuel storage	3.709e+06 \$	1.000e+00	10
22. 5. 4. 0	atmospheric tritium recovery	1.484e+04 \$/m ³ /hr	1.065e+02	10
22. 5. 5. 0	water tritium recovery systems	3.709e+06 \$	1.000e+00	10
22. 5. 6. 0	blanket tritium recovery systems	3.709e+06 \$	1.000e+00	10
22. 5. 7. 0	other	0.	1.000e+00	
22. 5. 0. 0	fuel handling & storage systems	0.	1.000e+00	
22. 6. 1. 1	blanket & coil maintenance equipment	0.	1.000e+00	
22. 6. 1. 2	components rotated into service to allow maint.	0.	1.000e+00	
22. 6. 1. 3	other maintenance equipment	0.	1.000e+00	
22. 6. 1. 0	maintenance equipment	0.	1.000e+00	
22. 6. 2. 0	special heating systems(start-up,trace, etc.)	0.	1.000e+00	
22. 6. 3. 0	coolant receiving, storage & make-up systems	0.	1.000e+00	
22. 6. 4. 0	gas systems	0.	1.000e+00	
22. 6. 5. 0	building vacuum systems	0.	1.000e+00	
22. 6. 0. 0	other reactor plant equipment	1.094e+04 \$/MWth	2.935e+03	13,14
22. 7. 1. 0	reactor isc equip.(burn control, diagnostics, etc.)	0.	1.000e+00	
22. 7. 2. 0	radiation monitoring systems	0.	1.000e+00	
22. 7. 3. 0	isolated indicating & recording gauges, etc.	0.	1.000e+00	
22. 7. 0. 0	instrumentation & control(isc)	2.341e+07 \$	1.000e+00	13,14
22.98. 0. 0	spare parts allowance	0. fraction	-1.000e+00	2,13,14
22.99. 0. 0	contingency allowance	0. fraction	-1.000e+00	2,13,14
22. 0. 0. 0	reactor plant equipment	0.	1.000e+00	

23. 1. 1. 0	turbine-generators & accessories	0.	1.000e+00	
23. 1. 2. 0	foundations	0.	1.000e+00	
23. 1. 3. 0	standby exciters	0.	1.000e+00	
23. 1. 4. 0	lubricating system	0.	1.000e+00	
23. 1. 5. 0	gas systems	0.	1.000e+00	
23. 1. 6. 0	reheaters	0.	1.000e+00	
23. 1. 7. 0	shielding	0.	1.000e+00	
23. 1. 8. 0	weather-proof housing	0.	1.000e+00	
23. 1. 0. 0	turbine-generators	4.758e+05 \$/unit	1.506e+02	2,13,14
23. 2. 0. 0	main steam (or other fluid) system	1.678e+03 \$/MWth	2.935e+03	12
23. 3. 1. 0	water intake common facilities	0.	1.000e+00	
23. 3. 2. 0	circulating water systems	0.	1.000e+00	
23. 3. 3. 0	cooling towers	0.	1.000e+00	
23. 3. 4. 0	other systems which reject heat to the atmosphere	0.	1.000e+00	
23. 3. 0. 0	heat rejection systems	6.319e+04 \$/unit	3.738e+02	10
23. 4. 1. 0	condensers	0.	1.000e+00	
23. 4. 2. 0	condensate system	0.	1.000e+00	
23. 4. 3. 0	gas removal system	0.	1.000e+00	
23. 4. 4. 0	turbine by-pass systems(excl. piping)	0.	1.000e+00	
23. 4. 0. 0	condensing systems	2.753e+04 \$/unit	6.309e+02	2,13,14
23. 5. 1. 0	regenerators & recuperators	0.	1.000e+00	
23. 5. 2. 0	pumps	0.	1.000e+00	
23. 5. 3. 0	tanks	0.	1.000e+00	
23. 5. 0. 0	feed heating system	2.640e+03 \$/unit	2.935e+03	2,13,14
23. 6. 1. 0	turbine auxiliaries	0.	1.000e+00	
23. 6. 2. 0	auxiliaries cooling system(excl. piping)	0.	1.000e+00	
23. 6. 3. 0	make-up treat. system(excl. piping)	0.	1.000e+00	
23. 6. 4. 0	chemical treat. & condensate purification systems	0.	1.000e+00	
23. 6. 5. 0	central lubrication service system(excl. piping)	0.	1.000e+00	
23. 6. 0. 0	other turbine plant equipment	6.482e+05 \$/unit	7.356e+01	2,13,14
23. 7. 0. 0	instrumentation & control(itc) equipment	9.820e+05 \$/unit	8.577e+00	2,13,14
23.98. 0. 0	spare parts allowance	0.	-1.000e+00	2,13,14
23.99. 0. 0	contingency allowance	0.	-1.000e+00	2,13,14
23. 0. 0. 0	turbine plant equipment	0.	1.000e+00	

24. 1. 1. 0	generator circuits	0.	1.000e+00	
24. 1. 2. 0	station service	0.	1.000e+00	
24. 1. 0. 0	switchgear	8.600e+03 \$/unit	1.291e+03	2,13,14
24. 2. 1. 0	station service & startup transformers	0.	1.000e+00	
24. 2. 2. 0	low voltage unit substation & lighting transformer	0.	1.000e+00	
24. 2. 3. 0	battery system	0.	1.000e+00	
24. 2. 4. 0	diesel engine generators	0.	1.000e+00	
24. 2. 5. 0	gas turbine generators	0.	1.000e+00	
24. 2. 6. 0	motor generator sets	0.	1.000e+00	
24. 2. 0. 0	station service equipment	1.420e+04 \$/unit	1.291e+03	13,16
24. 3. 1. 0	main control board for electric system	0.	1.000e+00	
24. 3. 2. 0	auxiliary power & signal boards	0.	1.000e+00	
24. 3. 0. 0	switchboards (incl. heat tracing)	5.400e+03 \$/unit	1.291e+03	2,13,14
24. 4. 1. 0	gen. station grounding sys. & cathodic protection	0.	1.000e+00	
24. 4. 0. 0	protective equipment	2.110e+06 \$	1.000e+00	13,14
24. 5. 1. 0	concrete cable tunnels, trenches & envelopes	0.	1.000e+00	
24. 5. 2. 0	cable trays & support	0.	1.000e+00	
24. 5. 3. 0	conduit	0.	1.000e+00	
24. 5. 4. 0	other structures	0.	1.000e+00	
24. 5. 0. 0	electrical structures & wiring containers	1.675e+07 \$	1.000e+00	13,14,+
24. 6. 1. 0	generator circuits wiring	0.	1.000e+00	
24. 6. 2. 0	station service power wiring	0.	1.000e+00	
24. 6. 3. 0	control wiring	0.	1.000e+00	
24. 6. 4. 0	instrument wiring	0.	1.000e+00	
24. 6. 5. 0	containment penetrations	0.	1.000e+00	
24. 6. 0. 0	power & control wiring	3.466e+07 \$	1.000e+00	13,14,+
24. 7. 1. 0	reactor building lighting	0.	1.000e+00	
24. 7. 2. 0	turbine building lighting	0.	1.000e+00	
24. 7. 3. 0	reactor auxiliaries building lighting	0.	1.000e+00	
24. 7. 4. 0	radioactive waste building lighting	0.	1.000e+00	
24. 7. 5. 0	fuel storage building lighting	0.	1.000e+00	
24. 7. 6. 0	miscellaneous buildings lighting	0.	1.000e+00	
24. 7. 7. 0	yard lighting	0.	1.000e+00	
24. 7. 0. 0	electrical lighting	8.200e+06 \$	1.000e+00	13,14,+
24.98. 0. 0	spare parts allowance	0. fraction	-1.000e+00	2,13,14
24.99. 0. 0	contingency allowance	0. fraction	-1.000e+00	2,13,14
24. 0. 0. 0	electric plant equipment	0.	1.000e+00	

25. 1. 1. 0	cranes, hoists, monorails, & conveyors	0.	1.000e+00	
25. 1. 2. 0	railway	0.	1.000e+00	
25. 1. 3. 0	roadway equipment	0.	1.000e+00	
25. 1. 4. 0	watercraft	0.	1.000e+00	
25. 1. 5. 0	vehicle maintenance equipment	0.	1.000e+00	
25. 1. 0. 0	transportation & lifting equipment	1.568e+07 \$	1.000e+00	13,14
25. 2. 1. 0	air systems(excl. piping)	0.	1.000e+00	
25. 2. 2. 0	water systems(excl. piping)	0.	1.000e+00	
25. 2. 3. 0	auxiliary heating boilers(excl. piping)	0.	1.000e+00	
25. 2. 0. 0	air & water service systems	1.235e+07 \$	1.000e+00	13,14
25. 3. 1. 0	local communications systems	0.	1.000e+00	
25. 3. 2. 0	signal systems	0.	1.000e+00	
25. 3. 0. 0	communications equipment	6.220e+06 \$	1.000e+00	13,14
25. 4. 1. 0	safety equipment	0.	1.000e+00	
25. 4. 2. 0	shop, laboratory, & test equipment	0.	1.000e+00	
25. 4. 3. 0	office equipment & furnishings	0.	1.000e+00	
25. 4. 4. 0	change room equipment	0.	1.000e+00	
25. 4. 5. 0	environmental monitoring equipment	0.	1.000e+00	
25. 4. 6. 0	dining facilities	0.	1.000e+00	
25. 4. 0. 0	furnishings & fixtures	1.200e+06 \$	1.000e+00	2
25.98. 0. 0	spare parts allowance	0.	fraction	-1.000e+00 2,13,14
25.99. 0. 0	contingency allowance	0.	fraction	-1.000e+00 2,13,14
25. 0. 0. 0	miscellaneous plant equipment	0.	1.000e+00	
26. 1. 0. 0	reactor coolant	2.927e+02 \$/kg	2.500e+05	15,18
26. 2. 0. 0	intermediate coolant	0.	1.000e+00	
26. 3. 0. 0	turbine cycle working fluids	0.	1.000e+00	
26. 4. 0. 0	other materials	2.500e+05 \$	1.000e+00	13,14
26. 5. 0. 0	Ar reactor-building cover gas	7.500e-01 \$/m ³	1.724e+05	
26.98. 0. 0	spare parts allowance	0.	fraction	-1.000e+00
26.99. 0. 0	contingency allowance	0.	fraction	-1.000e+00
26. 0. 0. 0	special materials	0.	1.000e+00	

90. 0. 0. 0	direct cost (not incl. spares and contingency)	0.		1.000e+00	
91. 0. 0. 0	construction services & equipment	1.000e-01	fraction	-1.000e+00	4,10
92. 1. 0. 0	systems engineering	0.		-1.000e+00	
92. 2. 0. 0	management	0.		-1.000e+00	
92. 3. 0. 0	quality assurance	0.		-1.000e+00	
92. 4. 0. 0	safety & environmental engineering	0.		-1.000e+00	
92. 0. 0. 0	home office engineering & services	1.000e-01	fraction	-1.000e+00	4,10
93. 1. 0. 0	construction management	0.		-1.000e+00	
93. 2. 0. 0	inspection	0.		-1.000e+00	
93. 3. 0. 0	preoperational testing	0.		-1.000e+00	
93. 0. 0. 0	field office engineering & services	1.000e-01	fraction	-1.000e+00	4,10
94. 1. 0. 0	project administration	0.		-1.000e+00	
94. 2. 0. 0	staff training & plant startup	0.		-1.000e+00	
94. 3. 0. 0	inventories & spares	0.		-1.000e+00	
94. 0. 0. 0	owner's cost	5.000e-02	fraction	-1.000e+00	4,10
95. 0. 0. 0	process contingency	0.	fraction	-1.000e+00	4,10
96. 0. 0. 0	project contingency	1.000e-01	fraction	-1.000e+00	4,10
97. 0. 0. 0	interest during construction (IDC)	1.124e-01	fraction	-1.000e+00	4,10
98. 0. 0. 0	escalation during construction (EDC)	0.	fraction	-1.000e+00	4,10
99. 0. 0. 0	total cost	0.		9.700e+02	

REFERENCES

- [1] S. C. Schulte, T. L. Wilke, and J. R. Young, "Fusion Reactor Design Studies-Standard Accounts for Cost Estimates," Battelle (Pacific Northwest Laboratory) report PNL-2648 (1978).
- [2] S. C. Schulte, W. E. Bickford, C. E. Willingham, S. K. Ghose, and M. G. Walker, "Fusion Reactor Design Studies - Standard Unit Costs and Cost Scaling Rules," Pacific Northwest Laboratory report PNL-2987 (1979).
- [3] D. L. Phung, "A Method for Estimating Escalation and Interest During Construction (EDC and IDC)," in *Proc. 2nd Miami Conf. on Alternative Energy Sources* (December 10-13, 1979).
- [4] W. R. Hamilton, D. C. Keeton, and S. L. Thomson, "Cost Accounting System for Fusion Studies," Oak Ridge National Laboratory report ORNL/FEDC-85/7 (1985).
- [5] J. G. Delene, H. I. Bowers, and M. L. Meyers, "Nuclear Energy Cost Data Base," U. S. DOE report DOE/NE-0044/3 (1985).
- [6] "Pressurized Water Reactor Plant," United Engineers and Constructors, Inc. report Wash-1230m 1 (1972).
- [7] A. A. Hollis, "An Analysis of the Estimated Capital Cost of a Fusion Reactor," AERE Harwell Laboratory report AERE-R.9933 (1981).
- [8] B. Badger, G. L. Kulcinski, R. W. Conn, C. W. Maynard, K. Audenaerde, *et al.*, "Tokamak Engineering Test Reactor," University of Wisconsin report UWFDm-191 (1977).
- [9] TFCX Design Team, "Cost Summary Addendum to the Preconceptual Design Report," Princeton Plasma Physics Laboratory report A-Axxx-8407-010 (1984).
- [10] S. L. Thomson, "Reference Cost Data for Fusion," Oak Ridge National Laboratory report ORNL/FEDC-86-8 (1986).
- [11] W. R. Spears, "The SCAN-2 Cost Model," NET Project report Nr. 62 (1986).
- [12] R. L. Hagenson and R. A. Krakowski, "Compact Reversed-Field Pinch Reactors (CRFPR): Sensitivity Study and Design-Point Determination," Los Alamos National Laboratory report LA-9389-MS (1982).

- [13] C. C. Baker, M. A. Abdou, R. M. Arons, A. E. Bolon, C. D. Boley, *et al.*, "STARFIRE – A Commercial Tokamak Fusion Power Plant Study," Argonne National Laboratory report ANL/FPP-80-1 (1980).
- [14] C. G. Bathke, D. J. Dudziak, R. A. Krakowski, W. B. Ard, D. A. Bowers, *et al.*, "The Elmo Bumpy Torus Reactor and Power Plant Conceptual Design," Los Alamos National Laboratory report LA-8882-MS (1981).
- [15] B. Badger, I. N. Sviatoslavsky, S. W. Van Sciver, G. L. Kulcinski, G. A. Emmert, D. T. Anderson, *et al.*, "UWTOR-M: A Conceptual Modular Stellarator Power Reactor," University of Wisconsin report UWFD-550 (1982).
- [16] K. Evans Jr., "A Tokamak Reactor Cost Model Based on STARFIRE/WILDCAT Costing," Argonne National Laboratory report ANL/FPP/TM-168 (1983).
- [17] J. Sheffield, R. A. Dory, S. M. Cohn, J. G. Delene, L. Parsly, D. E. T. F. Ashby, and W. T. Reiersen, "Cost Assessment of a Generic Magnetic Fusion Reactor," *Fusion Technol.* **9** (1986) 199.
- [18] B. G. Logan, C. D. Henning, G. A. Carlson, R. W. Werner, D. E. Baldwin, *et al.*, "MARS Mirror Advanced Reactor Study Final Report," Lawrence Livermore National Laboratory report UCRL-53480 (1984).
- [19] R. L. Hagenson, R. A. Krakowski, C. G. Bathke, R. L. Miller, M. J. Embrechts, *et al.*, "Compact Reversed-Field Pinch Reactors (CRFPR): Preliminary Engineering Considerations," Los Alamos National Laboratory report LA-10200-MS (1984).
- [20] R. L. Reid, R. J. Barrett, T. G. Brown, G. E. Gorker, R. J. Hooper, *et al.*, "The Tokamak Systems Code," Oak Ridge National Laboratory report ORNL/FEDC-84/9 (1985).
- [21] C. Copenhaver, R. A. Krakowski, N. M. Schnurr, R. L. Miller, C. G. Bathke, *et al.*, "Compact Reversed-Field Pinch Reactors (CRFPR): Fusion-Power-Core Integration Study," Los Alamos National Laboratory report LA-10500-MS (1985).
- [22] G. E. Gorker, "Electrical Systems for RFP Lithium Blanket Magnets," Oak Ridge National Laboratory report ORNL/FEDC-M-E/M-068 (1986).
- [23] T. R. Strobridge, "Cryogenic Refrigerators – An Updated Survey," National Bureau of Standards Technical note 655 (1974).

- [24] "MINIMARS Conceptual Design: Final Report," J. D. Lee, Ed., Lawrence Livermore National Laboratory report UCID-20773 (1986).
- [25] D. Ehst, C. C. Baker, J. Brooks, R. Buxbaum, and Y. Cha, "Tokamak Power Systems Studies—FY1986: A Second Stability Power Reactor," Argonne National Laboratory report ANL/FPP/86-1 (1987).