Application of Technologies in CANDU Reactors to Prevent/Mitigate the Consequences of a Severe Accidents

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Presentation Outline

- Important inherent safety feature of the CANDU reactors
- Severe Accident Progression in CANDU reactors
- Barriers to event progression
  Hydrogen production and management
- Instrumentation and equipment survivability assessments

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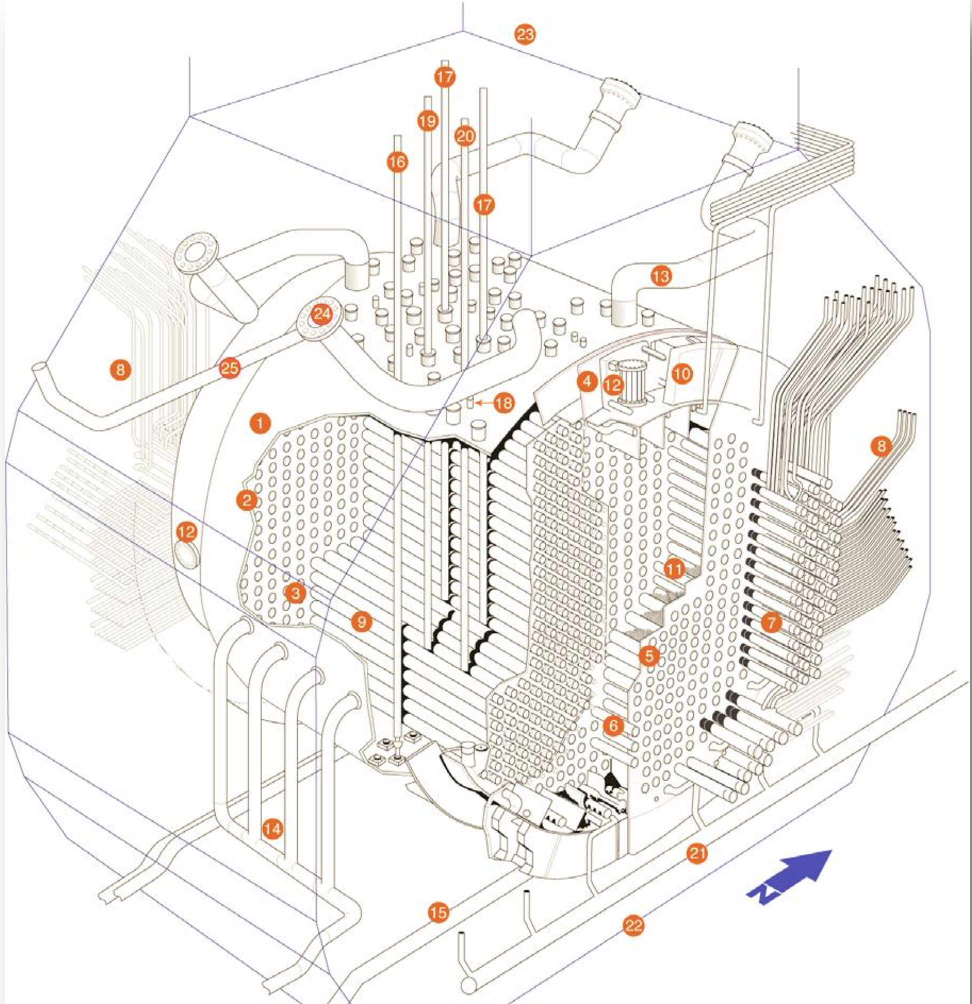
Acknowledgements

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

Important inherent safety feature of the CANDU reactors:

- Large water inventories surrounding the fuel can passively remove decay heat from the fuel for many hours after an accident, providing time and opportunity for operator intervention.
- The low temperature, low-pressure moderator surrounding the horizontal fuel channels provides an effective heat sink under some accident conditions, allowing the fuel channels to maintain their integrity even when internal cooling is not available.
- The externally cooled calandria vessel acts as a “core catcher” containing the core debris (corium), as long as it is submerged in the large volume of water in the calandria vault.



1 Calandria
2 Calandria Shell
3 Calandria Side Tube Sheet
4 Baffle Plate
5 Fuelling Machine Side Tube Sheet
6 Lattice Tube
7 Fuel Channel End Fitting
8 Feeders
9 Calandria Tubes
10 Shield Tank Solid Shielding
11 Steel Ball Shielding (End Shield)
12 Manhole
13 Moderator Discharge Pipes
14 Moderator Inlets
15 Moderator Outlets
16 Shut-off Unit
17 Adjuster Unit
18 Vertical Flux Detector
19 Control Absorber
20 Liquid Zone Control Unit
21 End Shield Cooling Piping
22 Shield Tank
23 Shield Tank Extension
24 Rupture Disc Assembly
25 Moderator Overflow

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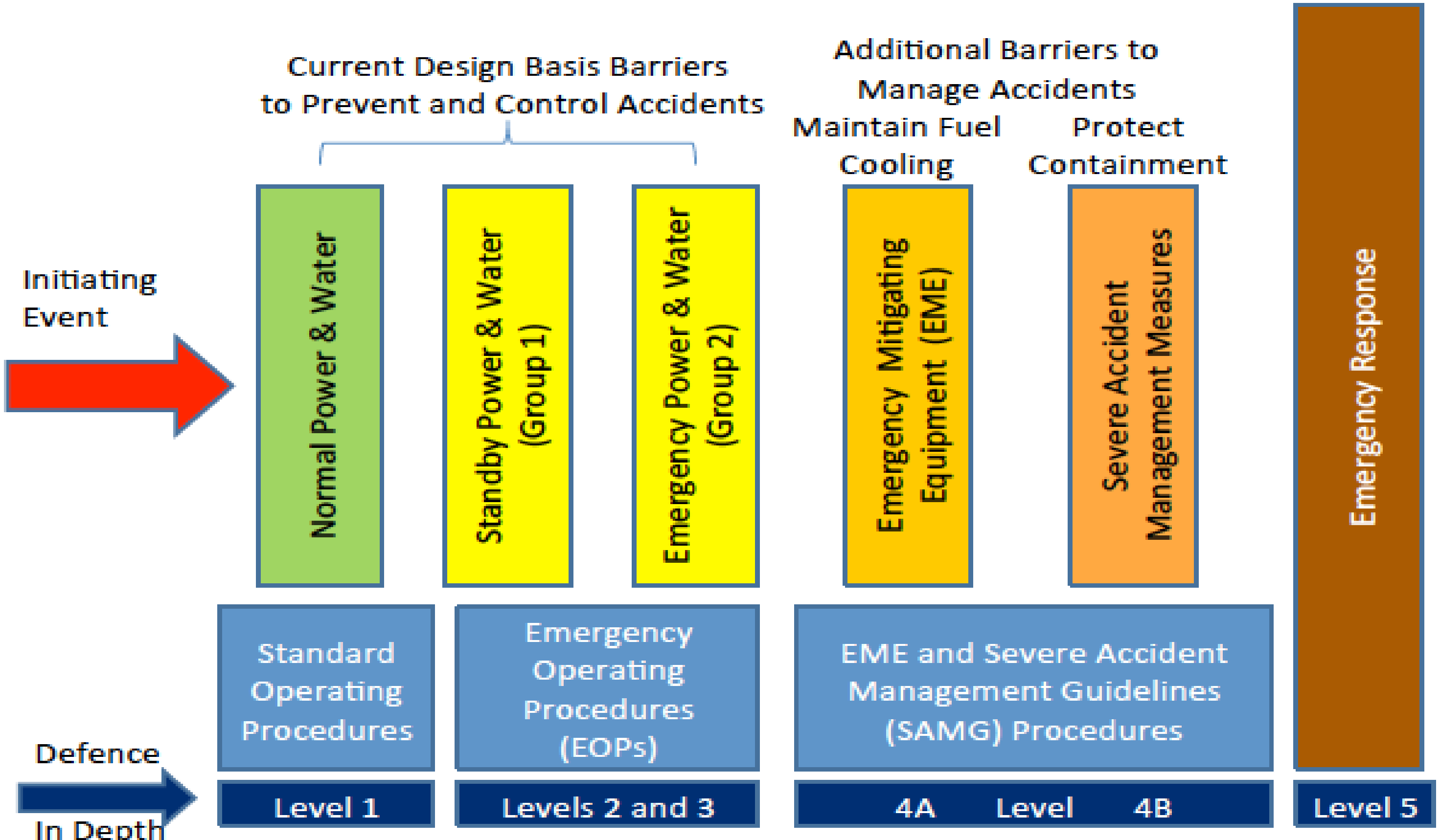
Framework for Accident Prevention, Control and Management



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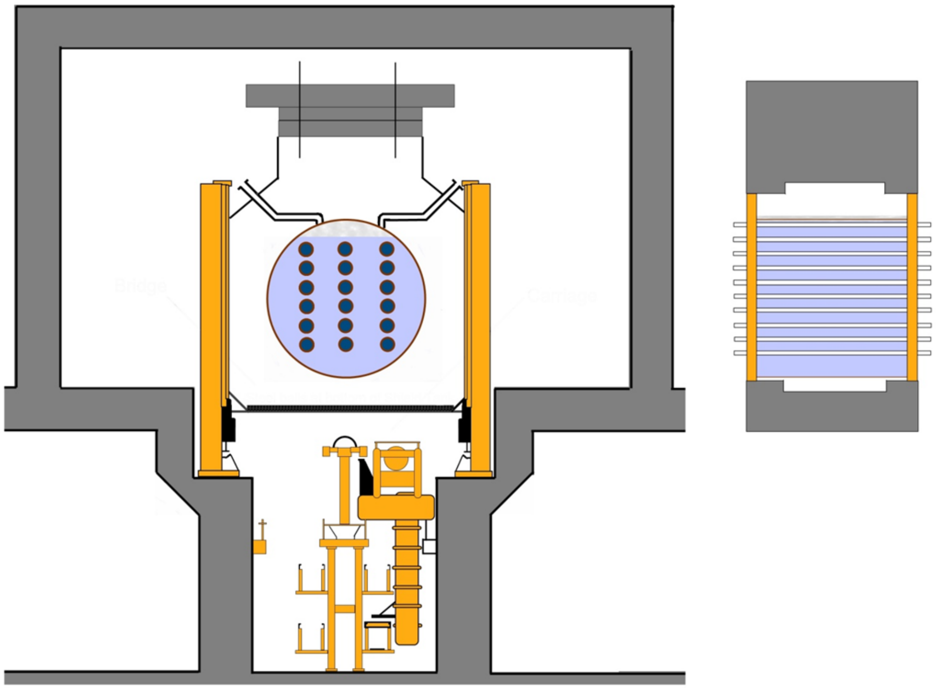
Severe Accident Progression – Core Damage States

- **Core Damage State (CDS1)** – Heat Transport System (HTS) has lost coolant. Fuel heats up within the fuel channels. Moderator provides cooling.



Calandria Face View

Calandria Side View

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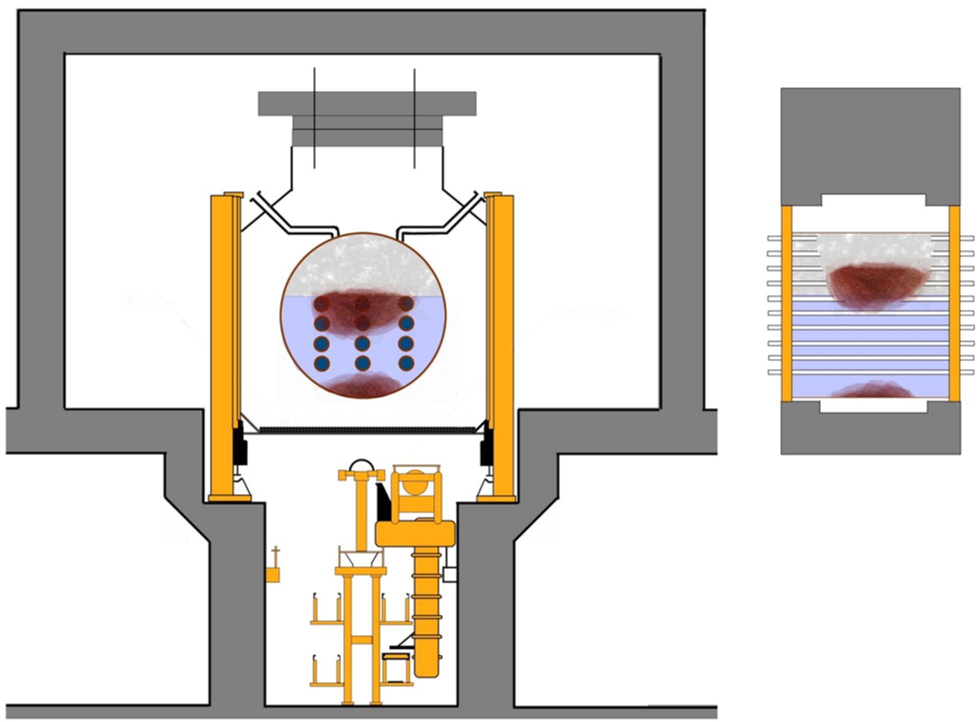
Severe Accident Progression (cont.)

- **CDS2** - Top rows of fuel channels are uncovered and fail if inadequately cooled. Disassembly commences. Moderator continues to provide cooling to channels and material still covered.

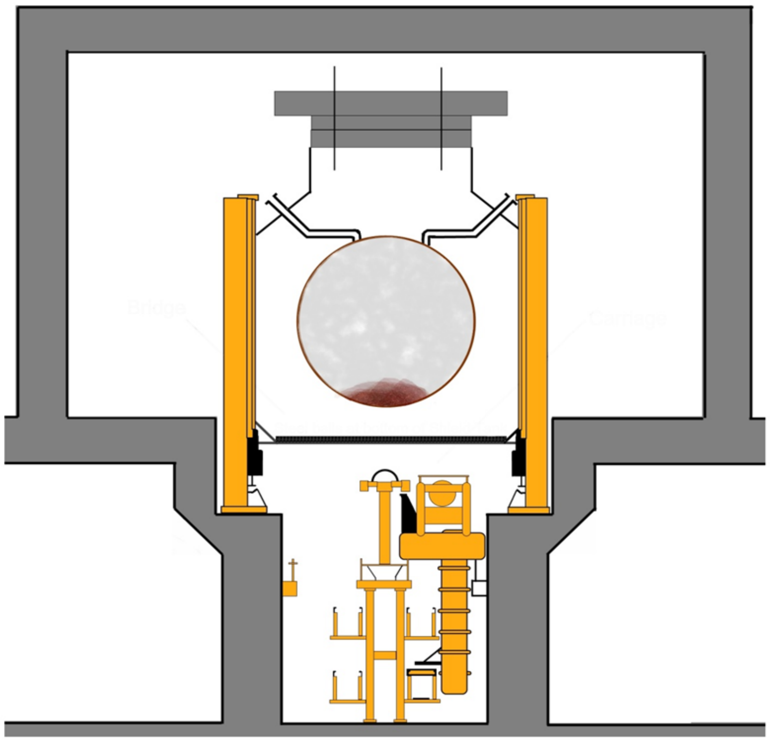


Calandria Face View

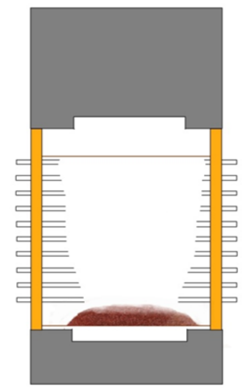
Calandria Side View

Severe Accident Progression (cont.)

- **CDS3** - Moderator inventory in the calandria has completely boiled off. Core debris is cooled through the calandria wall by shield tank inventory.



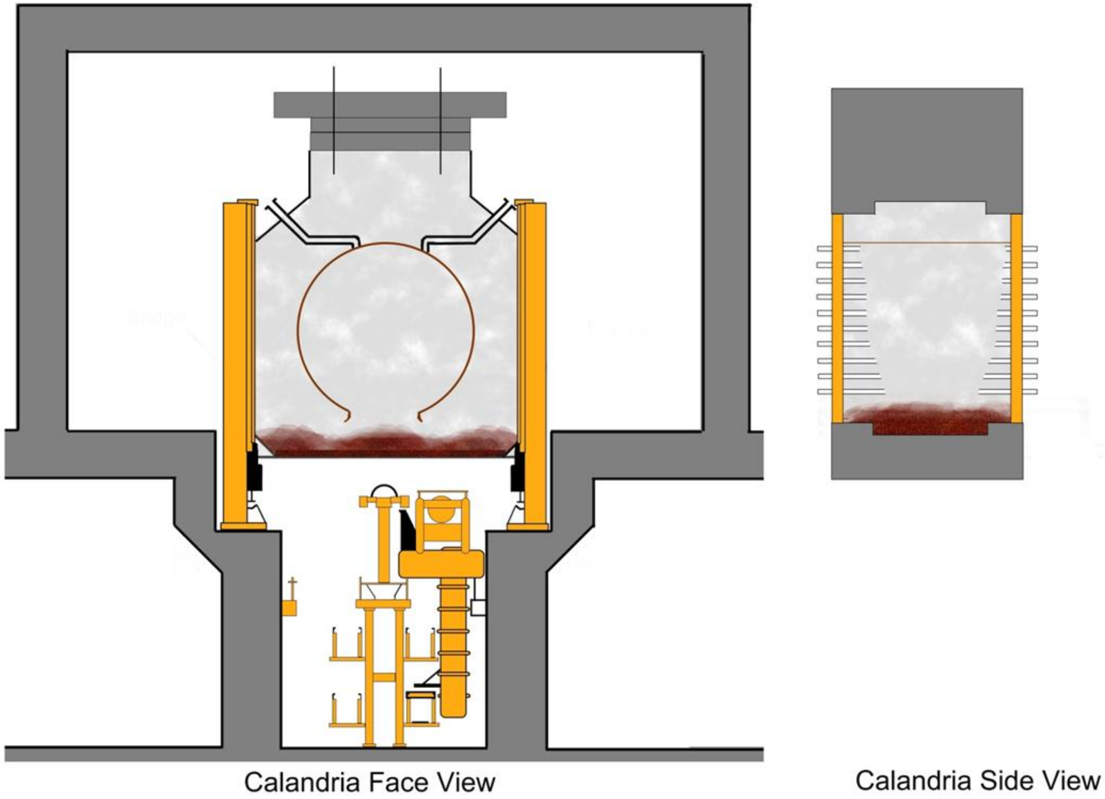
Calandria Face View



Calandria Side View

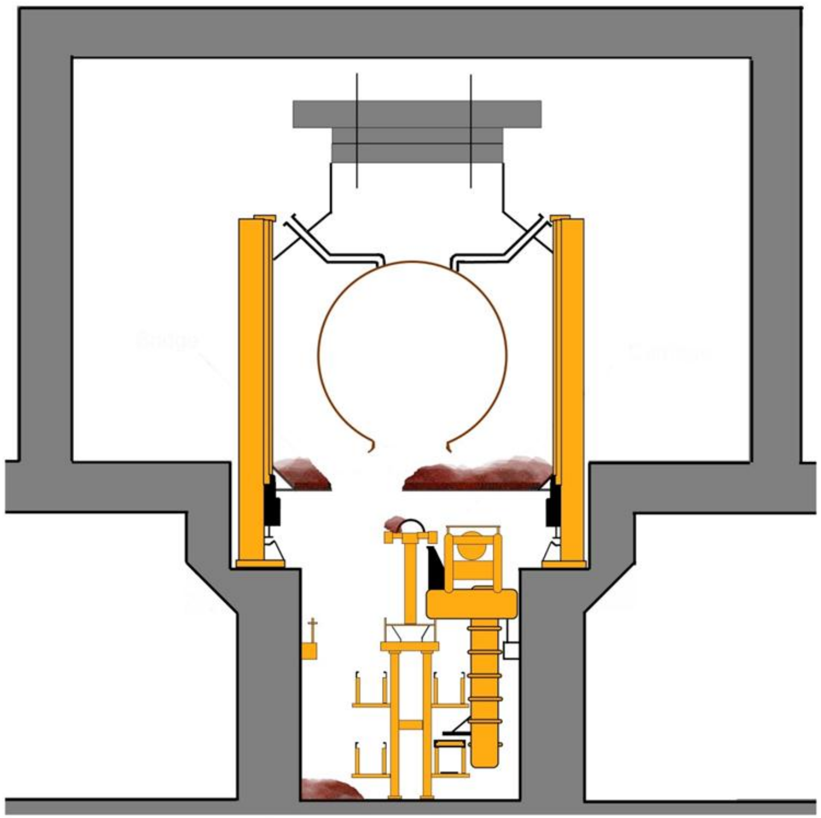
Severe Accident Progression (cont.)

- **CDS4** - Bottom of calandria vessel fails and debris is released into the shield tank. Debris is initially quenched and cooled by boiling off water in the shield tank.

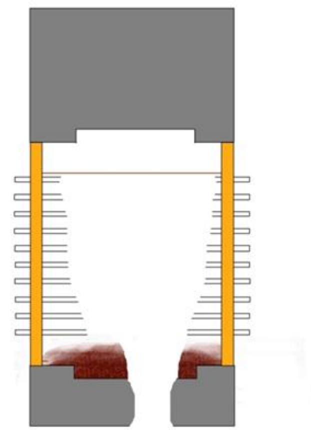


Severe Accident Progression (cont.)

- **CDS5** - Penetration of the shield tank floor occurs and the "corium" relocates to the fuelling machine duct.



Calandria Face View



Calandria Side View

Actions and defenses focused on stopping accident progression prior to a severe accident

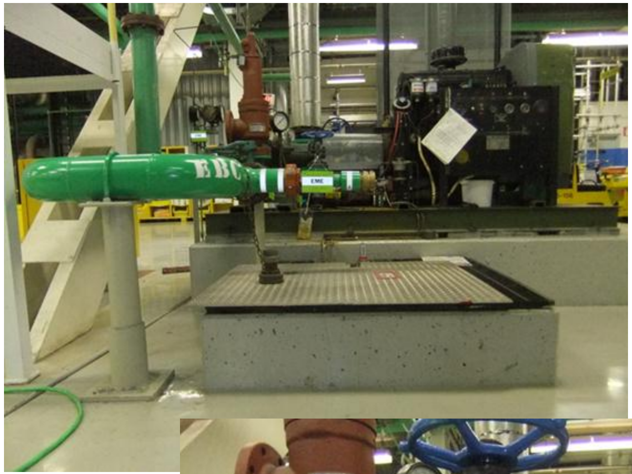
- The earlier in the event progression that the event is brought to a steady state, the more effective is the mitigating feature in preventing societal disruption
- Multiple barriers to ensure fuel cooling provides redundancy and also allows the event to be terminated at various stages should one barrier fail or become unavailable.
- These barriers to fuel cooling are provided using Emergency Mitigating Equipment (EME) consisting of portable water pumps and portable AC generators.
- Multiple barriers to prevent or mitigate a severe accident, ensure In-Vessel Retention (IVR) and prevent Core concrete Interaction (CCI) from occurring during DEC.

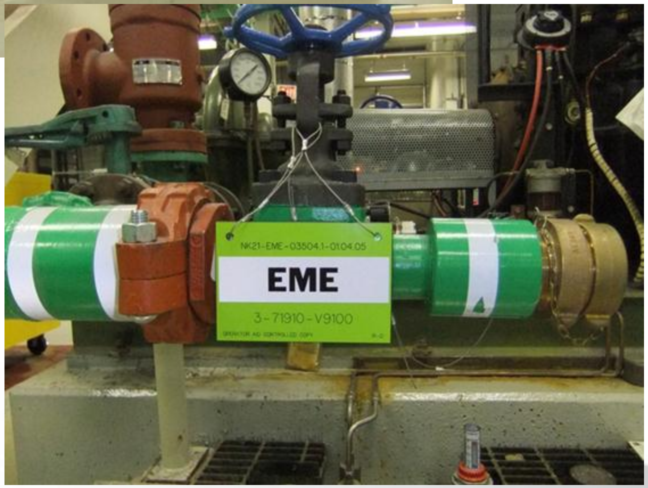
Barriers to Event Progression – Alternate Makeup Boiler **Makeup**

- Maintain boilers as a heat sink by providing alternate makeup to the boilers.
- Installation of fire hose quick-connects and associated piping modifications to the Inter Unit Feedwater Tie.
- Installation of quick-connect modifications to the Emergency Water System.
- Instrument air modifications to allow emergency opening of the Boiler Safety Relief Valves were installed on each unit – must be blocked open after 4 hours.
- Simulations were performed using the TUF (Two Unequal Fluid) computer code to predict system response following total loss of AC power.
- Sufficient initial inventory for up to 9hrs.

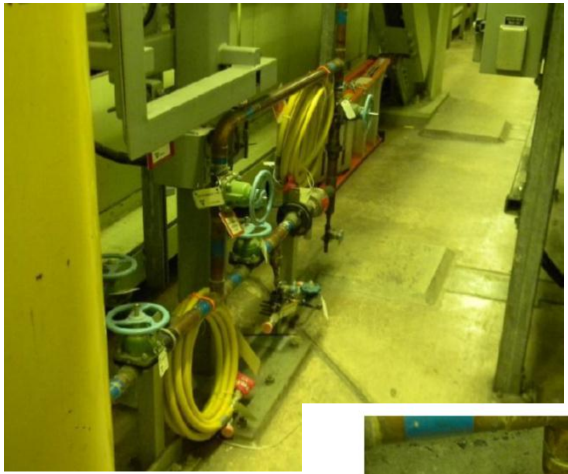
Alternate Boiler Steam Generator (SG)

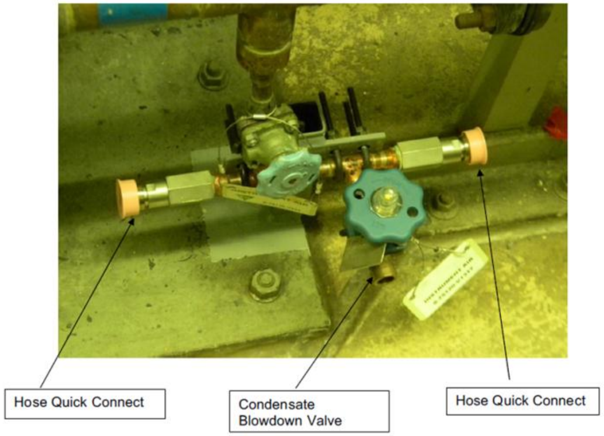
EME Connection to Boiler
Emergency Boiler Cooling (EBC)





Boiler SRV Operation Modification





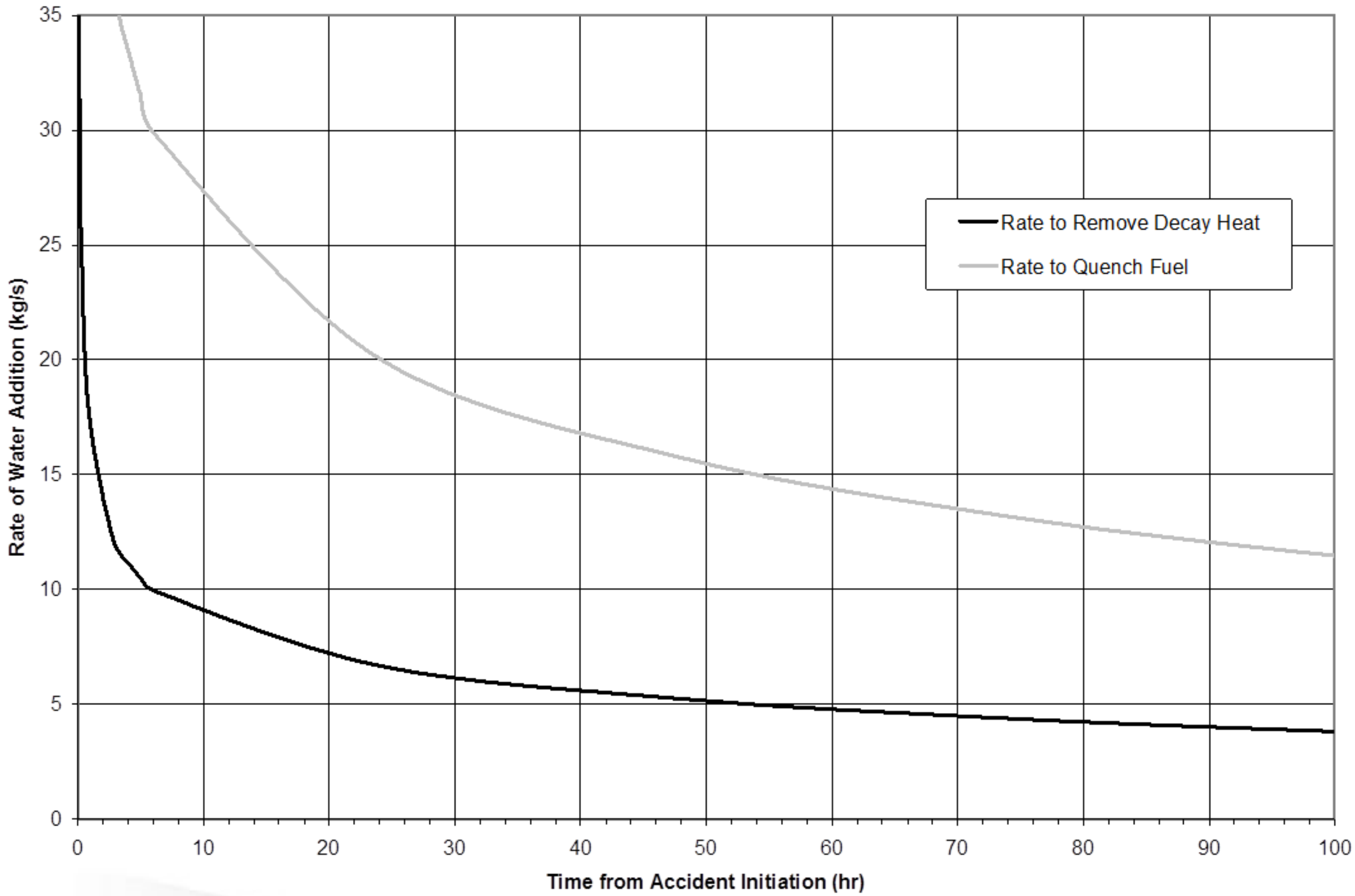
Barriers to Event Progression - Water Addition to the Heat Transport System (HTS)

- In order for the SGs to act as an effective heat sink, the HTS must be capable of removing decay heat from the fuel and transporting it to the SGs.
- High Emergency Coolant Injection System isolation valves power by portable generators.
- In the event of a SBO, this heat removal is via natural circulation, which requires that the heat transport system headers remain full.
- If an event degrades to the point where core structural damage occurs, HTS makeup provides an alternate means to add cooling water into the calandria vessel via the ruptured fuel channels, again ensuring IVR. PIPE-FLO Professional 2009 is the software used to complete the hydraulic analysis.
- Suitable permanent fire hose connection points and pathways into the HTS are being designed and installed and at least one other non-permanent connection point is being provided for additional flexibility to execute Severe Accident Management Guidelines (SAMG) actions in the event that the permanent connection point becomes unavailable or inaccessible.

Barriers to Event Progression - Emergency Moderator Makeup (EMM)

- If the SGs cannot be used as the primary heat sink, then severe core damage (SCD) can still be prevented by providing makeup water directly into the calandria vessel, removing the heat from the fuel channels via the calandria rupture disks and venting into containment.
- Even if channel failures occur resulting in a loss of core structural integrity (i.e., a Severe Accident), EMM will continue to provide cooling and will ensure that the core debris remains cooled inside the calandria vessel
- To ensure flexibility and simplicity, the permanent fire hose nozzle connections will be identical to the hose connections that were installed for SGs and HTS.
- Again, at least one other non-permanent is proposed to provide additional flexibility to execute SAMG actions in the event that the permanent connection point becomes unavailable or inaccessible.

Terminating Accident Progression by Water Addition



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Emergency Moderator Makeup Connection Point

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Barriers to Event Progression - Shield Cooling System Modifications

- If for some unforeseen reason it is not possible to add water to the calandria vessel, the shield tank which surrounds the reactor can also act as another barrier to prevent failure of the calandria vessel or shield tank, thereby ensuring IVR.
- In order for the shield tank to be effective as a heat sink in the long term, there must be a means to provide overpressure protection of the shield tank, and there must be a method of supplying cooling water into the shield tank.

EME – Fire Trucks

EME - Portable Diesel Generators

5 x 100 kW Generator plus 1 spare

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Hydrogen Production and Management

- Hydrogen can be produced during any of: the early phases of severe accident progression (hours), medium term (days) and in the long-term (weeks-months) by a number of mechanisms:
  - During CDS1: Interaction between steam and hot fuel bundles prior to channel disassembly
  - During CDS2: Interaction between steaming from moderator pool and hot fuel channel debris
  - During CDS3 (and 4): Oxidation of calandria and other reactor components
  - During CDS5 (and 4): Core Concrete Interaction (CCI)
  - Long-term: Radiolysis, corrosion products
  - Other: Degassing of dissolved hydrogen added to the coolant during normal operation

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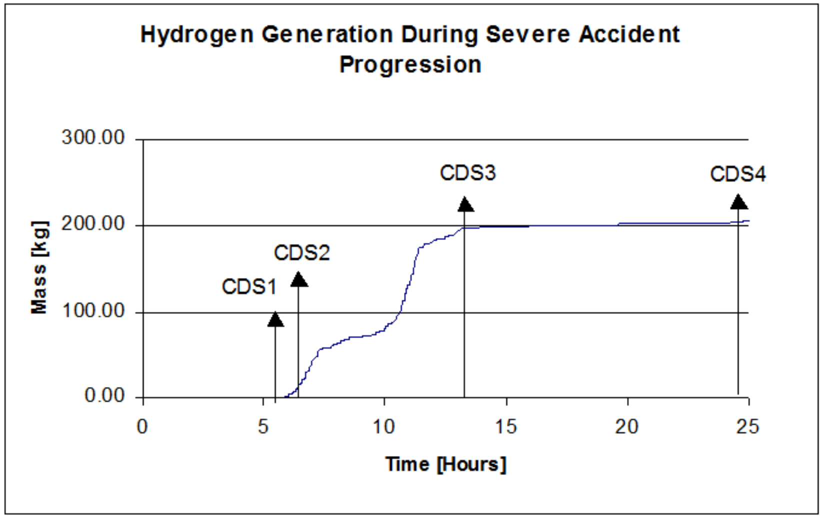
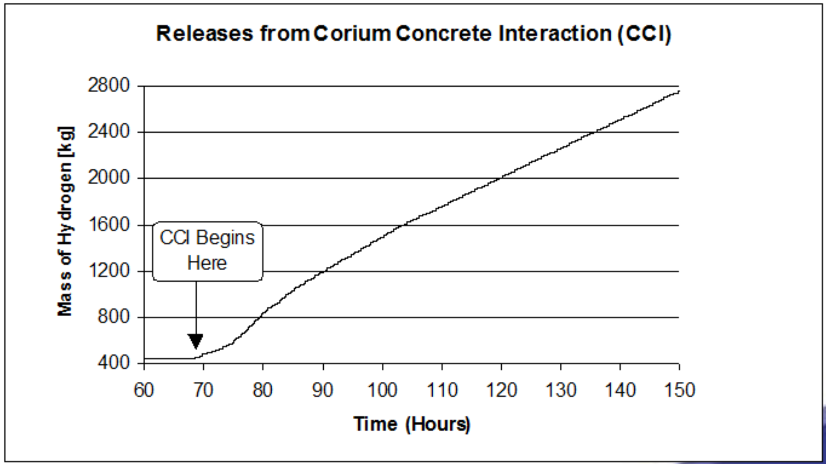
Hydrogen Production

- Predicted quantities of hydrogen are low during core disassembly phase
- Potential for much greater concentrations if Core Concrete Interaction (CCI) occurs





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Hydrogen Management

- Significant improvements to plant capability for mitigating hydrogen concerns have been made by the addition of passive auto-catalytic recombiner (PAR) units.
- In the event where IVR is successful, the hydrogen mitigating systems in place (i.e. PARS, igniters, Emergency Filtered Venting) are adequate based on available analyses.
- The installed/committed PARs capacity in CANDU plants is not intended to cope with the rate at which flammable gases can be generated during CCI. This has been recognized in the Candu Owners Group (COG) SAMG and appropriate guidance has been provided.
- MAAP4-CANDU analyses confirmed that containment is steam inerted in many of the severe accident sequences analysed.

Hydrogen Management (cont.)

- MAAP4-CANDU analyses have shown that there are other natural processes that may occur to reduce the amount of flammable gases accumulating in containment during CCI, such as auto-ignition and jet burns
- PARs have been shown to be effective in removing hydrogen in steam inerted environments starting at low hydrogen concentrations (2%)

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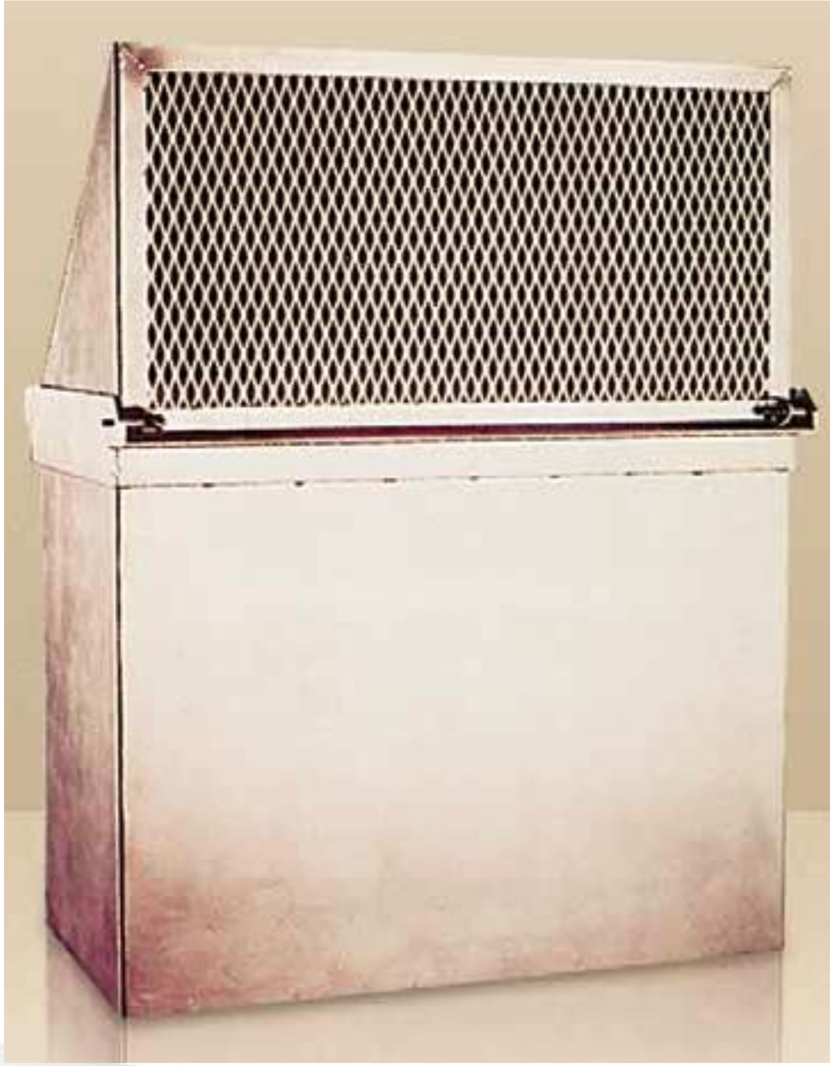
PAR Unit



Instrumentation and Equipment Survivability Assessment

- An instrumentation and equipment (I&E) survivability assessment was completed at all stations to provide a reasonable level of assurance that sufficient monitoring and equipment will be available for use during a SA to achieve a controlled, stable state after core damage under the unique containment environments.
- I&E must survive the initiating event and the resulting harsh conditions .
- Robustness assessment was used to determine survivability after an imitating event by determining a Review Level Conditions (RLC) – 1/10000 year event.
- The methodology used was based on work done by the Electric Power Research Institute (EPRI)], along with consideration of information provided for the AP1000 and other stations, and is in alignment with IAEA safety guides.

I&E Survivability Assessment (cont.)

- The developed methodology consists of five steps: (a) Define basic phases for CANDU severe accidents; (b) Extract high level mitigating and control actions; (c) Compile list of I&E for above actions; (d) Screen and align items with accident characteristics; and (e) Assess survivability.
- Reasonable assurance was provided by demonstrating survivability of the preferred line-ups, along with sufficient instrumentation to measure the strategy effectiveness. Where survivability of a preferred line-up or instrumentation could not be demonstrated, reasonable assurance was provided by demonstrating survivability of alternatives including using portable devices.

CANDU Excellence through Collaboration

Thank you for your attention.

Are there any questions?