CANDU Safety #13:
Small Loss of Coolant Accidents

F. J. Doria

Atomic Energy of Canada Limited

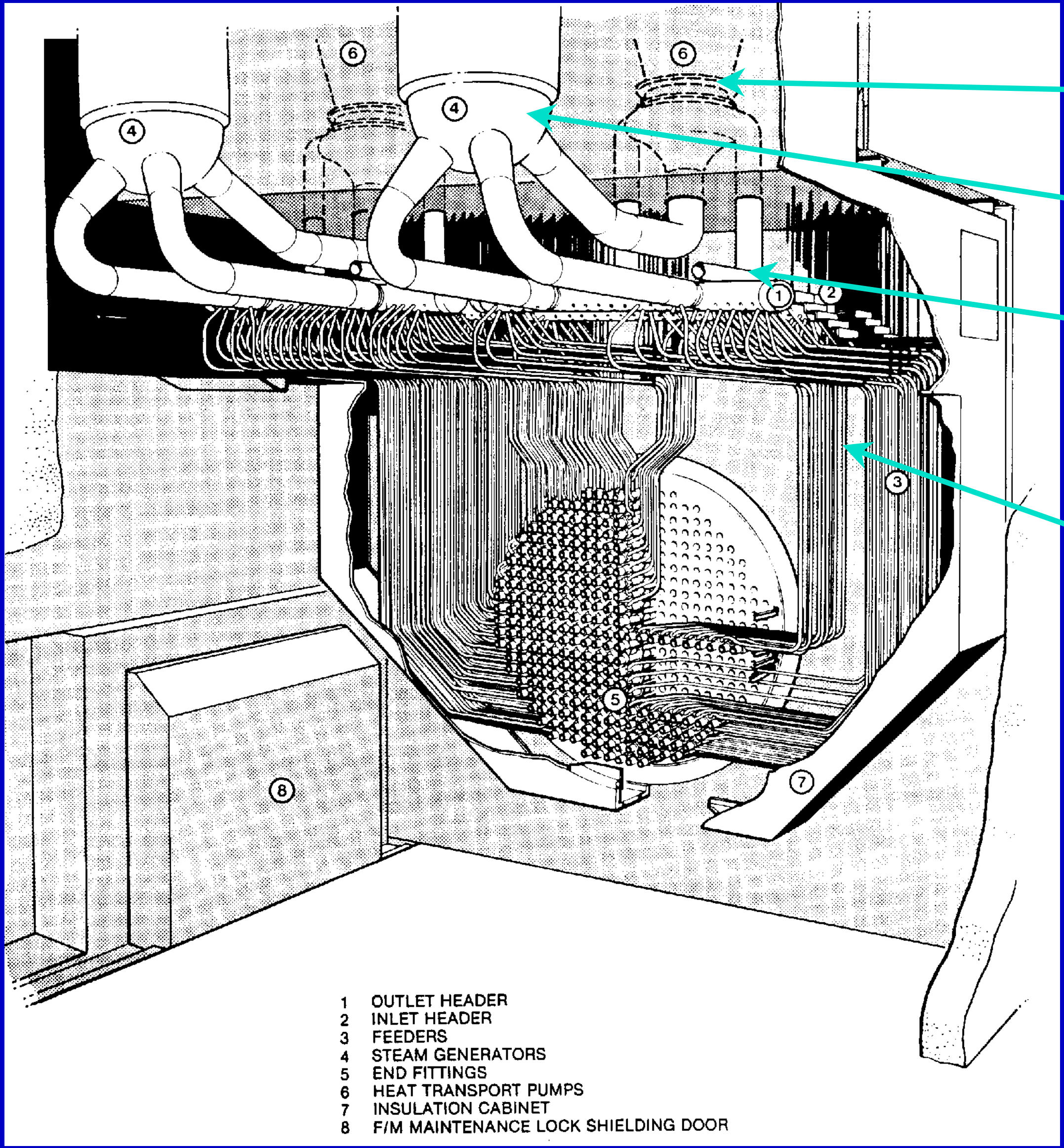
Overview

- Description of small loss-of-coolant accidents
- Event sequence for several small loss-of-coolant accidents
- Brief overview of analysis methodology
- Fuel and fuel channel behaviour during transient

Categories of Small Loss-of Coolant Accidents

- **Single-channel accidents**
  - **In-Core channel ruptures**
    - **Feeder stagnation breaks**
    - **Flow blockage**
    - **Spontaneous pressure tube rupture which leads to the consequential rupture of its calandria tube**
  - **Feeder off-stagnation breaks**
  - **End-fitting failure**
- **Small breaks in the primary heat transport system headers**

Feeder Stagnation Break (Reactor Face)



PHT Pumps

Steam generators

Inlet and Outlet Headers

Feeders

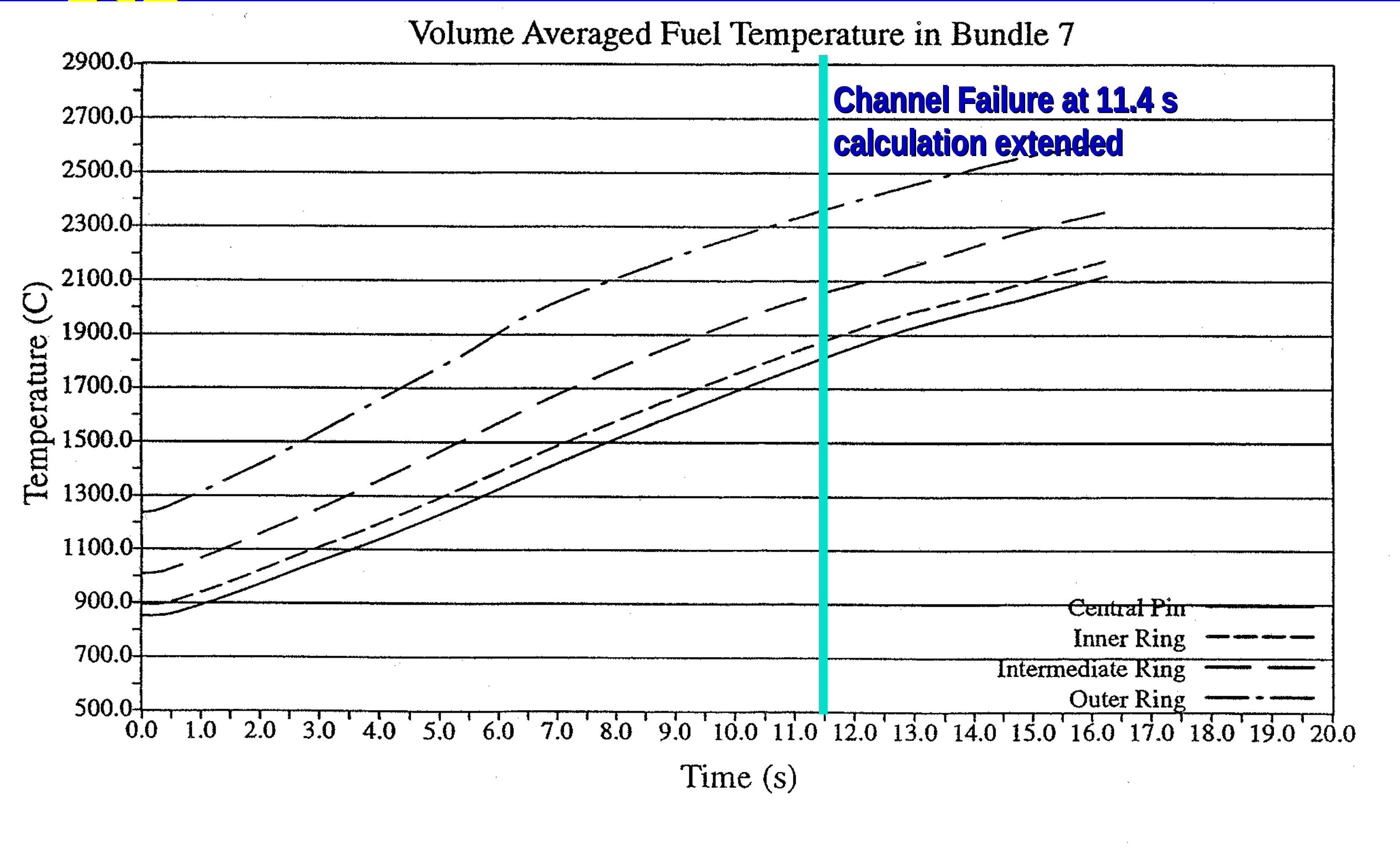
Feeder Location

Feeders

Feeder Stagnation Break Events

- Limited range of break sizes and feeder locations can lead to flow stagnation in the channel
- As the flow in the channel decreases, the reactor continues to be at power until reactor trip occurs after channel rupture (channel rupture calculated at 11.4 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
- 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
- Interaction between molten material generated in channel and the moderator water occurs
- Potential for channel failure propagation

High Powered Channel - Fuel Temperatures for ESR

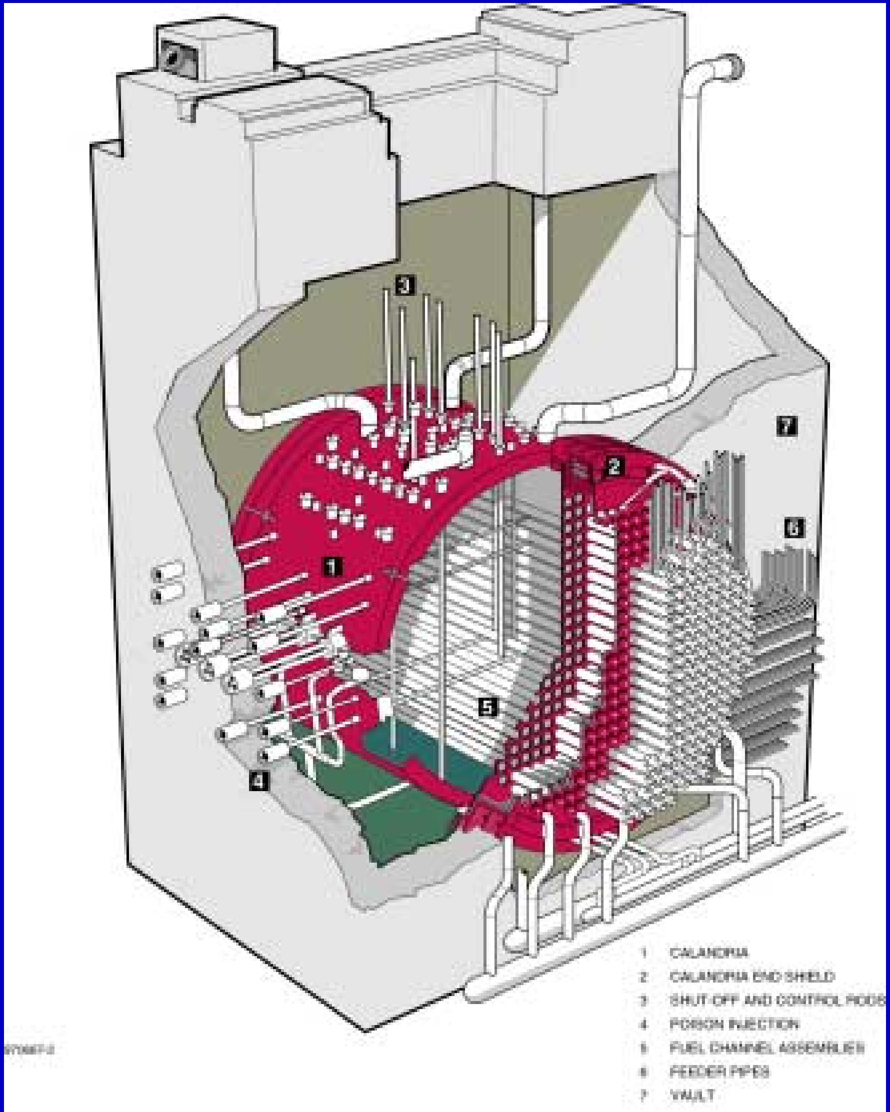


Analysis Objectives

- 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

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

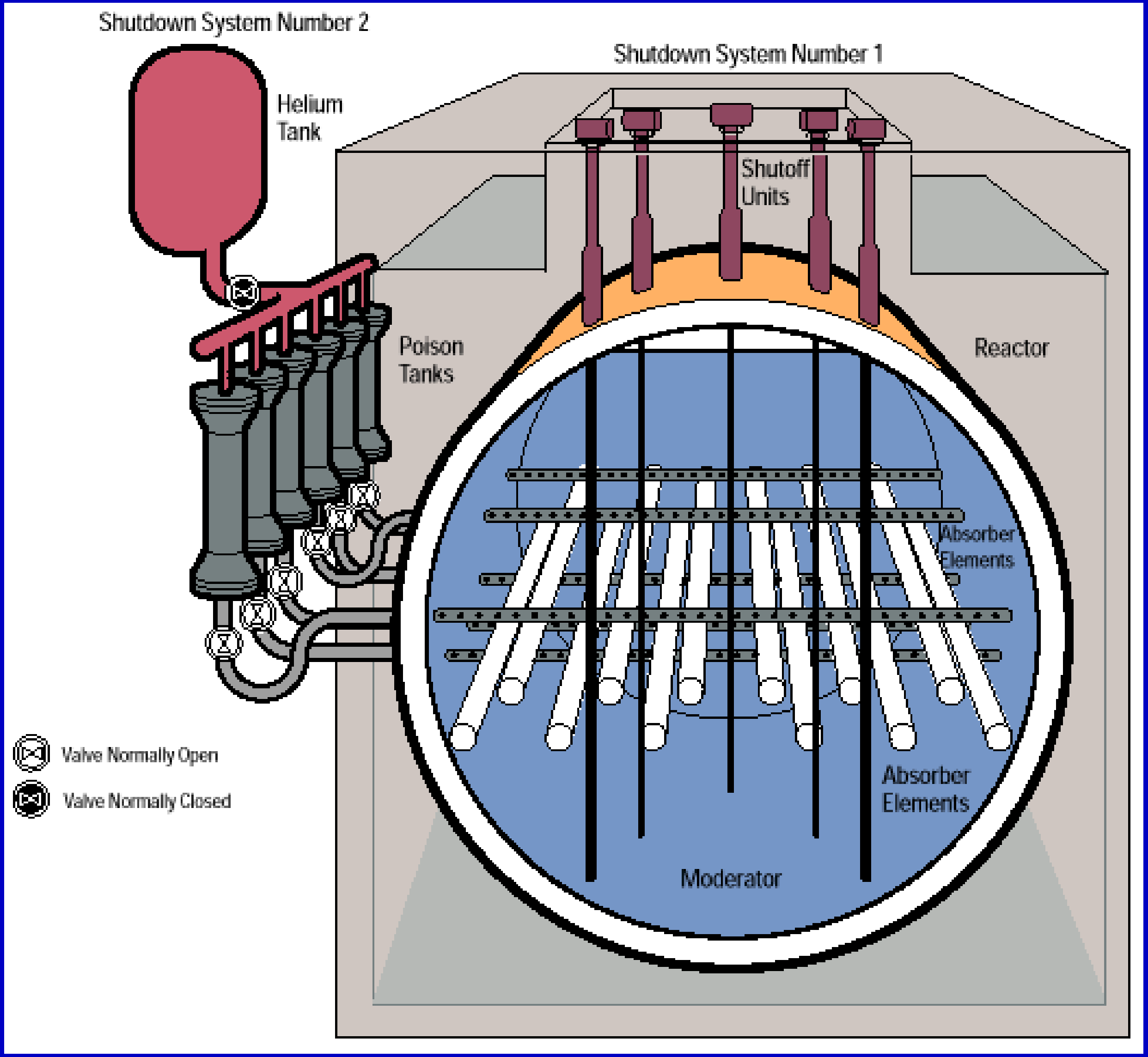


CANDU 6 Reactor Assembly

Shutoff Rod Guide Tubes

Potential Damage Mechanisms

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



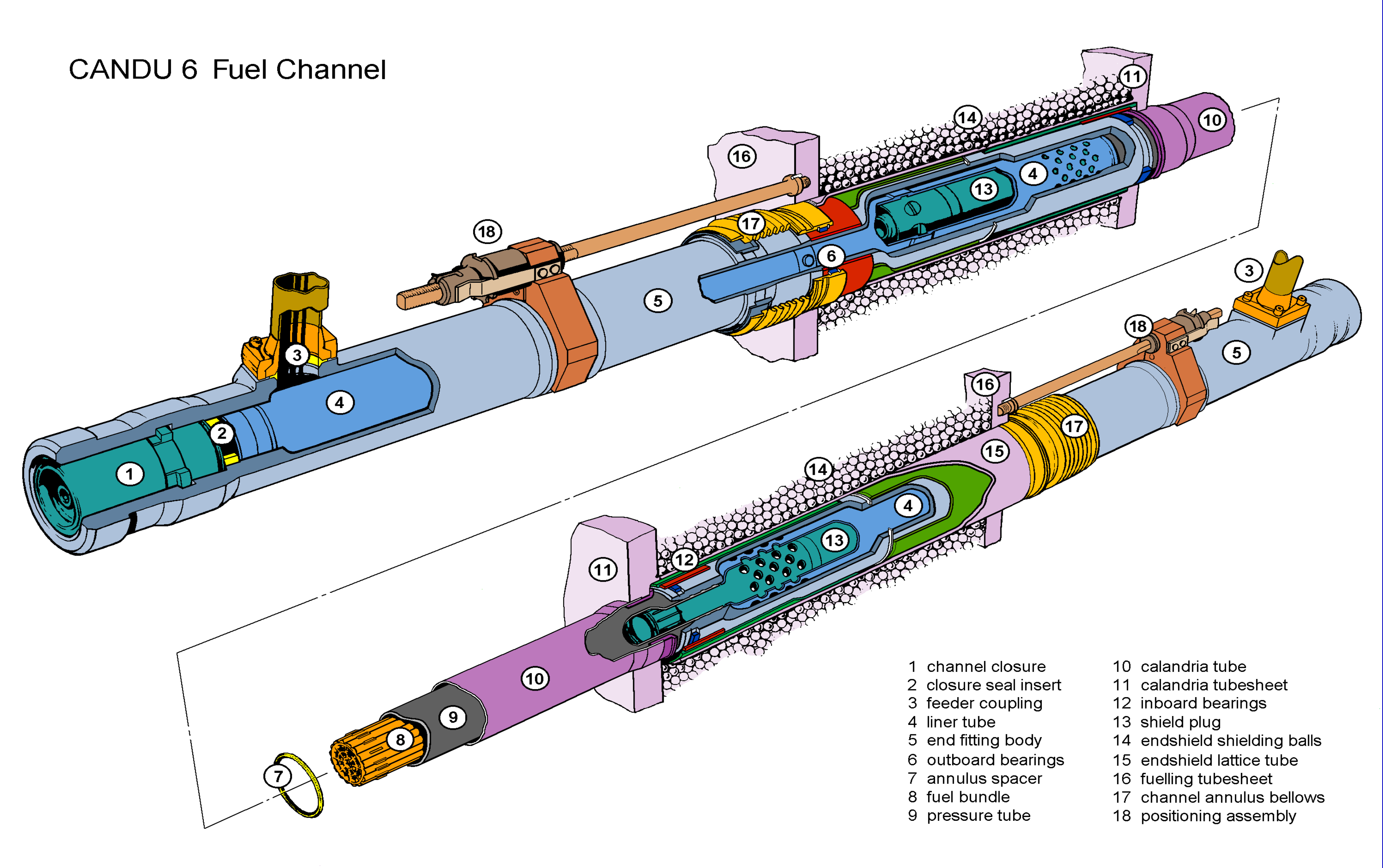
Safety Analysis Methodology for FSB

- **Fuel conditions prior to the onset of the accident**
  - ELESTRES calculates the fission product inventory of all elements in the channel
- **Transient Temperatures**
  - CATHENA calculates transient thermalhydraulics and fuel temperatures in the channel
- **Fuel Element (Sheath) Failure**
  - all elements in the channel are assumed to fail at the onset of the accident
- **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 release via 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 immediately released at the time of channel failure
- **TUBRUPT assesses in-core damage following molten-fuel-moderator interaction**

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

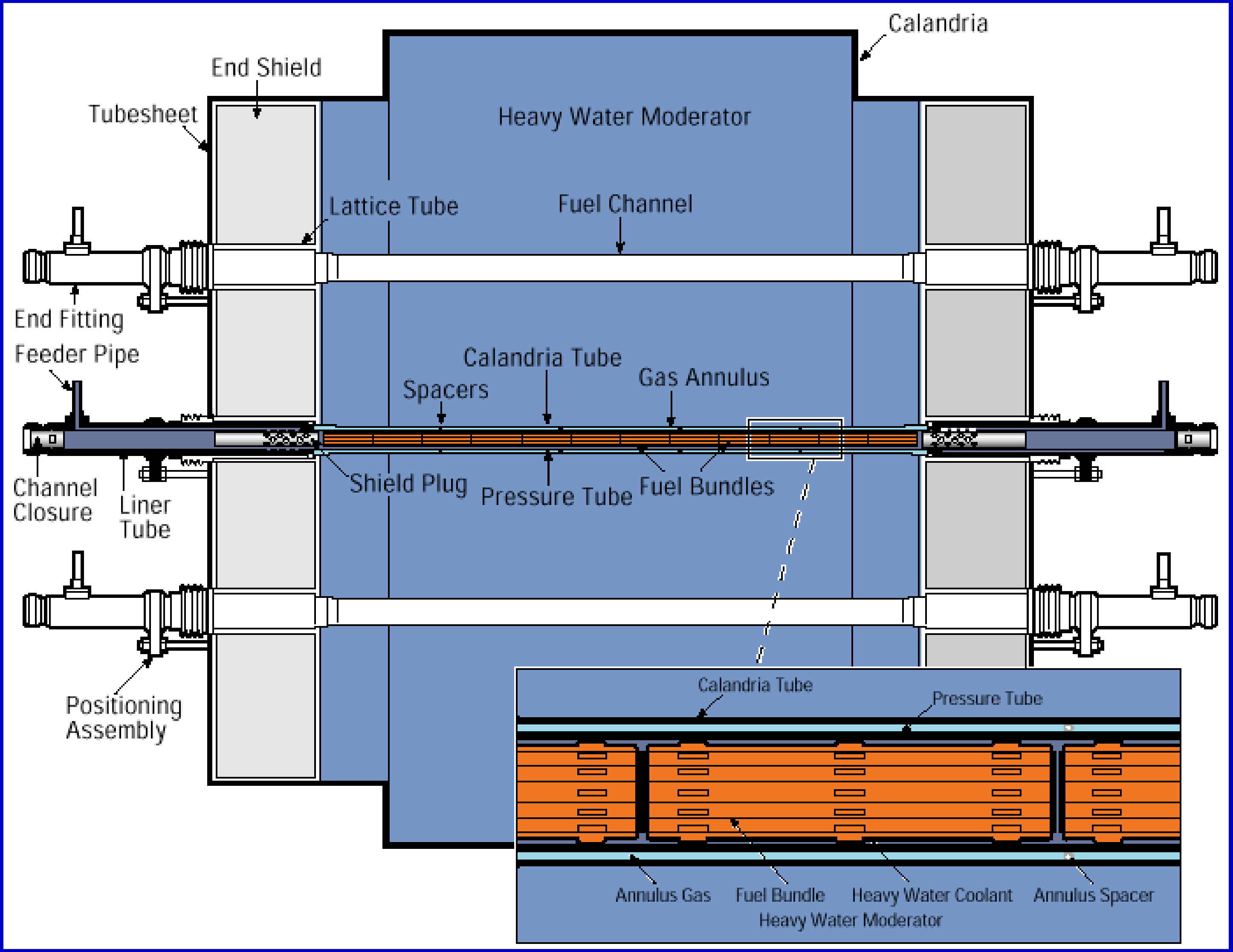
Flow Blockage Location



Spontaneous Pressure Tube Rupture

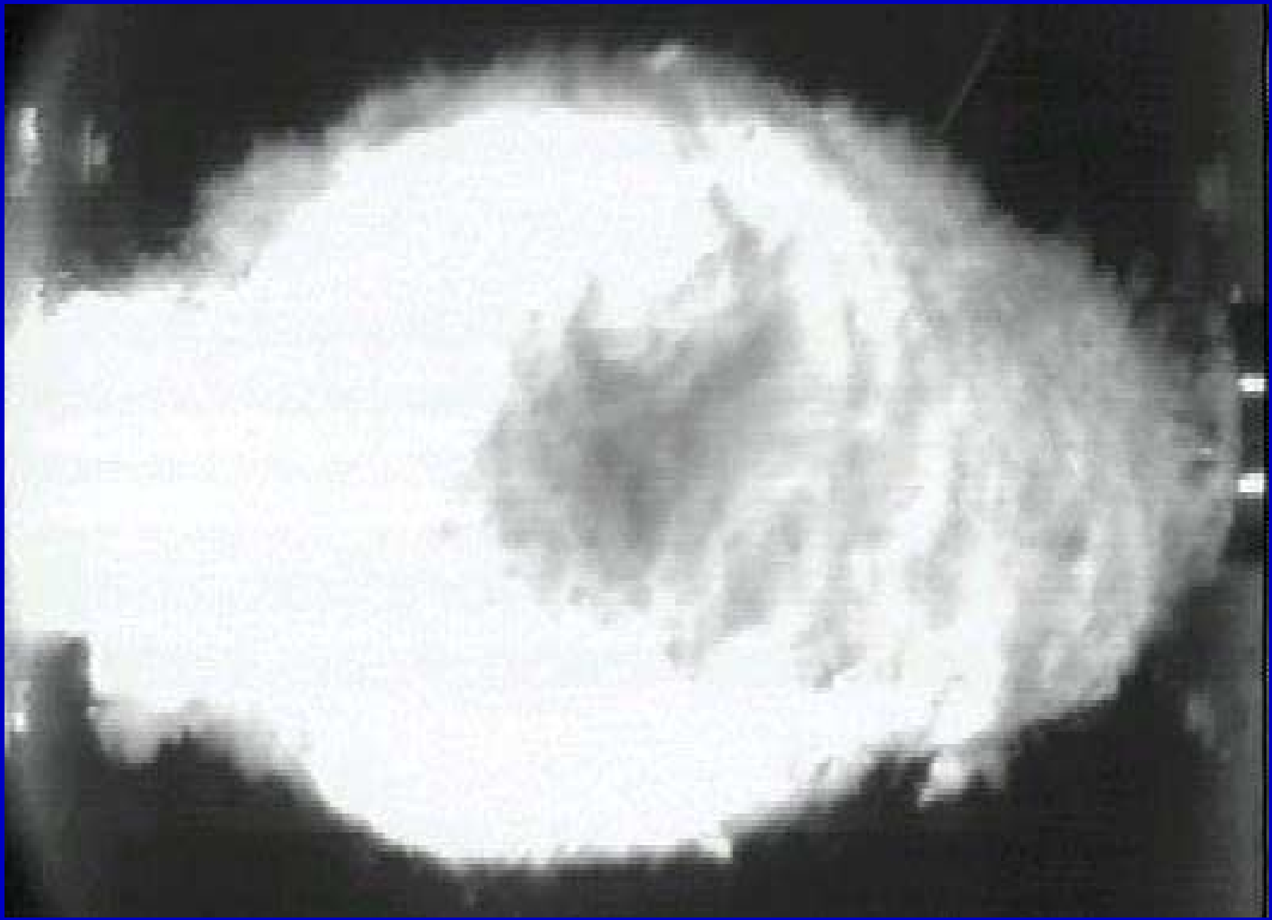
- A rupture occurs in the pressure tube
- The space between the pressure tube and calandria tube (annulus) fills with water and the calandria tube is assumed to rupture.
- The fuel bundles contained in the channel are ejected into the moderator and may fragment
- The fission products contained in the fuel element gap may be released upon sheath failure
- No temperature dependent fission product release occurs, since the fuel bundles are cooled in the moderator water
- In-core damage is assessed (adjacent channels, shutoff rod guide tubes, calandria vessel)
- Unlike a feeder stagnation break and flow blockage, there is no molten material generated during the event

Calandria Assembly



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



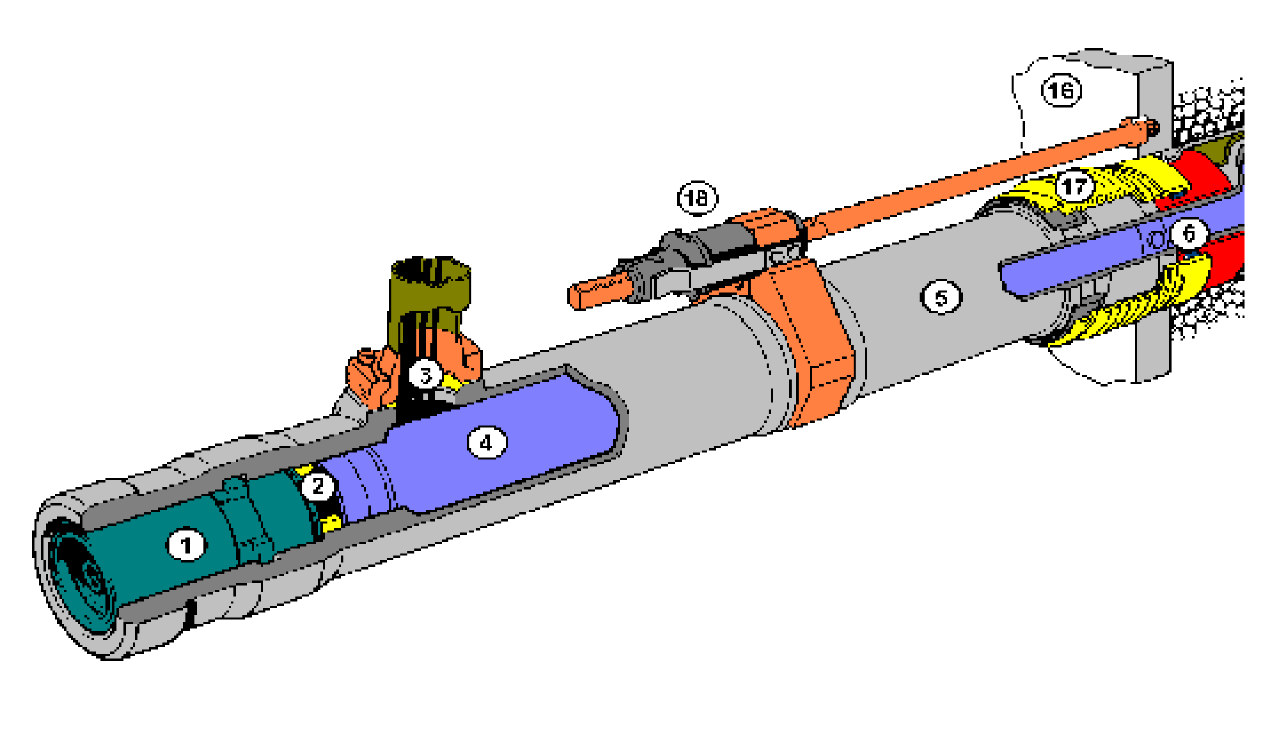
End-Fitting Failure

- 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

End-Fitting Failure

ITEMS

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



Safety Analysis Methodology (EFF)

- Fuel conditions prior to the onset of the accident
  - ELESTRES calculates the fission product inventory of all elements in the channel
- 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
- 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

EFF Methodology (cont'd)

- 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)

Feeder Off-Stagnation Break

- 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
- 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

Safety Analysis Methodology (FOSB)

- Fuel conditions prior to the onset of the accident
  - ELESTRES calculates the fission product inventory and distribution of of all elements in the channel
- Transient Temperatures
  - CATHENA is used to calculate the boundary conditions for the ELOCA code
  - ELOCA code is used to calculate the transient fuel element temperatures in the channel (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)

FOSB 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

Small Breaks in the Heat Transport System

- A small break occurs in the heat transport system
- Limited voiding (if any); no increase in reactor power
- Adequate reactor trip coverage is available to prevent any systematic fuel failures at the early stages of the accident
- After the reactor trips, the primary coolant pressure and temperature decrease rapidly
- When the pressure is reduced to the emergency core cooling setpoint of 5.5 MPa, the ECC signal is initiated automatically
- Following the injection, ECC refills the loop
- When containment pressure increases to the isolation setpoint (3.45 kPa above atmospheric pressure), containment isolation is automatically initiated