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

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Overview

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

LOCA with ECC Unavailable

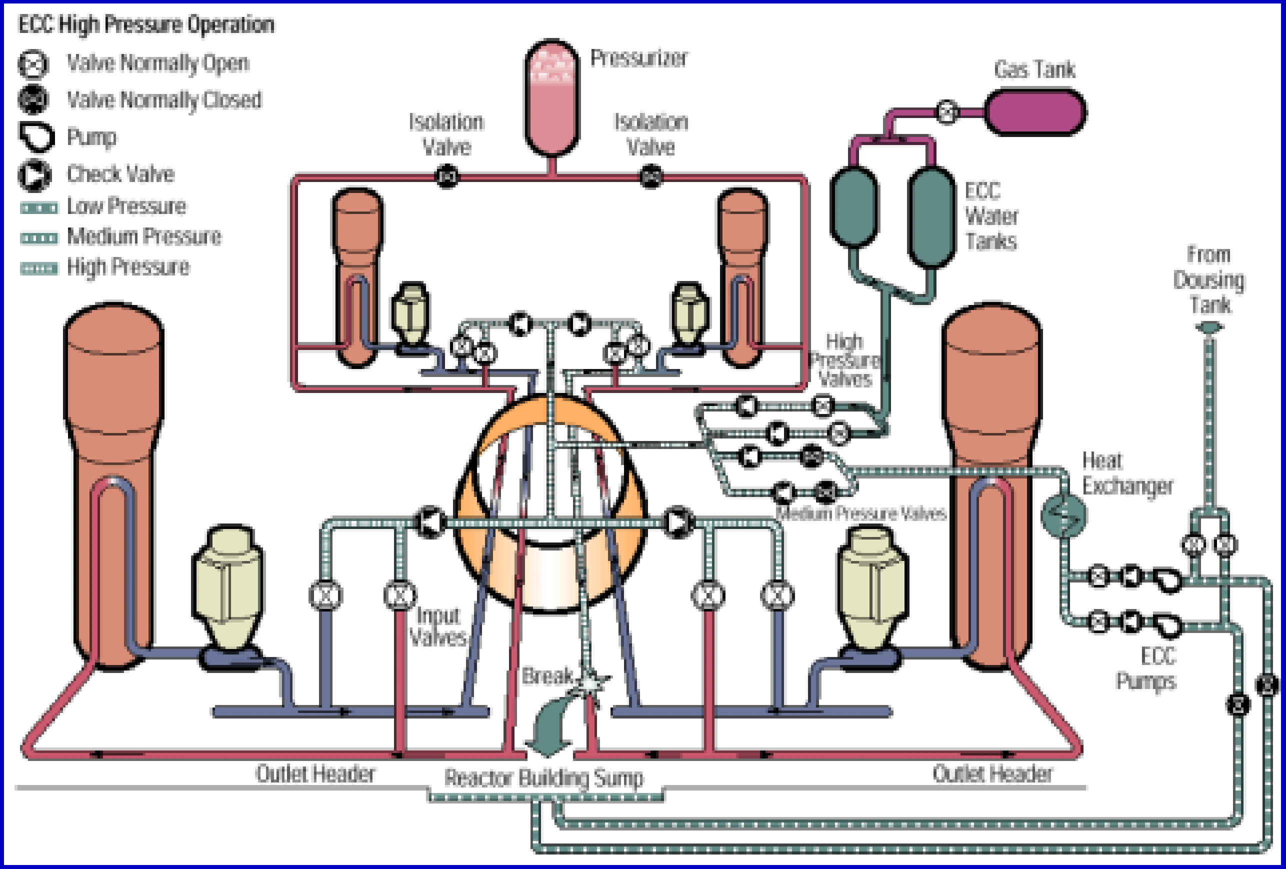
- **During a loss-of-coolant accident with coincident loss of emergency core cooling, the accident can be divided into two separate phases**
  - ***Blowdown phase***
    - **event sequence is similar to a loss-of-coolant accident**
  - ***Late heat up phase***
    - **reactor core does not receive cooling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

Event Sequence for Blowdown Phase

- **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**

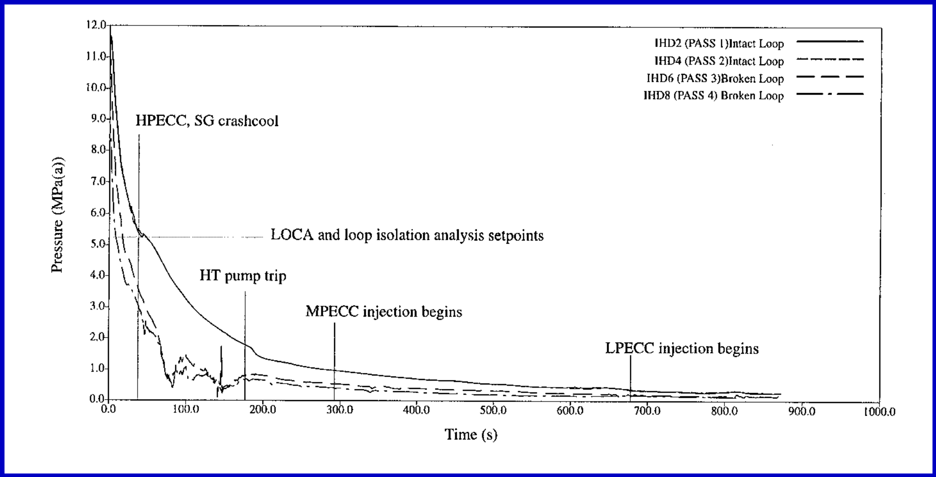
Emergency Core Cooling System

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

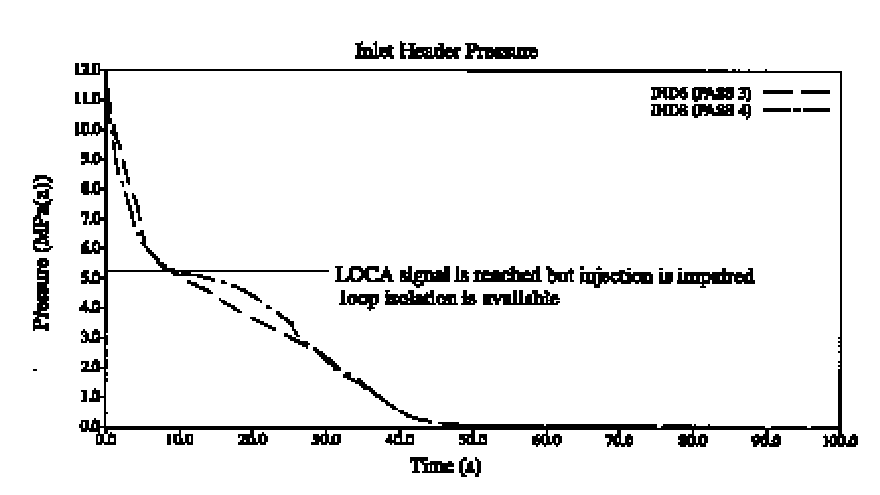


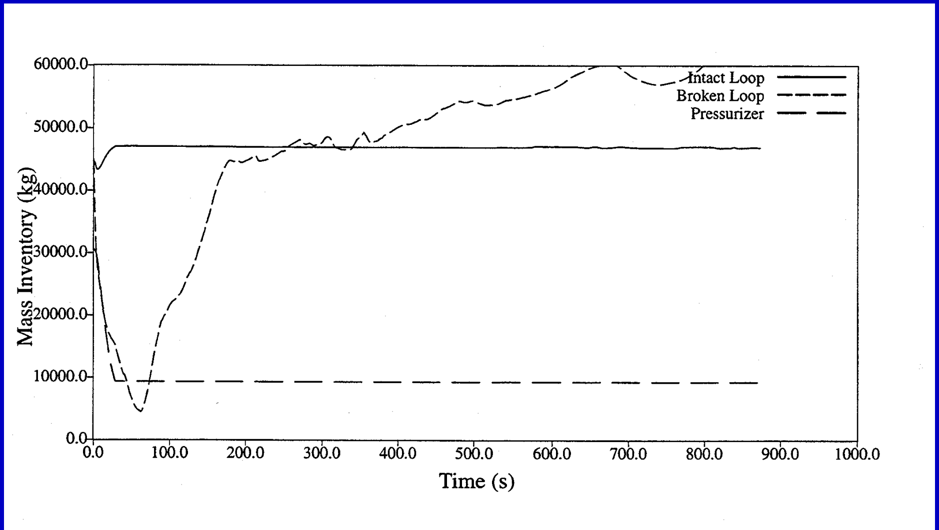
Header Depressurization Transient

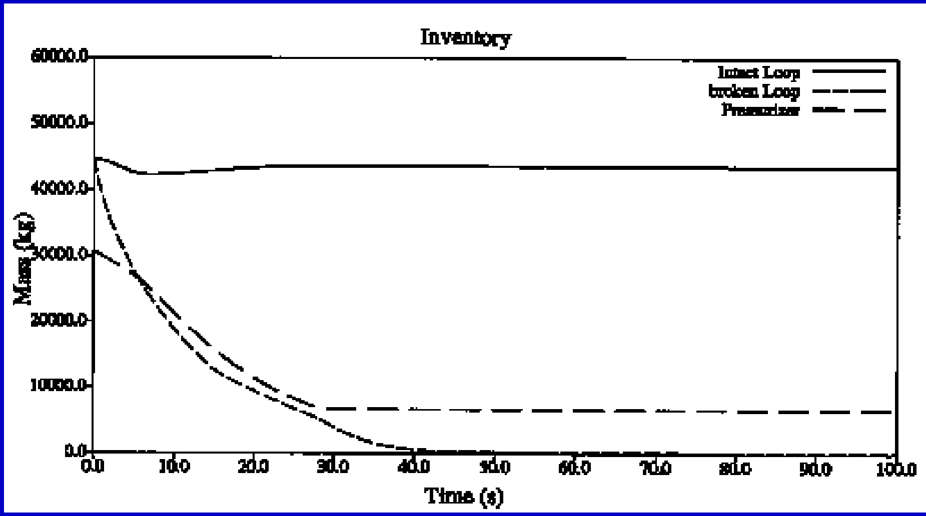
LOCA with ECC Injection



LOCA without ECC Injection







Event Sequence for Late Heatup Phase

- Degraded cooling conditions in channel while the fuel is at decay power results in severe overheating of the fuel
- High temperature fuel results in a considerable exothermic chemical reaction between the Zircaloy and the steam in the channels

$$Zr + 2H_2O \Longrightarrow ZrO_2 + 2H_2 + HEAT$$

- Pressure tubes heat up to the point where they sag or radially strain into contact with calandria tubes
- The type of pressure tube-calandria tube contact affects the heat rejected to moderator
- Moderator is a heat sink
- Fission product releases to containment are large; however, the doses to the public are within AECB guidelines

Analysis Acceptance Criteria

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

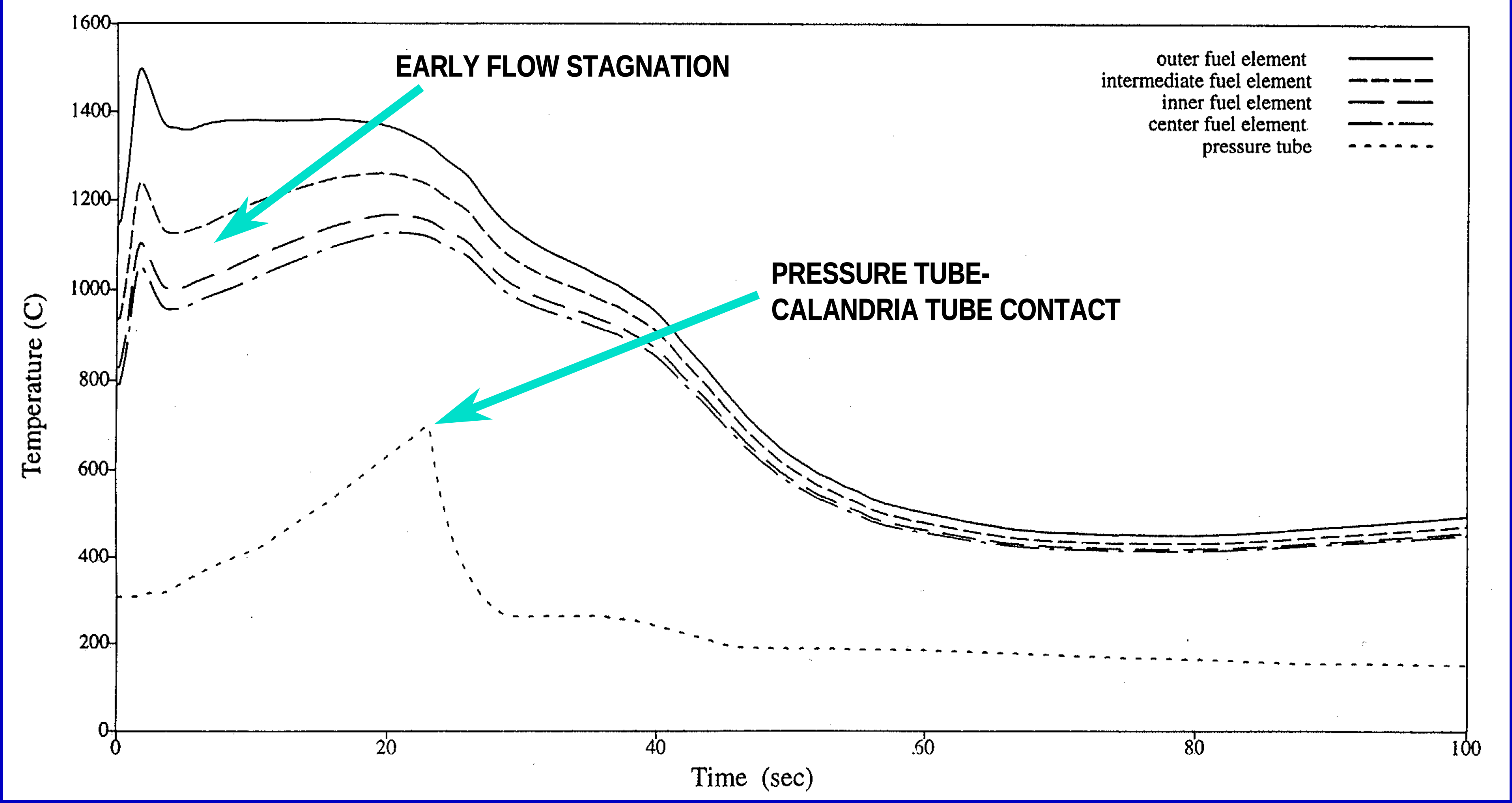
LOCA/LOECC Safety Analysis

- **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

- Fuel conditions prior to the onset of the accident
  - Same methodology as LOCA (i.e., core inventory is determined with codes such as ELESTRES)
- 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

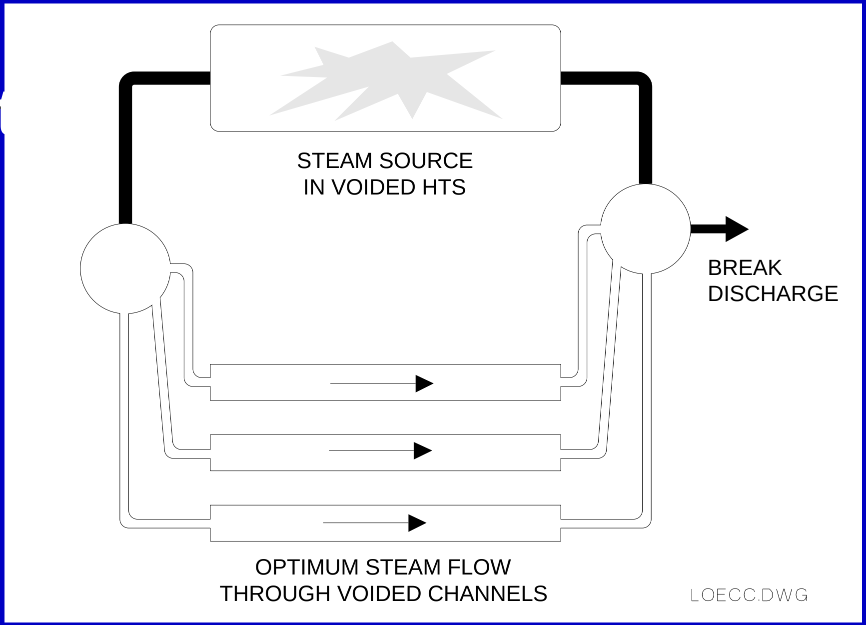


Late Heat up Phase Methodology

- Uncertainties in thermalhydraulic conditions (low flow) results in a switch to a parametric analysis (late heat up phase) from the deterministic analysis (blowdown phase)
- CHAN-II code accepts CATHENA conditions at the end of blowdown and performs the calculation for the late heat up phase
- Steam flowrate is varied parametrically to account for different possible sources of water
- 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

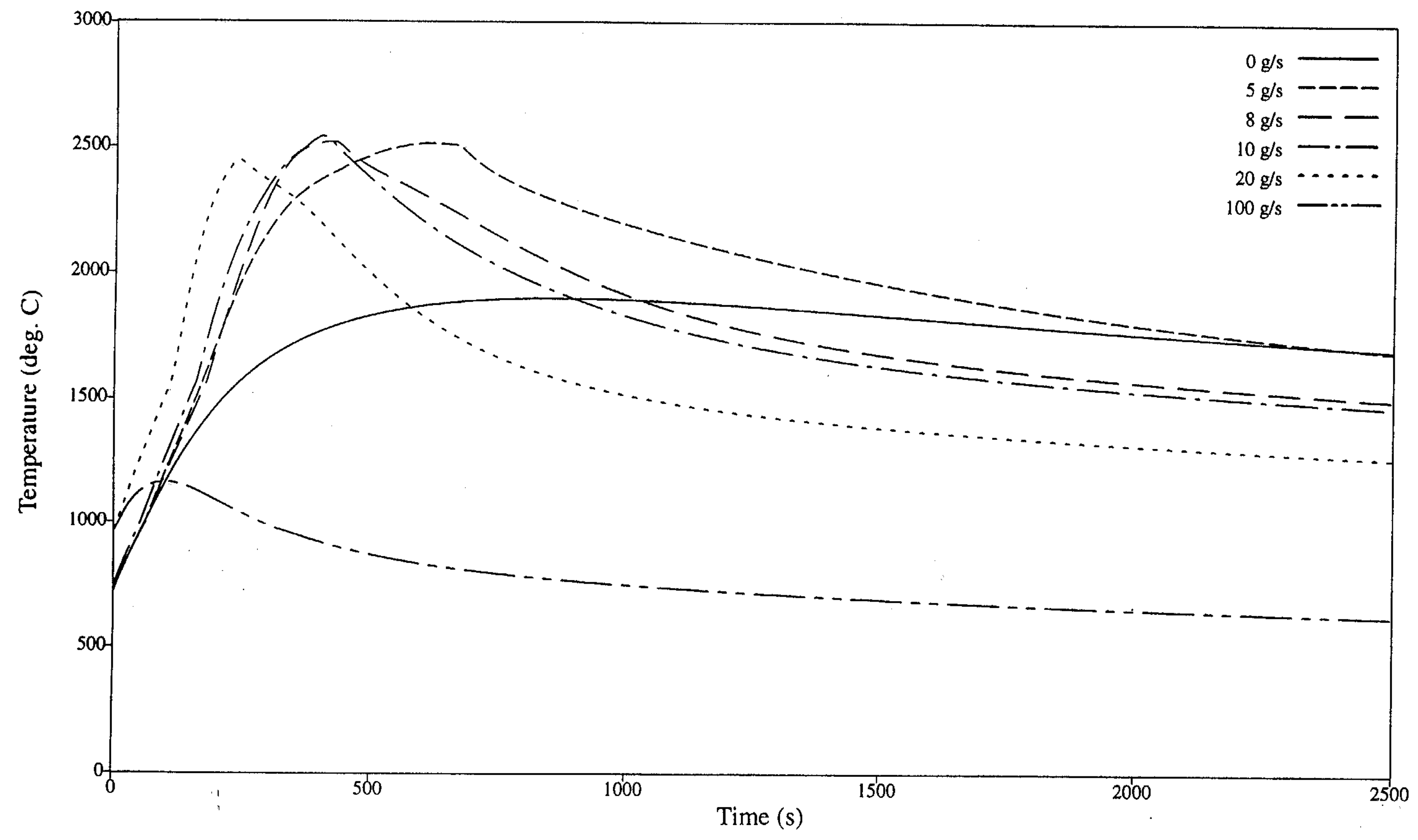
- CONSERVATIVE LICENSING ANALYSIS
  - At low flows (less than 5 g/s) there is too little steam to react
  - At higher flows (greater than 20 g/s) the steam removes much of the heat by convective cooling
  - Optimum sustained steam flows of 5 to 20 g/s in each channel
  - Steaming t



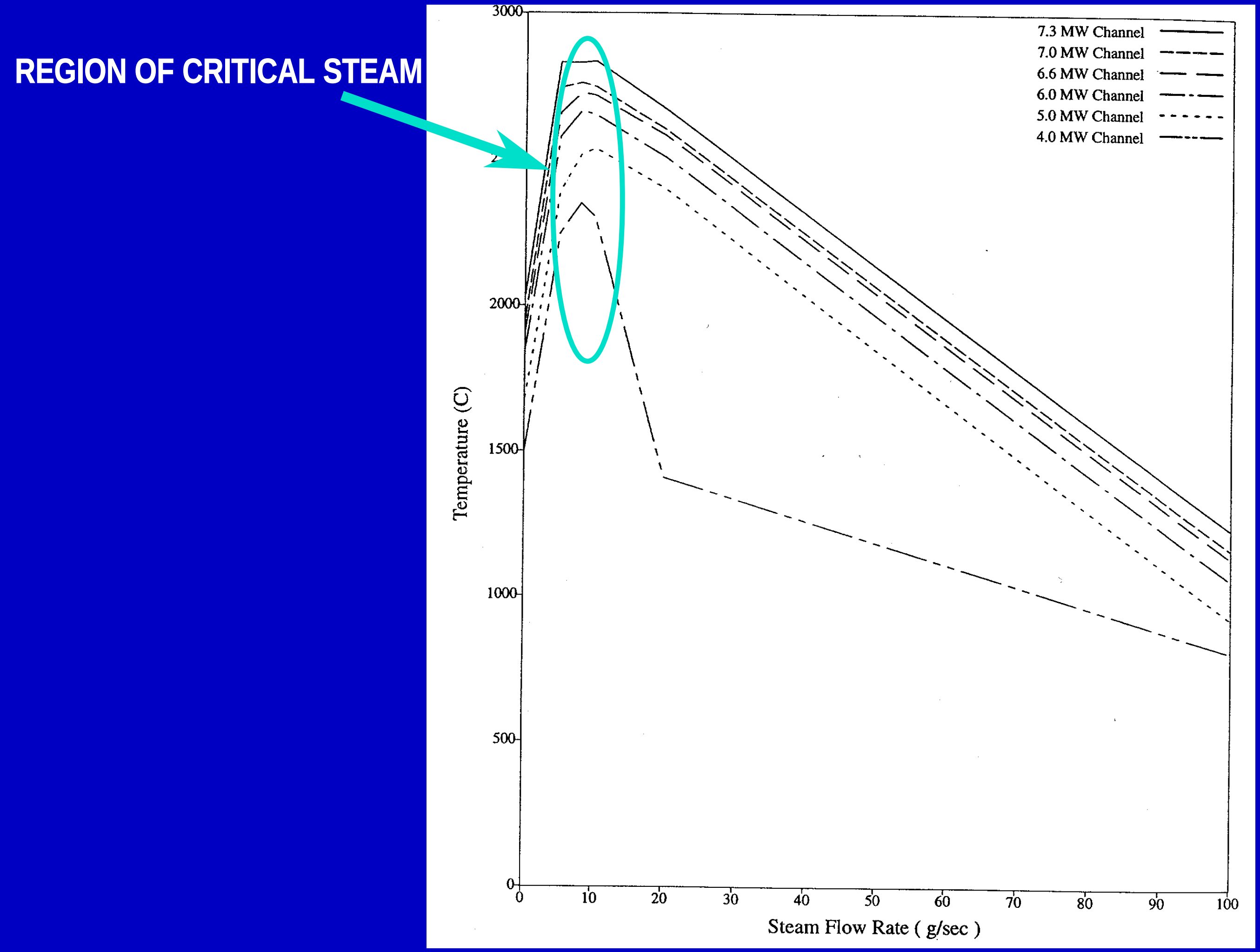
CHAN-II Maximum Fuel Temperatures -Various Steam Flows - late heatup phase

- **3 STAGES:**

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



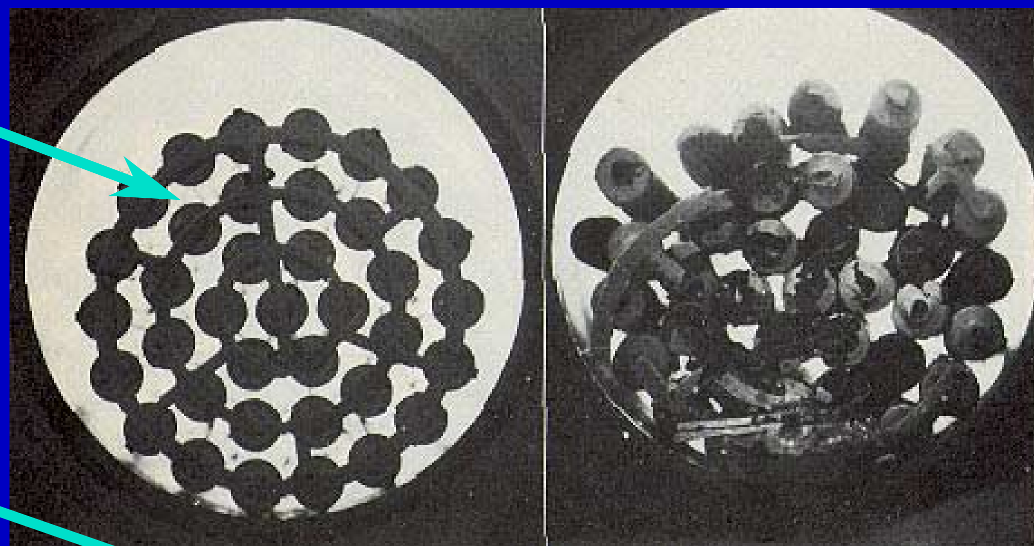
CHAN-II Maximum Fuel Temperatures Versus Steam Flow



High-Temperature Fuel Bundle Deformation

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

37-ELEMENT BUNDLE



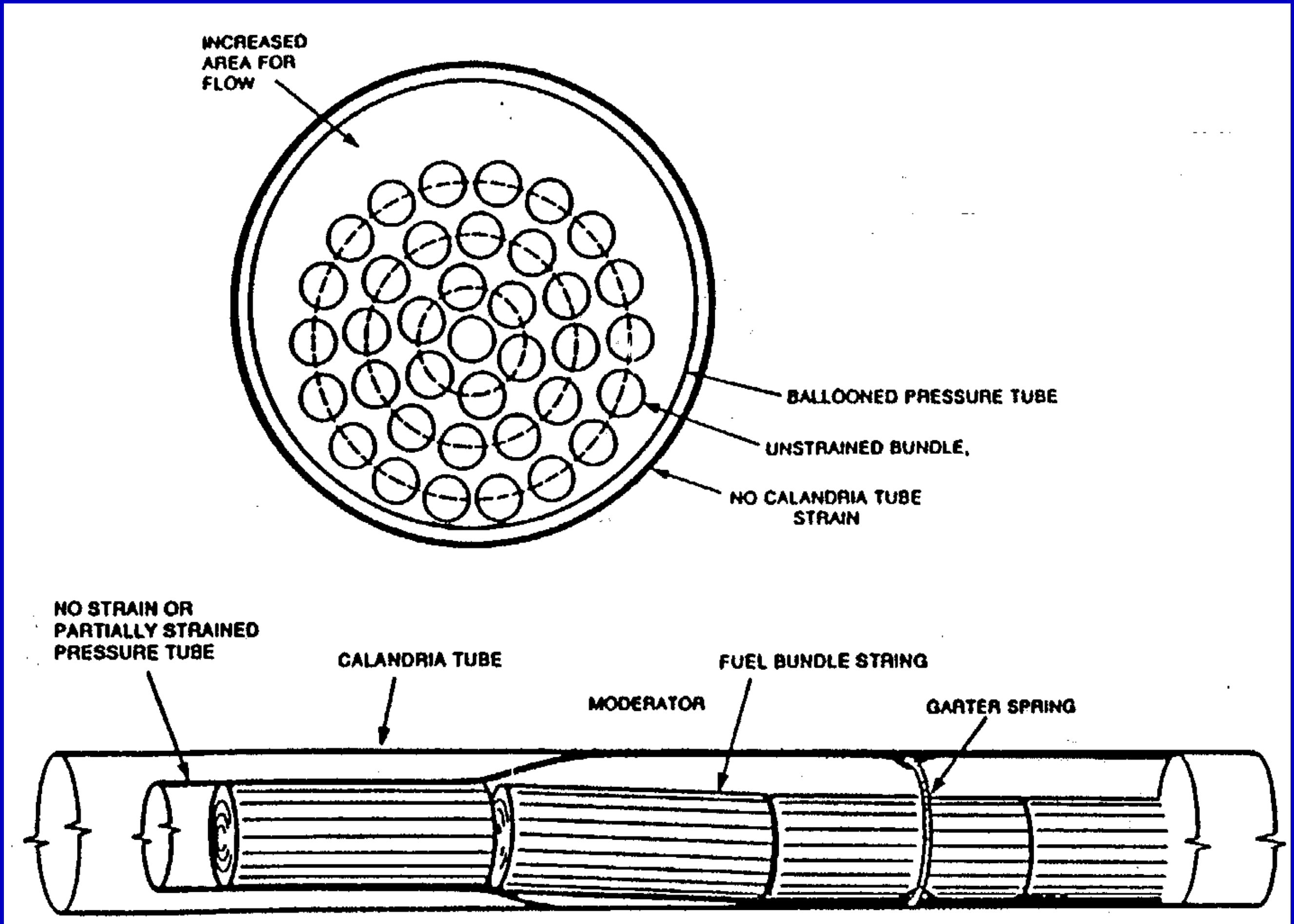
Post-Test Configuration (axial)

Pressure Tube Behaviour

- **BLOWDOWN PHASE: Under high channel pressures and elevated pressure tube temperatures, the pressure tube may balloon (strain) into contact with the surrounding calandria tube**
- **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**
- **This contact results in a heat flux from the hot pressure tube through the contacting cool calandria tube then to the surrounding moderator**
- **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)**

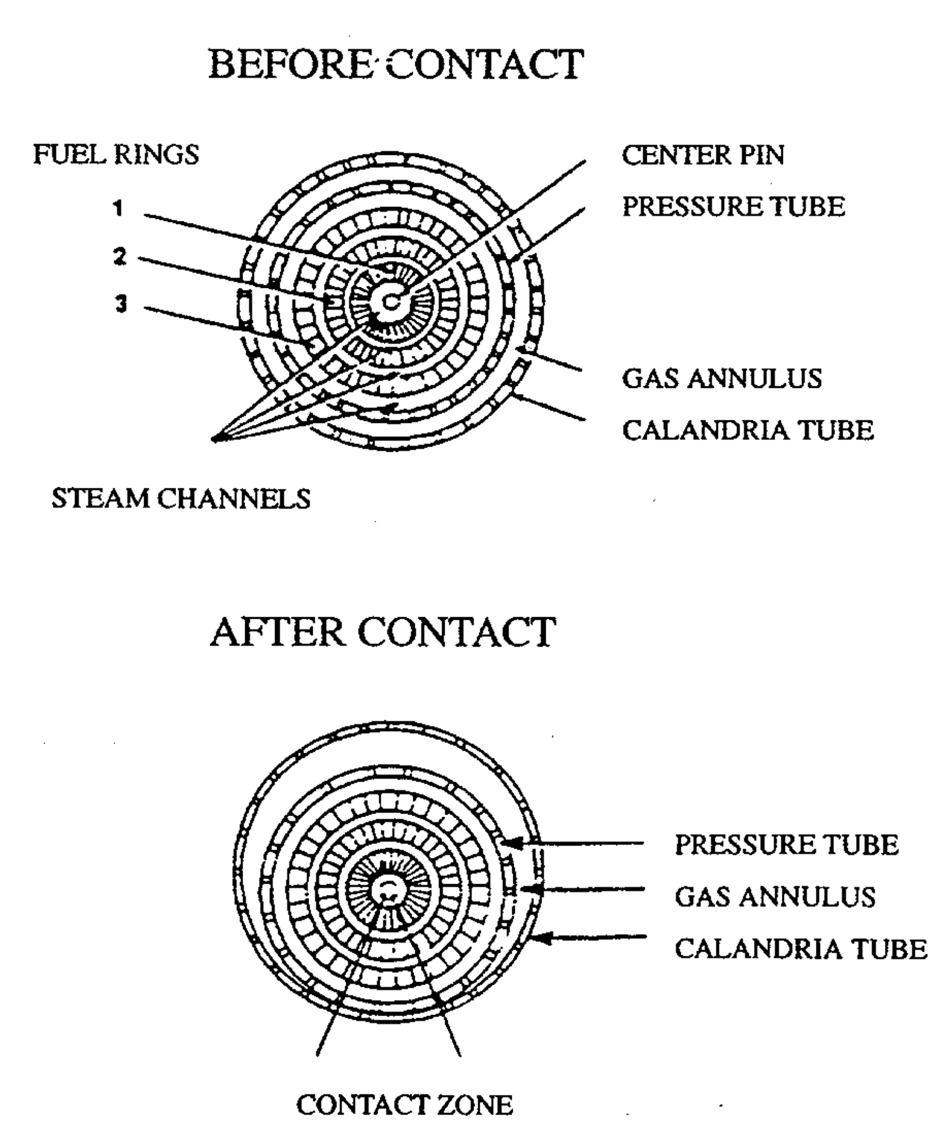
Pressure Tube-Calandria Tube Ballooning Contact

- During the blowdown phase of a LOCA/LOECC, some channels will have:
  - high pressure tube temperature, in conjunction with
  - high channel pressure
- This results in uniform pressure tube straining (ballooning)
- Following PT/CT contact,
  - good heat transfer through PT and CT to moderator
  - PT temperature decreases



Pressure Tube-Calandria Tube Sagging Contact

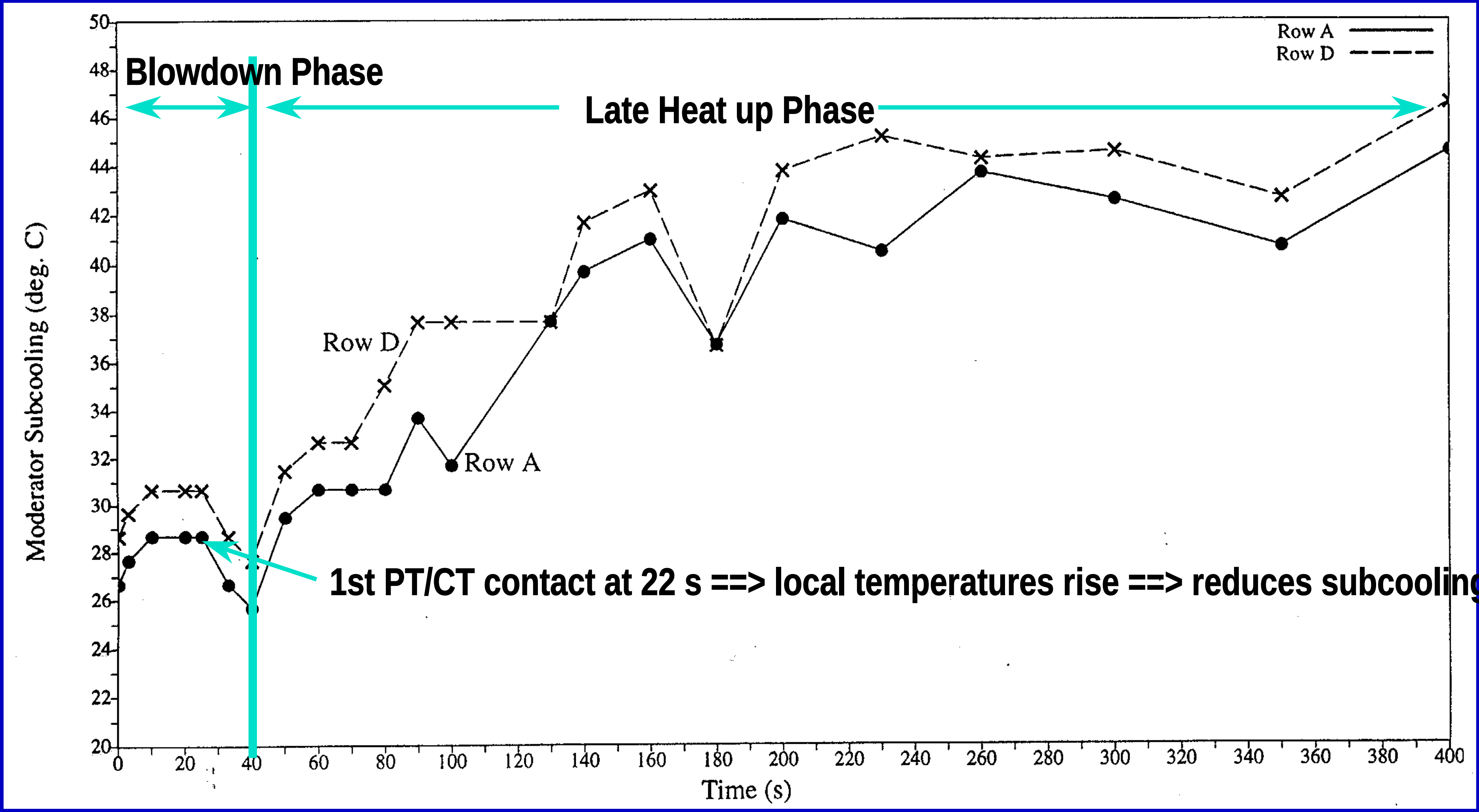
- During the late heatup phase of a LOCA/LOECC, some channels will have:
  - high pressure tube temperature
- Under the low channel pressure,
  - the pressure tube will sag into contact with the calandria tube
- Following PT/CT sagging contact,
  - good heat transfer through the contacting portion of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



Moderator Subcooling

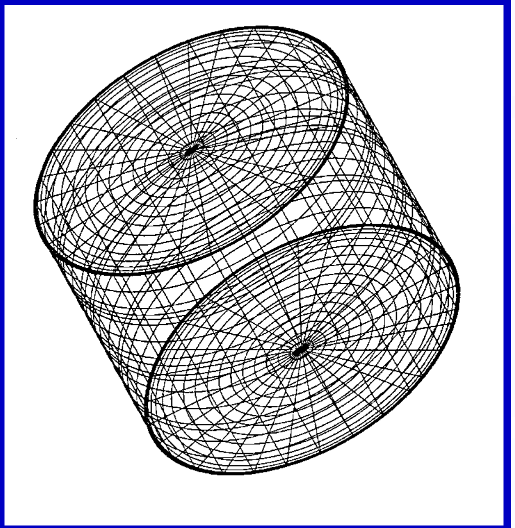
- **The maximum initial moderator local temperature, as calculated by the 3D PHOENICS code, is 81^{o}C.**
- **The available subcooling (i.e, defined as saturation temperature subtract local temperature) at the start of the transient for the top channel rows is 27^{o}C to 29^{o}C**
- **As heat is rejected 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^{o}C at approximately 40 s after the accident**
- **There is adequate cooling to ensure that channel integrity is not compromised**

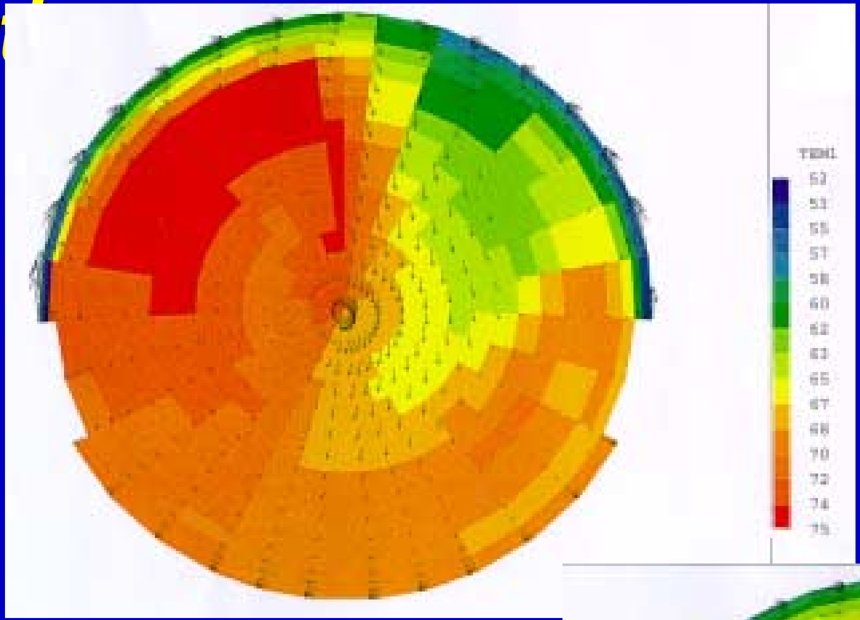
Moderator Subcooling During LOCA/LOECC



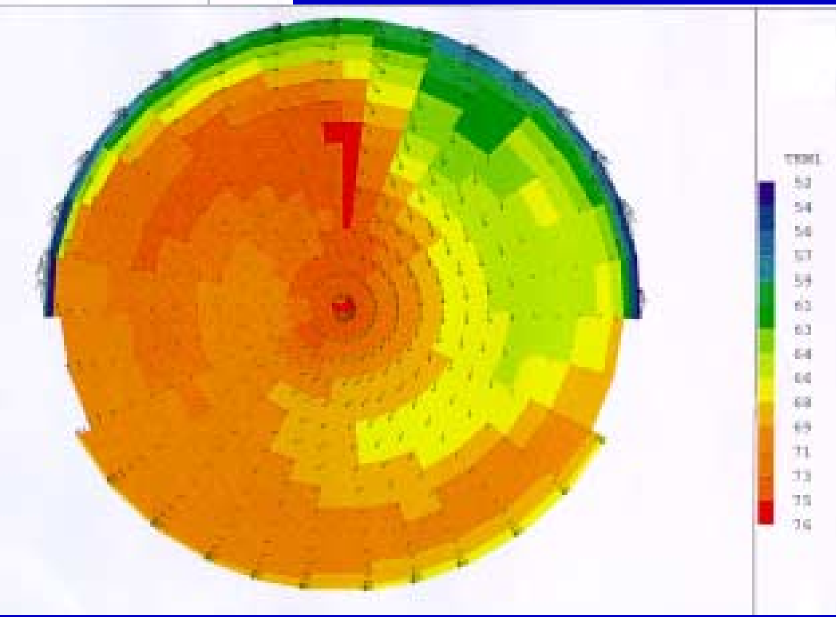
PHOENICS 3D Moderator Temperature Distribut

Moderator Grid





Steady-State
(near axial midplane)



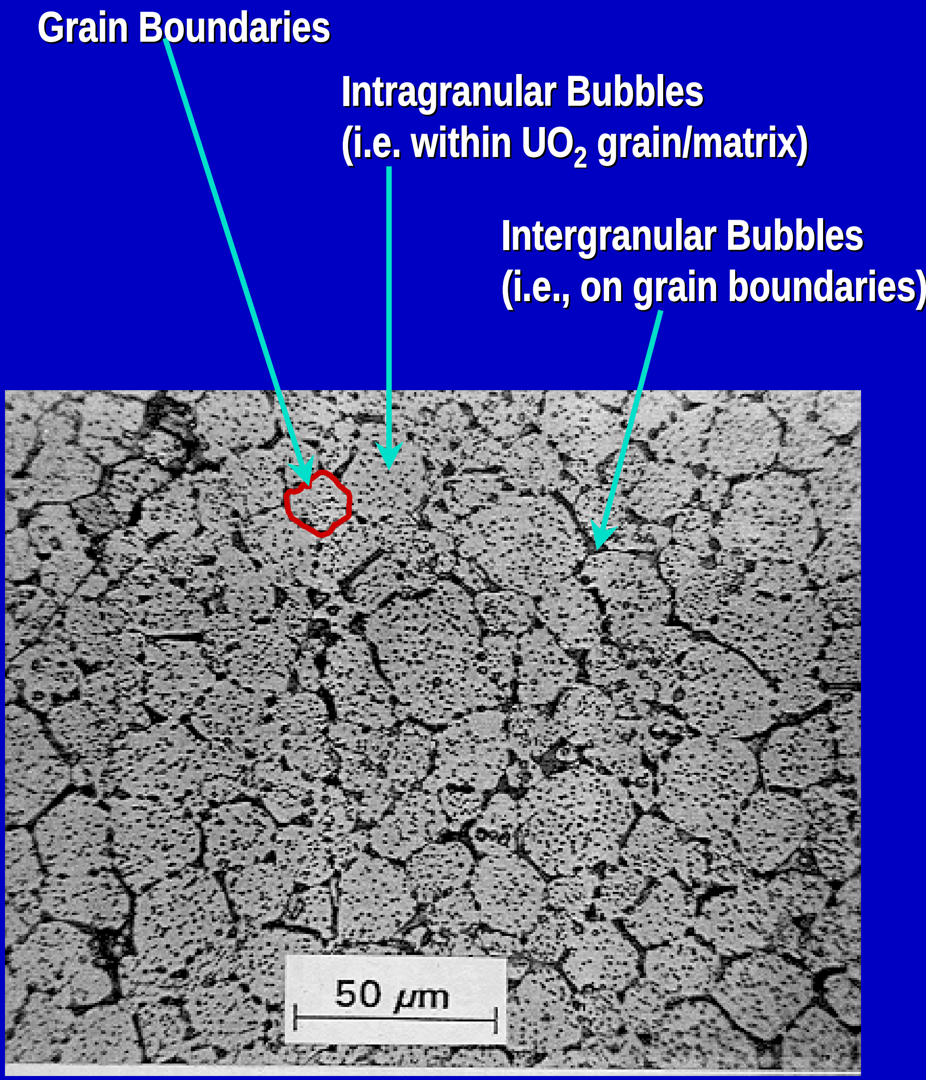
LOCA/LOECC at 40 s
(near axial midplane)

Fission Product Release

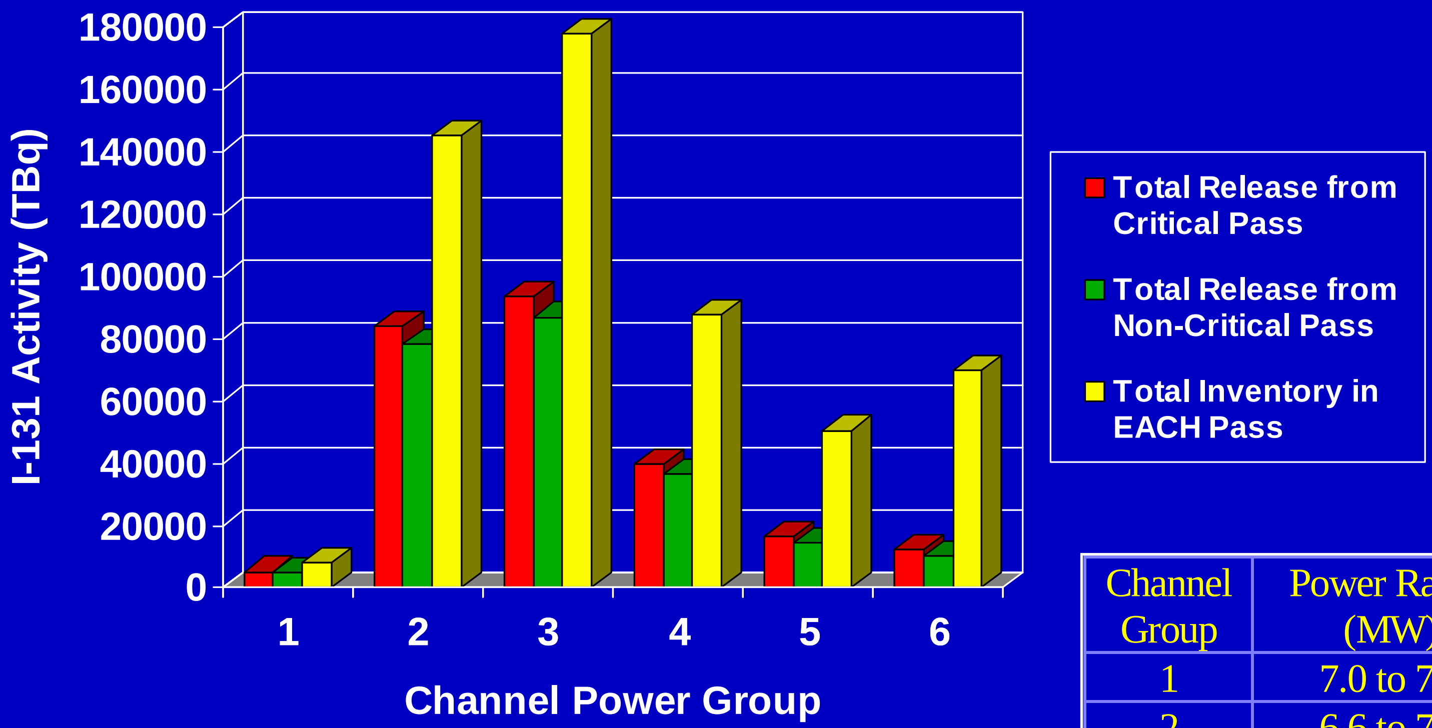
- Some dominant release mechanisms at high temperatures:
  - Diffusion of grain bound fission product inventory (i.e., intergranular inventory)
  - Enhanced diffusion due to fuel oxidation and/or fuel reduction
  - Zircaloy/UO_2 chemical interaction
- Fission Product Retention in Heat Transport System
  - 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

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



Fission Product Release Results



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

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

Containment Behaviour

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