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 (optional, see slides/notes offline).
  - Design options for HWR's.
  - HWR characteristics.
  - Design components (focus on CANDU-type)
    - CANDU (**CAN**ada **D**euterium **U**ranium)
  - Control devices.
  - Fuel cycles, thorium (optional, see slides/notes offline).
  - CANDU-PHWR features.

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
    - Various HWR Prototypes.
  - Alternative HWR Reactor Designs Proposed.

Goals

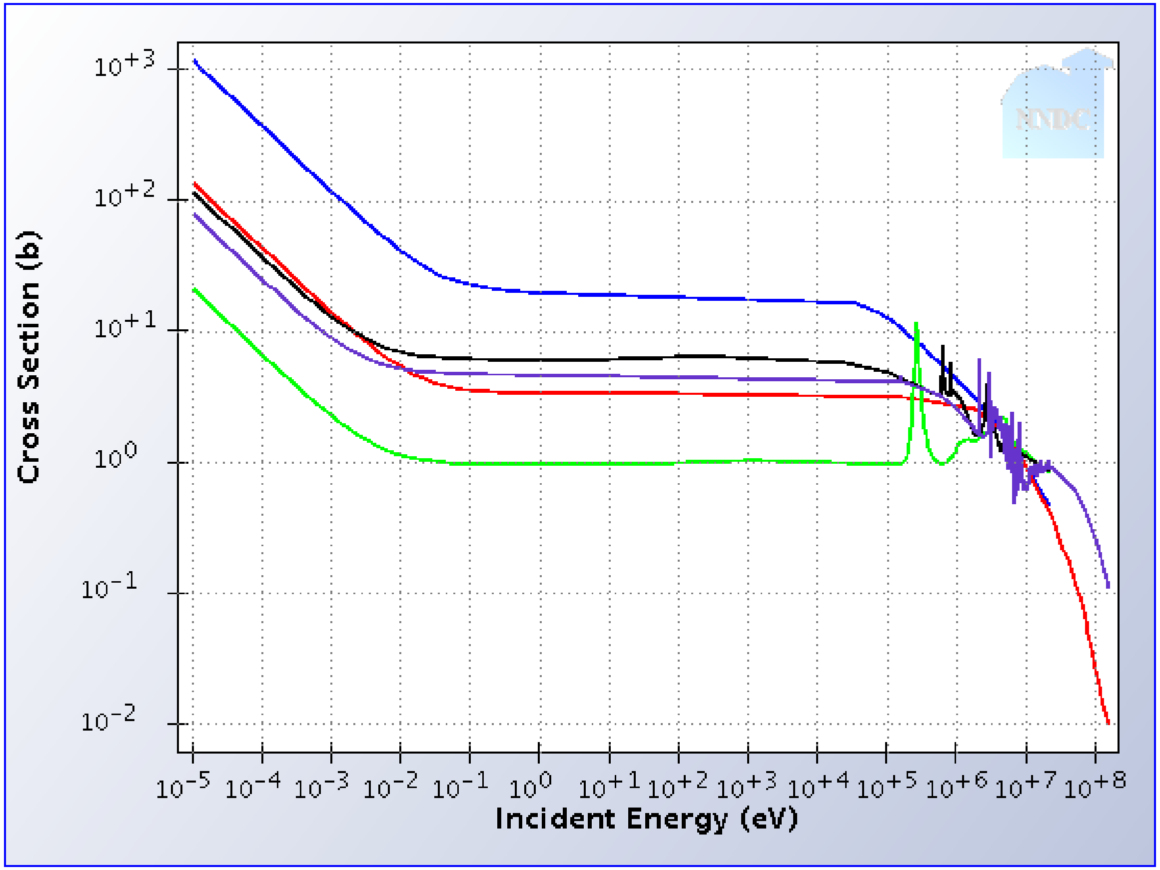
- Better understanding and appreciation of heavy water reactors.
  - Motivation.
  - How it works.
  - Design features.
  - Physics issues, engineering issues.
  - What you can do with HWR’s.
  - Long term prospects
  - Implications for future.

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 (storage/handling).
- Incentive to use thermal reactors.

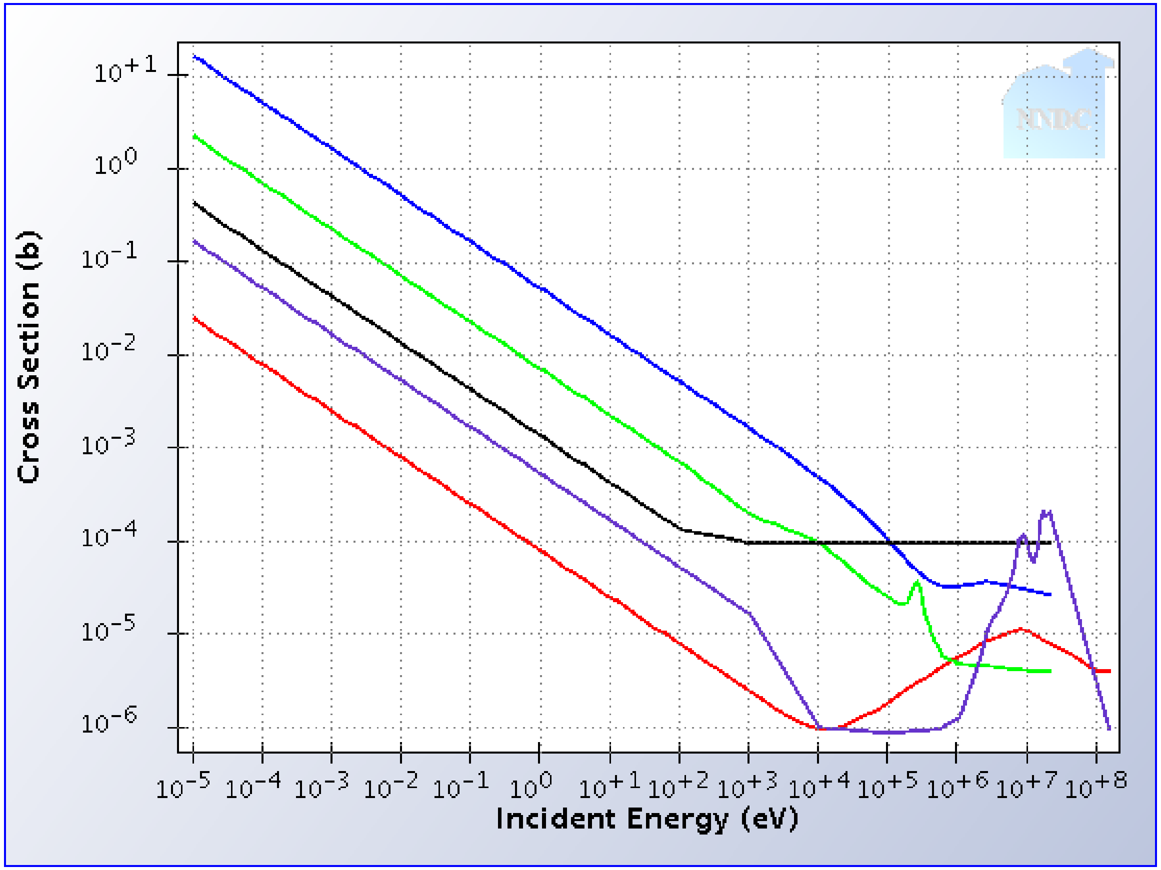
Isotopes for Moderation

- 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).
    - Do not need industrial infrastructure for enrichment of U-235 in U.
  - Higher burnups for a given enrichment.
    - Higher utilization of uranium resources.
  - Reduce parasitic neutron absorption in moderator.
    - Save neutrons, and spend them elsewhere.
      - For fission, for conversion.
    - Permits use of higher-absorption structural materials.
      - High P, High T environments – better efficiencies.
      - Materials to withstand corrosive environments.
  - Thermal breeders with U-233 / Th-232 cycle feasible.
    - 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.
- Abundance: ~0.015 % D_2O in water; need to concentrate it.
- Purity Required > 99.5 wt%D_2O
  - dk_{eff}/dwt%D_2O ~ +10 to +30 mk/wt%D_2O (1000 to 3000 pcm/wt%D2O)
  - Less sensitive for enriched fuel.
  - 1 mk = 100 pcm = 0.001 dk/k
- Cost:
  - ~300 to 500 \$/kg-D_2O; ~200 to 400 \$/kWe (using conventional methods).
  - New technologies will reduce the cost by at least 30%.
- 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.

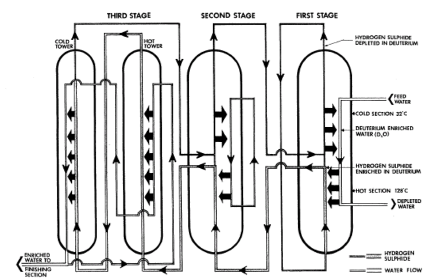


Fig. 5.7. Production of heavy water by GS hydrogen sulfide process (courtesy of Atomic Energy of Canada Limited).

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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 from Norway to U.K.
  - D_2O 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.
- Inadvertently, Joliot was instrumental in helping set Canada on course to develop heavy water reactors.

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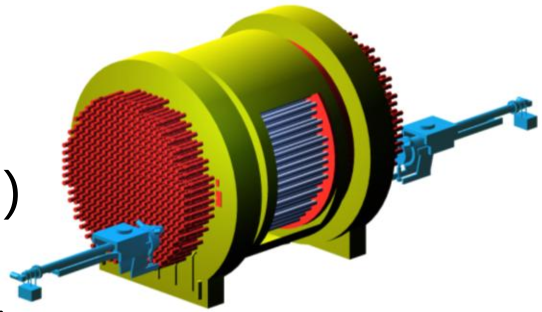
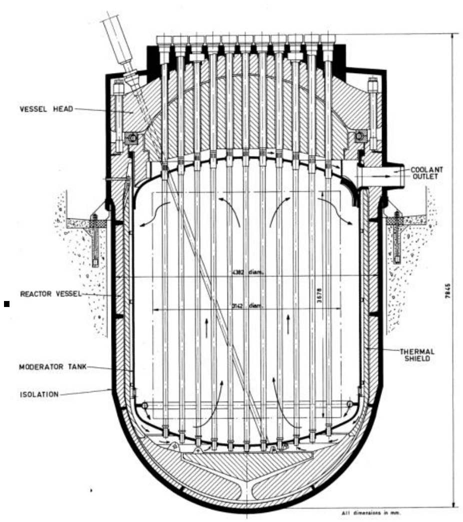
Vessel Design Options for HWR's



- 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.
  - Modular; easier to manufacture.
- 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.

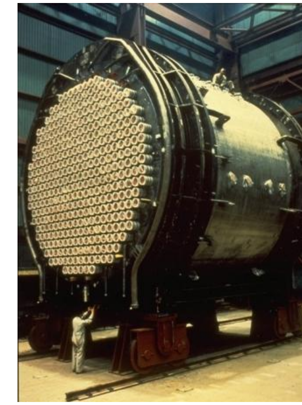


VERTICAL SECTION REACTOR MZFR

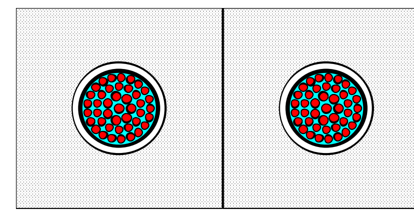
Primary Coolant Options

- 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.

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Primary Coolant Features: H_2O

- H_2O at 10 to 15 MPa (ACR-1000)
  - Pressurization to prevent boiling
  - T_{sat} ~ 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%.

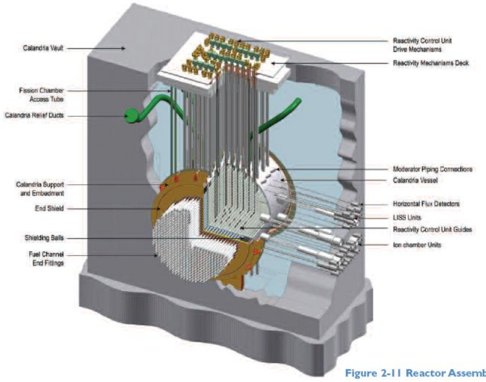
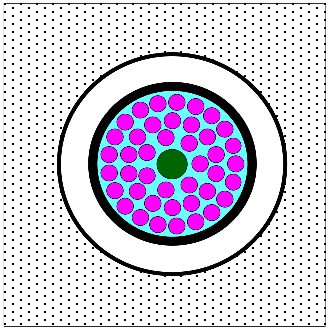


Figure 2-11 Reactor Assembly



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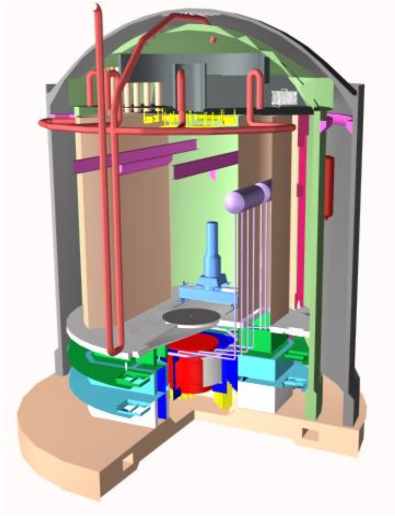
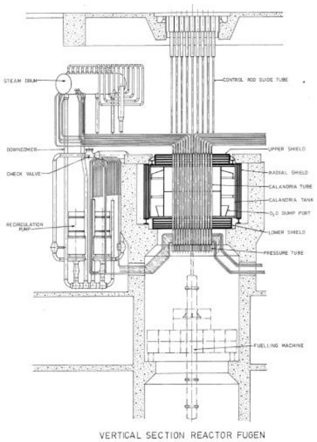
Primary Coolant Features: Boiling H_2O

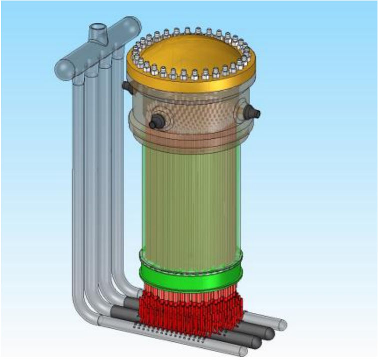
- Boiling H_2O at 5 to 7 MPa (T~264°C to 285°C)
  - Cheaper, lower capital costs.
  - Thinner PT's feasible; reduced neutron absorption.
  - Direct steam cycle
    - Eliminate steam generator; slightly higher efficiencies.
    - Up to 35%.
  - Neutron absorption in H_2O.
  - Must design lattice carefully 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.

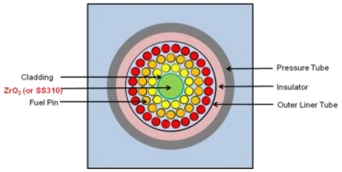




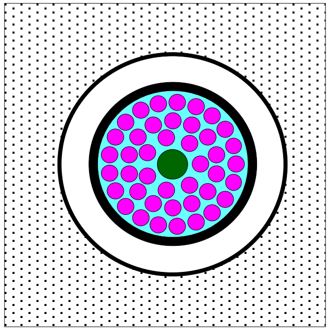
Primary Coolant Features
Super-critical H_2O

- 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 625°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).
    - Potential use of burnable neutron poisons, boron in moderator.





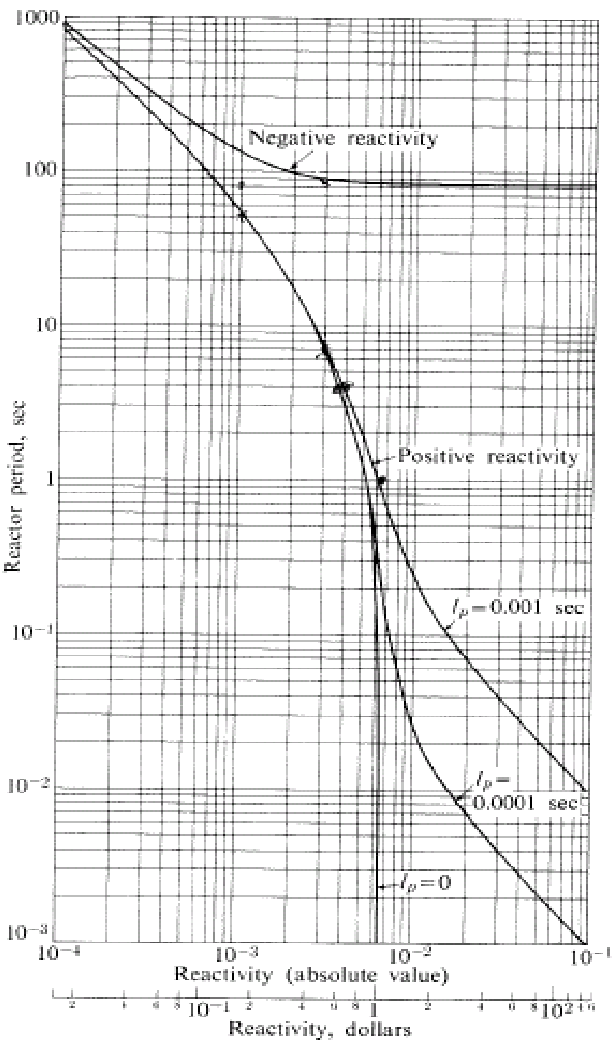
HWR Physics Characteristics



- Moderator isolated from fuel/coolant.
  - Kept 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 (-ve or +ve), depending on design.
    - Aim for small magnitude, slightly negative.

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.
  - For U-235 (Beta ~ 6.5 mk, 650 pcm)
  - $\Delta\rho$ = +6 mk (600 pcm) → Period ~ 1 sec.
  - Slower transient (much easier to control).
- Extra delayed neutron groups
  - Delayed neutron fraction (beta) increased.
  - Photo-neutrons from γ + D → n + H reaction.
  - Half-life of several photo-neutron precursors >> delayed neutron precursor (~55 seconds).
  - 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, UC good too, but UO_2 more practical in current reactors.
  - 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 spent LWR fuel / recovered uranium (RU).
    - Work in tandem with LWR's to maximize energy extraction.
      - E.g. use of (RU+DU) = NUE in Qinshan CANDU reactors in China.
    - Excellent neutron economy.
      - Can burn just about anything.
    - Important role for HWR's in global fuel cycle.

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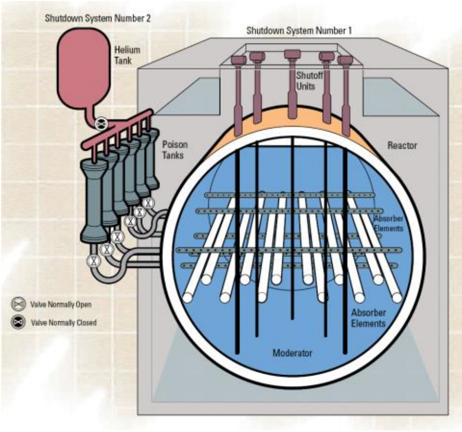
HWR Physics Characteristics

- 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 heats sink to dissipate heat.
    - D_2O moderator, also passive cooling by outer H_2O shield tank.
  - Emergency core cooling (ECC) system, full containment.



FJOH 2010 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's ~ 50 to 100 kW/litre.
    - 15 to 20 kW/litre feasible with tighter lattice pitch
      - E.g., ACR-1000, CANDU-SCWR.
  - 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.

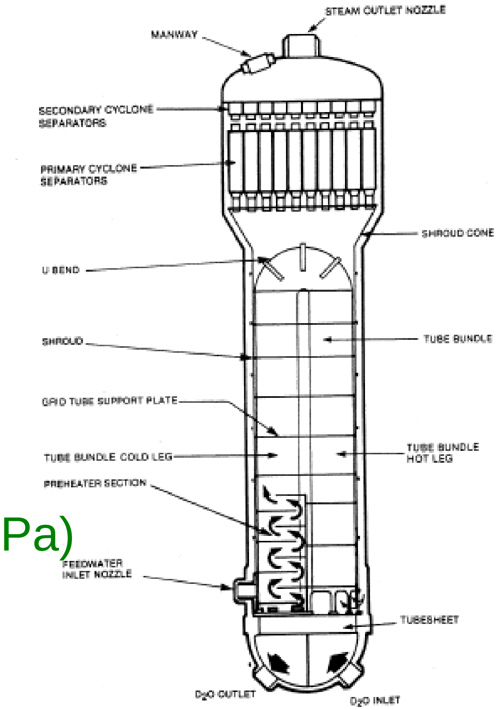


FIGURE 2.2-8 CANDU STEAM GENERATOR

- However, <u>remember</u>: Balance of Plant
  - Steam generators, steam turbines, condensers take up space.

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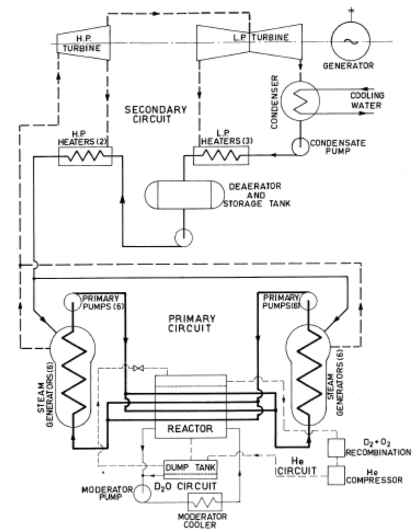
HWR Operational Characteristics

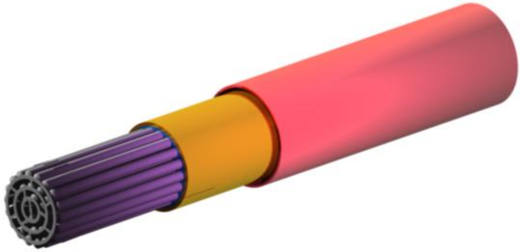
- ❑ Heat load to moderator
  - ➢ 5% to 6% of fission energy deposited.
  - ➢ Gamma-heating, neutron slowing down (2 MeV → 0.0253 eV).
- ❑ Thermal efficiencies (net)
  - ➢ Depends on choice of coolant, secondary cycle.
  - ➢ Typical: 28% to 32% for CANDU-type reactors.
    - Improved for larger, more 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 achievable with larger plants.



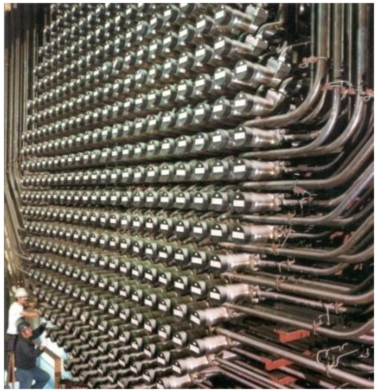
FLOW DIAGRAM REACTOR PICKERING

CANDU-PHWR Design Components

- Fuel Bundles (cluster of fuel pins)
  - Short, small (~10 cm diameter, ~ 50 cm long).
  - 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 (only if coolant type changed):
    - Fuel: UC, U_3Si
    - Clad: SAP (organics) or stainless steel (gas, liquid metal, super-critical 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, 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.
  - $CdSO_4$, and other compounds.
- Moderator level.
  - Additional reactivity control, for smaller reactors.
- Moderator dump tank (for emergency shutdown).
  - Initial designs; not used in later, larger reactors.
  - E.g., NPD-2, KANUPP.

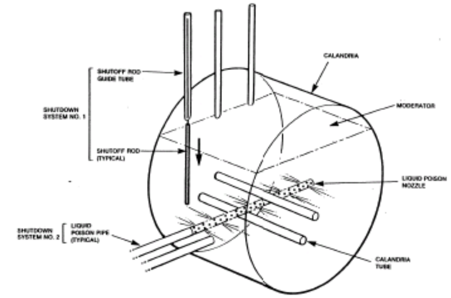


FIGURE 4.3-5 SHUTDOWN SYSTEMS: SHUTOFF RODS AND LIQUID "POISON" INJECTION

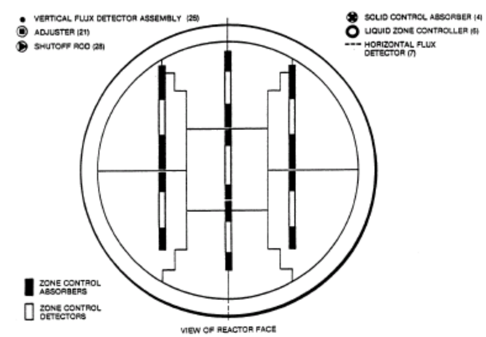
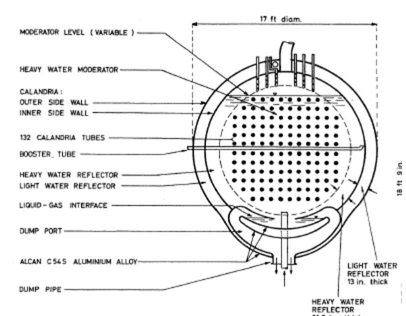


FIGURE 2.4-2 REACTIVITY MECHANISM LAYOUT



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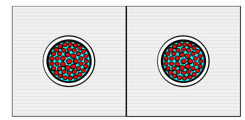
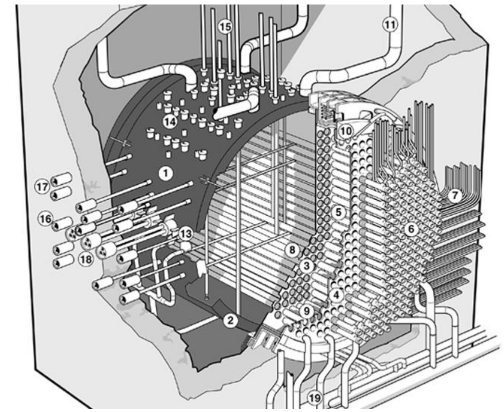
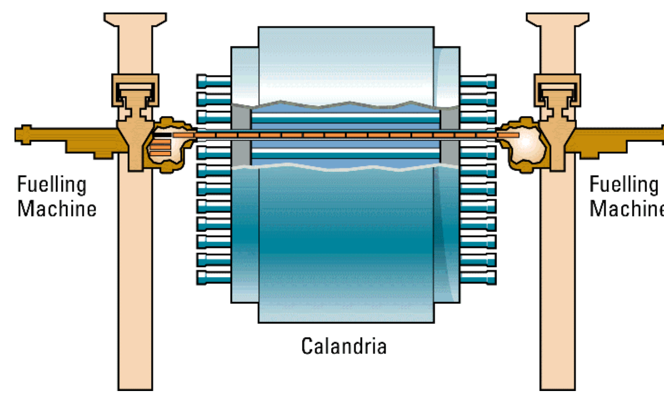
CANDU Reactor Technology

- **CAN**ada **D**euterium **U**ranium (CANDU)
- 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).







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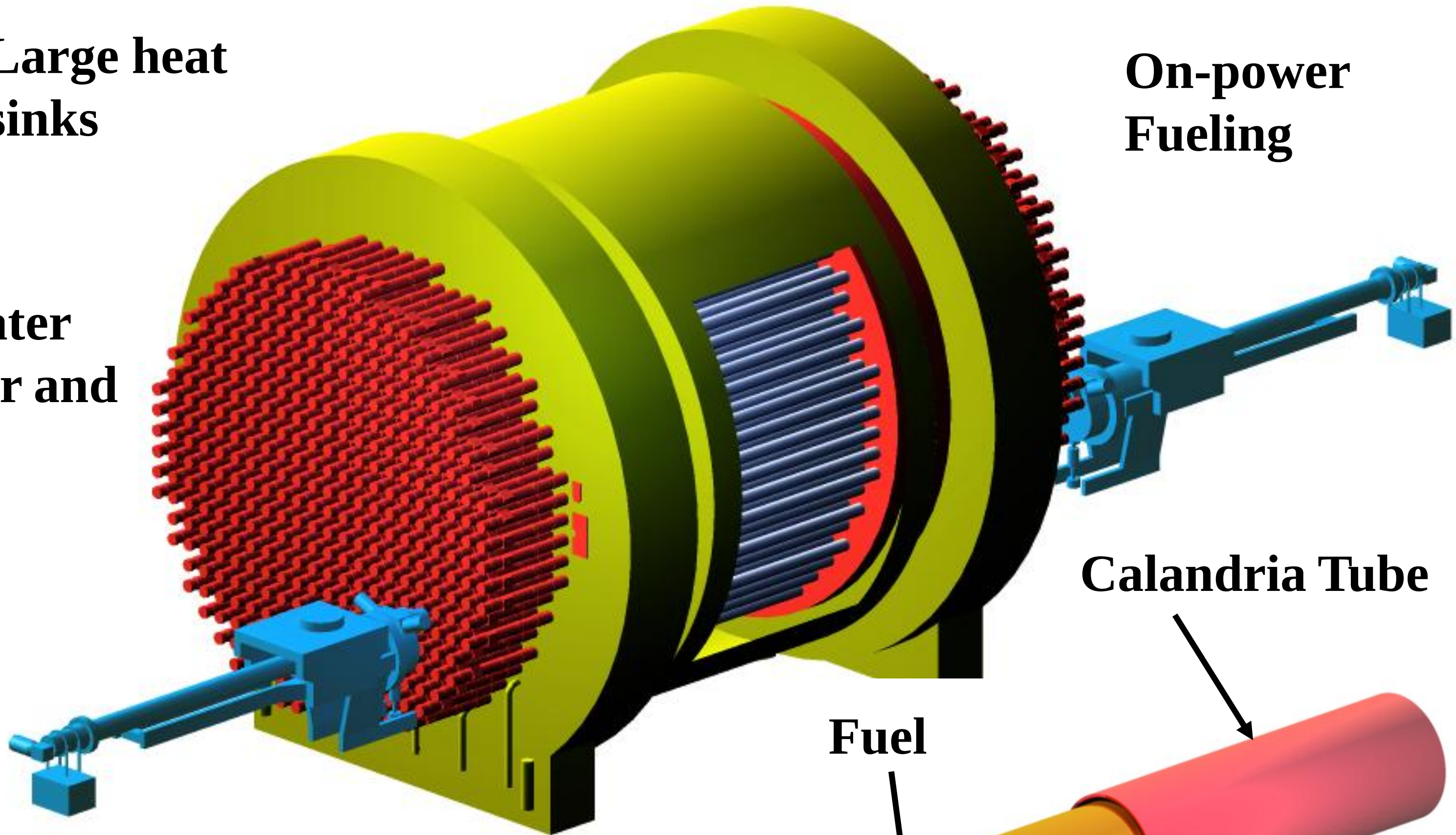
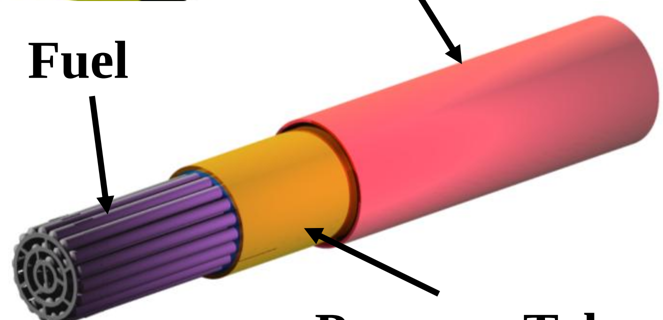
CANDU Reactor Technology

Large heat sinks

On-power Fueling

Heavy Water Moderator and Coolant





Modular Design

Simple fuel bundle

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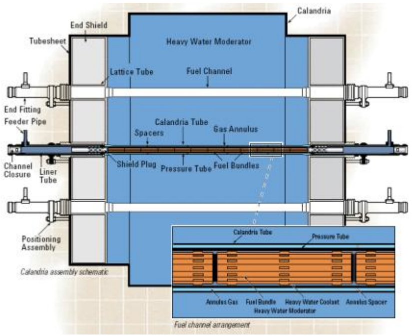
CANDU-PHWR Features

- ❑ 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 (~2000 pcm max); very little moderator poison.
  - ➢ Bi-directional fuelling; bi-directional cooling; more uniform burnup.
  - ➢ 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.
  - ➢ Local fabrication (do not need heavy forgings).
  - ➢ Refurbishment underway at Pt. Lepreau, Bruce, Wolsong CANDU reactors.



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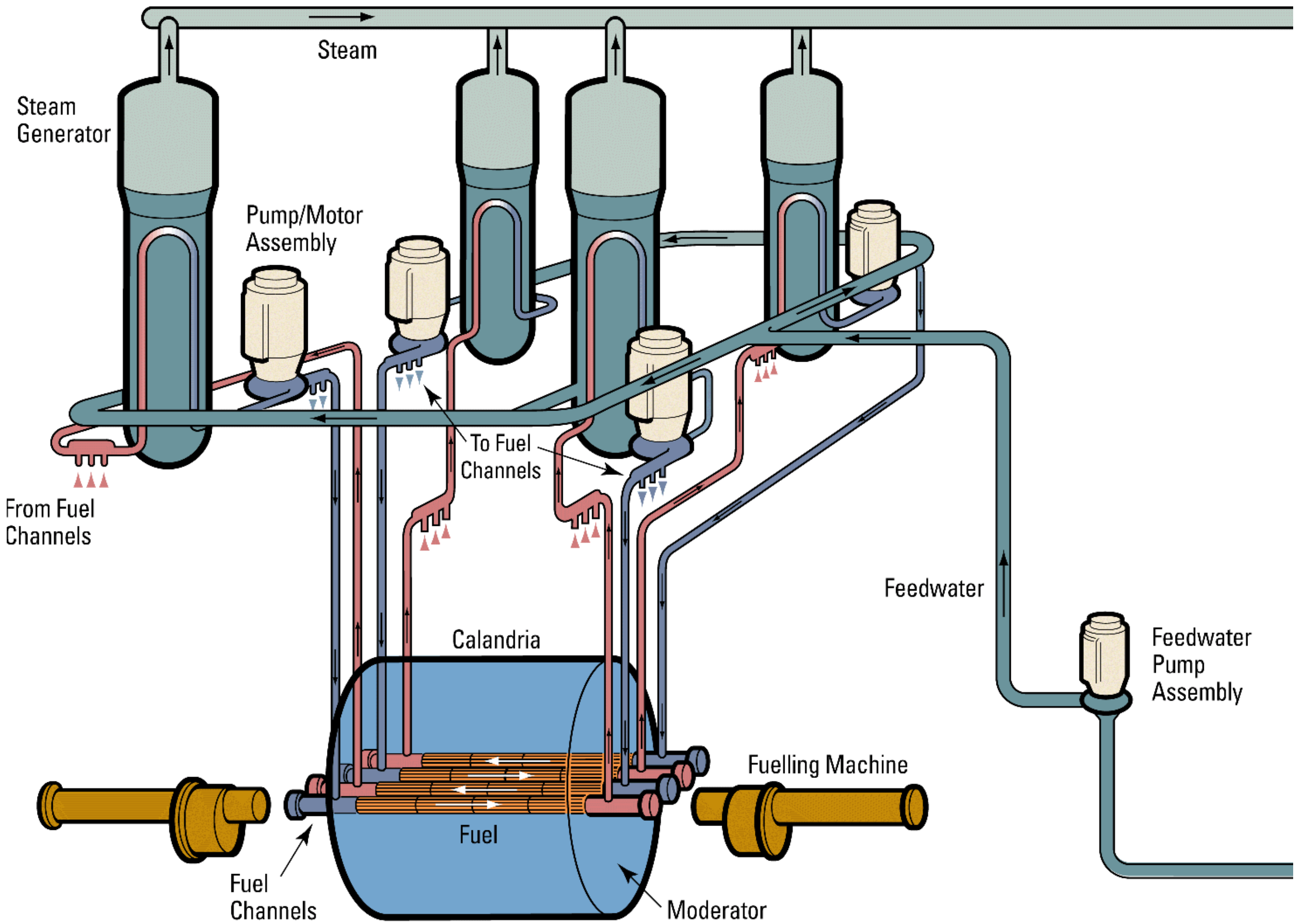
CANDU Nuclear Steam Plant

- Two heat transport loops.
- Bi-directional cooling.
- Bi-directional fuelling.



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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.

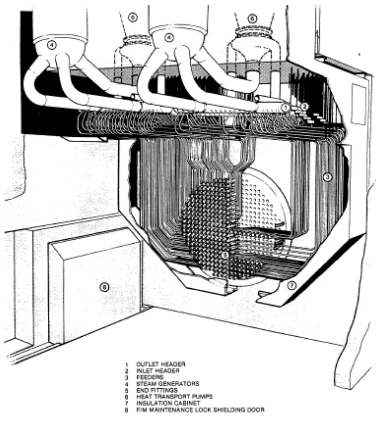

FIGURE 2.2-7 FEEDER AND HEADER ARRANGEMENT

- **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 uses: self luminous signs, fusion fuels, detectors.
    - E.g. use T for fusion reactor experiments (ITER); He-3 for detectors.

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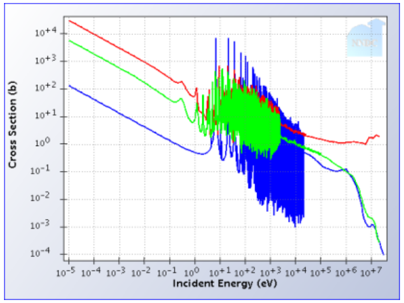
CANDU Safety Characteristics



- 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.
  - Thermal-hydraulic design (2 separate heat transport loops).
  - Voiding is not usually instantaneous to all channels.
    - Checkerboard voiding occurs first, reactivity increases more slowly.
  - Long neutron lifetime (~ 1 ms) in D_2O also 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.

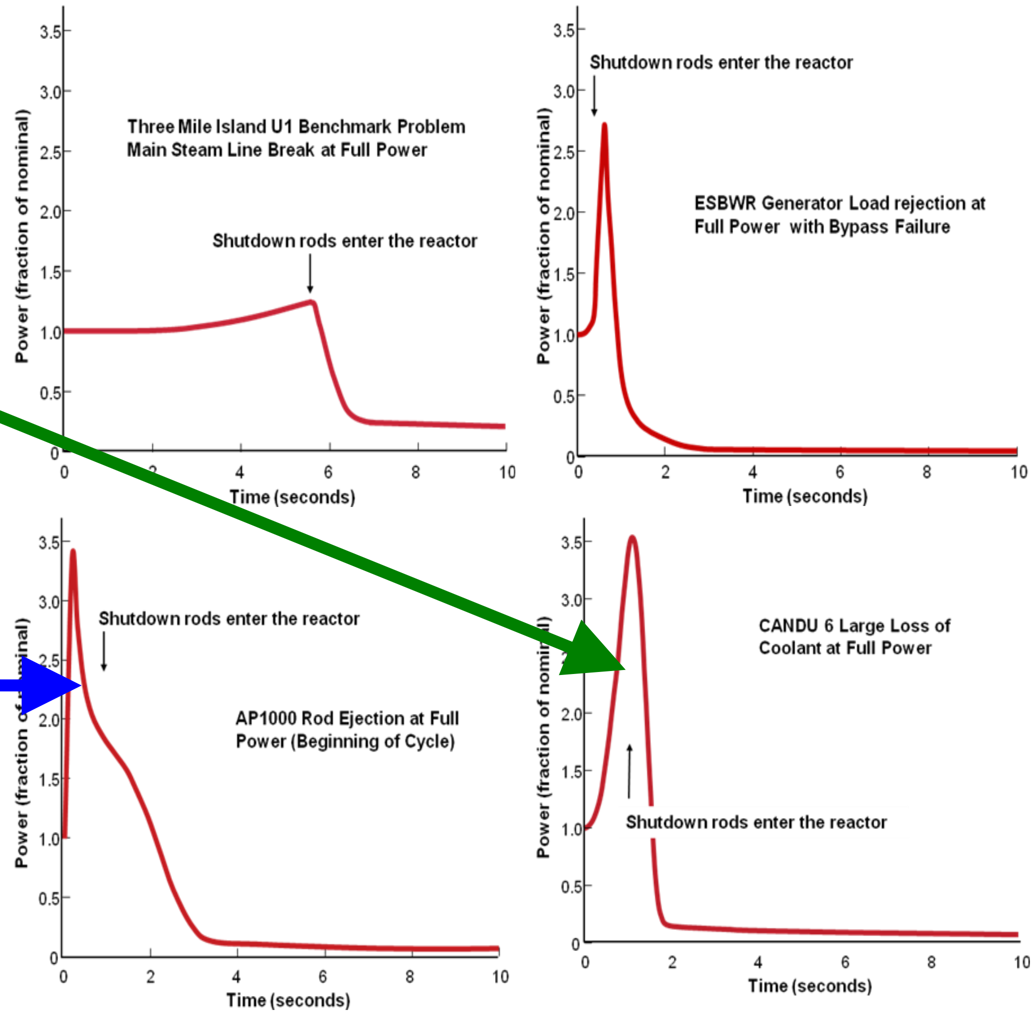
CANDU Safety Characteristics

- CANDU does well, by comparison to other reactor designs in postulated accident scenarios involving reactivity initiated accidents (RIA's).
  - Longer neutron lifetime due to D_2O moderator makes a big difference.
  - Lower rate of power increase.

- Benchmark Postulated Accident Scenario Comparisons, by design:
  - CANDU-6
    - Large Loss of Coolant Accident (LLOCA).
  - TMI-1 (Babcock & Wilcox Pressurized Water Reactor)
    - Main Steam Line Break (MSLB)
  - ESBWR (Economic, Simplified Boiling Water Reactor)
    - Generator trip with steam bypass failure.
  - AP-1000 (Advanced PWR – Westinghouse)
    - 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.
  - Lower power increase rate.
  - 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.
  - Longer neutron lifetime.



CANDU Safety Comparable to LWR's

- Special CANDU features:
  - Shutdown systems operate in low-pressure environment.
    - Multiple, independent shutdown systems (SDS1, SDS2).
    - Very high reliability.
  - Auxiliary cooling by large heat sinks:
    - D_2O moderator, H_2O shield tank.
  - Emergency Core Cooling (ECC)
    - H_2O in ECC acts as a neutron absorber, when it displaces D_2O.

- 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.

End of Lecture 1

- See full version of main lecture presentation for additional details and skipped slides.
- See Supplement 1 and Supplement 2.
  - Research reactors, measurements, R&D.
  - Alternative concepts, prototypes, history.
- See references, and suggested websites.
- Questions?

Schedule (Day 2)

- Day 2
  - CANDU History (Gen-I, Gen-II) (optional, see slides/notes offline)
    - NPD-2, Douglas Point
    - Pickering, Bruce, Darlington, CANDU-6
  - Gen-III / Gen-III+
    - Enhanced CANDU-6 (EC6), Advanced CANDU Reactor (ACR-1000)
    - 220-PHWR (India), 540-PHWR (India), AHWR (India)
    - TR-1000 (Russia) (optional, see slides/notes offline)
  - 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

CANDU History

- *NPD-2 (1962) (7-element fuel)*
- *Douglas Point (1968), Gentilly-1 (1972-1977) (19-element)*
- KANUPP (1972, Pakistan) – *See supplement 2.*
- RAPS 1,2 (India, 1973-1981) – *See supplement 2*.
- Pickering A/B (1971-1986) *(28-element fuel)*
- Bruce A/B (1976-1987) *(37-element fuel)*
- Darlington (1990-1993) *(37-element fuel)*
- CANDU-6 *(37-element fuel)*
  - Point Lepreau (1983), Gentilly-2 (1983)
  - Embalse (1984)
  - Wolsong (S. Korea, 1983-1999)
  - Cernavoda (Romania, 1996-2007)
  - Qinshan III (China, 2002-2003)

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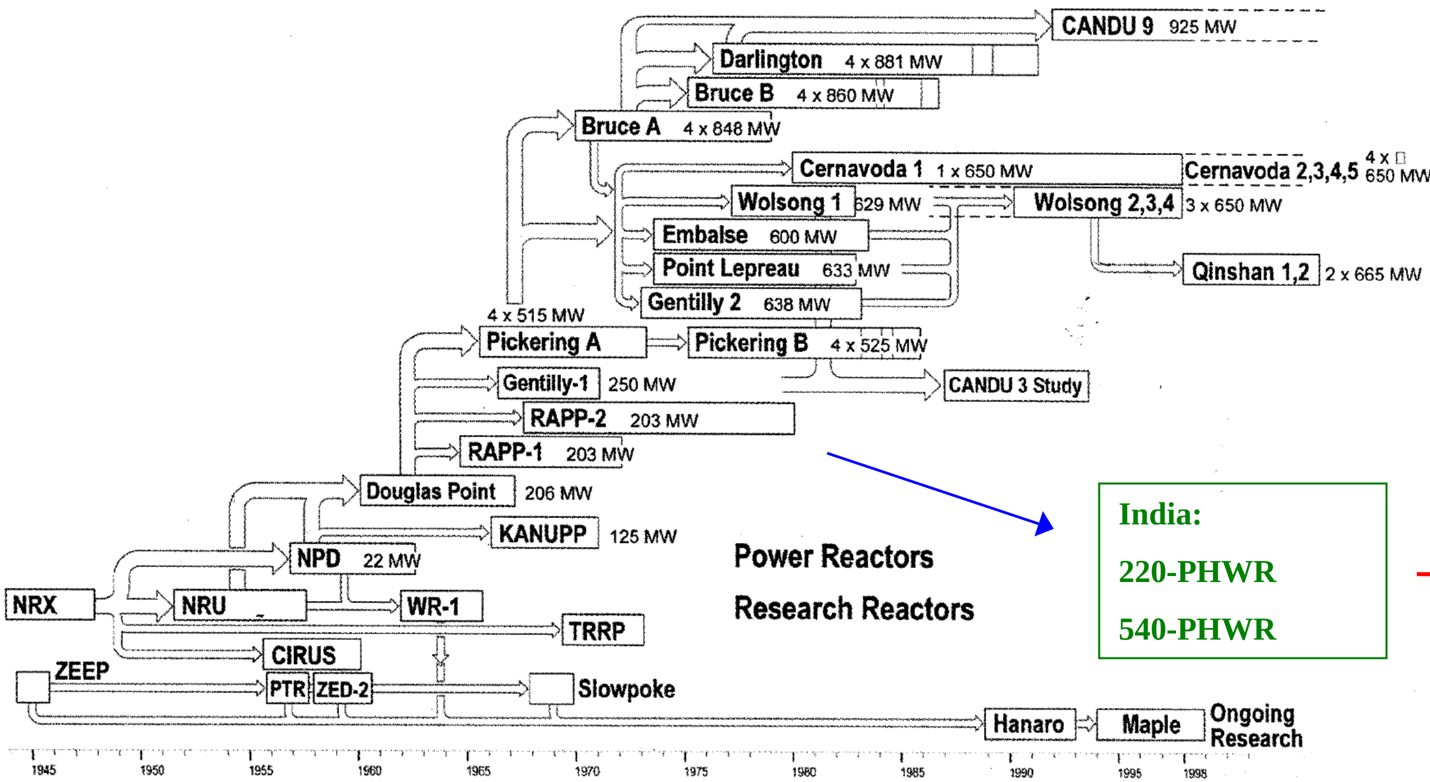
CANDU HWR Evolution

- 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

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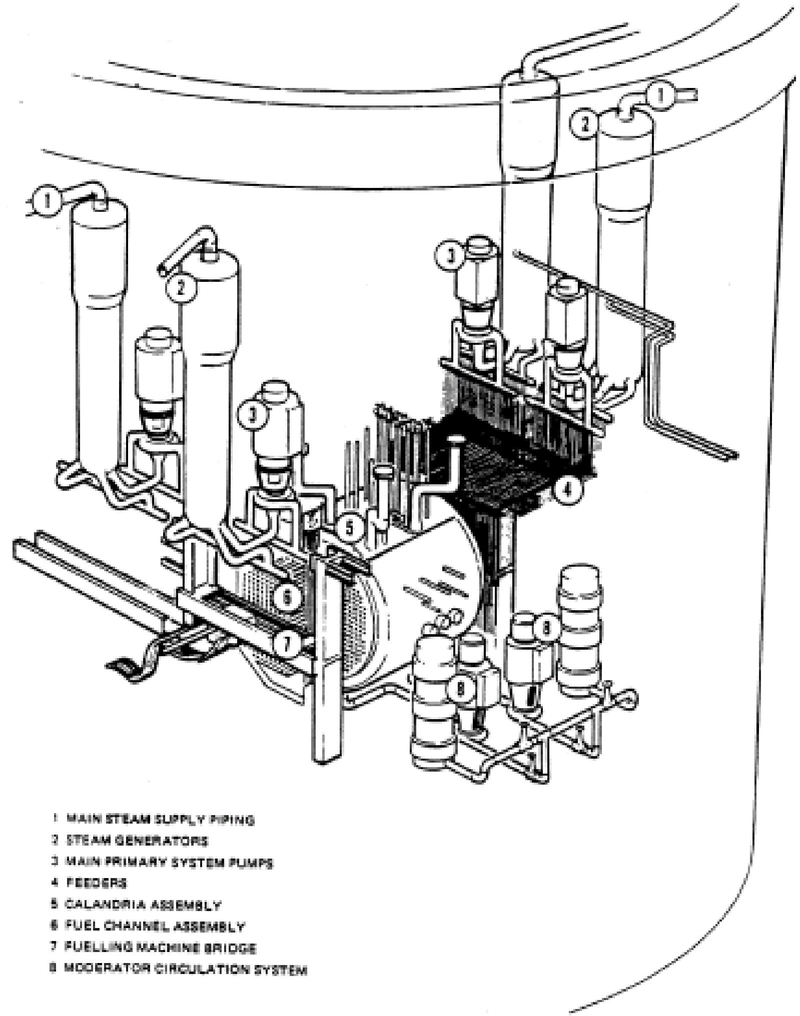
CANDU-6 (Canada, 1983-2007)

- Single-unit Station
  - 600 to 670 MWe net
  - 380 channels, 12 bundles/channel.
  - 37-element natural UO_2 bundles.



- Operations / Design Feedback
  - Pickering A/B, Bruce A/B.
- Domestic and International Deployment
  - Point Lepreau, Gentilly-2
  - Argentina, S. Korea (4),
  - Romania (2), China (2)

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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+)

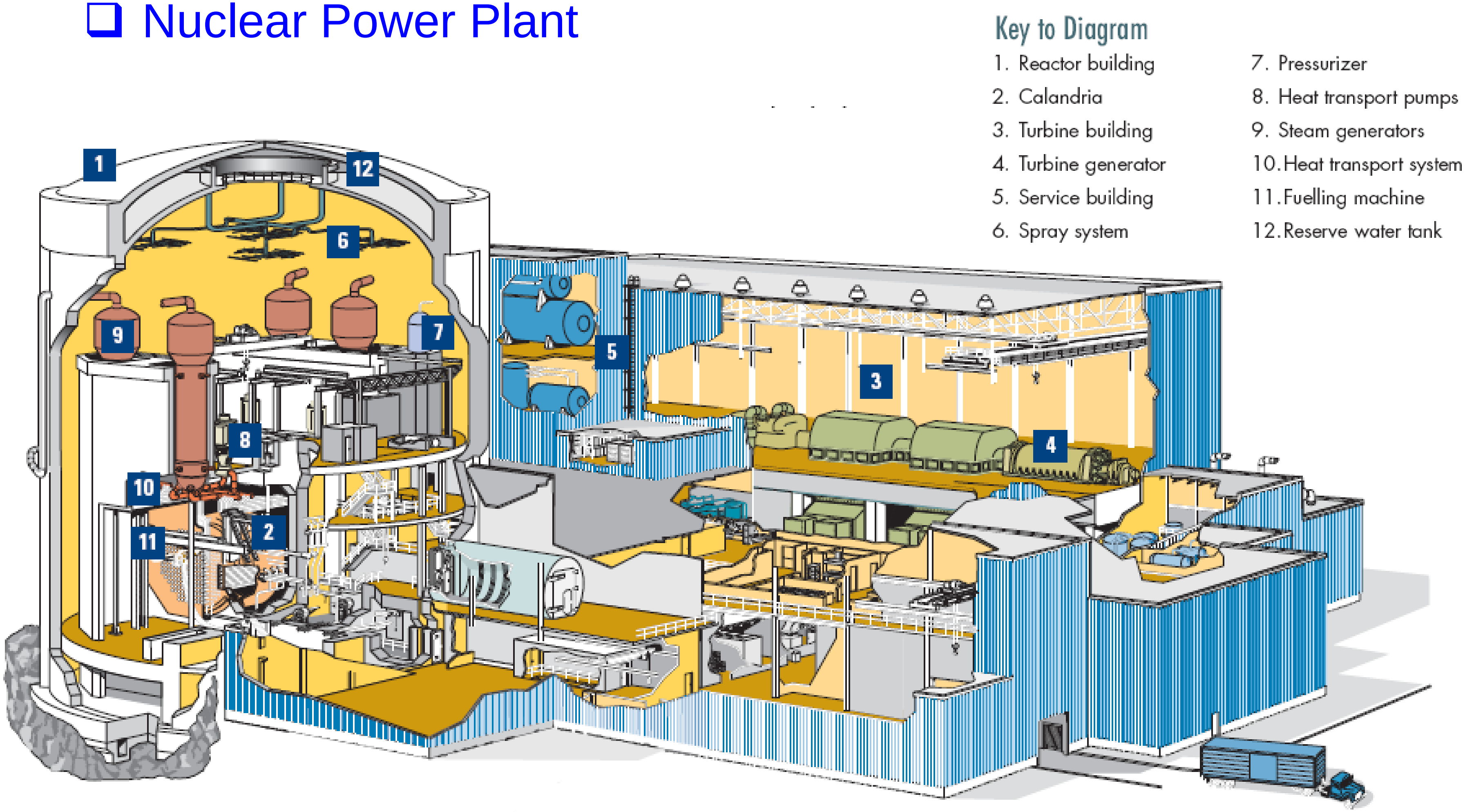
- Enhanced CANDU-6 (EC6).
  - Retains basic features of CANDU-6 reactor.
  - 700-MWe class reactor.
  - Good for both large and medium-sized markets.
  - Capable of daily load-following (100% → 75% → 100%), if necessary.
- Evolutionary improvements over CANDU-6:
  - Target life up to 60 years, >90% capacity 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 (Canada, Gen-III+)

❑ Nuclear Power Plant



FJOH 2010 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

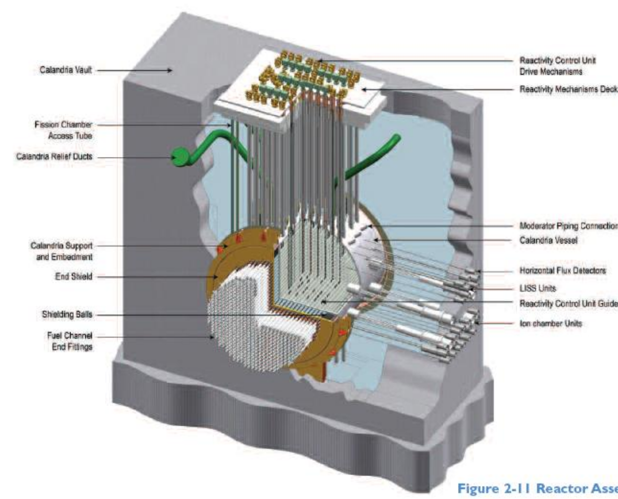
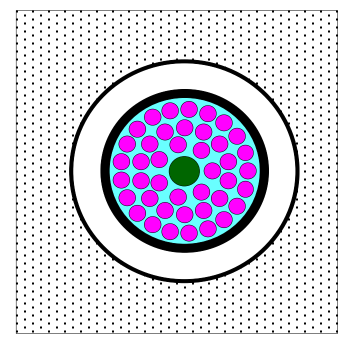


Figure 2-11 Reactor Assembly

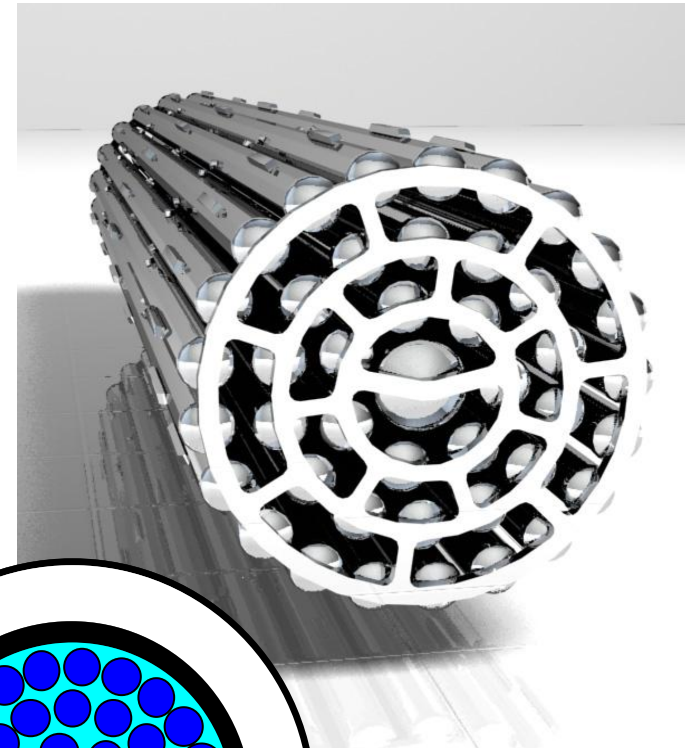
ACR-1000 (Canada, Gen III+)

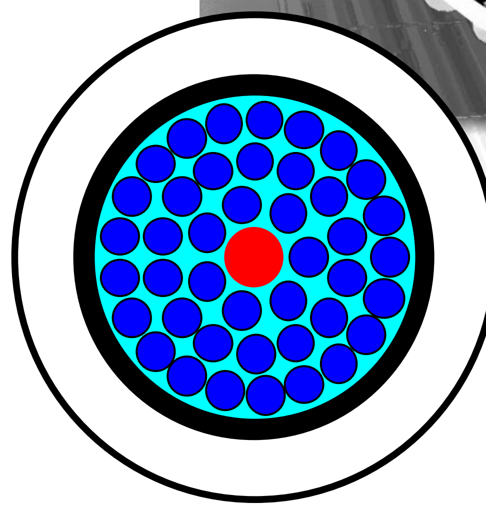
- Special features
  - Light water coolant (11 MPa, 319 C)
    - Reduced capital costs.
  - CANFLEX-ACR Fuel Bundle
    - 43-element design; enhanced heat transfer.
    - Enriched fuel (2 wt% to 3 wt%), central absorbing pin (Dy).
    - Burnup: 20,000 MWd/t (nominal), extend with experience.
  - Tighter lattice pitch (24 cm); thicker pressure tubes, larger calandria tubes.
    - More compact core; smaller reactor; higher power density.
    - Lower moderator-to-fuel ratio.
    - 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

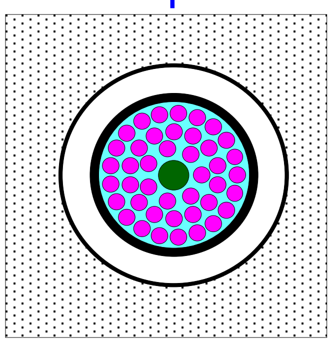


ACR-1000 (Canada, Gen-III+)

- 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







ACR-1000 (Canada, Gen-III+)

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

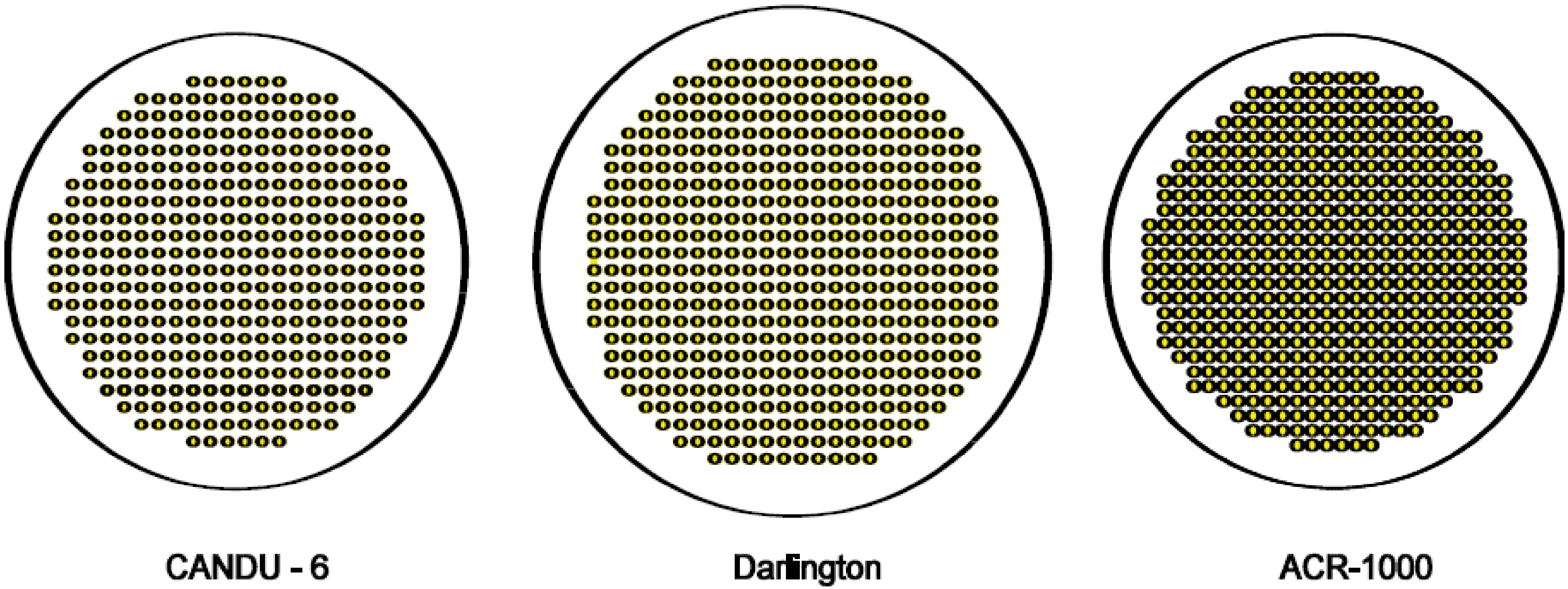


Figure 2-12 Comparison of Core Sizes

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ACR-1000 (Canada, Gen-III+)

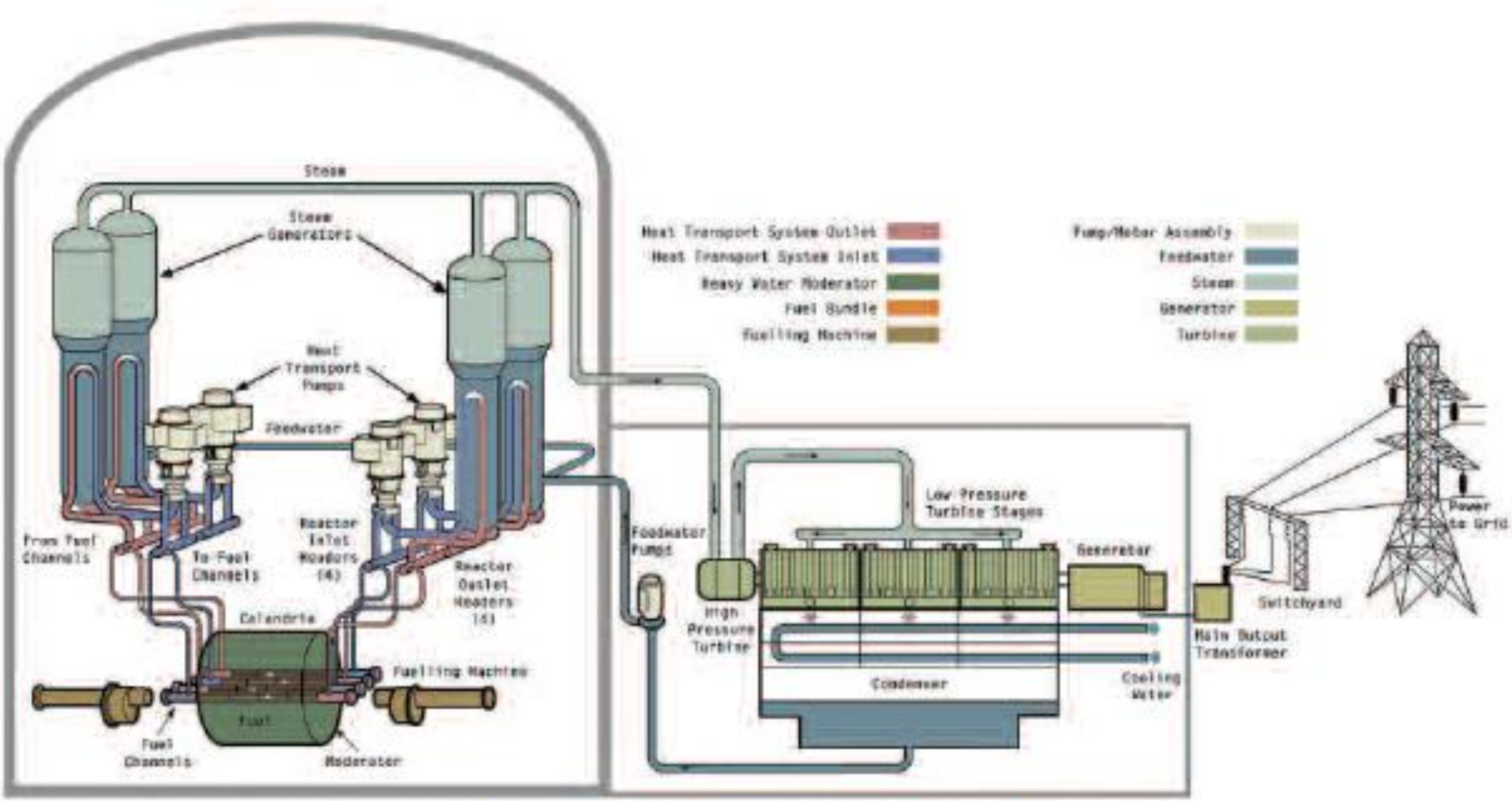

Figure 1-1 Overall ACR-1000 Plant Flow Diagram

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.

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ACR-1000 (Canada, Gen-III+)

Multiple barriers – defense in depth

- Fuel
  - UO_2 retains fission products.
  - Zr-4 Clad.
- Individual PT / CT channels.
- Moderator tank.
- Light water shield tank.
- Concrete reactor vault.
- Containment.
  - Steel liner.
  - Re-enforced Concrete.
- Reserve water system.
  - Gravity driven.

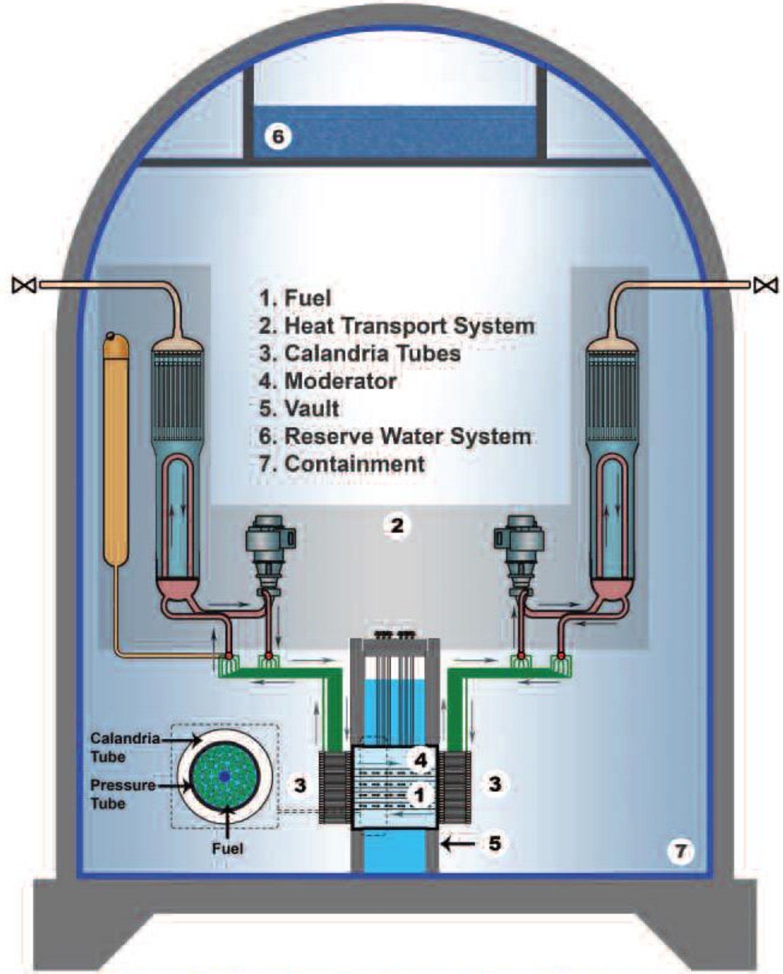

Figure 3-1 Barriers for Prevention of Releases

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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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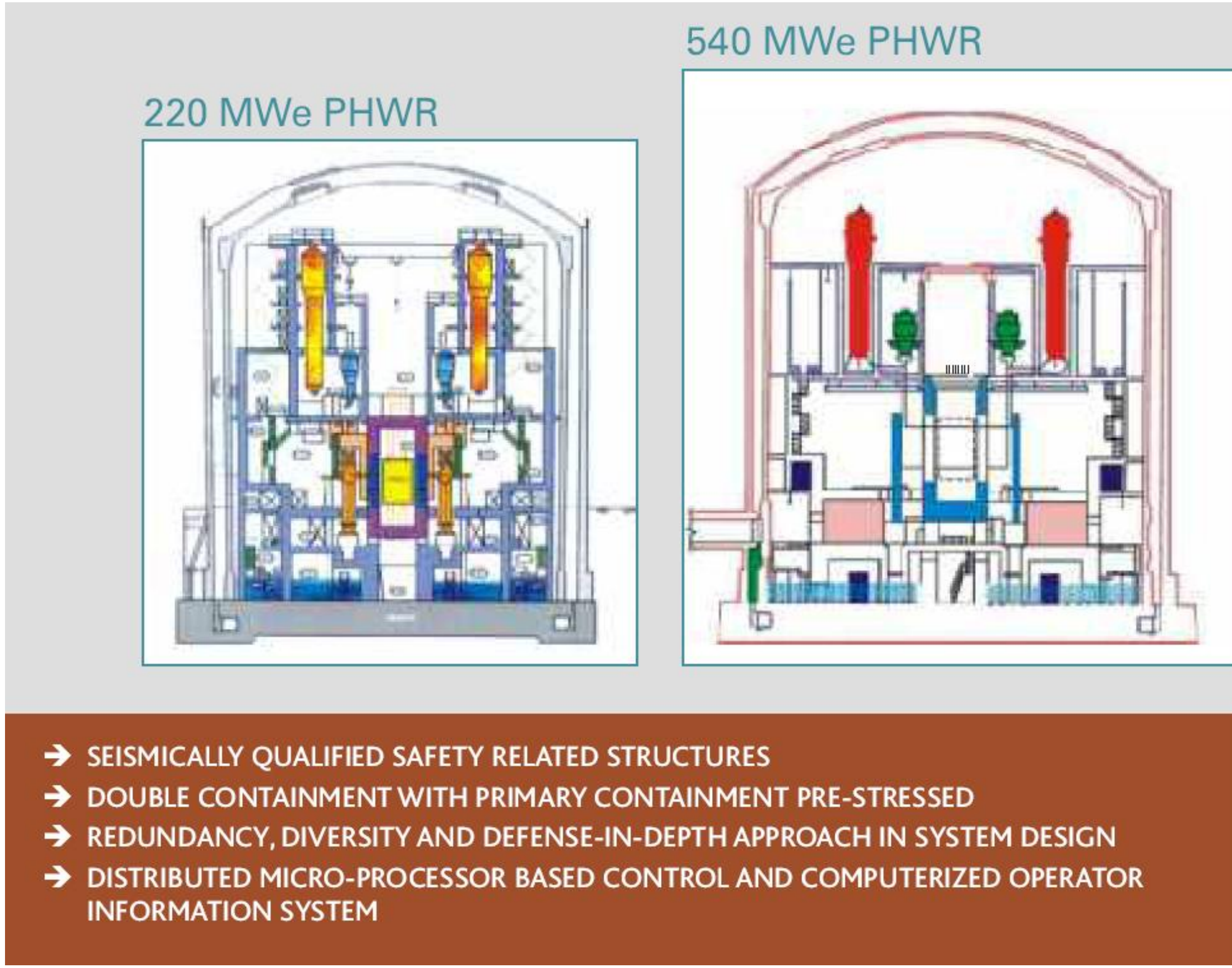
India's 220-MWe, 540-MWe PHWRs

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



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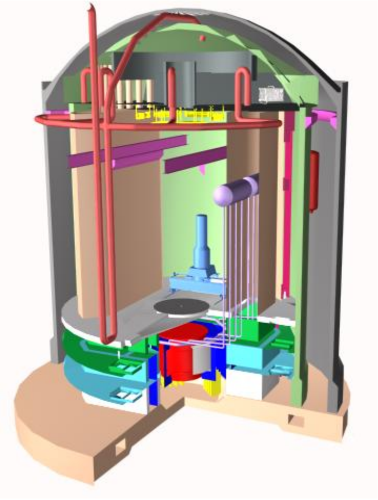
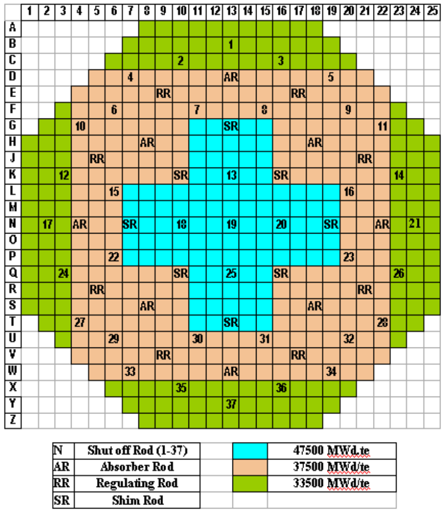
AHWR (India, Gen-III+)



- **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.

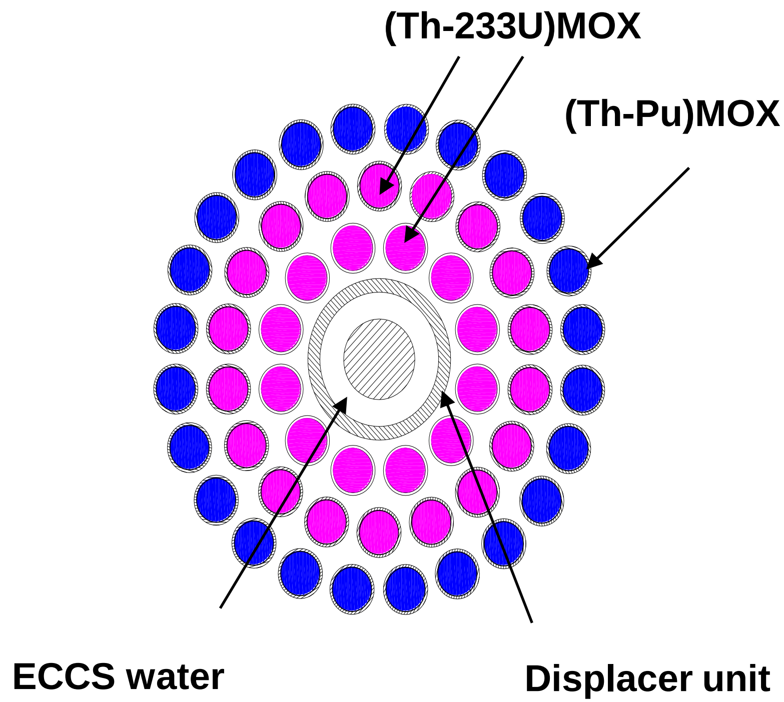


AHWR (India, Gen-III+)

- 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 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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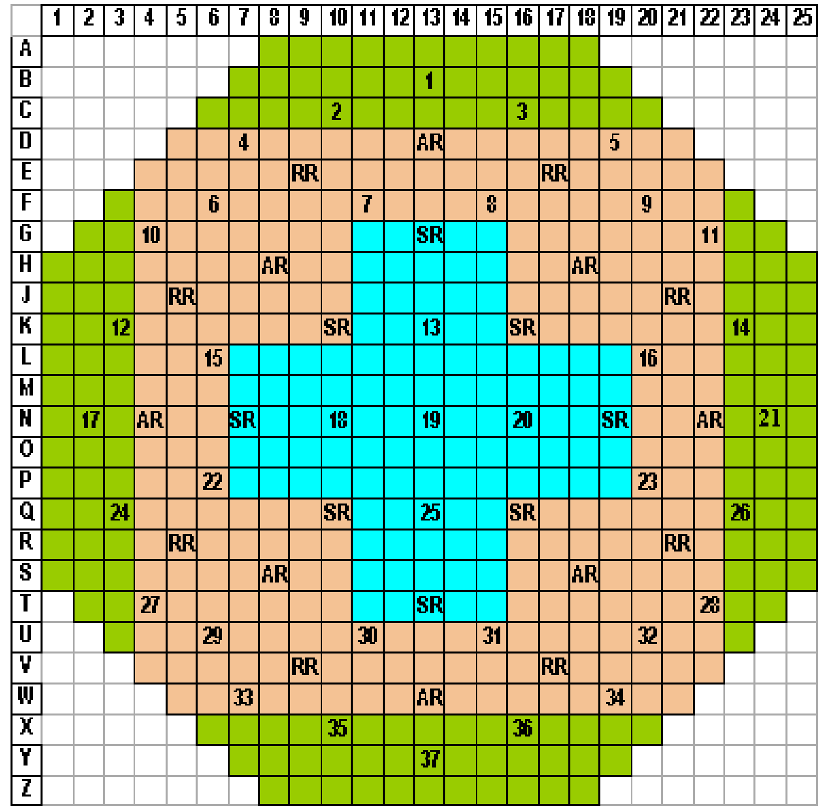
AHWR Standard Design

- 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		

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 (fuel temperature, void coefficients).
- Mined uranium requirement per unit energy is less for AHWR as compared with alternatives.
- Significant power fraction from U-233/Th-232:
  - 75% (Standard)
  - 66% (Self-sufficient U-233)
  - 39% (LEU)

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.

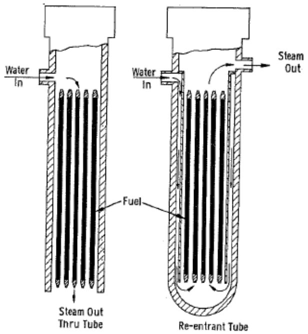
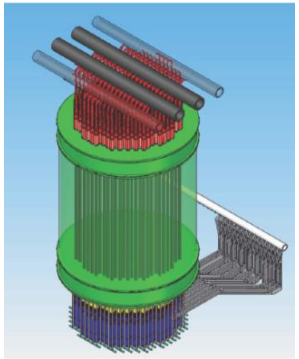


Fig. 10—Pressure tubes.



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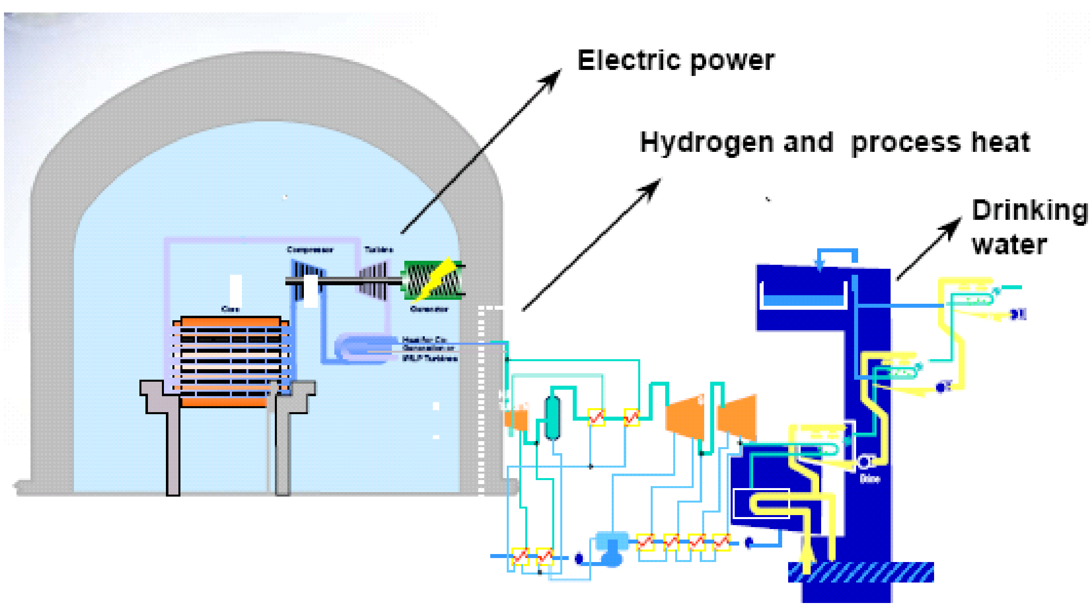
CANDU-SCWR (Canada, Gen-IV)

- 25 MPa, ~325°C inlet, 500 C to 625 C exit.
- Direct Cycle, Efficiency ~ 45% to 50%.
- >1000 MWe.



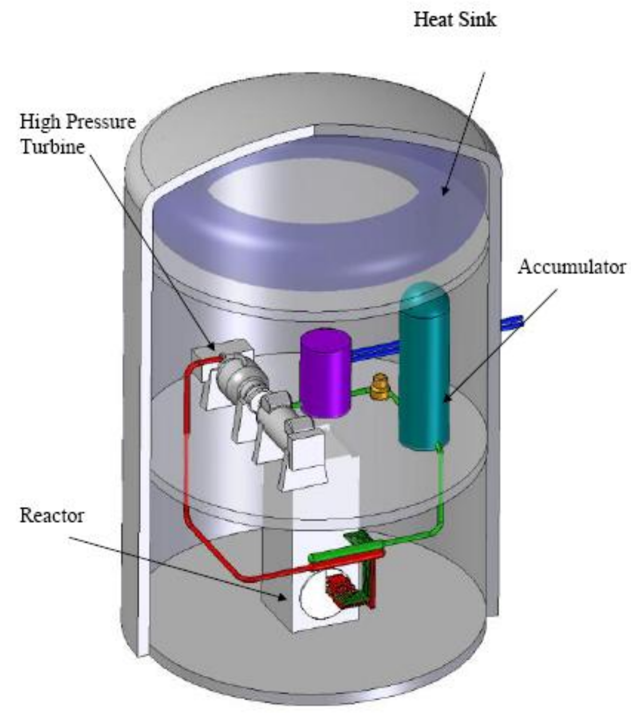
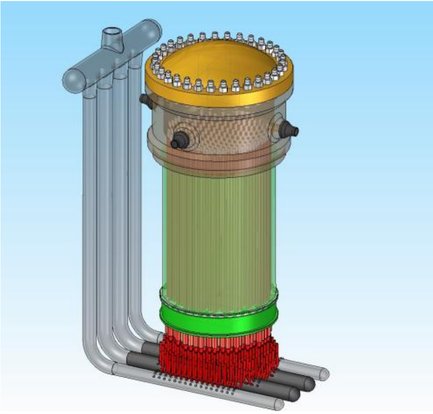


Figure 5: CANDU-SCWR Schematic.

CANDU-SCWR (Canada, Gen-IV)

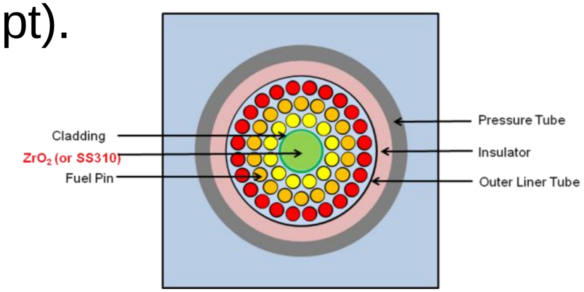
❑ CANDU Design features in CANDU-SCWR

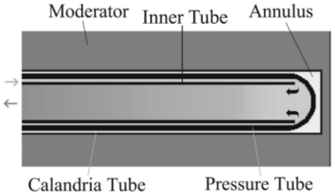
- Pressure tubes, with fuel bundles inside, or,
  - Pressure vessel under consideration as well.
- D_2O moderator at lower temp. (~80°C).
  - Auxiliary heat sink in case of postulated accident.



❑ Design changes, options considered:

- Tighter lattice pitch (22 cm to 27 cm).
- Thicker pressure tubes (or a pressure vessel concept).
- Vertical channels, instead of horizontal.
- Once-through, or re-entrant tubes with insulator or double wall between PT and fuel bundles.
- Multi-batch off-line refuelling.
  - Boron in moderator for excess reactivity hold down.
- Fuel bundle modifications.
  - Higher enrichment (materials, higher burnup).
  - More pins (54 to 61) for enhanced heat transfer.



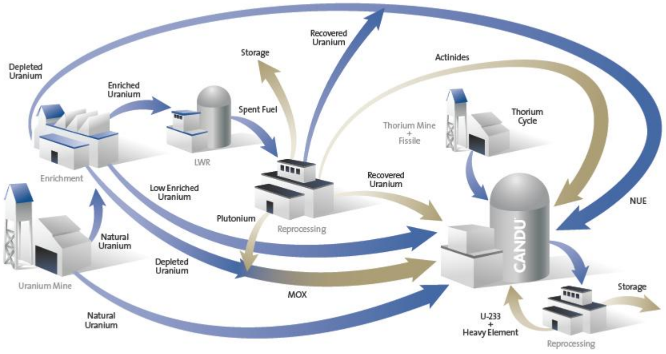


Gen-V HWR's ???

- 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.

Additional Future Roles for HWR's

- ❑ Advanced Fuel Cycles.
  - ➢ Synergism with LWR's and fast reactors.
    - Integrated nuclear energy system.
  - ➢ Extending nuclear fuel utilization.
  - ➢ Breed/burn 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.
      - 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.

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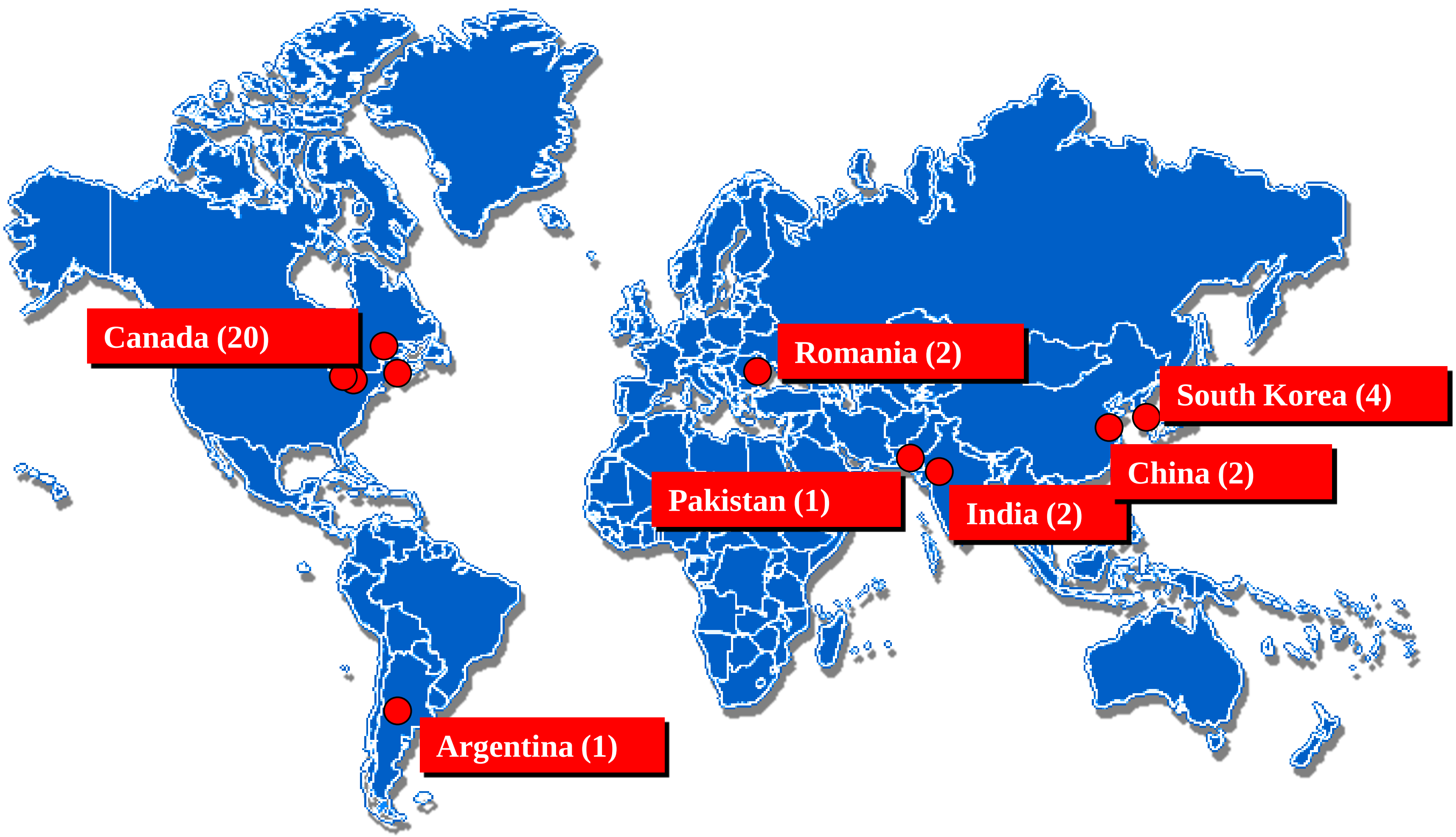
International Penetration of HWR's

- 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



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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:
      - 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 (LWR's).
  - 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.

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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.

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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).

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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.
    - Pressure tube reactors inherently modular.
  - AHWR is India's next-generation design.
    - Conserve uranium resources; maximize utilization.

Conclusions

International Interest in Heavy Water Reactors

- China – growing interest
  - Use of CANDU-PHWR for advanced fuel cycles.
  - Recycled uranium (RU), depleted uranium (DU), thorium.
    - Already testing natural uranium equivalent (NUE) fuel bundles made from RU and DU in Qinshan reactors.
  - Investigating CANDU-SCWR technology for long-term.
- Germany, U.K., Japan, France, Sweden, U.S.A, etc.
  - HWR prototypes developed and tested in past.
  - Resources to develop and sustain alternative technologies limited.
    - Focus on LWR's to save money in short-term.
  - 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.
  - <u>Plenty of business for everyone.</u>

End of Lecture 2

- See extended version of main lecture for more details and skipped slides.
- Also see Powerpoint presentations for:
  - Supplement 1
  - Supplement 2.
- For further reading:
  - See suggested references.
  - See suggested websites.

Frederic Joliot / Otto Hahn Summer School

- Visit www.fjohss.eu