AECL and HWR Experience

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Outline

- **The Canadian Nuclear Industry**
- **CANDU-PHWR Characteristics ; EC6, ACR1000**
- **Delivery of Projects**
- **CANDU Fuel cycles**

Canadian Nuclear Industry

- **Canada is a successful nuclear pioneer**
  - 60 years of nuclear technology development
  - Invented CANDU® power reactor and cancer therapy
- **$6B/year industry**
  - 70,000 workers, 150 companies Canada-wide
- **22 CANDU reactors in Canada**
  - CANDU generates ~50% of Ontario's power
- **World's largest exporter of uranium**

Bruce, ON

Gentilly, PQ

Pt. Lepreau, NB

Darlington, ON

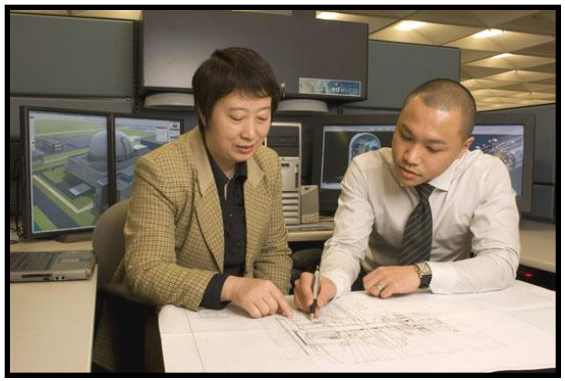
Atomic Energy of Canada Limited

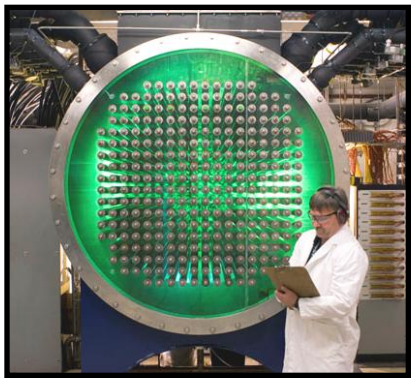
AECL
EACL

- Established in 1952 to lead the Canadian nuclear industry.
- 33 CANDU reactors in-service worldwide
- Over 4,800 employees
- CANDU recognized as one of the top 10 major engineering achievements of the past century in Canada.
- World records in construction and commissioning.
- Advanced R&D Facilities

A Total Nuclear Solution Company

- **Nuclear power design and construction**
  - Developer/ designer/ builder of the CANDU nuclear power reactor
- **Full lifecycle service packages**
  - Design, build, and service reactors in Canada and around world
- **Support services**
  - O&M support, plant life management programs, waste management
- **Comprehensive R&D facilities at Chalk River Laboratories**
  - Research reactors, hot cells, flow testing, metallurgy, heavy water, etc.





World Class Nuclear R&D

- **400+ laboratories**
- **Specialized test facilities supporting CANDU platform**
- **NRU & ZED-2 reactors**
  - –Canadian Neutron Beam Centre
  - –Hot cells & irradiation analysis
  - –Molten fuel interaction testing
  - –Robotics engineering
  - –Experimental fuels fabrication
  - –Flow testing and visualization
  - –High-temperature loops & autoclaves
  - –Underground Research Laboratory
  - –Metallurgy, heavy water, etc.

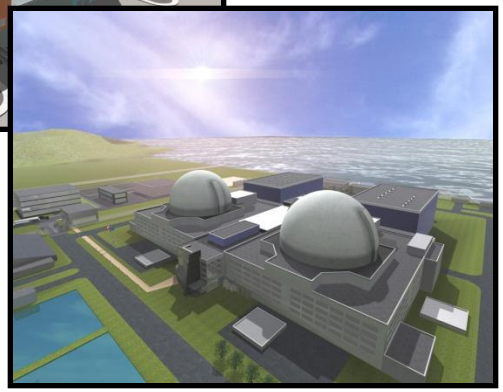
CANDU Products

The CANDU Reactor is AECL's flagship product:

–Enhanced CANDU 6 (EC6)

–ACR-1000

Enhanced CANDU 6



ACR-1000

AECL also delivers CANDU/PWR solutions:

–MACSTOR (Waste Mgmt.)

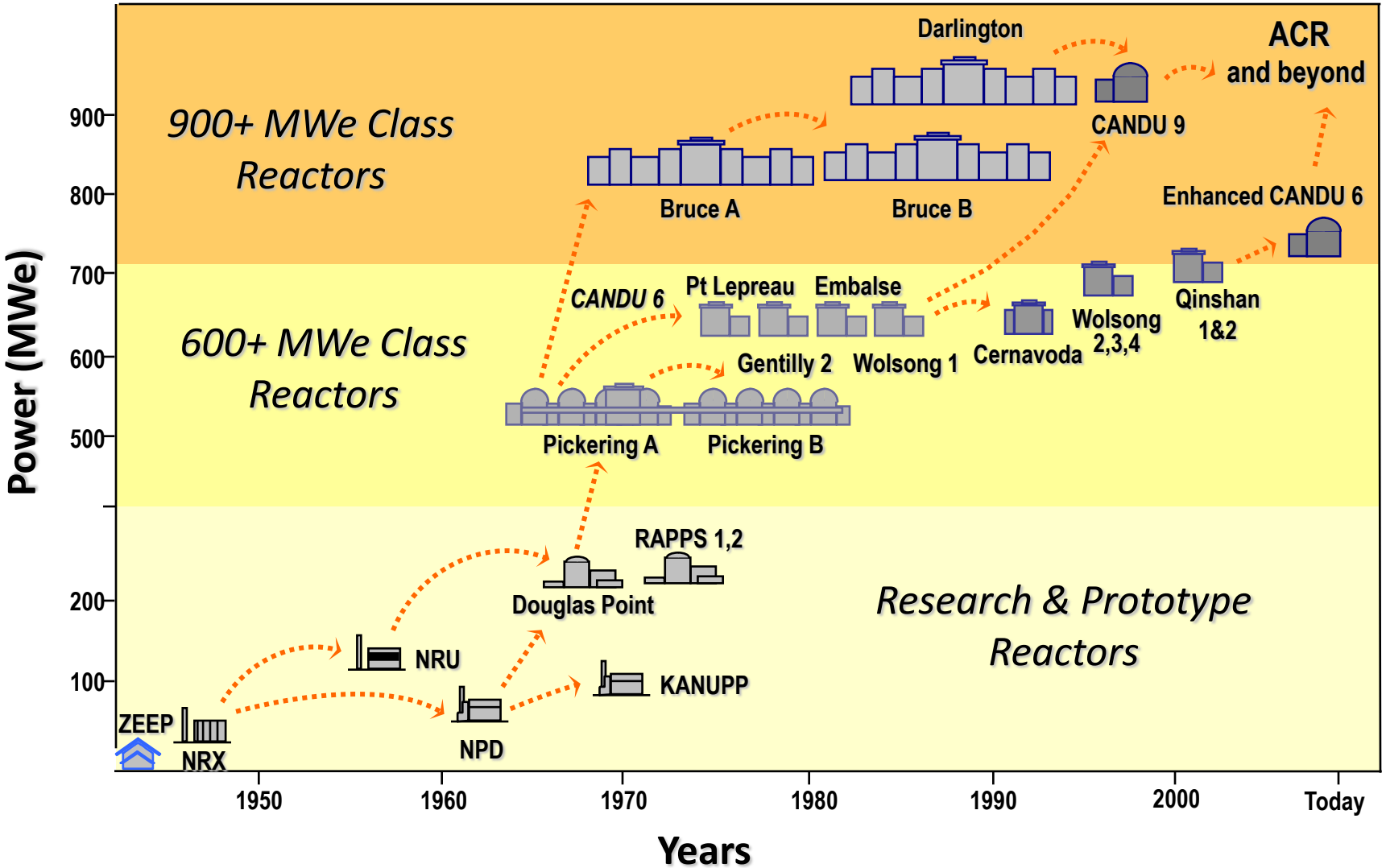
–ECC Strainers

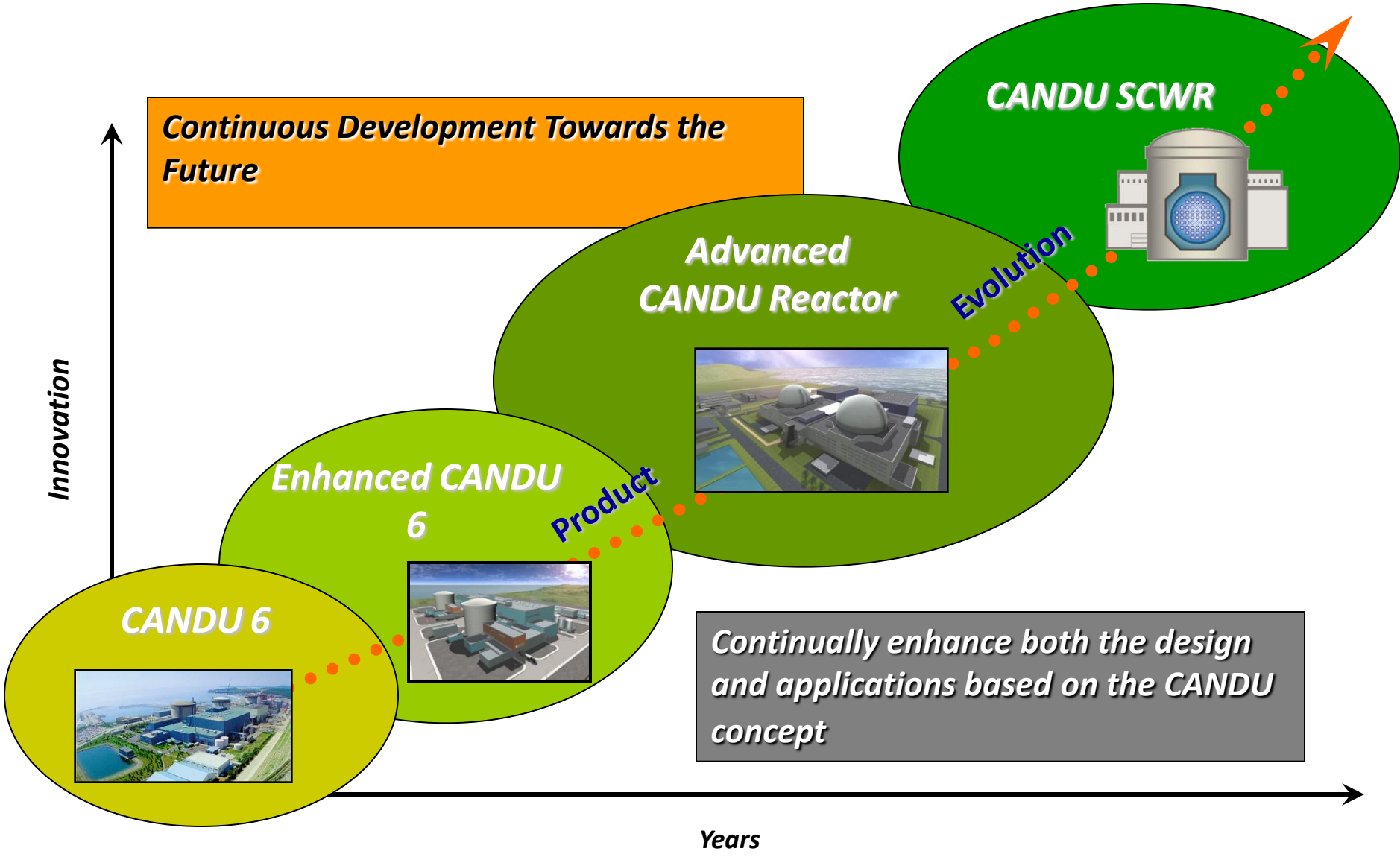
–Pump Seals

–Hydrogen Recombiners

MACSTOR 200

CANDU Development: A Strong History




Continuous Development Towards the Future
CANDU SCWR
Advanced CANDU Reactor
Evolution
Enhanced CANDU 6
Product
CANDU 6
Continually enhance both the design and applications based on the CANDU concept
Innovation
Years

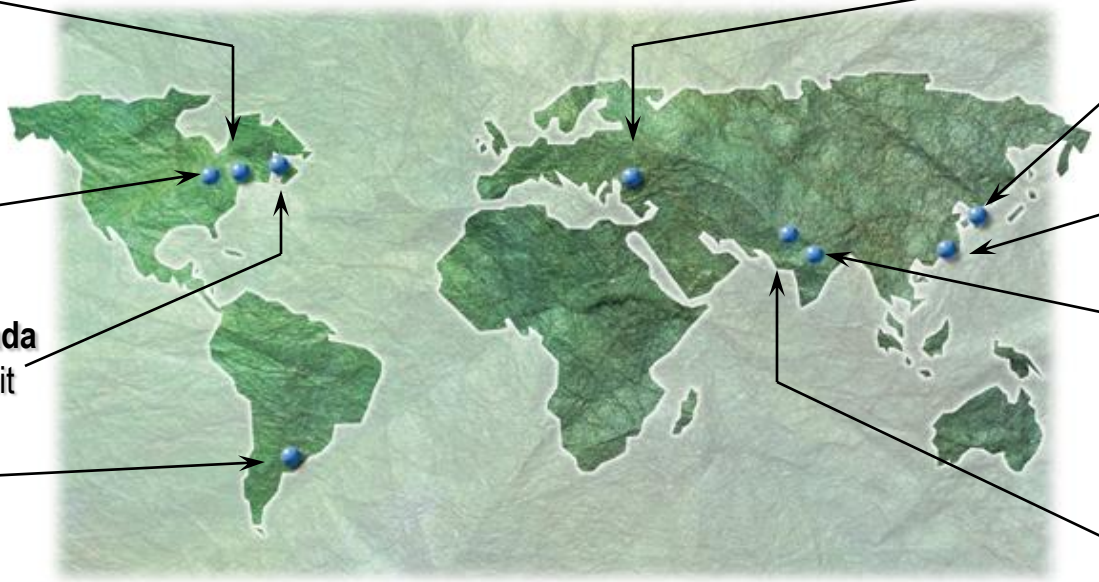
CANDU – A Global Success

Quebec, Canada
Gentilly 2 1 unit

Ontario, Canada
Darlington 4 units
Pickering 6 units
Bruce 8 units

N.Brunswick, Canada
Point Lepreau 1 unit

Argentina
Embalse 1 unit



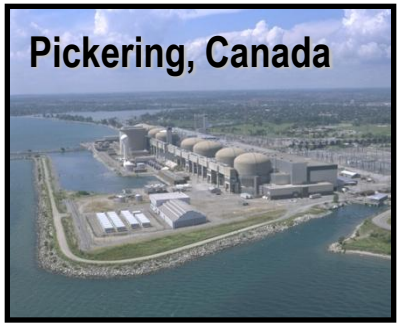
Romania
Cernavoda 2 units
+ 2 units planned

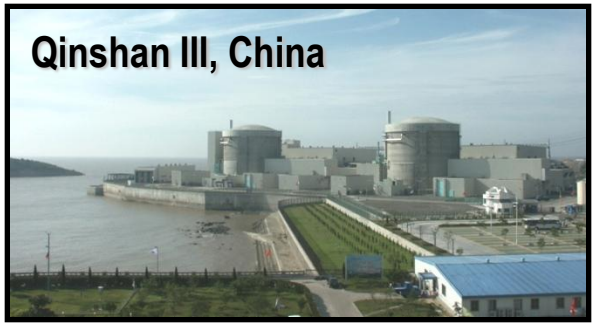
South Korea
Wolsong 4 units

China
Qinshan 2 units

India
2 CANDU units
15 PHWR units,
3 units under construction

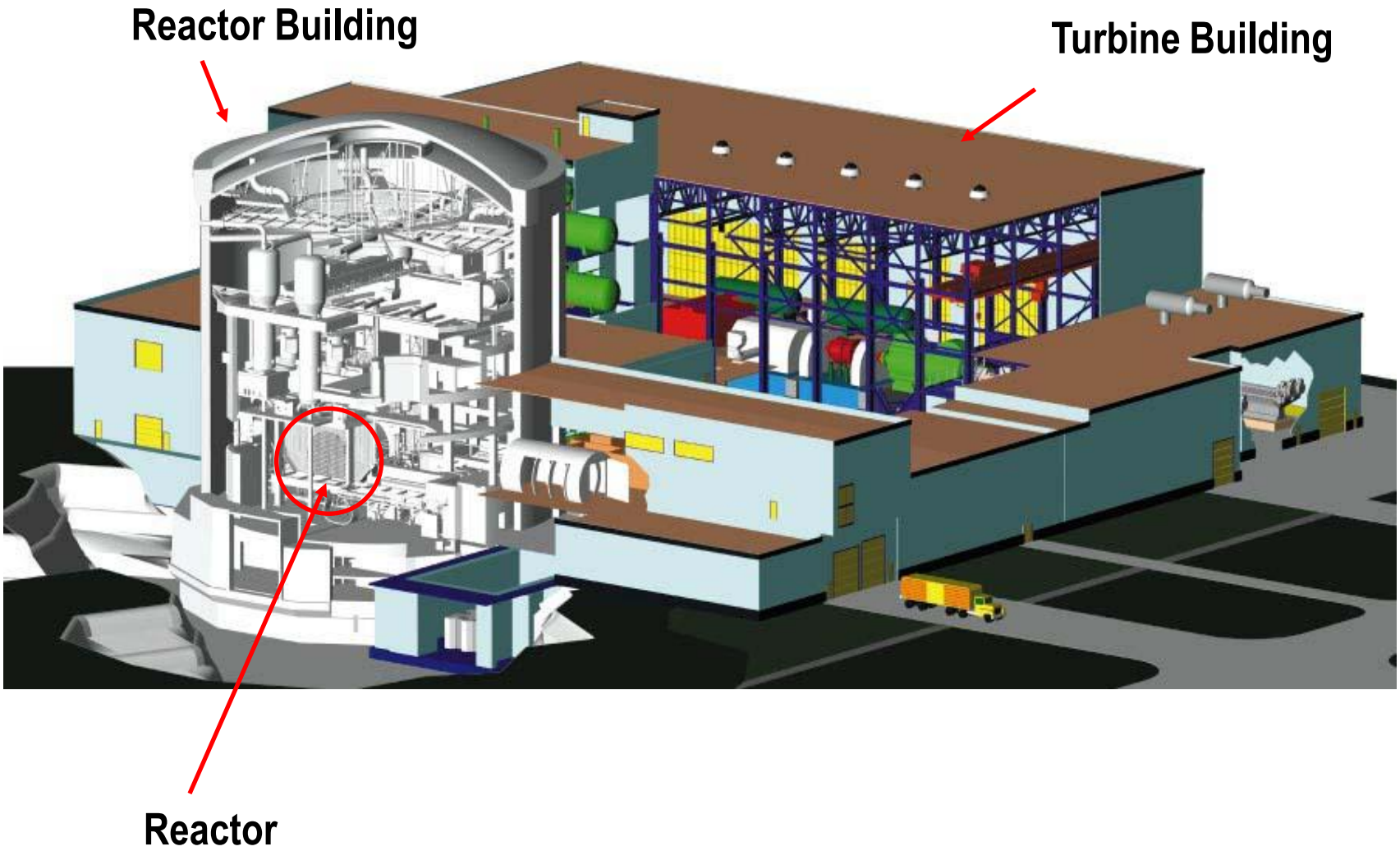
Pakistan
KANUPP 1 unit



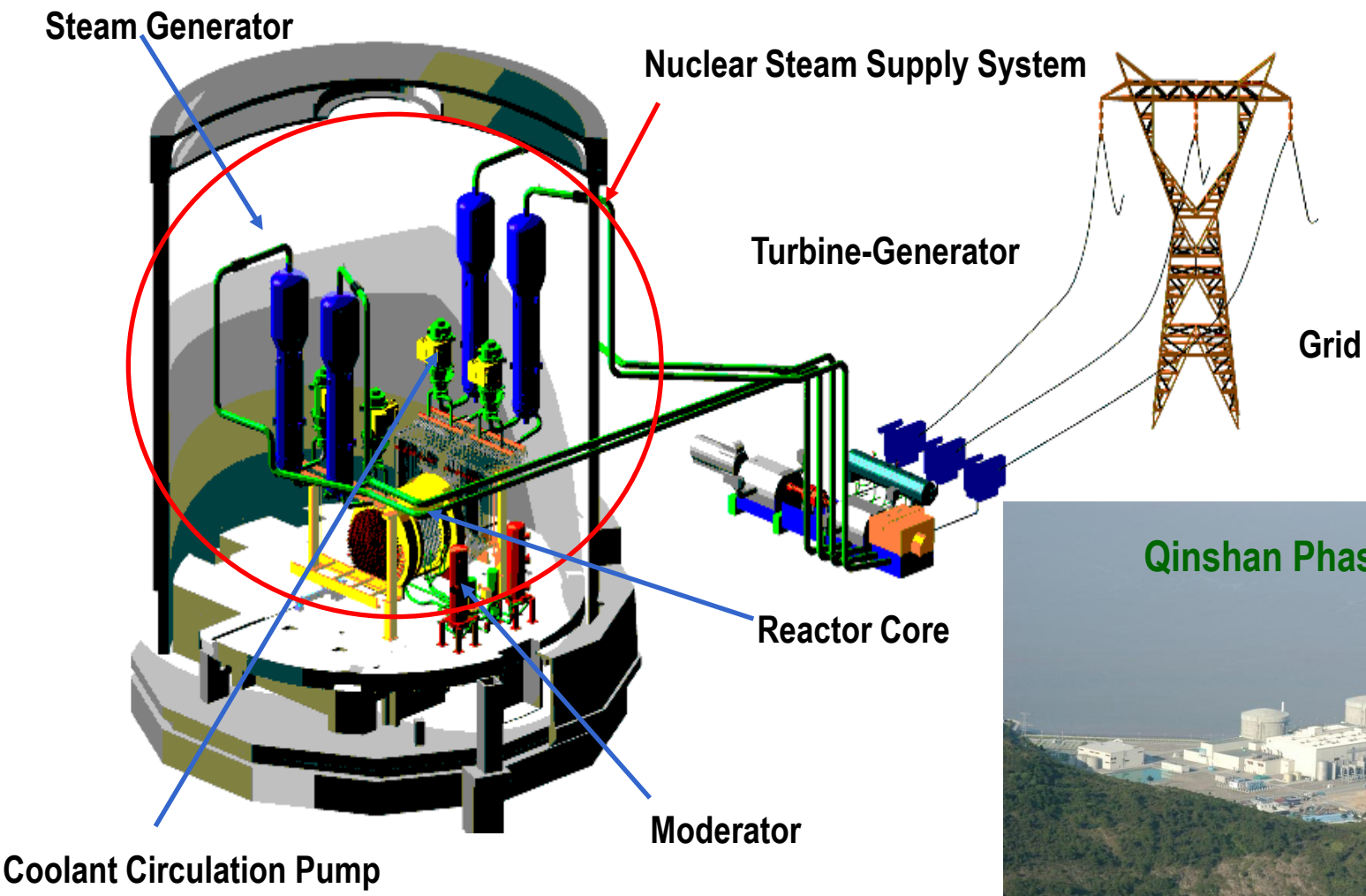


2. CANDU – PHWR Design Features

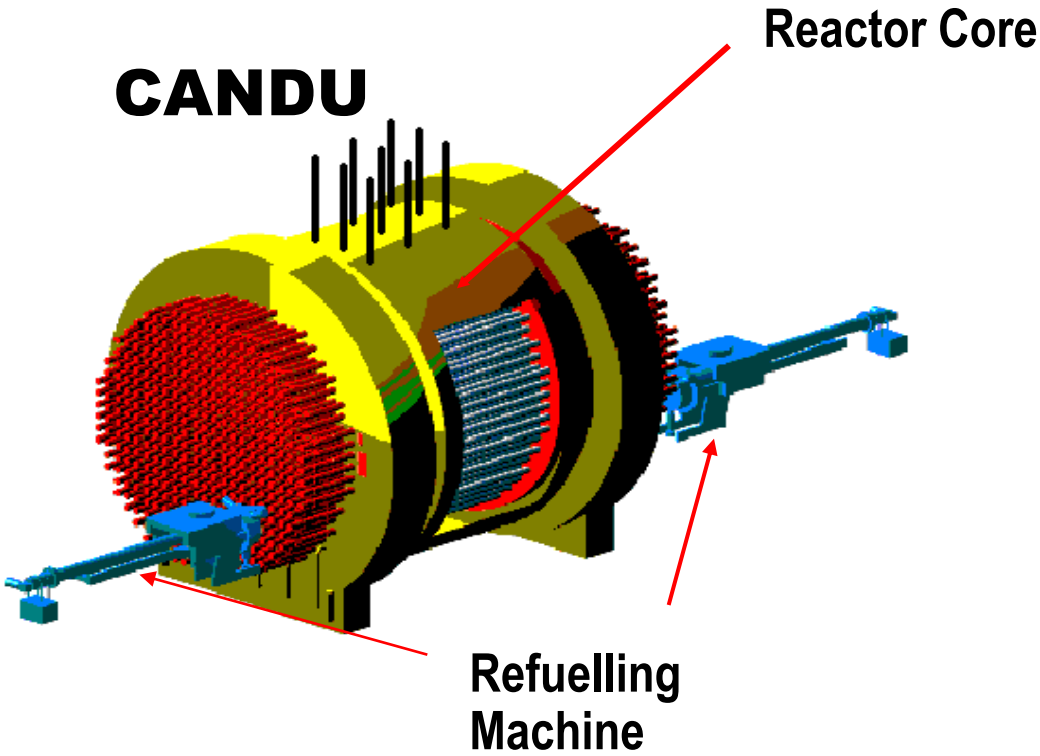
CANDU 6 (740MWe)

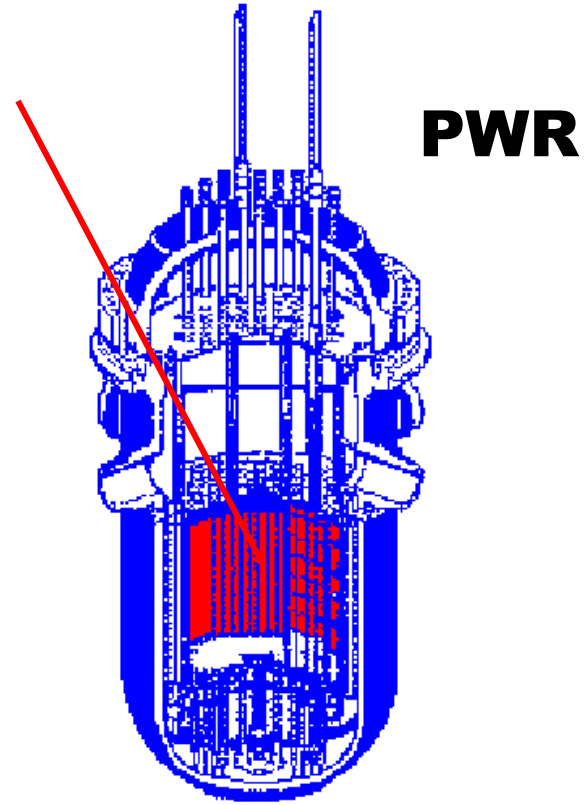

Reactor Building
Turbine Building
Reactor

Elements of CANDU NPP Plant



Pressure Tube Comparison with Pressure Vessel Reactor Cores



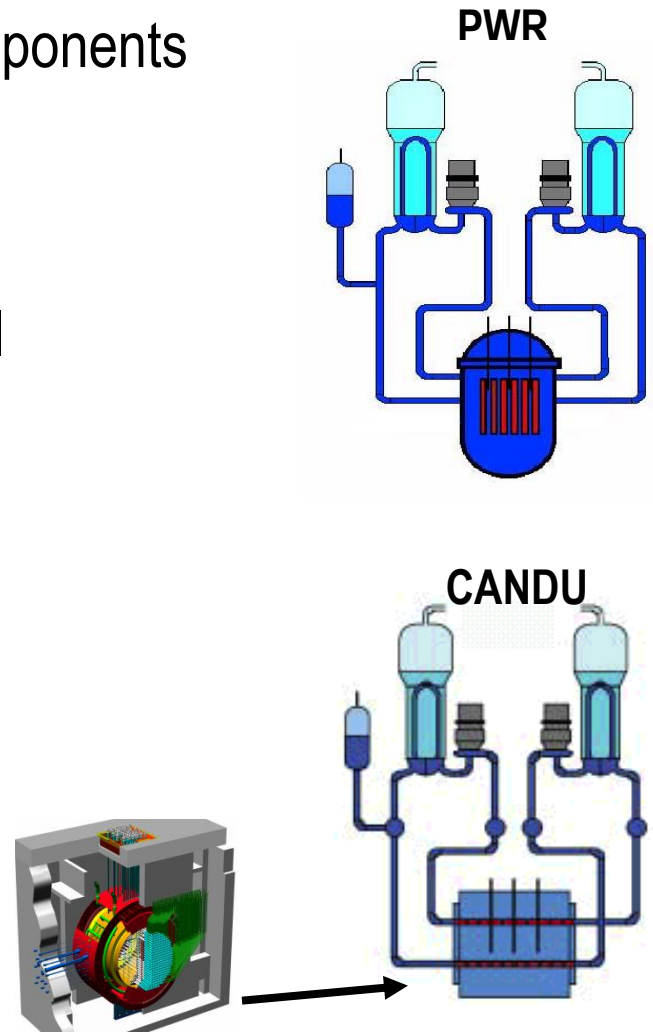


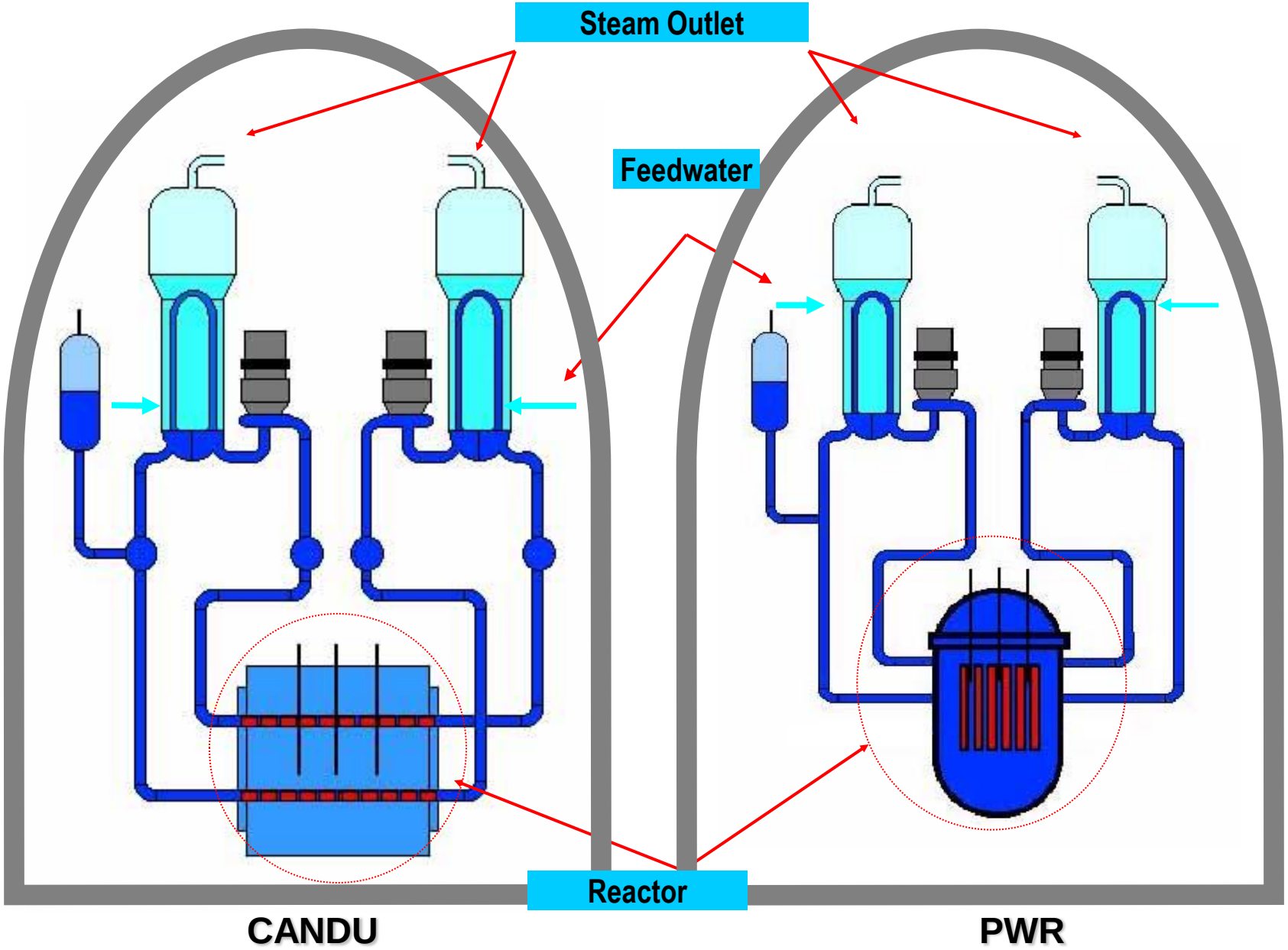
Modular reactor core consisting of many small diameter pressure tubes which contain fuel and coolant

Integral pressure vessel core which contain all fuel assemblies and coolant as well as reactor

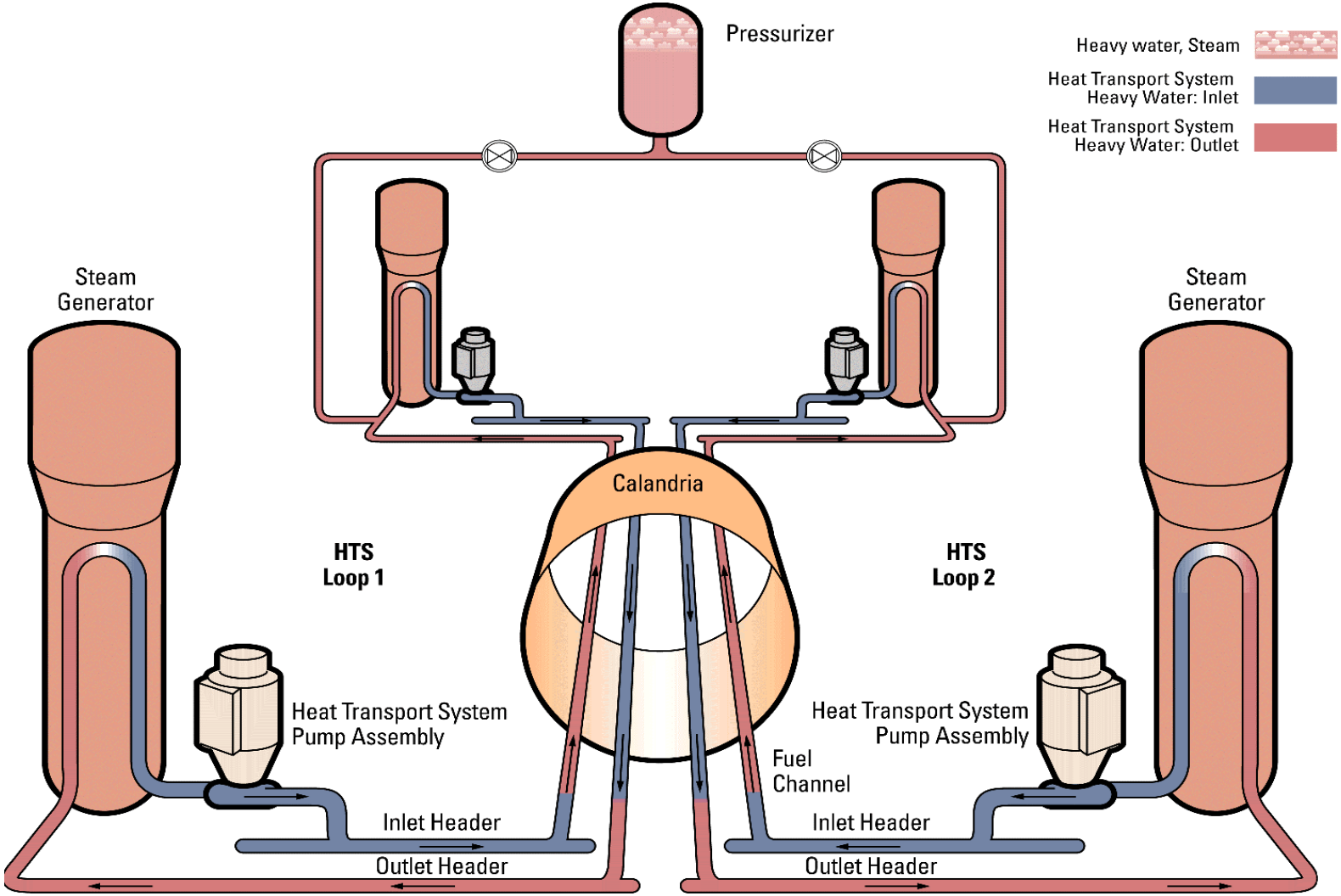
CANDU: Pressure Tube PWR

- Basic system principle and most plant components same as conventional PWR plant
- Five Key CANDU features
  - **Modular core consists of many small diameter pressure tubes**
  - **Heavy water coolant and moderator**
  - **Simple and short fuel bundle**
  - **On-power refuelling**
  - **Fuel cycle flexibility**

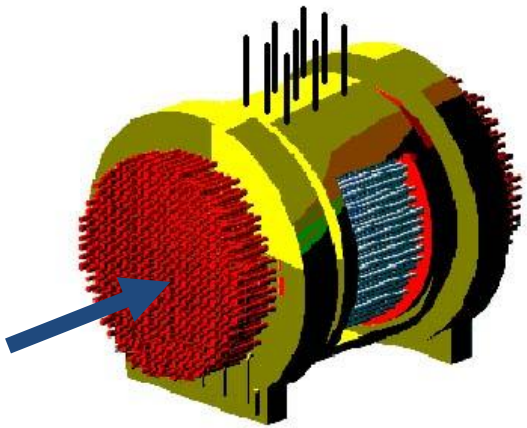


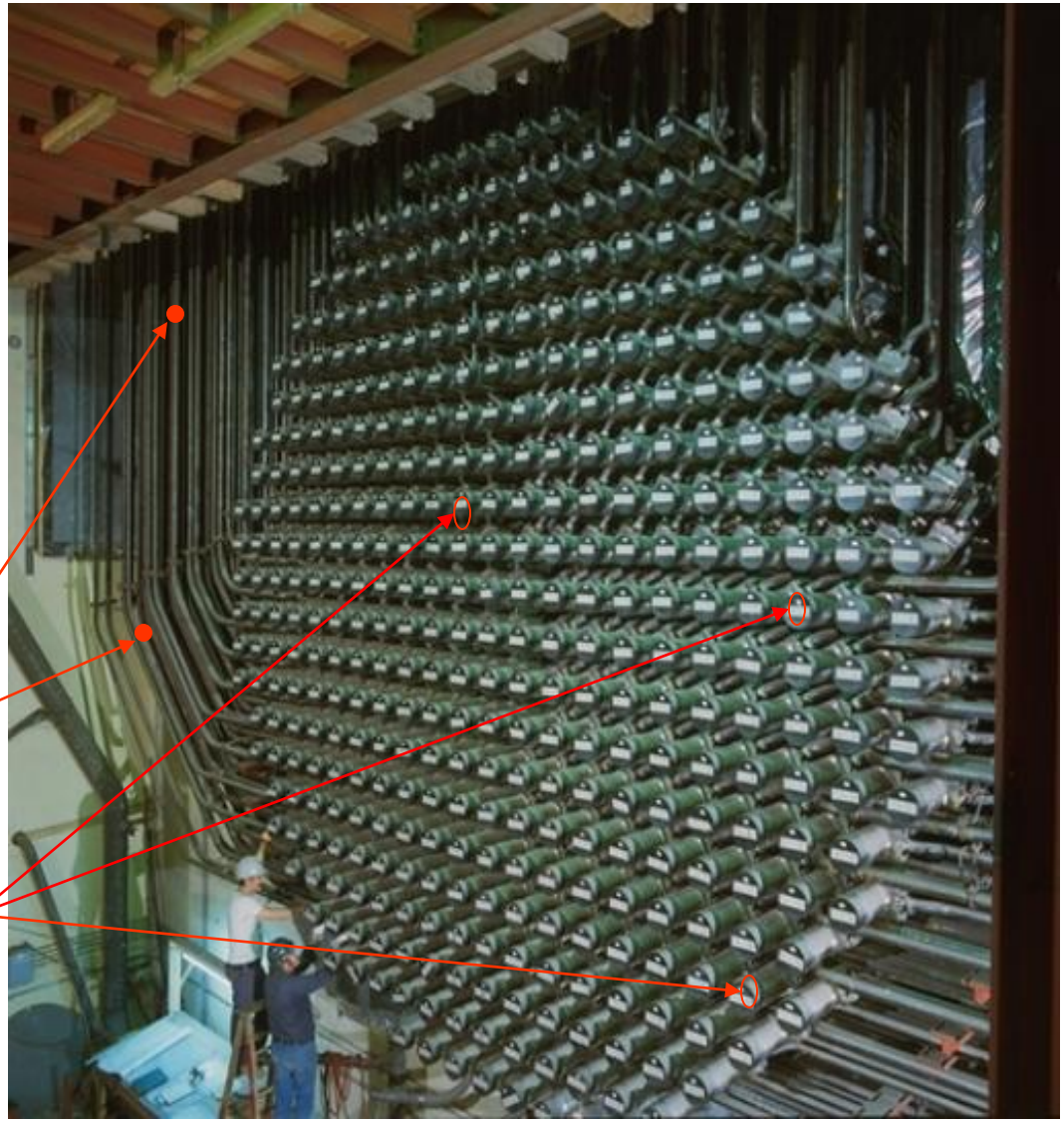

Steam Outlet
Feedwater
Reactor
CANDU
PWR

Heat Transport System



Reactor Face

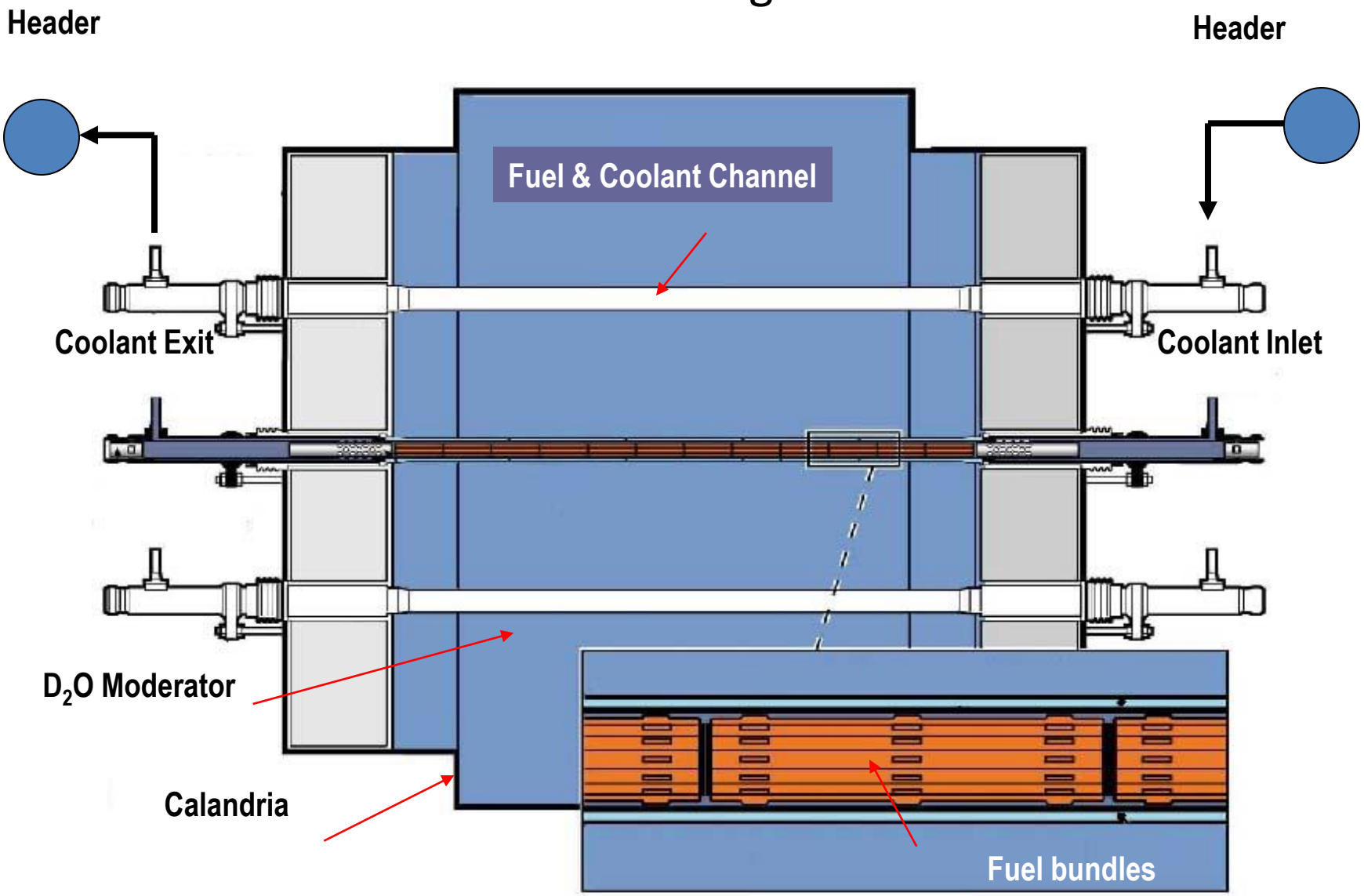




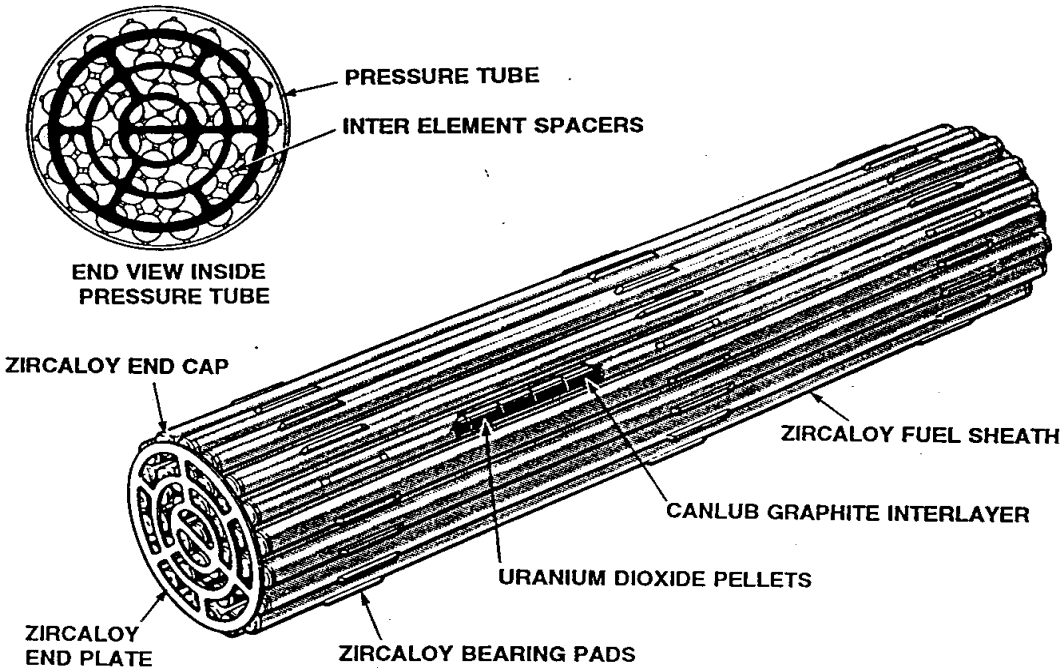
Feeder pipes

Channel closure

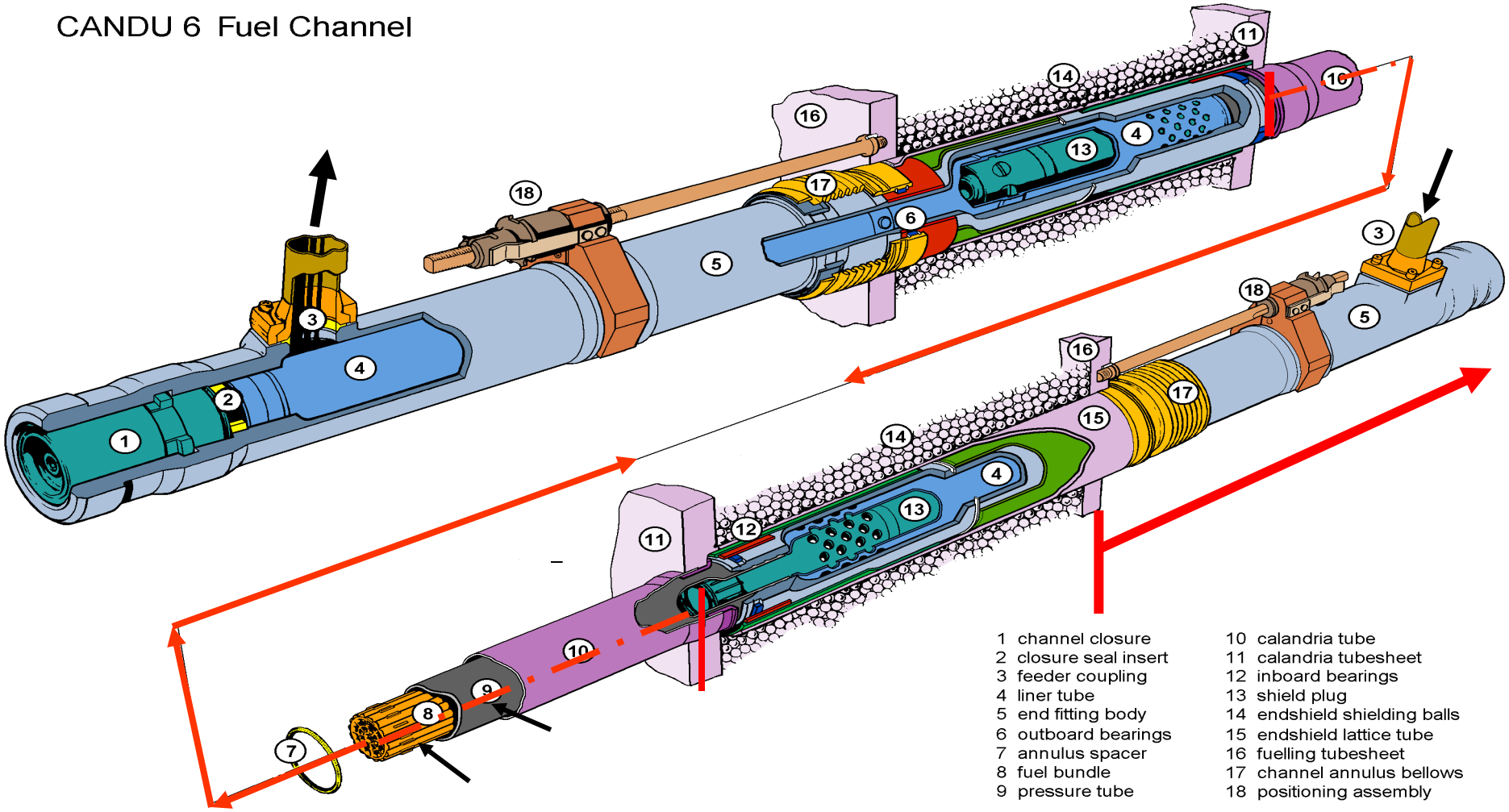
Schematic Diagram of Core



CANDU 37-Element Fuel Bundle



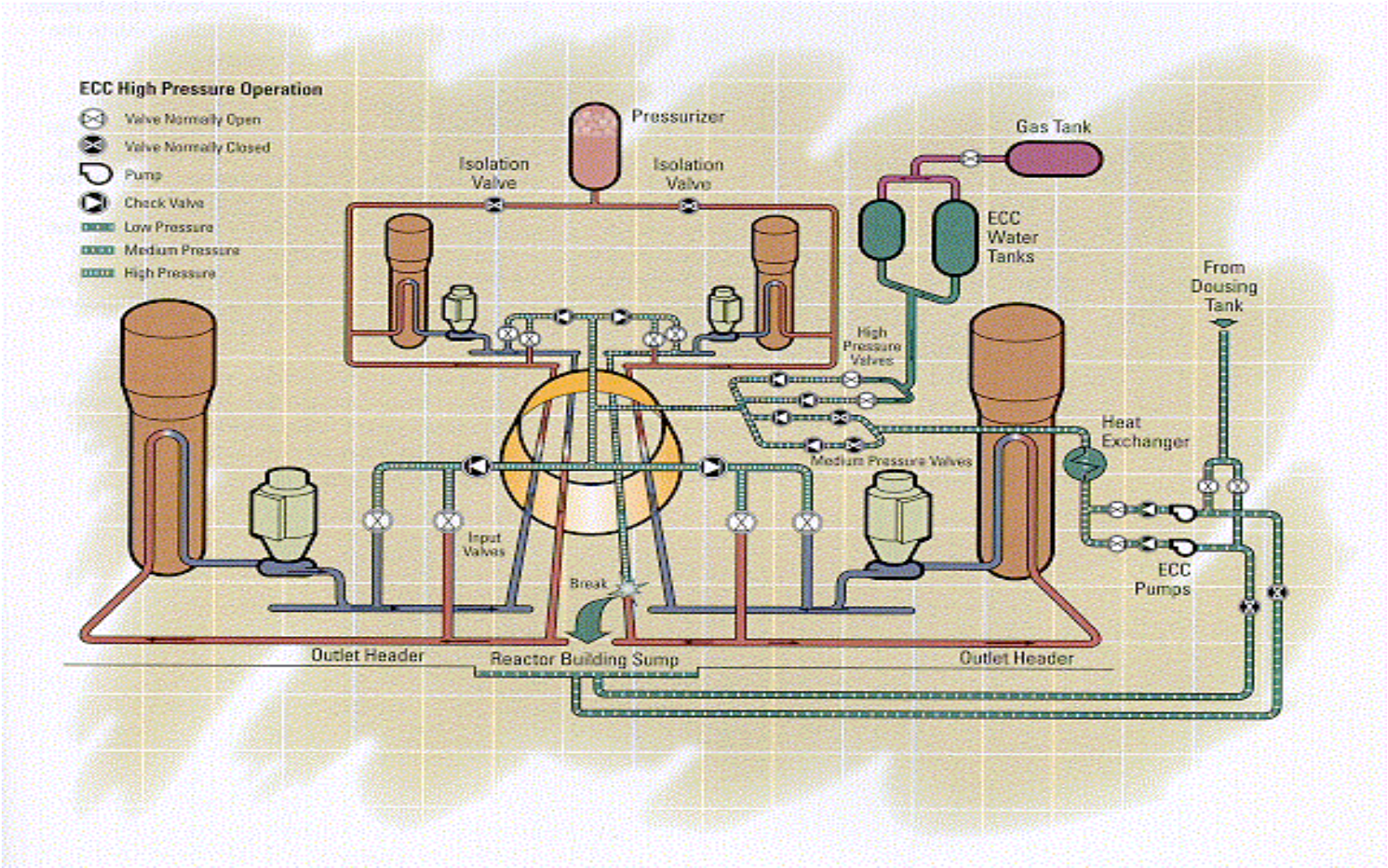
Fuel Channel Assembly



Emergency Core Cooling System

- All points injection into headers
- Three stages:
  - High pressure - external tanks
  - Medium pressure - dousing tank
  - Low pressure - building sump
- NOT the last line of defense
- CANDU can tolerate LOCA & ECCS failure

Emergency Core Cooling System (ECC)

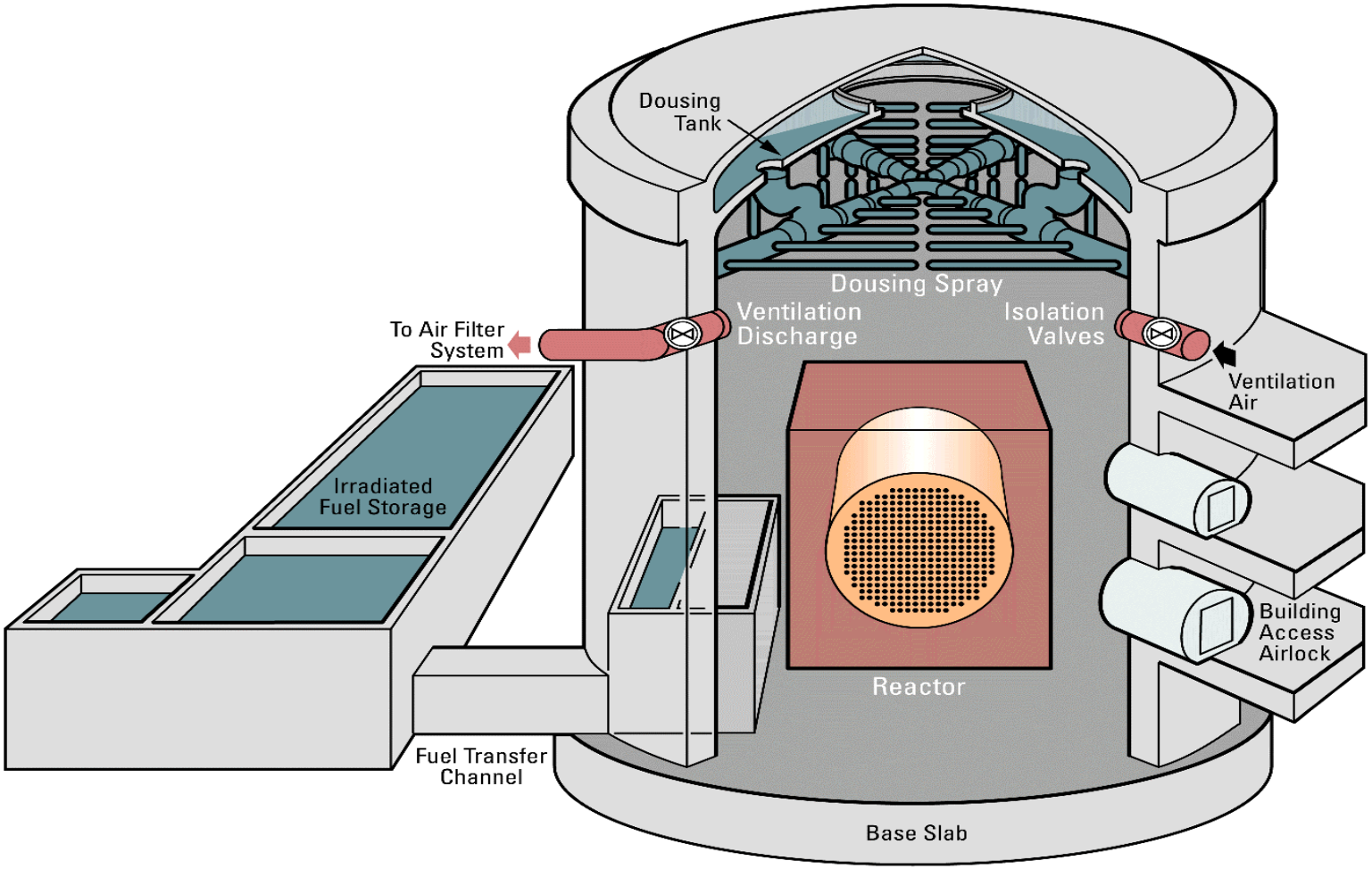


Containment of Radioactivity

- Containment defined as:

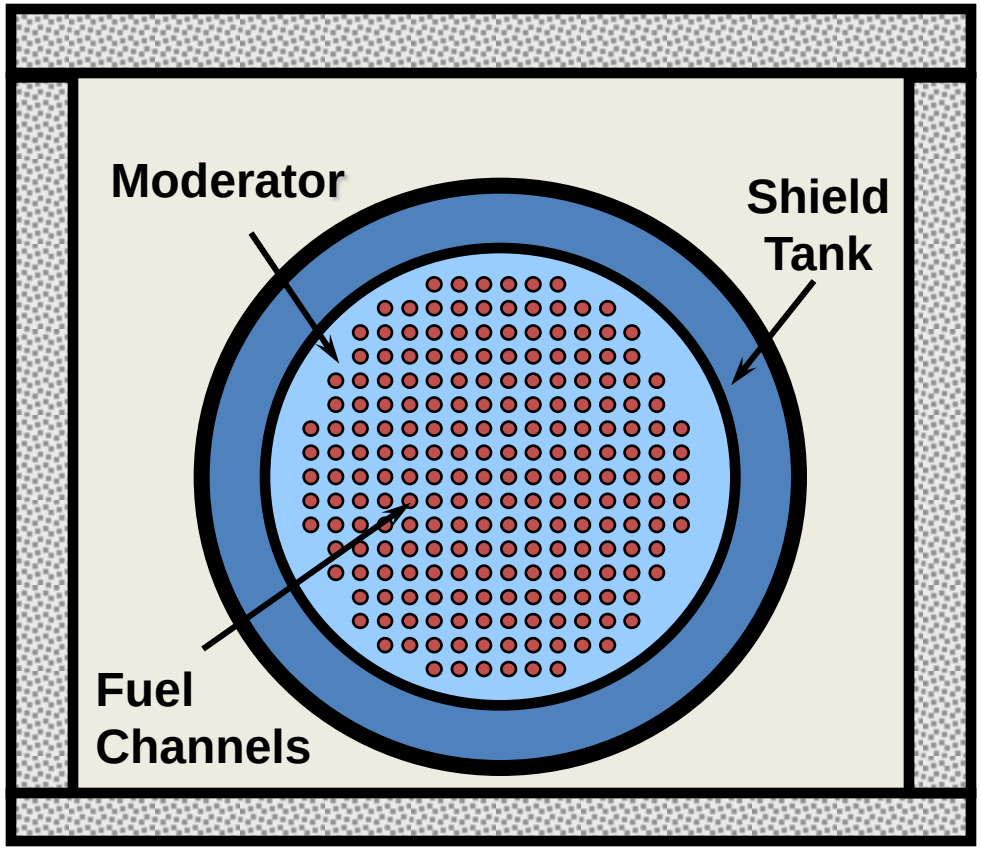
  Structure and supporting systems which provide the final barrier to limit radioactive releases to the environment to acceptable levels
- Containment is subdivided into:
  - Containment envelope R/B including extensions and penetrations
  - Containment penetrations and isolation
  - Atmosphere Control
    - Dousing system for pressure suppression
    - R/B Air Coolers for heat removal
    - Filtered Air Discharge (in the long term if required)

CANDU Containment Systems



Passive Heat Sinks: Inherent in Design

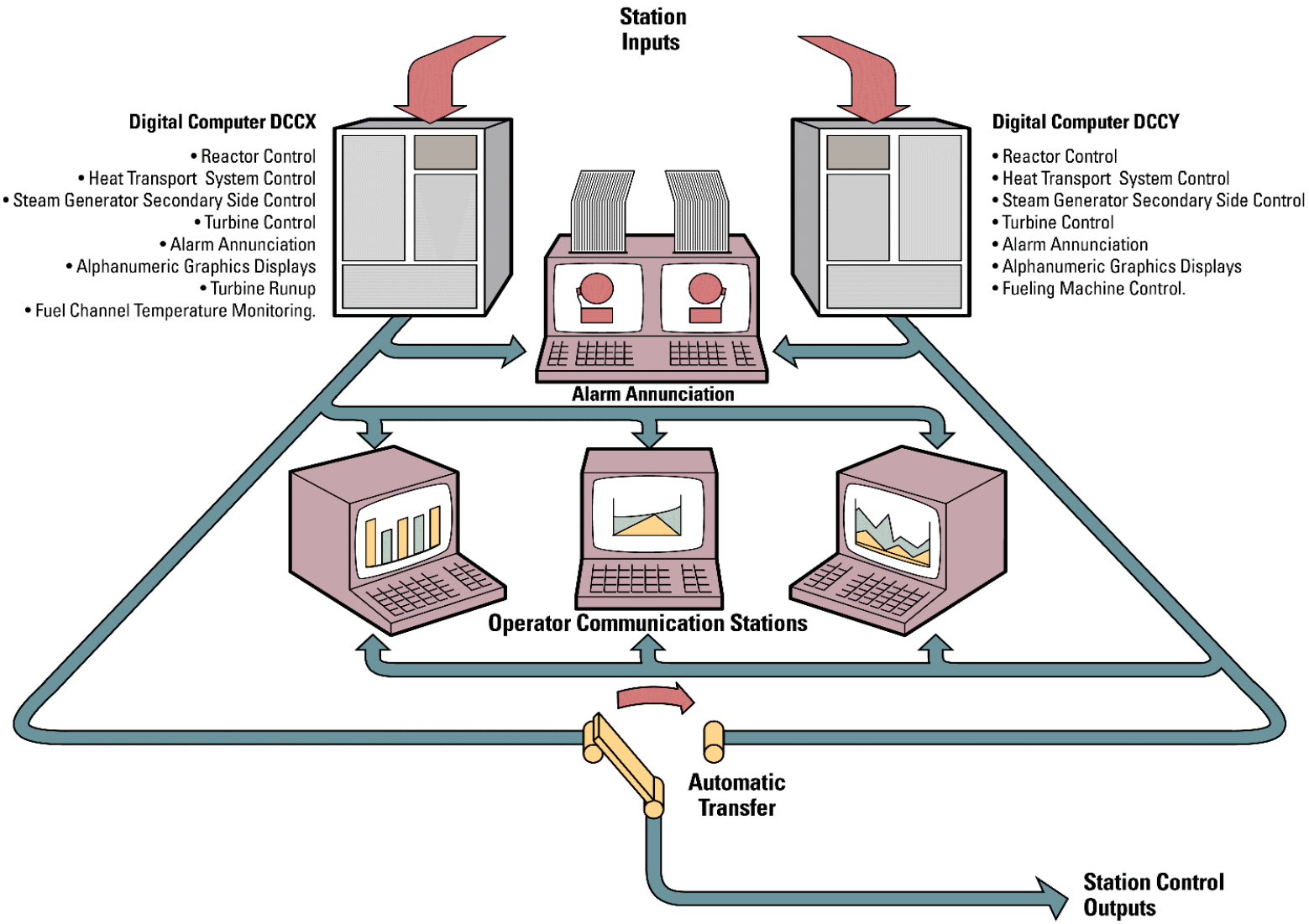
- Two large tanks of water surrounding the core with independent cooling systems
- Moderator water prevents fuel melting, even if emergency core cooling fails
- Shield tank contains debris in severe accident if moderator heat removal fails



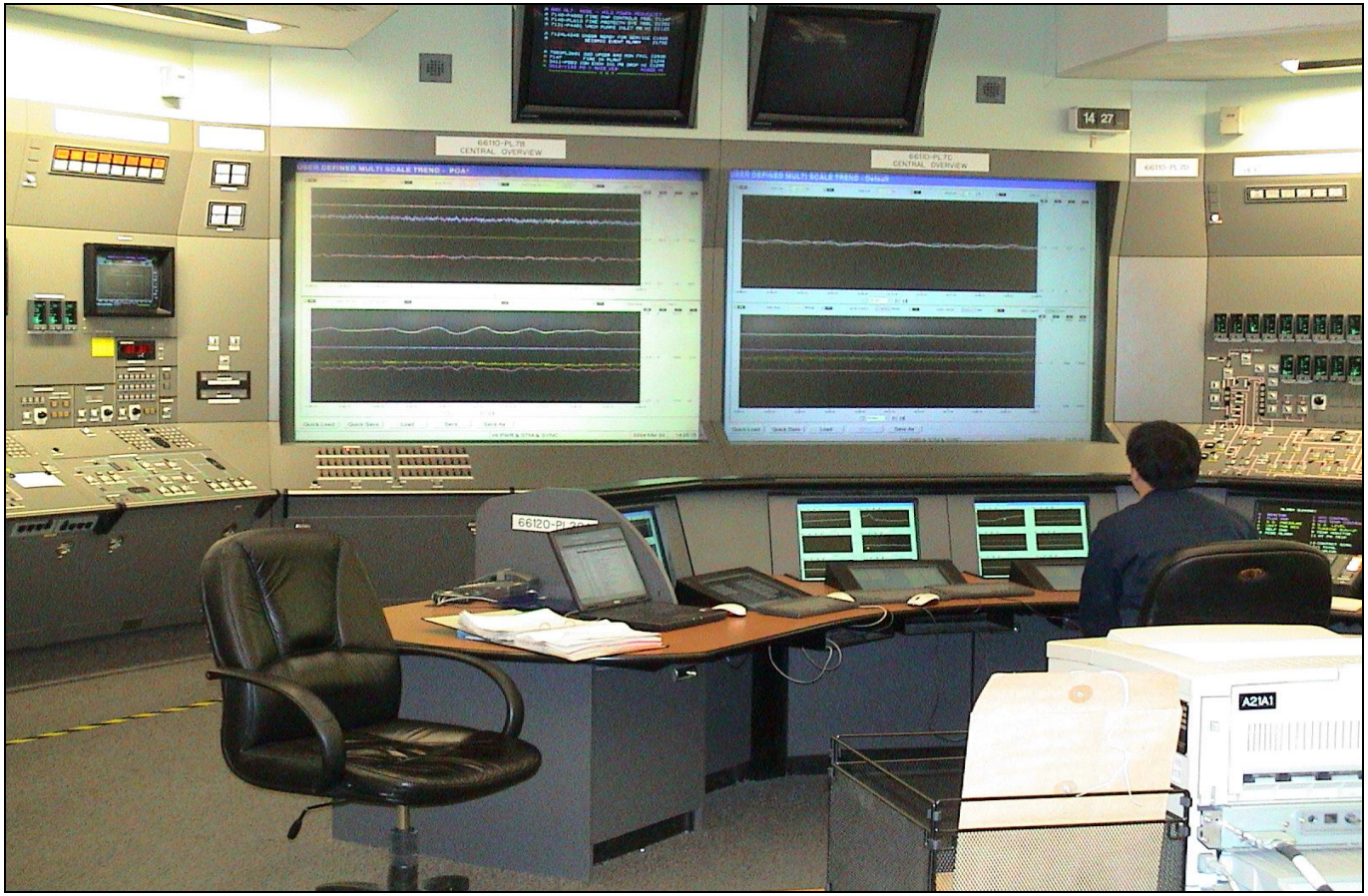
Computerized Reactor Control

- Dual computer system, each capable of station control
- Used for station control, alarm annunciation, graphic data display and data logging
- Availability > 99% (each)
- If both fail, station is automatically shut down

Station Instrumentation and Control



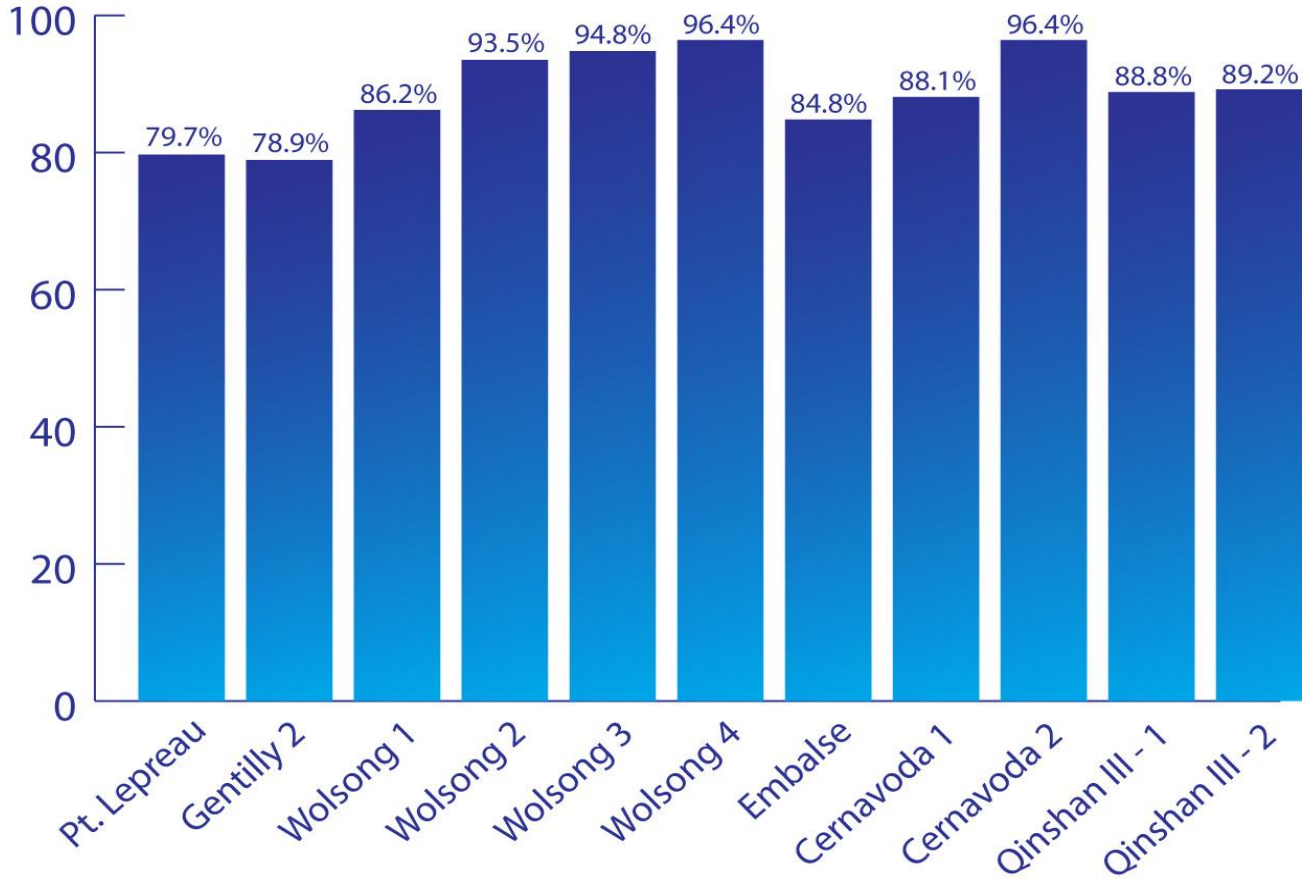
Qinshan Control Centre



Ergonomic operator console, touch displays, large screens, smart annunciation….

CANDU 6: Performance Excellence

- **89% average lifetime performance to December 2008**



Source: COG lifetime capacity factors to December 31, 2008

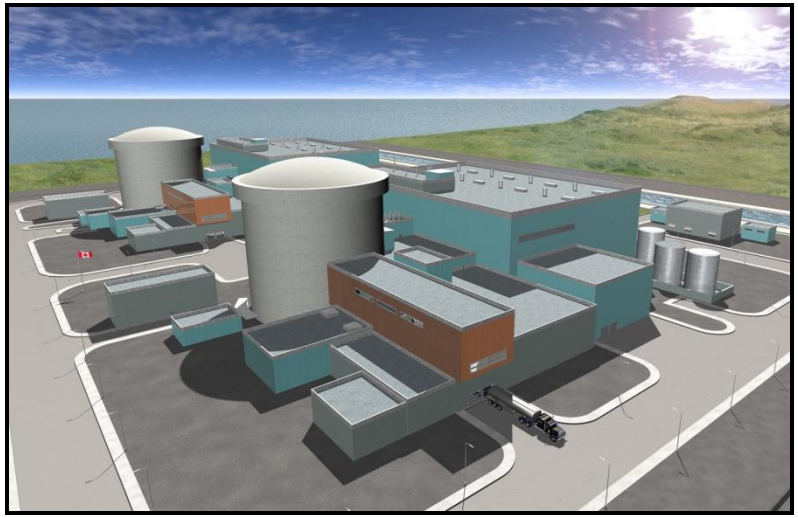
… that leads its peers

- **Korea**
  - 20 units operating > 1 year
  - 4 CANDU 6s, 16 PWRs
  - LCF rank to Dec 2007
    - CANDU # 1, 2, 3, 5
- **China**
  - 9 units operating > 1 year
  - 2 CANDU 6s, 7 PWRs
  - LCF rank to Dec 2007
    - CANDU # 1, 3

Lifetime Cumulative Capacity Factors reported by KHNP & CNNC

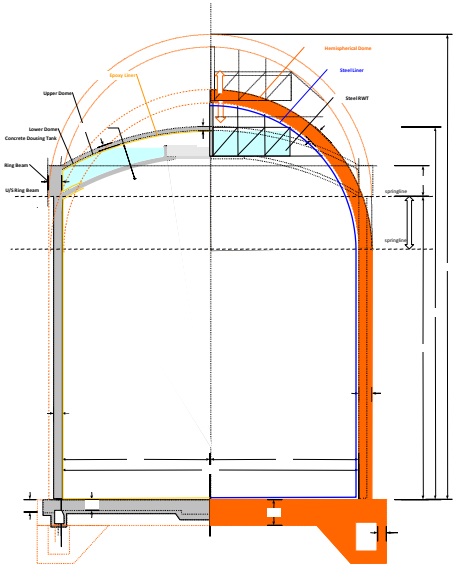
EC6: The Enhanced CANDU 6

- **Based on the Qinshan Phase III CANDU 6 plant in China**
- **Evolution of proven CANDU 6 design performing well on four continents; over 150 reactor-years of excellent, safe operation**
  - Heavy water cooled & moderated; natural uranium fuel
  - 700 MWe class
- **Improved economics**
- **Updated to latest codes, standards, and regulatory requirements**



EC6 Design Enhancements

- **Power uprate to 750 MWe (gross)**
  - Reduced pressure-drop across valves
  - Use of UFM (common uprate technique)
  - Improved turbine design
- **Reduced house load**
- **90% plant availability**
  - Reduced outage frequency & duration:
    - Improved on-line testing, increased parallel work, faster restart
- **60-year plant life**
  - Thicker pressure tubes, optimized chromium content in feeders
- **Enhanced containment**
  - Air-strike resistance, reduced leakage, improved testing
- **Updated control & D20 management**
- **Improved operating & safety margins**
- **Meets latest codes, standards, and regulations**

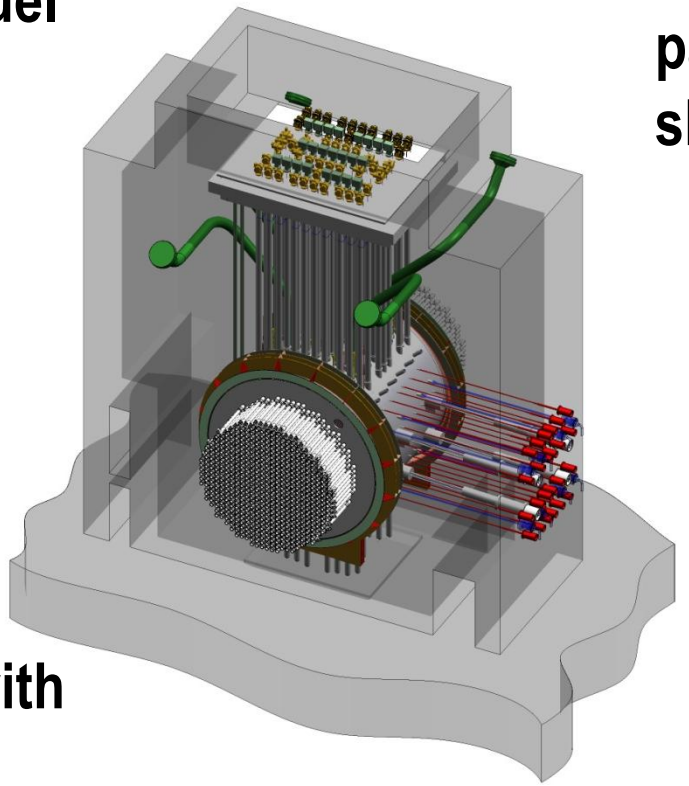


ACR 1000 Features

Retain Proven CANDU Strengths

Modular Horizontal Fuel Channel Core

Two independent passive fast shutdown system



Separate Low Temperature & Pressure Heavy Water Moderator

On-power Fuelling

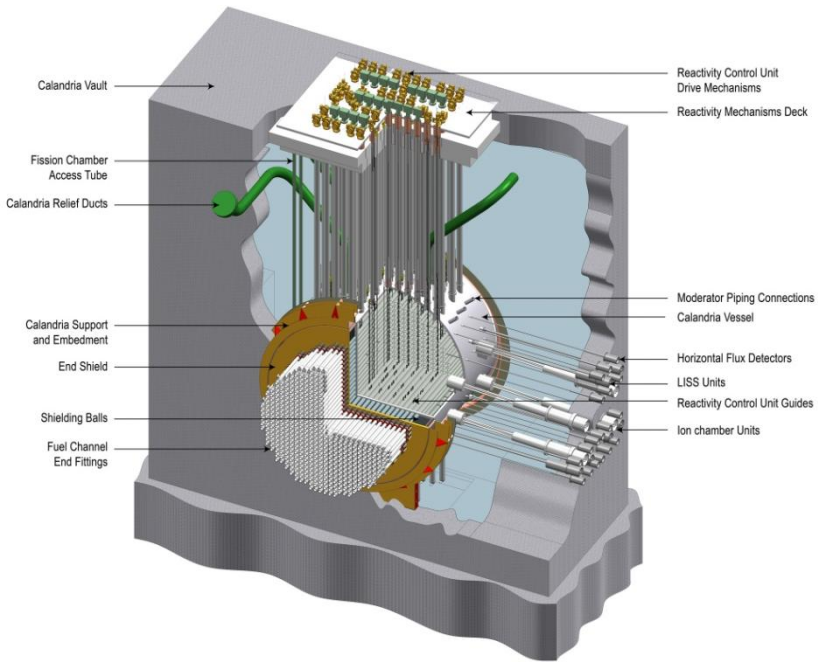
Reactor vault filled with shielding water surrounding the core

Simple fuel bundle

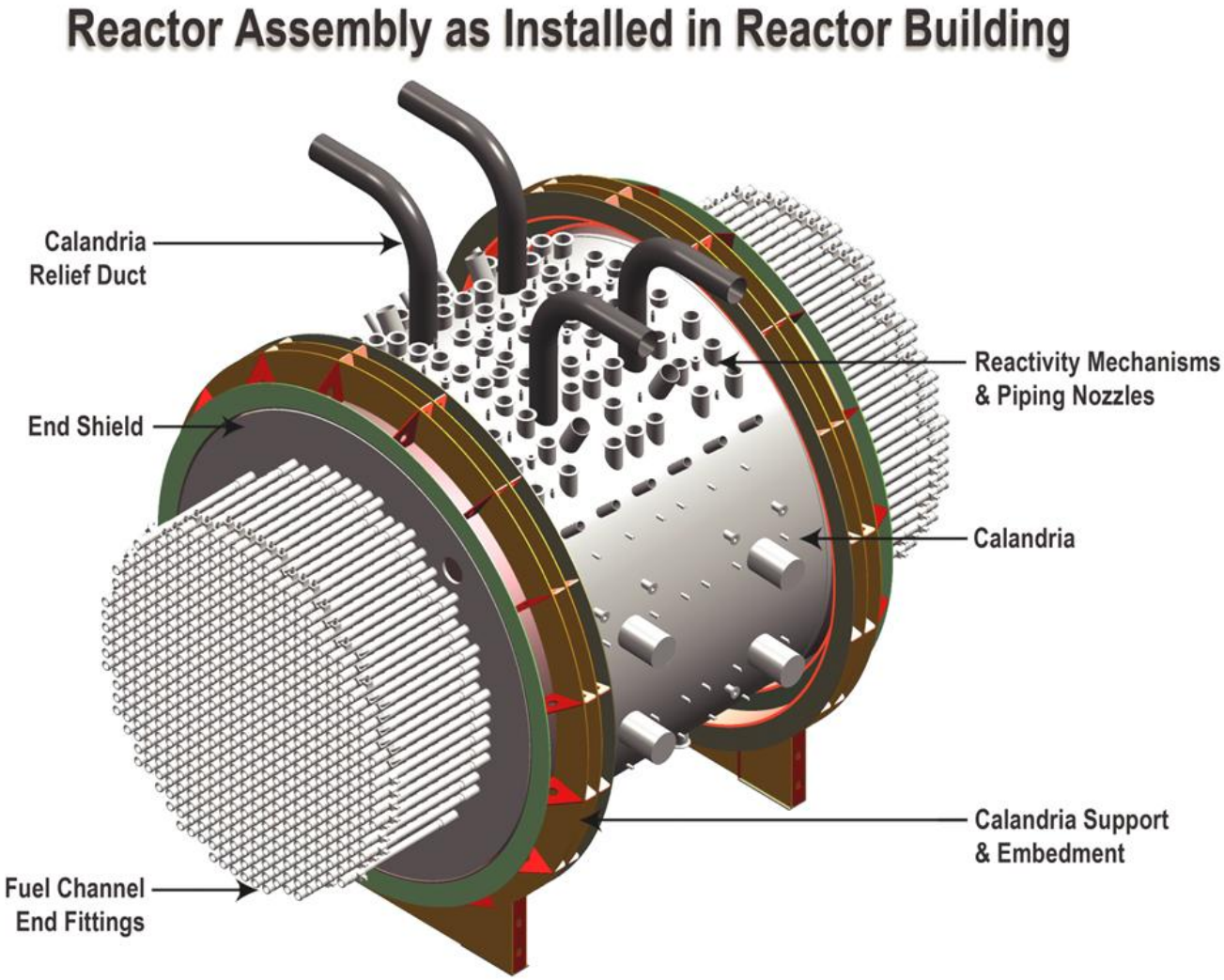
Key Innovative Features of ACR-1000

ACR-1000 incorporates design innovation and merges good features of both pressurized heavy and light water reactors

- **Uses SEU fuel (~ 2%U-235) and light water coolant**
- **Compact core & less heavy water**
- **ACR-1000, producing ~1100MWe (net)**
- **Higher reactor coolant pressure (~11.1 MPa) and secondary steam temperature and pressure (~ 275.5 ^{o}C / 5.9 MPa)**
- **Enhanced inherent safety features and improved performance**



Core

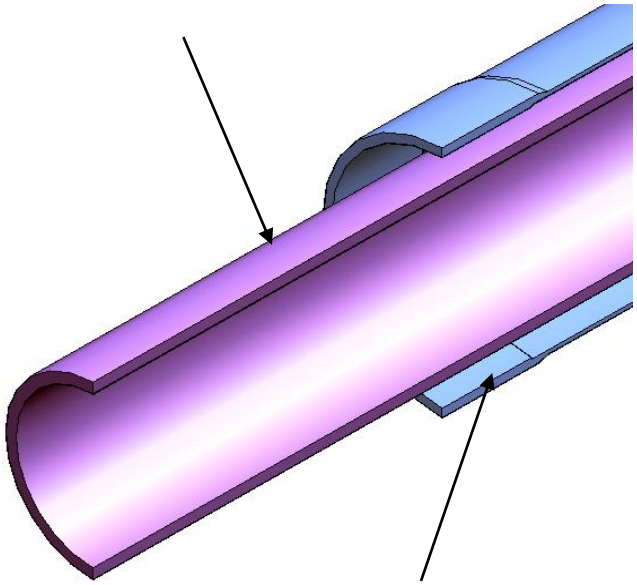

Reactor Assembly as Installed in Reactor Building
Calandria Relief Duct
End Shield
Fuel Channel End Fittings
Reactivity Mechanisms & Piping Nozzles
Calandria
Calandria Support & Embedment

Fuel Channels

- Zr 2.5wt% Nb alloy
- PT wall 50% thicker for 30 year operation:
  - Lower creep and sag
  - Increased strength to improve safety margins
- CT is larger diameter (160mm), thicker and stronger
- Failure of a pressure tube will not lead to CT failure

Pressure Tube

104 mm ID x 6.5 mm thick wall x Approx 6.5 m long



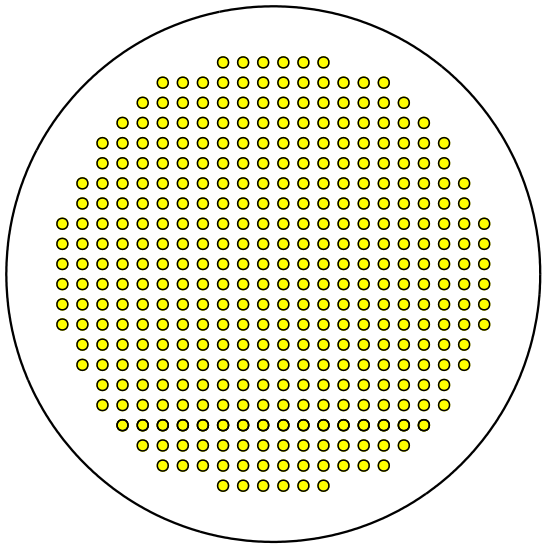
Calandria Tube

Body: 2.5 mm thick wall

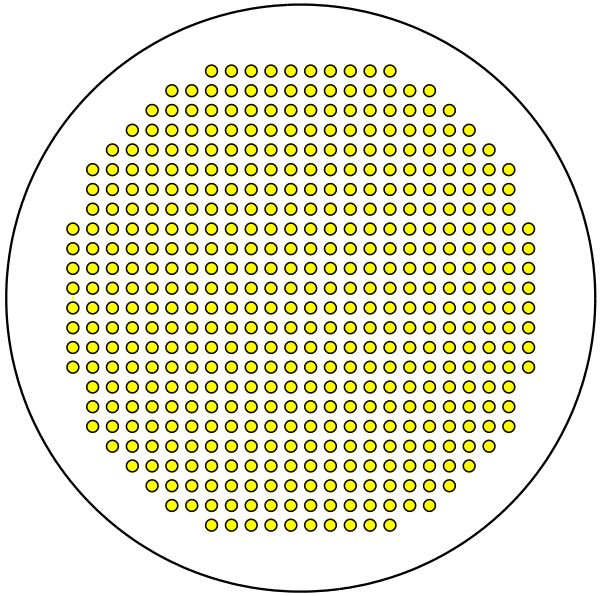
Ends: 4.5 mm thick wall

Length: approx 6m

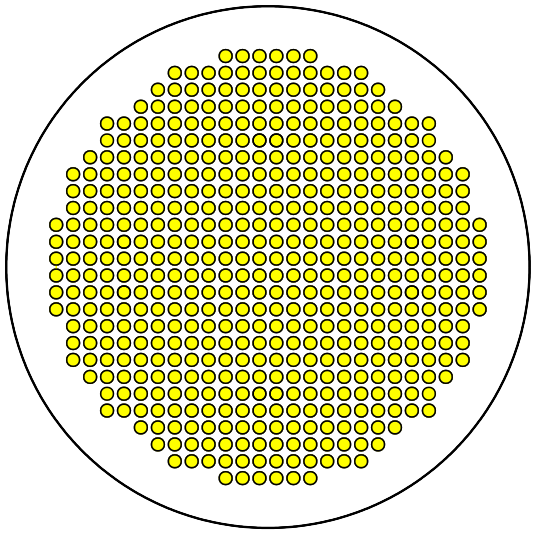
Reactor Core Size Comparison



CANDU 6, 728 MWe



Darlington, 935 MWe

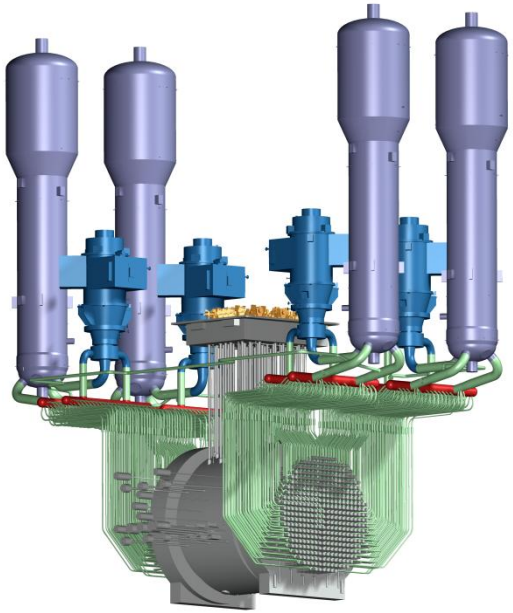


ACR-1000, 1165 MWe

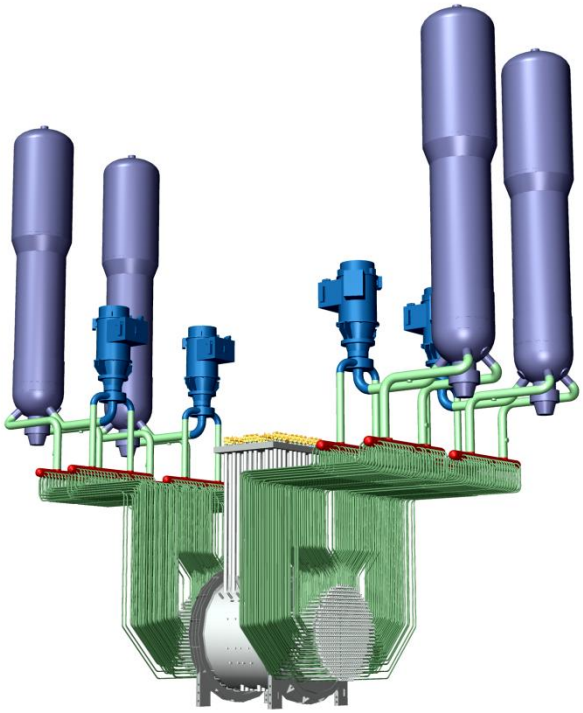
	CANDU 6	Darlington	ACR-1000
Number of Channels	380	480	520
Reactor Core Diameter	7.6	8.5	7.5
Lattice Pitch	286	286	240
Volume of D_20 in Moderator (m^3)	265	312	235
Volume of D_20 in HTS (m^3)	192	280	0
Total Volume D_20 (m^3)	466	602	240

- **Calandria 7.5m (similar to CANDU 6)**
- **Lattice 24 x 24 cm**
- **Heavy water hold-up reduced**

Proven HTS Equipment and Same Configuration as Darlington and CANDU 6



CANDU 6

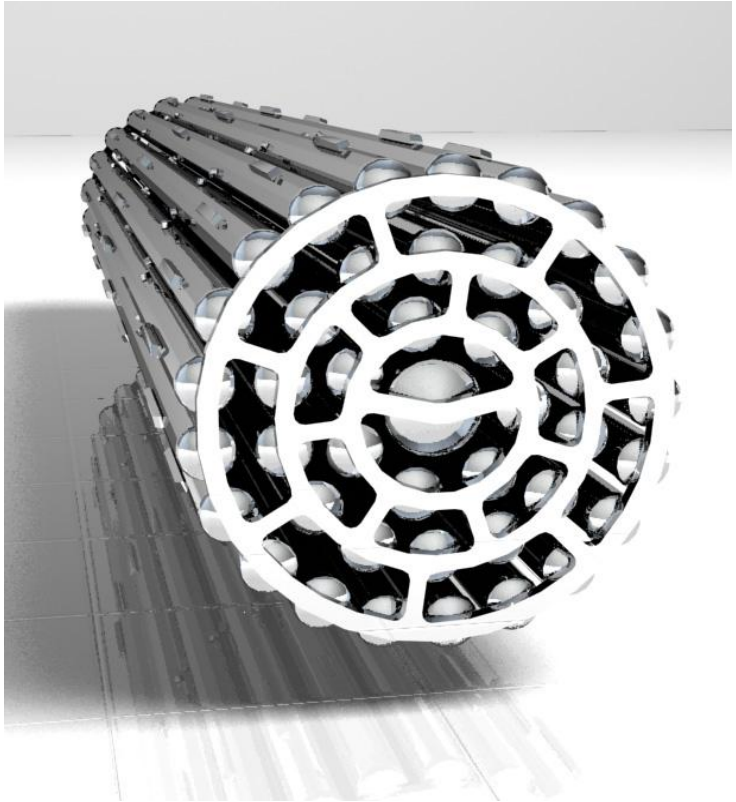


ACR-1000

	CANDU 6	Darlington	ACR-1000
No. of Loops	2	2	2
No. of HT Pumps	4	4	4
No. of SGs	4	4	4
No. of Headers	4 RIH, 4 ROH	4 RIH, 4 ROH	4 RIH, 4 ROH

Fuel

- 43-element CANFLEX fuel bundle
  - Same diameter and length as CANDU Classic
  - Greater subdivision for higher thermal margin
  - 42 elements contain 2.4 wt% LEU
  - Larger centre element contains yttrium-stabilised matrix of Zirconium oxide + Dy_2O_3 + Gd_2O_3 to produce slightly negative coolant void reactivity
- Reference burn-up ~20,000 MWd/te, higher in future



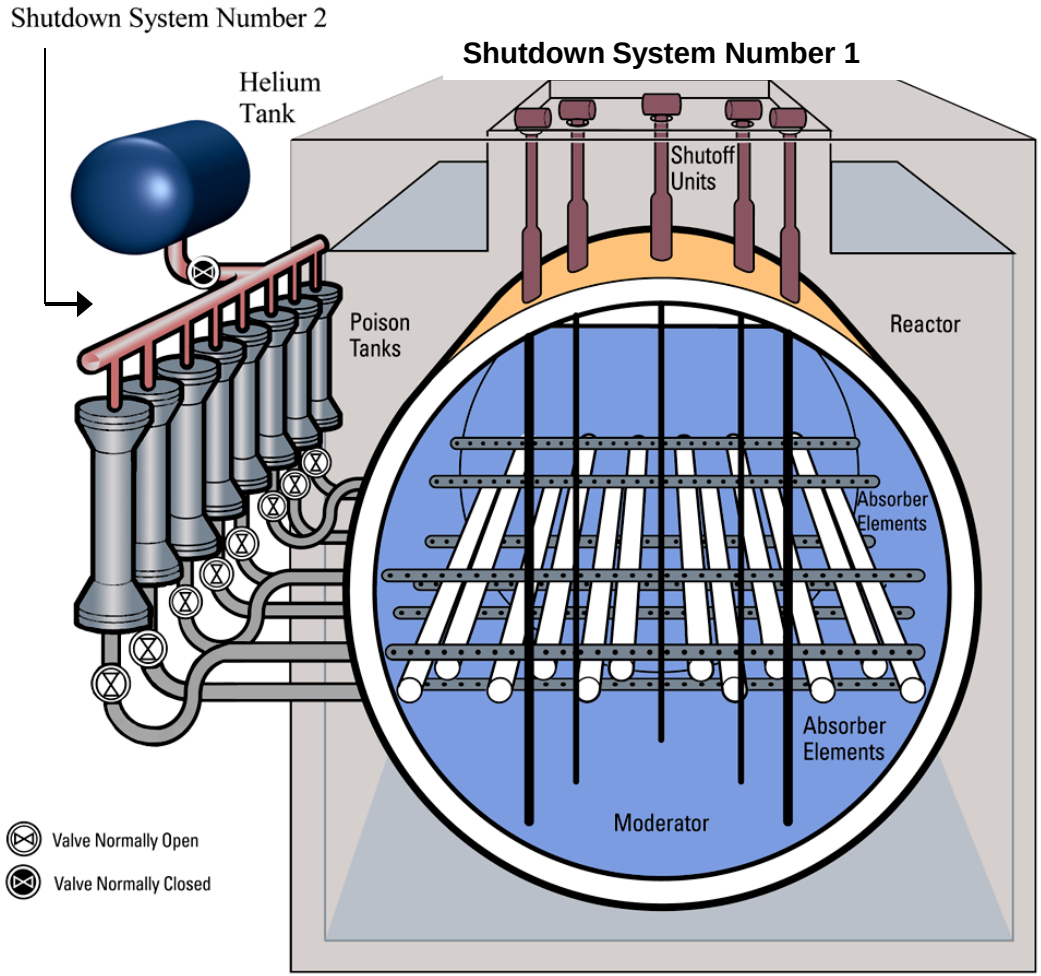
Safety Enhancements

- Protect the Core
  - Core damage probability reduced to ~3×10^{-7} events/year
  - Redundant heat sinks, defense in depth
  - Improved operator interfaces
- Use passive systems
  - High degree of reliability
  - Reduced testing requirements
- Design for external events

Dual and Passive Fast Shutdown Systems

- **Shutdown System 1 (SDS1)**
  - **Shut-off rods fall vertically into the low pressure moderator by gravity drop**

- **Shutdown System 2 (SDS2)**
  - **Liquid neutron absorber injected horizontally by gas pressure into the moderator**

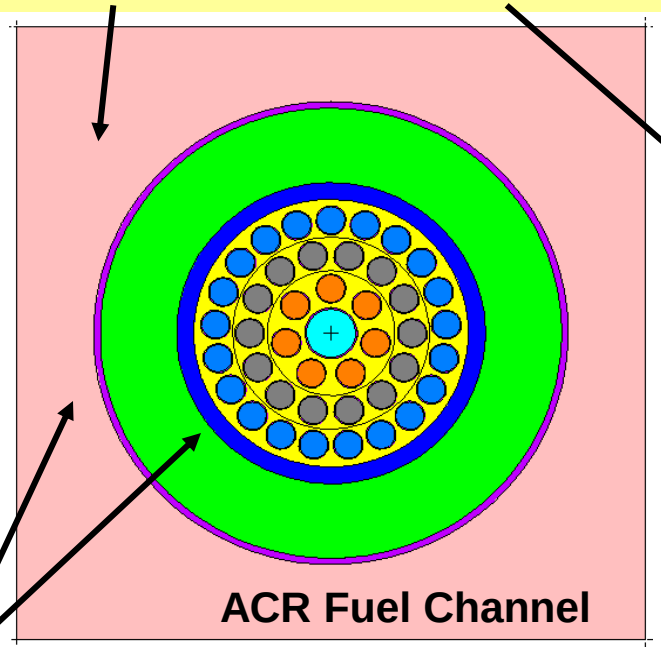


ACR-1000 Shutdown Systems 1 and 2

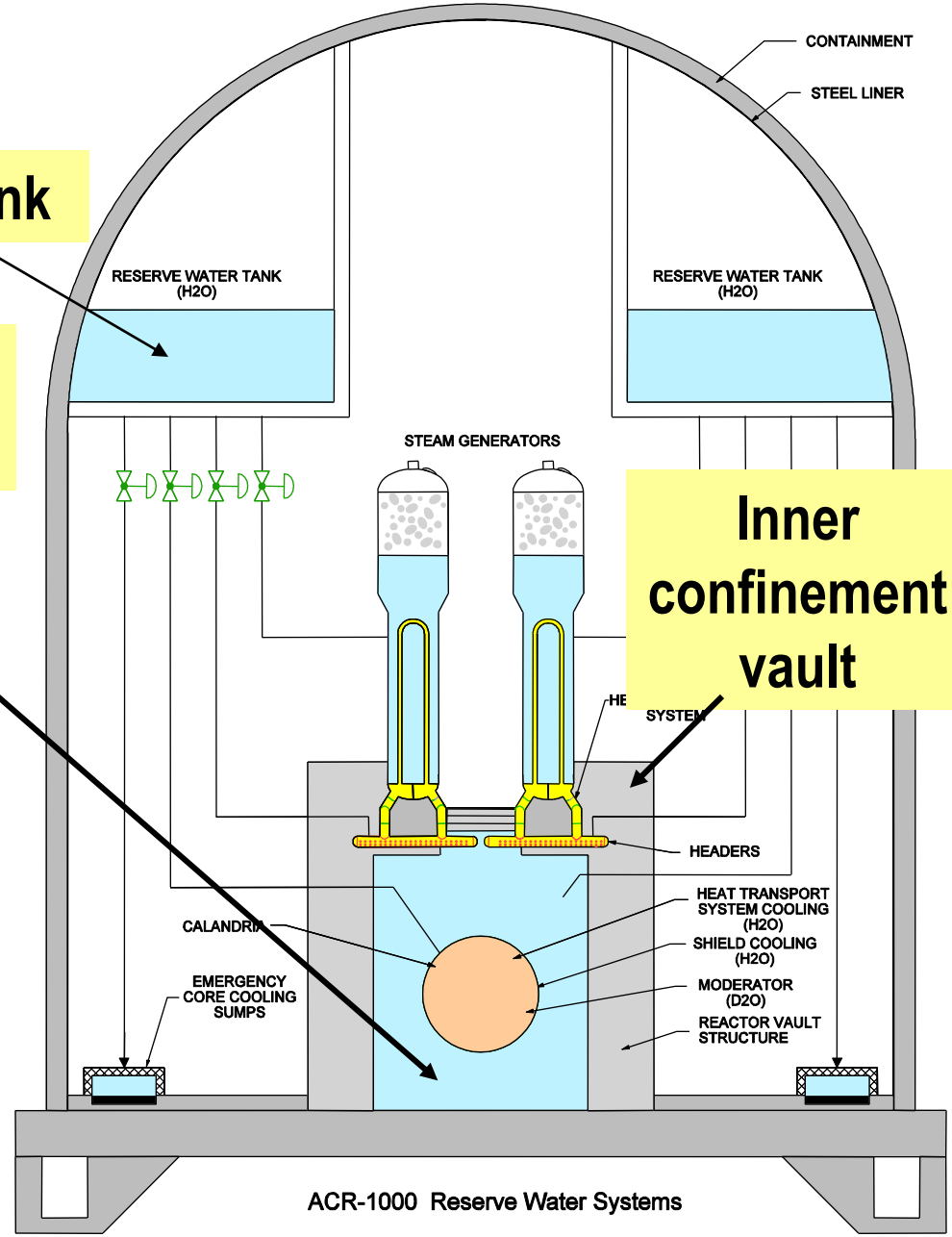
ACR-1000 Passive Safety

Reserve Water Tank

Passive heat sinks:
Moderator and shield tank water



Double core pressure boundary



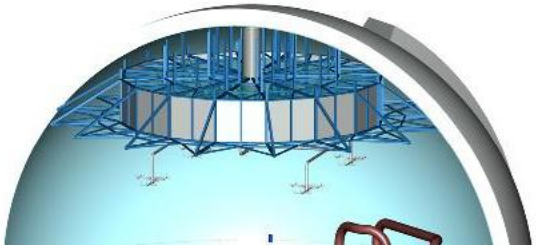
Inner confinement vault

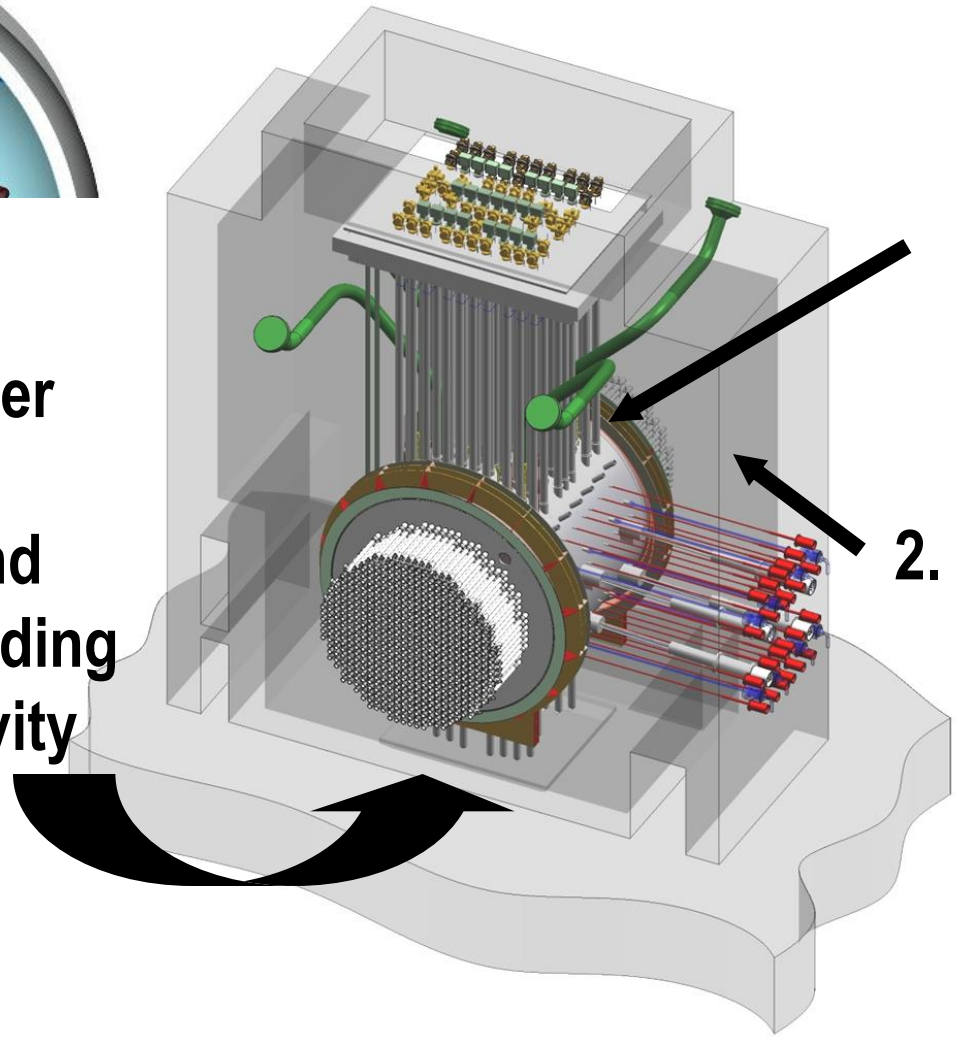
Severe Accidents

ACR-1000 includes the following features for severe accident mitigation:

- Passive Core Make-Up Tanks keep HTS full to assure thermosyphoning capability
- Reserve Water System (RWS) supplies by gravity to SGs provides inventory for long-term thermosyphoning
- Passive make-up to HTS from ECI and RWS delays accident progression
- Passive make-up to moderator and shield tanks from RWS delays accident progression
- Passive spray system supplied from RWS delays containment failure

Major Passive Heat Sinks for Severe Accident Mitigation & Management



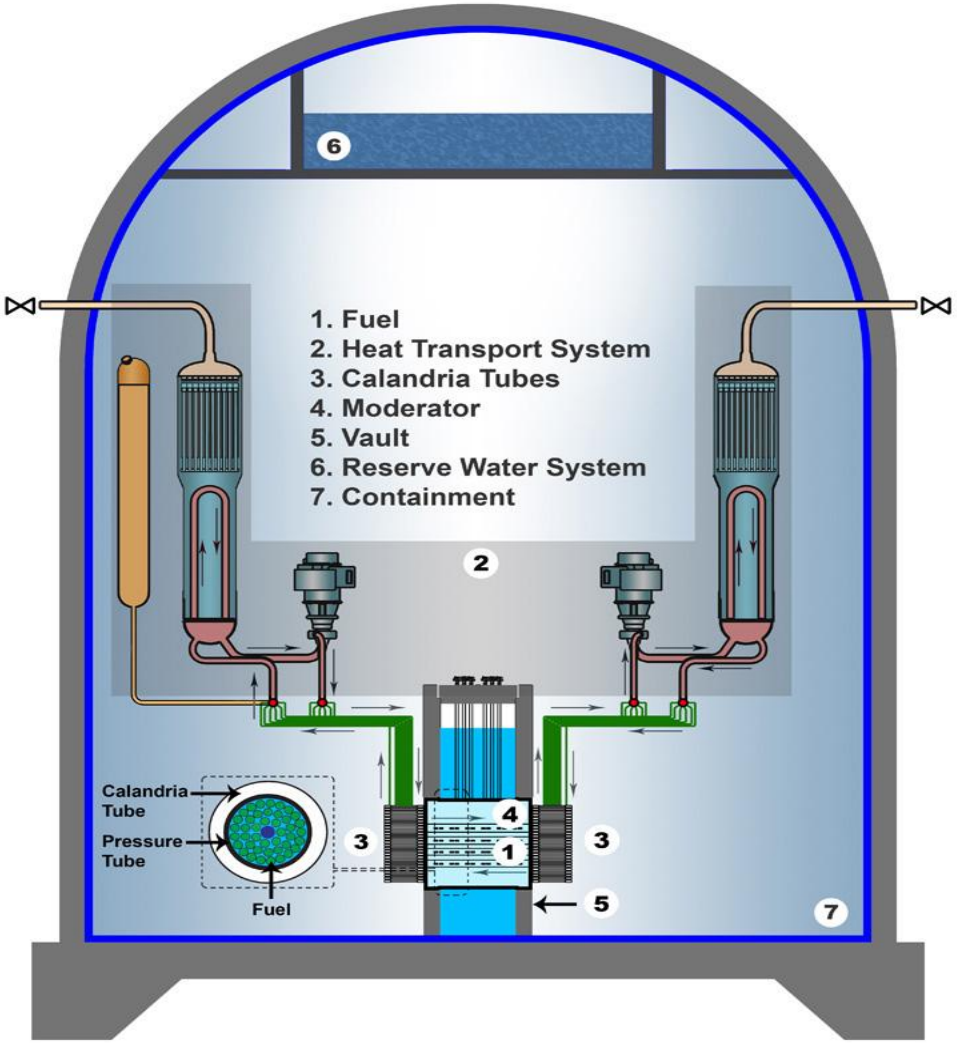


1. Calandria Water

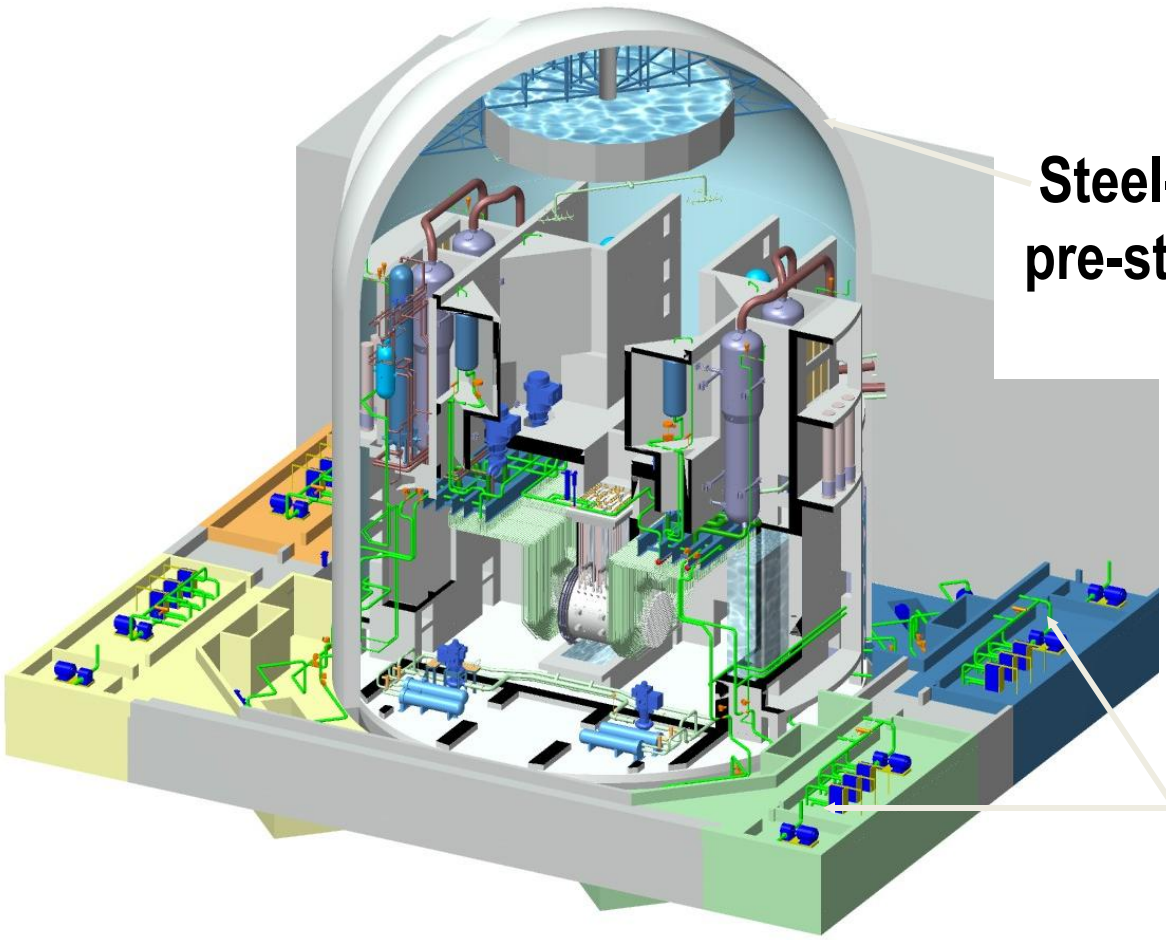
2. Shielding Vault Water

3. Water from Reserve Water Tank fills calandria, and reactor shielding vault by gravity

Seven Barriers for Prevention of Releases



Strong Containment Design



Steel-lined, 1.8 meter thick pre-stressed concrete walls

Safety support systems in quadrants around Reactor Building

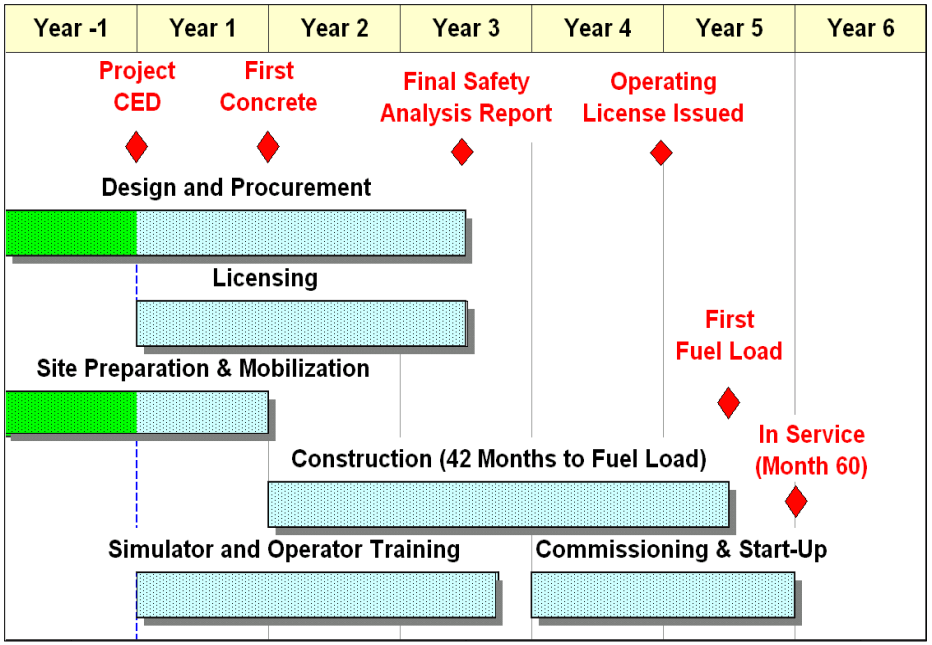
Four Quadrant Separation

- Essential cooling water and Long Term Cooling system equipment are separated into four divisions
- Four electrical buses supply electrical power to safety system
- Four channels are used for instrument and logic for safety systems
- Three quadrant capability at full power, allows on-line maintenance, and more flexibility in outages

Fast Construction Strategy for ACR-1000

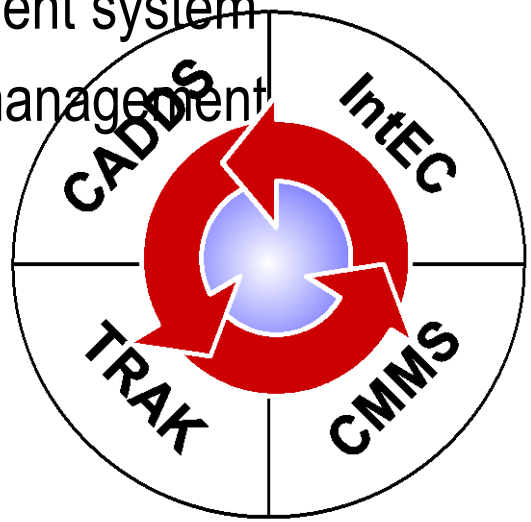
- Fast construction strategy implemented to all stages of design engineering to achieve a 42 months from the first concrete to fuel load for the nth unit
- High degree of modularization & pre-fabrication
  number of NSP modules
  increased from 15
  in Qinshan project to
  165 in ACR-1000

- **Open Top Construction, parallel construction, and up-to-date technologies**



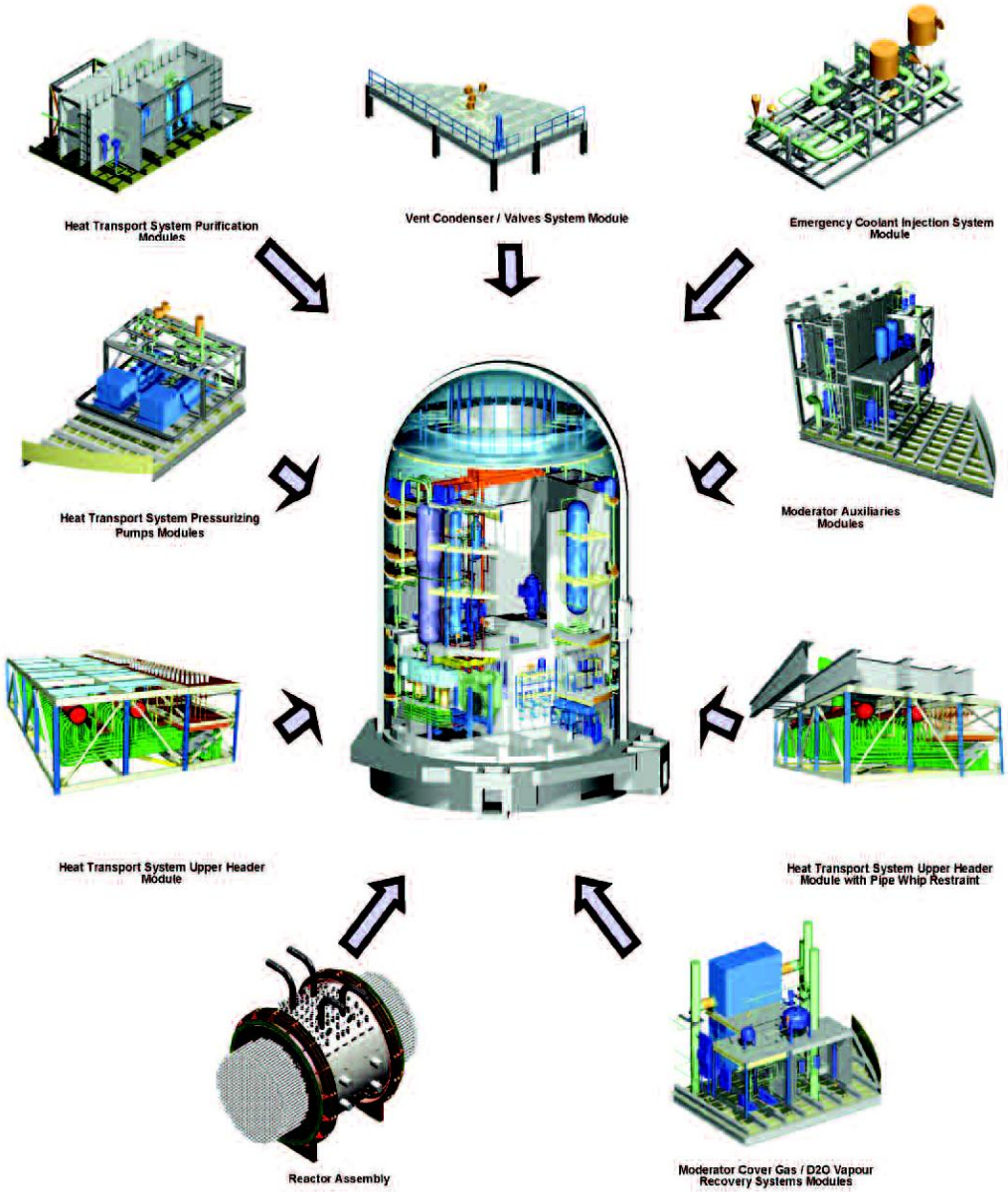
State-of-the-Art Project Management Technologies

- Integrated Project Management Tools
  - Intergraph 3D plant modelling and design
  - AECL's CMMS supply chain management system
  - AECL's TRAK electronic document management system
  - AECL's IntEC equipment wiring design and management



Large Civil Structure Modules

- **Structural Steel shipped to site**
- **Fabricated adjacent to Reactor Building**
- **Installation using VHL Crane**



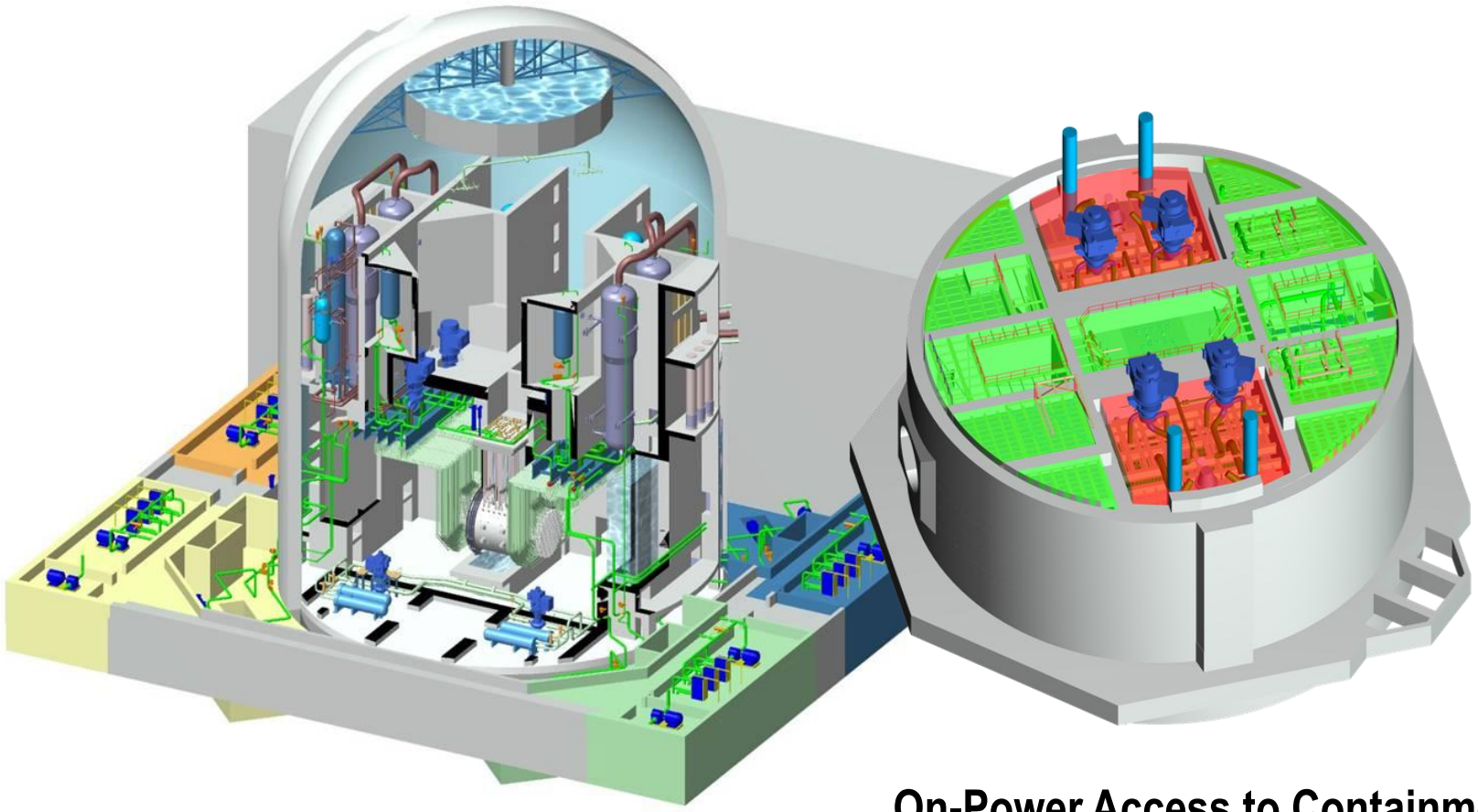
ACR-1000 uses more than 165 modules in Reactor Building

Operation and Maintenance

Designed for >90% average lifetime capacity factor over 60 years

- Based on the proven track record of CANDU 6 units which have achieved an average lifetime capacity factor 87%
- Incorporated experience feedback from operating reactors worldwide
- Three year planned outage frequency
- 21-day standard planned outage duration
- Low forced outage frequency
- Improved design for maintenance
- Fast and simplified outages
- Advanced Control Center design
- SMART CANDU™ plant life cycle information tools

One 21-day Outage Every Three Years

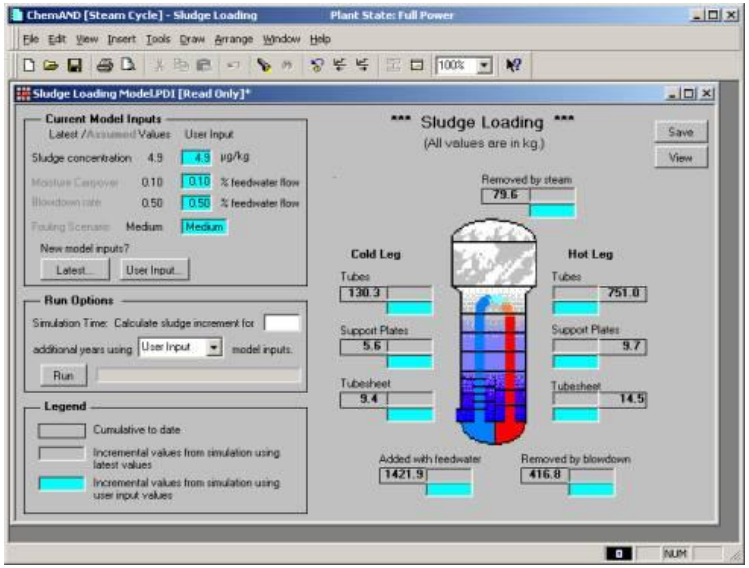


Quadrant Design for On-Power Maintenance

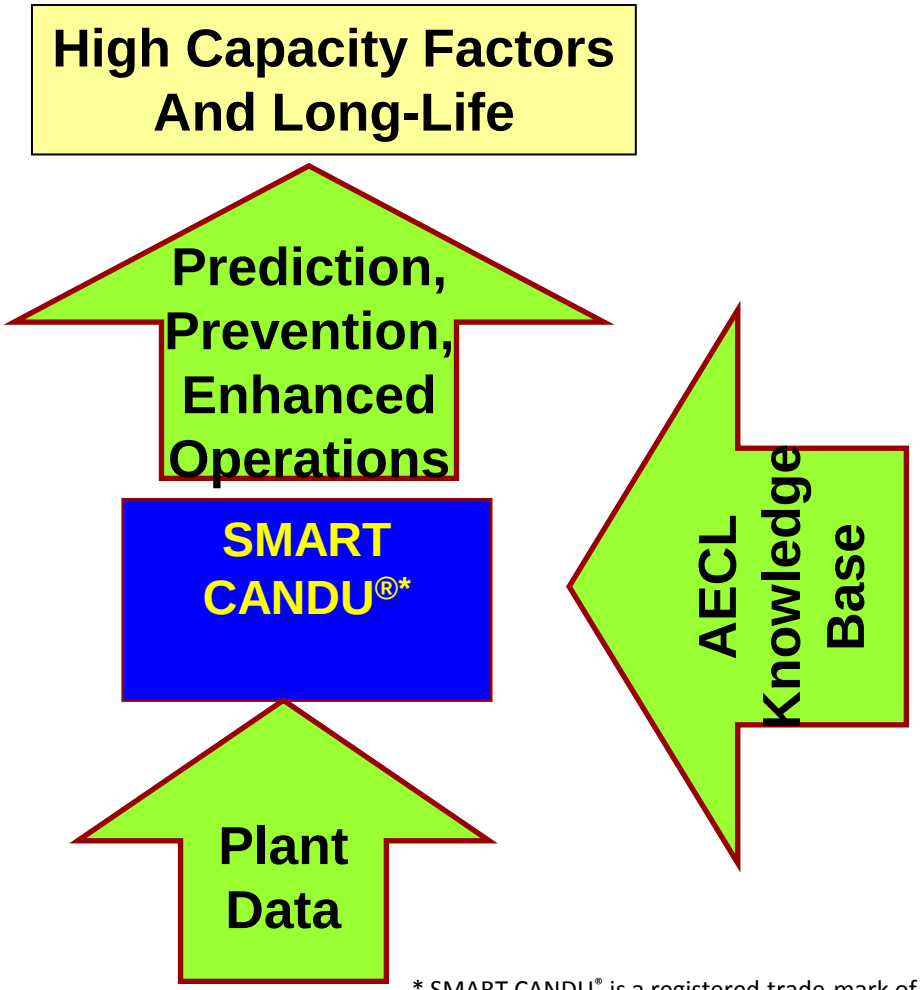
On-Power Access to Containment for Maintenance

Advanced Digital and Intelligent Support for Operation

- Advanced computerized process monitoring and control displays, improved ergonomics, large overview displays, advanced alarm management etc
- Advanced SMART CANDU plant performance monitoring and diagnostic system



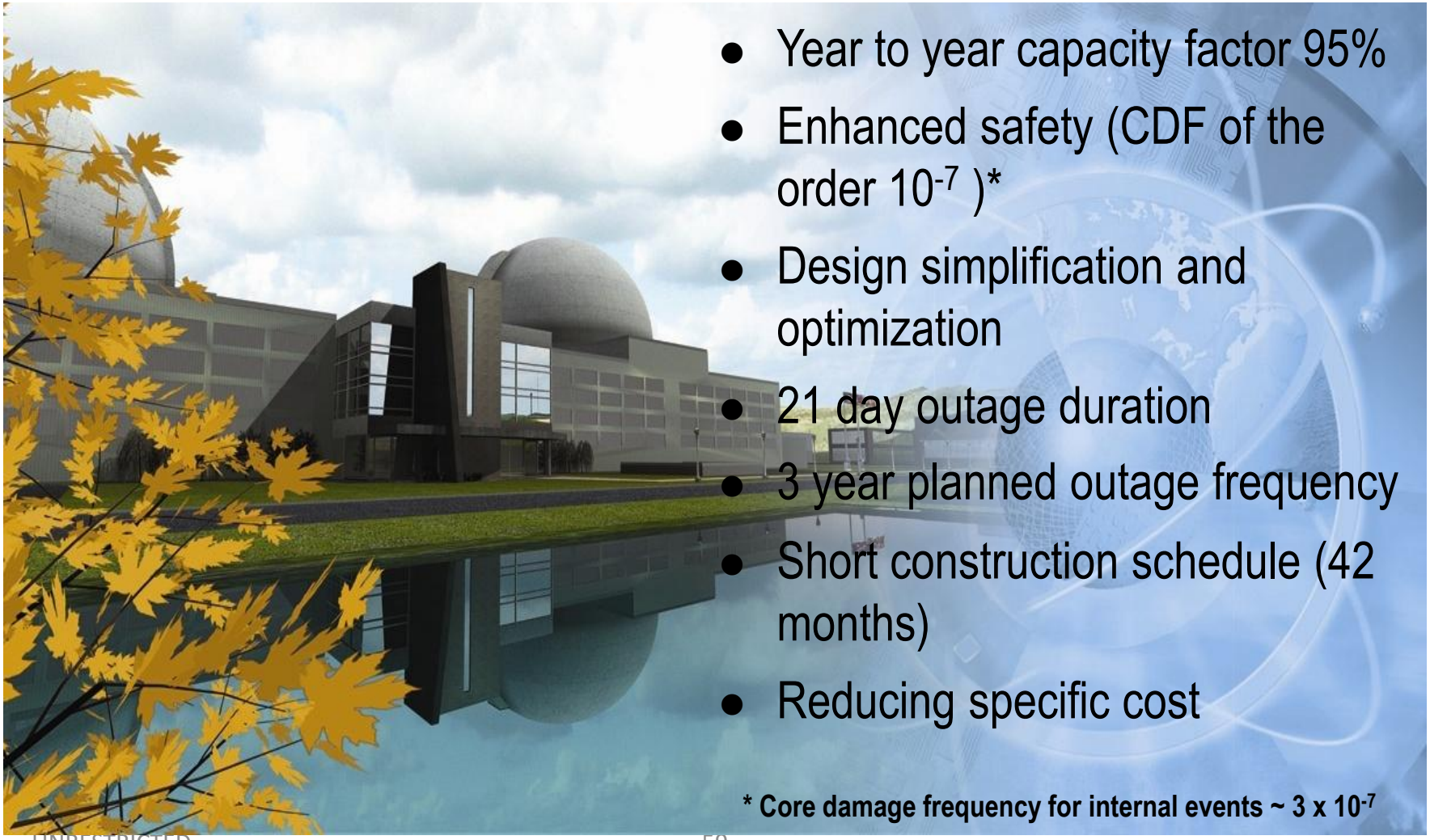
Improved Operability



* SMART CANDU® is a registered trade-mark of Atomic Energy of Canada Limited

- OPEX from Gen II plants
- Models of chemistry, corrosion and fouling in nuclear power plants
- Materials performance
- Equipment aging
- Inspection requirements
- Information management technology
- Plant aging management

ACR-1000:
Designed for High Performance and Fast Construction



- Year to year capacity factor 95%
- Enhanced safety (CDF of the order 10^{-7})*
- Design simplification and optimization
- 21 day outage duration
- 3 year planned outage frequency
- Short construction schedule (42 months)
- Reducing specific cost

*** Core damage frequency for internal events ~ 3 x 10^{-7}**

3. Delivery of Projects

CANDU 6: Delivery Performance

Qinshan Construction

In-Service	Plant	Status
1997	Wolsong Unit 2, South Korea	On budget, on schedule
1998	Wolsong Unit 3, South Korea	On budget, on schedule
1999	Wolsong Unit 4, South Korea	On budget, on schedule
2002	Qinshan Phase III, Unit 1, China	Under budget, 6 weeks ahead of schedule
2003	Qinshan Phase III, Unit 2, China	Under budget, 4 months ahead of schedule





Qinshan CANDU Project: A Great Success

Shortened Project Schedule to commercial operation:

- **43 days for Unit 1**
- **112 days for Unit 2**

World Records Achieved by Chinese Constructors

- Slipforming Unit 1 — 18 days
- Slipforming Unit 2 — 14 days
- FC installation Unit 1 — 69 days
- FC installation Unit 2 — 64 days
- SG installation — 8 hours
- Pressurizer installation — 8 hours

Savings in Cost :

- **Reduction of specific cost per KW installed**
- **Early income for the owner**

Key Factors to Success

- Project management (integrated approach covering engineering, construction, installation, commissioning, and operation, detailed planning and focal point accountability)
- Effective use of advanced engineering tools (AIM / TRAK, CADDS, IntEC, CMMS, P3)
- Computerized 3D design and modularization, electronic documentation system
- Advanced open-top access with VHL and parallel construction
- Comprehensive database and effective use of material and equipment management system
- Quality a priority and international quality program
- Effective and harmonious partnership & teamwork, dedication and hard work

Open Top Construction & Modularization

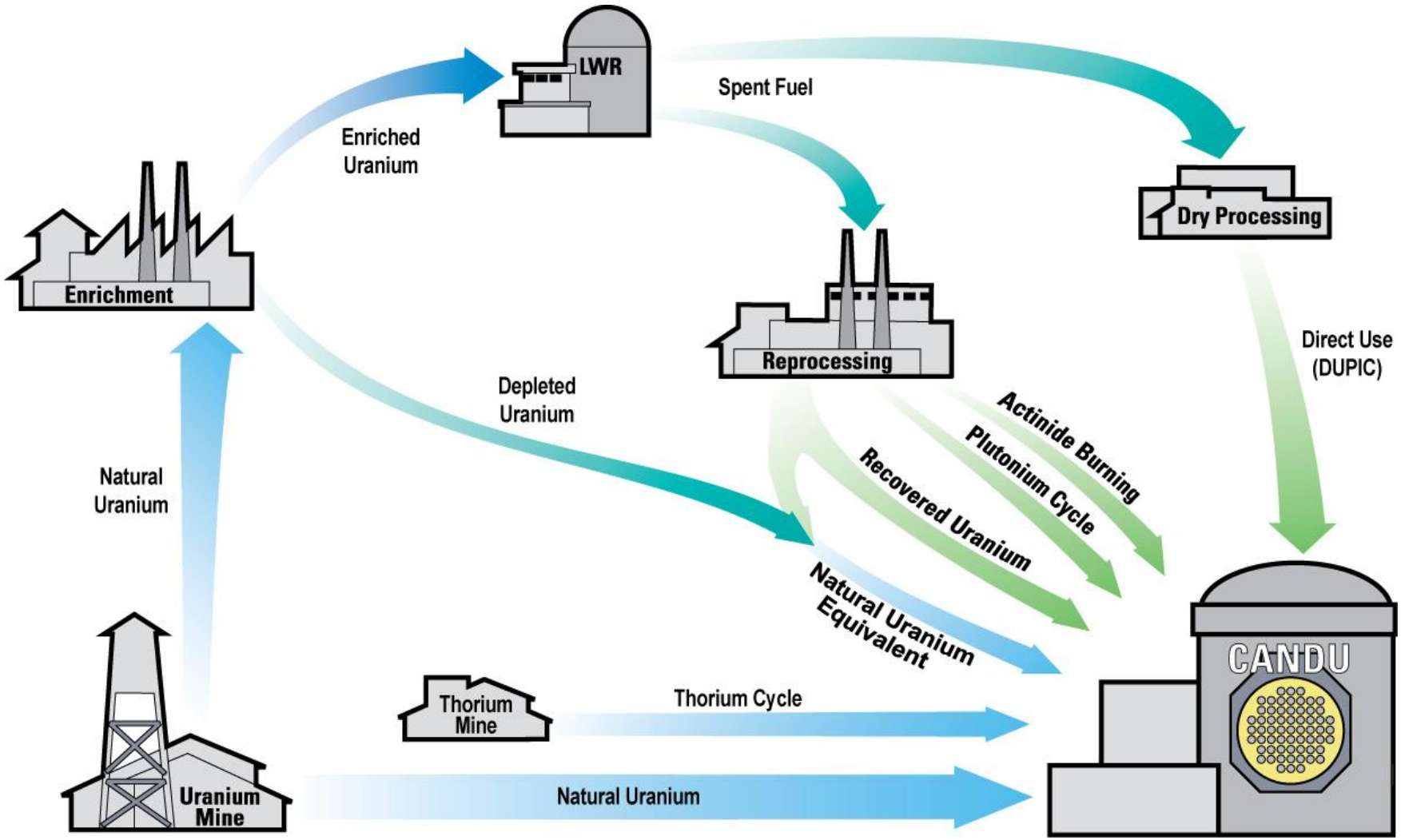
- **Steam generators installed in 8 hours each instead of previously at least two weeks**
- **Dousing system installed in prefabricated 6 segments within 5 days instead of previous 6 months**

Integrated Schedules

- 76 event contract milestone schedule
- 8500 event level 2 schedule showed
  - Design deliverables
  - Equipment deliveries
  - Construction & commissioning activities
- Integrated database of Level 3 schedule with more than 50,000 activities by construction contractors
- Parallel activities between civil and installation

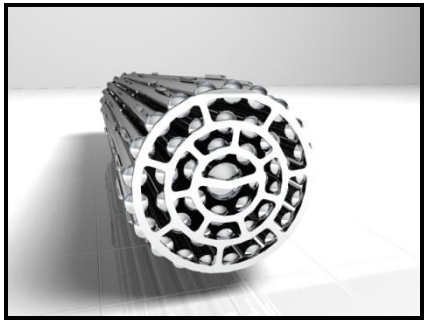
4. CANDU – Fuel Cycles

Fuel Cycle Sustainability

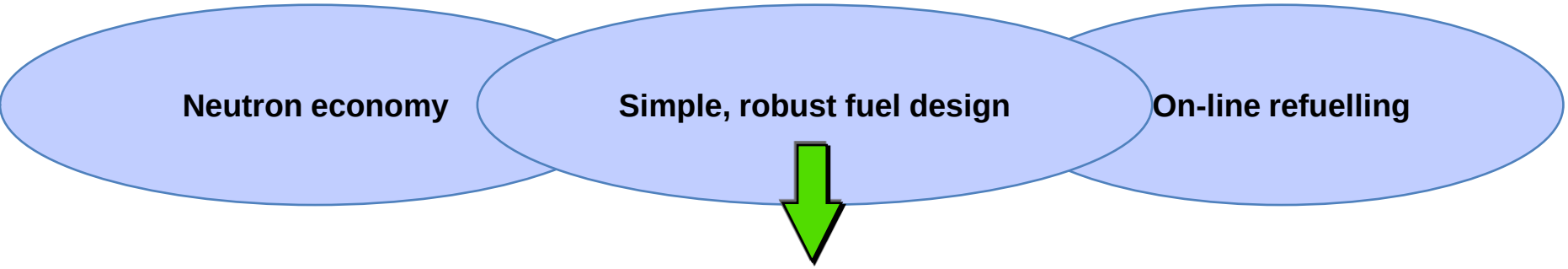


Emerging Fuel Cycles

- **Key Drivers for interest in fuel cycles**
  - Finite Uranium resources / Resource utilization
  - Spent fuel volume reduction
  - Synergy with other reactor types (LWR)
  - Utilization of alternate fuel types (Thorium, MOX, NUE)
- **Opportunity**
  - CANDU is well positioned to provide en
    security through fuel cycle flexibility



Positioning for the Future
CANDU High Fuel Efficiency & Flexibility



CANDU has the lowest uranium consumption and can burn

- Natural U
- Enriched U
- Recovered U
- Spent LWR fuel
- Mixed Oxides
- Thorium
- Actinide waste

} **depending on cost and strategic factors**

AECL's Work in Advanced Fuel Cycles

- AECL has carried out theoretical and experimental investigations on various advanced fuel cycles, including thorium, over many years
- Two fuels are the focus of current work
  - Natural Uranium Equivalent (NUE)
  - Thorium

What is NUE?

- NUE is an acronym for Natural Uranium Equivalent fuel
- It is a mixture of ≈ 70% Recycled Uranium (RU) and ≈ 30% Depleted Uranium (DU)
- RU contains ≈ 0.9% ^{235}U and DU contains ≈ 0.3% ^{235}U, the resulting mixture of NUE has a ^{235}U weight percentage that is ≈ Natural Uranium found in nature
- In practice the ^{235}U content of RU and DU will vary and the ratios of RU and DU required to produce NUE will also vary
- Partnership agreement to undertake the NUE program was signed on November 3, 2008
  - Third Qinshan Nuclear Power Company (TQNPC)
  - China North Nuclear Fuel Corporation (CNNFC)
  - Nuclear Power Institute of China (NPIC)

Thorium in CANDU

- AECL has performed extensive research and development work over the past 50 years on thorium use in CANDU reactors
- CANDU's excellent neutron economy, due to heavy water moderator and coolant, provides a basis for the efficient use of either an LEU or Pu driver in thorium fuel cycles
- Simplest application of thorium in the CANDU reactor is via a once-through fuel cycle
- Over time and through evolutionary modifications the CANDU reactor will be optimized for thorium operation in a recycling mode

Thorium Fuel Cycle in C6/EC6

- In the near term, a thorium once-through fuel cycle is the simplest thorium fuel cycle that can be rapidly implemented in CANDU 6 reactors
- Utilizes LEU as the driver fuel
- This configuration offers the following benefits:
  - A multi-fuel reactor capable of utilizing NU/NUE and LEU/Th
  - Synergistic relationship with LWRs - utilize recycled uranium
  - Minimal changes in reactor systems
  - Proven fuel bundle—CANFLEX
  - Initial LEU/Th fuel ~15,000 MWd/tHE
    gradually increased to 18-19,000 MWd/tHE
  - ~ 30% uranium savings compared to CANDU NU (50% better than standard LWR)
  - ^{233}U generated and "banked" for future use

- **Results in a practical, evolutionary, near-term solution based on the proven CANDU reactor and fuel → Minimal Risk**

Vision for CANDU Thorium Fuel Cycles

- Mid-Term vision for Thorium Fuel Cycles is to utilize EC6 with Th/Pu Fuel
  - EC6 Thorium CANDU Reactor (or a larger unit)
  - Th/Pu fuelled, semi-closed or closed
- Long-term vision for Thorium Fuel Cycles is to utilize a larger CANDU reactor fuelled with Th/Pu/U^{233}
  - Large Advanced Thorium CANDU Reactor
  - Th/Pu/U^{233} fuelled, closed cycle in synergy with breeders
  - Minimum (nearly zero) waste

Summary

- The CANDU–PHWR design has a proven record of safety ,performance worldwide with outstanding economics ,capacity factor and localization .
- The design intrinsically and extrinsically is suitable for various fuel cycles complementary to the LWR plants for sustainability of fuel cycles

Thank You !