UNENE Graduate Course
Reactor Thermal-Hydraulics Design and Analysis

McMaster University

Whitby

March 19-21, April 23-25, May 2, 2004

T-H Analysis

Dr Nik Popov

Outline

- Large LOCA
- Large LOCA with Loss of ECC
- Single Channel Events

Large LOCA: Importance of LOCA

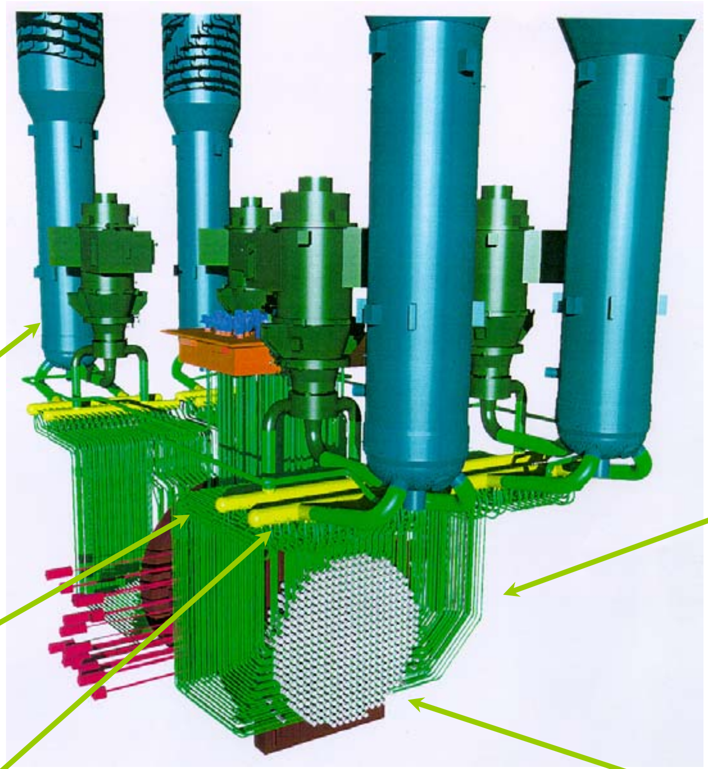
- Key event in plant safety assessment
- Sets most design requirements of safety systems
- Tests integrated performance of shutdown, emergency core cooling and containment systems
- Makes up majority of Category A.1 events

Large LOCA: Primary Heat Transport System

Postulated Break Locations

Steam Generators

PHT Pumps



Feeders

1) Pump Suction

2) Inlet Header

3) Outlet Header

Reactor Fuel Channels

Large LOCA: LOCA Definitions

- Small and large breaks in *large diameter piping* in HTS (e.g., headers, piping between pumps and SGs)
- *Break size of large breaks* expressed in terms of a guillotine break of the header which has a discharge area equal to twice its cross-sectional area
  - 100% break = 2 x area of pipe
- AECB consultative document C-6 defines *small breaks* as breaks up to size of largest feeder (2.5% or 150 cm^2)

Large LOCA: LOCA Definitions (Cont'd)

- For small breaks, RRS is assumed to compensate for reactivity increase, both in rate and depth
  - shutdown on process trips rather than neutronic trips
- *Very small breaks* (< 2 cm^2) do not initiate ECCS conditioning signal on containment pressure

Large LOCA: Break Size Characteristics

- Large Break
  - break size > 150 cm^2 in area
  - rapid, large power pulse
  - automatic shutdown on neutronic parameters
  - ECCS and containment initiated automatically
- Small Break
  - 2 to 150 cm^2 in area
  - RRS controls power
  - automatic shutdown on process parameters
  - ECCS and containment initiated automatically

Large LOCA: Break Size Characteristics

- Very Small Break
  - < 2 cm^2 in area
  - shutdown is manual or automatic
  - ECCS and containment not required

Large LOCA: Event Sequence

- Pipe break discharges coolant into containment
- Containment atmosphere pressure, temperature and humidity increase
- Depressurization voids core and increases reactivity
  - RRS cannot compensate power increase for larger breaks
  - RRS can compensate for some increase for smaller breaks
- Power increases until shut down by neutronic or process trip depending on break size and initial power
  - net effect is a short overpower pulse followed by rundown to decay power

Large LOCA: Event Sequence (Cont'd)

- Automatic containment isolation on high RB pressure signal
  - signal also conditions ECCS injection and SG crash cooldown
- HTS loses inventory
  - depressurization rate depends on break size and location.
- Dousing initiated when RB pressure setpoint is reached
  - RB pressure and temperature decrease
  - dousing may cycle between on and off
  - atmosphere also cooled by local air coolers
- Following reactor trip, turbine runs back
- Main FW system feeds SGs from condenser hotwell throughout the event

Large LOCA: Event Sequence (Cont'd)

- HTS flow decreases fastest in core pass downstream of break
  - for large breaks, flow will reverse in that pass
  - for "critical" breaks, flow momentarily falls very low
    - cooled by steam, fuel and sheath temperatures rise
      - sheath failure may occur
- After reactor trip, power falls to decay levels
  - sheath temperature depends on heat transfer to coolant

Large LOCA: Event Sequence (Cont'd)

- ECCS activated when broken loop pressure falls below setpoint
  - LOCA signal and loop isolation signal are generated
    - conditioned by high RB pressure
    - recent designs include conditionng signal on high moderator level or sustained low header pressure
  - LOCA signal initiates HP ECCS injection from accumulators
    - flow begins when loop pressure falls below injection pressure
  - SG crash cooling via MSSVs 30 s after LOCA signal

Large LOCA: Event Sequence (Cont'd)

- Loop isolation from each other, from purification system, from pressurizer and from feed and bleed system occurs
  - makeup to broken loop ceases from intact loop and pressurizer
  - makeup from feed and bleed system ceases
- MP ECCS from dousing tank starts on low water signal from accumulator tanks
- LP ECCS is initiated:
- manually by the operator on older station designs
- automatically on low dousing tank level indication for more recent plants

Large LOCA: Event Sequence (Cont'd)

- Fuel and sheath temperatures decrease with ECC injection
- HTS pumps provide forced circulation cooling until trip by protection system
  - cooling by thermosiphoning after pump trip
- Some PT/CT contacts may occur early in the transient
  - depends on break size and location
- If fuel sheath fails, some fission products are released into coolant
  - carried into containment via break, becomes airborne
  - most soluble radionuclides carried with the liquid phase to the floor

Large LOCA: Event Sequence (Cont'd)

  - plateout on walls, washout by dousing and decay occur
  - some fission products (in gas form) leak to the outside environment during the over-pressure period
- Long-term cooling of broken loop maintained by ECCS flow through circuit, with decay heat removal by ECCS heat exchangers and through the break
- Long-term cooling of the intact loop is maintained by thermosyphoning, and heat removal removal by SGs, or by the shutdown cooling system

Large LOCA: Small and Large LOCA Cases

- All safety systems available
- Containment system impairments
  - impairment of containment envelope
    - deflated airlock seals
    - open airlock doors (beyond design basis)
  - impairment of isolation system (partial and total)
  - impairment of dousing system (partial and total)
  - total loss of local air coolers

Large LOCA: Small and Large LOCA Cases (Cont'd)

- ECCS impairments
  - failure of ECC injection
  - failure of HTS loop isolation
  - failure of SG crash cooldown
    - if crash cool signal is not duplicated (older stations)
- Loss of Class IV power
  - containment impairments
  - ECCS impairments

Large LOCA: Safety Systems Available

<u>Acceptance Criteria</u>

- Dose Limits
  - R-10 Single Failure limit (more restrictive)
  - C-6 Class 3 limit
- Shutdown
  - R-8 two independent SDS requirement
- Fuel Channel Integrity
  - R-8 and R-9
    - No energetic breakup of fuel during power-pulse
    - Sufficient to show that maximum stored energy in hottest fuel element <840 kJ/kg UO_2

Large LOCA: Safety Systems Available (Cont'd)

- No fuel channel failure due to internal overheating
  - No PT failure due to local strain (PT local true strain is <100% at any location)
  - For PT/CT contact, CT should remain intact (no film-boiling/dryout on CT)

Sufficient to show PT < 600 ^oC, to ensure no channel failure

Large LOCA: Safety Systems Available (Cont'd)

- Containment structural integrity
  - R-7
  - Sufficient to show that
    - peak pressure does not exceed design pressure of 124 kPa(g)
    - transient differential pressure across RB internal walls does not impair integrity

Large LOCA: Analysis Disciplines

- Power transient
- Circuit and channel thermalhydraulics
- Fuel sheath and fission product release
- Fuel channel integrity
- Moderator response
- Containment
  - thermalhydraulics
  - fission product behaviour, release from containment
- Dispersion and Dose

Large LOCA: Safety Analysis

- Involves determining:
  - fuel normal operating conditions
  - fuel and fuel channel temperatures during LOCA transient
  - fission product release during transient
  - containment analysis
  - dose and dispersion analysis

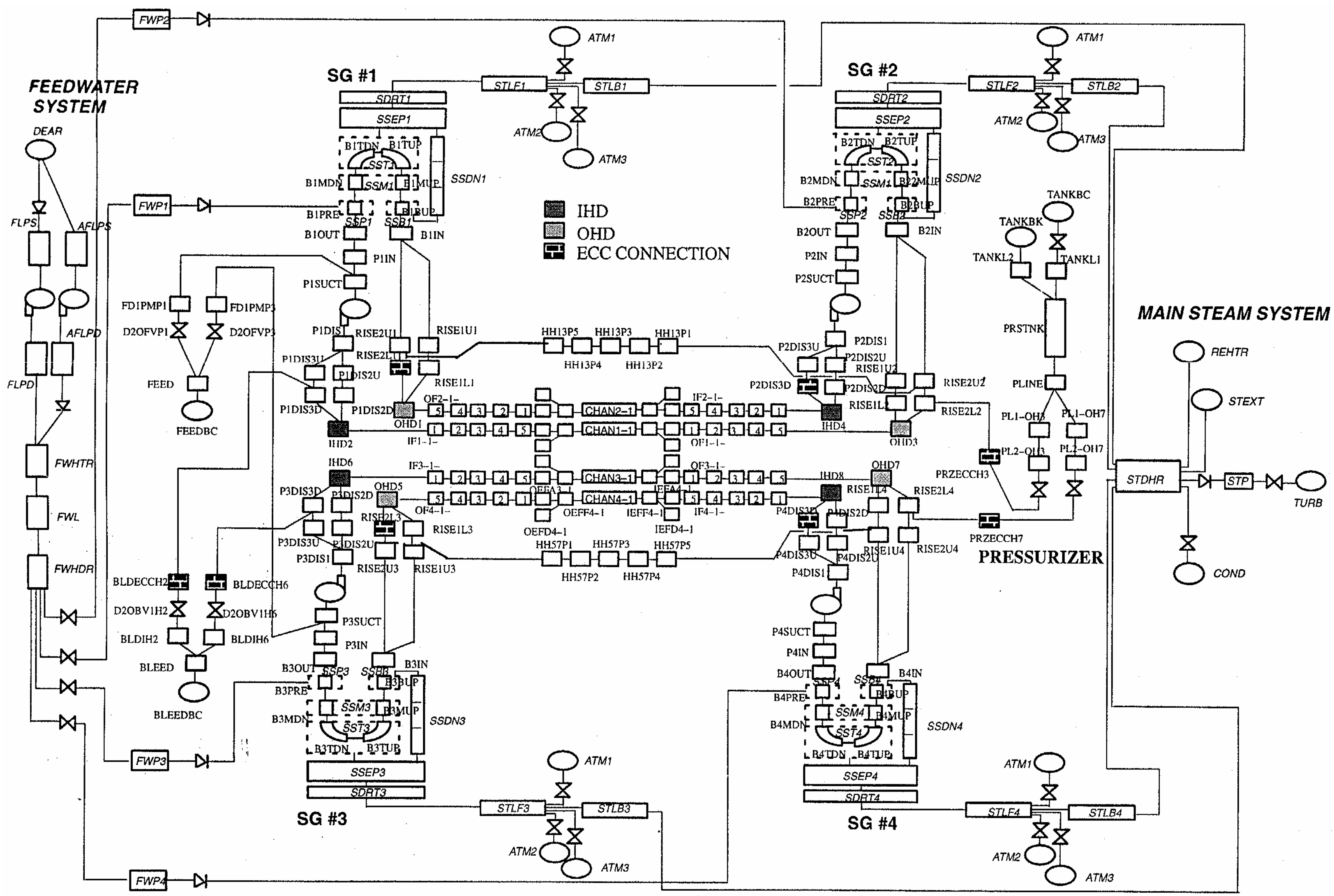
Large LOCA: Fuel Conditions Prior to the Onset of the Accident

- Normal operating conditions is modelled by the ELESTRES computer code
- Main Input Requirements
  - fuel element (pellet and sheath) dimensions & properties
  - power/burnup history
  - coolant temperature and pressure
- Important Output Parameters
  - fission product distribution
  - internal gas pressure
  - fuel temperatures
  - pellet strain

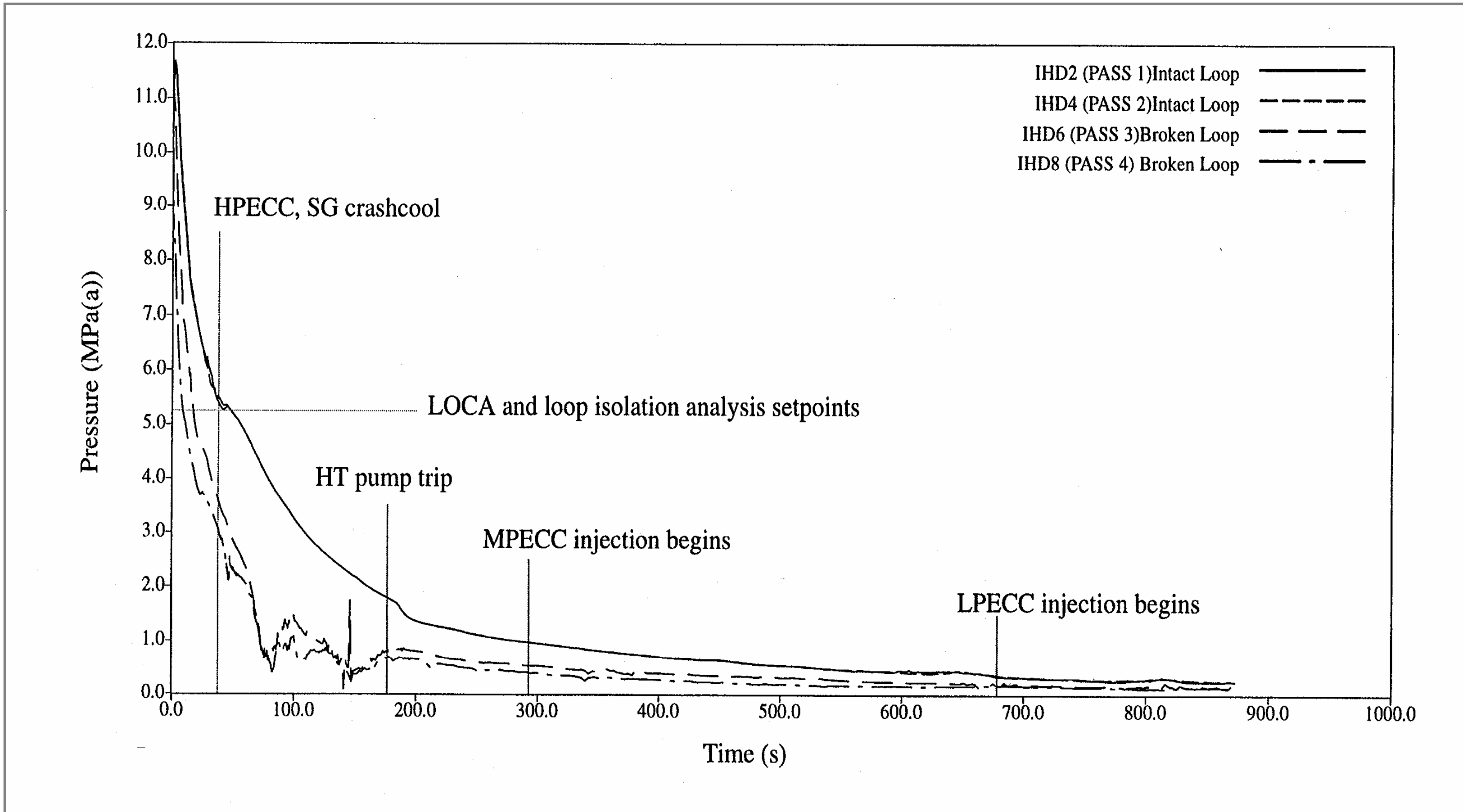
Large LOCA: Transient Temperatures

- Thermalhydraulic behaviour is calculated by the CATHENA circuit model
  - Reactor Inlet Header Break (RIH)
    - 20%, 25%, 30%, 35%, 40% & 100%
  - Pump Suction Pipe Break (PS)
    - 40%, 45%, 50%, 55%, 60%, 70% & 100%
  - Reactor Outlet Header Break (ROH)
    - 80%, 90%, 95% & 100%
- A critical break size is identified for each break location and a detailed CATHENA single-channel analysis is performed:
  - 35% RIH , 55% PS & 100% ROH

Large LOCA: Primary Heat Transport System Model

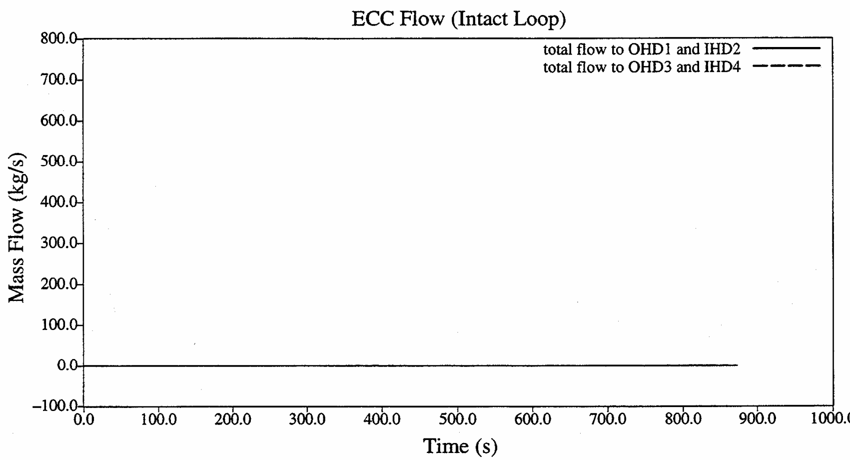


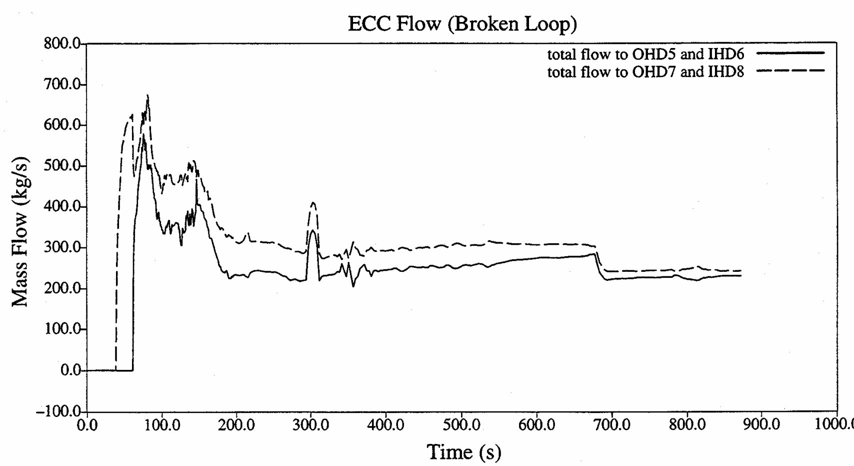
Large LOCA: Depressurization in Inlet Headers (35% RIH Break)



Large LOCA: ECC Flows

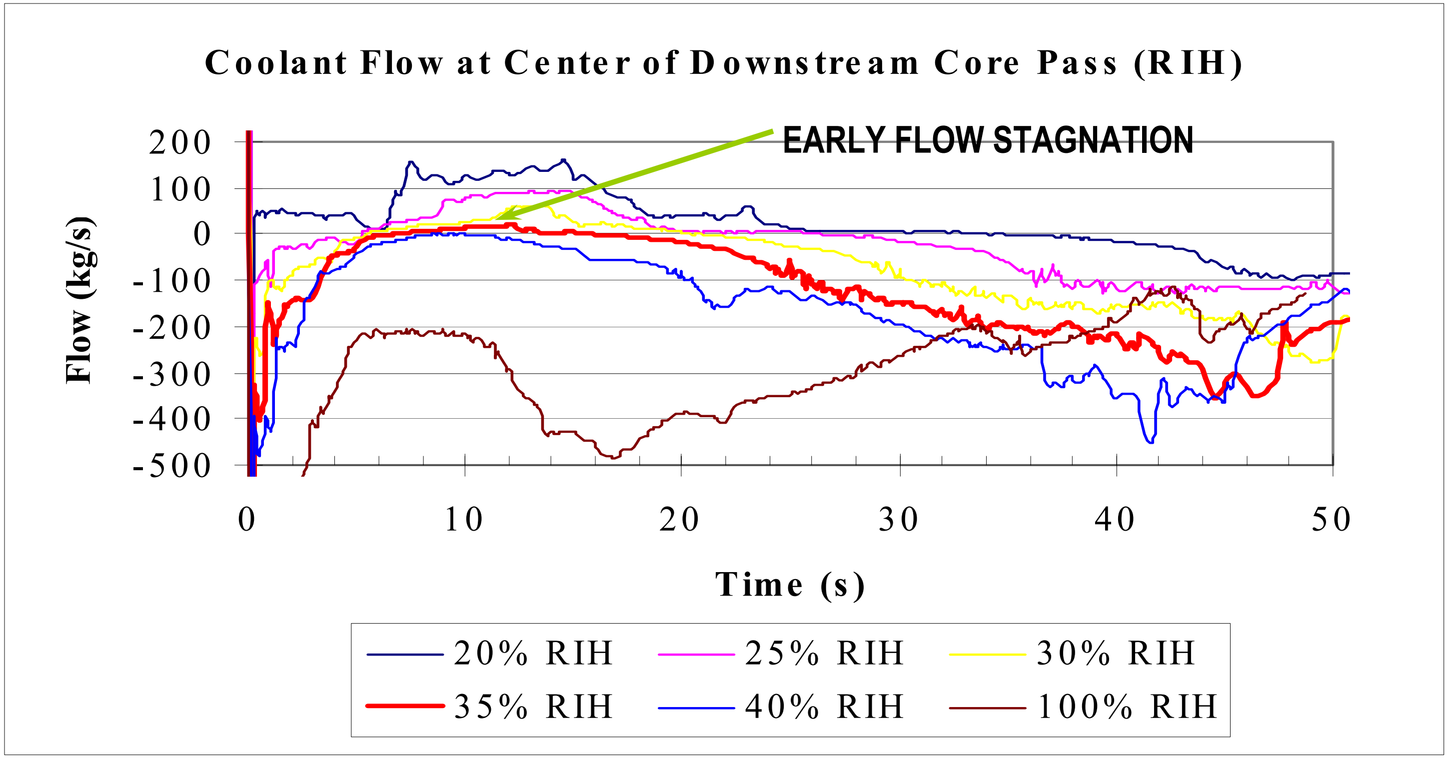
- No ECC flow into the intact loop, since
  - intact loop pressure > broken loop pressure (intact loop was isolated from the broken loop)
  - Intact loop pressure > ECC supply pressure
- LOCA signal & loop isolation initiated at 9 s after accident
- Loop isolation complete by 29 s
- ECC flows into the broken loop, 3 stages
  - High-pressure injection initiation (38 s)
  - Medium-pressure injection (293 s)
  - Low-pressure injection (678 s)





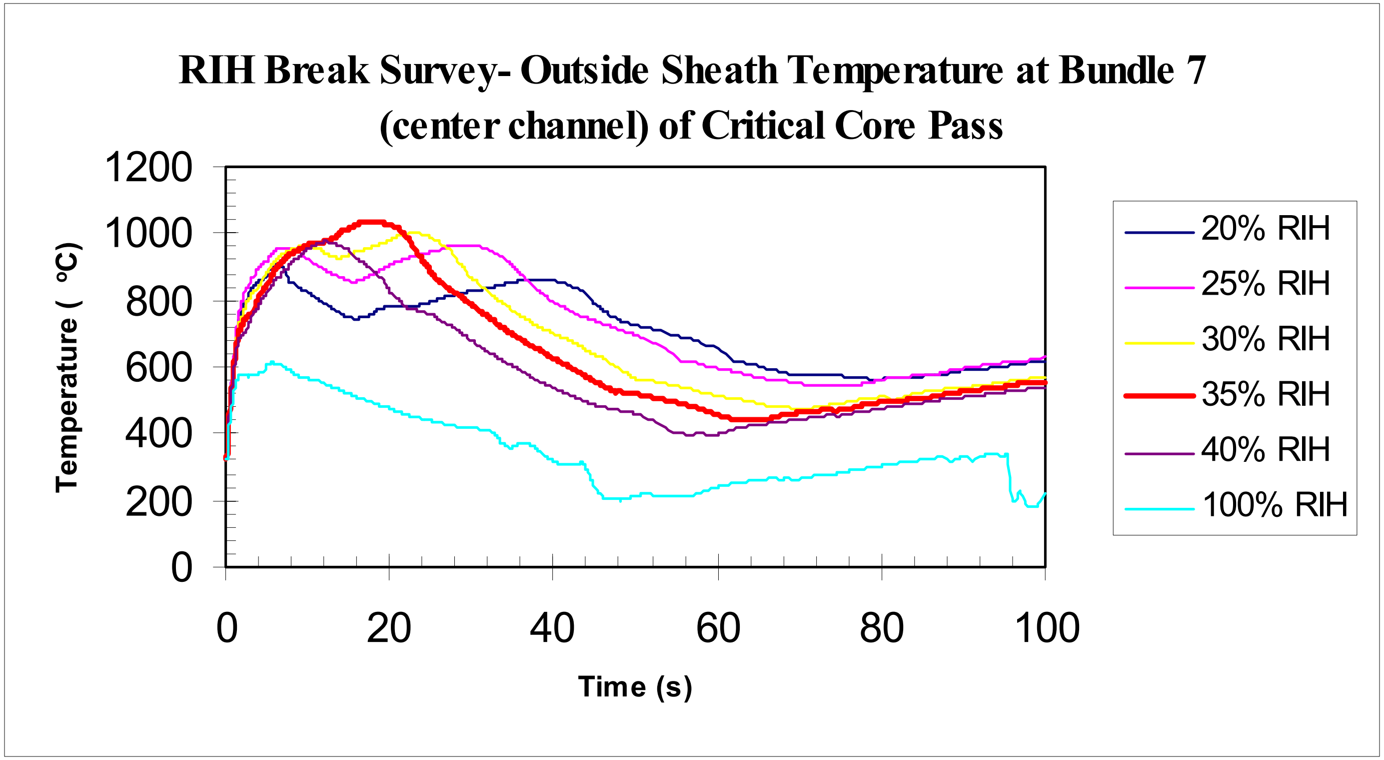
Large LOCA: Break Survey for RIH breaks

- large breaks ==> sustained reverse flow
- small breaks ==> forward flow
- medium breaks ==> stagnation
- Critical break is 35% RIH



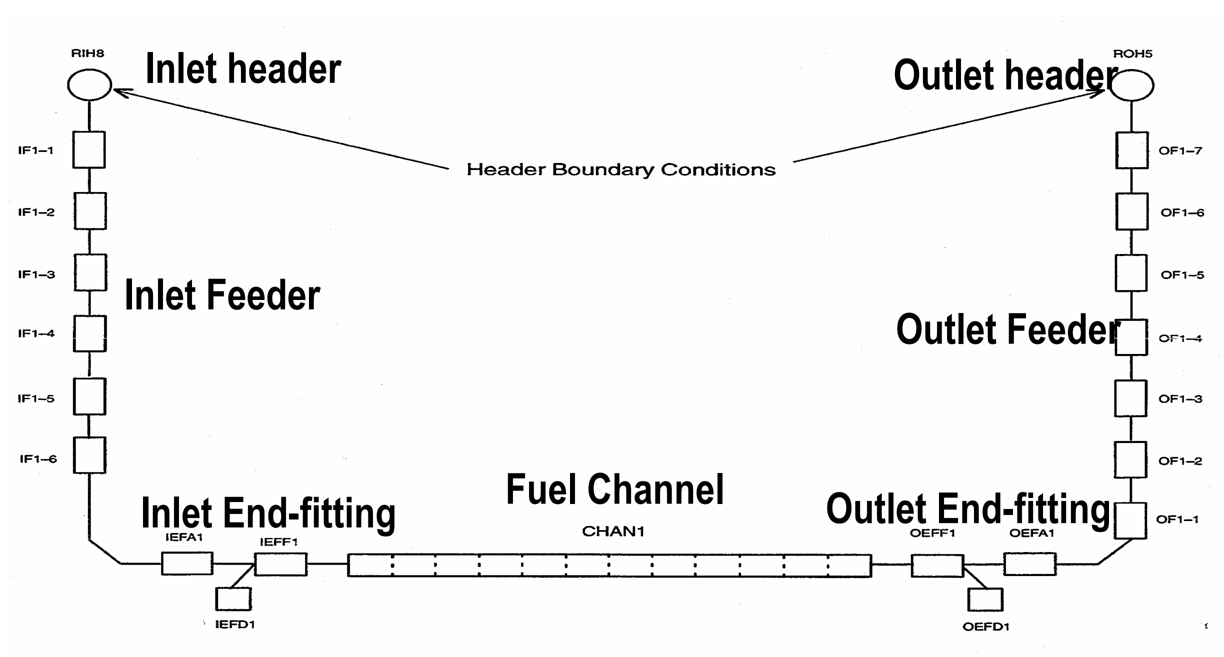
Large LOCA: Break Survey for RIH breaks

- Temperature transient corresponds to flow conditions
- Flow stagnation ==> temperatures increase
- Break in flow stagnation ==> temperatures drop
- Critical break is 35% RIH



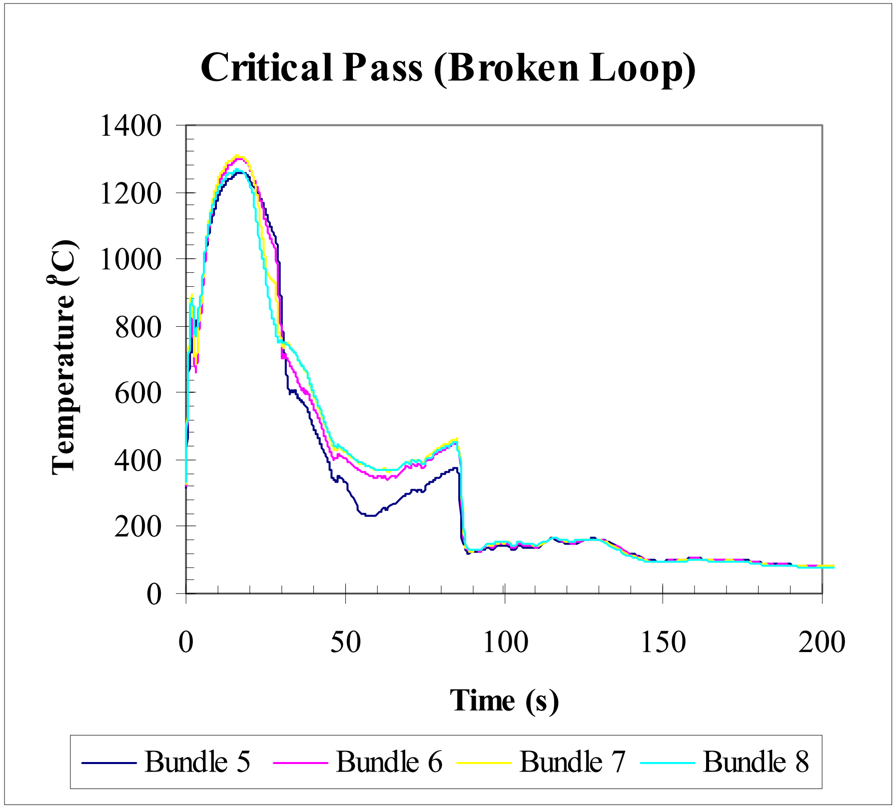
Large LOCA: Single Channel Model for 35% RIH Critical Break

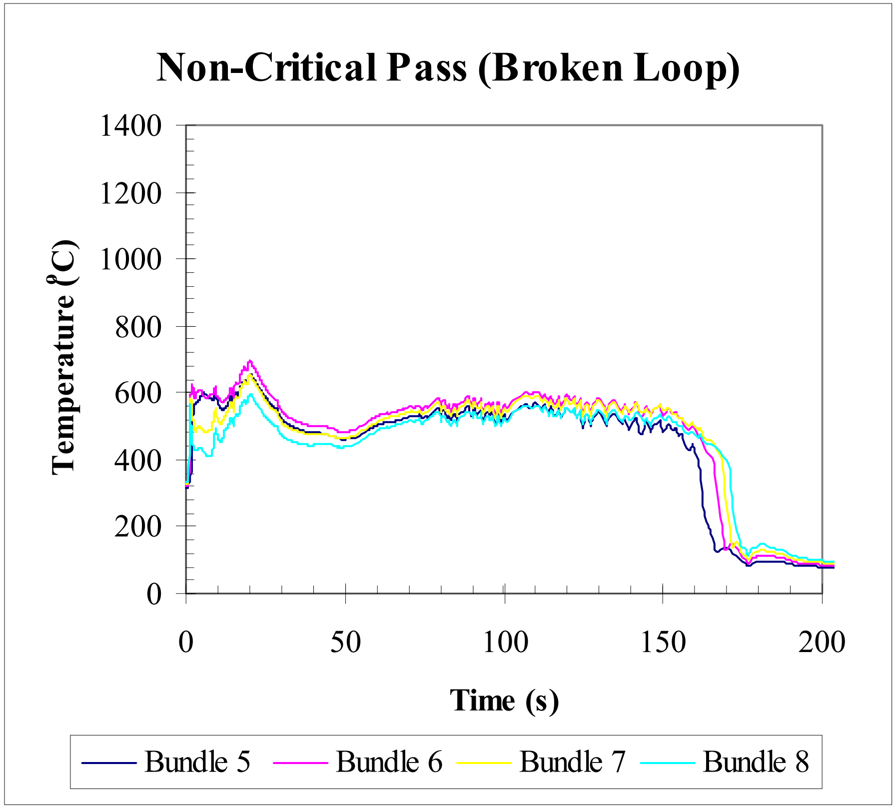
- Header boundary conditions (pressure, enthalpy, void)
- 6 inlet feeder segments
- Inlet end-fitting model
- 12 channel segments (for 12 bundles)
- Outlet end-fitting model
- 7 outlet feeder segments



Large LOCA:
Single Channel Analysis of 35% RIH Critical Break

Channel 06 (7.3 MW); Outer Elements; Sheath Temperatures





Large LOCA: Detailed Fuel Element Analysis

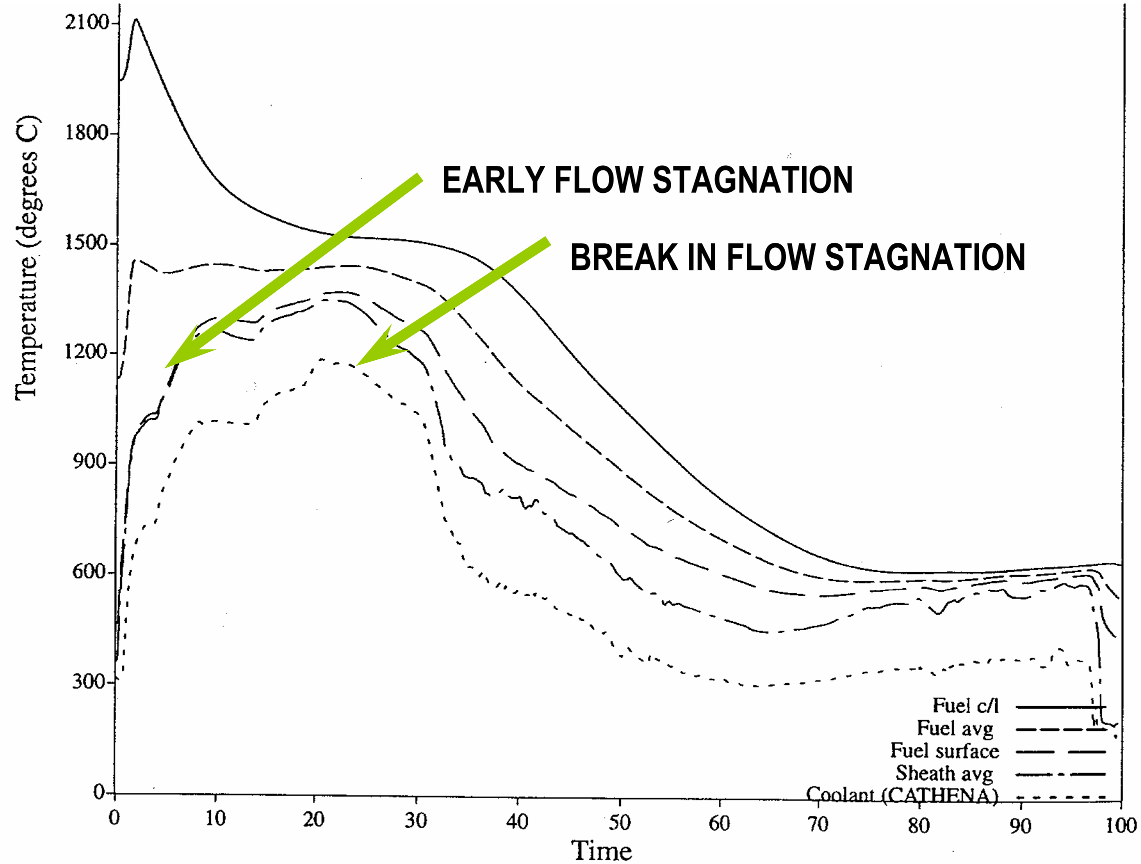
- Objective of analysis is to predict the potential for sheath failure during the LOCA
- Boundary conditions from single-channel CATHENA analysis is provided to ELOCA code
  - coolant temperature,
  - coolant pressure,
  - sheath-to-coolant heat transfer coefficient,
  - ELESTRES normal operating conditions, and
  - power pulse
- For excessive straining: the increase in sheath temperature and high internal gas pressure in conjunction with low coolant pressure may result in sheath failure

Large LOCA: Fuel Element Failure Mechanisms

- Failure Mechanisms can include
  - sheath strain
  - beryllium - braze penetration
  - sheath embrittlement due to oxygen uptake
  - oxide layer cracking
- Fission product release from failed fuel:
  - probability of sheath failure threshold exceeded
  - all sheaths fail in critical core pass (1/4 core free inventory)

Large LOCA: Detailed Fuel Analysis ELOCA code

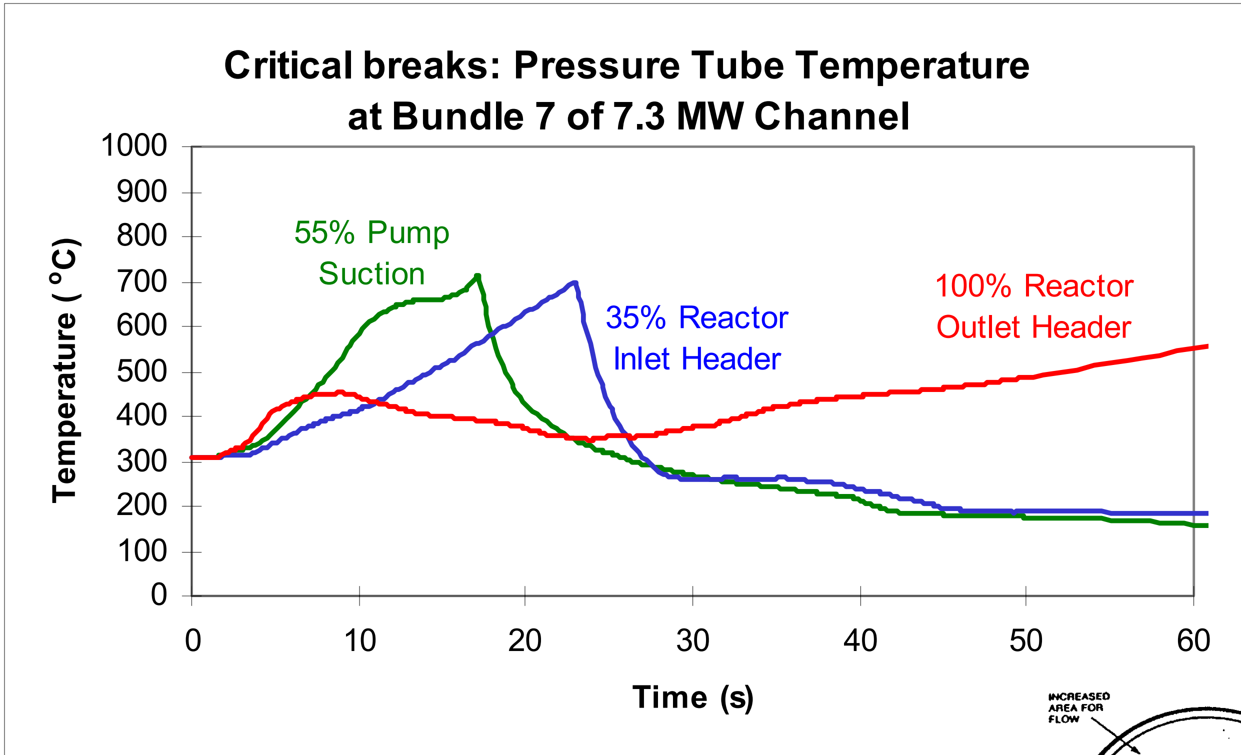
- Sheath temperatures for a 30% RIH LOCA scenario
- Outer elements of bundle position 6
- High-powered Channel O6 (7.3 MW)

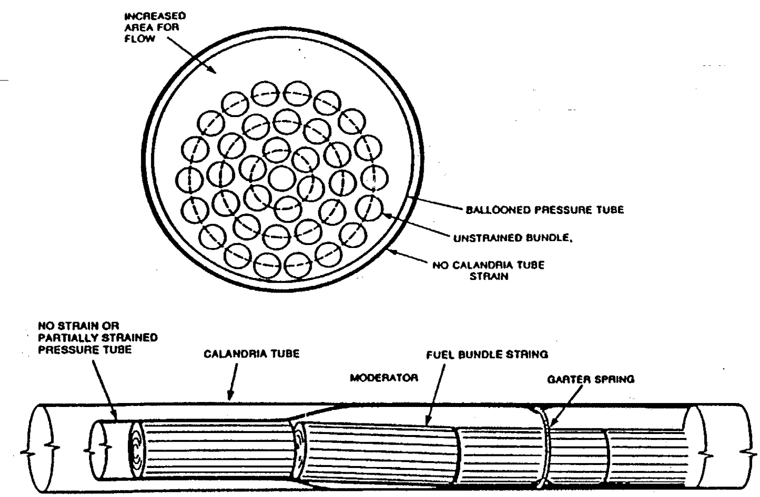


Large LOCA: Pressure Tube Behaviour

- Pressure tube deformation is expected for LOCA breaks resulting in high pressure tube temperatures at high channel pressure
  - PT temperature > ~650°C
  - internal pressure > 1 MPa
- Objective of analysis is to determine pressure tube temperature at time of contact with its surrounding calandria tube
- Moderator temperatures are sufficiently low enough to prevent film boiling (dryout) on the outer surface of the calandria tube after the pressure tube-calandria tube contact
- Localized hotspots on the pressure tube due to bearing-pad/pressure tube contact results in localized deformation of tube
- No channel failures during a large break LOCA

Large LOCA: Pressure Tube Temperatures

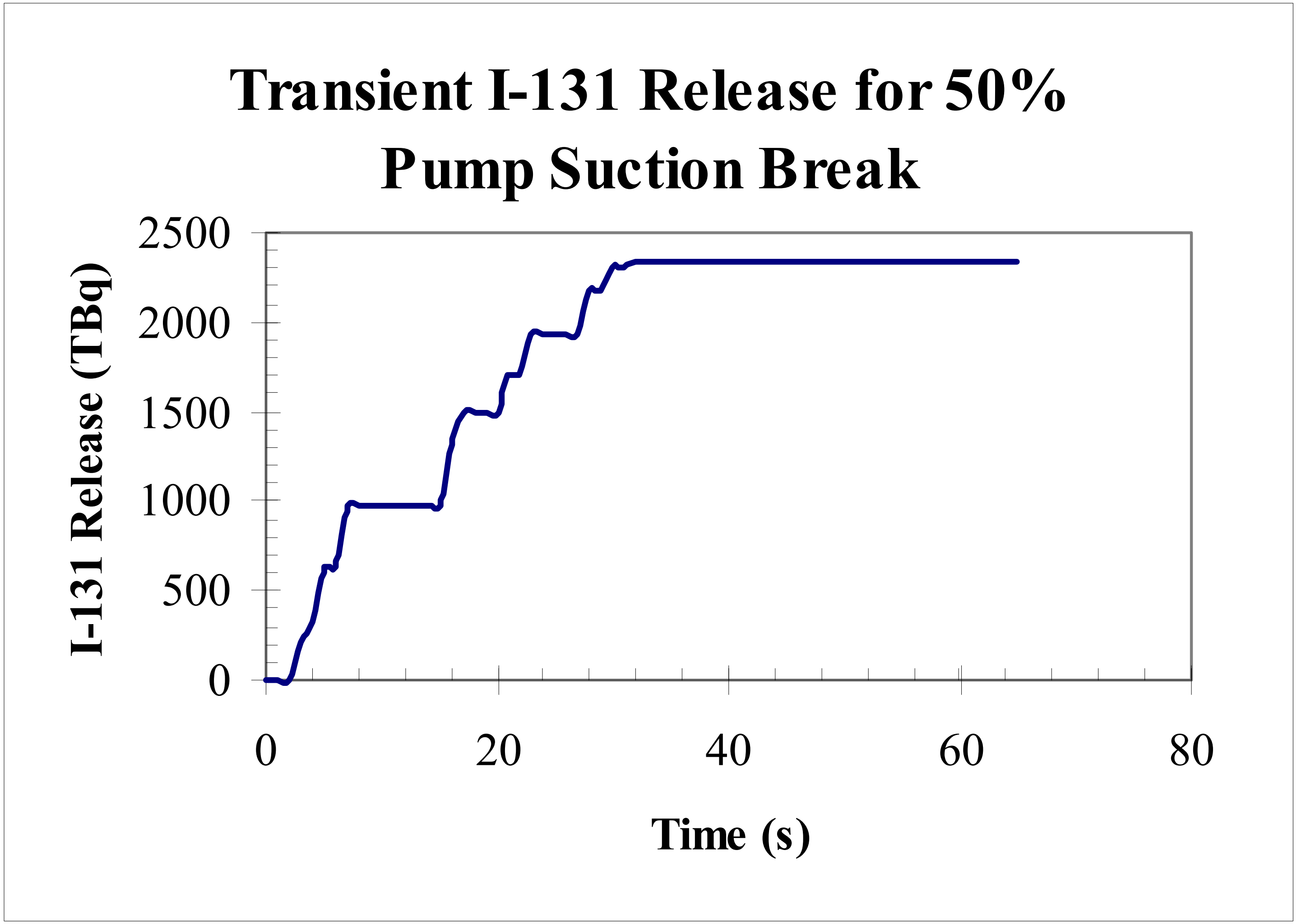




Large LOCA: Fission Product Release

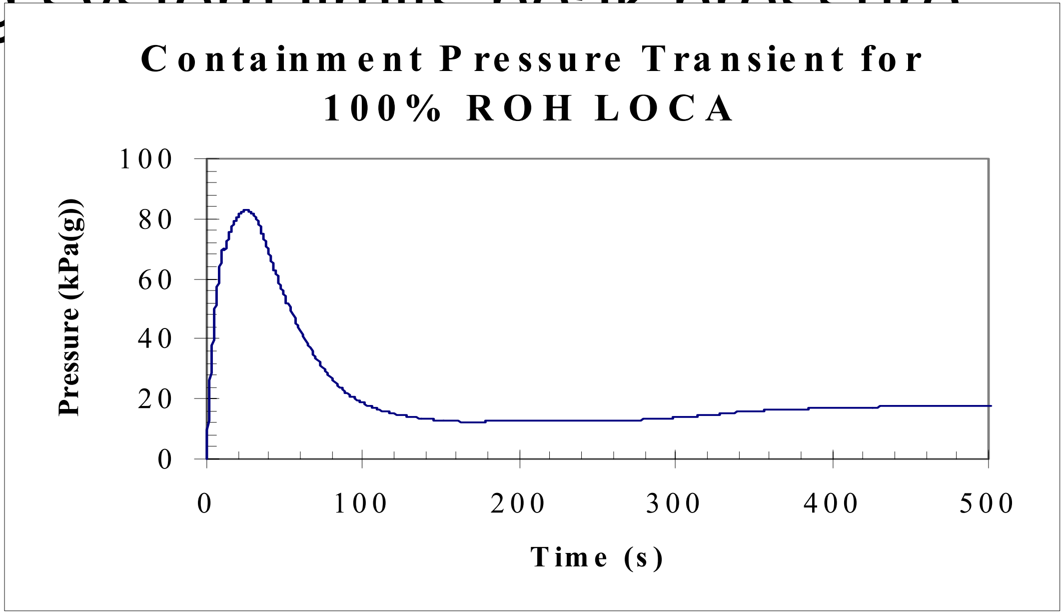
- The gap inventory plays a key role in the fission products released during the transient (i.e., sheath failure ==> retention & transport of fission products in the gap ==> released to heat transport system)
- Secondary release phenomena may include diffusion, fuel oxidation, Zircaloy-UO_2 reaction and fuel cracking
- LOCA Methodology
  - entire gap inventory is assumed to be released upon sheath failure
  - 1% of fission products residing on grains and grain boundary is assumed to be released
    - account for the possibility of secondary release mechanisms
- Fission product retention in HTS not credited

Large LOCA: Fission Product Release Transient



Large LOCA: Containment Behaviour

- Pressure increases rapidly due to large mass/energy discharge to containment atmosphere
- Peak Pressure is below design pressure of 124 kPa (g)
- Dousing system limits peak pressure



LLOCA + LOECC
Large LOCA and Loss of Emergency Cooling

- Goal is prevention of fuel damage
- Analysis shows
  - shutdown systems prevent prolonged high power sheath dryout
  - ECCS refill prevents prolonged flow stratification

LLOCA + LOECC: Summary

- Large LOCA
  - sets many safety system parameters
  - stagnation breaks:
    - at inlet header
      - PT strain is predicted
      - channel remains intact
    - at outlet header
      - fuel sheath strain
      - doses acceptable

LLOCA + LOECC: Summary

- Small LOCA
  - reactor trip and ECCS injection prevent fuel sheath failures
- Very small LOCA (leaks)
  - manual recovery

LLOCA + LOECC: 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

LLOCA + LOECC: Event Description

- 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

LLOCA + LOECC: Event Sequence for Blowdown

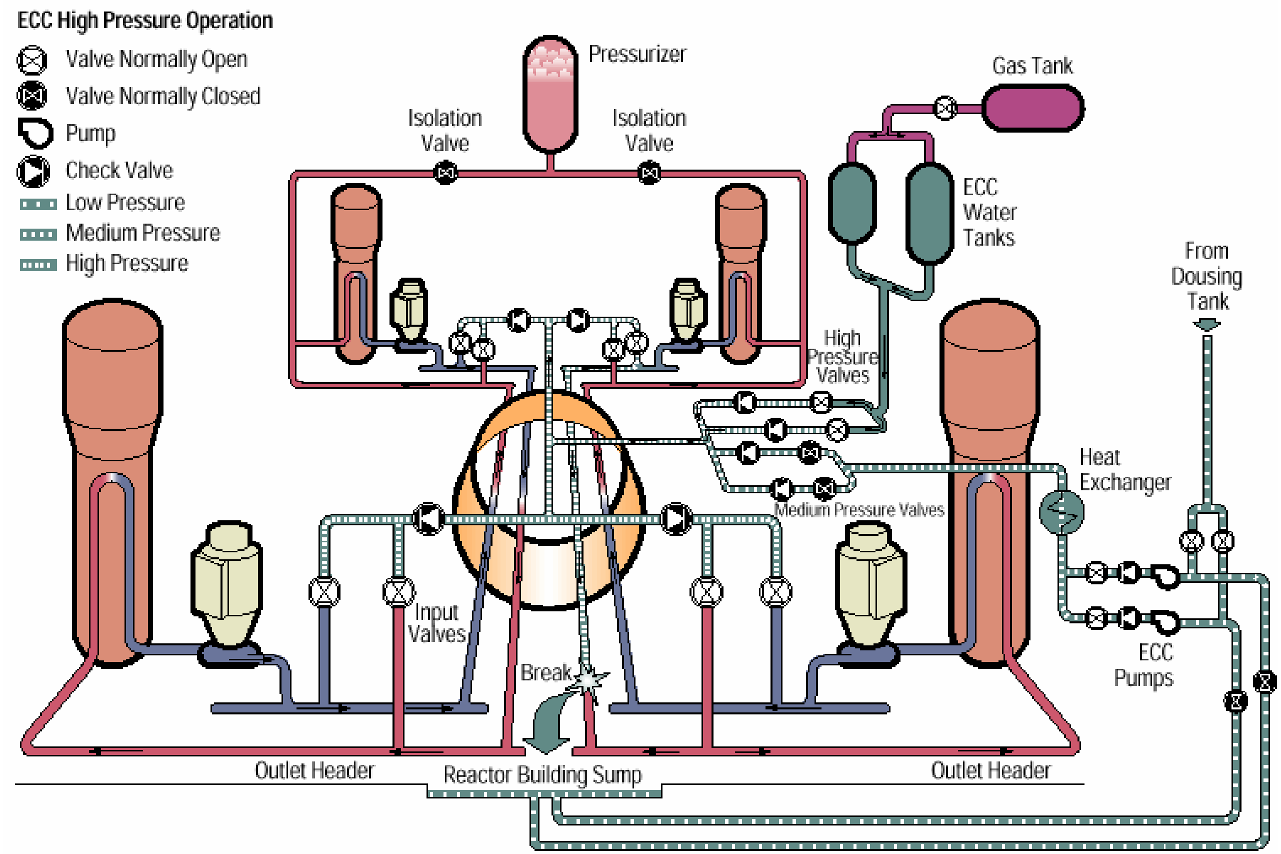
- Similar to LOCA
  - A break occurs in a large diameter pipe in PHT system, discharging coolant into containment
  - PHT system depressurizes causing coolant voiding and an increase in reactivity
  - Reactor power increases until the reactor is shutdown on a neutronic trip or process trip
  - The PHT flow decreases fastest in the core pass downstream of the break

LLOCA + LOECC: Event Sequence for Blowdown

- 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;
  - for this event, 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 circulation and thermosyphoning in the intact loop, fuel cooling is adequate

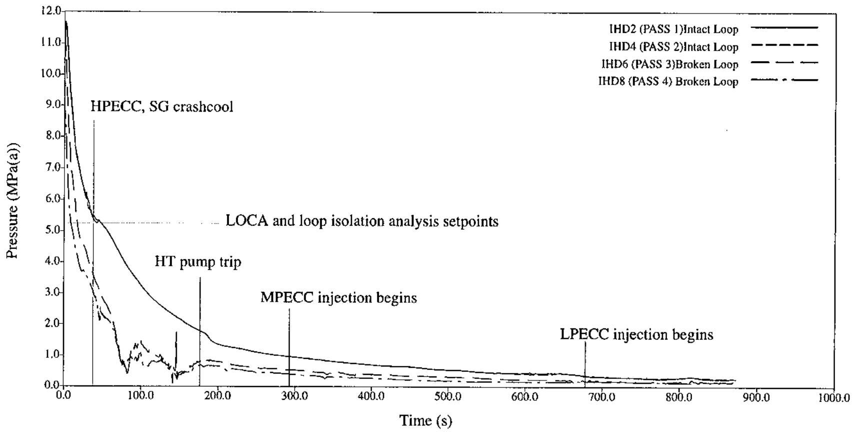
LLOCA + LOECC: Emergency Core Cooling System

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

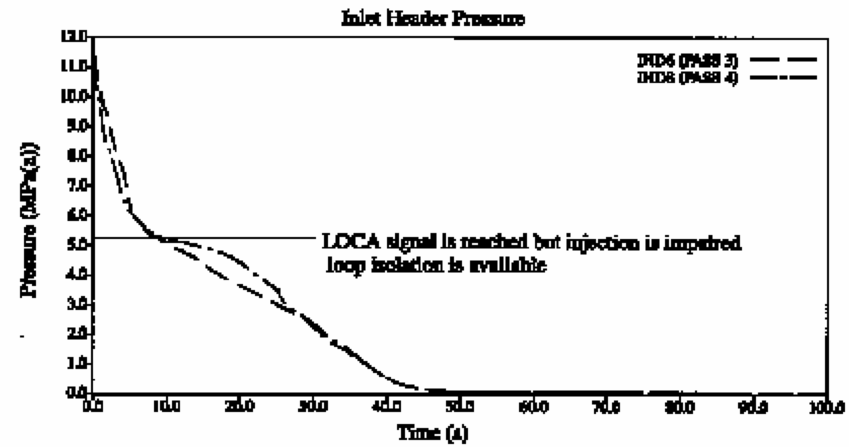


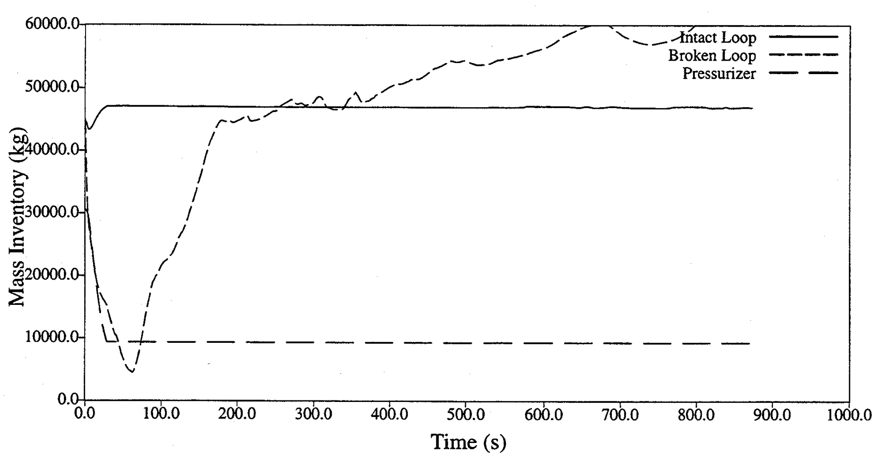
LLOCA + LOECC: Header Depressurization

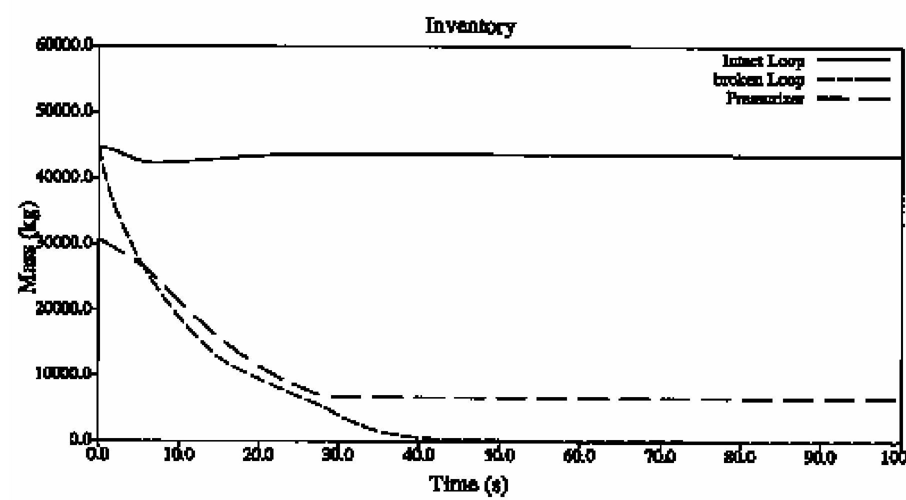
LOCA with ECC Injection



LOCA without ECC Injection







LLOCA + LOECC: Event Sequence for Late Heatup

- 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

  $Zr + 2H_2O ==> ZrO_2 + 2H_2 + HEAT$
- 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

LLOCA + LOECC: 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 is maintained
- The concentration of hydrogen inside containment remains below the threshold concentration for DDT and fast deflagration
  - structural integrity of containment is maintained

LLOCA + LOECC: Safety Analysis

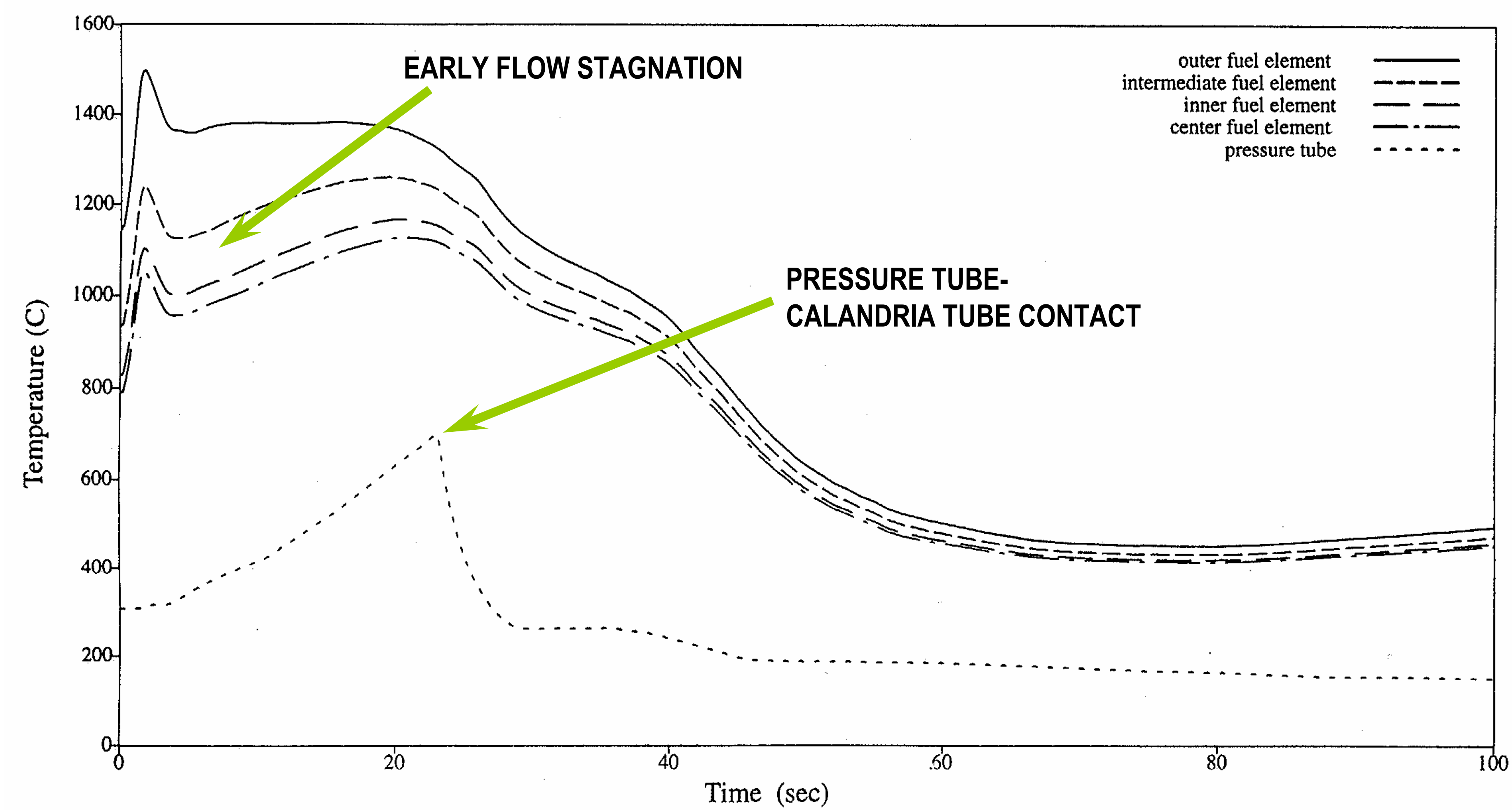
- Similar to the loss-of-coolant accident, this analysis involves determining:
  - fuel normal operating conditions
  - fuel and fuel channel temperatures during LOCA transient
  - fission product release during transient
  - moderator temperature transient
  - containment behaviour
  - dispersion and public dose

LLOCA + LOECC: 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
  - critical break sizes are used to calculate the thermalhydraulic behaviour for a LOCA/LOECC (CATHENA) during the blowdown phase

LLOCA + LOECC:

CATHENA Temperatures during Blowdown Phase of Accident (35% RIH; Bundle 7; 7.3 MW channel; critical core pass)



LLOCA + LOECC: Late Heat up

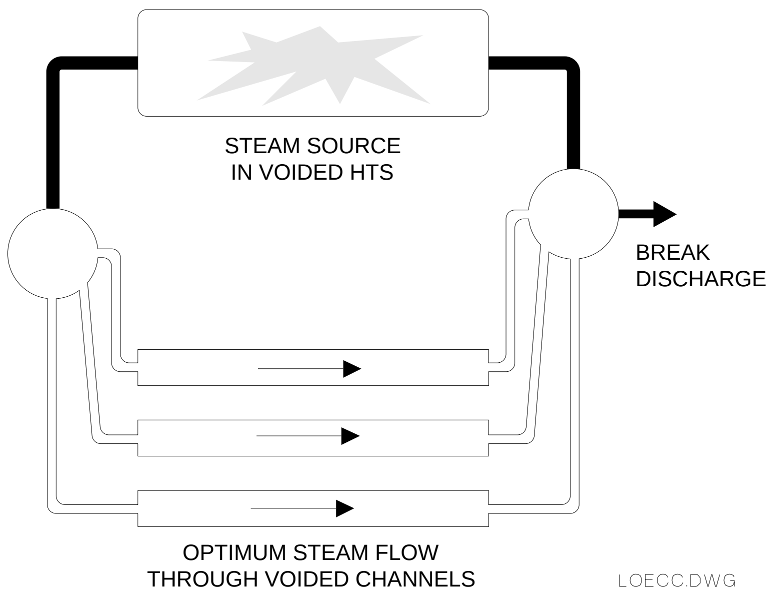
- Uncertainties in thermalhydraulic conditions (low flow) result in a switch to a parametric analysis (late heat up phase) from the deterministic analysis (blowdown phase)
- CHAN-II code accepts CATHENA conditions at the end of blowdown and performs the calculation for the late heat up phase
- Steam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

LLOCA + LOECC: Late Heat up

- 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

LLOCA + LOECC: Sustained Constant Steam Flow

- 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 through core lasts indefinitely

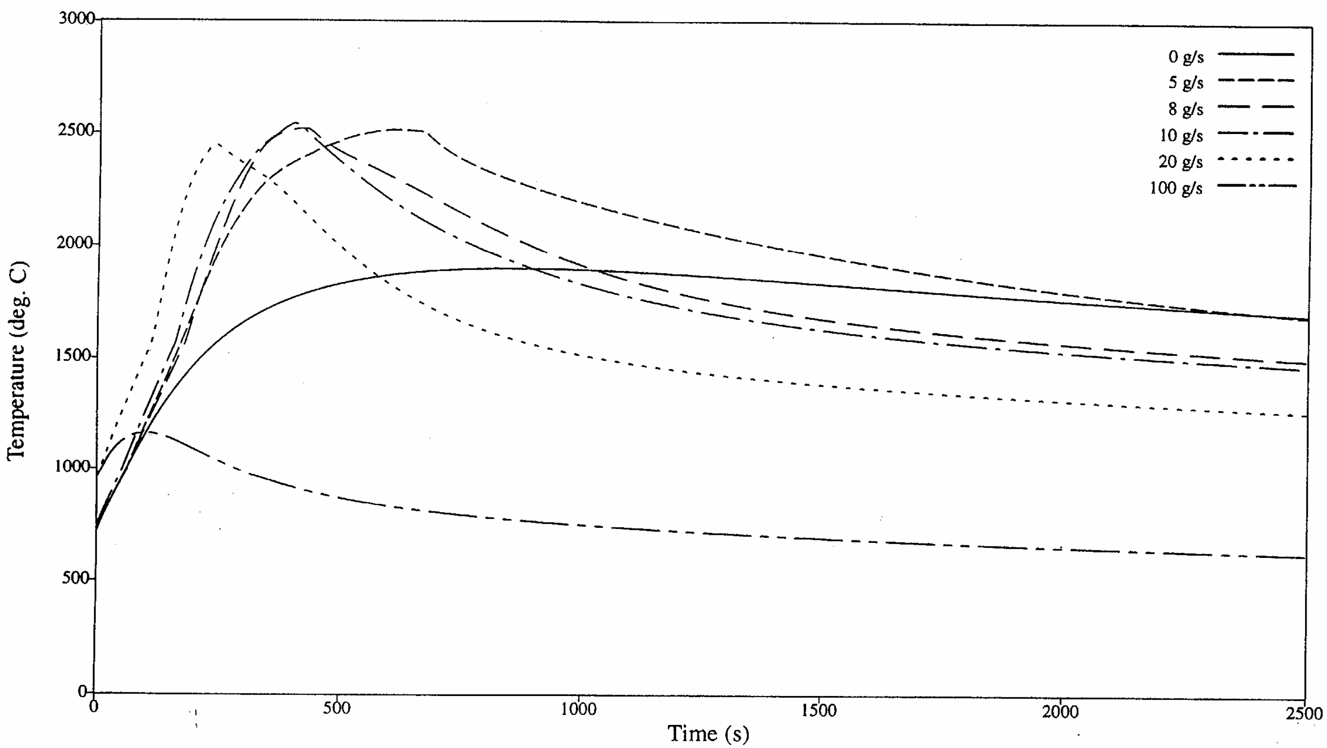


LLOCA + LOECC:

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

- **3 STAGES:**

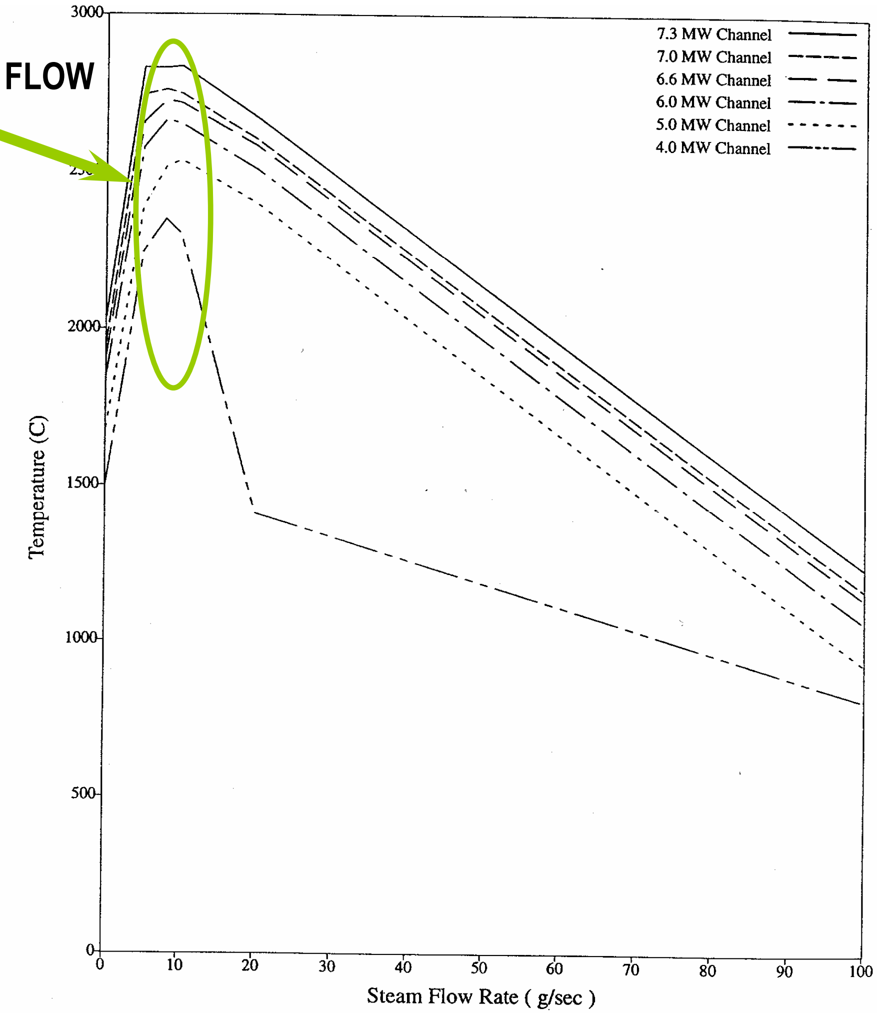
1) Initial heatup 2) Exothermic steam-Zircaloy reaction 3) Cooldown to steady-state



LLOCA + LOECC:

CHAN-II Maximum Fuel Temperatures Versus Steam Flow

REGION OF CRITICAL STEAM FLOW

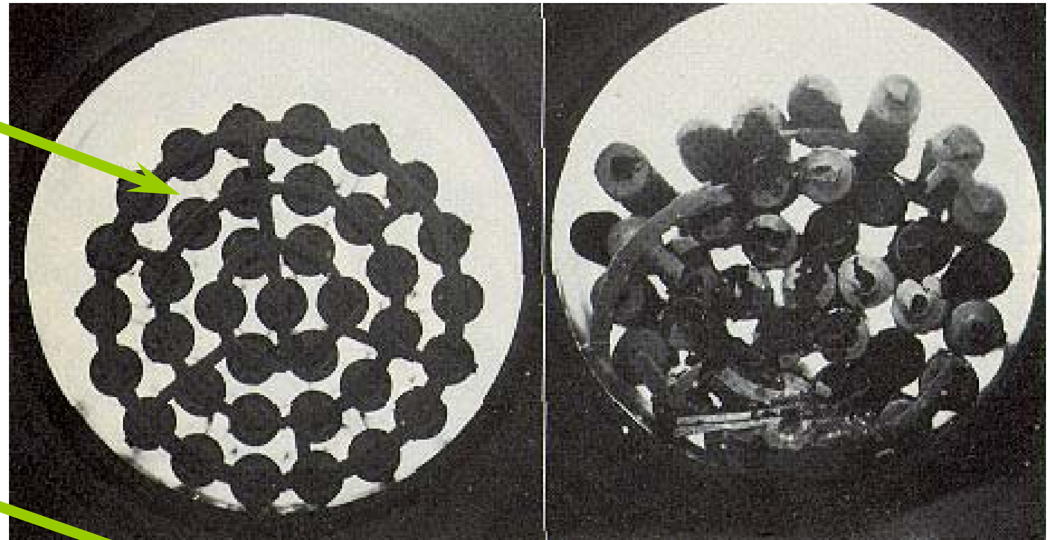


LLOCA + LOECC:

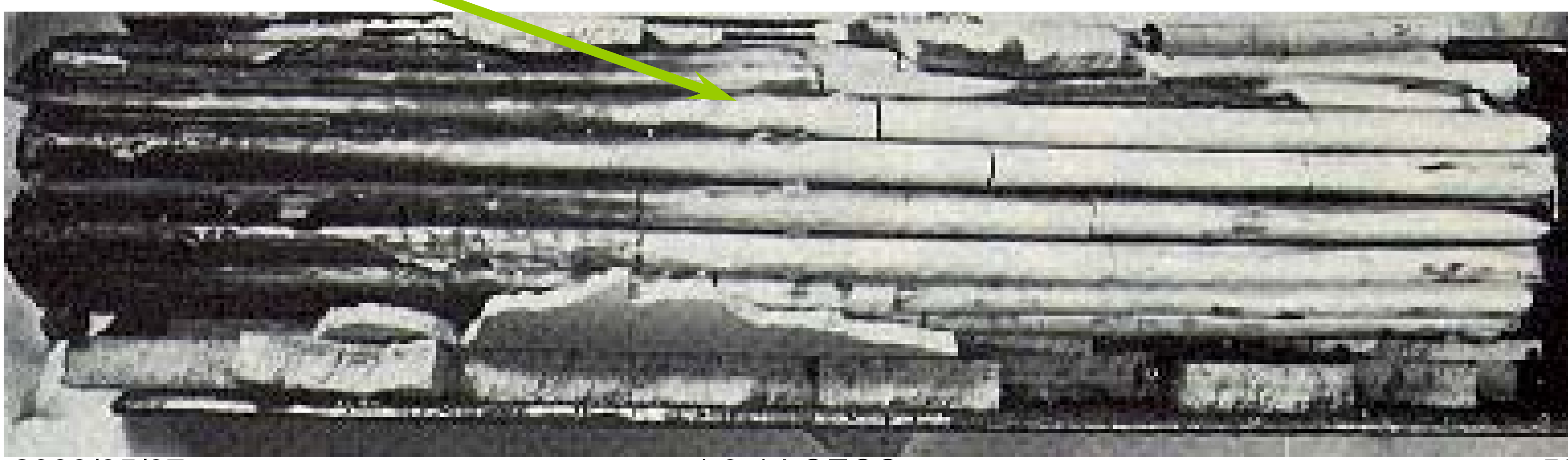
High-Temperature Fuel Bundle Deformation

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

37-ELEMENT BUNDLE



Post-Test Configuration (axial)



LLOCA + LOECC: Pressure Tube Behaviour

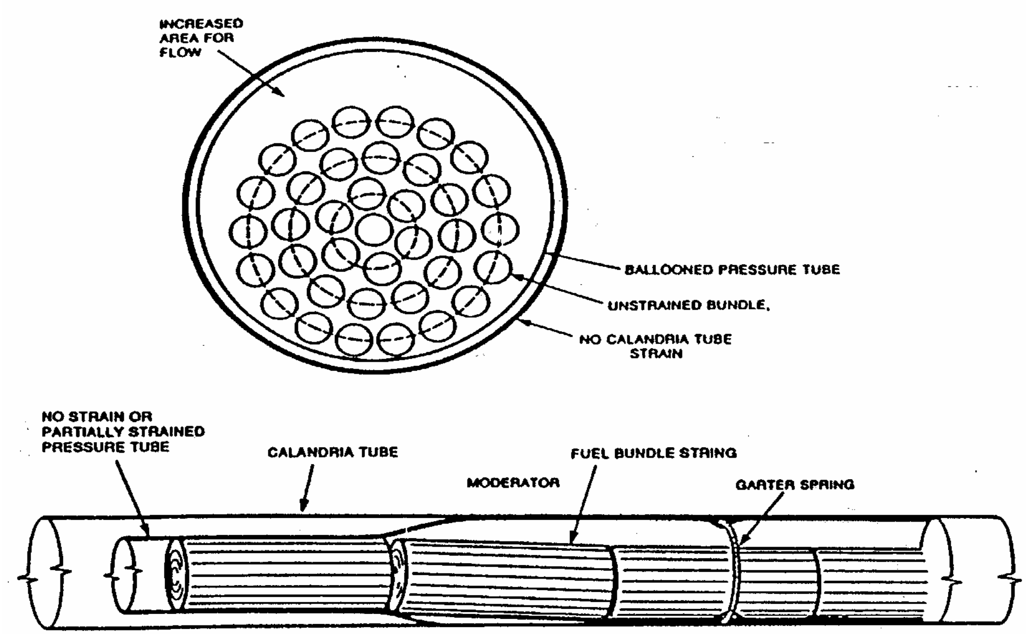
- Blowdown Phase
  - under high channel pressures and elevated pressure tube temperatures, the pressure tube may balloon (strain) into contact with the surrounding calandria tube
- Late Heatup Phase
  - under low channel pressures and elevated pressure tube temperatures, the pressure tube may sag into contact with the surrounding calandria tube

LLOCA + LOECC: Pressure Tube Behaviour

- PT/CT contact results in a heat flux from the hot pressure tube through the contacting cool calandria tube 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)

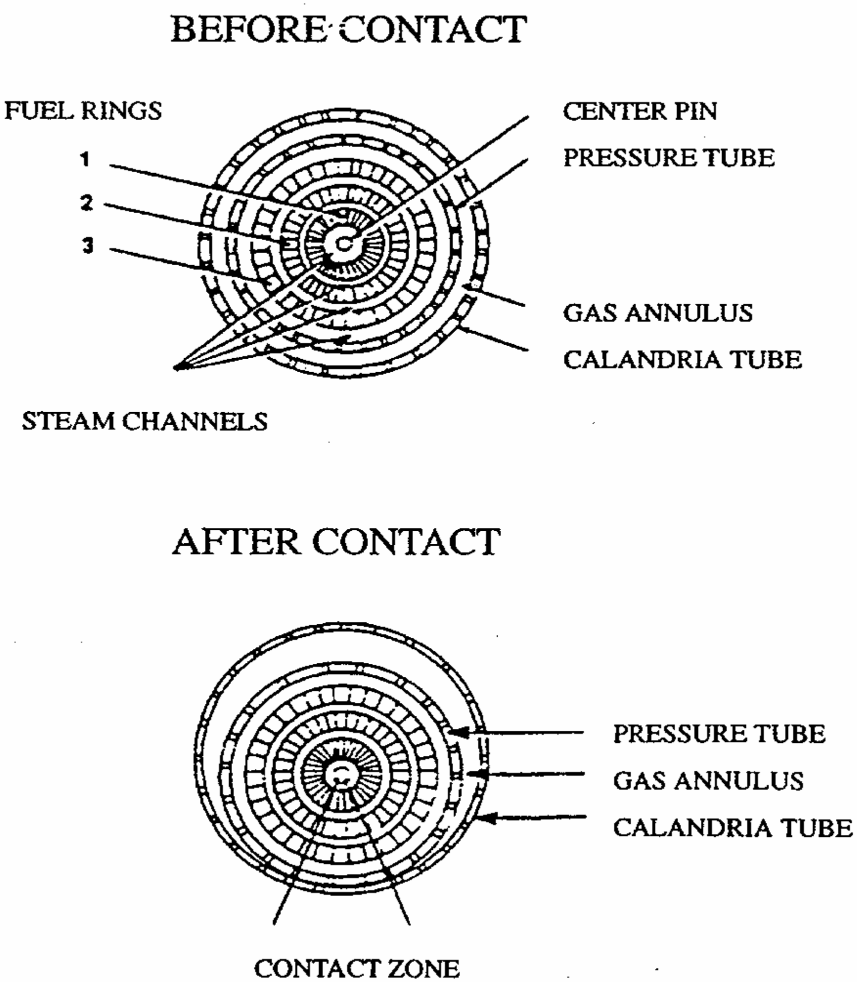
LLOCA + LOECC:
Pressure Tube-Calandria Tube Ballooning Contact

- 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



LLOCA + LOECC: Pressure Tube-Calandria Tube Sagging Contact

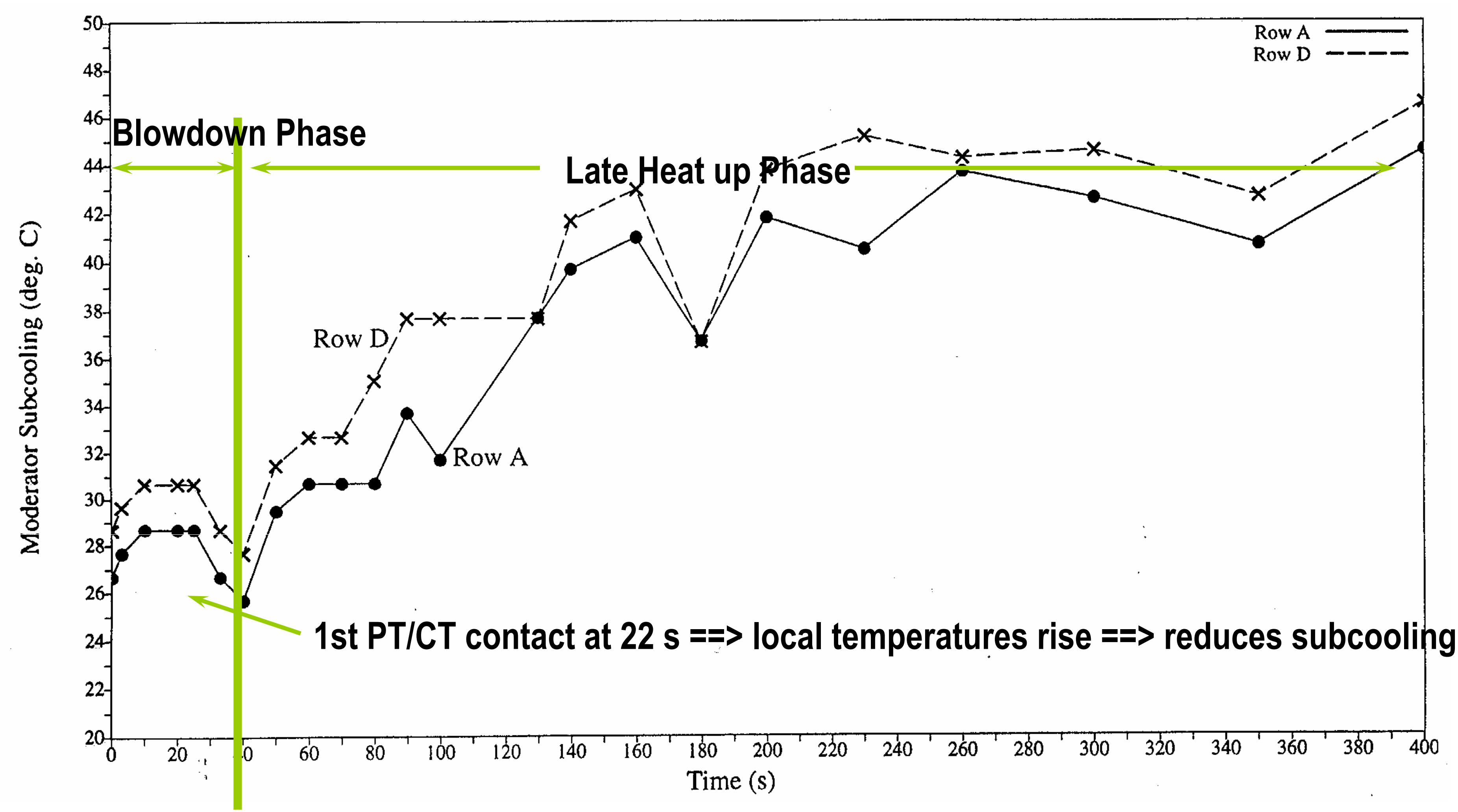
- During the late heatup phase of a LOCA/LOECC, some channels will have:
  - high pressure tube temperature
- Under the low channel pressure,
  - the pressure tube will sag into contact with the calandria tube
- Following PT/CT sagging contact,
  - good heat transfer through the contacting portion of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



LLOCA + LOECC: Moderator Subcooling

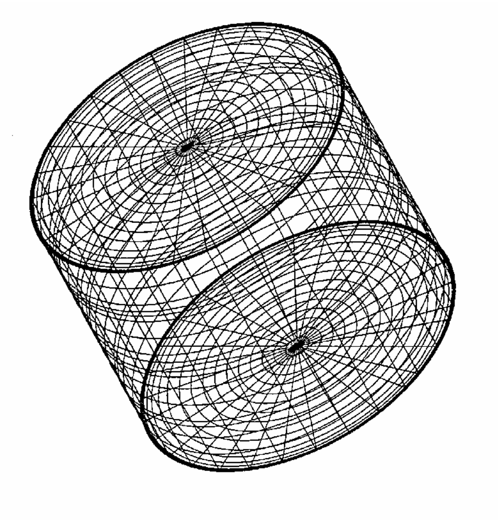
- The maximum initial moderator local temperature, as calculated by the 3D PHOENICS code, is 81^{o}C
- The available subcooling (i.e, defined as saturation temperature subtract local temperature) at the start of the transient for the top channel rows is 27^{o}C to 29^{o}C
- As heat is rejected to the 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

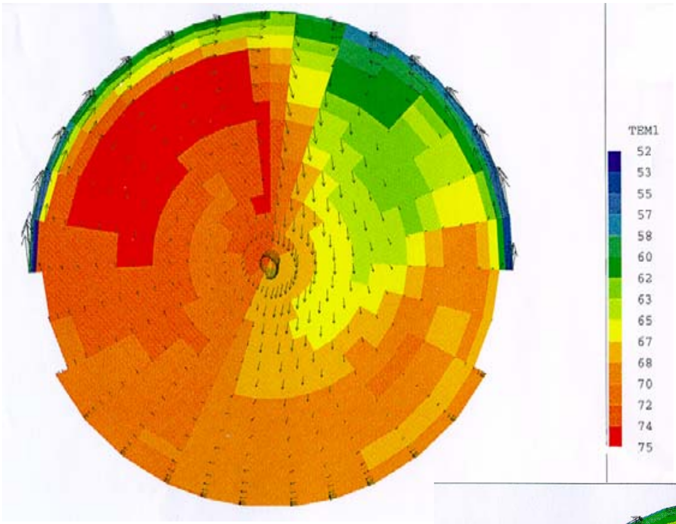
LLOCA + LOECC: Moderator Subcooling



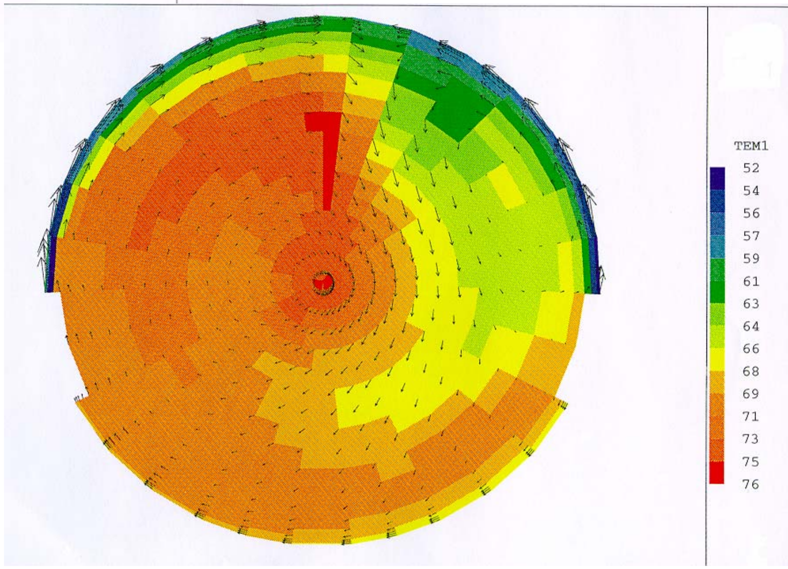
LLOCA + LOECC: PHOENICS 3D
Moderator Temperature Distribution

Moderator Grid





Steady-State
(near axial midplane)



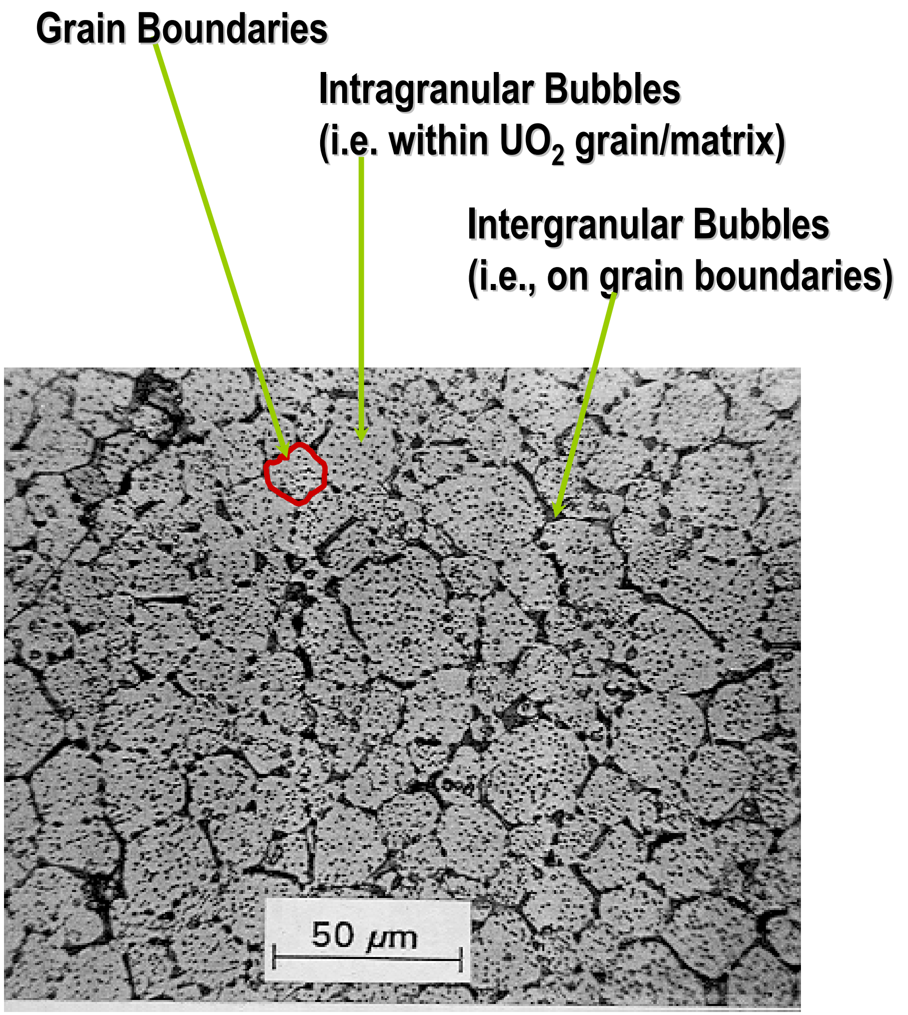
LOCA/LOECC at 40 s
(near axial midplane)

LLOCA + LOECC: Fission Product Release

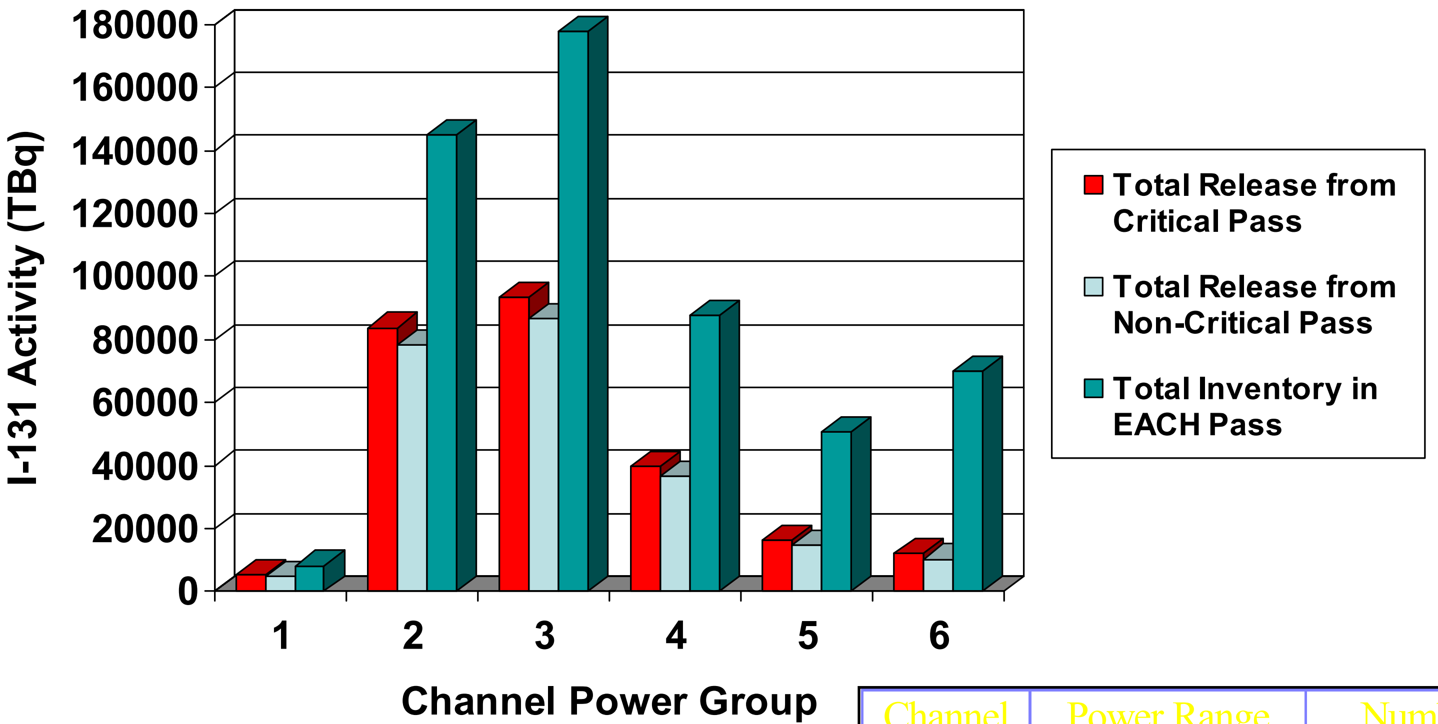
- Some dominant release mechanisms at high temperatures:
  - diffusion of grain bound fission product inventory (i.e., intergranular inventory)
  - enhanced diffusion due to fuel oxidation and/or fuel reduction
  - Zircaloy/UO_2 chemical interaction
- Fission product retention in HTS currently not credited

LLOCA + LOECC: 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



LLOCA + LOECC: Fission Product Release



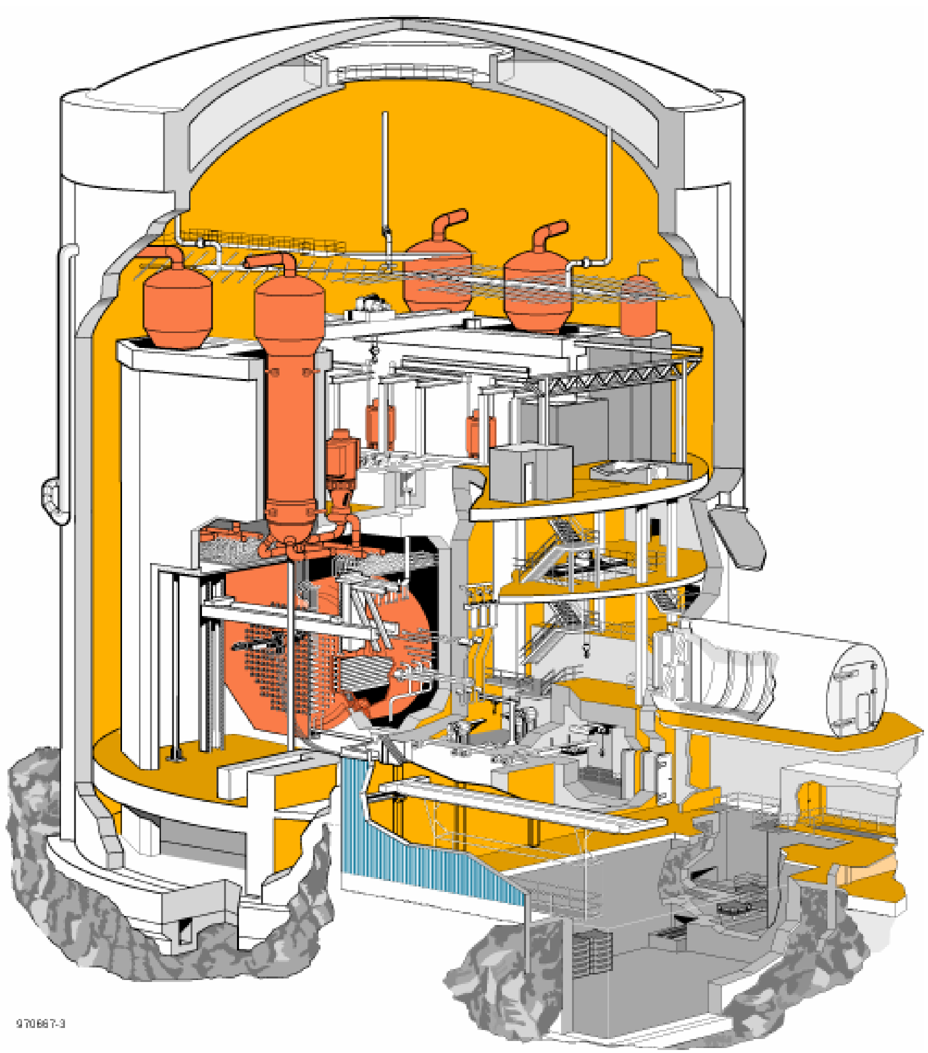
Channel Group	Power Range (MW)	Number of Channels in Core
1	7.0 to 7.3	5 (1.3%)
2	6.6 to 7.0	88 (23.2%)
3	6.0 to 6.6	111 (29.2%)
4	5.0 to 6.0	62 (16.3%)
5	4.9 to 5.0	42 (11%)
6	0.0 to 4.0	72 (18%)

LLOCA + LOECC: 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

LLOCA + LOECC: 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.



Single Channel Events: Overview

- Description of single channel events
- Event sequence
- Brief overview of analysis methodology
- Fuel and fuel channel behaviour during transient

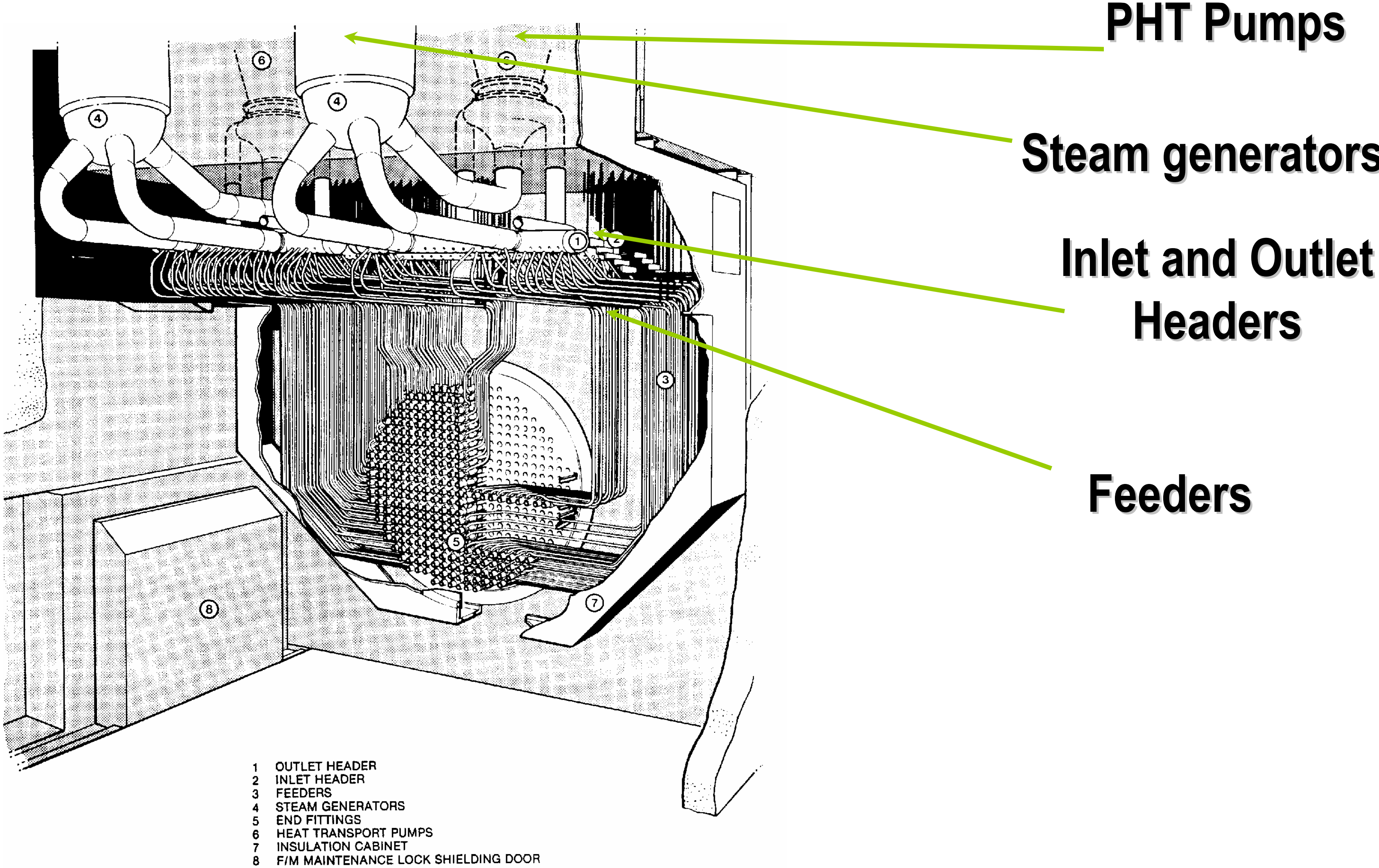
Single Channel Events: Overview

- Feeder Pipe breaks
  - small break in inlet feeder can lead to channel flow stagnation
    - causes in-core channel rupture
- Pressure Tube Rupture
  - leads to the consequential rupture of its calandria tube
- Channel Flow Blockage
  - complete (or nearly complete) flow blockage can cause in-core channel rupture
- End-fitting failure

Single Channel Events: Feeder Pipe Breaks

- Break Size Spectrum
  - good fuel cooling for small and large breaks (behaviour similar to small breaks in reactor inlet headers and outlet headers)
  - narrow range of inlet feeder break size causes fuel and fuel channel damage:
    - “stagnation” breaks - lead to stagnant flow in the downstream channel
      - pressure tube / calandria tube fails
    - “off-stagnation” breaks - lead to reverse flow in the downstream channel without failing the PT
    - Both breaks can lead to release of fission products directly into containment, without significant holdup in the HTS

Single Channel Events: Feeder Stagnation Break



Single Channel Events: Feeder Location

Single Channel Events:

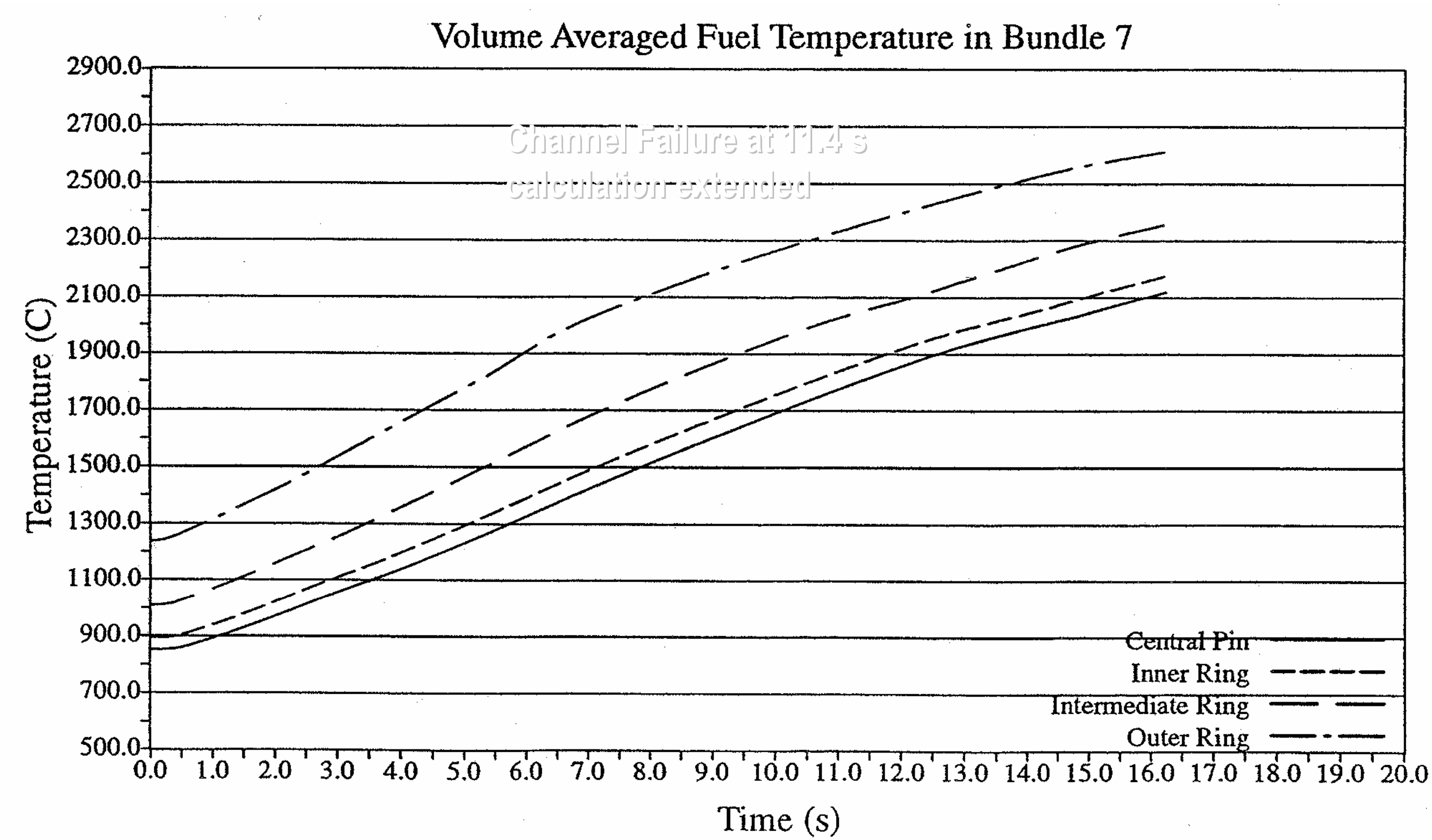
FSB - Feeder Stagnation Break

- Limited range of break sizes and break locations along inlet feeders can lead to flow stagnation in the channel
  - ~12 cm^2 maximum (near the inlet header)
  - ~6 cm^2 minimum (near the end fitting)
- Break discharge to containment 50 - 100 kg/s
- Fuel heats up at full power in a steam/hydrogen atmosphere
- Large radial temperature profiles on the pellets occur due to full reactor power conditions

Single Channel Events: Feeder Stagnation Break

- Temperatures can reach fuel melting at the pellet centerline prior to channel rupture & sheath temperatures could exceed the Zircaloy melting temperature of 1760^{o}C
- As the flow in the channel decreases, the reactor continues to be at power until reactor trip occurs after channel rupture
  - PT rupture calculated at ~11 s due to non-uniform strain
  - calandria tube ruptures shortly thereafter
- Interaction between molten material generated in channel and the moderator water occurs
- Fission products released via moderator relief ducts
- Potential for channel failure propagation

Single Channel Events: High Powered Channel Fuel Temperatures for FSB

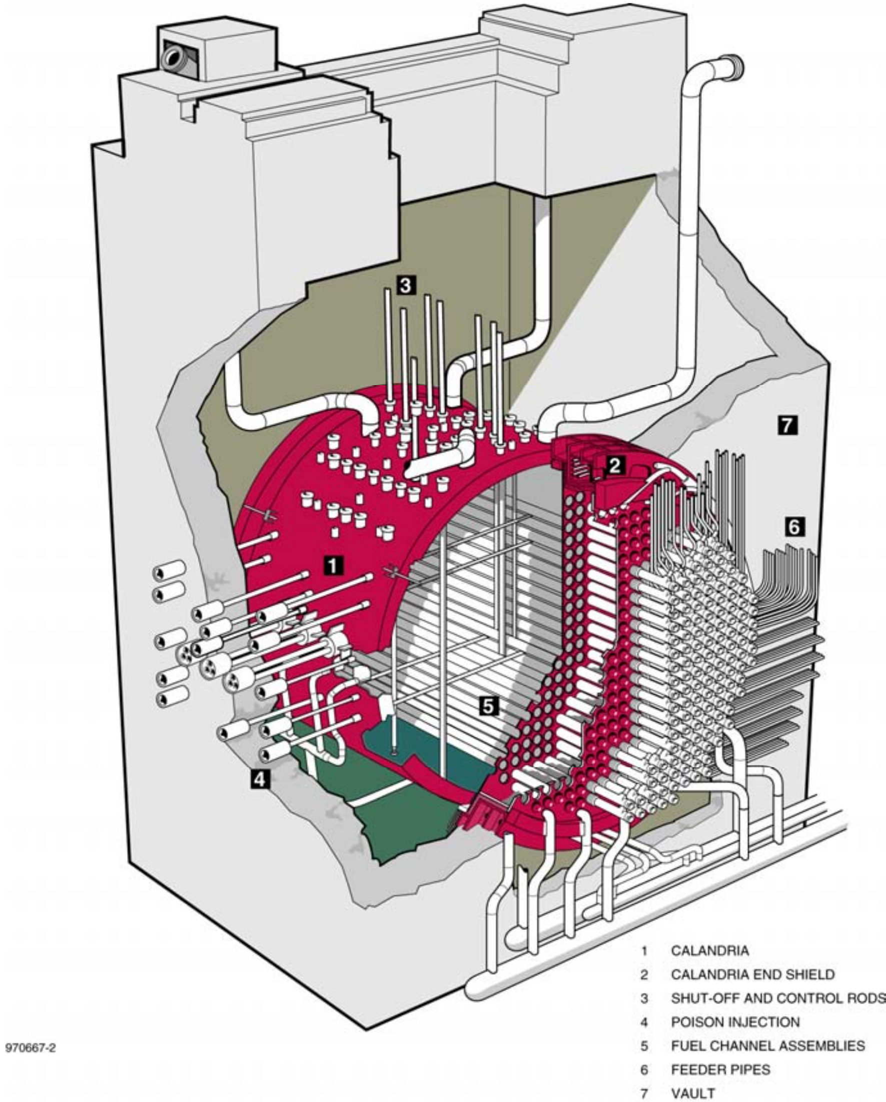


Single Channel Events: Analysis Objectives

- Assess fission product release from fuel in the affected channel
- Assess integrity of in-core components following channel rupture due to phenomena such as hydrodynamic transient, pipe whip, fuel projectile and ablation
  - adjacent channels (propagation failure)
  - shut-off rod guide tubes (sufficient negative reactivity to keep the reactor sub-critical)
  - calandria vessel (loss of moderator)
- Remainder of heat transport system is affected as for a small pipe break

Single Channel Events: In-Core Components

- Molten material ejected from ruptured channel at 10 MPa (channel pressure)
- Molten material fragmentation occurs; large surface area
- Heat transfer from molten material to moderator
- Molten material interaction
- Potential damage to in-core components

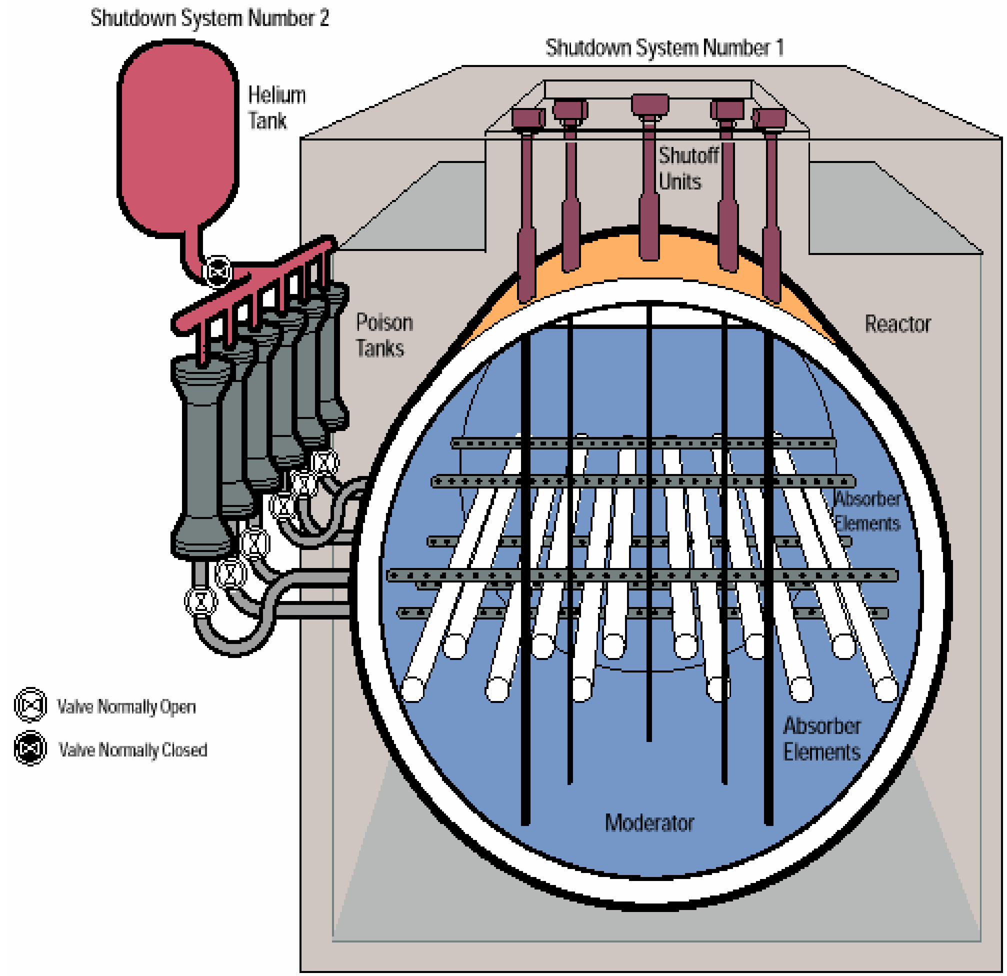


CANDU 6 Reactor Assembly

Single Channel Events: Shutoff Rod Guide Tubes

Potential Damage Mechanisms

- λ hydrodynamic transient
- λ pipe whip
- λ fuel ejection
- λ jet force impingement
- λ ablation due to molten material ejection



Single Channel Events: Safety Analysis Methodology for FSB

- Fuel conditions prior to the onset of the accident
  - calculate the fission product inventory of all elements in the channel (ELESTRES)
- Transient Temperatures
  - calculate transient thermalhydraulics and fuel temperatures in the channel (CATHENA)
- Fuel Element (Sheath) Failure
  - all elements in the channel are assumed to fail at the onset of the accident

Single Channel Events: Safety Analysis Methodology for FSB (Cont'd)

- Fission Product Release
  - Entire gap inventory of an element is released at the time of sheath failure (i.e., onset of the accident)
  - Grain bound and grain boundary inventory is released
    - Gehl's model and Zircaloy/UO_2 reaction model
  - After channel failure the rapid cooling of the fuel may result in fuel cracking due to induced thermal stresses
    - therefore, the remaining grain boundary inventory is assumed immediately released at the time of channel failure
- TUBRUPT assesses in-core damage following molten-fuel-moderator interaction

Single Channel Events: Flow Blockage Scenario

- A severe flow blockage reduces the flow such that the fuel heats up rapidly at full power
- Reactor trips following channel rupture
- The fuel heats up under similar conditions as a feeder stagnation break
- Analysis objectives are the same as for a feeder stagnation break
- Safety Analysis Methodology:
  - ELESTRES, CATHENA, TUBRUPT code; entire fission product inventory in the blocked channel is released at the onset of the accident
  - following channel rupture, fission products are released into the moderator; unlike a feeder stagnation break accident where fission products are released into containment

Single Channel Events: Off-Stagnation Feeder Break

- Break in inlet feeder large enough to cause reverse flow in channel
  - doesn't lead to PT failure
- Slightly larger than stagnation breaks:
  - 13 cm^2 (near header)
  - 7 cm^2 (near end fitting).
- Low coolant flow rate through the channel
- Reduction in coolant flow rate over an extended period of time results in elevated fuel temperatures during the transient

Single Channel Events: Off-Stagnation Feeder Break (Cont’d)

- However, the reduction in coolant flow is not sufficient to cause fuel channel failure prior to reactor trip
- Low steam flow over a extended period of time results in fuel oxidation

Single Channel Events:
Safety Analysis Methodology (Off-Stagnation)

- Fuel conditions prior to the onset of the accident
  - calculate the fission product inventory and distribution of of all elements in the channel
- Transient Temperatures
  - calculate the boundary conditions (CATHENA)
  - calculate the transient fuel element temperatures in the channel (ELOCA) accounting for FPR during transient
- Fuel Element (Sheath) Failure
  - The failure of the first element in the channel is predicted by the ELOCA code in conjunction with failure criteria (all elements are assumed to fail at this time)

Single Channel Events: Off-Stagnation Methodology (Cont'd)

- Fission Product Release
  - the entire gap inventory of an element is released at the time of sheath failure plus any fission products released from the fuel up until the time of failure is included
  - Upon sheath failure, the fuel matrix is exposed to high temperature steam and fuel oxidation occurs resulting in additional releases
  - Models to simulate the high temperature transient behaviour
    - diffusional releases,
    - steam oxidation of fuel

Single Channel Events: Feeder Breaks - Results

- Fission Product Releases
  - soluble fission products retained in moderator (stagnation breaks) or mix with water at break (off-stagnation)
  - airborne water aerosols retained in containment
    - where no impairment of containment envelope is assumed
  - containment overpressure mild
  - activity release from intact containment would be small
- In-core damage (stagnation break)
  - up to 5 SOR guide tubes impaired
- Core net reactivity (stagnation break)
  - up to -7.4 mk

Single Channel Events: Pressure Tube Rupture Assessment

- Calandia tube intact - assumptions:
  - PT rupture occurs at channel inlet end near first bundle
  - Rupture area larger than channel or annulus areas
  - Break area of 150 cm^2 at end of bellows retaining ring
- Results:
  - Dryout at bundle location 7
    - but sheath and centreline temperatures low
    - fission products, if any, would be transported to outlet header
    - only a small fraction discharged through ruptured bellows

Single Channel Events: Pressure Tube Rupture Assessment (Cont'd)

- Assessment with failed Calandria Tube investigates:
  - calandria integrity
  - integrity of adjacent fuel channels
  - molten material
  - SOR guide tube damage
  - SDS1 depth for LOECC
- Major focus of analysis is for failed calandria tube case

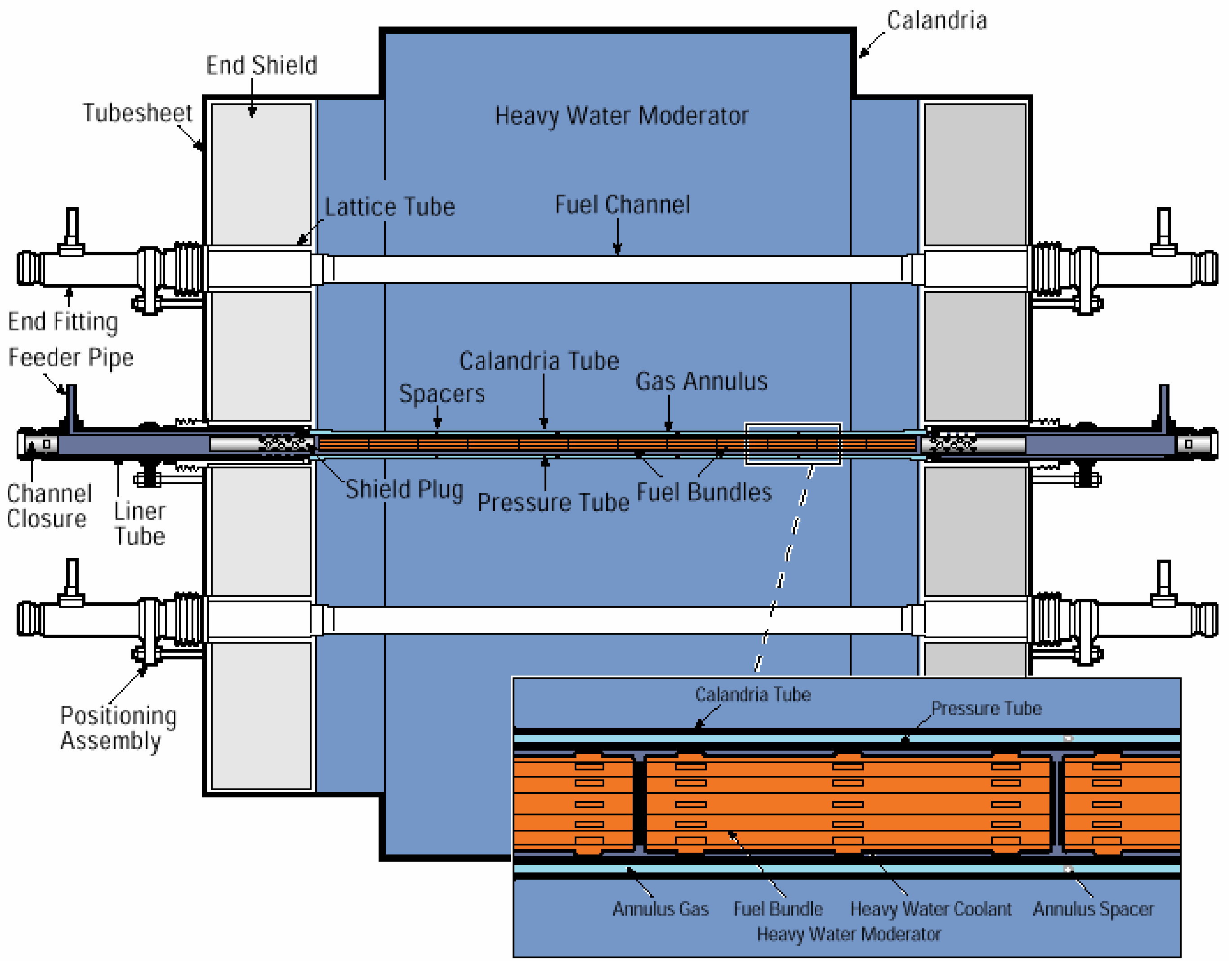
Single Channel Events: PT Rupture - Event Sequence

- A rupture occurs in the pressure tube
- The space between the pressure tube and calandria tube (annulus) fills with water and the calandria tube is assumed to rupture
- The fuel bundles contained in the channel are ejected into the moderator and may fragment
- The fission products contained in the fuel element gap released upon sheath failure
- No temperature dependent fission product release occurs, since the fuel bundles are cooled in the moderator water
- Moderator discharges into containment
- HTS pressure decreases; void increases

Single Channel Events: PT Rupture - Event Sequence (Cont'd)

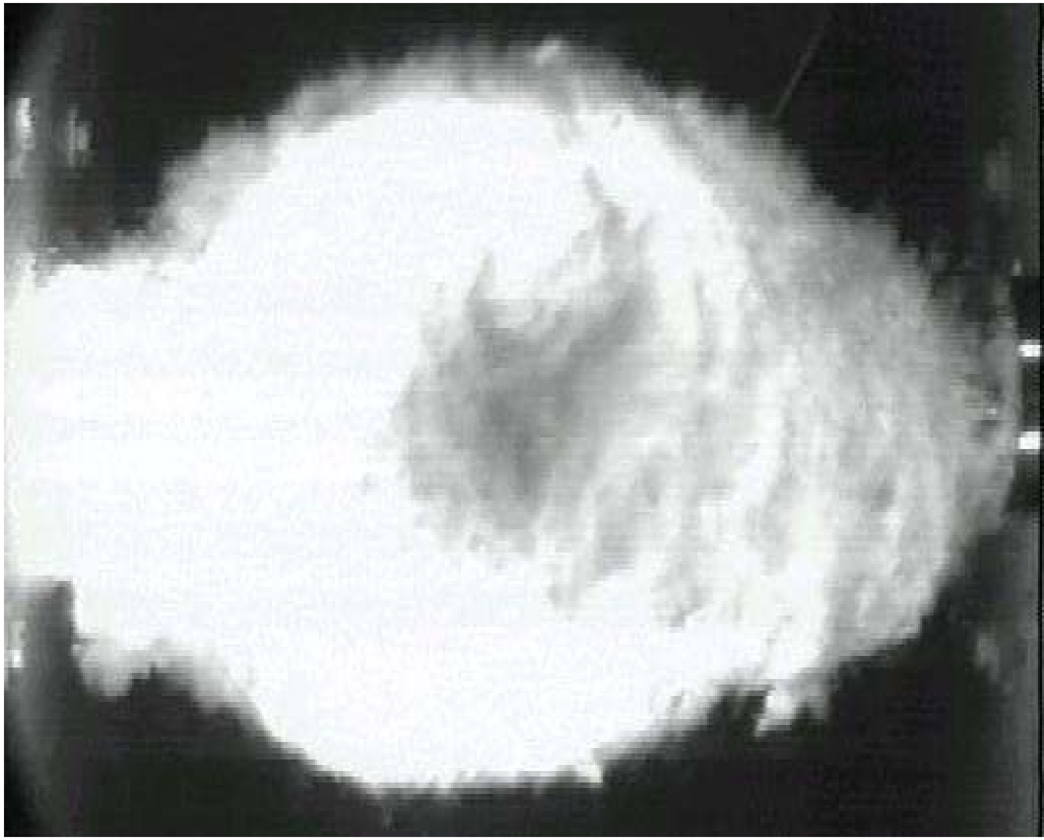
- RRS maintains power constant; no neutronic trip
- Reactor trip on low HTS pressure or low pressurizer level
- ECCS initiation; large negative reactivity
- Operator action at 15 minutes
- In-core damage is assessed (adjacent channels, shutoff rod guide tubes, calandria vessel)
- Unlike a feeder stagnation break and flow blockage event, there is no molten material generated during the event

Single Channel Events: Calandria Assembly



Single Channel Events: Bubble Growth

- Hot-pressurized water is discharged into the cool moderator water
- Coolant flashing occurs
- Steam bubble formation
- Bubble expands/contracts
- Pressurization of surrounding water
- Loading in-core structures
- Short term transient on order of milliseconds



Single Channel Events: PT Rupture - Analysis Methodology

- Damage to calandria, other fuel channels, and SOR guide tubes of interest
- Mechanisms include
  - hydrodynamic forces
  - jet impingement
  - pipe whip
  - fuel bundle ejection
- General assumptions
  - 2.5 m longitudinal break
  - gas annulus fills with coolant prior to CT rupture
  - partial CT collapse (20%) at 820 kPa

Single Channel Events: PT Rupture - Analysis Methodology (Cont’d)

- Peak pressure at inner calandria shell
  - –less than 2 MPa(a)

Single Channel Events: PT Rupture - Integrity of Adjacent Channels

- Effect of:
  - pressure load
  - coolant jet force
  - turbulent flow-induced vibration
  - impact of fuel, PT, CT fragments
- Experimental results show:
  - collapse of CT or in some cases CT damage, BUT no adjacent PT failure

Single Channel Events: PT Rupture - SOR Guide Tube Damage

- Hydrodynamic force calculated by TUBRUPT
  - transient back pressure of shield water modelled
- Deposited energy:
  - less than 600 J, SOR fully inserted
  - 600 - 1200 J, SOR 50% inserted
  - larger than 1200 J, no SOR insertion
- Jet force, pipe whip, fuel projectile damage calculated
- Various break locations considered for total SOR guide tube damage
- Results
  - Maximum of 7 SORs impaired out of 28

Single Channel Events: PT Rupture - SDS Depth

- Reactivity effects
  - displacement of poisoned moderator
  - downgrading of moderator purity
  - moderator temperature
  - primary coolant voiding
  - coolant temperature
  - fuel temperature
  - shutoff rods

Single Channel Events: PT Rupture - Reactivity Results

- Plutonium peak core at 15 minutes:

Parameter (Reactivity Change)	***Reactivity (mk) at 15 minutes***
Moderator Poison Displacement	10.5
Coolant Void	13.3
Coolant Temperature	0.3
Fuel Temperature	4.1
Degrading Moderator	-4.8
Moderator Temperature	-0.1
Shutoff Rods	-27.1
Net Reactivity	***-3.9***

Single Channel Events: End-Fitting Failure

- In a postulated end-fitting failure (i.e., closure plug failure), the fuel bundles are ejected from the channel into the reactor vault
- Fuel break up occurs upon impact with surrounding structures
- The fuel is under decay power conditions and degraded cooling conditions
- Fuel elements exposed to air environment
- Air oxidation of the fuel becomes the dominant fission product release mechanism

Single Channel Events: Flow Blockage

- Prevention
  - ultrasonic flow measurement in each channel during commissioning
  - channel temperature monitoring system
  - fuelling machine differential pressure monitoring system

Single Channel Events: Flow Blockage Characteristics

- Rapid fuel and pressure tube heat up
- Timing of PT/CT failure
  - PT/CT contact time - ballooning criterion
  - bottom element sheath melting + 2 s - sheath melting criterion (more likely scenario)
- Molten fuel sheath and fuel

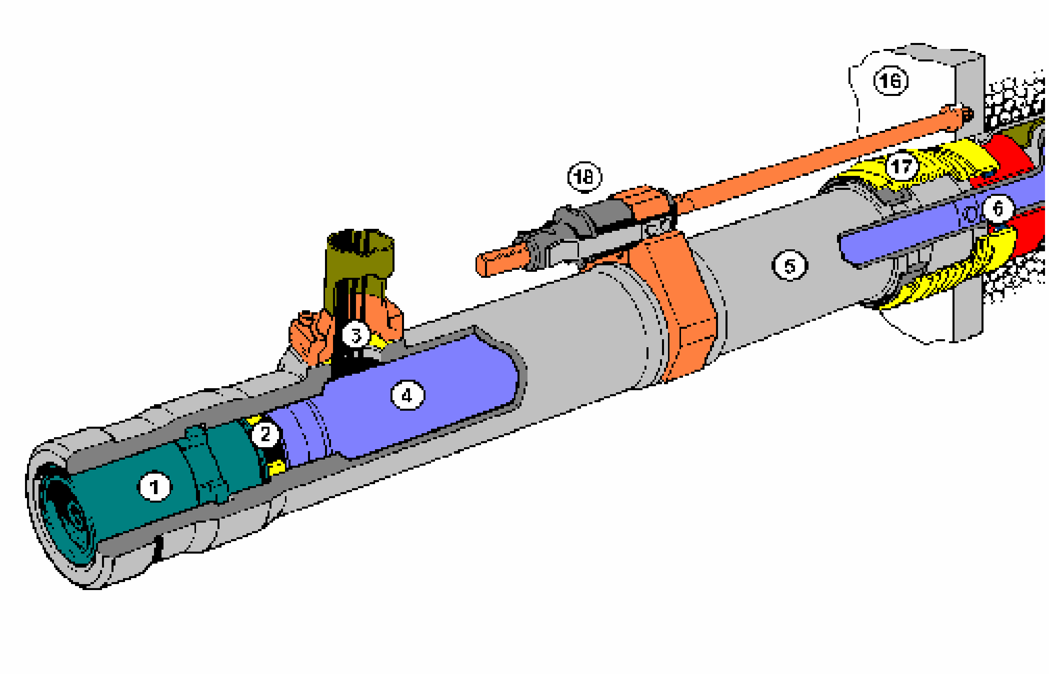
Single Channel Events: Flow Blockage Characteristics (Cont'd)

- Results:
  - 6 to 40 kg of molten material
  - permanent collapse of adjacent CTs, but no failure of PTs
  - damage to SOR guide tubes, but sufficient reactivity depth remains
  - calandria elastically stressed, but remains intact

Single Channel Events: End Fitting Failure

ITEMS

1. Channel closure plug
3. Feeder coupling
4. Liner tube
5. End-fitting body
17. Bellows



Single Channel Events: EFF - Characteristics

- Fuel bundles ejected to fuelling machine vault
- Prompt fission product release upon mechanical damage to fuel
- Possible fuel oxidation leading to release of bound fission products
- Dousing keeps containment pressure low and washes out soluble fission products (e.g.,I^{131})

Single Channel Events: EFF Safety Analysis Methodology

- Fuel conditions prior to the onset of the accident
  - calculate the fission product inventory of all elements in the channel (ELESTRES)
- Transient Temperature
  - fuel temperature transients are a function of the initial (in-reactor) fuel temperatures, decay heating rate and heat removal rate
  - calculated by the REDOU computer code

Single Channel Events: EFF Methodology

- Fuel Element (Sheath) Failure
  - ejected fuel bundles are assumed to break into pieces
  - UO_2 pellets are assumed to be completely ejected from the sheath and broken into fragments
- Fission Product Release
  - the gap inventory and exposed fraction of the grain boundary inventory (i.e., surface area of particle size) are released at the time of failure
  - under air oxidation conditions, the fuel transforms from UO_2 to U_4O_9 and then to U_3O_8
  - REDOU code is used to predict transient fission product release (grain bound and remaining grain boundary inventory)

Single Channel Events: Summary

- Feeder Breaks
  - stagnation and off-stagnation breaks
- Pressure Tube Rupture
  - calandria intact
  - sufficient shutdown depth
  - adjacent channels intact
- Flow Blockage
  - similar to PT rupture for severe blockage
  - small amount of molten material

Single Channel Events: Summary

- End Fitting Failure
  - mechanical damage to fuel bundles
  - fuel oxidation
- Public doses below AECB limits in all cases

Questions?