Genealogy of CANDU Reactors: Appendices

prepared by

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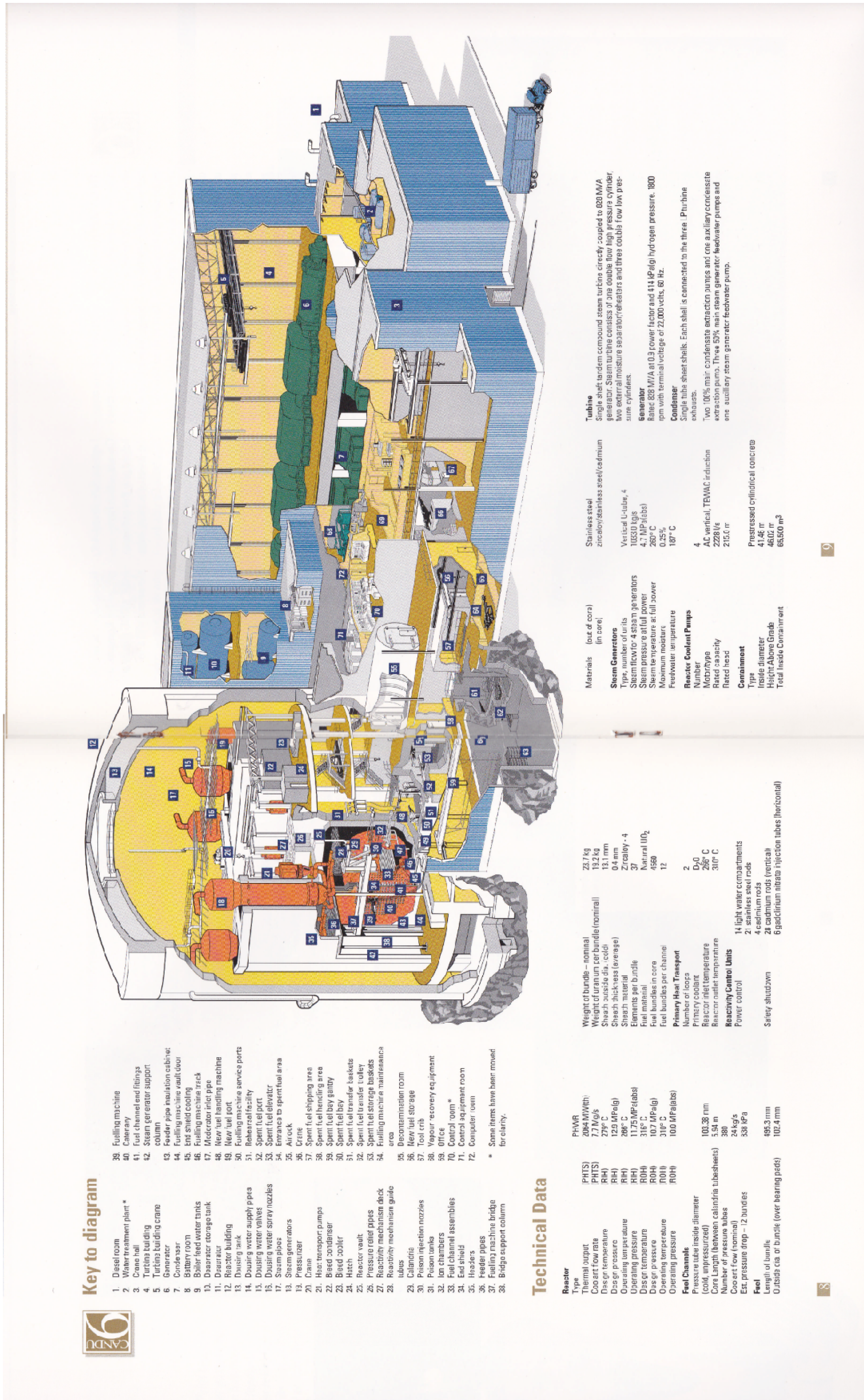
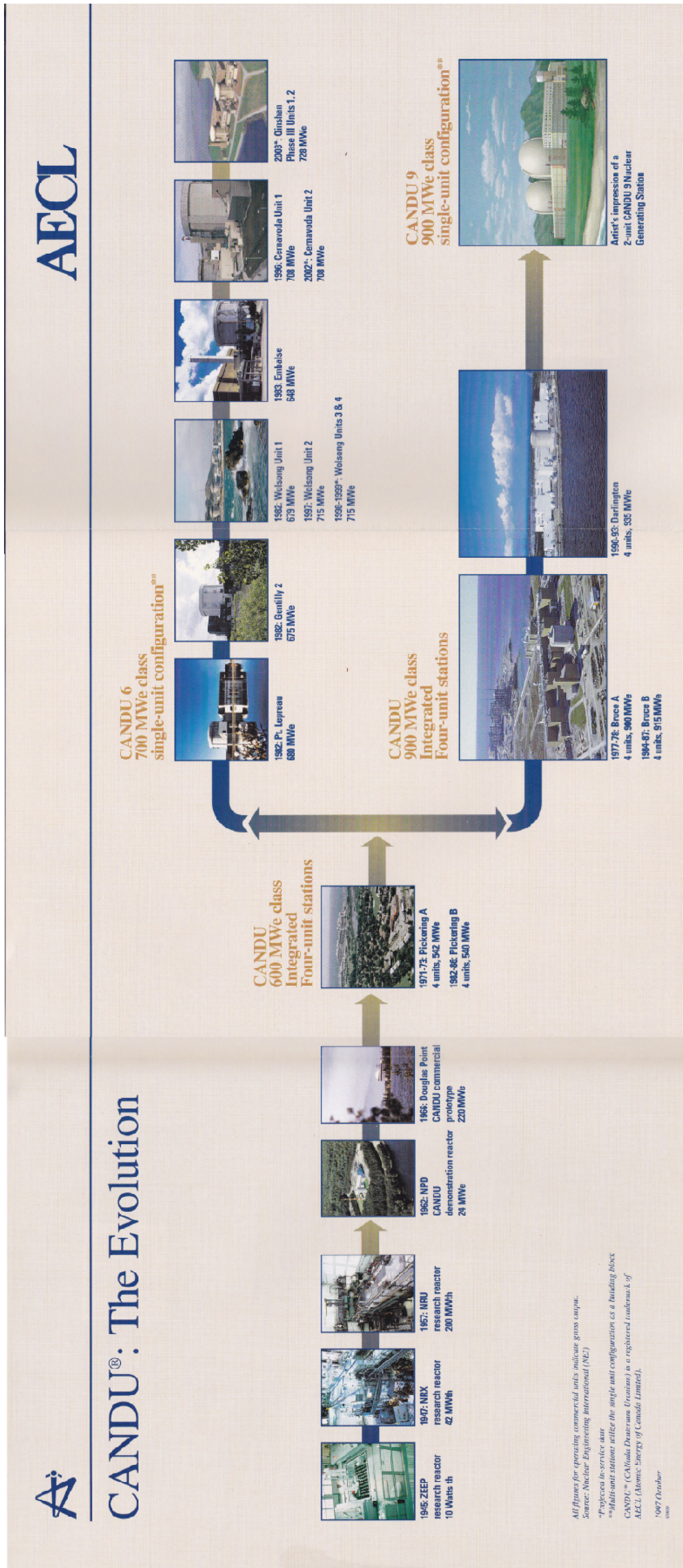
Table of Contents

Appendix A – Cutaway View of CANDU 6 Reactor Plant



Appendix B – CANDU Evolution



Appendix C – Single Unit Station Data (5 pages)

The data presented are typical values for 600 MW and 950 MW CANDU nuclear generating stations. Actual values for a specific customer and site are dependent upon the turbine generator design and condenser cooling water temperature.

	600 MW	950 MW
HEAT GENERATION BALANCE		
Fission Power Distribution:		
Heat Generation In:		
Fuel	2029.7 MW(th)	3192 MW(th)
Sheaths and Bundle Structure	7.24 MW(th)	11.4 MW(th)
Coolant	12.2 MW(th)	19.2 MW(th)
Pressure Tubes	12.23 MW(th)	19.2 MW(th)
Total (Fuel Channels)	2061.4 MW(th)	3242 MW(th)
Moderator	78.3 MW(th)	123 MW(th)
Reflector	4.4 MW(th)	8.6 MW(th)
Calandria Tubes	4.3 MW(th)	6.7 MW(th)
Calandria Shell	2.1 MW(th)	3.5 MW(th)
Tubesheets	1.4 MW(th)	3.7 MW(th)
End Shields	0.6 MW(th)	1.1 MW(th)
Other Calandria Components (Including Reactivity Mechs. and Guide Tubes)	2.4 MW(th)	3.4 MW(th)
Shields, Structures Outside Calandria and End Shields	1 MW(th)	1.5 MW(th)
Total (Other Reactor Components)	94.5 MW(th)	152 MW(th)
Total Fission Heat	2155.9 MW(th)	3394 MW(th)
HEAT TRANSFER BALANCE (PRIMARY)		
Heat Transport System:		
Heat from fuel channels	2061.4 MW(th)	3242 MW(th)
Heat Loss to Moderator	3 MW(th)	5 MW(th)
Heat Loss to End Shields	2.4 MW(th)	3.6 MW(th)
Total Heat Loss (Mod. and Shields)	5.4 MW(th)	8.6 MW(th)
Net Fission Heat to Coolant	2056 MW(th)	3233.4 MW(th)
Heat Loss to H.T. Piping	3 MW(th)	4.5 MW(th)
Heat Loss to H.T. Auxiliaries	6 MW(th)	8.9 MW(th)
Total Heat Loss	9 MW(th)	13.4 MW(th)
Net Fission Heat to Steam Generators	2047 MW(th)	3220 MW(th)
Pump Energy Appearing in Coolant	*17 MW(th)*	*38 MW(th)*
Total Heat Transferred to Steam Generators	2064 MW(th)	3258 MW(th)

	600 MW	950 MW
Moderator System:		
Heat Generated in Moderator	*78.3 MW(th)*	*123 MW(th)*
Heat Generated in Reflector	4.4 MW(th)	8.6 MW(th)
Heat Generated in Calandria Tubes	4.3 MW(th)	6.7 MW(th)
Heat Generated in Guide Tubes and Reactivity Mechanisms	2.4 MW(th)	3.4 MW(th)
Heat from Fuel Channels	3 MW(th)	5 MW(th)
Heat from Calandria Shell and Tubesheets	1.6 MW(th)	2.6 MW(th)
Total Fission Heat to Moderator	94 MW(th)	149 MW(th)
Heat Loss to Moderator Piping	0.3 MW(th)	0.2 MW(th)
Net Fission Heat to Moderator	93.7 MW(th)	149 MW(th)
Pump Energy Appearing in Moderator	0.7 MW(th)	1.5 MW(th)
Net Heat to Moderator	94.4 MW(th)	150 MW(th)
Shield Cooling System:		
Heat from Calandria Shell & Tubesheet	1.9 MW(th)	4.6 MW(th)
Heat from End Shields	0.6 MW(th)	1.1 MW(th)
Heat from Thermal Shield Structures Outside Calandria/End Shields	1 MW(th)	1.5 MW(th)
Heat from Fuel Channels	2.4 MW(th)	3.6 MW(th)
Net Fission Heat to Shield System	5.9 MW(th)	11 MW(th)
Auxiliary Systems:		
Heat from Heat Trans. Aux.	6 MW(th)	6.9 MW(th)
Heat from Heat Trans. Piping	3 MW(th)	4.5 MW(th)
Heat from Moderator Piping	0.3 MW(th)	0.2 MW(th)
Net Fission Heat to Aux. Systems	9.3 MW(th)	14 MW(th)
Summation:		
Net Fission Heat to Steam Generators	2047 MW(th)	3220 MW(th)
Net Fission Heat to Moderator	93.7 MW(th)	149 MW(th)
Net Fission Heat to Shield System	*5.9 MW(th)*	*11 MW(th)*
Net Fission Heat to Aux. Systems	9.3 MW(th)	14 MW(th)
Total Fission Heat	2155.9 MW(th)	3394 MW(th)

	600 MW	950 MW
HEAT TRANSFER BALANCE (SECONDARY)		
Net Heat Input to Turbine Cycle	2060.3 MW(th)	3347 MW(th)
Generator Output — Nominal	675.7 MW(e)	1121 MW(e)
Heat Rejected by T/G	1384.6 MW(th)	2226 MW(th)
UNIT ENERGY BALANCE		
Generator Output (Gross — Nominal)	675.7 MW(e)	1121 MW(e)
Station Service Power (Estimated)	50 MW(e)	90 MW(e)
Generator Output (net)	625.7 MW(e)	1031 MW(e)
EFFICIENCY (TYPICAL)		
Efficiency of Fission Heat Conservation and Transmission to Steam Generators	94.9% (2047/2155.9 x 100)	94.9% (3220/3394 x 100)
Overall Station Efficiency	29% (625.7/2155.9 x 100)	30.4% (1031/3394 x 100)

REACTOR PHYSICS AND DYNAMICS

The following data is valid for certain typical conditions assumed in reactor physics design. Actual values are dependent upon design for a specific customer.

	600 MW	950 MW
Core Data		
Number of cells	380	600
Cell Array	Square	Square
Lattice Pitch	28.6 cm	28.6 cm
Core Radius (Effective)	314.3 cm	395.2 cm
Core Length	594.4 cm	594.4 cm
Extrapolated Length	606 cm	606 cm
Average Reflector Thickness at Mid Point	65.46 cm	70 cm
Total Fission Power	2180 MW	3394 MW
Total Thermal Power	2060 MW	3237 MW
Nominal Channel Power	6.5 MW	6.5 MW
Nominal Bundle Power	800 kW	800 kW
Equilibrium Xenon Load	28 mk	28.2 mk
FUEL		
General:		
Fuel	Compacted and sintered natural UO_2 pellets	Compacted and sintered natural UO_2 pellets
Form	Fuel bundle assembly of 37 elements	Fuel bundle assembly of 37 elements

	600 MW	950 MW
Weight		
Total weight of UO_2 in reactor	95 Mg	153 Mg
Total weight of U in reactor	84 Mg	135 Mg
Pellets:		
Quantity (approx./element)	30	30
Form	Cylindrical pellets with concave dished ends	Cylindrical pellets with concave dished ends
Diameter (nominal)	12.16 mm	12.16 mm
Stack length (nominal)	480 mm	480 mm
Element assembly:		
Material	Zircaloy-4	Zircaloy-4
Weight	2.319 kg	2.319 kg
Outside diameter	13.08 mm	13.08 mm
Bundle assembly:		
Quantity in reactor	4560	7200
Quantity per fuel channel	12	12
Length of bundle	495 mm	495 mm
Outside diameter	102.4 mm	102.4 mm
Weight of bundle	23.5 kg	23.5 kg
REACTIVITY DEVICE WORTHS		
Total Zone Control Worth	7.5 mk	8.1 mk
Total Adjuster Worth	15 mk	16.4 mk
Total Mechanical Control Absorber Worth	10.5 mk	7.1 mk
Total Static Worth of Shutoff Units	80 mk	67.3 mk
Total Worth of Poison Injection	600 mk	600 mk
REACTOR BUILDING		
Form	Upright cylinder with flat base and double dome	Upright cylinder with flat base and double dome
Material	Reinforced pre-stressed concrete	Reinforced pre-stressed concrete
Diameter (inside)	41.45 m (136 ft)	52.0 m (170 ft)
(Outside)	43.59 m (143 ft)	54.2 m (178 ft)
Height (Basement to inside top of dome	51.21 m (168 ft)	64.5 m (212 ft)
Design Pressure	124.1 kPa(g) (18 psig)	138 kPa(g) (20 psig)
Wall thickness	1.07 m (3.5 ft)	1.1 m (3.6 ft)

	600 MW	950 MW
Reactor Containment		
Net Building Air Volume	48 477 m³ (1 712 000 ft³)	106 000 m³ (3 743 000 ft³)
Base slab thickness	1.68 m (5.51 ft)	3m (9.84 ft)
Wall height (not incl. dome)	42.3 m (138.8 ft)	54.0 m (177.2 ft)
Thickness of dome at crown	0.60 m (1.97 ft)	0.61 m (2 ft)
Ring beam thickness	2.20 m (7.2 ft)	1.9 m (6.2 ft)
Ring beam height	4.3 m (14.1 ft)	4.3 m (14.1 ft)
Internal dome thickness	0.39 m (1.25 ft)	0.4 m (1.3 ft)
REACTOR		
Type	Horizontal pressure tube	Horizontal pressure tube
coolant	Pressurized heavy water (D_2O)	Pressurized heavy water (D_2O)
Moderator	Heavy Water (D_2O)	Heavy Water (D_2O)
Inlet Temperature	49°C (120°F)	51°C (123°F)
Outlet Temperature	77°C (170°F)	66°C (151°F)
Moderator Flow Rate	940 L/s (12 400 Igpm)	2200 L/s (29 000 Igpm)
Cooling Capacity	120 MW(th)	155 MW(th)
Fuel	Natural UO_2	Natural UO_2
Number of Channels	380	600
Reactivity Control:		
Main Method	On power refuelling and moderator poison control	On power refuelling and moderator poison control
Trim	H_2O zone control assemblies and vertical control absorber rods	H_2O zone control assemblies and vertical control absorber rods
Poison Override	Vertical adjuster rods	Vertical adjuster rods
Shutdown:		
System no. 1	Spring-augmented gravity-accelerated shutoff rods	Spring-augmented gravity-accelerated shutoff rods
System no. 2	Moderator poison injection	Moderator poison injection
Flux Flattening:		
Axial	Vertical adjuster rods	Vertical adjuster rods
Radial	Differential fuelling and vertical adjuster rods	Differential fuelling and vertical adjuster rods
Flux Control	H_2O Zone Control	H_2O Zone Control

	600 MW	950 MW
FUEL CHANNEL ASSEMBLIES		
Quantity	380	600
Length:		
Overall including end fittings	10.82 m (35.5 ft)	11.15 m (36.6 ft)
Channel Flow (maximum)	24 kg/s (190 000 lb/h)	26.5 kg/s (210 000 lb/h)
Inlet temperature*	266.6°C (511.8°F)	266.2°C (511.1°F)
Outlet temperature*	312°C (594°F)	312°C (594°F)
Inlet pressure*	11.04 MPa(a) (1601 psia)	11.17 MPa(a) (1620 psia)
Outlet pressure*	10.3 MPa(a) (1494 psia)	10.29 MPa(a) (1492.9 psia)
Pressure Tubes		
Quantity	380	600
Material	Zirconium/ Niobium Alloy	Zirconium/ Niobium Alloy
Length Trimmed for Installation (approx.)	6.30 m (20.66 ft)	6.32 m (20.75 ft)
Inside Diameter, Minimum	103.38 mm (4.07 in)	104 mm (4.09 in)
Wall Thickness, Minimum	4.19 mm (0.165 in)	
STEAM GENERATORS		
Name	Primary Heat Transport System Steam Generator	Primary Heat Transport System Steam Generator
Quantity	4	8
Type	Vertical U-tube with integral steam drums and preheater	Vertical U-tube with integral steam drums and preheater
Heat transferred*	2064 MW(th)	3258 MW(th)
Heat transfer area per steam generator	3127 m² (34 200 ft²)	3066 m² (33 000 ft²)
Fluid	D_2O	D_2O
Flow Rate**	7.6 Mg/s (60.3 x 10⁶ lb/h)	13.5 Mg/s (107.1 x 10⁶ lb/h)
Shell Side Data:		
Fluid	H_2O	H_2O
Steam Flow**	1.047 Mg/s (8.31 x 10⁶ lb/h)	1.612 Mg/s (12.79 x 10⁶ lb/h)
Feedwater Flow**	959 kg/s (7.615 x 10⁶ lb/h)	1536 kg/s (12.19 x 10⁶ lb/h)
Blowdown Flow** (continuous)	1.00 kg/s (8000 lb/h)	2.0 kg/s (15 900 lb/h)

* Maximum power channel at 100% power (measured at fuel)
** total for four steam generators (600 MW) total for eight steam generators (950 MW)

	600 MW	950 MW
Feedwater inlet temperature	187°C (368°F)	177°C (350°F)
Pressure at drum nozzle	4.69 MPa(a) (681 psia)	5.07 MPa(a) (735 psia)
Temperature at drum nozzle	260°C (500°F)	265°C (509°F)
Quality at drum nozzle	99.75%	99.75%
HEAT TRANSPORT PUMPS		
Quantity	4	4
Type	Vertical, centrifugal, single suction double discharge	Vertical, centrifugal, single suction double discharge
Duty	Continuous	Continuous
Fluid	D_2O	D_2O
Flow Rate	2228 L/s (29 400 Igpm)	3959 L/s (52 258 Igpm)
Temperature	266°C (511°F)	266°C (511°F)
Head	215 m (705 ft)	245 m (803 ft)
REACTIVITY CONTROL		
Shut-Off Units (Shutdown System No. 1)		
Quantity	28	38
Shutoff Rods: Type	Stainless steel-clad cadmium tube	Stainless steel-clad cadmium tube
Insertion Sequence	Simultaneous drop, spring augmented, gravity-accelerated	Simultaneous drop, spring augmented, gravity-accelerated
Static Reactivity Worth, approx.	-80 milli-k (28 rods)	-67.3 milli-k (36 rods)
Drive Mechanism: Rod insertion mechanism	Free-wheeling winch and cable	Free-wheeling winch and cable
Rod deceleration system	Rotary hydraulic damper on winch	Rotary hydraulic damper on winch
Withdrawal mechanism	Motor & gear train engaged to winch by a dc electro-magnetic friction clutch	Motor & gear train engaged to winch by a dc electro-magnetic friction clutch
Liquid Injection Shutdown System (Shutdown System No. 2)		
Quantity	6	8
Type	Horizontal nozzle tubes inject liquid poison directly into moderator when system is actuated	Horizontal nozzle tubes inject liquid poison directly into moderator when system is actuated

	600 MW	950 MW
Poison	Gadolinium nitrate in D_2O (8000ppm solution)	Gadolinium nitrate in D_2O (8000ppm solution)
Reactivity worth		
Short term (after 2 sec.)	-55 mk (min.)	
Long term (after 1 min.)	-300 mk (min.)	
Liquid Zone Control Units		
Quantity	6 (4 x 2 compartments and 2 x 3 compartments)	8 (4 x 3 compartments and 4 x 2 compartments)
Reactivity Worth, approx. maximum	~ 7.5 milli-k	~ 8.1 milli-k
Type	Vertical through-tubes, divided into compartments that can be partially or completely filled with light water.	Vertical through-tubes, divided into compartments that can be partially or completely filled with light water.
Mechanical Control Absorber Units		
Absorber Rods: Quantity	4	4
Type	Stainless steel-clad cadmium tube	Stainless steel-clad cadmium tube
Insertion Sequence + Method: Reactor Stepback	Simultaneous, free drop, gravity acceleration	Simultaneous, free drop, gravity acceleration
Reactor Setback	Simultaneous, motor driven	Simultaneous motor driven
Withdrawal Sequence + Method	Simultaneous, motor driven	Simultaneous motor driven
Insertion & Withdrawal Time	Variable (130 sec minimum)	Variable (150 sec minimum)
Reactivity Worth, approx.	-10 milli-k	-7.1 milli-k
Adjuster Units		
Quantity	21	27
Absorber Element: Type	Variable thickness tube plus centre rod	Variable thickness tube plus centre rod
Material	Stainless Steel	Stainless Steel
Withdrawal and Insertion Sequence	1 bank at a time	1 bank at a time
Withdrawal or Insertion Time, Each Bank	60 ± 5 seconds	60 ± 5 seconds
Poison Override Time	30 minutes	30 minutes
Total Reactivity Worth, approx.	~ 15 milli-k	~ 16.4 milli-k

	600 MW	950 MW
Moderator Liquid Poison System		
Long Term Reactivity Control:		
Poison	Boric Anhydride	Boric Anhydride
Solubility Limit in D_2O at 20°C (68°F)	27 g/L	27 g/L
Concentration of Boron in the Moderator to simulate −28.5 mk*	3.5 ppm	3.5 ppm
Concentration of Poison in the Poison Tank	10.56 g/L	10.56 g/L
Rate of Poison Solution Addition to Achieve −0.75 mk/min	117 mL/s (1.54 Igpm)	170 mL/s (2.24 Igpm)
Startup Reactivity Control:		
Poison	Gadolinium Nitrate Hexahydrate	Gadolinium Nitrate Hexahydrate
Solubility Limit in D_2O at 25°C (77°F)	2.35 kg/L	2.35 kg/L
Concentration of Gadolinium in the Moderator to Simulate −28.5mk*	0.89 ppm	0.89 ppm
Concentration of Poison in the Poison Tank	3.99 g/L	3.99 g/L
Rate of Poison Solution Addition to Achieve −0.75 mk/min	78.1 mL/s (1.03 Igpm)	113 mL/s (1.49 Igpm)
Vertical Flux Detector Units		
No. of Assemblies	26	28
Type	Factor sealed, encapsulated, multi-detector assembly; self-powered, platinum and vanadium detectors	Factory sealed, encapsulated, multi-detector assembly; self-powered platinum and vanadium detectors

* −28.5 mk is the reactivity required to compensate for complete absence of equilibrium xenon in the reactor fuel.

	600 MW	950 MW
Horizontal Flux Detector Units		
No. of Assemblies	7	14
Type	Factory sealed, encapsulated, multi-detector assembly; self-powered, platinum and vanadium detectors	Factory sealed, encapsulated, multi-detector assembly; self-powered, platinum and vanadium detectors
TURBINE GENERATOR AND AUXILIARIES		
Design temperature of circulating water 22°C (71.6°F)		
Generator gross output	675.7 MW(e)	1121 MW(e)
Turbine cycle heat rate	10 937 kJ/kWh	10 460 kJ/kWh
Steam cycle gross efficiency	32.8%	34.4%
Main steam flow, MCR	1047 kg/s (8,310 x 10^3 lb/h)	1612 kg/s (12 794 x 10^3 lb/h)
Turbine Generator		
Live steam flow to valves	957 kg/s	1532.5 kg/s
Live steam flow to reheater	89.9 kg/s	77.2 kg/s(2nd Stage)
Live steam pressure at valves	4.55 MPa(a) (660 psia)	4.93 MPa(a) (715 psia)
Live steam temperature at valves	258°C (496.6°F)	263°C (505.4°F)
Pressure of HP exhaust steam	665.3kPa(a) (96.5 psia)	545.4 kPa(a) (79.1 psia)
Quality of HP exhaust steam	88.24%	86.5%
Inlet pressure of LP steam	588.4 kPa(a) (85.3 psia)	500 kPa(a) (72.5 psia)
Inlet temperature of LP steam	242.2C (468.68°F)	247.4°C (477.3°F)
Quality of LP exhaust steam	89.5%	91.0%
Turbine generator speed	1800 rpm	1800 rpm
Number of HP cyclinders	1, double flow	1, double flow
Number of LP cylinders	3, double flow	3, double flow
Number of moisture separators	4	2
Number of reheaters	2	2
Numbers and diameter of steam inlets	4 x 61 cm (4 x 24 in)	4 x 61 cm (4 x 24 in)
Generator Type	Direct coupled, hydrogen/water cooled	Direct coupled, hydrogen/water cooled