Sequences of ACR Limited and Severe Core Damage Accidents

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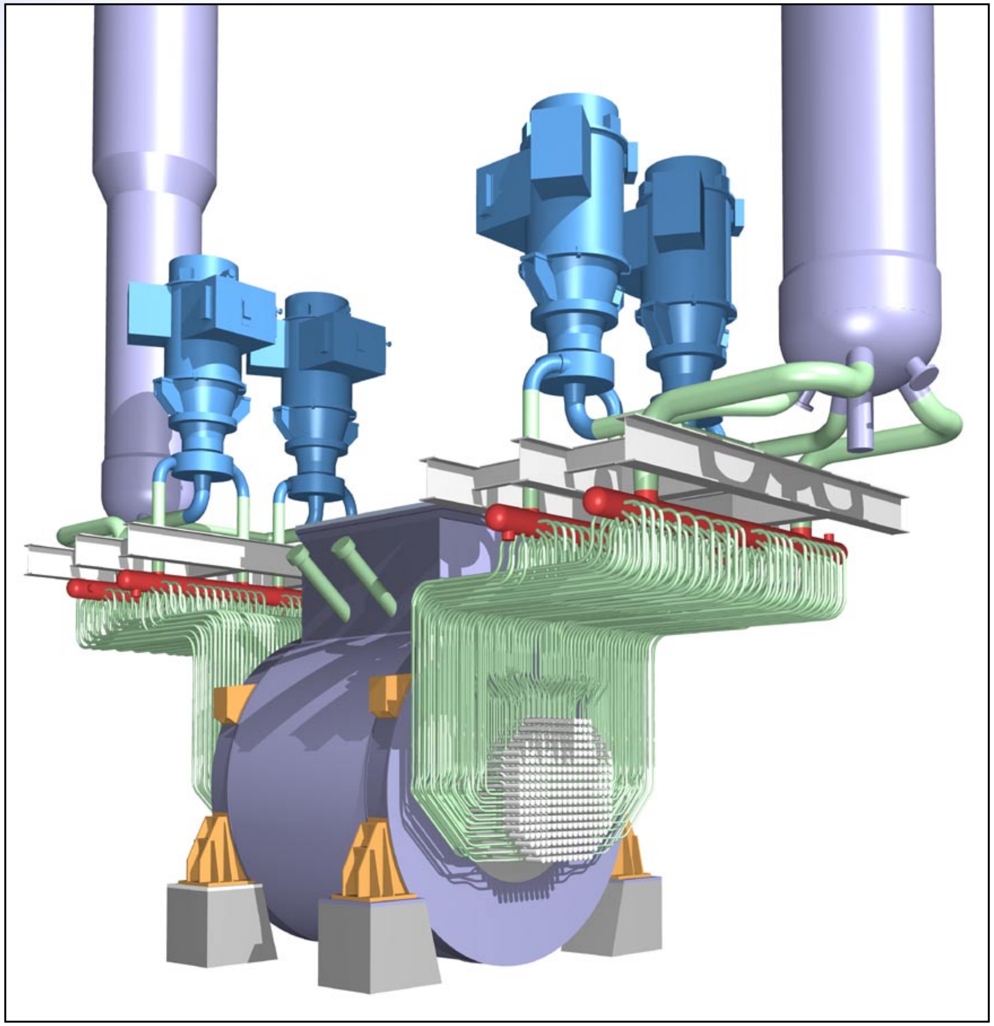
Outline

- ACR Features
- Definitions
- Sequences
  - Severe Flow Blockage
  - LOCA + LOECC
  - LOCA + LOECC, and loss of Moderator cooling
  - Station Blackout
- Phenomenology
- Summary

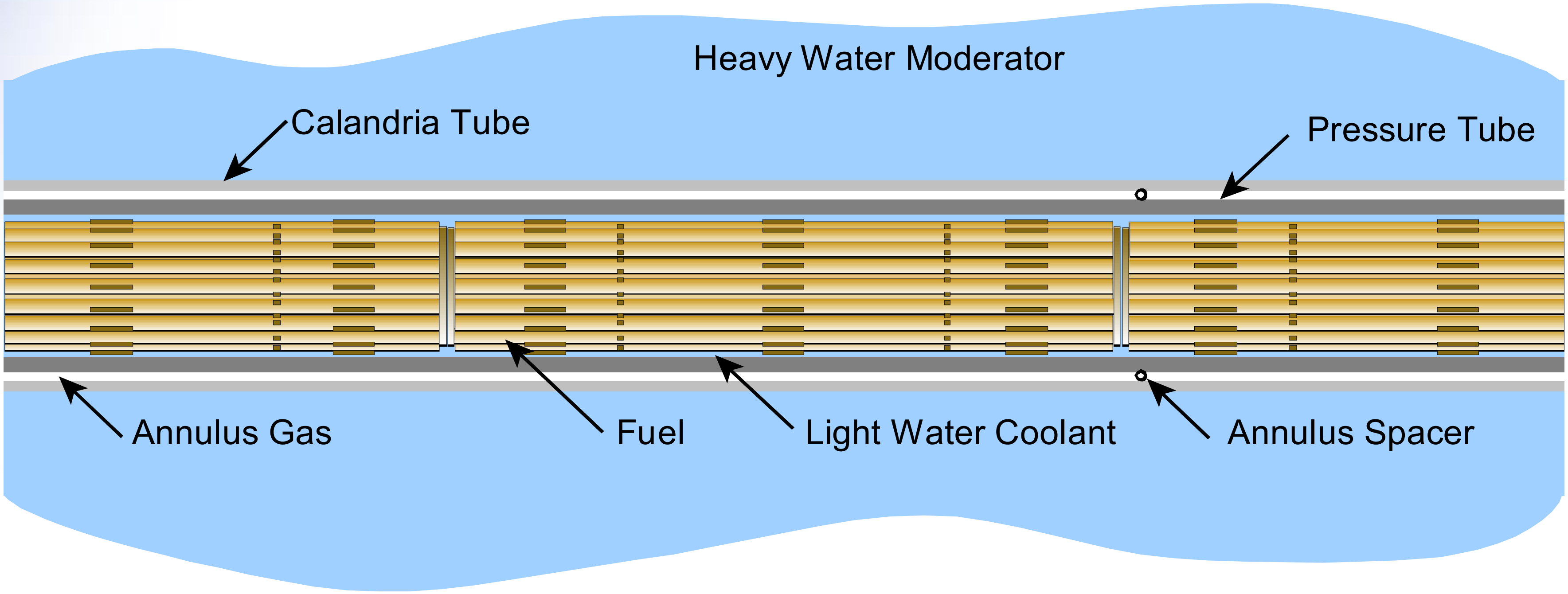
ACR Reactor Coolant System Layout



Similar to LWR above the headers

Below headers, feeders and horizontal fuel channels instead of a pressure vessel

Fuel Channel Details



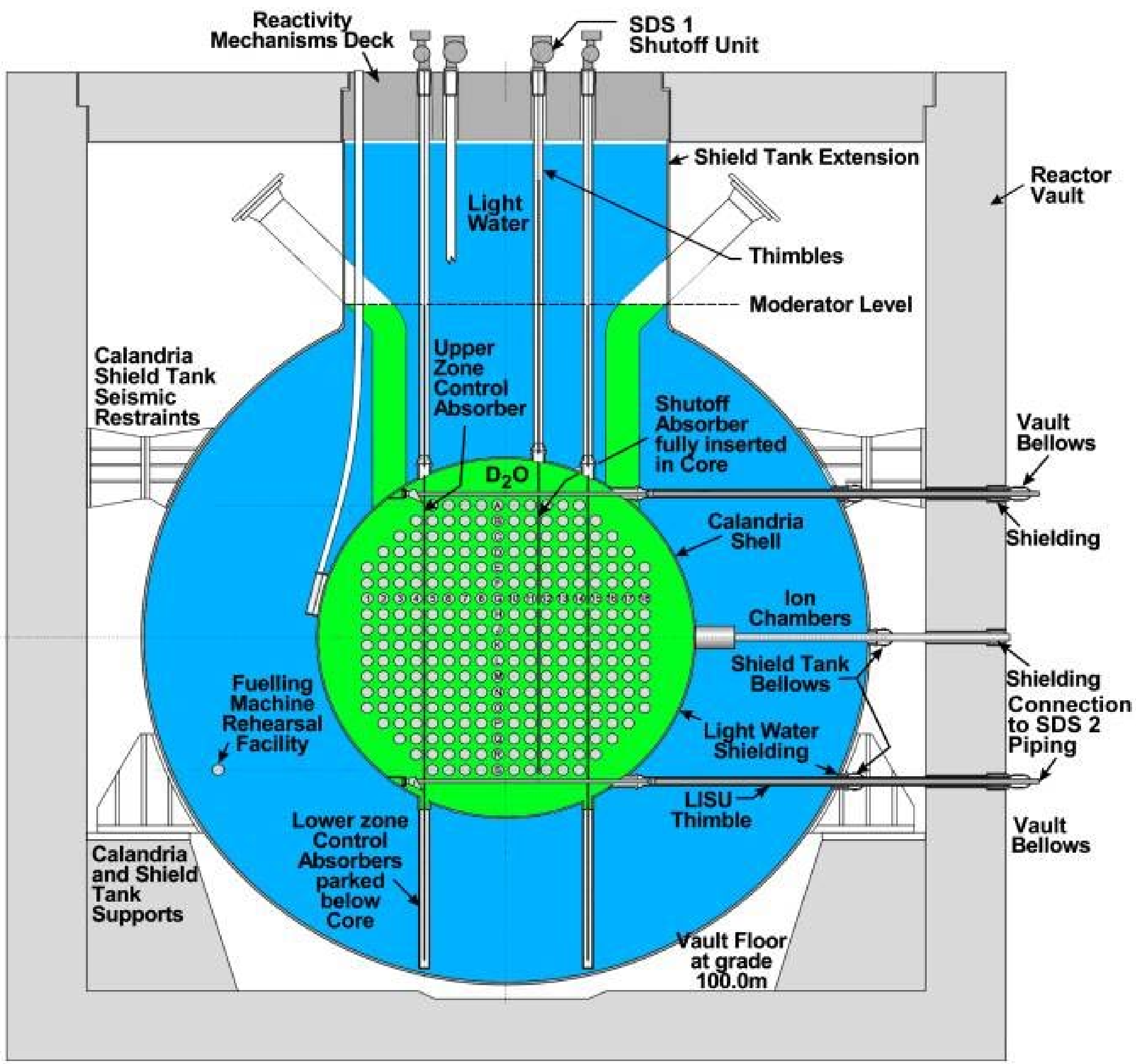
Fuel is UO_2 clad with Zircaloy-4, in short bundles

Moderator is unpressurized heavy water below 100°C

Inherent Safety Features

- Small negative coolant void reactivity for ACR means there is no additional energy from power pulse on voiding
- Reactivity control devices do not penetrate the RCS boundary
- The moderator system provides a backup heat sink capable of maintaining core coolability and geometry for LOCA + LOECC
- The moderator vessel and the shield tank have sufficient thermal capacity to slow down severe core damage progression and allow time for the operator to implement severe accident management measures.

Front View of ACR



- Calandria vessel contains 102 m^3 of heavy water
- Shield tank contains 456 m^3 of light water
- Control and shutdown mechanisms in Calandria not RCS
- Area below shield tank will be flooded during an accident

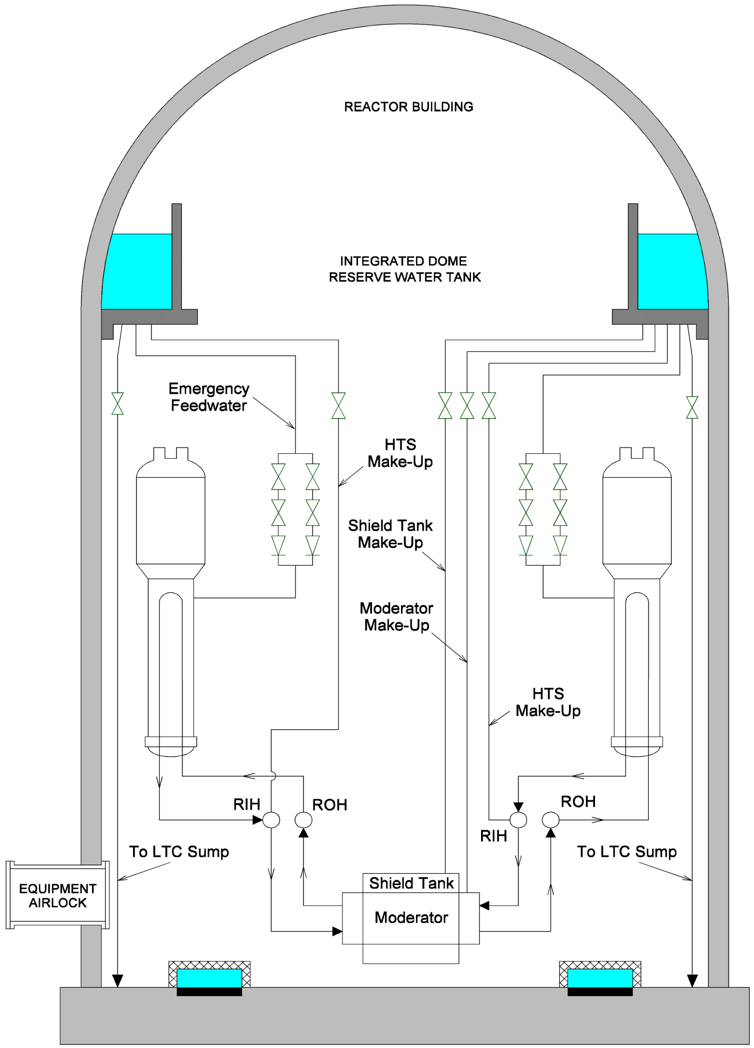
Design Features Relevant to Core Damage Accidents

- The following features have been included in the ACR design that prevent and/or mitigate core damage accidents:
  - Control system and two independent shut-down systems each capable of safely shutting down the reactor, removing concern of ATWS
  - Two independent trains of ECC reduces likelihood of complete loss of ECC
  - Local Air Coolers remove heat from containment and reduce the risk of overpressurization
  - Passive autocatalytic hydrogen recombiners can prevent energetic combustion
  - Steel-lined, pre-stressed concrete, for low containment leakage

Design Features Relevant to Core Damage Accidents (cont.)

- **Features have also been included to ensure that for severe core damage accidents, the core is contained and ex-vessel phenomena are prevented:**
  - **Reserve Water System allows passive makeup of moderator, preventing accident from progressing to severe core damage**
  - **In the event moderator cooling is lost and can not be made up, the Reserve Water System can be used to make up the shield tank, thereby containing the core within the calandria vessel**
  - **Containment designed so that water (from the RCS and the Reserve Water Tank) will pool under and around the shield tank, adding another layer of protection against debris penetration**

Reserve Water System



Reserve Water System capacity: 2500 Mg

Can supply make-up water to:

- Reactor Coolant System
- Secondary Side
- Moderator System
- Shield Tank
- Sump for Long-Term Cooling

Low Frequency Core Damage Accidents

Low frequency core damage accidents for CANDU reactors can be divided into two classes:

- ***Limited Core Damage Accidents*: improbable events for which the channel core geometry is maintained**
- ***Severe Core Damage Accidents*: highly improbable events for which there is the possibility of core disassembly**

Limited Core Damage Accidents

- Improbable events, that typically result from a combination of failures, in particular an initiating event and total failure of a safety system
  - e.g. LOCA with LOECC
- Limits are set on the dose to the public, and there are targets for performance of barriers to facilitate meeting dose limits
  - e.g. LOCA + LOECC: must have adequate moderator subcooling to prevent fuel channel failures
- Accident sequences are analyzed with detailed models and design centered assumptions (proposed to CNSC)

Limited Core Damage Accidents – Dose Limits

Requirements	Event Class	
	4 (mSv)	5 (mSv)
Effective Dose	100	250
Lens of the eyes	1000	1500
Skin (averaged over 1 cm^2)	4000	5000

Limited Core Damage Accidents – Performance Targets

- Fuel: limit failures
- Fuel Channel
  - no fuel channel failures (in non-affected channels)
  - Ensure sufficient moderator subcooling margin for pressure tube sagging into contact with calandria tube
- Containment
  - Peak pressure below design pressure
  - Hydrogen concentration to remain below DDT limit
- Other: Calandria remains intact

Severe Core Damage Accidents

- Extremely improbable events that typically result from a combination of several events, such as an initiating event and failure of multiple safety systems
  - e.g. LOCA + LOECC, loss of moderator cooling and loss of Reserve Water Tank make-up
- While there can be loss of channel geometry, water in the calandria vessel delays core collapse
- Shield tank, with make up from the Reserve Water Tank, prevents failure of the calandria vessel
- Targets are set for summed frequencies of severe core damage and large releases
- Accidents are analyzed with integral models and design-centered assumptions

Severe Core Damage Accidents: Performance Targets

- Target for summed frequency of Severe Core Damage events is $<10^{-5}$/year
- Target for summed frequency of sequences leading to large releases is $<10^{-6}$/year
- Summed frequencies include external events (except seismic – a seismic margin assessment will be performed for earthquakes)
- Targets to be demonstrated by PRA

Examples of Events

- **Limited Core Damage Accidents**
  - Small LOCA + LOECC
  - End Fitting Failure + LOECC
  - Large LOCA + LOECC
  - Pressure Tube / Calandria Tube Failure + LOECC
  - Steam Generator Tube Rupture + LOECC
  - Stagnation Feeder Break
  - Severe Channel Flow Blockage
- **Severe Core Damage Accidents**
  - LOCA + LOECC, with loss of moderator cooling
  - Station Blackout (Loss of all AC Power)

Flow Blockage

- A flow blockage event affects one of the hundreds of fuel channels in a CANDU core, and the consequences depend on the extent of the blockage
- For blockages up to ~98% of the flow area:
  - In extreme cases, there can be dryout of the fuel cladding and failure releasing fission products to the RCS
  - The pressure tube remains intact, and any releases are contained in the RCS
- Severe flow blockages in excess of ~98% of the flow area (very rare) can lead to failure of a single channel

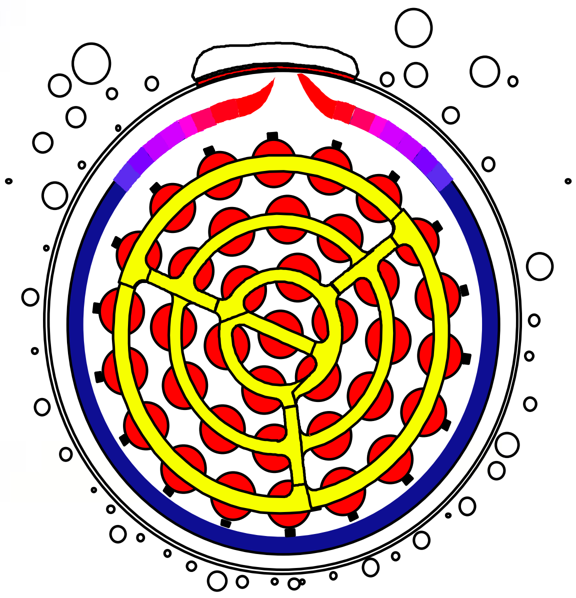
Severe Flow Blockage

- **Sequence of Events:**
  - Conditions in affected channel: reduced coolant flow, full pressure, full power
  - Fuel rapidly heats up, transferring heat to the pressure tube
  - As the pressure tube temperature increases, it will start to balloon outward under the system pressure
  - Pressure tube is likely to fail due to strain localization (circumferential temperature gradient)
  - If there is essentially complete blockage (less than 0.5% of the flow area remaining), there could be limited melting of fuel cladding before pressure tube failure

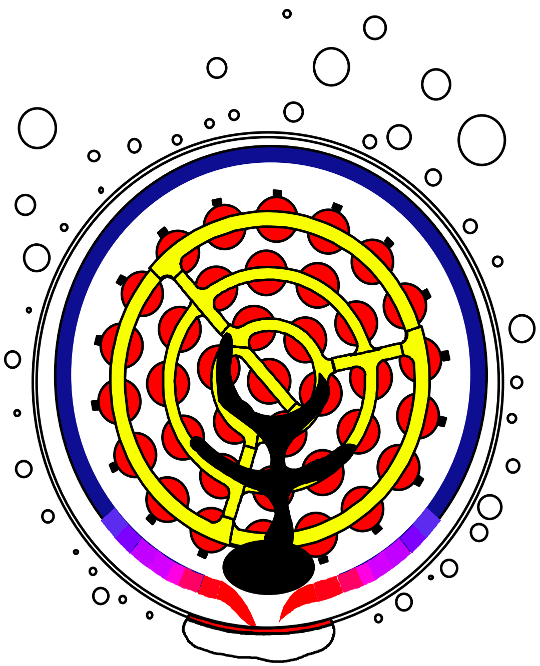
Severe Flow Blockage (cont.)

- Sequence of Events (cont.)
  - Rupture of the pressure tube pressurizes the annulus with the calandria tube, causing the channel bellows to fail
  - If the pressure tube does not fail prior to ballooning contact with the calandria tube, small amounts of molten material will cause failure of both tubes
    - Discharge of steam, hot fuel, etc., from the channel into the moderator will cause some limited damage to core components
  - In either case (pressure tube failure, or pressure and calandria tube failure) the reactor trips and there are no further consequences

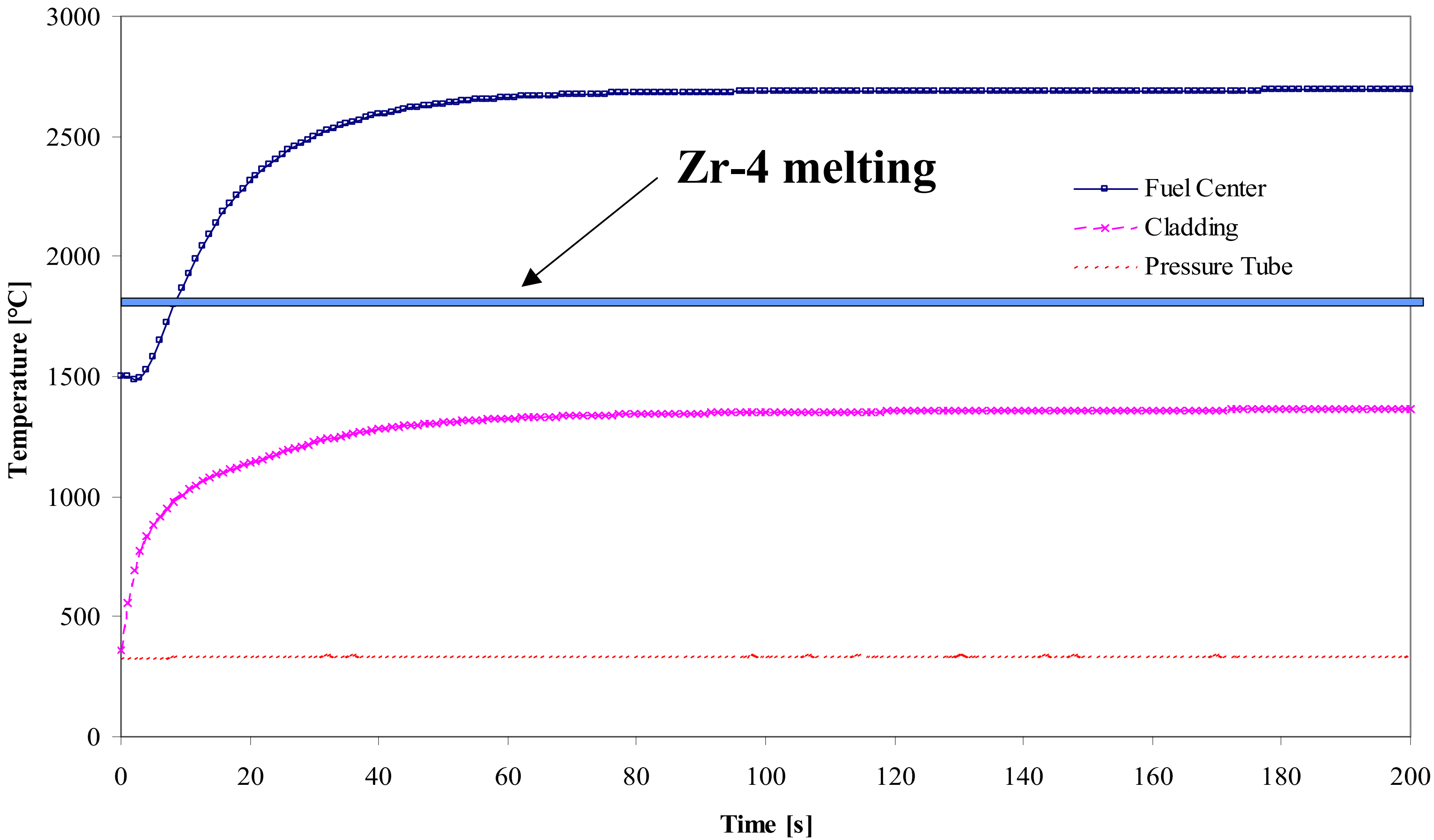
Channel Failure in Severe Flow Blockage



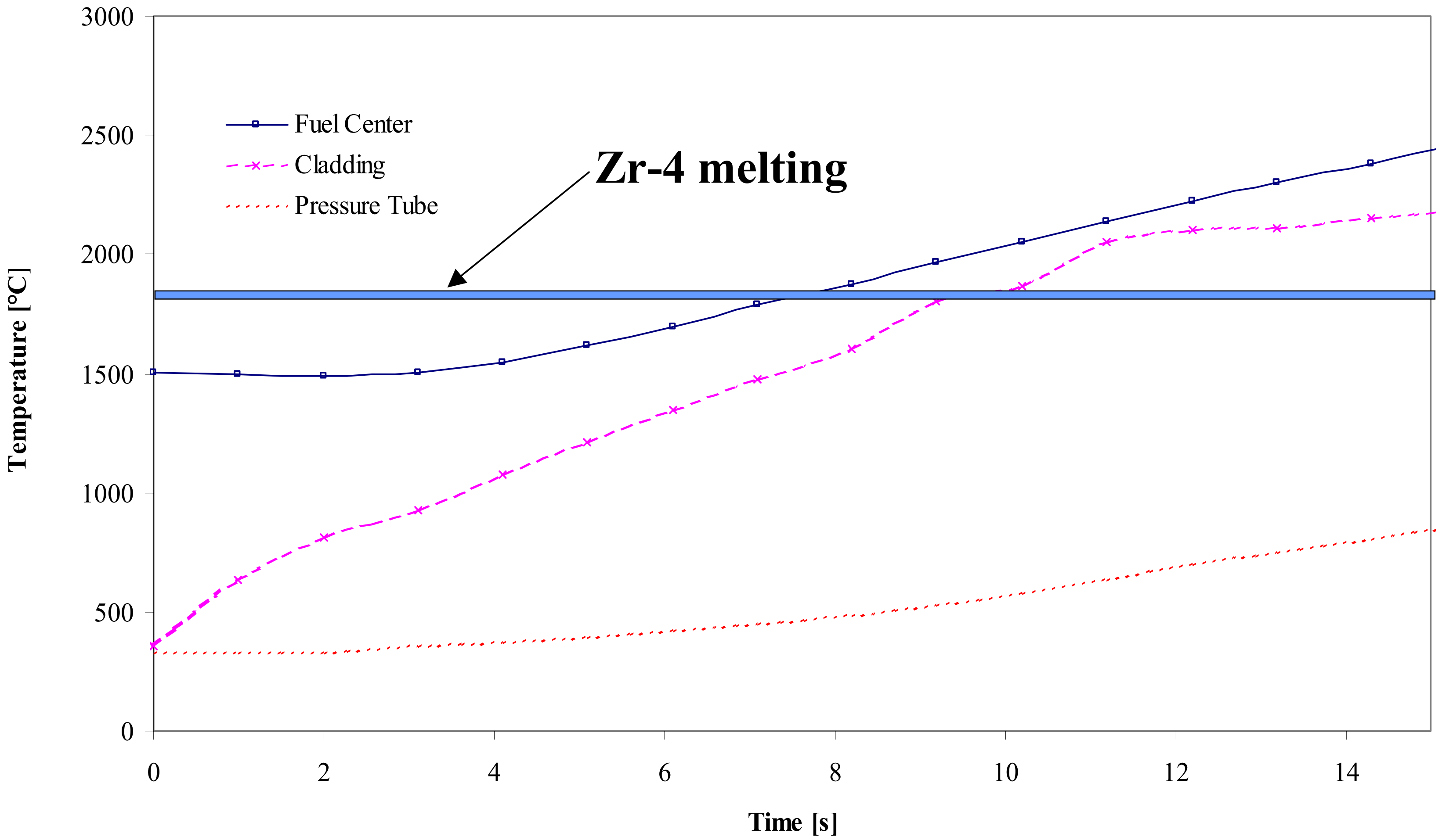
Stratified flow
(likely scenario)



Molten Material Contact
(before & after ballooning)



Temperature Profile for a 7.5 MW Channel (98% Area Reduction)



Temperature Profile for a 7.5 MW Channel (100% Area Reduction)

LOCA with Loss of ECC

- Consequences depend on break size and degree of ECC impairment. Dual trains of ECC makes complete loss of ECC improbable
- Presence of moderator around the fuel channels serves to prevent fuel channel failure and limit the consequences of the accident
- Water from Reserve Water Tank can be used to
  - Back-up the moderator
  - Make up the Reactor Coolant System to limit fuel temperatures

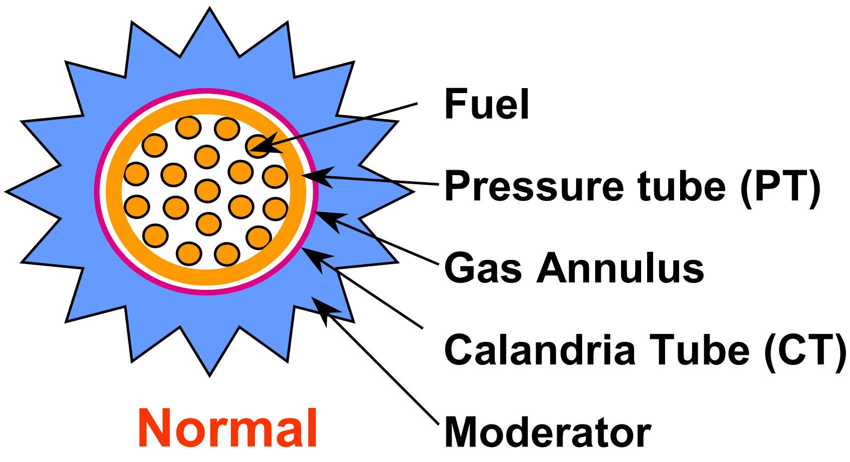
LOCA with loss of ECC (cont.)

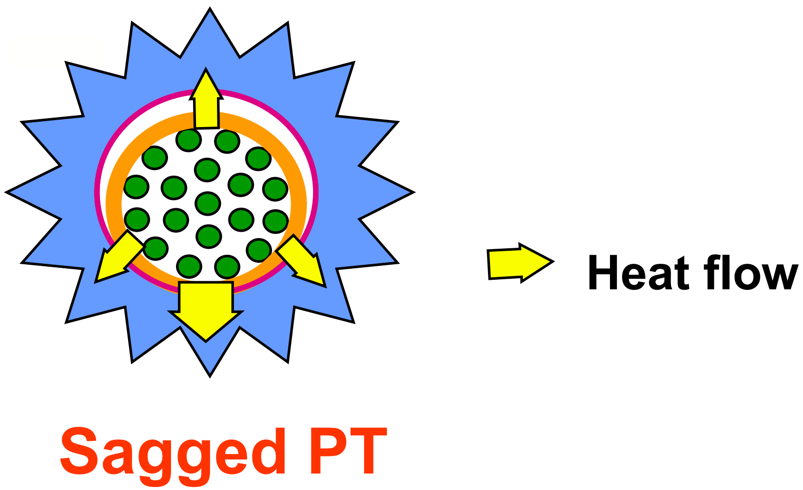
- **Sequence of events:**
  - Reactor coolant system depressurizes, cooling to fuel reduced
  - Fuel heats up, deforms and transfers heat to pressure tubes
  - As pressure tube temperatures exceed ~600°C, they start to deform
  - Pressure tubes sag into contact with surrounding calandria tubes
  - Stored energy in the pressure tube, and heat from fuel is conducted to the moderator
  - Integrity of fuel channel depends on moderator subcooling preventing extensive film boiling

LOCA with loss of ECC (cont.)

- **Sequence of events (cont.):**
  - Heat from fuel is removed by moderator circulation system
  - Core channel geometry is maintained
  - Fuel can be severely damaged, but melting is limited
  - Released fission products are transported toward the break, with retention in RCS due to condensation, impaction, pool-scrubbing, etc.
  - Effluent from RCS enters containment (steam, water, hydrogen, fission products)
  - Local Air Coolers remove heat and prevent containment overpressurization
  - Hydrogen recombiners prevent energetic hydrogen reactions
  - Fission products retained in containment, primarily in the aqueous phase

Heat Rejection to Moderator





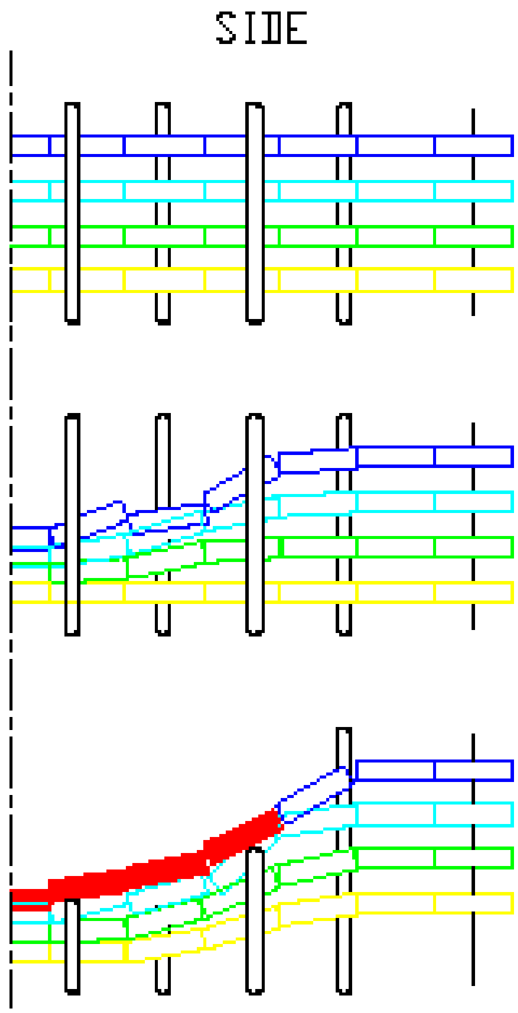
LOCA+LOECC, loss of Moderator cooling

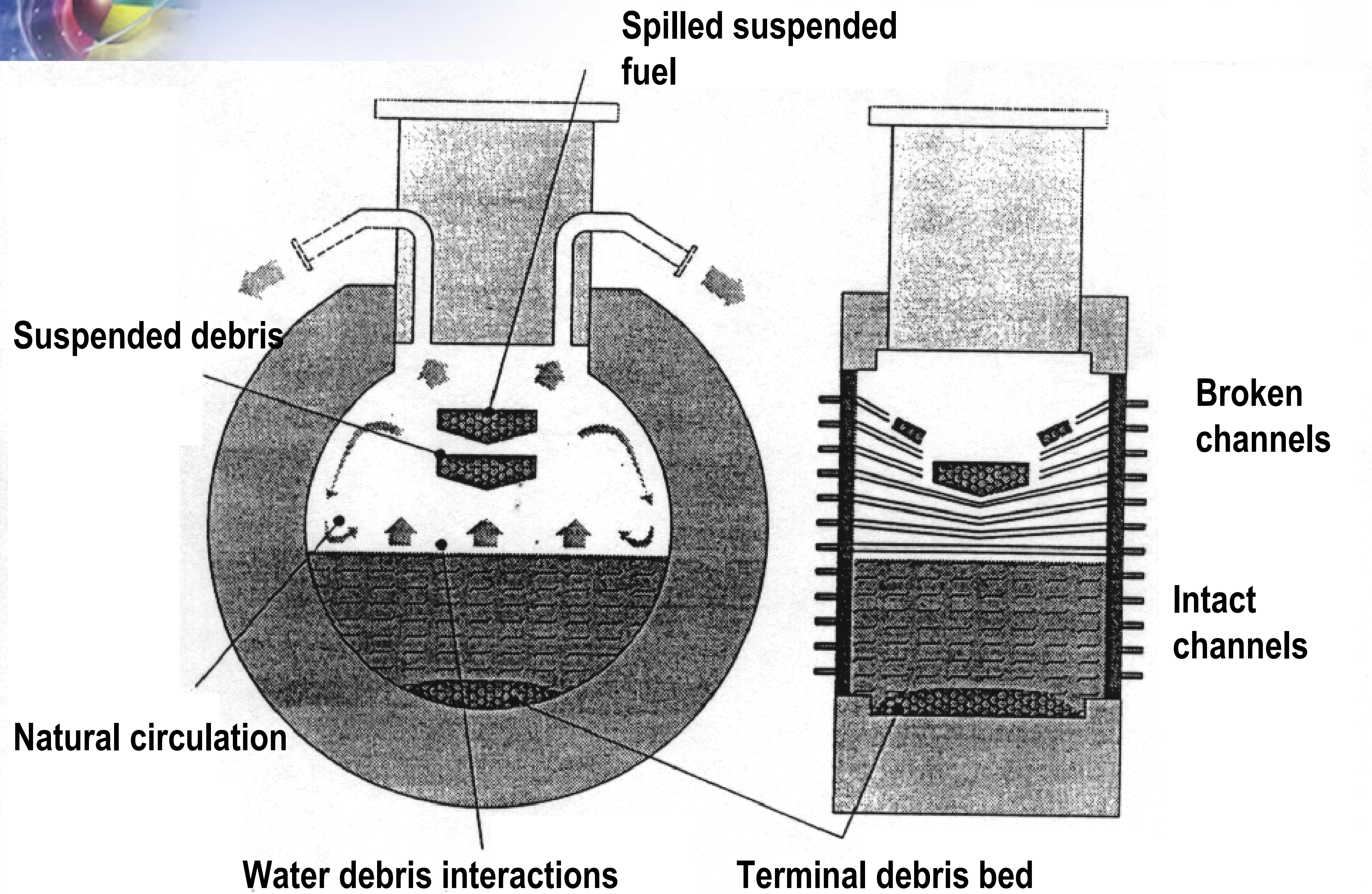
- **In a LOCA + LOECC, the moderator maintains cooling for fuel channels and prevents loss of channel geometry**
- **In the highly unlikely event that moderator cooling is impaired, the Reserve Water Tank is used to make-up the moderator and prevent loss of core geometry**
- **Loss of RWT make-up to the moderator results in a severe core damage sequence**

LOCA+LOECC, Severe Core Damage Sequence

- **Typical sequence of events:**
  - Primary system depressurizes, cooling to fuel reduced
  - Fuel heats up, deforms and transfers heat to the pressure tubes
  - Pressure tubes heat up and sag into contact with calandria tubes
  - Heat load from fuel channels slowly boils off the moderator (no RWT make-up)
  - Uncovered fuel channels heat up, gradually collapse and break up
  - Debris initially supported by lower channels
  - Eventually lower channels fail and debris bed forms in bottom of calandria

Channel Disassembly




Spilled suspended fuel
Suspended debris
Broken channels
Intact channels
Natural circulation
Water debris interactions
Terminal debris bed

LOCA+LOECC, Severe Core Damage Sequence

- **Sequence of events (cont.):**
  - After all moderator is expelled, debris bed heats up
  - Shield tank cooling and make-up from the Reserve Water Tank keeps calandria intact, containing the core
  - Fission products are released during early fuel transients, and during core degradation and melting
  - Hydrogen is released from extensive oxidation reactions
  - Local Air Coolers prevent overpressurization of containment by hot effluent from the Reactor Cooling System
  - Hydrogen recombiners prevent energetic reactions
  - Fission products retained in containment, primarily in aqueous phase

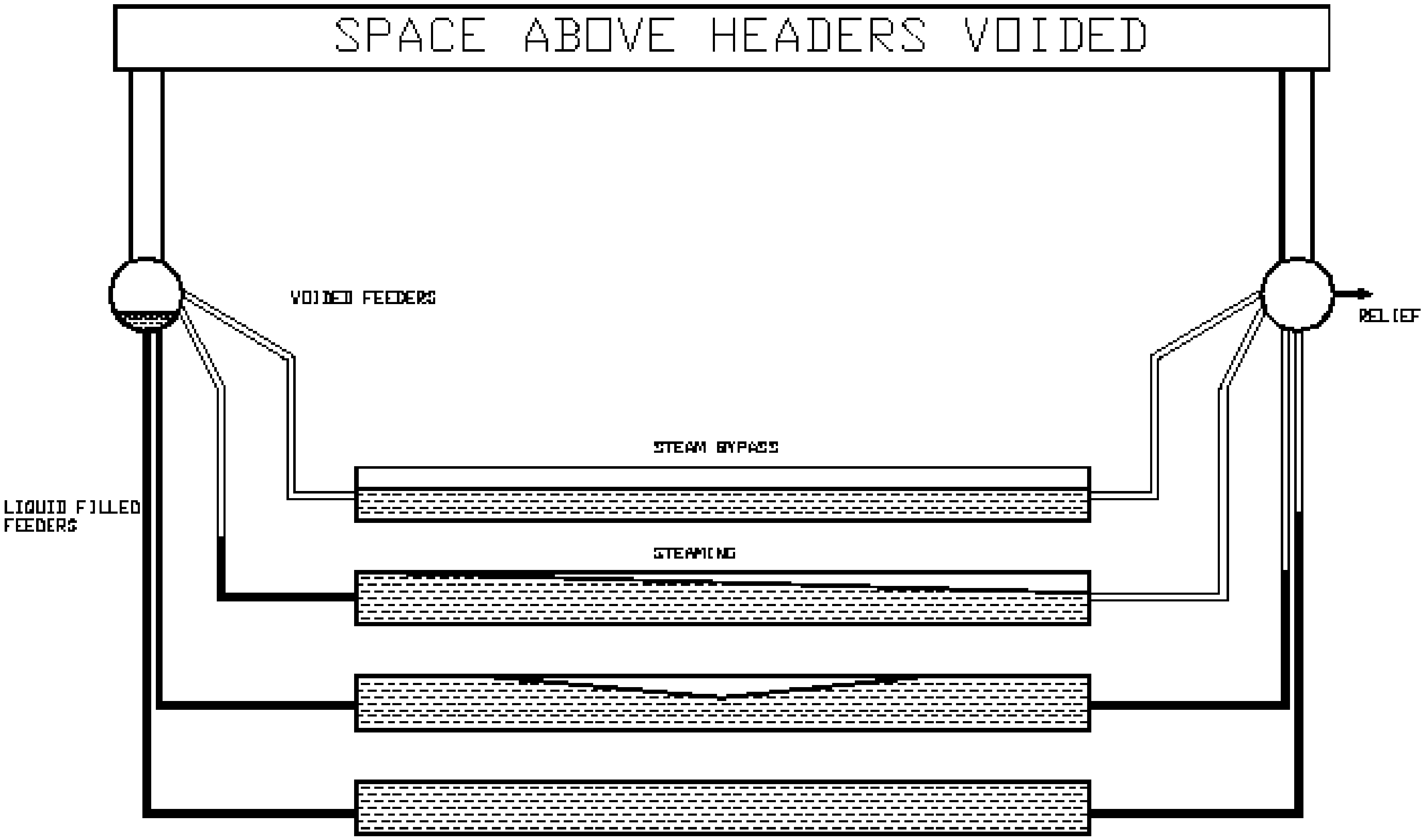
Station Blackout

- Loss of all AC power (station blackout) is highly unlikely because there are two separated sets of diesels, any one of which can support station safety requirements
- If it does occur, back-up batteries can be used to operate station safety systems
- Presence of water reservoirs in calandria, shield tank and Reserve Water Tank serve to slow down the accident progression and allow time for operator intervention

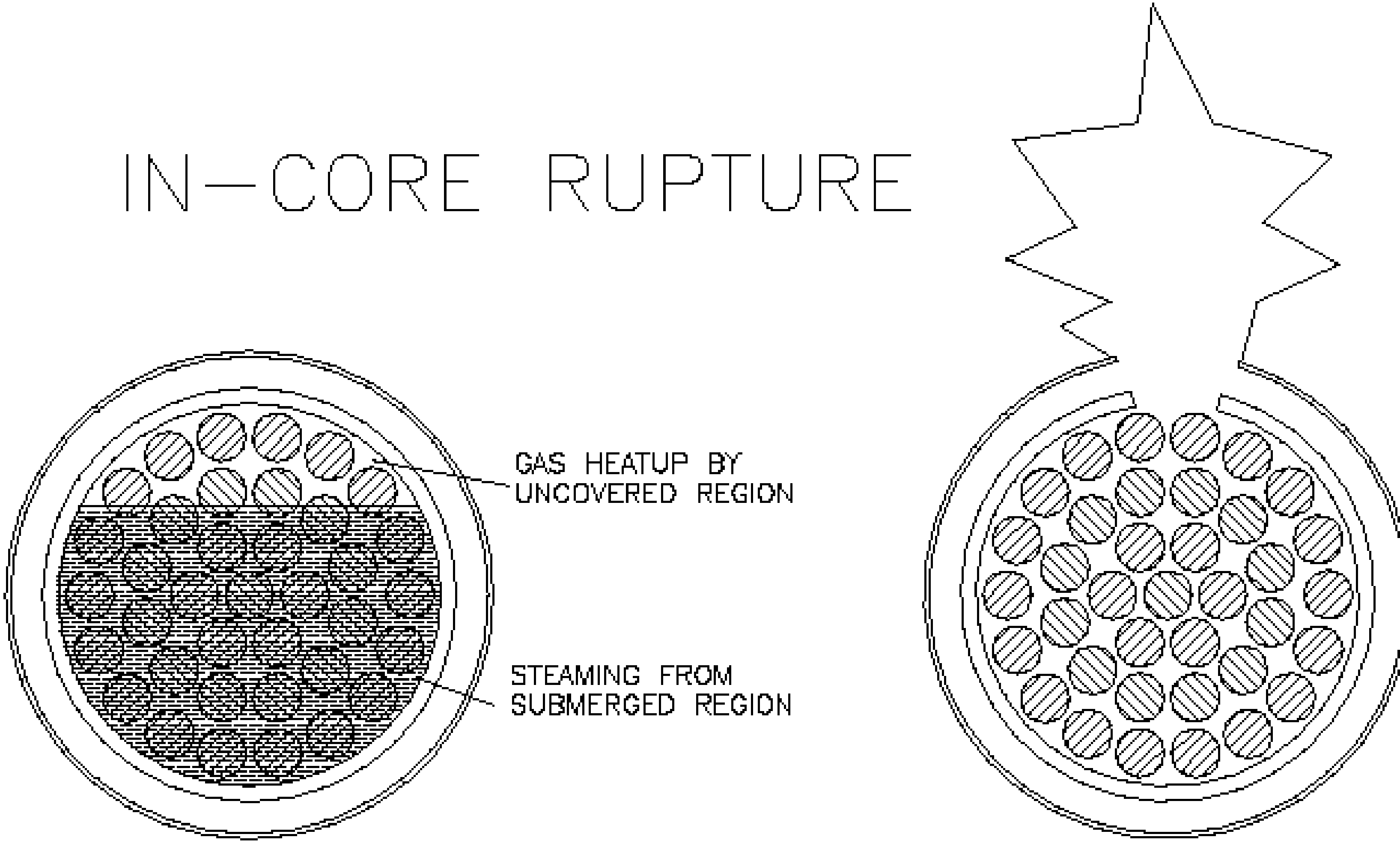
Station Blackout

- **Sequence of events**
  - After pumps rundown, flow maintained by natural circulation, heat being rejected to the secondary side
  - Failure of secondary side cooling leads to heat up and pressurization to the Reactor Coolant System set point
  - Coolant is lost through liquid relief valves
  - Pressure tube in hottest channel balloons and fails (similar to flow blockage)
  - RCS depressurizes introducing forced flow in remaining fuel channels
  - Remaining fuel channels sag into contact with calandria tubes, and accident progresses as for LOCA + LOECC with loss of Moderator cooling

Channel Failure at High Pressures



Channel Failure at High Pressures



Core Damage Accident Phenomena

Accident Progression

<u>Inside calandria</u>

1. Fuel heat-up and degradation
2. Fission product release and transport
3. Channel heat-up and thermal hydraulics
4. Moderator heat-up and boil-off
5. Core disassembly
6. Debris behaviour

Parallel processes*

A. Hydrogen combustion
B. Containment thermal hydraulic response
C. Fission product behavior

(*) Separate system codes are available for parallel processes, but integrated codes like MAAP4 CANDU do integrated calculations

Phenomenology

- Consequences of severe accidents are determined by the behavior of:
  - Fuel
    - Degradation mechanisms
    - Interaction of molten fuel with the moderator
  - Fuel channels
    - Deformation mechanisms
  - Fission products
    - Within primary system
    - In containment
  - Containment
    - Hydrogen combustion

Phenomenology (cont.)

- Understanding of the behavior of CANDU reactors is backed up by an extensive research base, including experiments on:
  - Separate effects tests on fuel cladding, fission product chemistry, fuel channel thermal mechanical properties, etc.
  - Integrated tests on fission product behavior, fuel channel behavior, hydrogen combustion, etc.
  - Full-scale tests of pressure tube behavior, instrumented fuel transients
- Where applicable, the database for LWRs has been applied to CANDUs, e.g.:
  - Fission product separate-effects experiments
  - PHEBUS experiments

Computer Codes

- MAAP4-CANDU
  - Integrated code for modeling severe accident behavior in CANDUs
- ELESTRES
  - Fuel behavior under normal operating conditions
  - Provides initial conditions for ELOCA
- ELOCA
  - Models fuel thermo-mechanical behavior under temperature transients
- CATHENA
  - Main thermalhydraulics code
  - Includes detailed models for thermal mechanical response of fuel channels

Computer Codes (cont.)

- SOURCE
  - Models fission product release from fuel
- SOPHAEROS
  - Models fission product transport in the primary system
- SMART
  - Models aerosol behavior in containment, and includes a simplified, mechanistic iodine model – IMOD
- GOTHIC
  - Models containment thermalhydraulics
  - Calculates hydrogen distribution and the pressure from combustion in the event of an ignition

Summary

- ACR can accommodate low probability events, including those that can lead to limited core damage; e.g.
  - LOCA + LOECC: can lead to deformation of primary pressure boundary and extensive fuel damage, but moderator cooling preserves core geometry and fuel coolability
  - Severe Flow Blockage: consequences limited to one channel
- For highly improbable accidents leading to severe core damage, there are a number of features that limit the consequences; e.g.
  - Moderator, shield tank and passive reserve water system reservoirs provide sufficient time for operator intervention
- Phenomenology of severe core damage accidents in ACR is supported by an extensive technology base and backed up by validated computer programs

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