The Canadian Deuterium Reactor (CANDU)
and
The Advanced CANDU Reactor (ACR)

Developed for the Members of the

Global Sustainability Alliance

By: Joseph D. Fournier B.Sc.E.E., M.Sc.E.E.

CANDU Reactor in China

Preamble

The **CANDU** (**Canada Deuterium Uranium**) is a Canadian pressurized heavy-water reactor design used to generate electric power. The acronym refers to its deuterium oxide (heavy water) moderator and its use of (originally, natural) uranium fuel.

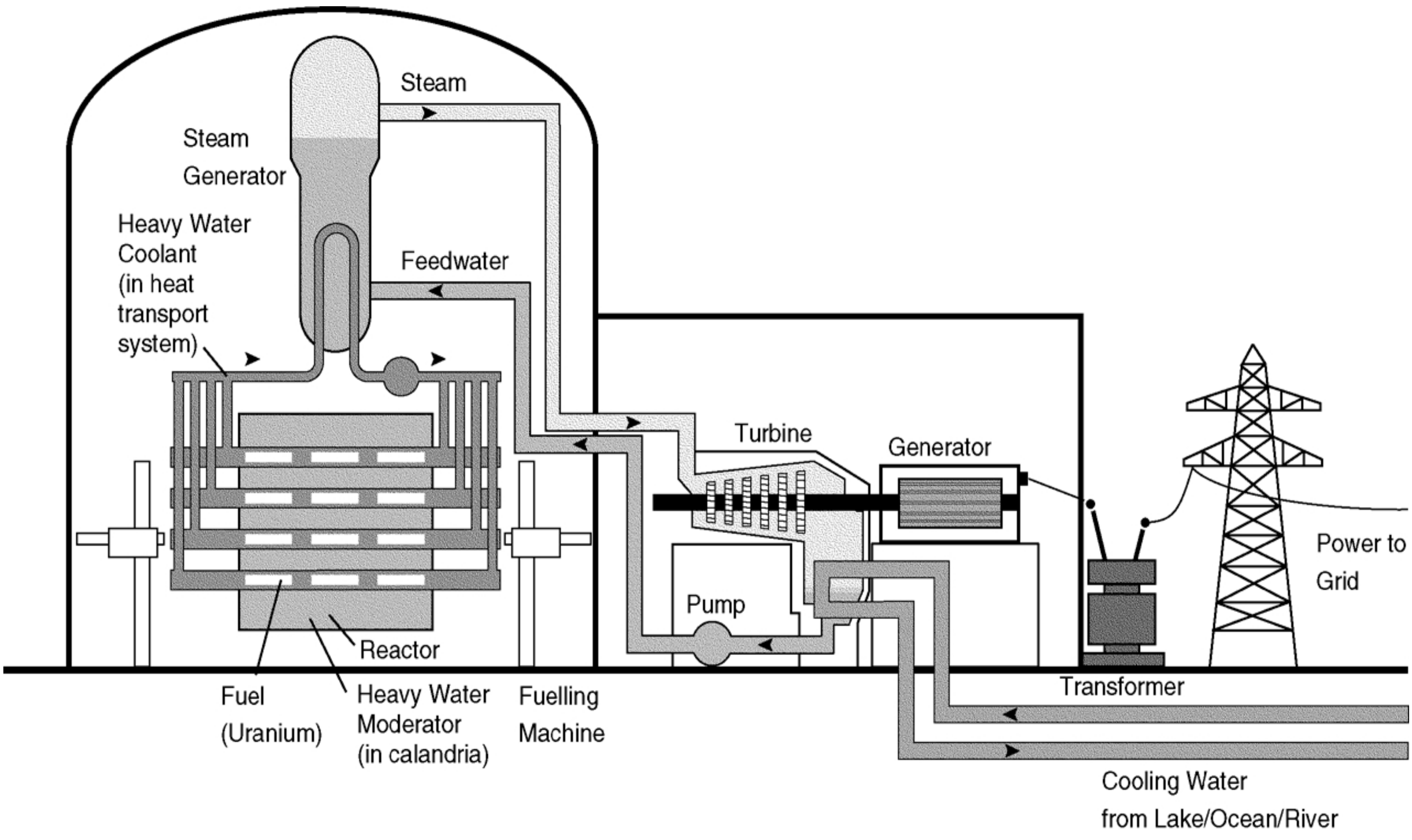
CANDU reactors were first developed in the late 1950s and 1960s by a partnership between Atomic Energy of Canada Limited (AECL), the Hydro-Electric Power Commission of Ontario, Canadian General Electric, and other companies.

Outline

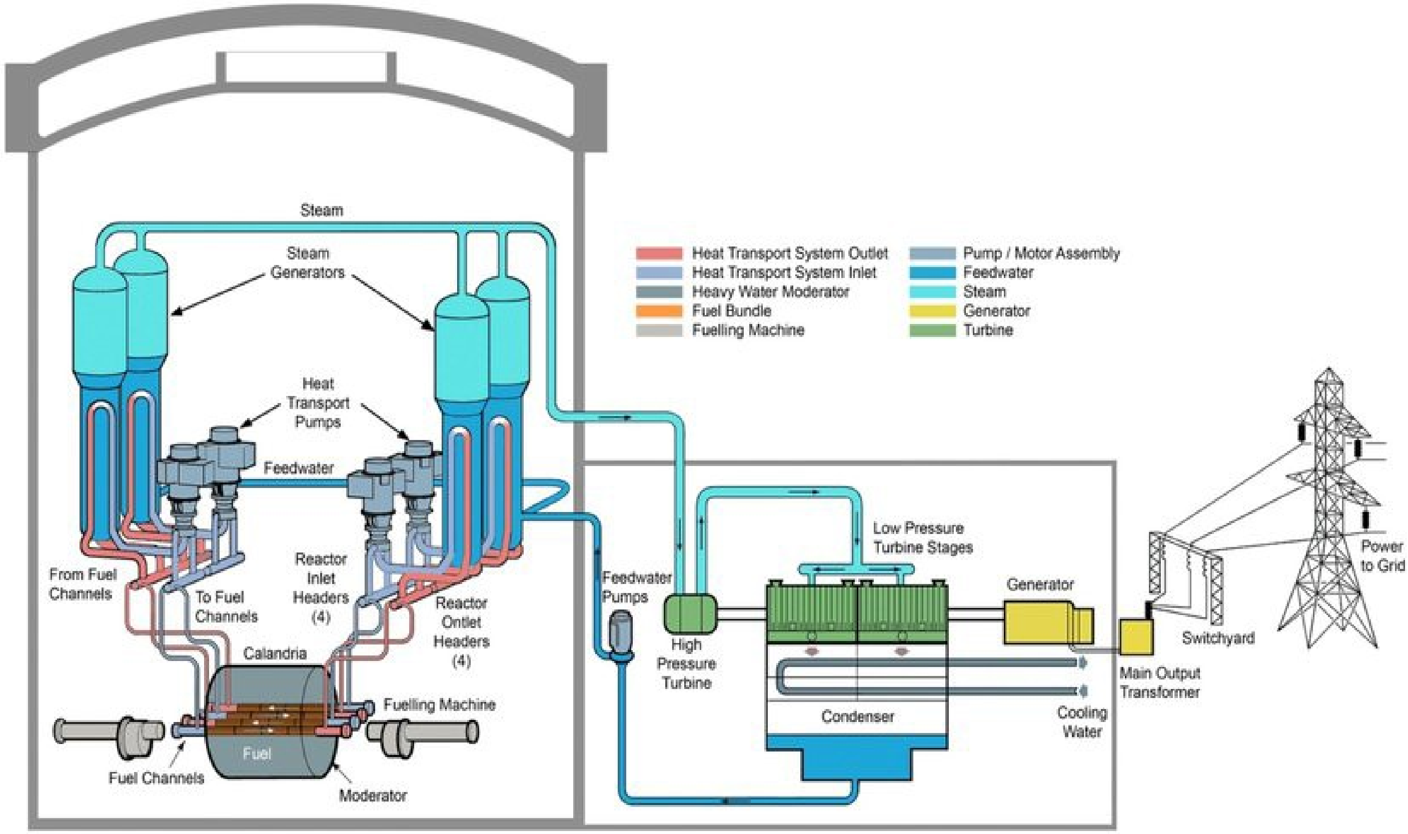
The CANDU and ACR Reactors consist of:

- Reactor Assembly
- Pressure Tubes
- Fuel
- On-Power Refuelling
- Heat-Transport System
- Moderator System
- Reactivity Devices

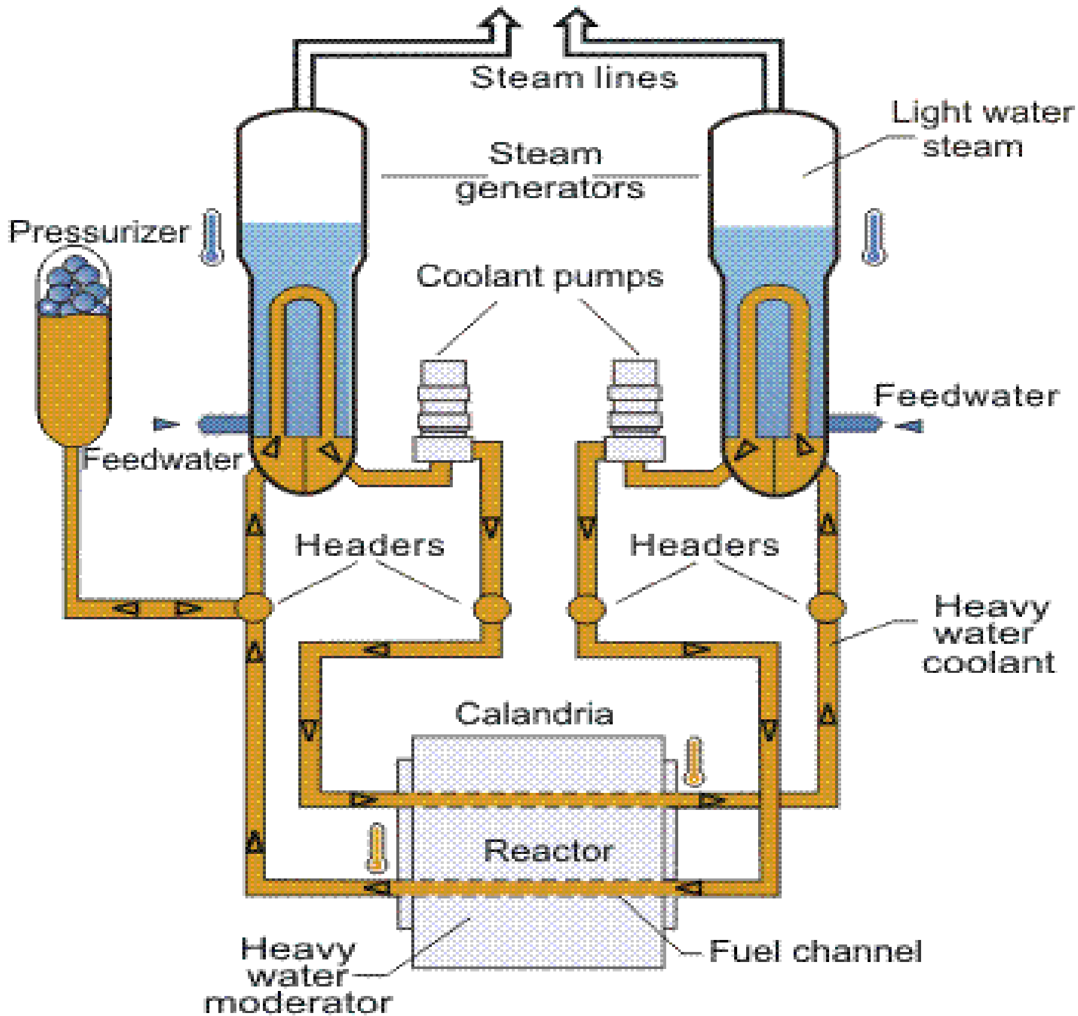
Schematic of a CANDU Nuclear Power Plant



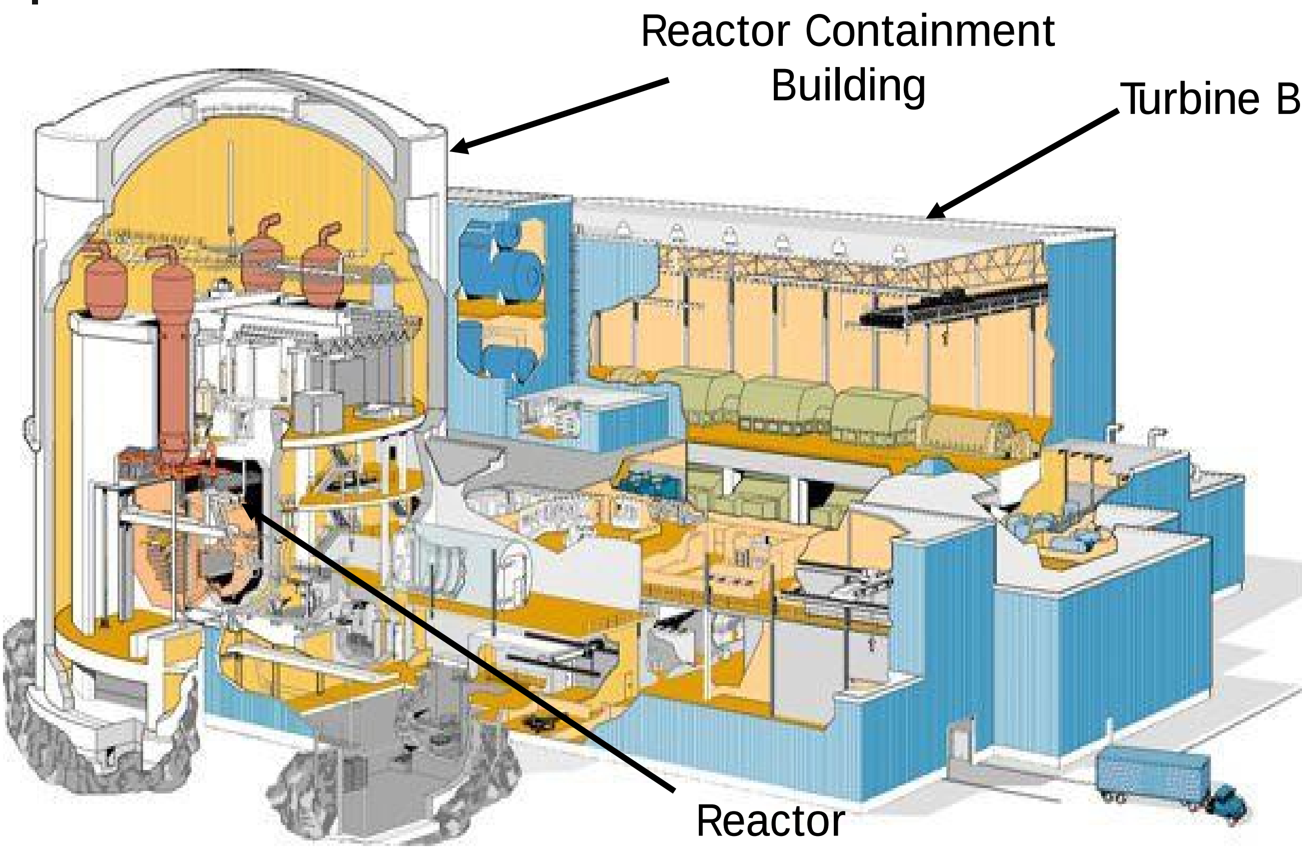
ACR CANDU **Nuclear Power Plant**



Schematic of a CANDU Steam Cycle

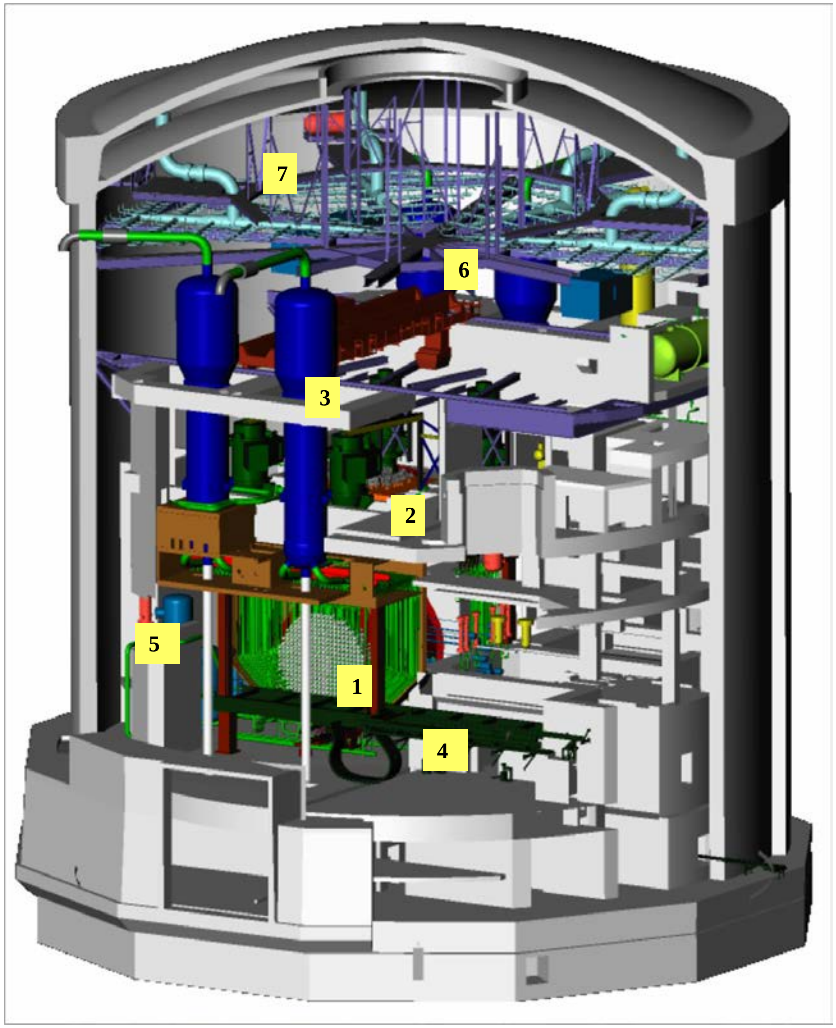


CANDU Plant



CANDU-6 Reactor

1. **Reactor face**
2. **Reactor coolant pump**
3. **Steam generator**
4. **Fuelling machine carriage**
5. **Moderator heat exchanger**
6. **Dousing water system**
7. **Dousing water tank**

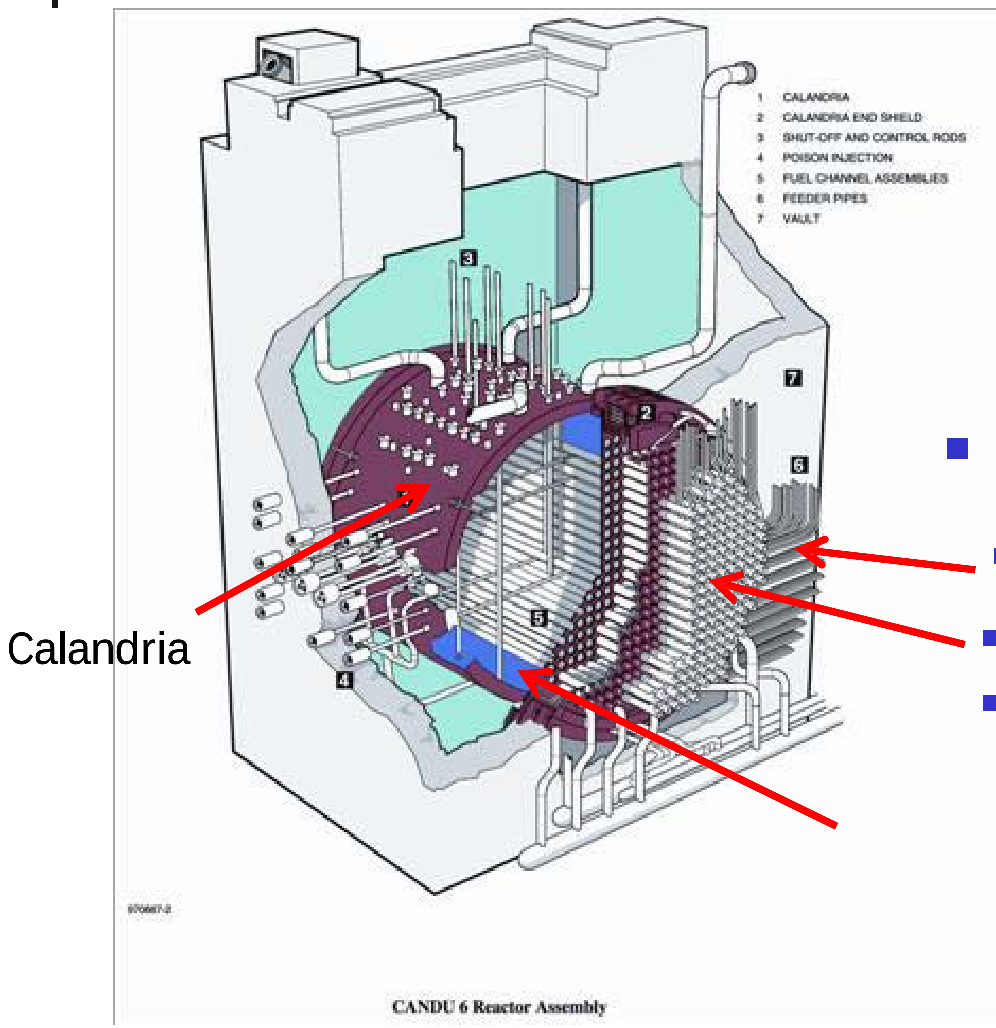


CANDU Core Design

CANDU

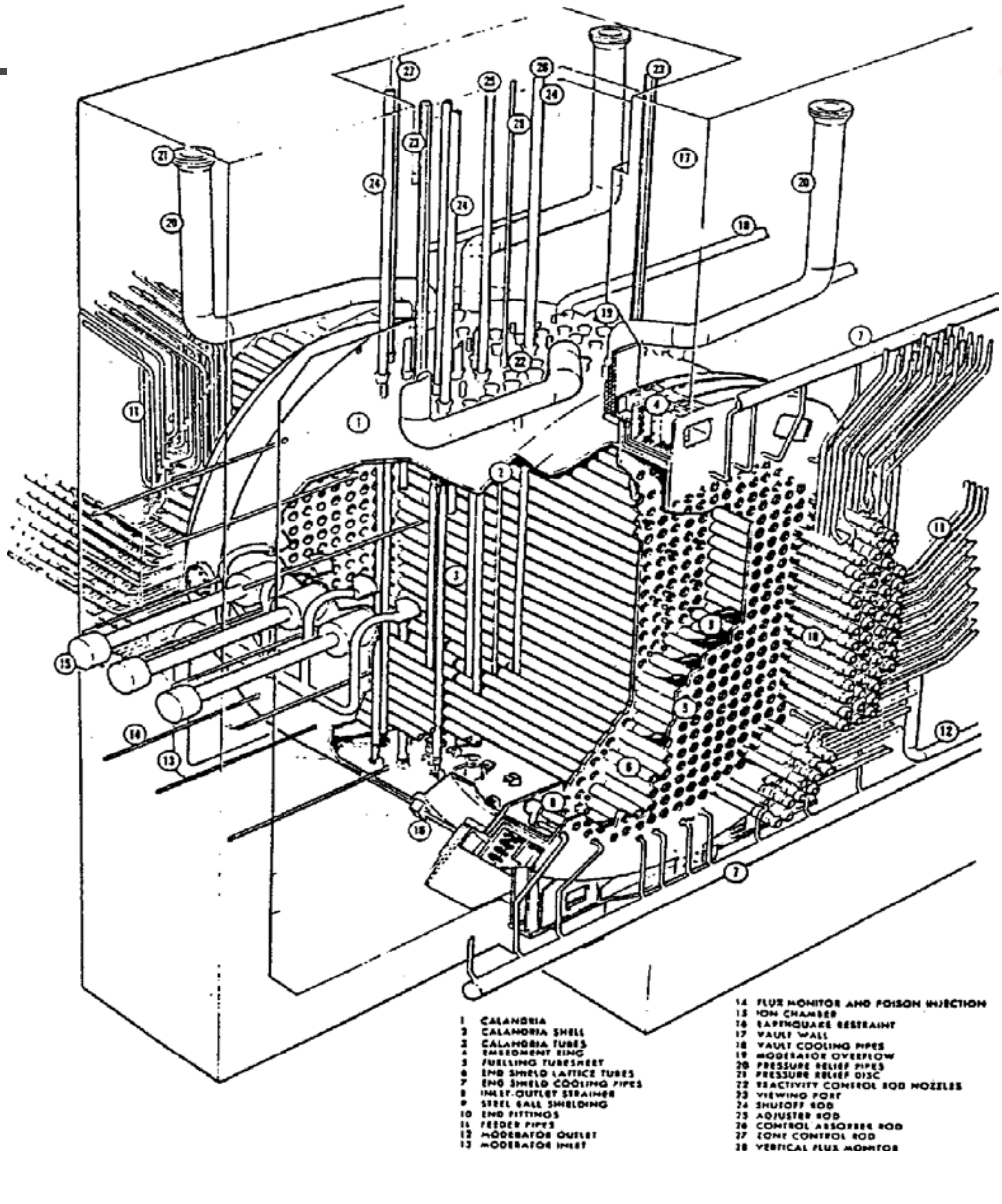
- Natural-uranium fuel
- Heavy-water coolant
- Heavy-water moderator
- Separate coolant and moderator
- Pressure tubes
- Small, simple fuel bundle
- On-power refuelling

CANDU-6 Reactor



- **Vault**
  - Feeders
  - Pressure Tubes
  - (Fuel Channels)

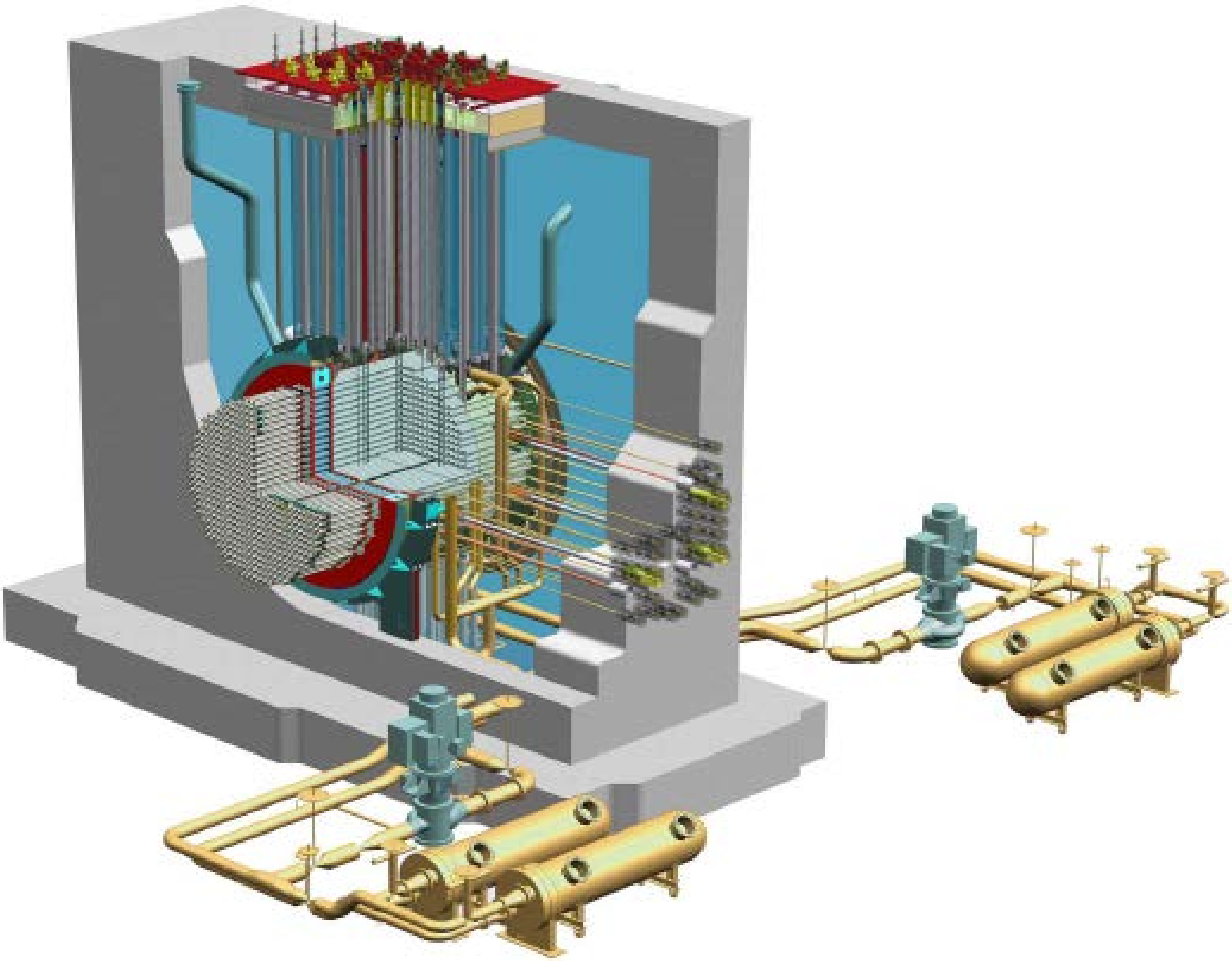
CANDU Core Design



Reactor Assembly

- The reactor assembly contains the reactor core and the reactivity control devices
- Major components of reactor assembly are:
  - Calandria Vessel
  - End-Shields
  - Shield Tank
  - Fuel Channels
  - Reactivity Control Devices

Reactor Assembly



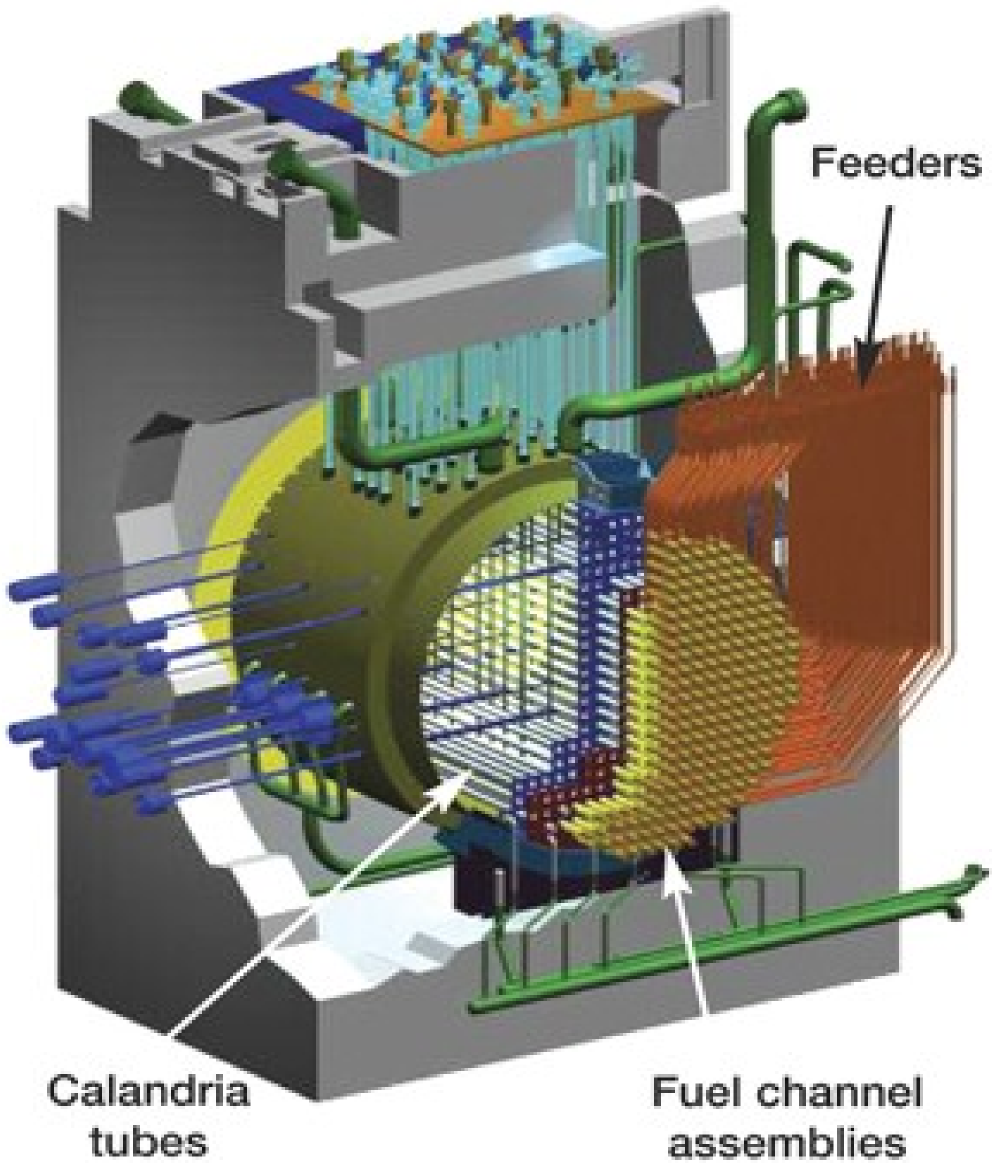
Calandria Vessel

- Low-pressure tank
- Includes calandria tube and supports pressure tubes
- Contains heavy water moderator
- Contains reactivity control devices and shutdown systems
- Embedded in light-water reactor vault (which provides radiation shielding)

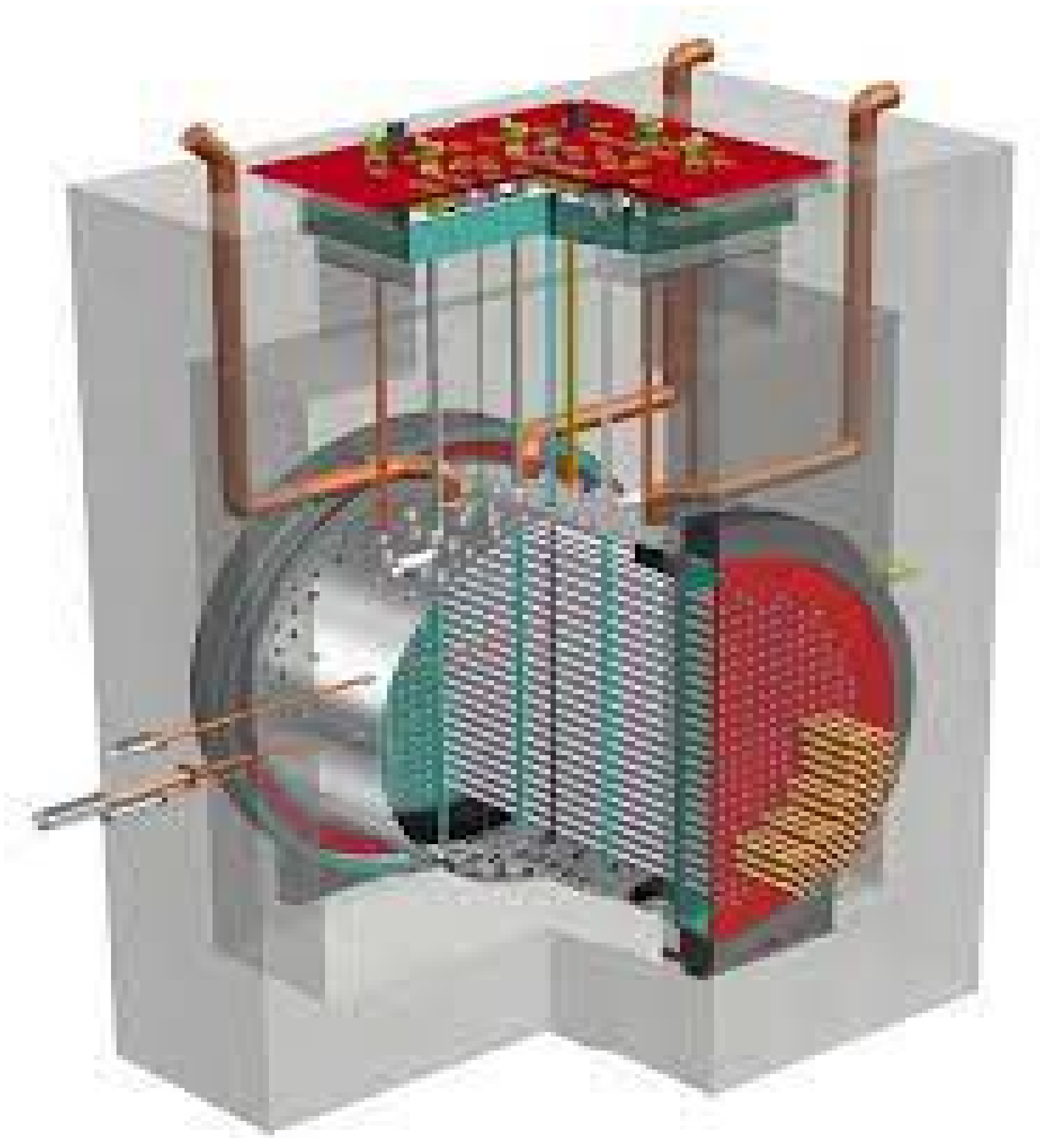
Calandria Assembly

- The horizontal cylindrical calandria is closed and supported at both ends by two end shields
- The end shields contain material for thermal and biological shielding
- The end shields are spanned by the 284 lattice tubes which support and align the fuel channels
- Each end fitting is supported in its lattice tube on two sliding bearings that permit axial movement of the channel due to thermal expansion and elongation due to irradiation
- The fuel channel assembly is positioned axially within the reactor by means of positioning assembly

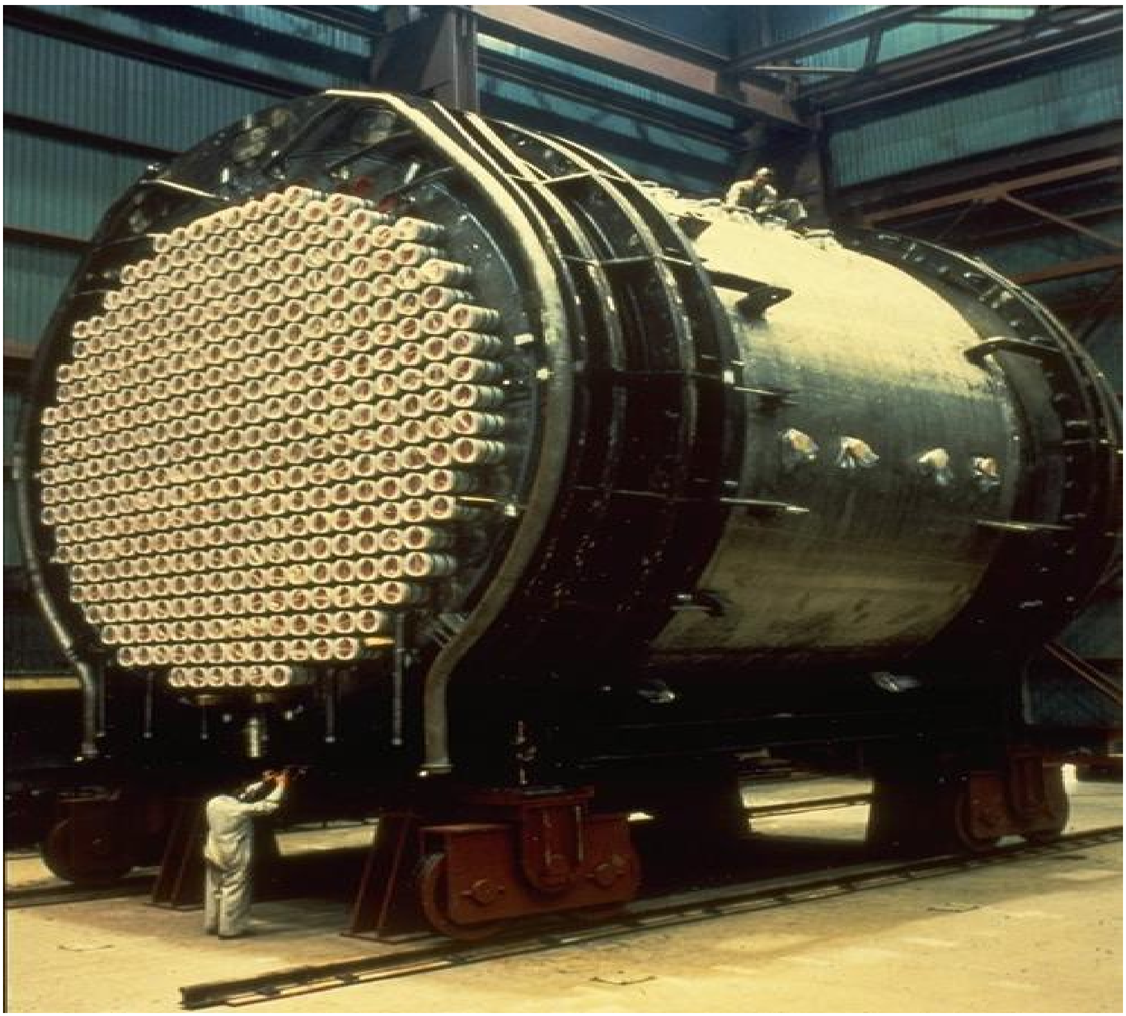
CANDU 6 Calandria



CANDU 6 Calandria



CANDU 6 Calandria with Pressure Tubes Installed



Calandria, Showing Fuel Channels

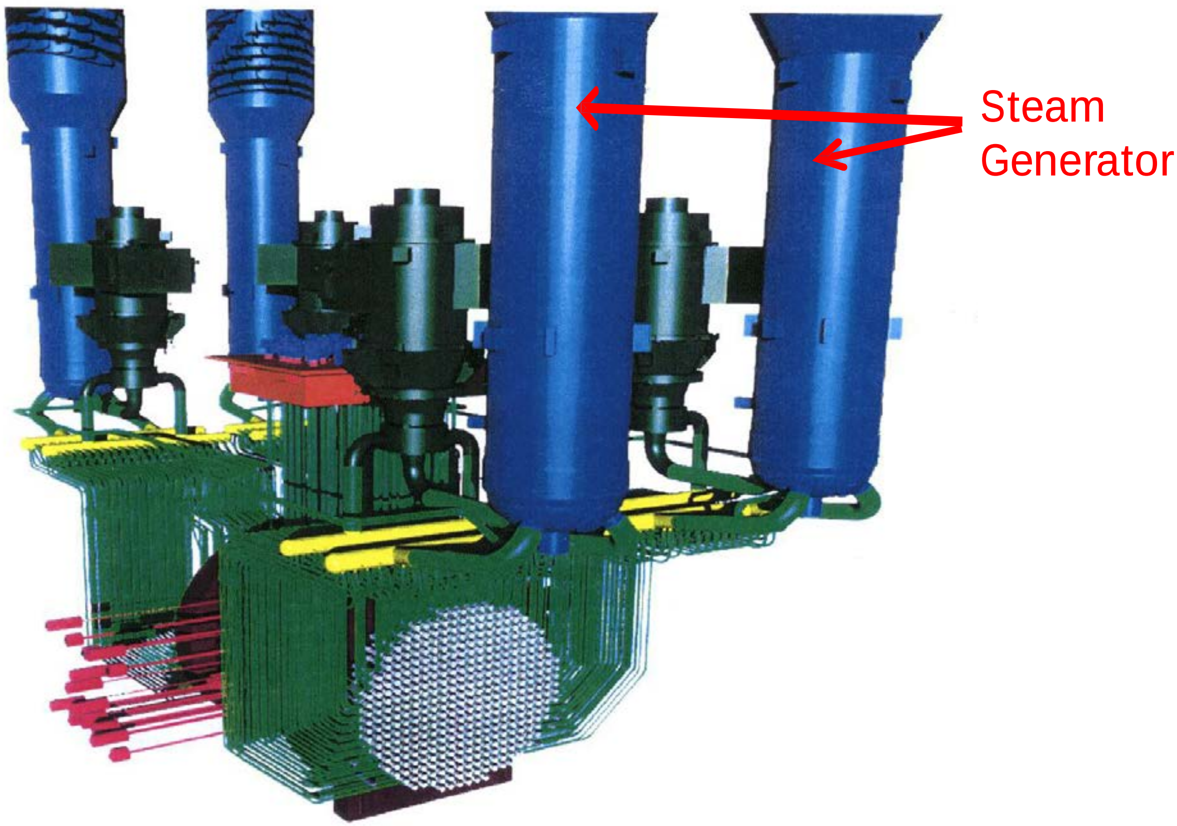
Pressure-Tube Core Design

- Sub-divided reactor coolant system, no large pressure vessel.
  - Cool moderator separated from hot coolant.
- Zr-2.5%Nb pressure tubes constitute CANDU ‘pressure vessel’.
  - Individual pressure tubes are replaceable.
  - Modular component – allows scaling of reactor size.
  - Zirconium alloy provides neutron economy.
- Interstitial reactivity devices (between fuel channels).

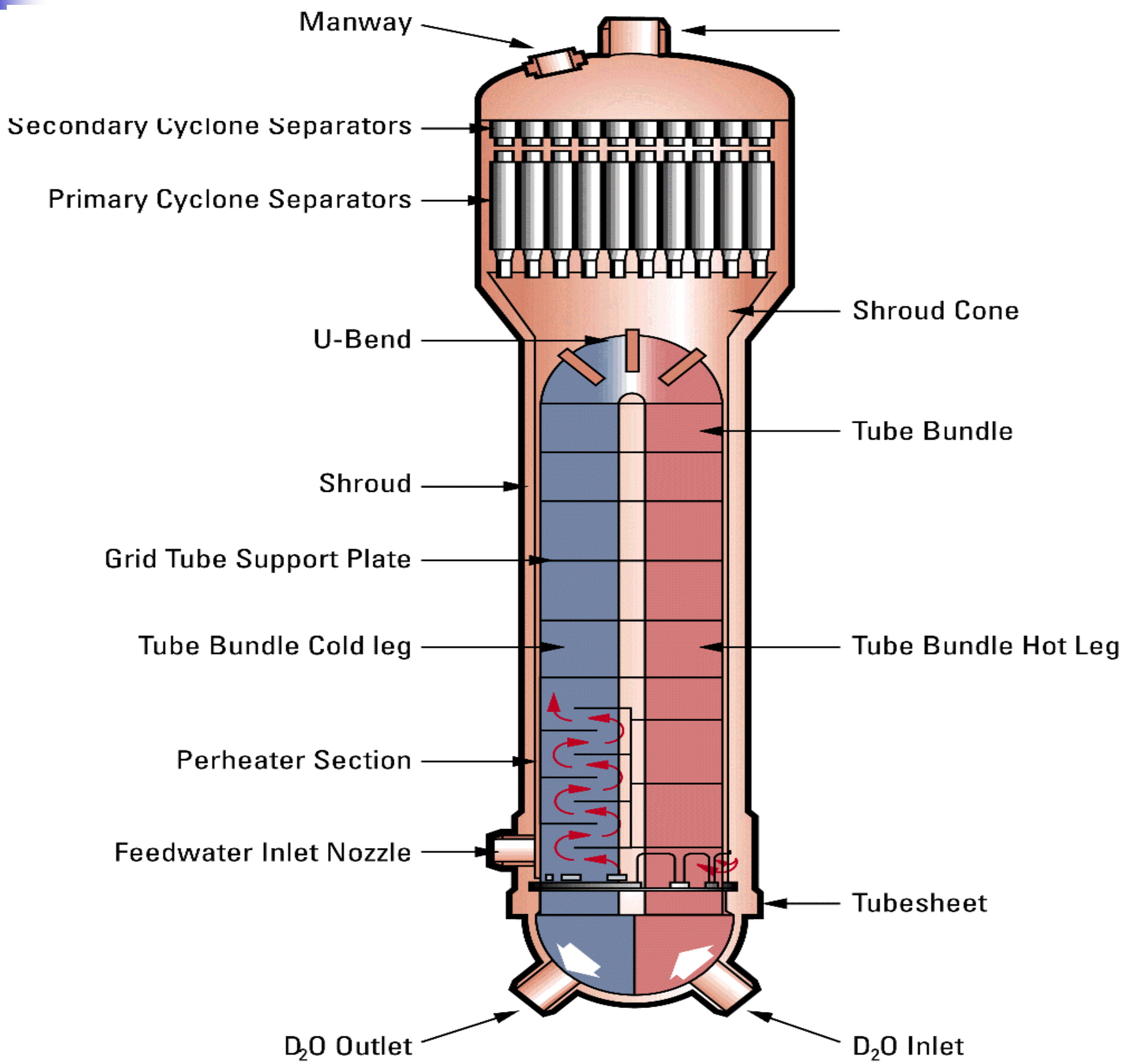
CANDU Reactor Systems

- Reactor Assembly
- Fuel and Fuel Channels
- Heat Transport System
- Moderator System
- Reactivity Devices (Control & Safety Systems)

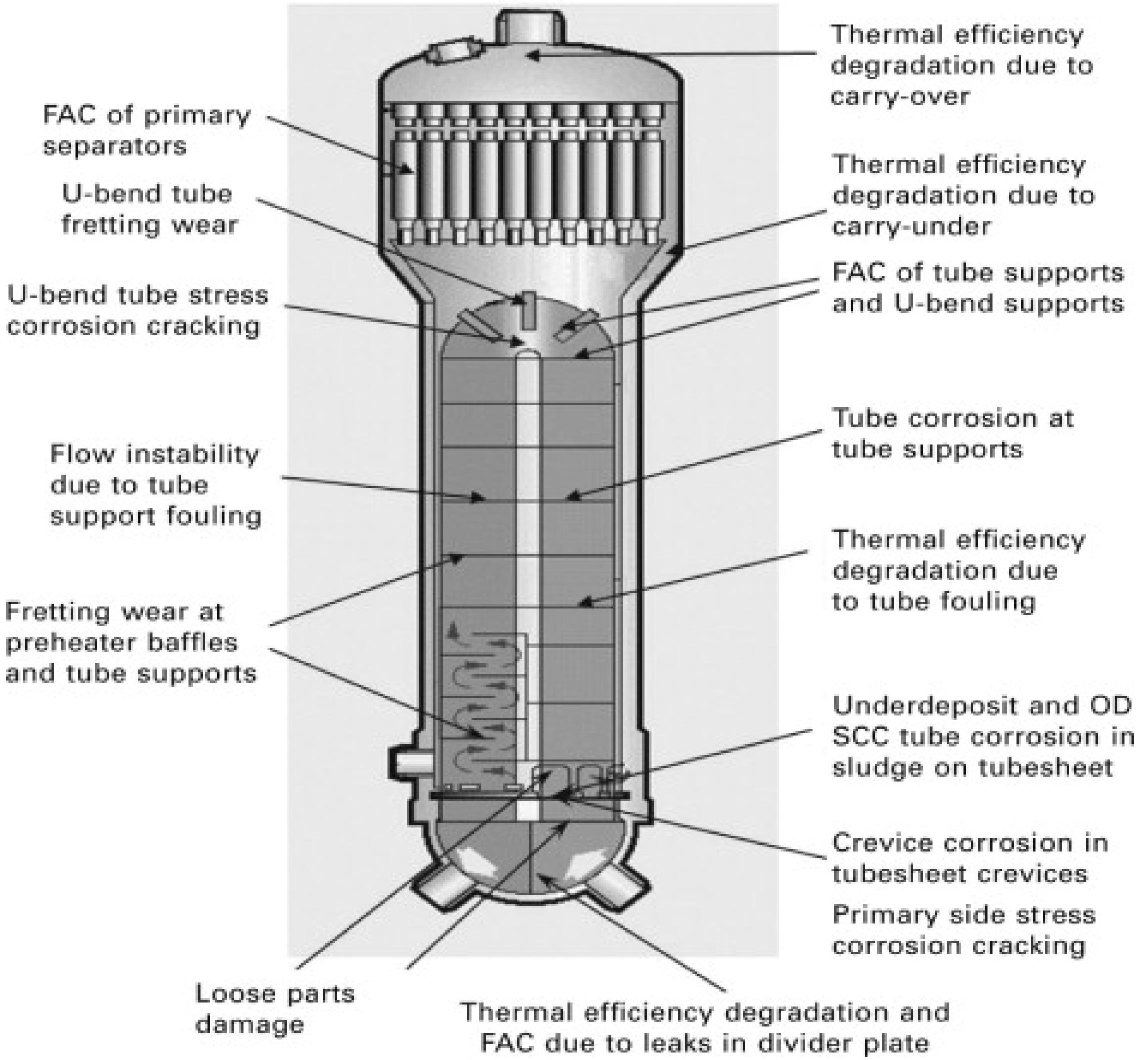
STEAM GENERATOR



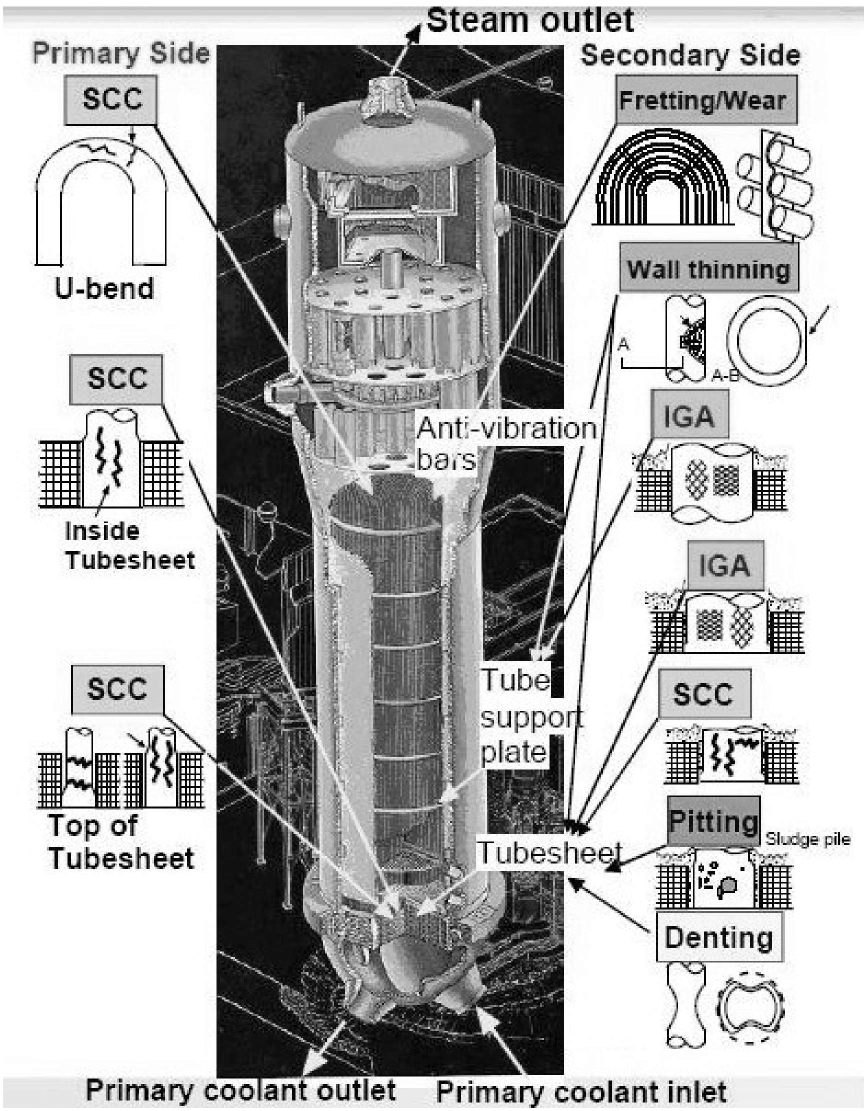
STEAM GENERATOR



STEAM GENERATOR



STEAM GENERATOR

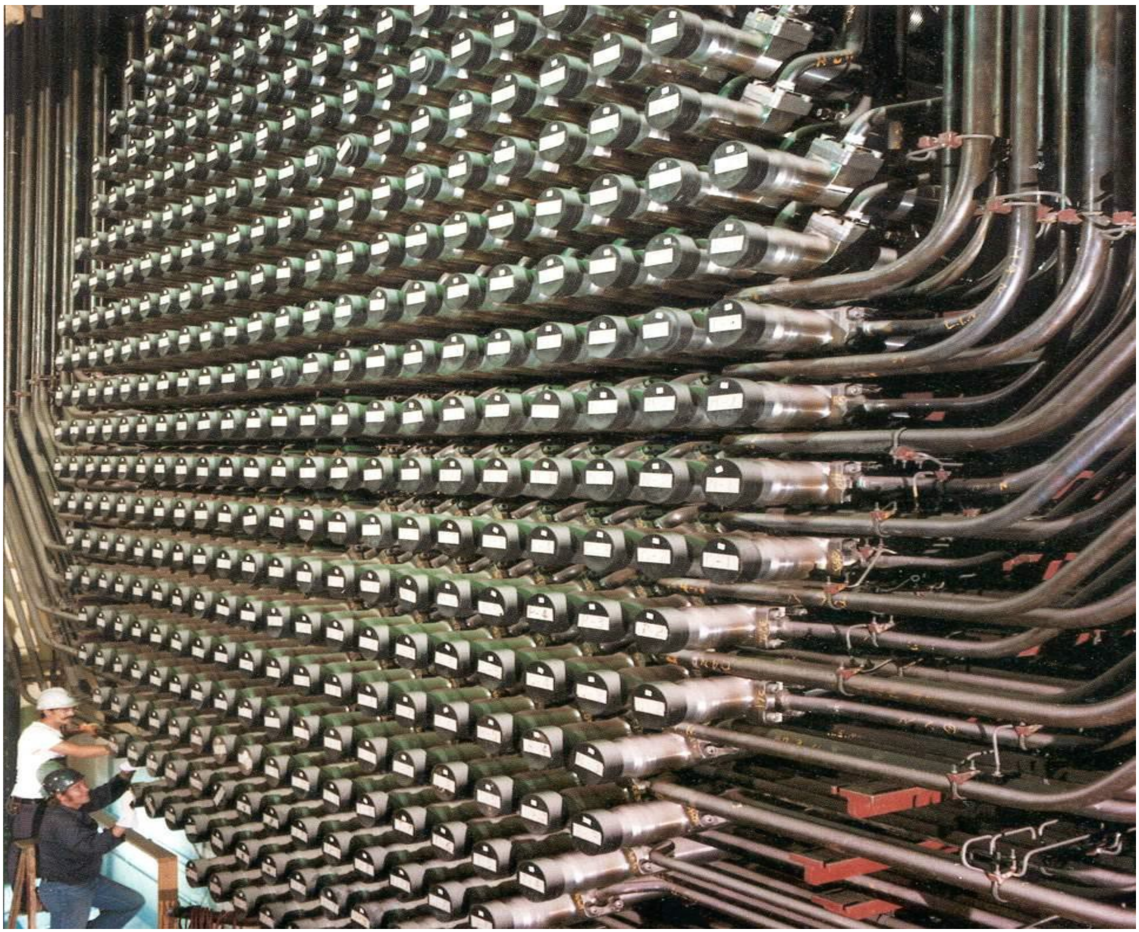


STEAM GENERATOR

Tube Bundles

Reactor Face

End Fittings and Feeders



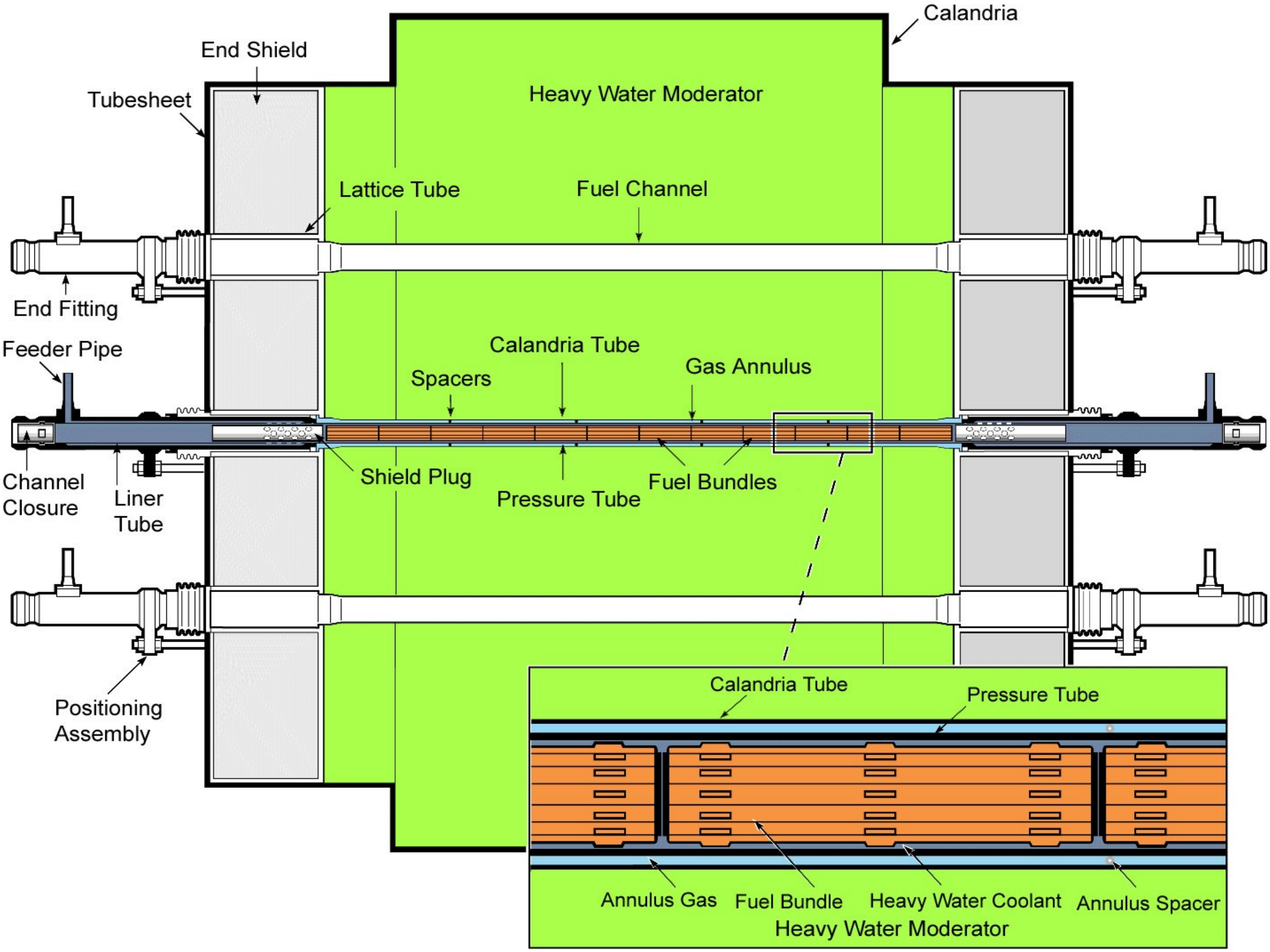
Outline

- CANDU Fuel Channels
- ACR Fuel Channel Design Overview
    - Fuel Channel Major Design Requirements
    - Fuel Channel Components Description
- Interfaces between Fuel Channels and other Systems

CANDU Reactor Core

- In a CANDU reactor, the high pressure coolant and fuel is contained in several hundred small diameter horizontal channels (Fuel Channels)
- The Fuel Channels are insulated from the moderator by the gas in the annulus formed between the pressure tube and the concentric calandria tube
- The calandria tubes are part of the calandria vessel pressure boundary that is the container for the low pressure, low temperature, heavy water moderator.
- Any local failure of the moderator boundary will not result in the failure of the reactor coolant system boundary

Fuel Channel Arrangement (CANDU-6)



Fuel Channel Design Requirements

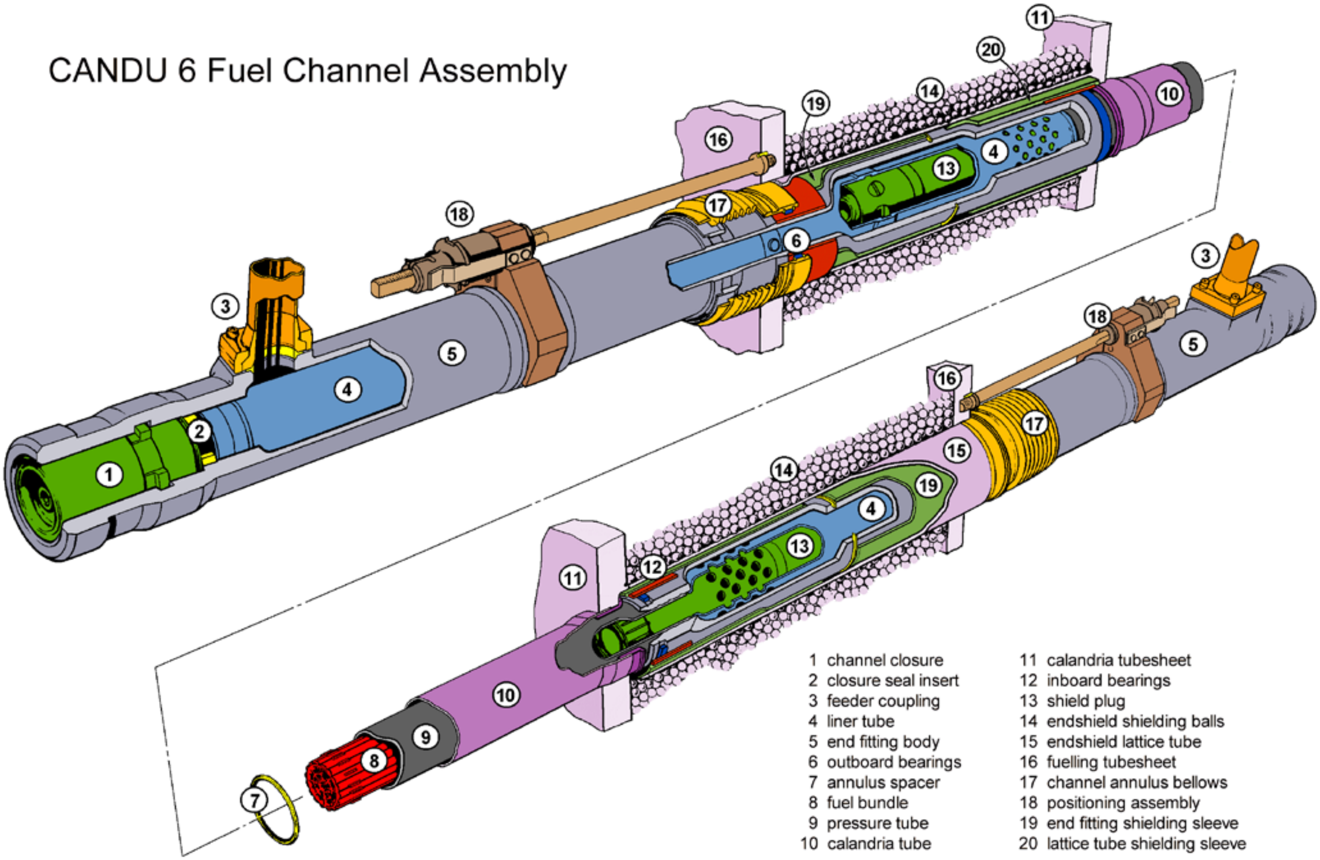
- Supports twelve fuel bundles and positions them axially in the core
- Allows on-power refuelling
- Directs flow of coolant through fuel bundle string
- Accommodates dimensional and material changes during operating life
- Permits pressure tube inspection and fuel channel replacement, if necessary (Single-Channel and Large-Scale Retubing)
- Pressure tube has high fracture toughness
- Failure of a pressure tube does not lead to failure propagation through the core.
- Pressure boundary consists of closure plugs (2), end fittings (2), and pressure tube

Fuel Channel Components

- Components
  - Pressure tube
  - End fittings with liner tube
    - Joint between pressure tube and end fitting
  - Shield Plug
  - Spacers in annulus between pressure tube and calandria tube
  - Calandria tube (not part of the fuel channel pressure boundary)

- Components that interface with other systems
  - Feeder connections
  - Restraint
  - Bellows and connection to annulus gas system
  - Closure Plug

Fuel Channel Components



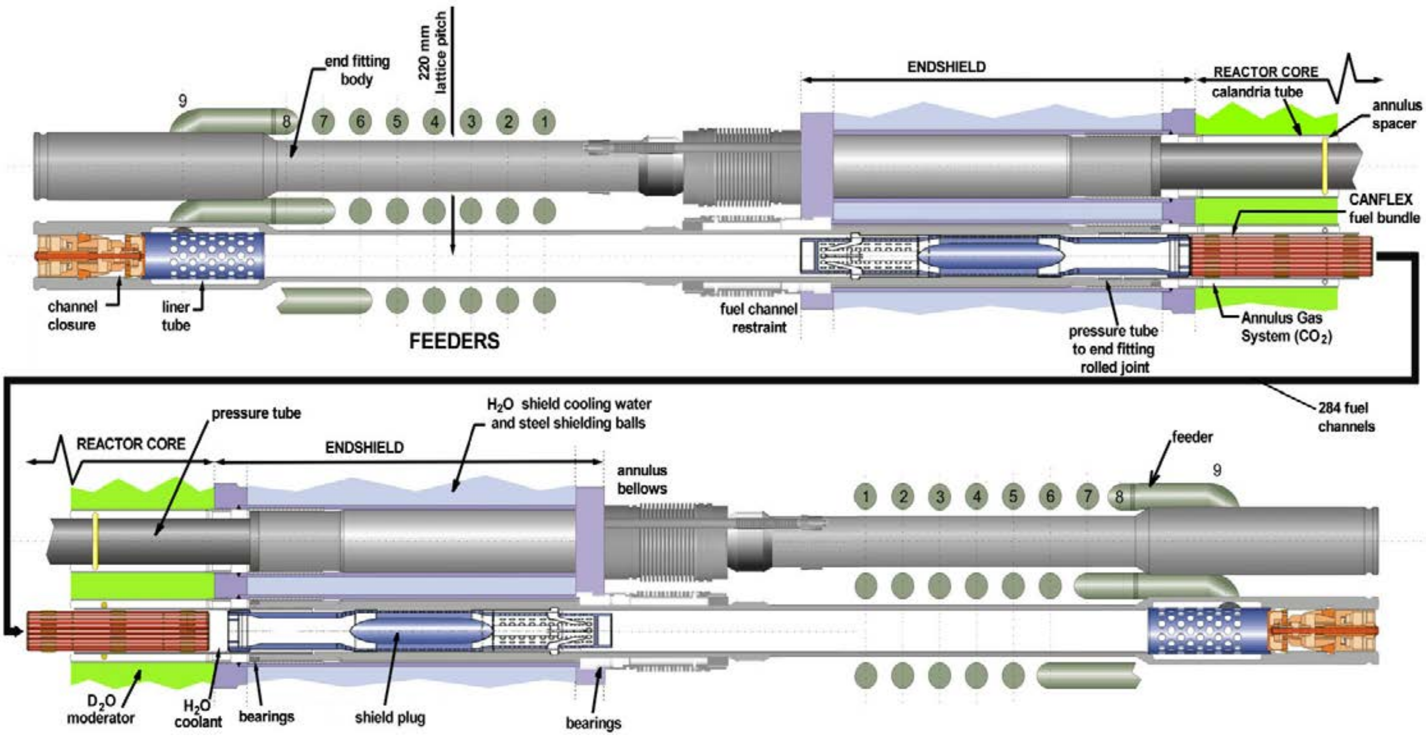
ACR Fuel Channel

- The ACR FC design is evolutionary, making use of features and materials successfully proven on other CANDU reactors, modified as necessary to suit ACR requirements.
- Compared to existing CANDU 6, ACR design has
  - slightly increased operating temperature, increased pressure
  - different fast neutron flux distribution
  - smaller lattice pitch
  - longer operating life

Fuel Channel Design

	CANDU 6	ACR-700
No. of Fuel Channels	380	284
Overall FC Length	10804 mm (425.35")	11616 mm (457.32")
Lattice pitch	286 mm (11.25")	220 mm (8.66")
PT material	Zirconium 2.5wt% Niobium alloy	Zirconium 2.5wt% Niobium alloy
PT wall thickness	4.2 mm (0.165")	6.5 mm (0.256")
PT max. operating temperature	311 ^{o}C (592 F)	325 ^{o}C (617 F)
PT max. operating pressure	11 MPa (1595 psi)	13 MPa (1886 psi)
PT max. operating flux (for E>1MeV) (n/m2/s)	3.7×10^{17}	4.1×10^{17} (for 7.5MW channel power)
Calandria tube material	Zircaloy-2	Zircaloy-4
Calandria tube wall thickness	1.4 mm (0.054")	2.5 mm (0.098")
PT/CT Gap	8 mm (0.31")	16.5 mm (0.65")
Fuel channel operating life	30 years at 80% capacity	30 years at 90% capacity

ACR Fuel Channel



Pressure Tube (PT)

- Designed in accordance with the Class 1C requirements of CSA Standards N285.0 and CAN/CSA-N285.2, with reference to Section III Subsection NB of the ASME Boiler and Pressure Vessel Code
- PT stresses are evaluated for both beginning of life and end of operating life conditions to account for pressure tube dimensional changes that occur over the PT life
- ACR stresses are reduced relative to CANDU-6 design

ACR Pressure Tube (PT)

- **The ACR PT is an extruded and drawn (cold worked) tube made of a zirconium 2.5wt% niobium alloy, per CSA Standard N285.6.1, the same material as all recent CANDU reactors**
- **Design stress values are covered by CSA Standard CAN/CSA- N285.6.7, Table 7.1, not an ASME Class 1 material**
- **The amount of cold work is about 27%, same as for other CANDU reactors**
- **The material chemistry is optimized to achieve the best in-reactor performance (fracture toughness, resistance to Delayed Hydride Cracking, deformation, H ingress)**
- **Prototype pressure tubes have been manufactured**
- **Testing of the prototype is underway**
- **The end of tube that exits the extrusion press first is to be installed at the outlet end of the fuel channel, to limit diametral strain due to creep and growth (same as the latest CANDU design)**

Assessments of Pressure Tube Aging

- **Assessments of PT deformation, H ingress, fracture and DHC are based on existing models and data**
  - **Extrapolated to 30 years and ACR conditions**
  - **Assume highest power channel, largest material variability**
  - **Conservative estimates of benefits of improvements to PT (compared with historical data on which models are based)**
- **Effects of deformation and H ingress will be acceptable over 30 years at 90% capacity**
- **Fracture behavior will also be acceptable**
- **Testing will be performed to confirm assessment results**

End Fitting (EF)

- EFs are attached to the pressure tube ends as an out-of core extension of the PT and contain shielding and coolant flow features
- The EF provides connection to feeder pipes at both ends (part of the Reactor Coolant System)
- The EFs are sealed by removable channel closure plugs which provide access for the fueling machines
- Each EF contains a shield plug which locates the fuel bundles
- The liner tube inside each end fitting diffuses flow at feeder entrance/exit

End Fitting (EF)

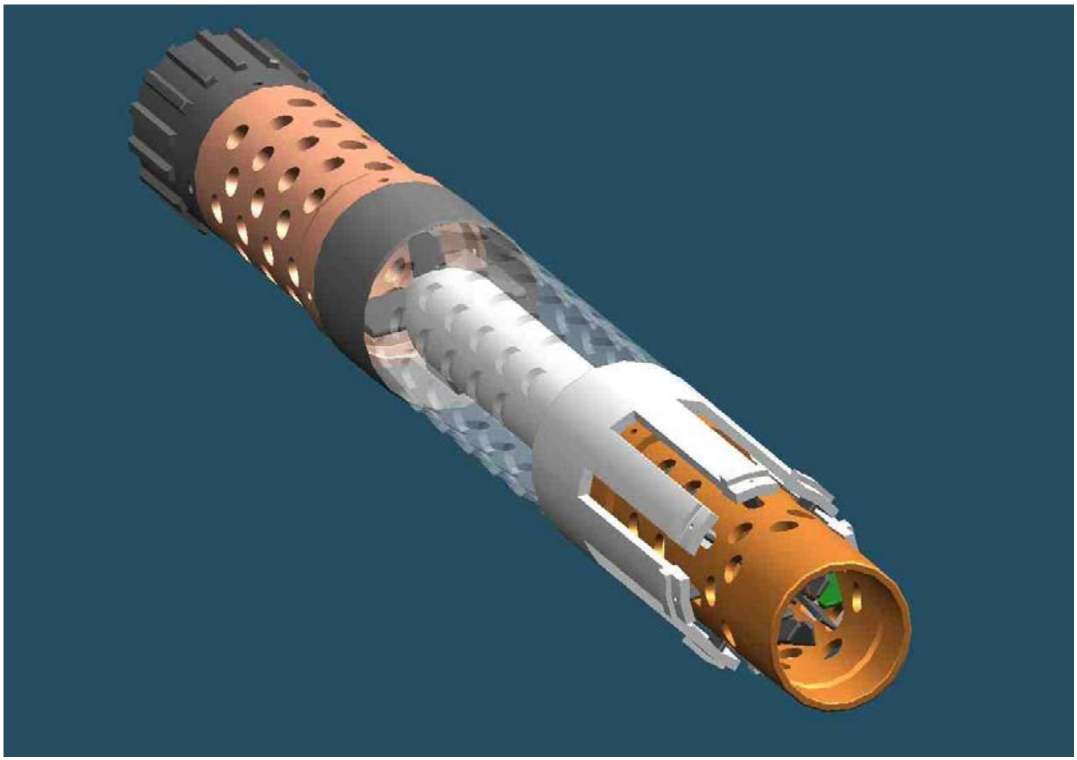
- EF material is a combination of high strength (required for the pressure tube rolled joint area to assure a strong, leak- tight connection) and good corrosion resistance (to prevent deterioration of the various seal faces)
- Material – modified Type 403 stainless steel to the requirements of CSA Standard N285.6.8, not an ASME Class 1 material
- The EFs are forged in one piece, heat treated and then machined to the finished size
- The EF is designed in accordance with the Class 1 requirements of CSA Standards N285.0, with reference to Section III, Subsection NB of the ASME Boiler and Pressure Vessel Code

ACR Liner Tube

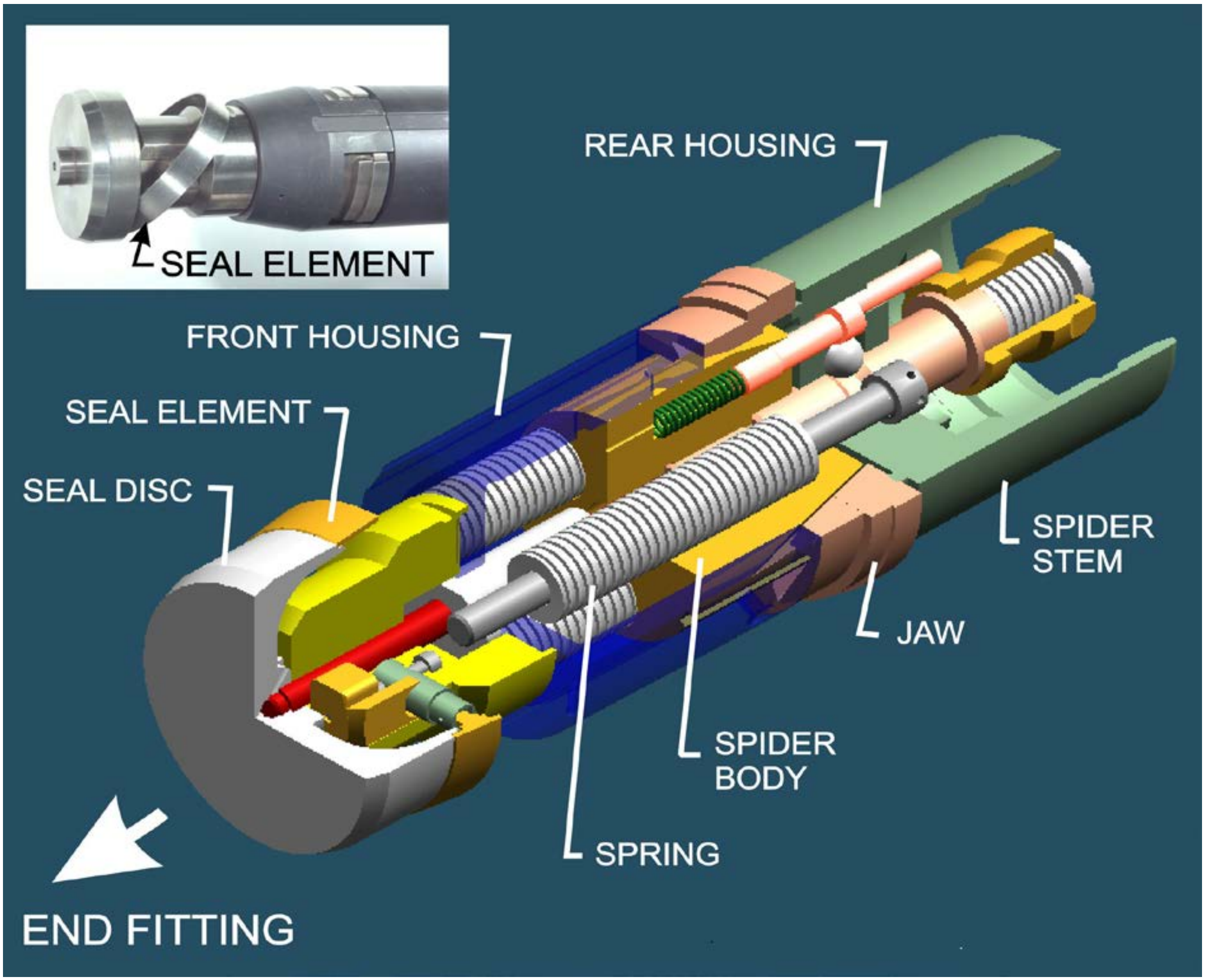
- 410 stainless steel (same as recent CANDU designs)
- Design objectives for liner tube:
  - perforations provide adequate flow area so that the coolant pressure drop across the liner tube is minimised
  - accommodates passage of ACR shield plug and fuel bundles during refueling

Shield Plug

- The ACR shield plug is based on a flow through design
- The shield plug is attached in the bore of the end fitting to locate the fuel bundles and to provide shielding



ACR Channel Closure



ACR Channel Closure

- Removable pressure boundary component to permit fuel changing designed in accordance with the Class 1C requirements of CSA Standards N285.0, with additional requirements provided in CAN/CSA-N285.2, with reference to Section III, Subsection NB of the ASME Boiler and Pressure Vessel Code
- The basis of the channel closure design is a flexible metallic ring that makes a face seal against an edge in the end fitting
- The design relies on reactor coolant pressure to assist in the sealing operation
- A safety lock is incorporated into the latching mechanism to prevent inadvertent removal of the channel closure

Pressure Tube Rolled Joint

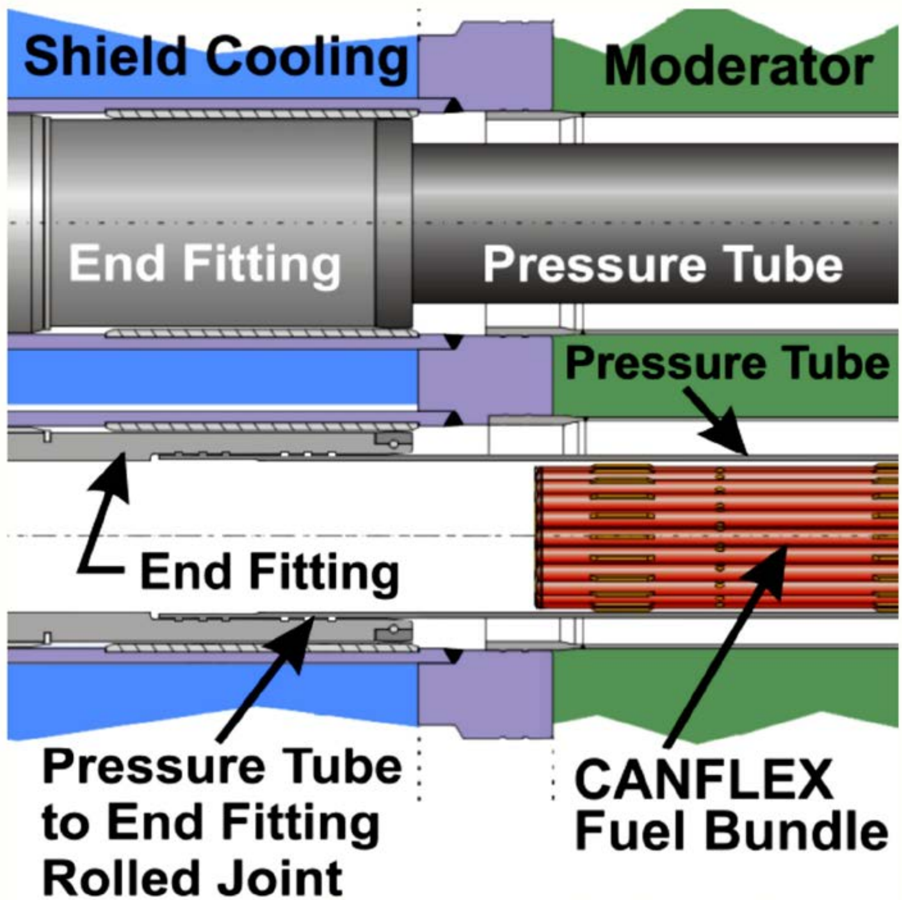
- Each end of the PT is roll expanded into an end fitting
- When the rolled joint is being made the PT undergoes a wall reduction and the material extrudes both radially into grooves in the EF (producing local ridges on the outside of the PT) and axially as well
- The material extruded into the grooves is responsible for the axial strength of the joint
- The parameters monitored during testing are:
  - helium leak rate
  - residual stress distribution in the PT and EF material
  - pull- out strength
  - stress relaxation effects
- Excellent performance of over 20,000 rolled joints in service provide confidence that the rolled joints in the ACR-700 reactor will perform well

Pressure Tube Rolled Joint

- The rules, which the rolled joint must meet, are covered in CSA Standard CAN/CSA- N285.2
- Finite element stress analysis is used to confirm that the stresses in the rolled joint region meet the allowable limits specified by Section III Subsection NB of the ASME Boiler and Pressure Vessel Code

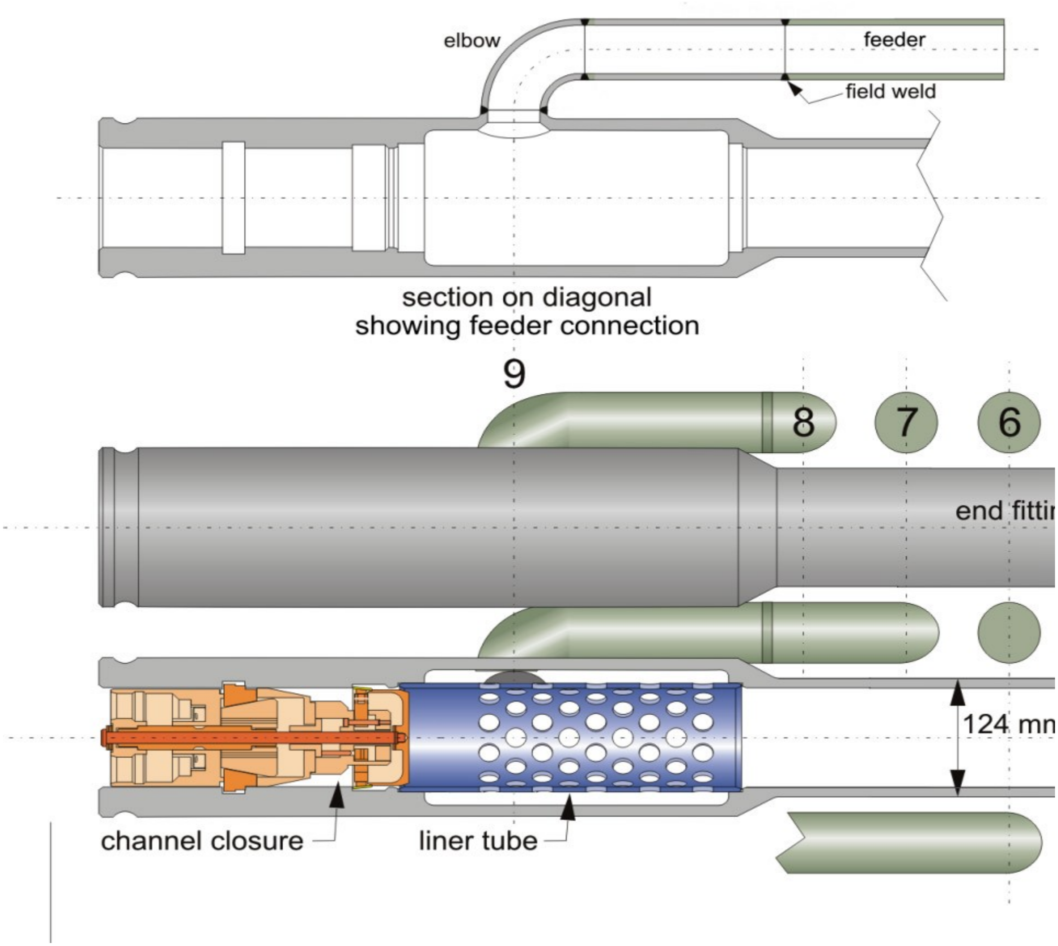
ACR Pressure Tube Rolled Joint

- Groove number, spacing, and geometry same as CANDU 6
- Zero-clearance rolled joint is used to limit the tensile residual stresses resulted from rolling process (same as CANDU 6)
- EFs at both ends of FC have double sets of rolling grooves to facilitate retention of EFs during retubing

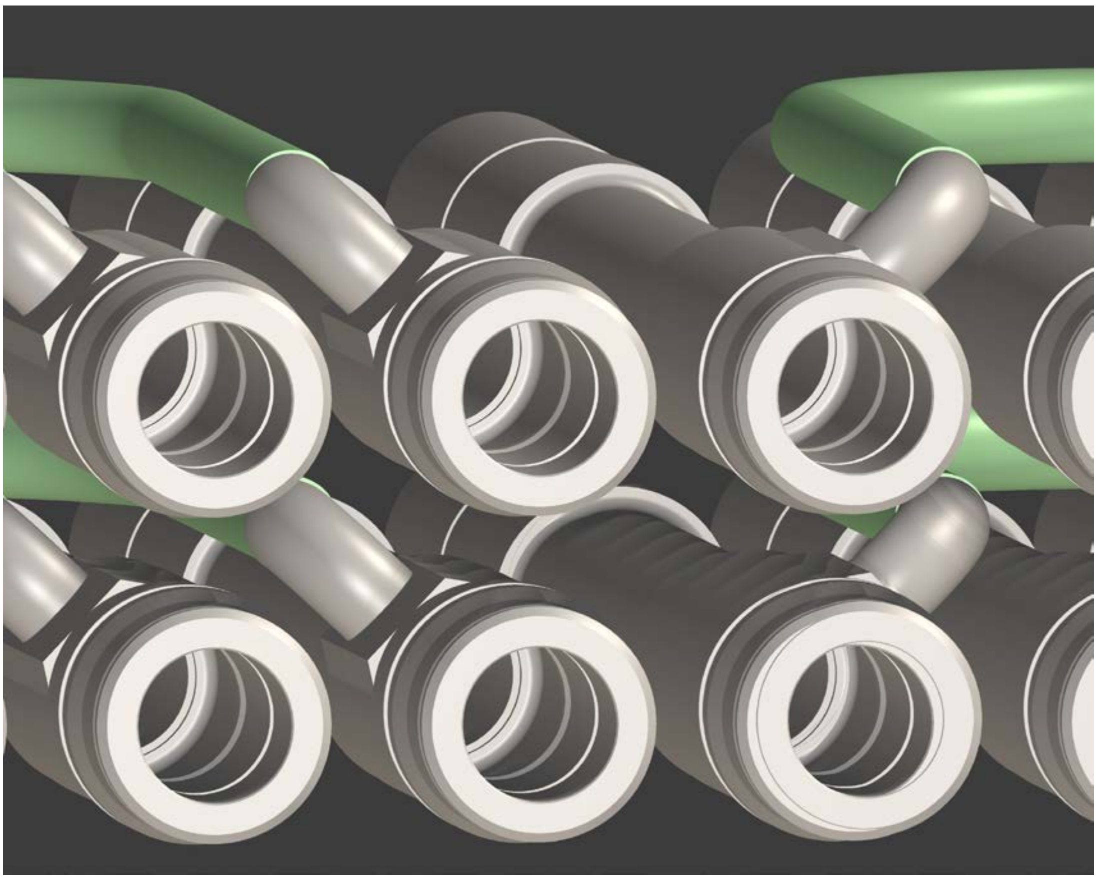


ACR Feeder Connection

Inconel alloy 625 feeder elbow factory-welded to the extruded feeder port



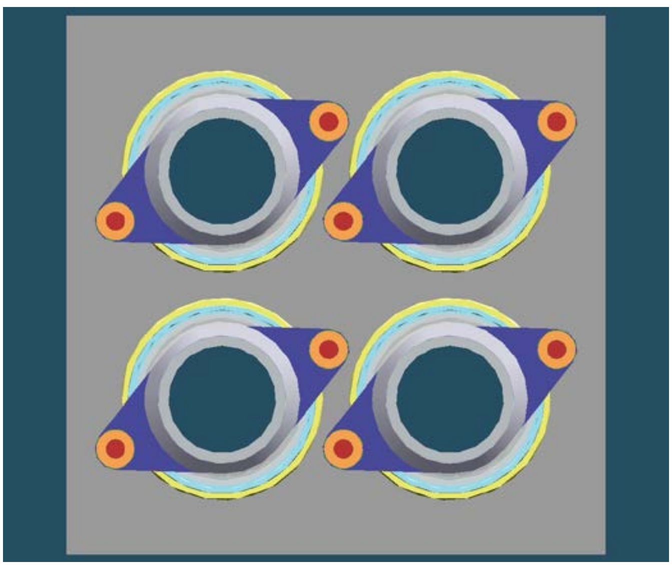
ACR Feeder Arrangement

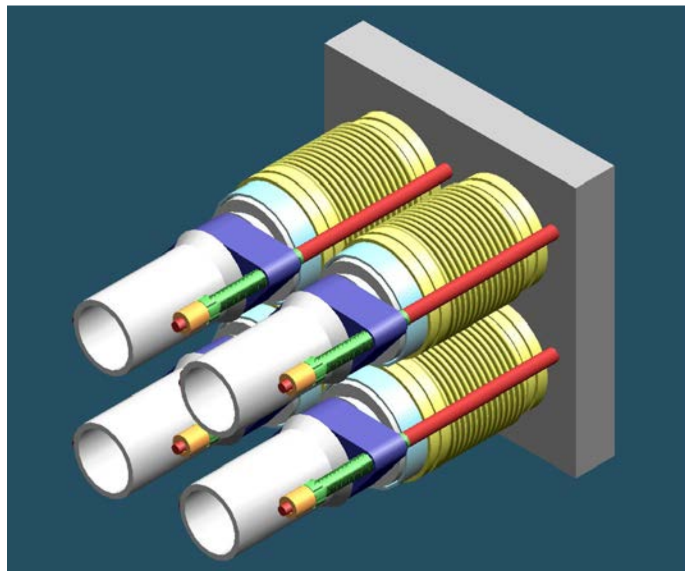


Fuel Channel Restraint

- Double-stud and yoke design positioning assembly design
- Quick lock/unlock mechanism at ~15 yrs so that fuel channel elongation is shared between both sides of the reactor
- Double stud design will provide sufficient strength for DBE loads while keeping components small enough to ensure installability, efficient locking/unlocking, and replaceability
- Note CANDU 6 used a single stud design

ACR Fuel Channel Restraint





Annulus Bellows

- Each end of the annulus between a calandria tube and a pressure tube is sealed by an Inconel bellows
- The bellows allows axial motion of the channels and also supports the torque of the end fitting from the feeder piping
- The ACR bellows is similar in design to the CANDU 6 bellows and is similarly installed
- The material (Inconel 600) is the same as CANDU 6
- A small diameter tube welded to the bellows connects the sealed annulus that surrounds each fuel channel to the annulus gas system

Annulus Spacer

- Four annulus spacers keep each pressure tube separated from the calandria tube, preventing direct contact between the tubes during all operating conditions
- They allow calandria tube to provide support for the pressure tube
- They are positioned about a meter apart so that pressure tube sag will not result in contact with the calandria tube surrounding it
- ACR design uses a tight-fitting garter spring, similar to the recent CANDU 6 designs, only bigger diameter due to the bigger annulus
- It features a welded coil (for structural integrity) around a girdle wire
- The material is the same as recent CANDU designs — Inconel X-750 for the coil and Zircaloy-4 for the girdle wire

Calandria Tube

- The ACR calandria tube is made of Zircaloy-4
- The outside diameter of the calandria tube is 156 mm
- The wall thickness is 2.5 mm (0.098”) in the body of the tube and 4.5 mm (0.177”) at the ends to facilitate a rolled joint at the calandria tubesheet
- Note ACR calandria tube has larger diameter and it is thicker and stronger than CANDU 6 version
- The calandria tube is part of the calandria vessel pressure boundary, therefore it is designed in accordance with the Class 2C requirements of CSA Standards N285.0 and CAN/CSA-N285.2, with reference to Section III Subsection NC of the ASME Boiler and Pressure Vessel Code

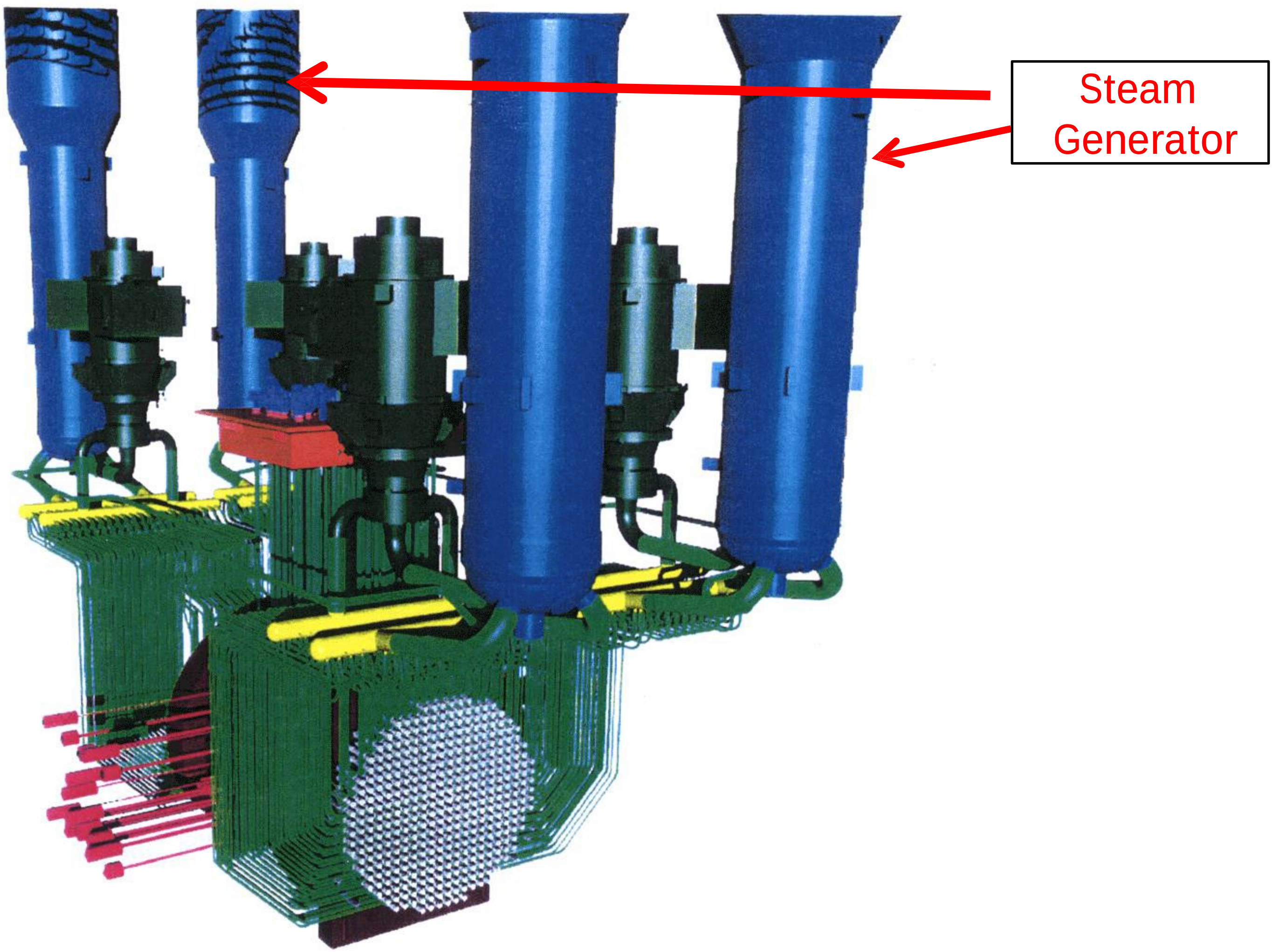
Fuel Channel Components Design

FC Component	Code and Standard
Reactor Coolant Pressure Boundary Components	
Pressure Tube and PT to EF Rolled Joint	- Class 1C requirements of CSA Standards N285.0 and CAN/CSA-N285.2, with reference to Section III Subsection NB of the ASME Code
End Fitting	- Class 1 requirements of CSA Standards N285.0, with reference to Section III Subsection NB of the ASME Code
Closure Plug	- Class 1C requirements of CSA Standards N285.0, with additional requirements provided in CAN/CSA-N285.2, with reference to Section III, Subsection NB of the ASME Code
Non-Pressure Boundary Components	
Liner tube, Bearings, Spacers, and Shield Plug	Good engineering practice with adequate development, analysis and testing
Restraint	Section III, Subsection NF of the ASME Code
Bellows	Class 6 requirements of CSA Standard N285.0, with reference to Section VIII of the ASME Code
Calandria Tube (Calandria Vessel Pressure Boundary)	Class 2C requirements of CSA Standards N285.0 and CAN/CSA-N285.2, with reference to Section III Subsection NC of the ASME Code

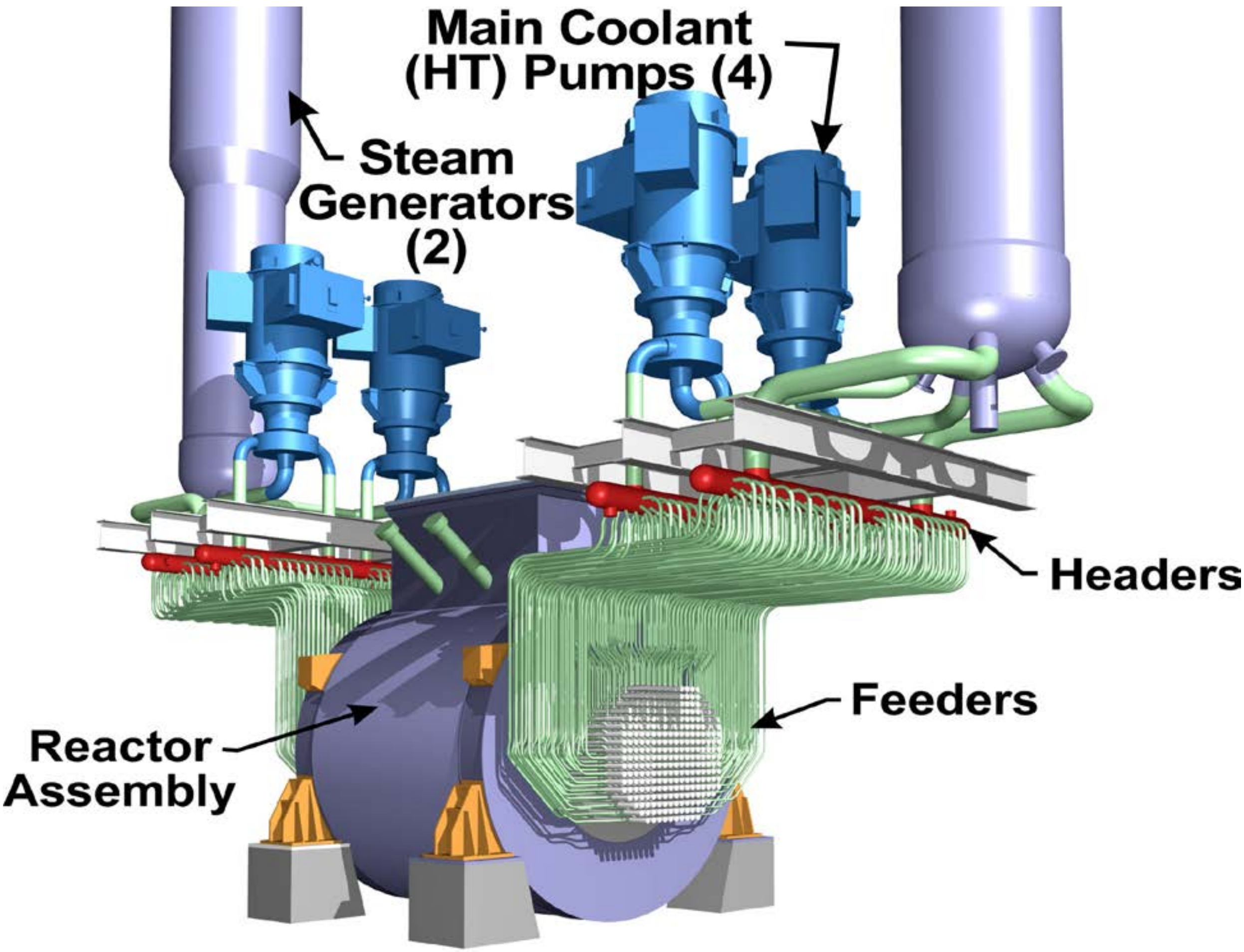
Interfacing Systems

- The following systems/structures interface with the Fuel Channel Assembly
  - **Reactor Coolant System**
  - **Fuel**
  - **Fueling Machine**
  - **Annulus Gas System**
  - **Calandria Assembly**

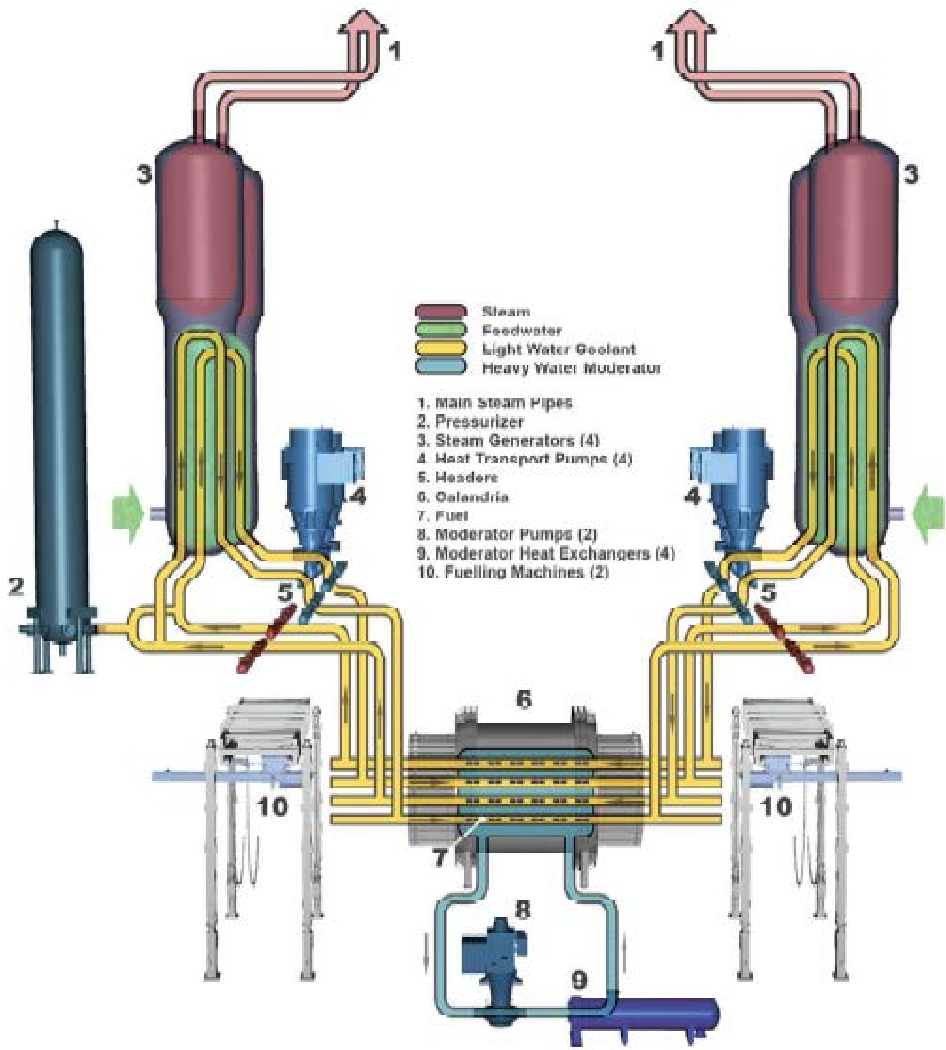
CANDU 6 Heat Transport System



ACR Reactor Coolant System Layout



ACR Reactor Coolant System Layout



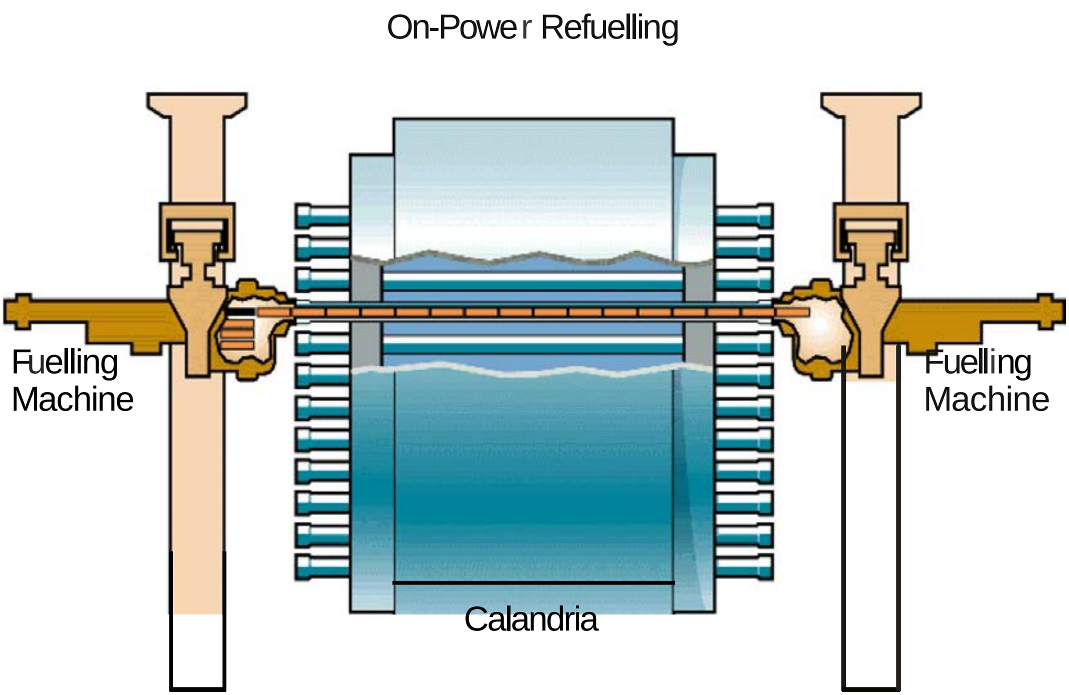
On-Power Refuelling

- Refuelling for long-term maintenance of reactivity: required because reactivity eventually decreases as fuel is irradiated (fission products accumulate and total fissile content decreases).
- In CANDU 6, average refuelling rate ~ 2 channels per Full-Power Day (FPD), using the 8-bundle-shift refuelling scheme (8 new bundles pushed in channel, 8 irradiated bundles pushed out).
- 4-bundle-shift and 10-bundle-shift refuelling schemes have also been used in other CANDUs.
- Selection of channels is the job of the station physicist.

Fueling Machine

- Performs on-power fuel changing
- Extension of Reactor Coolant System pressure boundary during fuel changing
- Designed in accordance with Section III, Subsection NB of the ASME Boiler and Pressure Vessel Code, with additional requirements provided in CAN/CSA-N285.2
- There is a safety lock that prevents fueling machine detachment from the end fitting during fueling

Fuelling machines at both ends of the reactor remove spent fuel, insert new fuel



CANDU 6 Fueling Machine

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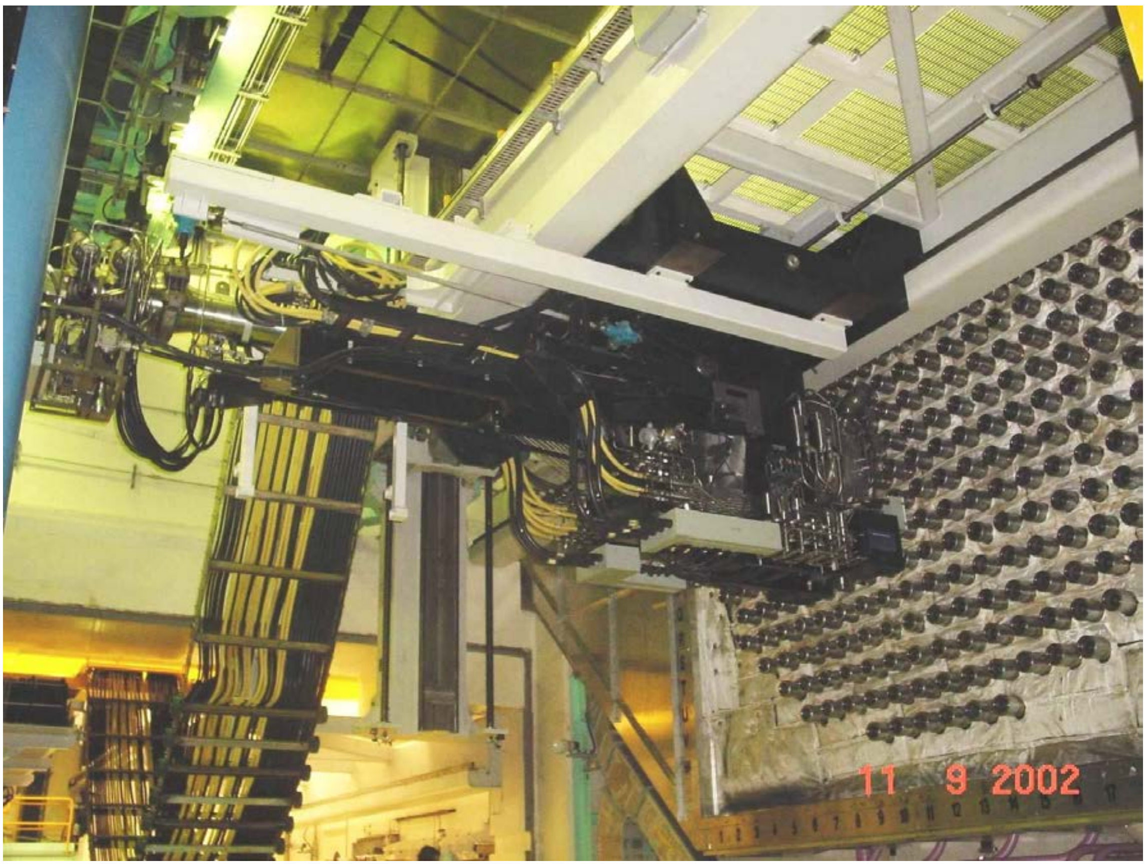


CANDU Fuel

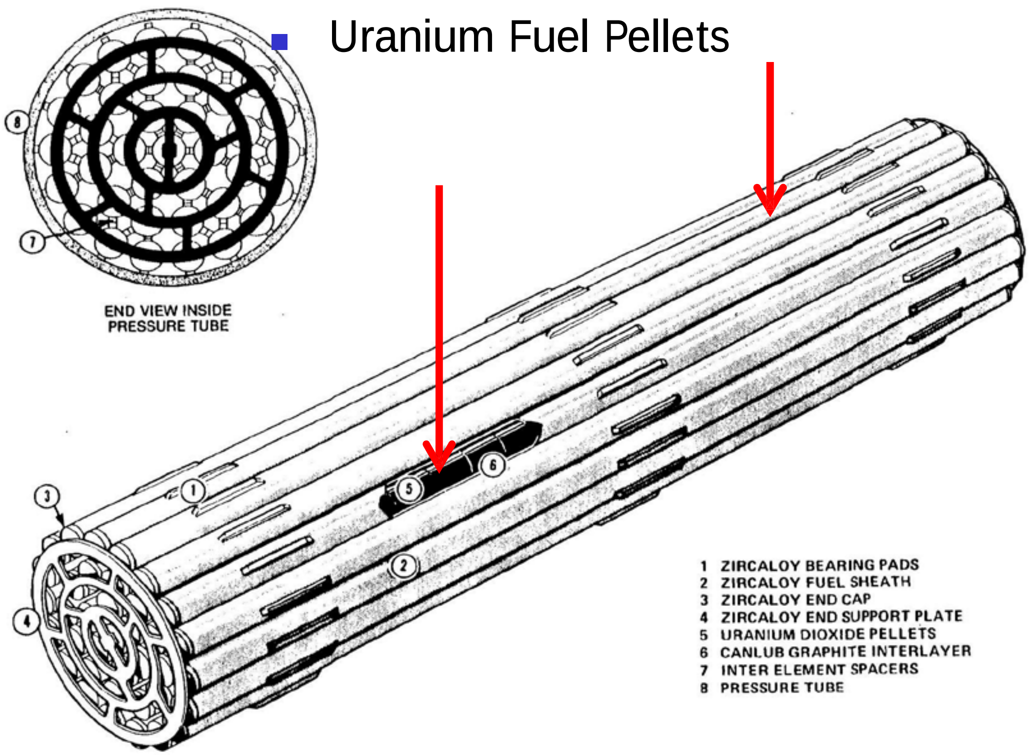
- Natural uranium (~0.7% ^{235}U).
- High-density uranium oxide (UO_2) fuel pellets in Zircaloy-4 cladding.
- Short (0.5 m) fuel elements arranged in cylindrical fuel bundles.

Fuel

- There are 12 fuel bundles in each pressure tube
- In ACR the fuel bundle used is 43-element CANFLEX
- Each fuel bundle is supported on bearing pads which maintain proper clearance between the bundle and the pressure tube
- ACR uses two bundle shift and an average of about 20 channel visits per week (ACR-700)

CANDU-Element Fuel Bundle

- Zircaloy Fuel Sheath
- Uranium Fuel Pellets

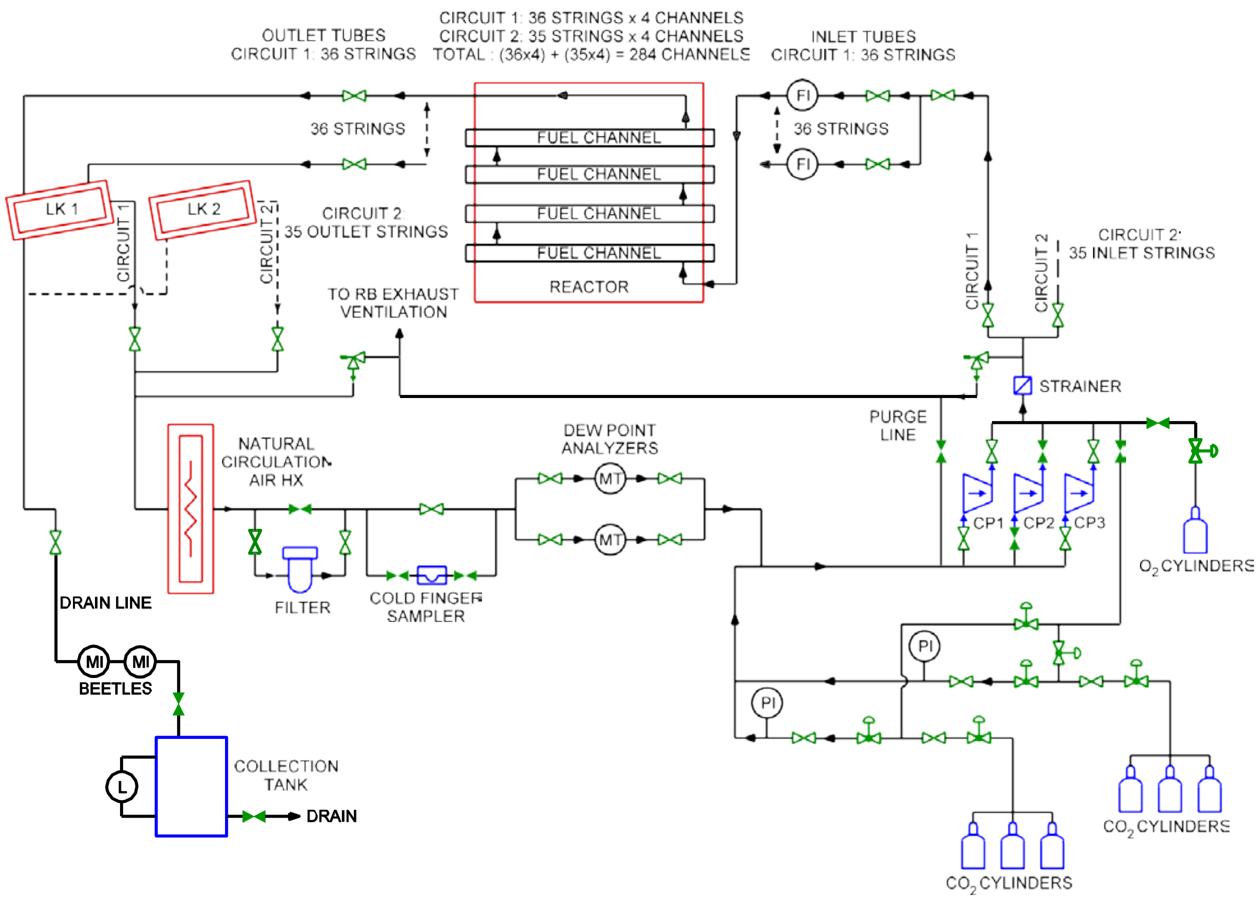


Annulus Gas System (AGS)

- The AGS circulates dry CO_2 gas and monitors the moisture content of the gas in order to detect any water leakage from either the moderator or the reactor coolant
- The annulus gas:
  - Thermally insulates the hot pressure tube from the cold calandria tube
  - Provides protective atmosphere outside of the pressure tube
- Addition of a small amount of O_2 to annulus gas limits hydrogen ingress at outside of pressure tube

- Design improved for leak detection capabilities:
  - Larger flow rate
  - Reduced number of channels per string
  - Increased number of parallel circuits

ACR Annulus Gas System



CANDU-6 Heat-Transport System Design

Reactor Coolant Parameters

❑ Outlet header pressure	10 MPa
❑ Outlet header temperature	310ºC
❑ Outlet header steam quality (max.)	4.0%
❑ Inlet header temperature	266ºC

Secondary Side Conditions

❑ Steam pressure	4.7 MPa
❑ Steam quality	<0.25%
❑ Feedwater temperature	187ºC

Moderator System

- Low-temperature (< 80^{o}C), low-pressure system.
- Independent of reactor coolant system.
- Normal heat removal is ~4-5% of full power.
- Contains reactivity devices located outside of high- pressure heat transport system.
- Potential heat sink if Emergency Core Cooling is unavailable during a Loss-of-Coolant Accident (LOCA).

CANDU Reactivity Devices

For Regulation (Control):

- 14 liquid-zone-control compartments (H_2O filled)
- 21 adjuster rods
- 4 mechanical control absorbers
- Moderator poison
- For Emergency Shutdown:
- 2 Shutdown Systems: SDS-1 & SDS-2

CANDU Special Shutdown Systems

Two independent, fully capable shutdown systems:

- ❑ **SDS-1 (cadmium rods enter core from top)**
- ❑ **SDS-2 (injection of gadolinium neutron “poison” from side.**