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PHWR Group of Countries

Implementation of Lessons Learned from Fukushima Accident in CANDU Technology

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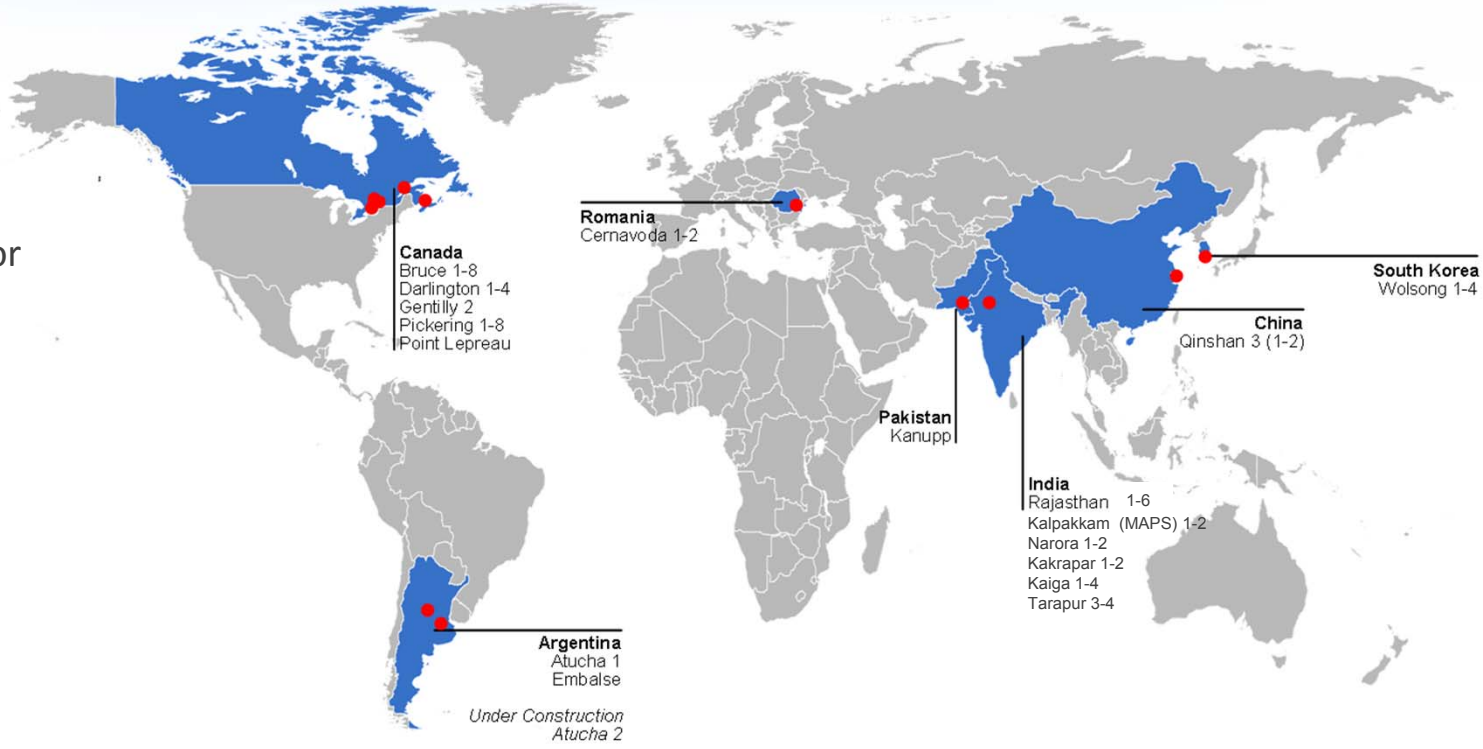
Countries Operating CANDU

Pressurized Heavy Water Reactor (PHWR)

CANDU reactors have operated for over 700 reactor years across 34 reactors in 7 countries

Source: CANDU Energy Inc.

No major events in CANDU reactor history



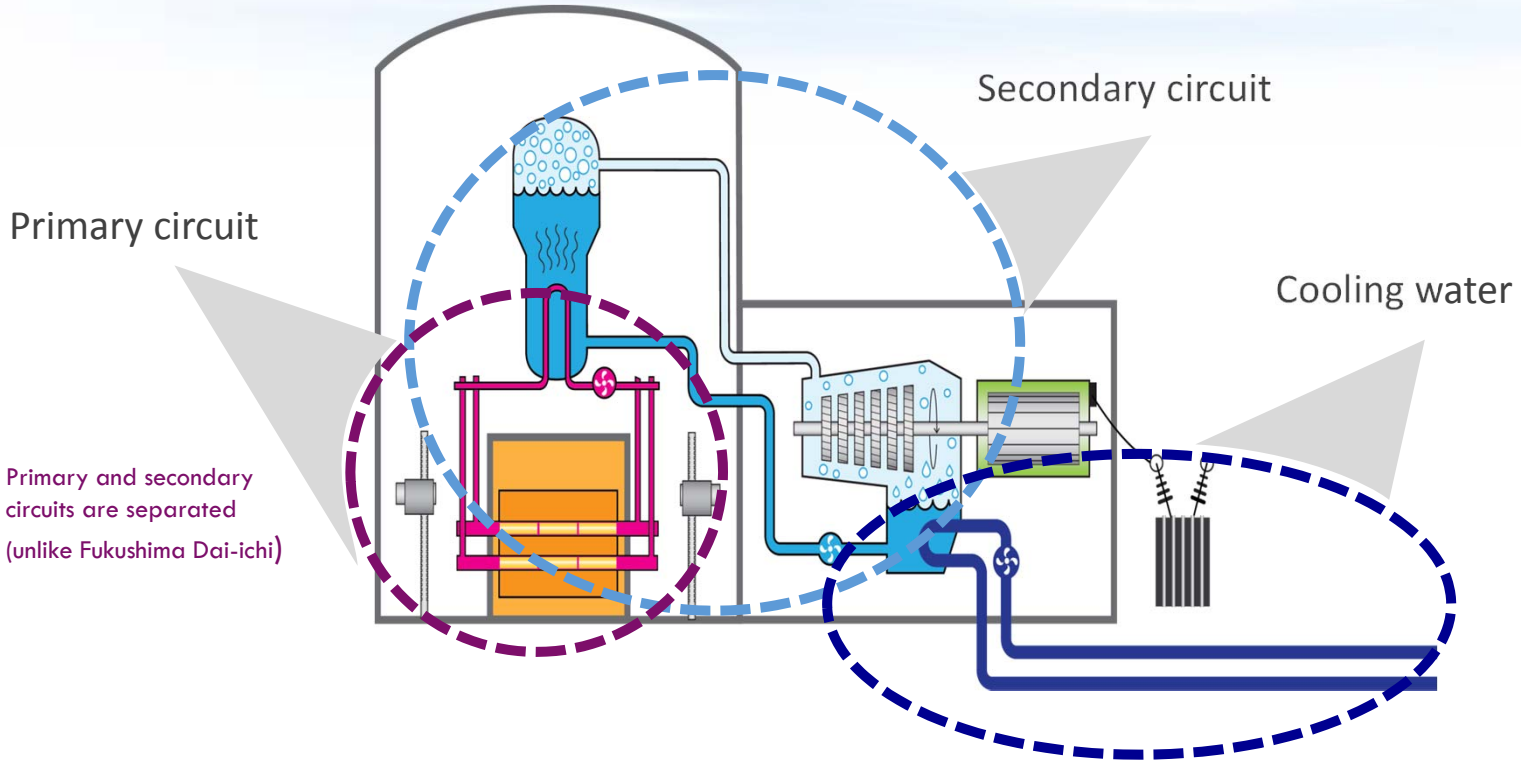
Outline/Objectives

- CANDU Design Overview
- Inherent Robustness of CANDU/PHWR Design to Severe Accident
- Status of Fukushima Actions in CANDU Countries
  - Strengthening Defence-in-Depth
  - Enhancing Emergency Response
- Summary

CANDU Design Overview

Based on the CANDU-6 design

CANDU Nuclear Power Plant

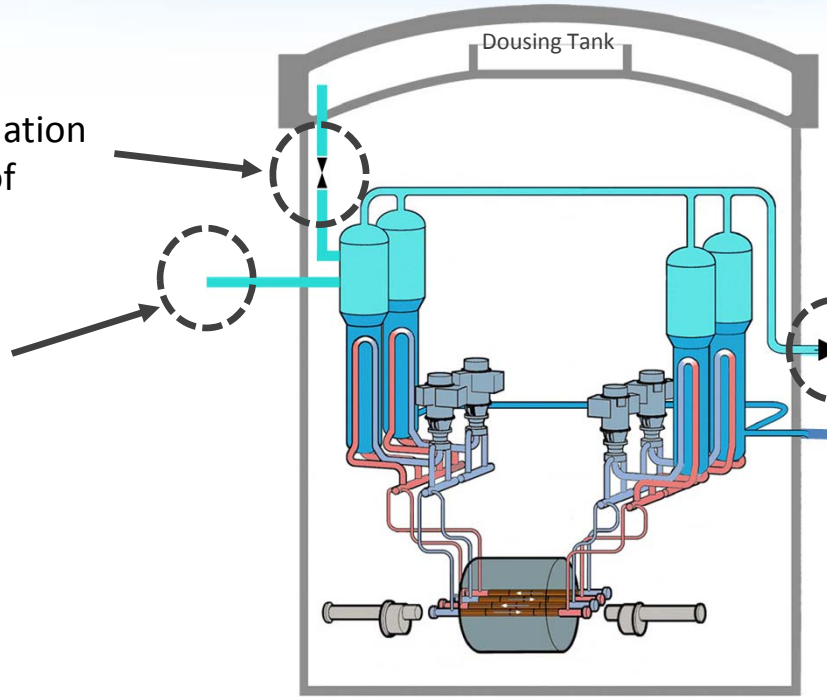


CANDU Design Overview

Based on the CANDU-6 design

Opens automatically
Boiler makeup water isolation valves fail open on loss of power or instrument air

Emergency water supply (simplified)



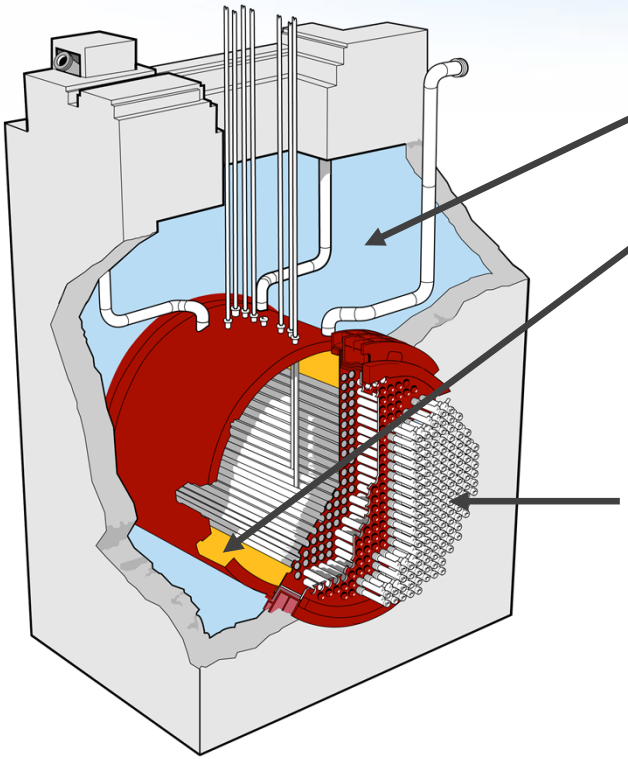
Main Steam Safety Valves (MSSVs)
Opens automatically to depressurize primary and secondary sides

Feedwater supply

Source: CANDU Energy Inc.

CANDU Design Overview

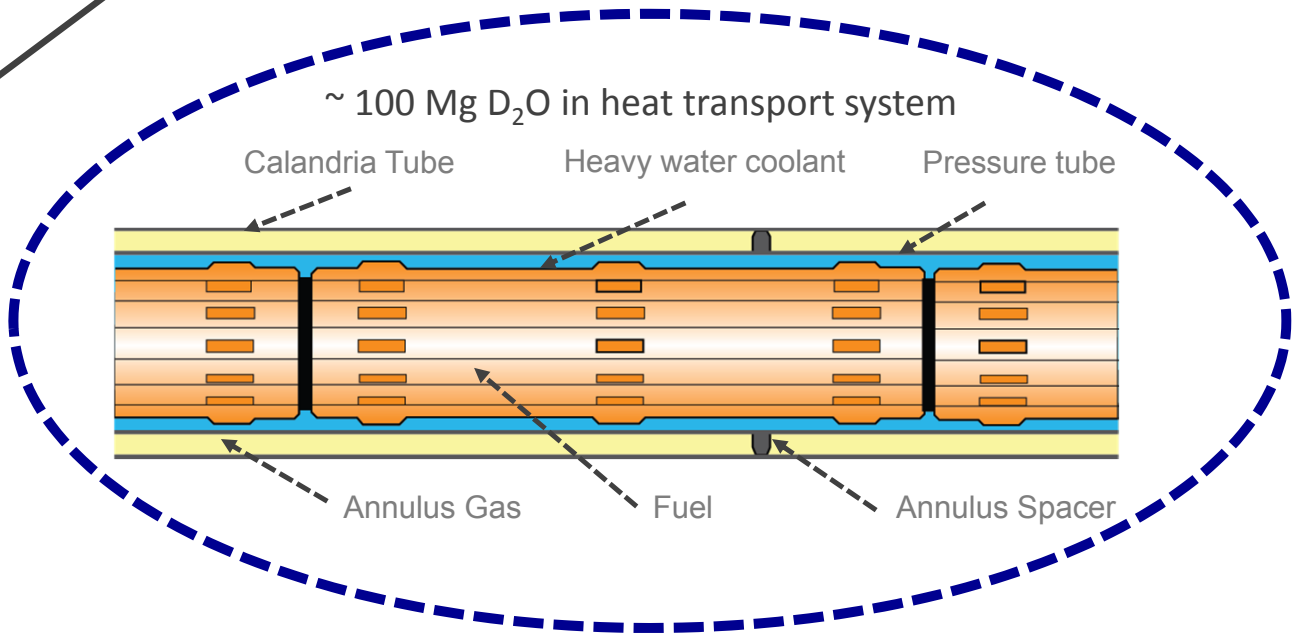
Passive Heat Removal



~ 500 Mg H_2O in calandria vault

~ 200 Mg D_2O calandria vessel

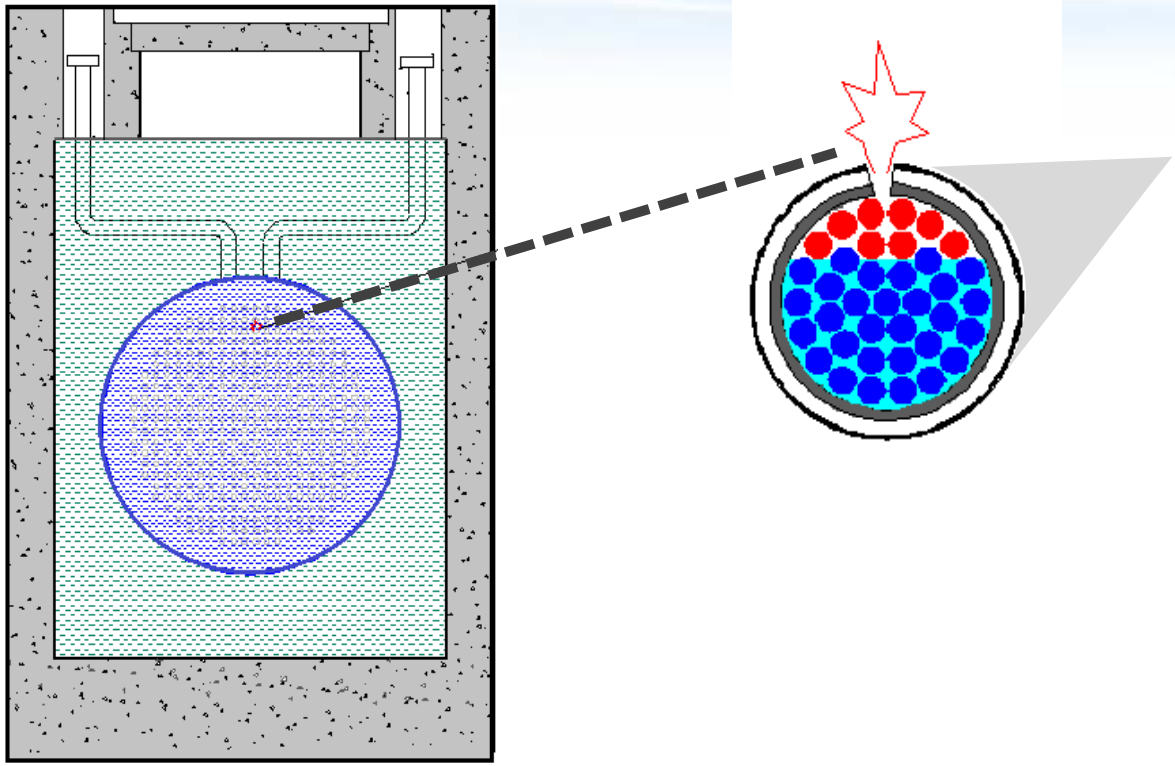
~ 100 Mg D_2O in heat transport system



Inherent Robustness of CANDU Design to Severe Accident

Scenario: Unmitigated Total Loss of Heat Sinks

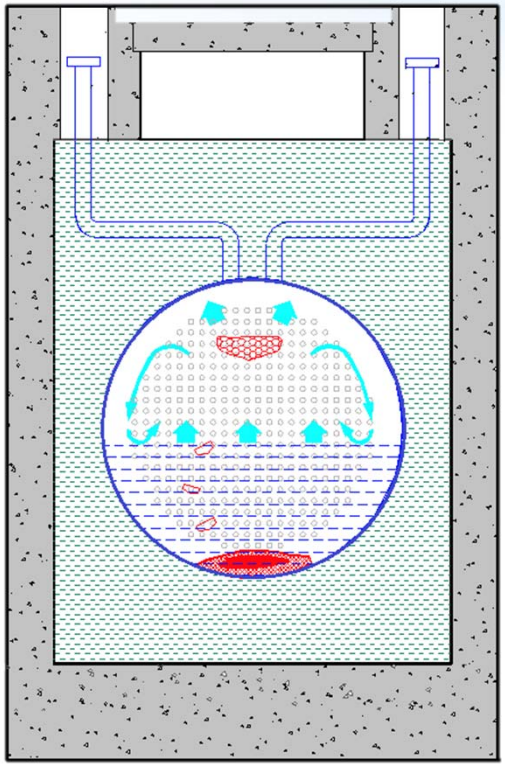
Core Heat-up Leading to In-core Fuel Channel Ruptures

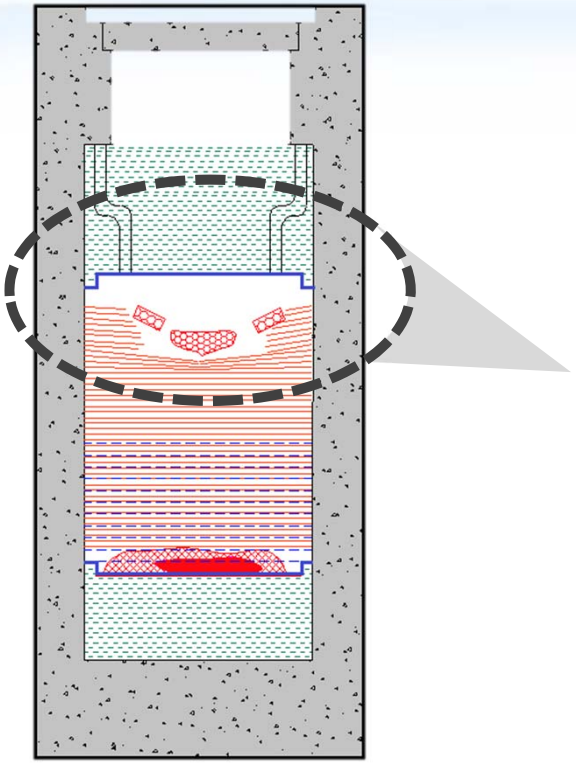


Channel rupture at high pressure can be delayed by ~ 1-7 days by gravity feed using existing dousing tank water inventory

~ 4 hours for unmitigated total loss of heat sinks due to natural circulation cooling

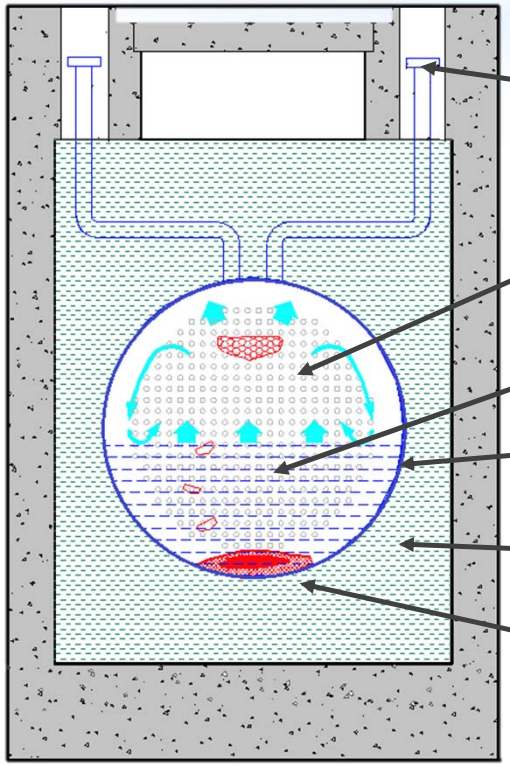
Suspended Debris Bed





Core debris from disassembled channels held up by intact channels

Core Collapse



Calandria Vessel Rupture Disc

Core collapses into residual water pool in calandria vessel

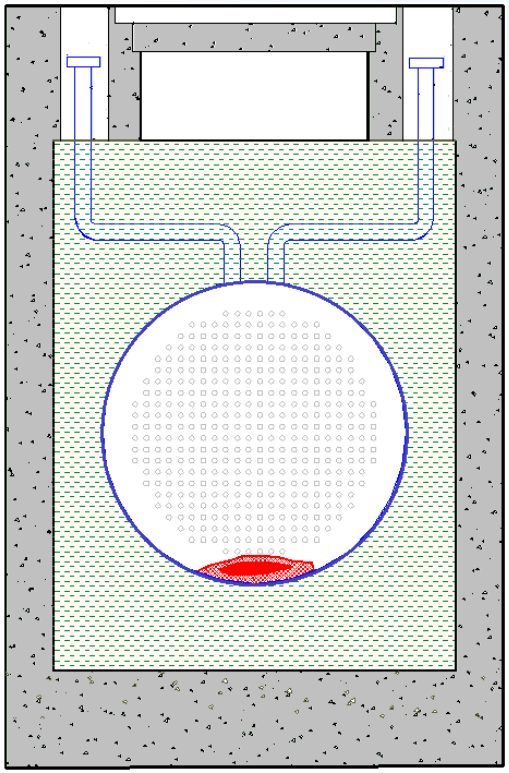
Residual water pool boil-off continues

Calandria vessel

Reactor vault water subcooled at this point

Porous terminal debris bed quenches

Corium In-vessel Retention



~ 40 hours to calandria vessel failure for unmitigated total loss of heat sinks

Calandria vessel failure not expected until calandria vault water level is below corium level inside calandria vessel

A design change to permit water makeup to calandria vault will maintain calandria vessel integrity

Status of Fukushima Actions in CANDU Countries

- *Strengthening Defence-in-Depth*
  - *Protect Fuel*
  - *Prevent Severe Core Damage*
  - *Protect Containment*
  - *Protect Spent Fuel Pools*
- *Enhancing Emergency Response*
  - *Protect Public*

Response to Fukushima Accident

Assessments equivalent to stress tests

- Argentina – performed stress test similar to EU
- Canada, China, India, Korea and Pakistan completed independent comprehensive safety assessment
  - Wolsong-1 (Korea) Continued Operation is contingent upon implementation of results from '*Augmented Stress Test*'
- Romania – performed EU Stress Test

CANDU safety improvements through lessons learned

Protect Fuel (1/3)

Planned or Implemented Design Improvements

- Emergency Mitigating Equipment (EME)
  - Mobile water pumps and diesel-generators
- Water makeup connections to:
  - Steam Generators (pumped/gravity feed from Dousing Tank/Deaerator)
  - Primary Heat Transport System (PHT)
  - Emergency Core Cooling (ECC) System
  - Emergency Water Supply System
- Provision to open Main Steam Safety Valves after station blackout

Strengthening defence-in-depth

Protect Fuel (2/3)

Planned or Implemented Design Improvements (cont'd)

- Improvements to safety related systems to enhance capability and reliability to better cope with accidents
- Upgrades of power systems to improve reliability, longevity of battery supply, improved backup for critical loads
  - Improved load shedding to extend battery availability
  - Battery charging capability and UPS system backup
  - Upgrades to power supply for key instrumentation (e.g., Local Air Cooler)
- Protection against flooding (barriers, water-tight doors, sealing penetrations)

Strengthening defence-in-depth

Protect Fuel (3/3)

Analyses and Reassessments

- Re-evaluation of site-specific magnitudes of external events, including multi-unit events:
  - High winds
  - Seismic margin assessment / Seismic PSA
  - Tsunami / Storm Surges
  - Flooding
  - Significance of station blackout event on spent fuel bundles inside fueling machine

Strengthening defence-in-depth

Prevent Severe Core Damage (1/2)

Planned or Implemented Design Improvements

- Water makeup connections to:
  - Calandria vessel (moderator)
  - Calandria vault (shield tank)
- Improve pressure relief capability of calandria/vault
- Instrumentation upgrades arising from qualification for Severe Accident (SA) conditions
  - Installation of seismic trip system

Strengthening defence-in-depth

Prevent Severe Core Damage (2/2)

Analyses and Reassessments

- Severe accident studies including modelling for multi-unit plant events
- Reassessment of Main Control Room & Secondary Control Room habitability
- Instrumentation qualification for Severe Accident conditions

Strengthening defence-in-depth

Protect Containment (1/2)

Planned or Implemented Design Improvements

- Installation / enhancement of Containment Venting
- Installation of Passive Autocatalytic Recombiners (PARs)
- Instrumentation to measure hydrogen in containment

Strengthening defence-in-depth

Protect Containment (2/2)

Analyses and Reassessments

- Enhancement of **Filtered** Containment Venting System
- Severe Accident Management Guidelines (SAMGs)
- Instrumentation for SA conditions monitoring
  - qualify existing or new
- Control Facilities habitability during SA
- Improved modelling of SAs for multi-unit plants

Strengthening defence-in-depth

Protect Spent Fuel Pools

Planned or Implemented Design Improvements

- Instrumentation to measure water level and temperature
- Piping and connections for external addition of water
- Develop and implement *Abnormal Operating Procedure* for loss of cooling

Analyses and Reassessments

- Structural integrity check for temperatures above design values

Strengthening defence-in-depth

Protect the Public (Onsite)

Planned or Implemented Design (or Procedural) Improvements

- Enhancing On-site / Off-site emergency preparedness and response
  - Training for severe accidents
  - Provision of satellite phones and improved on-site emergency communication
- Enhancing preparedness and execution of station emergency drills
  - Improvement of *Abnormal Operating Procedures* for specific scenarios
- On-site emergency management facility capable of withstanding extreme events
  - Maintaining site self-sufficiency through availability of water and emergency power

Enhancing Emergency Response

Protect the Public (Offsite)

Planned or Implemented Procedural Improvements

- Establish/Confirm national level oversight process for offsite nuclear emergency response
- Reassessment of emergency management, in particular for multi-unit events
- Emergency drills up to full scale involving all levels of government
  - Review and increase in frequency and scope as necessary

Enhancing Emergency Response

Summary

Safety Enhancements

- Protecting Fuel
  - Deployment of back-up mitigation equipment
  - Makeup water capability to SG/PHT/ECC/Dousing Spray
- Preventing Severe Core Damage
  - Makeup water capability to moderator system and calandria vessel/vault
- Protecting Containment
  - Passive Recombiners and containment venting
  - SAMG validation/exercise
- Protecting Spent Fuel Pools
  - Makeup water capability and instrumentation
- Protecting the Public
  - Containment filtered venting
  - Integrated emergency plans and full scale emergency exercises

Summary

Safety Benefits

- Enhanced accident prevention
  - Risk reduction by a factor of 2 to 10, depending on accident scenarios
- Improved accident mitigation
  - Potential radiological consequence reduced to as low as practicable
- Improved public protection
  - Effective strategies for sheltering and evacuation

Thank You

PHWR Group of Countries

Argentina, Canada, China, India, Korea, Pakistan, Romania