Adventure with the CANDU Reactor Technology

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Acknowledgement

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Outline of the Seminar

- History & Origin of CANDU Reactor Technology
- General Description of CANDU Reactor Technology
  - Reactor
  - Fuel Channels
    - Fuel
    - Refuelling
    - Fuel Flexibility
  - Heat Transport System
  - Safety Systems
  - Severe Accidents Mitigation
- Concluding Remarks

* Note: each category is compared to the equivalent one with PWR technology

Motto:

“One cannot understand the Present not knowing the Past”

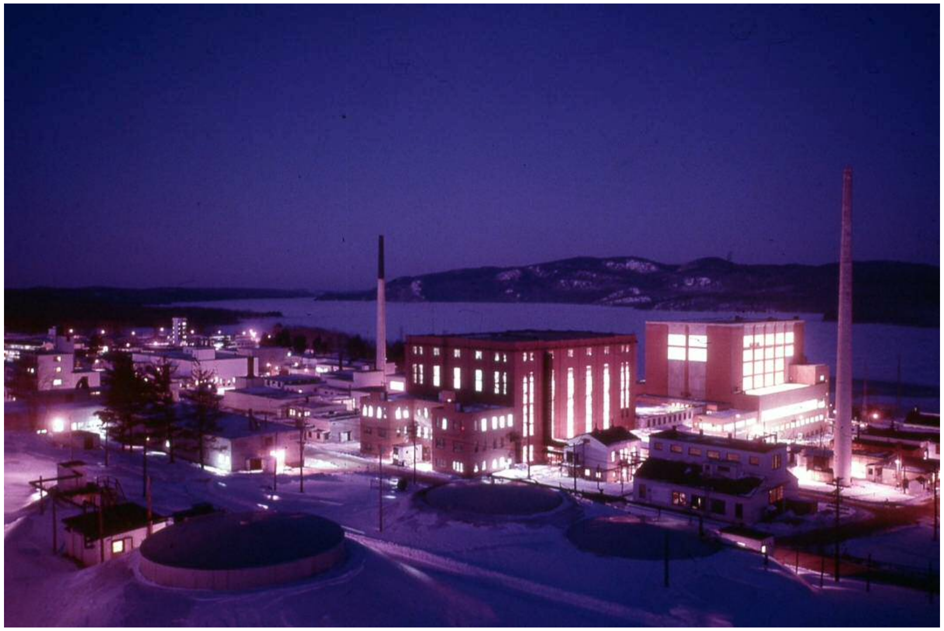
Impressive Beginning & Evolution of CANDU

CANDU Technology Place of Birth

Chalk River Laboratories

Nobel Prizes – Dr. B. Brockhouse (1994) & Dr. A. B. McDonald (2015)

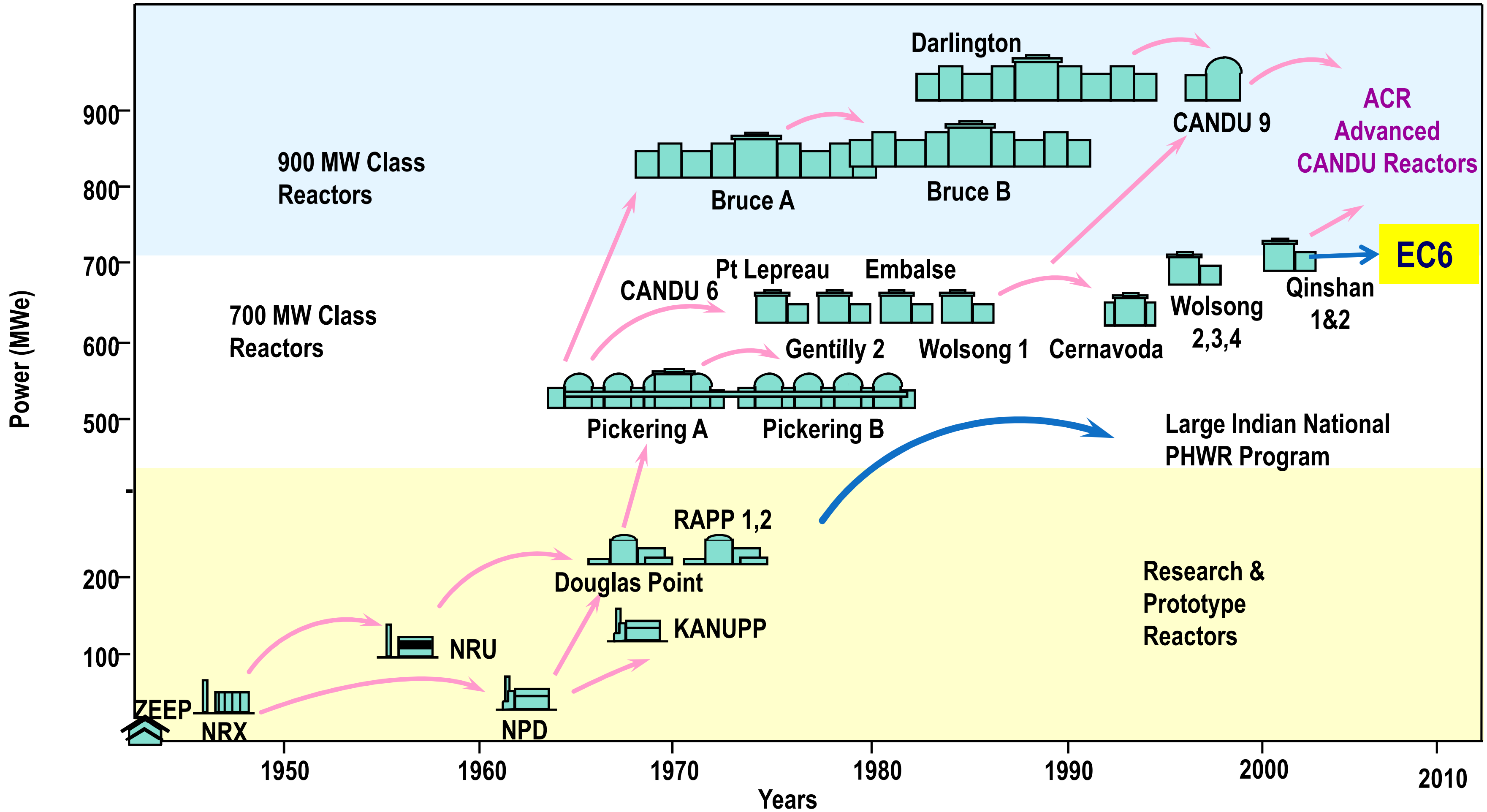
Chalk River Nuclear Laboratories



Town of Deep River

CANDU: Built on a Strong History

CANDU = CANadian Deuterium Uranium



Reactor years in service: ZEEP - 25, NRX - 46 and NRU- 61

CANDU – Global Success

- CANDU & CANDU-derived Reactors World Wide
- The global fleet of CANDU and CANDU-derived reactors currently includes 50 reactors. Of these, 43 are operational, 4 are being refurbished and 3 have been laid up. (www.candu.org),
- The total capacity of all currently operational CANDU and CANDU-derived reactors is 21,424 MWe.

Enhanced CANDU 6 Reactor

- **Canadian Nuclear Safety Commission (CNSC) Pre-Licensing Review – high confidence of licensability in Canada**
  - Phase 1 Review completed April 2010
  - Phase 2 Review completed April 2012
  - Phase 3 Review completed July 2013
- **With the generic pre-licensing completed in Canada, the Polish Regulator, Państwowa Agencja Atomistyki (PAA), can utilize the Canadian evaluations for their construction & operating licenses review of EC6 without much difficulty**
- **On September 24, 2014 – CNSC and PAA have signed MOU (Vienna, Austria) to cooperate and exchange nuclear regulatory information**

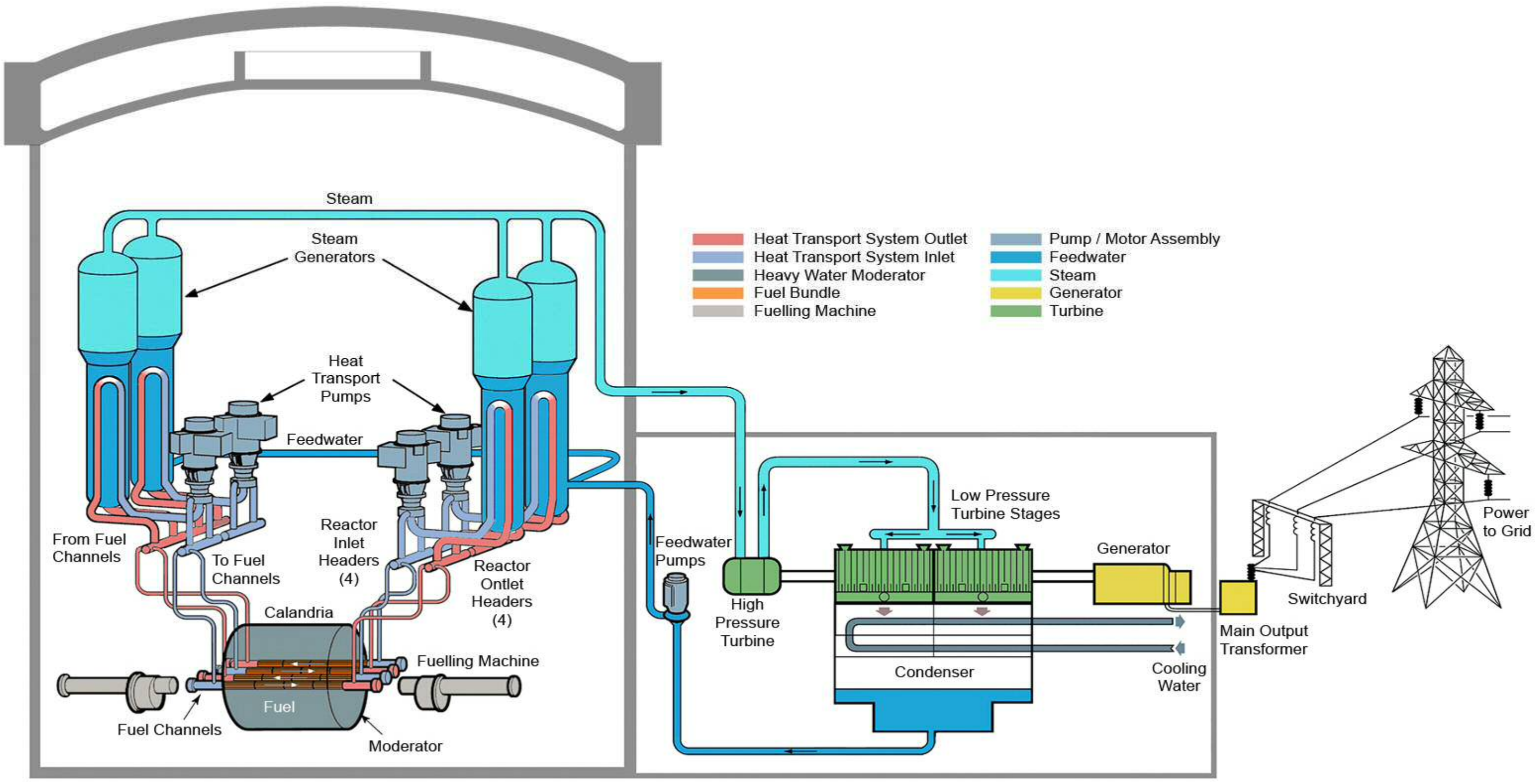
Enhanced CANDU 6 Reactor – EC6®

- EC6 - a proven (constructed and operated), low risk new-build option
- Reference C6 plant: Qinshan Phase III, China:
  - built under budget
  - built: 1st unit in 2002 - 6 weeks & 2nd unit in 2003 - 4 months ahead of schedule
  - avg 90.8% CF acc. to 2012 COG report
- EC6 740 MWe class reactor using Natural Uranium fuel
- EC6 target design life up to 60 years
- EC6 annual lifetime CF > 92% (incl. retubing outage)
- EC6 year-to-year CF > 94% (based on 30-day outage every 3 years

Qinshan Main Control Room

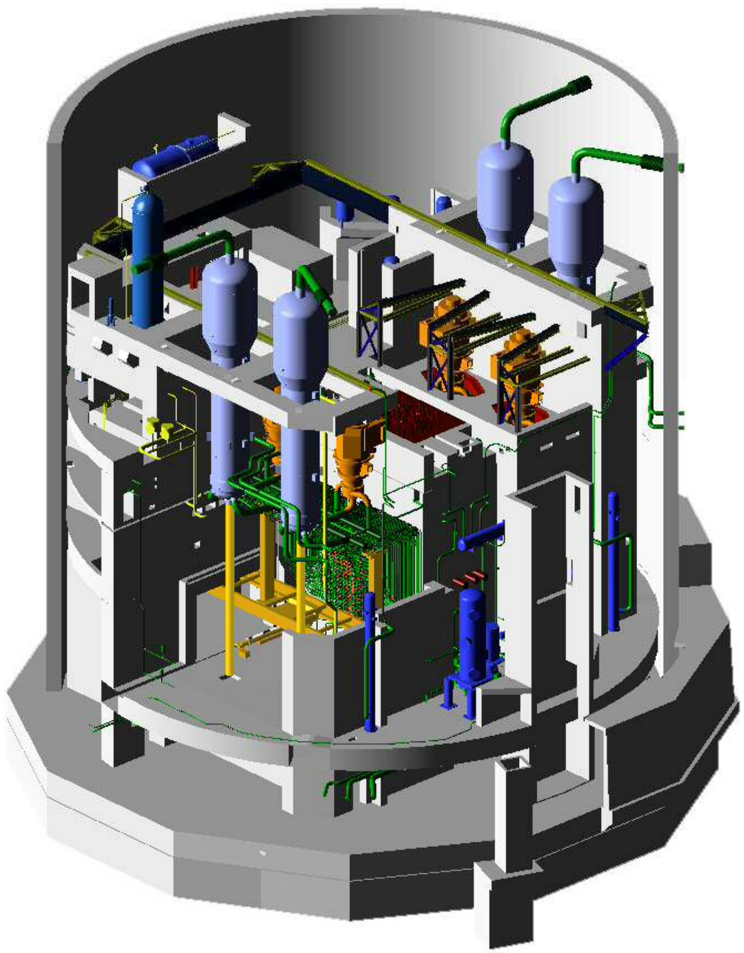
General Description of Enhanced CANDU 6 (EC6 ®) & Comparison of its Main Features with PWR Technology

NPP with Enhanced CANDU 6 Reactor



* NPP with PWR has a similar layout, primary & secondary heat transport systems and major equipment

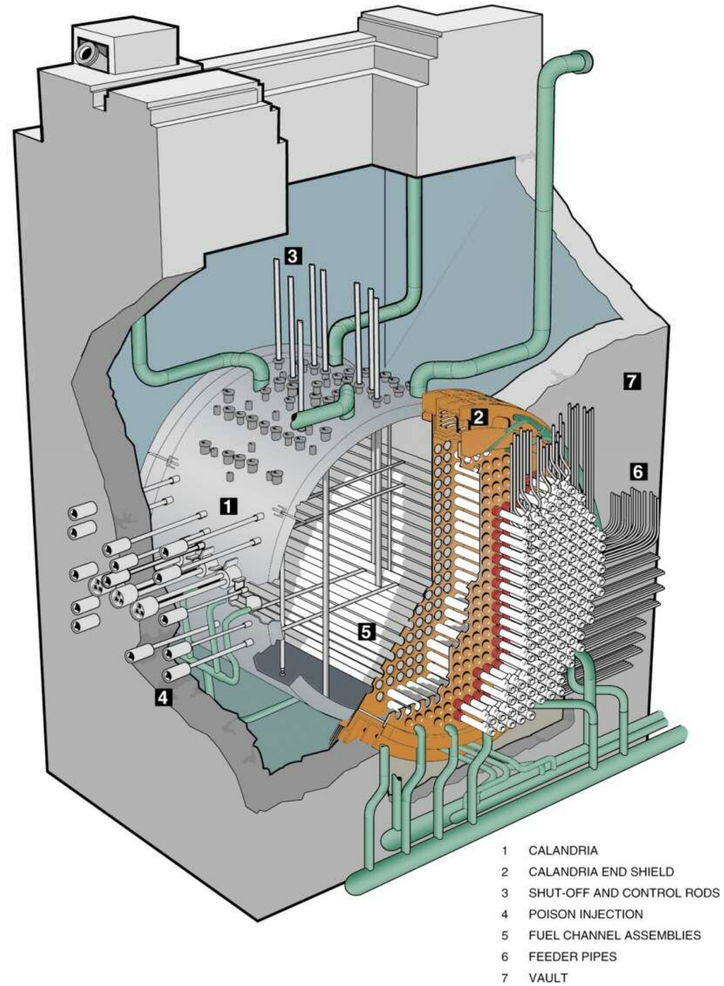
Reactor Building of EC6



* **EC6 -** reactor building is **accesible** during full-power operation (for maintenance, testing etc.;) while those buildings of **LWRs** are **not accessible.**
* **EC6** - all work is done by the NPP personnel while **LWRs** – during refuelling outages – hundreds of people from outside enter NPP to do all the work at once – a huge enterprise (planning, logistics, security, training of contractors, coordination, etc...)

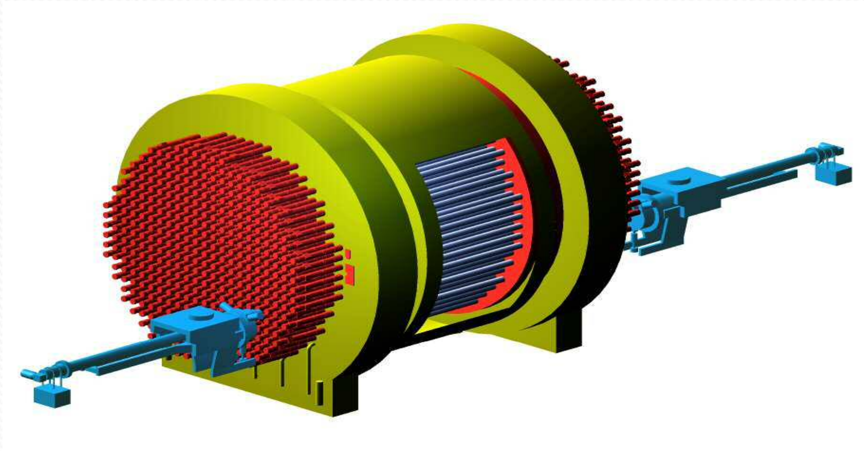
EC6 Reactor - Characteristics

- Modular design – fuel channel reactor
- Reactor core diameter 7.6 m
- 380 horizontal fuel channels
- Lattice pitch 286 mm
- Thermal output 2,084 MWth
- <u>Fueled by Natural Uranium </u>– high neutron economy
- Moderated and cooled by D_2O
- Separation of coolant from moderator
- Moderator of low pressure and temperature
- Calandria vessel contains the moderator of a large volume – *<u>passive heat sink</u>*
- All reactivity control mechanisms (control, shut-off rods and poison injection) and reactivity measuring devices in moderator *<u>(inherent safety)</u>*
- Calandria vessel with fuel channels placed in a concrete light-water filled vault *<u>(a passive heat sink)</u>*
- Relatively easy to manufacture and assembly



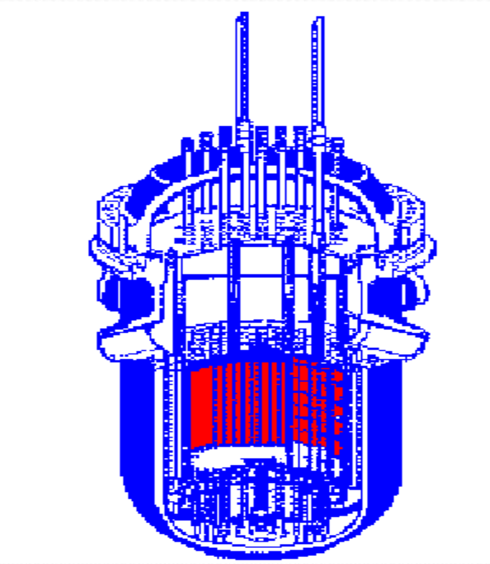
Comparison of CANDU & PWR

CANDU



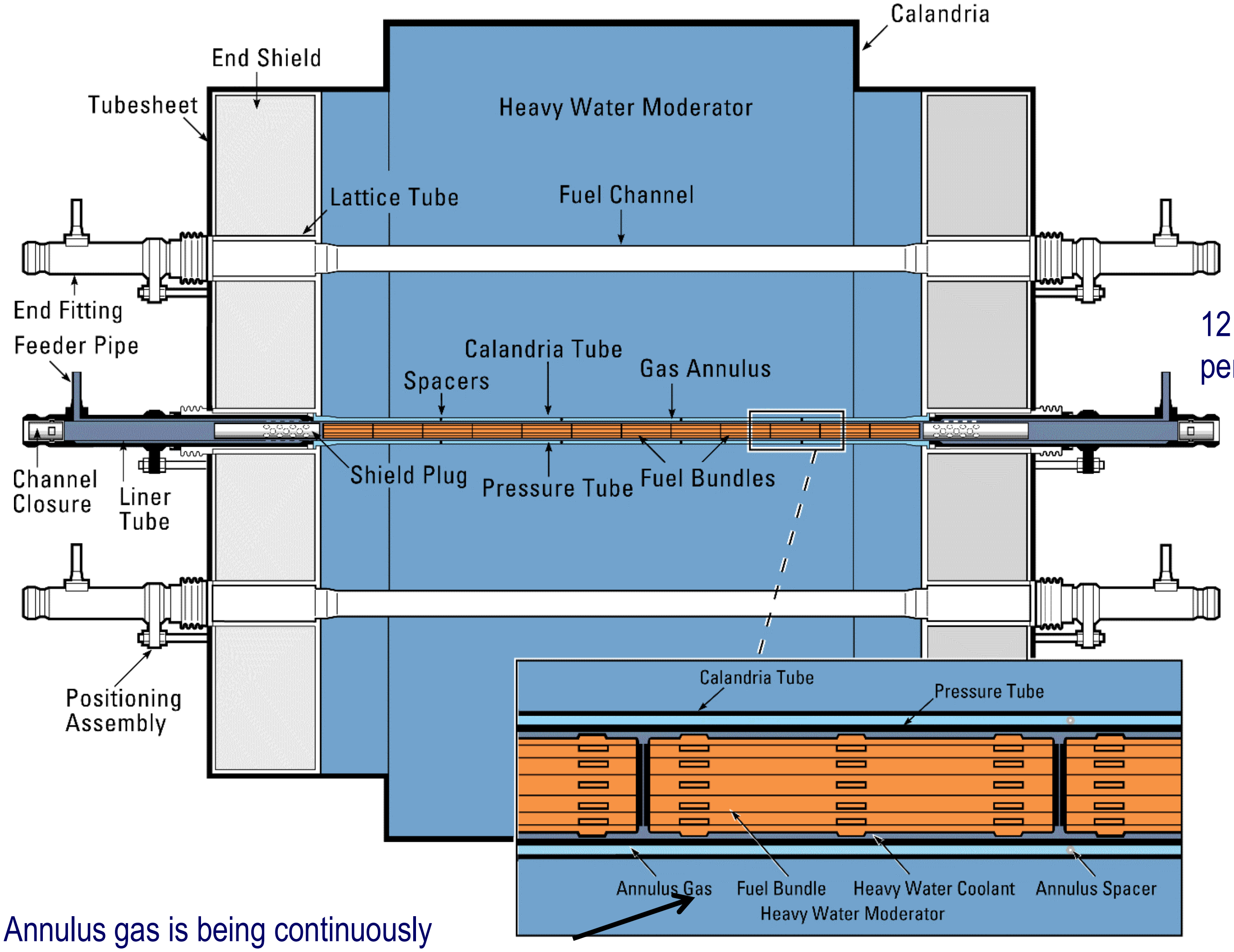
- Distributed core
- Modular design – separate fuel channels
- Small diameter, thin horizontal pressure tubes
- Power increase by increase of a number of fuel channels (and number of fuel bundles)
- No Boron to control reactivity

PWR



- Integrated core
- Single pressure vessel
- Power increase by increase in vessel diameter and its wall thickness (and number of fuel assemblies)
- Boron present to control reactivity

EC6 Reactor Assembly



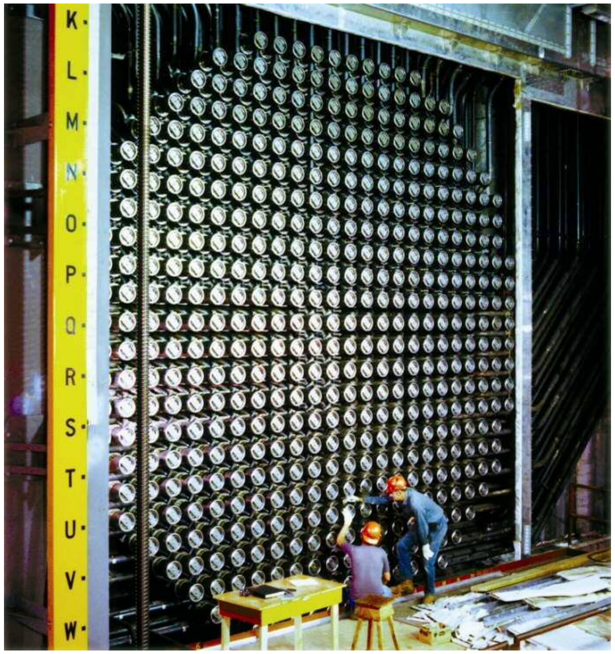
12 fuel bundles per channel

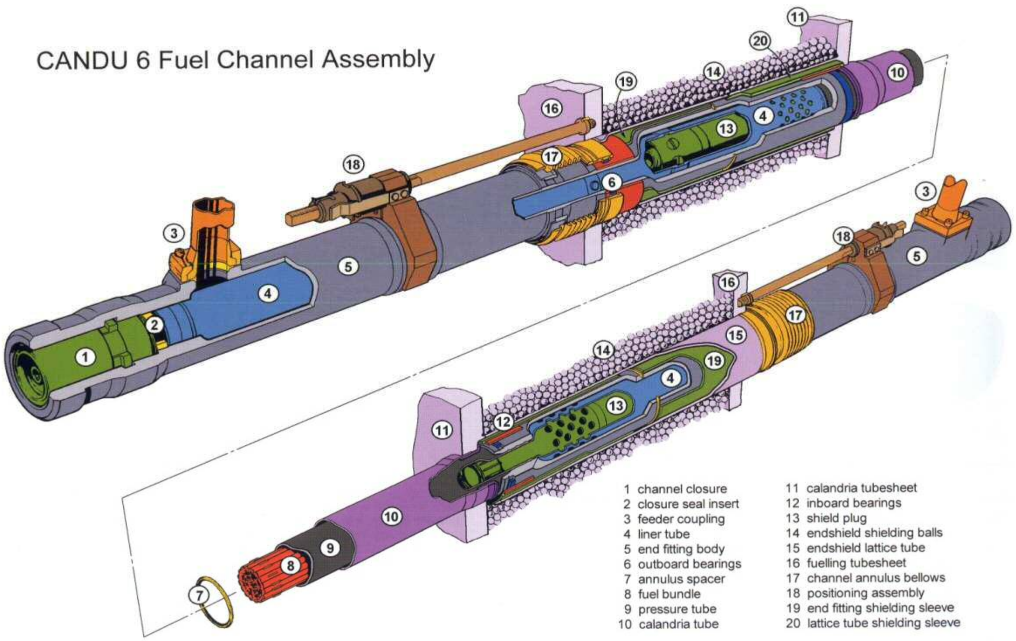
Continuous monitoring of coolant - if detected fuel defect – immediate fuel removal from the affected channel to minimize contamination of HTS & doses to personnel;

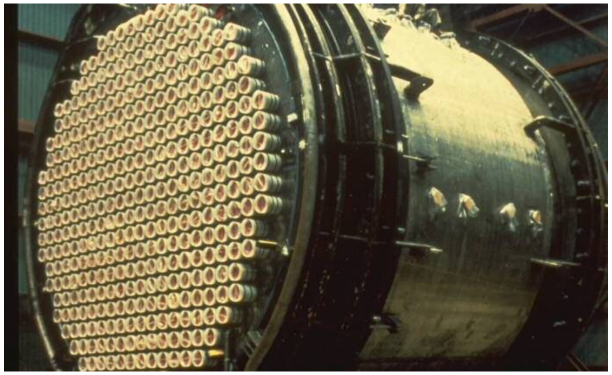
* PWR has to be shut down to remove a failed fuel usually done at planned outages for refuelling

Annulus gas is being continuously monitored for humidity content (to detect any crack in pressure boundary) - ***inherent safety feature***

CANDU Fuel Channel Assembly Details







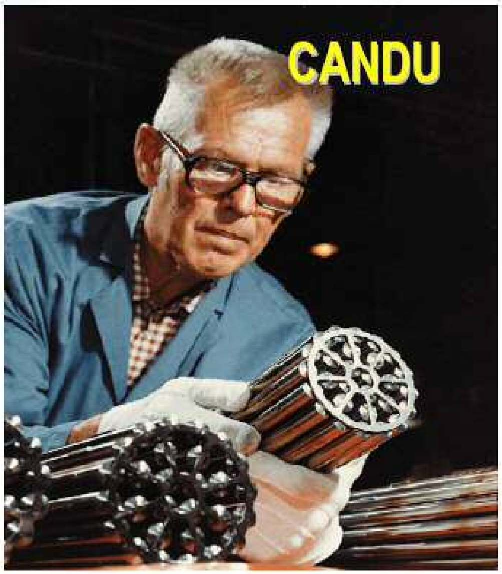
Pressure tubes constitue CANDU "pressure vessel"

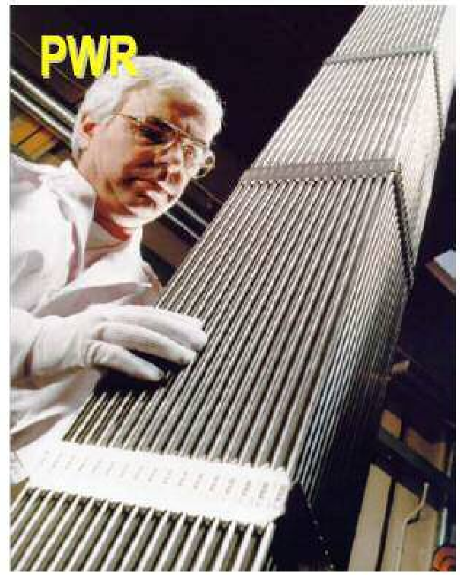
- Individual pressure tubes are replaceable
- Zirconium alloy provides neutron economy
- Modular component – allows scaling of reactor size

CANDU 6 Calandria for Qinshan

Fuel Design - CANDU vs PWR

Fuel Comparison





- natural uranium
- short bundles (0.5 metres)
- on-power refuelling
- remove defected fuel during operation

- enriched uranium
- long bundles (3.8 metres)
- shut down to refuel
- remove defective fuel only when shut down to refuel

Fuel Bundles – CANDU vs PWR

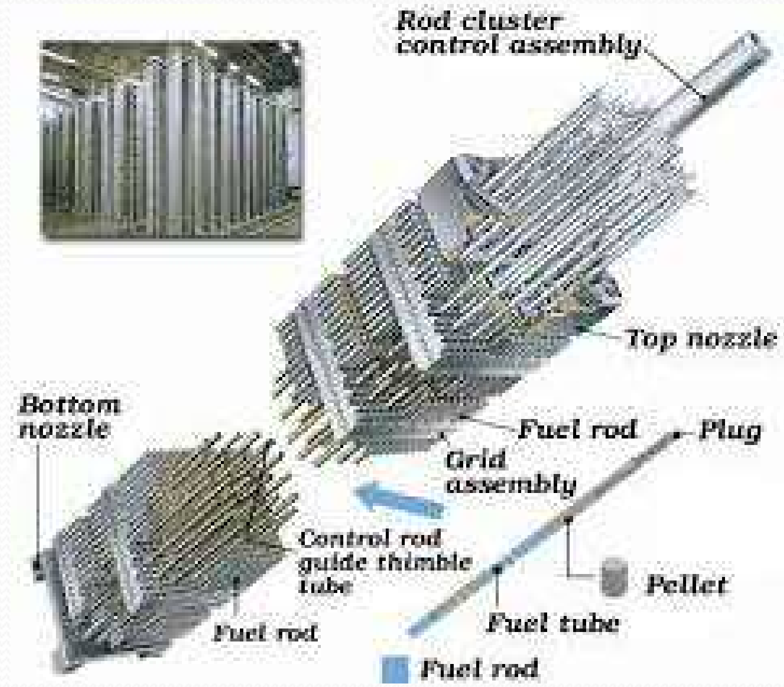
CANDU

"**Collapsible**" cladding (or sheath) under normal operating conditions = excellent heat transfer

Natural uranium – no criticality issue for fresh & spent fuel in light water – ***inherent safety feature***

All CANDU countries produce fuel themselves = energy security!

PWR



Self standing fuel elements with pellet- sheath gas gaps

Special care to be taken to avoid recriticality while storing and transporting PWR enriched fuel

EC6 Refuelling – on Full Power

Operation & Economics

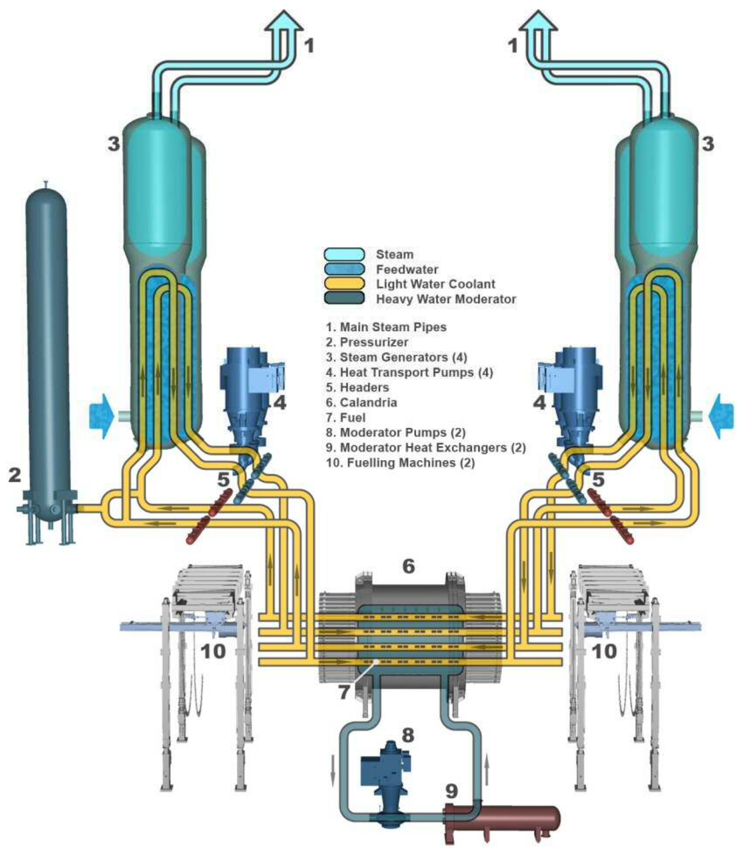
Regular, routine fuel bundle insertion (fresh fuel) and removal (spent fuel) **on full power** leads to:

- high performance
- low operating costs
- greater flexibility in scheduling outages
- enables long periods between maintenance outages
- fuelling scheme – 8-bundle shift

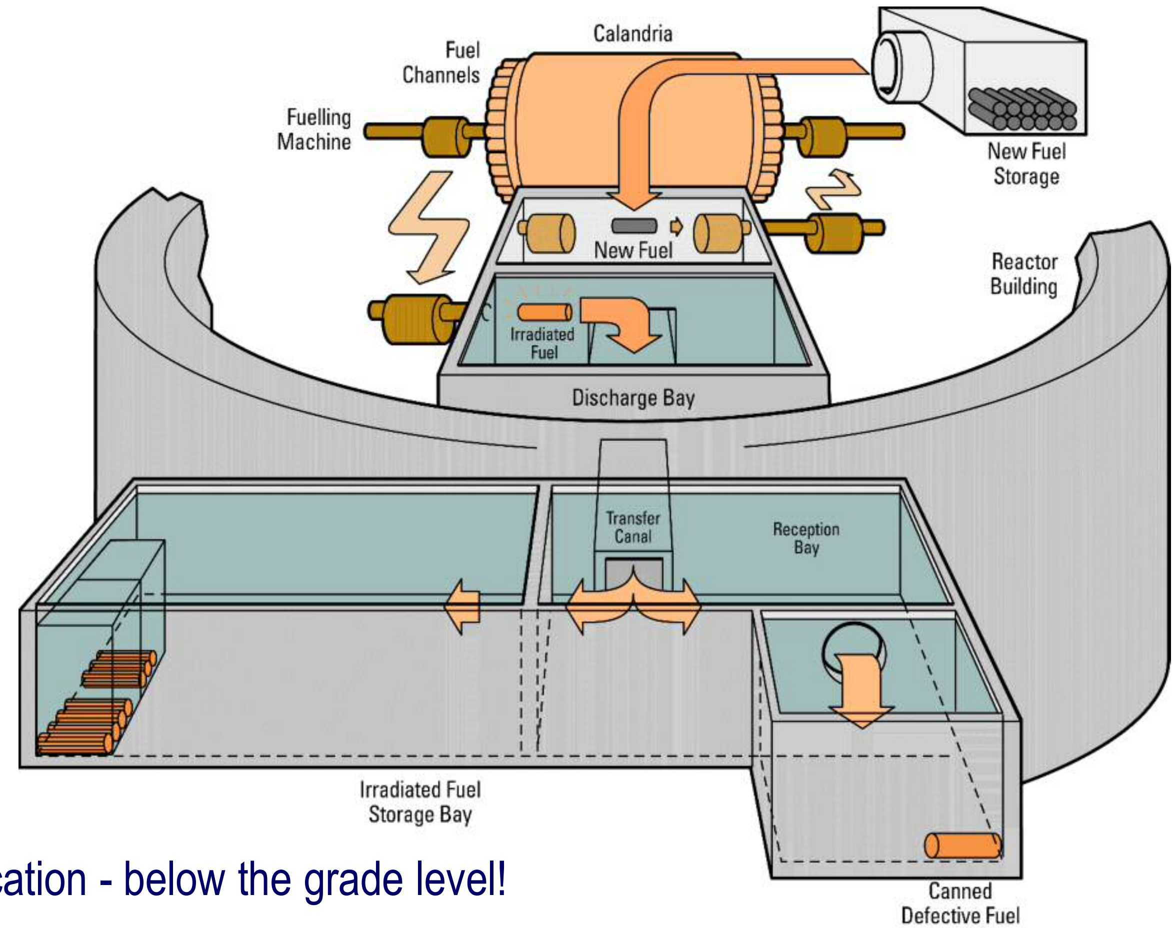
Please note: Pickering 7 - 894 days of continuous operation (26-04-1992 till 7-10-1994 = ~2.5 years)

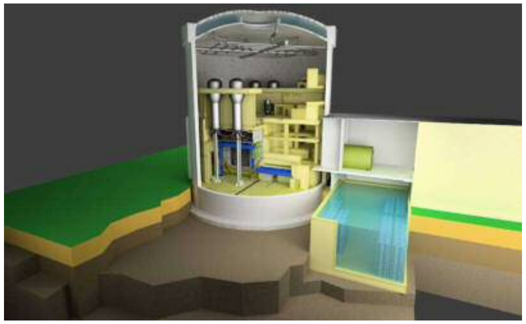
Safety

- maintains a minimum core excess reactivity
- maintains a constant power shape in the core
- maintains an equilibrium fuel burnup (steady-state source term for potential releases)
- shutdown system effectiveness does not change during a fuelling cycle
- permits on-power removal of failed fuel



EC6 Fuel Handling





• PWR requires in-containment refueling water storage tank (IRWST) near reactor at the reactor head level; (Fukushima case...)

Location - below the grade level!

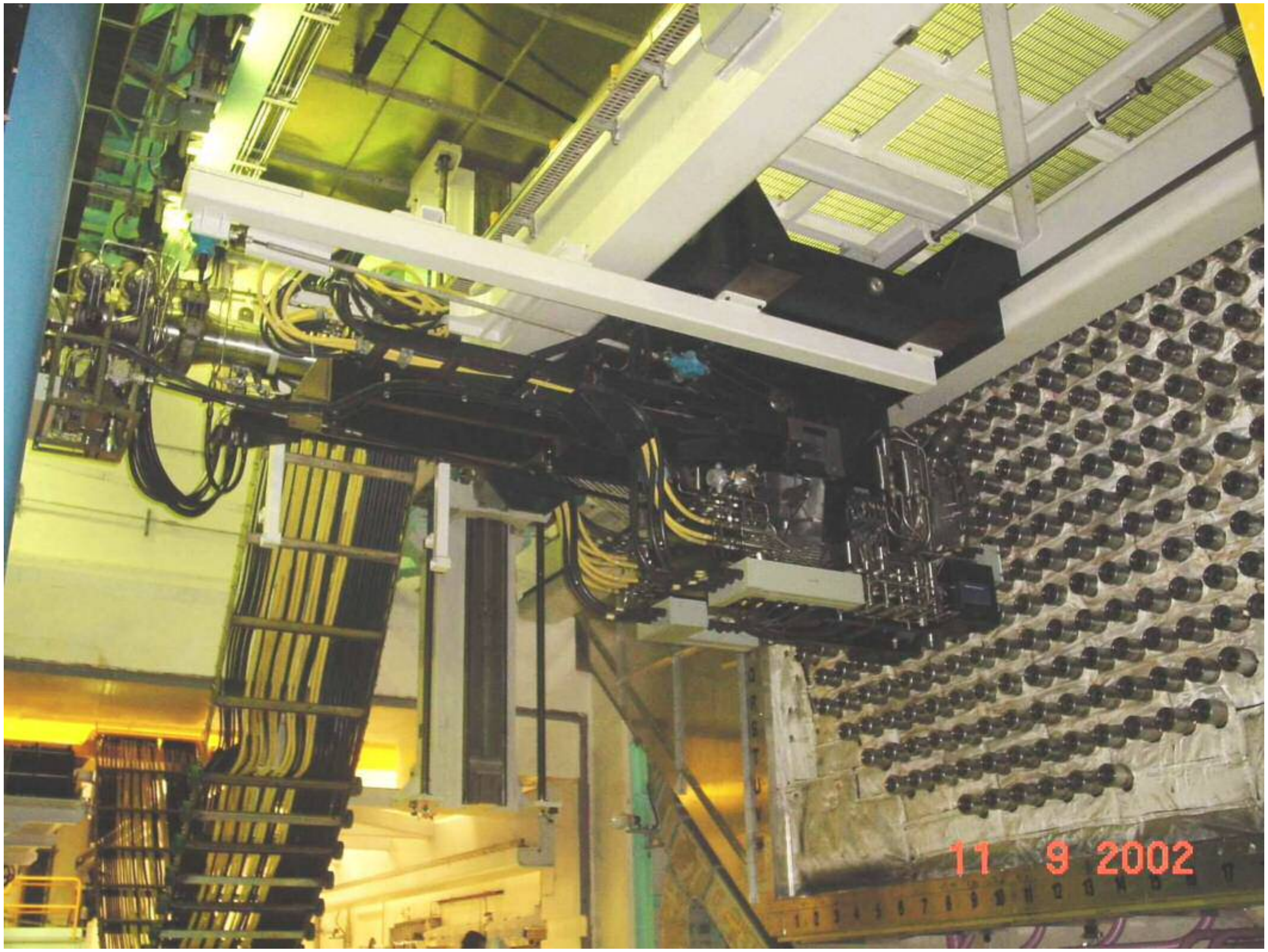
No criticality concerns in new fuel storage & spent fuel bay!

EC6 Fuelling Machine at Reactor Face

EC6 fuelling machines are designed and manufactured by Candu Energy Inc.

Refuelling on power is fully computerized and remotely controlled

* Refueling of PWR requires reactor shut down, depressurization and cooling down of HTS, reactor head removal etc.

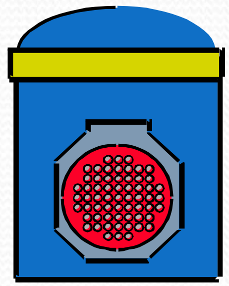


EC6 Fuelling Machine in Maintenance Lock

Fuel of CANDU & PWR

Natural Uranium

0.7% U-235



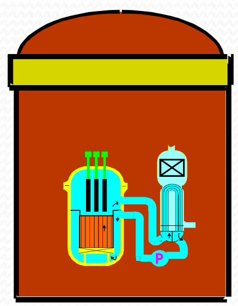
CANDU

Spent NU CANDU Fuel

0.23% U-235
0.27% Pu_f

Enriched Uranium

3.5% U-235

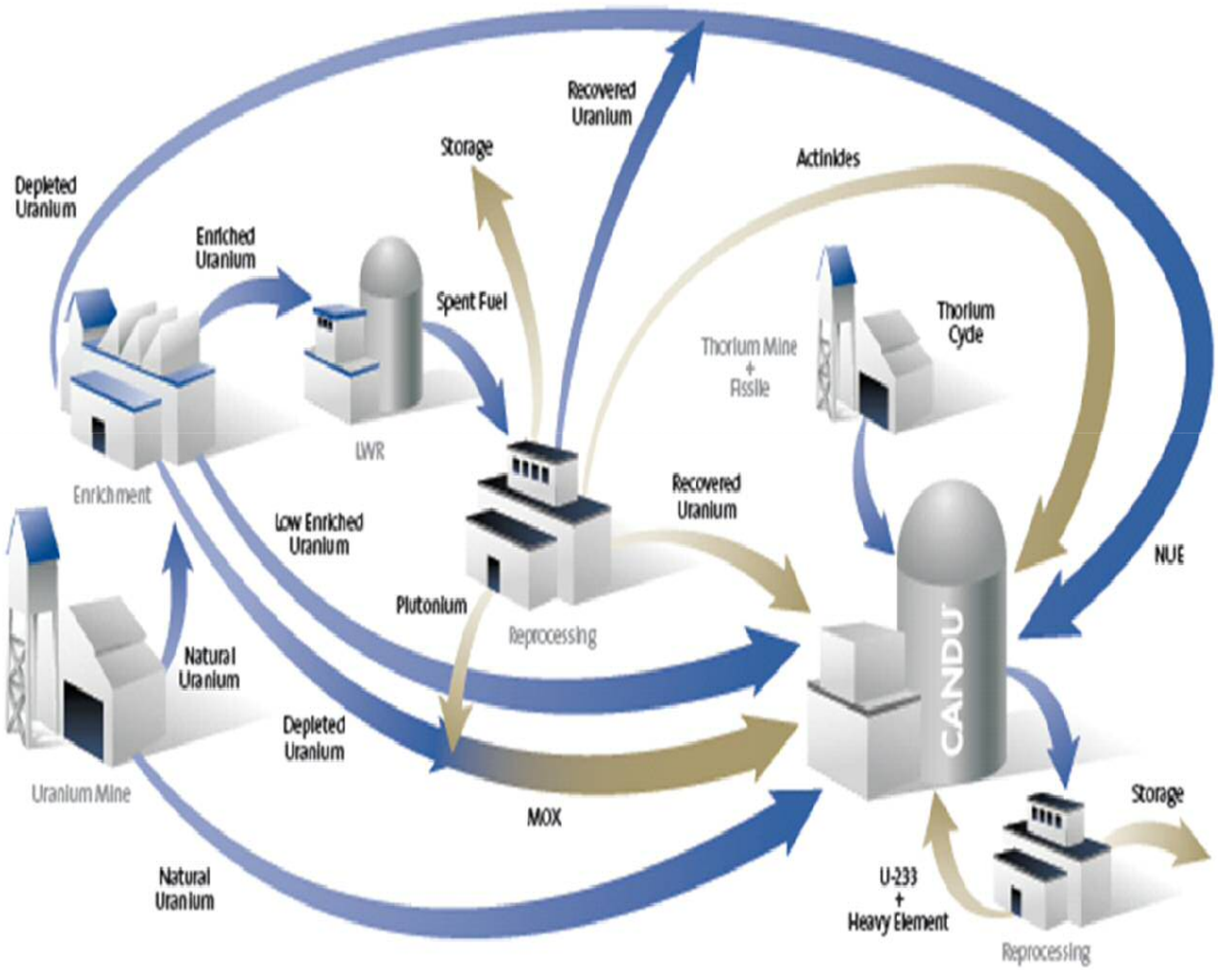


PWR

Spent PWR Fuel

0.9% U-235
0.6% Pu_f

CANDU Fuel Cycle Flexibility



1. Natural Uranium

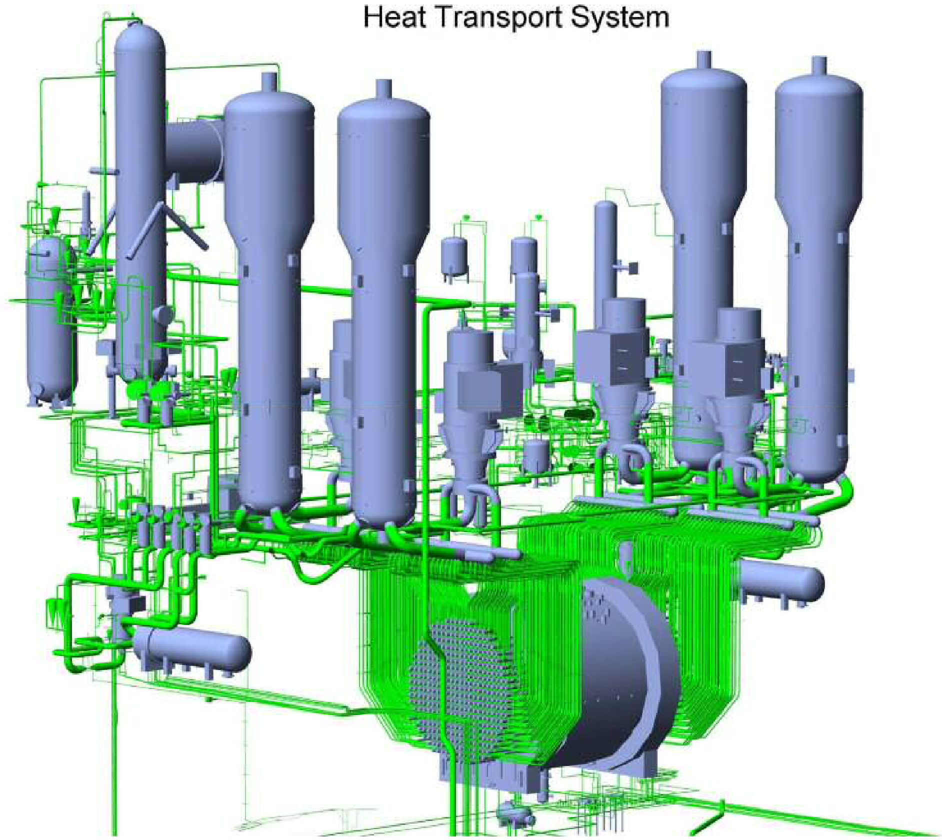
2. LWR “Recovered” fuels
   - NUE (RU/DU)
   - Direct RU
   - MOX
   - Actinide reduction

3. “Fertile” Fuels
   - Th/LEU
   - Th/Pu

4. “Closed Cycle” fuels
   - Th/^{233}U/Pu

EC6 Heat Transport System

- Two independent circuits/loops
- 2 pumps and 2 steam generators per loop
- All core-external circuit components located above core - ***passive natural circulation in the event of loss of pumped flow***
- Entire reactor coolant system pressure boundary inside containment



Reactor Coolant Parameters:

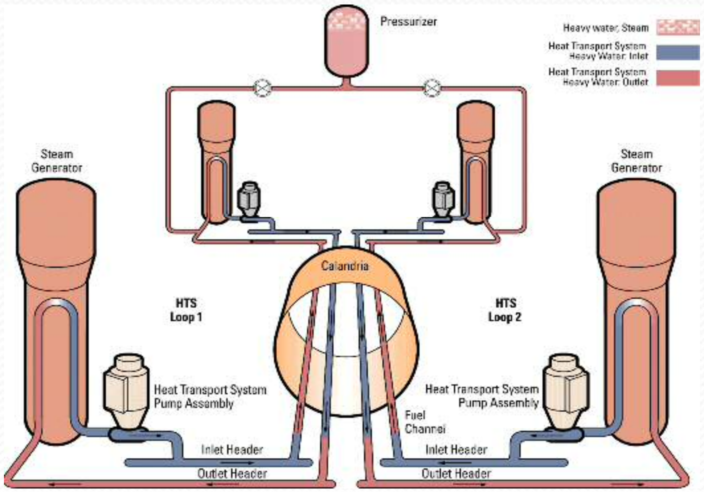
- Reactor inlet header pressure 11.05 MPa(g)
- Reactor outlet header pressure 9.89 MPa(g)
- Reactor outlet header temperature 310ºC
- Reactor inlet header temperature 265ºC
- Single channel max flow 28.5 kg/s

Secondary Side Conditions:

- Steam temperature 260ºC
- Feedwater temperature 187ºC

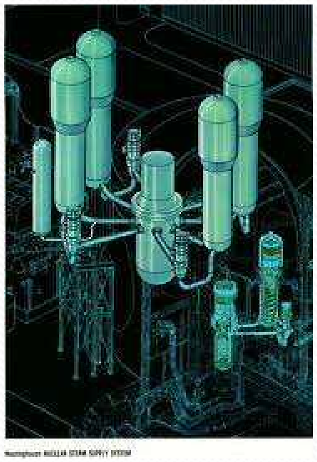
CANDU vs PWR

CANDU



- Two-loop HTS
- More uniform spatial core power distribution with **bidirectional flow** in adjacent channels
- Less impact on power distribution of reactivity devices
- LOCA (break one feeder tube) 1/380 of fuel affected
- LBLOCA (break of one header - 50% of fuel affected (one broken loop)

PWR



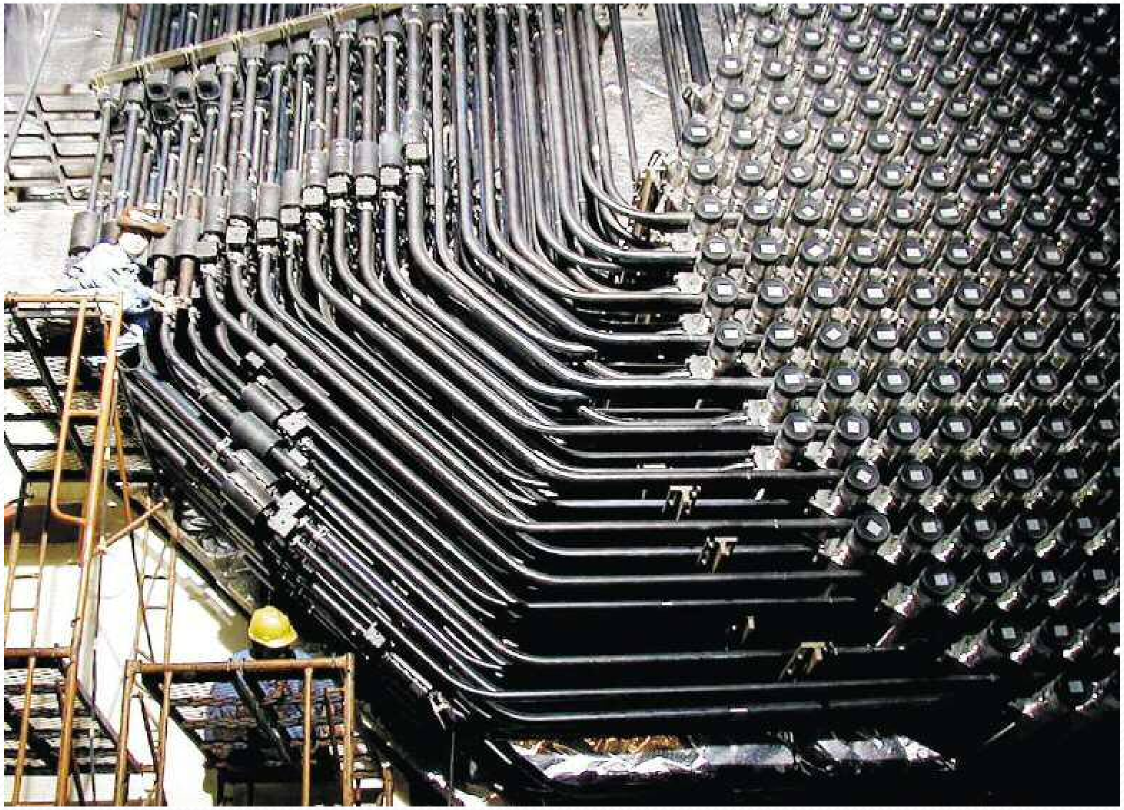
- Skewed spatial core power profile with **upward flow** through the core
- Power distribution more affected by reactivity devices
- LOCA - all coolant and all fuel affected

CANDU Feeder Header Frame Assembly

Critical part of the Heat Transport System

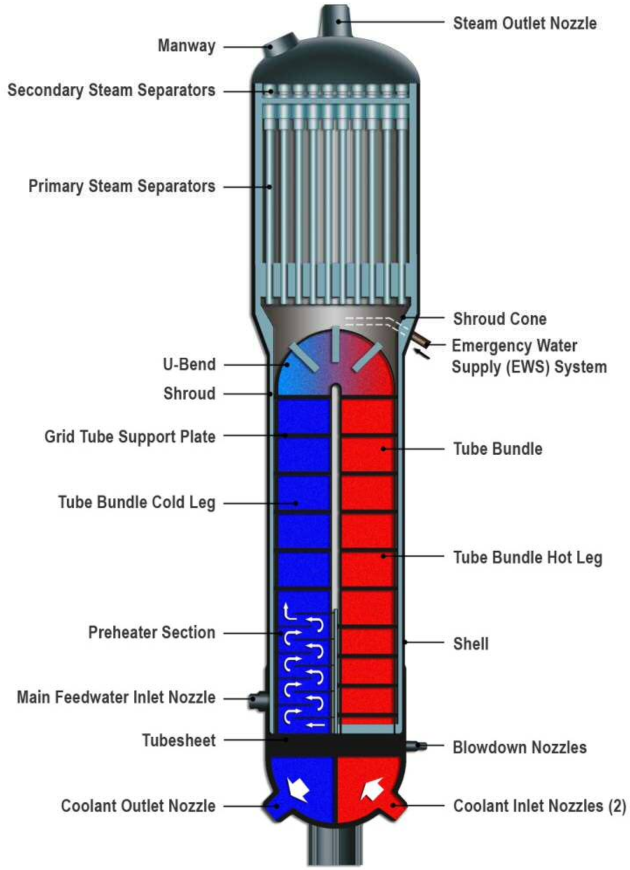
Code Class CSA N285.0 Class 1(ASME Sec III, Class 1)

Designed by Candu Energy manufactured by heavy industry, like Babcock and Wilcox Canada, also manufactured in Korea, Romania and Argentina.

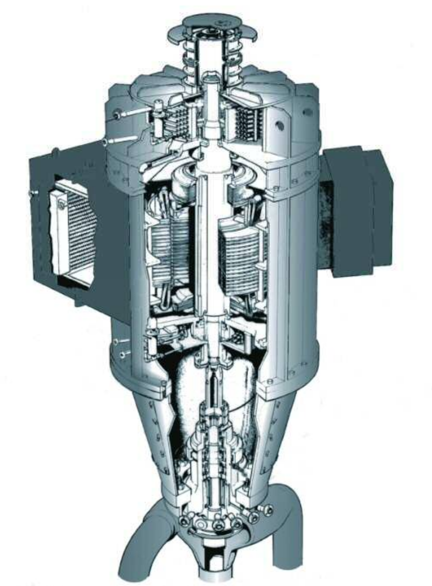


Major Equipment of Heat Transport System

Steam Generator(s)



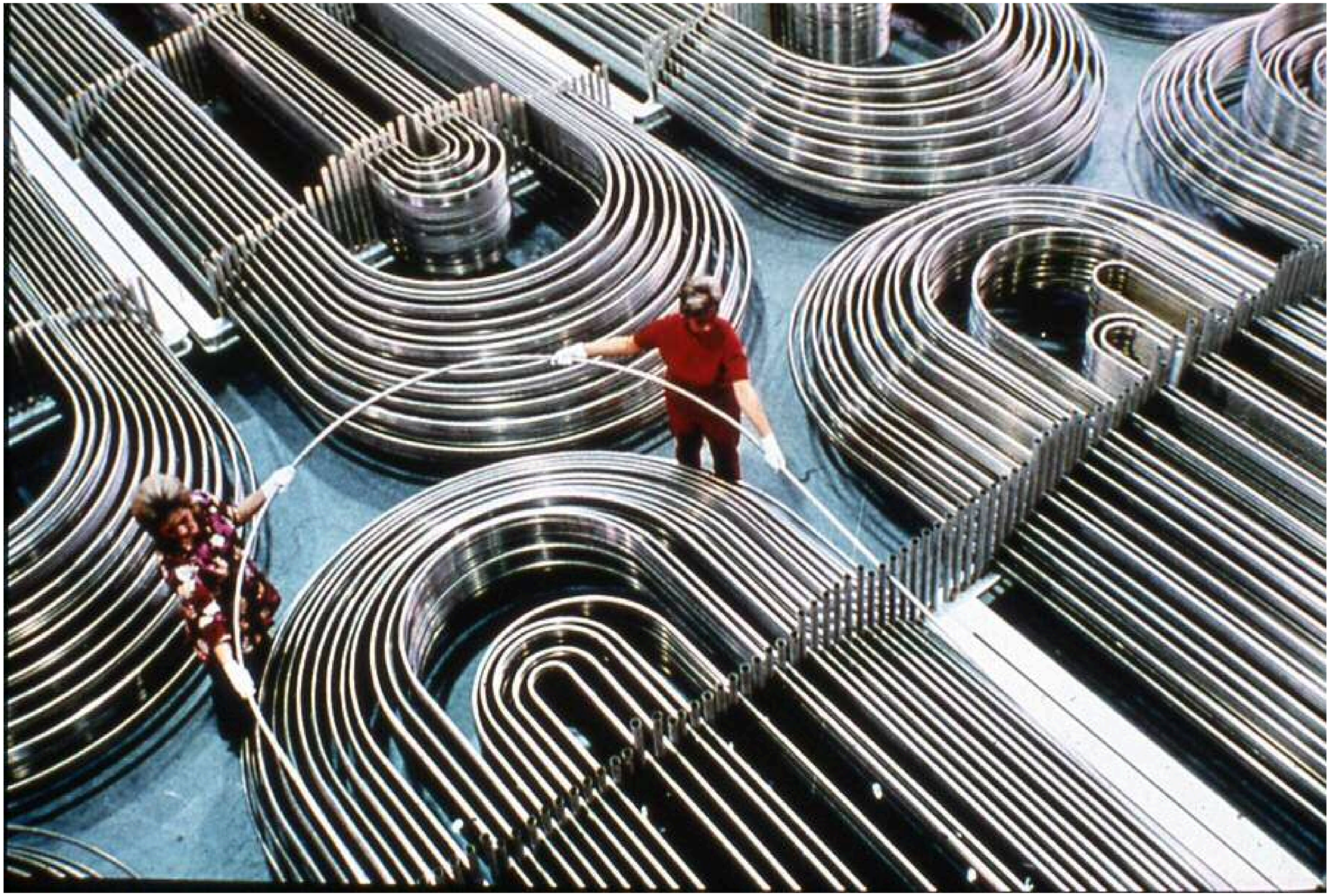
Main Pump(s)



CANDU 6 Qinshan Steam Generator

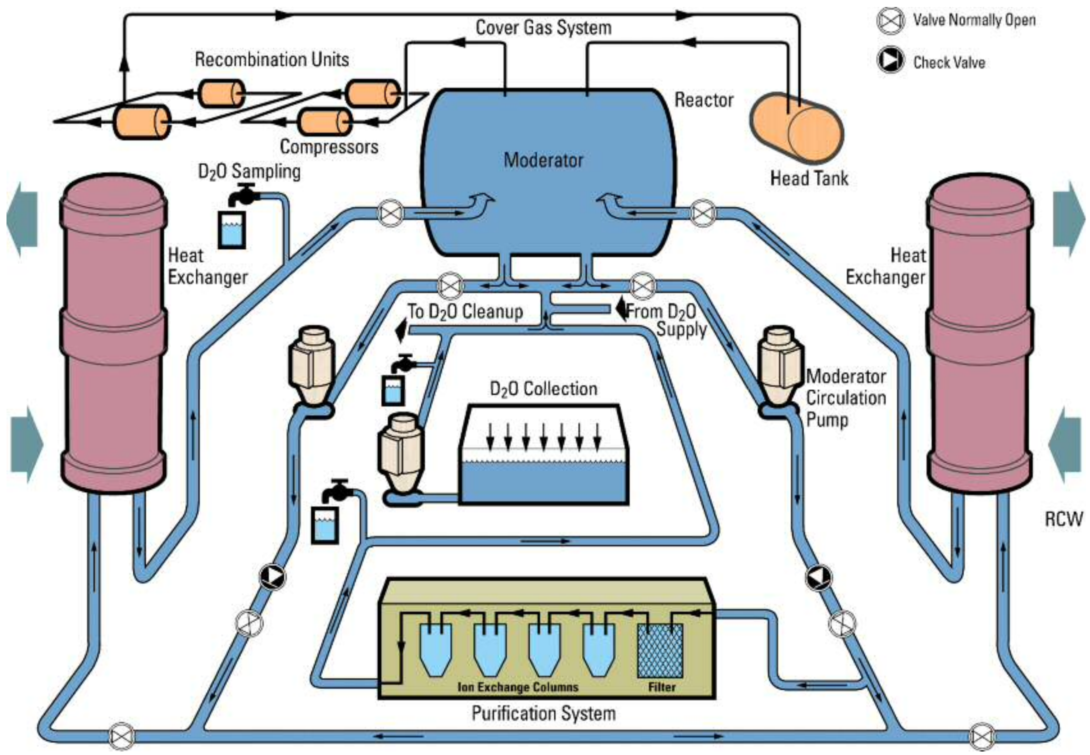
First SGs replacement has occurred in CANDU NPPs at the time of refurbishment (after 30+ years of operation) while quite often happened in PWR fleet in the USA

U-Tubes of Steam Generator



EC6 Moderator System

- Low temperature (< 80°C) system
- Low pressure system
- Independent of reactor coolant system
- Normal heat removal is ~4% of full power
- Contains shutdown systems outside of high-pressure HTS
- Low temperature moderator cannot increase pressure of containment (add energy) during a LOCA
- ***Passive heat sink*** if ECC is unavailable during a LOCA and during BDBAs



* PWR does not have such a system

Heavy Water

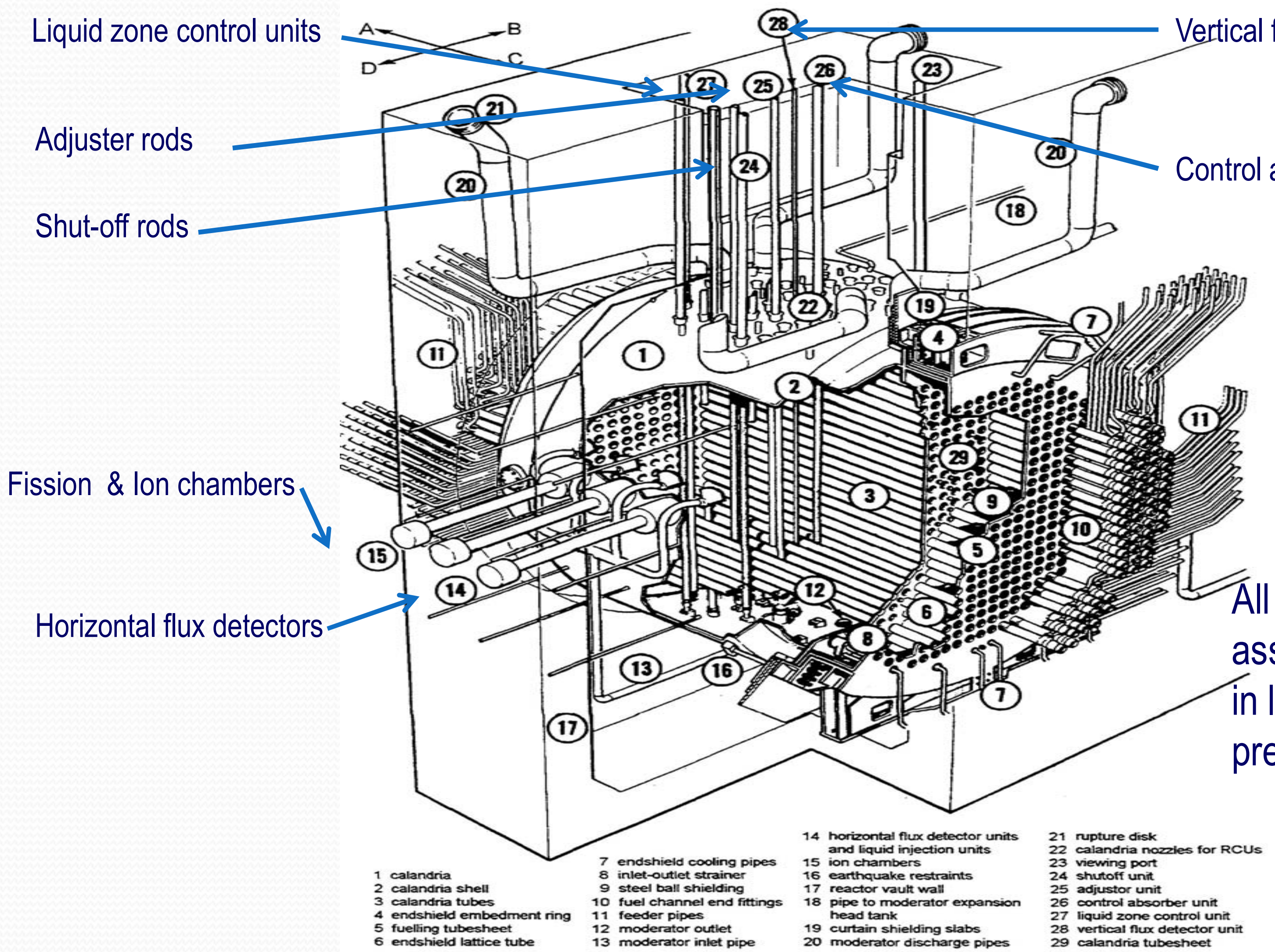
<u>Advantages:</u>

- Very small neutron absorption = excellent neutron economy
- Long prompt neutron lifetime (~0.9 ms vs ~0.03 ms w light water)
- <u>= essential inherent safety feature of CANDU reactors:</u>
  - ~ 30 times longer reactivity transients then in LWR
  - longer time available for activation of Shutdown Systems
  - Less probable fuel fragmentation during rapid transients
- Generation of photo-neutrons – additional source of delayed neutrons – further slowdown of reactivity transients and easier power control = <u>further inherent safety feature of CANDU reactors</u>

<u>Disadvantages:</u>

- Cost
- Maintenance of isotopic purity
- Generation of Tritium – harmful, but CANDU has engineering features to monitor and control its effects

EC6 Reactivity Mechanisms



All reactivity devices & associated instrumentation in low-temperature & low-pressure moderator

EC6 Reactivity Mechanisms

Liquid Zone Compartments

- This is the primary mechanism used to control the bulk and spatial power in the reactor (for normal positive/negative reactivity addition)
- The level in the zones is controlled by the Reactor Regulating System (RRS)

Control Absorber Rods and Adjusters

- Used by RRS when reacticivity change beyond the capability of the liquid zones is needed
- Driven in and out with controlled speed and using predefined sequences

Supplementary Absorber Rods

- Manually driven or dropped into the core to supplement Shutdown System (SDS) 1 in the long term and for **rod-based** Guaranteed Shutdown State (GSS)

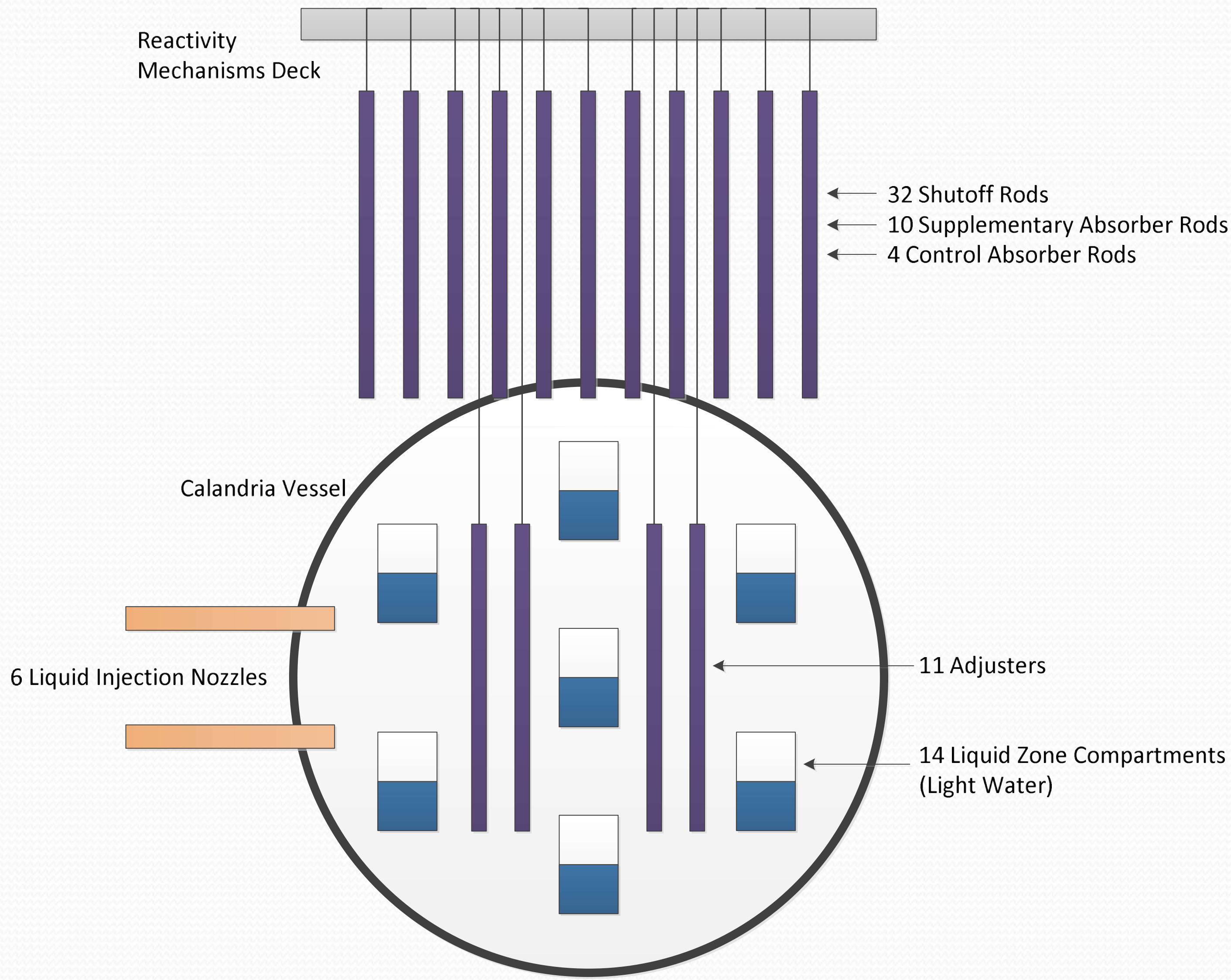
Shutoff Rods

- Rapidly dropped into the core on an SDS1 trip

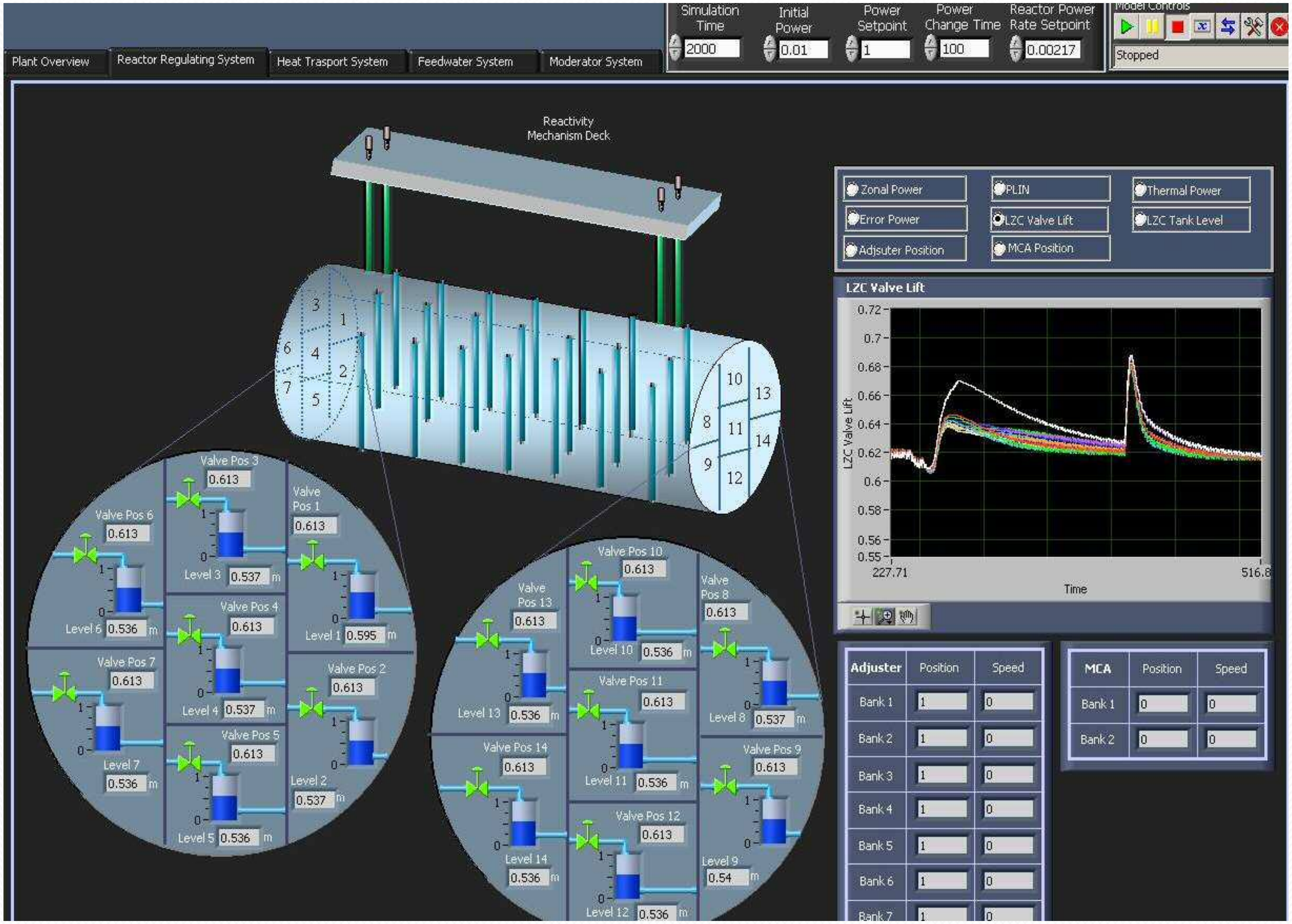
Liquid Injection Nozzles

- Used to inject liquid neutron poison into the core on an SDS2 trip

EC6 Reactivity Mechanisms



Liquid Zone Compartments



EC6 Shutdown Systems - Passive

SDS1

- 32 SS-clad cadmium rods
  - vertically oriented
  - spring-assisted gravity drop

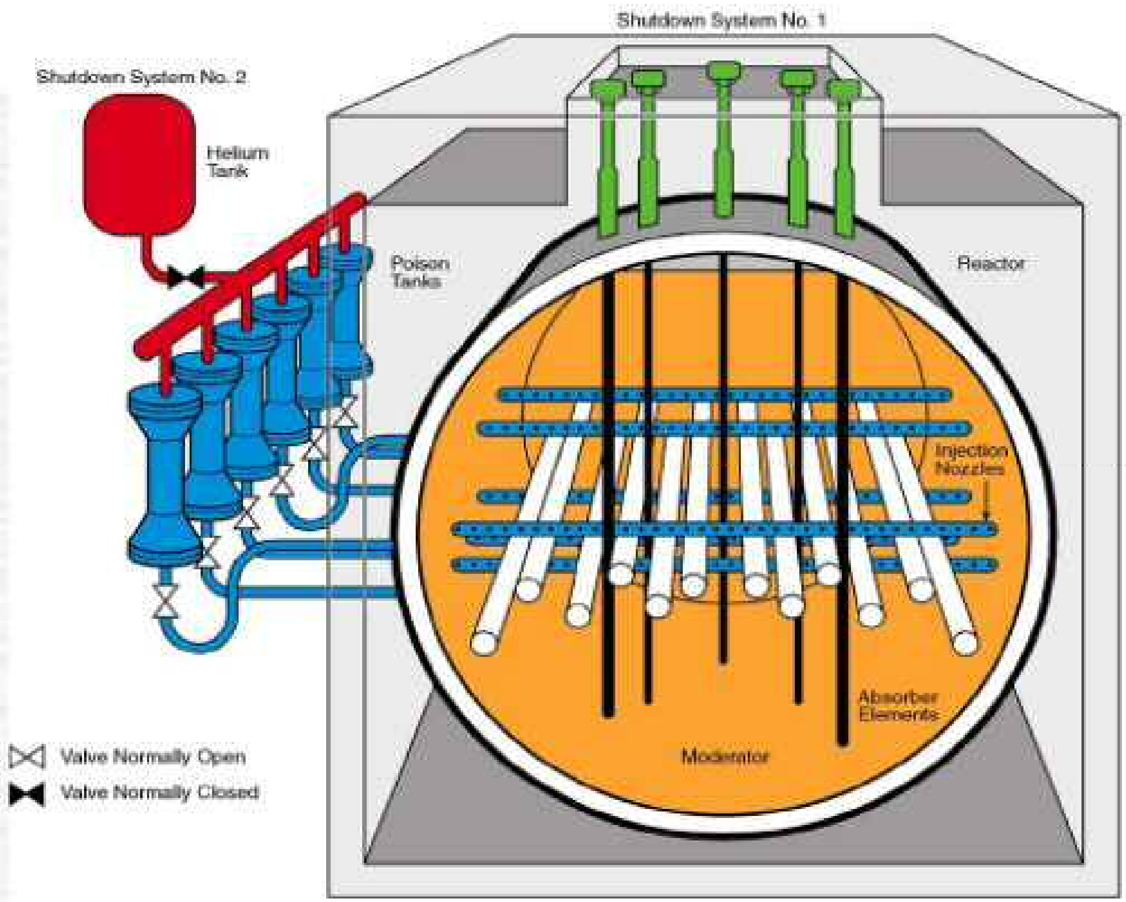
SDS2

- 6 injection nozzles for gadolinium nitrate solution
  - horizontal insertion
  - driven by high-pressure He

Control

- reactor control separate from safety shutdown (detectors & trip signals)

- All located in cool & low pressure moderator (no rod ejection)



EC6 Safety Enhancements – Safety Design Approach - Safety Grouping

Group 1	Safety Function	Group 2
RRS	**Control to promptly shutdown**	
SDS#1		**SDS#2**
ECC	**Remove residual heat from core - transfer heat to ultimate heat sink**	**EHRS** (passive makeup to steam generator)
RCW/RSW cooling to ECC Hx powered by Class II		Emergency water to ECC Hx powered by EPS
LAC (local air coolers)		SARHRS (separate power & Hx cooling)
LAC (local air coolers)	**Confine Radioactive Materials**	SARHRS (separate power & Hx cooling)
		RB Containment (robustness & security)
MCR (main control room)	**Monitor and Control**	SCA (secondary control area)
TSC (technical support center)		ESC (emergency support center)

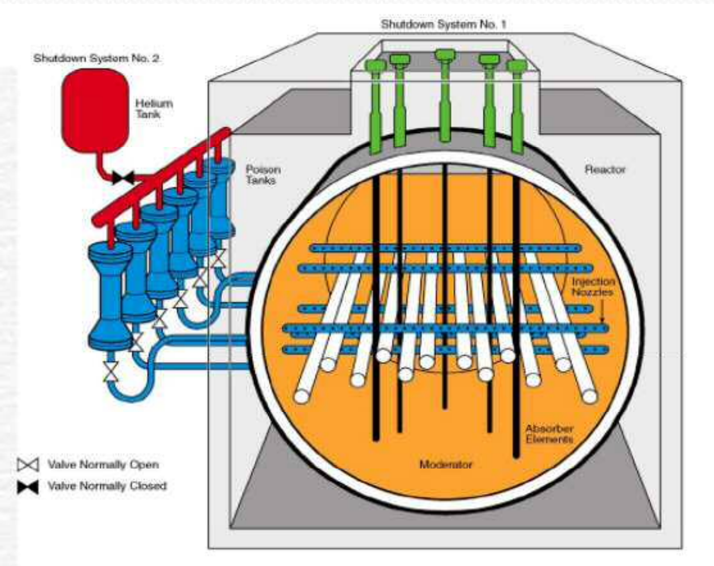
New system	SARHRS, ESC
Enhanced system	SDS#1, SDS#2, EHRS, RB Containment, MCR, TSC, SCA

Design Philosophy: Defense-in-depth; Two independent Groups

grouping & separation of safety systems and safety support systems to increase reliability by diversity, independency, robustness and redundancy

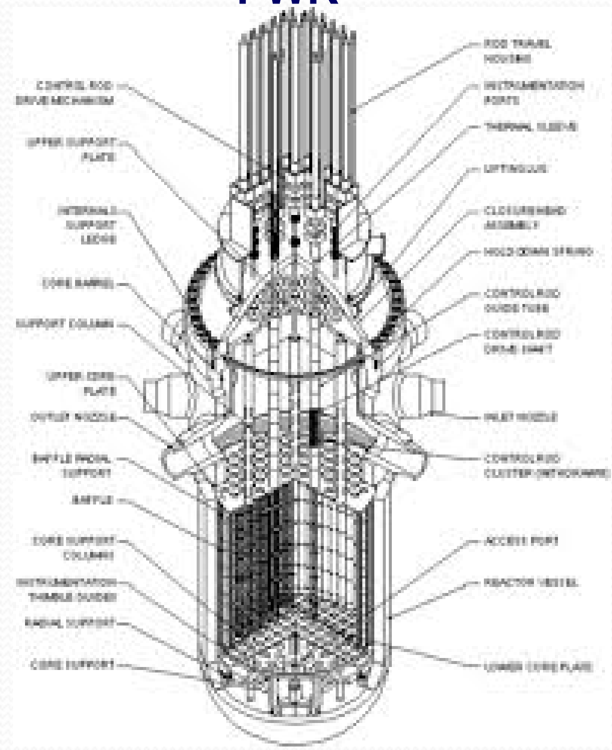
Reactivity Devices – CANDU vs PWR

CANDU



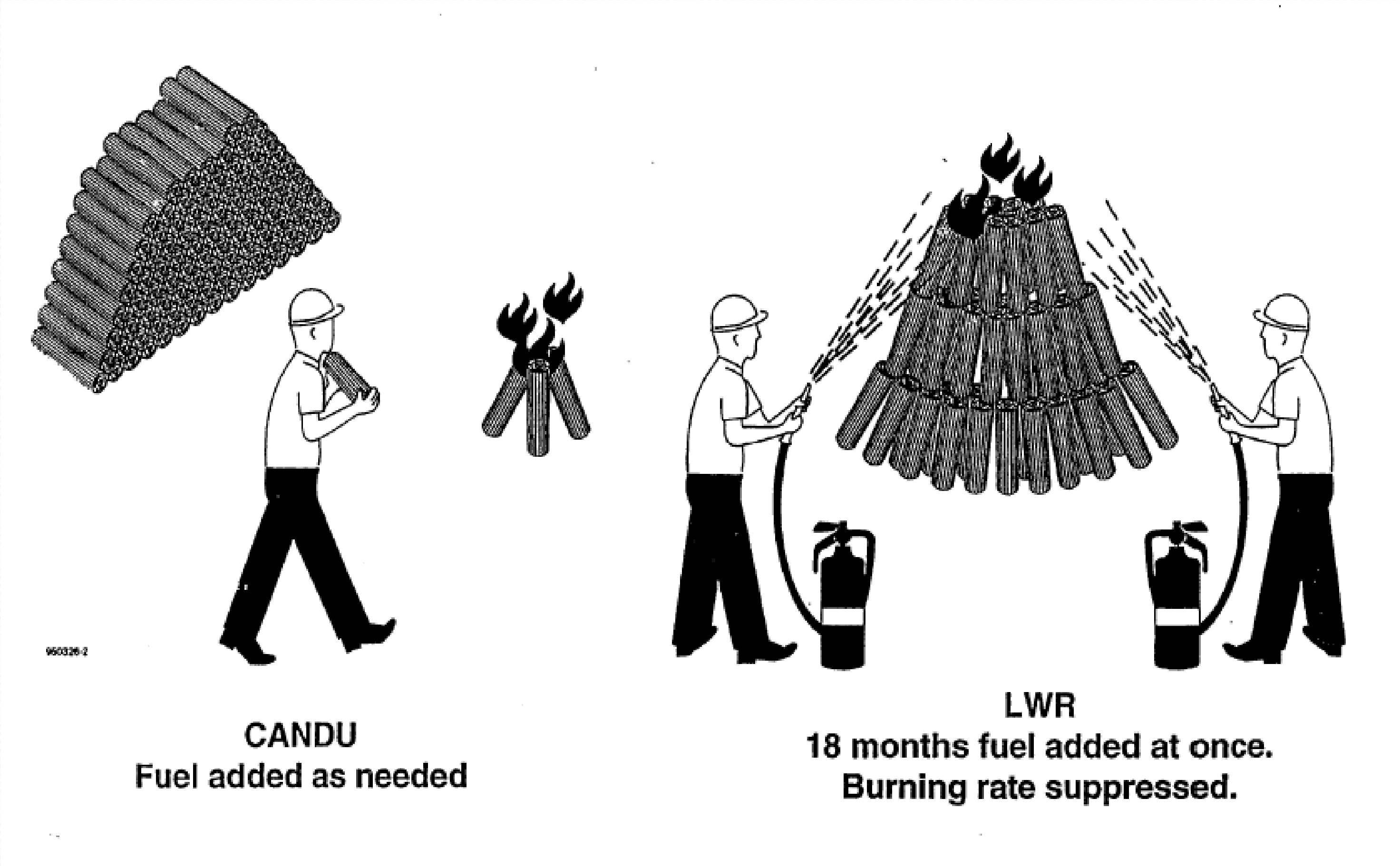
- All reactivity controlling devices (i.e., control rods, safety rods & poison injection nozzles) and nuclear instrumentation located in low-temperature & low-pressure moderator
- Outside pressure boundary
- Control rod ejection impossible
- (Large calandria vessel area for reactivity control mechanisms)

PWR



- Control, safety rods and nuclear instrumentation located in high-temperature & -pressure coolant
- Piercing pressure boundary
- Control rod ejection event must be analyzed
- Same for accidental boron dilution
- (Limited reactor head area for reactivity control mechanisms)

Reactivity & Power Control - CANDU vs PWR



On-power refuelling + liquid zone compartments

Boron + rod cluster control assemblies (RCCAs)

EC6 - Passive Heat Removal for Severe Accident Mitigation

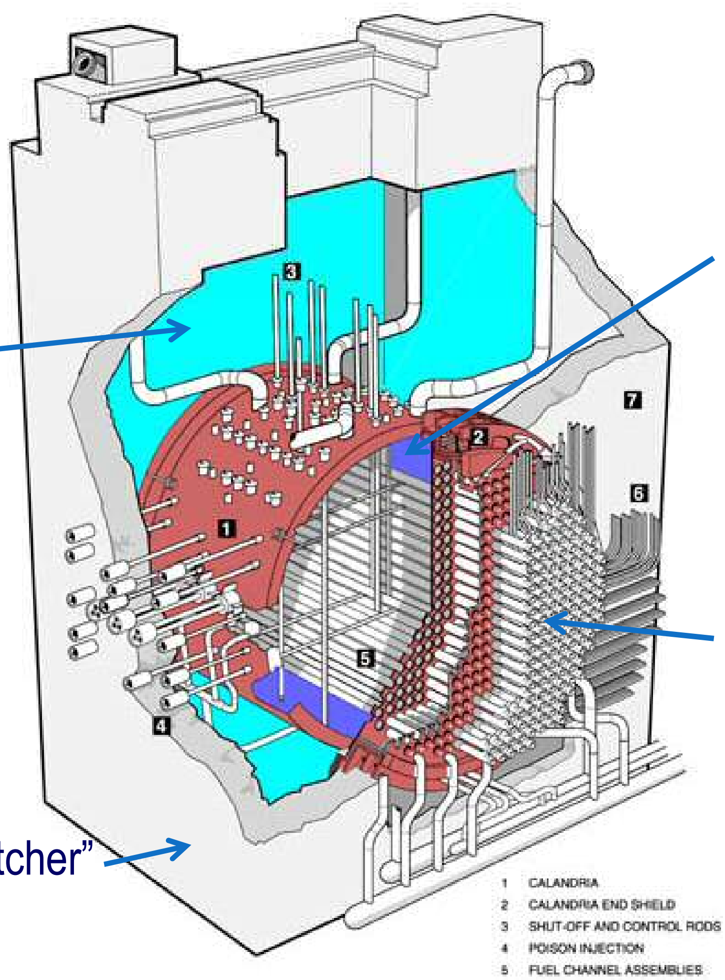
Unique EC6 Safety Advantages

With Natural Uranium fuel there is ***no risk of re-criticality*** upon loss of core configuration or in any corium – no need for neutron poison

Calandria Vault
- large source of H_2O water – 520 Mg
- many hours to heat up and boil off

3000 Mg of water available!

Reactor vault bottom = "corium catcher"



Reserve Water Tank (RWT)
- huge source of H_2O water – 2000 Mg
- fills the Calandria vessel and its vault, SGs by gravity

Moderator
- large source of D_2O water - 274 Mg)
- several hours to heat up and boil off

ECC – high pressure system
- H_2O water – 210 Mg

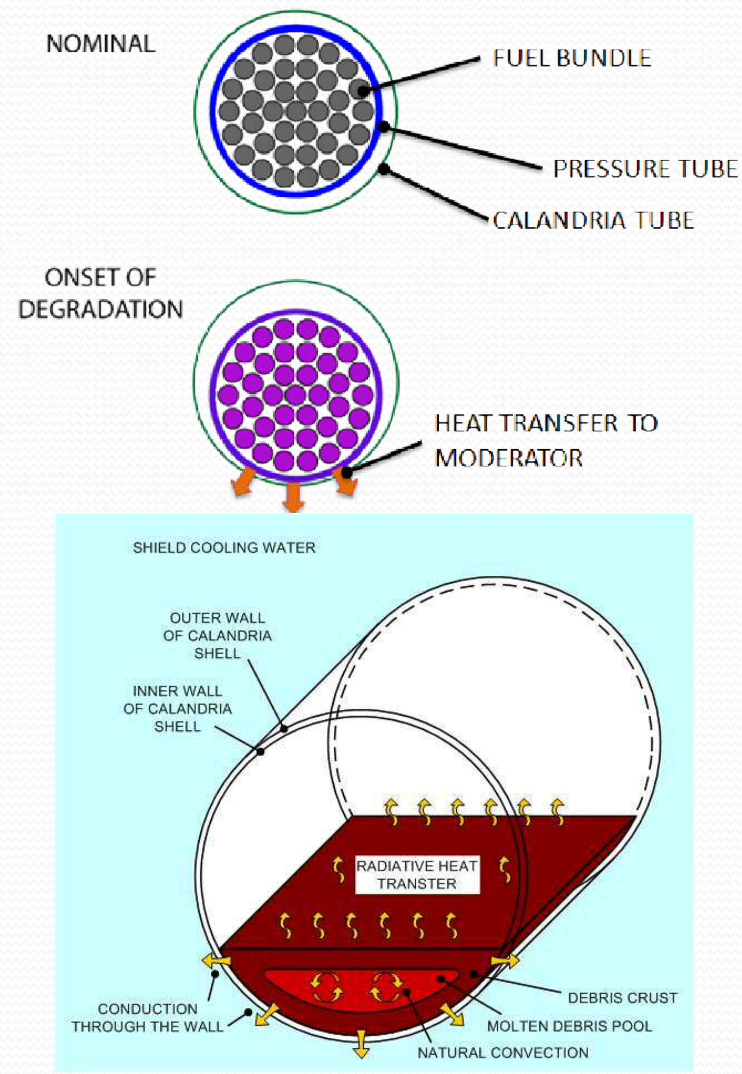
Core Damage Accidents in EC6 Reactors

Limited Core Damage Accident (LCDA)

- Pressure tubes sag/strain into contact with calandria tubes establishes a heat rejection pathway to the moderator.
- Optimization of moderator inlet and outlet nozzle configuration on the calandria for increased moderator sub-cooling enhanced moderator heat sink

Severe Core Damage Accident (In-VSCD)

- If the moderator heat sink fails (or is exhausted), the fuel channels will fail and the core channel debris (corium) will settle to the bottom of the calandria vessel
- However, reactor vault water plus make-up water <u>will limit severe core damage progression</u>

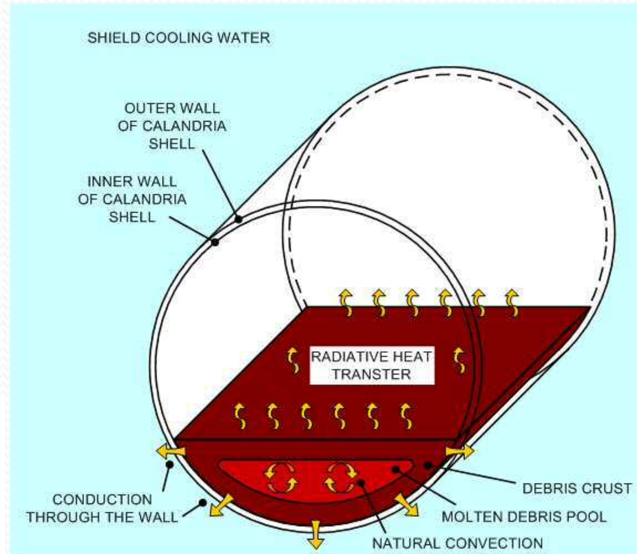


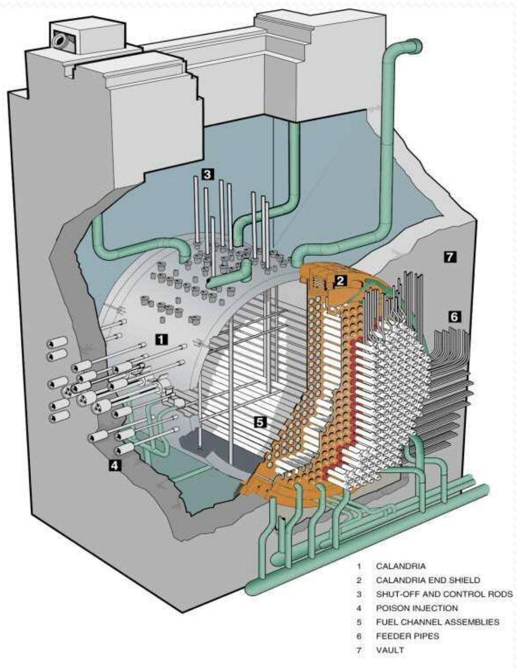
* Large ratio of heat transfer area to fuel volume as opposed to that of PWR

Core Damage Accidents in EC6 Reactors

Severe Core Damage Accident (Ex-VSCD)

- If molten corium escapes due to leakage or damage to the externally cooled calandria vessel, and when its external cooling is exhausted (no reactor vault water, no make-up water), in a very low probability case, the core debris may fall on the reactor vault floor that is lined with refractory material to minimize generation of non-condendensable gases





EC6 Safety Enhancement – Defence-in-Depth

Plant Design Envelope

	Operational States		Accident Conditions				
Plant State	**Normal Operation**	**Anticipated Operational Occurrence**	**Design Basis Accident**	**Beyond Design Basis Accidents**			
				Design Extension Conditions		**No further mitigative features available in design**	
				LCDA	**Severe Accidents**		

		Severe Core Damage Prevention		Severe Core Damage -Mitigation	
Robustness of Design	Control/Process Systems	Safety Systems	Moderator System	Severe Accident Recovery and Heat Removal System	Defense-in-Depth Features
Normal Operation	AOO	a / DBA	b / LCDA	In-VSCD	Ex-VSCD/Large Release

SCDA

Defence in Depth	Level 1	Level 2	Level 3	Level 4	Level 5
Event Frequency Yr^{-1}:		$> 10^{-2}$	$10^{-2} - 10^{-5}$	$< 10^{-5}$	$< 10^{-6}$

← Complimentary Design Features →

a. Events, such as internal hazards and external events, which are not explicitly considered as accidents, but whose consequences are encompassed by them (such as Design Basis Threats).
b. Beyond design basis accidents, without limited or severe core degradation.

EC6 Safety Enhancements – Balance of Prevention & Mitigation Features

Robustness of Design	Control/Process Systems	Severe Core Damage Prevention: Safety Systems		Severe Core Damage Prevention: Moderator System		Severe Core Damage -Mitigation: SARHRS	Severe Core Damage -Mitigation: Defense-in-Depth Features
Normal Operation	AOO	a	DBA	b	LCDA	In-VSCD	Ex-VSCD/Large Release

SCDA

Thicker PT & Seamless CT

SDS1 – enhanced reactivity insertion

SDS2 – additional detectors

Post-Accident Monitoring

EHRS – SG heat sink

Reserve Water Tank – emergency water to SGs, ECC & EHRS

SARHRS – makeup to RWT, calandria & vault

Low Flow Spray

Low leakage, steel-lined, thick-walled, high pressure containment

Vault refractory

Hydrogen Igniters & PARs

Containment Filtered Venting

On/Off Site Mobile Equipment

Preventative

Mitigative

a. Events, such as internal hazards and external events, which are not explicitly considered as accidents, but whose consequences are encompassed by them (such as Design Basis Threats).
b. Beyond design basis accidents, without limited or severe core degradation.

SMART CANDU™ Information Tools

- The EC6 comes equipped with the **SMART CANDU** software suite, an integrated package of software tools and work processes aimed at optimizing CANDU plant performance throughout its operational life cycle
- **SMART CANDU** technologies are designed to use the Candu Energy Inc. knowledge base embedded in predictive models, to transform discrete bits of plant data into actionable information used to support operational decisions, maintenance planning and life cycle management

The SMART CANDU suite of tools includes:

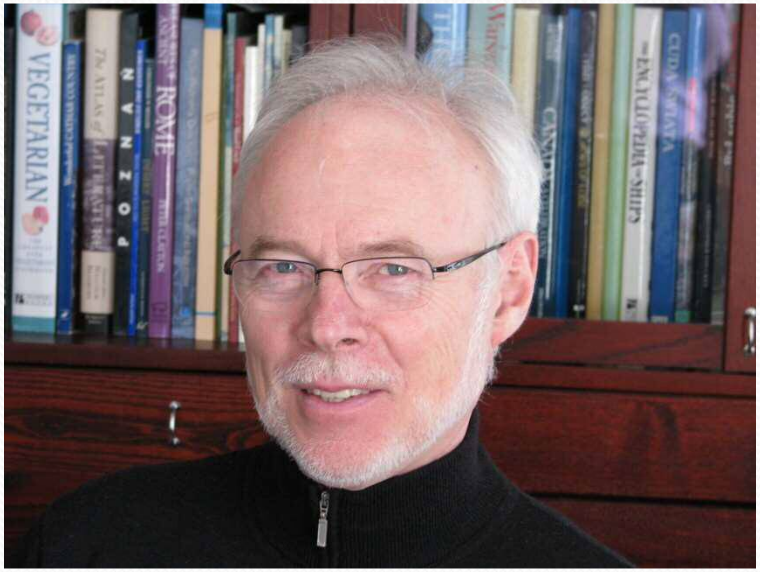
- **ChemAND®4**: Health monitor for plant chemistry that predicts:
  - future performance of components, and
  - determines maintenance requirements and optimal operating conditions.
- **ThermAND**: Health monitor for heat transfer systems and components that ensures optimal margins and maximum power output

Concluding Remarks

- The EC6 design builds on the proven CANDU 6 design at Qinshan, based on five decades of excellent operating and safety performance
- The EC6 is a Gen. III design that meets up-to-date regulatory requirements and customer expectations
- The EC6 design has incorporated extensive enhancements and provides additional margins for both inherent or passive and engineered safety features, and heat removal systems to prevent & mitigate severe accidents
- The EC6 design has provided further design features that extends the defence-in-depth provisions for beyond design basis events, based on lessons learned from Fukushima nuclear event

Personal Note ...

My best wishes to the NCBJ staff to successfully accomplish the HTGR Project!



To complement the lecture - please read my paper *"Wybrane Projektowe Awarie Reaktywnościowe w Reaktorach LWR i CANDU ",* published in Polish, Postępy Techniki Jądrowej, Vol. 53, Z. 4, Warszawa 2010

I am ready to help!
SD

Strona NCBJ: "Energetyka Jądrowa"- **atom.edu.pl**
"Praca w przemyśle jądrowym" (Stefan Doerffer) napisana na życzenie pana Prof. Andrzeja Strupczewskiego w 2009 r.