CANDU Safety
#17 - Severe Core Damage Accidents

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Severe Accidents & Severe Core Damage

- severe accident
  - no coolant in the fuel channels
    - e.g., LOCA + Loss of Emergency Core Cooling
  - no fuel melting
  - channel geometry preserved
- severe core damage accident
  - severe accident plus failure of moderator heat removal
  - loss of channel geometry

Initiating Event + Loss of Shutdown

- **sequence:**
  - **initiating event, plus**
  - **failure of reactivity control system, including setback & stepback, plus**
  - **failure of shutdown system 1, plus**
  - **failure of shutdown system 2**
- **not a significant risk contributor due to very low frequency**
- **nevertheless was analyzed on Pickering-A by Ontario Hydro**
  - **public enquiry after Chernobyl on nuclear power in Ontario**
  - **Pickering-A shutdown mechanisms slower & less independent than later plants**

Pickering-A Loss of Shutdown

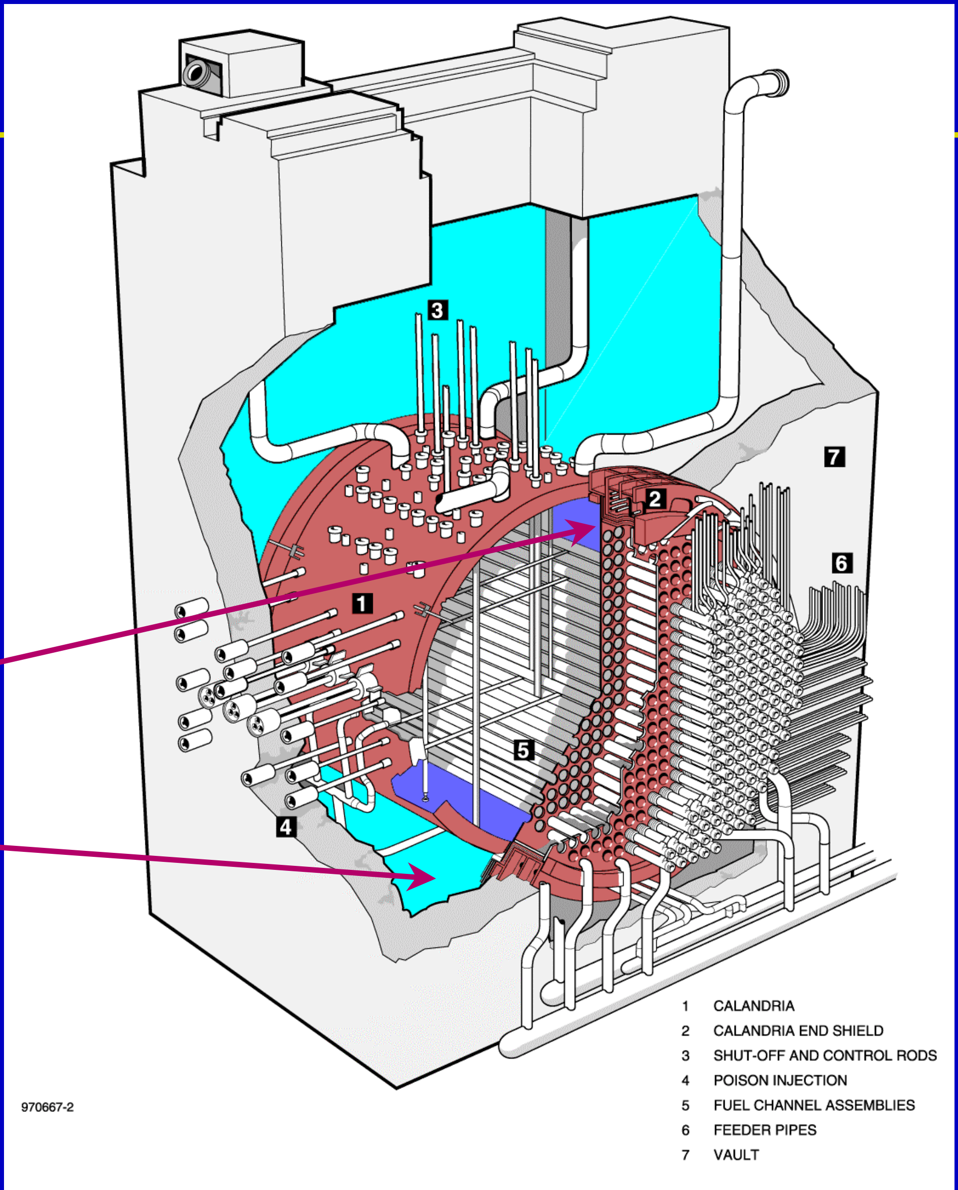
- **initiating event: large LOCA**
- **both shutdown mechanisms (rods, dump) fail**
- **power rises & fuel begins to melt at 3 seconds**
- **molten fuel fails some pressure tubes in ~3.7 seconds**
- **30% of the channels failing create bubble in moderator and shut down the reactor**
- **calandria weld fails and discharges steam into containment**
- **containment pressure only slightly higher than design**
- **CANDU fuse: failure of “lead” channels & displacement of moderator shuts down the reactor before a very large energy pulse can develop**

Initiating Event + Loss of Heat Removal

- **examples:**
  - **LOCA plus Loss of ECC plus loss of moderator cooling**
  - **loss of main feedwater + loss of auxiliary feedwater + loss of shutdown cooling + loss of Emergency Water System**
  - **loss of Class IV power + loss of Group 1 Class III power + loss of Group 2 Class III power**
- **lines of defence:**
  - **boiloff of moderator water**
  - **boiloff of shield tank water**

Water Near Core

System	*Continuous Heat Removal Capability (% full power)*	*Time to heat up and boil off, no heat removal*
Moderator	4.4%	> 5 hours
Shield Tank	0.4%	10 to 20 hours



CANDU 6 Reactor Assembly

Event Sequence for a Loss of All Heat Sinks

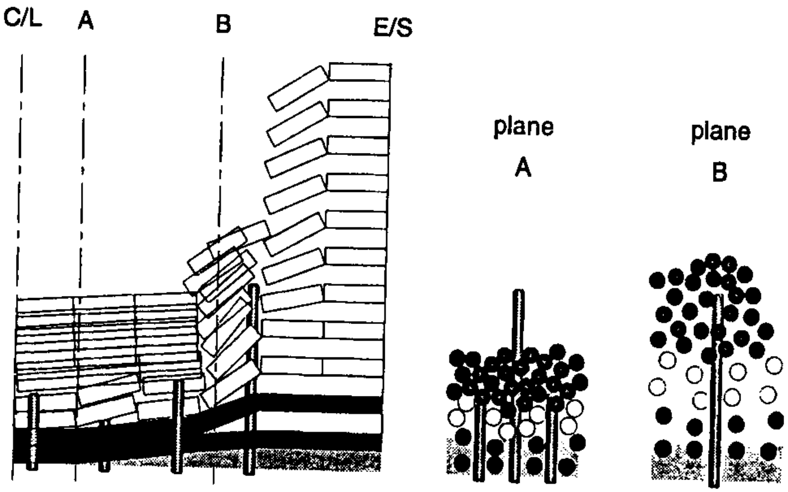
Time (hr)	Event
0	Loss of heat sinks, reactor shutdown
0.75	Steam Generators boil dry, liquid relief valves open, fuel cooling degrades
0.83	A few pressure tubes fail and depressurize heat transport system
0.86	High pressure ECC initiated; medium pressure ECC assumed to fail
1.1	Heat transport system empty
5	Moderator boiled off, channels sagged to bottom of calandria
25	Vault water boiled off to top of debris bed, calandria fails
Days	Interaction of debris with vault floor & penetration to containment basement

Channel Collapse Mode

UNCOVERED CHANNELS DEFORM BY SAGGING

SEGMENTS SEPARATE BY MEMBRANE STRETCHING WHEN SUFFICIENT DEFLECTION DISTANCE AVAILABLE

DEFORMATION AT LOCAL TEMPERATURE >1200°C



SEPARATION AT DISTANCE TO LIQUID LEVEL >1 m

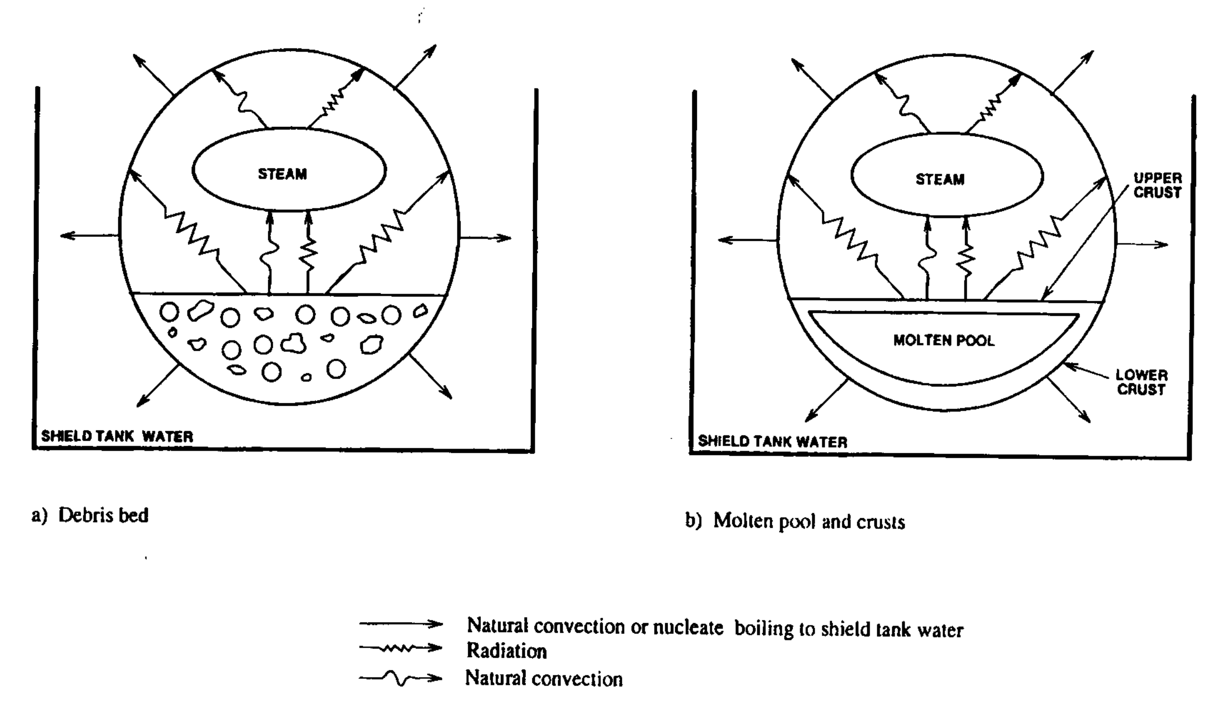
SUBMERGED CHANNELS FAIL AT ROLLED JOINT WHEN SUFFICIENT DEBRIS LOAD BUILDS UP (CORE COLLAPSE)

Characteristics of Debris Bed

- top channels collapse when moderator is half voided, so they sag into a pool of water
- debris likely to be composed of coarse pieces of ceramic materials
- bed will not be molten until all the moderator water is boiled off - will then dry out and heat up due to decay heat & remaining Zircaloy-steam reaction
- no energetic fuel-coolant interaction
- models for heat transfer from debris bed to calandria walls developed by T. Rogers et al. for dry debris, and also debris with molten centre

Debris Bed Models

- uniform porous mixture of UO_2, ZrO_2 and/or Zircaloy
- fuel decay heat + metal water reaction
- thermal radiation to inner surface of calandria from top of the bed
- conduction through bottom of calandria to shield tank water



Debris Bed Heatup

- melting of debris starts about 7 hours after the event
- upper & lower surfaces of debris bed stay below melting temperature

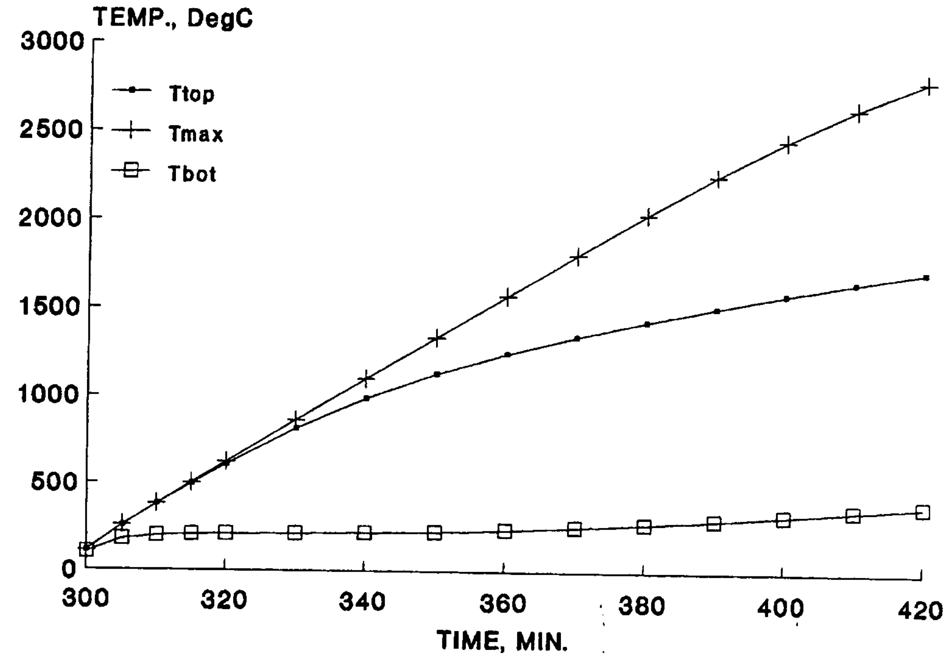


Figure 7 Heat Up of Core Debris in CANDU 6 Calandria, Reference Conditions

Calandria Wall Temperatures

- outer surface temperature below 140C
- stainless steel wall
- do not expect creep under applied stresses

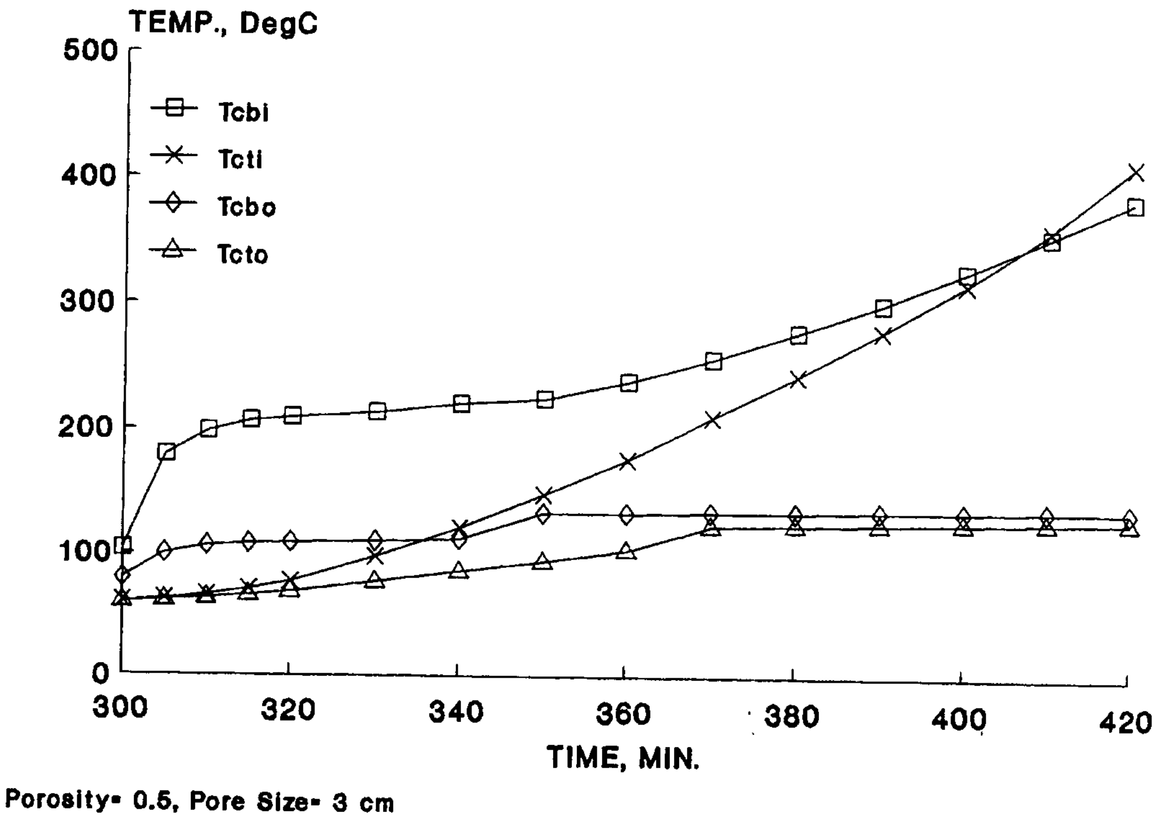


Figure 8 Calandria Wall Temperatures, Heat Up of Core Debris, CANDU 6 Calandria

Surface Heat Flux to Shield Tank

- heat flux to shield tank 15 times less than CHF
- calandria will remain intact while shield tank water boils off
- behaviour insensitive to porosity and timing of metal-water reaction

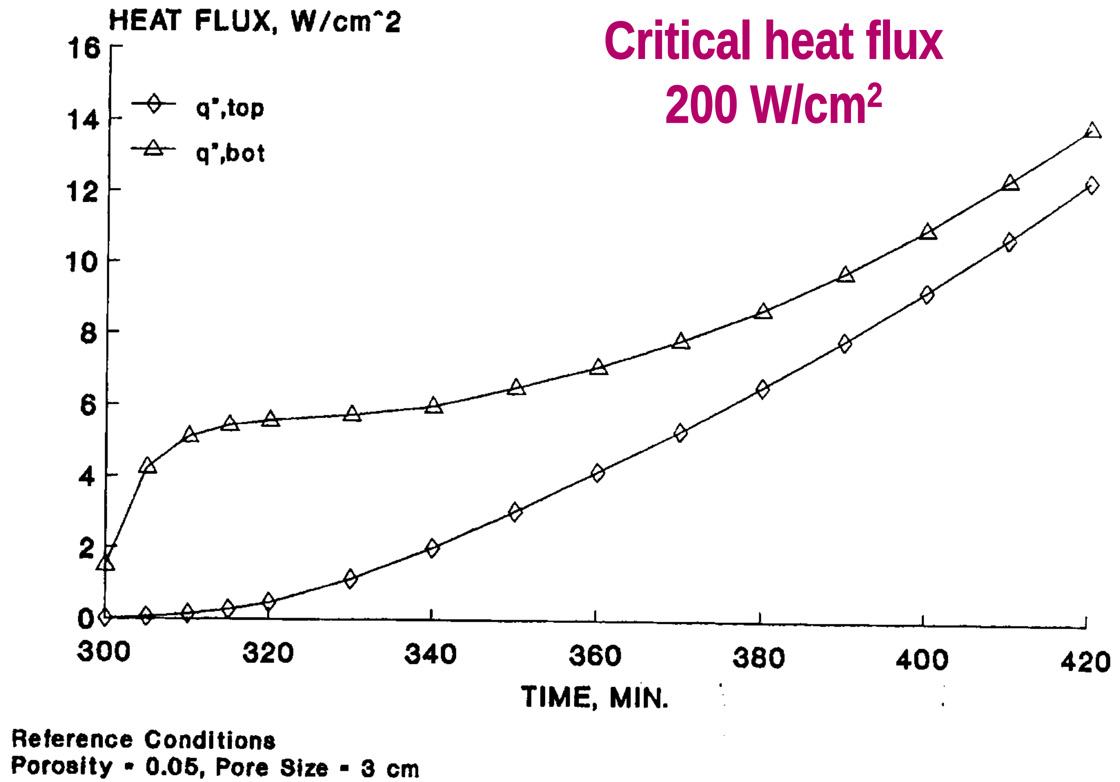


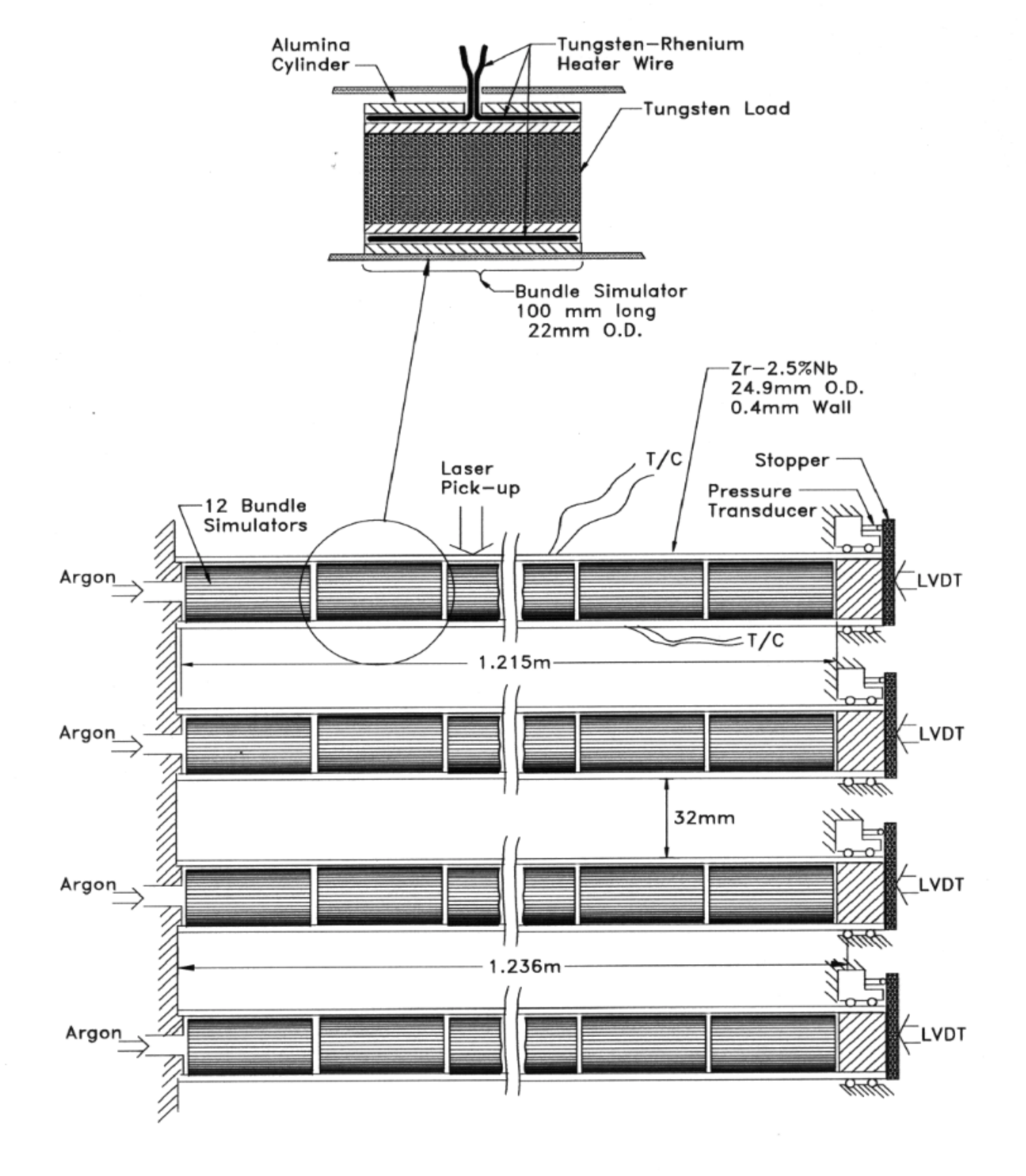
Figure 9 Heat Fluxes on Calandria Wall, Heat Up of Debris in CANDU 6 Calandria

Uncertainties

- mechanical and thermal behaviour of end-shields
- capability of shield tank to relieve steam
- local effects in molten pool and hot-spots
- lack of experimental validation of debris melting transient
- demonstration of core collapse mode

Small Scale Tests on Channel Collapse

- small scale study underway, ~ 1/5 scale
- scaling to retain full size stress levels, ratio of bundle size to channel length and channel length to pitch height of assembly



Containment

- containment heat removal (local air coolers) may or may not be available depending on the accident
- if *not* available, pressure initially controlled by dousing sprays
- will eventually rise above design pressure
- structure will remain intact due to leakage through cracks and pressure relief

Observations

- severe core damage in CANDU is very different from LWRs
- low power density (16 MW/Mg of fuel at full power)
- long heatup times (hours)
- gradual collapse of the core into a coarse debris bed
- dispersion of the debris in the large calandria
  - shallow molten pool about 1 metre deep
- presence of two large sources of water in or near the core
- potential to stop or slow down the accident at two points:
  - channel boundary (moderator)
  - calandria boundary (shield tank)

Conclusions

- severe accident mitigation requirements for new reactors stress the importance of two design measures:
  - core debris spreading area
  - ability to add water to cool debris
- CANDU has built them in: calandria spreads the debris, and shield tank provides cooling water
- long time scales allow for severe accident counter-measures and emergency planning
- some potential design enhancements for future plants:
  - independent makeup to moderator and shield tank
  - backup containment heat removal