Strength through Co-operation

Research and Development in Support of Beyond Design Basis Accidents (BDBA) Response in CANDU Nuclear Power Plants

Gabriel Balog
Director, Research and Development
CANDU Owners Group

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Presentation Outline

- Canadian Response to Fukushima
- Examples of Accident Analysis and R&D in Response to Beyond Design Basis Accidents:
  - Accident Progression – Core Response
  - Accident Progression – Containment Response
  - In-Vessel Retention – Technical Basis
  - In-Vessel Retention – Experimental Basis
  - Other Areas of Investigation
- Future Work

Acknowledgements

- Atomic Energy of Canada Limited (Now Canadian Nuclear Laboratories CNL)
- Candu Energy Inc.
- AMEC NSS
- Kinectrics

Canadian Response to Fukushima

- Prior to the Fukushima- Daiichi accident, in Canada accident analysis was already being undertaken and plant modifications were being installed to strengthen the ability to cope with Beyond Design Basis Accidents:
  - Comprehensive PSAs for internal and external hazards
    - All units, all states, level 1 and level 2
  - Plant modifications to prevent and mitigate severe accidents (site dependent:
    - Emergency Moderator Makeup
    - Calandria Vault Makeup
    - Containment Filtered Venting Systems
- The Fukushima-Daiichi accident led to a focused and unified response, both by the CANDU industry and the Canadian regulator (CNSC).

Canadian Response to Fukushima

- Industry formed the CANDU Industry Integration Team (CIIT) under the CANDU Owners Group (COG)
  - CIIT included both domestic and international participants
  - Sponsorship by the industry CNOs
  - Interface with Canadian regulator
- CNSC formed a Task Force and Produced an Action Plan (37 Fukushima Action Items)
- CANDU Owners Group (COG) Joint Project 4426: "CANDU Severe Accident Support to Industry-Post Fukushima"
  - JP4426 included elements of Safety Analysis and R&D addressing Beyond Design Basis/Severe Accident Behaviour and Response

Canadian Response to Fukushima

Operational states		Accident conditions →		
Normal operation	Anticipated operational occurrence	Design-basis accident	Beyond-design-basis accident →	
			Design extension conditions	Practically eliminated conditions →
			No severe fuel degradation	Severe accidents →
Design basis			**Design extension Conditions (DEC)**	Not considered as design extension →

- Response to DECs:
  - Prevent
  - Terminate
  - Mitigate

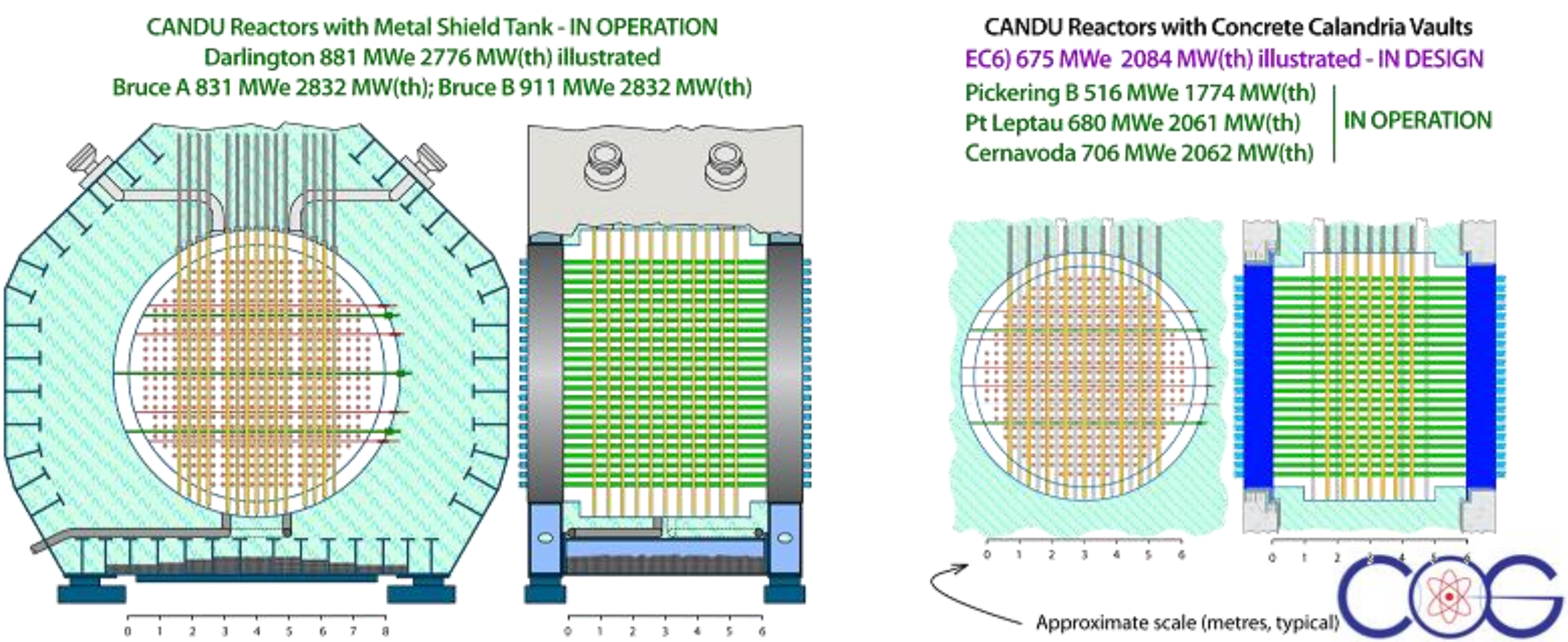
Using Complementary Design Features including portable Emergency Mitigating Equipment (EME)

Canadian Response to Fukushima

- Example: Emergency makeup water:
  - Into Steam Generators
  - Into Heat Transport System
  - Into Moderator System
  - Into Shield Tank
  - Into Irradiated Fuel Bays

Canadian Response to Fukushima

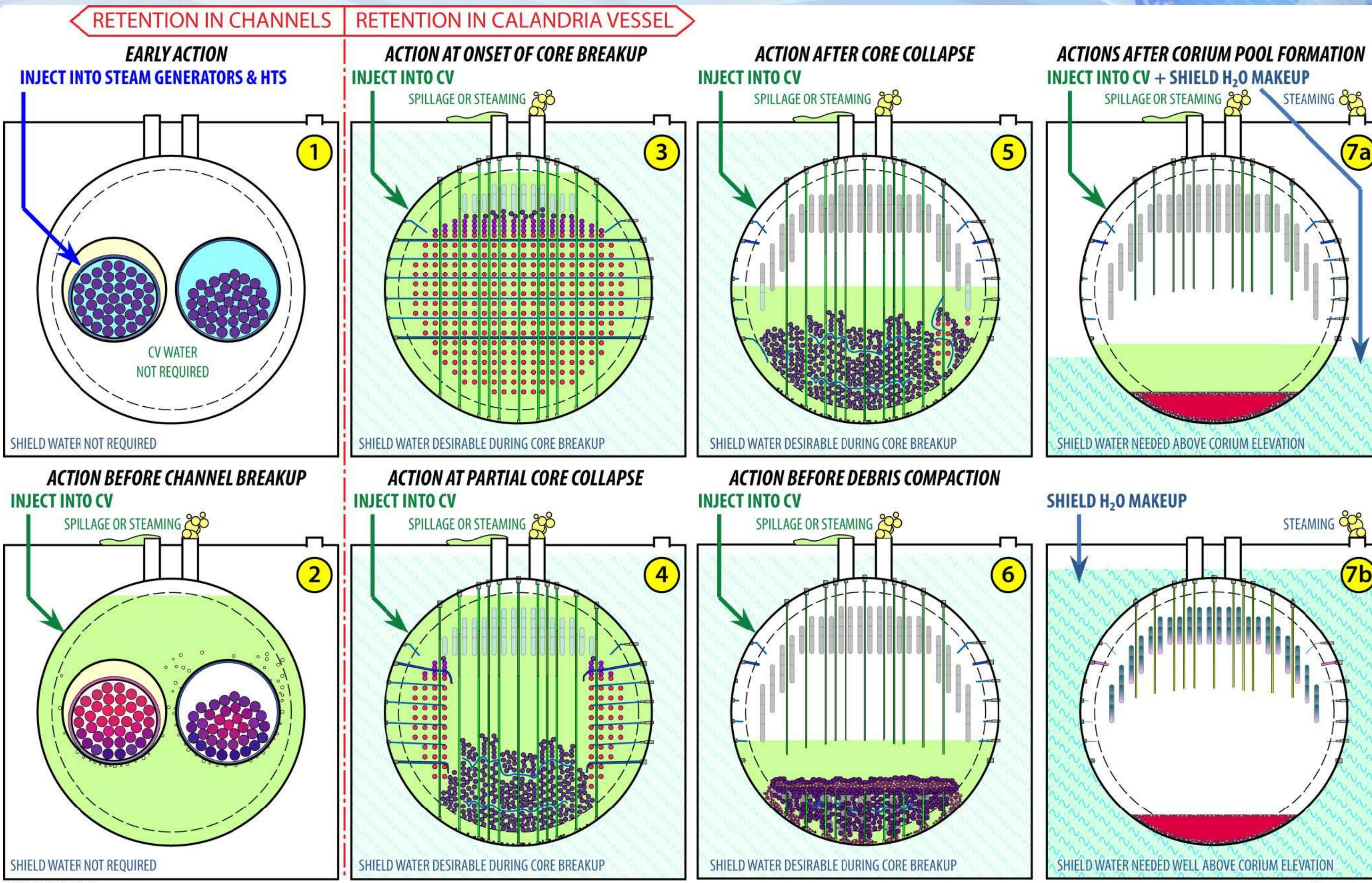
- CANDU NPPs offer several options for maintain core cooling, severe accident prevention and mitigation
- Physically separate Fuel Channels, Calandria Vessel and Shield Tank (or Calandria Vault) act as passive heat sinks which can be augmented by makeup using portable equipment – About 700 Mg of cold, low pressure water surrounds the fuel channels



Accident Progression Following Total Loss of Heat Sink

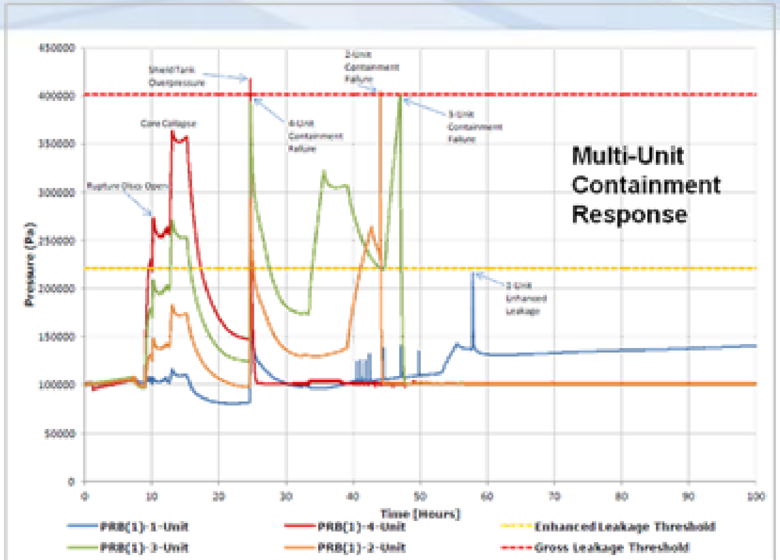
- Extensive Safety Analysis was carried out both as part of ongoing PSAs and in direct response to the Fukushima accident to quantify accident progression, determine capability of Emergency Mitigating Equipment (EME) and assess containment challenges
  - Deterministic Safety Analysis carried out with MAAP4-CANDU
  - Code/methodology modifications were required to address multi-unit accidents in plants with shared containments (Bruce, Pickering, Darlington)
  - The analysis examined the accident progression and the efficacy of Complementary Design Features and EME to terminate or mitigate the accident and to prevent containment failure and fission product release.
  - The efficacy of various Containment Filtered Venting Systems were also examined
  - Habitability of Control Facilities, accessibility of key equipment, due to harsh environments were also assessed

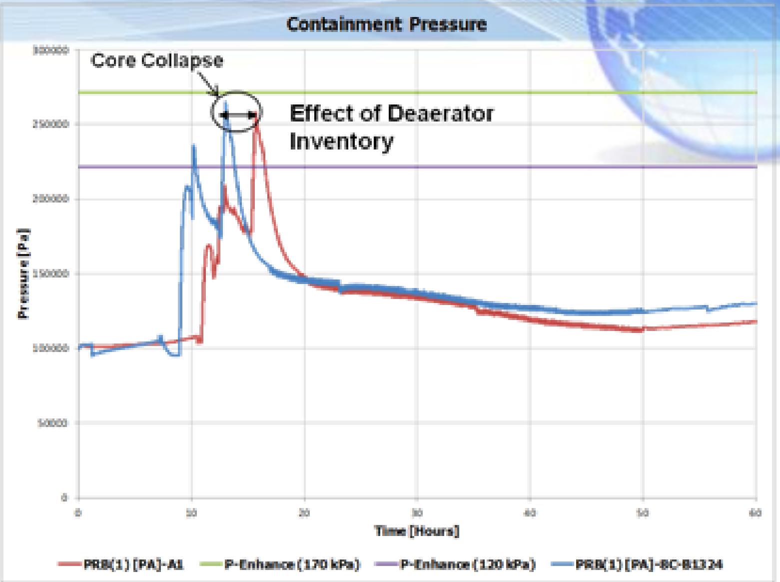
Accident Progression Following Total Loss of Heat Sink – Core Response

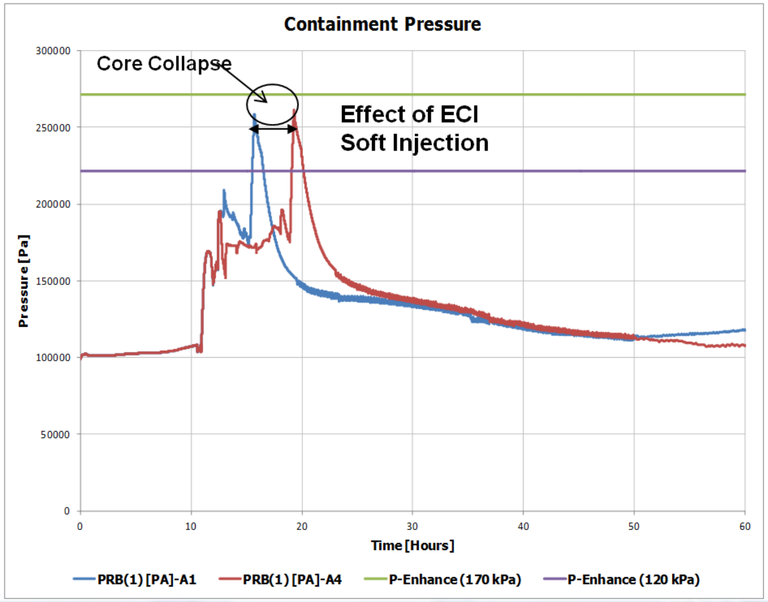


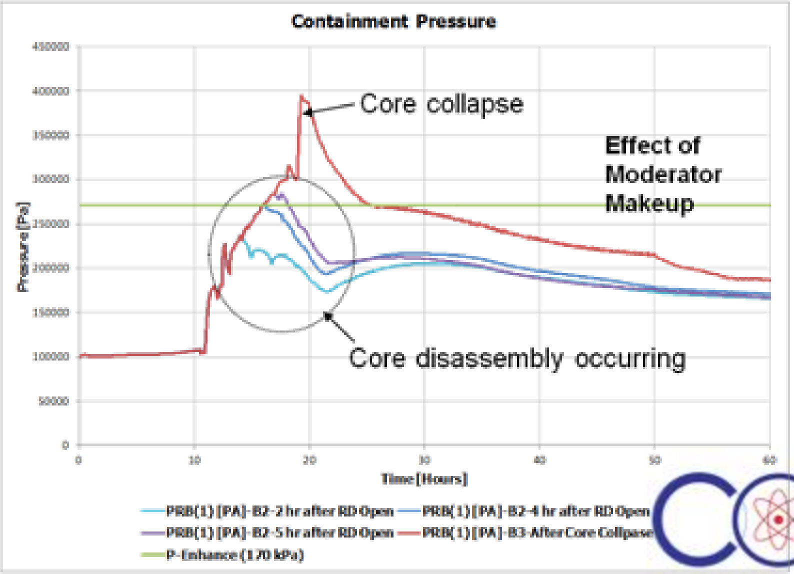
CANDU IVR Options Conceptual

Accident Progression Following Total Loss of Heat Sink – Containment Response

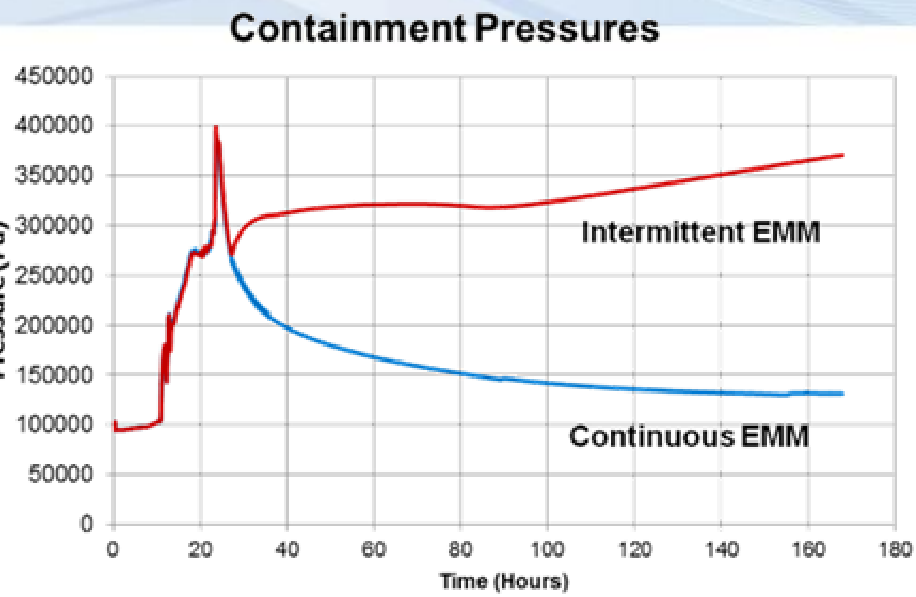


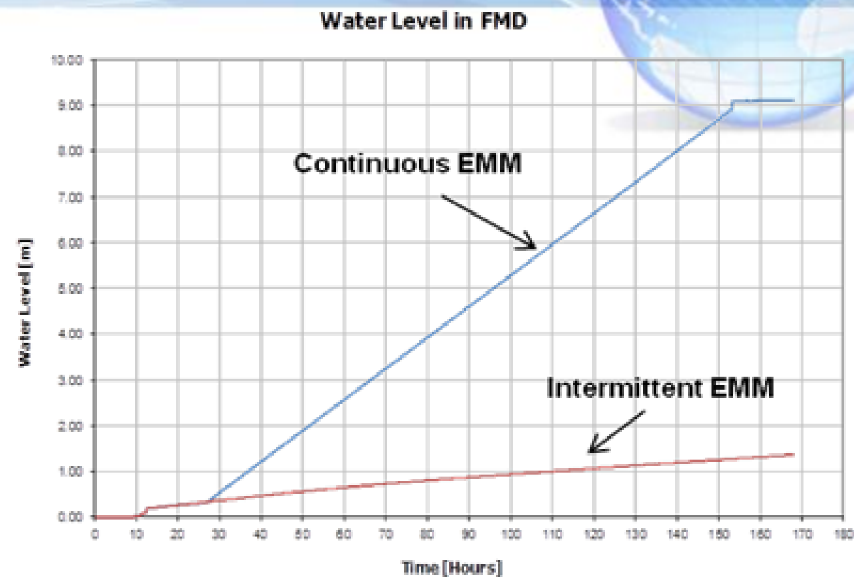


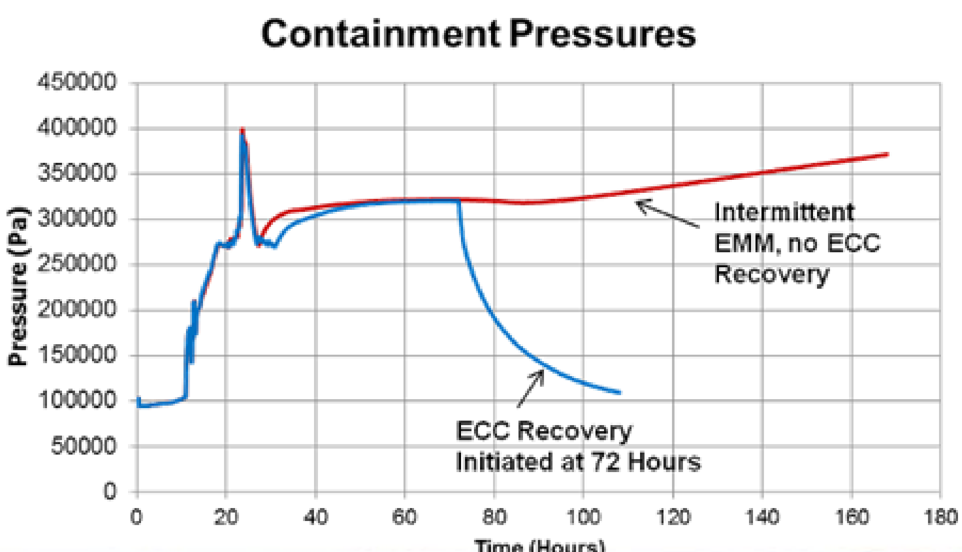




Accident Progression Following Total Loss of Heat Sink – Containment Response







EMM = Emergency Moderator Makeup

In Vessel Retention – Technical Basis

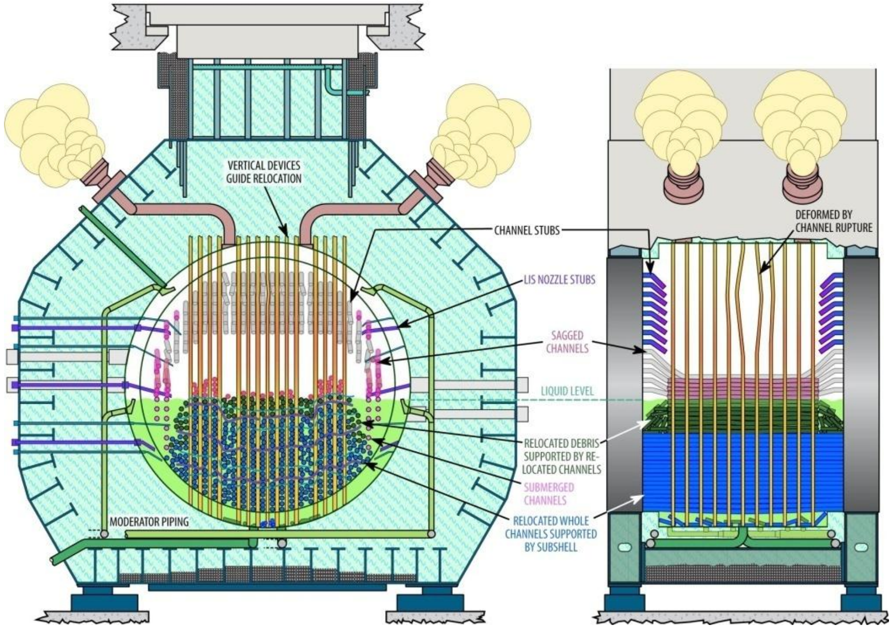
- CANDU In-Vessel Retention - Summary of Supporting Technical Basis (Degraded Core Retention in CANDU Calandria Vessels)[1]
  - Topical Report providing a comprehensive consolidation of information on In-Vessel retention (IVR) strategy.
  - Focused on the phenomena and challenges dealing with maintaining calandria integrity during severe accidents.

[1]Prepared by Candu Energy Inc

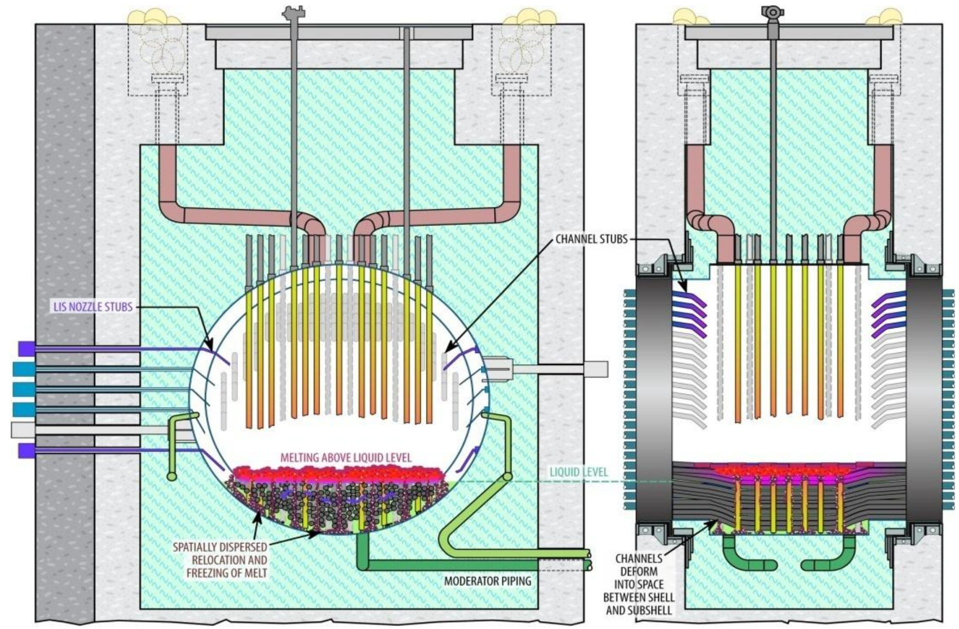
SECTIONS THROUGH MID-PLANES

In Vessel Retention – Technical Basis

- Report focused on the ability to maintain IVR using either internal vessel cooling (cooling water into the calandria) or external vessel cooling (shield tank or calandria vault).



Collapsed Core with liquid in calandria



Compacted Core with Liquid in Calandria Vault

In Vessel Retention – Technical Basis

- The report concluded that IVR can be sustained by:
  - Internal cooling (water makeup to the calandria vessel (provided significant core compaction has not occurred. Calandria vessel flooding also minimizes hydroge production.
  - External cooling (water makeup to the calandria vault/shield tank) after the core is fully degraded and molten.
  - A combination of the two.
- These two methods of cooling require the addition of Complementary Design Features to allow moderator and shield tank/calandria vault makeup at some plants.

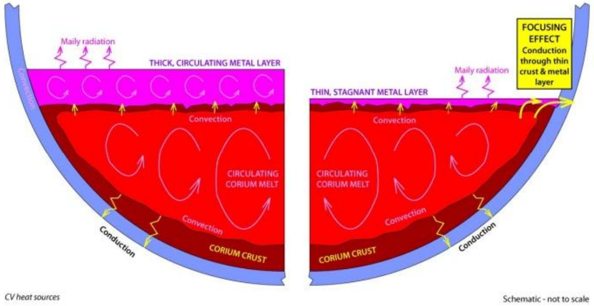
In Vessel Retention – Experimental Basis

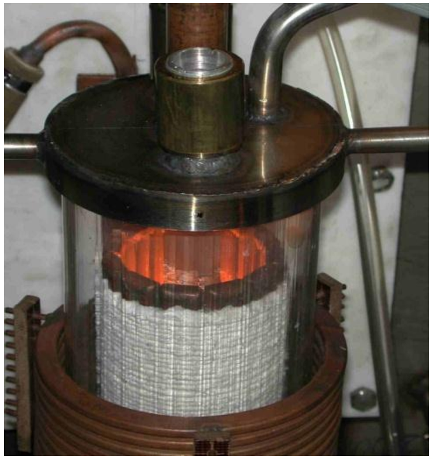
- CANDU In-Vessel Retention – Summary of Experiments on Corium Behaviour and Interaction with the Calandria Vessel[1]
- Experiments were designed to address three issues:
  - Issue 1: Can a focusing effect, induced by melt stratification, cause a failure of the calandria vessel?
  - Issue 2: Can a calandria vessel fail by chemical interaction between corium and vessel wall material?
  - Issue 3: Can a reactor component under specific physico-chemical conditions interact with the calandria vessel steel and challenge the calandria vessel's mechanical integrity?

[1]Prepared by Atomic Energy of Canada Limited (Now Canadian Nuclear Laboratories)

In Vessel Retention – Experimental Basis

- MATICAN equilibrium tests were designed to assess the potential for corium stratification and heat flux focusing at the calandria vessel wall[1]
  - 6 equilibrium tests were conducted at the RASPLAV-3 facility in Russia under varying conditions of oxidation, Zr/U ratio, and temperature.
  - The experiments showed that corium melt will not result in stratification within the range of zirconium oxidation expected in CANDU reactors (i.e., 0 to 35%).
  - Therefore vessel failure due to corium melt formation is unlikely to occur.

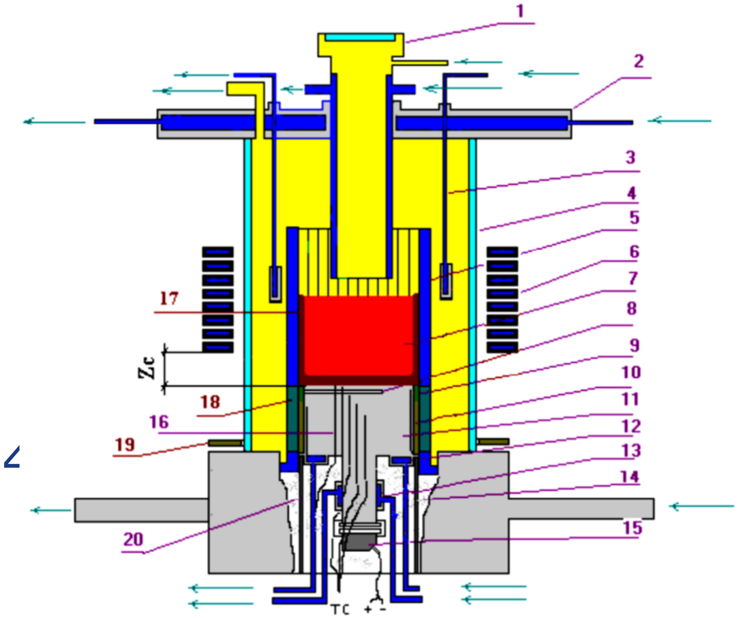




[1]MATerial Interaction tests for CANdu reactors

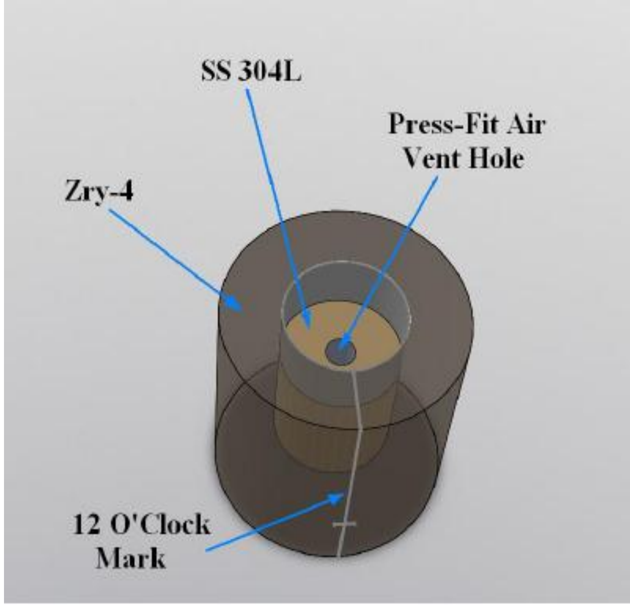
In Vessel Retention – Experimental Basis

- MATICAN wall interaction tests were designed to assess the potential for chemical interaction between the corium and vessel wall
  - 2 corium-vessel interactions tests were conducted at the RASPLAV-3 facility to measure rate and depth of corrosion interaction between corium and calandria vessel steel.
  - Results were dependent on calandria wall temperature.
  - No loss of wall thickness occurs at a wall temperature of 900°C.
  - At 1200°C, a reduction in wall thickness of 4 mm was observed after 21 hours.



In Vessel Retention – Experimental Basis

- Material Interaction Tests (MIT) were conducted by AECL at Chalk River Laboratories to determine the potential for interaction between CANDU materials (Zircaloy-4, Zircaloy-2 and Zr-2.5% Nb and UO_2) to undergo physico-chemical interactions with the steel vessel.
  - 14 MIT tests were conducted with different corium materials, temperatures (900°C, 1000°C and 1200°C) and interaction times
  - No interaction was observed at a wall temperature of 900°C. Minor melt formation and diffusion was observed at 1000°C. More significant melt formation and diffusion were observed at 1200°C.
  - Experiments performed with oxidized Zry showed no interaction Zry and SS .



Additional Areas Investigated

- Instrumentation and Equipment Survivability
- Plant and Control Area Habitability
- Containment Challenges
- SAMG Considerations for Low Power, Multi-Unit Accidents
- SAMG for Spent Fuel Bay Accidents
- Ability of Spent Fuel Bays to Withstand Sustained Loss of Heat Sink Events
- Effect of Beyond Design Basis External Hazards/Cliff Edge Effects

Ongoing and Future R&D Activities

- In Vessel Retention
  - Reduction of Uncertainties in Severe Core Damage Accident Analysis and In-Vessel Retention
  - Critical Heat Flux Measurements on the Outside Calandria Vessel Wall at Various Azimuthal Angles
  - Critical Heat Flux Measurements in the End Shields
  - Critical Heat Flux Measurements at Step Between Calandria Main and Sub-Shells
  - Calandria Vessel Heat Stress Response During In Vessel Retention
- Passive Autocatalytic Recombiners (PARs)
  - Effectiveness of PARs for BDBAs
  - Characterization of PARs Contaminants
  - PARs as Ignition Sources
  - Hydrogen Isotope Effects on PARs
- Participation in OECD/NEA Projects
  - HYMERES
  - STEM
  - THAI

CANDU Excellence through Collaboration