



***CANDU Safety #16:
Large Loss-of-Coolant Accident with Coincident
Loss of Emergency Core Cooling***

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Overview

- λ Event sequence for a large break loss-of-coolant accident with loss of emergency core cooling
- λ Acceptance criteria used to assess the results of the analysis
- λ Fuel and pressure tube behaviour during transient
- λ Fission product release
- λ Containment



LOCA with ECC Unavailable

- λ During a loss-of-coolant accident with coincident loss of emergency core cooling, the accident can be divided into two separate phases
 - *Blowdown phase*
 - λ event sequence is similar to a loss-of-coolant accident
 - *Late heat up phase*
 - λ reactor core does not receive cooling from the emergency core cooling (ECC) safety system
 - λ severe overheating of the fuel at decay power levels occurs

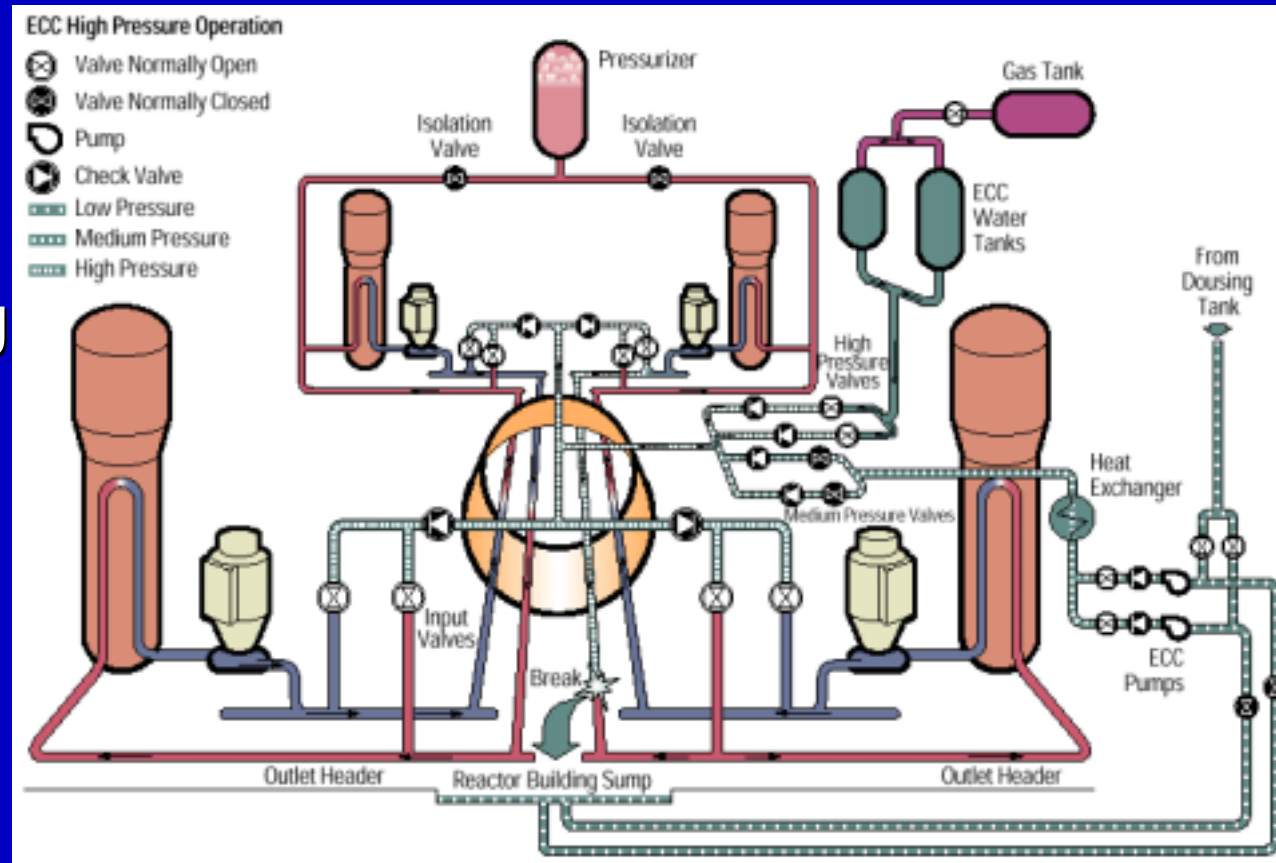
★ Event Sequence for Blowdown Phase

λ Similar to LOCA

- A break occurs in a large diameter pipe in PHT system, discharging coolant into containment
- PHT system depressurizes causing coolant voiding and an increase in reactivity
- Reactor power increases until the reactor is shutdown on a neutronic trip or process trip
- The PHT flow decreases fastest in the core pass downstream of the break
- Onset of fuel dryout results in an increase in fuel temperature
- Once the PHT pressure is reduced to the ECC activation setpoint, ECC would normally be activated; however, ECC is assumed to be unavailable
- Cooling of the intact heat transport loop is similar to the case with ECC available since the two loops are isolated. With forced

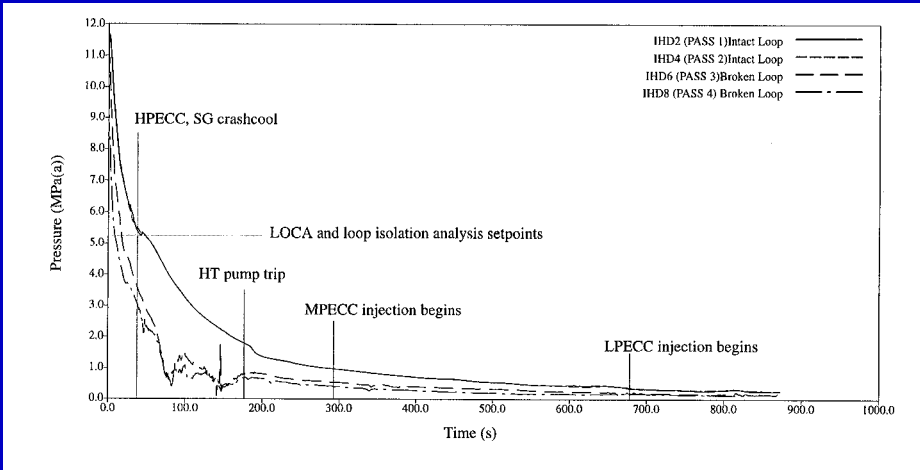
★ Emergency Core Cooling System

- λ High pressure injection by gas
- λ Medium pressure injection by ECC pumps and dousing tank water supply
- λ Low pressure injection by ECC pumps and reactor building sump
- λ This system is assumed unavailable

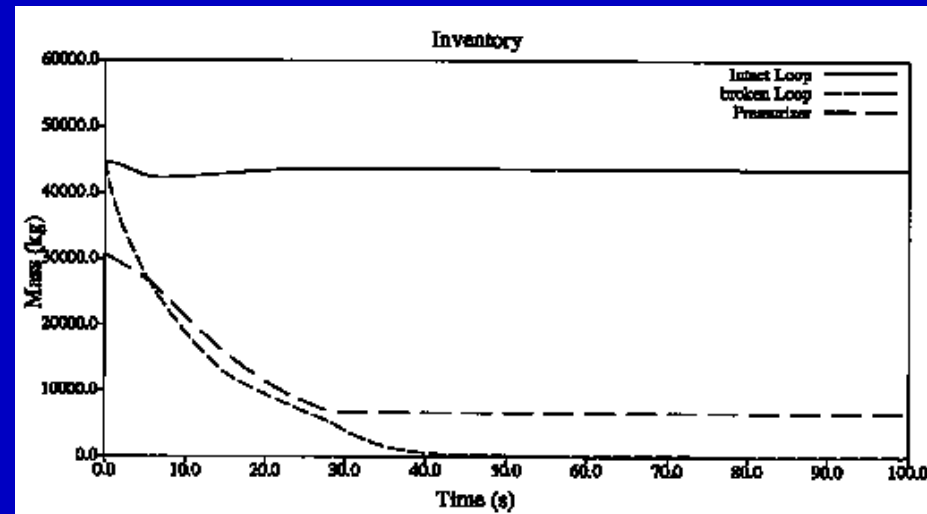
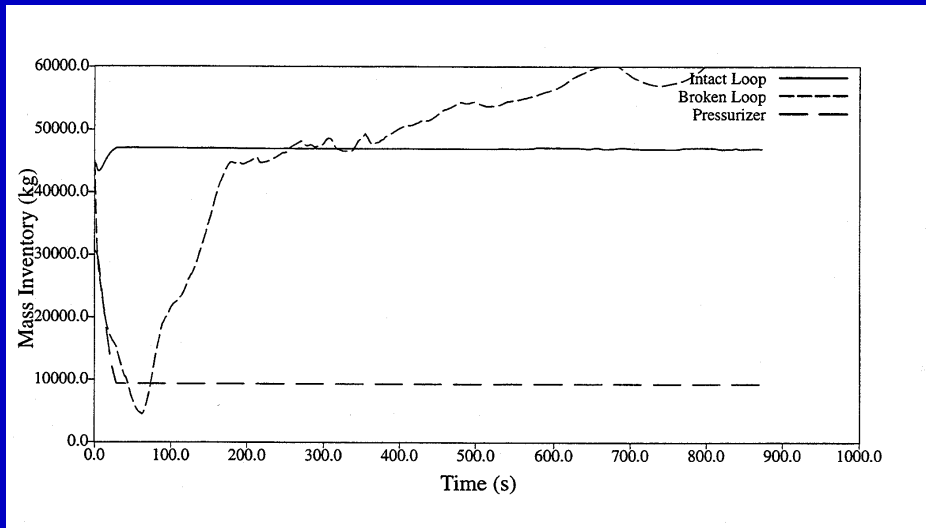
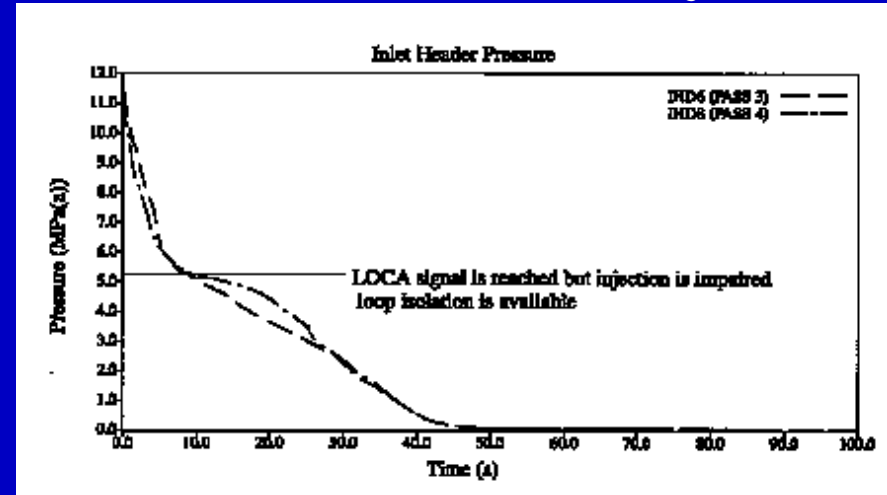


Header Depressurization Transient

LOCA with ECC Injection



LOCA without ECC Injection





Event Sequence for Late Heatup Phase

- λ Degraded cooling conditions in channel while the fuel is at decay power results in severe overheating of the fuel
- λ High temperature fuel results in a considerable exothermic chemical reaction between the Zircaloy and the steam in the channels
 - $$\text{Zr} + 2\text{H}_2\text{O} \Rightarrow \text{ZrO}_2 + 2\text{H}_2 + \text{HEAT}$$
- λ Pressure tubes heat up to the point where they sag or radially strain into contact with calandria tubes
- λ The type of pressure tube-calandria tube contact affects the heat rejected to moderator
- λ Moderator is a heat sink
- λ Fission product releases to containment are large; however, the doses to the public are within AECB guidelines



Analysis Acceptance Criteria

- λ Dose limits are not exceeded
- λ Two independent shutdown systems will arrest the reactivity and power excursion, and will maintain the reactor in a shutdown state
- λ Fuel channel integrity is not compromised
- λ The structural integrity of the containment must be maintained
- λ *The concentration of hydrogen inside containment remains below the threshold concentration for explosion (this is an additional criterion as compared to LOCA)*



LOCA/LOECC Safety Analysis

- λ Like the loss-of-coolant accident, the analysis involves determining:
 - Fuel normal operating conditions
 - Fuel and fuel channel temperatures during LOCA transient
 - Fission product release during transient
 - Moderator temperature transient
 - Containment behaviour
 - Dose



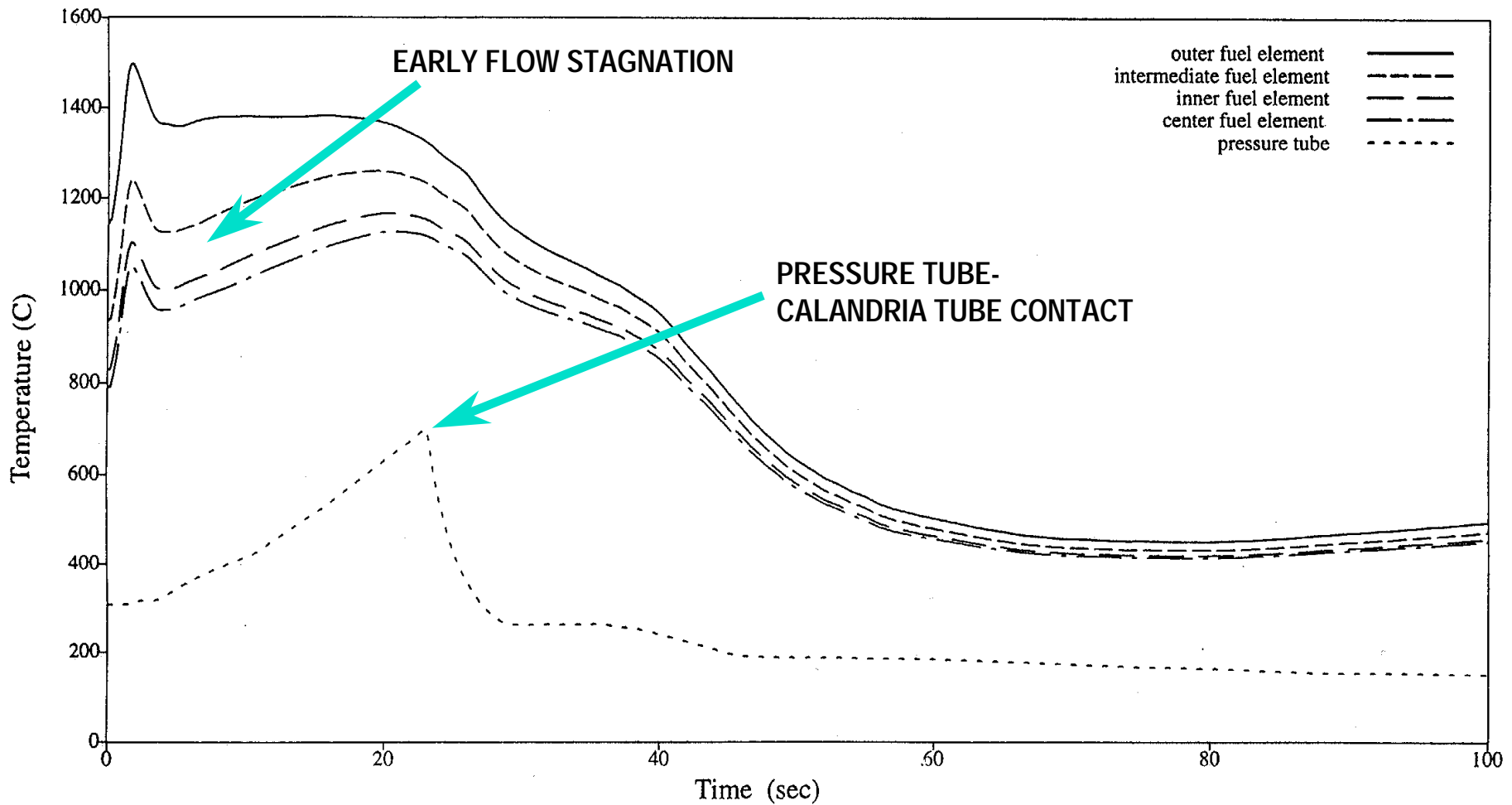
Safety Analysis Methodology

- λ Fuel conditions prior to the onset of the accident
 - Same methodology as LOCA (i.e., core inventory is determined with codes such as ELESTRES)
- λ Transient Temperatures
 - The critical break sizes are used to calculate the thermalhydraulic behaviour for a LOCA/LOECC (CATHENA) during the blowdown phase



CATHENA Temperatures during Blowdown

Phase of Accident (35% RIH; Bundle 7; 7.3 MW channel; critical)



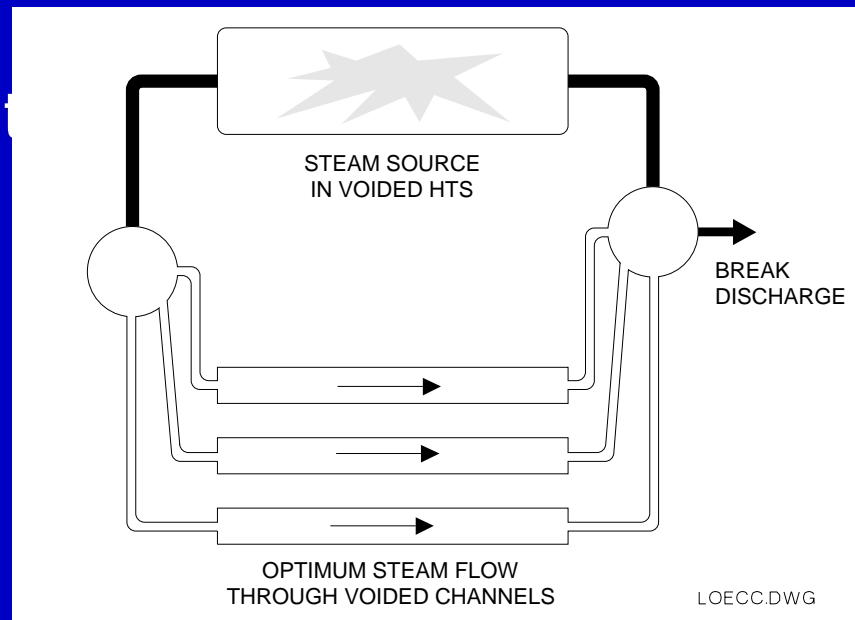
Late Heat up Phase Methodology

- λ Uncertainties in thermalhydraulic conditions (low flow) results in a switch to a parametric analysis (late heat up phase) from the deterministic analysis (blowdown phase)
- λ CHAN-II code accepts CATHENA conditions at the end of blowdown and performs the calculation for the late heat up phase
- λ Steam flowrate is varied parametrically to account for different possible sources of water
- λ Limiting (“critical”) steam flowrate is that which maximizes the fuel temperatures
 - competing effect between the increased convective cooling at high steam flows and
 - insufficient steam to feed the exothermic Zircaloy-steam reaction at low steam flows

★ Sustained Constant Steam Flow in Channel

λ CONSERVATIVE LICENSING ANALYSIS

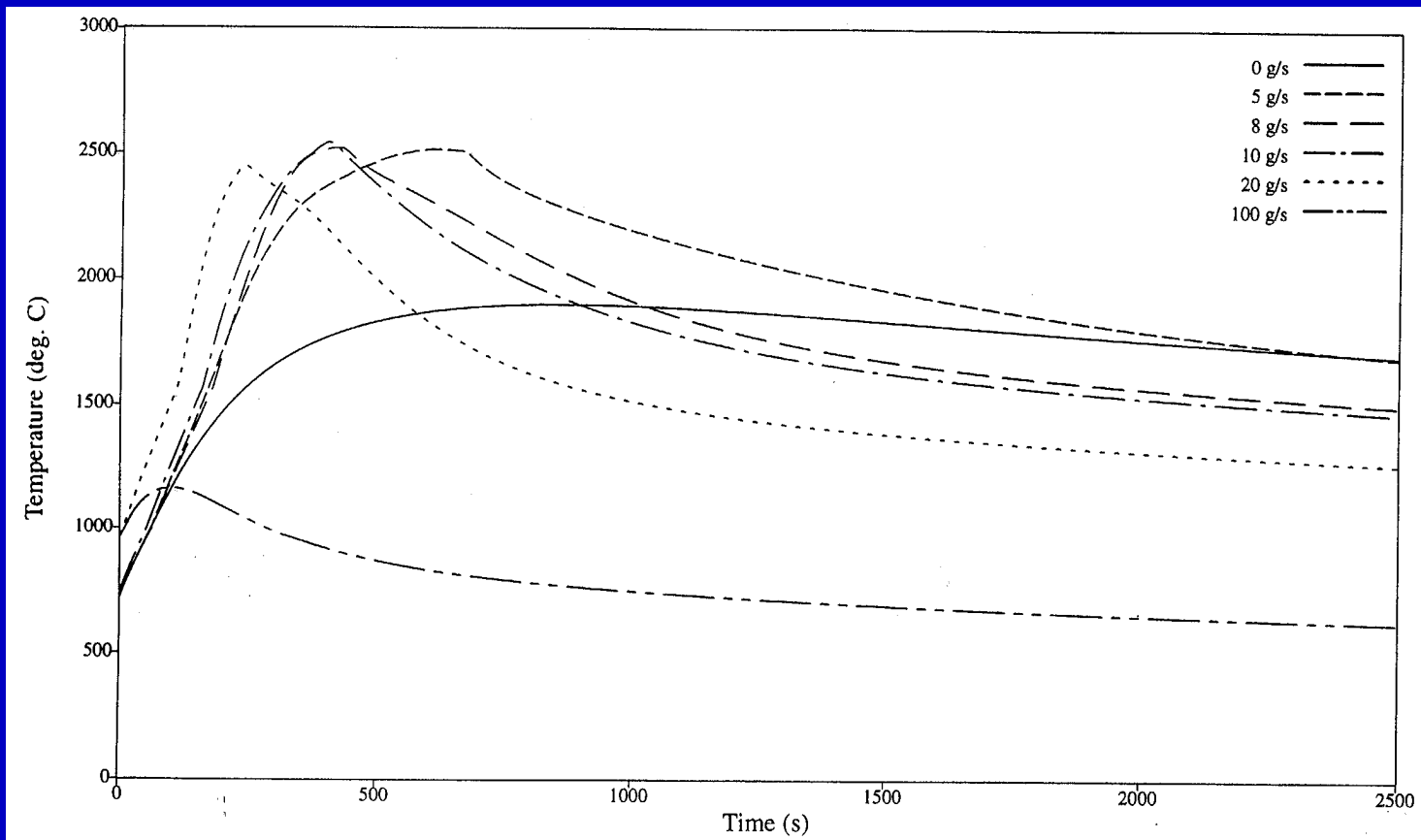
- At low flows (less than 5 g/s) there is too little steam to react
- At higher flows (greater than 20 g/s) the steam removes much of the heat by convective cooling
- Optimum sustained steam flows of 5 to 20 g/s in each channel
- Steaming t



★ CHAN-II Maximum Fuel Temperatures - Various Steam Flows - late heatup phase

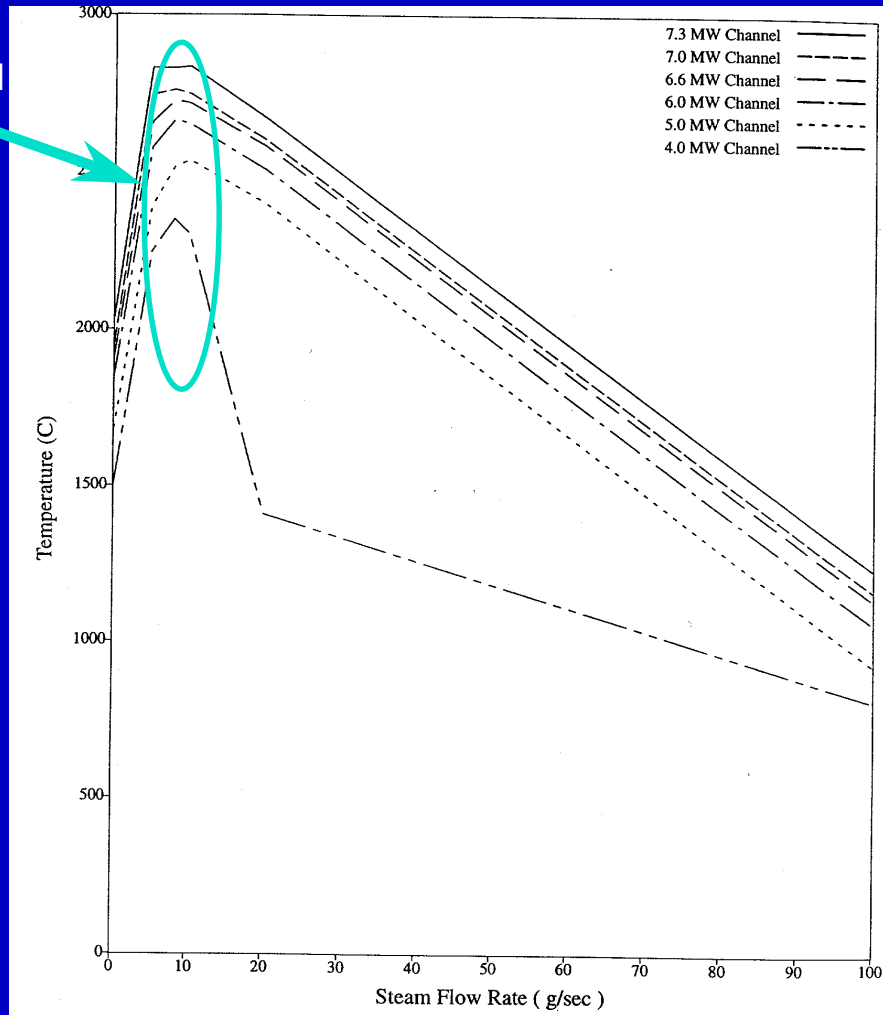
λ 3 STAGES:

1) Initial heatup 2) Exothermic steam-Zircaloy reaction 3) Cooldown to steady-state



★ CHAN-II Maximum Fuel Temperatures Versus Steam Flow

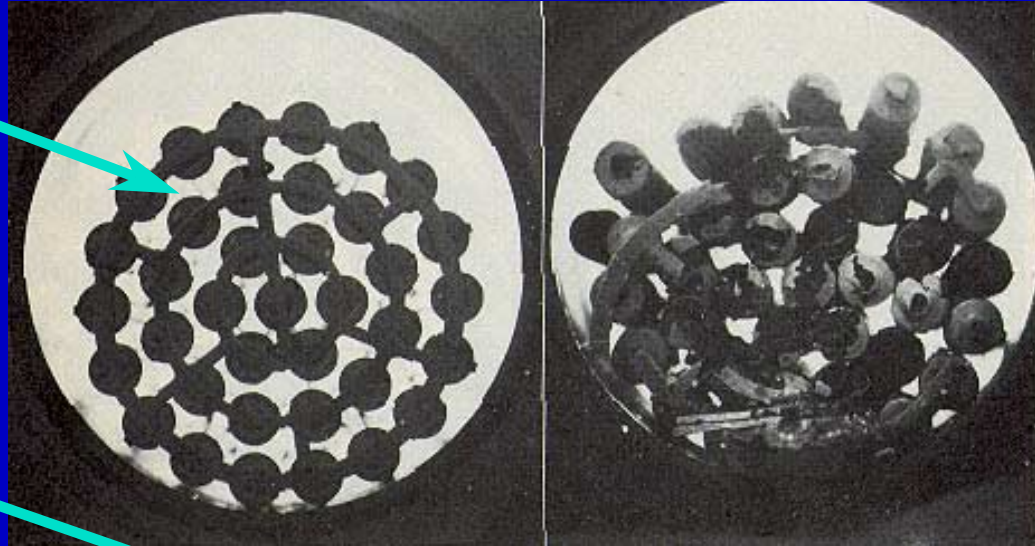
REGION OF CRITICAL STEAM



★ High-Temperature Fuel Bundle Deformation

Pre-Test Configuration (radial) Post-Test Configuration (radial)

37-ELEMENT
BUNDLE



Post-Test
Configuration (axial)





Pressure Tube Behaviour

- λ **BLOWDOWN PHASE:** Under high channel pressures and elevated pressure tube temperatures, the pressure tube may balloon (strain) into contact with the surrounding calandria tube
- λ **LATE HEAT UP PHASE:** Under low channel pressures and elevated pressure tube temperatures, the pressure tube may sag into contact with the surrounding calandria tube
- λ This contact results in a heat flux from the hot pressure tube through the contacting cool calandria tube then to the surrounding moderator
- λ Provided dryout on the outer surface of the calandria tube is precluded, the pressure tube temperature will decrease and the calandria tube temperature will increase (heat rejected to the moderator; acts as a heat sink)

☆ Pressure Tube-Calandria Tube Ballooning

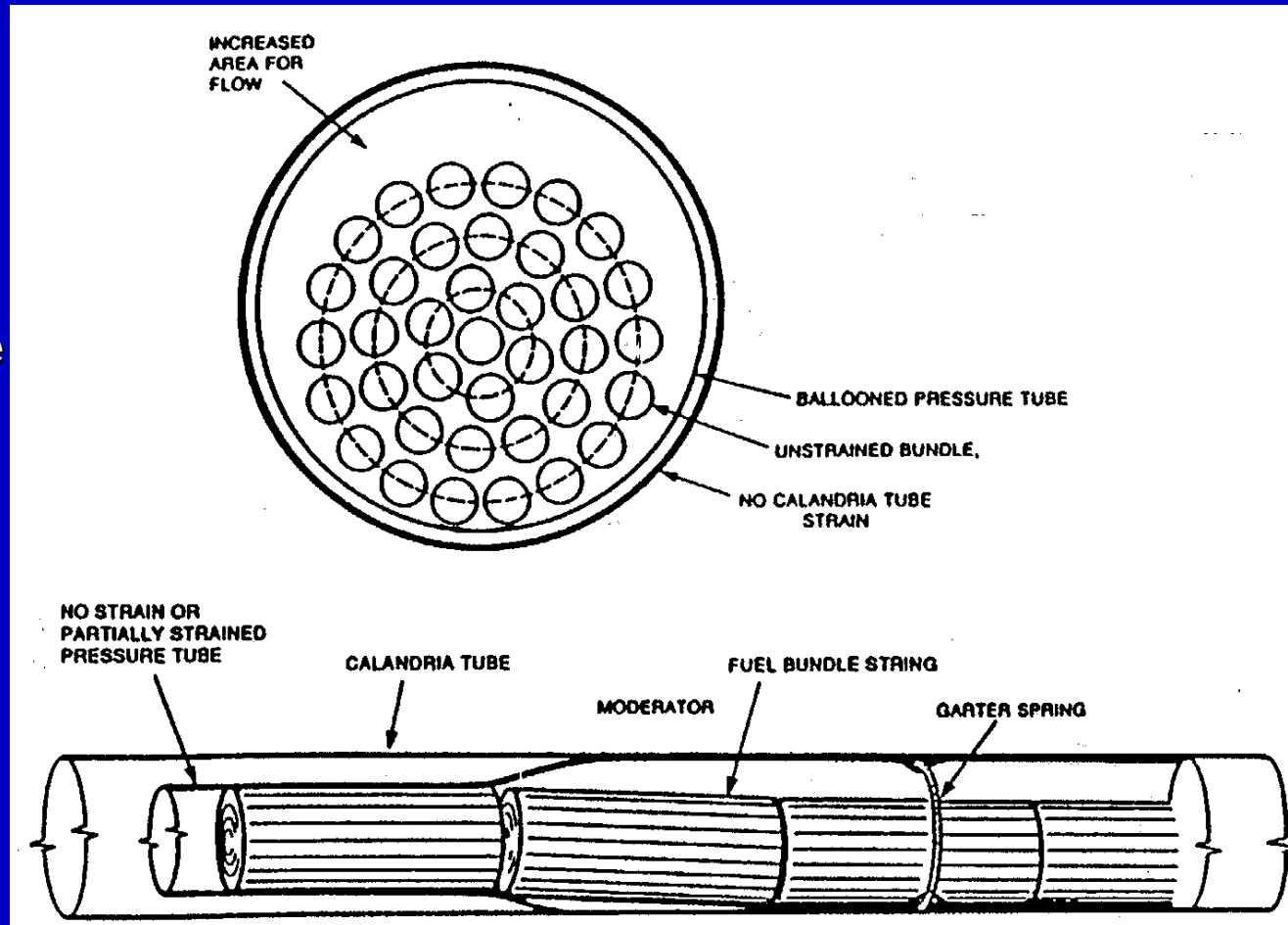
λ During the **blowdown** phase of a LOCA/LOECC, some channels will have:

- high pressure tube temperature, in conjunction with
- high channel pressure

λ This results in uniform pressure tube straining (ballooning)

λ Following PT/CT contact,

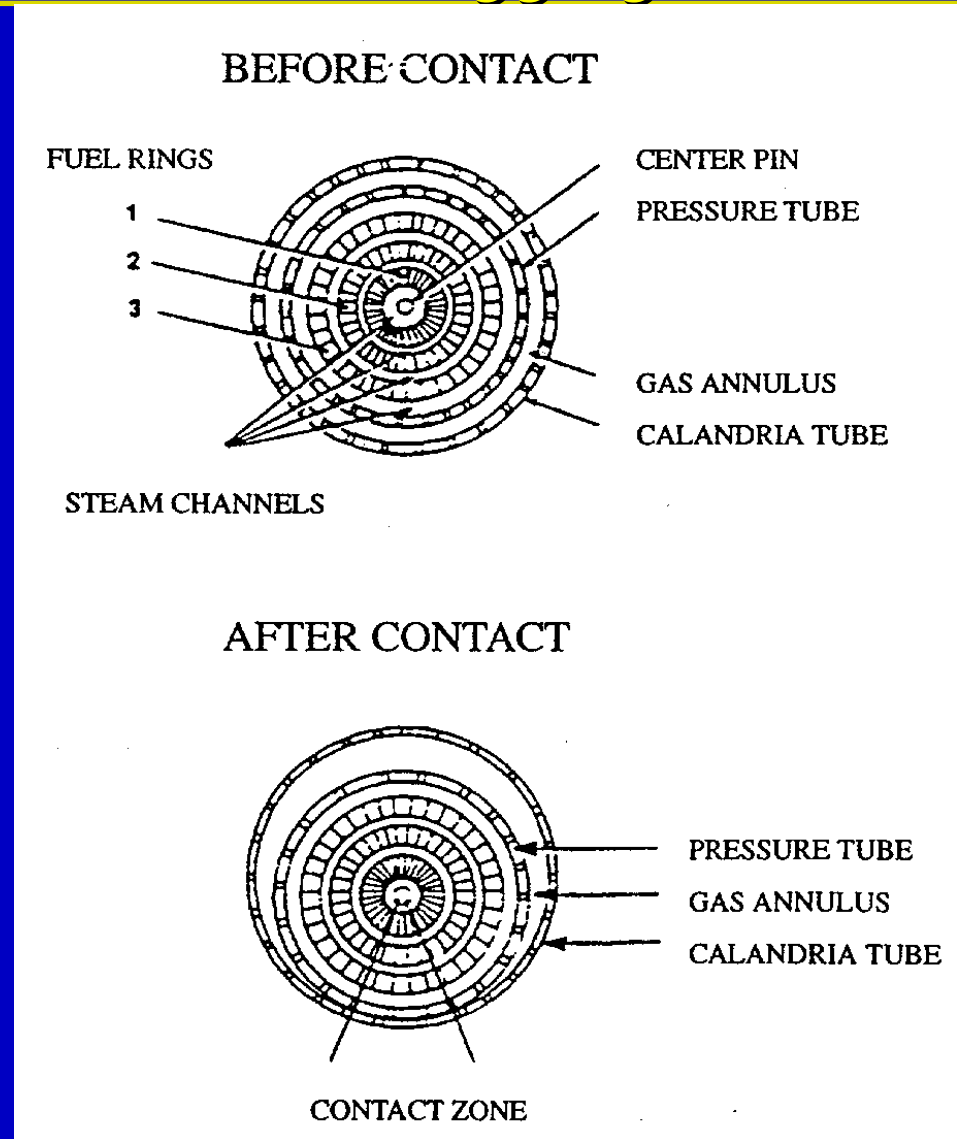
- good heat transfer through PT and CT to moderator
- PT temperature decreases



☆ Pressure Tube-Calandria Tube Sagging

Contact

- λ During the late heatup phase of a LOCA/LOECC, some channels will have:
 - high pressure tube temperature
- λ Under the low channel pressure,
 - the pressure tube will sag into contact with the calandria tube
- λ Following PT/CT sagging contact,
 - good heat transfer through the contacting portion of the PT and CT, and to the moderator
 - PT temperature decreases



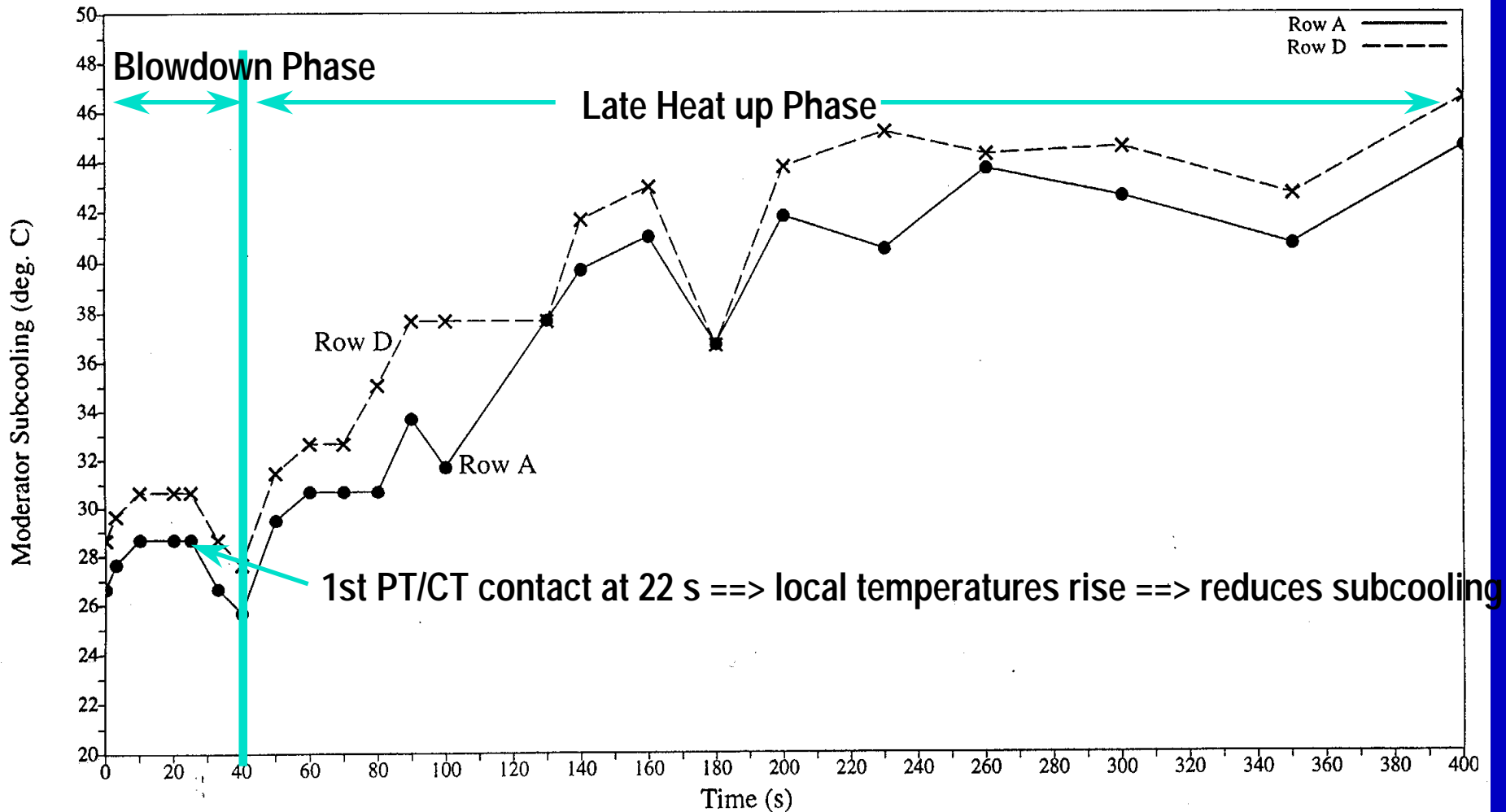


Moderator Subcooling

- λ The maximum initial moderator local temperature, as calculated by the 3D PHOENICS code, is 81°C.
- λ The available subcooling (i.e, defined as saturation temperature subtract local temperature) at the start of the transient for the top channel rows is 27°C to 29°C
- λ As heat is rejected to the moderator through the contacting pressure tubes and calandria tubes, the local temperatures increase and reduce the moderator subcooling to a minimum of 26°C at approximately 40 s after the accident
- λ There is adequate cooling to ensure that channel integrity is not compromised



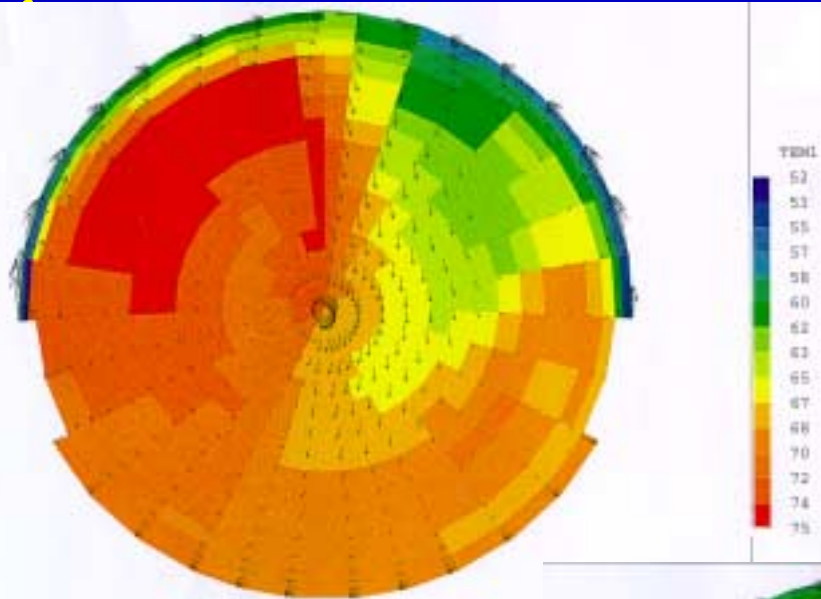
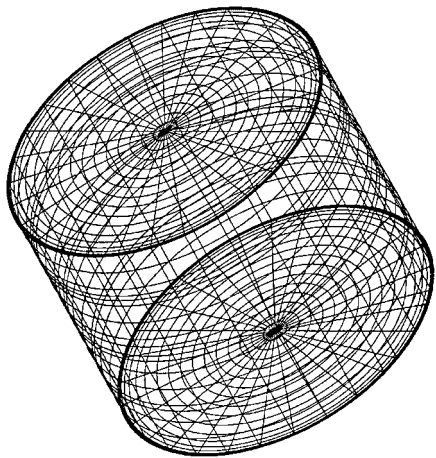
Moderator Subcooling During LOCA/LOECC



PHOENICS 3D Moderator Temperature

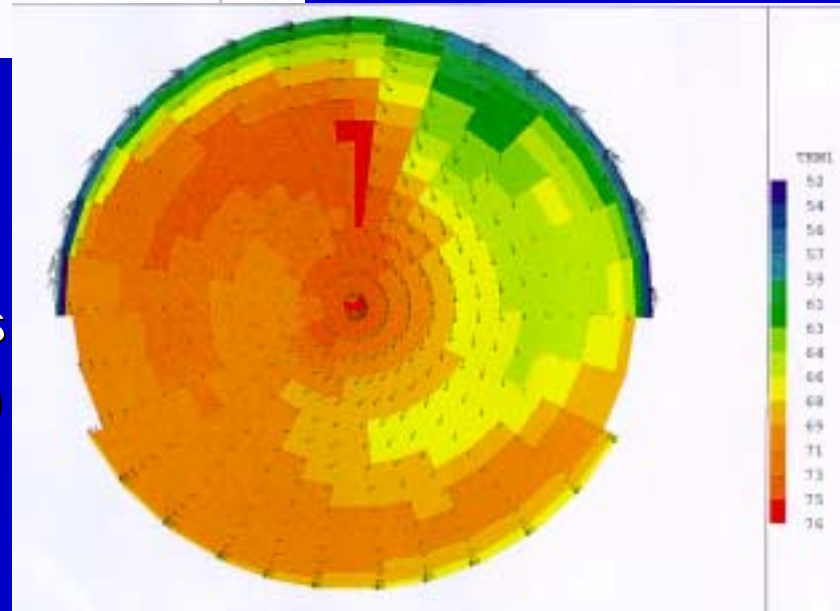
Moderator Grid

Distribu



Steady-State
(near axial midplane)

LOCA/LOECC at 40 s
(near axial midplane)



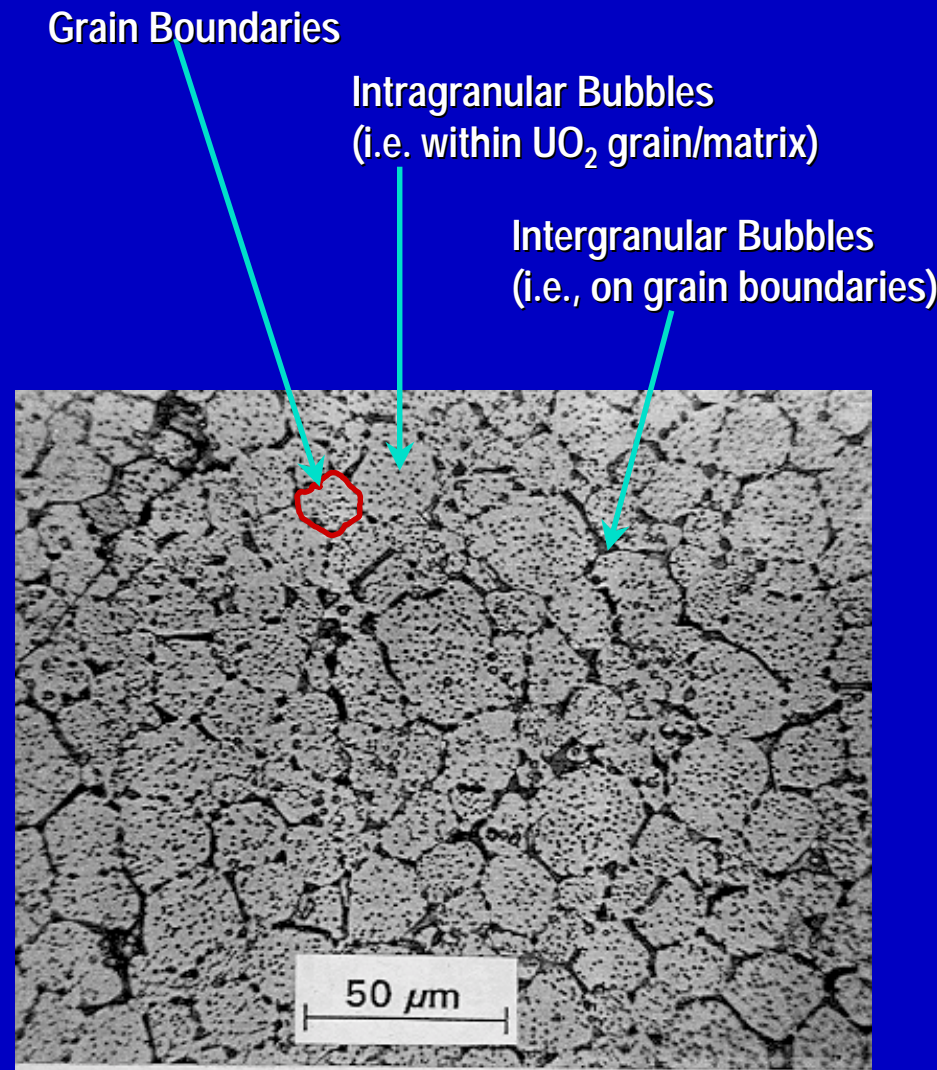


Fission Product Release

- λ Some dominant release mechanisms at high temperatures:
 - Diffusion of grain bound fission product inventory (i.e., intergranular inventory)
 - Enhanced diffusion due to fuel oxidation and/or fuel reduction
 - Zircaloy/ UO_2 chemical interaction
- λ Fission Product Retention in Heat Transport System
 - large surface area in primary heat transport system (for example, end-fitting, feeders) for fission product deposition
 - The retention of fission products in the system are currently not credited in the analysis; however, plan to credit in future

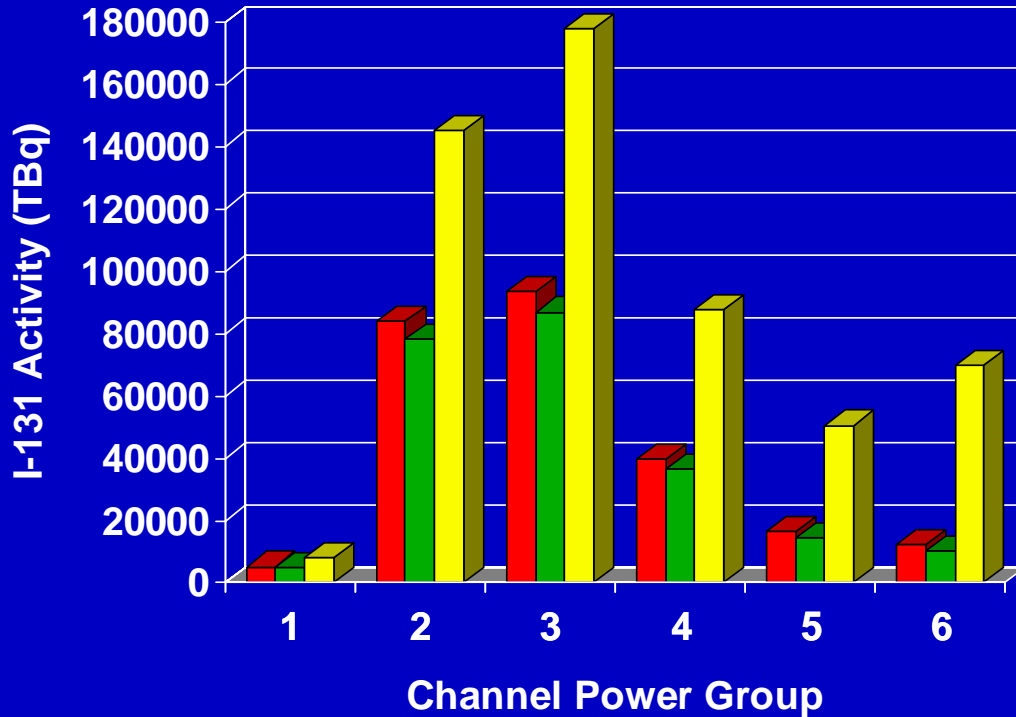
Fission Product Release

- λ Experiment performed at AECL Chalk River Lab
- λ Insert Bruce reactor fuel type into furnace; hold at 1550°C and exposed to steam environment over long period of time (2.5 hours)
- λ Small intragranular bubbles
- λ Grain boundaries almost completely outlined with intergranular bubbles
- λ Result: large percentage of measured fission products (i.e., cesium) released





Fission Product Release Results



■ Total Release from Critical Pass
■ Total Release from Non-Critical Pass
■ Total Inventory in EACH Pass

Channel Group	Power Range (MW)	Number of Channels in Core
1	7.0 to 7.3	5 (1.3%)
2	6.6 to 7.0	88 (23.2%)
3	6.0 to 6.6	111 (29.2%)
4	5.0 to 6.0	62 (16.3%)
5	4.9 to 5.0	42 (11%)
6	0.0 to 4.0	72 (18%)



Hydrogen Generation and Containment Analysis

- λ At the elevated temperatures, hydrogen is produced from the steam-Zircaloy reaction (reaction with sheaths and pressure tubes) and discharged through break into containment
- λ Containment Analysis
 - Objectives:
 - λ evaluate the peak pressure in containment
 - λ assess hydrogen concentration and distribution inside containment
 - λ determine radionuclide releases to environment for dose calculations

Containment Behaviour

- λ Peak Pressure of 83 kPa (g) is below design pressure of 124 kPa (g)
- λ The peak hydrogen concentration remains below the acceptance limit.

