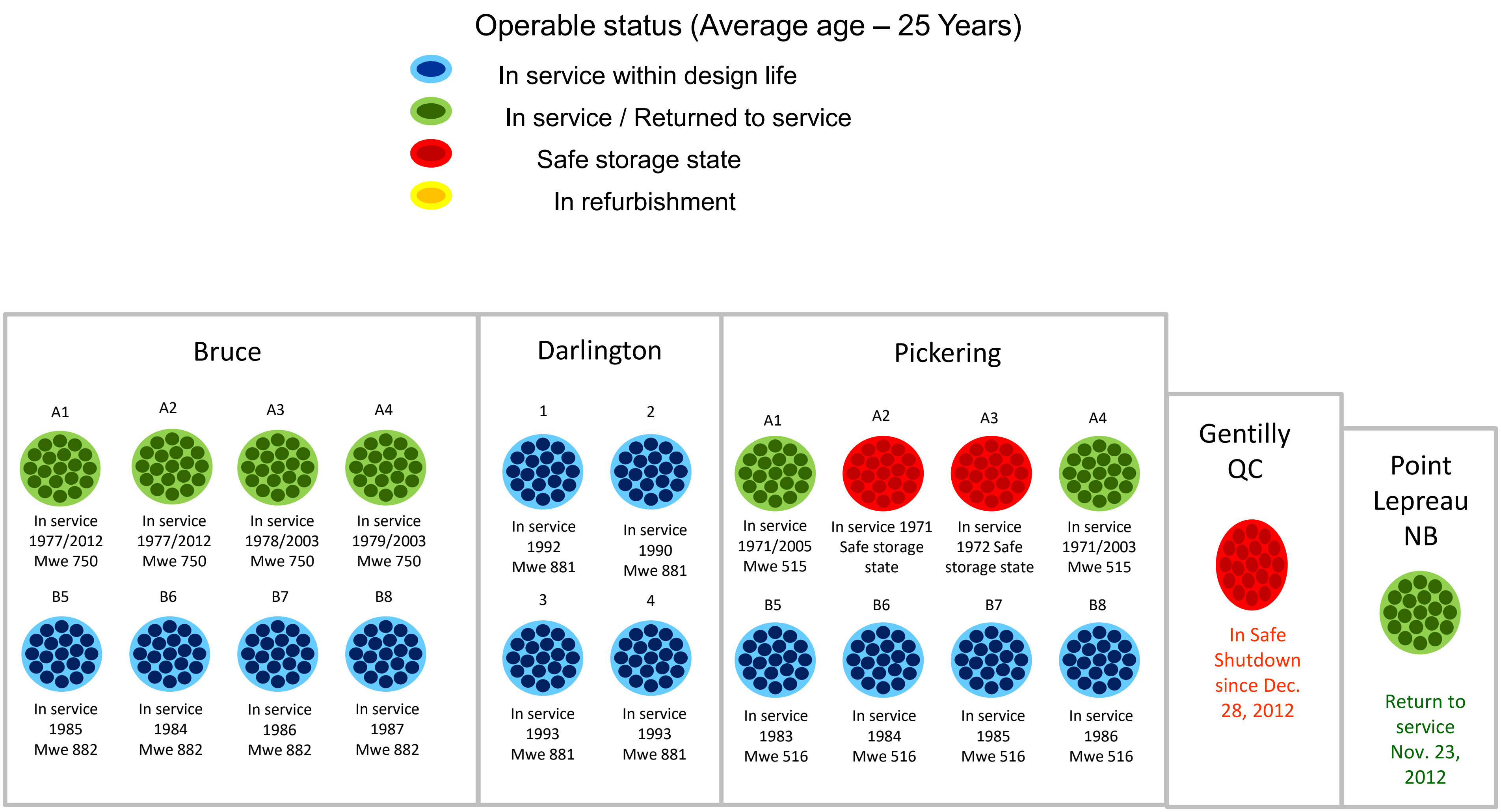
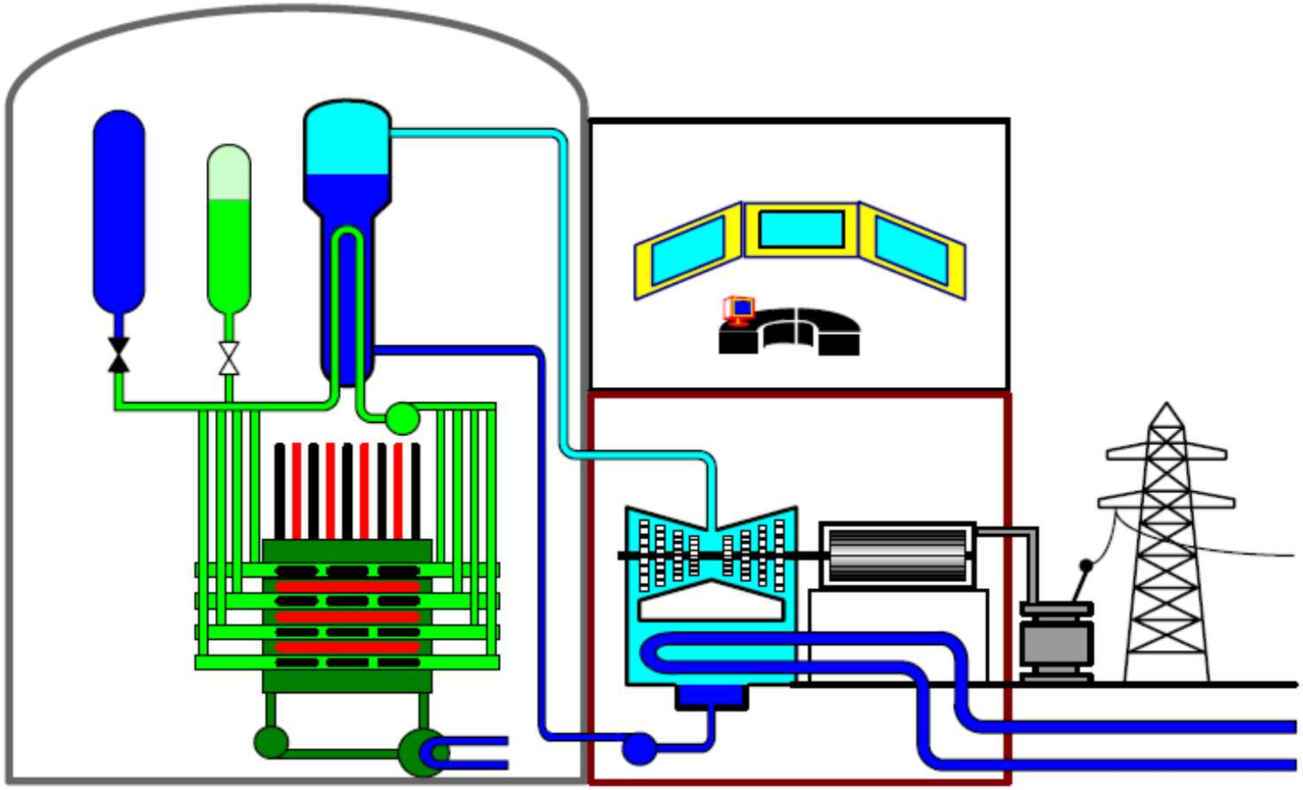
Canada's Operating Power Reactors

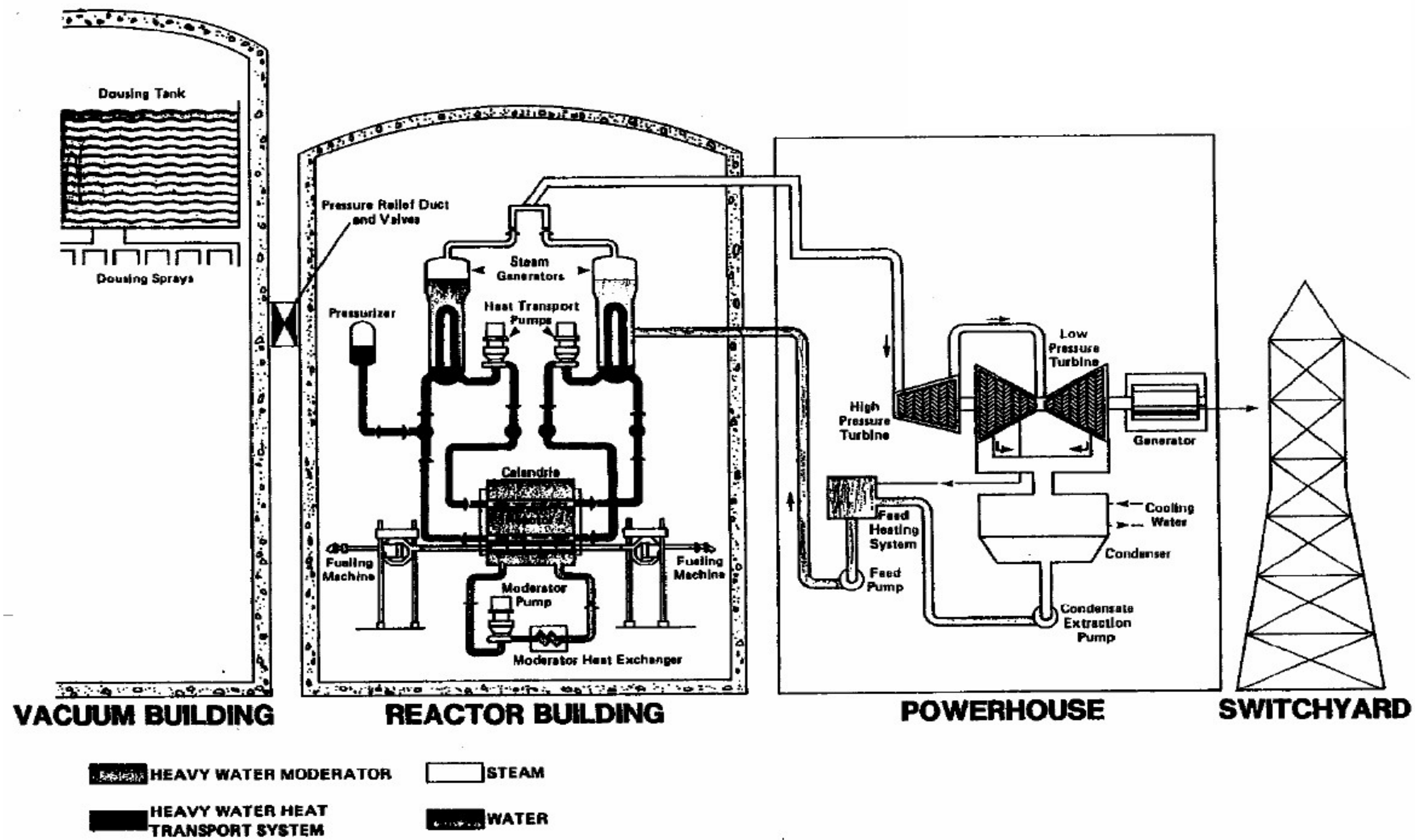


Principles Of Power Generation

[Independent Electricity System Operator (IESO)]



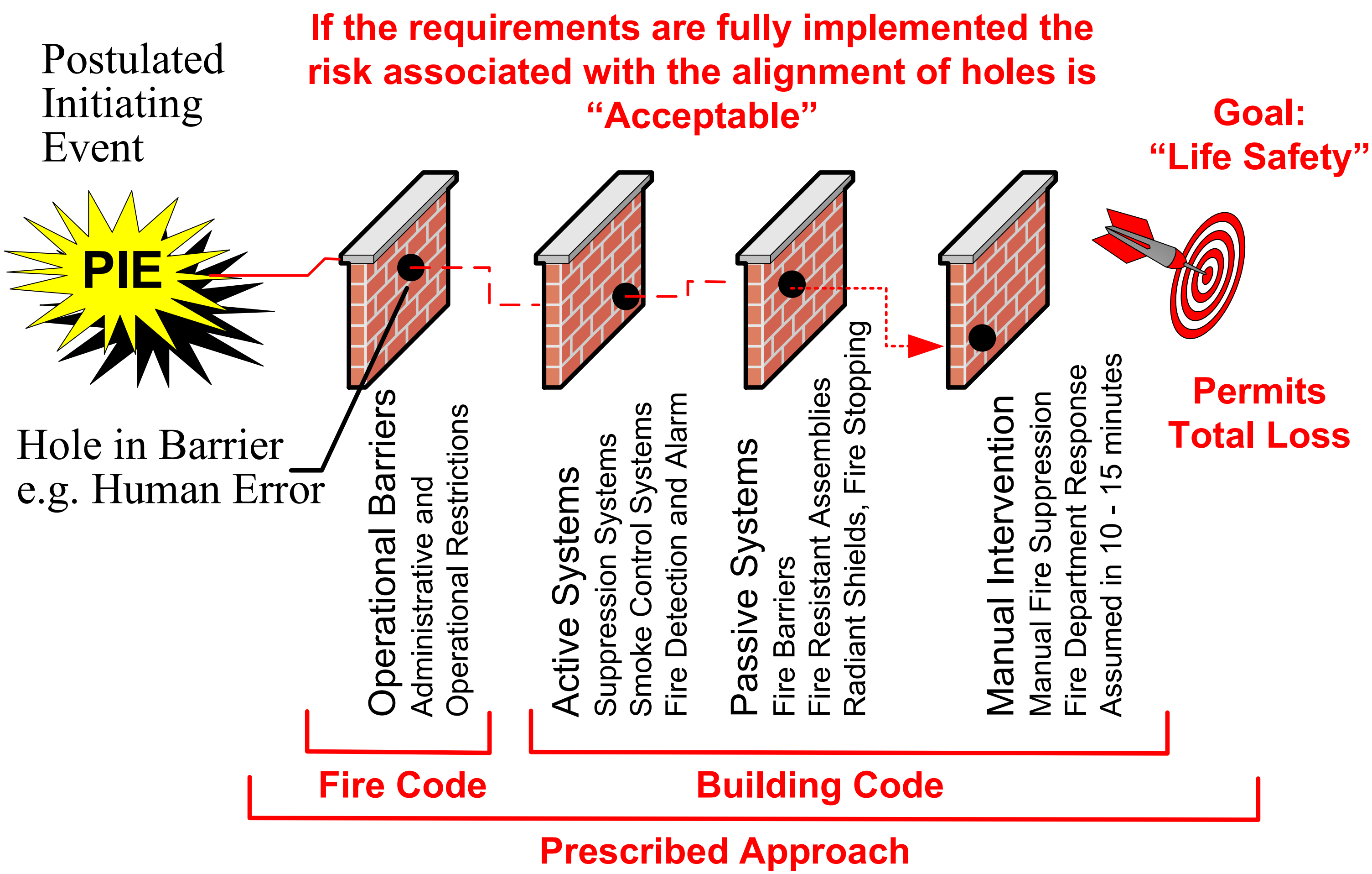
CANDU PRESSURIZED HEAVY WATER REACTOR



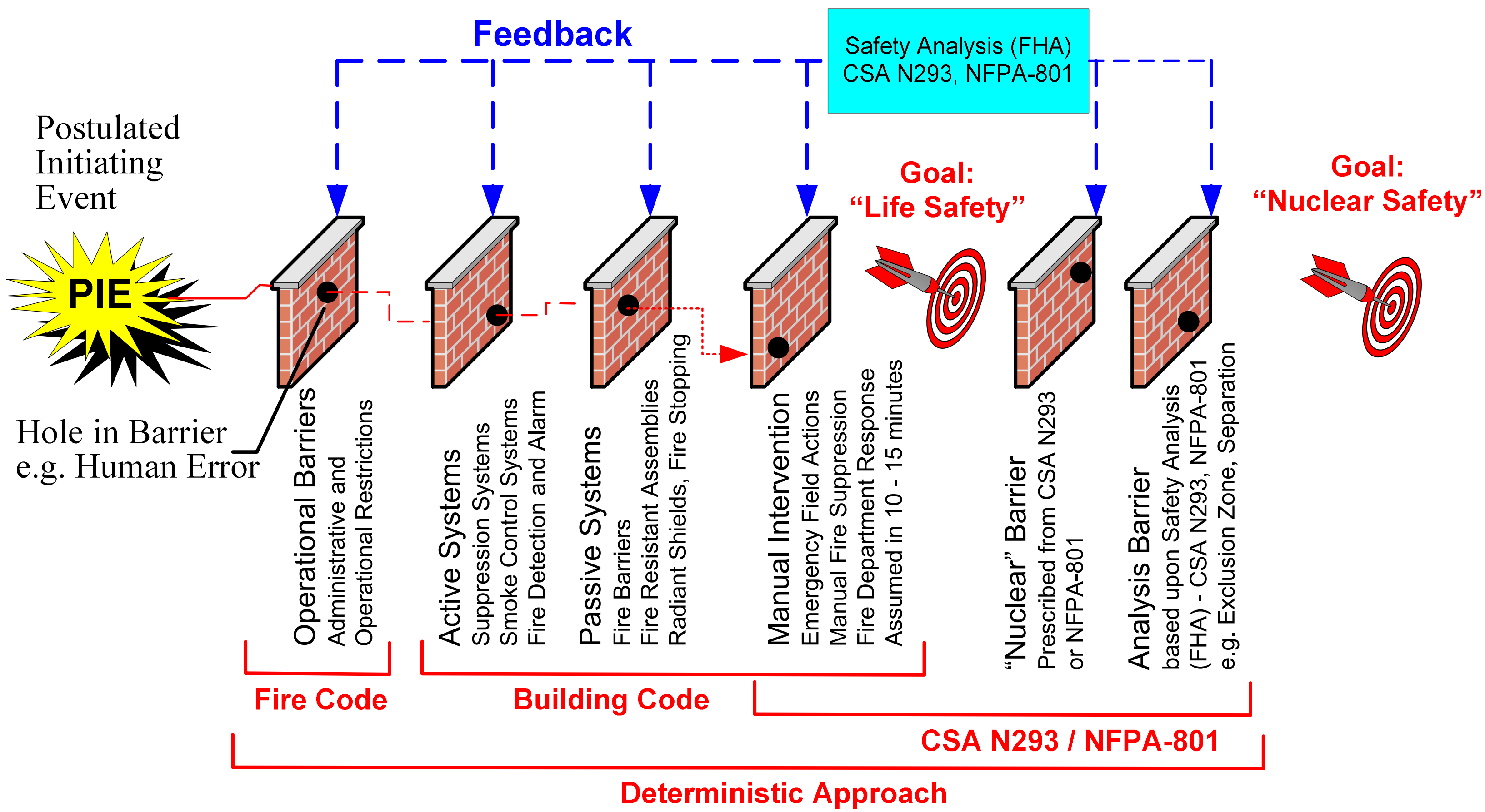
Defense In Depth

- The practice of having multiple, redundant, and independent layers of safety systems to act as barriers protecting workers, the public and the environment from large releases of fission products.
- **3 C Principle:**
  - Control
  - Cool
  - Contain

Defense In Depth-Commercial Building



Defense In Depth – Nuclear Facility



Nuclear Power Considerations: Economic

- The economic advantage over fossil fuel comes from the cost of uranium fuel
  - In 1990, nuclear fuel costs in Ontario were about 10% of the fuel cost compared to fossil
    - A large coal plant uses 20,000 tonnes of coal a day. The equivalent nuclear plant uses 20 fuel bundles, each with less than 20kg of uranium
- People who predicted cheap nuclear power overlooked costs that offset fuel savings
  - Nuclear plants are expensive to finance, build and maintain
  - Capital costs are 3X higher compared with fossil fuel plants
  - It takes 3-4 years longer to construct, commission and bring into service

Nuclear Power Considerations: Economic

- Experience with CANDU reactors shows nuclear power is much less expensive than fossil fuel power when nuclear plants are kept running 80% or more of the time
- Good performance over the life of a reactor will result in a significant cost advantage of nuclear over fossil fuel
- Poor operation can make nuclear power very expensive
- The advantage of uranium over fossil fuels will likely increase as world oil and gas supplies dwindle and concerns about greenhouse gases grow

Nuclear Power Considerations: Environment

- Effects of nuclear and fossil fuelled plants on the environment are very different
- A large coal plant without scrubbers generates, per day:
  - 15,000 tonnes of CO_2
  - 200 tonnes of acid gas (NOx and SOx)
  - Several tonnes of fly ash and 500 tonnes of ash
  - More than a tonne of arsenic and mercury
- Scrubbers can help remove some of the above, but not CO_2
- A nuclear plant will produce less than half a tonne of waste (~20 bundles/day x ~20kg/bundle = ~400 kg/day)
  - Spent fuel has the potential to be more harmful to the environment/humans than fossil fuel waste due to radiation
  - Spent fuel must be isolated from the environment for a very long time to protect the environment

Nuclear Power Considerations: Efficiency

- Equipment that turns heat energy into mechanical energy is never very efficient.
  - A fossil fuel plant throws away 60% or more of heat energy produced
  - A nuclear power plant can throw away as much as 70%
  - An Internal Combustion engine is worse: 80% or more heat produced is wasted
- Steam condensers in a nuclear plant reject ~65% of the total heat produced (this heat is passed on to a water body such as a lake)
- A further 5% of the total energy produced is lost to the moderator system and ultimately passed on to a water body

CANDU Design Overview

- CANDU (CANada Deuterium Uranium)
- Neutron economy
- Natural uranium Fuel
- Separated heavy water (D_2O) coolant and moderator
- Distributed core (fuel channels)
- On-power fuelling

Main CANDU Reactor Systems

- Reactor Assembly
- Fuel and Fuel Channel
- Heat Transport System
- Pressure and Inventory Control System
- Moderator System
- Special Safety Systems

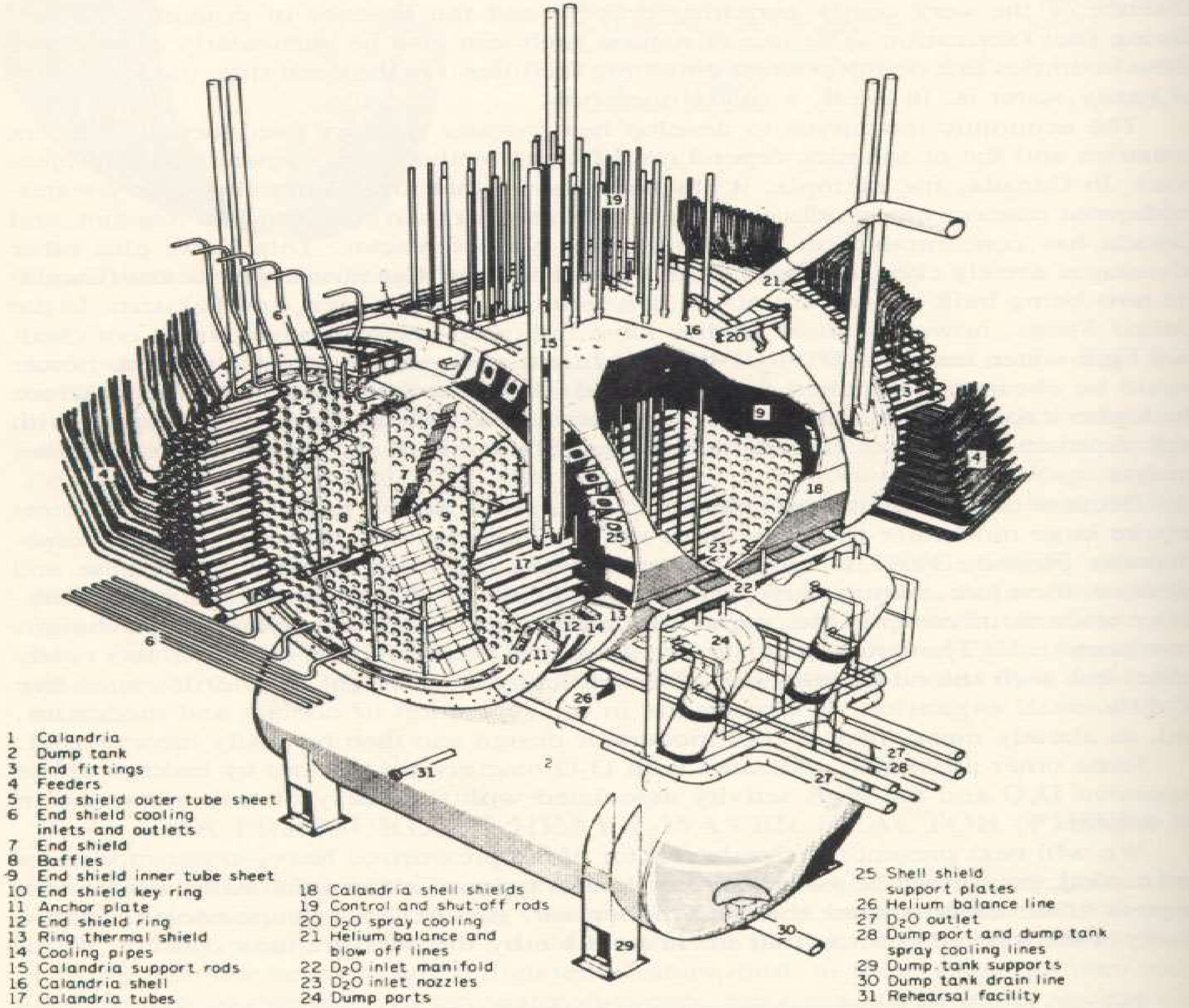
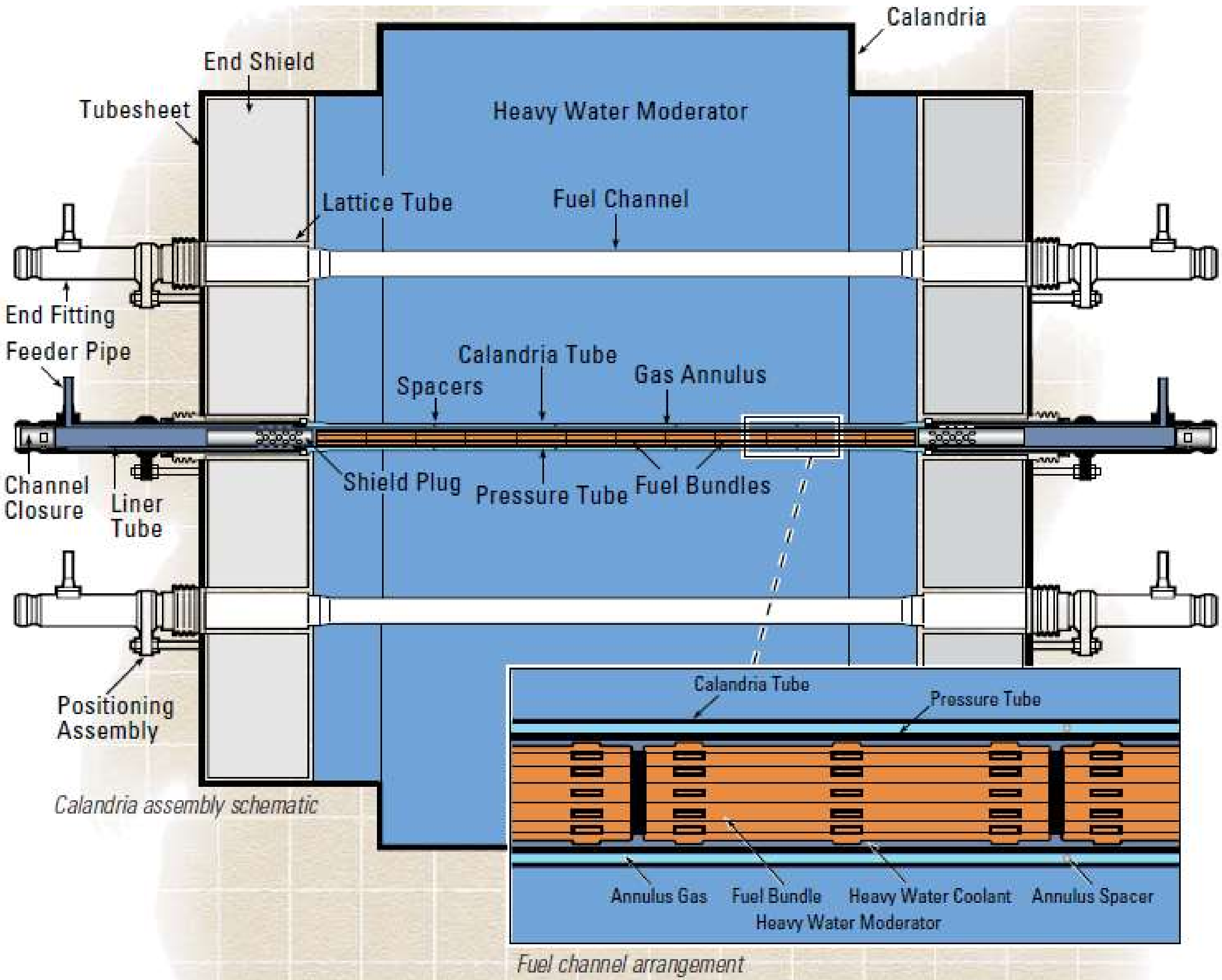


Figure 10-38 The Pickering heavy-water (Candu) reactor assembly. *(Courtesy Atomic Energy of Canada, Limited.)*



Calandria assembly schematic

Fuel channel arrangement

Calandria

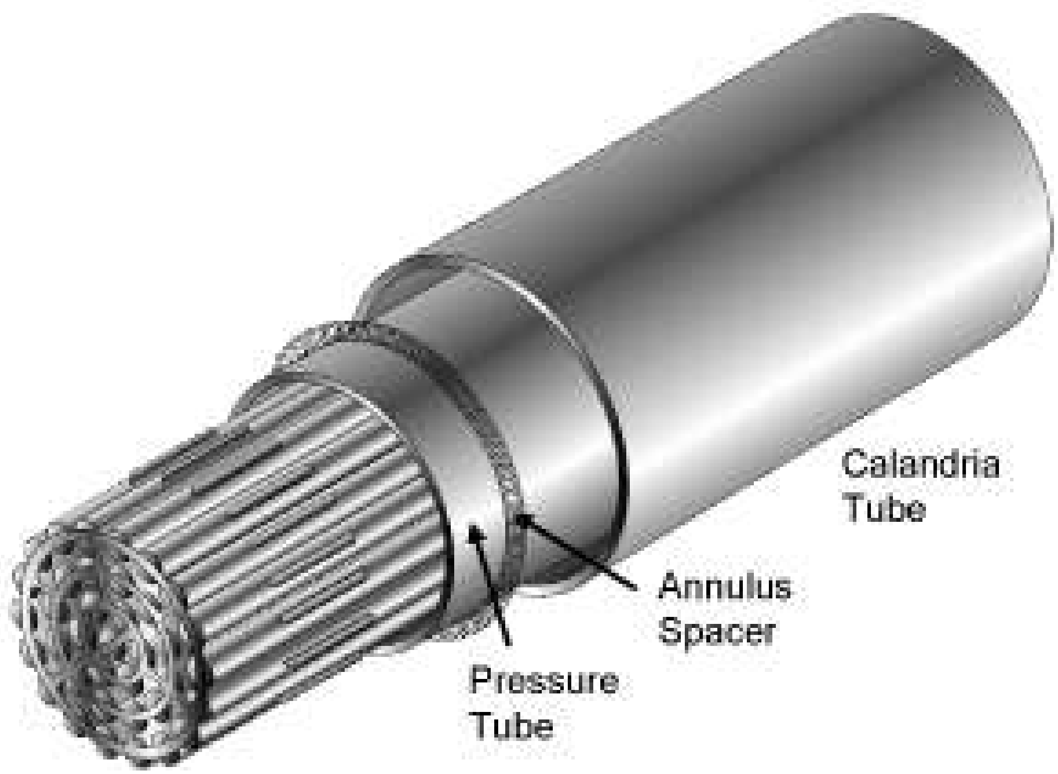
- Low pressure tank
- Supports calandria tubes and pressure tubes
- Contains heavy water moderator
- Contains reactivity devices and shut down systems
- Embedded in light water shield tank
- Provides passive emergency heat sink in the event of a loss of coolant accident + loss of emergency cooling

AECL
EACL
CANDU
WOLSONG 2
MANUFACTURED BY
FABRIQUE PAR
GEC ALSTHOM
ELECTROMECANIQUE
TRACY (QUÉBEC)
CANADA
SUPPLIED BY
NPM
TNT
D

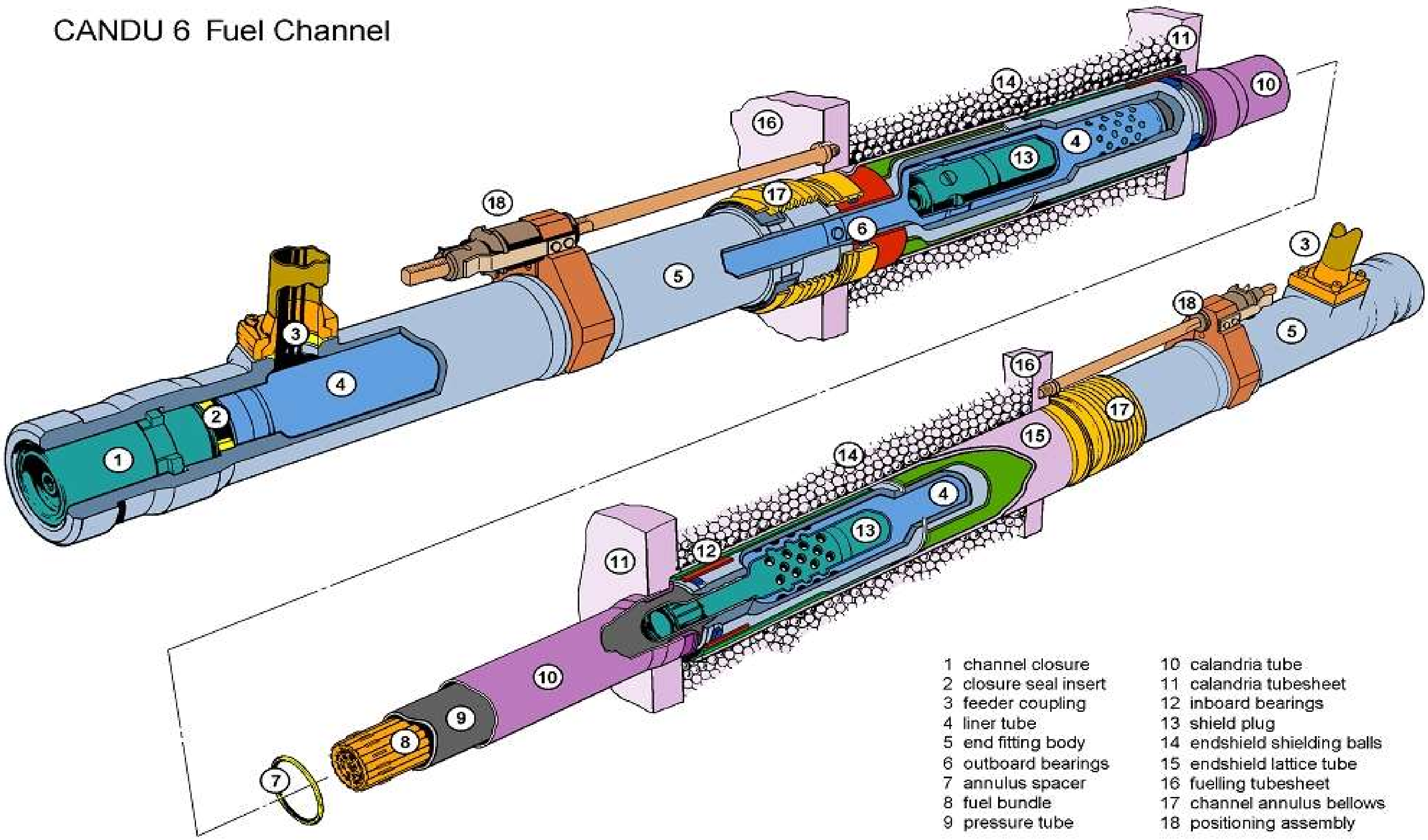
Fuel Channel Core Design

- Sub-divided reactor coolant system, no large pressure vessel
- Cool moderator separated from coolant
- Zr-2.5%Nb pressure tubes constitute CANDU pressure vessel
- Individual pressure tubes are replaceable
- Interstitial reactivity devices (between fuel channels)
- Distributed core allows cooling to be maintained with failure of small diameter reactor coolant system (a pressure tube or a feeder pipe)

Pressure Tube Arrangement

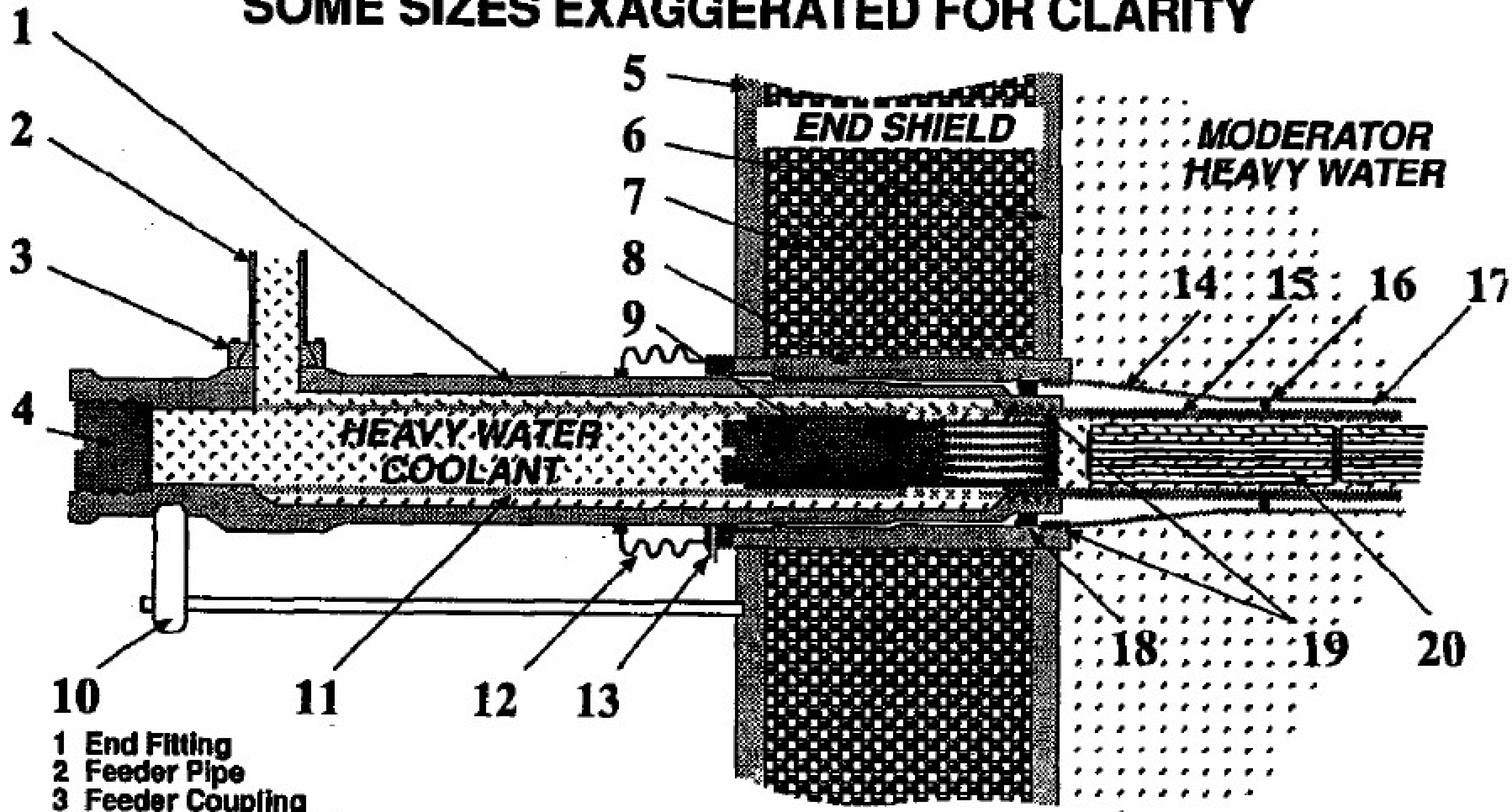


CANDU 6 Fuel Channel



SIMPLIFIED SECTION OF END FITTING

SOME SIZES EXAGGERATED FOR CLARITY



1 End Fitting
2 Feeder Pipe
3 Feeder Coupling
4 Channel Closure Plug
5 End Shield
 - Fuelling Machine Side Tube Sheet
6 End Shield
 - Calandria Side Tube Sheet
7 End Shield - Steel Balls
8 End Shield - Lattice Tube
9 Shield Plug

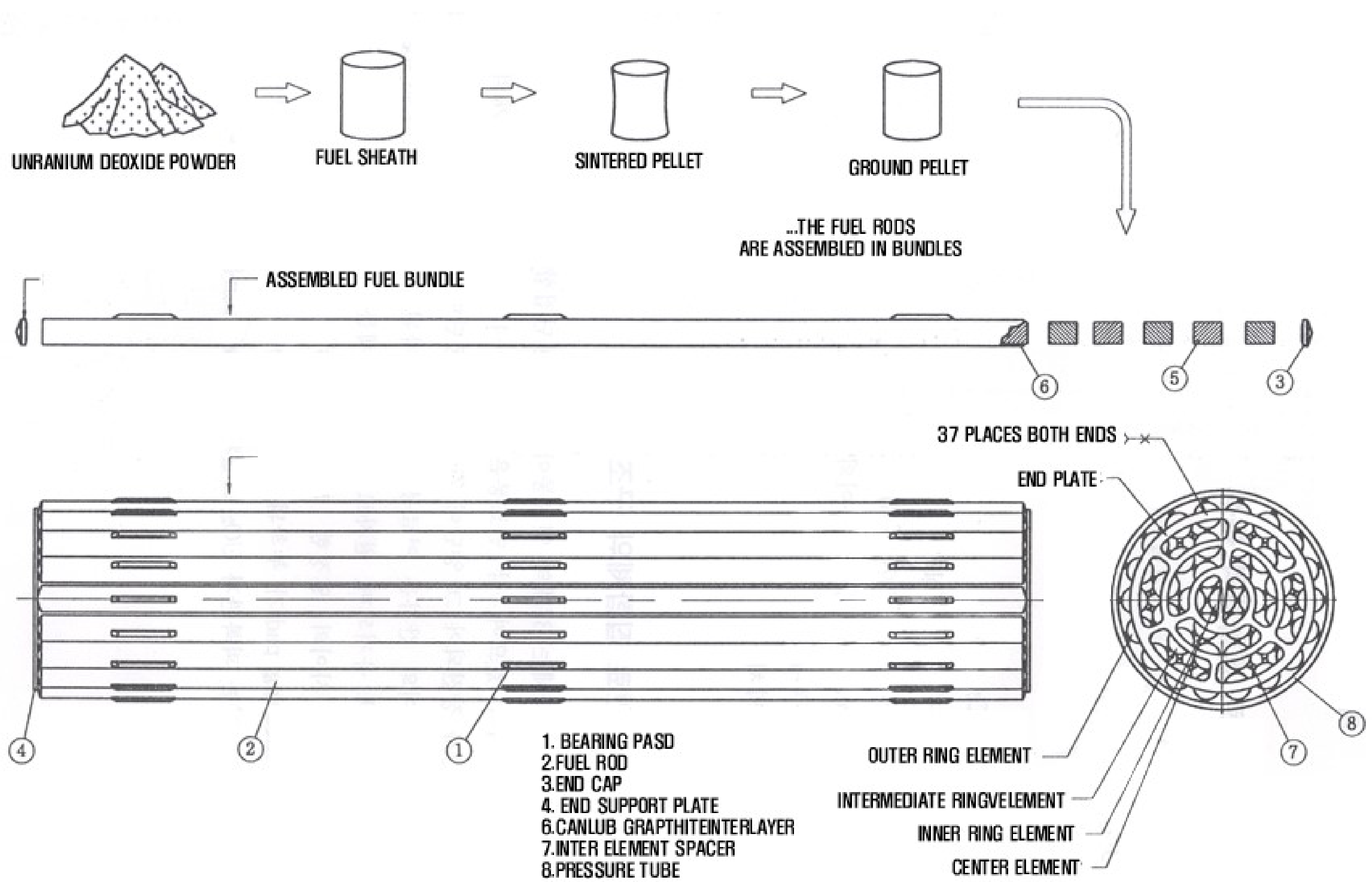
10 Channel Locking/Unlocking Mechanism
11 Liner Tube
12 Annulus Bellows
13 Annulus Gas Connection

14 Calandria Tube
15 Pressure Tube
16 Garter Spring Spacer
17 Annulus
18 Journal Bearing
19 Rolled Joints
20 Fuel Bundle

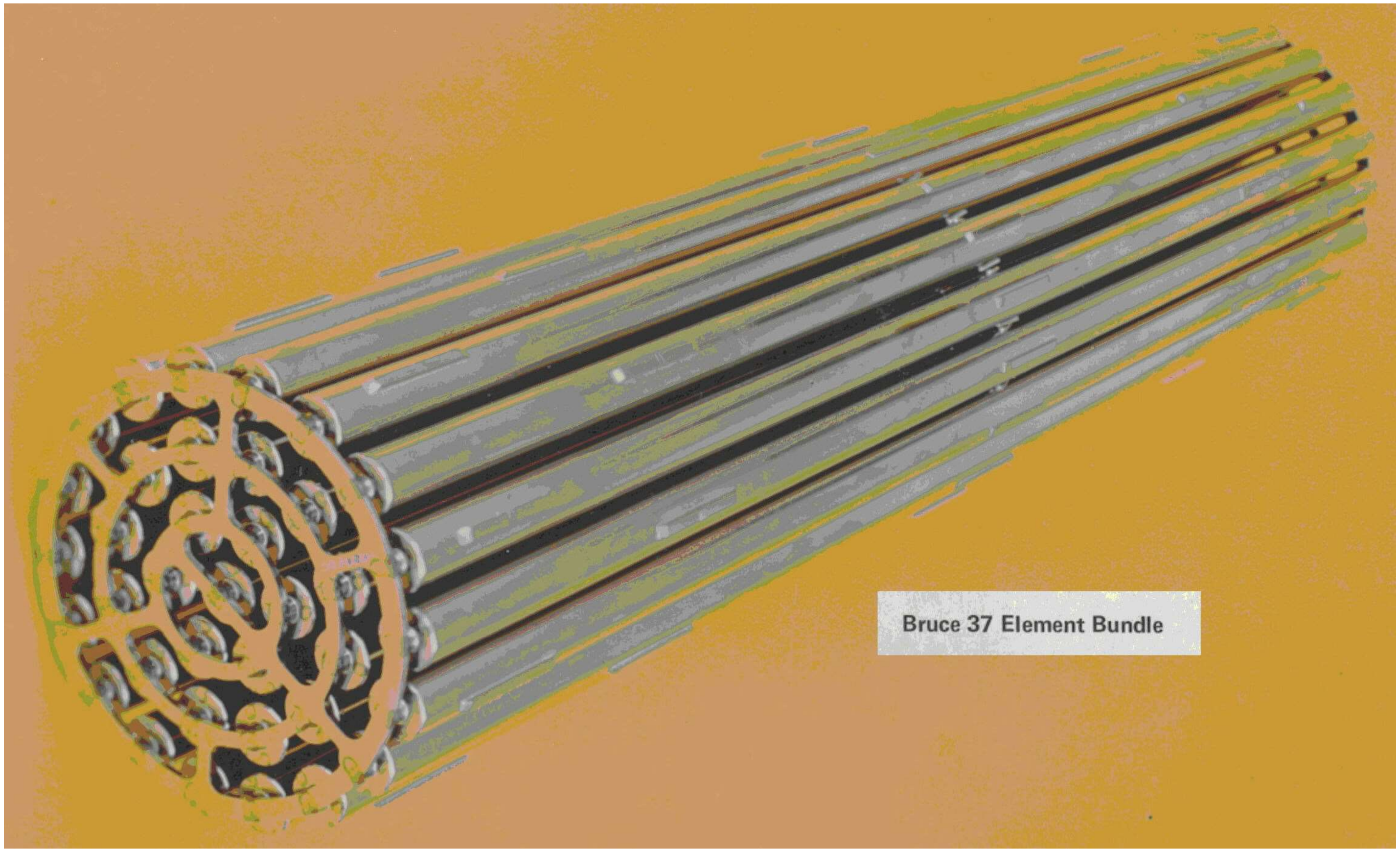
CANDU Fuel Bundle

- Natural uranium (0.7% ^{235}U)
- High density uranium oxide (UO_2) fuel pellets in Zircaloy-4 cladding
- Collapsible cladding under normal operating conditions.
- Short (0.5 m) fuel elements arranged in cylindrical fuel bundle

CANDU Fuel Bundle

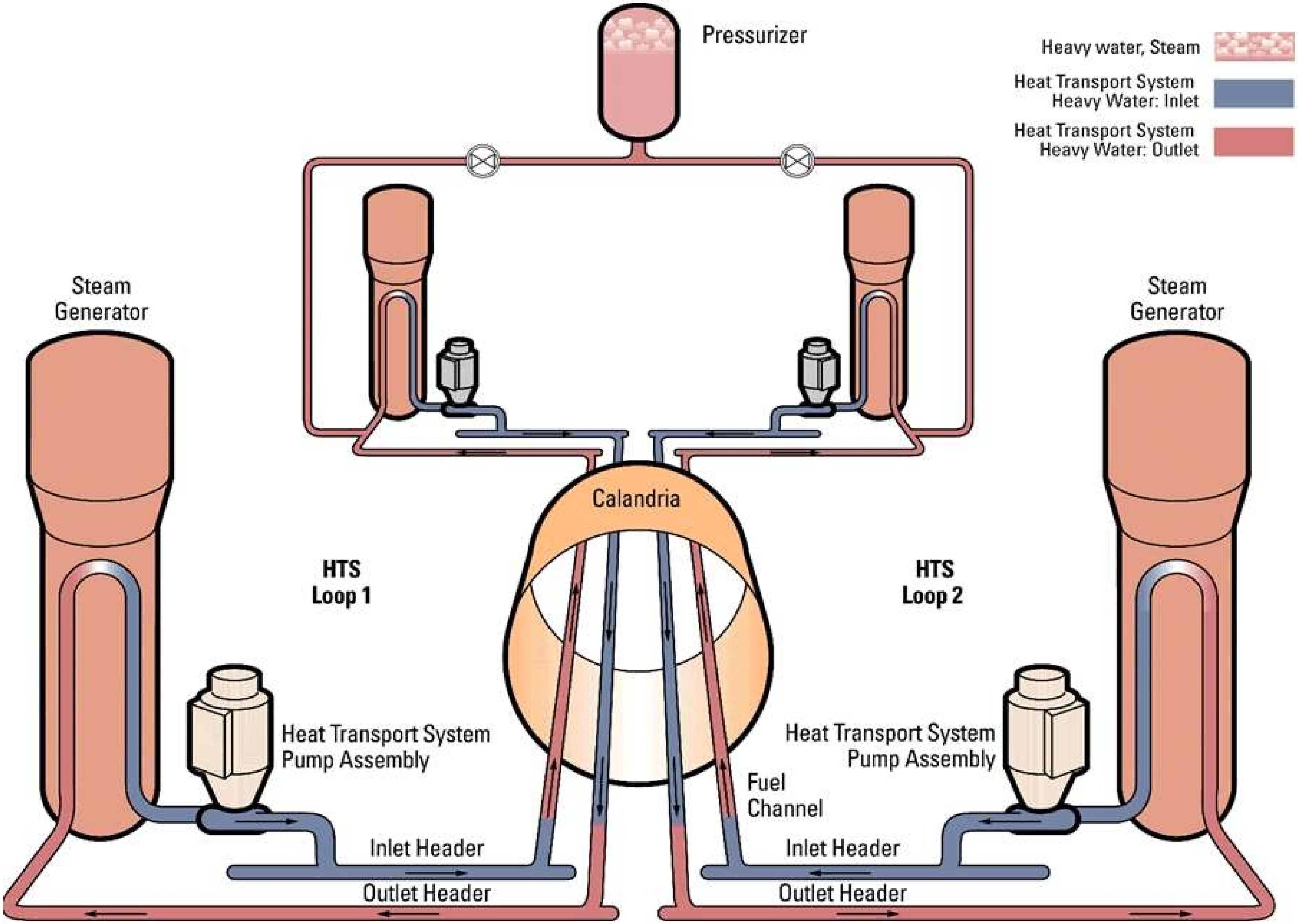


Bruce 37 Element Fuel Bundle



Heat Transport System

- Two independent circuits arranged as Figure of 8 with pumps and steam generators.
- System components sized to minimize D_2O inventory
- All core-external circuit components located above core to facilitate natural circulation in the event of loss of pumped flow.
- Entire reactor coolant system pressure boundary inside containment


Pressurizer
Heavy water, Steam
Heat Transport System
Heavy Water: Inlet
Heat Transport System
Heavy Water: Outlet
Steam
Generator
Steam
Generator
Calandria
HTS
Loop 1
HTS
Loop 2
Heat Transport System
Pump Assembly
Heat Transport System
Pump Assembly
Fuel
Channel
Inlet Header
Outlet Header
Inlet Header
Outlet Header

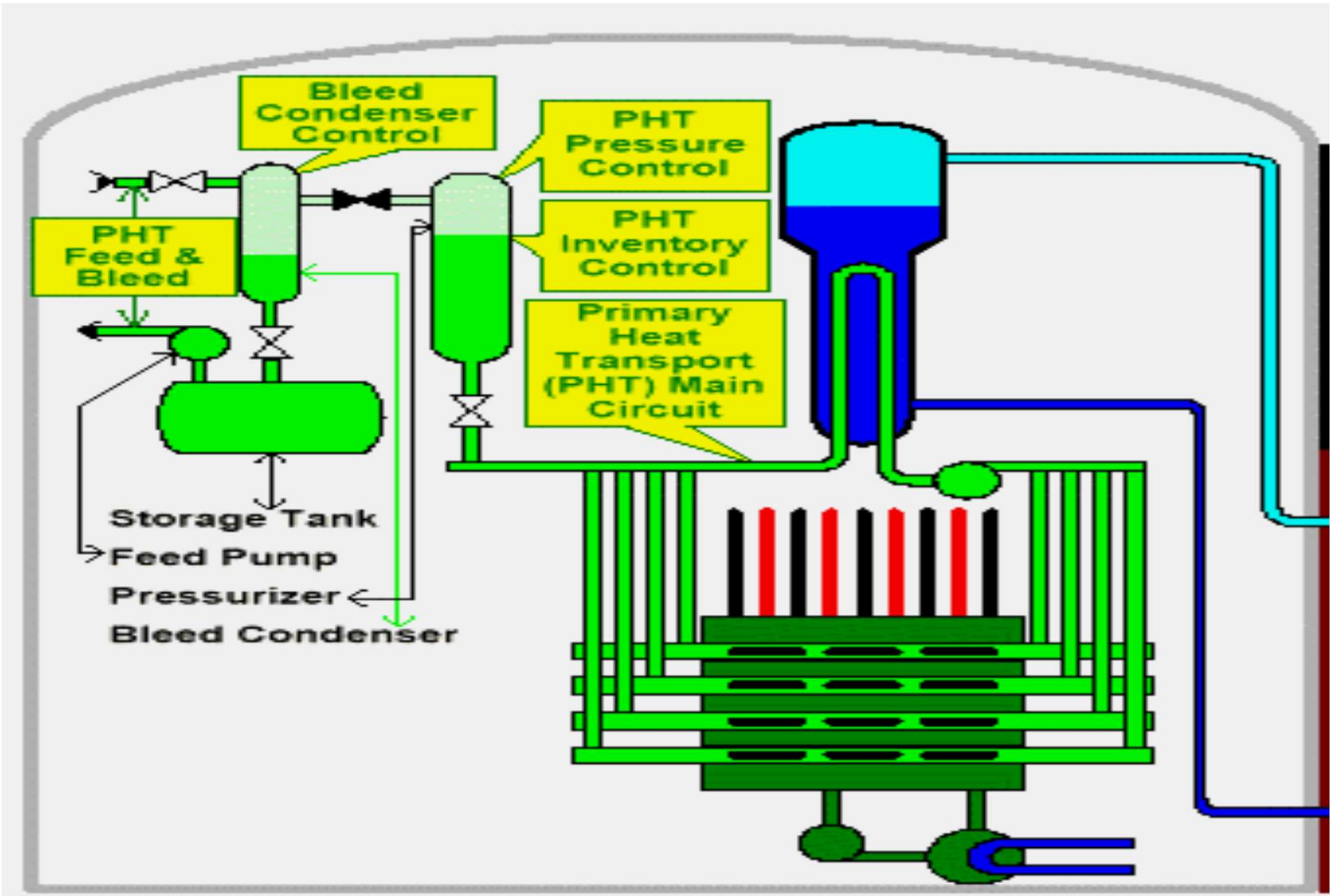
CANDU 6 Heat Transport System Parameters

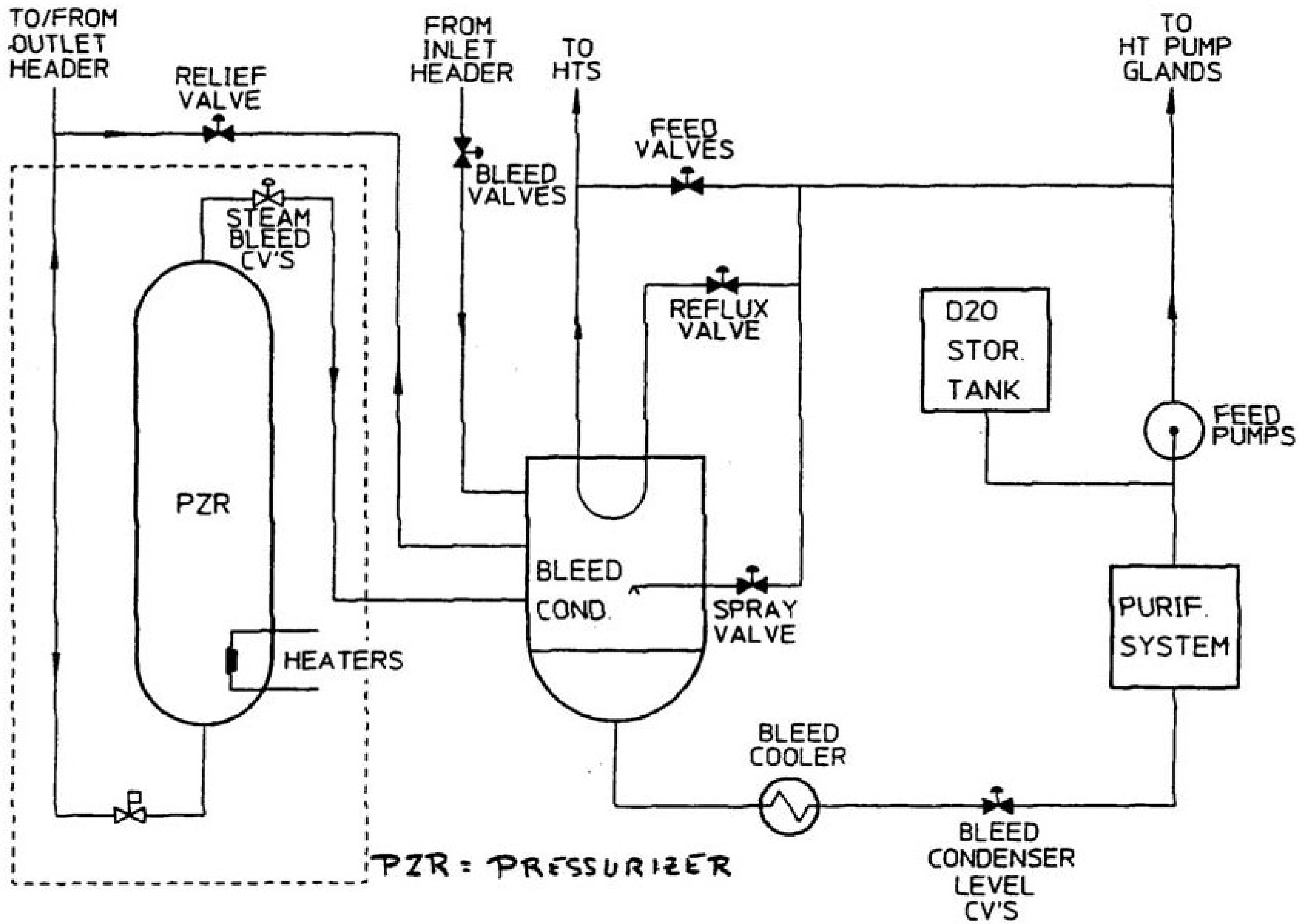
- Outlet Header Pressure 10 MPa
- Outlet header temperature 310^o C
- Outlet header steam quality (max. 4%)
- Inlet header temperature 266^o C

Secondary Side Conditions

- Steam Pressure 4.7 MPa
- Steam quality 99.75%
- Feed water temperature 175^o C

Heat Transport Pressure and Inventory Control

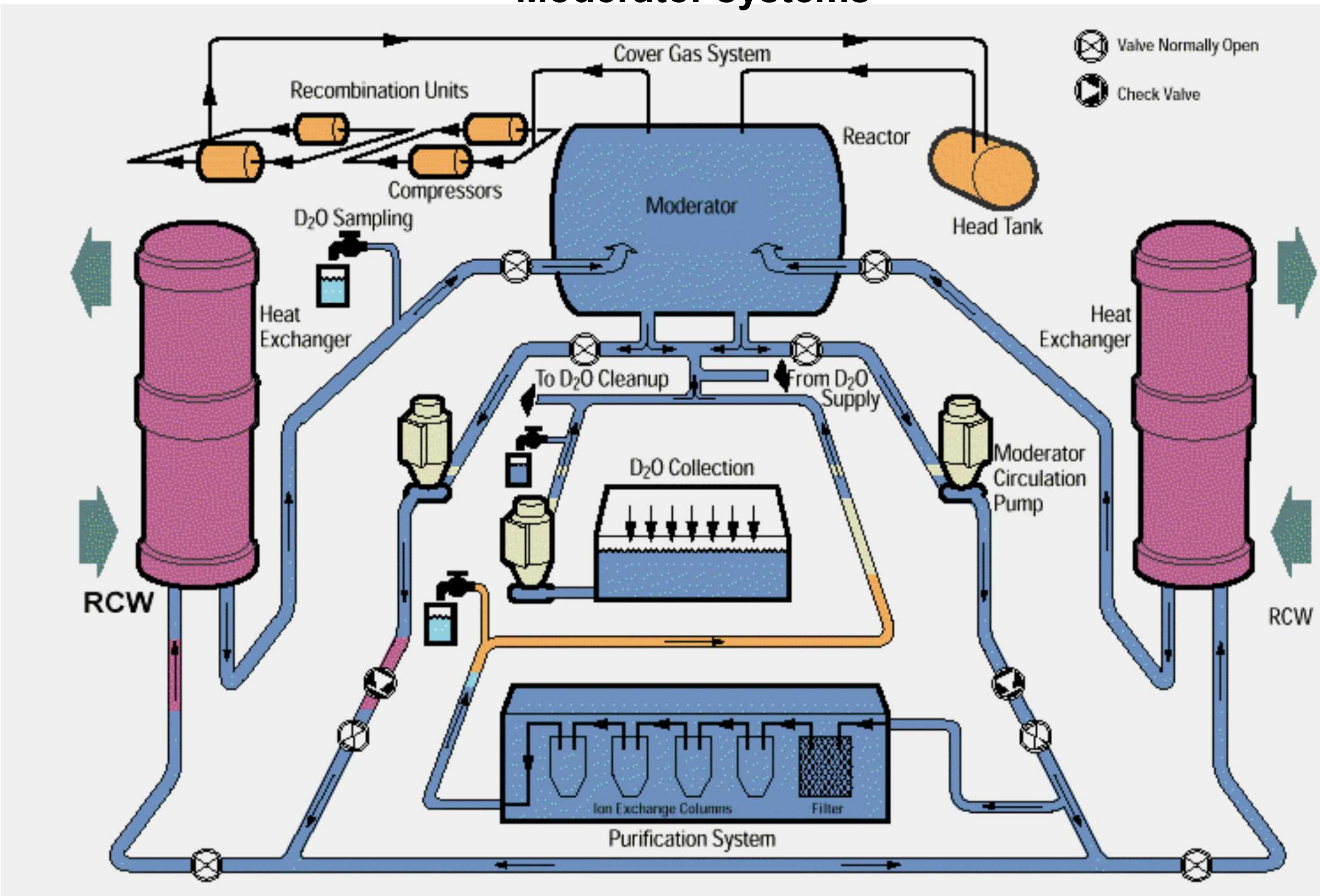



TO/FROM
OUTLET
HEADER
RELIEF
VALVE
FROM
INLET
HEADER
TO
HTS
TO
HT PUMP
GLANDS
FEED
VALVES
BLEED
VALVES
STEAM
BLEED
CV'S
REFLUX
VALVE
D2O
STOR.
TANK
FEED
PUMPS
PZR
BLEED
COND.
SPRAY
VALVE
PURIF.
SYSTEM
HEATERS
BLEED
COOLER
BLEED
CONDENSER
LEVEL
CV'S
PZR = PRESSURIZER

Heat Transport Pressure and Inventory Control

- Holds the PHT system pressure at the set point.
- Supply continuous coolant flow to the purification system.
- Accommodate volume changes (swell and shrink) of hot coolant during power maneuvers.
- Provide a pressure relief path in case of system over-pressurization

Moderator systems



Moderator System

- Low temperature low pressure system
- Independent of the reactor coolant system
- Normal heat removal is approximately 4% of full power
- Potential heat sink if emergency core cooling is not available during LOCA
- Contains shutdown systems outside high pressure heat transport system

CANDU Safety Systems

- Design philosophy- Defense-in-depth with multiple barriers
- Separation of safety systems and safety support systems to increase reliability (diversity and independence)
- Reliable special safety systems

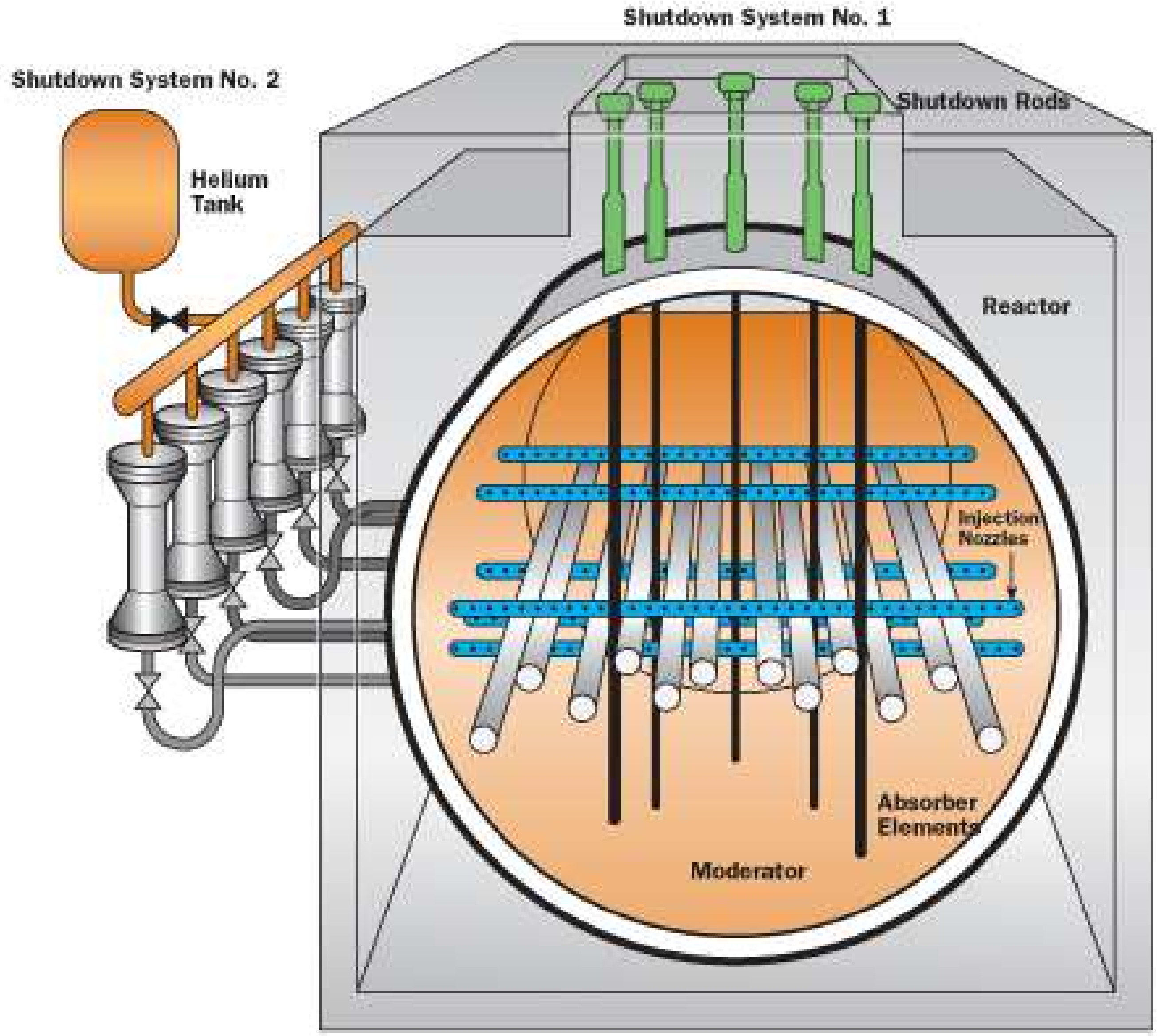
Safety System Functions

- Shutdown the reactor
- Remove the decay heat
- Prevent the release of radioactivity
- Monitor the state of the plant

Special Safety Systems

- Shutdown system 1 (SDS1): Fast acting shutoff rods
- Shutdown system 2 (SDS2): Fast acting Poison injection
- Emergency Core Cooling (ECC)
- Containment (including isolation functions)

Shutdown Systems



Shutdown System1

- 28 stainless steel clad cadmium rods
- Vertically oriented and spring assisted gravity drop.
- Independent of SDS 2
- Independent of reactor control (regulating) system

Shutdown System 2

- 6 injection nozzles for gadolinium nitrate solution (poison)
- Horizontal insertion driven by high pressure He.
- Independent of SDS 1
- Independent of reactor control (regulating) system

Removal of Decay Heat

- With an intact heat transport system
  - Steam generator +main feed water system, or
  - Steam generator + auxiliary feed water system, or
  - shutdown cooling system
  - Emergency water system
- With a large break in the HTS
  - Emergency core cooling
- For severe accident (ECC failure)
  - Moderator and shield tank

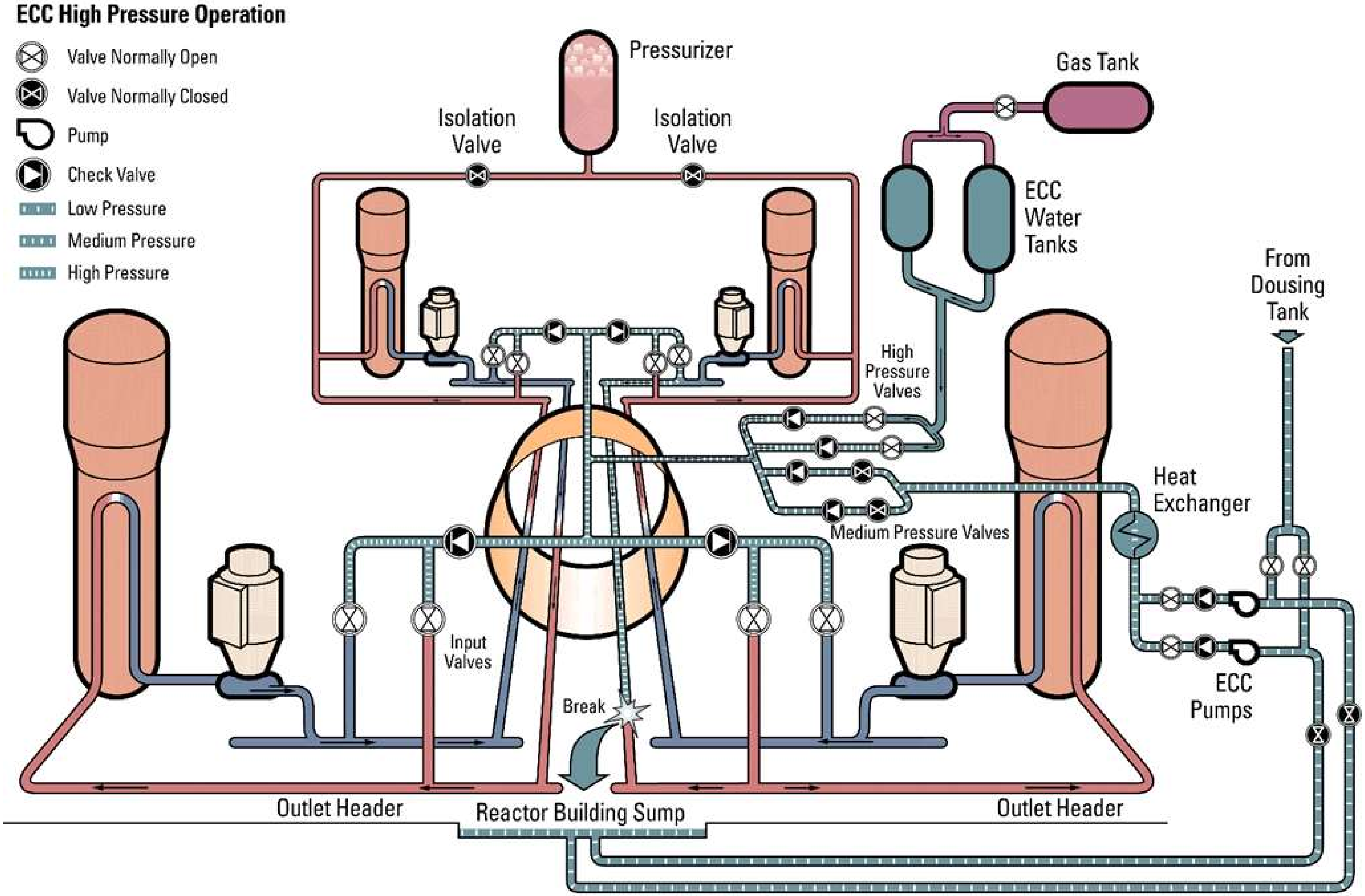
Emergency Core Cooling (ECC) System

- Injection in all headers of the HTS
- Three stages

-High pressure injection, water from external tank

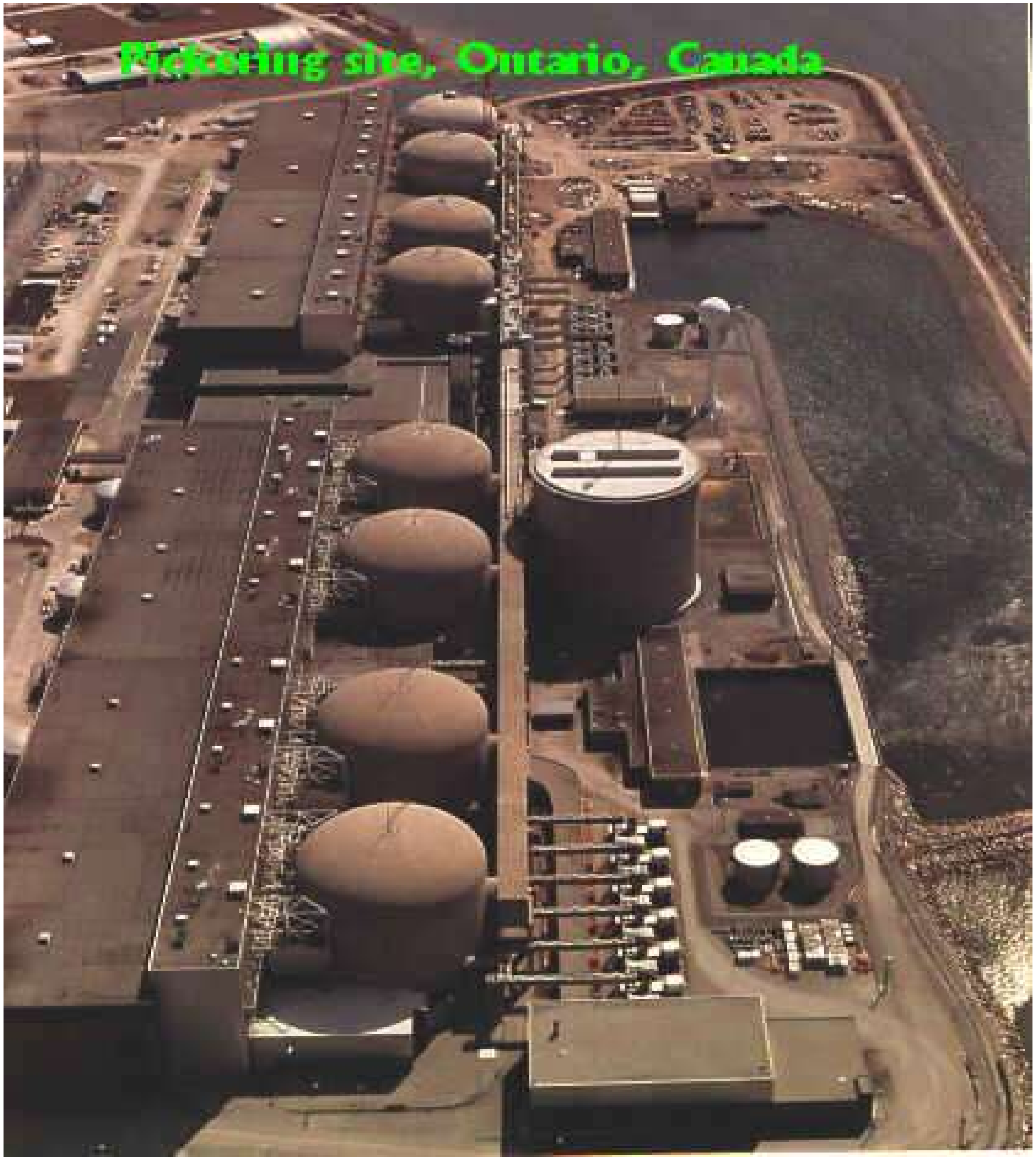
- Medium pressure, water from dousing tank

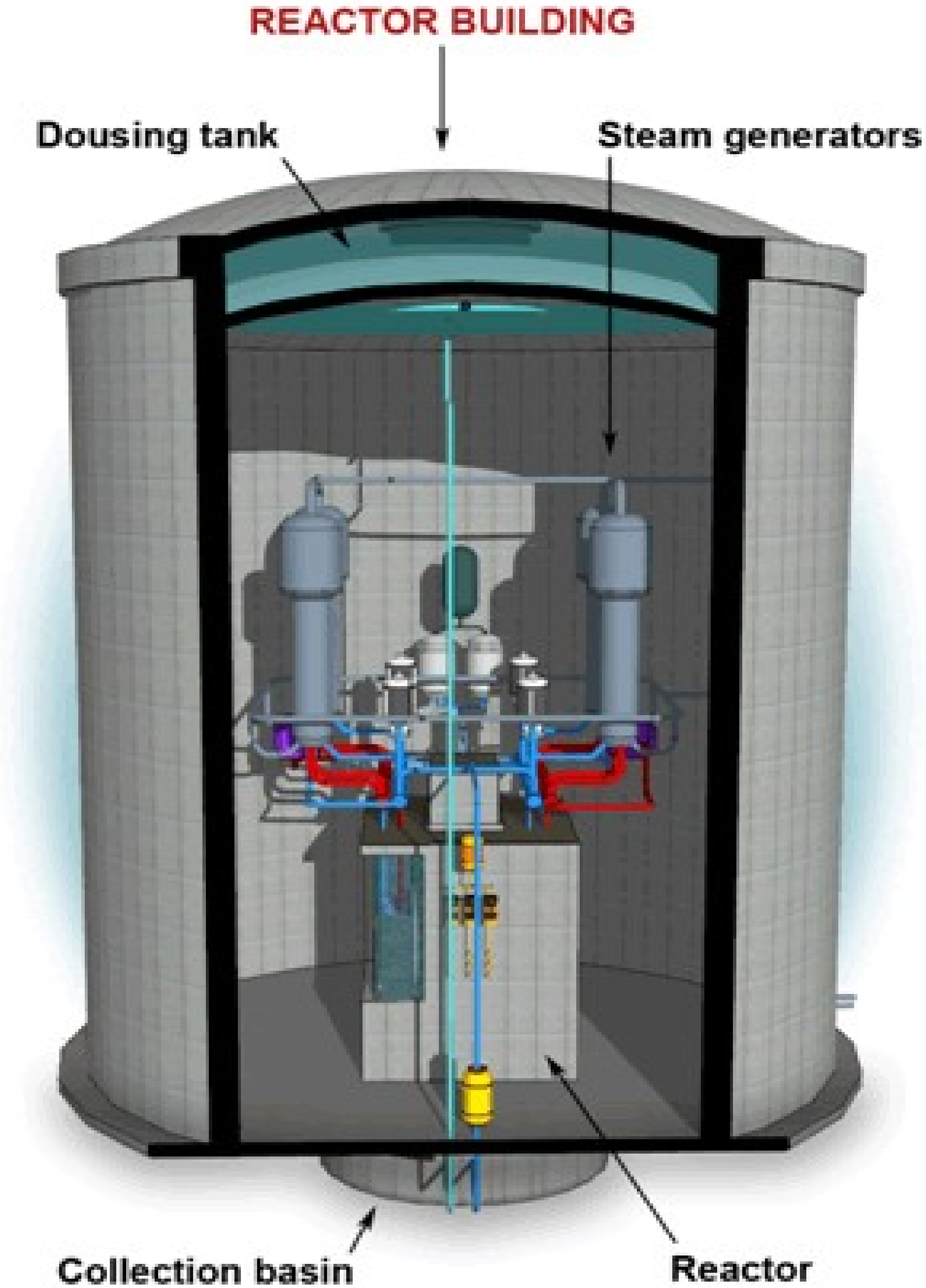
- Low pressure, water recirculated from containment sump


ECC High Pressure Operation
Valve Normally Open
Valve Normally Closed
Pump
Check Valve
Low Pressure
Medium Pressure
High Pressure
Pressurizer
Isolation Valve
Isolation Valve
Gas Tank
ECC Water Tanks
From Dousing Tank
High Pressure Valves
Heat Exchanger
Medium Pressure Valves
Input Valves
ECC Pumps
Break
Outlet Header
Reactor Building Sump
Outlet Header

Containment System

- Pre-stressed post-tensioned concrete building with high flow dousing sprays for active pressure suppression.
- Encloses reactor and all of the heat transport system.
- Low leak rate
- Automatic isolation of penetrations in the event of an accident.

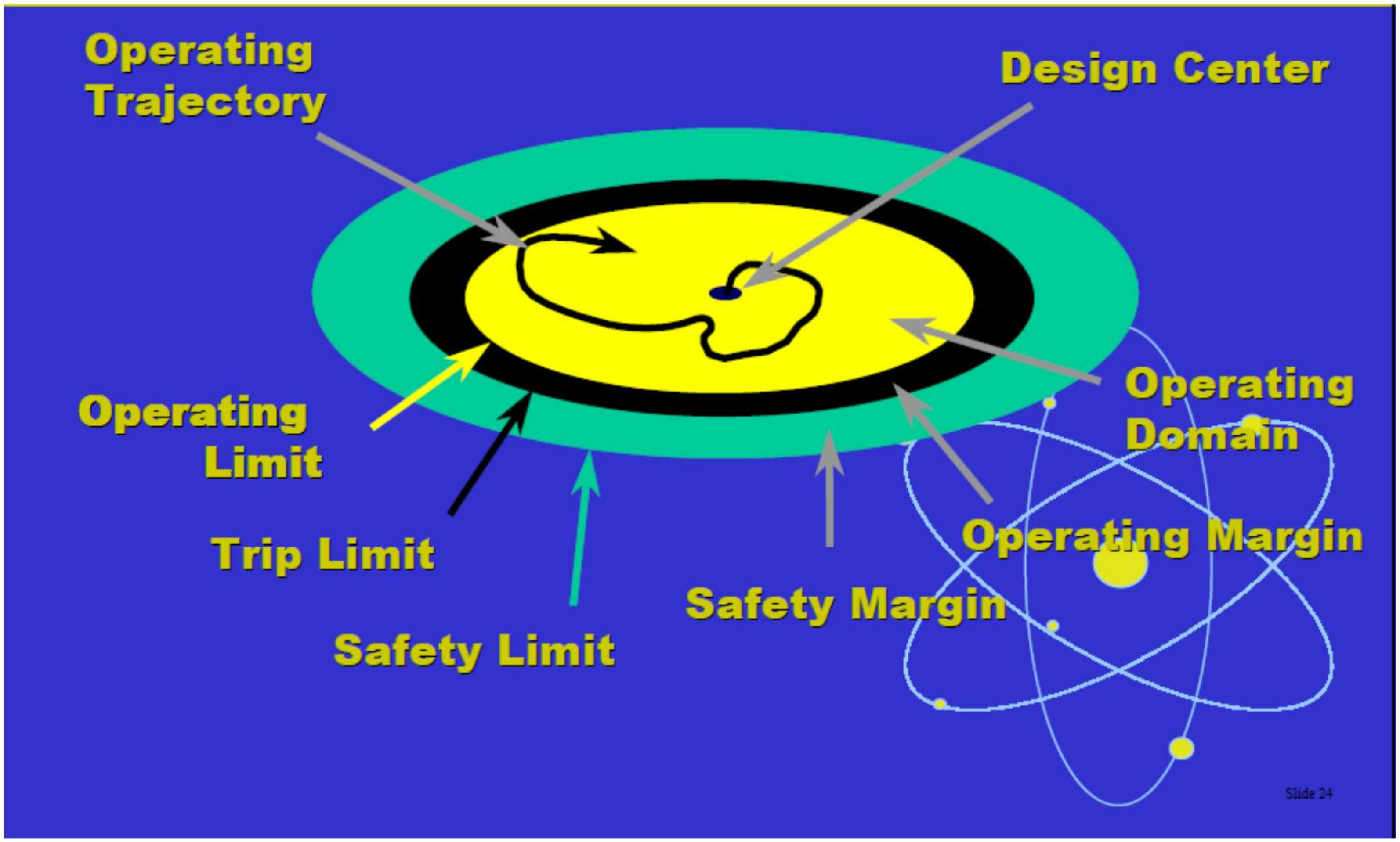

Pickering site, Ontario, Canada


REACTOR BUILDING
Dousing tank
Steam generators
Collection basin
Reactor

Nuclear Power Plant Safety Systems - YouTube

Understanding Nuclear Power Plants: Total Station Blackout - YouTube

CANDU Operating Envelope



CANDU PRESSURIZED HEAVY WATER REACTOR