University of Zagreb, Croatia

ACR-1000: Advanced CANDU Reactor Design for Improved Safety, Economics and Operability

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AECL EACL

Presentation Objectives

- **Overview of the ACR-1000 design**
  - **Safety and economics**
  - **Operability and maintainability**
  - **Constructability and modularity**
- **Project schedule and implementation**

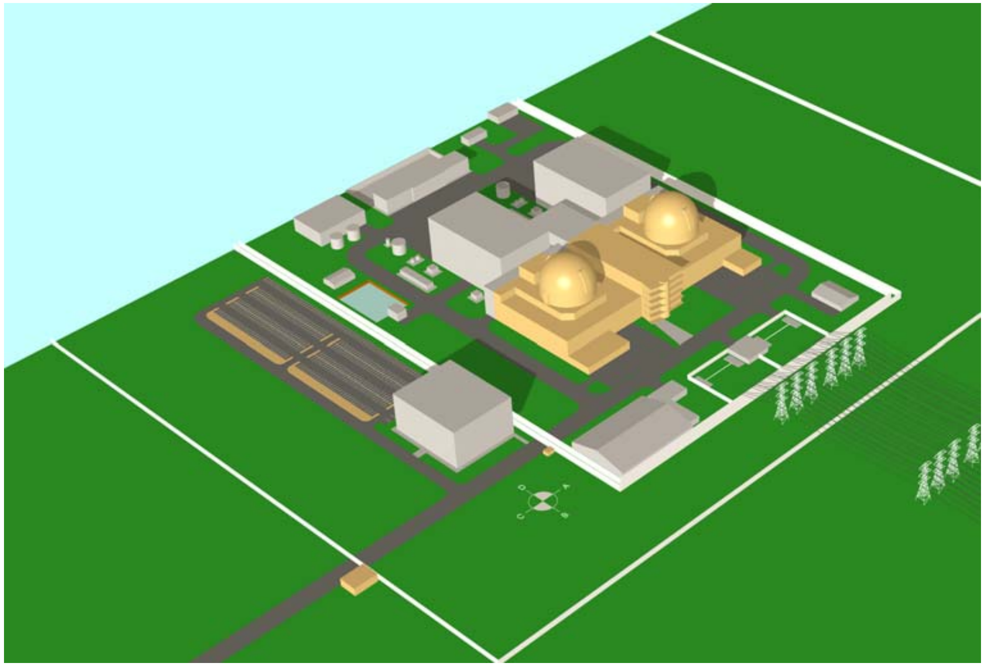
ACR Plant Design Philosophy

The integrated design approach addresses the following objectives:

- Meet Canadian regulatory requirements, codes and standards
- Optimize product, improve safety, constructability, operations and maintenance
- Meet specific market and customer requirements
- Attain a high quality, reliable facility with a high operating capacity factor
- Accelerated schedule compared to current NPPs
- Minimize required capital investment and O&M costs

General Requirements

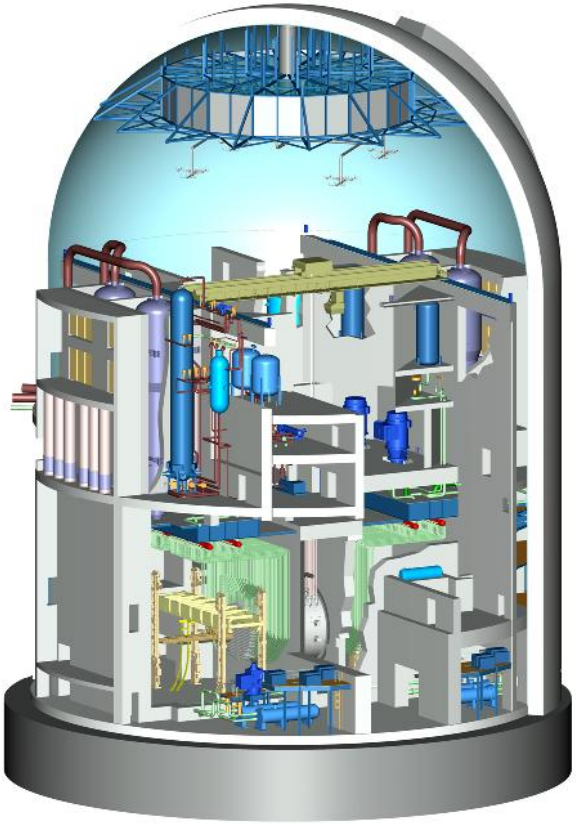
- Output ~ 1200 MWe gross
- Improved thermal efficiency (~ 37%)
- Integrated 2 unit design (adaptable for different site conditions and for single unit application)
- Designed for fast construction 46 months from first concrete to fuel loading for first unit)
- Project duration from first containment concrete to in Service 54 months for first unit
- Proven technology with evolutionary design with enhanced passive features, and verified improved features
- Design margins for end of plant operating life
- Meets increased safety requirements of Gen III+ reactors

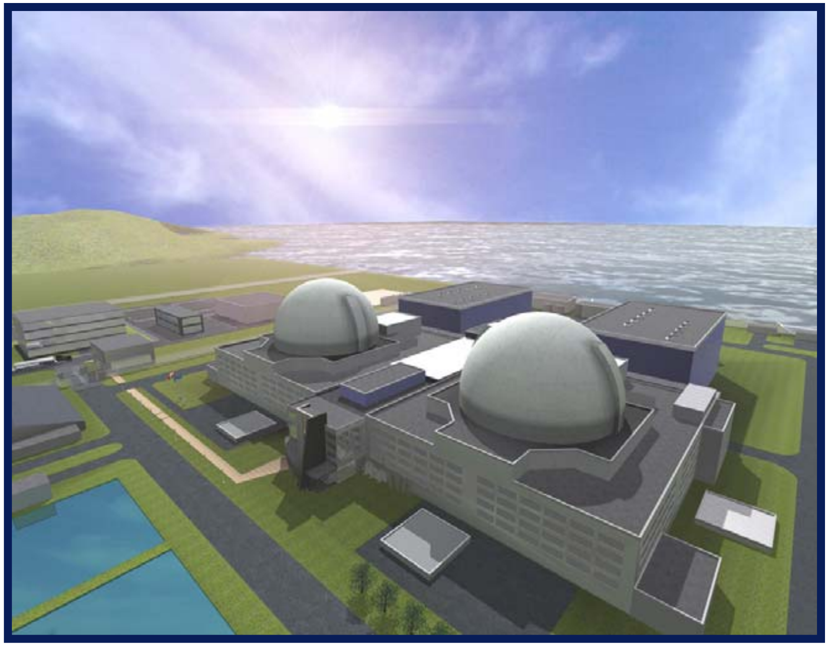


AECL's Reactor Product for New Build

ACR-1000

- **1200 MWe class**
- **Generation III+ technology**
- **Combines experience of CANDU 6 with new CANDU concepts**
- **Enhanced safety, economics, operability**





Keeping the CANDU Tradition…

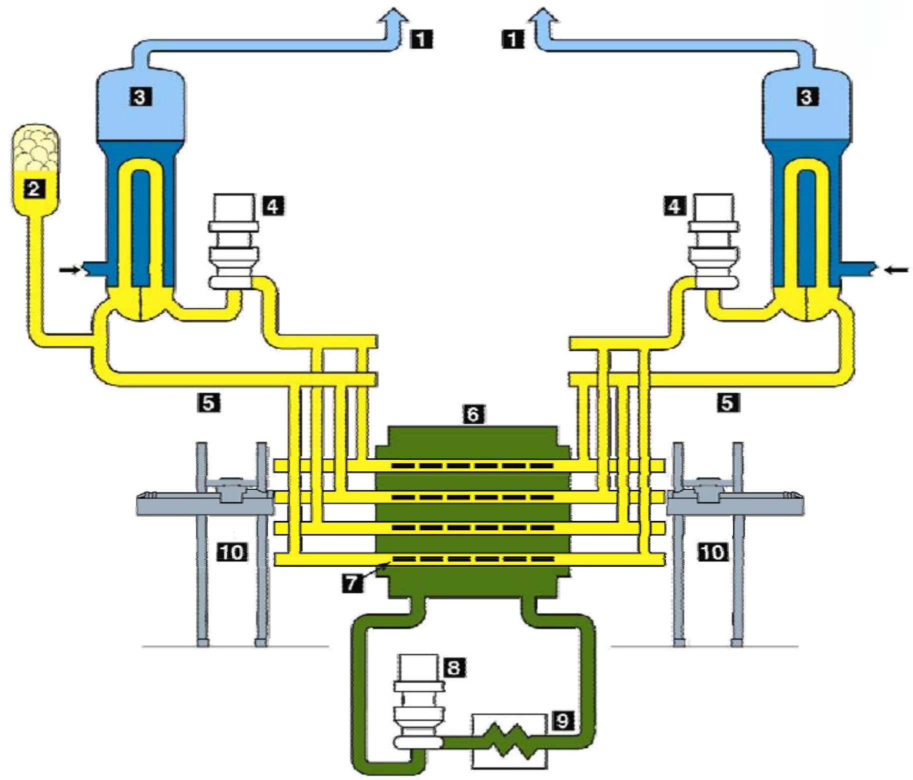
ACR evolves from the Successful CANDU 6 Family of Units:

- Modular horizontal fuel channels
- Simple fuel bundle design
- Cool, low pressure heavy water moderator
- On-power fuelling
- Passive shutdown systems
- Established equipment
- Established licensing basis

Qinshan Phase III, China
Most recent CANDU 6 plant completed in 2002/3, ahead of time and under budget

Nuclear Steam Plant (NSP) Overview

- Nominal gross/net output ~1165/1085 MWe
- 520 parallel, horizontal pressure tubes located within the calandria tubes
- Calandria filled with heavy water moderator
- Light water reactor coolant system
- LEU Fuel with burn-up up to ~20,000 MWd/te
- Moderator and Shield tank act as passive heat sinks.



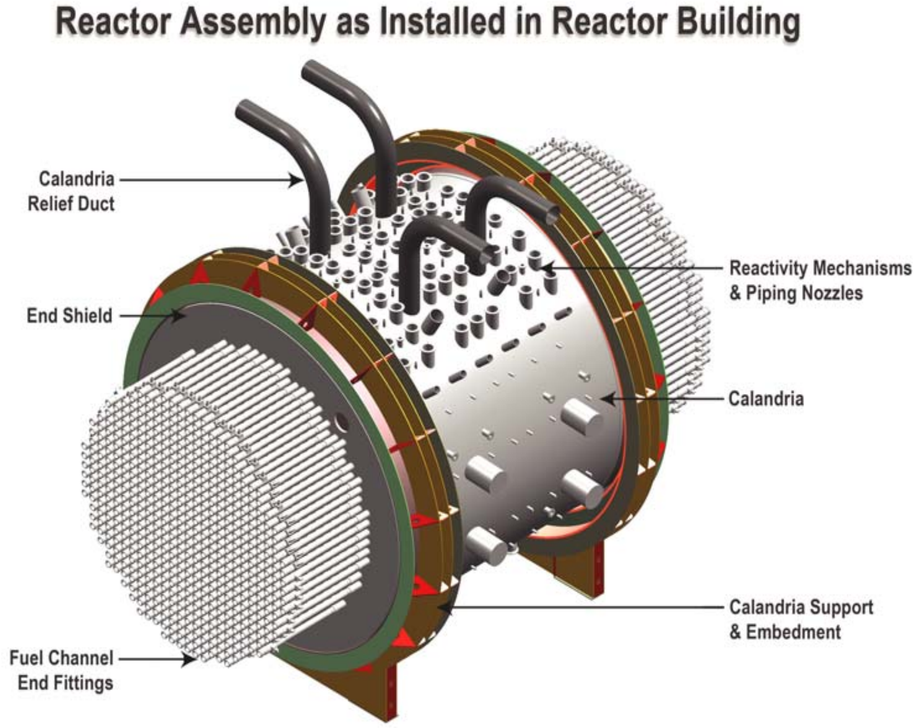
	Steam
	Feedwater
	Light Water Coolant
	Heavy Water Moderator

1	Main Steam Pipes
2	Pressurizer
3	Steam Generators
4	Heat Transport Pumps
5	Headers
6	Calandria
7	Fuel
8	Moderator Pumps
9	Moderator Heat Exchangers
10	Fuelling Machines

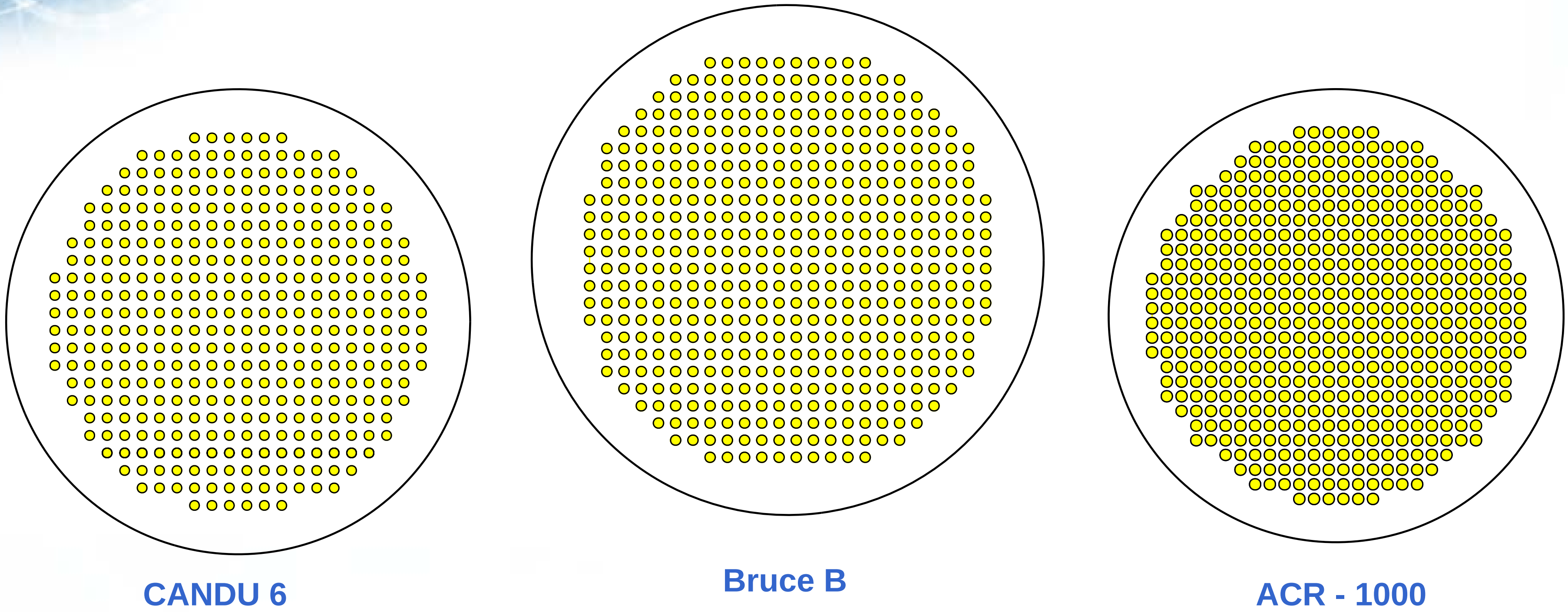
ACR-1000

ACR-1000 innovations:

- Low enriched fuel, light water coolant, reduced D_2O inventory
- Higher steam pressure for increased efficiency
- Smaller reactor core with improved stability enables highe output
- Design optimized for high capacity factor, operability and maintainability over 60 year life
- Much larger thermal margins - designed for end-of-life conditions



Reactor Core Design Comparison



	CANDU 6	Bruce B	ACR-1000
Number of Channels	380	480	520
Reactor Core Diameter (m)	7.6	8.5	7.6
Lattice Pitch (mm)	286	286	240
Vol of D_2O in Moderator (m^3)	265	305	250
Vol of D_2O in HTS (m^3)	192	280	0
Total Vol of D_2O (m^3)	466	600	250

- **Calandria 7.6m (similar to CANDU 6)**
- **Lattice 26 x 26**
- **Heavy water hold-up reduced**

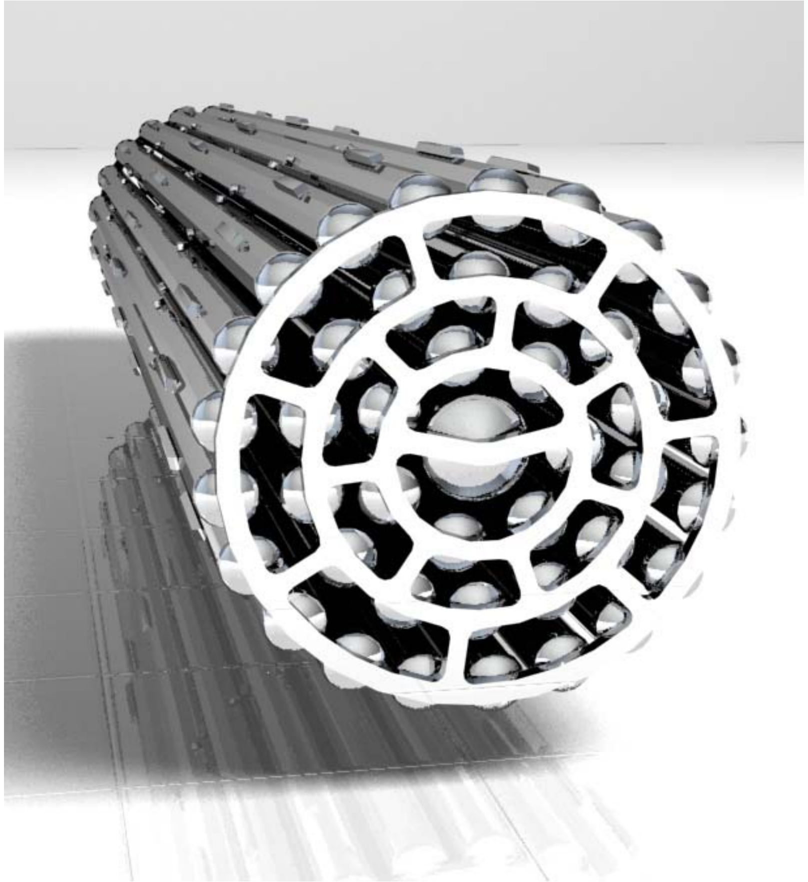
ACR Compact Core & Fuel Design

- **Reduced lattice pitch**
- **Reduced heavy water inventory**
- **Flat core neutron flux with increased stability**
- **Increased safety margins via optimized power profile and reactivity coefficients**

- **ACR-1000 fuel composition is optimized to provide small and negative coolant void reactivity (CVR) under nominal design conditions (including consideration of aged pressure tubes)**
- **The safety analysis ensures that, with adequate margin for uncertainties:**
  - **The power coefficient is always negative**
  - **Safety limits are met: no PT ballooning, no prompt criticality, no excessive fuel temperature.**

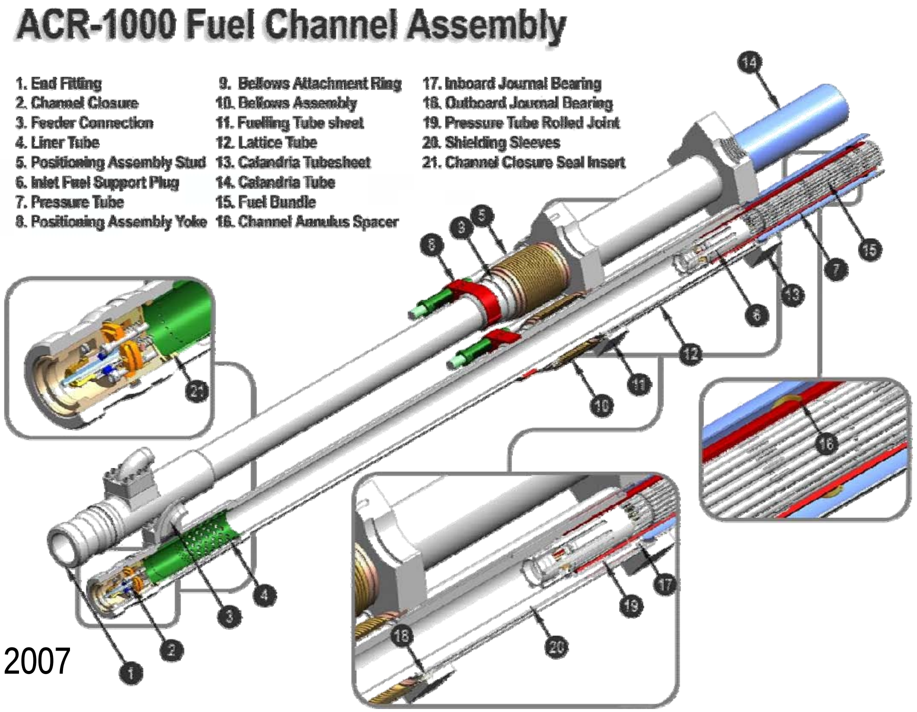
ACR-1000 Lattice

- **CANFLEX-ACR fuel bundle**
  - **42 same size LEU elements (same as outer elements of classical CANFLEX)**
  - **Larger center element contains Dy/Gd**
  - **2.4% LEU**
  - **Target burnup up to 20 MWd/kgU**



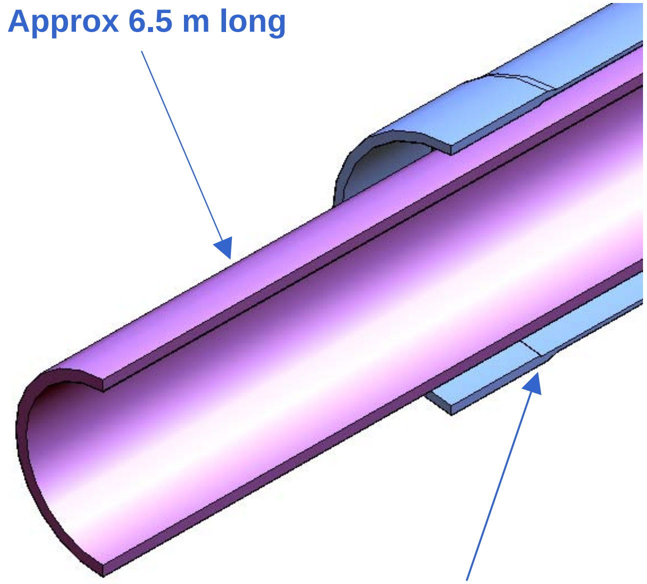
ACR-1000 Fuel Channels

- The ACR-1000 fuel channel design is based on existing CANDU designs, with increased margins for extended operating life
- The fuel channel design has been modified to suit reduced lattice pitch and thicker pressure tube
- The ACR-1000 development and qualification program for fuel channels is underway
- The ACR-1000 PT material is made of zirconium 2.5wt% niobium alloy, same material as recent CANDU reactors



Pressure Tube

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



Calandria Tube

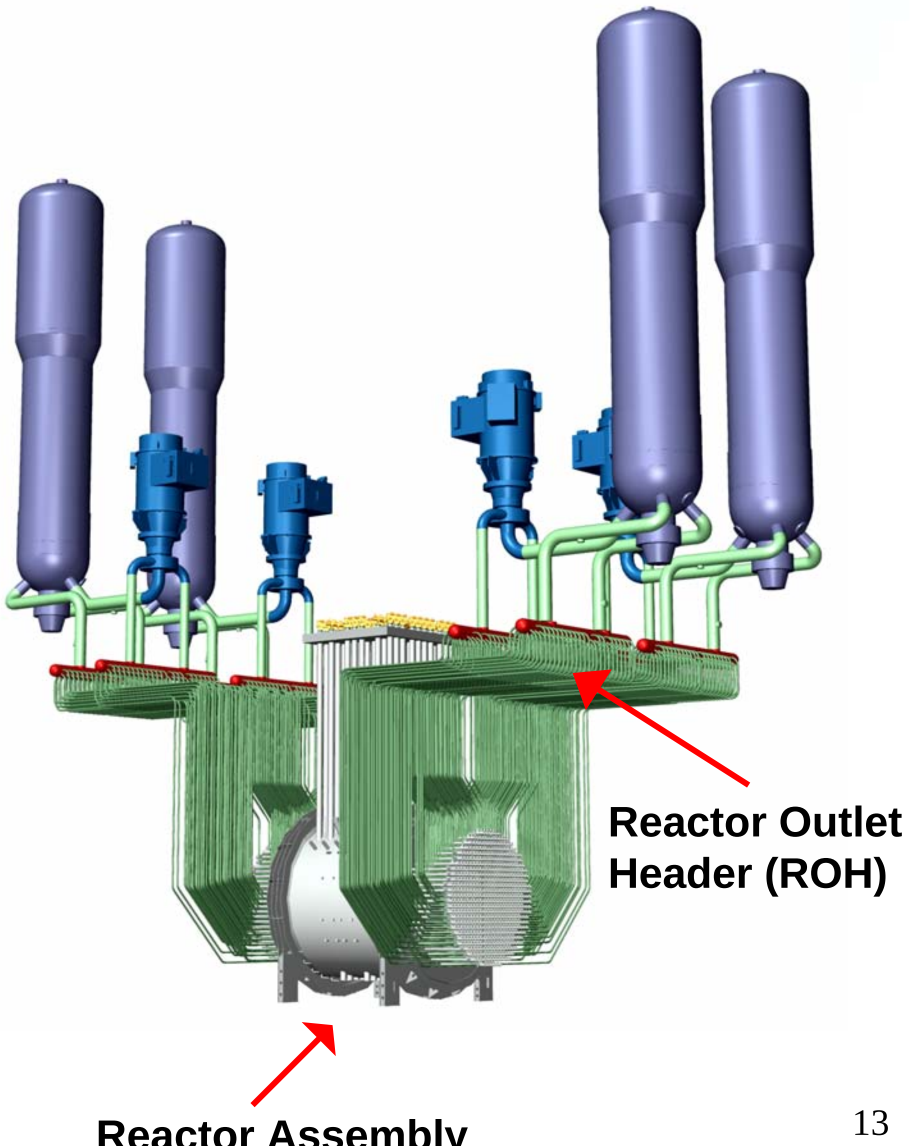
Body: 2.5 mm thick wall

Ends: 4.5 mm thick wall

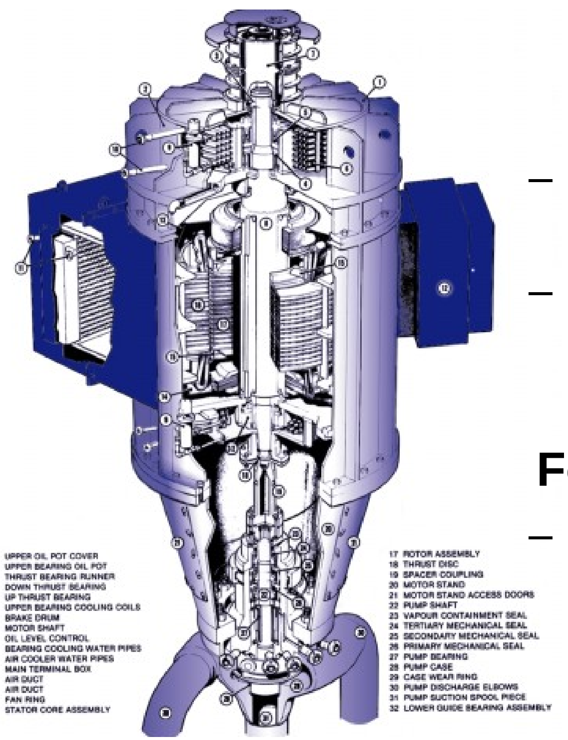
Length: approx 6m

Heat Transport (HT) System

- Heat Transport System – 2 loop arrangement, same as CANDU 6
- Increased thermal margin by having 1°C sub-cooling
- Higher HT System operating conditions
  - ROH pressure 11.1 MPa(g)
  - ROH temp 319°C
- Higher steam pressure for increased efficiency,
  - SG pressure 5.9 MPa(g)
  - SG Temperature 275°C
  - Feedwater temperature 217°C
  - Turbine cycle efficiency 36.6%



Heat Transport System Pump



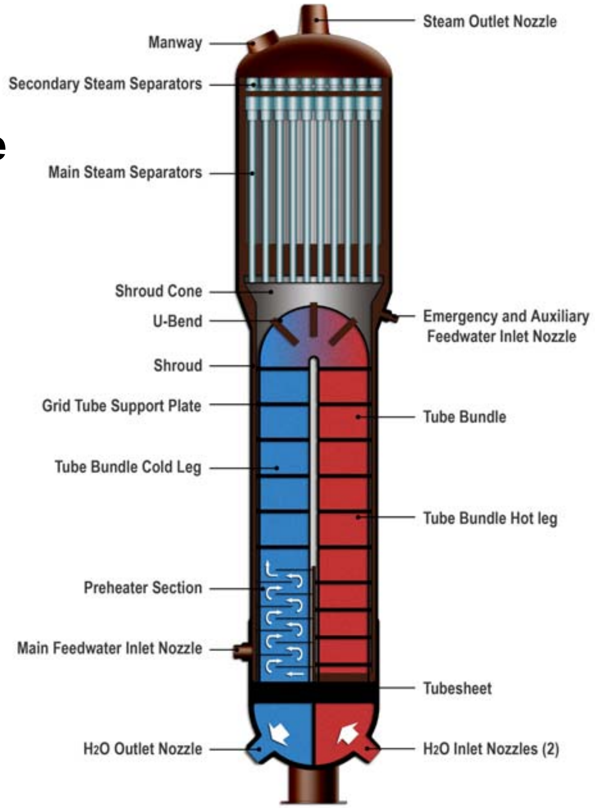
Steam Generators

- **Improved chemistry, lattice bar design, stainless supports, I-800 tubes, routine cleaning**
- **Better manufacturing tolerance eliminating fretting**
- **Increased blowdown and blowdown recycling**

Feeders

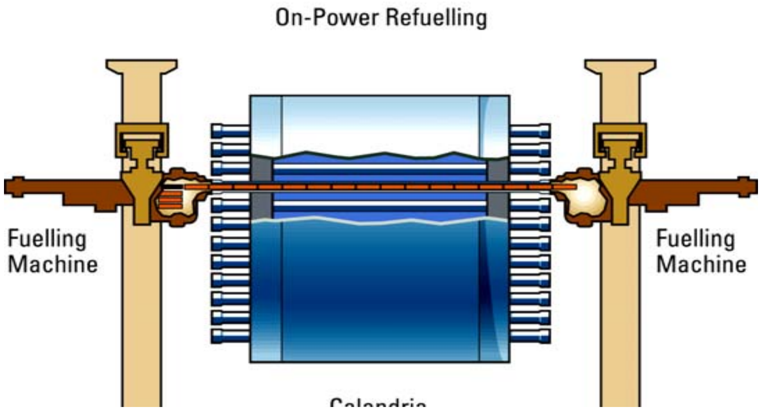
- **Feeder material selected to eliminate flow assisted corrosion – use stainless steel**
- **No residual stress from construction, much improved startup chemistry reducing stress corrosion cracking potential**

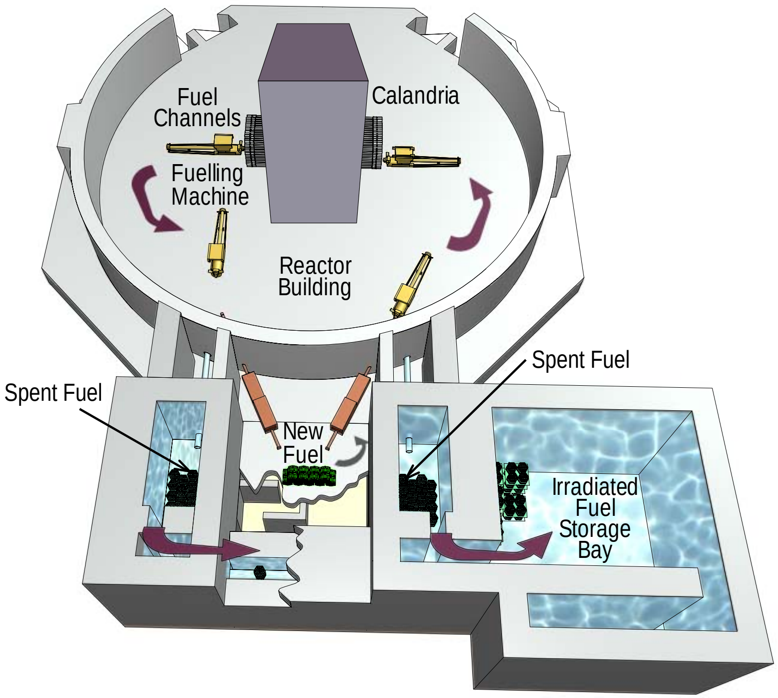
Steam Generator



On-Power Fuelling – Basic Operation

- **Each fuel channel contains 12 fuel bundles**
- **Two fuelling machines are connected to each end of a channel at the same time**
- **8 or 2 bundles of irradiated fuel are removed and 8 or 2 bundles of fresh fuel are inserted**
- **The fuelling machines also connect to the new and irradiated fuel ports and fuels channels in sequence.**

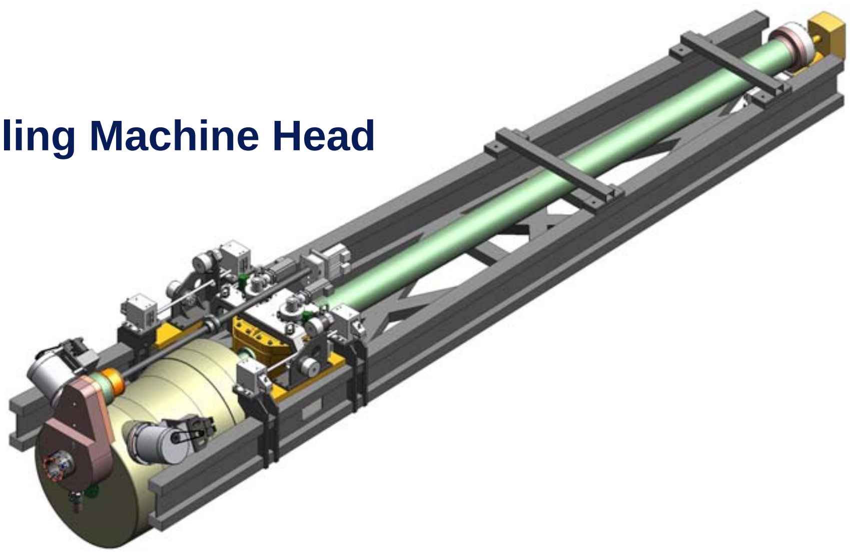


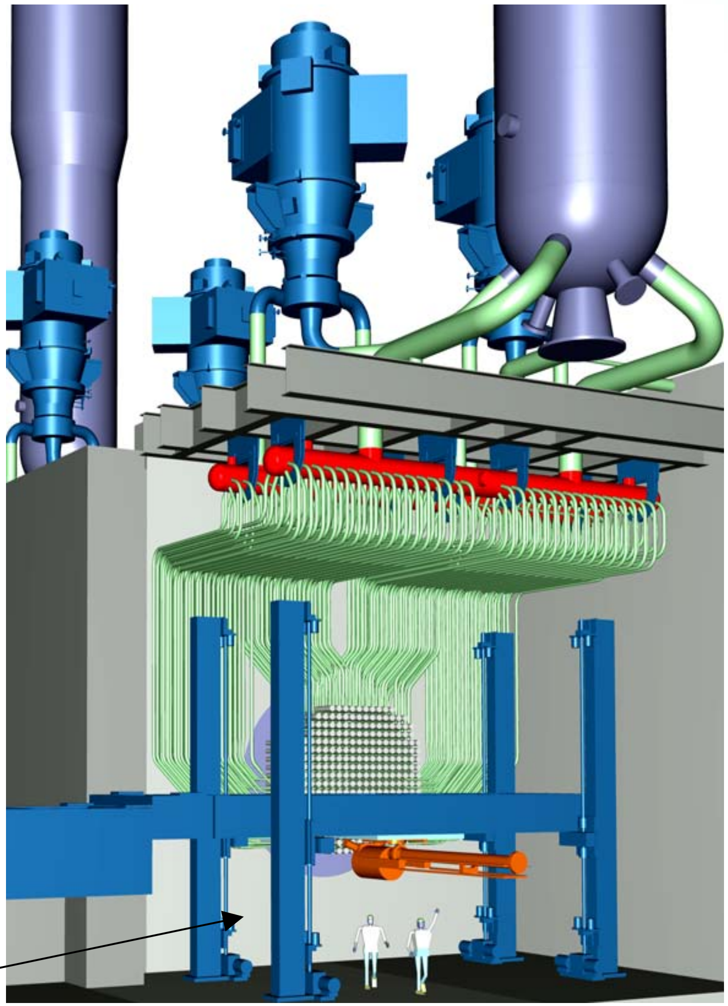


On-Power Fuelling - Benefits

- No re-fueling outage (flexibility in planned outage timing)
- Permit reduced planned outage frequency
- Can detect and remove failed fuel on-power

Fueling Machine Head



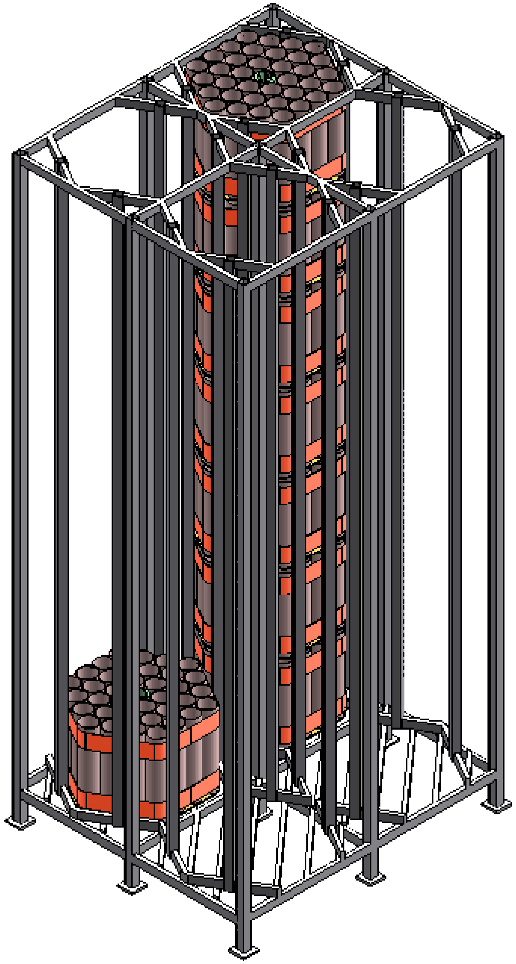


Fueling Machine

Fuel Storage Basket

- Fuel Storage basket based on dry store basket.
- Includes individual fuel tubes for safety strength and criticality protection
- Baskets sealed after loading at spent fuel transfer giving larger assemblies for tracking

- Baskets stacked in vertical frames
- Baskets stored in small stacks in reception bays for initial decay then moved to larger stacks in main bay.
- Baskets moved to flasking bay for dry store



ACR-1000 Improvement Areas

- Safety Enhancements
  - Enhanced passive safety
  - Factor of ten improvement in core damage frequency
- Operational Enhancements
  - Capacity Factor >90% over 60-year lifetime
  - Operating margins to End of Life
  - Maintenance based design
  - Target: event-free operation
- Improved Construction
  - Shorter construction schedule
  - New project models, vendors take more risk
  - Reduce cost by 25% or more

ACR-1000 Safety Enhancements

- Meets IAEA standards e.g., for safeguards, IAEA Safety Standard NSR-1 including single failure criterion
- Meets Canadian regulations, codes and standards
- Incorporates and enhances established CANDU advantages:
  - Two independent shutdown systems
  - Inherent passive heat sinks
  - Simplified reactor control and safety mechanisms in cool, low-pressure environment
  - High degree of automation, lessens operator burden
  - Improved separation and redundancy of safety and safety support systems to facilitate maintenance and improve operating reliability, e.g., four safety channels

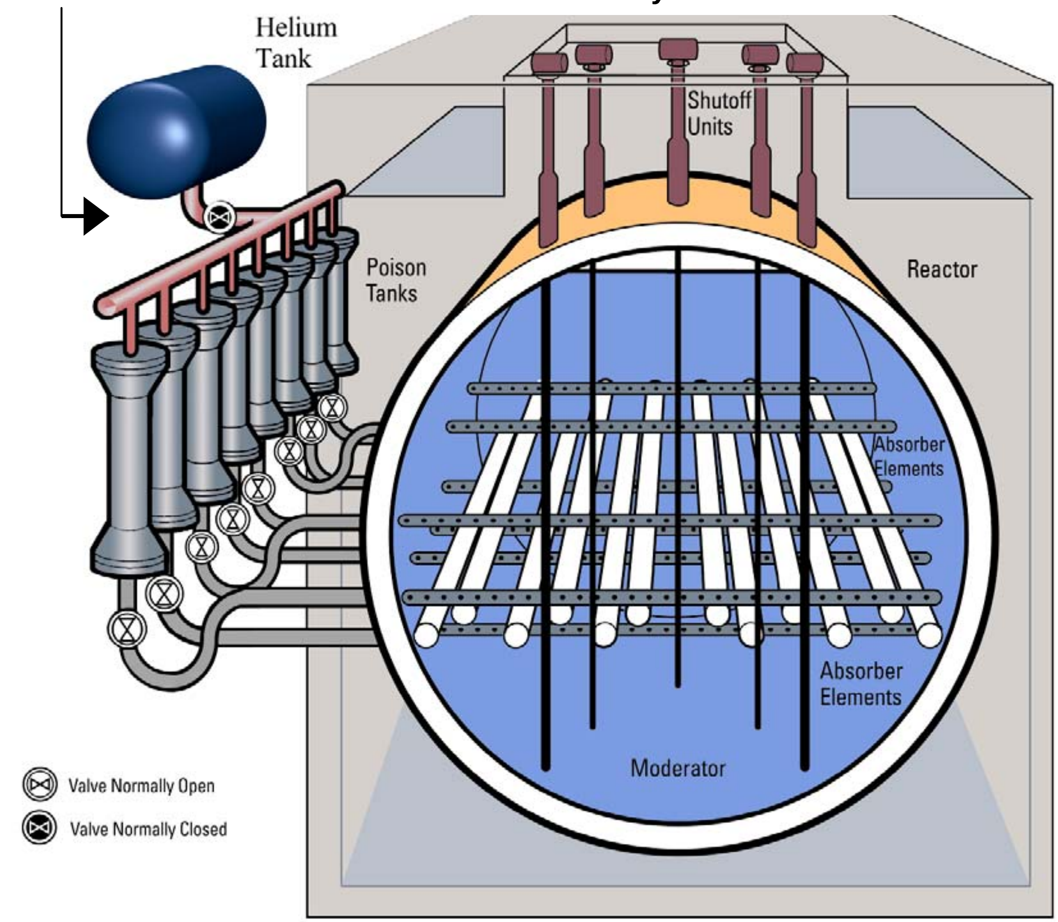
ACR-1000 Safety Enhancements

- Enhanced resistance to severe core damage through passive mitigation such as passive makeup to moderator and reactor vault heat sinks
- Robust steel-lined reactor building structure to address evolving safety and security licensing basis -- aircraft crash, etc.
- Core damage and large release mitigation going beyond international standard for advanced plants
  - Total severe core damage frequency standard: < 10-5/ reactor-year
  - ACR-1000 frequency for internal events: ~ 3 x 10-7/ reactor-year

Dual Fast Acting Shutdown Systems

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

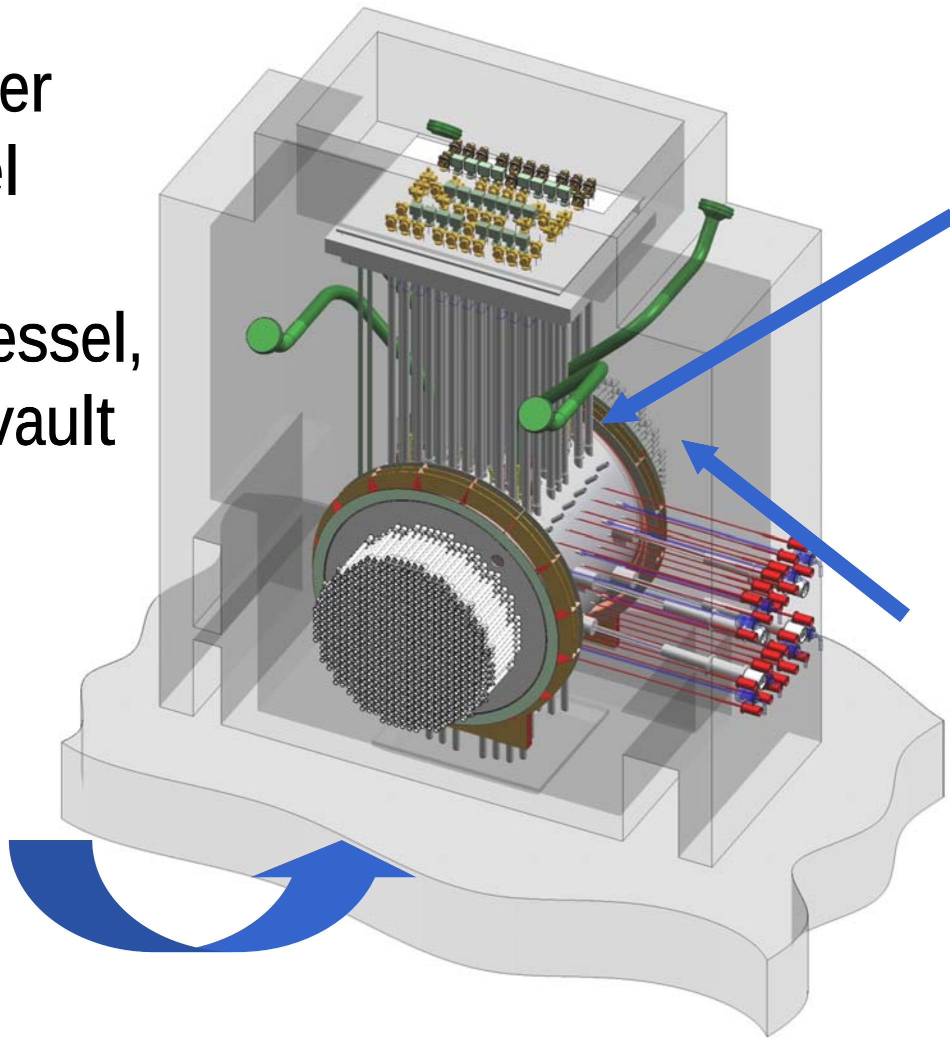
- **Shutdown system 2 (SDS2)**
  - **Liquid neutron absorber injected horizontally by gas pressure into the moderator**



ACR-1000 Shutdown Systems 1 & 2

Three Major Passive Heat Sinks

3. Reserve Water Tank fills fuel channels, moderator vessel, and reactor vault by gravity



1. Moderator Vessel Water

2. Reactor Vault Shielding Water

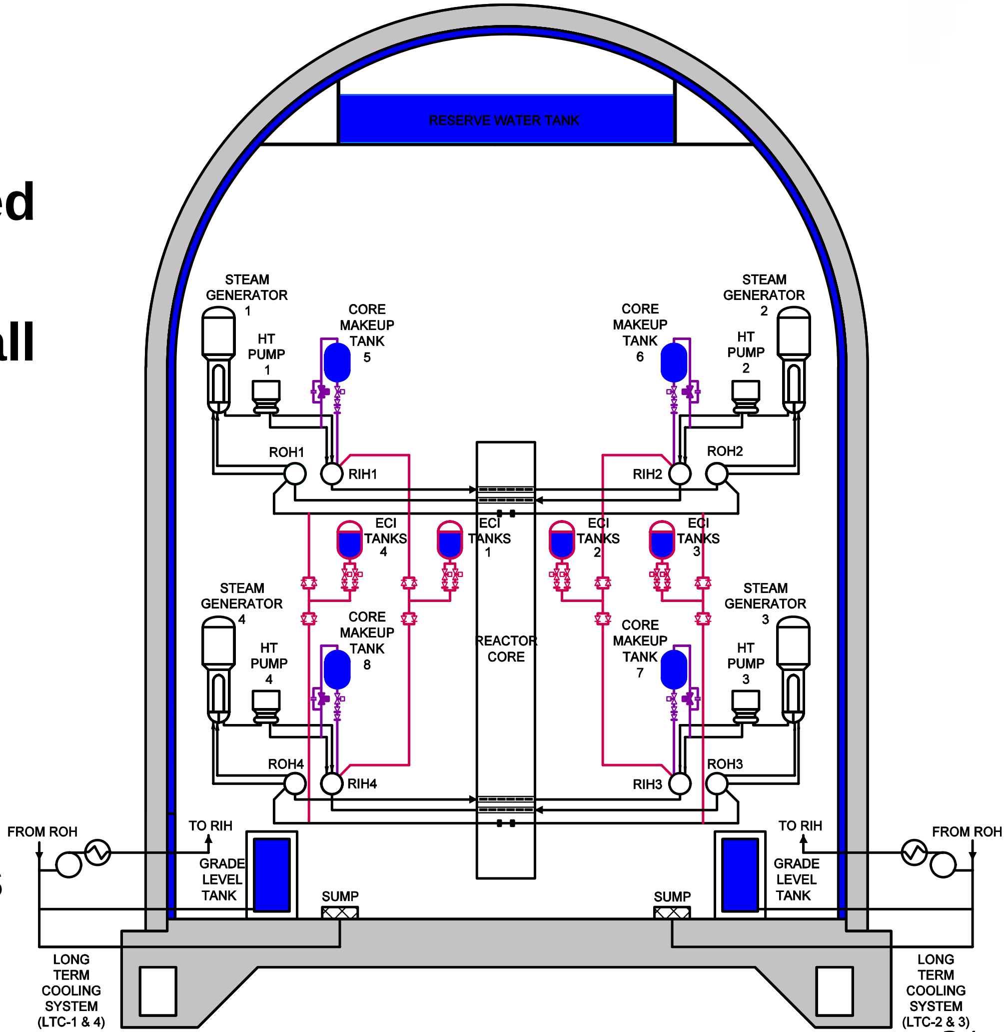
ACR-1000 ECC Design

- Core makeup tanks for passive reactor coolant make-up during depressurizations
- Core make-up ensures natural circulation cooling capability for all event scenarios
- Emergency coolant injection (ECI) from accumulator tanks located in RB with check valves for high pressure injection with rapid response
- Long Term Cooling pumps for makeup and recovery cooling

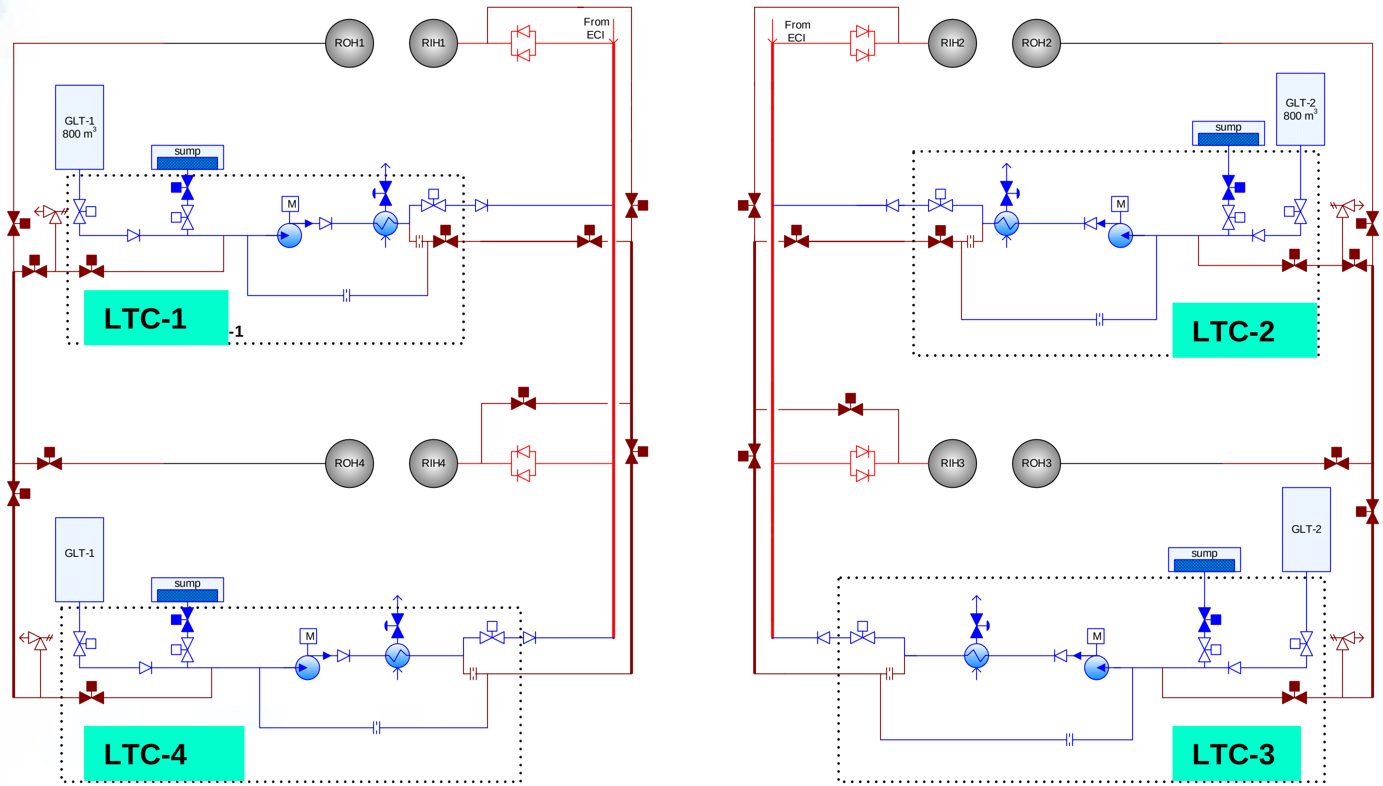
Emergency Core Cooling (ECC) System

- **Two Stage ECC System**:
  - ➢ **Initial injection from pressurized ECI tanks located inside Reactor Building (RB)**
  - ➢ **ECI tanks are connected to all reactor headers**
  - ➢ **Core makeup tanks connected to reactor inlet headers**

  LTC pumps and heat exchangers located in Reactor Auxiliary Building (RAB) adjacent to RB sumps



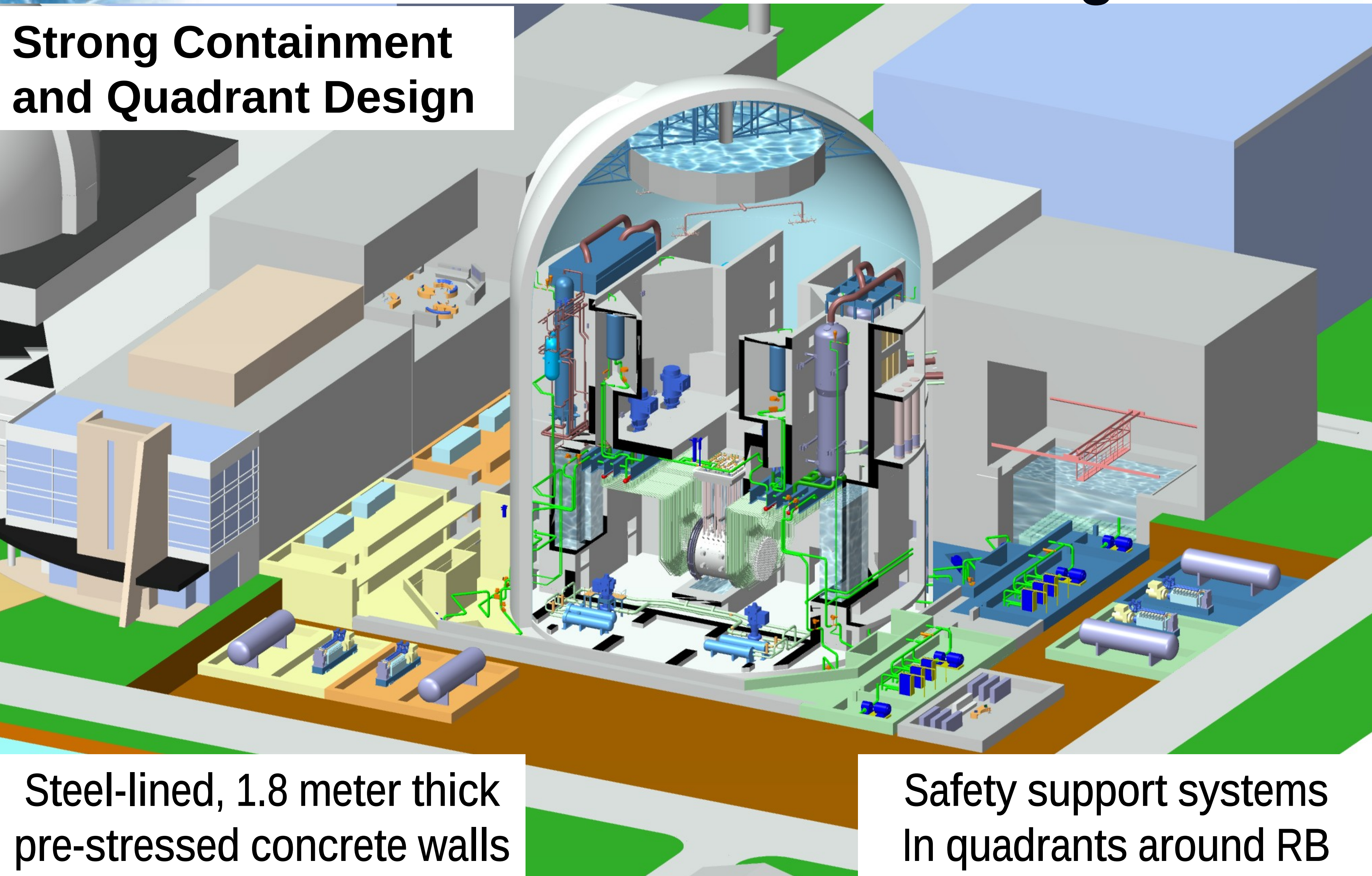
Long Term Cooling (LTC) System



- LTC system provides fuel cooling in the long term recovery stage of a LOCA
- Comprised of 4 redundant divisions located in 4 separate quadrants of the RAB.
- LTC pumps are powered by seismically and environmentally qualified Class III (Emergency Power) electrical system.
- The LTC system also provides maintenance cooling after a normal shutdown.

ACR-1000 Reactor Building

Strong Containment and Quadrant Design



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

Safety support systems In quadrants around RB

Four Quadrant Separation Benefits

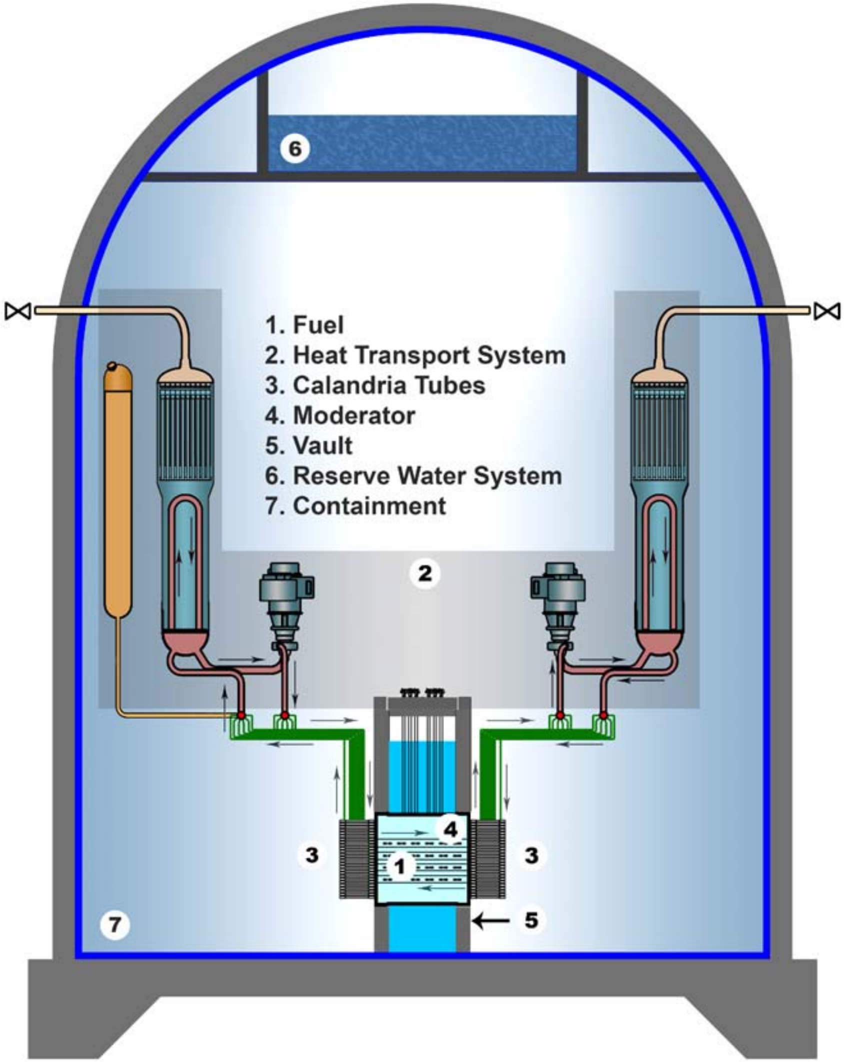
Safety Benefits:

- Improved fire protection (barriers):
  - Improved separation of redundant components
  - Improves PSA
- Improved human factors:
  - Reduced possibility of spurious trips (such as during testing while refueling) increases clarity of operating procedures

Operational Benefits:

- Improved plant operability (capacity factor):
  - Flexibility in removing equipment from service for maintenance during plant operation
  - Outages may be shortened by doing work in parallel,

Levels of Defense-in-Depth

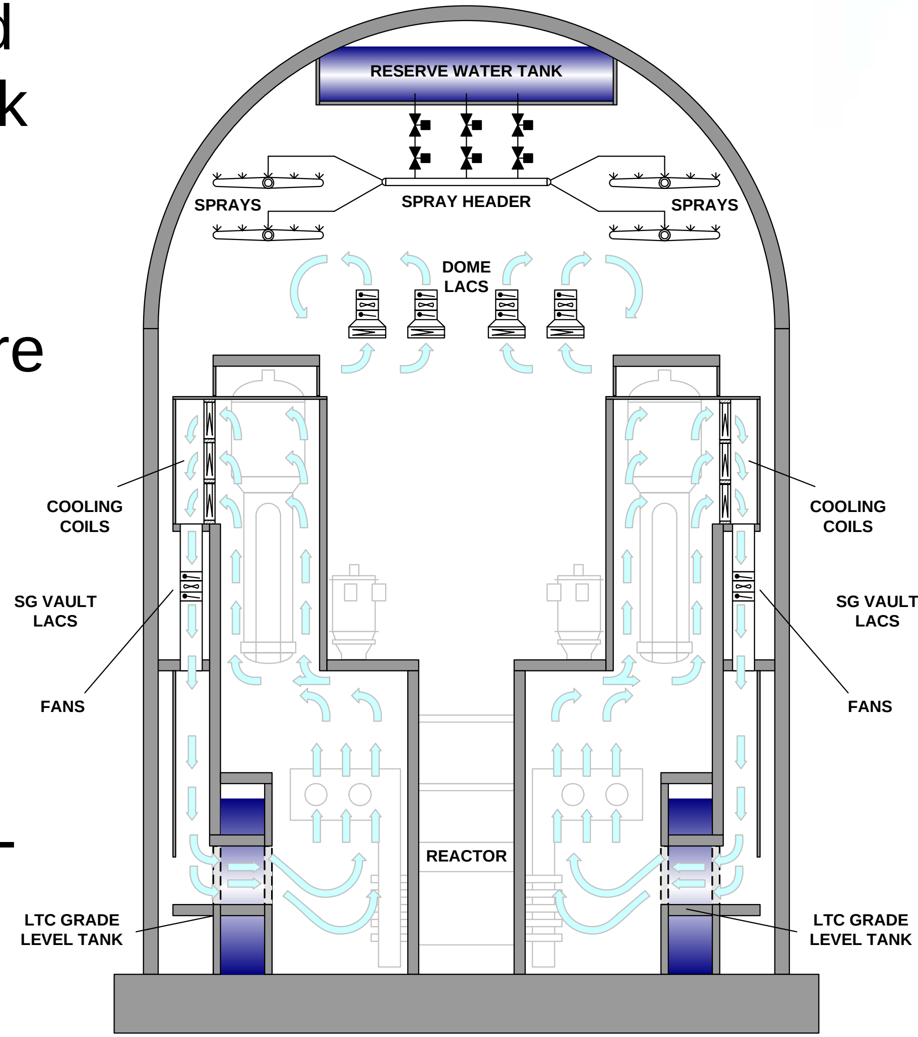


Severe Accidents

- **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) supply by gravity to steam generators provides inventory for long-term thermosyphoning**
  - **Passive make-up to HTS from ECI and RWS delay accident progression**
  - **Passive make-up to moderator and shield tanks from RWS delay accident progression**
  - **Passive make-up to reactor vault from RWS maintains cooling of core inside calandria**
  - **Passive spray system supplied from RWS maintains containment cooling**

Reactor Building Structure

- Additional loads are considered in the design. Steam Line Break sets design pressure (approx. 350 kPa)
- Robust reactor building structure upgraded to address evolving security licensing basis
- Reactor Building structure designed for aircraft crash with 1.8 m thick wall
- RB equipment is accessible on-power through 2 airlocks (no inflatable seals)



Operation and Maintenance

- **Designed for >90% average lifetime capacity factor**

  - Advanced Control Center design
  - Low forced outage frequency
  - Three year planned outage frequency
  - General design for maintenance
  - 21-day standard planned outage duration
  - Mid-life (30 years) pressure tube re-tubing outage of less than one year.
  - SMART CANDU^{TM} plant life cycle information tools

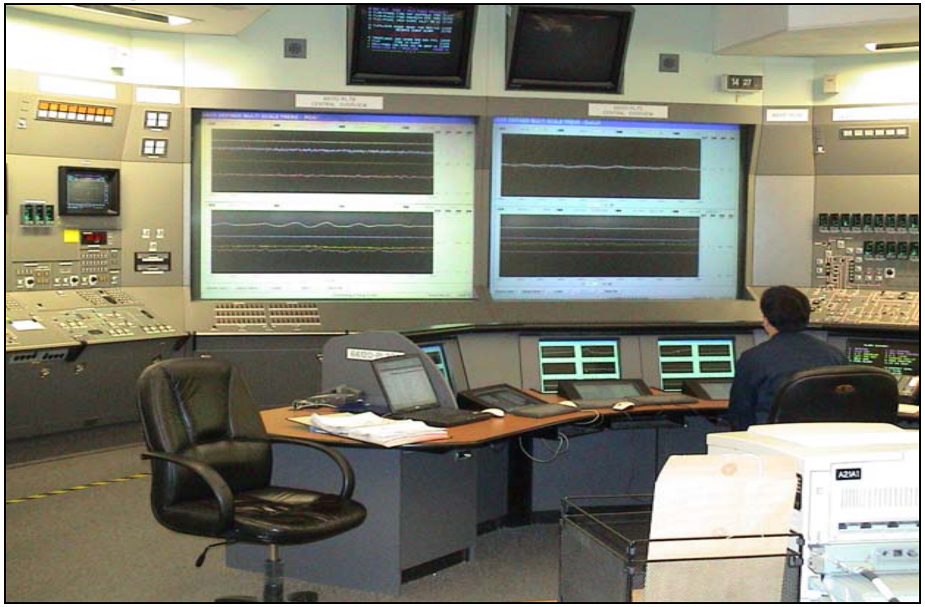
ACR-1000 Control Centre

Major focus of the ACR-1000 Advanced Control Centre design is:

- **Build on the improved display and layout used in the Qinshan CANDU 6 Main Control Room**
- **Improve operability of the plant and build on past experience**
- **Systematically integrate human factors into the design process**
- **Decrease likelihood of operator or maintainer errors**
- **Improve the operator's awareness of system and plant status through Human Factors engineering analysis**
- **Provide improved maintenance/diagnostic capabilities**

Qinshan Control Centre

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



Low Forced Outage Frequency

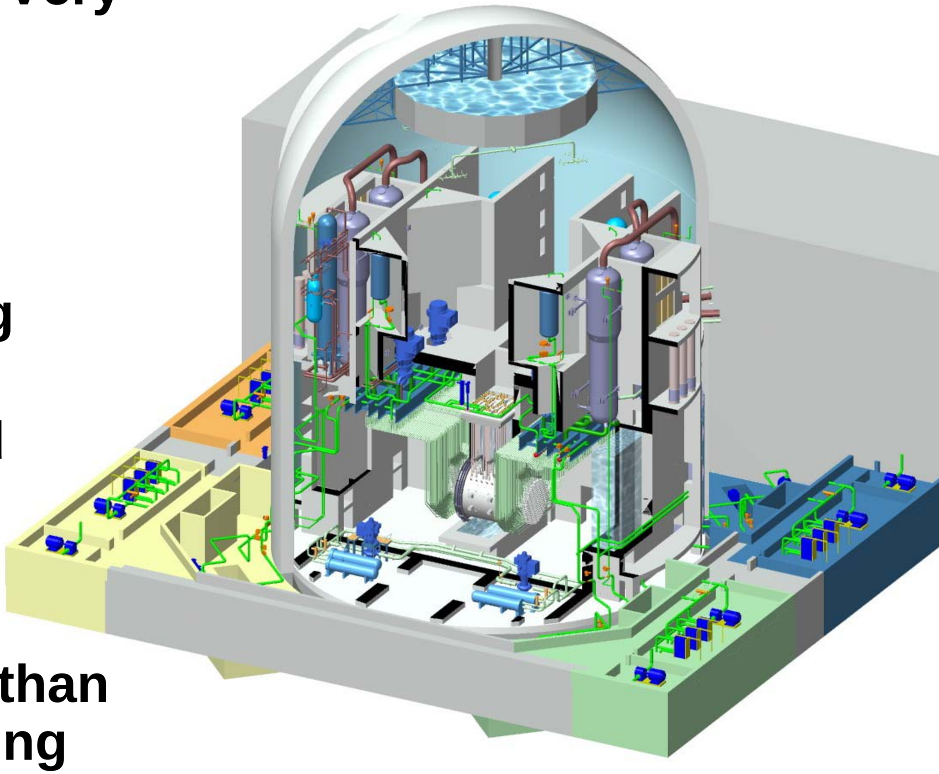
- Well maintained quality equipment
- Increased access for on-line maintenance
- 4 divisions of major safety & safety support systems provides additional redundancy and reliability to allow on-power maintenance of one division
- 4 channel safety systems, minimizes risk of spurious trips
- Increased automation of shutdown system testing.
- Operability, maintainability and human factors designed in
- Increased automation of unit operations
- Better information tools
- 3 year planned outage intervals

Guaranteed Shutdown State (GSS)

- Faster application and removal of Guaranteed Shutdown State (GSS) will result in reducing operator work load and shorten critical path activities during outages
- Rod based GSS provided to:
  – Meet customer-identified requirement to provide design not requiring moderator-poison-based GSS
  – The GSS design will have to meet all requirements for both short unplanned outages as well as longer planned maintenance outages
  – The final configuration of GSS rods is of the same general design as SDS1 shutoff rods: boron-carbide neutron absorber blocks contained within stainless-steel sheathing
  – Two sizes of GSS rods are used: wide 200-mm (as in SORs) and narrow 100-mm

Construction Strategy

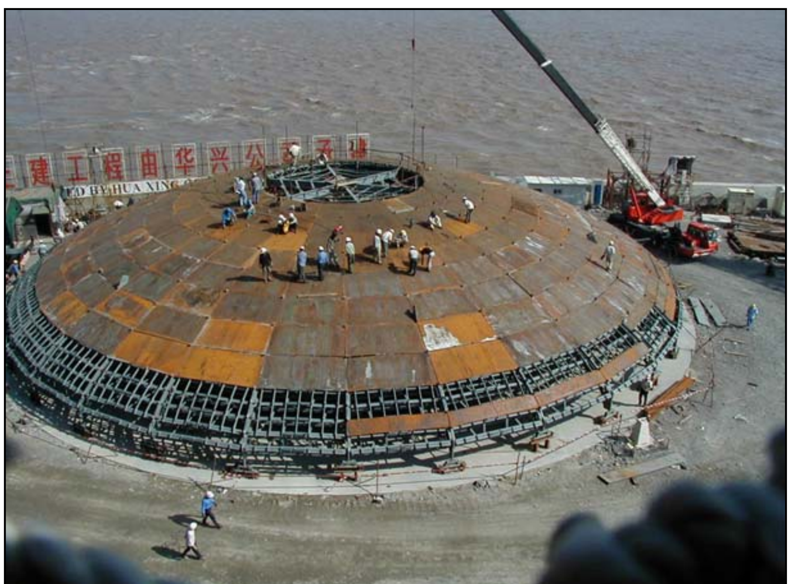
- Prefabrication/Modularization
- RB Open Top Construction using Very Heavy Lift (VHL) Crane
- Parallel construction and module fabrication
- Use of up-to-date technologies
  - Use of 3-D modeling and wiring databases in the field
- Extensive Modularization coupled with "Vertical Installation Compartment" used in Reactor Building construction
- ACR is designed to employ more than 165 modules in the Reactor Building
- Input from Module Fabricators and Construction have been incorporated into the module design



ACR Module Types

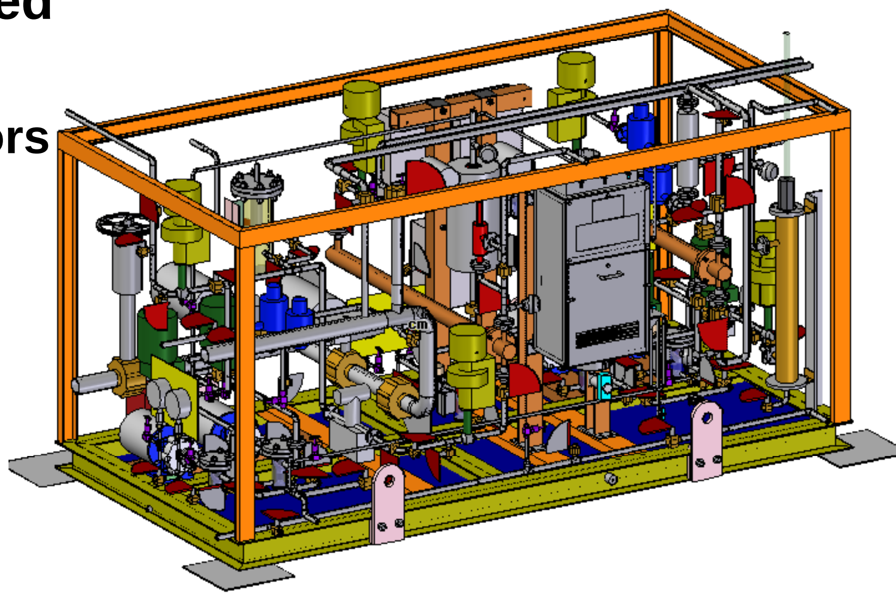
Four major module types considered:

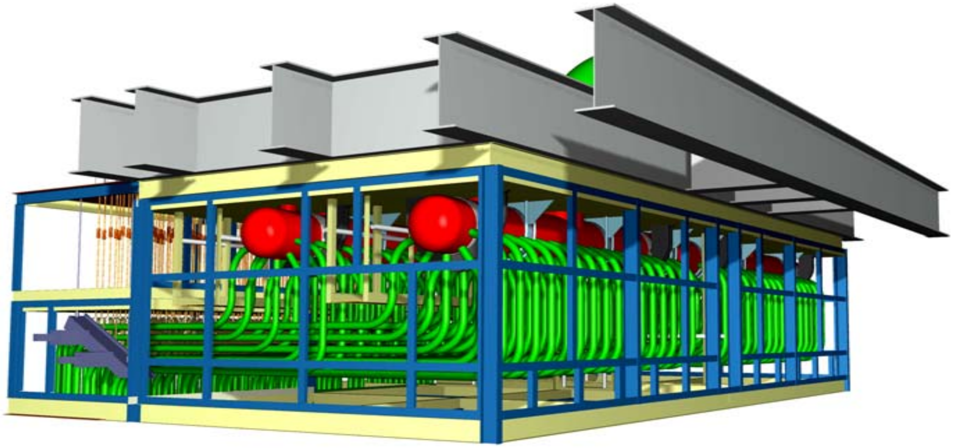
- **Large Civil Structure Modules**
  - **Structural Steel shipped to site**
  - **Fabricated adjacent to Reactor Building**
  - **Installation using VHL Crane**



ACR Module Types

- **Piping Valve/ Modules Pre-Assembled on Skids**
  - Pre-assembled in Supplier/ Fabricators shop
  - Shipped by road/ rail/ sea
- **Instrumentation Racks/ Pre-assembled Panels**
  - Pre-assembled in Suppliers shop
  - Shipped by road/ rail/ sea

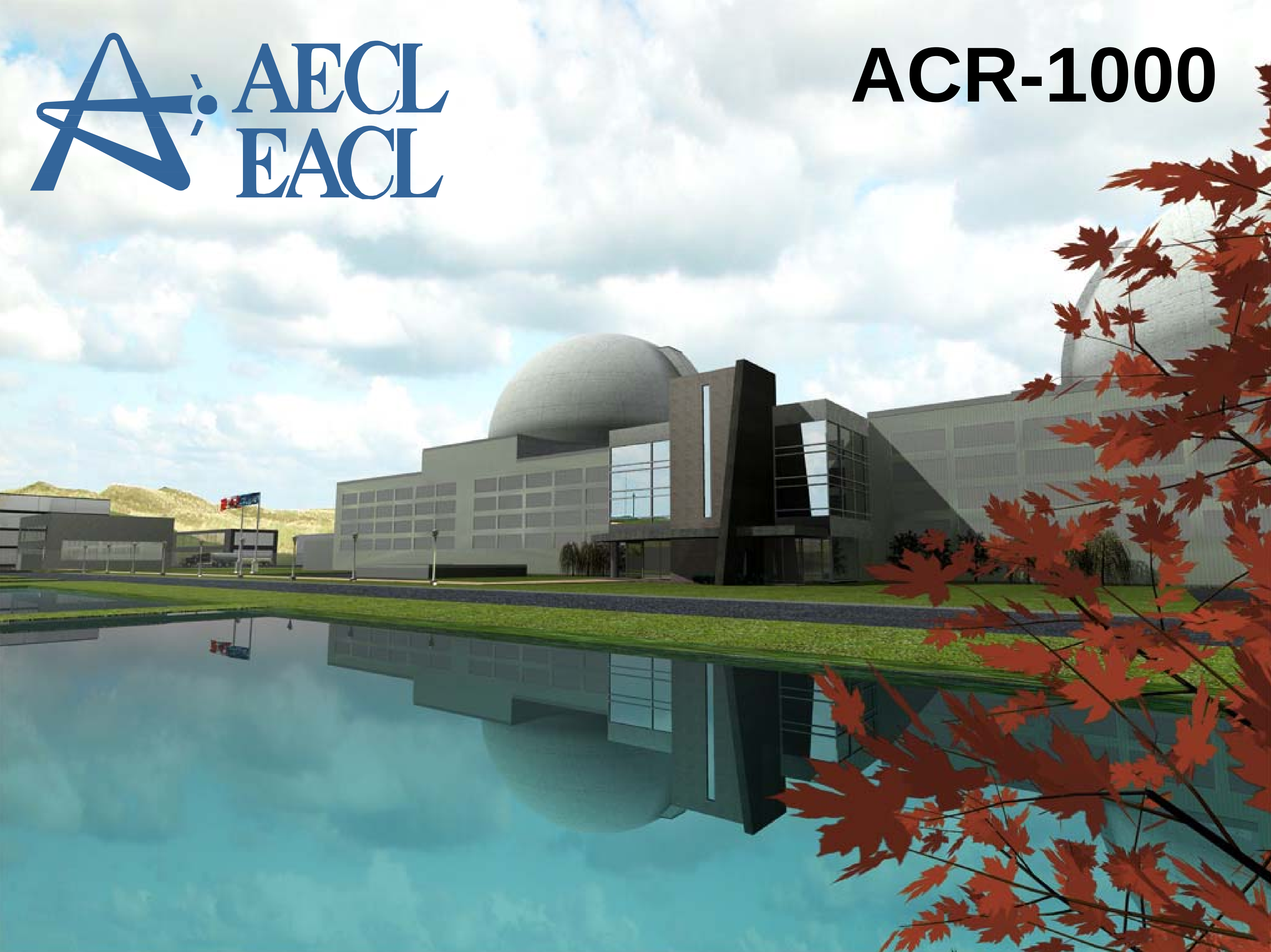




ACR Feeder Header Module

Summary of ACR Design

- **AECL has invested significantly in the “Generic ACR Technology Development” Program for the ACR-1000**
- **Activities being carried out in Design, Licensing, Development and Testing, Supply Chain Management, and Commissioning and Operations assessment**
- **Significant design enhancements have been made for the benefit of the Customer: Safety, Performance, Operability, Maintainability and Constructability**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