TOPIC 5

Gen-III Systems – From the Initial Requirements to the Designers' Choices

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5.4. Advanced Heavy Water Reactors (AHWRs)

Main Lecture

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Schedule (Day 1)

- Day 1
  - Physics background.
  - Heavy water separation.
  - Design options for HWR’s.
  - HWR characteristics.
  - Design components (focus on CANDU-type)
  - Control devices.
  - Fuel cycles, thorium (optional, if time permits).
  - CANDU-PHWR features.
  - CANDU History (Gen-I, Gen-II) (optional, if time permits)
    - NPD-2, Douglas Point
    - Pickering, Bruce, Darlington, CANDU-6

Schedule (Day 2)

- ☐ Day 2
  - CANDU History (Gen-I, Gen-II) (optional, if time permits)
    - NPD-2, Douglas Point
    - Pickering, Bruce, Darlington, CANDU-6
  - Gen-III+
    - Enhanced CANDU-6 (EC6), ACR-1000
    - 220-PHWR (India), 540-PHWR (India), AHWR (India)
    - TR-1000 (Russia)
  - Gen-IV (optional, if time permits).
    - SCOTT-R (old concept), CANDU-SCWR
  - Gen-V: ??? (optional, if time permits)
  - Additional Roles, International Penetration
  - Dominant Factors, Future Motivation
  - Conclusions

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
  - ➢ Gen-III+ (EC6, ACR-1000, AHWR)
  - ➢ Gen-IV (CANDU-SCWR)
- ☐ Additional Information (see Supplements 1 and 2)
  - ➢ HWR R&D, prototypes, alternative HWR concepts.

What We Won’t Cover

- ☐ See supplementary presentations for further reading.
- ☐ R&D Activities for HWR ‘s - Supplement 1
  - Types of Measurements/Testing.
  - Heavy Water Research Reactors and Critical Facilities.
  - International Participation (Past and Present).
  - Present R&D Efforts and Needs for HWR’s.
- ☐ Additional Information – Supplement 2
  - Alternative Deuterium-Based Moderators
  - Alternative Uses for D_2O
  - Alternative Coolants
  - International Participation in HWR Technology
  - Alternative HWR Reactor Designs
  - Cancelled / Abandoned HWR Projects
    - Timing and special circumstances.

Goals

- ☐ Better appreciation of heavy water reactors.
  - ➢ Some historical review.
  - ➢ We can learn from the past.
  - ➢ Variables change with time.
    - Materials science technologies, manufacturing.
    - Enrichment, availability of resources.
    - Public understanding, political climate.
- ☐ Better understanding.
  - ➢ Motivation.
  - ➢ How it works.
  - ➢ Design features.
  - ➢ Physics issues, engineering issues.
  - ➢ Long term prospects, implications for future.

Reactor Physics Considerations

- ☐ Goal is to sustain fission reactions in a critical assembly using available fissile (and fertile) isotopes.
  - Fissile (e.g., U-235, U-233, Pu-239, Pu-241)
  - Fertile (e.g., breed Pu-239 from U-238, U-233 from Th-232)
  - Fissionable (eg. U-238, Th-232 at high energies)
    - Also: isotopes with low thermal fission cross sections:
      - Pu-238, Pu-240, Pu-242, Am-241, Am-243, Cm-244, and other MA's.
- ☐ 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.

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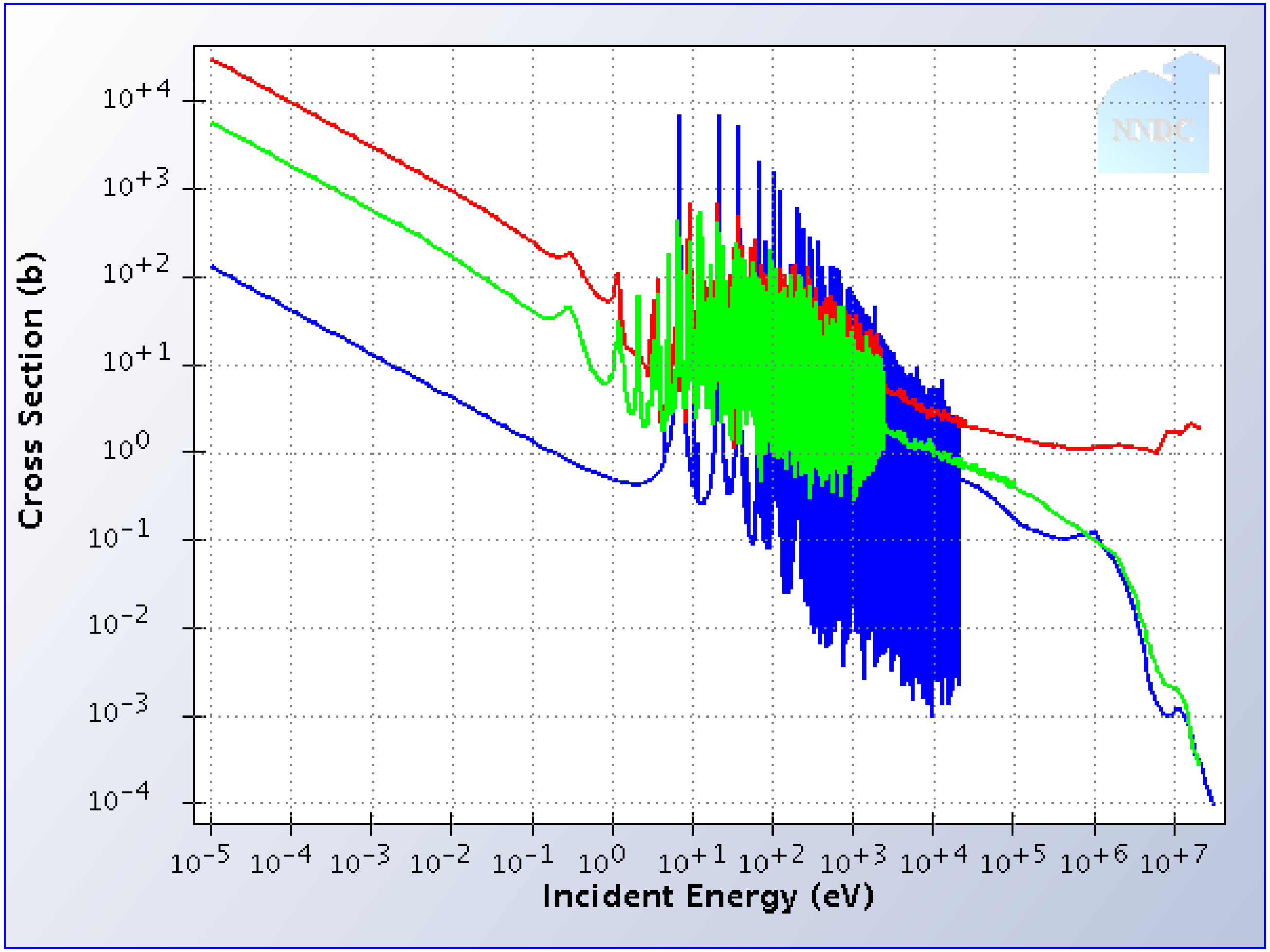
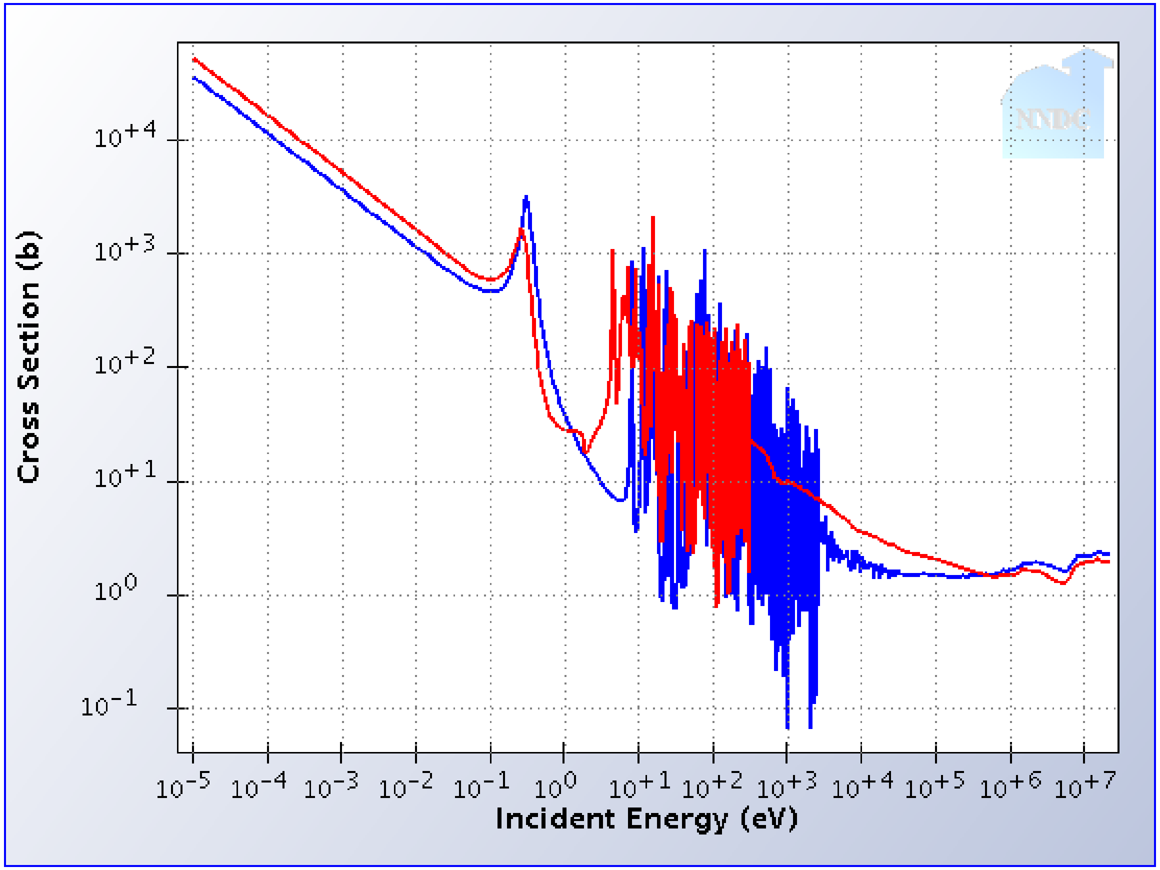
U-235 / U-238

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



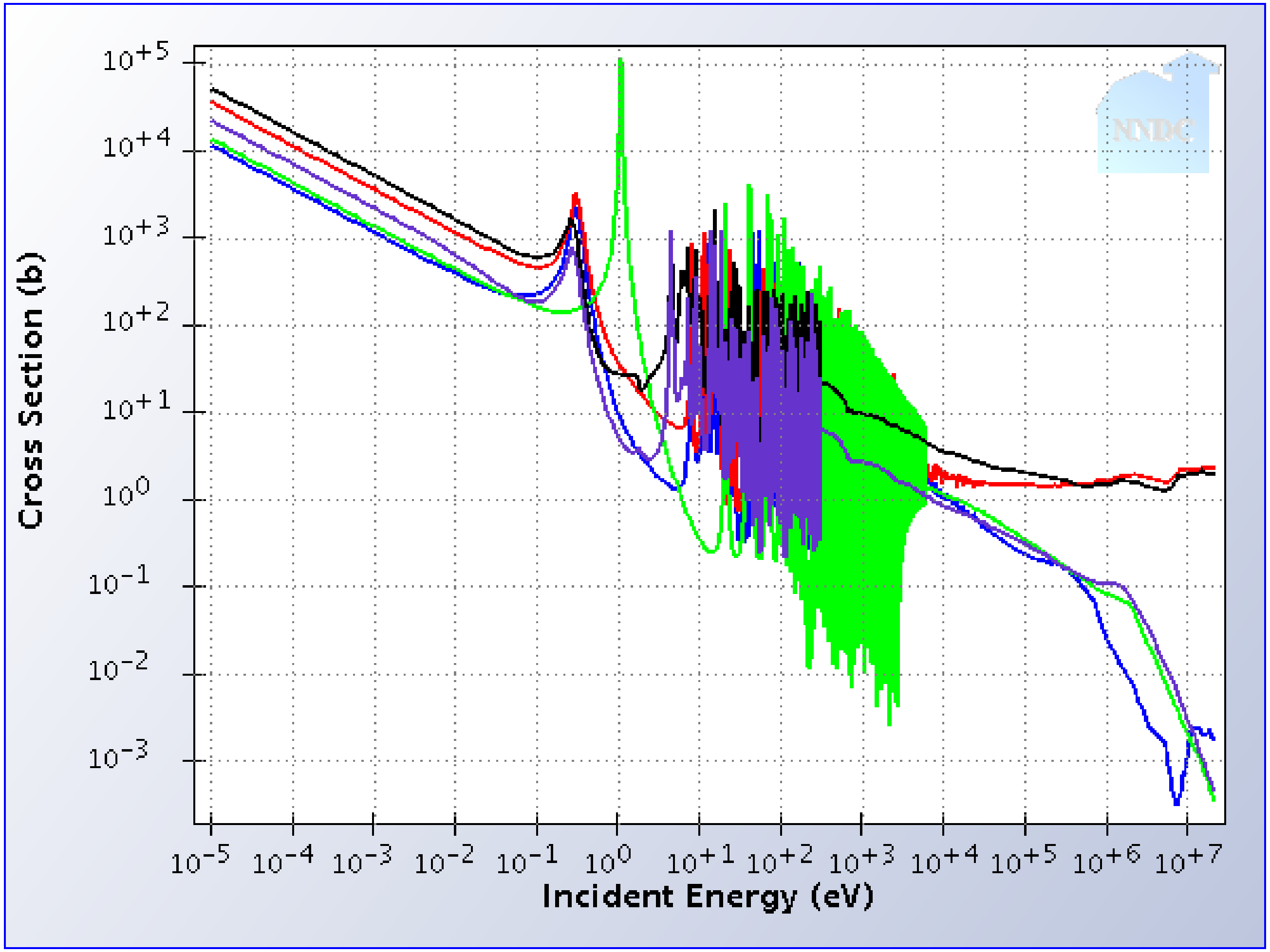
Pu-239 / Pu-241

- Fission cross sections



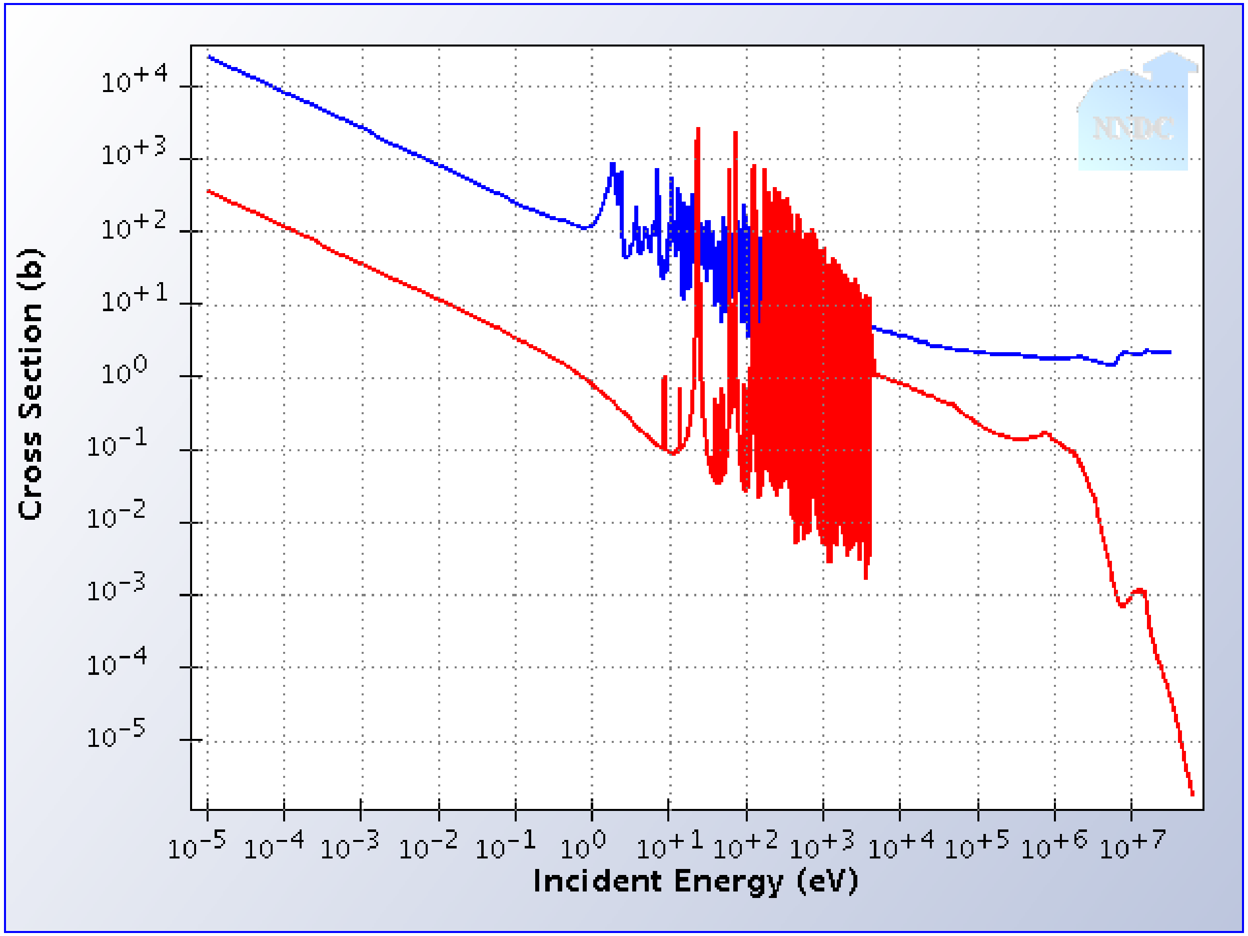
Pu-239 / Pu-240 / Pu-241

- ❑ Fission, capture.
- ❑ Resonances.



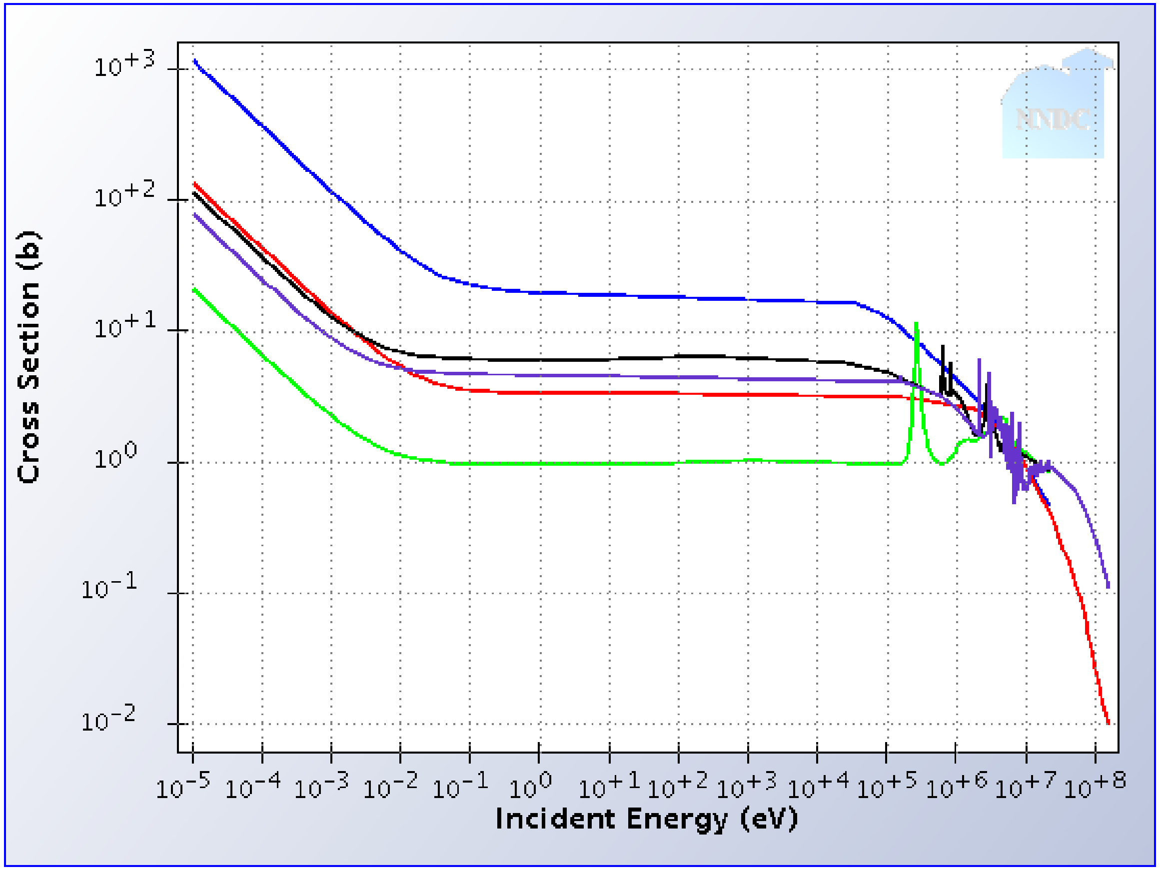
U-233 / Th-232

- Th-232 Capture, U-233 fission.



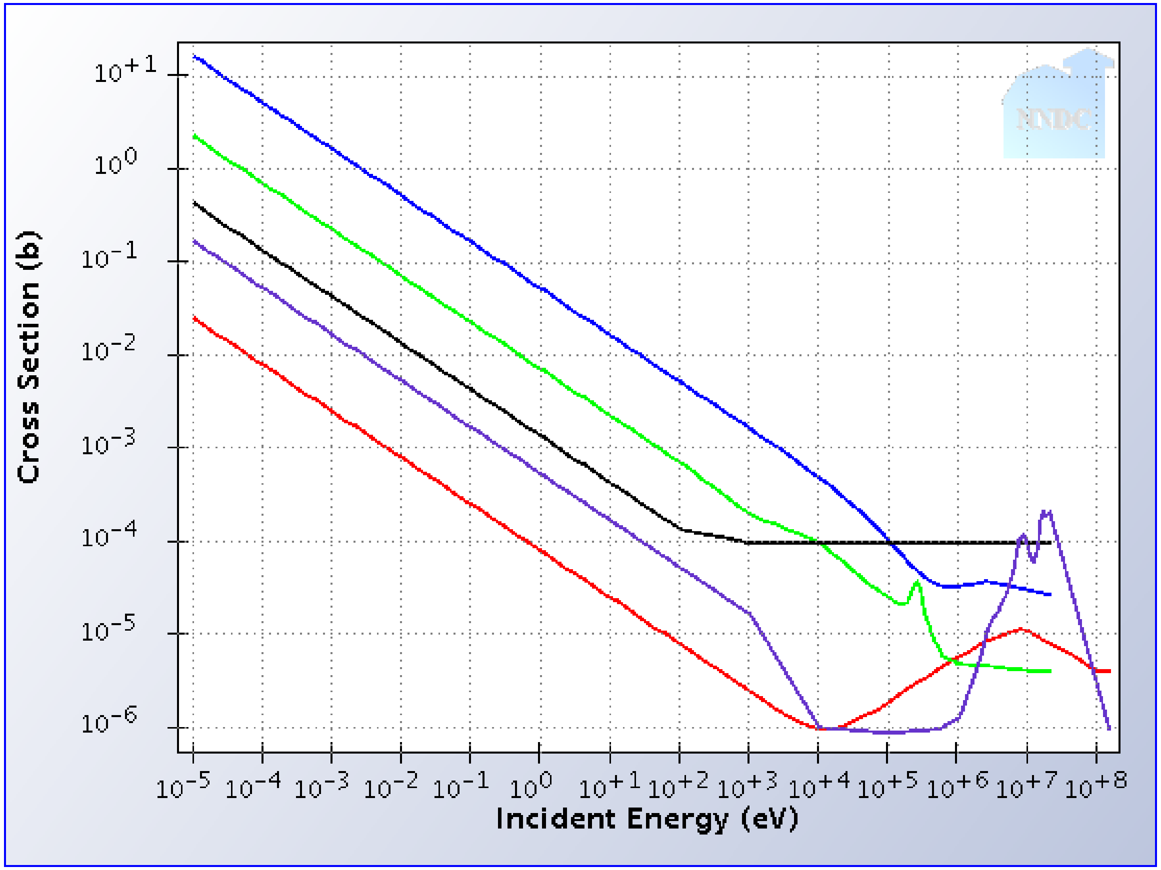
Isotopes for Moderation

- ❑ **H, D, ^{7}Li, Be, C – Scatter Cross Sections**
- ❑ **Hydrogen highest.**



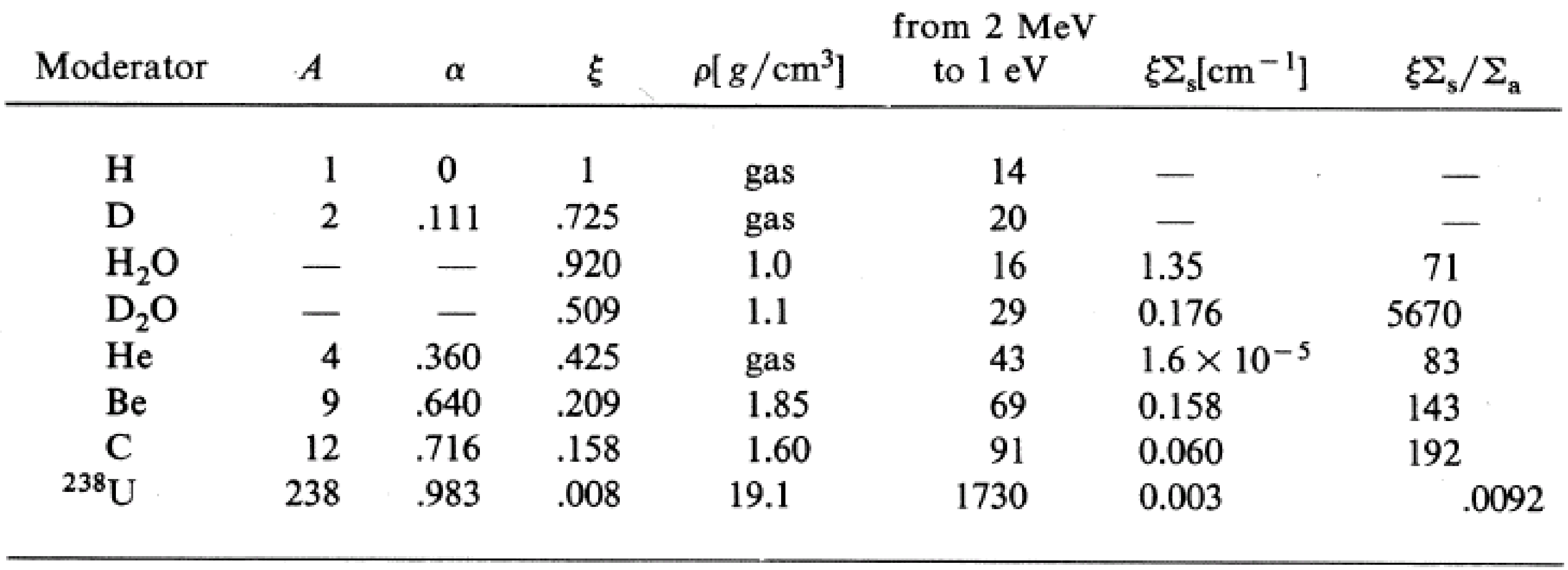
Isotopes for Moderation

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



Options for Moderator

- Hydrogen-based moderator (H_2O, $ZrH_{1.6}$, C_xH_y, etc.)
  - Shortest neutron slowing down distance, but absorption.
- Deuterium-based moderator (D_2O, $ZrD_{1.6}$, C_xD_y, etc.)
  - 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, ~5,670 >> 71 (H_2O)
- ☐ What does this get you?
  - ➢ Can use lower enrichment (e.g., natural uranium).
  - ➢ Higher burnups for a given enrichment.
    - Higher utilization of uranium resources.
  - ➢ Reduce parasitic neutron absorption in moderator.
    - Save neutrons, and spend them elsewhere.
      - o For fission, for conversion.
    - Permits use of higher-absorption structural materials.
      - o High P, High T environments – better efficiencies.
      - o Materials to withstand corrosive environments.
  - ➢ Thermal breeders with U-233 / Th-232 cycle feasible.
    - C.R. ~ 1.0, or higher, depending on design.

It's all about neutron economy!

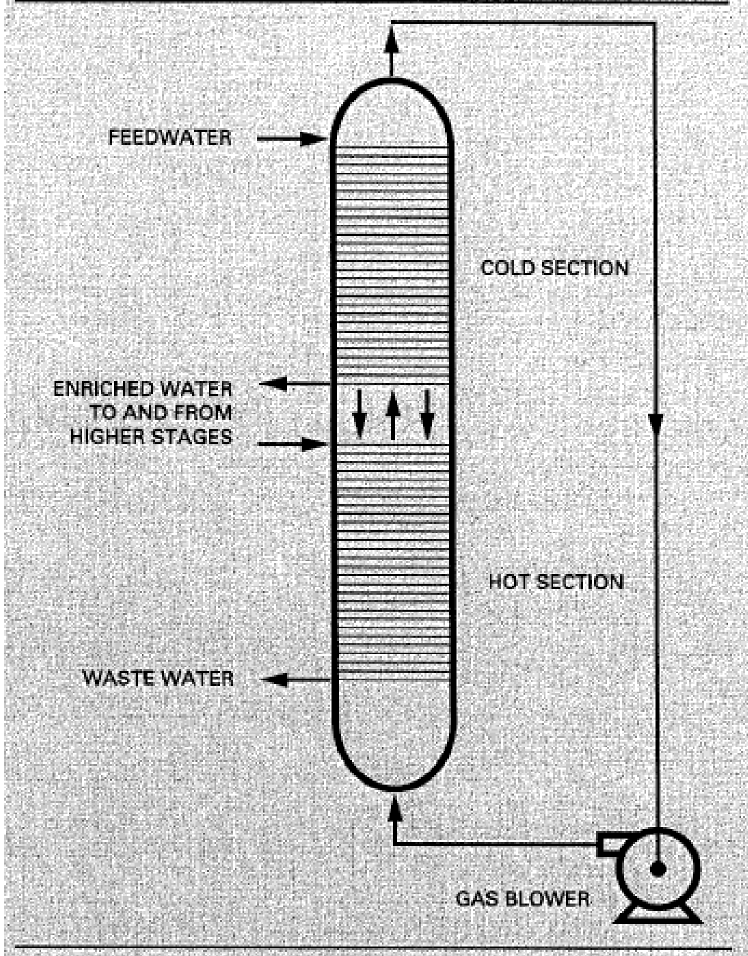
D_2O Characteristics

- ☐ 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.
  - ➢ 1 mk = 100 pcm = 0.001 dk/k
- ☐ Cost:
  - ➢ ~300 to 500 \$/kg-D_2O; ~200 to 400 \$/kWe
  - ➢ New technologies will reduce the cost.
- ☐ Quantity Required
  - ➢ ~450 tonnes for CANDU-6 (~ 0.67 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)
  - ➢ H_2O electrolyzes preferentially.
  - ➢ Used today for upgrading.
- ❑ 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.

FIGURE 17.A1
GS Process Tower



D_2O Extraction for Water

- GS Hydrogen Sulfide Separation Process

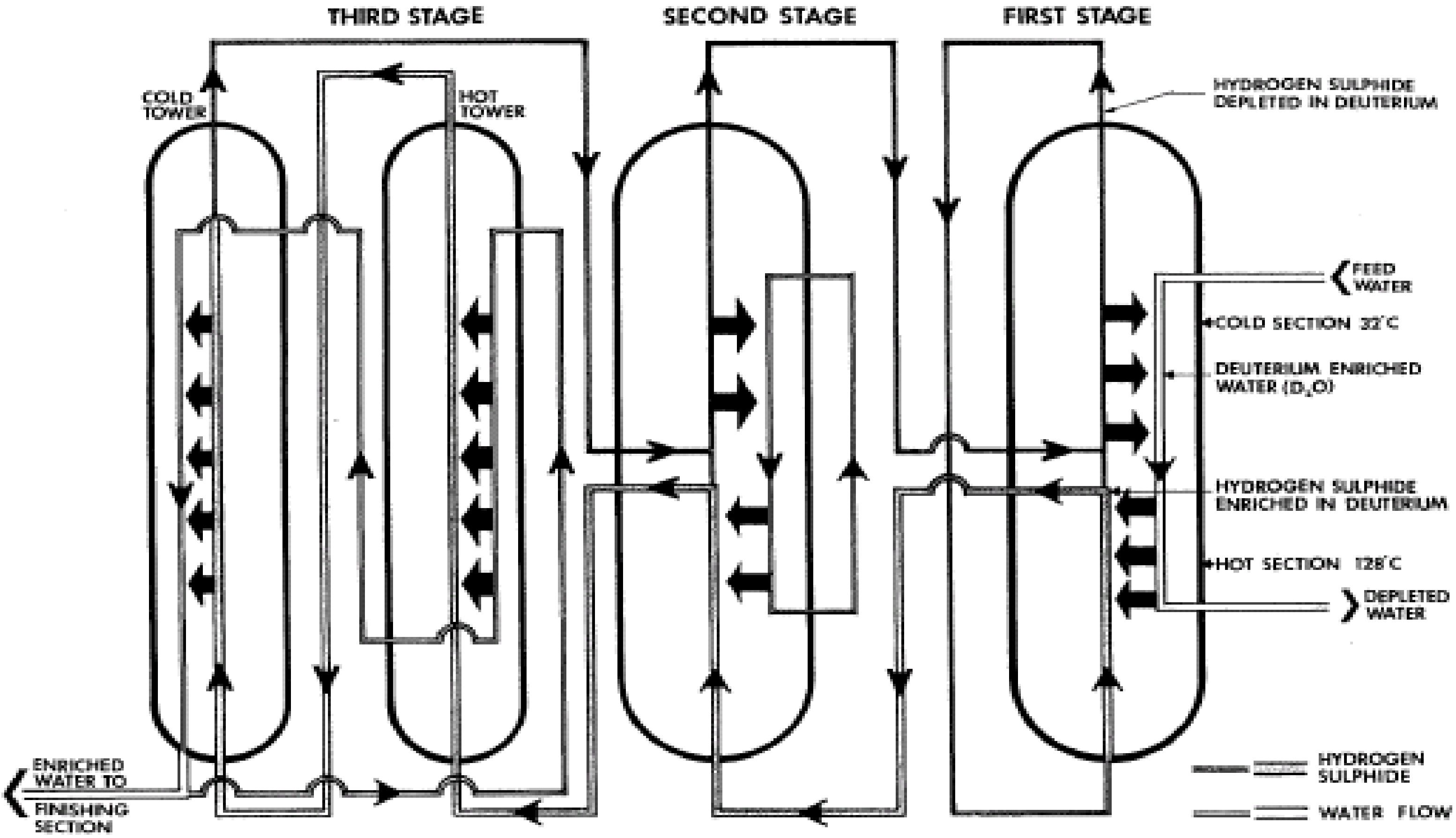


Fig. 5.7. Production of heavy water by GS hydrogen sulfide process (courtesy of Atomic Energy of Canada Limited).

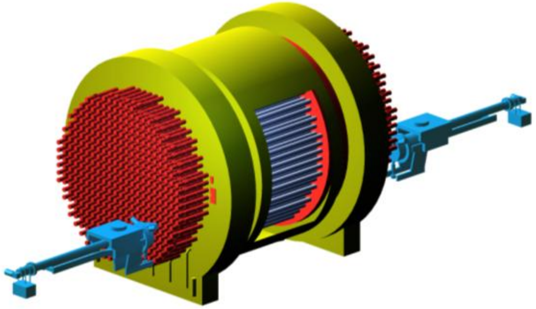
D_2O Extraction for Water

- 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; at least 30% reduction.
- References:
  - An Early History of Heavy Water, by Chris Waltham, 2002.
    - http://www.physics.ubc.ca/~waltham/pubs/d2o_19.pdf
  - 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

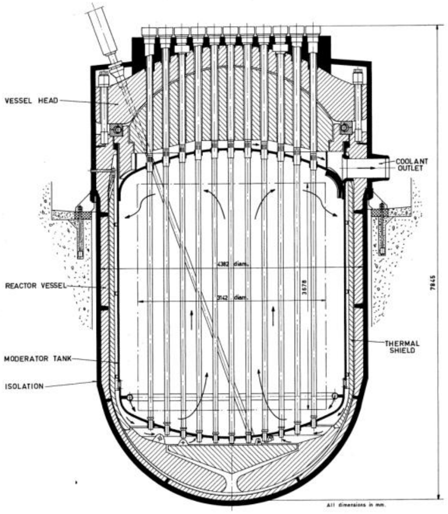
Frederic Joliot Connection to Heavy Water

- ☐ http://www.physics.ubc.ca/~waltham/pubs/d2o_19.pdf
- ☐ Frederic Joliot
- ☐ Colleagues with Hans von Halban, and Lew Kowarski.
- ☐ Recognized in 1939 that D_2O would be the best moderator.
- ☐ Helped smuggle 185 kg of HW to U.K. (originally from Norway)
  - ➢ Eventually went to Canada (along with Kowarski).
- ☐ If not for WWII, the world's first man-made self-sustaining critical chain reaction in uranium may have occurred in France using D_2O + natural uranium (NU).
- ☐ Assisted in developing France's first research reactor
  - ➢ ZOE, 1948
  - ➢ Heavy water critical facility.

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.
  - Used in CANDU, EL-4, CVTR designs.
- ☐ 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.
  - Used in MZFR, Atucha 1, KS-150 designs.



VERTICAL SECTION REACTOR MZFR

Primary Coolant Options

- 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)
  - Use previously in SGHWR, FUGEN, Gentilly-1 Prototypes.
- Supercritical H_2O at 25 MPa (Gen-IV)
  - SCOTT-R (Westinghouse study, 1960’s)
  - CANDU-SCWR (AECL, Gen-IV program)
- Other coolants
  - E.g., gas, organics, liquid metals, molten salt.
  - See Supplement 2 for additional information.

Primary Coolant Features – D_2O

- D_2O at 10 to 15 MPa (CANDU, Atucha)
  - Used in conjunction with steam generator.
  - Low absorption cross section; good neutron economy.
  - Conventional steam-cycle technology.
  - Coolant Void Reactivity (CVR)
    - Resonance absorption in U-238, U-235 changes with voiding.
    - Depends on fuel / lattice design.
      - Pin size, enrichment, moderator/fuel ratio, etc.
    - 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 (net) usually limited to < 34%; 30% to 31% is typical.

Primary Coolant Features: H_2O

- H_2O at 10 to 15 MPa (ACR-1000)
  - Pressurization to prevent boiling (T< 342°C at 15 MPa)
  - Cheaper, lower capital costs.
  - Conventional steam-cycle technology.
  - Higher neutron absorption; reduced neutron economy.
  - Must design lattice carefully to ensure small CVR.
    - H_2O is a significant neutron absorber, as well as a moderator.
    - Use of enriched fuel, poison pins.
  - Water chemistry / corrosion for long-term operation.
  - Hydriding of Zircaloy-PT
  - Net efficiencies usually limited to ~ 34%.
    - Higher P and T may allow increase to ~36%.

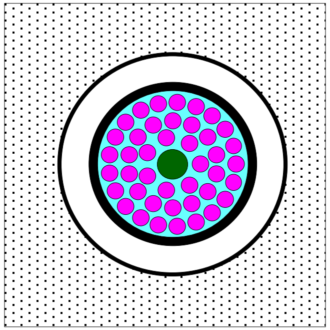
Primary Coolant Features: Boiling H_2O

- ❑ Boiling H_2O at 5 to 7 MPa (T~264°C to 285°C)
  - ➢ Cheaper, lower capital costs.
  - ➢ Thinner PT's feasible; reduced neutron absorption.
  - ➢ Direct steam cycle
    - Eliminate steam generator; slightly higher efficiencies.
    - Up to 35%.
  - ➢ Neutron absorption in H_2O.
  - ➢ Must design lattice carefully to ensure negative CVR.
    - Smaller lattice pitch; enriched and/or MOX fuel.
    - Moderator displacement tubes.
    - More complicated reactivity control system.
  - ➢ Water chemistry / corrosion; hydriding of Zircaloy-PT
  - ➢ Radioactivity in steam turbine.
  - ➢ Demonstrated in SGHWR, Gentilly-1, FUGEN prototypes.

Primary Coolant Features
Super-critical H_2O

- ❑ Supercritical H_2O at 25 MPa (T~400°C to 600°C)
  - Similarities to boiling H_2O.
  - Higher efficiencies possible, ~45% to 50%.
  - Thicker PT's required (~ 2; reduced neutron economy).
  - Severe conditions; corrosive environment
    - T~400°C to 600°C.
    - High-temp. materials required – reduced neutron economy.
    - Use of ZrO_2, MgO, or graphite liner for PT
  - Design to ensure low CVR
    - Enrichment, pitch, pin size, poisons.
  - Careful design for prevention/mitigation of postulated accidents
    - De-pressurization from 25 MPa.
  - More challenging to design for on-line refuelling.
    - May require off-line, multi-batch refuelling (reduced burnup).
    - Use of burnable neutron poisons, boron in moderator.

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.
    - Somewhat smaller in magnitude.
  - Void reactivity (+ve or -ve), depending on design.
    - Aim for small magnitude.
  - Power coefficient (usually negative), depending on design.
    - Aim for small magnitude, slightly negative.

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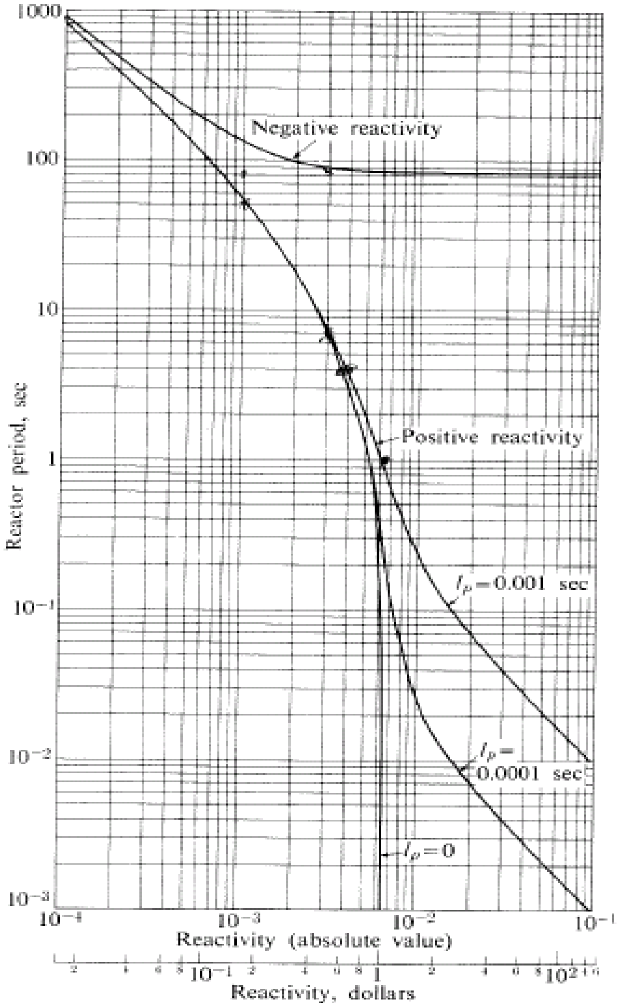
HWR Physics Characteristics

- ❑ Special Feature of HWR’s:
- ❑ Longer neutron lifetime.
  - ➢ Neutrons diffuse for a longer period of time before being absorbed (because of D_2O)
  - ➢ ~ 1 ms vs. LWR (<0.05 ms); ~20× longer.
  - ➢ $\Delta\rho$ = +6 mk (600 pcm) → Period ~ 1 sec.
  - ➢ Slower transient (much easier to control).
- ❑ Extra delayed neutron groups
  - ➢ Photo-neutrons from $\gamma + D \rightarrow n + H$ reaction.
  - ➢ Half-life of several photo-neutron precursors >> longest lived delayed neutron precursor (~55 seconds).
  - ➢ Measurements show long-lived photo-neutron sources with half-lives ranging from ~2 minutes to ~300 hours.



HWR Physics Characteristics

- Conversion Ratio (C.R.).
  - C.R. = 0.7 to 0.9 (depends on enrichment, parasitic losses).
    - U-metal ideal, but UO_2, UC more practical.
  - C.R. > 1.0 possible for U-233 / Th-232 thermal breeder.
    - Careful design of lattice required to maximize neutron economy.
- Burnup of fuel.
  - Natural U → ~ 5 GWd/t to 10 GWd/t (CANDU ~8 GWd/t).
  - Slightly enriched U → ~ 10 GWd/t to 30 GWd/t.
  - Feasible to use recovered uranium (RU) / spent LWR fuel.
    - Work in tandem with LWR’s to maximize energy extraction.
    - Excellent neutron economy.
      - Can burn just about anything.
    - Important role for HWR’s in global fuel cycle.

HWR Physics Characteristics

- ❑ PT D_2O reactors, some unique safety features.
  - ➢ Multiple, independent shutdown systems feasible.
    - Shutdown rods.
    - Moderator poison injection (B-10, Gd, etc.).
    - Low-pressure environment for moderator.
  - ➢ Longer reactor period
    - More time for shutdown systems to work.
  - ➢ Multiple barriers to contain fission products.
    - Fuel clad.
    - Pressure Tube.
    - Calandria Tube.
  - ➢ Large heat sink to dissipate heat.
    - D_2O moderator.
  - ➢ Emergency core cooling (ECC) system, full containment, vacuum building (typical for CANDU reactors).

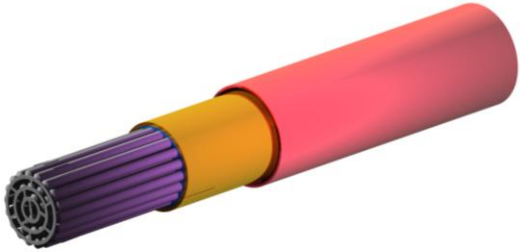
HWR Physics Characteristics

- Power Density in Core.
  - Major 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
      - E.g., ACR-1000
  - 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.
- However, remember: Balance of Plant
  - Steam generators, steam turbines, condensers take up space.

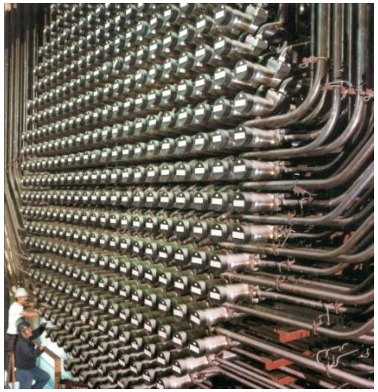
HWR Operational Characteristics

- ❑ Heat load to moderator
  - ➢ 5% to 6% of fission energy deposited.
  - ➢ Gamma-heating, neutron slowing down (2 MeV → 0.0253 eV).
- ❑ 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.
    - Possible to increase to ~33% to 34%.
  - ➢ 32% to 34% feasible for HWBLW-type reactors.
  - ➢ Gas, organic, liquid metal: 35% to 50% (stretch).
    - At very high T, potential to use gas turbines (Brayton cycle).
    - Or, combined cycles (Brayton + Rankine).
  - ➢ Economies of scale with larger plants.

CANDU-PHWR Design Components



- 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 (rolled joints to fit with steel tube sheet)
- Feeders/Headers.
  - Stainless steel (special mechanical rolled joints with PT)

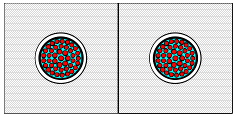


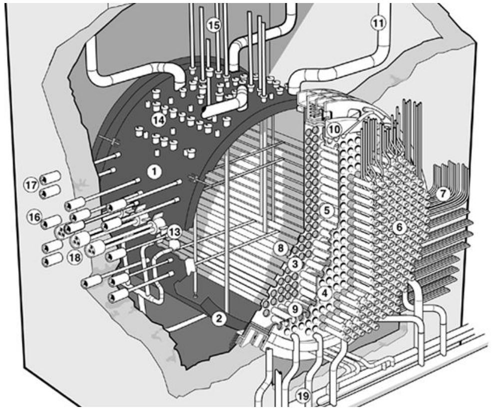
HWR Control Devices

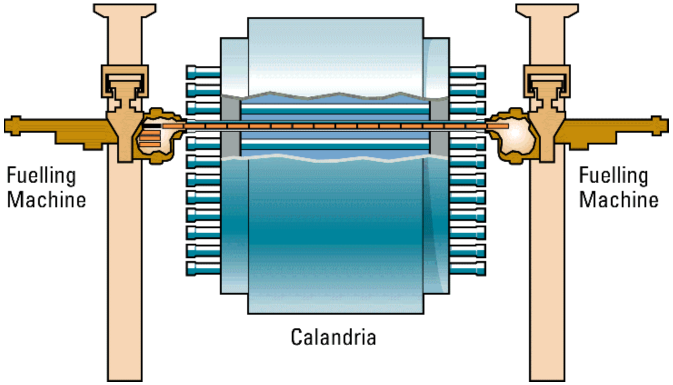
- ❑ Control rods (stainless steel – SS, etc.)
- ❑ Shutdown rods (B_4C, Cd/Ag/In, SS/Cd, etc.)
- ❑ Adjusters (flatten flux shape) – Cobalt, SS
- ❑ Zone controllers
  - ➢ Tubes with liquid H_2O used to adjust local reactivity.
  - ➢ Mechanical zone controllers with neutron absorbing material.
- ❑ Moderator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

CANDU Reactor Technology

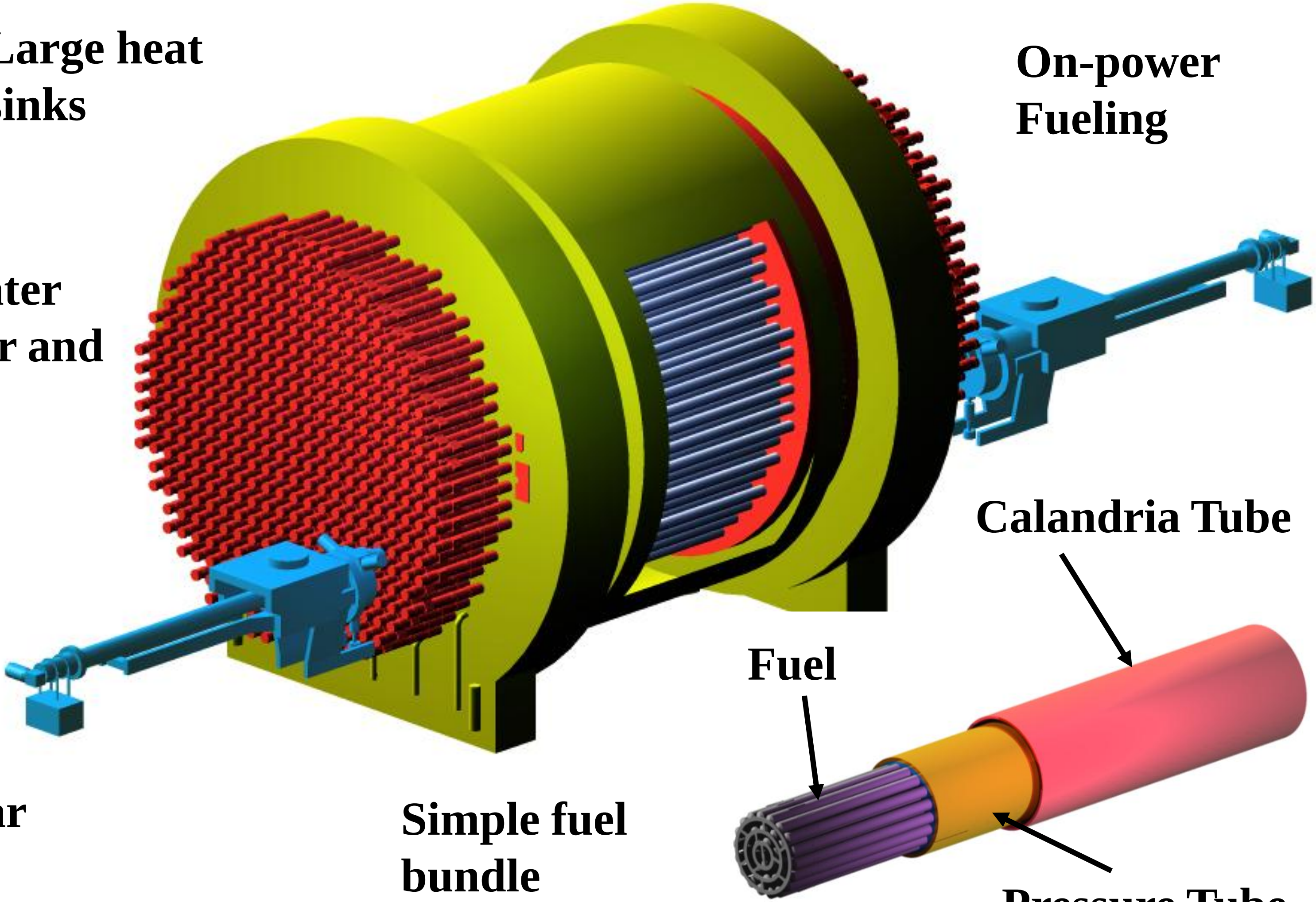
- D_2O Moderator (~70°C, low pressure) in calandria.
- D_2O Coolant (~10 MPa, 250°C – 310°C)
- Pressure Tubes, Calandria Tubes
- 28.58-cm square lattice pitch
- Natural uranium fuel (UO_2) in bundles
  - 37-element (CANDU-6, Bruce, Darlington)
  - 28-element (Pickering)
- Burnup ~ 7,500 MWd/t (nominal).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







CANDU Reactor Technology



Large heat sinks

On-power Fueling

Heavy Water Moderator and Coolant

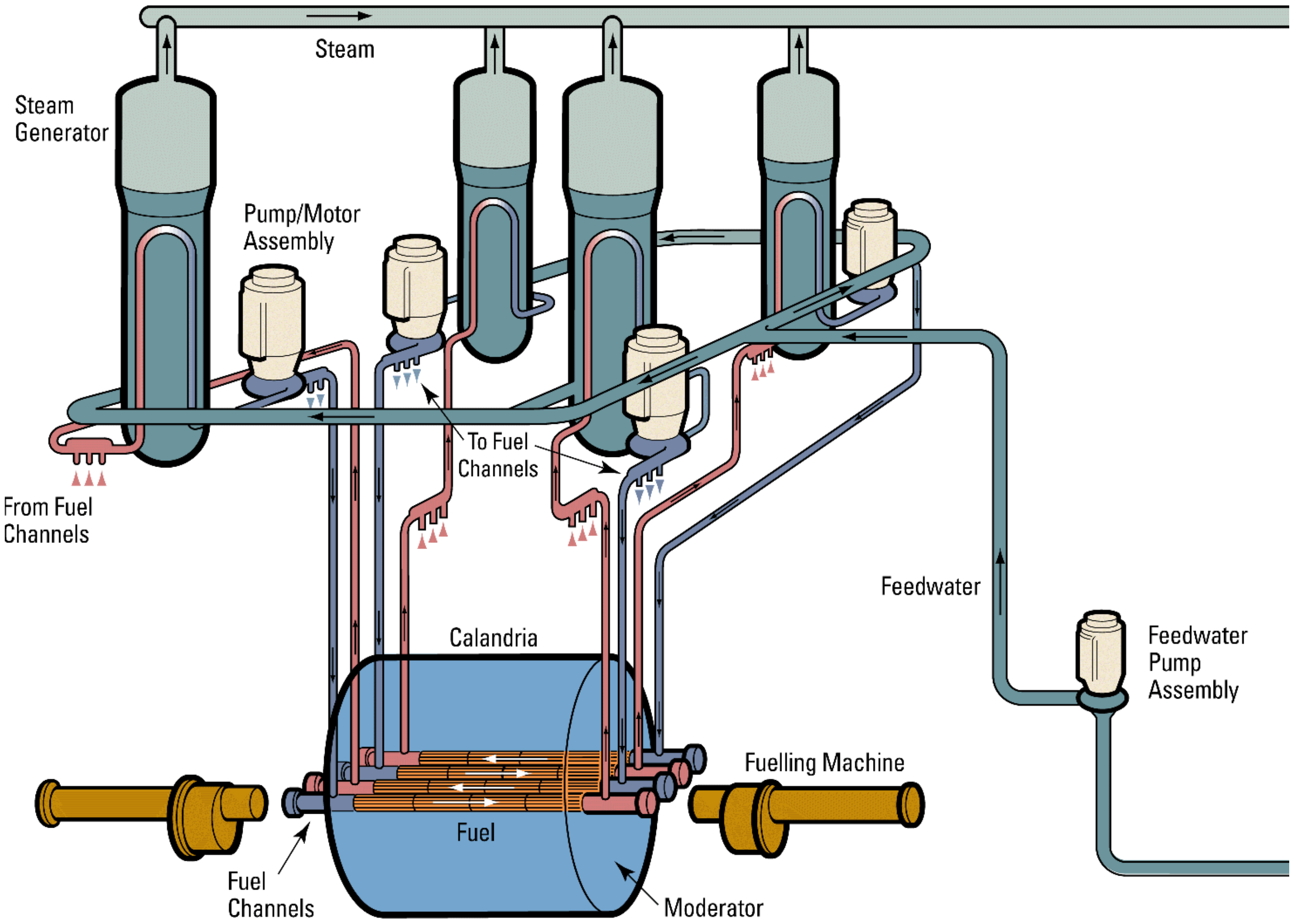
Modular Design

Simple fuel bundle

CANDU-PHWR Features

- ❑ Excellent neutron economy.
  - ➢ High conversion ratios (C.R.>0.8).
  - ➢ Operate on natural uranium (NU); enrichment not required.
  - ➢ High fuel utilization; conservation of resources.
- ❑ Continuous On-line refuelling.
  - ➢ Low excess reactivity.
  - ➢ Higher fuel burnup for a given enrichment.
    - 30% more burnup than 3-batch refuelling.
    - Maximize uranium utilization (kWh/kg-U-mined).
  - ➢ High capacity factors (0.8 to 0.95).
- ❑ Modular construction.
  - ➢ Pressure tubes; replaceable; reactor can be refurbished.
    - o Currently underway at Pt. Lepreau, Bruce, Wolsong CANDU reactors.
  - ➢ Local fabrication (do not need heavy forgings).

CANDU Nuclear Steam Plant



CANDU-PHWR Operational Issues

- Plumbing
  - Feeders / headers for each PT.
  - Joints and seals.
  - Pressure tubes.
    - Sag and creep.
    - Corrosion, embrittlement (D, H).
    - Periodic inspection and assessment.
- Fuelling Machines
  - Maintenance; high radiation environment.
- Tritium production ($n + D \rightarrow T + \gamma$)
  - Removal, handling, storage ($T_{1/2}$ = 12.3 years).
    - $T \rightarrow He\text{-}3 + \beta^-$
  - By-product for use in self-luminous signs, fusion fuels.

CANDU Safety Characteristics

- ☐ Slightly positive coolant void reactivity (CVR).
  - ➢ Reactivity increases when coolant changes to void.
  - ➢ Due to slight shift in neutron energy spectrum.
  - ➢ Reduced resonance absorption in U-238.
  - ➢ What matters, is that the magnitude is relatively small.
  - ➢ Magnitude of reactivity coefficients should be as small as possible
    - Whether positive, or negative.
- ☐ But, there are several key mitigating circumstances.
  - ➢ Voiding is not usually instantaneous to all channels.
  - ➢ Long neutron lifetime (~ 1 ms) in D_2O leads to slower transient.
    - Plenty of time for engineered shutdown systems to work.
    - Possibly more time than is available for shutdown and ECCS systems in postulated LWR accident scenarios.

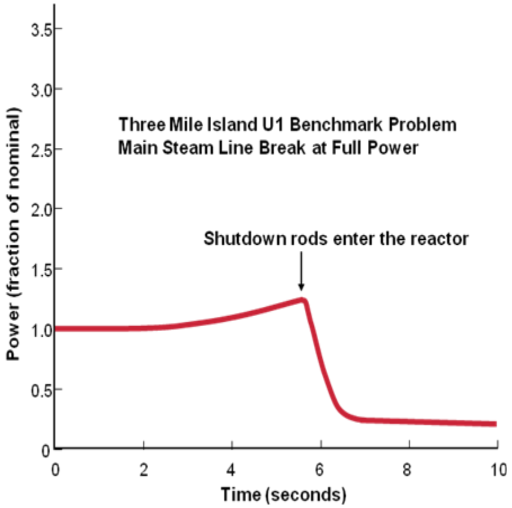
CANDU Safety Characteristics

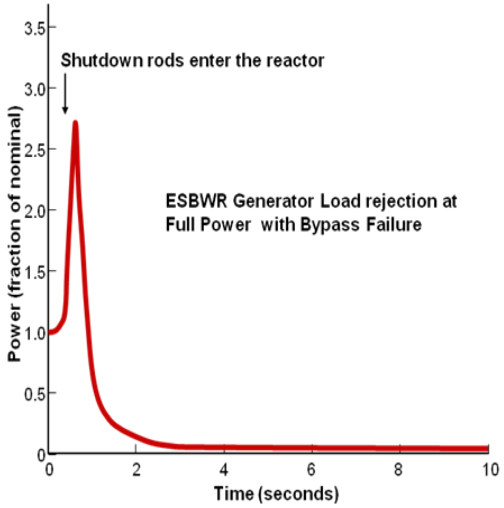
- ☐ CANDU does well, by comparison to other reactor designs in postulated accident scenarios involving reactivity initiated accidents (RIA's).
  - ➢ Longer neutron lifetime due to heavy water moderator makes a big difference.

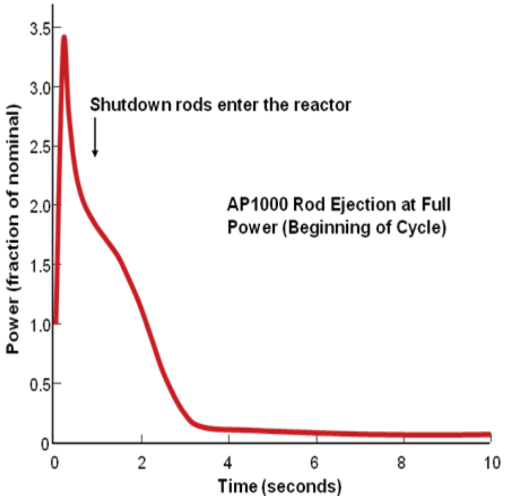
- ☐ Benchmark Postulated Accident Scenario Comparisons, by design:
  - ➢ CANDU-6
    - Large Loss of Coolant Accident (LLOCA).
  - ➢ TMI-1 (B&W PWR)
    - Main Steam Line Break (MSLB)
  - ➢ ESBWR
    - Generator trip with steam bypass failure.
  - ➢ AP-1000
    - Rod ejection accident at hot full power (HFP), or hot zero power (HZP)

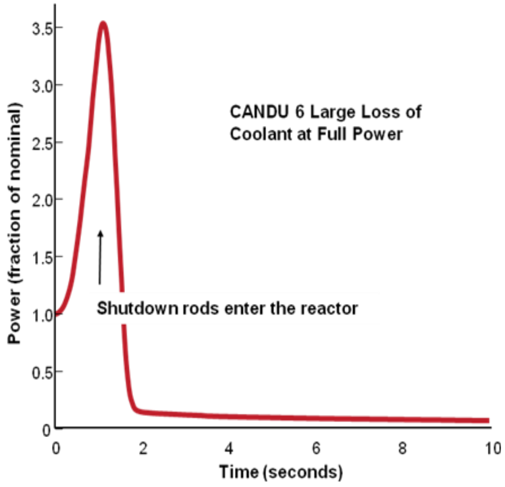
CANDU During LLOCA

- ❑ Peak fuel enthalpy for CANDU-6 under LLOCA:
  - ➢ ~639 J/g
  - ➢ Pulse width longer.
  - ➢ Rate of power increase slower.
  - ➢ Reduced chance of fuel damage.
- ❑ Peak fuel enthalpy in AP-1000 REA, HFP:
  - ➢ ~758 J/g
  - ➢ Pulse width shorter.
- ❑ Longer pulse width decreases chance of fuel failure.
  - ➢ CANDU transient slower.
  - ➢ Long neutron lifetime.







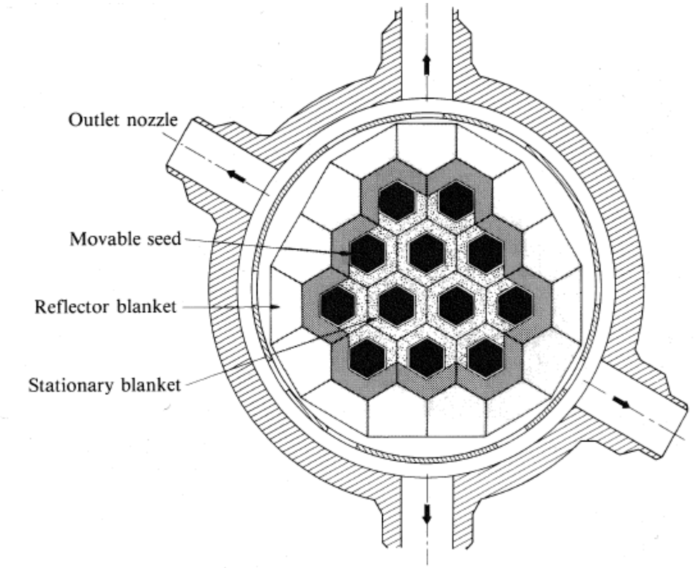


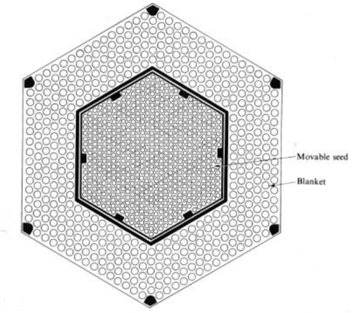
CANDU Safety Comparable to LWR's

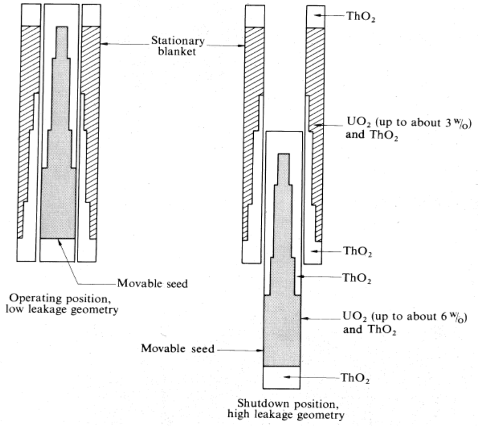
- ☐ Special CANDU features:
  - ➢ Shutdown systems operate in low-pressure environment.
    - Very high reliability.
  - ➢ Auxiliary cooling by a large heat sink – moderator.
- ☐ Key Reference:
  - ➢ A.P. Muzumdar and D.A. Meneley, "LARGE LOCA MARGINS IN CANDU REACTORS - AN OVERVIEW OF THE COG REPORT", *Proceedings of the 30th Annual Conference of the Canadian Nuclear Society*, May 31 - June 3, 2009.

Thorium Fuel Cycles in HWR's

- Thermal breeders with thorium have been demonstrated.
  - LWBR, light water, PWR.
  - Shippingport, PA, U.S.A.
  - 1977-1981
  - Special, heterogeneous seed-blanket design with movable seed.
  - C.R. ~1.013.
  - Core-average burnup:
    - ~4,200 MWd/t.
  - Proof that thermal-breeding works, although maybe not economical with such a low burnup before re-processing.







Thorium Fuel Cycles in HWR's

- HWR's have better neutron economy in thermal spectrum.
  - C.R. > 1.0 feasible with Th-based fuels.
    - Typically with 1.5 wt% to 2 wt% (average) U-233/Th-232.
    - Lower flux / power density.
      - Reduce capture in Pa-233.
  - Challenging to have a practical, economical reactor system.
  - Goals:
    - First: higher uranium utilization.
    - Second: thorium utilization.
    - Third: self-sufficiency on a pure U-233/Th-232 cycle.

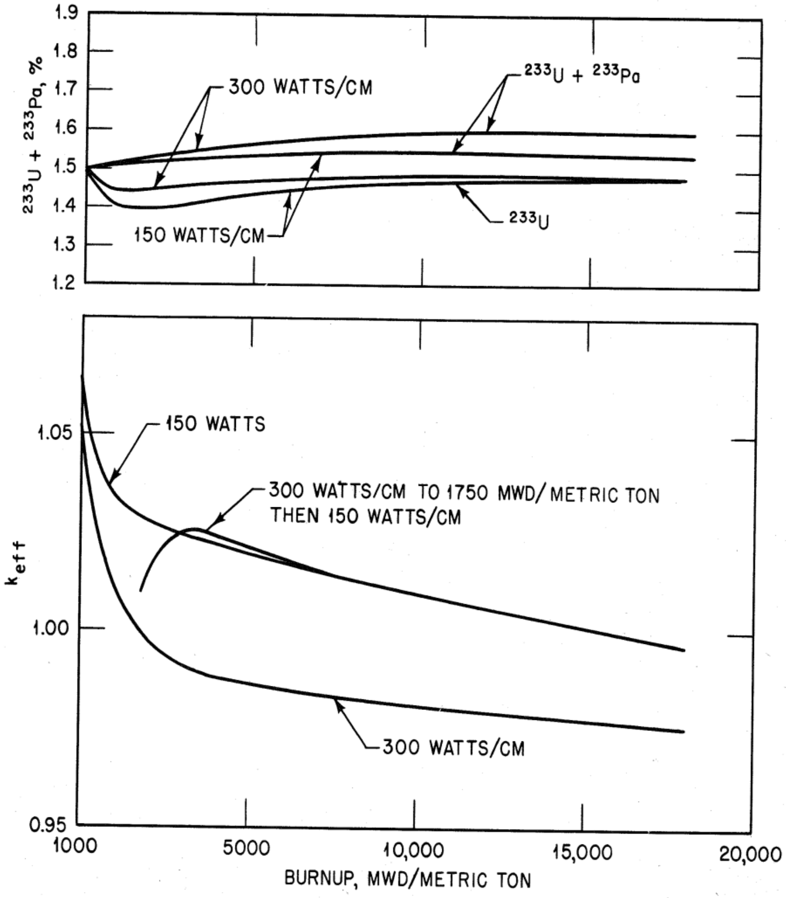


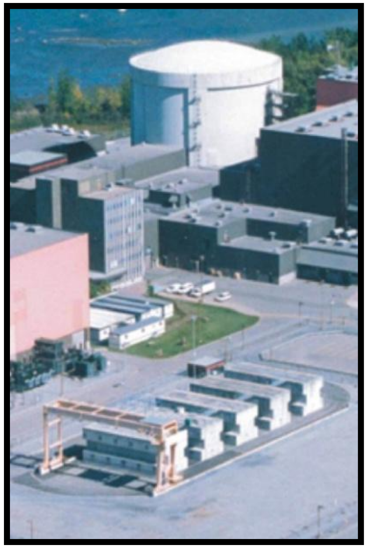
Fig. 2—The k_{eff} and content of $^{233}U + ^{233}Pa$ as a function of burnup at different power levels. Fuel-rod radius, 0.65 cm; moderator-to-fuel volume ratio, 14.8; core size, 100 m^3; and reflector thickness, 60 cm.

Thorium Fuel Cycles in HWR's

❑ Design options:

- Once Through Thorium (OTT) cycles.
  - Design for high burnup, uranium conservation.
  - Homogeneous or heterogeneous fuel, and fuel bundle design options.
  - LEU and/or Pu used as fissile material; Th is fertile.
  - U-233 is bred and burned in situ, along with LEU and Pu.
  - Spent fuel put into storage until economical to recycle.
- Self-sufficient Equilbrium Thorium (SSET) cycles.
  - Design for C.R. > 1.0, maximize burnup as much as possible.
  - Makeup feed material is Th-232.
  - Spent fuel reprocessed.
    - Fission products removed.
    - U-233, Th-232 recycled (Pa-233 allowed to decay to U-233).
  - Design for economical periodic reprocessing of fuel.

Canadian Used Fuel Management



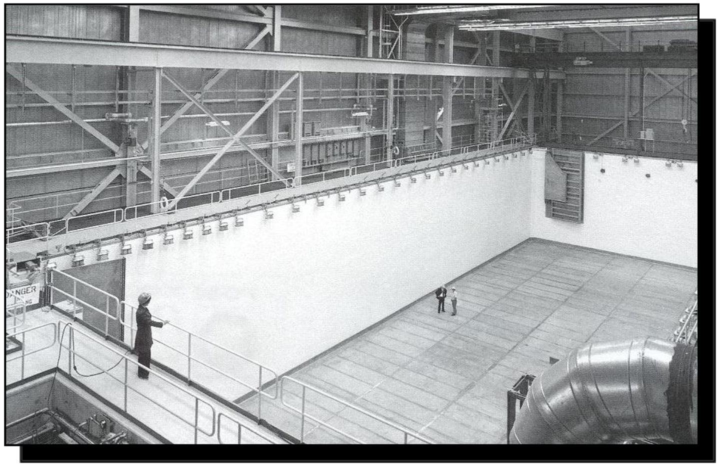
- ❑ On-site storage.
  - ➢ First ~10 years in water pool.
  - ➢ Next ~70-100 years in concrete containers.
  - ➢ MACSTOR® in use in Canada, S. Korea, Romania.
- ❑ 20-year AECL program validated long-term storage & disposal technologies.
- ❑ 2007 June 14 Natural Resources Canada approved NWMO recommended “adaptive phased approach”
  - ➢ Deep geological repository.
  - ➢ Flexibility through phased decision making process.
  - ➢ Optional interim step of shallow underground storage.
  - ➢ Continuous monitoring.
  - ➢ Potential for retrieval.
    - Recycle / re-process U, Pu, Minor Actinides (MA)
    - A future resource when supplies of NU become expensive.
    - Long-term disposal of fission products.

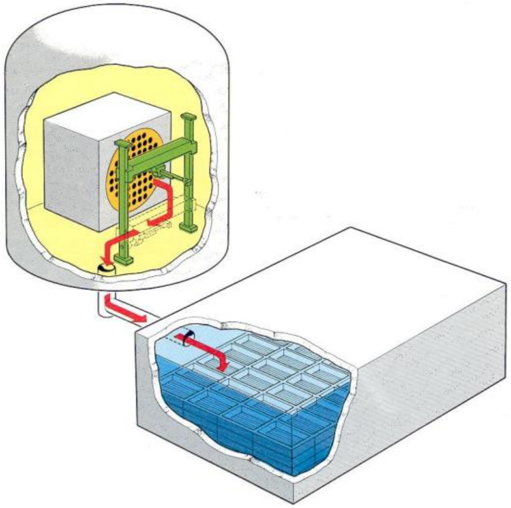
nwmo

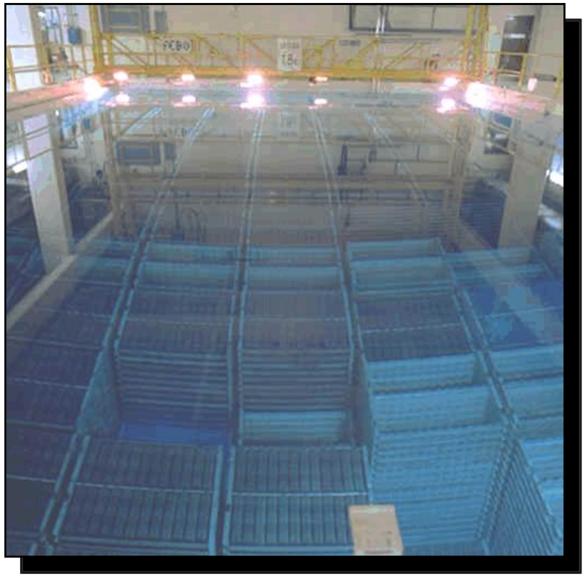
NUCLEAR WASTE MANAGEMENT ORGANIZATION

SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

CANDU Spent-Fuel On-Site Storage Water-filled Bays (Short Term)







Used Fuel Storage In Reactor Pool

CANDU Bundle Storage Baskets for Dry Storage

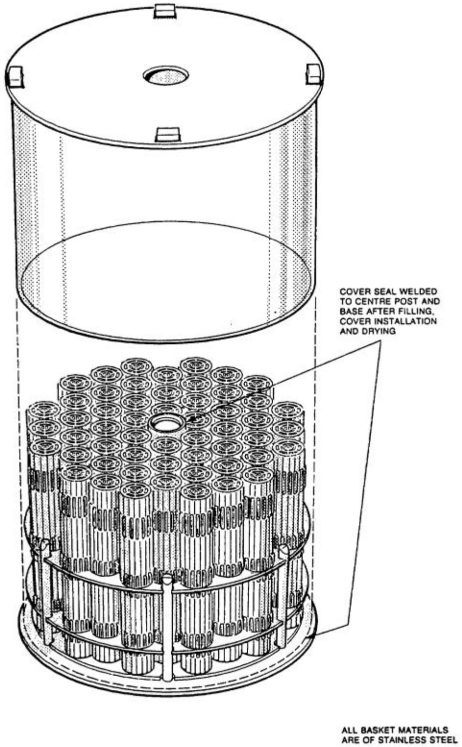
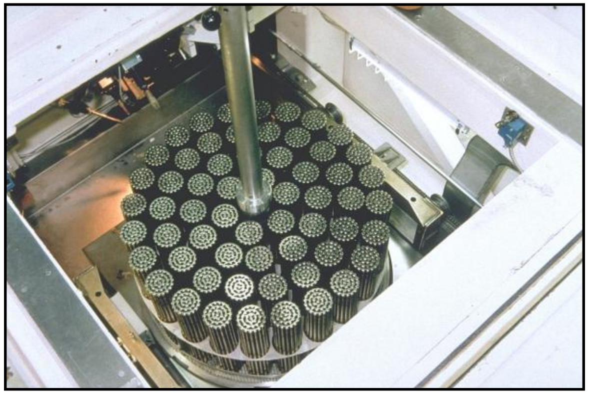
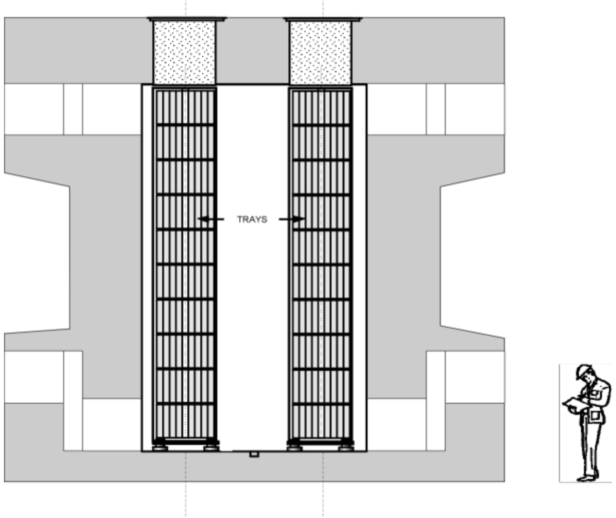


FIGURE 3-69 STORAGE BASKET

CANDU Spent-Fuel On-Site Storage

- Modular above-ground air-cooled concrete bunkers (longer term)



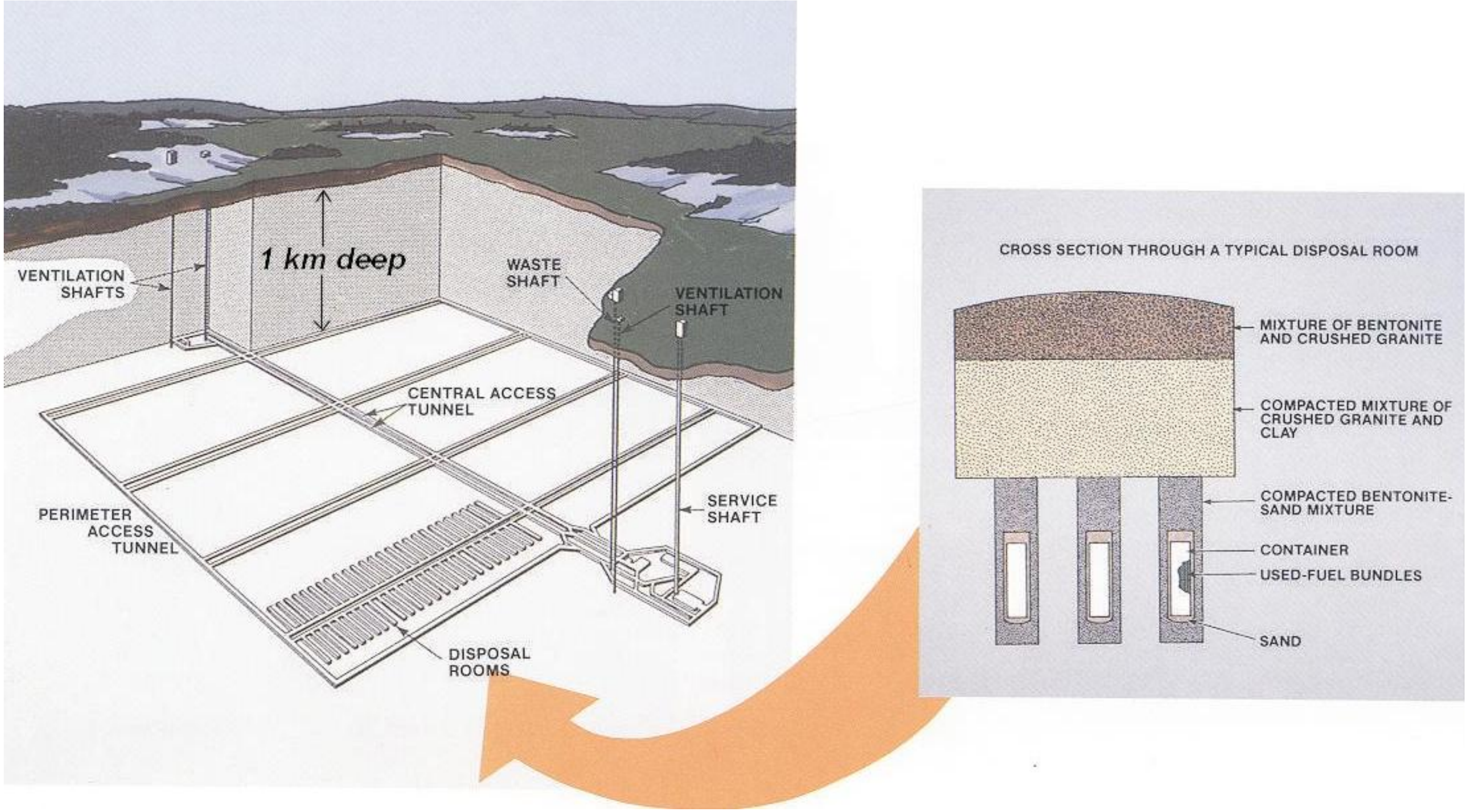


MACSTOR Dry Storage Facility

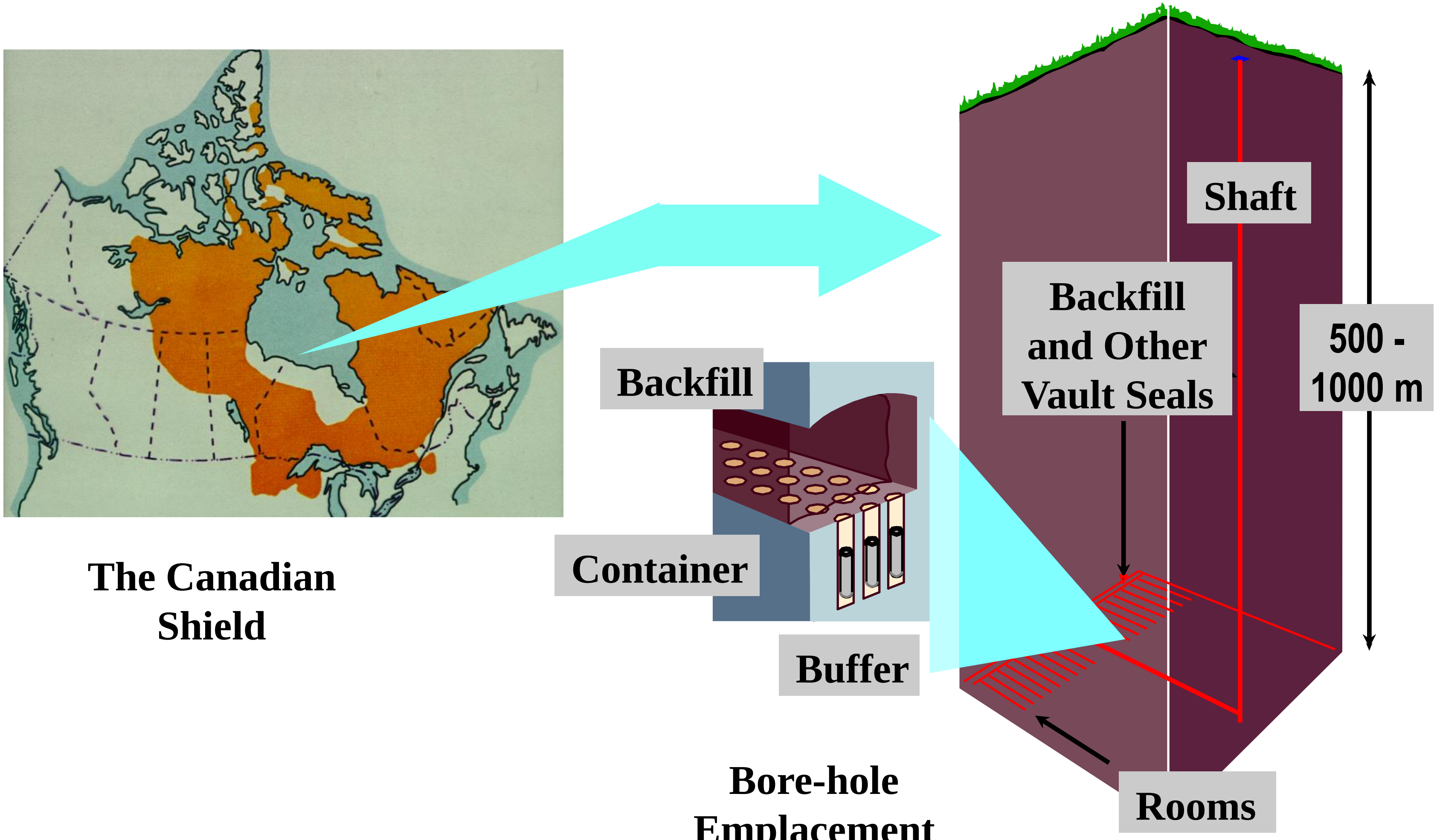
Photo from Hydro-Québec

Spent Fuel Very Long-term Storage

- Deep geological repository; retrievable if necessary.



Permanent Disposal of Used Fuel



The Canadian Shield

Bore-hole Emplacement

CANDU History

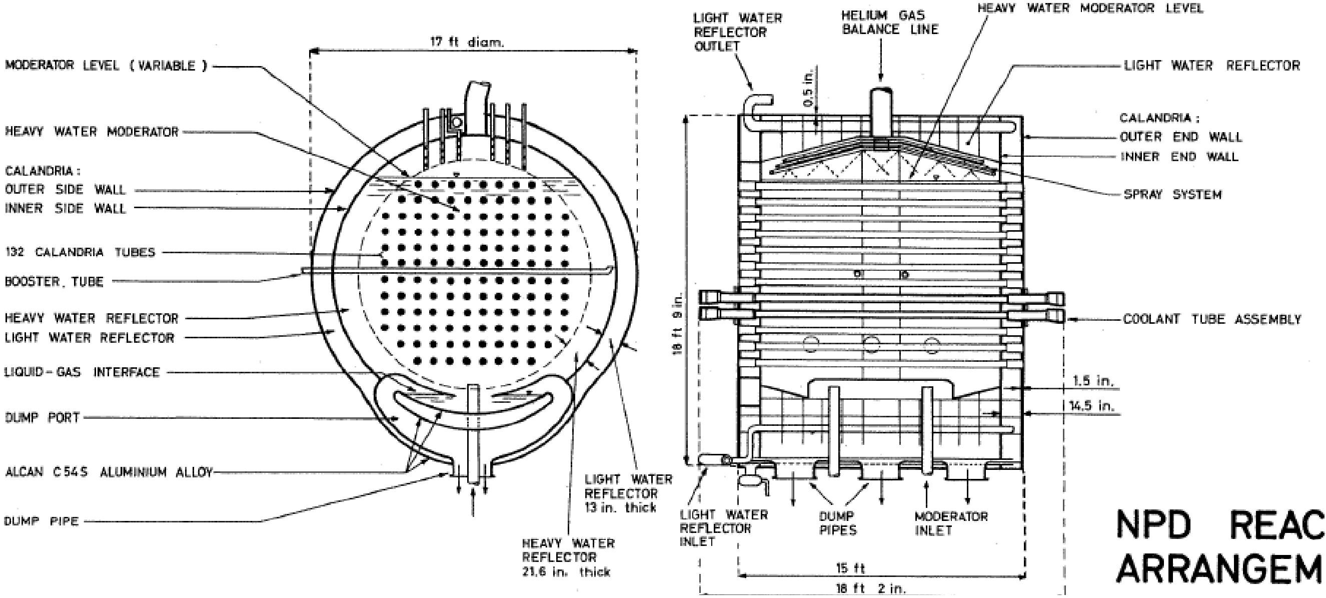
- *NPD-2 (1962)*
- *Douglas Point (1968), Gentilly-1 (1972-1977)*
- KANUPP (1972, Pakistan) – *See supplement 2.*
- RAPS 1,2 (India, 1973-1981) – *See supplement 2*.
- Pickering A/B (1971-1986)
- Bruce A/B (1976-1987)
- Darlington (1990-1993)
- CANDU-6
  - Point Lepreau (1983), Gentilly-2 (1983)
  - Embalse (1984)
  - Wolsong (S. Korea, 1983-1999)
  - Cernavoda (Romania, 1996-2007)
  - Qinshan III (China, 2002-2003)

NPD-2 (Canada, 1962)

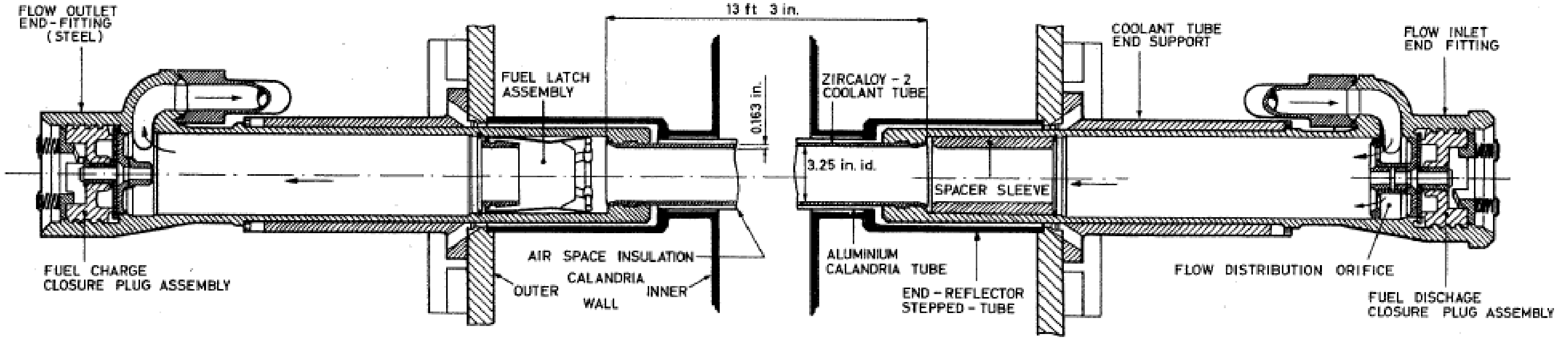
- **N**uclear **P**ower **D**emonstration – **2**
- Operated 1962-1985; shutdown 1987.
- 89 MW_{th} / 19 MW_e (21.7% efficiency)
- World’s first HWR to produce electricity.
- Pressure tubes, on-line refuelling.
- Short (0.5-m) natural-uranium fuel bundles.
- Test bed for CANDU technologies.
  - Demonstration of feasibility of PHWR concept.
  - Debugging D_2O leakage, trips, reactivity control.
  - Fuel performance, alternative designs.
  - Feedback in design and operations of Douglas Point, Pickering, Bruce, and CANDU-6.
- Training center for operations.
  - Experience for later CANDU designs.

NPD-2 (Canada, 1962)

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



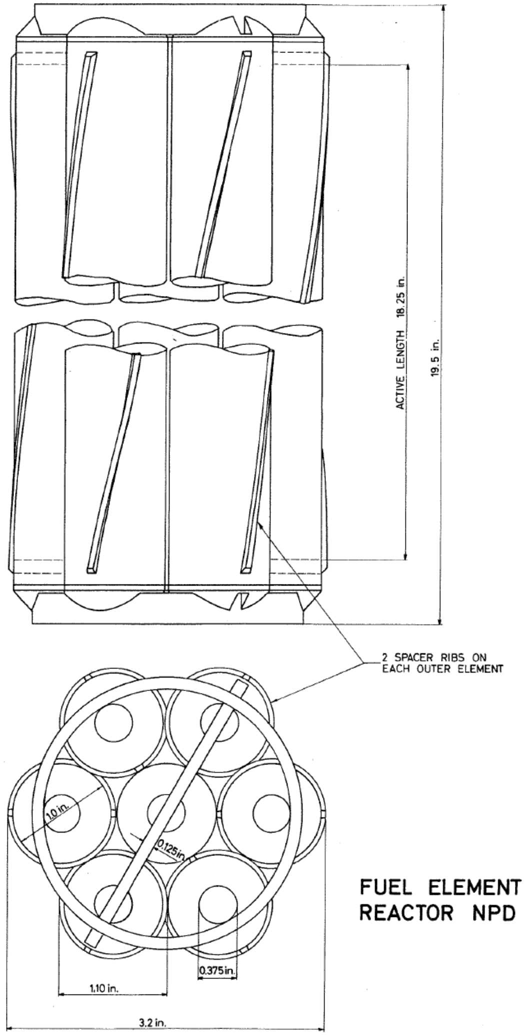
NPD REACTOR ARRANGEMENT



COOLANT TUBE ASSEMBLY

NPD-2 (Canada, 1962)

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



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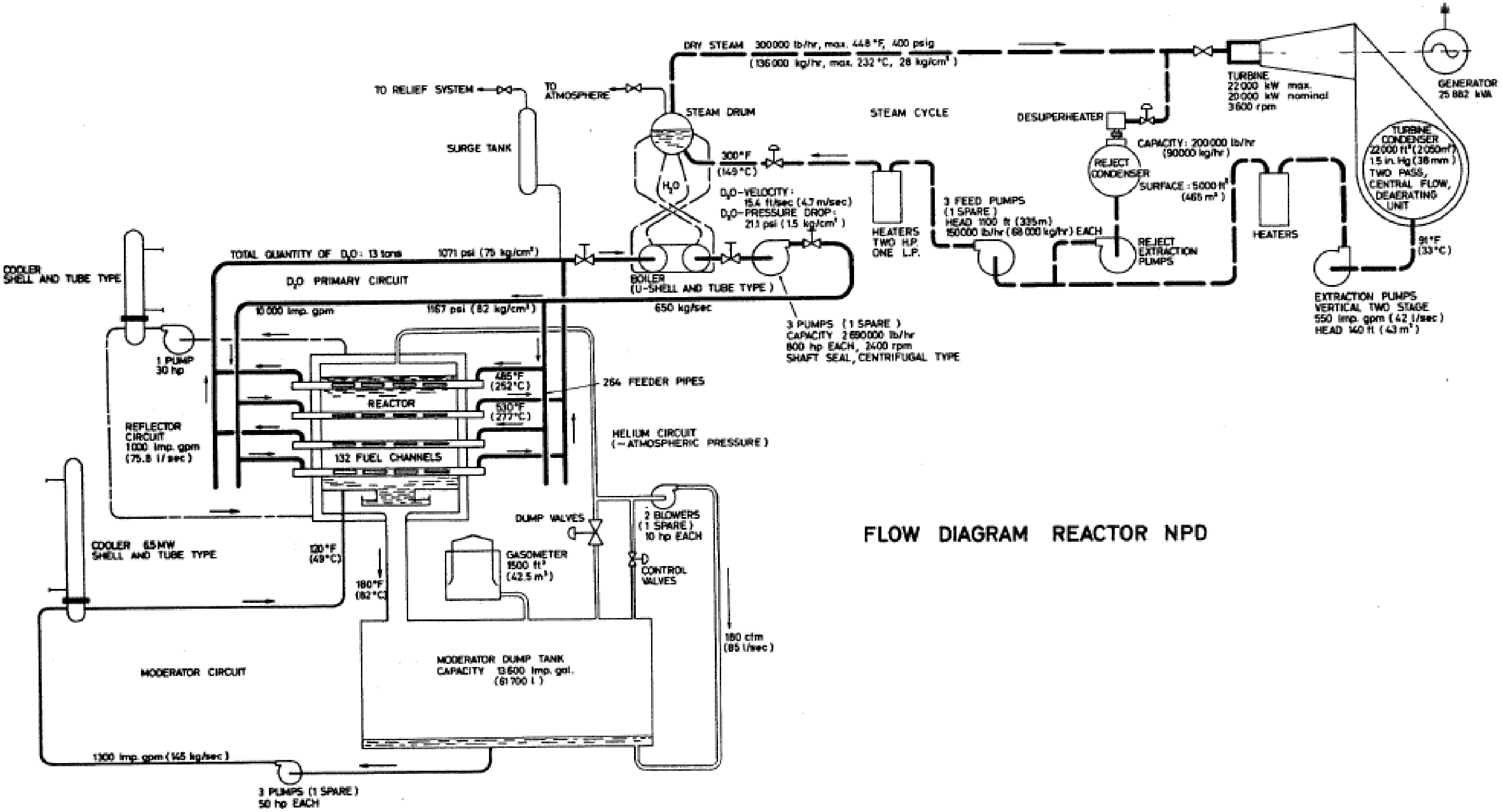
NPD-2 (Canada, 1962)

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

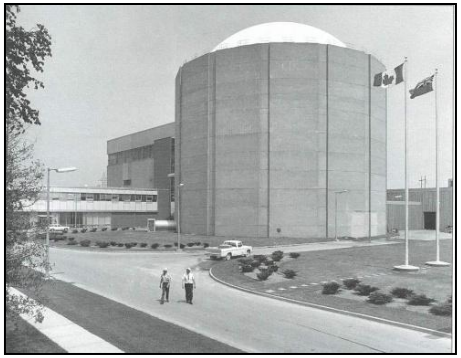


FLOW DIAGRAM REACTOR NPD

NPD-2 (Canada, 1962)

- ❑ Rolphton, Ontario (west of Chalk River Laboratories)

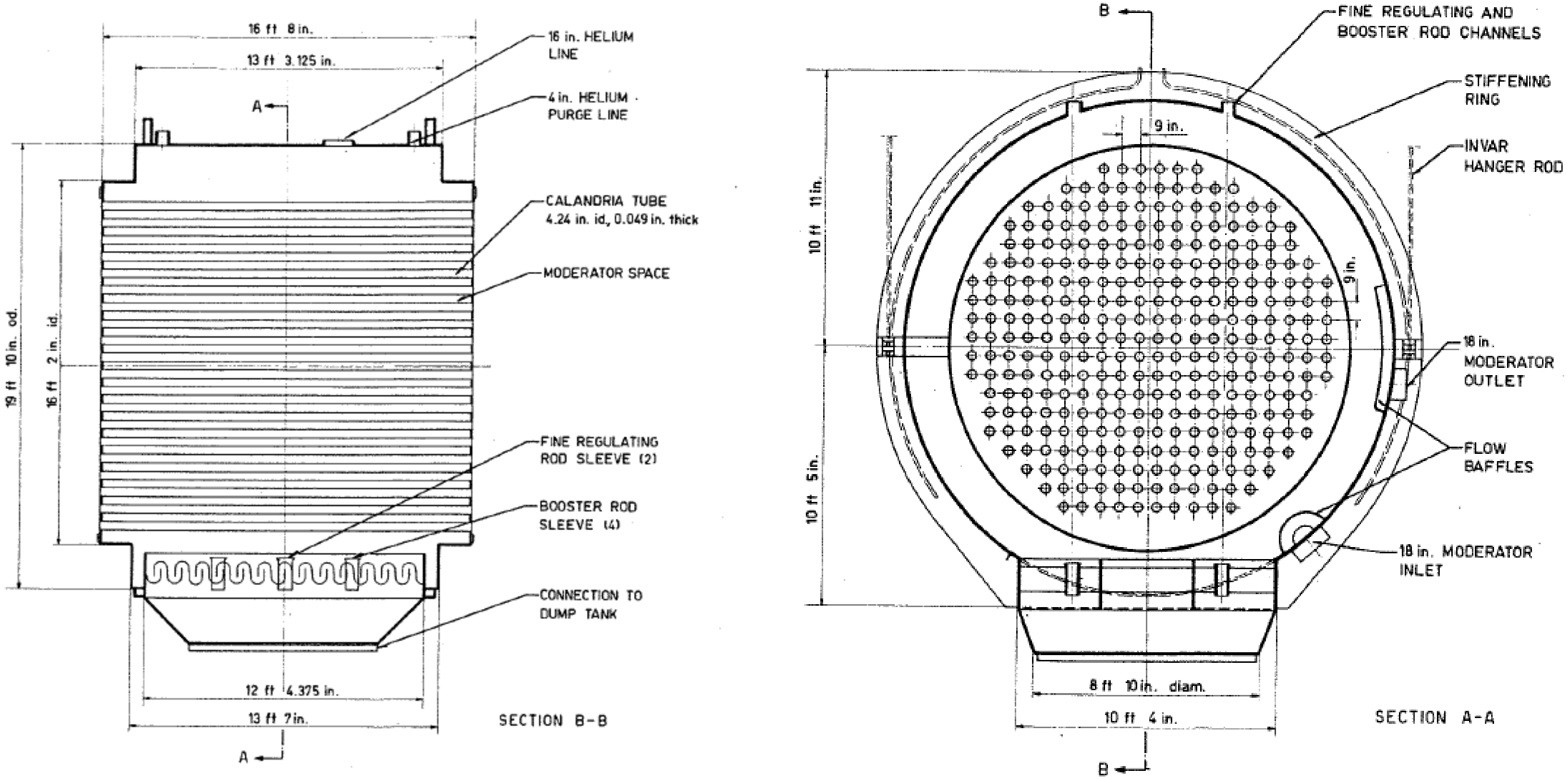
Douglas Point (Canada, 1968)



- Prototype for commercial PHWR.
  - **CAN**adian **D**euterium **U**ranium (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, η_{th}~29%, 4.77 kW/litre.
- D_2O Coolant at 9.9 MPa, 293 C.
- Steam generators / drums.
  - Steam at 4.1 MPa, 250 C

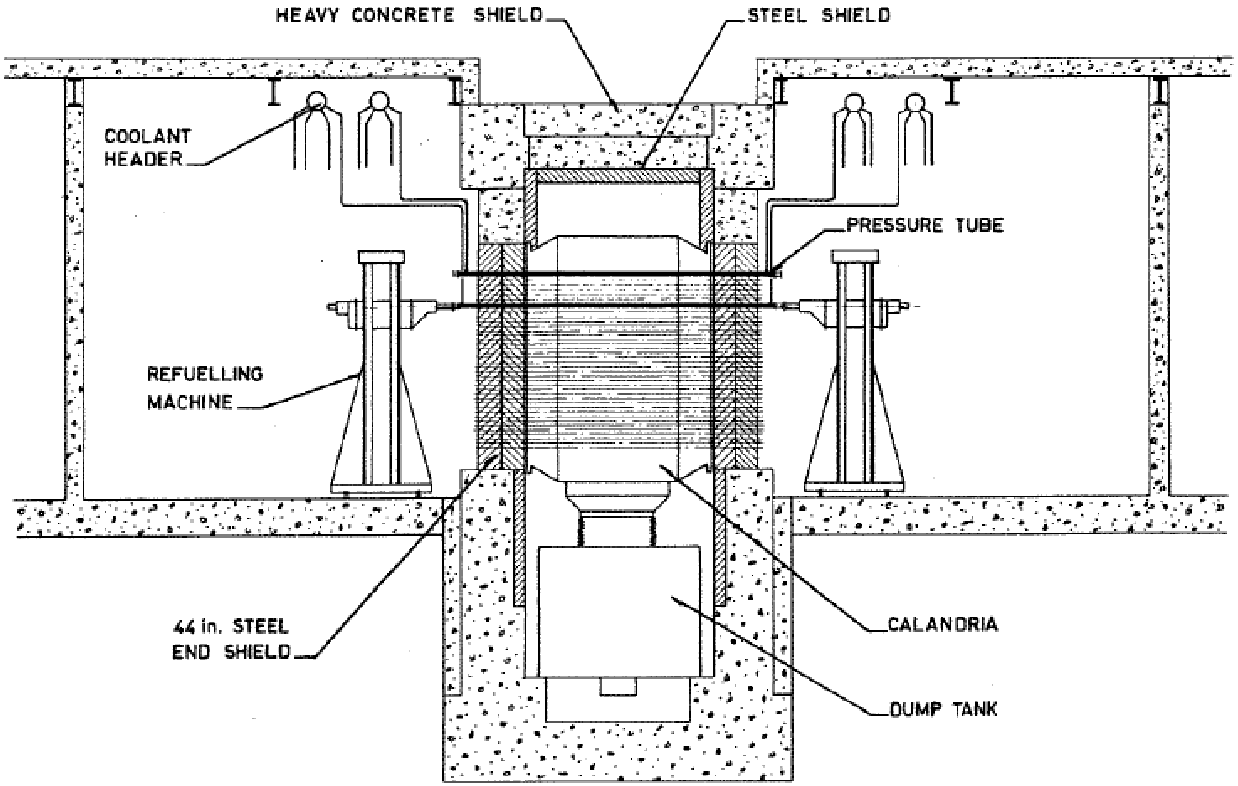
Douglas Point (Canada, 1968)

- ❑ 306 Pressure Tubes, Zr-2, 8.3 cm id
- ❑ 22.86-cm lattice pitch (smaller than NPD-2)
- ❑ Control: $CdSO_4$; mod. level, dump; booster rods, adjusters.



Douglas Point (Canada, 1968)

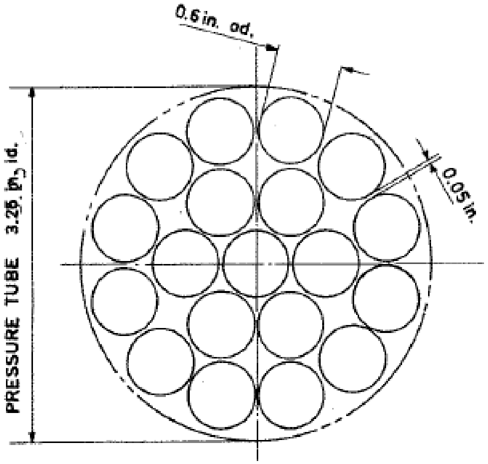
- On-line refuelling
  - 5 bundles per day, 2 per shift, 9-hour intervals

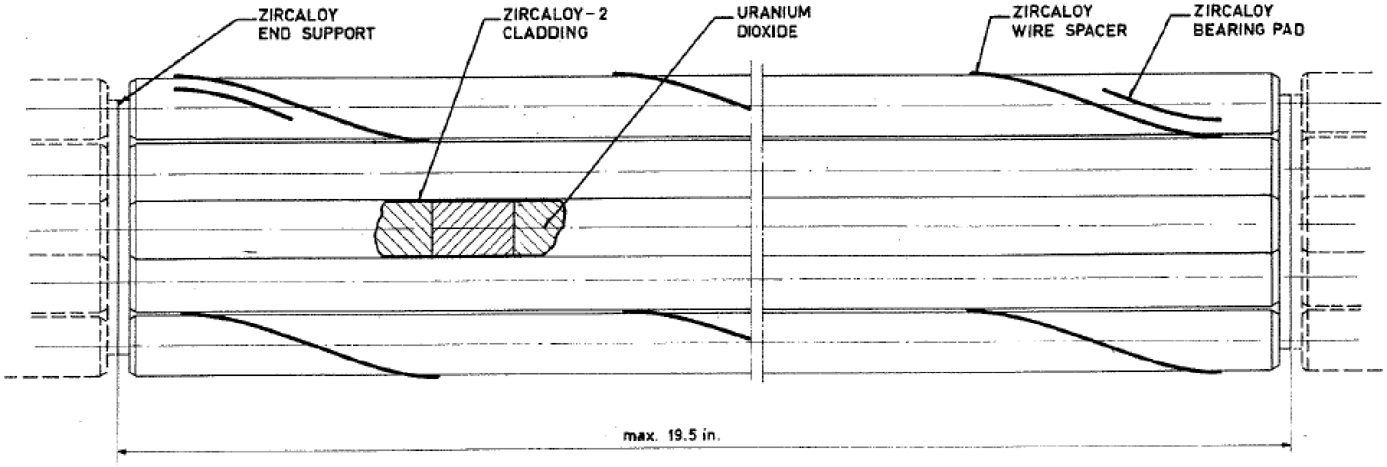


REACTOR VAULT

Douglas Point (Canada, 1968)

- 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

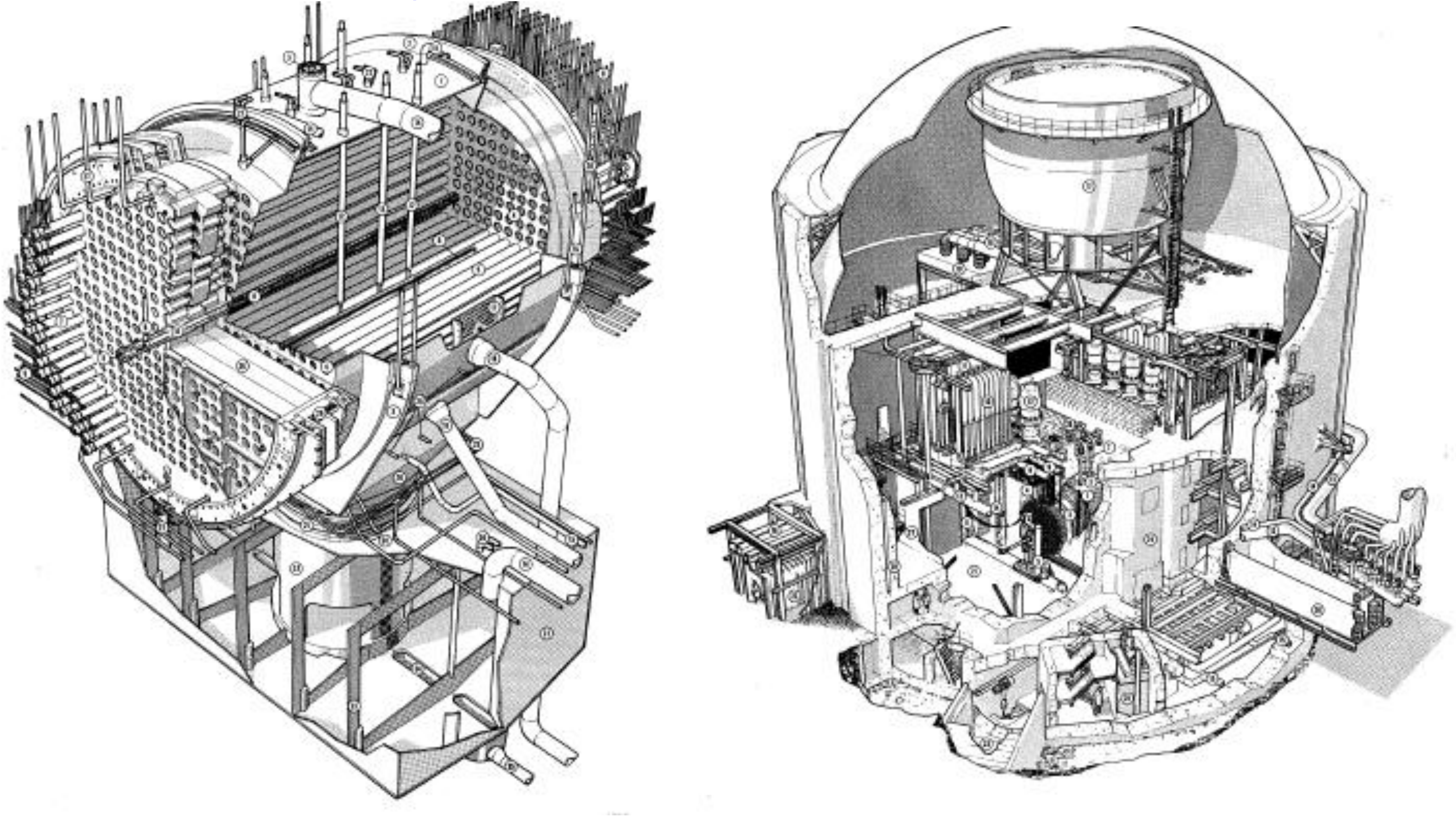




FUEL ELEMENT REACTOR CANDU

Douglas Point (Canada, 1968)

- ❑ Reactor core, containment views.



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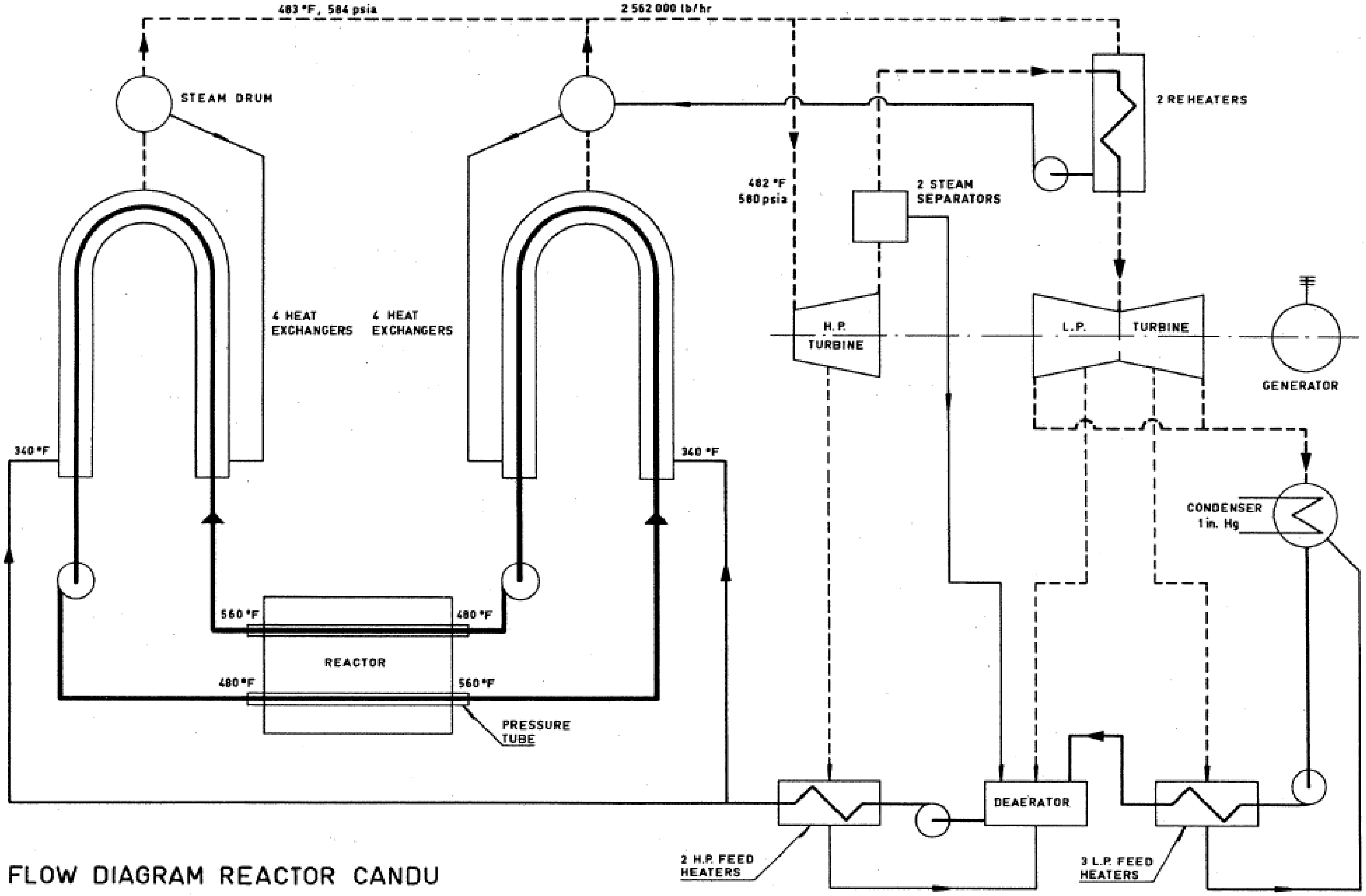
Douglas Point (Canada, 1968)

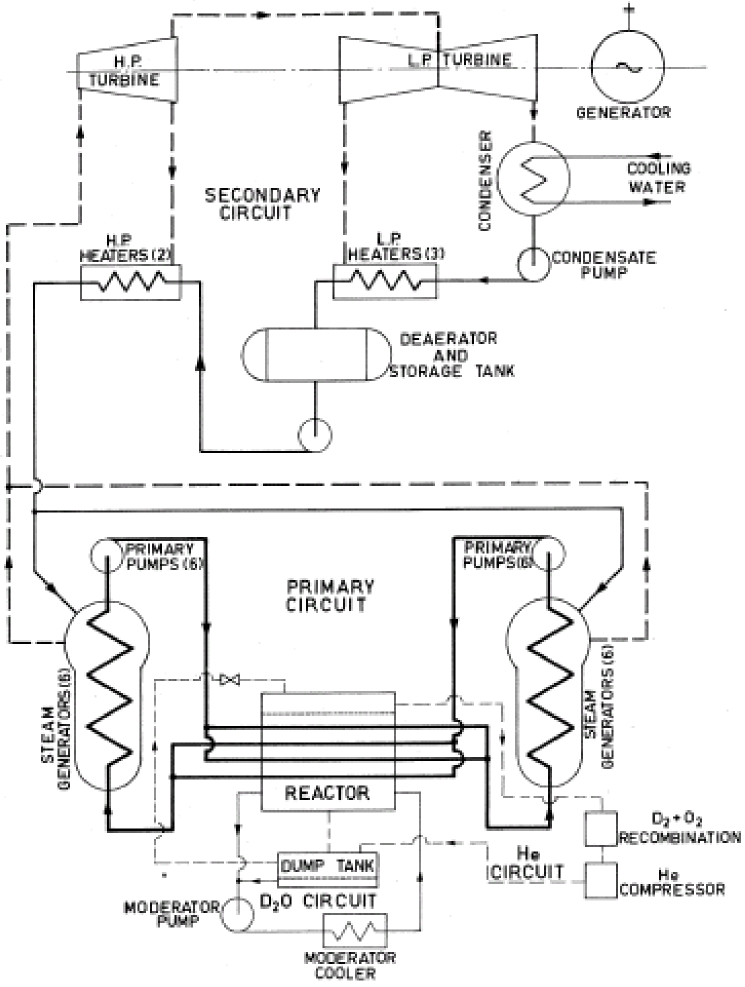
- Heat transport flow diagram



FLOW DIAGRAM REACTOR CANDU

Pickering (Canada, 1971-1986)

- Multi-unit station
  - Scale up Douglas Point.
  - Feedback from NPD-2.
- 390 Zr-2.5Nb pressure tubes
  - 28.58-cm pitch (bigger than NPD-2)
- 28-element fuel bundles.
  - Natural uranium UO$_2$.
  - C~0.82
  - 8,000 to 9,000 MWd/t burnup
  - 12 per channel.
- Pickering A (1971-1973)
  - 4x515 MW$_e$
  - First commercial reactors.
  - Units A1 and A4 operating today.
- Pickering B (1982-1986)
  - 4x516 MW$_e$ (1982-1986)
  - Operating today.



FLOW DIAGRAM REACTOR PICKERING

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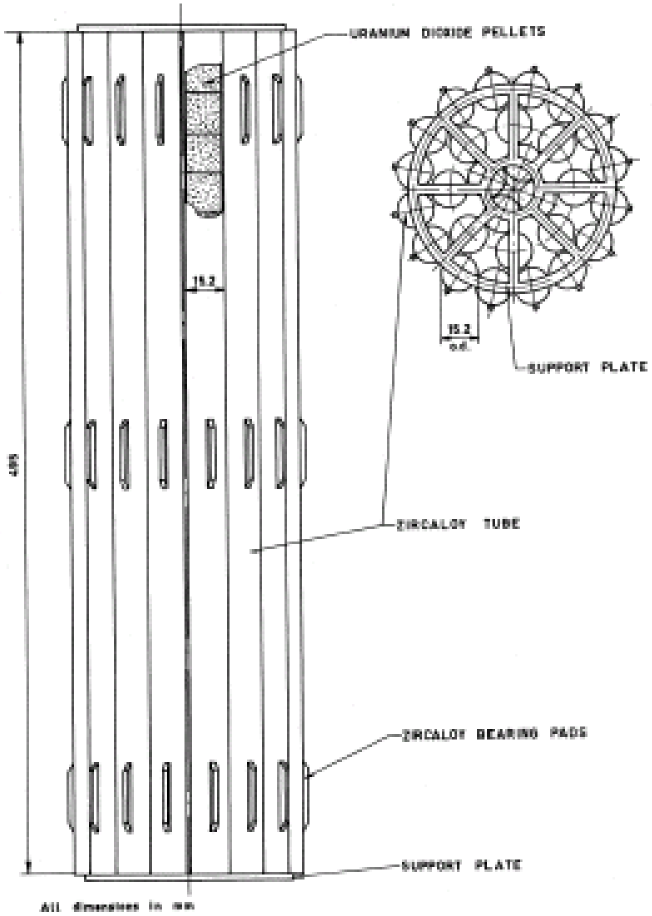
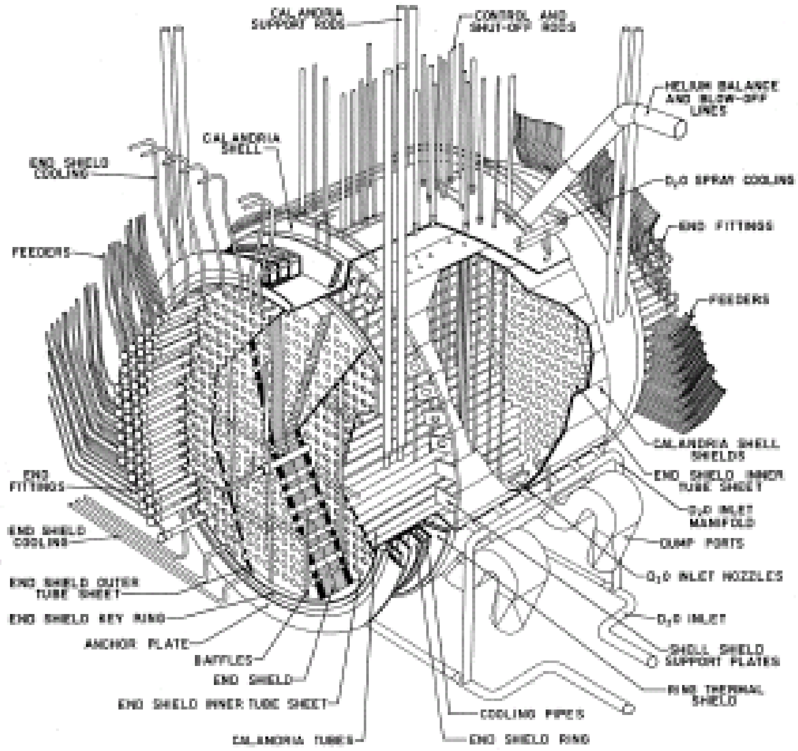
Pickering (Canada, 1971-1986)

- 28-element fuel bundles, 390 channels.

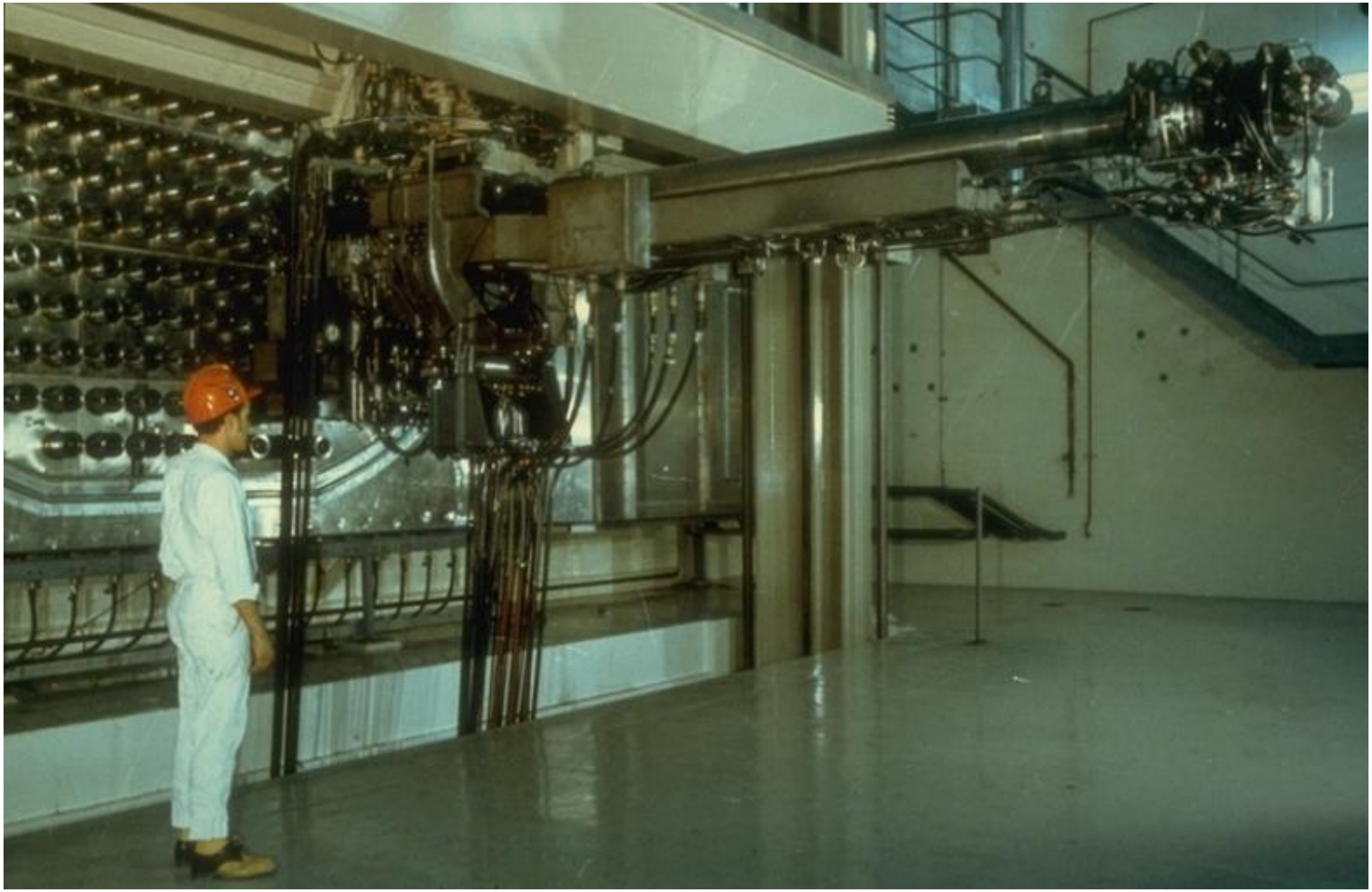


FUEL BUNDLE REACTOR PICKERING



ISOMETRIC VIEW REACTOR PICKERING

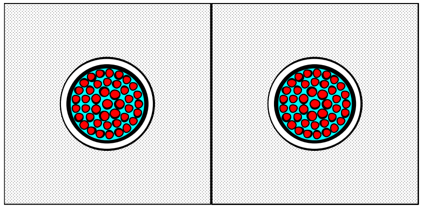
Pickering Fuelling Machine



Pickering (Canada, 1971-1986)

CANDU - Bruce / Darlington (Canada, 1976-1993)

- Multi-unit CANDU 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.
  - Burnup: ~7,500 MWd/t to 9,000 MWd/t.
    - Reduced resonance shielding with smaller pins, but,
    - Larger core with reduced neutron leakage.
- CANDU 9 (1990’s product development)
  - Single-unit 900-MWe class CANDU station based on Bruce/Darlington designs.



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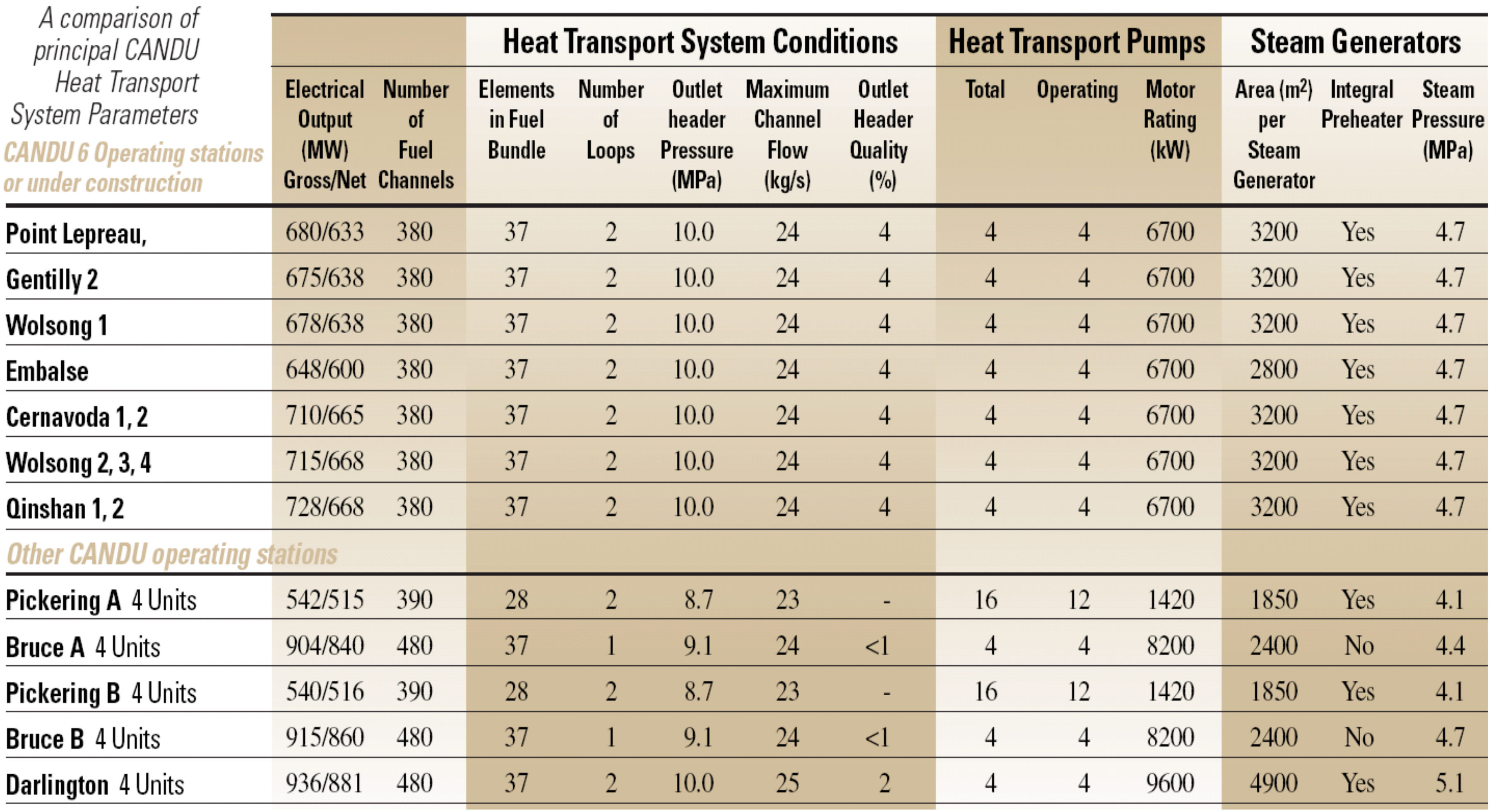
CANDU - Bruce / Darlington (Canada, 1976-1993)

- 840 MW_e to 881 MW_e



A comparison of principal CANDU Heat Transport System Parameters

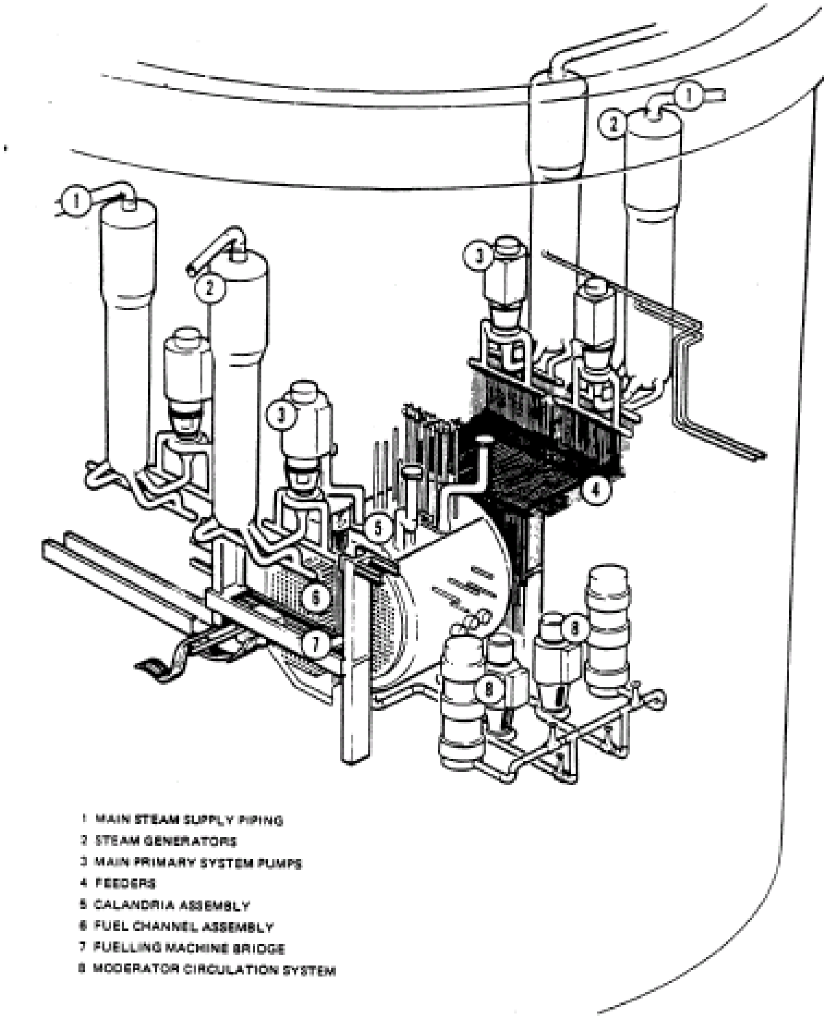
			Heat Transport System Conditions					Heat Transport Pumps			Steam Generators		
	Electrical Output (MW) Gross/Net	Number of Fuel Channels	Elements in Fuel Bundle	Number of Loops	Outlet header Pressure (MPa)	Maximum Channel Flow (kg/s)	Outlet Header Quality (%)	Total	Operating	Motor Rating (kW)	Area (m²) per Steam Generator	Integral Preheater	Steam Pressure (MPa)
CANDU 6 Operating stations or under construction													
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 - Darlington (1990-1993)

- ☐ Construction during 1980's (350-tonne steam generator).

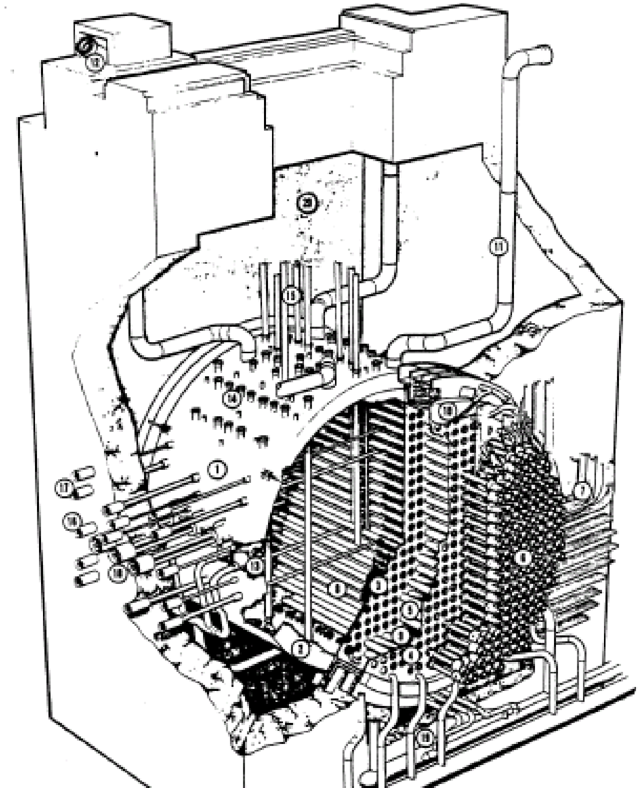
CANDU-6 (Canada, 1983-2007)

- ☐ Single-unit Station
  - ➢ 600 to 670 MWe net
  - ➢ 380 channels.
- ☐ Operations / Design Feedback
  - ➢ Pickering, Bruce.
- ☐ Domestic
  - ➢ Point Lepreau, Gentilly-2
- ☐ International
  - ➢ Argentina, S. Korea,
  - ➢ Romania, China



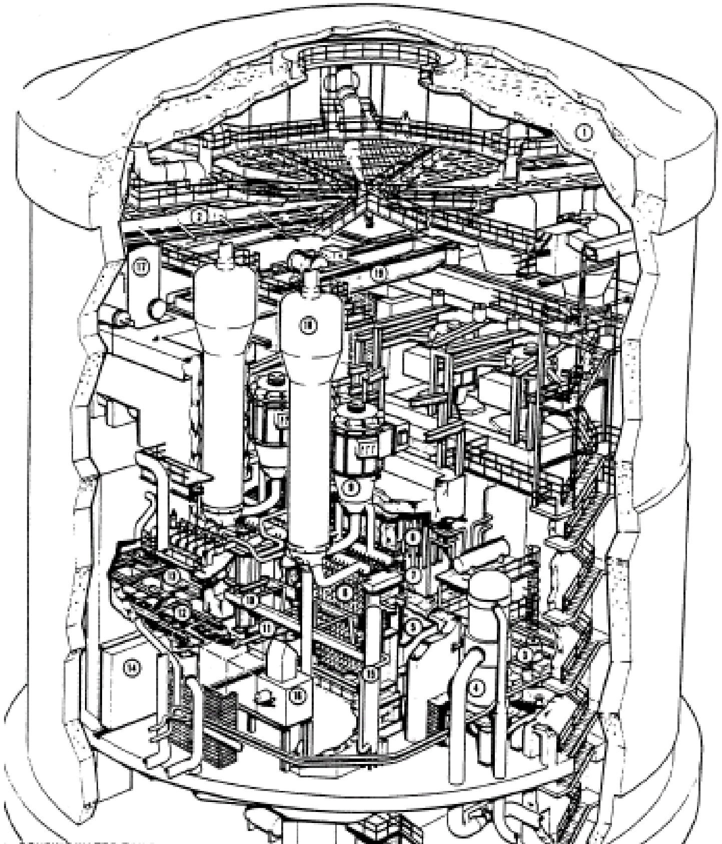
CANDU-6 (Canada, 1983-2007)

- Core, containment views.



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

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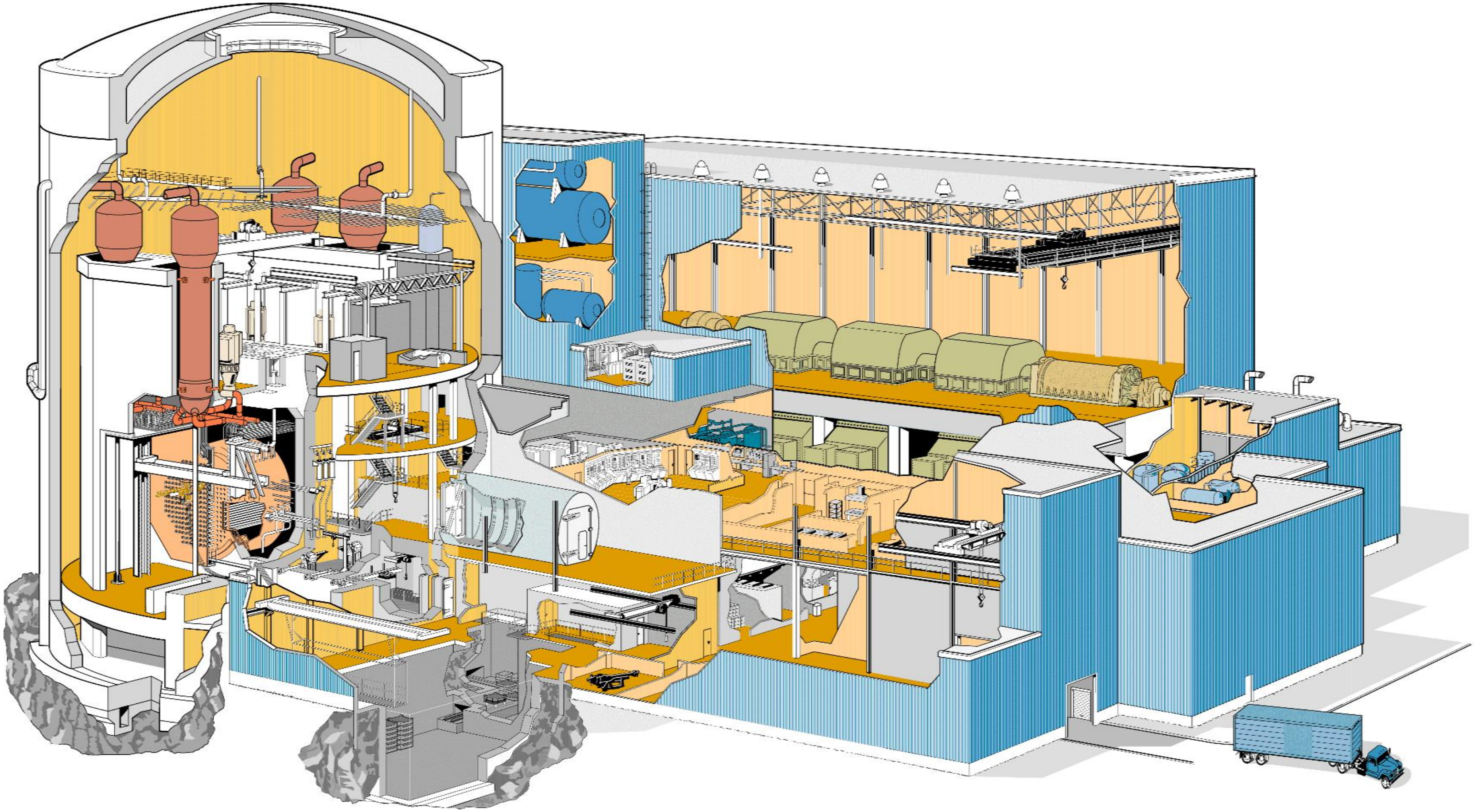
CANDU-6 (Canada, 1983-2007)



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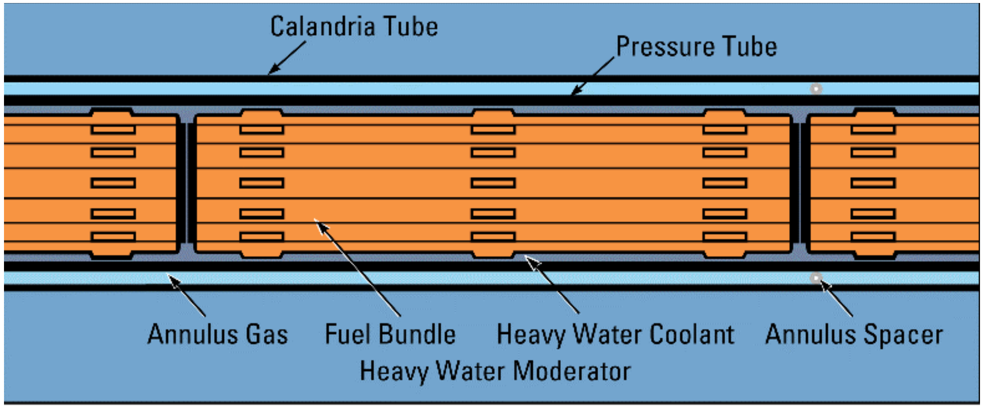
CANDU-6 (Canada, 1983-2007)

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



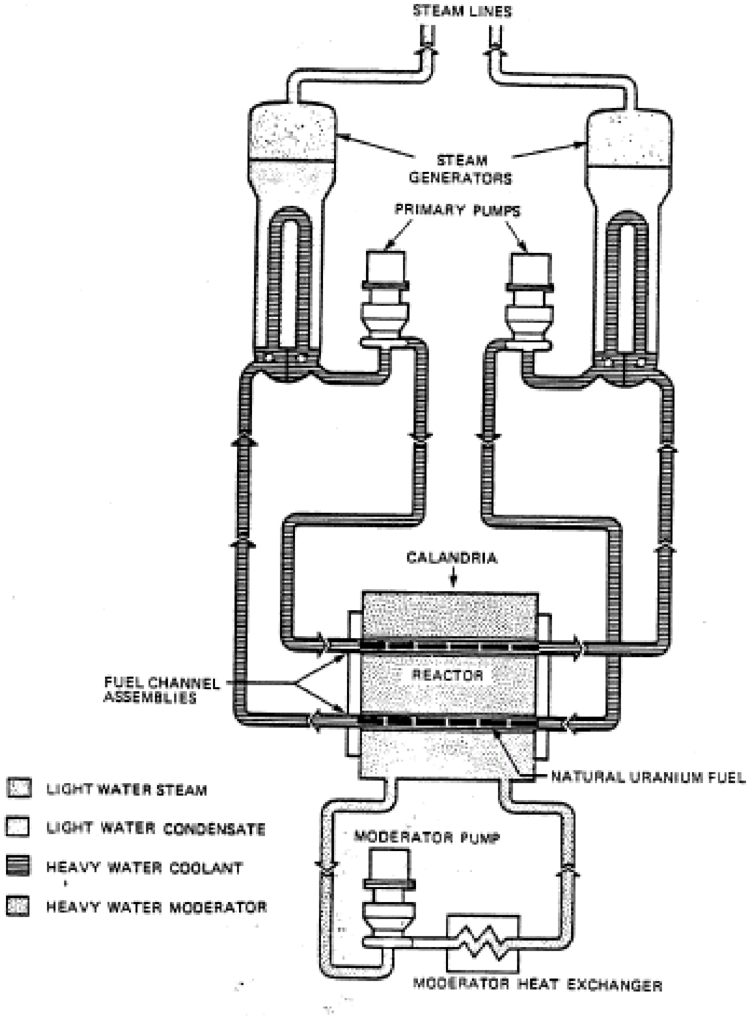


FIGURE 2.2.1 CANDU NUCLEAR STEAM SUPPLY SYSTEM

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CANDU-6 (Canada, 1983-2007)

- ❑ Steam generator.
- ❑ Reactor face.

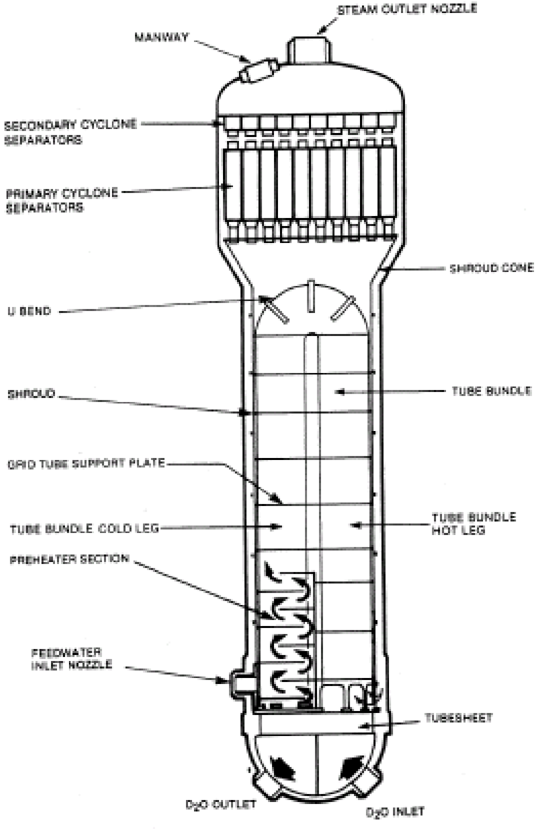


FIGURE 2.2-8 CANDU STEAM GENERATOR

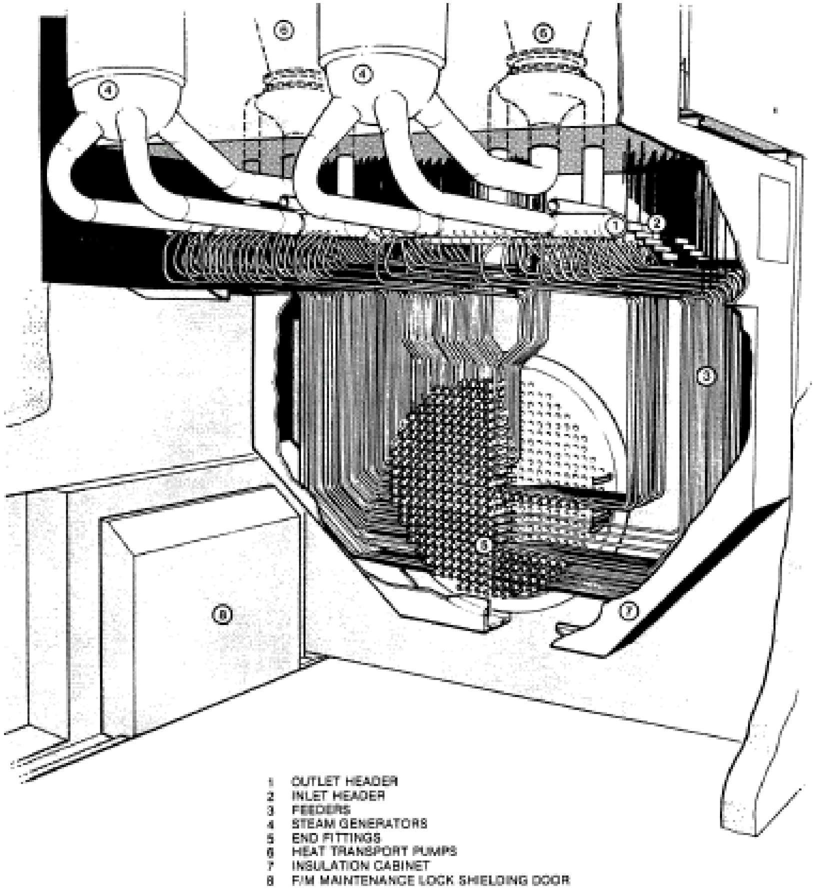
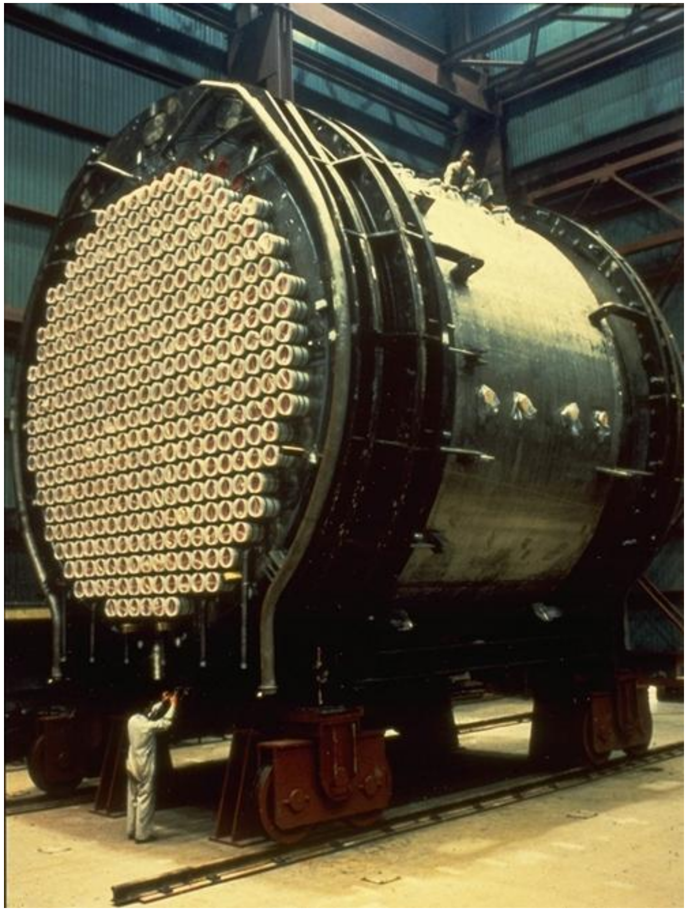
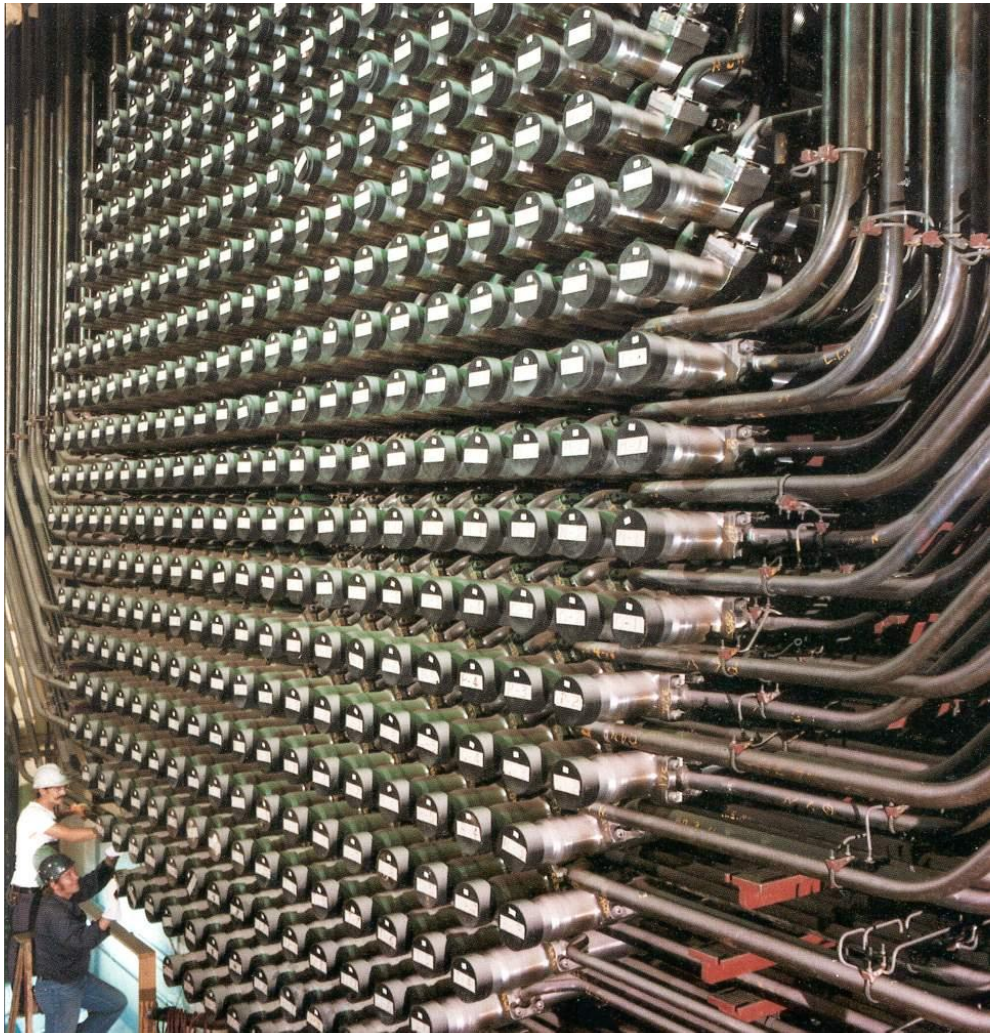


FIGURE 2.2-7 FEEDER AND HEADER ARRANGEMENT

CANDU-6 (Canada, 1983-2007)

- ☐ Headers and feeders for each channel.





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CANDU-6 – Reactivity Control

- ☐ Flux Detectors
  - ➢ Vertical / Horizontal
  - ➢ Vanadium, Inconel / platinum.
- ☐ Adjuster Rods.
- ☐ Shutoff Rods.
- ☐ Solid Control Absorber.
- ☐ Liquid Zone Controller
  - ➢ H_2O filled.
  - ➢ He cover gas.

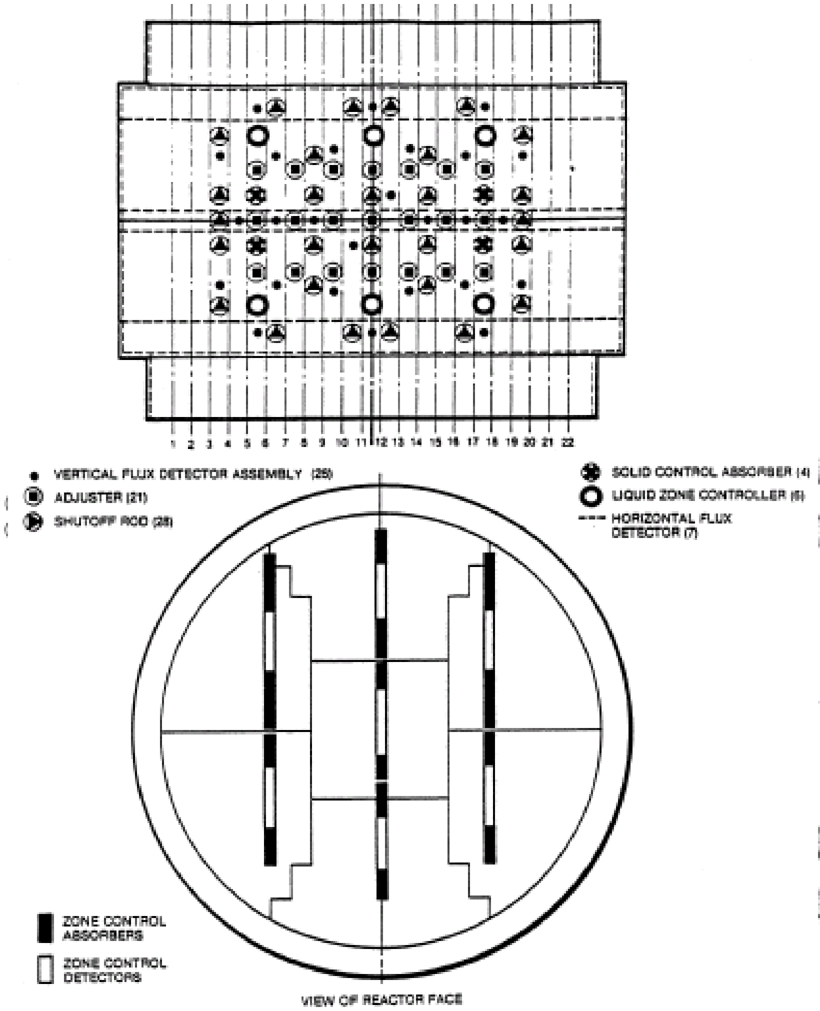


FIGURE 2.4-2 REACTIVITY MECHANISM LAYOUT

CANDU-6 Reactivity Control

- ❑ The reactor is kept exactly critical (k_{eff}=1.000) during operation.
  - ➢ Neutron production (through fission) exactly equals neutron loss (through absorption and leakage from core).
    - $k_{eff} = P / (A + L) = 1.000$
- ❑ 14 liquid zone controllers provide both bulk reactivity control, and spatial control of the power distribution.
  - ➢ Water level in each zone control unit is separately controlled.
    - To maintain the reactor critical.
    - To maintain the power in each zone to the required level.

CANDU-6 – Shutdown Systems

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

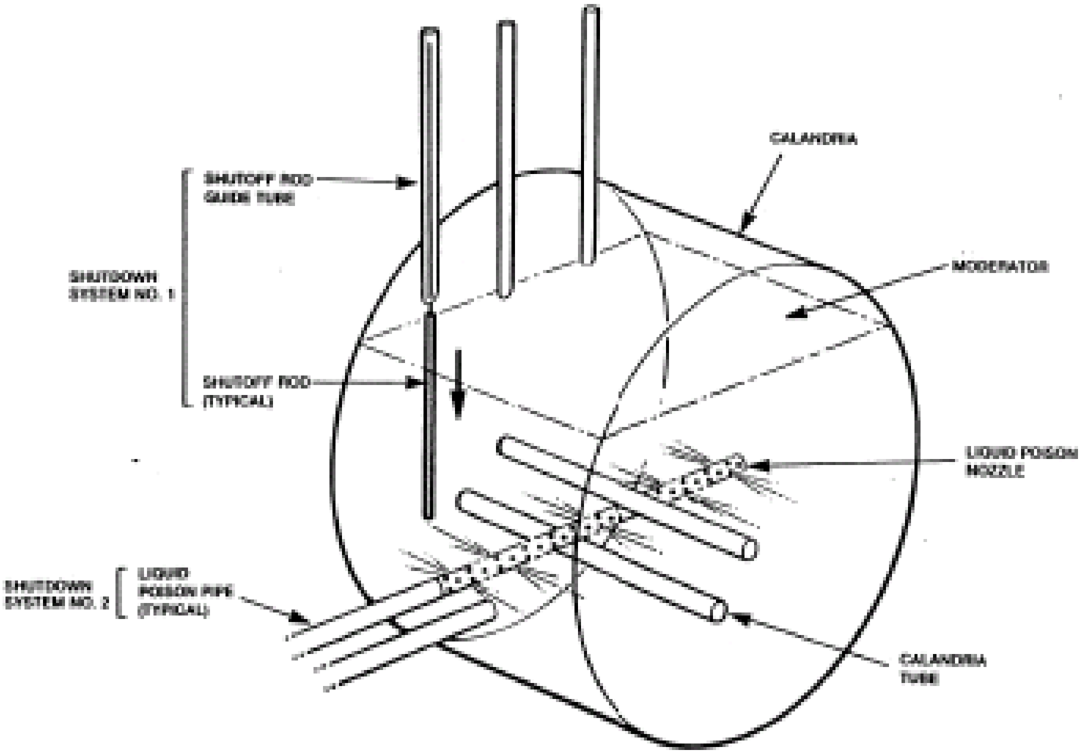
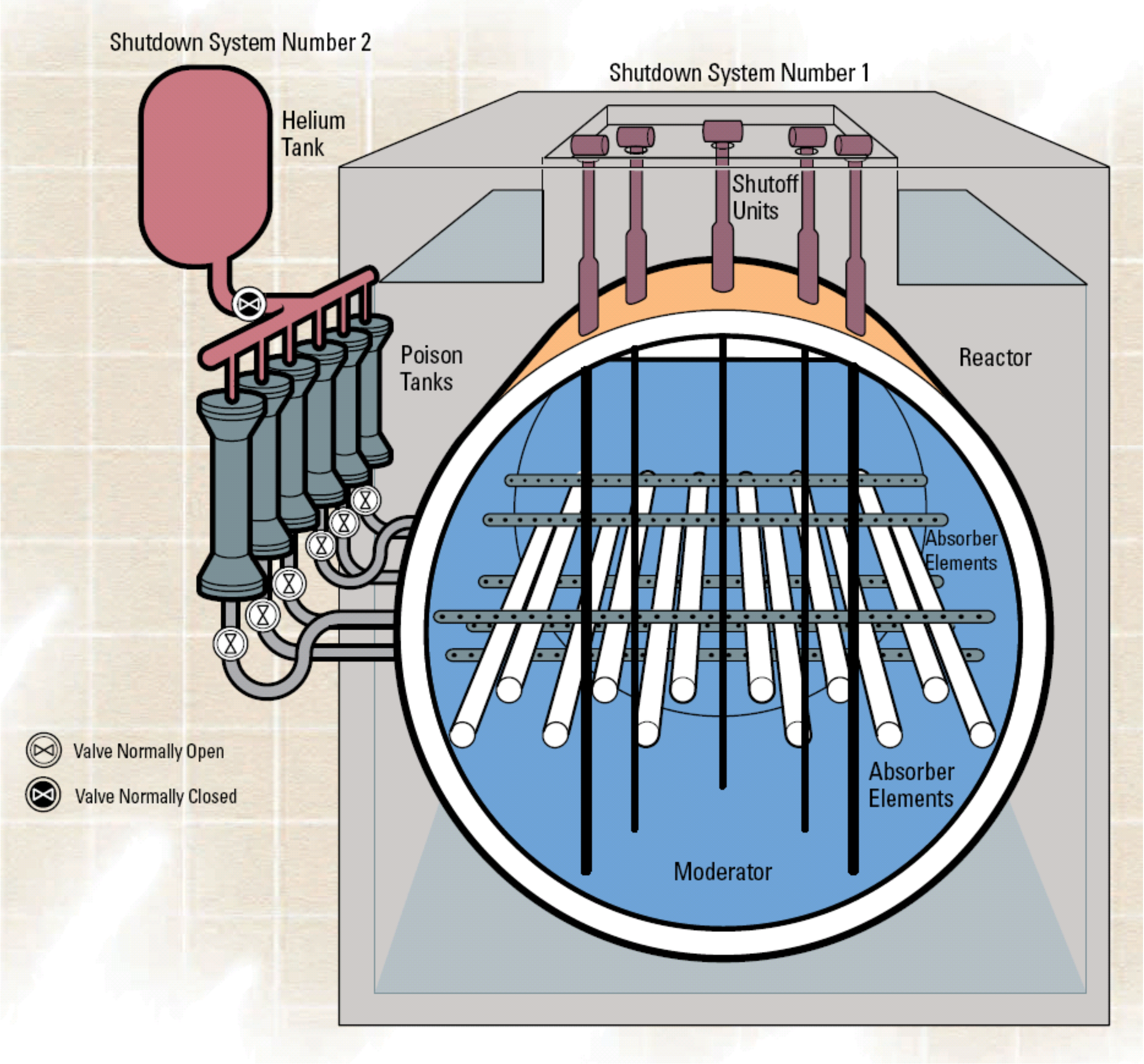


FIGURE 4.3-5 SHUTDOWN SYSTEMS: SHUTOFF RODS AND LIQUID "POISON" INJECTION

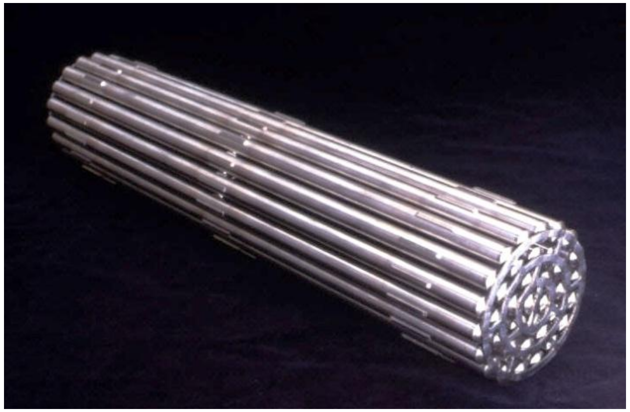
CANDU-6 – Shutdown Systems

- ❑ SDS1
    - ➢ Mechanical Rods
- ❑ SDS2
    - ➢ Poison injection.
    - ➢ Gadolinium
    - ➢ Boron



CANDU-6 – Re-fuelling

- ☐ 2 fuelling machines
    - ➢ Charge/discharge
- ☐ 12 bundle string
- ☐ 8-bundle shift
    - ➢ 8 new bundles
    - ➢ 4 old bundles removed
    - ➢ end plugs replaced
- ☐ ~110 bundles / week
    - ➢ Bundle in core for ~280 – 300 days.



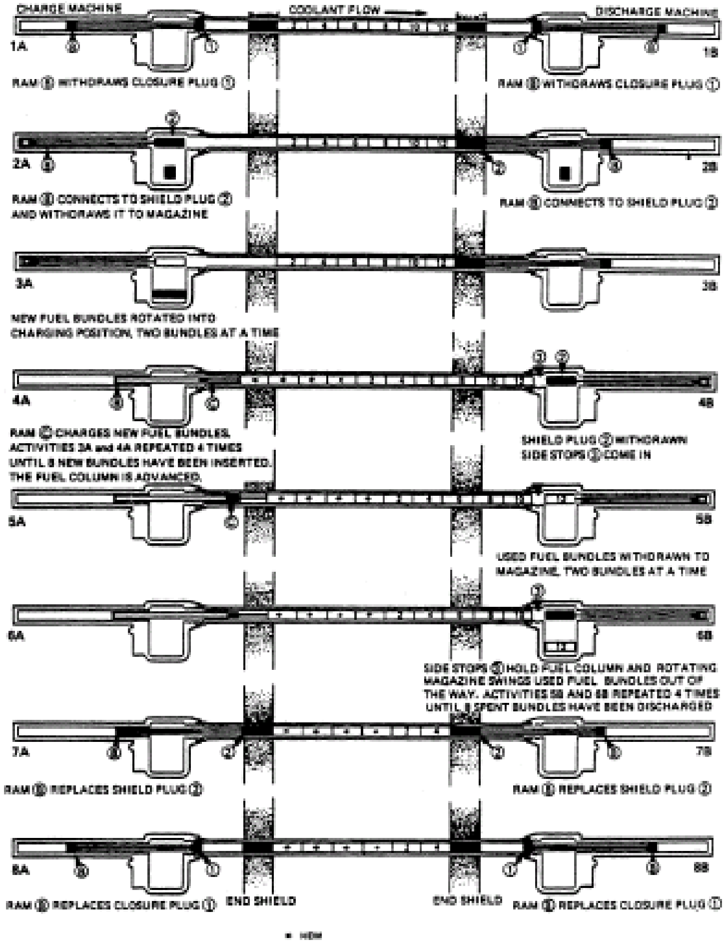


FIGURE 5.0-2 8-BUNDLE CHANGING SEQUENCE IN A CANDU 600 MW(e) PHWR

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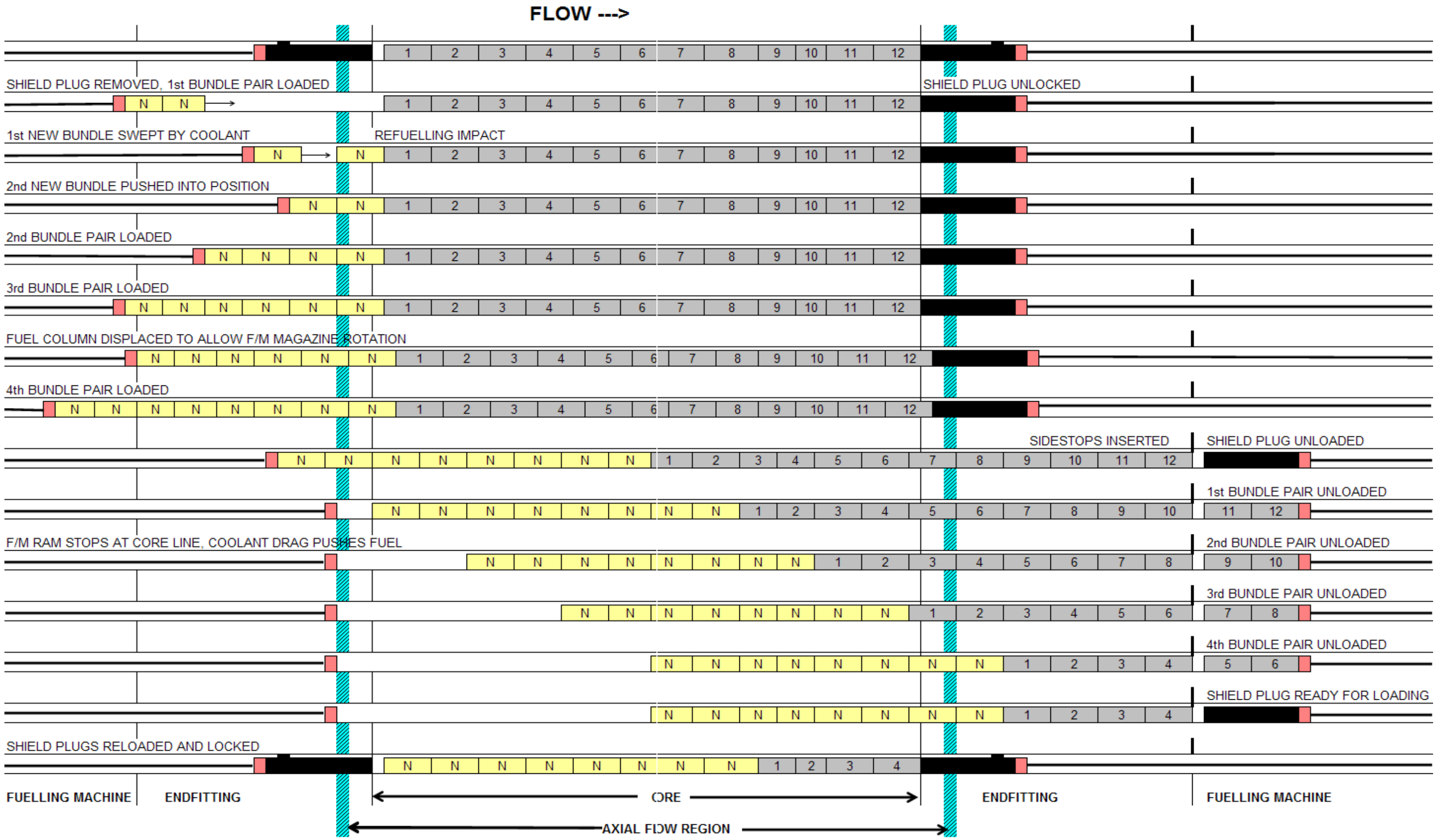
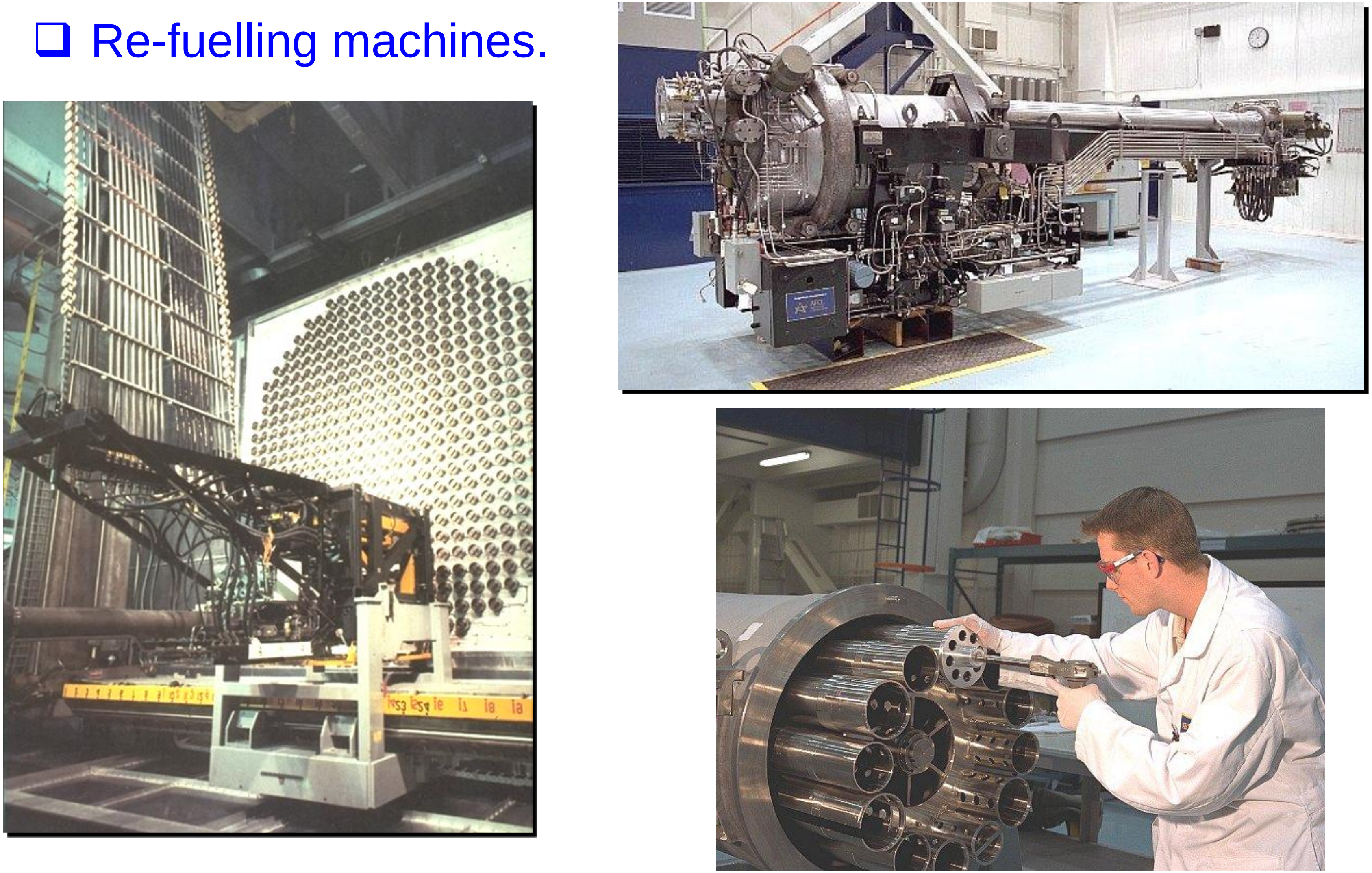
CANDU-6 Re-fuelling Scheme



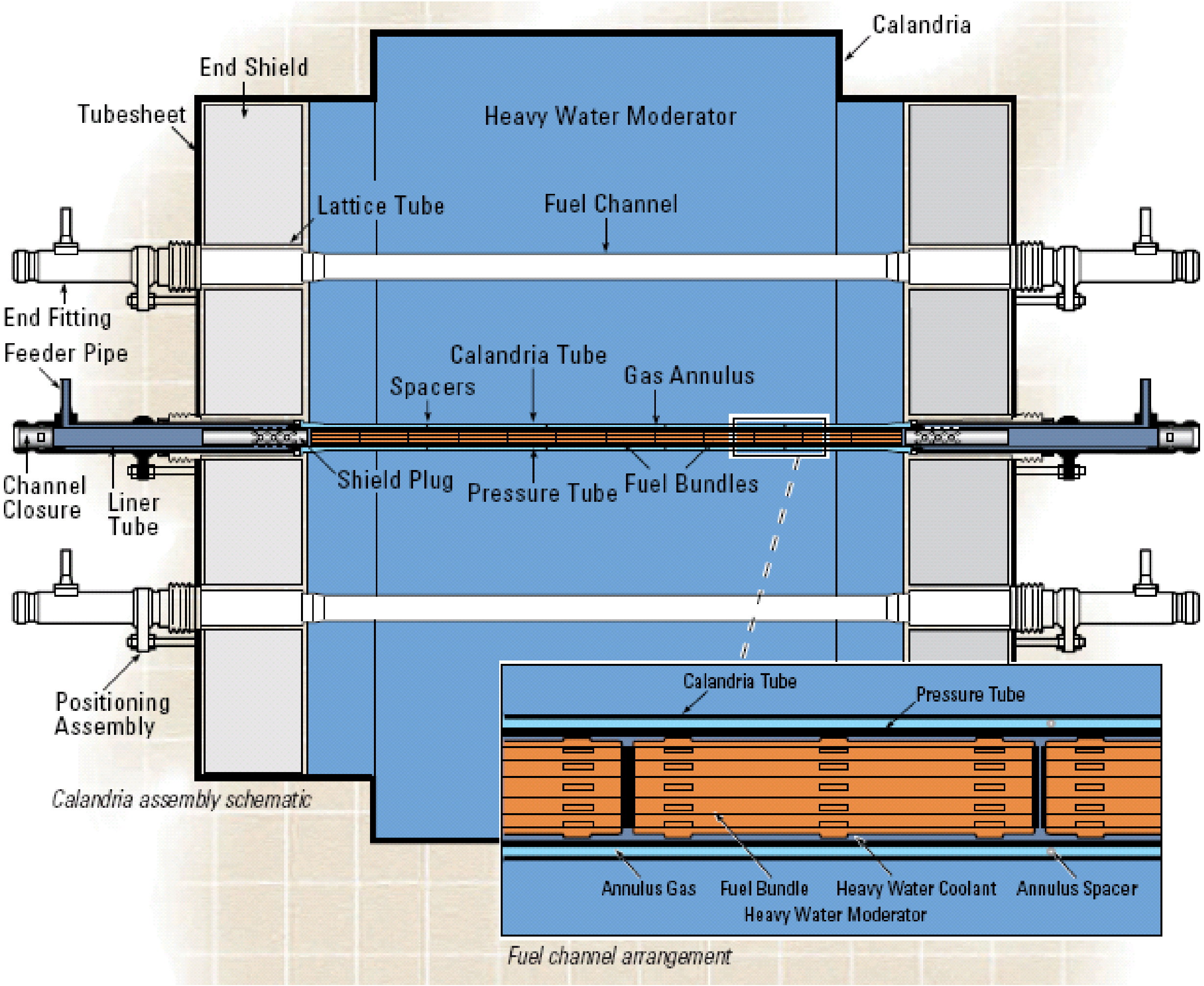
CANDU-6 – Re-fuelling Machines

- ❑ Re-fuelling machines.



CANDU-6

- Core fuelling.



Calandria assembly schematic

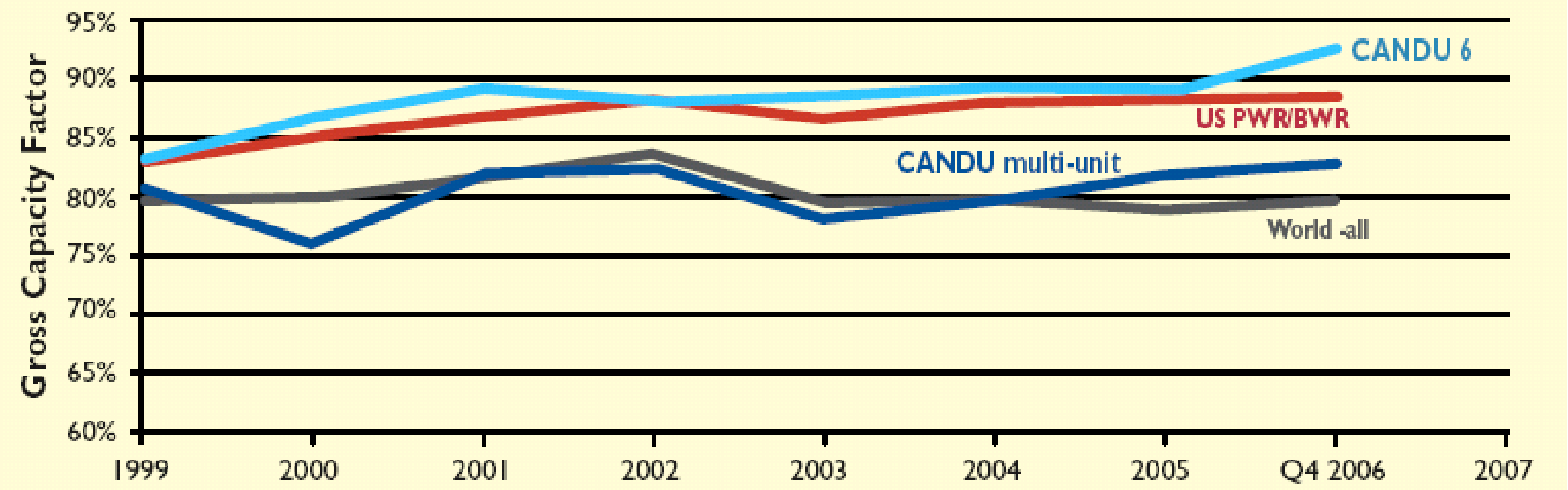
Fuel channel arrangement

CANDU-6 Performance

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

CANDU 6/PHWR Performance Trends (1999 - 2006)

Reference: CANDU Owners Group Newsletter



COGnizant Volume 12, Issue 6, 2007, 2006 U.S. and world data based on Q4 results (courtesy of NEI)
The graph is for comparison of trends only

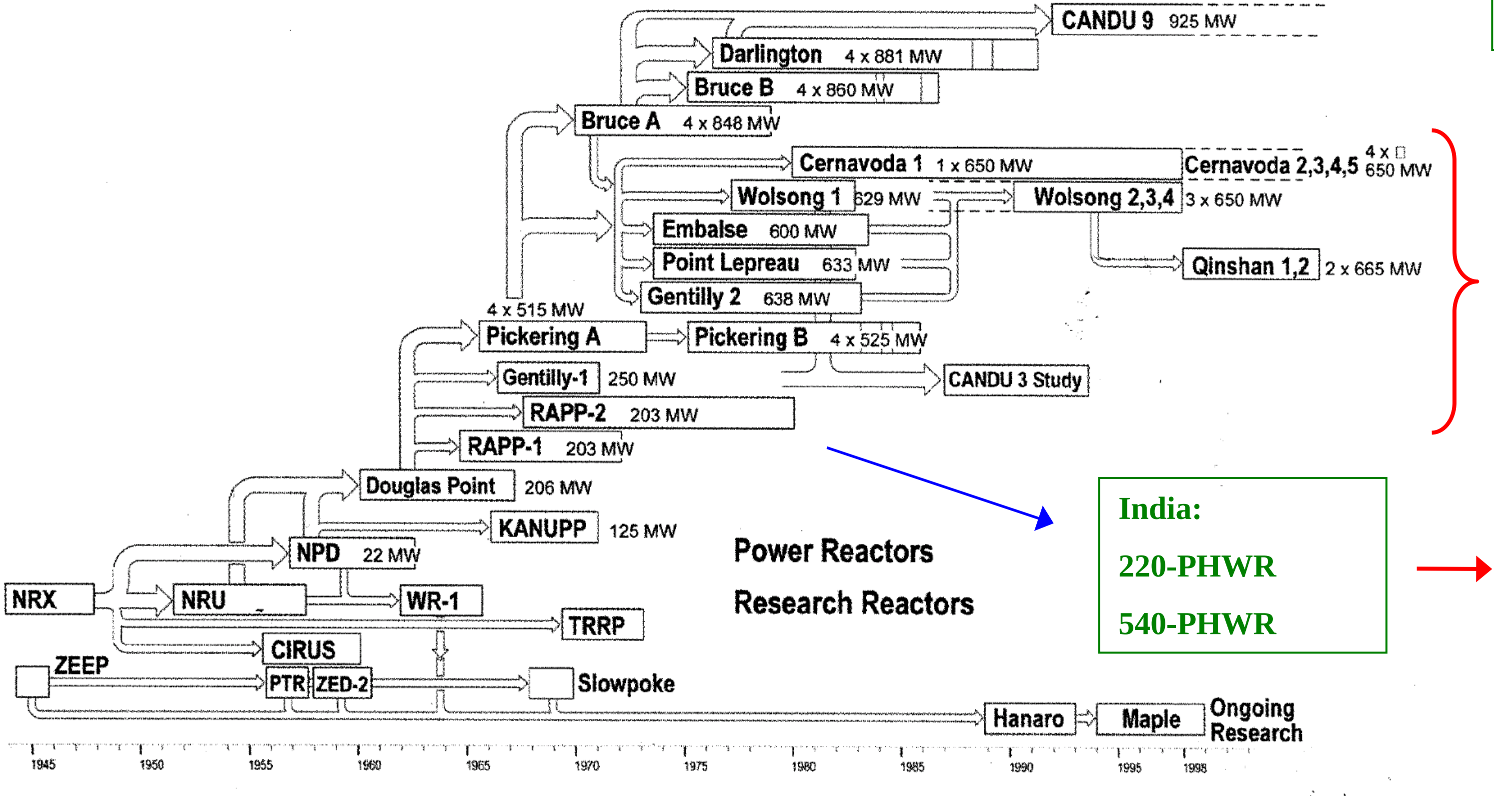
Figure 5-1 Comparison of Gross Capacity Factors

CANDU-6

- Qinshan III (China) (2002-2003)

CANDU HWR Evolution

- ☐ Research, prototypes, commercial.



Gen V

CANDU-X / HWR ???

Gen IV

CANDU-SCWR

Gen III+

EC6

ACR-1000

India:

220-PHWR

540-PHWR

India:

700-PHWR

AHWR

Gen III+ HWRs

- ☐ Evolutionary design changes.
- ☐ Various improvements on existing designs.
  - ➢ Monitoring, control systems.
  - ➢ Component materials and manufacturing.
  - ➢ Corrosion science, chemistry control.
  - ➢ Operations and maintenance, inspections.
- ☐ Feedback from past experience (+50 years).
- ☐ More modularity, standardization.
  - ➢ Reduced construction time, economies of scale.
- ☐ Enhanced safety.
- ☐ Better resource utilization; conservation of resources.
- ☐ Aim for reduced capital, operational costs.
- ☐ Aim for lower cost of electricity.

Gen III+ HWR's

- EC6 (Enhanced CANDU-6)
  - Feedback from CANDU-6, Pickering, Bruce, Darlington, etc.
- ACR-1000 (Advanced CANDU Reactor)
  - Feedback from CANDU-6, Pickering, Bruce, Darlington, etc.
  - Feedback from FUGEN (Japan), SGHWR (U.K.), Gentilly-1.
  - Feedback from LWR industry.
- India's 220-MWe, 540-MWe, 700-MWe PHWR's
  - Evolutionary improvements on existing designs.
  - Similar to Douglas Point, Pickering, CANDU-6 designs.
- AHWR (Advanced Heavy Water Reactor – India)
  - Extensive domestic R&D.
  - Feedback from domestic PHWR's (220-MWE, 540-Mwe class).
  - Some feedback from FUGEN, SGHWR?

EC6 (Canada, Gen III+)

- ☐ Enhanced CANDU-6 (EC6).
  - ➢ Retains basic features of CANDU-6 reactor.
  - ➢ 700-MWe class reactor.
  - ➢ Good for both large and medium-sized markets.
- ☐ Evolutionary improvements over CANDU-6:
  - ➢ Target life up to 60 years, >90% capacity factor.
  - ➢ Modern steam turbines with higher efficiency and output.
    - ~680 MWe (net) / 2064 MWth, 32% to 33% net efficiency.
  - ➢ Increased safety and operating margins.
  - ➢ Additional accident resistance and core damage prevention features.
    - Addition of a reserve water system for passive accident mitigation.
  - ➢ A suite of advanced operational and maintenance information tools.
    - SMART CANDU®.
  - ➢ Improved plant security and physical protection.

EC6 (Canada, Gen III+)

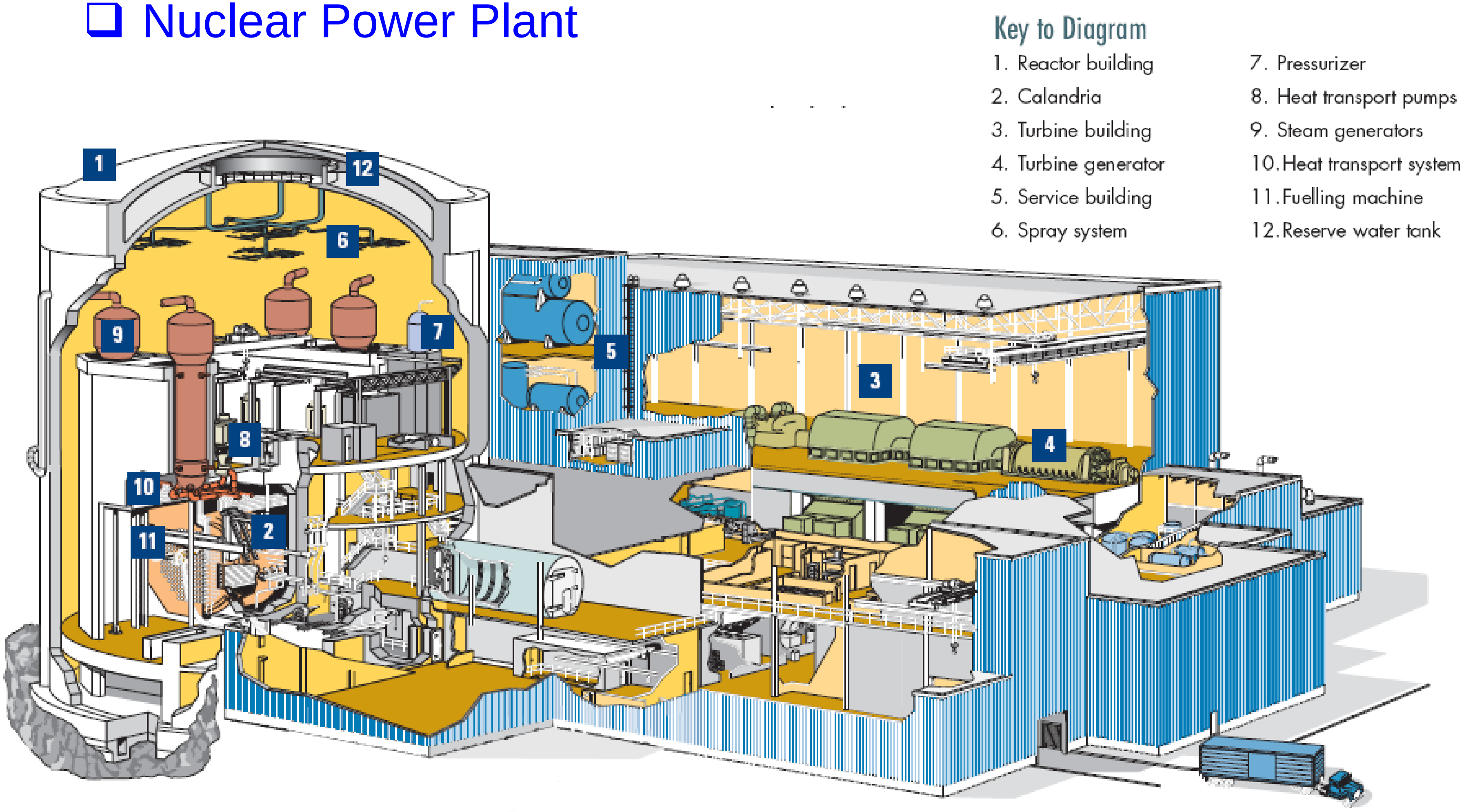
- ❑ Evolutionary improvements over CANDU-6 (continued):
  - ➢ Improved plant operability and maintainability.
    - Overall plant design.
    - Advanced control room design.
  - ➢ Improved severe accident response.
  - ➢ Advanced fire protection system.
  - ➢ Improved containment design features.
    - Steel liner and thicker containment.
    - Provide for aircraft crash resistance.
  - ➢ Reduced potential leakages following accidents.
  - ➢ Increased testing capability.
  - ➢ Construction schedule of 57 months achieved.
    - By use of advanced construction methods.
    - Total project schedule as short as 69 months.

EC6 Improvements

- Use of improved material and plant chemistry specifications based on operating experience from CANDU plants,
  - Life-limiting components such as heat transport system feeders and headers have been enhanced with higher chromium content to limit the effect of feeder corrosion
- Implementation of advanced computer control and interaction systems
  - For monitoring, display, diagnostics and annunciation.
- Utilization of integrated SMART CANDU suite
  - For monitoring plant chemistry of systems and components
  - Providing predictive maintenance capability.
- Ensuring capability for return to full power on restoration of the electrical grid.
  - The EC6 reactor has the capability to continue operating and delivering house load without connection to the grid, therefore enabling a rapid return to full power upon reconnection.

EC6 (Canada, Gen-III+)

- Nuclear Power Plant



Key to Diagram

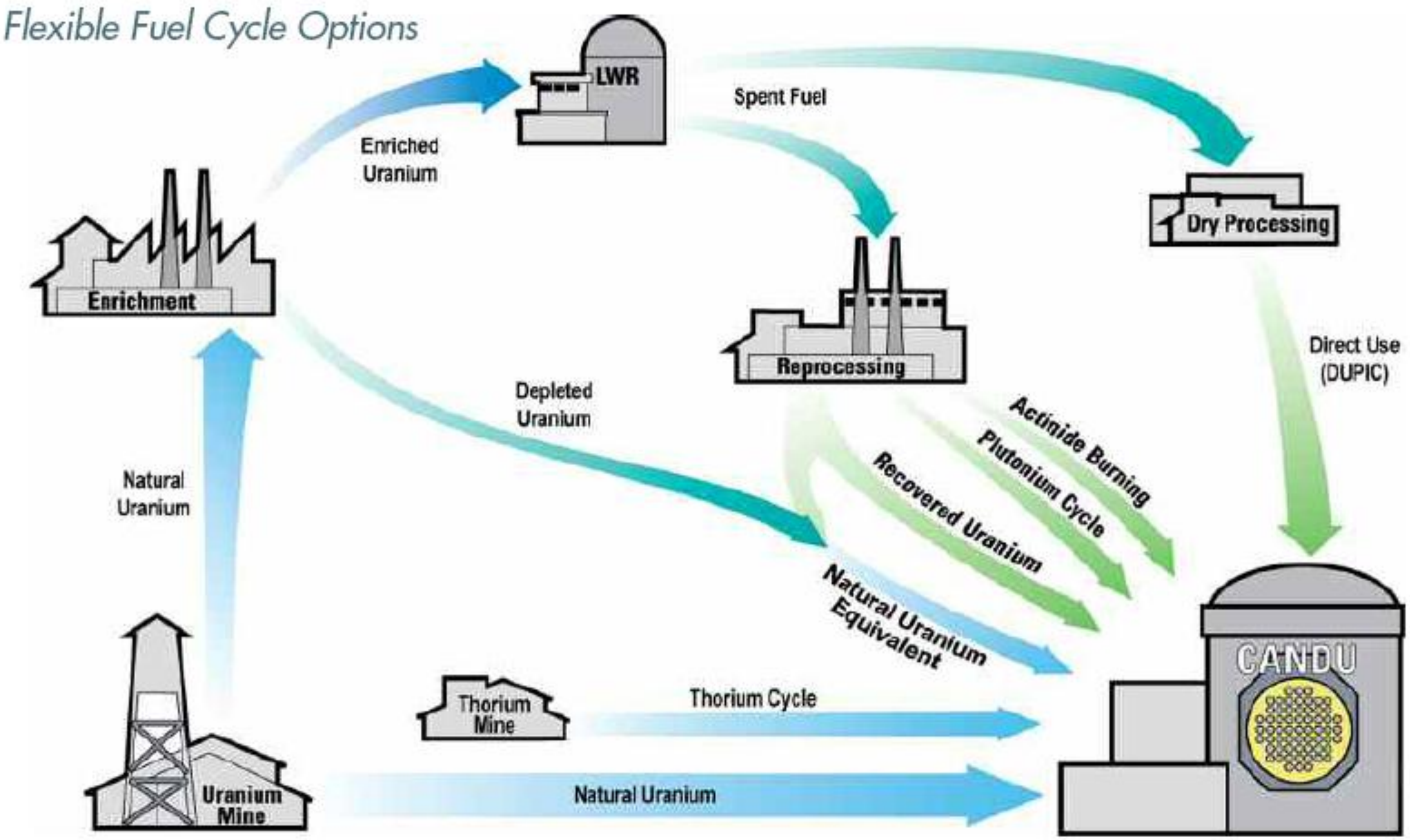
1. Reactor building
2. Calandria
3. Turbine building
4. Turbine generator
5. Service building
6. Spray system
7. Pressurizer
8. Heat transport pumps
9. Steam generators
10. Heat transport system
11. Fuelling machine
12. Reserve water tank

Emerging Fuel Cycles for EC6

- A high-burnup mixed oxide (MOX)
  - Could utilize plutonium from conventional reprocessing or more advanced reprocessing options (such as co-processing).
  - MOX: mixture of natural uranium and plutonium.
- DUPIC (Direct Use of Spent PWR Fuel in CANDU)
  - Represents recycle option that has a higher degree of proliferation resistance than conventional reprocessing.
  - DUPIC uses dry processes for converting spent fuel from PWRs for use in the EC6 reactor without separating the plutonium.
- A thorium cycle or CANDU/Fast Breeder Reactor system.
  - Long-term energy security can be assured through either of these.
  - The Fast Breeder reactor would operate as a “fuel factory” to provide the fissile material to power a number of lower-cost, high-efficiency EC6 reactors.
  - EC6 could breed and burn U-233 from Th-232.

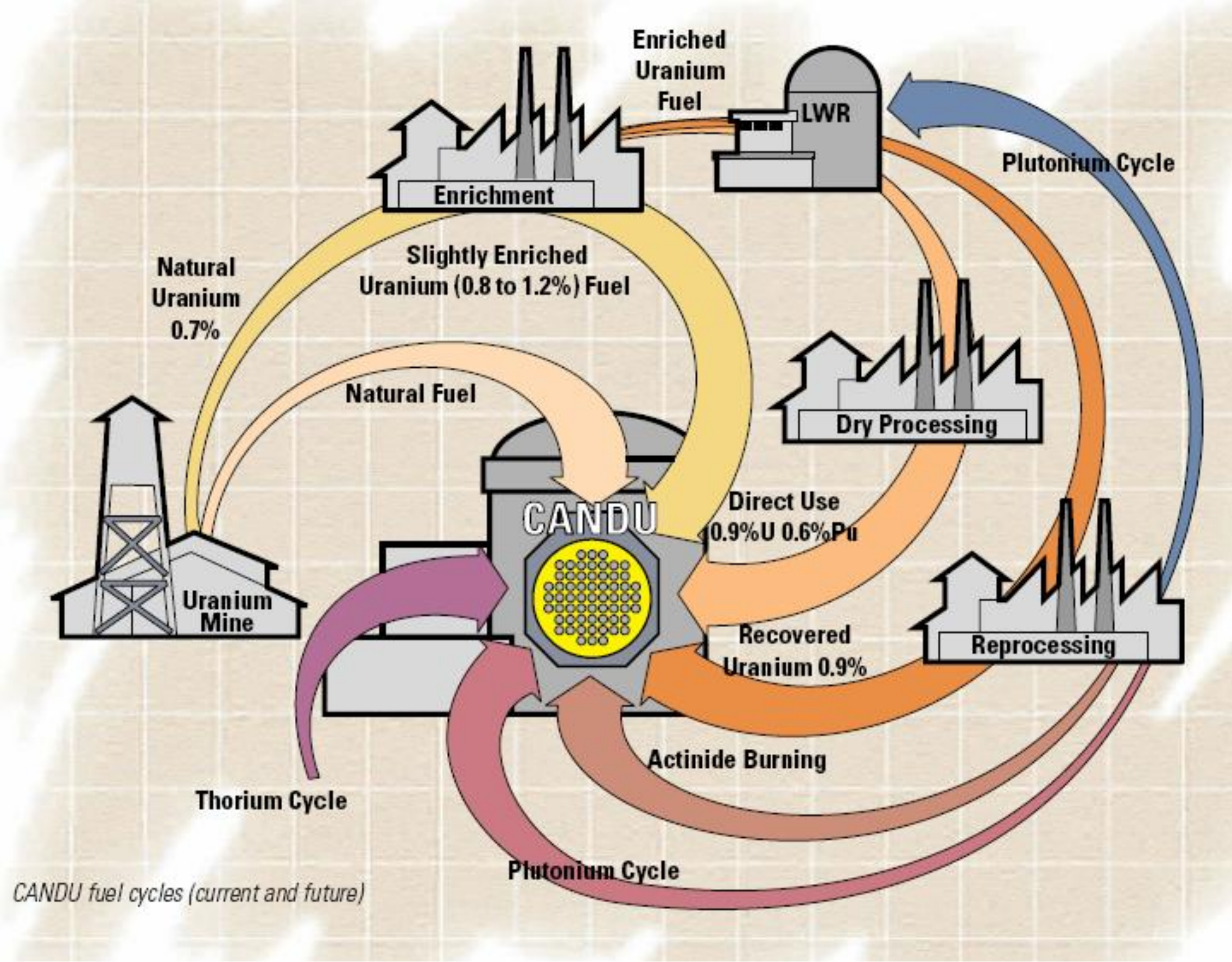
Emerging Fuel Cycles for EC6

- NU, LEU, RU, NUE.



Emerging Fuel Cycles for EC6

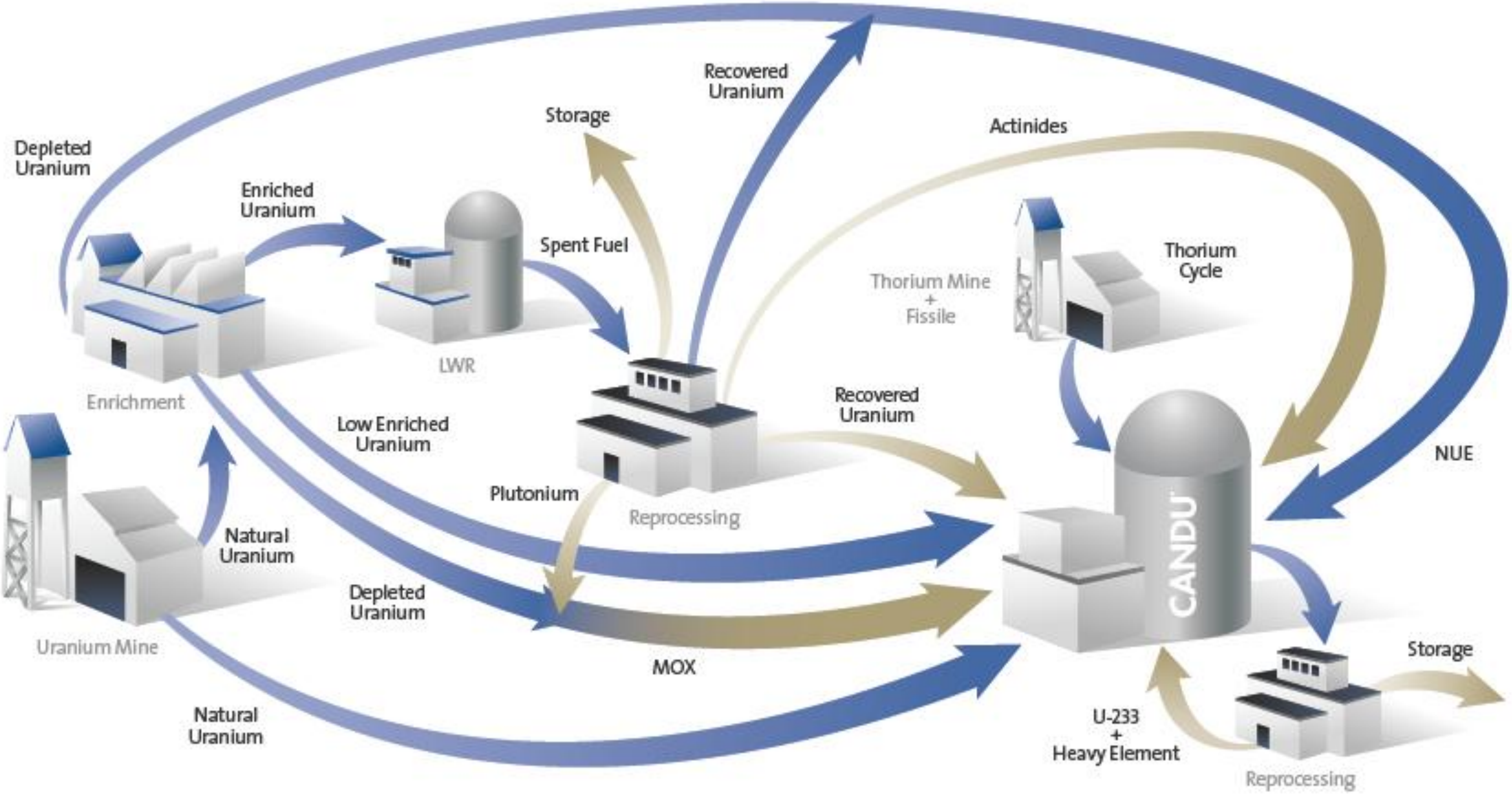
- MOX, DUPIC, Pu/Th, U/Th (OTT, SSET)



CANDU fuel cycles (current and future)

Emerging Fuel Cycles for EC6

- ❑ Flexibility to burn many types of materials:
  - ➢ NU, NUE, RU, DUPIC, LEU, MOX, Pu, U-233/Th, MA



Thorium Cycles in EC6 Reactors

- High neutron economy, on-line refuelling makes CANDU reactors well-suited for utilizing thorium.
- Once Through Thorium (OTT)
  - 42 or 54-element fuel bundles.
  - 3 wt% to 14 wt% (Pu or LEU)/Th driver/fertile.
  - 20 GWd/t to 45 GWd/t burnup.
- Self-Sufficient Equilbrium Thorium (SSET)
  - ~1.5 wt% to 2.0 wt% U-233/Th
  - Low burnup: ~10 GWd/t.
    - C.R. drops below 1.0 at higher burnups.
    - Must reprocess to recycle U-233.
    - Remove fission products.
  - Improvements.
    - Lower flux, remove Zr-91 from PT/CT, remove adjuster rods, higher purity D_2O.
    - Alternative heterogeneous designs.

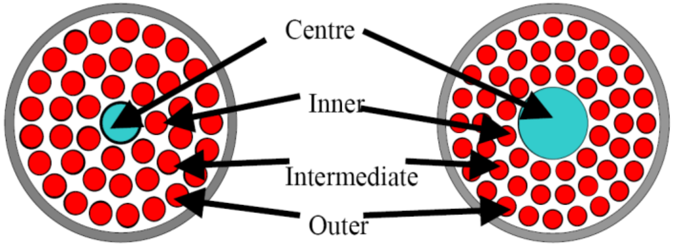


Fig. 1. Fuel bundle design for the low burnup cases (left) and the high burnup cases (right).

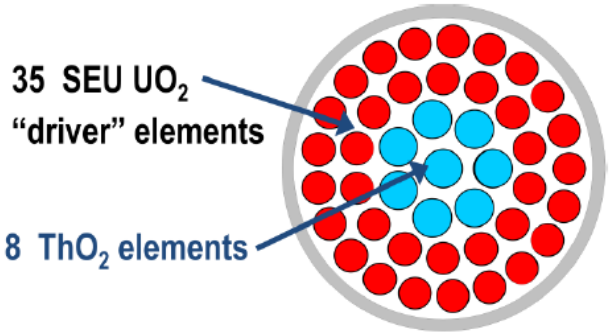


FIGURE 1: LEU/TH CANDU FUEL BUNDLE

ACR-1000 (Canada, 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.
- Modular construction, competitive design
  - Lower capital costs.
  - Local fabrication of components.
  - Lower-cost electricity.

Figure 2-2 Reactor Building

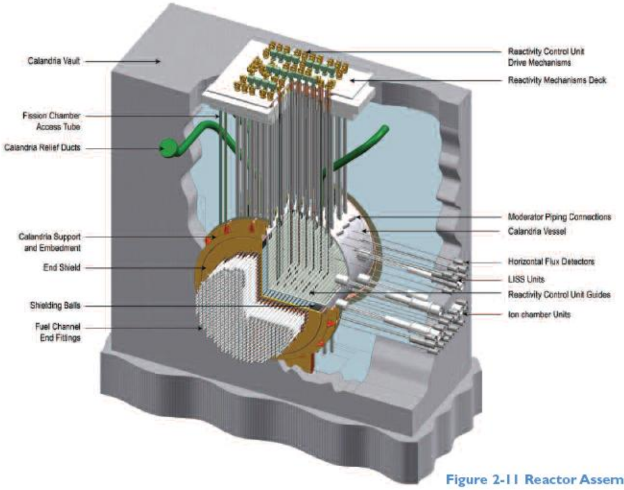
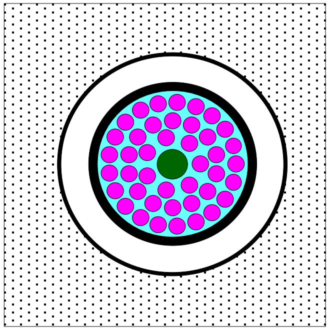


Figure 2-11 Reactor Assembly

ACR-1000 (Canada, Gen III+)

- ☐ 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).
    - Burnup: 20,000 MWd/t (nominal), extend with experience.
  - Tighter lattice pitch; thicker pressure tubes, larger calandria tubes.
    - More compact core; smaller reactor; higher power density.
    - Negative coolant void reactivity.
  - Heavy water inventory reduced to ~ 1/3 of CANDU.
    - Reduced capital costs.
  - Reactivity devices
    - No adjusters.
    - Liquid zone control (LZC) replaced: mechanical zone control (MZC) rods



ACR-1000 (Canada, Gen III+)

- Special features
  - Safety systems
    - Steel-lined large containment.
    - Long-term cooling system to perform long term ECC and maintenance cooling.
    - High-pressure emergency feedwater system.
  - Severe accident prevention / mitigation.
    - Reserve Water Tank for passive makeup to reactor cooling system, steam generators, calandria and reactor vault.
    - Moderator improved circulation.
    - Purpose is to prevent / contain severe accident within the calandria.

ACR-1000 (Canada, Gen-III+)

❑ Plant Layout

Figure 2-2 Reactor Building

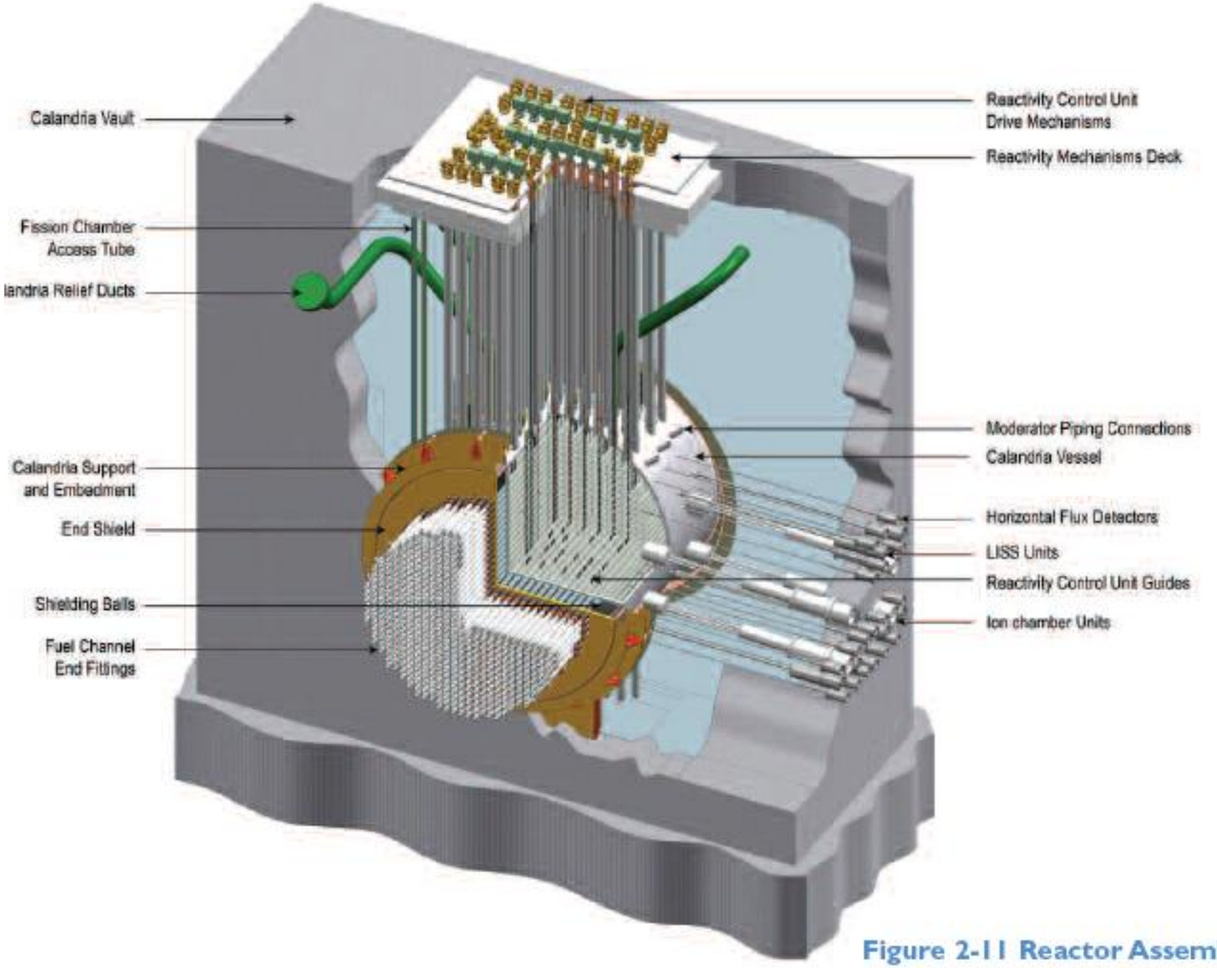
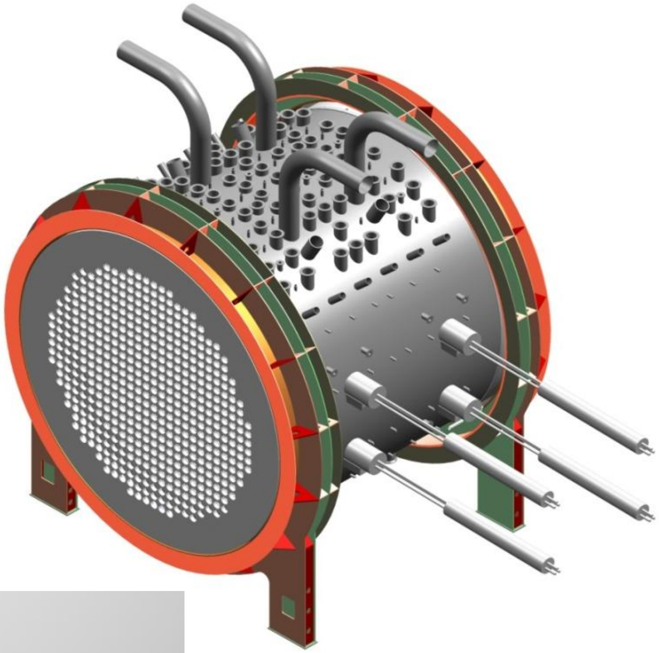
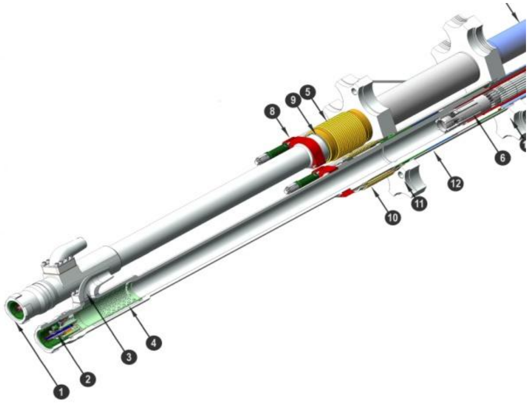


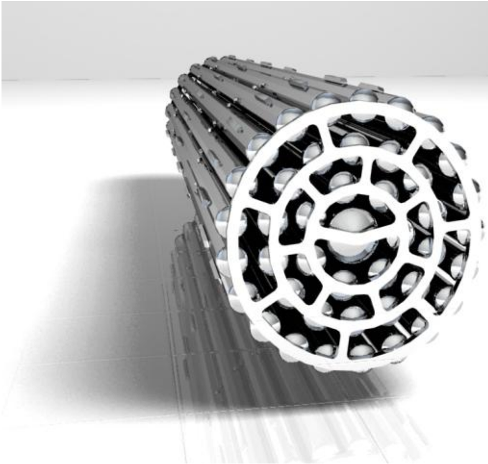
Figure 2-11 Reactor Assembly

ACR-1000 (Canada, Gen-III+)



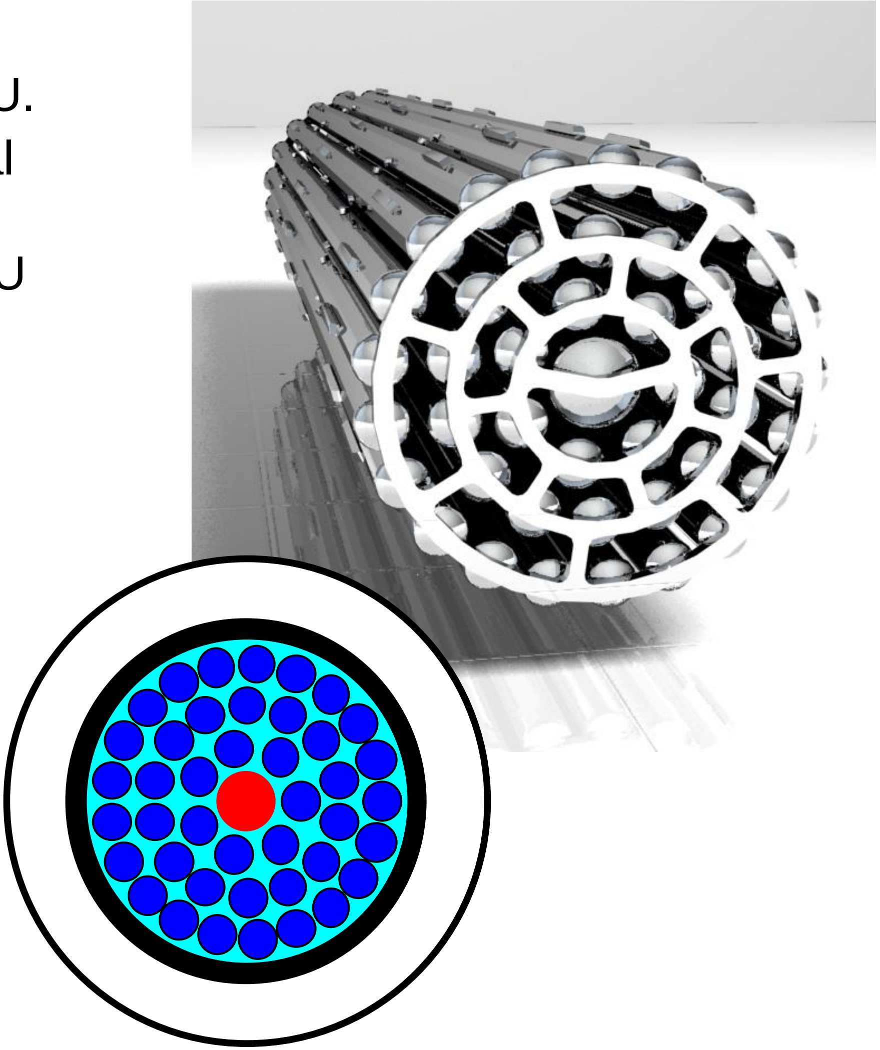
- Vertical and horizontal penetrations.
  - SDS-1, SOR, MZC
  - SDS-2
- Reactor assembly same size as CANDU 6 with more fuel channels, and higher power.
- Simple bundle design with low enriched uranium (LEU) Reference Fuel
  - 20,000 MWd/t burnup.

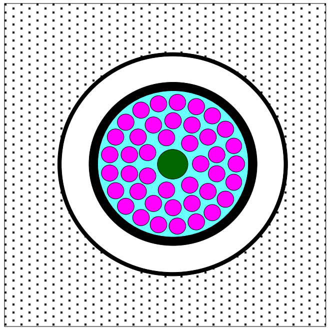




ACR-1000 (Canada, Gen-III+)

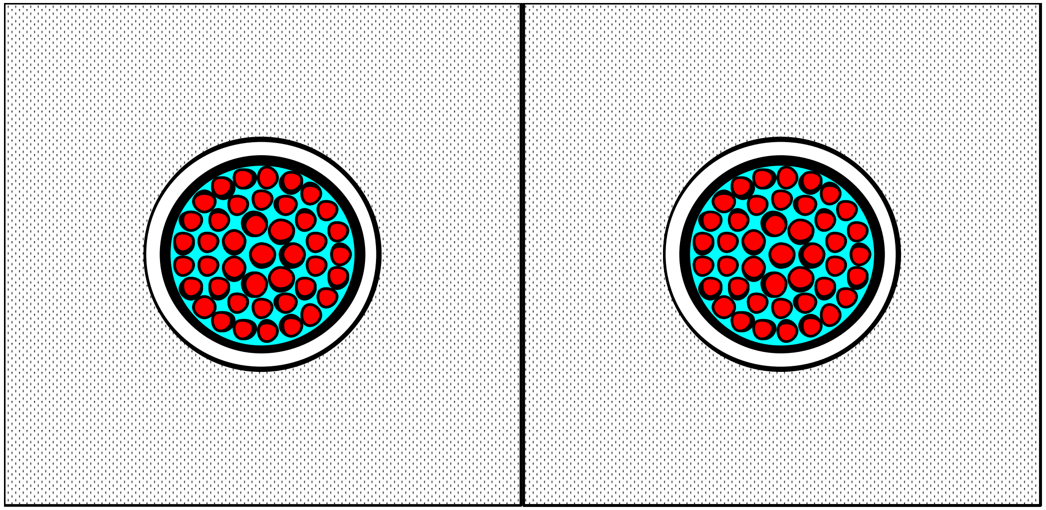
- 43-element CANFLEX fuel bundle
  - Same diameter and length as CANDU.
  - Greater subdivision for higher thermal margin (lower heat flux).
  - 42 elements contain ~ 2 to 3 wt% LEU
    - Uranium dioxide; Zr-4 clad.
  - Central poison element
    - Yttrium-stabilised matrix
    - $ZrO_2 + Dy_2O_3 + Gd_2O_3$
    - More neutron absorption during voiding.
- Reference burn-up ~20,000 MWd/t





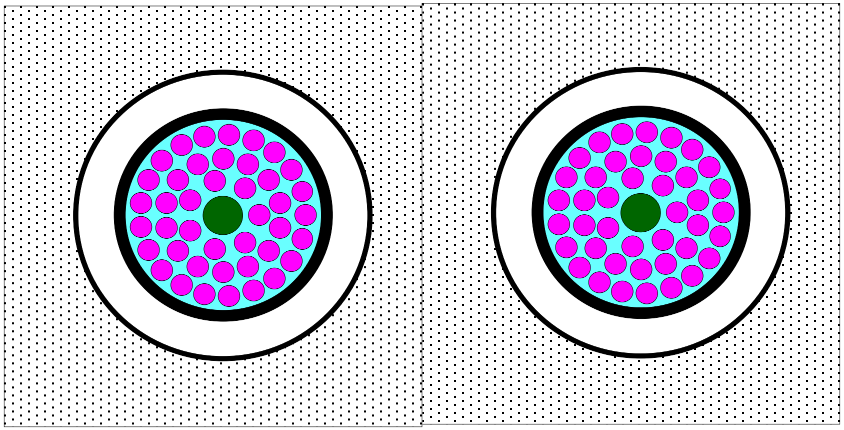
Compare CANDU and ACR Lattices

- ❑ ACR-1000 lattice pitch tighter than CANDU-6



CANDU 6

Lattice Pitch = 28.58 cm



ACR

Lattice Pitch = 24.0 cm

ACR-1000 (Canada, Gen-III+)

- ❑ CANFLEX-ACR Fuel Bundle

Figure 2-19
CANFLEX®-ACR Fuel Bundle

ACR-1000 (Canada, Gen-III+)

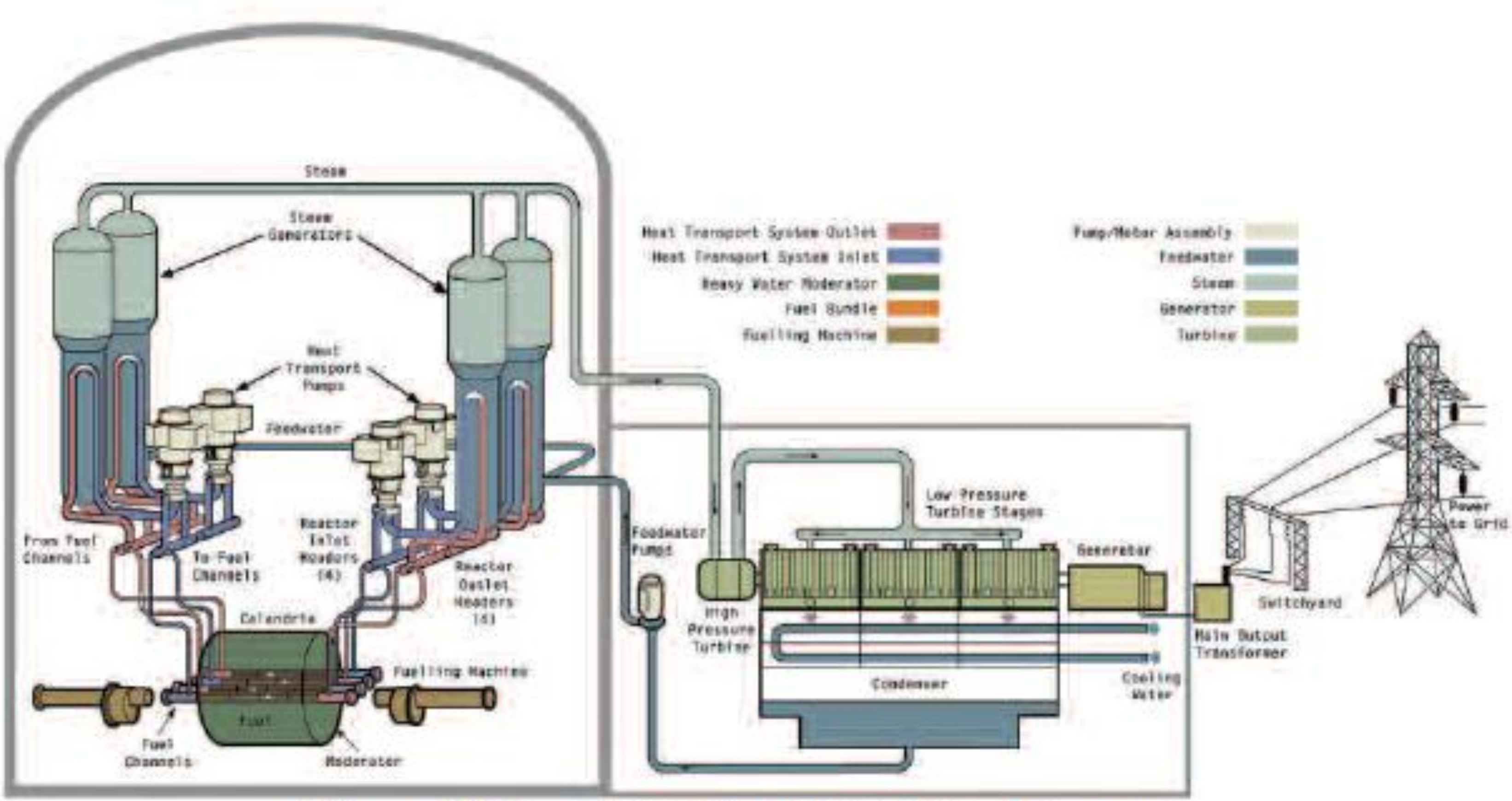


Figure 1-1 Overall ACR-1000 Plant Flow Diagram

ACR-1000 (Canada, Gen-III+)

- ❑ Heat Transport System
- ❑ Containment.

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

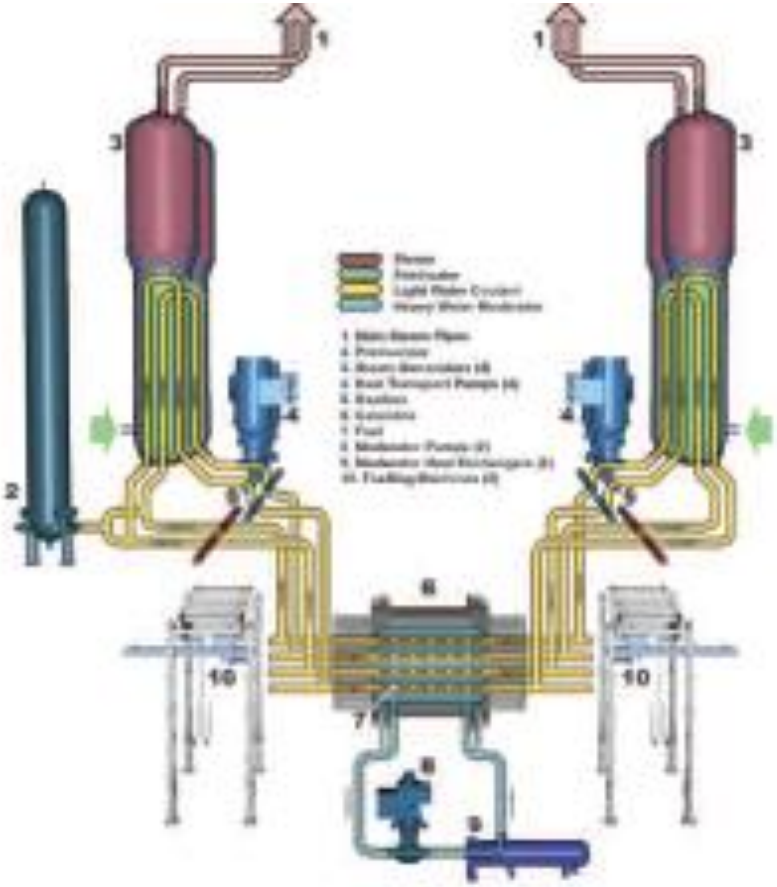
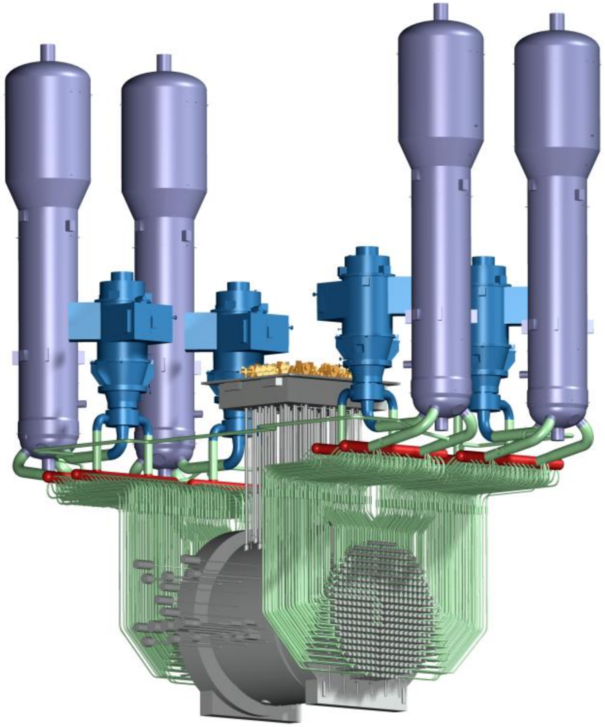


Figure 2-3 Nuclear Systems Schematic

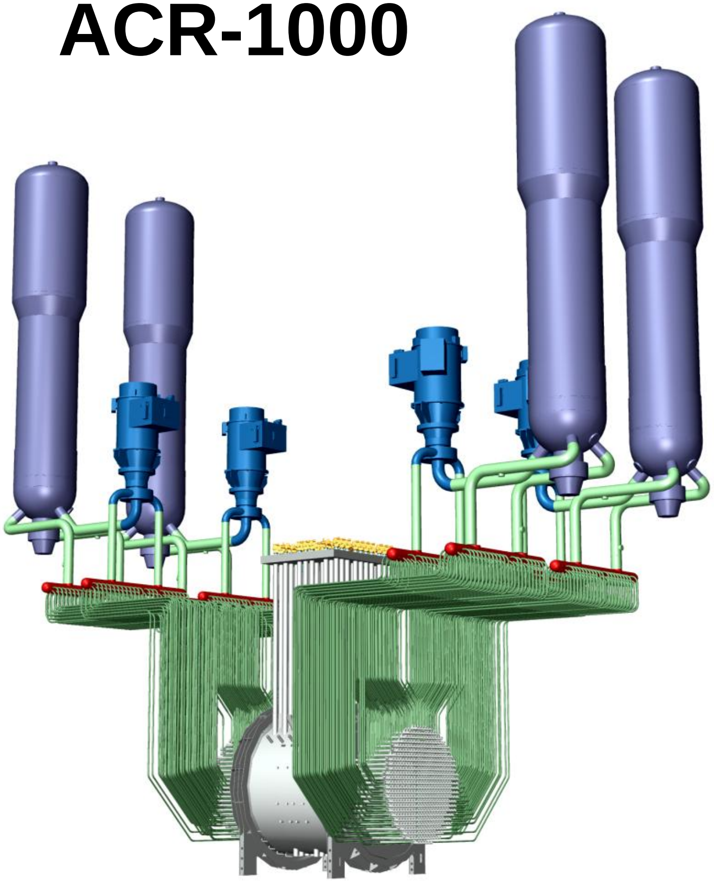
ACR-1000 (Canada, Gen-III+)

- Evolutionary Nuclear Steam Supply System (NSSS)
  - Same reactor coolant system as CANDU-6 and Darlington

CANDU-6



ACR-1000



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ACR-1000 (Canada, Gen-III+)

- Larger thermal / electrical power level.
  - Suitable for markets requiring 1000-MWe-class reactors.
- More compact reactor (higher power density).
  - Reduced capital costs (smaller containment).

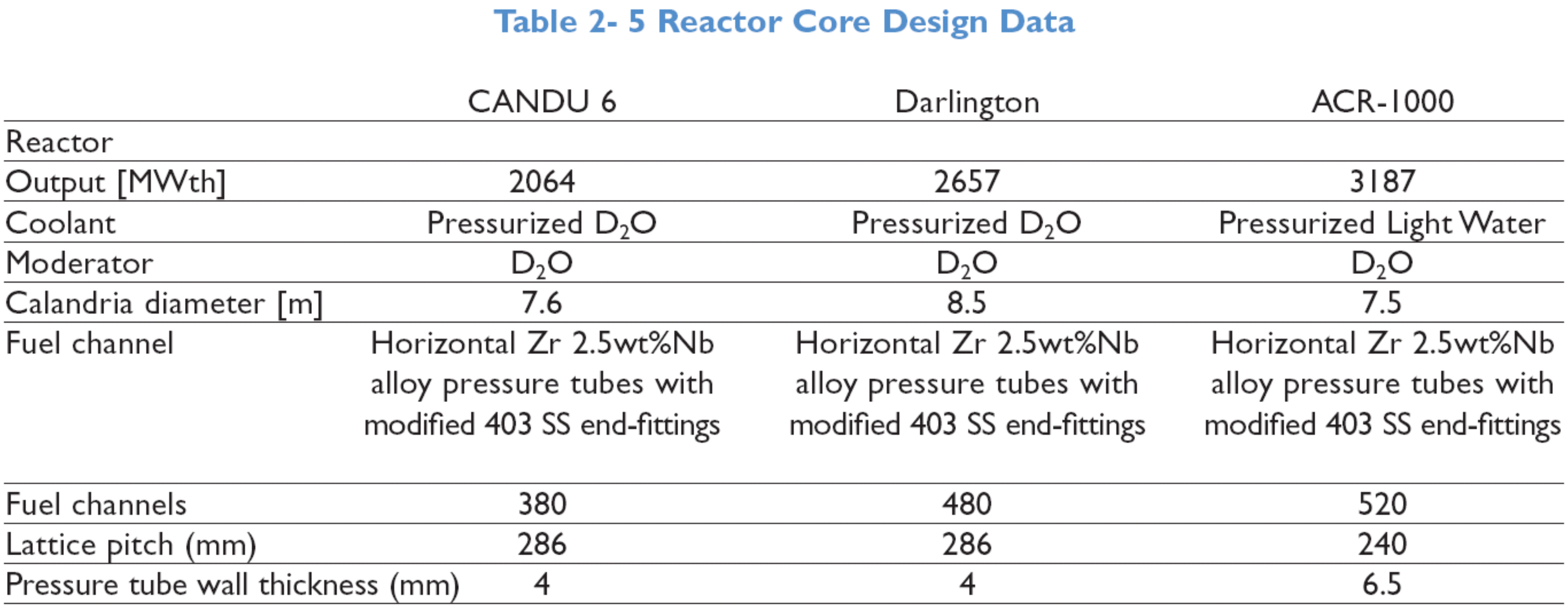

Table 2- 5 Reactor Core Design Data

	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 (Canada, Gen-III+)

- ❑ Higher primary circuit pressure and temperature

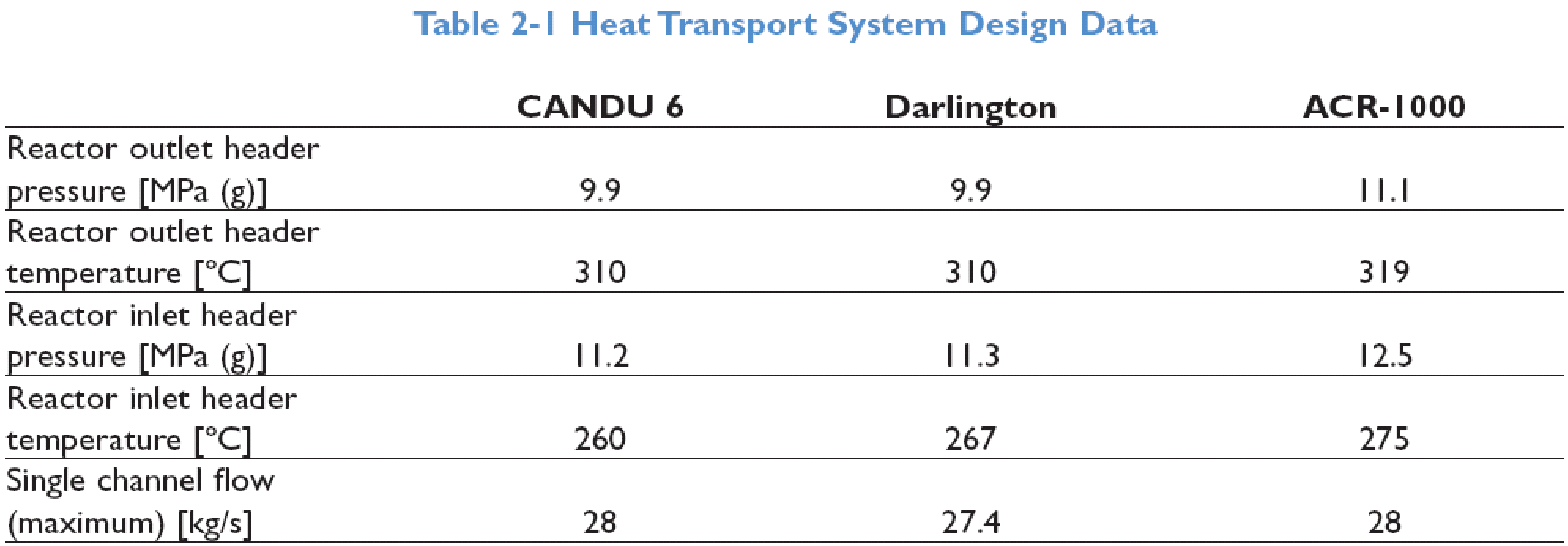

Table 2-1 Heat Transport System Design Data

	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 (Canada, Gen-III+)

- Increased steam pressure and temperature.
  - Less wet steam.
  - Higher thermal efficiency (~34% net)

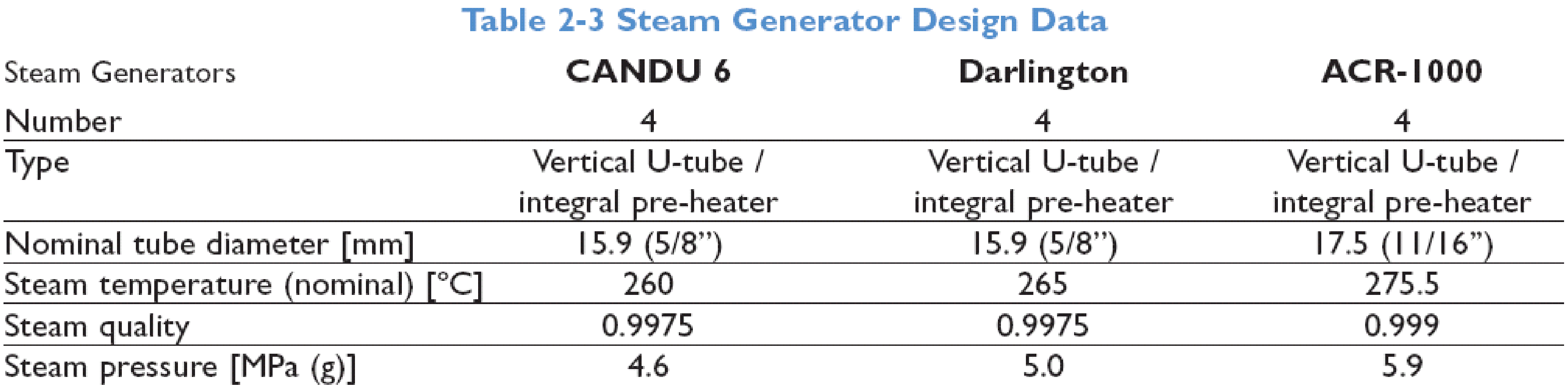

Table 2-3 Steam Generator Design Data

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 (Canada, Gen-III+)

- Heavy water inventory reduced by ~66%.
  - From ~0.67 Mg/MWe to ~ 0.23 Mg/MWe
  - Approximately 1/3 of the D_2O required.
  - Capital cost savings.

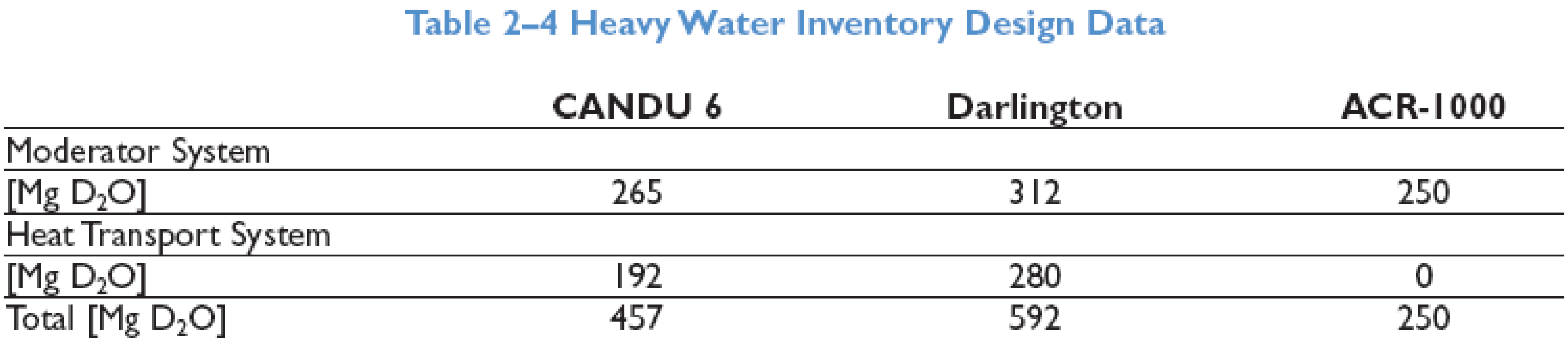

Table 2–4 Heavy Water Inventory Design Data

	CANDU 6	Darlington	ACR-1000
Moderator System [Mg D_2O]	265	312	250
Heat Transport System [Mg D_2O]	192	280	0
Total [Mg D_2O]	457	592	250

ACR-1000 (Canada, Gen-III+)

- ACR-1000 has higher power density.
  - ~ same size as CANDU-6, but ~60% more power.

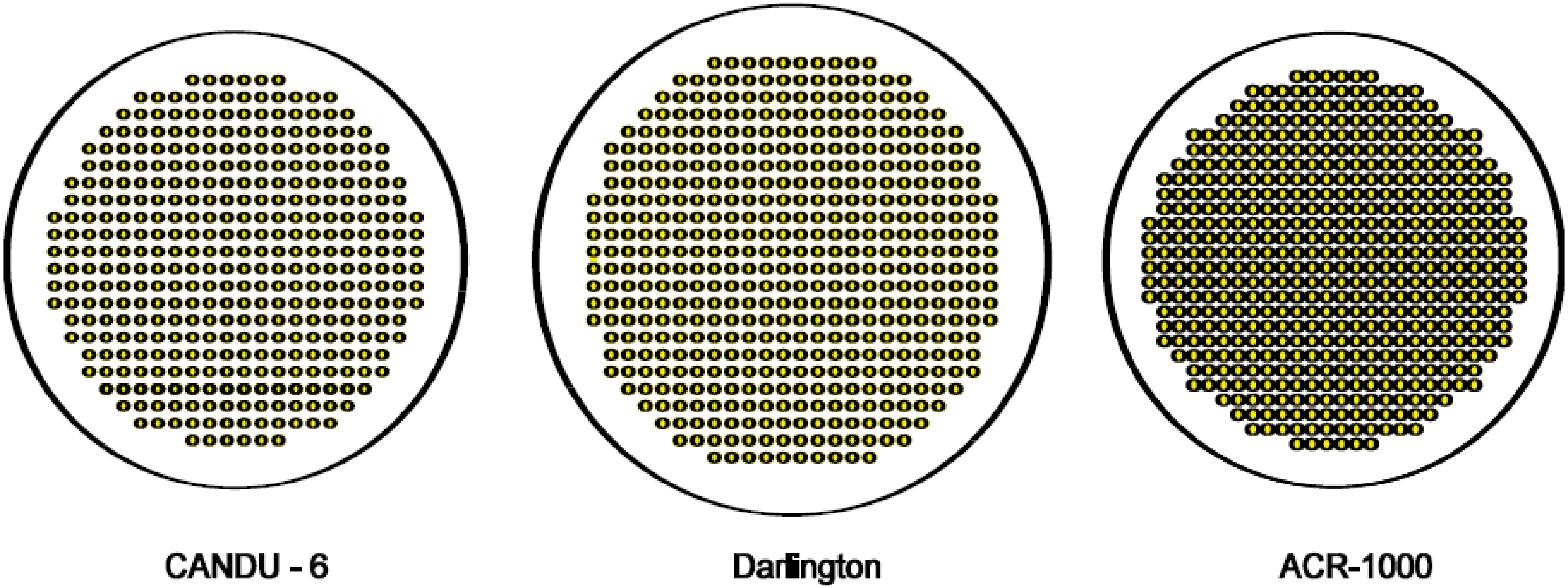

Figure 2-12 Comparison of Core Sizes

ACR-1000 (Canada, Gen-III+)

- Fueling Machine at Reactor Face

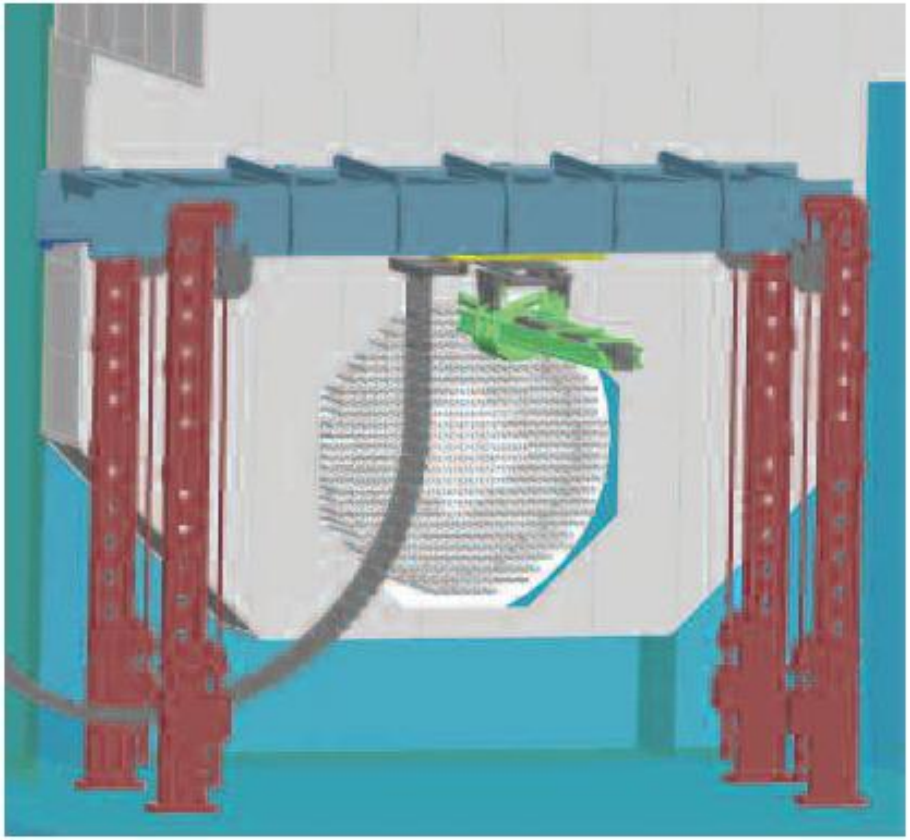

Figure 2-16 Fuelling Machine and Carriage

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ACR-1000 (Canada, Gen-III+)

☐ Multiple barriers – defense in depth

- Fuel
  - UO_2
  - Clad
- Individual PT / CT
- Moderator tank.
- Containment.
  - Steel liner.
  - Re-enforced Concrete.

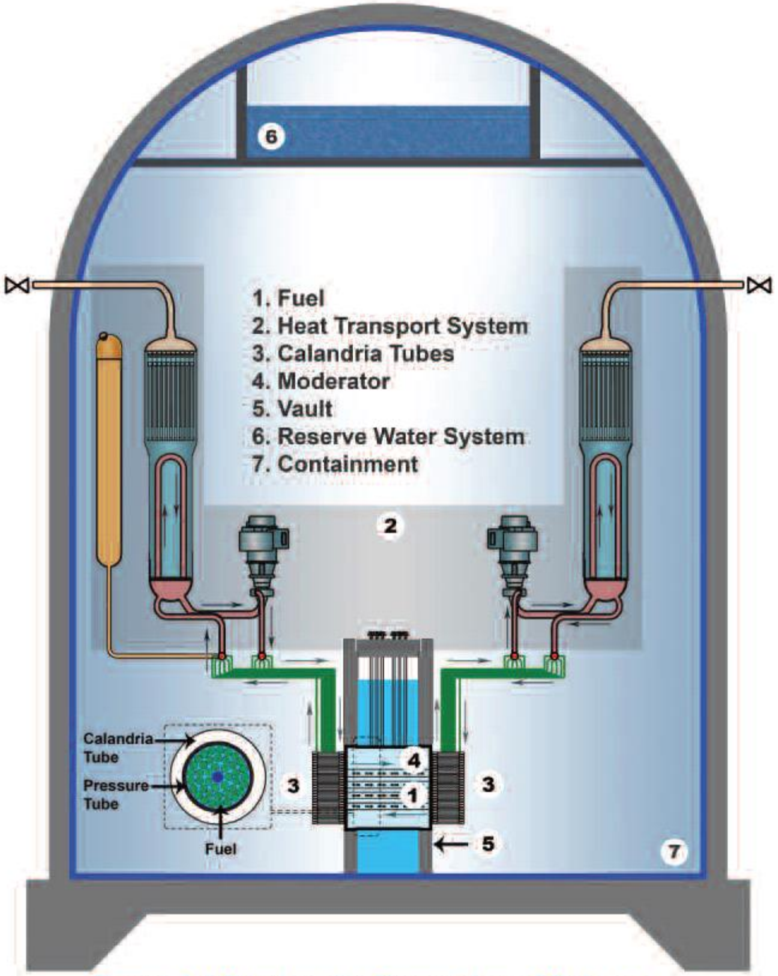


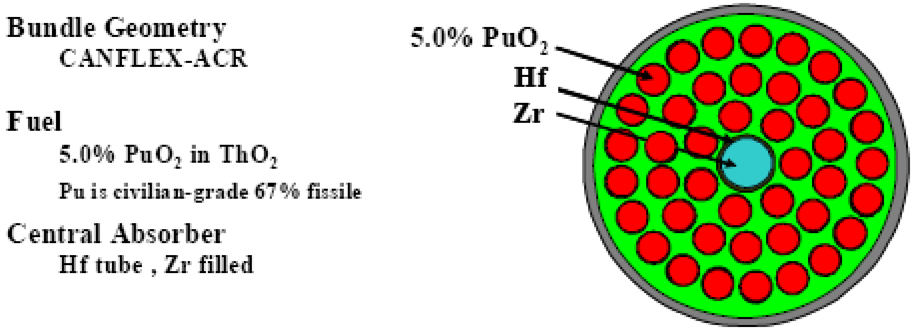
Figure 3-1 Barriers for Prevention of Releases

ACR-1000 (Canada, Gen-III+)

- ❑ Twin-unit stations
- ❑ Generation III+
- ❑ 1200 MWe-class reactor
- ❑ Evolutionary, based on CANDU 6
- ❑ Enhancements:
  - ➢ Passive Safety
  - ➢ Reduced Cost
  - ➢ Ease of Operability
  - ➢ Low Risk Delivery

Thorium Cycles in ACR-1000

- ❑ Once Through Thorium (OTT)
  - ➢ 5 wt% Pu in Th
  - ➢ U-233 bred and burned in situ.
  - ➢ 21 GWd/t.
  - ➢ Spent fuel stored.
- ❑ Self-Sufficient in U-233.
  - ➢ U-233+Pu+Th
  - ➢ Less Pu required.
  - ➢ U-233 recycled.
    - Self-sustaining in U-233.
  - ➢ 21 GWd/t.

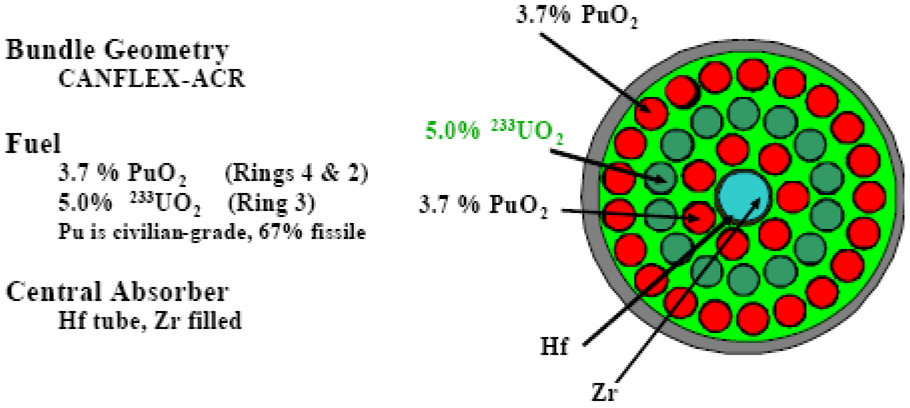


Bundle Geometry
CANFLEX-ACR

Fuel
5.0% PuO_2 in ThO_2
Pu is civilian-grade 67% fissile

Central Absorber
Hf tube , Zr filled

Fig. 3. Fuel Bundle Configuration for Once-through Th Fuel Cycle in ACR-1000 (with Recycled ^{233}U) 21 MWd/kgHE Burnup



Bundle Geometry
CANFLEX-ACR

Fuel
3.7 % PuO_2 (Rings 4 & 2)
5.0% $^{233}UO_2$ (Ring 3)
Pu is civilian-grade, 67% fissile

Central Absorber
Hf tube, Zr filled

Fig. 4. Fuel Bundle Configuration for Closed Th Fuel Cycle in ACR-1000 (with Recycled ^{233}U) 21 MWd/kgHE Burnup.

ACR-1000 (Canada, Gen-III+)

- ☐ Canadian Regulatory Review
  - ➢ Pre-Project Design Review by Canadian Nuclear Safety Commission (CNSC) started 2008 April and to be completed in 2009.
    - Generic Safety Case Report delivered to CNSC 2008 June.
    - CNSC confirmed design meets Canadian regulatory requirements.
- ☐ Potential Opportunities
  - ➢ Alberta
    - Four-unit site preparation licence applied for by Bruce Power Alberta.
  - ➢ Ontario: Ontario Power Generation (OPG), Electrical Utility
    - New builds under consideration in Ontario (2 to 4 new reactors).
    - Delay in making decisions due to short-term reduced electricity demand as result of world-wide economic downturn.
    - Technology will be selected by competitive process.
  - ➢ New Brunswick: Point Lepreau 2
    - ACR-1000 under consideration, while other options investigated.
    - First priority is the successful refurb of Point Lepreau 1 (CANDU-6)

India's Gen III+ HWR Projects

- PHWR
  - D_2O-moderated, D_2O-cooled pressure-tube reactors.
  - 220-MWe, 540-MWe, 700-MWe class PHWR's.
  - Size options to fit local market requirements.
  - Similar to CANDU designs:
    - Douglas Point (~220 MWe)
    - Pickering (~540 MWe)
    - CANDU-6 (~700 MWe)
  - But, evolutionary design improvements.
- Advanced Heavy Water Reactor (AHWR)
  - Under current development in India.
  - Boiling light water coolant, thorium-based fuels.
  - General similarities to SGHWR, FUGEN prototypes.
    - Fuel bundle design with many innovations.

India’s Gen-III+ PHWR’s

- Developed for smaller-sized markets.
- 220-MWe class PHWR.
  - Similar to Douglas Point CANDU design
  - Zr-2.5%Nb PT’s.
  - 19-element UO2 fuel bundles with bearing pads.
    - 10 bundles per channel.
  - 4 modern steam generator units.
- 540-MWe class PHWR.
  - Similar to Pickering CANDU design (390 channels).
    - But with 37-element NU fuel bundles, 12 bundles/channel.
    - 392 Channels, Zr-2.5%Nb PT, Zr-4 CT.
    - 4 Vertical U-tube steam generators.
- 700-Mwe class PHWR
  - Based on India’s indigenous 540-MWe PHWR design, with increased power output, with some similarities to CANDU-6.

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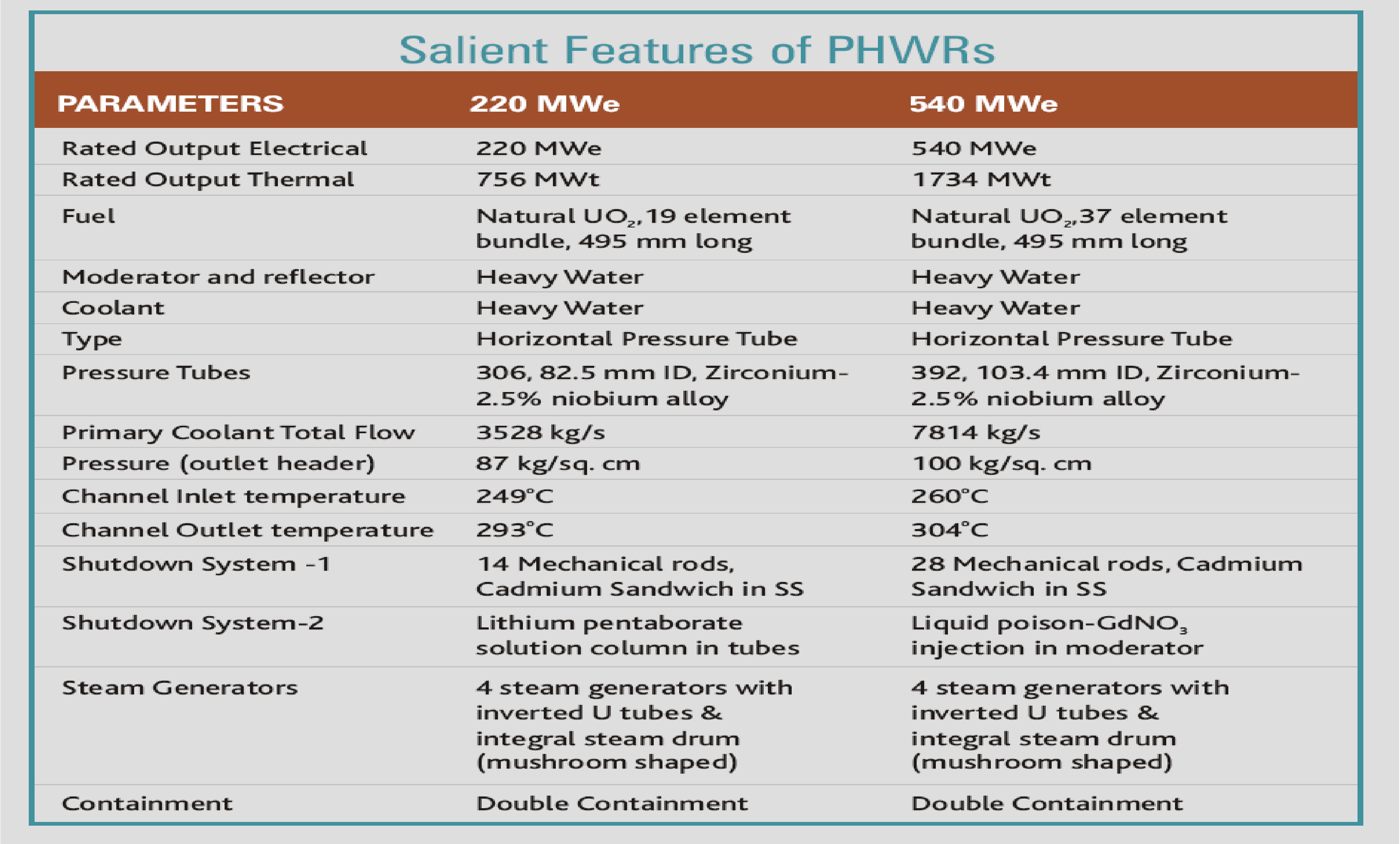
India’s 220-MWe, 540-MWe PHWRs

- See: http://www.npcil.nic.in/pdf/NPCIL_Brochure11_05_09.pdf

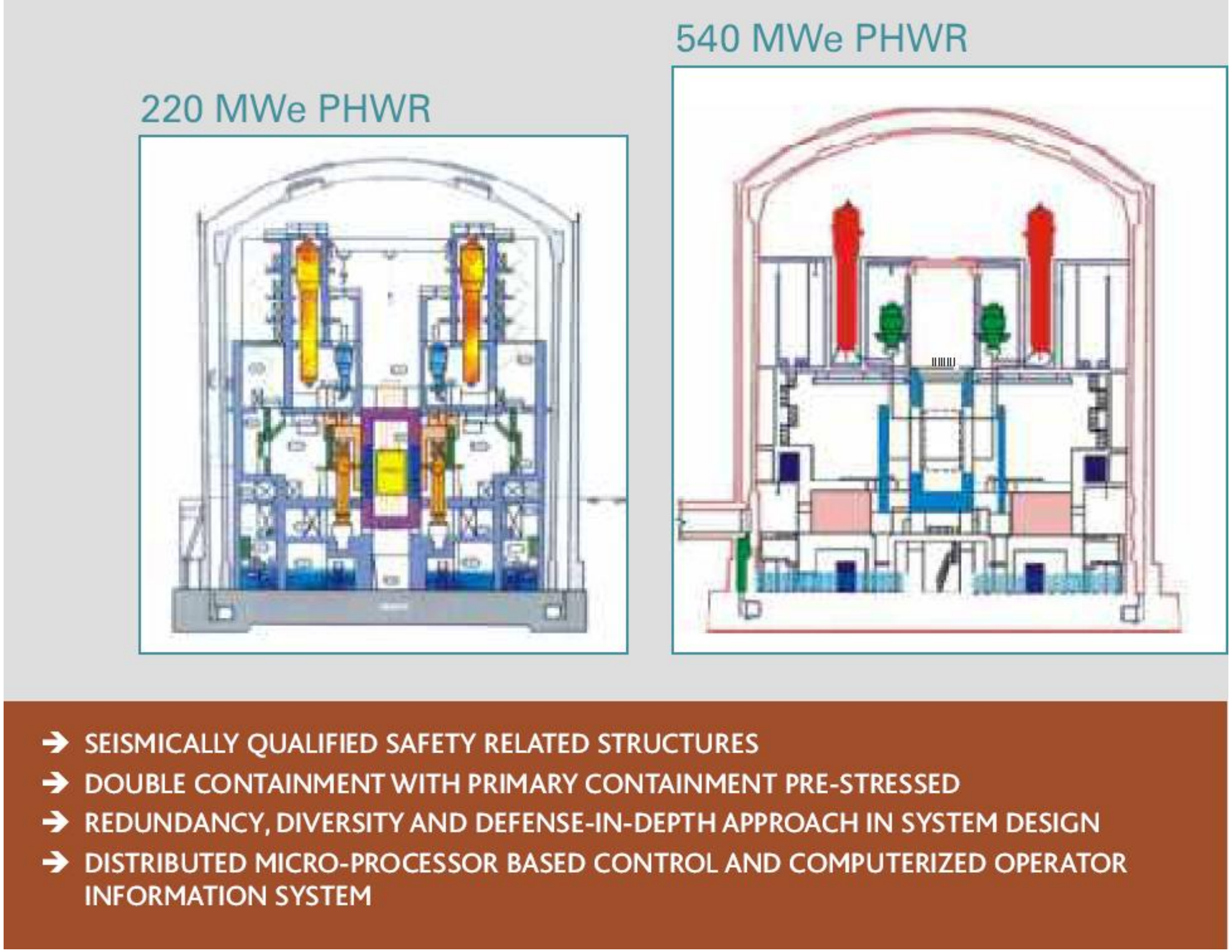


Salient Features of PHWRs

PARAMETERS	220 MWe	540 MWe
Rated Output Electrical	220 MWe	540 MWe
Rated Output Thermal	756 MWt	1734 MWt
Fuel	Natural UO_2,19 element bundle, 495 mm long	Natural UO_2,37 element bundle, 495 mm long
Moderator and reflector	Heavy Water	Heavy Water
Coolant	Heavy Water	Heavy Water
Type	Horizontal Pressure Tube	Horizontal Pressure Tube
Pressure Tubes	306, 82.5 mm ID, Zirconium-2.5% niobium alloy	392, 103.4 mm ID, Zirconium-2.5% niobium alloy
Primary Coolant Total Flow	3528 kg/s	7814 kg/s
Pressure (outlet header)	87 kg/sq. cm	100 kg/sq. cm
Channel Inlet temperature	249°C	260°C
Channel Outlet temperature	293°C	304°C
Shutdown System -1	14 Mechanical rods, Cadmium Sandwich in SS	28 Mechanical rods, Cadmium Sandwich in SS
Shutdown System-2	Lithium pentaborate solution column in tubes	Liquid poison-$GdNO_3$ injection in moderator
Steam Generators	4 steam generators with inverted U tubes & integral steam drum (mushroom shaped)	4 steam generators with inverted U tubes & integral steam drum (mushroom shaped)
Containment	Double Containment	Double Containment

India’s 220-MWe, 540-MWe PHWRs

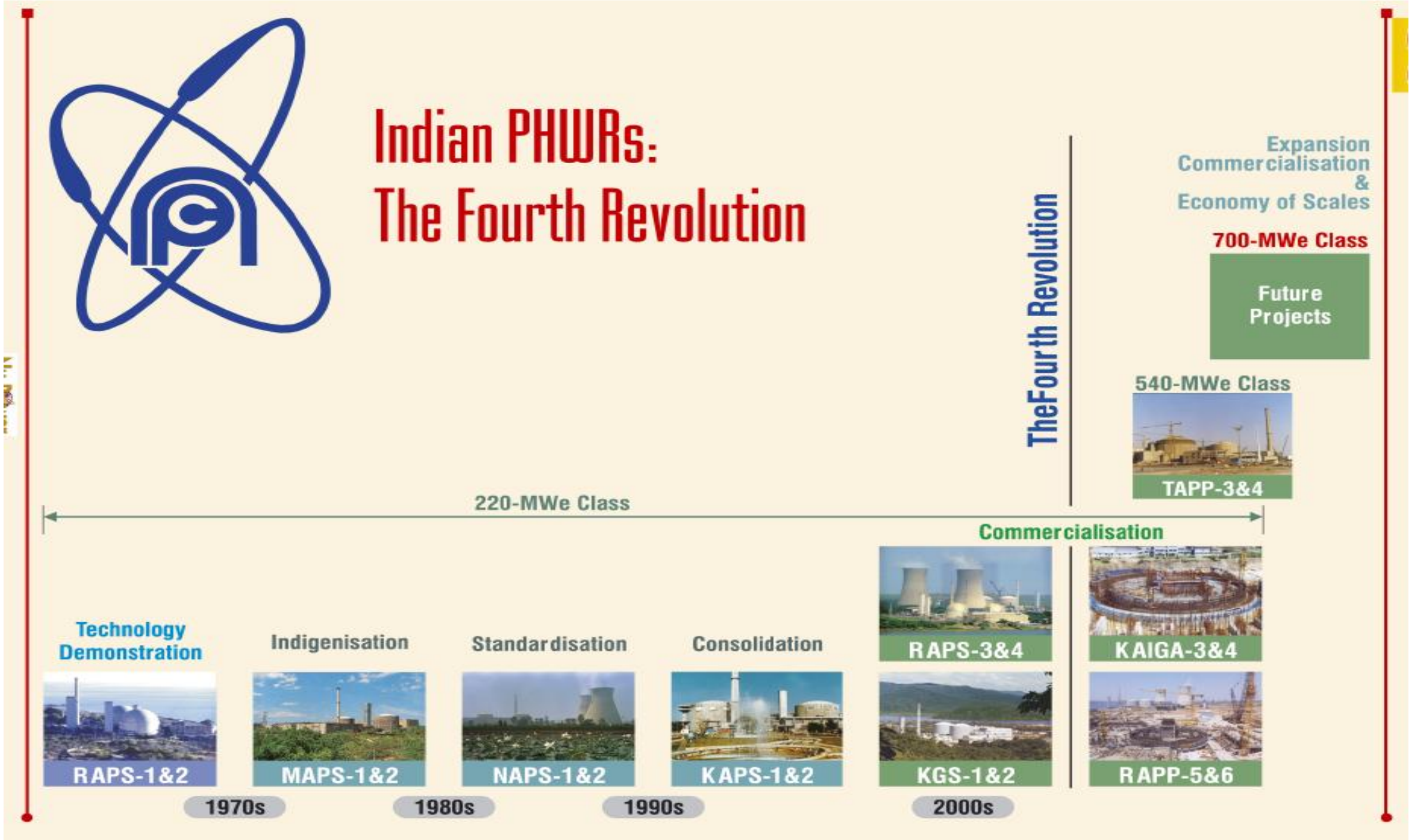
- ☐ Smaller-sized markets.
- ☐ Modern steam generators.
- ☐ Modern steam turbines.



- ➔ SEISMICALLY QUALIFIED SAFETY RELATED STRUCTURES
- ➔ DOUBLE CONTAINMENT WITH PRIMARY CONTAINMENT PRE-STRESSED
- ➔ REDUNDANCY, DIVERSITY AND DEFENSE-IN-DEPTH APPROACH IN SYSTEM DESIGN
- ➔ DISTRIBUTED MICRO-PROCESSOR BASED CONTROL AND COMPUTERIZED OPERATOR INFORMATION SYSTEM

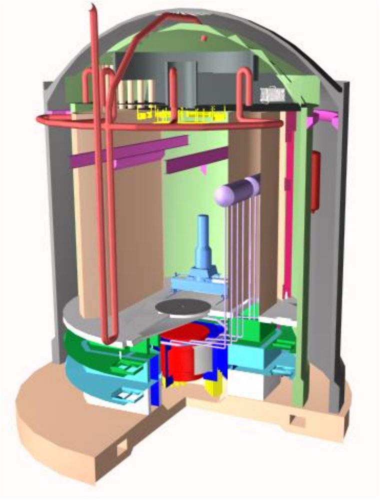
India’s PHWR Evolution

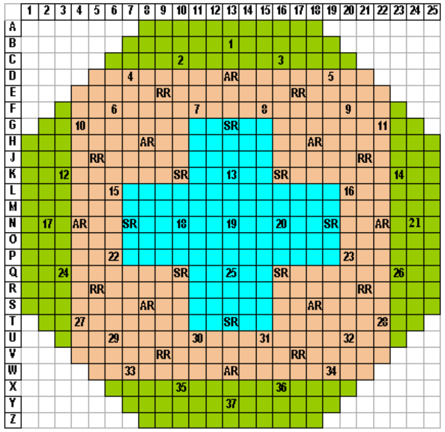
- Commercialization of indigenous PHWR’s.



AHWR (India, Gen-III+)

- ❑ **A**dvanced **H**eavy **W**ater **R**eactor
  - ➢ Prototype design under optimization and refinement.
  - ➢ Work continues on various design options.
  - ➢ Pu from PHWR, fast reactor, or spent LWR fuel.
  - ➢ U-233 from fast reactor, or self-sustaining.
- ❑ Goals:
  - ➢ Advanced technologies required for Gen-III+
  - ➢ Demonstrate thorium fuel cycle technologies.
  - ➢ Fuel cycles with reduced environmental impact.
- ❑ Heavy water moderated.
- ❑ Boiling light water-cooled.
- ❑ Steam to turbines at 6.8 MPa, 284°C.
- ❑ 920 MW_{th} / ~300 MW_e (net)
  - ➢ ~32% efficient (for prototype).
- ❑ 452 vertical fuel channels, 61 control channels.
- ❑ 22.5-cm pitch, 54-element fuel assemblies.





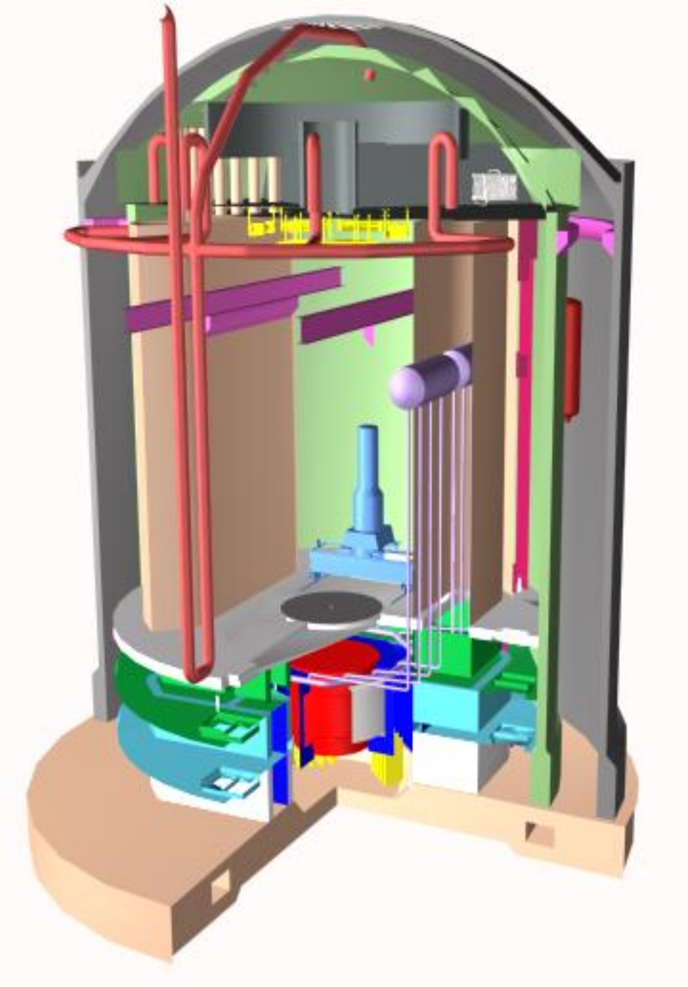
N	Shut off Rod (1-37)	🟦	47500 MWd/te
AR	Absorber Rod	🟧	37500 MWd/te
RR	Regulating Rod	🟩	33500 MWd/te
SR	Shim Rod		

AHWR (India, Gen-III+)

- ❑ Hundred year design life of the reactor.
- ❑ No exclusion zone beyond plant boundary required.
- ❑ Heavy water at low pressure reduces potential for leakages.
- ❑ Elimination of major components and equipment:
  - ➢ Primary coolant pumps and drive motors.
  - ➢ Associated control and power supply equipment.
  - ➢ Save electrical power.
- ❑ SDS1: 37 shut off rods.
  - ➢ B_4C rods.
- ❑ SDS2: Liquid poison injection in moderator.
  - ➢ Lithium Pentaborate poison for shutdown.
- ❑ 24 Control Rods.
- ❑ Passive (natural) shutdown system
  - ➢ Poison injection into moderator through valve actuated by increase in steam pressure.

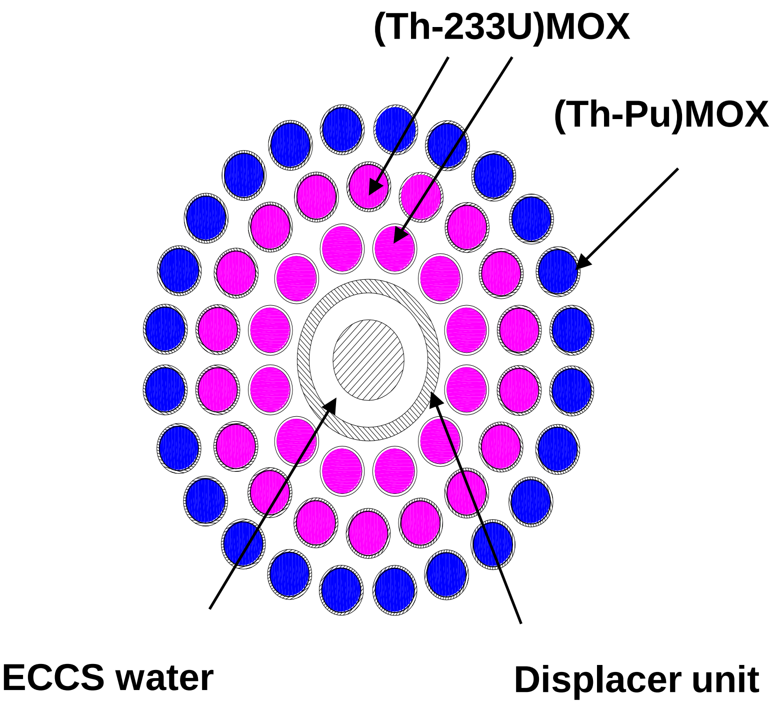
AHWR Passive Safety Features

- ❑ Core cooling by natural circulation.
- ❑ Negative void coefficient of reactivity.
- ❑ Large heat sink
  - ➢ Gravity Driven Water Pool
- ❑ Passive Core decay heat removal.
- ❑ Passive containment cooling.
- ❑ Emergency core cooling injection in fuel assembly design.
- ❑ Passive poison injection in moderator
  - ➢ In event of non-availability of primary/secondary shutdown systems.
- ❑ Core submergence.
- ❑ Double Containment.



AHWR Standard Fuel

- Fuel: $(U\text{-}233,Th)O_2 + (Pu/Th)O_2$
  - ~75% power from U-233 fission.
  - ~20% power from Pu
  - ~5% power from U-235
  - Burnup: ~38 GWd/t (average).
- Inner Ring (12 pins)
  - 3 wt% U-233 in Th.
- Middle Ring (18 pins)
  - 3.75 wt% U-233 in Th.
- Outer ring (24 pins)
  - 4.0/2.5 wt% Pu in Th.
- Central displacer unit.
  - Central displacer rod.
  - Lower half of Zircaloy, upper half of SS.
  - Within Zircaloy tube which is filled with ECCS water.



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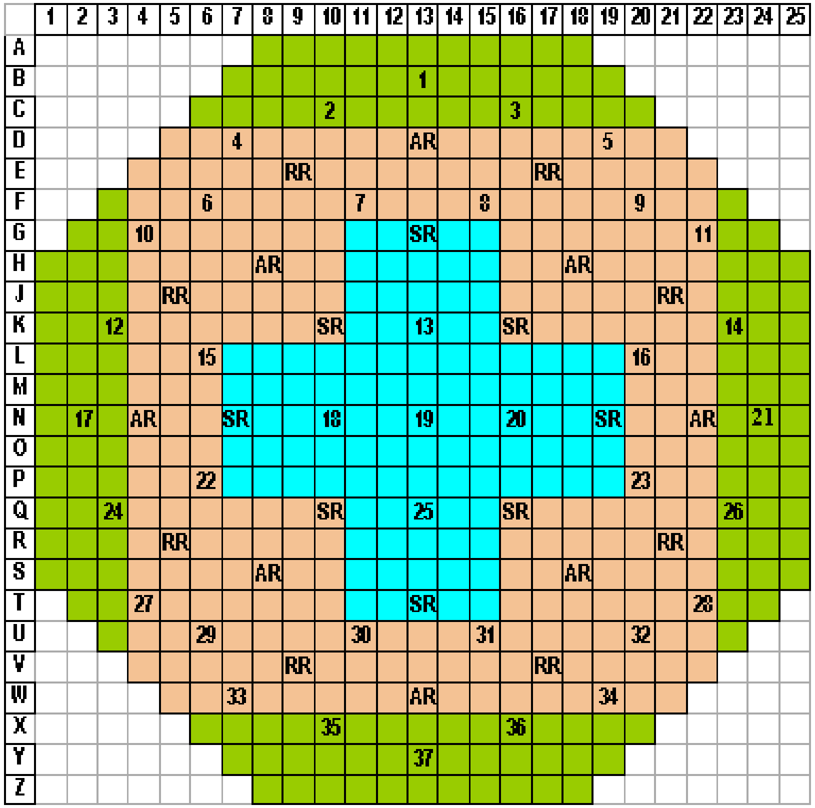
AHWR Standard Design

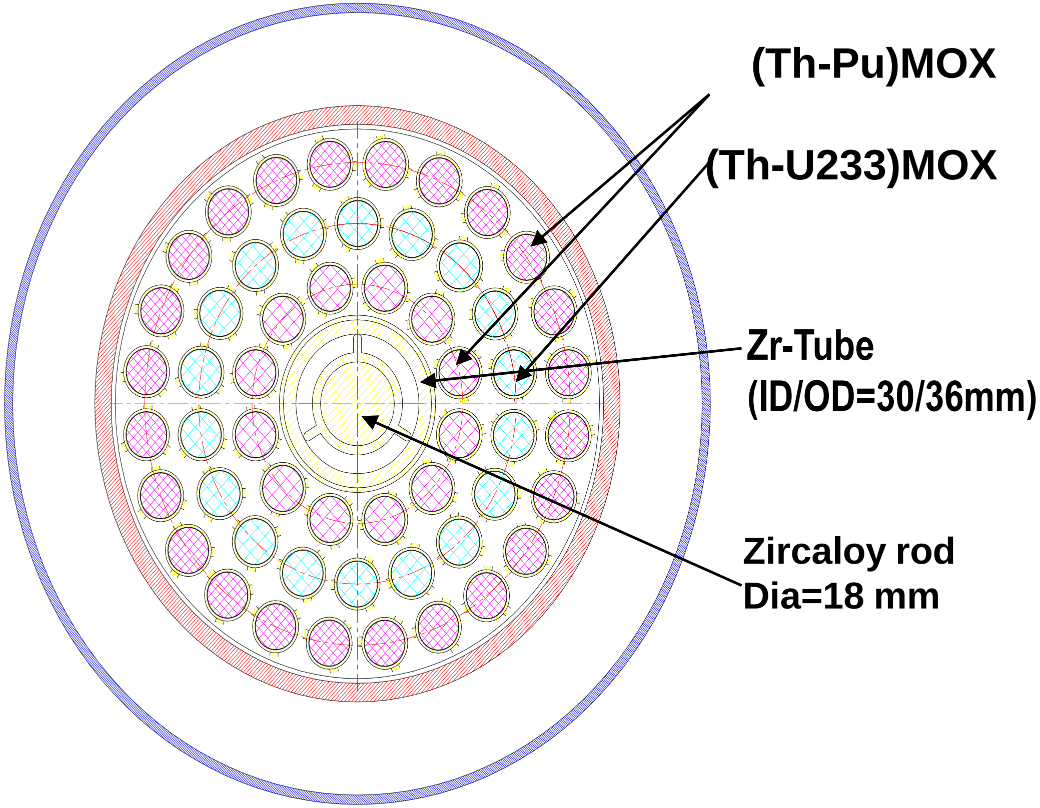
- ❑ Burnup ranges from 33 to 48 GWd/t
  - ➢ 3 burnup zones.
  - ➢ Average 38 GWd/t.
  - ➢ 73 channels refuelled / year.
    - **~1/6 of core / year.**
- ❑ Low Pu consumption
  - ➢ Annual Pu requirement 123 kg.
- ❑ Annual U-233 requirement 163 kg
  - ➢ Deficit in U-233 by 22 kg (13.5%)
- ❑ CVR from operating conditions:
  - ➢ -8 mk to -4 mk, varies with burnup.
- ❑ SDS-1(35 SORs) meet the shutdown margin in operating and accidental conditions.



N	Shut off Rod (1-37)	🟦	47500 MWd.te
AR	Absorber Rod	🟧	37500 MWd/te
RR	Regulating Rod	🟩	33500 MWd/te
SR	Shim Rod		

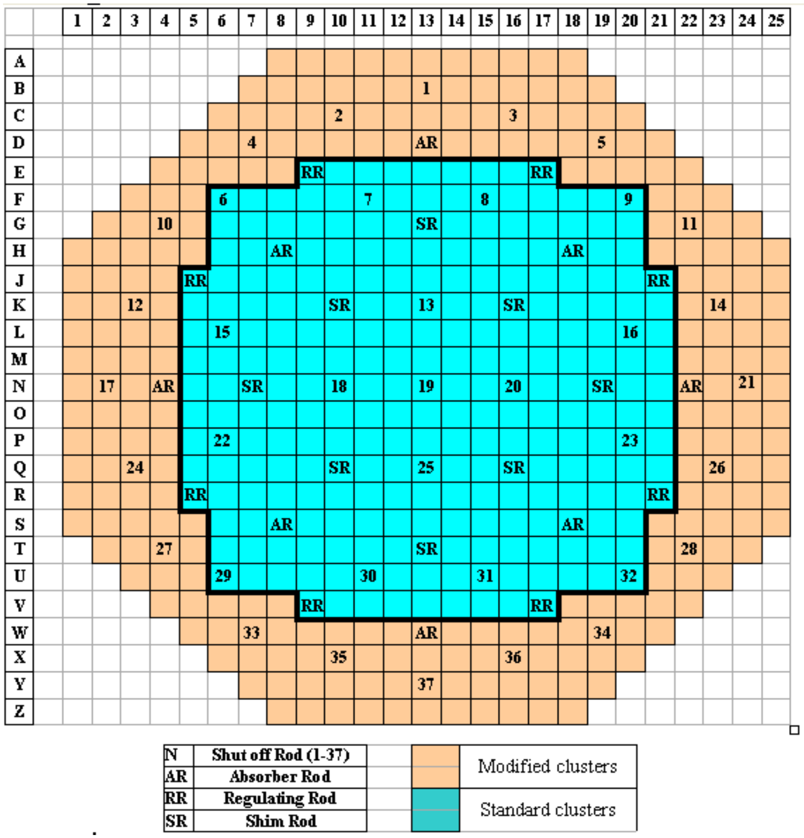
Modified Design to Achieve Self-sufficient U-233

- ☐ Modified Cluster design
- ☐ Inner Ring (12 pins)
  - ➢ 4 wt% Pu in Th
- ☐ Middle Ring (18 pins)
  - ➢ 3.75 wt% U-233 in Th
- ☐ Outer ring (24 pins)
  - ➢ 2.5/4.0 wt% Pu in Th
- ☐ Central displacer rod
  - ➢ Zircaloy within a zircaloy tube throughout the cluster



Equilibrium Core for Self-Sufficient U-233 Production.

- ☐ Modified clusters - outer 228 channels.
- ☐ Standard clusters - inner 224 channels.
- ☐ Refuel 78 (39+39) channels / year.
- ☐ 73 kg of Pu / year
  - ➢ Makeup required.
- ☐ 144 kg of U-233 needed/year
  - ➢ ~1.85 kg/cluster (average).
  - ➢ Self-sustaining; no makeup required.
- ☐ Burnup: 29 GWd/t to 48 GWd/t
  - ➢ 3 burnup zones.
  - ➢ 35.5 GWd/t average.
- ☐ ~65% power from U-233/Th-232.
- ☐ Reactivity coefficients similar.
- ☐ Void reactivity slightly more negative.



N	Shut off Rod (1-37)
AR	Absorber Rod
RR	Regulating Rod
SR	Shim Rod

🟧 Modified clusters

🟦 Standard clusters

Average discharge burn up 35.5 GWd/te.

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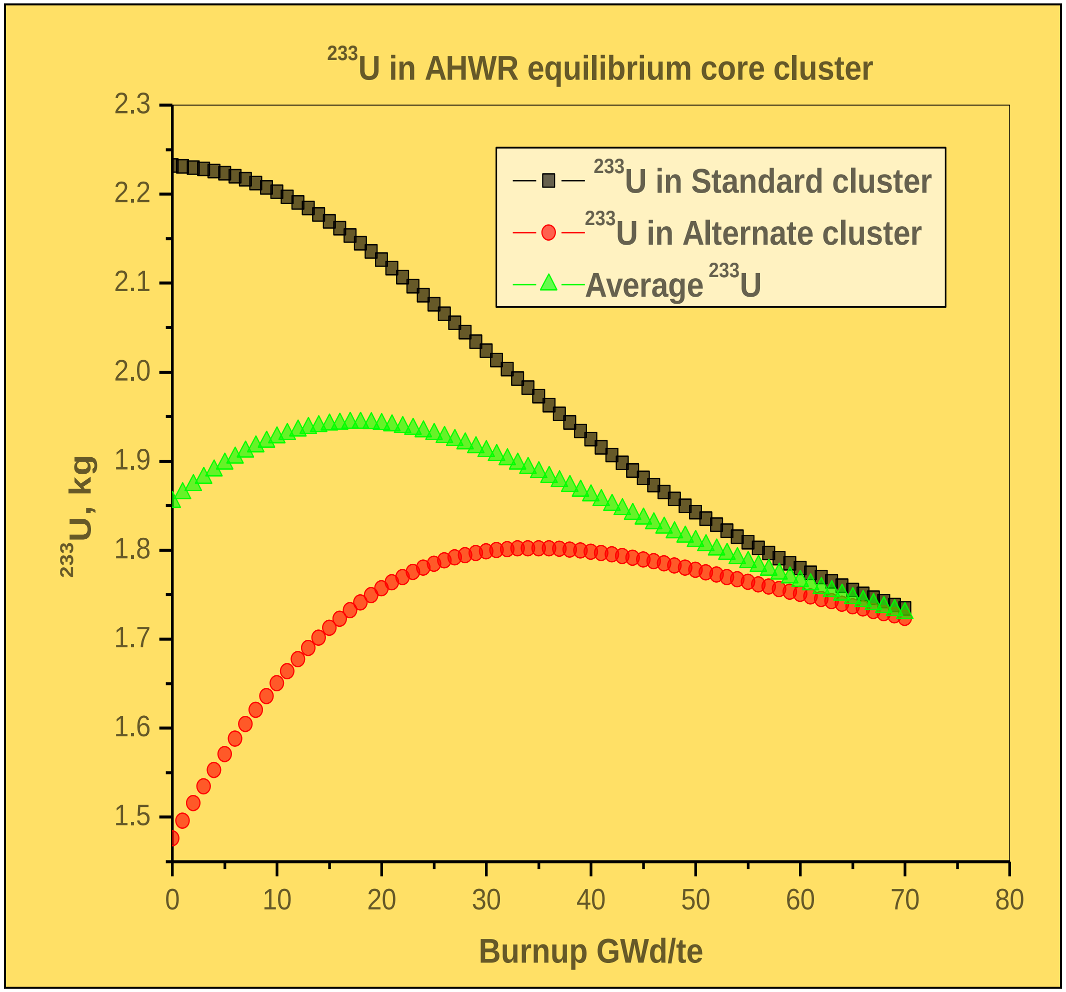
Two Cluster Types for Self-sufficiency of U-233 in AHWR

- ☐ Equal numbers of standard and alternate clusters.
- ☐ Leads to equilbrium U-233 production that gives concentration that is same at average exit burnup (~35 GWd/t) as at beginning.
- ☐ Makeup Pu still required.
  - ➢ Fast reactor.
  - ➢ PHWR reprocessed?
  - ➢ LWR reprocessed?

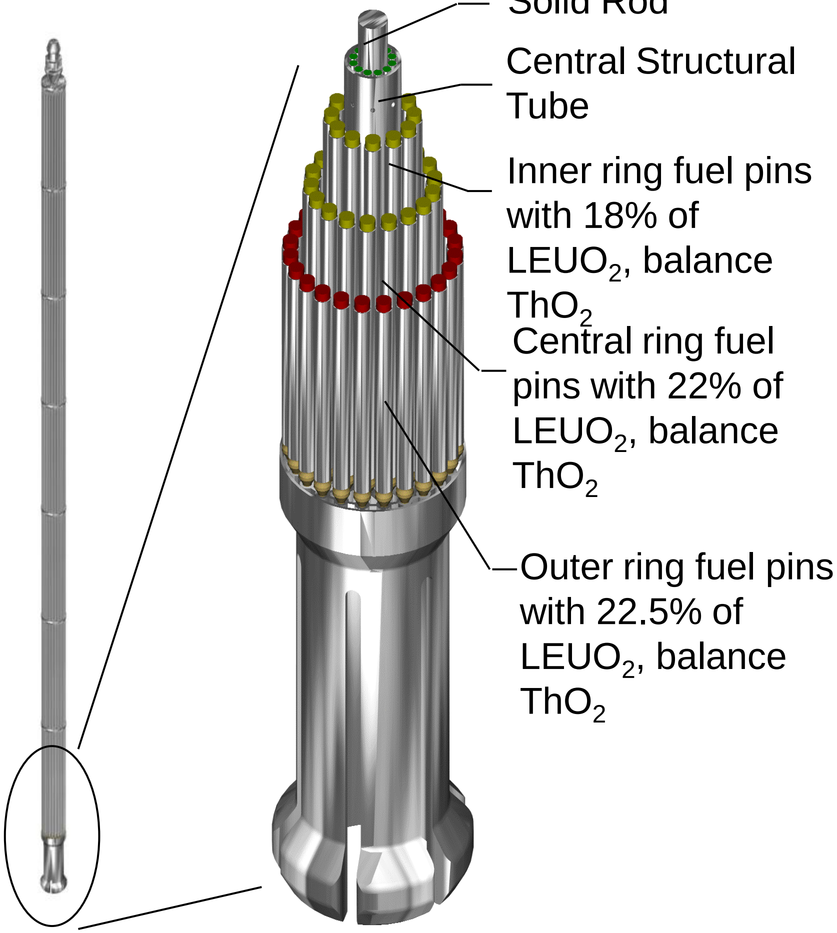


AHWR Core Designs Comparison

Core features	Self Sustaining	Standard
Power to the coolant,	MWth 920	MWth 920
Power from Thorium/U233, %	65	75
a) No. of Fuel channels refuelled per year. b) Pu, kg, required per year c) U233(net), kg, required per year.	78(39+39) 173 NIL	73 123 22
No. of SOR Worth: Total/2 max. worth rods are not available: mk	37 70.4/ 51.9	37 74.1/ 51.4
No. of Control rods (AR/RR/SR) Worth, mk	24 (8+8+8) 11.4/10.9/12.1	24 (8+8+8) 10.9/10.9 /10.6
Fuel temperature coefficient Δk/k/°C:	-2.1×10^{-5}	-2.1×10^{-5}
Channel temperature coefficient, Δk/k/°C	2.1×10^{-5}	1.9×10^{-5}
Void coefficient, Δk/k / % void	-5.9×10^{-5}	-5.7×10^{-5}
Moderator temperature coefficient, Δk/k/°C	5.5×10^{-5}	5.2×10^{-5}
Coolant temperature coefficient, Δk/k/°C	4.6×10^{-5}	4.2×10^{-5}

AHWR-LEU (India, Gen-III+)

- ☐ Alternative to using Pu in AHWR.
  - ➢ Use LEU $(U,Th)O_2$
  - ➢ AHWR design flexible.
- ☐ LEU in AHWR cluster.
  - ➢ 19.75 wt% U-235/U
  - ➢ Inner ring:18.0 wt% UO_2
  - ➢ Middle ring: 22.0 wt% UO_2
  - ➢ Outer ring: 22.5 wt% UO_2
  - ➢ Fertile ThO2 is balance of fuel.
  - ➢ Net fissile U/ (Th+U): 4.21 wt%
  - ➢ Input natural uranium (NU) required:
    - **17.84 tonnes /TWhe**
- ☐ Average discharge burnup:
  - ➢ ~64 GWd/t.



AHWR-LEU (India, Gen-III+)

- ❑ Inherent safety characteristics.
- ❑ Reactivity coefficients negative.
- ❑ Sufficient reactivity worth of shutdown systems ensured under all accidental conditions.
- ❑ CVR more negative.
  - ➢ ~ -8.7 mk

Average discharge burnup (MWd/te)	64,000	
Energy per tonne mined uranium (MWd/te)	7,826	
Power from thorium (%)	39	
Number of control rods (Worth in mk)	Absorber	8 (10.9)
	Regulating	8 (11.6)
	Shim rod:	8 (9.9)
Regulating rod worth (67% in) (mk)	5.33	
Number of shutoff rods (Total worth in mk)	45 (-83.25)	
Total worth shutoff rods if two maximum worth rods are unavailable (mk)	-60.28	
Fuel temperature coefficient ($\Delta k/k/K$)	-2.82×10^{-5}	
Channel temperature coefficient ($\Delta k/k/\ C$)	-3.73×10^{-5}	
Void coefficient ($\Delta k/k/\%$ void)	-8.72×10^{-5}	
Moderator temperature coefficient ($\Delta k/k/\ C$)	-3.09×10^{-5}	

AHWR-LEU (India, Gen-III+)

- At exit burnup of ~64 GWd/t
  - ~66% power from U-233 bred from Th-232.
  - ~17% power from U-235 .
  - ~17% power from Pu bred from LEU.
- AHWR-LEU provides better utilization of NU resources.
  - Significantly less mined natural uranium required than for LWRs.
  - 39% power by fission of U-233 from in-situ conversion of Th-232
    - (Burnup average).
  - Spent fuel.
    - Uranium 8 wt% fissile
      - Can reuse in other reactors (e.g., PHWR).
    - Plutonium.
      - Reuse in fast reactors.
  - Less than 50% of MA produced per TWhr relative to modern LWR's.

AHWR (India, Gen-III+)

- Several fuel options for AHWR, flexibility:
  - Standard $(Th,Pu)O_2$ cluster.
  - Mixed core of two cluster types $(Th,Pu)O_2$ for U-233 self-sufficiency.
  - LEU in (U,Th)O2 clusters.
- High burnups:
  - ~38 GWd/t (Standard)
  - ~35 GWd/t (Self-sufficient U-233)
  - ~64 GWd/t (LEU)
- Negative reactivity coefficients.
- Mined uranium requirement per unit energy is less for AHWR as compared with alternatives.
- Significant power fraction fro U-233/Th-232:
  - 75% (Standard)
  - 66% (Self-sufficient U-233)
  - 39% (LEU)

AHWR (India, Gen-III+)

- ☐ U, Pu recovered from spent (LEU,Th)O_2 with 8 wt% fissile
  - ➢ Use in other reactors.
- ☐ Pu production reduced, relative to alternatives (PHWR, LWR).
- ☐ Minor Actinide (MA) production reduced relative to PWR's.
- ☐ Radio-toxicity due to AHWR lower, compared to PWR or PHWR.
- ☐ U-232 and Pu-238 present in reprocessed U and Pu from AHWR makes fuels more proliferation-resistant.

TR-1000 (Russia, 1989) Gen-III+, Gen-IV HWR ???

- ❑ TR-1000 (Russia)
    - ➢ 1989 concept proposal.
    - ➢ Based on past experience with KS-150 / A1 Bohunice GCHWR technology.
    - ➢ CO_2 coolant, 9.8 MPa, 400°C to 450°C outlet.
    - ➢ Metallic Natural U, or U/Pu, clad with Zr-alloy, C.R.>0.80
    - ➢ Burnup ~ 10 GWd/t
    - ➢ Pre-stressed concrete pressure vessel.
- ❑ 3200 MW_{th} / 1000 MW_e
- ❑ Steam at 7 MPa, 400 C.
- ❑ Net efficiency ~31%.
- ❑ Design for recycling Pu.

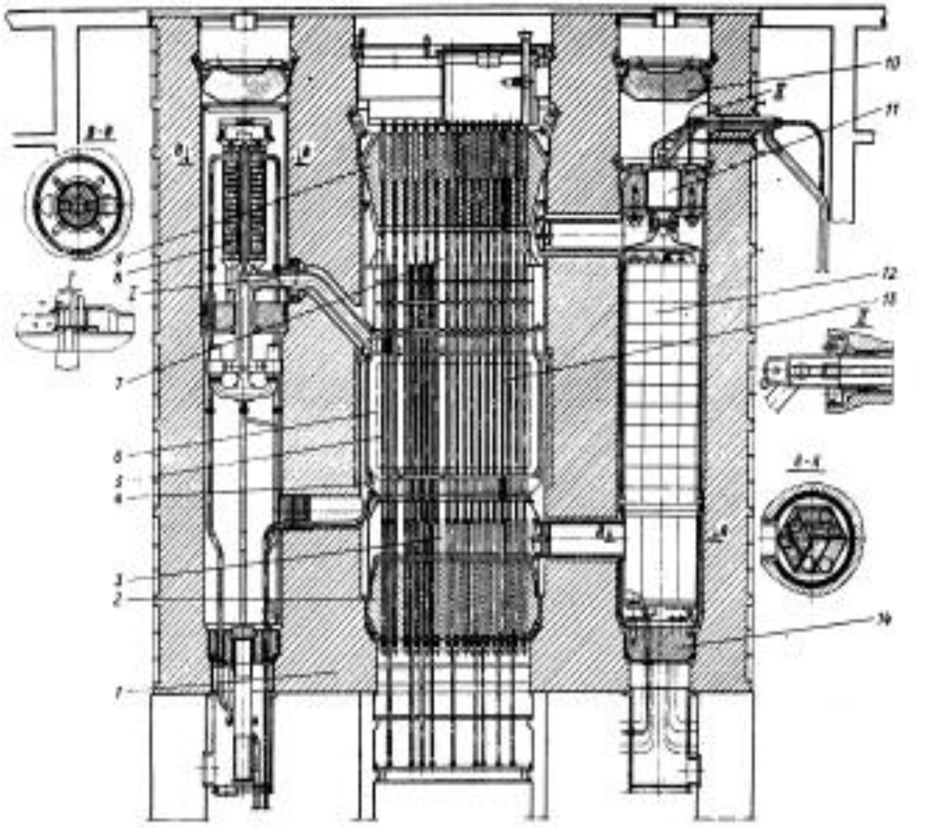


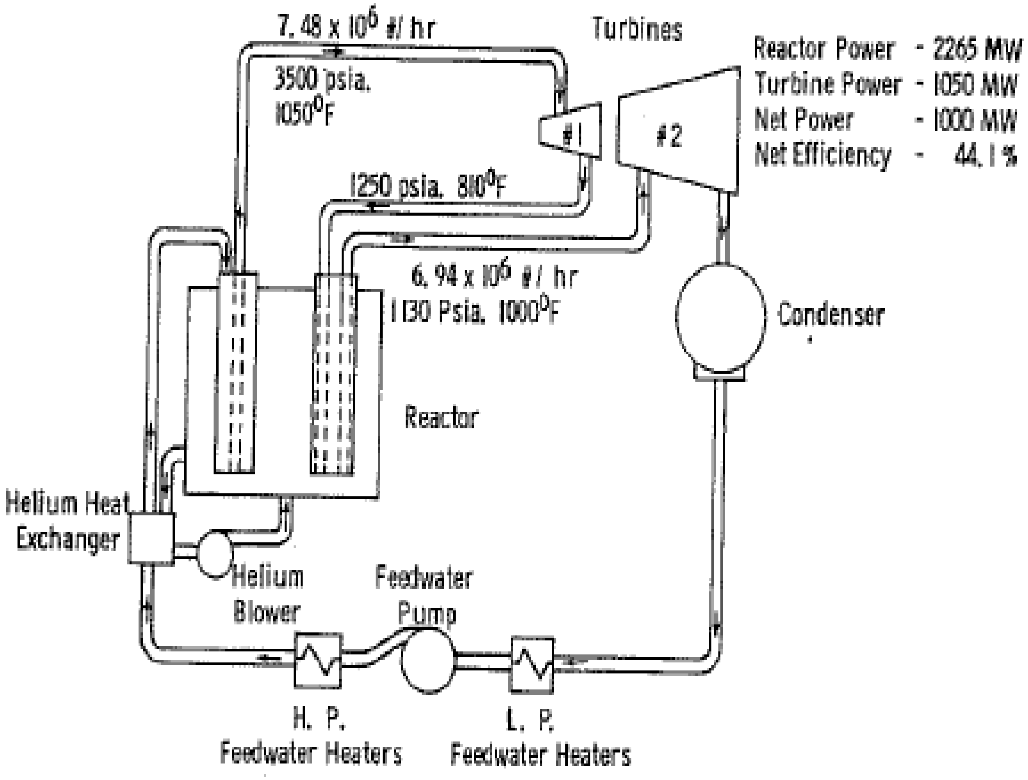
Fig. 1. TR-1000 reactor arrangement: 1) prestressed reinforced concrete shell; 2) lower central vessel plug; 3) inlet (hot) chamber; 4) heavy water tank; 5) fuel channel; 6) core; 7) discharge (cold) chamber; 8) moderator heat exchanger and presurizer; 9) central vessel upper cover; 10) steam generator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

Gen-IV HWR’s

- Super-critical HWR
  - Super-critical coolant, not reactivity !
  - H_2O at 25 MPa, 530 C to 625 C.
    - D_2O is an alternative coolant.
  - Not quite liquid, not quite vapor
  - 45% to 50% net thermal efficiencies possible.
- Early Concept:
  - SCOTT-R Reactor (1962), Westinghouse USA
  - **S**uper **C**ritical **O**nce **T**hrough **T**ube **R**eactor
- Today / Tomorrow:
  - CANDU-SCWR
  - Combine CANDU technology with supercritical H_2O.
  - Parametric design studies underway.

SCOTT-R (1962, Westinghouse)

- ❑ Supercritical, with nuclear re-heat.
- ❑ $\eta_{th} > 44\%$



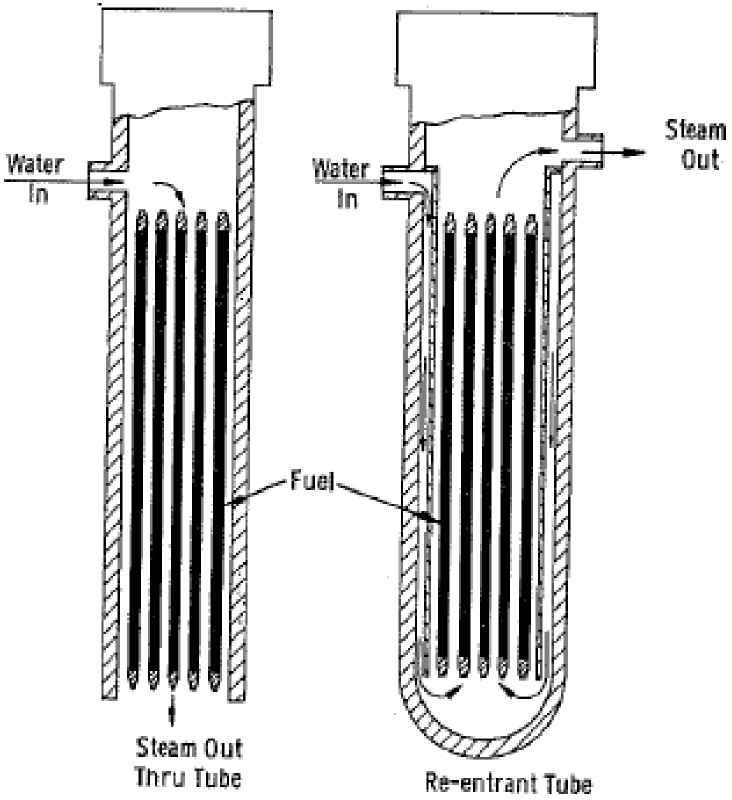
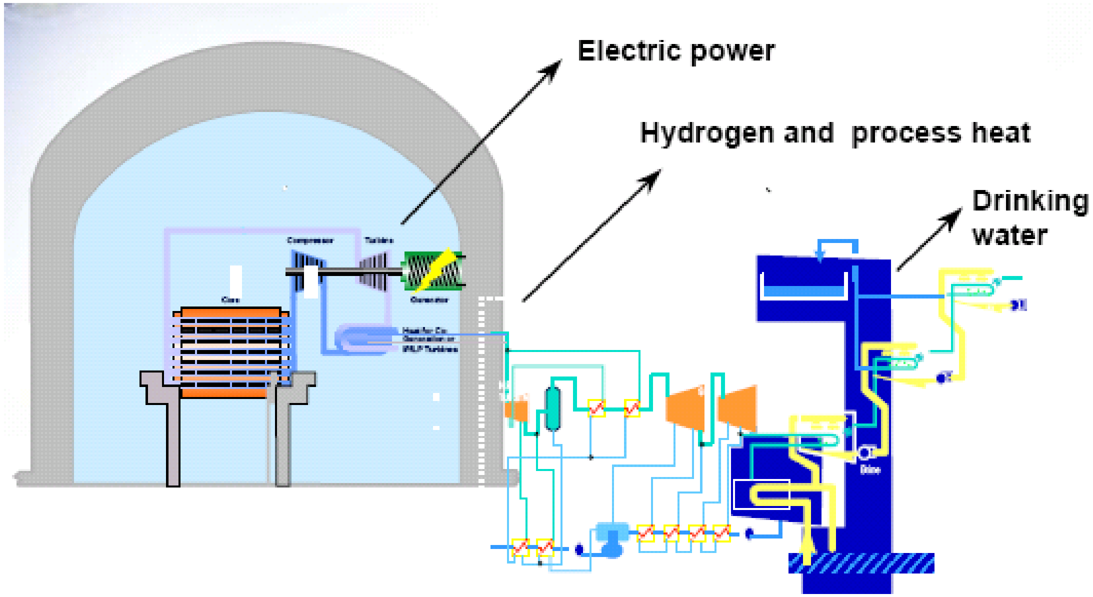


Fig. 10—Pressure tubes.

CANDU-SCWR (Canada, Gen-IV)

- ❑ 25 MPa, ~325°C inlet, 500 C to 625 C exit.
- ❑ Direct Cycle, Efficiency ~ 45%.
- ❑ >1000 MWe.



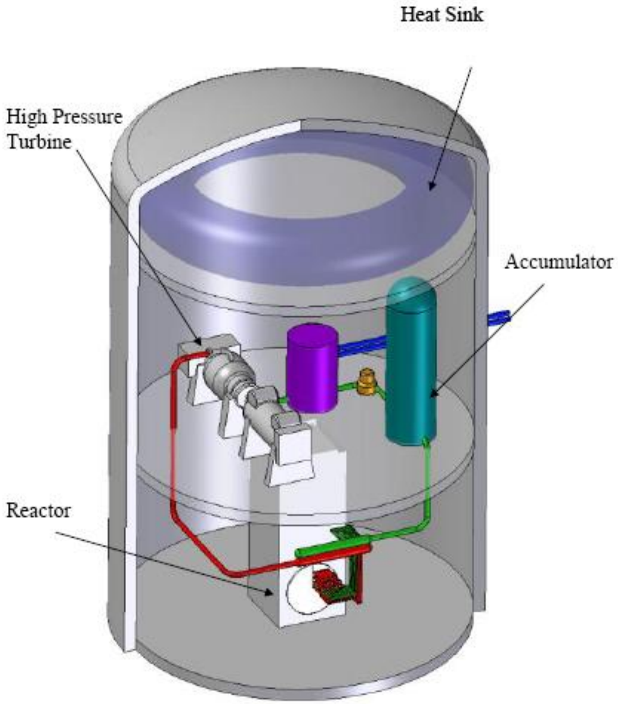


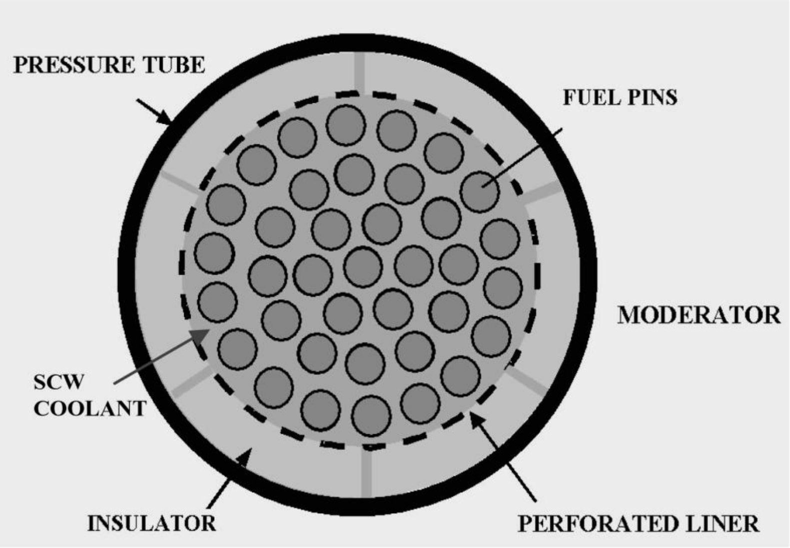
Figure 5: CANDU-SCWR Schematic.

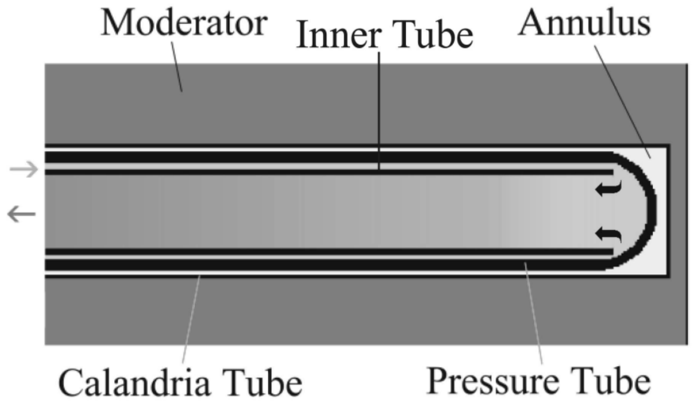
CANDU-SCWR (Canada, Gen-IV)

- ☐ CANDU Design features in CANDU-SCWR
  - ➢ Pressure tubes, with fuel bundles inside.
    - But, pressure vessel concept under consideration as well.
  - ➢ D_2O moderator at lower temp. (~80°C), pressure.
    - Also an auxiliary heat sink in case of postulated accident.
- ☐ Design changes/options considered for CANDU-SCWR.
  - ➢ Horizontal or vertical channels.
  - ➢ Thicker pressure tubes.
  - ➢ Once-through, or re-entrant tubes.
  - ➢ Insulated liner or double wall between PT and fuel bundles.
  - ➢ Multi-batch off-line refuelling.
    - Boron dissolved in moderator for excess reactivity hold down.
  - ➢ Fuel bundle modifications.
    - Enrichment (compensate for materials, higher burnup).
    - Number of pins.

CANDU-SCWR (Canada, Gen-IV)

- ❑ Channel Design options
  - ➢ High Efficiency Channel (HEC)
  - ➢ Re-Entrant Channel (REC)
- ❑ PT Materials
  - ➢ New Zirconium alloys
    - Zr-3.5%Sn-0.8%Nb-0.8%Mo
      - o “Excel” alloy.
- ❑ Insulators
  - ➢ Porous Yt-stabilized ZrO_2 (YSZ)
- ❑ Thin Liner Tube (HEC), Inner Tube (REC)
  - ➢ Ni-alloys, ferritic-martensitic materials.
  - ➢ Low-swelling stainless steels.





CANDU-SCWR (Canada, Gen-IV)

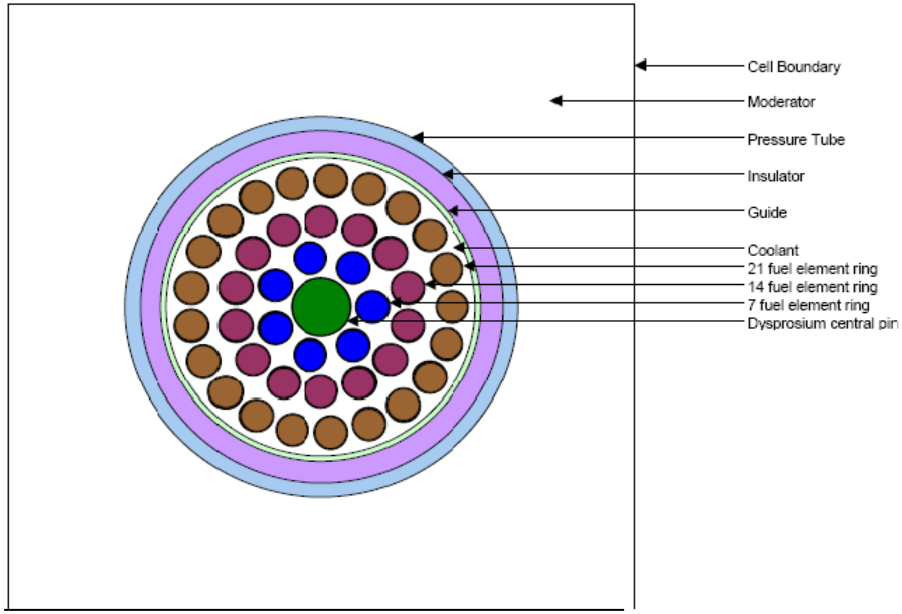
- Fuel options:
  - LEU and/or $(Pu,Th)O_2$.
    - 3 wt% to 5 wt% LEU, or 5 wt% to 10 wt% Pu in Th.
    - Target exit burnup: ~40 GWd/t (3-batch refuelling).
  - Enrichment, more excess reactivity to compensate for:
    - Neutron absorption by special materials for SCW environment.
    - Thicker PT, super-critical water coolant.
    - Multi-batch re-fuelling.
  - Greater fuel pin sub-division.
    - Enhanced heat transfer surface area.
    - 42 pins, or 55 fuel pins.
  - Clad
    - Stainless steel, high-chromium alloys.
- Lattice pitch options: 22 cm to 29 cm

CANDU-SCWR (Canada, Gen-IV)

- ❑ Design options to minimize coolant void reactivity.
  - ➢ Vary lattice pitch (to adjust M/F).
    - 22 cm to 27 cm.
  - ➢ Gap between CT and PT (like ACR-1000).
  - ➢ Moderator displacer tubes (like SGHWR).
  - ➢ Vary thickness/porosity of insulators.
  - ➢ Vary geometry to put fuel at outside (similar to AHWR).
  - ➢ Burnable neutron absorber pins (like ACR-1000).
- ❑ One particular design.
  - ➢ 27-cm square lattice pitch.
  - ➢ 300 vertical channels.
  - ➢ 2540 MW_{th}.
  - ➢ 3-batch cycle, 315-day cycle length.
  - ➢ 4 wt% LEU, ~28.5 GWd/t exit burnup.

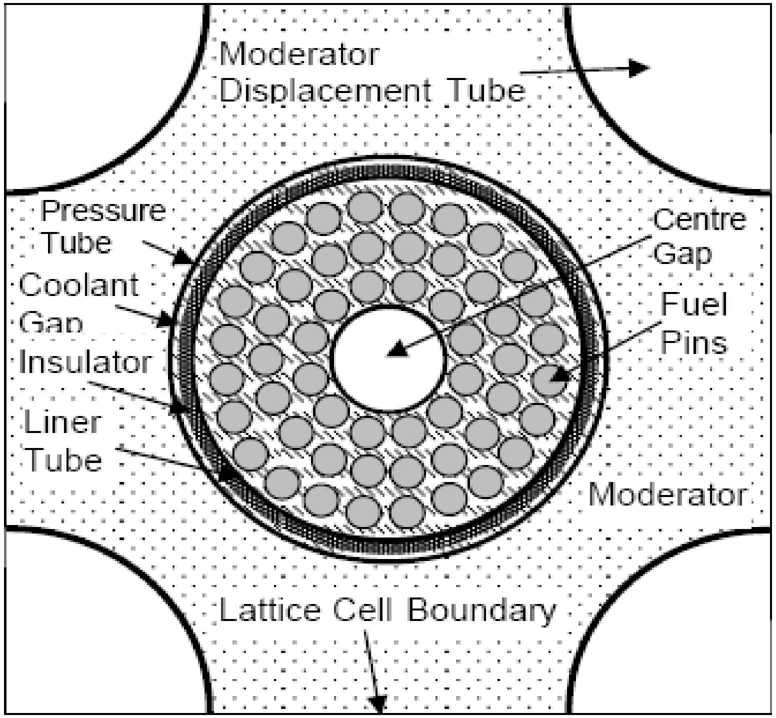
CANDU-SCWR (Canada, Gen-IV)

- CANFLEX-ACR inside HEC
  - 42-element bundle.
    - Stainless steel clad.
  - Central BNA pin.
    - 30 wt% Dy_2O_3 in ZrO_2
  - Variation of:
    - 20 cm to 29 cm pitch.
    - Insulator thickness, porosity
    - Pressure tube thickness
    - 3.5 wt% to 5 wt% LEU
  - Burnup (3 batch):
    - 13 GWd/t to 33 GWd/t
  - CVR
    - -11 mk to +8 mk



CANDU-SCWR (Canada, Gen-IV)

- REC Design Concept
  - 55-element bundle.
  - Moderator displacement tubes.
    - Reduce moderator/fuel ratio.
    - Ensure negative coolant void reactivity (CVR).
  - Central tube with gap for
    - Solid, gas, or stagnant coolant.
  - 4 wt% LEU.
  - 31 GWd/t exit burnup
    - 3-batch refuelling.
  - CVR varies -7 mk to -25 mk.



Gen-V HWR's ???

- ☐ Advances in:
  - ➢ Materials science, manufacturing, process engineering.
  - ➢ Corrosion sciences, chemical engineering.
  - ➢ Isotope separation techniques.
  - ➢ Engineering design, computational analysis tools.
  - ➢ Balance of plant design, power conversion cycles.
- ☐ Revisit old ideas postulated, tested, with modifications.
  - ➢ 1950's, 1960's, etc.
- ☐ Use D_2O or alternative deuterated compounds as the moderator for high-neutron economy; save neutrons.
- ☐ Design goals
  - ➢ High thermal efficiency (>50%).
  - ➢ High conversion ratios, or thermal-breeding (e.g. with Th/U cycle).
  - ➢ High burnup / resource utilization.
  - ➢ Low long-term cost of electricity.

Gen-V HWR’s ???

- Consider alternative coolants:
  - Gases: CO_2, He, Ne, etc. at high pressure (~10 MPa).
    - Option to use in direct Brayton (gas turbine) cycle.
  - Liquid metals Pb, Pb/Mg, Na, Li-7
  - Organic coolants.
  - Molten salts.
- Consider alternative fuel forms.
  - Pu-metal, U-metal, Th-metal alloys.
  - PuC, ThC, UC in graphite blocks, pebble bed, or particle beds.
  - Carbon-tube clad, vitro-ceramics.
  - Porous or annular fuel pellets
    - Passive or active venting/removal of fission product gases.
  - Liquid metal fuel – allow U, Pu, Th to melt.
    - Contain within carbon tubes; high thermal conductivity.

Gen-V HWRs ???

- ❑ Balance of Plant / Power Conversion Cycles:
  - ➢ Super-critical H_2O secondary cycle.
    - In combination with liquid metal or gaseous primary coolant.
    - Demonstrated in existing fossil fuel plants.
  - ➢ Brayton Cycles with gaseous coolants.
    - Compact turbines – major capital savings costs.
  - ➢ Stirling cycles.
    - Approach near-Carnot efficiencies: $\eta_{th\text{-}Carnot} = 1 - T_c/T_h$
    - If $T_c = 300$ K; T_h=1000 K, then is η_{th} ~70% possible?
  - ➢ Combined cycles:
    - Brayton (gas turbine) + Rankine (steam).
  - ➢ Dissociating coolants in turbines: $N_2O_4 + \text{heat} \rightarrow 2\ NO_2$
  - ➢ Other???
- ❑ Ultimately, driven by safety and cost-of-electricity.

Additional Future Roles for HWR’s

- ☐ Advanced Fuel Cycles.
  - ➢ Synergism with LWR’s and fast reactors.
    - Integrated nuclear energy system.
  - ➢ Extending nuclear fuel utilization.
  - ➢ Breeding and burning of U-233 from Th-232.
    - Once-through-thorium (OTT), or,
    - Self-sufficient equilibrium thorium (SSET).
  - ➢ 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.

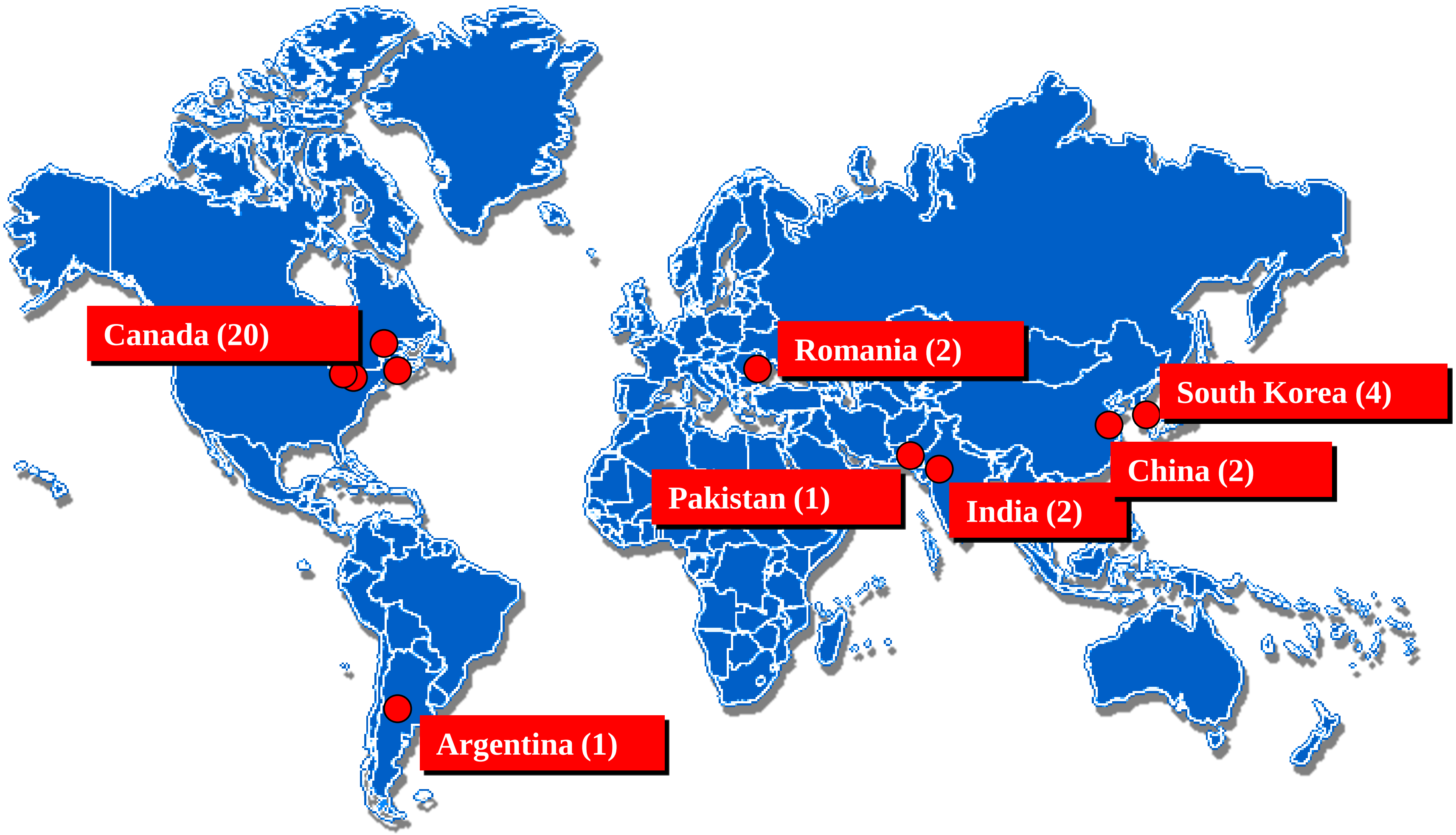
Additional Future Roles for HWR’s

- ❑ 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.
      - o Synthetic gasoline, diesel, methanol, ethanol, etc.
- ❑ High-temperature Steam
  - ➢ Enhanced recovery and upgrading of hydrocarbons
    - Oilsands, coal
  - ➢ Role for alternative HWR designs to produce very high-temperature steam.
    - CANDU-SCWR, gas-cooled HWR’s.

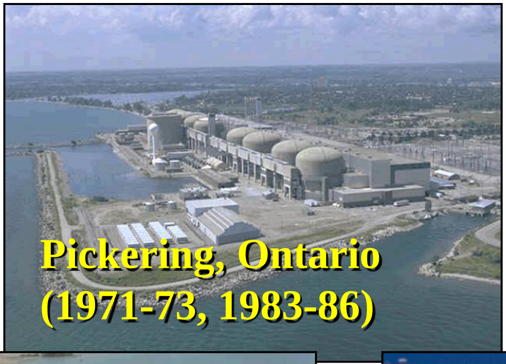
International Penetration of HWR’s

- ❑ World installed and operating nuclear capacity (2009):
  - ➢ 439 Reactors, ~375 GWe net
- ❑ World installed HWR capacity (2009):
  - ➢ 48 Reactors, ~25 GWe net
  - ➢ 20 Reactors in Canada, ~15 GWe net
  - ➢ 28 HWR abroad
    - India (17), South Korea (4), China (2), Romania (2), Argentina (2), Pakistan (1)
- ❑ HWR’s: ~11% of reactors, ~7% of net power
- ❑ Current commercial HWR’s tend to be smaller in size:
  - ➢ ~200 MWe to ~900 MWe
  - ➢ But, ACR-1000 is sized (~1085 MWe, net) for larger markets.

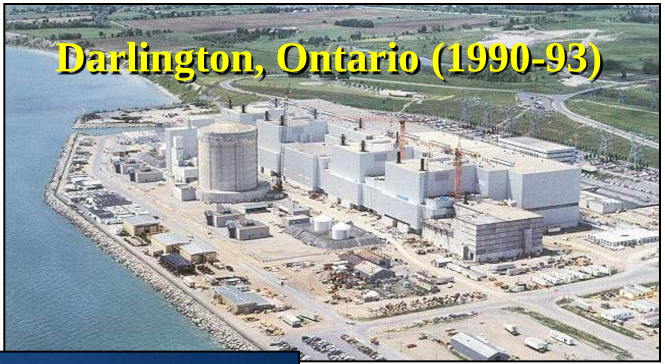
CANDU Reactors Around the World



CANDU's in Canada

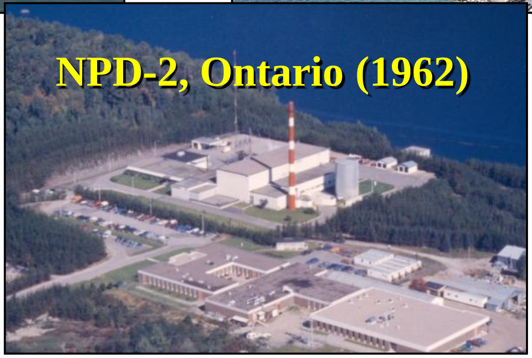


Pickering, Ontario
(1971-73, 1983-86)



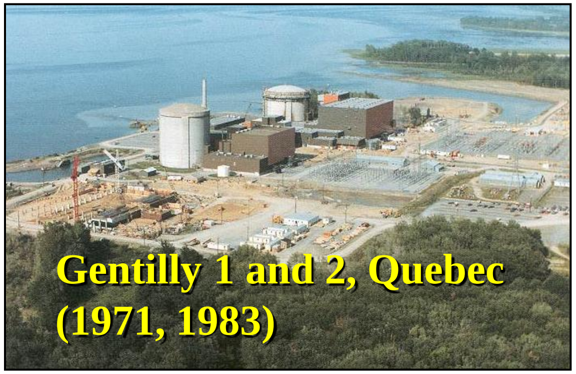
Darlington, Ontario (1990-93)

Bruce, Ontario
(1977-79, 1985-87)



NPD-2, Ontario (1962)

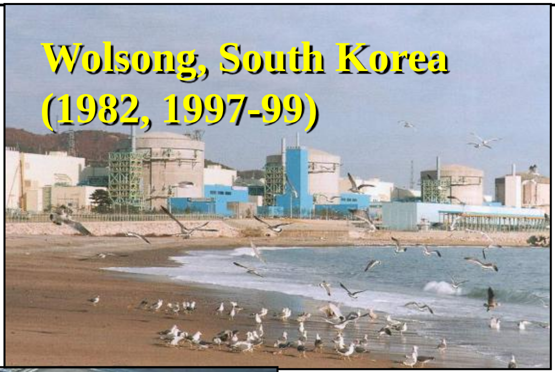
Douglas Point,
Ontario (1966)



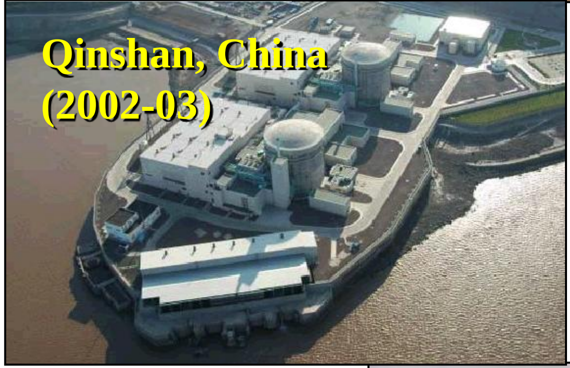
Gentilly 1 and 2, Quebec
(1971, 1983)

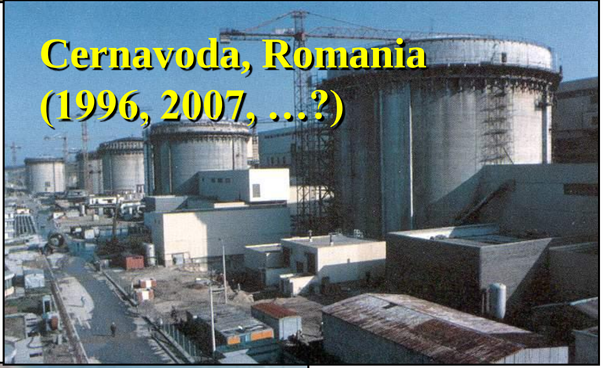
Pt. Lepreau, New Brunswick
(1983)

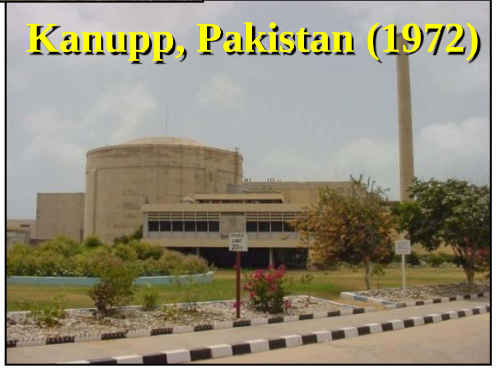
CANDU's Around the World


Wolsong, South Korea
(1982, 1997-99)


Embalse, Argentina
(1984)


Qinshan, China
(2002-03)


Cernavoda, Romania
(1996, 2007, …?)


Kanupp, Pakistan (1972)


Rajasthan, India
(1973, 1982)

FJOH 2010

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 a moderator.
    - Pathway initially chosen by other nations:
      - o U.K. (Magnox, AGR), France (GCR), Russia (RBMK).
- ❑ Weapons/Defence and Naval programs.
  - ➢ Development of industrial infrastructure for uranium enrichment.
    - U.S.A., Russia, U.K., France, China.
  - ➢ Use of PWR's for naval submarines, and aircraft carriers.
    - Unique application for which PWR's well-suited.
    - Compact cores, simple reactor design.
    - Cost of fuel is not a concern for defence budget.
  - ➢ Large investment in LWR technology.
    - Major head start on alternatives.
    - BWR technology benefited from R&D for PWR's.

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.
  - Recycled and down-blended HEU from weapons programs.
- Competing Technologies.
  - Resources to support more than one or two technologies limited.
  - Many countries switched / focused on LWR technology.
    - U.S.A., Russia:
      - Knowledge and experience base is large.
    - France, Germany, Sweden, Switzerland, Belgium, etc.
    - Czech, Slovakia, Ukraine, Taiwan.
    - Japan, S. Korea; others have followed suit
  - U.K.: Magnox and AGR's were performing well in 1970's.
    - Technical difficulties; now seeking standardization for new reactors.

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.
  - ➢ Need to exploit alternative fuels:
    - Recycled uranium, plutonium from LWR’s.
    - Thorium fuel cycle (breeding and burning U-233).
- ❑ 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.
  - Gen-IV and beyond.
  - Issues for large pressure vessels.
    - Manufacturing challenges, availability, local fabrication.
  - Modular design with pressure tubes more feasible.
    - Particularly for super-critical-water coolant designs.
  - Renewed motivation to use super-critical water, organic, gas, liquid metal, or molten salt coolants.
    - To achieve high thermal efficiencies → ~50%
    - PT design with maximum neutron economy possible.
  - Use of thermal neutron spectrum is attractive.
    - Lower fuel enrichment required than in a fast reactor.
    - Longer neutron lifetime, especially in a D_2O reactor, is an enhanced safety feature.

Conclusions

❑ Heavy Water Reactor Advantages.

- ➢ **Excellent neutron economy**, better utilization of resources.
- ➢ Special safety features:
  - Large heat sink, multiple shutdown systems, longer neutron lifetime.
- ➢ Modular construction (pressure tubes)
  - Local manufacturing.
- ➢ On-line refuelling → high capacity factors, higher fuel utilization.
- ➢ 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 (alternative coolants).

Conclusions

❑ International Interest in Heavy Water Reactors

- Canada – main focus: mature technology / commercialized
  - Technology development since 1945.
  - CANDU design development; CANDU-6 exported abroad.
  - EC6 and ACR-1000 are Gen-III+ designs, 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.
  - HWR 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 in the future, as world demand for nuclear energy increases.

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.
    - Exploitation of thorium-based fuels.
  - ➢ Increasing cost of fuel favors HWR technology.
- ❑ Increasing role for HWR’s in nuclear energy supply
  - ➢ World demand for nuclear energy growing.
  - ➢ Keeping several options open 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.

Acknowledgements

- *Bronwyn Hyland, Jeremy Pencer, Geoff Edwards*
- *Darren Radford, Bhaskar Sur, Richard Didsbury*
- *Michaela Ovanes, Peter Chan, Jeremy Hopwood.*
- *Michele Kubota*
- *Ken Kozier, Jeremy Whitlock*
- *Peter Boczar (retired)*
- *Dan Meneley (UOIT)*
- *P.D. Krishnani (BARC)*
- *Many others …*

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- *And many more ....*

Useful Websites

- Canada (AECL):
  - http://www.aecl.ca/site3.aspx
  - http://www.aecl.ca/Assets/Publications/Posters/CANDU-Evolution.pdf
  - http://www.aecl.ca/Reactors/CANDU6.htm
  - http://www.aecl.ca/Assets/Publications/C6-Technical-Summary.pdf
  - http://www.aecl.ca/Assets/Publications/EC6-TS_Eng.pdf
  - http://www.aecl.ca/Assets/Publications/ACR1000-Tech-Summary.pdf
  - http://www.aecl.ca/Assets/Publications/Fact+Sheets/ACR-1000.pdf

- Canada (other):
  - http://www.nuceng.ca/
  - http://www.cns-snc.ca/home_eng.html
  - http://www.nuclearfaq.ca/
  - http://www.physics.ubc.ca/~waltham/pubs/d2o_19.pdf

Useful Websites

- Canteach website: a treasure chest of information on HWR's.
  - Many reports, papers, presentations, images, etc.
  - http://canteach.candu.org/
  - http://canteach.candu.org/catalog.html
  - http://canteach.candu.org/image_index.html

Useful Websites

- India:
  - http://www.npcil.nic.in/nupower_vol13_3/ahwr.htm
  - http://www.powermag.com/print/issues/departments/global_monitor/
  - http://www.iaea.org/inisnkm/nkm/aws/fnss/fulltext/te_1319_16.pdf
  - http://www.npcil.nic.in/annualreport08_09.pdf
- Other:
  - http://www-pub.iaea.org/MTCD/publications/publications.asp
  - http://www.world-nuclear.org/info/inf08.htm
  - http://en.wikipedia.org/wiki/CANDU_reactor
  - http://inisdb.iaea.org/
- Wallcharts (images) of reactors:
  - http://econtent.unm.edu/cdm4/browse.php?CISOROOT=/nuceng
- Just Google, Yahoo, or Wikipedia “heavy water reactor”

On-line Videos

- CANDU-6
  - http://poweringthefuture.nbpower.com/en/Library/Videos.aspx?id=opp
  - http://www.videos.aecl.ca/C6_flythru02.mpg

- ACR-1000
  - http://www.videos.aecl.ca/ACR-1000.wmv

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