Lecture 10 - Accident Analysis
– cont'd

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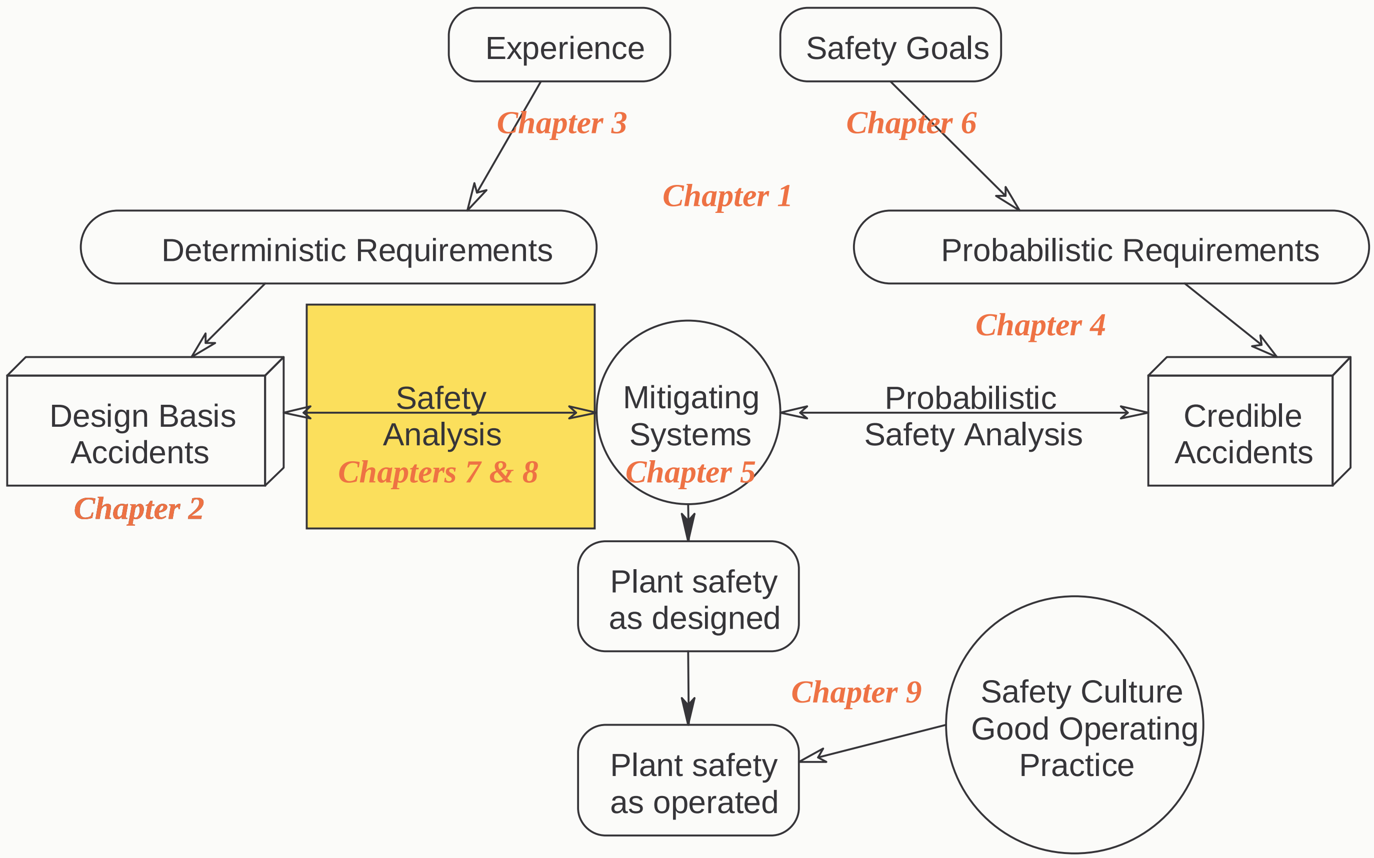
Where We Are



Experience
Safety Goals
Chapter 3
Chapter 6
Chapter 1
Deterministic Requirements
Probabilistic Requirements
Chapter 4
Design Basis Accidents
Chapter 2
Safety Analysis
Chapters 7 & 8
Mitigating Systems
Chapter 5
Probabilistic Safety Analysis
Credible Accidents
Plant safety as designed
Chapter 9
Safety Culture Good Operating Practice
Plant safety as operated

Severe Accidents

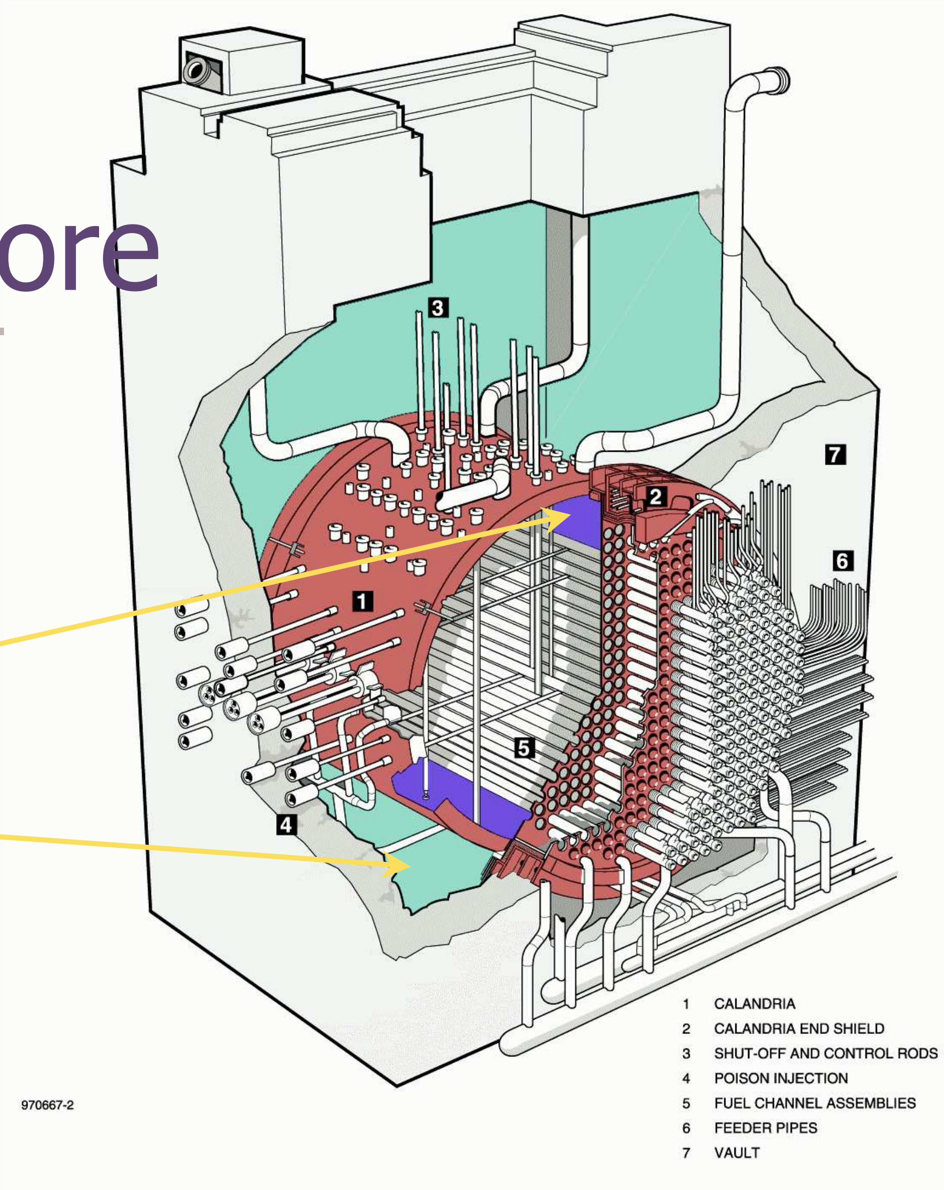
- Beyond Design Basis Accidents
  - core geometry is preserved
  - fuel may be damaged but remains inside intact pressure tubes
- Severe core damage accidents
  - fuel channels fail and collapse to the bottom of the calandria

Examples

- Loss of coolant + Loss of Emergency Core Cooling (BDBA)
- Loss of all secondary side heat sinks + Loss of shutdown cooling system, moderator available (BDBA)
- Loss of coolant + Loss of Emergency Core Cooling + Loss of moderator heat removal (SCDA)

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



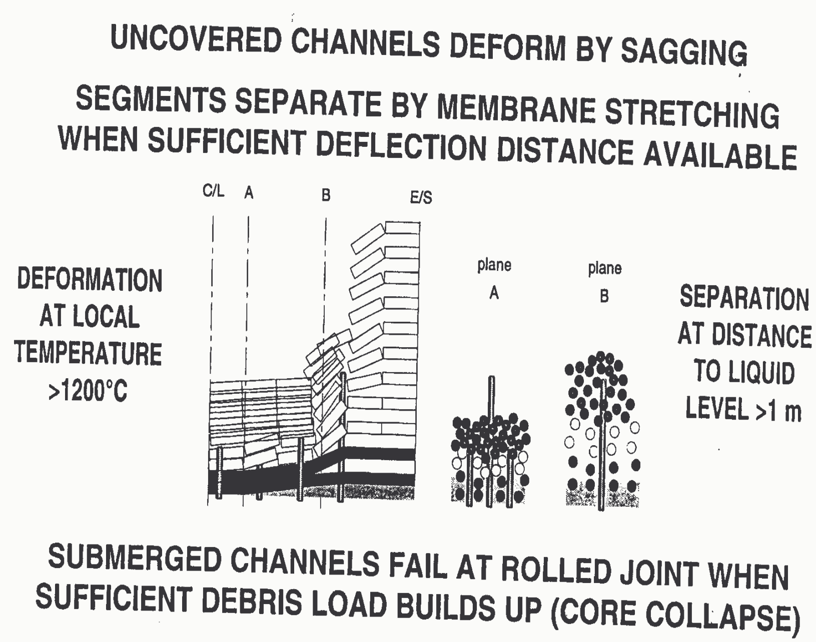
CANDU 6 Reactor Assembly

Loss of Core Geometry - 1

- E.g., Loss of all heat sinks + inability to depressurize HTS
- Pressure rises to relief valve setpoint
- Loss of water through relief valves
- Overheating of fuel and pressure-tubes at high pressures
- Failure of a few pressure tubes (6-10 MPa) – depressurize HTS

Loss of Core Geometry - 2

- Remaining pressure tubes strain to contact calandria tube
- Boil-off of moderator
- Sag & failure of channels at *low* pressure at ~1200C as moderator level falls
- Collapse of channels onto lower neighbours

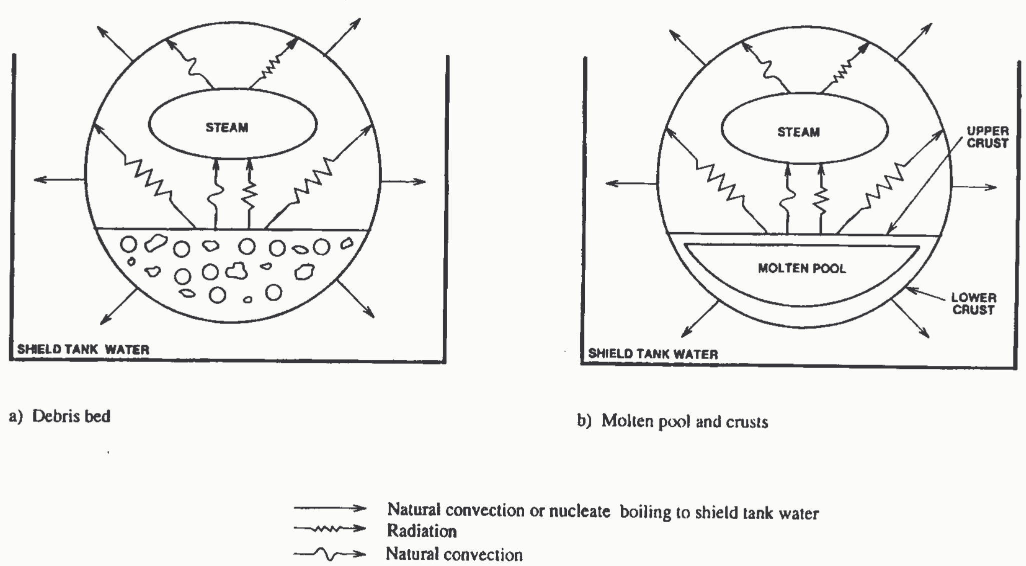


Characteristics of Debris Bed

- 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
- No criticality, even for ACR
- 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

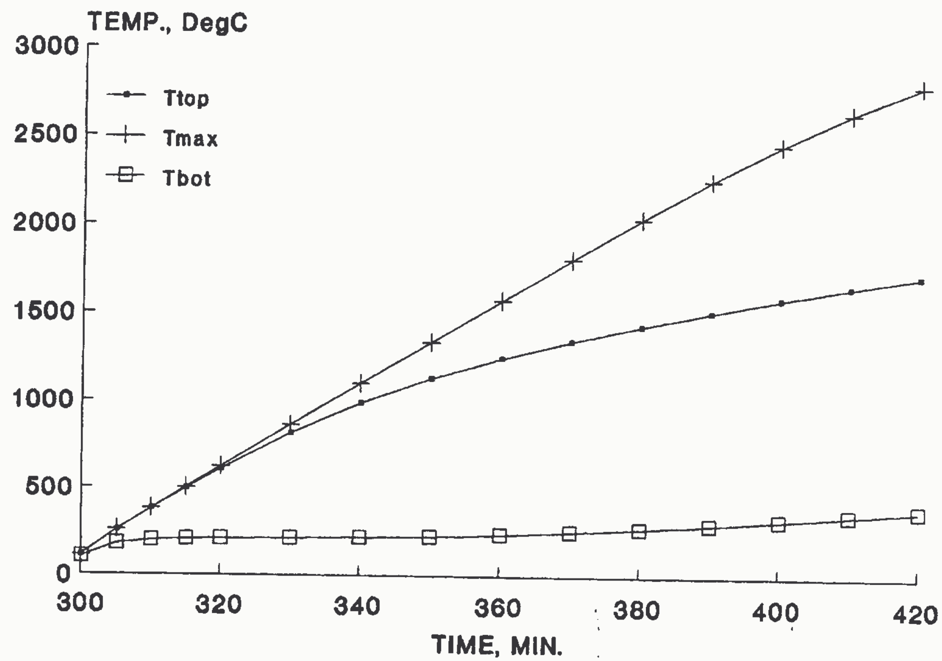


Figure 7 Heat Up of Core Debris in CANDU 6 Calandria, Reference Conditions

Calandria Wall Temperatures

- Outer surface temperature below 140C
- Stainless steel wall
- Do not expect creep under applied stresses

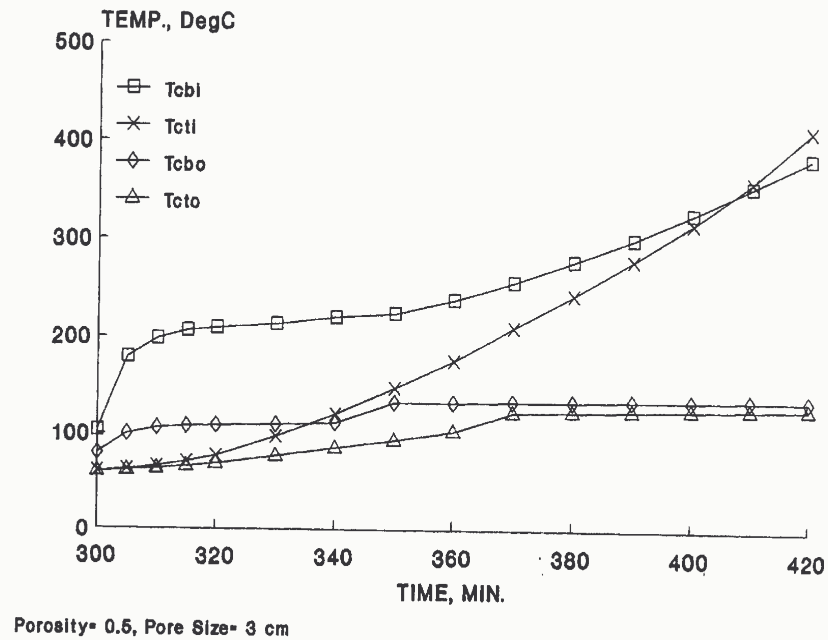


Figure 8 Calandria Wall Temperatures, Heat Up of Core Debris, CANDU 6 Calandria

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

Critical heat flux
200 W/cm^2

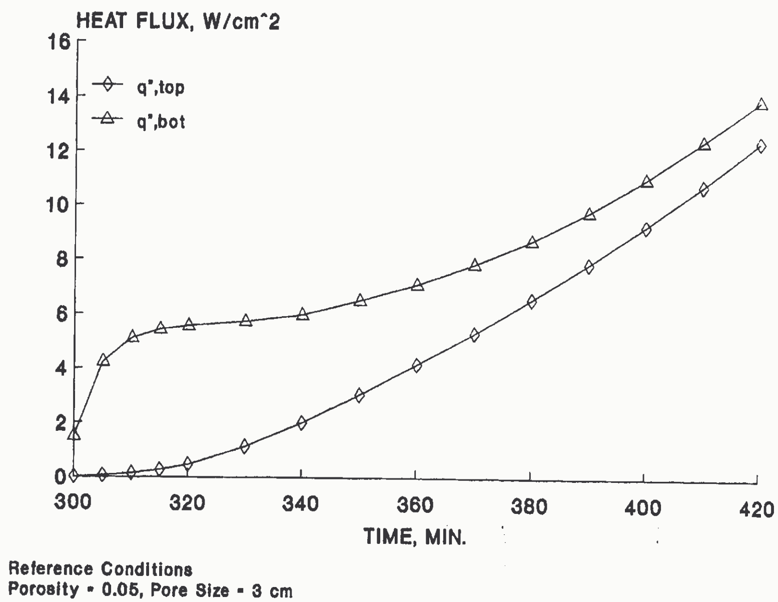


Figure 9 Heat Fluxes on Calandria Wall, Heat Up of Debris in CANDU 6 Calandria

Summary of Time-scales

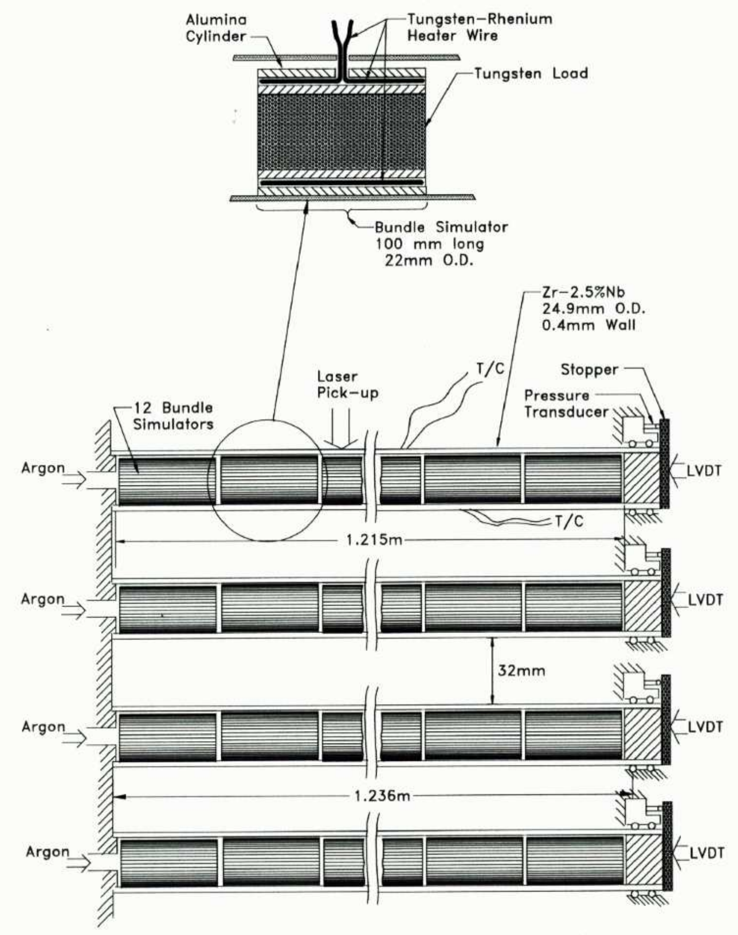
Time (hr)	Event
0	Loss of heat sinks, reactor shutdown
0.75	Steam Generators boil dry, liquid relief valves open, fuel cooling degrades
0.83	A few pressure tubes fail and depressurize heat transport system
0.86	High pressure ECC initiated; medium pressure ECC assumed to fail
1.1	Heat transport system 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

Uncertainties

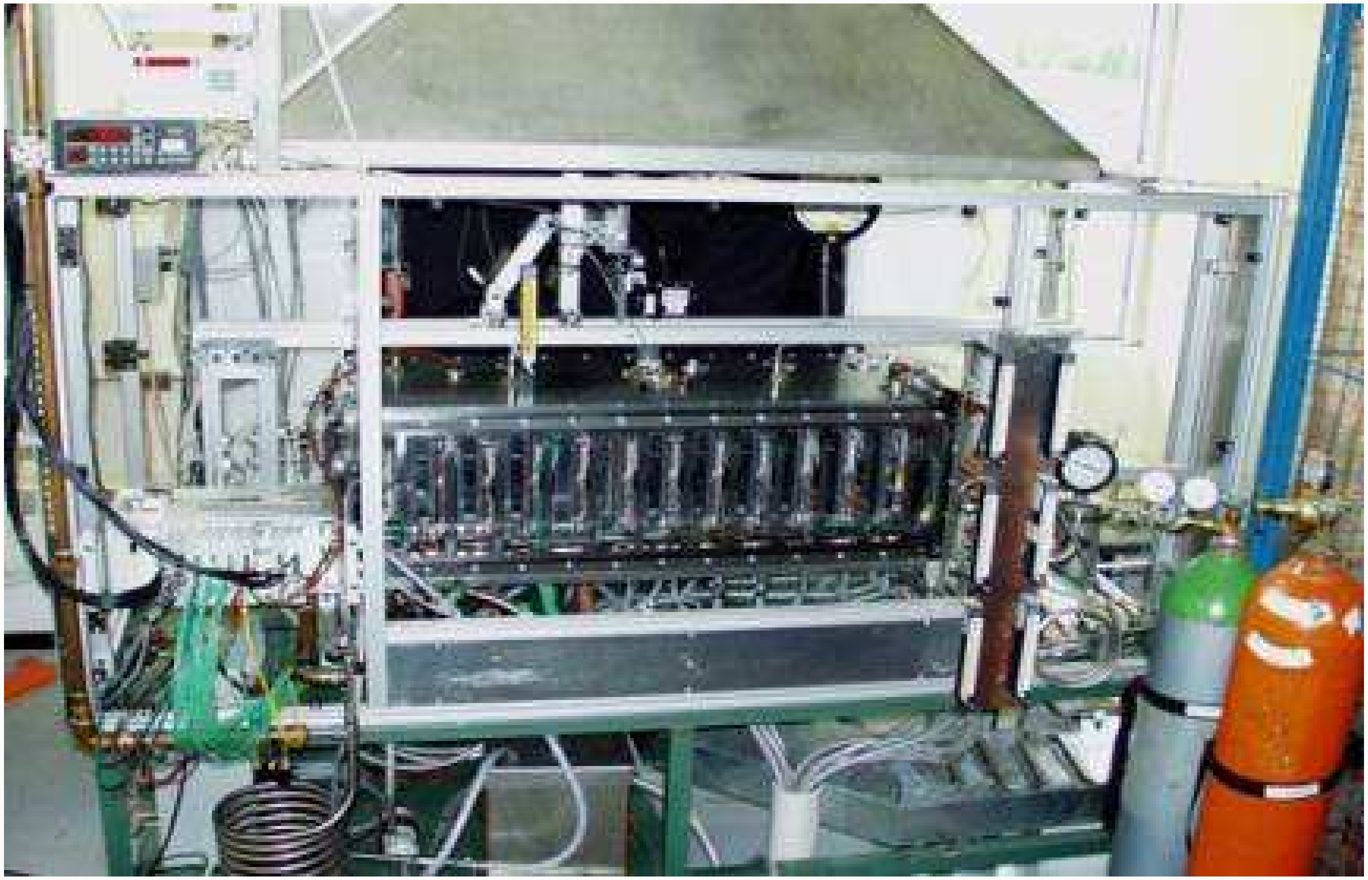
- Mechanical and thermal behaviour of end-shields
- Capability of shield tank to relieve steam
- Local effects in molten pool and hot-spots
- Lack of experimental validation of debris melting transient
- Demonstration of core collapse mode

Tests on Channel Collapse

- 1/5 scale study
- Scaling retains full size stress levels, ratio of bundle size to channel length and channel length to pitch height of assembly



Test Rig

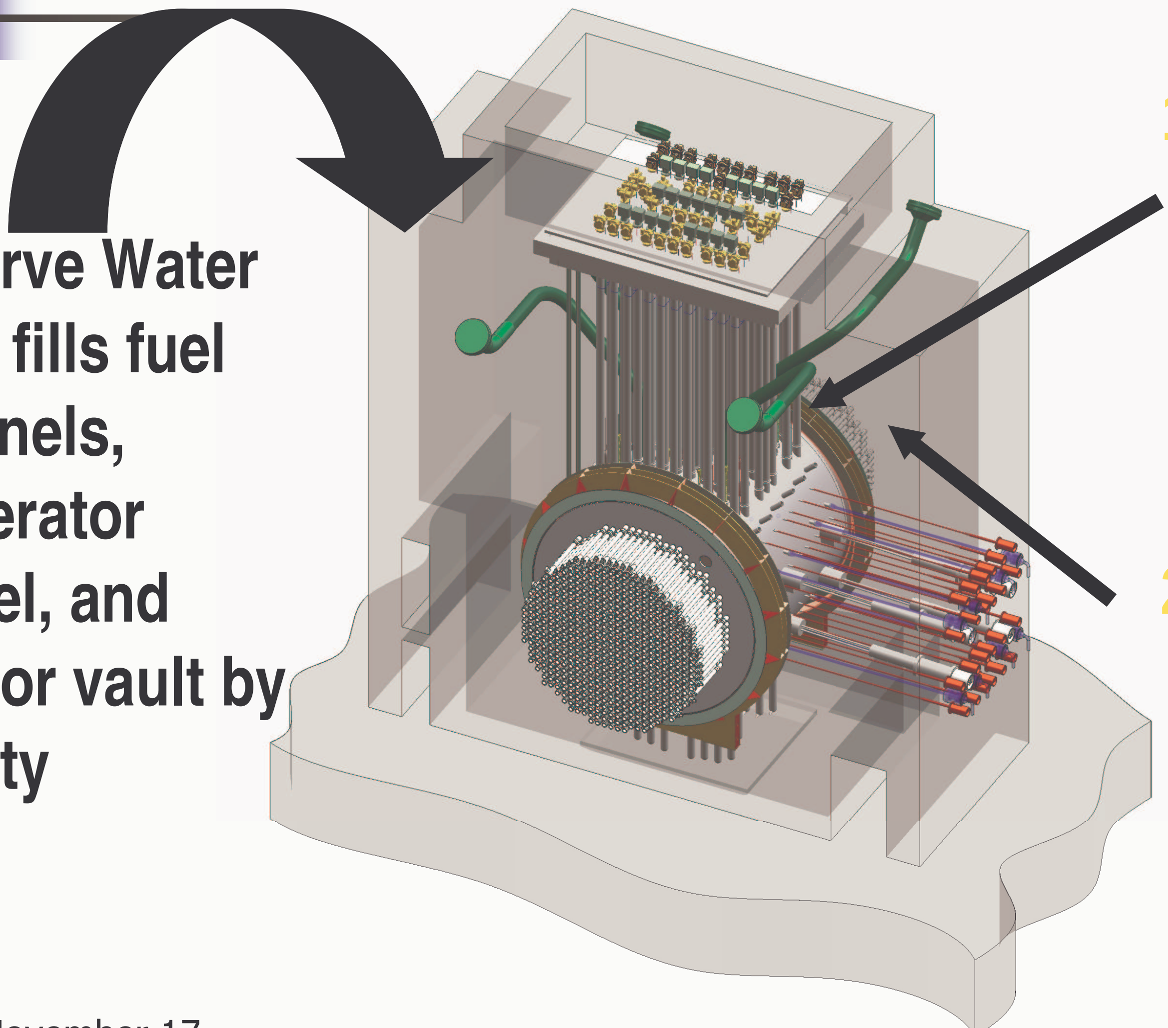


Channel Failure Mode

Channel Collapse – Early Results

- Significant sag occurs only above 800C.
- Sag is creep-controlled
- PT wall thins at the bundle junctions - debris may be two to three bundles long
- The end-load is not sufficient to pull out the channel from the end-fitting

ACR Severe Accidents



1. **Moderator Vessel Water**
2. **Reactor Vault Shielding Water**
3. **Reserve Water Tank fills fuel channels, moderator vessel, and reactor vault by gravity**

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
- With no heat sink, will eventually rise above design pressure
- Structure will remain intact due to leakage through cracks and pressure relief
- Mitigation: venting, dedicated heat removal chain, re-route LTC, firewater etc.

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)
- Hydrogen control a necessity in short- and long-term

Coherent vs. Incoherent

LWRs

- Fuel melts rapidly (minutes) and "candles" down to the bottom of the vessel
- Vessel fails suddenly ejecting molten fuel
- Potential for steam explosion in vessel and in containment

CANDU

- Fuel melts slowly (hours) and slumps gradually down to the bottom of the vessel
- Vessel fails after a day; shield tank provides further barrier
- Continual steam release - explosion less likely

Severe Accident Conclusions

- Severe accident mitigation requirements for new reactors stress two design measures:
  - core debris spreading area
  - ability to add water to cool debris
- CANDU: calandria spreads the debris, and shield tank provides cooling water
- Long time scales allow for severe accident counter-measures and emergency planning
- Independent makeup to moderator and shield tank for EC6 and ACR
- Future: backup or passive containment heat removal

Uncertainty Analysis

- Disadvantages of conservative approach:
  - Overestimates / exaggerates risk
  - Misleadingly small margins
  - Useless as operator guide
  - Distorts safety resource allocation
- UA useful only with *best-estimate methods (BE+UA) – aka BEAU*

Types of Uncertainty

- Physical models
  - Model bias
  - Experimental scatter
  - Example: WIMS predicts coolant void reactivity for 37-element fuel with a bias of –1.6 mk. and an experimental uncertainty of ±1mk.
- Plant idealization
  - Example: How many spatial nodes for convergence?
- Plant data
  - Example: Uncertainty in flow measurement

Focus of Uncertainty Analysis

- UA stated only for key safety parameters output by the code & compared to acceptance criteria
  - E.g., peak fuel temperature
  - E.g., *not* internal parameter such as fission gas pressure

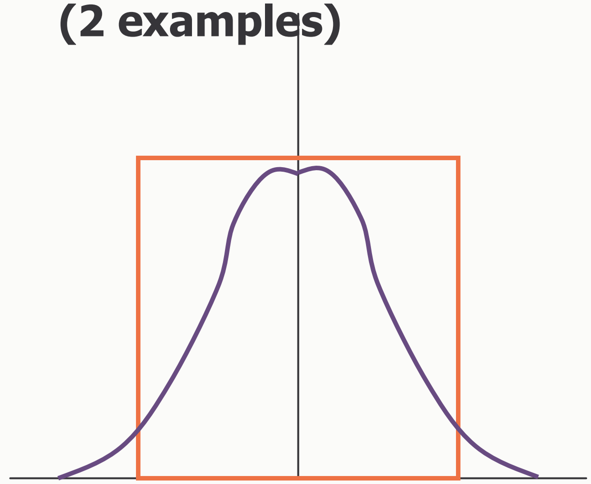
Issue

- Assume there are < 8 contributors to a key parameter
  - E.g., key parameter is fuel temperature in LOCA power pulse
  - Contributors are void reactivity, sheath-to-coolant heat transfer, delayed neutron fraction etc.
- Cannot afford to vary 8 simultaneously using fundamental codes
- Surrogate needed (curve fitting or functional form)

Simplified Methodology

- Generate cases for variation of *n* contributory parameters using fundamental code
- Fit surface with functional form
- Test goodness of fit
- Sample surface based on statistical distribution of each parameter

Probability distribution of Contributory parameter (2 examples)



Graphical Example