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Joint ICTP-IAEA Workshop on Nuclear Reaction Data for Advanced Reactor Technologies

19 - 30 May 2008

Heavy Water Reactors:
1. Physics, Concepts and History

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Canada

Heavy Water Reactors:
1. Physics, Concepts and History

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Joint ICTP-IAEA Workshop on
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Outline

- Many topics to cover (by no means complete)
- Fundamental Physics
- Design Options
- Physics and Engineering Issues
- Review of Conventional HWR Power Reactors
  - Prototypes / Experiments (Historical)
  - Commercial Reactors
- Present Day and Near Future
- Additional Information (see Appendix)
  - Other HWR concepts.

Goals

- Better appreciation of heavy water reactors.
  - Historical review.
  - We can learn from the past.
  - Variables change with time.
- Better understanding.
  - Motivation.
  - How it works.
  - Design features.
  - Physics issues, engineering issues.
  - Long term prospects, implications for future.

References

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- AECL, *Canada Enters the Nuclear Age*, McGill-Queen's University Press, Montreal, (1997).
- AECL, *CANDU 6 Technical Outline*, TDSI-105, Mississauga, Ontario, Canada, January (1992).

A Few Useful References

- British Nuclear Energy Society, *Steam Generating and Other Heavy Water Reactors*, Proc. of Conf. 14-16 May, (1968).
- Power Reactor and Nuclear Fuel Development Corporation (Japan), *The 9th JUICE Meeting on Heavy Water Reactors*, Tokyo, March 11, (1982).
- R.L. Loftness, *Nuclear Power Plants*, D.Van Nostrand, Princeton, NJ, (1964).
- I.R. Cameron, Nuclear Fission Reactors, Plenum Press, New York, (1982).
- J.J. Duderstadt and L.J. Hamilton, Nuclear Reactor Analysis, John Wiley & Sons, New York, (1976).
- J.R. Lamarsh, Introduction to Nuclear Engineering, 2nd Edition, Addison-Wesley, Reading, Massachusetts, (1983).
- J.H. Wright, *Nuclear Heat Sources for Modern Steam Turbines*, Proc. of American Power Conference, Vol. 24, pp.183-194, (1962).
- J.G. Duffy and C.C. Graves, *Design of 10 MWe SDR*, Nuclear Engineering and Science Conference, April 6-9, 1959, Cleveland, Ohio.

- *And many more ....*

A Few Useful Websites

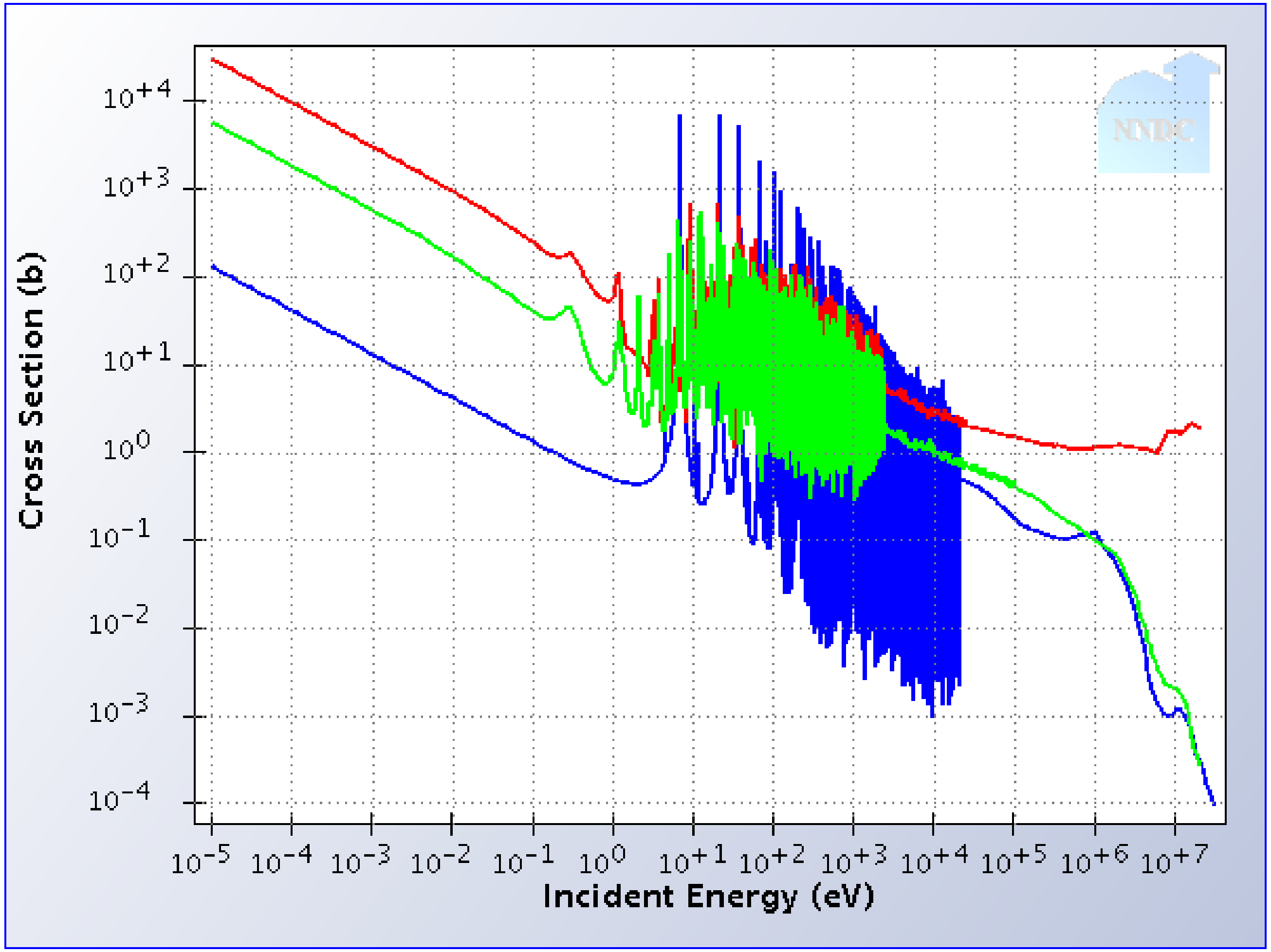
- http://www.aecl.ca/site3.aspx
- http://www.aecl.ca/Assets/Publications/C6-Technical-Summary.pdf
- http://www.aecl.ca/Assets/Publications/ACR1000-Tech-Summary.pdf
- http://www.nuceng.ca/
- http://canteach.candu.org/
- http://canteach.candu.org/image_index.html
- http://www.cns-snc.ca/home_eng.html
- http://www.nuclearfaq.ca/
- http://www.npcil.nic.in/nupower_vol13_3/ahwr.htm
- Just Google or Yahoo "heavy water reactor"

Reactor Physics Considerations

- Goal is to sustain fission reactions in a critical assembly using available fissile (and fertile) isotopes.
- Fission cross section for various isotopes
  - Thermal spectrum: ~ 500 barns to 1000 barns
  - Fast spectrum: ~ 1 barn to 10 barns
- Minimize enrichment requirements
  - Cost
  - Safety
- Incentive to use thermal reactors

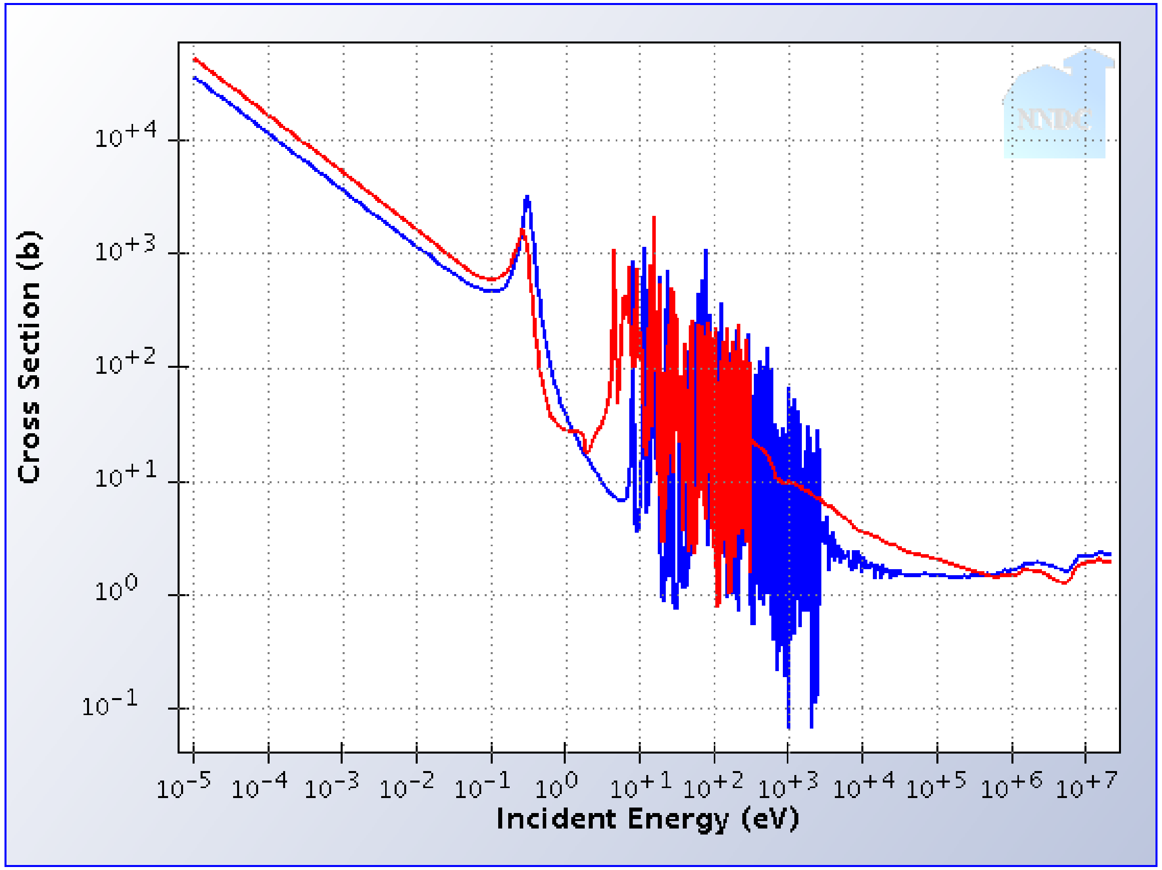
U-235 / U-238

- U-235 Fission, U-235 capture, U-238 capture

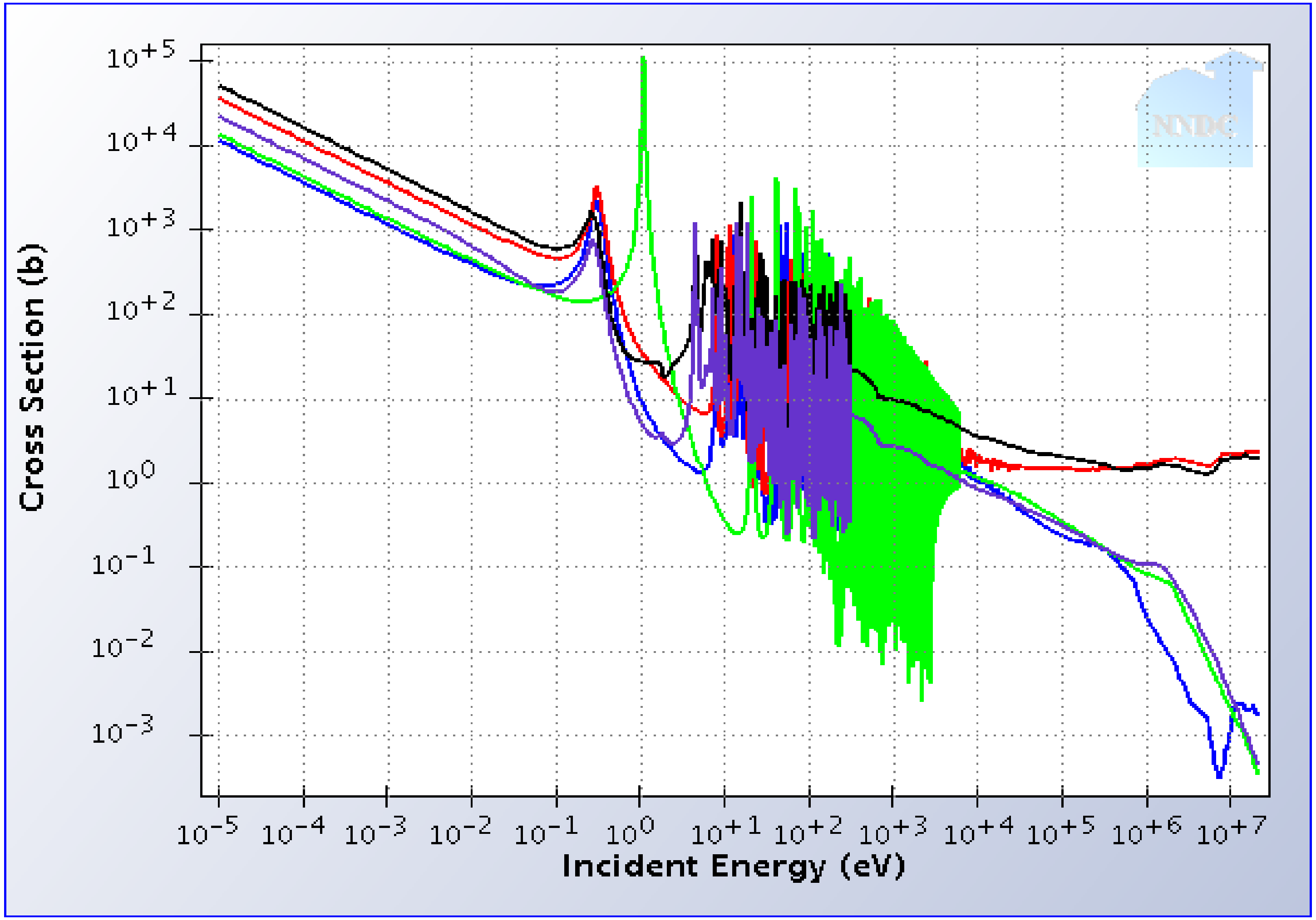


Pu-239 / Pu-241

- **Fission cross sections**



Pu-239/Pu-241 Fission, capture
Pu-240 capture



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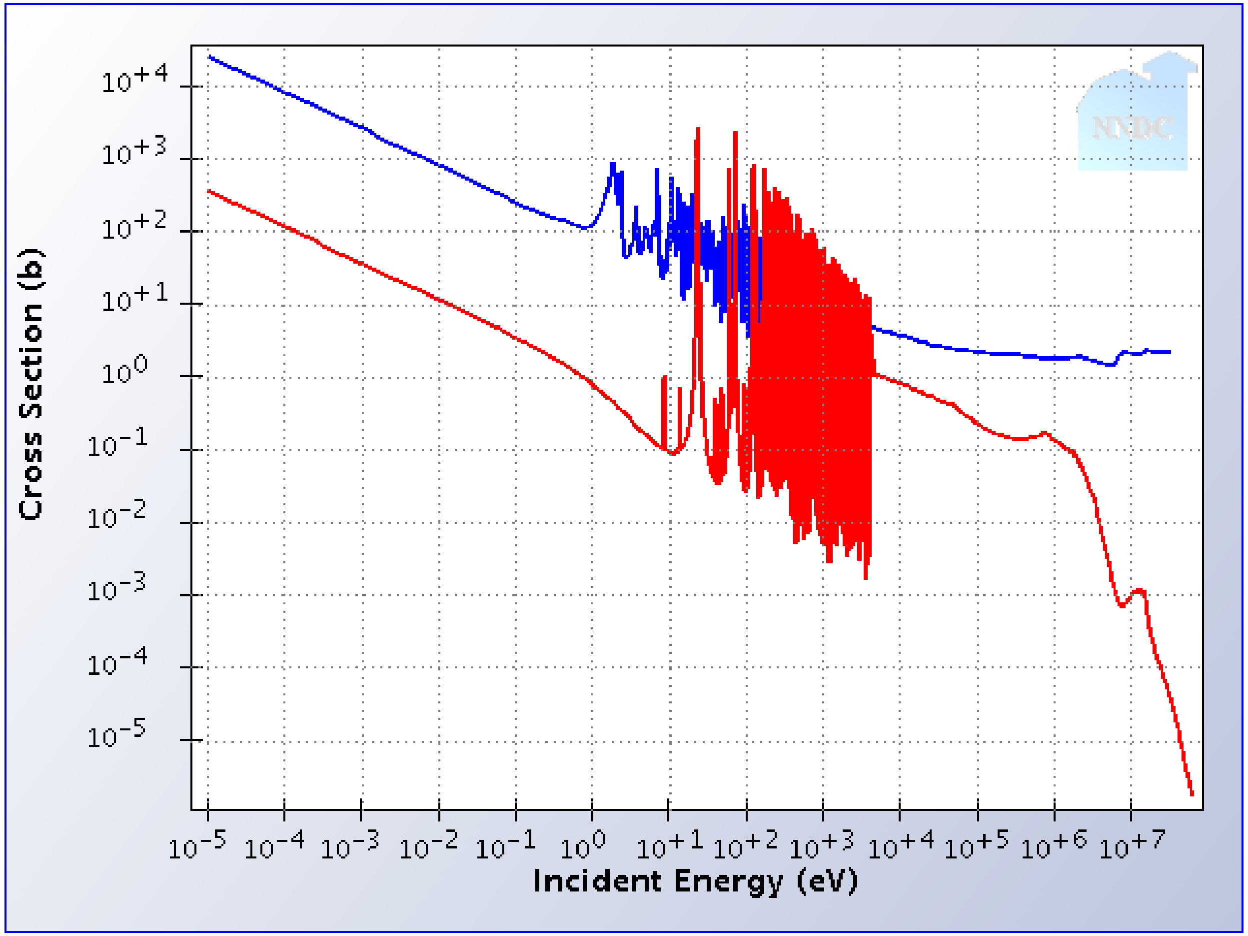
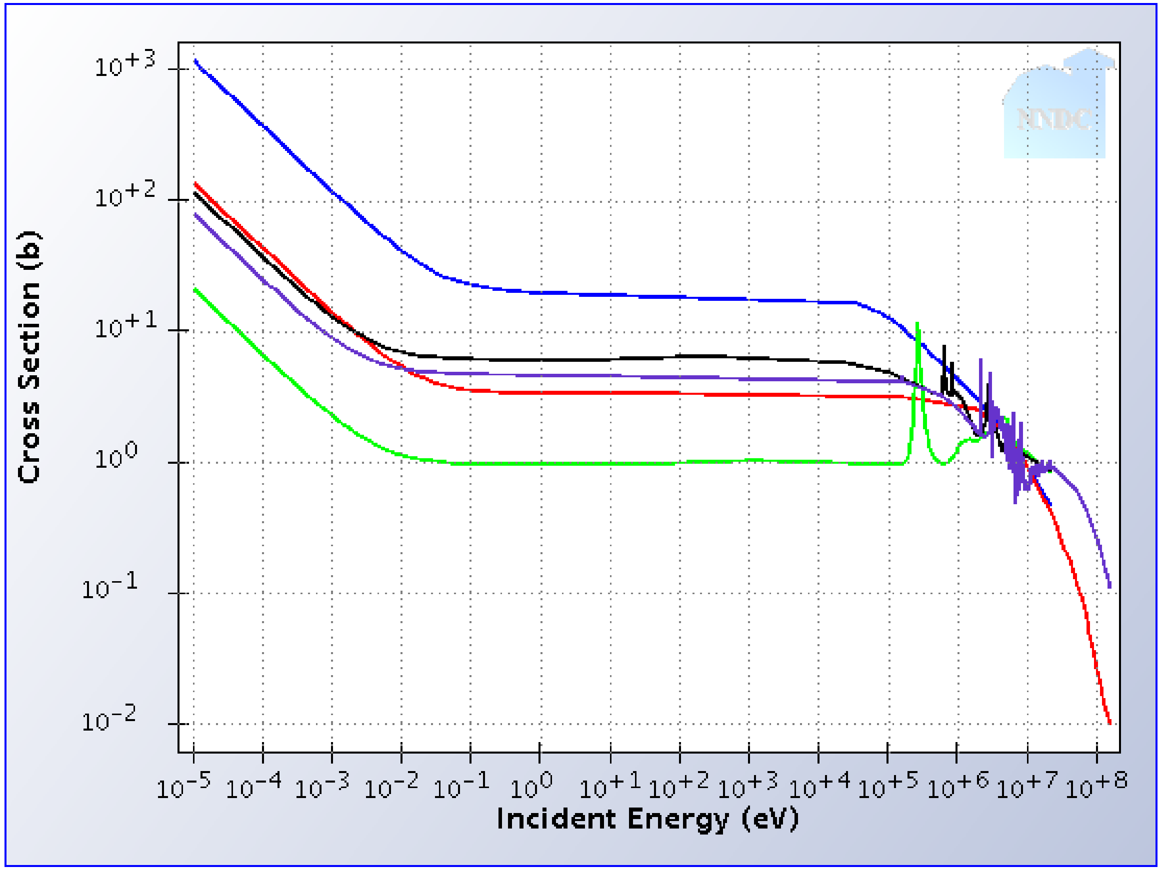
U-233 / Th-232

- Capture, fission.



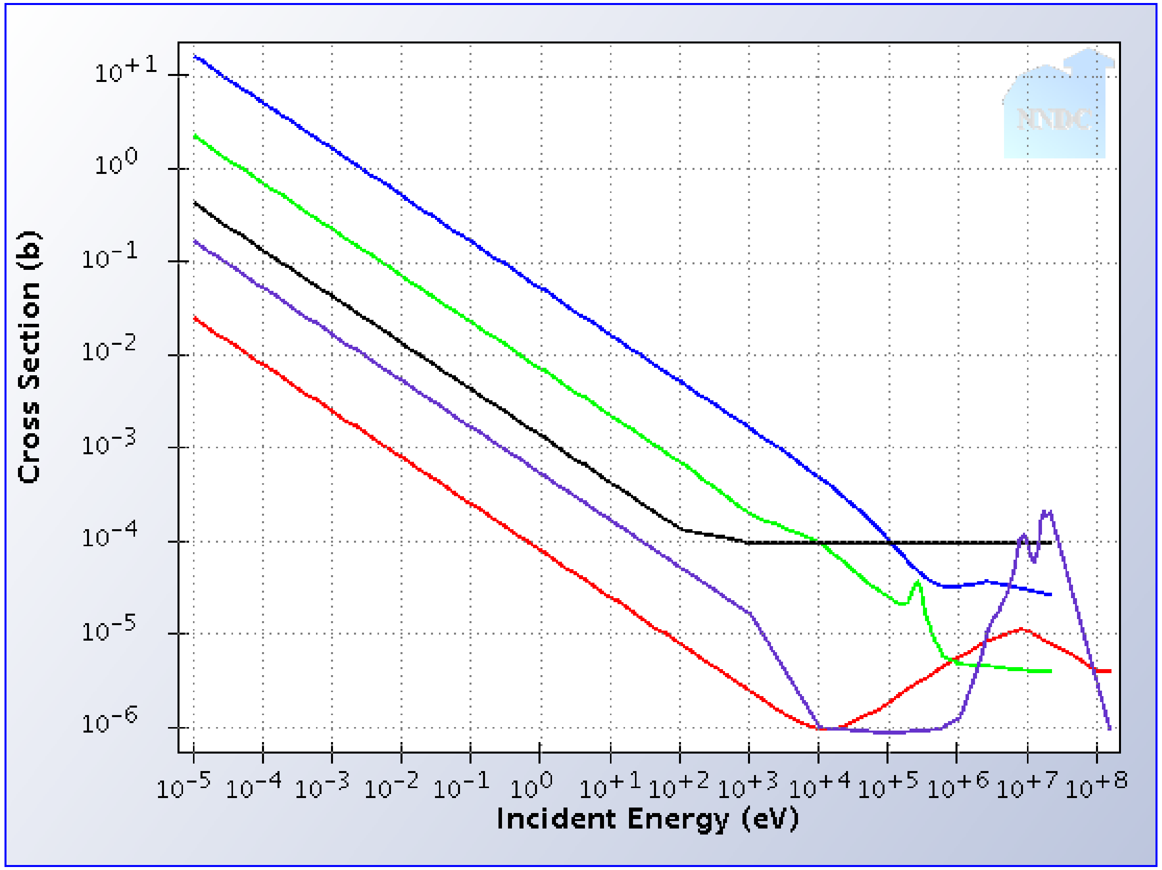
Isotopes for Moderation

- H, D, ^{7}Li, Be, C – Scatter Cross Sections



Isotopes for Moderation

- H, D, ^{7}Li, Be, C – Capture Cross Sections



Options for Moderator

- **Hydrogen-based moderator**
  - shortest neutron slowing down distance, but absorption
- **Deuterium-based moderator**
  - Moderating ratio 30 to 80 times higher than alternatives
  - Excellent neutron economy possible

Moderator	A	α	ξ	$\rho[g/cm^3]$	from 2 MeV to 1 eV	$\xi\Sigma_s[cm^{-1}]$	$\xi\Sigma_s/\Sigma_a$
H	1	0	1	gas	14	—	—
D	2	.111	.725	gas	20	—	—
H_2O	—	—	.920	1.0	16	1.35	71
D_2O	—	—	.509	1.1	29	0.176	5670
He	4	.360	.425	gas	43	1.6×10^{-5}	83
Be	9	.640	.209	1.85	69	0.158	143
C	12	.716	.158	1.60	91	0.060	192
^{238}U	238	.983	.008	19.1	1730	0.003	.0092

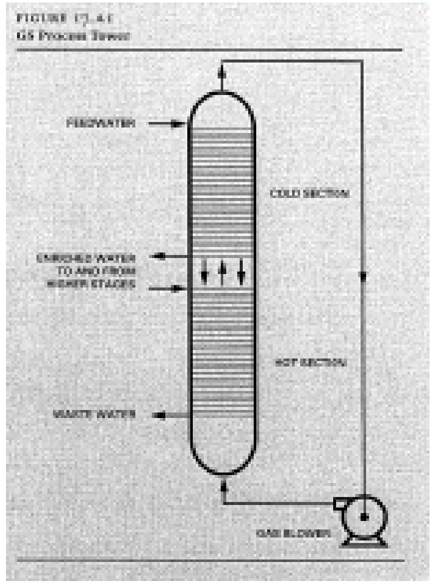
D_2O Moderator Advantages

- Excellent moderating ratio, > 5500
- What does this get you?
  - Can use lower enrichment (natural uranium)
  - Higher burnups for a given enrichment.
  - Reduce parasitic neutron absorption in moderator
    - Save neutrons, and spend them elsewhere.
    - Permits use of higher-absorption structural materials
      - High P, High T environments – better efficiencies.
      - Materials to withstand corrosive environments.
  - Thermal breeders with U-233 / Th-232 cycle feasible.

D_2O Characteristics

- Thermal-hydraulic properties similar to H_2O.
- Purity Required > 99.5 wt%D_2O
  - dk_{eff}/dwt%D_2O ~ +10 to +30 mk/wt%D_2O
  - less sensitive for enriched fuel.
- Cost:
  - ~300 to 500 $/kg-$D_2O$; ~200 to 400 $/kWe
  - New technologies will reduce the cost.
- Quantity Required
  - ~450 tonnes for CANDU-6 (~ 0.65 tonnes/MWe)
  - ~$150 to $200 million / reactor
  - Upper limit for D_2O-cooled HWR reactors.
    - Use of lower moderator/fuel ratio (tighter-lattice pitch) and/or
    - Alternative coolants can drastically reduce D_2O requirements.

D_2O Extraction from Water



- **Electrolysis (1930's / 1940's)**
  - **Norsk Hydro (WWII)**
  - **Trail, BC (Canada)**
- **GS (Girdler-Sulfide) Process**
  - **1960's to 1980's; industrial scale.**
  - **Reversible thermal/chemical process**
  - **$HDO + H_2S \rightarrow H_2O + HDS$**
  - **Deuterium moves to sulfide form at hot temp. (130° C)**
  - **Deuterium moves back to oxide form at cool temp.**
  - **Multiple stages with hot/cold streams.**

D_2O Extraction for Water

- **GS Hydrogen Sulfide Separation Process**

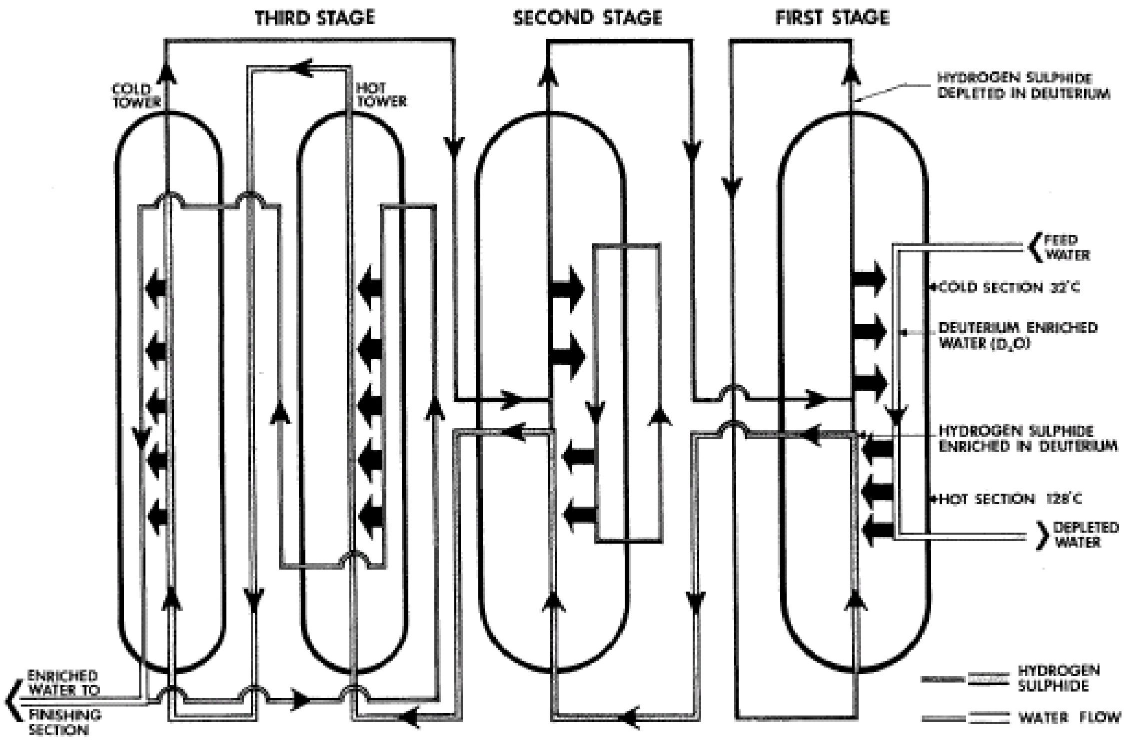
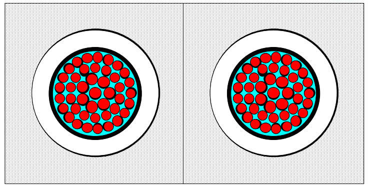


Fig. 5.7. Production of heavy water by GS hydrogen sulfide process (courtesy of Atomic Energy of Canada Limited).

D_2O Extraction for Water

- Alternative and new processes under advanced development and refinement
  - Combined Industrial Reforming and Catalytic Exchange (CIRCE)
  - Combined Electrolysis and Catalytic Exchange (CECE)
  - Bi-thermal Hydrogen–Water (BHW) processes
  - Other physical and chemical processes (ammonia/water, etc.)
- Newer processes more efficient
  - More cost-effective.
- Reference:
  - Heavy Water: A Manufacturer's Guide for the Hydrogen Century, by A.I. Miller, Canadian Nuclear Society Bulletin Vol 22, No 1, 2001 February
  - www.cns-snc.ca/Bulletin/A_Miller_Heavy_Water.pdf

Design Options for HWR's



- **Pressure tubes (PT)**
  - Thick-wall pressure tube is main boundary
  - D_2O moderator at low T (<100°C), low P (1 atm)
  - PT sits inside calandria tube (CT)
  - PT, CT must be low neutron absorber (Zircaloy)
  - Low-P coolants (organic, liquid metal) may allow thinner PT/CT.
- **Pressure vessel (PV)**
  - Thin-walled PT/CT used to isolate fuel channels.
  - Moderator at higher P (10 to 15 MPa), T (~300°C).
  - Thick pressure vessel (~20 cm to 30 cm).
  - Pre-stressed reinforced concrete is an option.

Coolant Options (Current)

- D_2O at 10 to 15 MPa (CANDU, Atucha)
- H_2O at 10 to 15 MPa (ACR-1000)
- Boiling H_2O at 5 to 7 MPa (AHWR)
- Supercritical H_2O at 25 MPa (Gen-IV)
  - SCOTT-R (Westinghouse study, 1960's)
  - CANDU-SCR (AECL, Gen-IV)

Coolant Features – D_2O

- D_2O at 10 to 15 MPa (CANDU, Atucha)
  - Low absorption cross section; neutron economy.
  - Conventional steam-cycle technology.
  - Void reactivity
    - Depending on fuel / lattice design.
    - May be slightly positive, or negative.
  - Higher capital costs; minimizing leakage.
  - Tritium production and handling, but useful by-product.
  - Water chemistry / corrosion for long-term operation.
  - Hydriding of Zircaloy-PT.
  - Efficiencies usually limited to < 34% (30% to 31% typical).

Coolant Features – H_2O

- H_2O at 10 to 15 MPa (ACR-1000)
  - – Cheaper, lower capital costs
  - – Conventional steam-cycle technology.
  - – Higher neutron absorption; reduced neutron economy.
  - – Must design lattice carefully to ensure negative CVR.
  - – Water chemistry / corrosion for long-term operation.
  - – Hydriding of Zircaloy-PT
  - – Net efficiencies usually limited to ~ 34%.

Coolant Features – Boiling H_2O

- Boiling H_2O at 5 to 7 MPa
  - – Cheaper, lower capital costs
  - – Thinner PT's feasible.
  - – Direct steam cycle
    - Eliminate steam generator; slightly higher efficiencies.
  - – Neutron absorption in H_2O
  - – Must design lattice carefully to ensure negative CVR.
    - Smaller lattice pitch; enriched and/or MOX fuel.
    - More complicated reactivity control system.
  - – Water chemistry / corrosion; hydriding of Zircaloy-PT
  - – Radioactivity in steam turbine.

Coolant Features – Supercritical H_2O

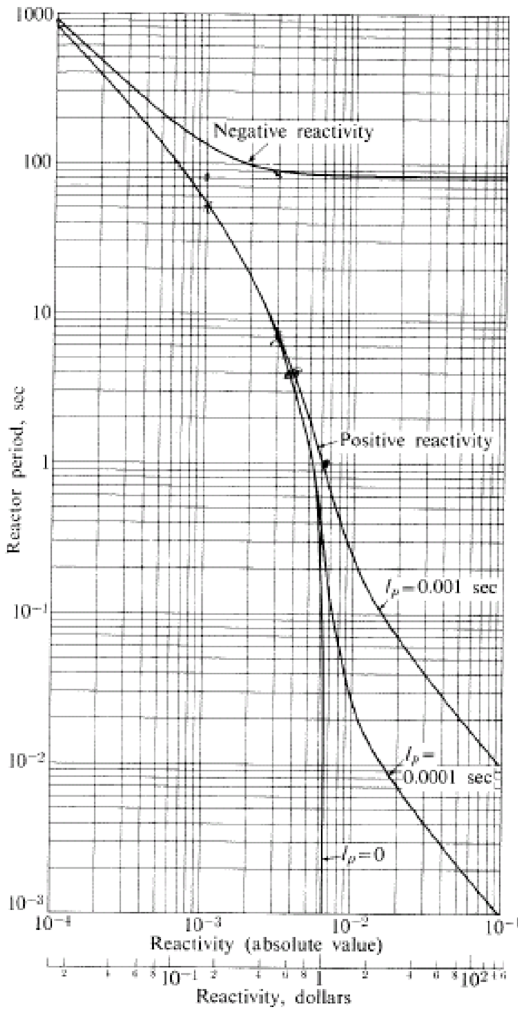
- Supercritical H_2O at 25 MPa
  - Similarities to boiling H_2O.
  - Higher efficiencies possible, ~45%.
  - Thicker PT's required; reduced neutron economy.
  - Severe conditions; corrosive environment
    - T~550°C to 600°C.
    - High-temp. materials required – reduced neutron economy.
    - Use of ZrO_2, MgO, or graphite liner for PT
  - Careful design for postulated accidents
    - Depressurization from 25 MPa.
  - More challenging to design for on-line refuelling.

HWR Physics Characteristics

- Moderator isolated from fuel/coolant
  - Keep at lower temp (< 100°C, for PT reactors)
- Physics properties depend on:
  - Moderator / fuel ratio
  - Fuel pin size (resonance self shielding)
  - Composition / enrichment (U, Pu, Th)
  - Coolant type (D_2O, H_2O, gas, organic, liquid metal, etc.)
- Reactivity Coefficients
  - Fuel temperature comparable to LWR.
  - Void reactivity (+ or -), depending on design.
  - Power coefficient (+ or -), depending on design.

HWR Physics Characteristics

- **Longer neutron lifetime.**
  - ~ 1 ms vs. LWR (~0.1 ms)
  - $\Delta\rho$ = +6 mk $\rightarrow$ Period ~ 1 sec
  - Slower transient (easier to control)
- **Extra delayed neutron group**
  - Photo-neutrons from γ + D $\rightarrow$ n + H reaction.
  - Half-life of photo-neutron precursors > longest lived delayed neutron precursor (~55 seconds).



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HWR Physics Characteristics

- Conversion Ratio
  - C = 0.7 to 0.9 (depends on enrichment, parasitic losses)
    - U-metal ideal, but UO_2, UC more practical
  - C > 1.0 possible for U-233 / Th-232 thermal breeder
    - Careful design of lattice required to maximize economy.
- Burnup of fuel
  - Natural U $\rightarrow$ ~ 5 GWd/t to 10 GWd/t (CANDU ~8 GWd/t)
  - Slightly enriched U $\rightarrow$ ~ 10 GWd/t to 30 GWd/t
  - Feasible to use recovered uranium / spent LWR fuel
    - Work in tandem with LWR's to maximize energy extraction.
    - Potential role for HWR's in GNEP

HWR Physics Characteristics

- PT D_2O reactors, some unique safety features
  - Multiple, independent shutdown systems feasible
    - Shutdown rods
    - Moderator poison injection (B10, Gd, etc.)
    - Low-pressure environment for moderator.
  - Longer reactor period gives time for shutdown to work
  - Multiple barriers
    - Fuel clad
    - Pressure Tube
    - Calandria Tube
  - Large heat sink to dissipate heat

HWR Physics Characteristics

- Power Density in Core
  - Factor in size/cost of reactor
    - How much concrete are you going to use?
  - Depends on enrichment, lattice pitch, coolant.
  - D_2O/H_2O cooled: ~ 9 to 12 kW/litre
    - (LWR ~ 50 to 100 kW/litre)
    - 15 to 20 kW/litre feasible with tighter lattice pitch (ACR)
  - Gas-cooled: ~ 1 to 4 kW/litre
    - 10 to 15 kW/litre feasible with high pressures (10 MPa)
  - Organics, Liquid Metal ~ 4 to 10 kW/litre
    - 10 to 15 kW/litre feasible

HWR Operational Characteristics

- Heat load to moderator
  - 5% to 6% of fission energy deposited
  - Gamma-heating, neutron slowing down.
- Thermal efficiencies (net)
  - Depends on choice of coolant, secondary cycle.
  - Typical: 28% to 31% for CANDU-type reactors.
    - Improved for larger, more modern plants.
    - Improvements in steam turbines, balance of plant.
  - 32% to 34% feasible for HWBLW-type reactors.
  - Gas, organic, liquid metal: 35% to 50% (stretch).
  - Economies of scale with larger plants.

Design Components (CANDU)

- Fuel / Bundles
  - UO_2 clad in Zircaloy-4; collapsed cladding.
  - Graphite interlayer (CANLUB) to improve durability.
  - Brazed spacers, bearing pads, appendages
    - Maintain element separation; enhance cooling
  - Alternatives
    - Fuel: UC, U_3Si
    - Clad: SAP (organics) or stainless steel (gas, liquid metal, SC H_2O)
- Pressure Tubes
  - Zr-2.5%Nb alloy (corrosion, toughness, strength)
- Calandria Tubes
  - Zircaloy-2
- Feeders/Headers
  - Stainless steel (special mechanical joints with PT)

Control Devices

- Control rods (stainless steel – SS, etc.)
- Shutdown rods (B_4C, Cd/Ag/In, SS/Cd, etc.)
- Adjusters (flatten flux shape) – Cobalt, SS
- Zone controllers
  - Tubes with liquid H_2O used to adjust local reactivity.
- Moderator poison options
  - Boric acid for long-term reactivity changes
  - Gadolinium nitrate injection for fast shutdown
  - $CdSO_4$
- Moderator level
  - Additional means for reactivity control
- Moderator dump tank
  - Initial designs; not used in later

HWR (CANDU) Features

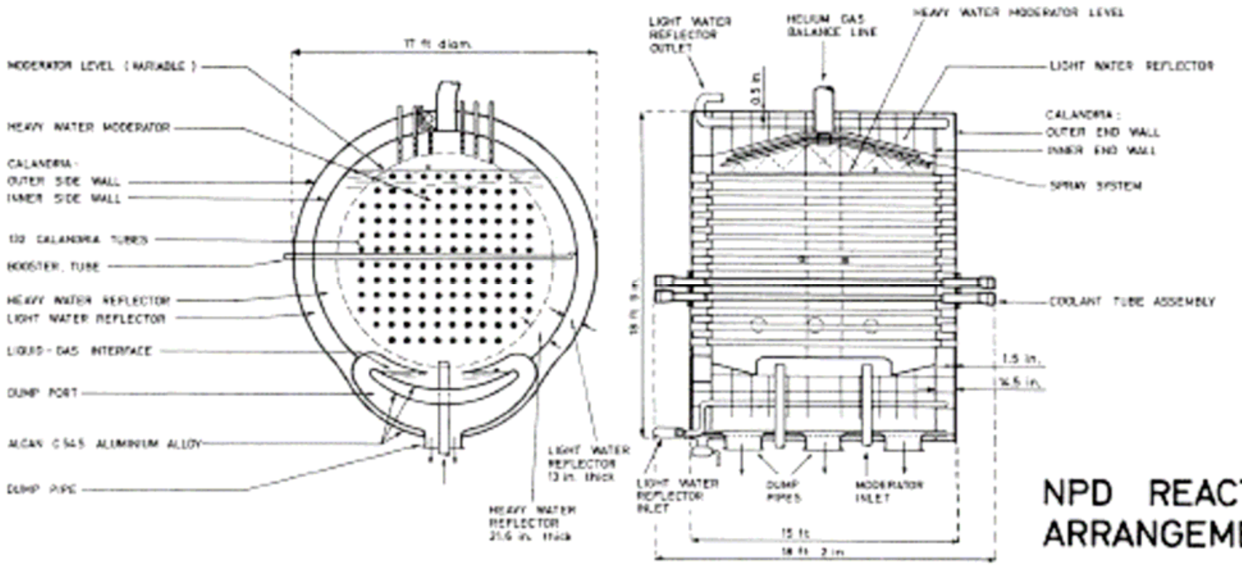
- Excellent neutron economy.
  - High conversion ratios.
  - Operate on natural uranium
  - High fuel utilization; conservation of resources.
- On-line refuelling.
  - Low excess reactivity.
  - Higher fuel burnup for a given enrichment.
  - High capacity factors (0.8 to 0.95)
- Modular construction
  - Pressure tubes; replaceable
  - Local fabrication

NPD-2 (Canada)

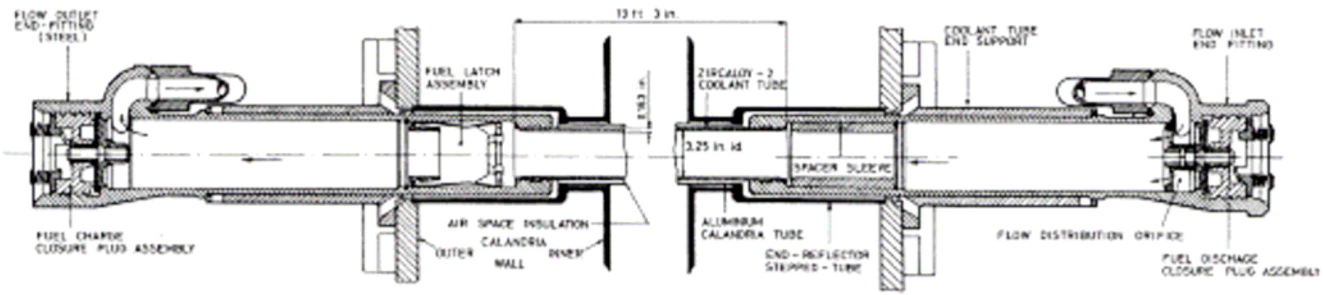
- Operated 1962-1985; shutdown 1987.
- 89 MW_{th} / 19 MW_e (21.7% efficiency)
- World's first HWR to produce electricity.
- Pressure tubes, on-line refuelling.
- Short (0.5-m) natural-uranium fuel bundles.
- Test bed for CANDU technologies.
  - Demonstration of feasibility of PHWR concept.
  - Debugging D_2O leakage, trips, reactivity control
  - Fuel performance, alternative designs.
- Training center for operations.
  - Experience for later CANDU designs

NPD-2 (Canada)

- 132 PT’s Zr-2
- 26-cm pitch
- Control
  - – Mod. Level
  - – Mod. Dump
  - – Booster rod



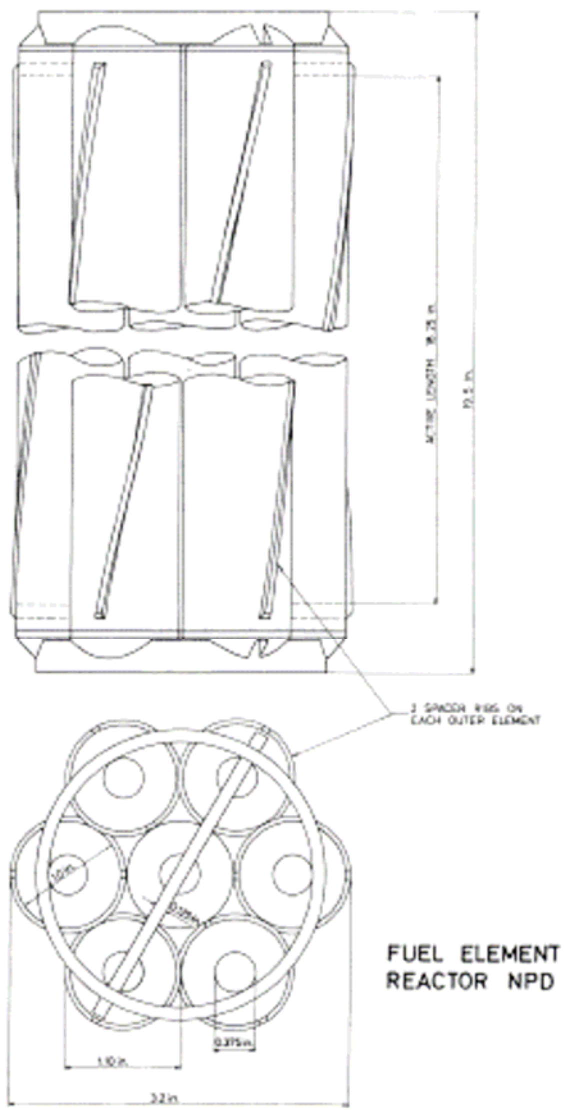
NPD REACTOR ARRANGEMENT



COOLANT TUBE ASSEMBLY

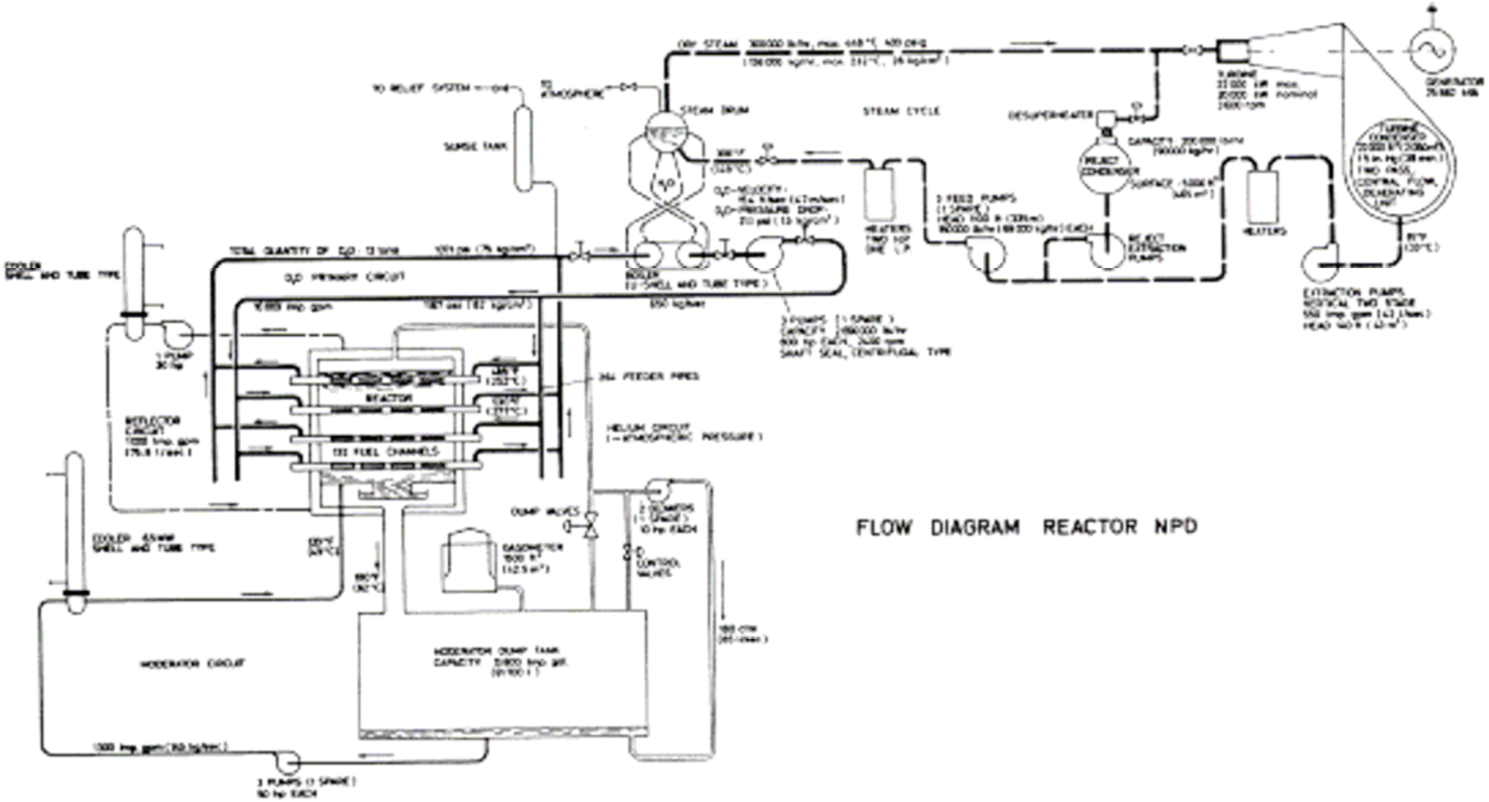
NPD-2 (Canada)

- 0.5-metre bundles
- 7 elements, wire-wrap
- Natural UO_2, Zr-2 clad
- C=0.8
- 7,300 MWd/t burnup



NPD-2 (Canada)

- 2.6 kW/litre, 7.9 MPa, 277°C
- Steam at 2.7 MPa, 232°C

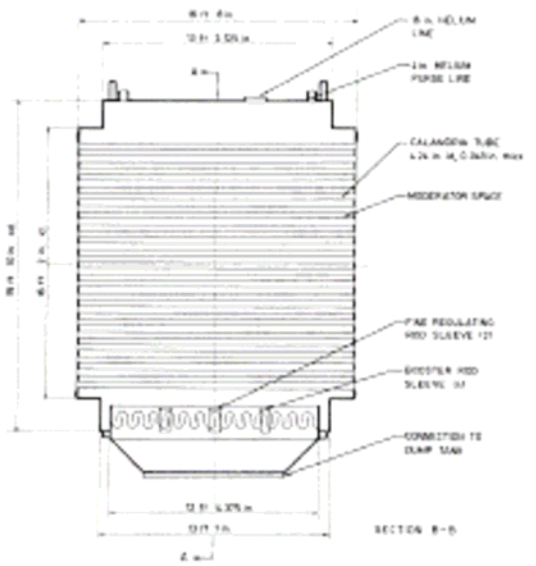


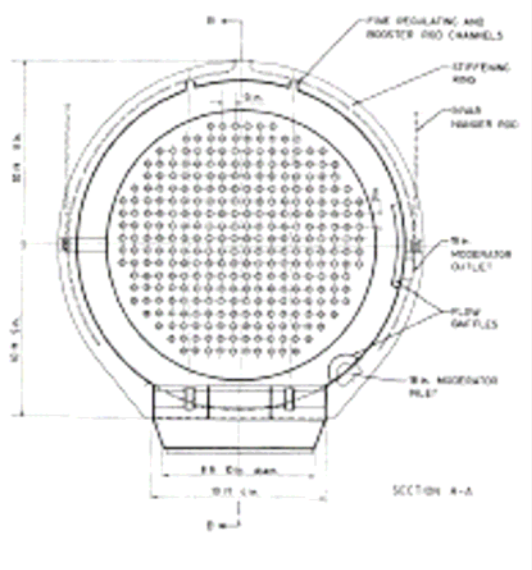
Douglas Point (Canada)

- Prototype for commercial PHWR
  - CANadian Deuterium Uranium (CANDU)
  - Lessons learned from NPD-2.
  - Construction/commissioning (1961-1967)
  - Operated 1968-1984
  - Larger-scale test bed for equipment and operations.
    - Debugging HW leaks.
- 693 MW_{th} / 200 MW_e, 29%, 4.77 kW/litre
- D_2O Coolant at 9.9 MPa, 293°C
- Steam generators / drums
  - Steam at 4.1 MPa, 250°C

Douglas Point

- 306 Pressure Tubes, Zr-2, 8.3 cm id
- 22.86-cm lattice pitch
- Control
  - CdSO$_4$; mod. level, dump; booster rods, adjusters

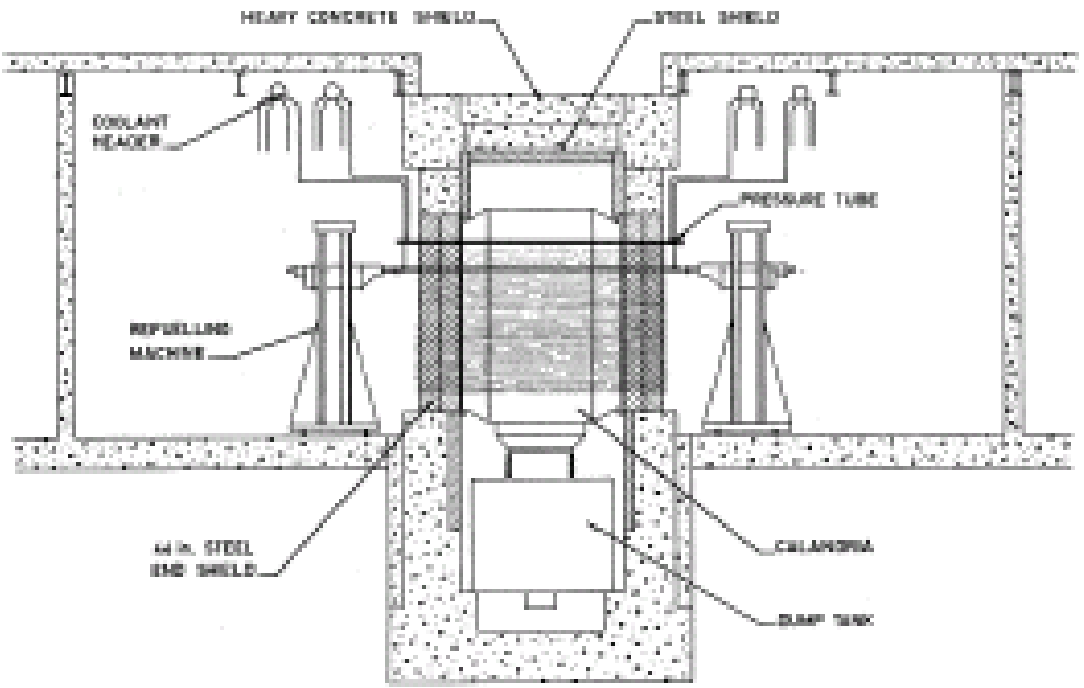




REACTOR CANDU

Douglas Point (Canada)

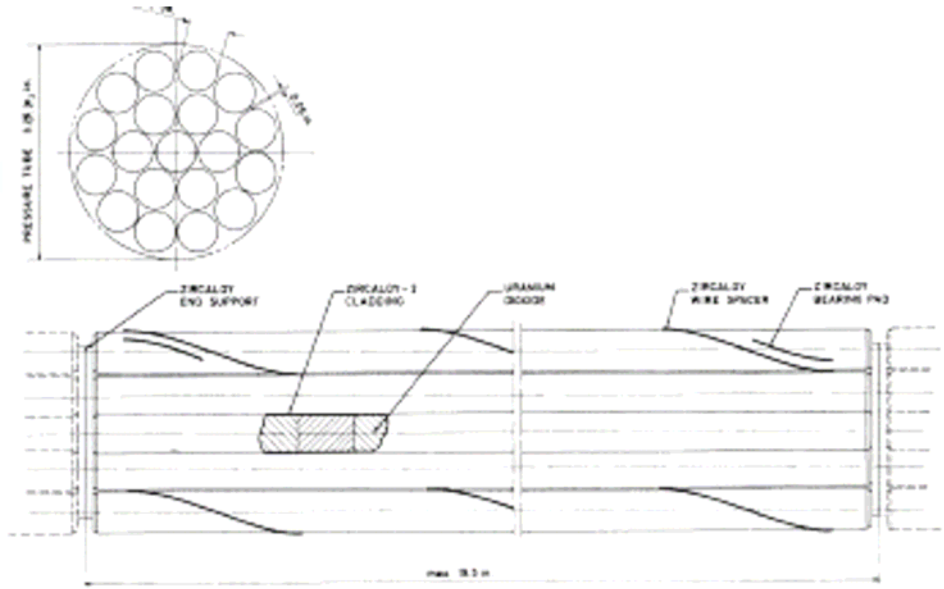
- On-line refuelling
  - 5 bundles per day, 2 per shift, 9-hour intervals



REACTOR VAULT

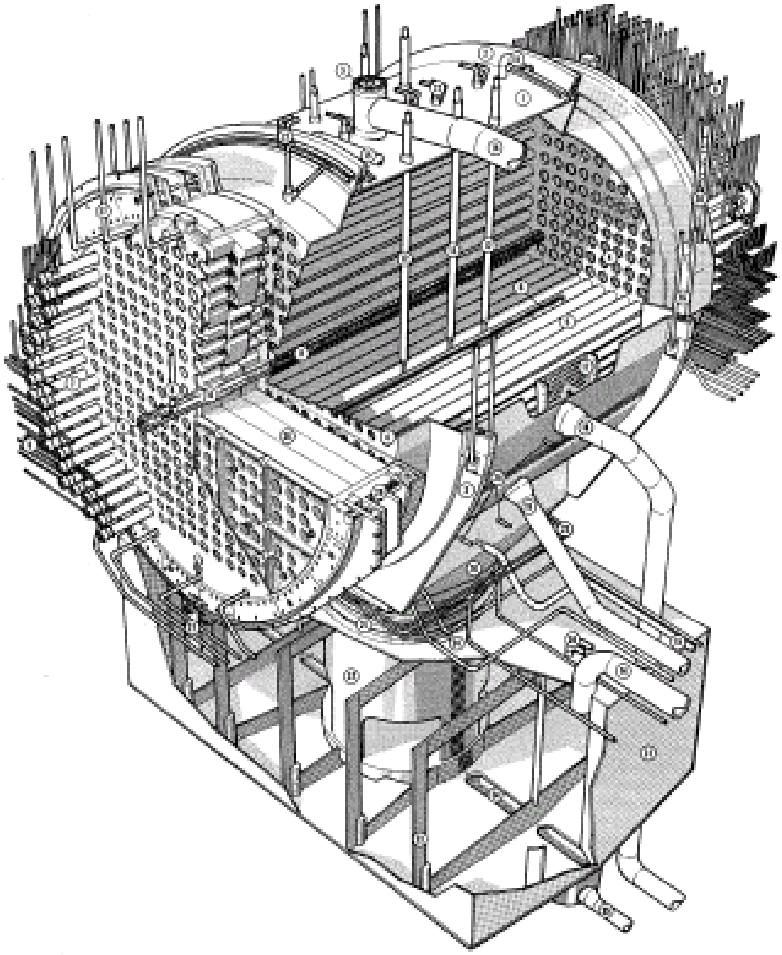
Douglas Point

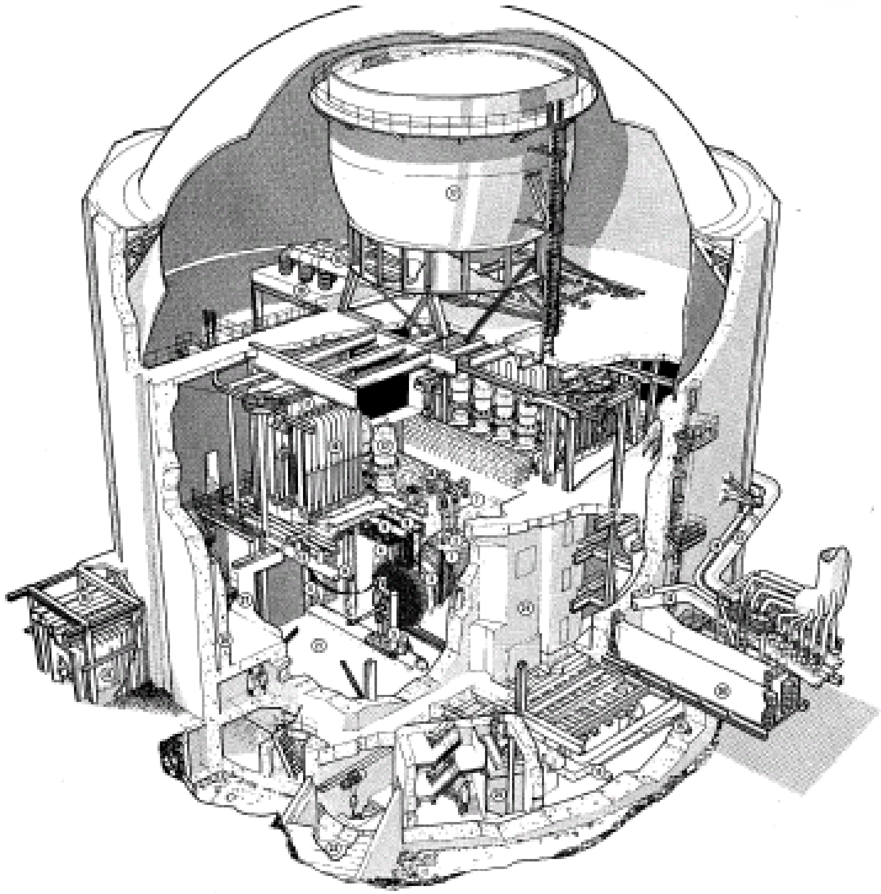
- **19-element bundles (12 per channel)**
  - **Natural UO_2, Zr-2 clad, wire-wraps, 0.5-m long**
- **~9,750 MWd/t burnup**
  - **Larger fuel pins, C=0.72**



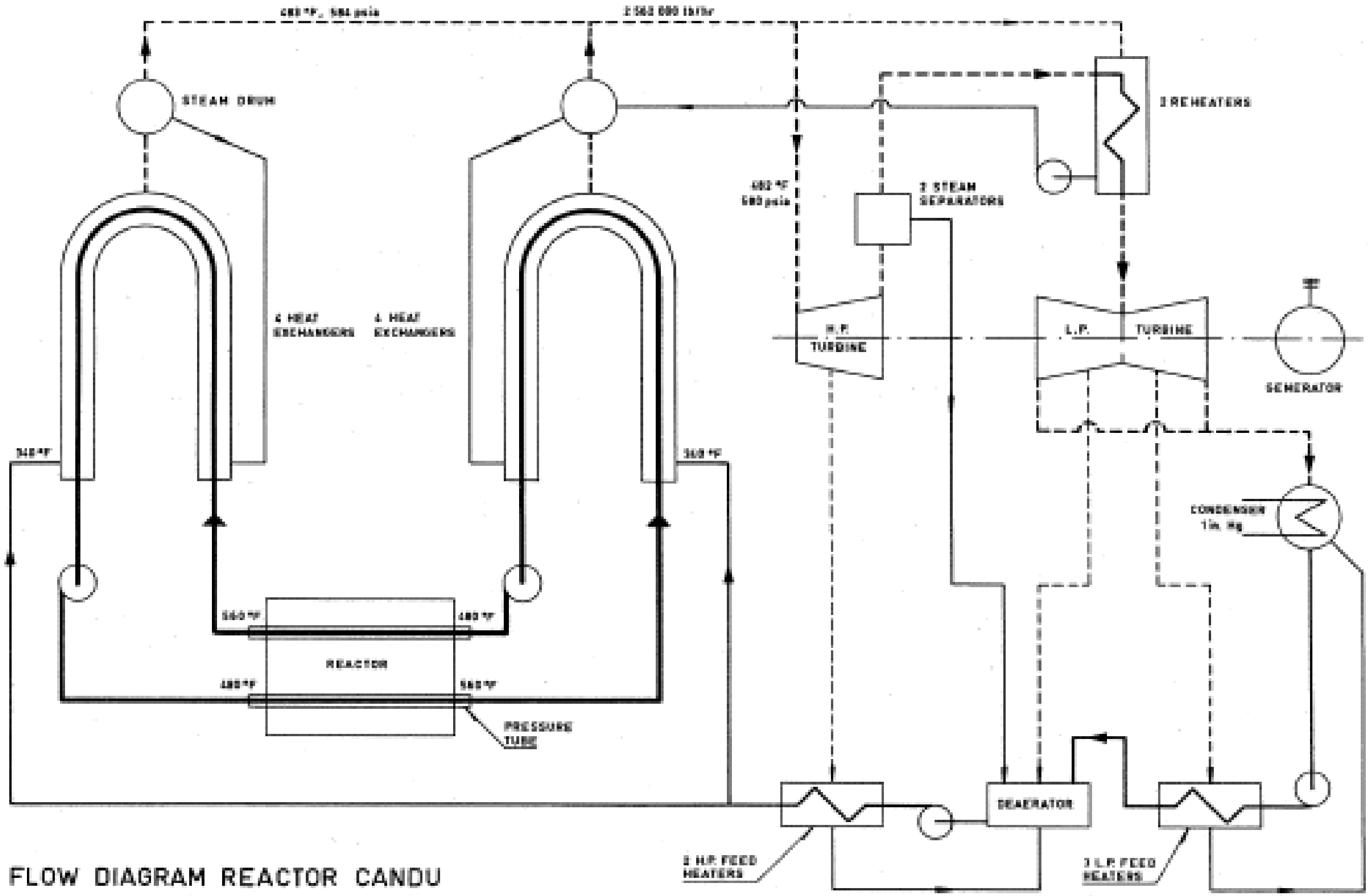
FUEL ELEMENT REACTOR CANDU

Douglas Point



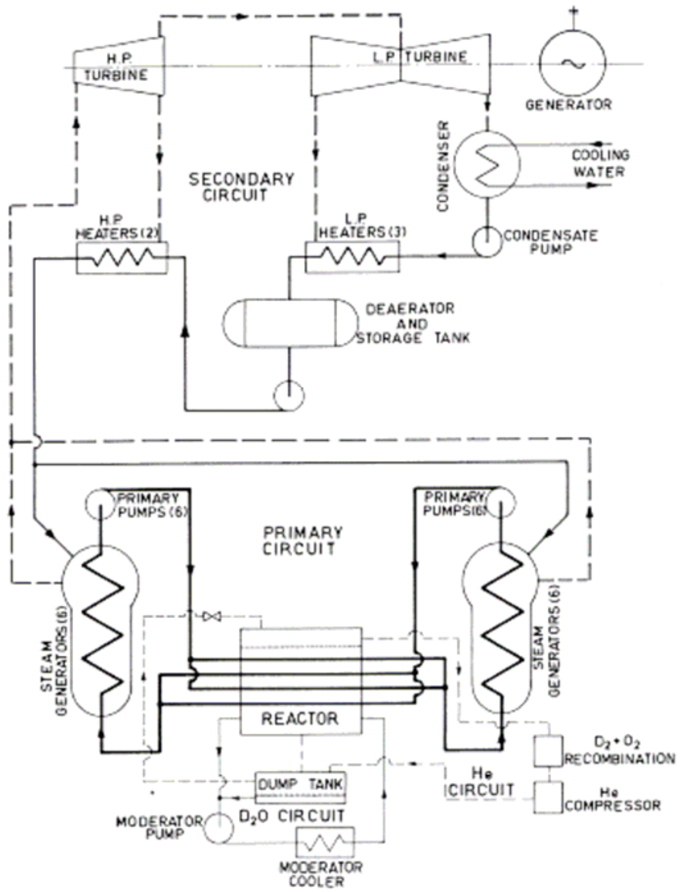


Douglas Point (Canada)



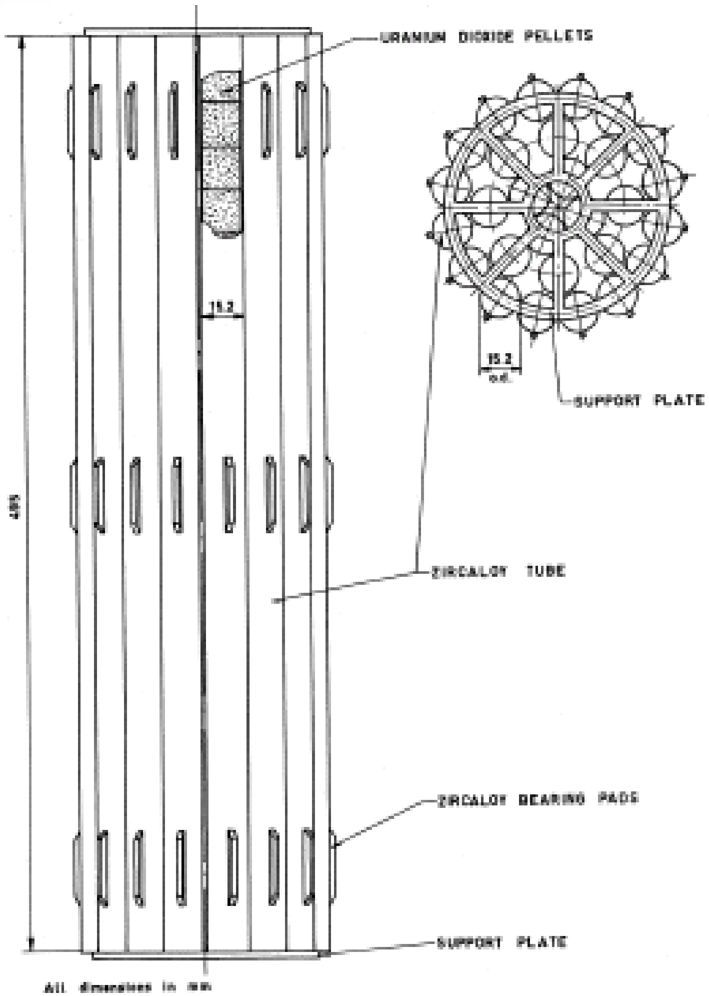
Pickering

- Multi-unit station
  - Scale up Douglas Point
- 390 pressure tubes
- 28-element fuel
  - Natural uranium; larger pins.
  - C~0.82
  - 8,000 to 9,000 MWd/t burnup
- Pickering A (1971-1973)
  - 4x515 MW_e
  - First commercial reactors.
- Pickering B (1982-1986)
  - 4x516 MW_e (1982-1986)

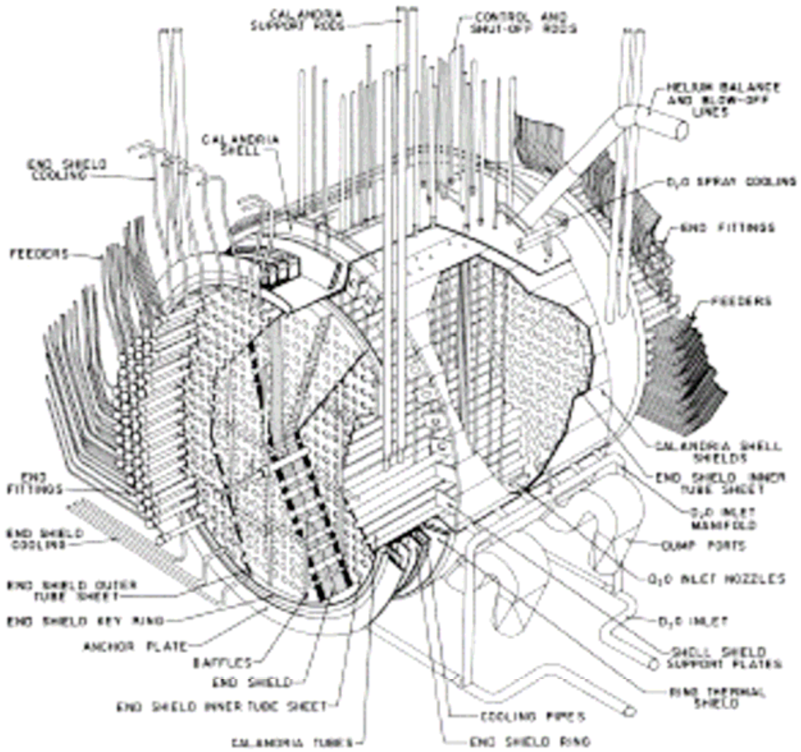


FLOW DIAGRAM REACTOR PICKERING

Pickering



FUEL BUNDLE REACTOR PICKERING



ISOMETRIC VIEW REACTOR PICKERING

Bruce / Darlington CANDU's

- **Multi-unit stations**
  - Single vacuum building; shared equipment.
  - Bruce A (1976-1979): 4 x 740 MW_e (upped to 840 MW_e)
  - Bruce B (1984-1987): 4 x 750 MW_e (upped to 860 MW_e)
  - Darlington (1990-1993): 4 x 881 MW_e (net)
- **480 Pressure Tubes, 12-13 bundles / channel**
- **37-element natural uranium fuel bundles (0.5-m)**
  - Fuel pins smaller than
    - 7-rod (NPD-2), 19-rod (Douglas Point), 28-rod (Pickering)
    - Enhanced heat transfer; higher bundle powers
  - ~7,500 MWd/t to 9,000 MWd/t burnup
    - Reduced resonance shielding with smaller pins, but,
    - Larger core with reduced neutron leakage.

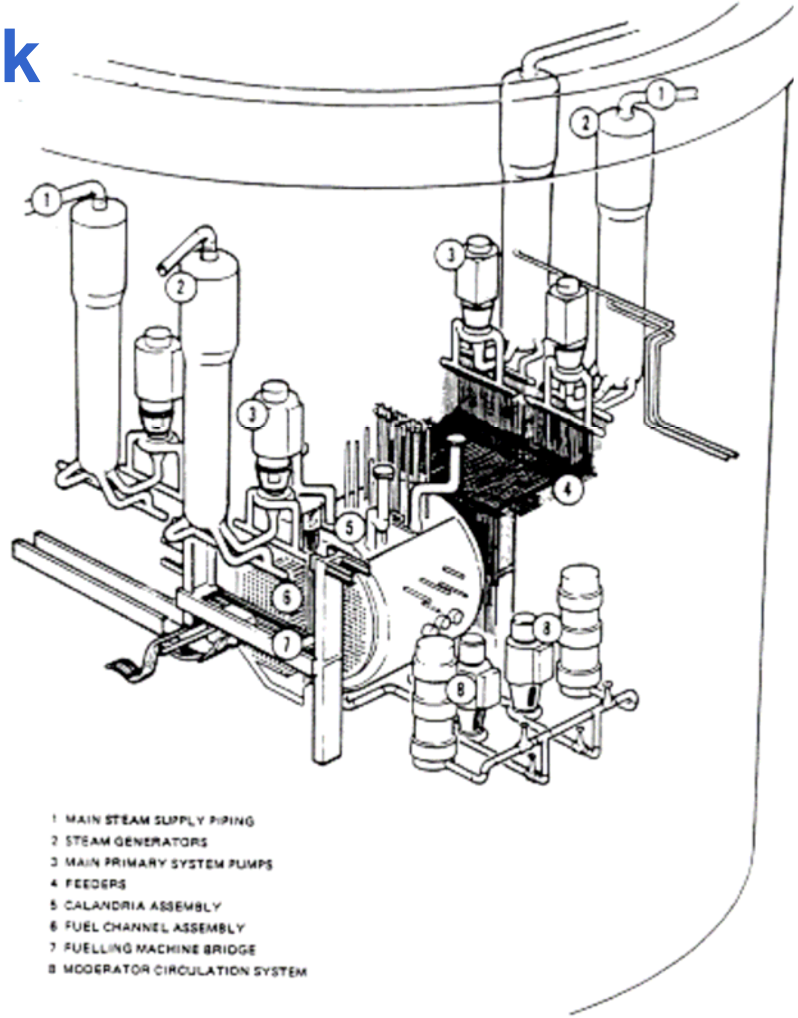
Bruce / Darlington CANDU's

- **840 MW$_e$ to 881 MW$_e$**

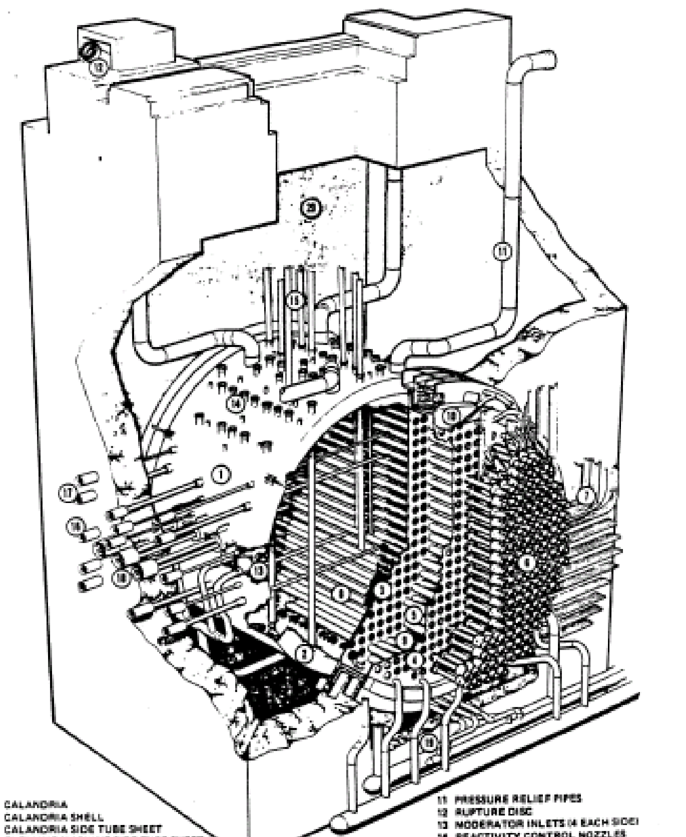
A comparison of principal CANDU Heat Transport System Parameters			Heat Transport System Conditions					Heat Transport Pumps			Steam Generators		
CANDU 6 Operating stations or under construction	Electrical Output (MW) Gross/Net	Number of Fuel Channels	Elements in Fuel Bundle	Number of Loops	Outlet header Pressure (MPa)	Maximum Channel Flow (kg/s)	Outlet Header Quality (%)	Total	Operating	Motor Rating (kW)	Area (m^2) per Steam Generator	Integral Preheater	Steam Pressure (MPa)
Point Lepreau,	680/633	380	37	2	10.0	24	4	4	4	6700	3200	Yes	4.7
Gentilly 2	675/638	380	37	2	10.0	24	4	4	4	6700	3200	Yes	4.7
Wolsong 1	678/638	380	37	2	10.0	24	4	4	4	6700	3200	Yes	4.7
Embalse	648/600	380	37	2	10.0	24	4	4	4	6700	2800	Yes	4.7
Cernavoda 1, 2	710/665	380	37	2	10.0	24	4	4	4	6700	3200	Yes	4.7
Wolsong 2, 3, 4	715/668	380	37	2	10.0	24	4	4	4	6700	3200	Yes	4.7
Qinshan 1, 2	728/668	380	37	2	10.0	24	4	4	4	6700	3200	Yes	4.7
Other CANDU operating stations													
Pickering A 4 Units	542/515	390	28	2	8.7	23	-	16	12	1420	1850	Yes	4.1
Bruce A 4 Units	904/840	480	37	1	9.1	24	<1	4	4	8200	2400	No	4.4
Pickering B 4 Units	540/516	390	28	2	8.7	23	-	16	12	1420	1850	Yes	4.1
Bruce B 4 Units	915/860	480	37	1	9.1	24	<1	4	4	8200	2400	No	4.7
Darlington 4 Units	936/881	480	37	2	10.0	25	2	4	4	9600	4900	Yes	5.1

CANDU-6

- Single-unit Stations
- Operations / Design Feedback
  - Pickering, Bruce
- Domestic
  - Point Lepreau, Gentilly-2
- International
  - Korea, Argentina, Romania, China

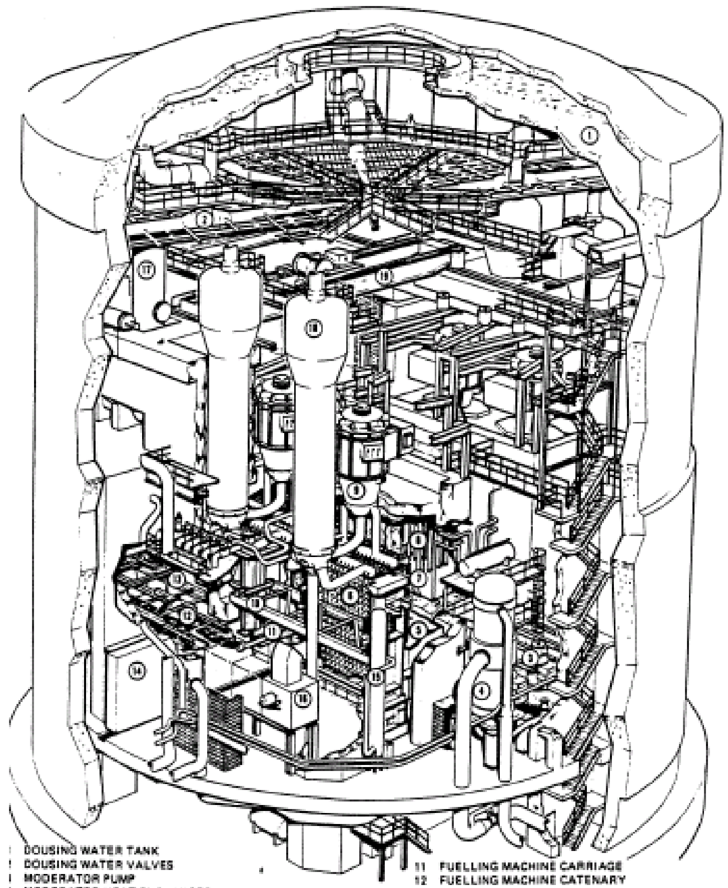


CANDU-6



1 CALANDRIA
2 CALANDRIA SHELL
3 CALANDRIA SIDE TUBE SHEET
4 FUELLING MACHINE SIDE TUBE SHEET
5 LATTICE TUBES
6 END FITTINGS
7 FEEDERS
8 CALANDRIA TUBES
9 STEEL BALL SHIELDING
10 ANNULAR SHIELDING SLAB
11 PRESSURE RELIEF PIPES
12 RUPTURE DISC
13 MODERATOR INLETS (4 EACH SIDE)
14 REACTIVITY CONTROL NOZZLES
15 REACTIVITY CONTROL DEVICES
16 HORIZONTAL FLUX DETECTORS (9)
17 POISON INJECTOR NOZZLES (6)
18 ION CHAMBER HOUSING (3 EACH SIDE)
19 END SHIELD COOLING PIPING
20 CALANDRIA VAULT (LIGHT WATER SHIE'

FIGURE 2.1-1 REACTOR ASSEMBLY

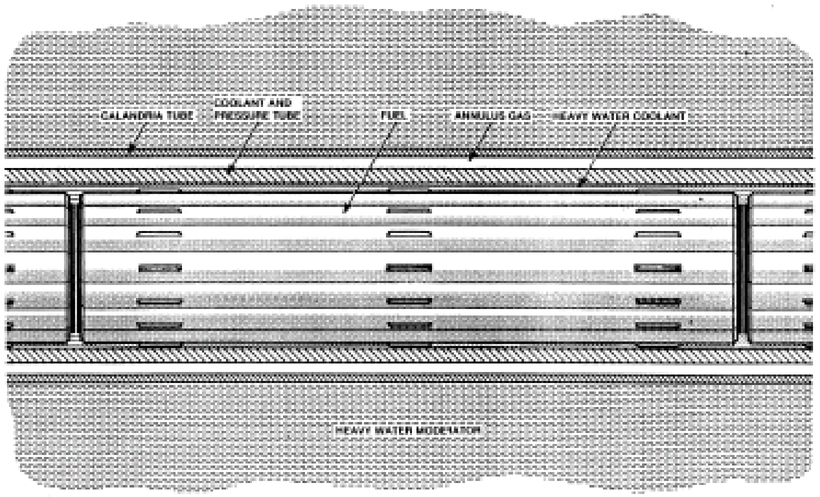


DOUSING WATER TANK
DOUSING WATER VALVES
MODERATOR PUMP
MODERATOR HEAT EXCHANGER
FEEDER CABINETS
REACTOR FACE
REACTOR
REACTIVITY MECHANISM
HEAT TRANSPORT SYSTEM PUMP
FUELLING MACHINE BRIDGE
11 FUELLING MACHINE CARRIAGE
12 FUELLING MACHINE CATENARY
13 FUELLING MACHINE MAINTENANCE LOCK
14 FUELLING MACHINE MAINTENANCE LOCK DOOR
15 END SHIELD COOLING WATER DELAY TANK
16 VAULT COOLER
17 PRESSURIZER
18 STEAM GENERATOR
19 STEAM GENERATOR ROOM CRANE

FIGURE 1.3-5 600 MW(e) REACTOR BUILDING CUTAWAY

CANDU-6

- **37-element fuel**
  - 28.58-cm square pitch
  - same as Bruce/Darlington
- **~7,500 MWd/t burnup**



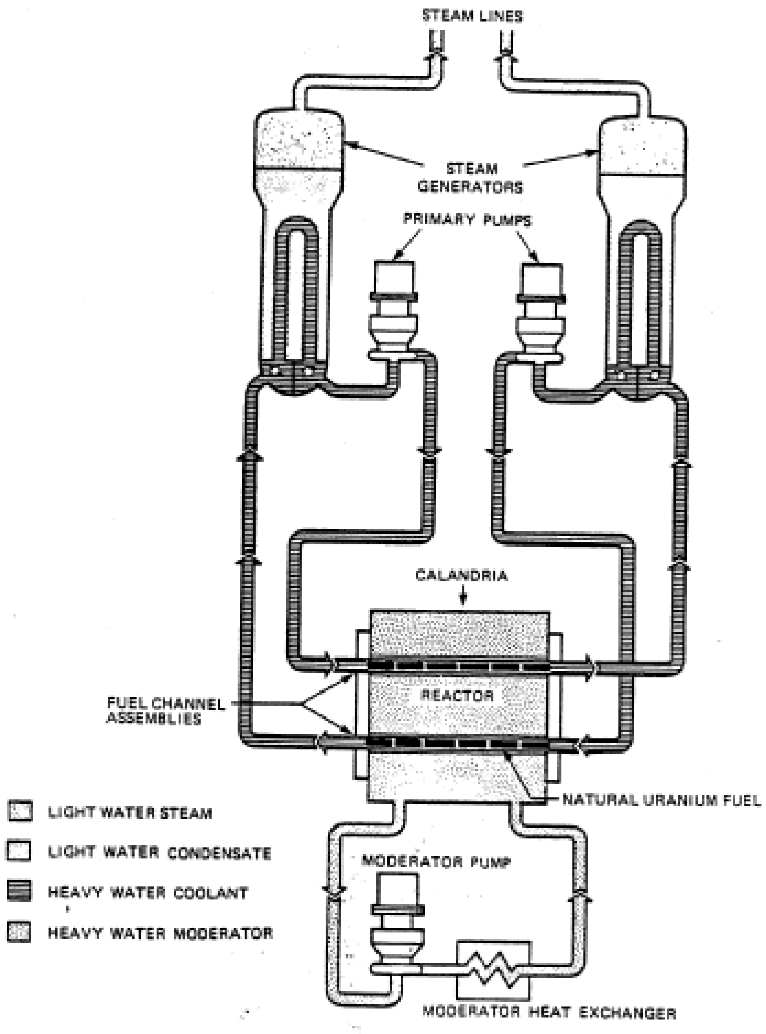


FIGURE 2.2.1 CANDU NUCLEAR STEAM SUPPLY SYSTEM

CANDU-6

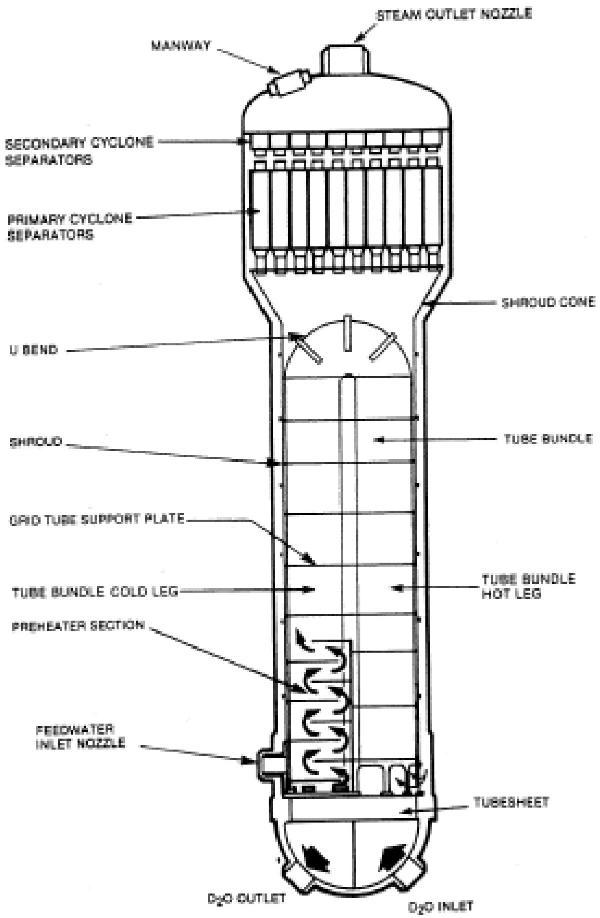


FIGURE 2.2-8 CANDU STEAM GENERATOR

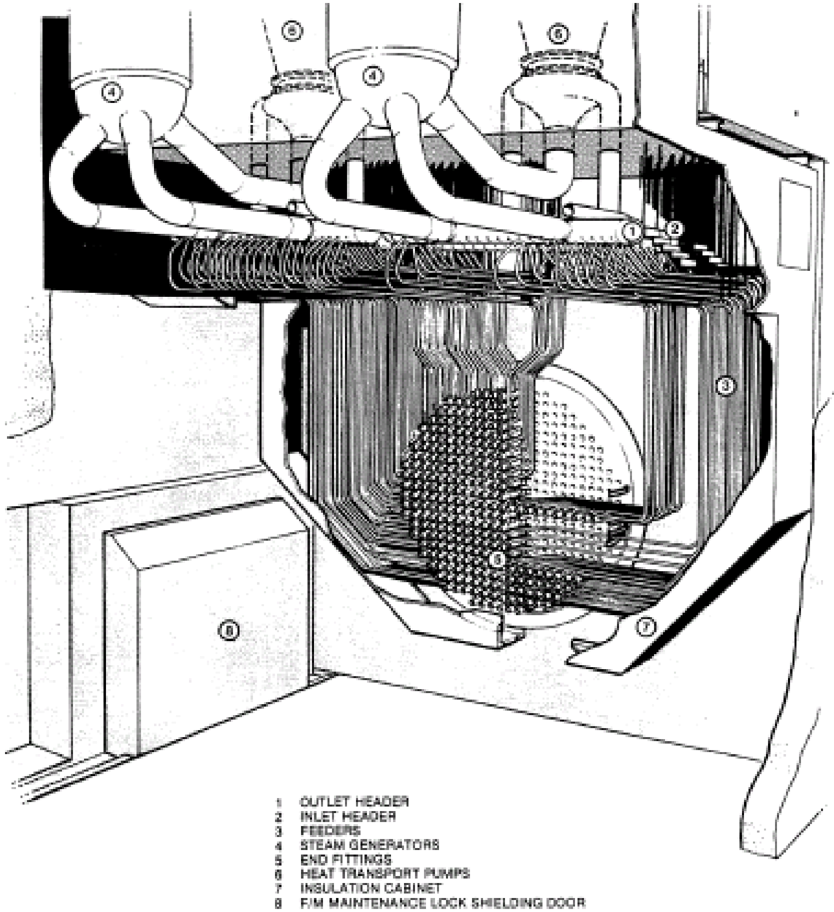


FIGURE 2.2-7 FEEDER AND HEADER ARRANGEMENT

CANDU-6

- **Flux Detectors**
  - Vertical / Horizontal
  - Vanadium, Inconel / platinum.
- **Adjuster Rods**
- **Shutoff Rods**
- **Solid Control Absorber**
- **Liquid Zone Controller**
  - H_2O

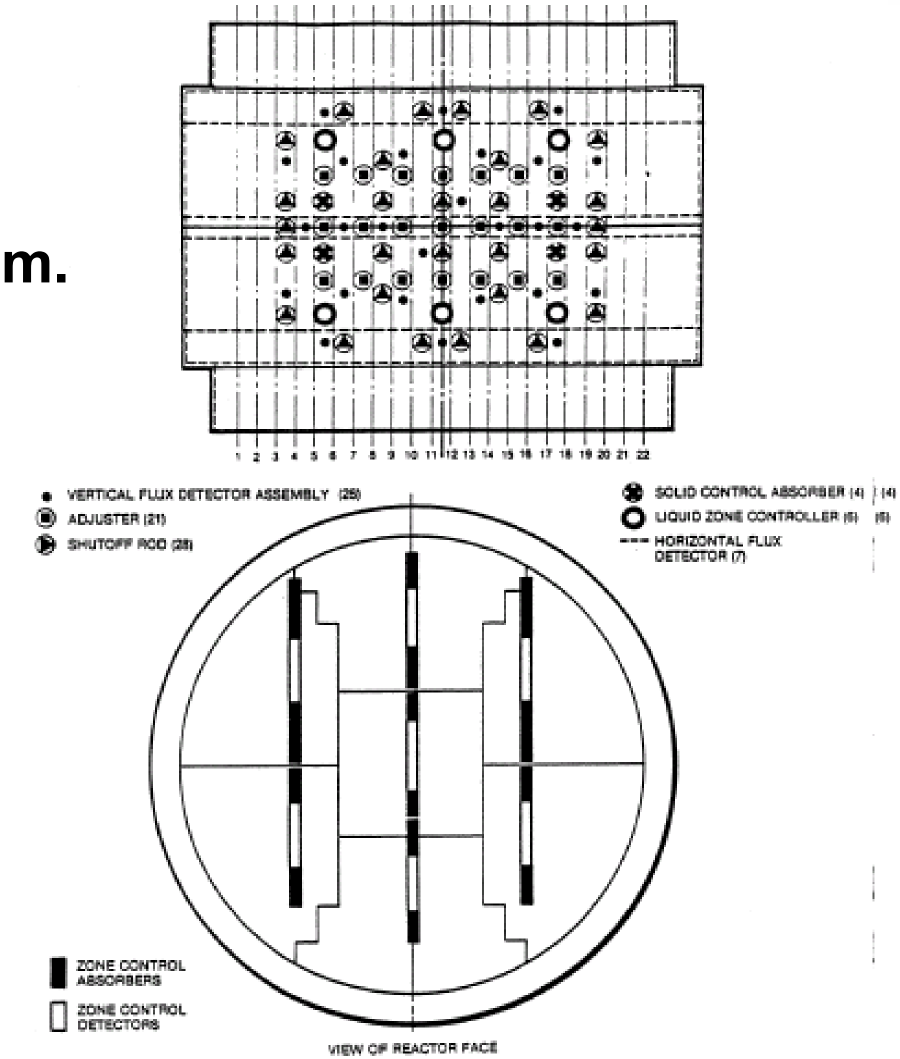


FIGURE 2.4-2 REACTIVITY MECHANISM LAYOUT

CANDU-6

- Shutdown System (SDS1 and SDS2)
- Shutoff Rods
- Poison Injection
- Gd, Boron
- Redundancy
- Independent

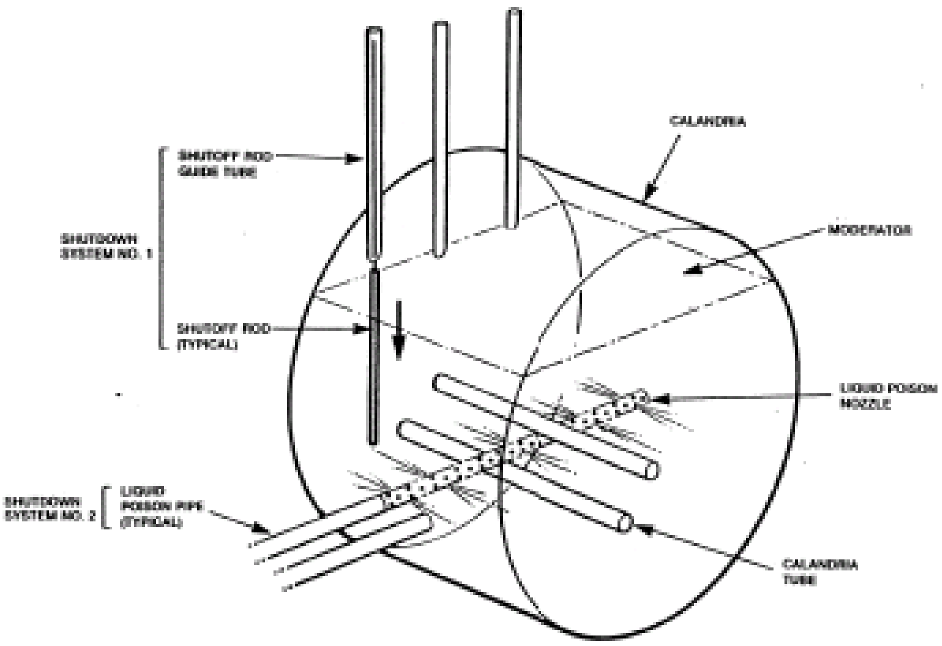
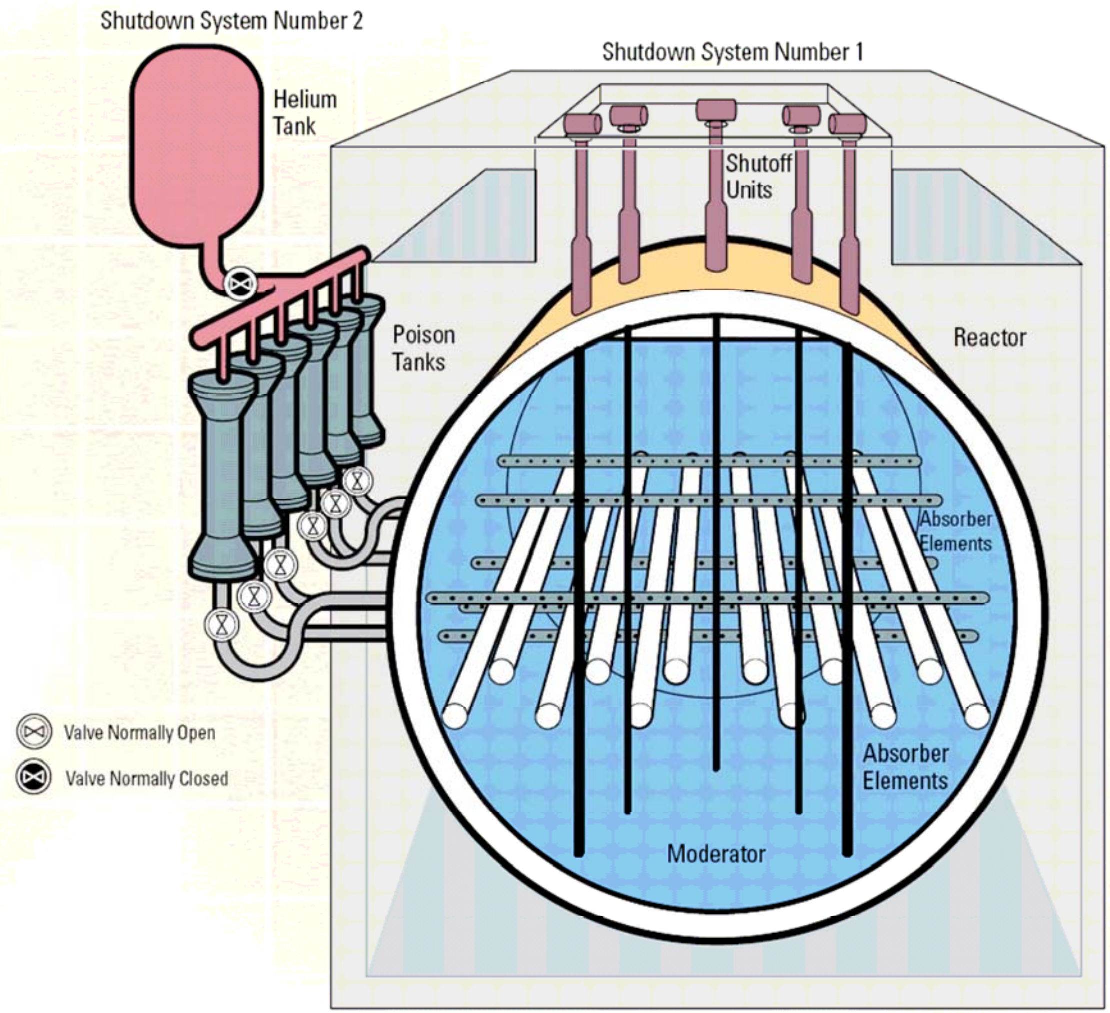


FIGURE 4.3-5 SHUTDOWN SYSTEMS: SHUTOFF RODS AND LIQUID "POISON" INJECTION

CANDU-6

- **SDS1**
  - Mechanical Rods
- **SDS2**
  - Poison injection.
  - Gadolinium
  - Boron



CANDU-6

- 2 fuelling machines
- charge/discharge
- 8-bundle shift
- 12 bundle string
- 8 new bundles
- 4 old bundles moved
- end plugs replaced

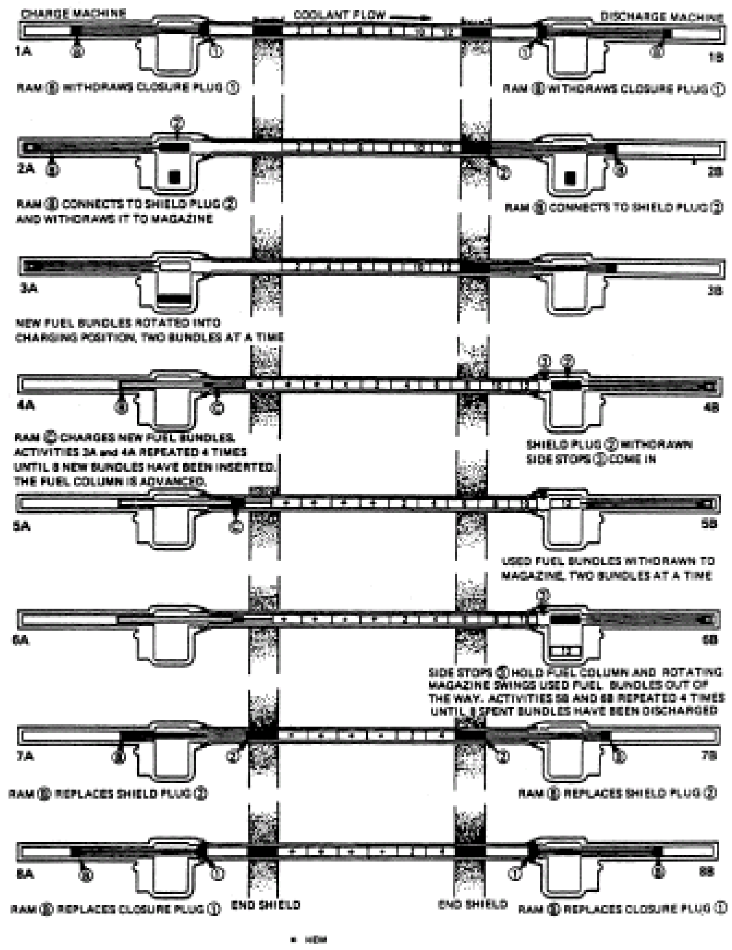
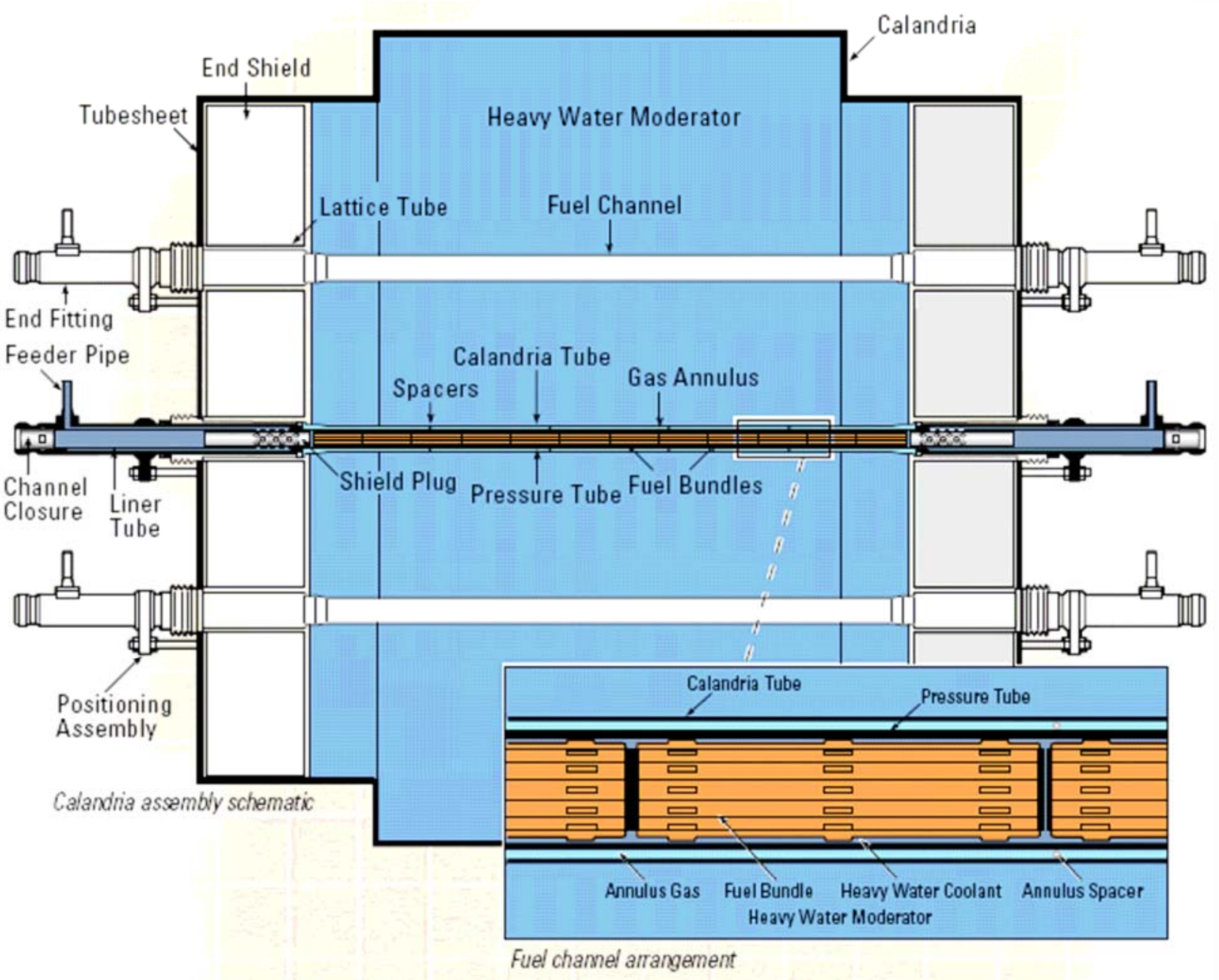


FIGURE 5.0-2 8-BUNDLE CHANGING SEQUENCE IN A CANDU 600 MW(e) PHWR

CANDU-6

- **Core fuelling.**



Calandria assembly schematic

Fuel channel arrangement

CANDU-6 Performance

- **High capacity factors (up to 93% average)**

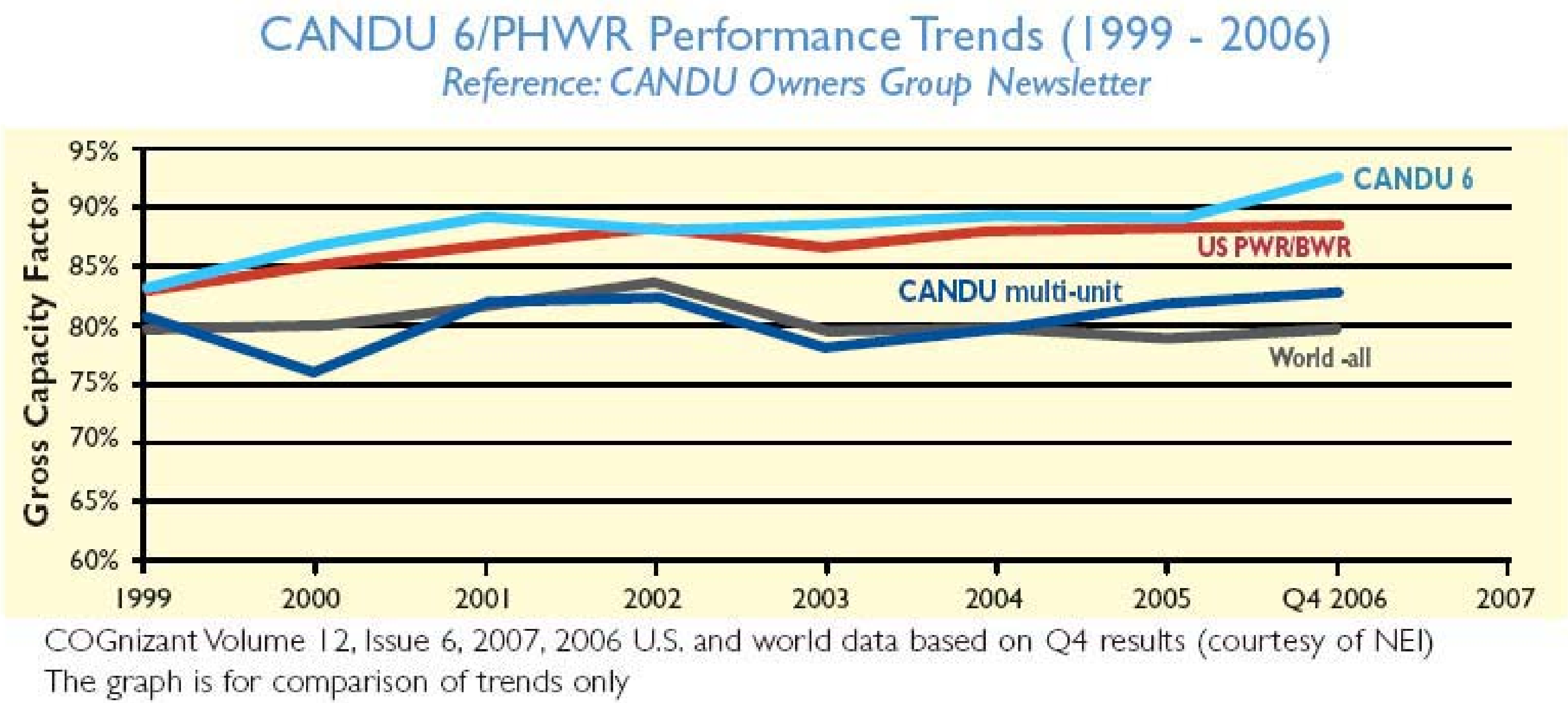


Figure 5-1 Comparison of Gross Capacity Factors

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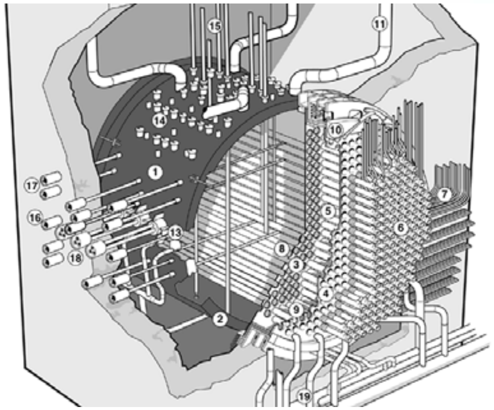
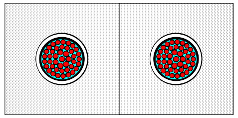
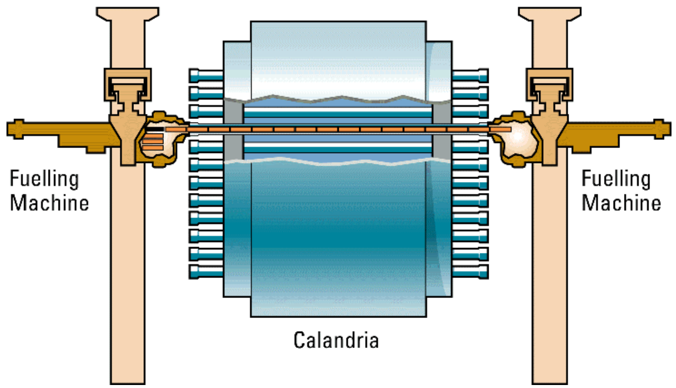
CANDU Reactor Technology

- D_2O Moderator (~70°C, low pressure) in calandria.
- D_2O Coolant (~10 MPa, 250°C – 310°C)
- Pressure Tubes, Calandria Tubes
- 28.58-cm square lattice pitch
- Natural uranium fuel (UO_2) in bundles
  - 37-element (CANDU-6, Bruce, Darlington)
  - 28-element (Pickering)
- Burnup ~ 7,500 MWd/t (nominal).
  - 8,000 to 9,000 MWd/t for larger cores.
- On-Line Refueling (8 to 12 bundles per day)
- Two independent shutdown systems.
  - SDS1 (shutoff rods), SDS2 (poison injection).

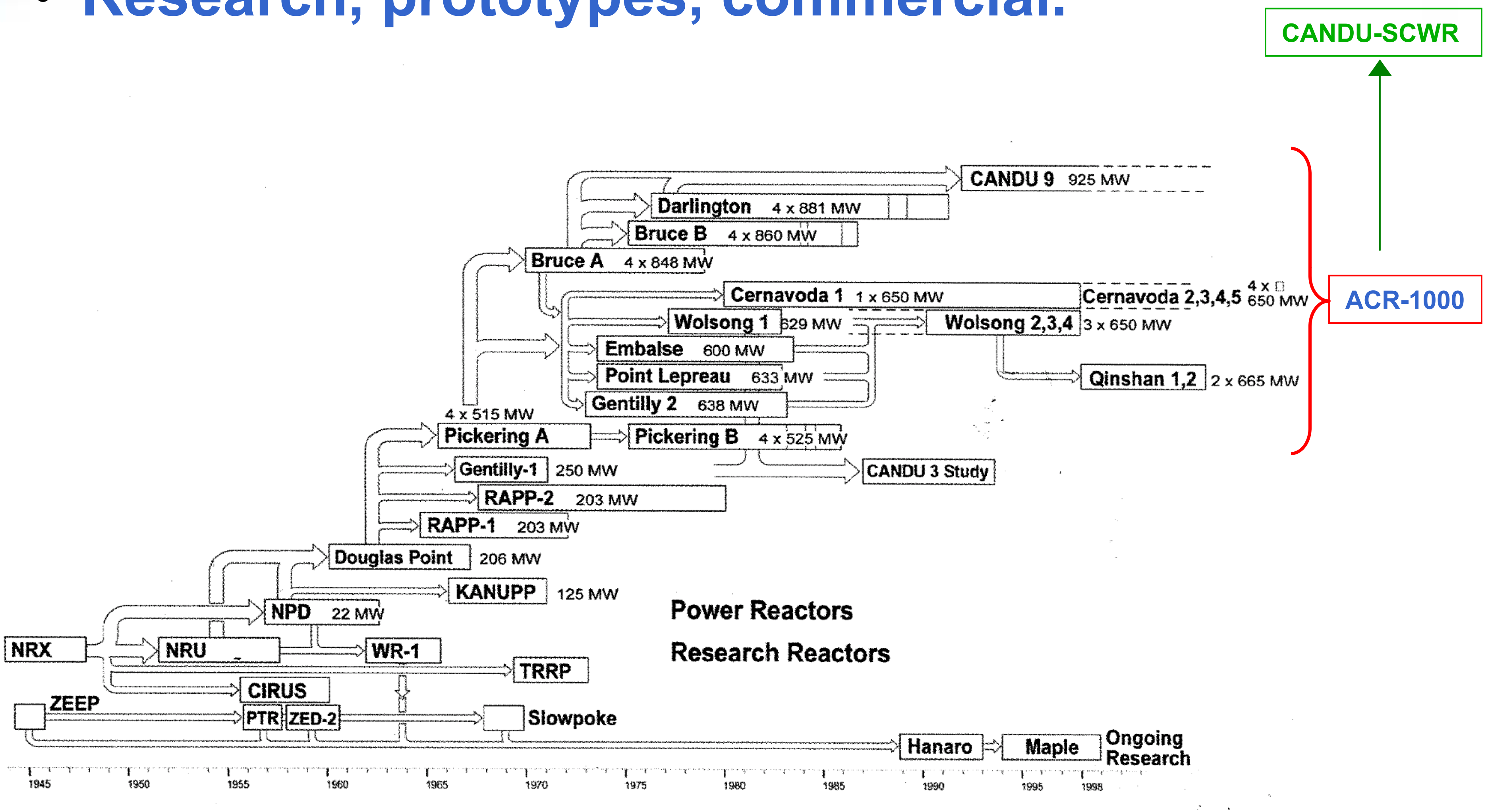






CANDU Evolution

- Research, prototypes, commercial.



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ACR-1000 (Gen III+)

- Advanced CANDU Reactor
  - Base on CANDU-6 design features
    - Pressure tubes
    - Heavy water moderator
    - Short fuel bundles – online refueling.
    - Multiple shutdown systems.
    - Balance-of-plant similar, but higher steam P, T.
  - 3187 MW_{th} / 1085 MW_e (net)
    - Higher coolant pressure/temperatures
    - 34% net efficiency.

ACR-1000

- **Special features**
  - **Light water coolant (11 MPa, 319°C)**
    - **Reduced capital costs.**
  - **CANFLEX-ACR Fuel Bundle**
    - **43-element design; enhanced heat transfer.**
    - **Enriched fuel (2 wt% to 3 wt%), central absorbing pin (Dy).**
    - **20,000 MWd/t burnup (nominal), extend with experience.**
  - **Tighter lattice pitch; larger calandria tubes.**
    - **More compact core; smaller reactor.**
    - **Negative coolant void reactivity.**
- **Modular construction, competitive design**
  - **Lower capital costs.**
  - **Local fabrication of components.**
  - **Economical electricity.**

ACR-1000

Plant Layout

Figure 2-2 Reactor Building

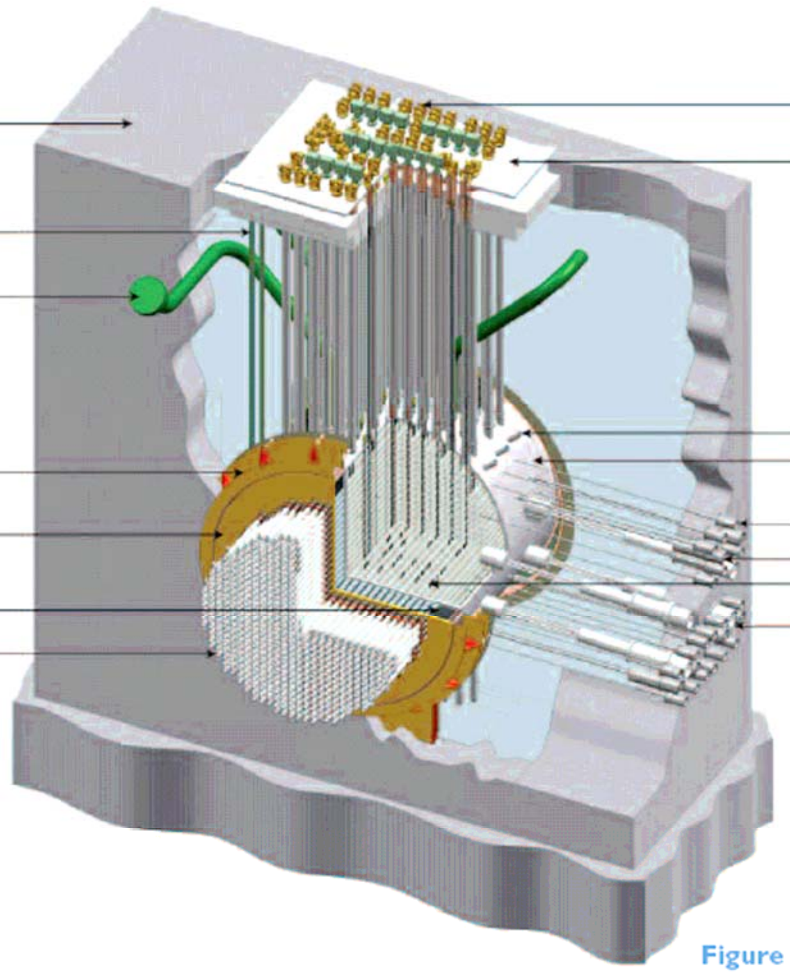


Figure 2-11 Reactor Assembly

ACR-1000

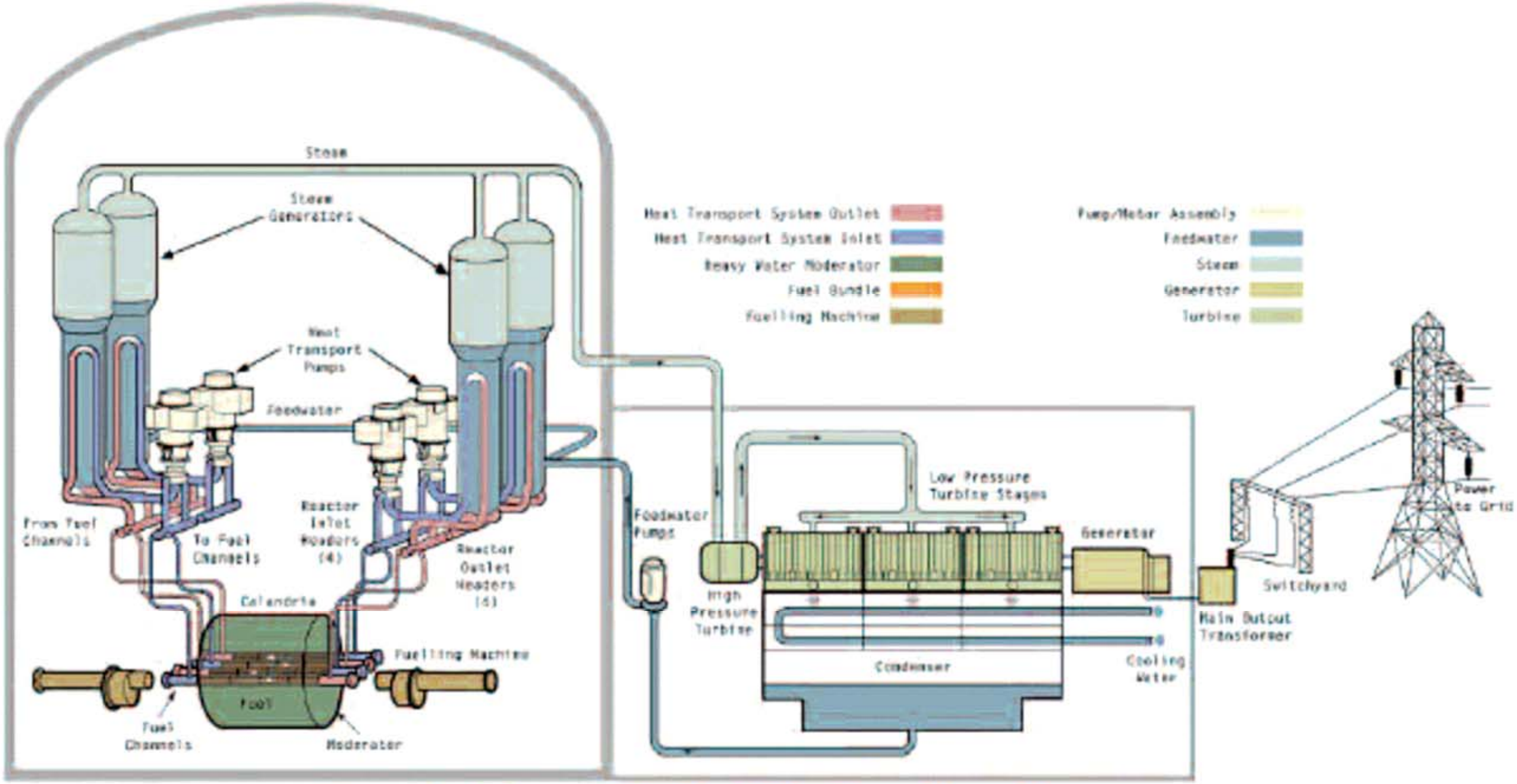


Figure 1-1 Overall ACR-1000 Plant Flow Diagram

ACR-1000

- **Heat Transport System**

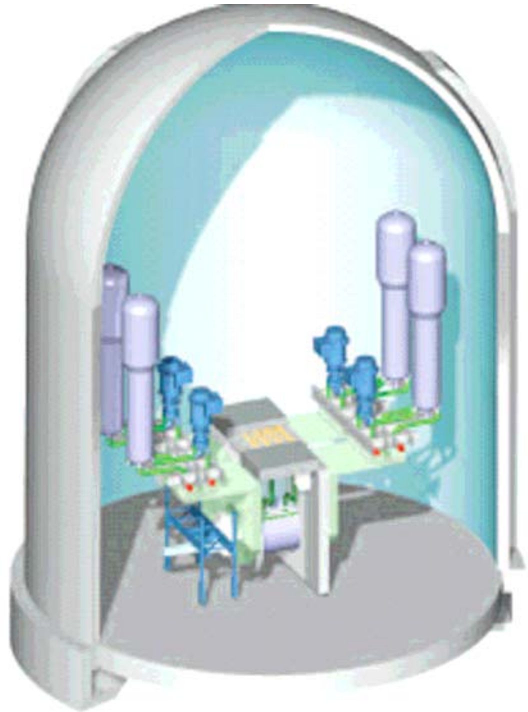


Figure 2-6 3D View of Heat Transport System in Reactor Building

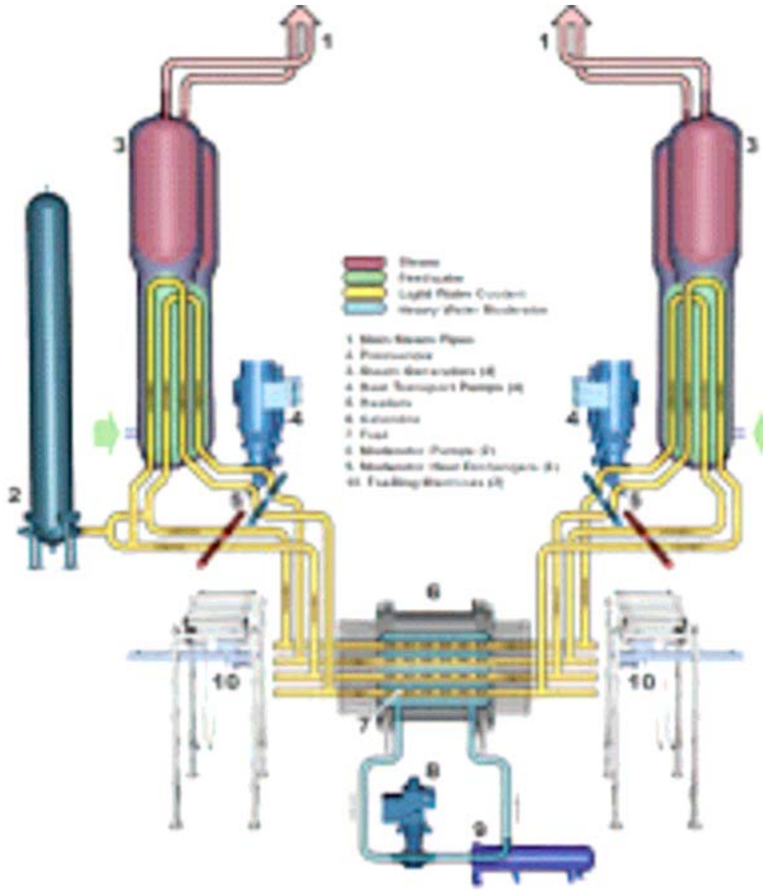


Figure 2-3 Nuclear Systems Schematic

ACR-1000

- **Comparison with CANDU-6, Darlington**

Table 2- 5 Reactor Core Design Data

	CANDU 6	Darlington	ACR-1000
Reactor			
Output [MWth]	2064	2657	3187
Coolant	Pressurized D_2O	Pressurized D_2O	Pressurized Light Water
Moderator	D_2O	D_2O	D_2O
Calandria diameter [m]	7.6	8.5	7.5
Fuel channel	Horizontal Zr 2.5wt%Nb alloy pressure tubes with modified 403 SS end-fittings	Horizontal Zr 2.5wt%Nb alloy pressure tubes with modified 403 SS end-fittings	Horizontal Zr 2.5wt%Nb alloy pressure tubes with modified 403 SS end-fittings
Fuel channels	380	480	520
Lattice pitch (mm)	286	286	240
Pressure tube wall thickness (mm)	4	4	6.5

ACR-1000

- **Comparison with CANDU-6, Darlington**

Table 2-1 Heat Transport System Design Data

	CANDU 6	Darlington	ACR-1000
Reactor outlet header pressure [MPa (g)]	9.9	9.9	11.1
Reactor outlet header temperature [°C]	310	310	319
Reactor inlet header pressure [MPa (g)]	11.2	11.3	12.5
Reactor inlet header temperature [°C]	260	267	275
Single channel flow (maximum) [kg/s]	28	27.4	28

ACR-1000

- **Comparison with CANDU-6, Darlington**

Table 2-3 Steam Generator Design Data

Steam Generators	CANDU 6	Darlington	ACR-1000
Number	4	4	4
Type	Vertical U-tube / integral pre-heater	Vertical U-tube / integral pre-heater	Vertical U-tube / integral pre-heater
Nominal tube diameter [mm]	15.9 (5/8”)	15.9 (5/8”)	17.5 (11/16”)
Steam temperature (nominal) [°C]	260	265	275.5
Steam quality	0.9975	0.9975	0.999
Steam pressure [MPa (g)]	4.6	5.0	5.9

ACR-1000

- **Comparison of Core Sizes**

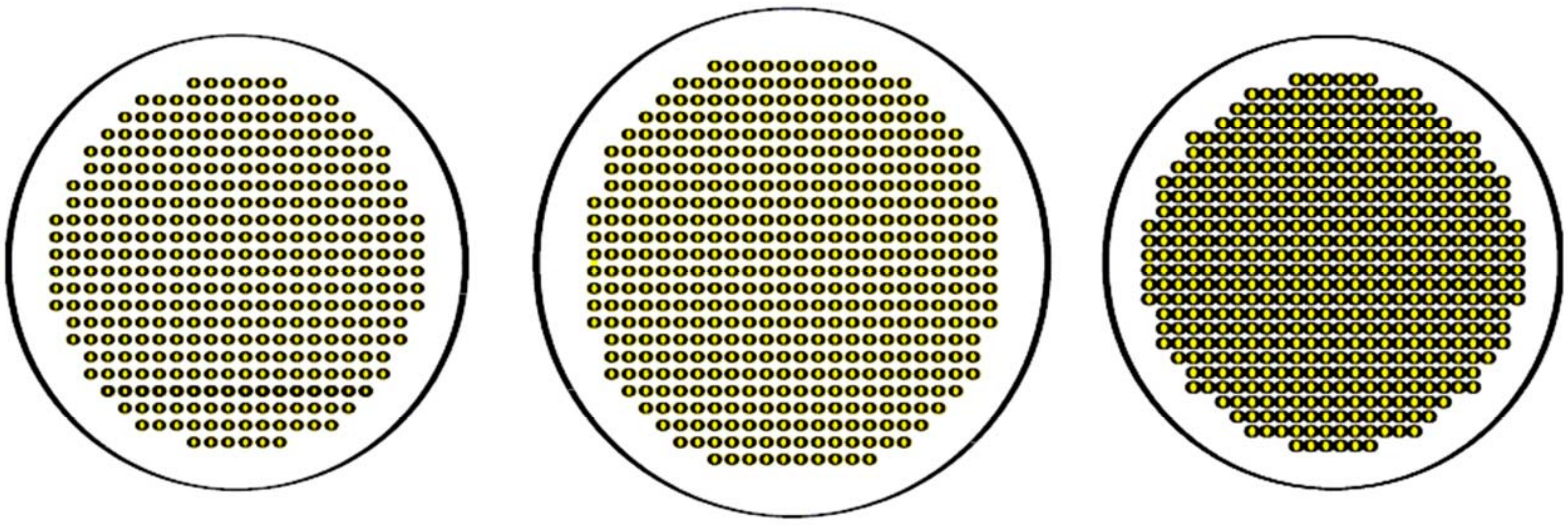


Figure 2-12 Comparison of Core Sizes

ACR-1000

- **Fueling Machine at Reactor Face**

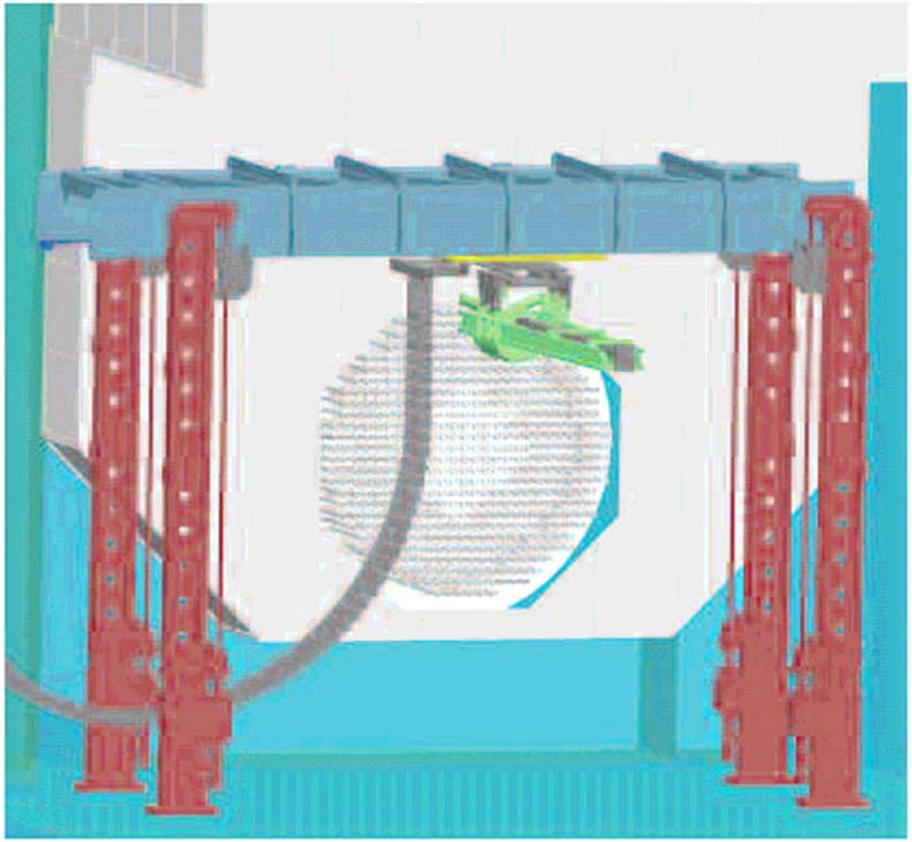


Figure 2-16 Fuelling Machine and Carriage

ACR-1000

- **CANFLEX-ACR Fuel Bundle**

Figure 2-19
CANFLEX®-ACR Fuel Bundle

ACR-1000

- **Multiple barriers – defense in depth**

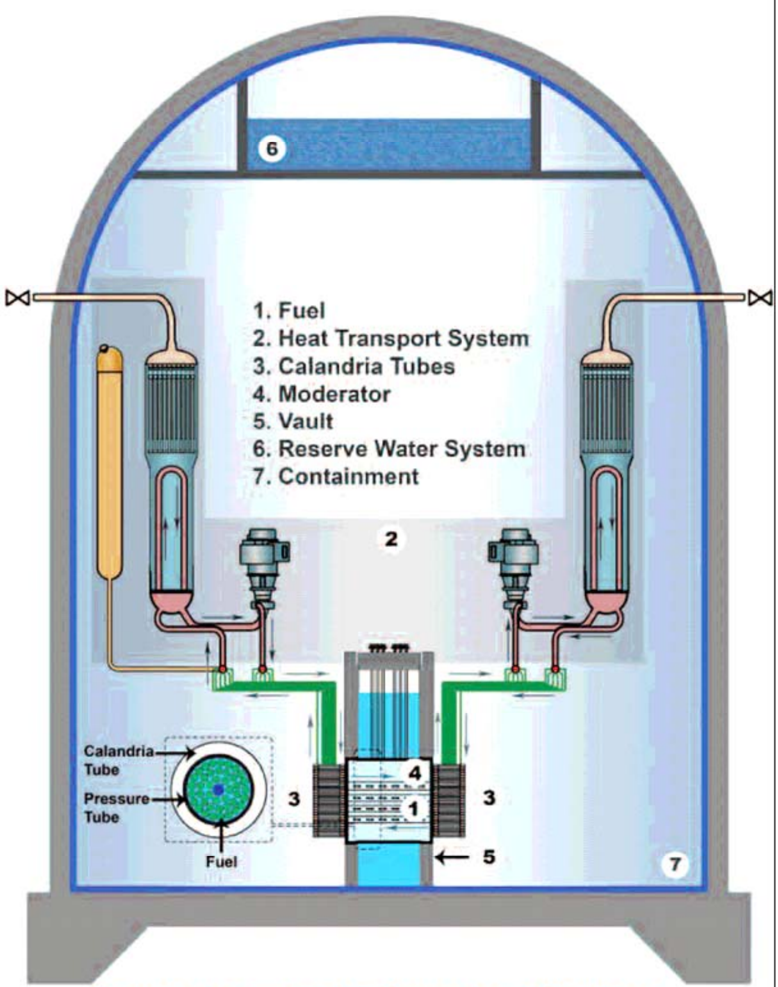
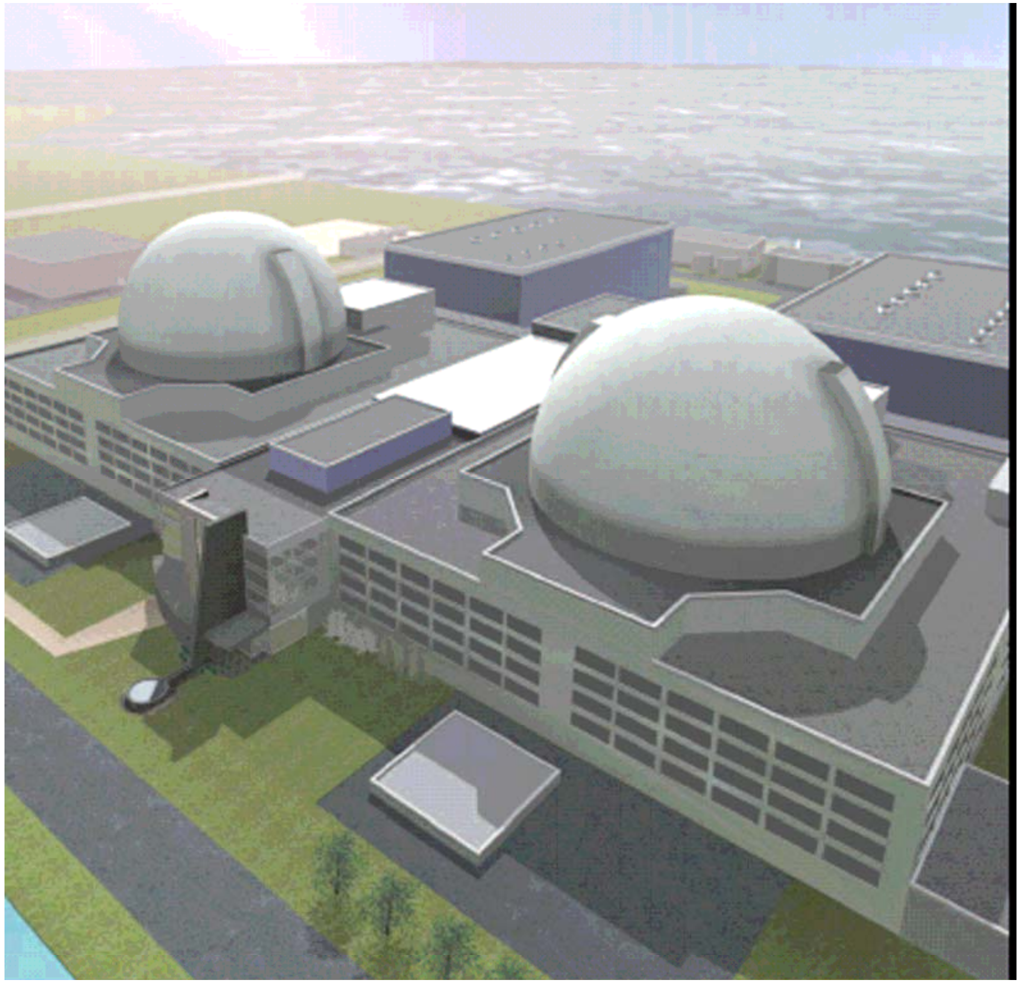


Figure 3-1 Barriers for Prevention of Releases

ACR-1000

- **Twin-unit stations**



Other Gen III+ HWR Projects

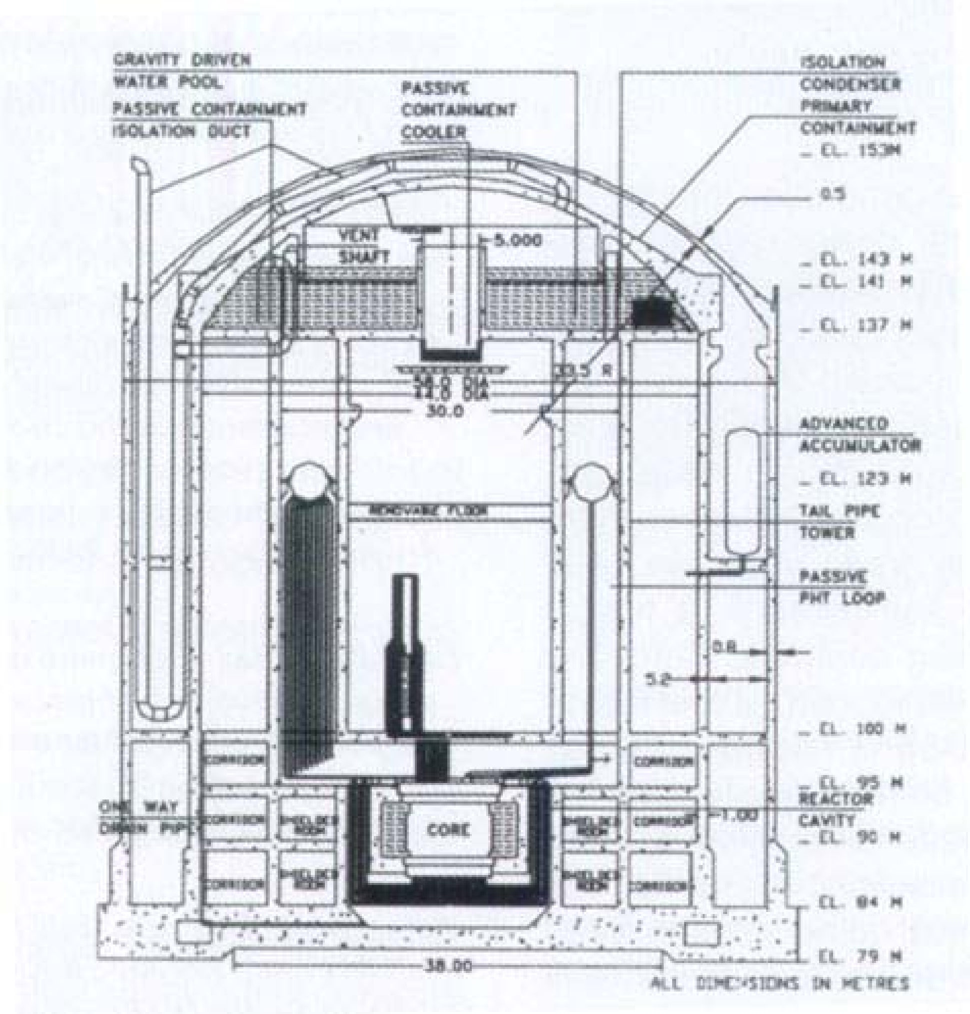
- **Advanced Heavy Water Reactor (AHWR)**
  - Under current development in India.
  - Boiling light water coolant, thorium-based fuels
- **TR-1000 (Russia)**
  - 1989 concept proposal.
  - CO_2 coolant, 9.8 MPa, 400°C to 450°C outlet.
  - Metallic Natural U, or U/Pu, CR>0.80, 10 GWd/t
  - Pre-stressed concrete pressure vessel

AHWR (India, 2008)

- 750 MW_{th} / 235 MW_e (net)
- Boiling light water, 424 Vertical channels
- 29.4-cm pitch, 52-element assemblies
- $(Th,Pu\text{-}3\%)O_2$ and $(Th,{}^{233}U)O_2$ fuel pins.
- ^{233}U production self-sustaining.
- Approx. 2/3 of energy coming from Thorium
- 20,000 MWd/t burnup
- 6.8 MPa, 284°C steam
- B_4C rods, Lithium Pentaborate poison for shutdown

AHWR (India)

- **Reactor Building**



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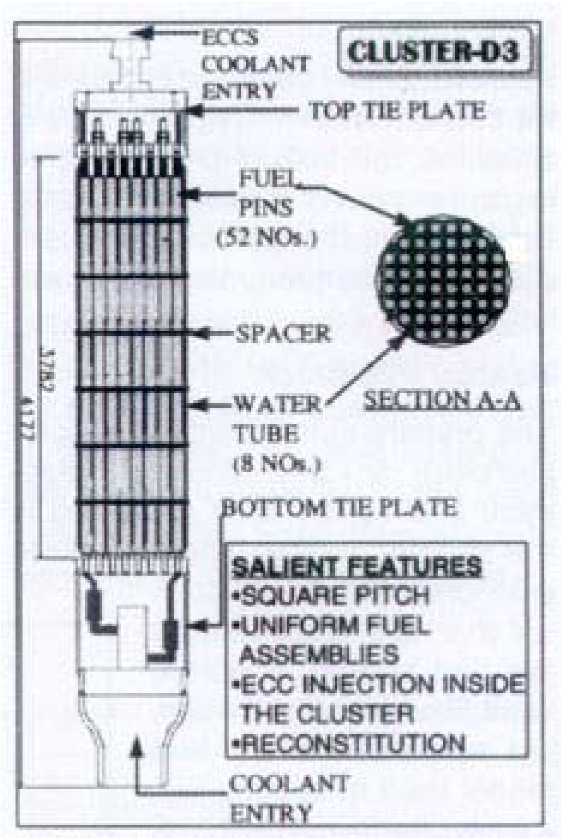
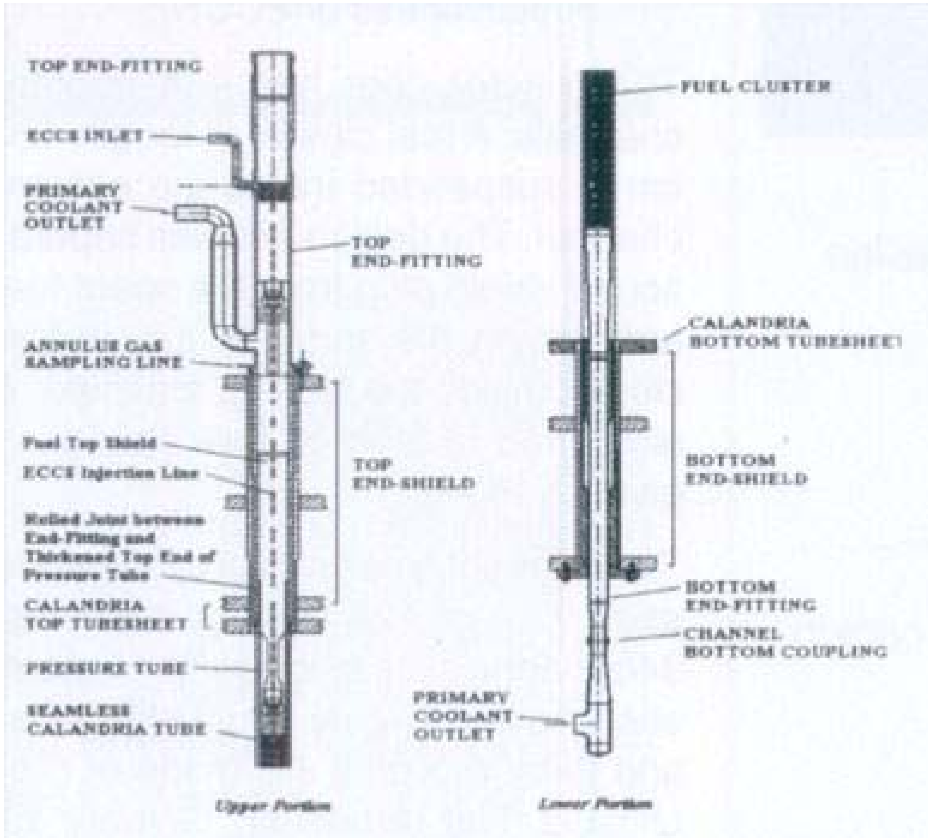
AHWR (India)

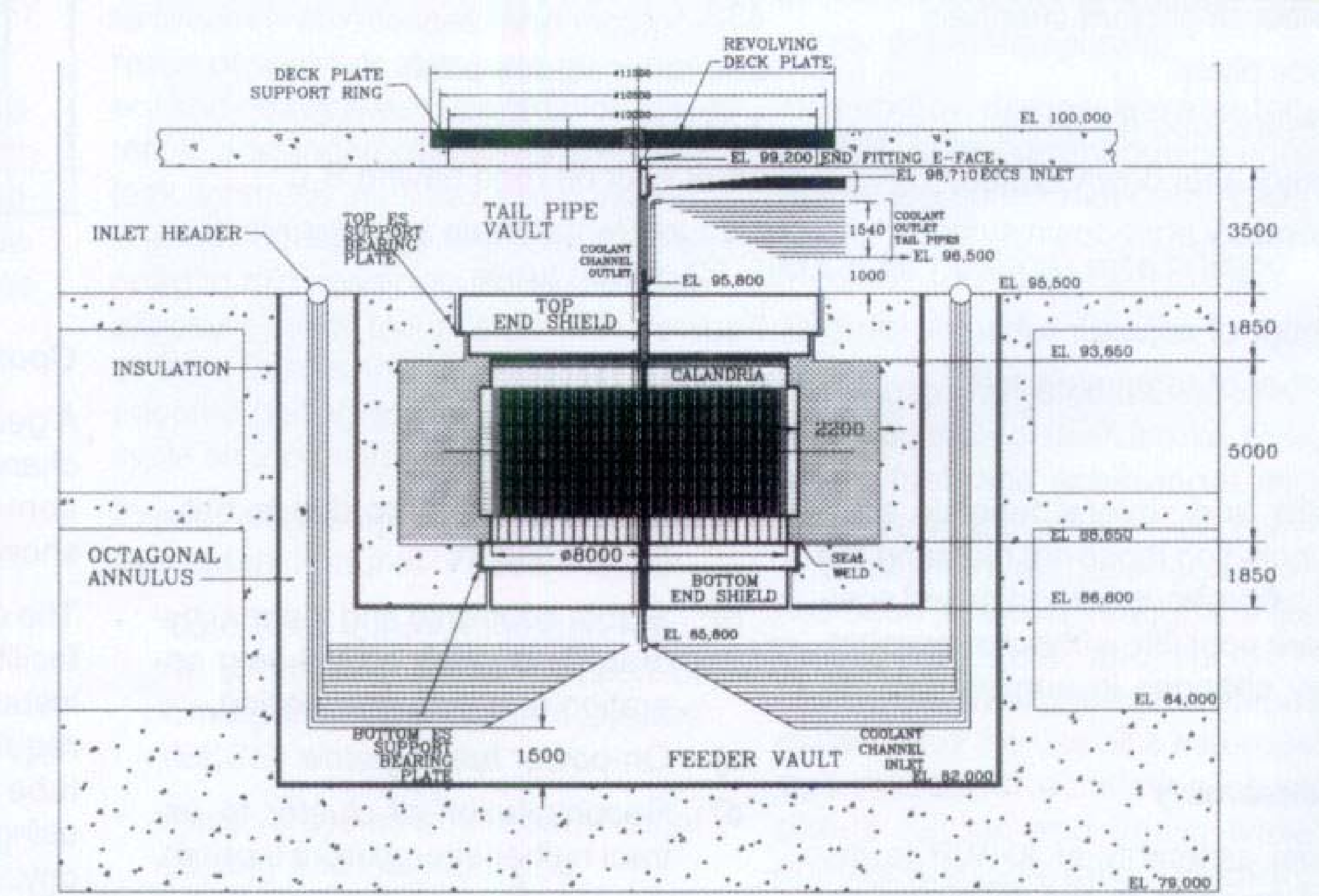
- **52 fuel pins, (Th,Pu)O_2 and (Th^{233},U)O_2**





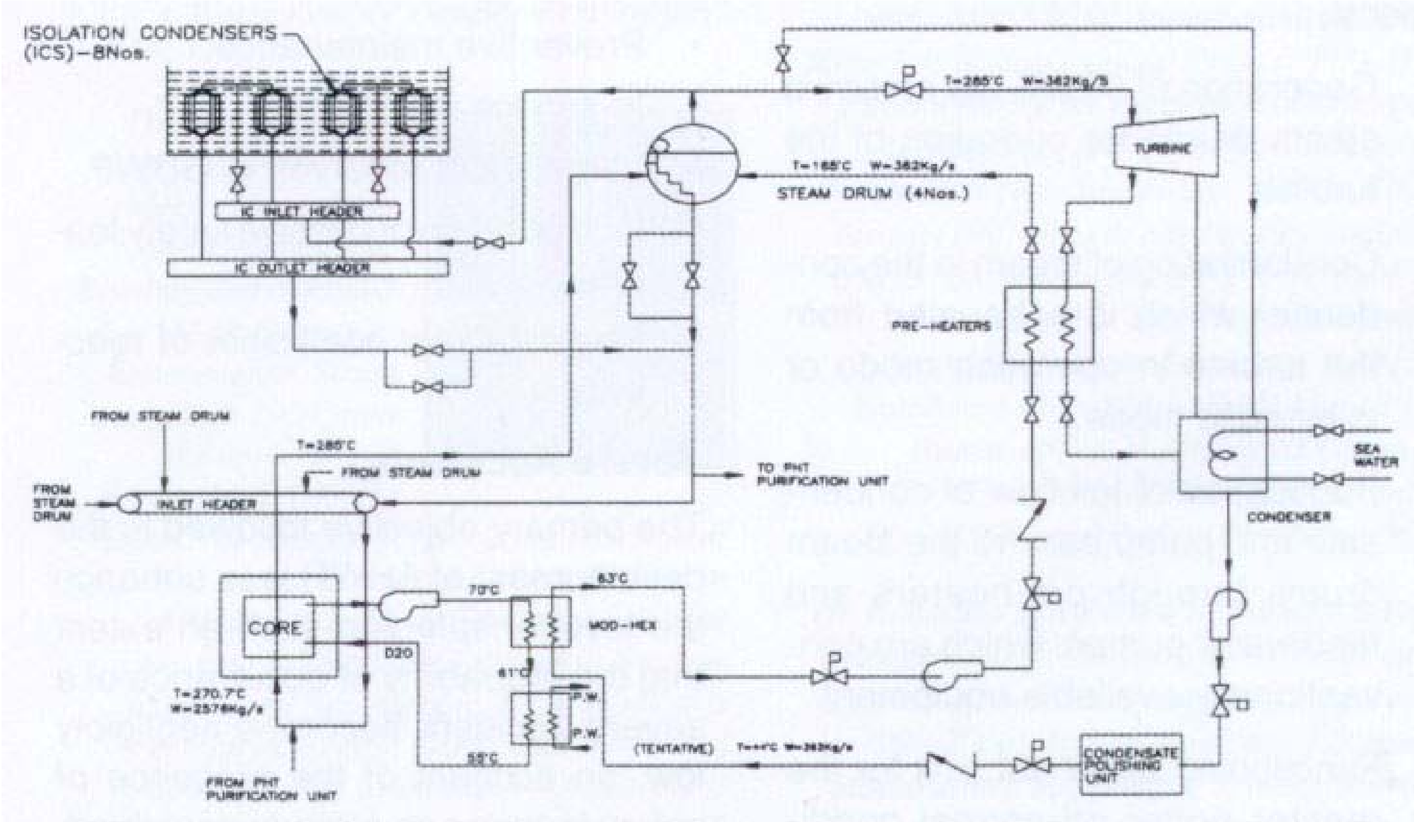
AHWR (India)

- Core layout



AHWR (India)

- **Flow diagram**



TR-1000 (Russia, 1989)

- Based on KS-150 / A1 Bohunice technology.
- 3200 MW_{th} / 1000 MW_e
- Net efficiency ~31%.
- Pre-stressed concrete.
- CO_2 at 420°C to 450°C.
- Steam at 400°C.
- Design for recycling Pu.

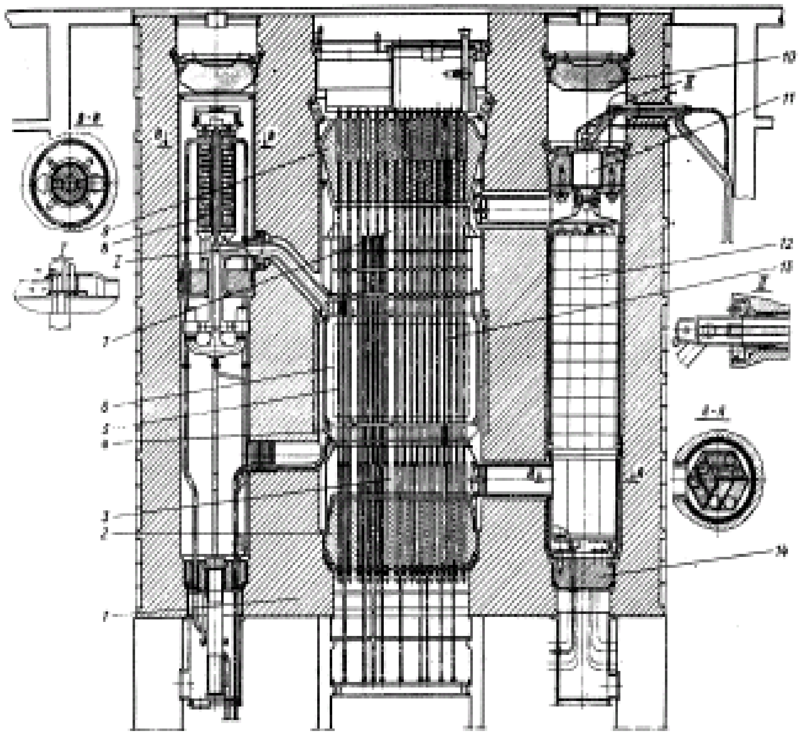


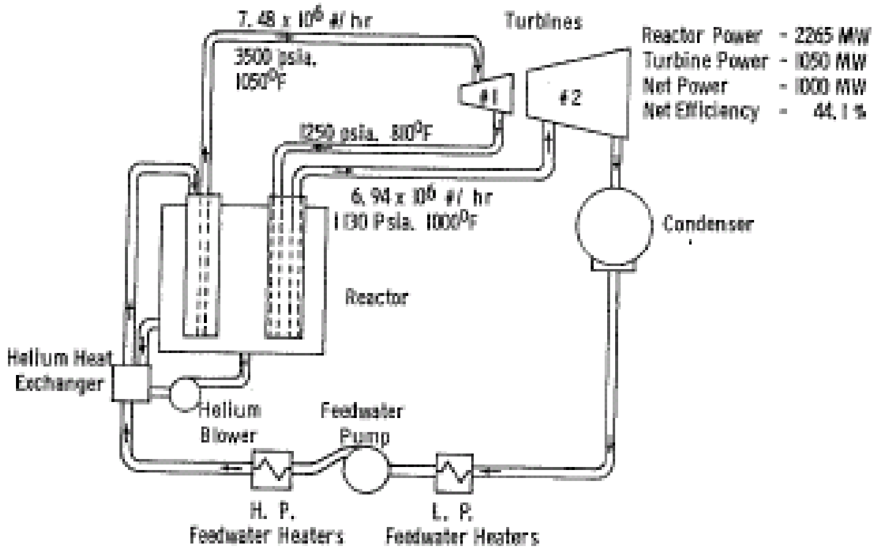
Fig. 1. TR-1000 reactor arrangement: 1) prestressed reinforced concrete shell; 2) lower central vessel plug; 3) inlet (hot) chamber; 4) heavy water tank; 5) fuel channel; 6) core; 7) discharge (cold) chamber; 8) moderator heat exchanger and presurizer; 9) central vessel upper cover; 10) steam generator vessel cover; 11) main circulator (turbocompressor); 12) steam generator module; 13) fuel assembly; 14) steam generator support plug.

Supercritical Reactors (Gen-IV)

- Supercritical coolant, not reactivity !
  - 25 MPa, 530°C to 625°C.
  - Not quite liquid, not quite vapor
  - 40% to 45% thermal efficiencies
- Early Concept:
  - SCOTT-R Reactor (1962), Westinghouse USA
  - Super Critical Once Through Tube Reactor
- Today / Tomorrow:
  - CANDU-SCWR
  - Combine CANDU technology with supercritical H_2O.

SCOTT-R (1962, Westinghouse)

- **Supercritical, with nuclear re-heat**
- **η_{th} > 44%**



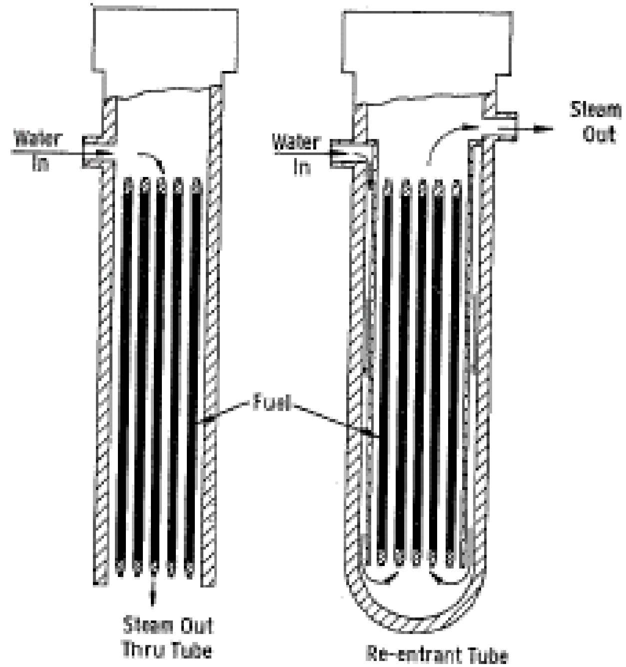
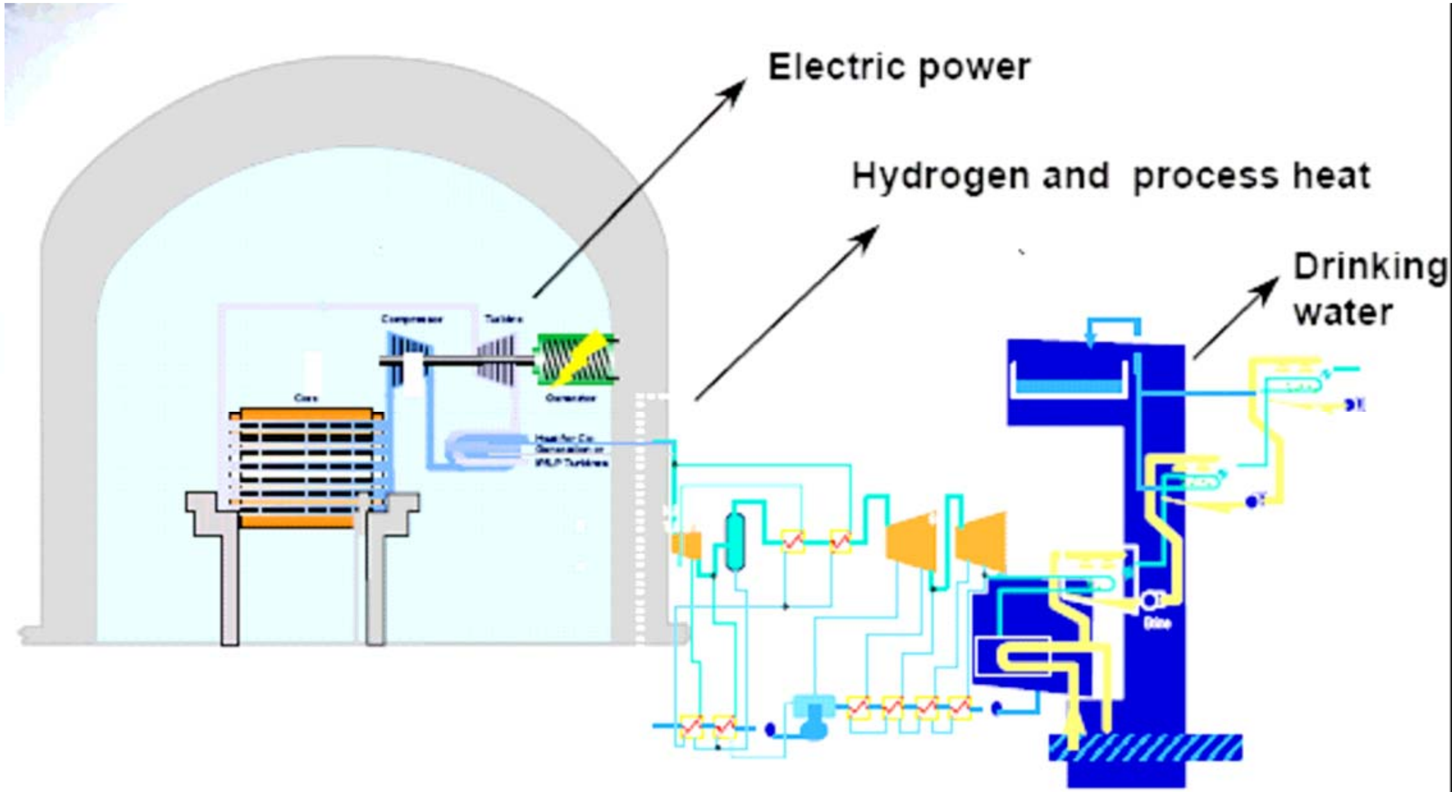


Fig. 10—Pressure tubes.

CANDU-SCWR (Gen-IV)

- 25 MPa, 500°C to 625°C, >1000 MWe
- Direct Cycle, Efficiency ~ 45%



Additional Future Roles for HWR's

- Advanced Fuel Cycles
  - Synergism with LWR's and fast reactors
    - Integrated nuclear energy system
  - Extending nuclear fuel utilization
  - Minimizing waste management issues
    - Burning of Pu and higher actinides
- Water Desalination
  - Fresh water is short supply world wide.
  - Power for reverse-osmosis plants.
  - Waste heat for low-temperature distillation.

Additional Future Roles for HWR's

- Hydrogen Production
  - High-temperature electrolysis
  - Thermal/chemical processes
  - Direct use in fuel cells for transportation, or,
  - Upgrading of low-grade hydro-carbon fuels
    - Coal, bitumen, biomass, peat
      - Synthetic gasoline, diesel, methanol, ethanol, etc.
- High-temperature Steam
  - Enhanced recovery and upgrading of hydrocarbons
    - Oilsands, coal

International Penetration of HWR's

- **World installed nuclear capacity (2006):**
  - 444 Reactors, ~372 GWe net
- **World installed HWR capacity (2006):**
  - 46 Reactors, ~24 GWe net
  - 22 Reactors in Canada, ~15 GWe net
  - 24 HWR abroad
    - India (13), South Korea (4), China (2), Romania (2), Argentina (2), Pakistan (1)
- **HWR's: ~10% of reactors, ~6% of net power**

Why are HWR's not the Dominant Technology Today?

- Partly Historical / Competing Technologies
  - Cost of producing D_2O.
  - Graphite much cheaper, although not as good.
- Weapons and Naval programs
  - Development of industrial infrastructure for uranium enrichment.
    - U.S.A, Russia, U.K., France
  - Use of PWR's for naval submarines.
    - More compact cores, simple reactor design.
  - Large investment in LWR technology.
    - Major head start on alternatives.

Why are HWR's not the Dominant Technology Today?

- Uranium supplies available and cheap (for now)
  - Canada, Australia, U.S.A., Kazakhstan, Africa, etc.
- Enriched uranium supplies assured (for now)
  - Important for Europe, Japan, Korea
- Competing Technologies
  - Financial resources to support more than one or two technologies limited
    - Many countries switched / focused on LWR technology
      - France, Germany, Sweden, Switzerland, Belgium, etc.
      - Japan, Korea; others have followed suit
      - Knowledge and experience base is large (U.S.A., Russia)
    - U.K.: Magnox and AGR's were performing well in 1970's.

Motivating Factors to Use more HWR's in the Future

- **Fuel Costs**
  - **As uranium demand increases and cost goes up.**
  - **High conversion ratios become important.**
  - **HWR design variants will be advanced converters**
    - **Possibly more cost effective than using Fast Breeders alone**
- **Integrated Reactor Systems**
  - **HWR's complementary to LWR's and Fast Reactors**
    - **Extending fissile and fertile fuel resources with high CR.**
    - **Burning of Pu and Actinides from spent fuel of LWR's and FR.**
    - **Minimizing spent fuel and waste for long-term storage.**

Motivating Factors to Use more HWR's in the Future

- **Next-generation Designs**
  - Issues for large pressure vessels
    - Manufacturing challenges, availability, local fabrication.
  - Modular design with pressure tubes more feasible.
    - Particularly for supercritical-water coolant designs.
  - Renewed motivation to use supercritical water, organic, gas, liquid metal, or molten salt coolants.
    - To achieve high efficiencies → ~50%
    - PT design with maximum neutron economy possible.

Conclusions

- Heavy Water Reactor Advantages
  - Excellent neutron economy, better utilization of resources.
  - Special safety features
    - Heat sink, multiple shutdown, longer neutron lifetime
  - Modular construction (pressure tubes)
    - Local manufacturing.
  - On-line refuelling → high capacity factors.
  - Flexibility for fuel and coolant types.
- Technology Improvements
  - Reducing cost of D_2O using advanced separation technologies
  - Better materials, sealing, less corrosion, easier maintenance.
    - Similar goals for other technologies.
  - Improving thermal efficiencies.

Conclusions

- International Interest in Heavy Water Reactors
  - Canada – main focus: mature technology / commercialized
    - Technology development since 1945.
    - CANDU design development; CANDU-6 exported abroad.
    - ACR-1000 is next-generation product with reduced capital costs.
  - India – long-term interest with large supplies of thorium
    - PHWR's patterned after / similar to Canada.
    - Independent / domestic technology development.
    - AHWR is India's next-generation design.
  - Germany, U.K., Japan, France, Sweden, U.S.A, etc.
    - Prototypes developed and tested.
    - Resources to develop and sustain alternative technologies limited.
    - Secured supply of cheap uranium has put focus on LWR technology, but this could change.

Conclusions

- Future for HWR Technology
  - Reducing capital costs; improving efficiencies.
  - Use of enriched fuel; alternative coolants.
  - Complement other technologies (faster breeders, LWR's, etc.)
    - Spent fuel from LWR's could be used in HWR's.
  - Increasing cost of fuel favors HWR technology.
- Increasing role for HWR's in nuclear energy supply
  - World demand for nuclear energy growing.
  - Keeping all options available is prudent.
  - HWR's are an important part of the nuclear energy mix
    - Today, and even more so in the future.
  - Plenty of business for everyone.

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50th Anniversary of NRU

- 50 years of science and technology.
- Millions of patients treated from medical radioisotopes.
- Test bed for CANDU technology.
- Neutron scattering experiments.
- Materials testing
  - Space Shuttle Challenger SRB casing / welds.
- Thousands of visiting researchers.
- www.aecl.ca/nru50