The ACR Class 1 Pressure Boundary

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AECL TECHNOLOGIES INC.

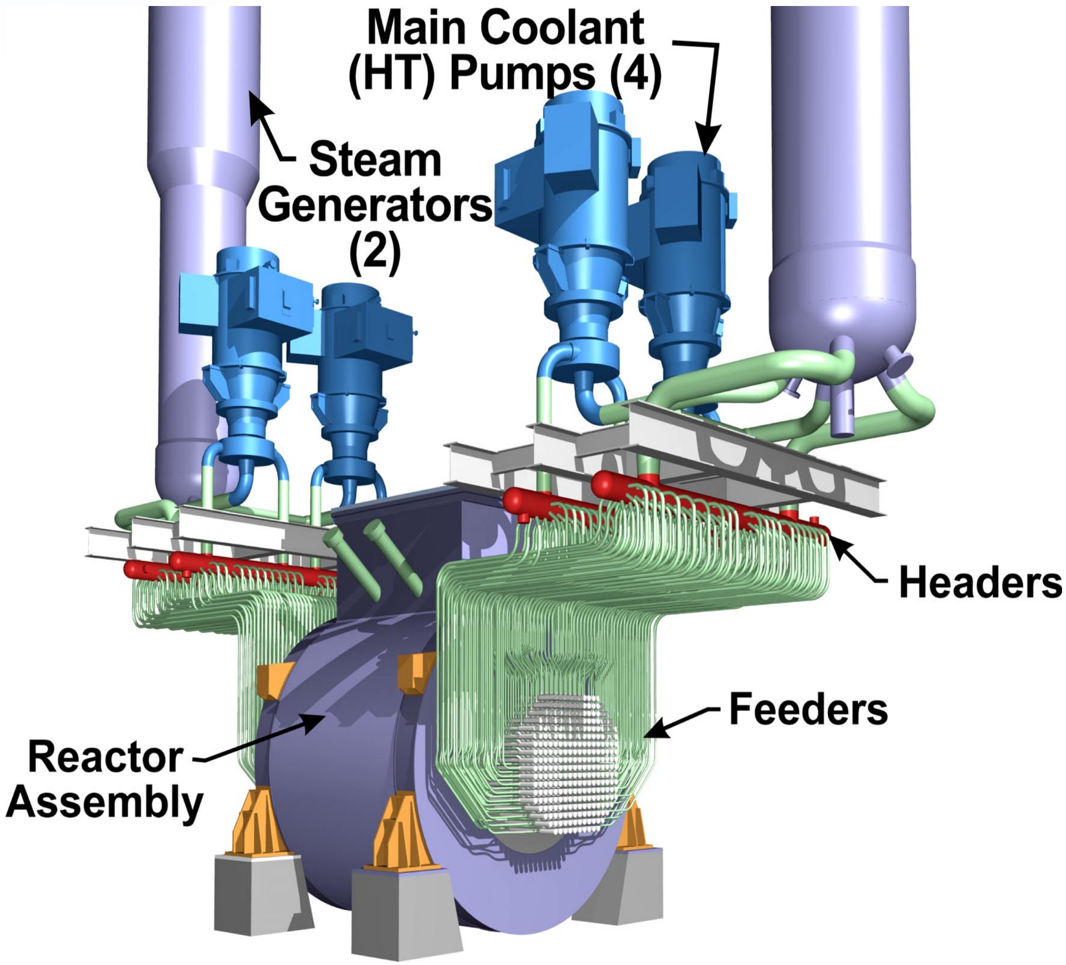
Outline

- Pressure Boundary Features of the ACR
- CANDU Experience
- Pressure Tube Leak-before-Break
- Fuel Channel Standards
  - Pressure Tubes
  - End Fittings
  - Channel Closures for on-power refueling
  - Inspection
    - Material Surveillance
- Summary

Pressure Boundary Features of the ACR

- **Piping, valves, pressure vessels – designed to ASME**
- **Feeder pipes – multiple, small diameter, pipes from headers to fuel channels – also designed to ASME**

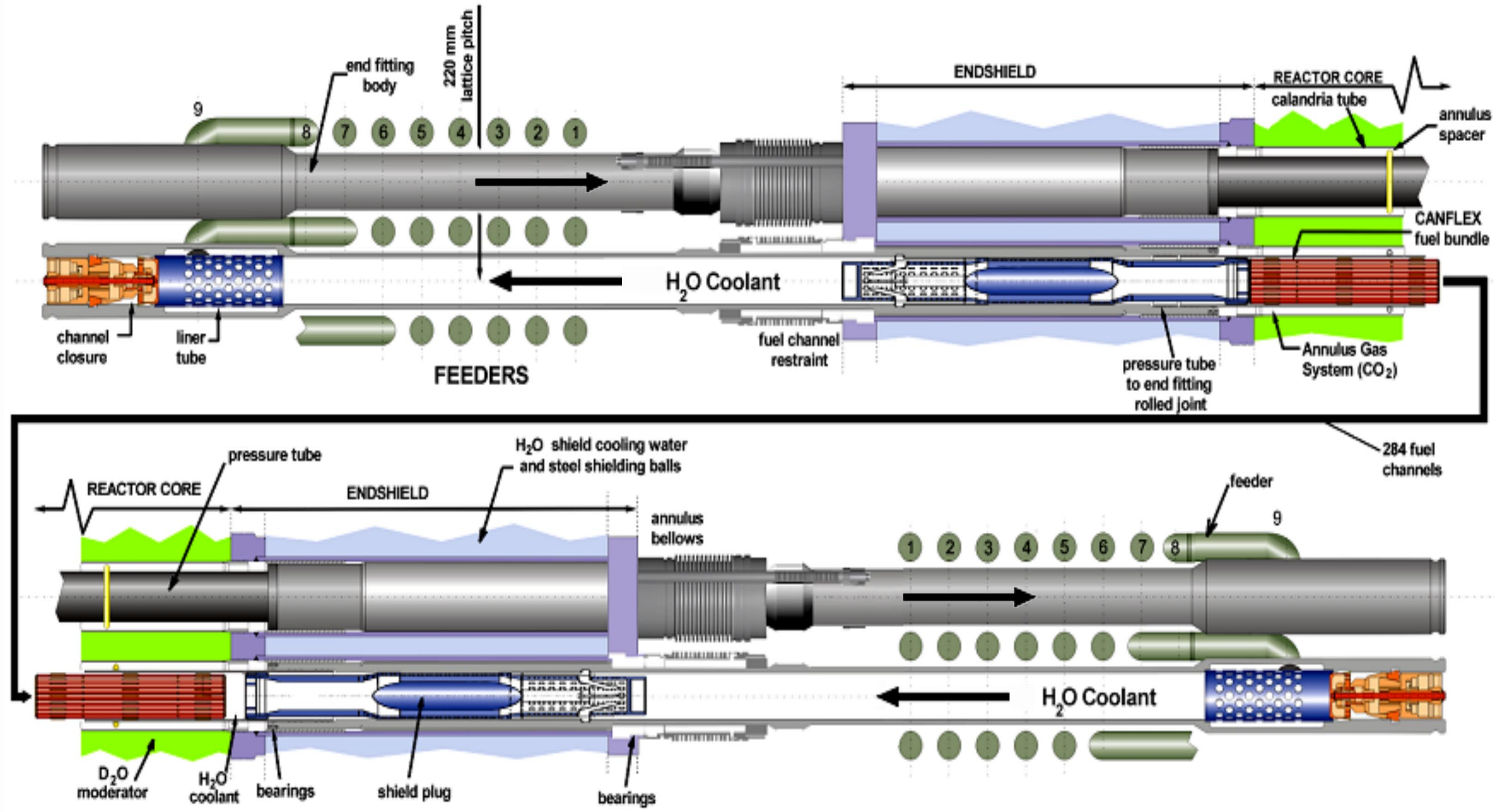
Reactor Coolant System



Pressure Boundary Features of the ACR

- **Fuel Channel – designed to Canadian Standards**
  – **Designed to meet intent of ASME with accommodation for pressure tube and refueling requirements**
    - **Material exceptions**
      – **Zr-2.5%Nb pressure tube**
      – **Modified 403 SS end fitting**
    - **Design differences**
      – **Rolled joint between pressure tube and end fitting**
      – **Channel closure for refueling**

ACR Fuel Channel



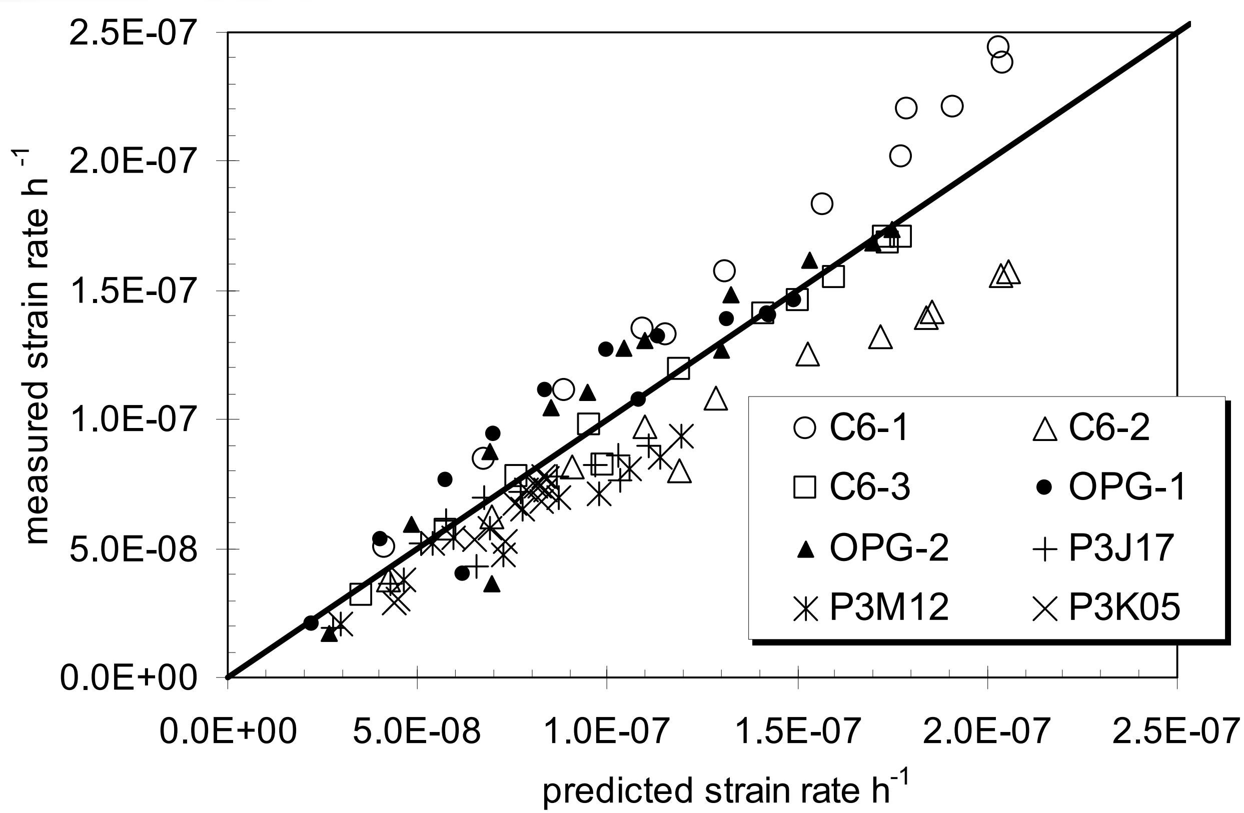
CANDU Fuel Channel Experience

- Power-reactor experience with pressure tube reactors in CANDU community began 41 years ago
- Approximately 400 reactor-years of operation of large CANDU's worldwide starting in 1971
- Longest-operating, Zr-2.5%Nb pressure tubes currently have ~ 150,000 hours of operation

CANDU Experience

- Pressure tubes change dimensions over their lifetime
  - Maximum 4.5% diametral expansion and ~7% wall thinning expected in ACR during a 30 year pressure tube lifetime
    - Due to irradiation creep and growth in anisotropic material
- Dimensional changes are accommodated by design
  - Zr-2.5% Nb deformation performance is well-understood and predictable within acceptable bounds
    - Experience and R&D programs cover the range of ACR conditions
    - Elongation accounted for in feeder clearances and stresses
    - Impact of diametral expansion on fuel cooling is taken into account

Diametral Strain Rates



CANDU Experience

- **Pressure tube creep ductility limits are large**
  - **Material deformation under irradiation is occurring with stress exponent close to 1, i.e. strain rate is almost proportional to stress**
  - **Low stress exponents correspond to very high strains to failure (superplastic behavior)**
  - **Tests of pressure tube materials indicate high failure strains**
  - **Material surveillance of tubes removed from service has not identified any microstructural changes indicative of a potential creep ductility limit**

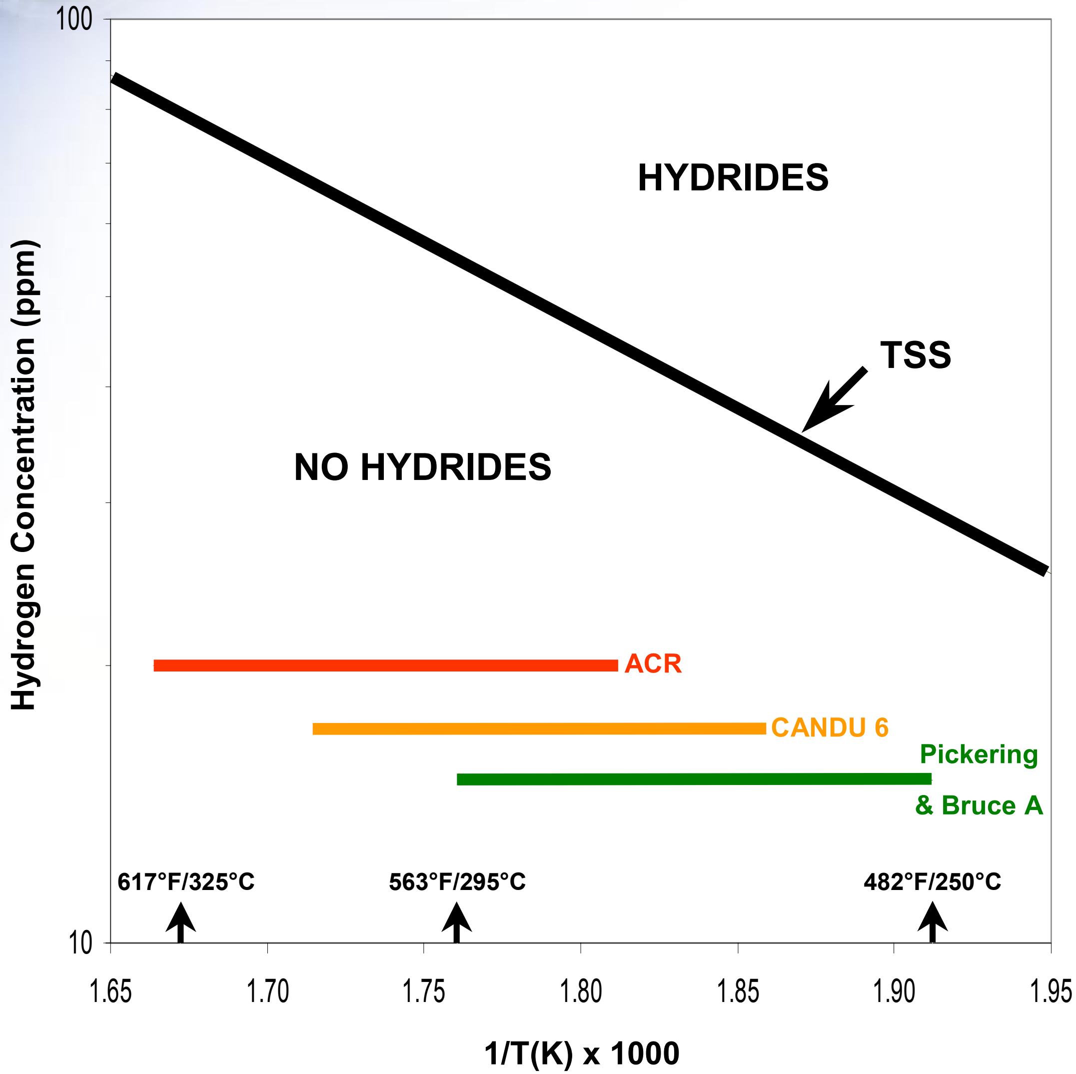
CANDU Experience

- Pressure Tube Integrity
  - No pressure tube leaks due to design / material performance since 1986
    - Early leaks due to high residual stresses near rolled joints and delayed hydride cracking (DHC)
    - Rupture of Zircaloy-2 pressure tube at power due to contact with calandria tube and hydride blistering
    - One rupture at cold conditions from long manufacturing flaw
  - Design, manufacturing and assembly issues that led to early failures have been solved
    - Development of low-stress rolled joint eliminated high residual stresses in pressure tubes near the joints and prevents crack initiation
    - New channel spacer design prevents contact between pressure tube and calandria tube and thereby prevents potential hydride blister formation in the pressure tubes
    - Improved manufacturing practices and better inspection reduces the possibility of long manufacturing flaws

CANDU Experience

- **DHC mechanism has been carefully studied and is well understood**
  - **Cracking not possible at operating temperature given that hydrogen content of tube remains below the hydrogen solubility limit at temperature**
  - **Crack initiation avoided by low-residual-stress joint technique and clean system preventing debris flaw formation**
  - **Cracking at lower temperature avoided by pressure reduction**

Source and Consequences of Hydrogen Ingress

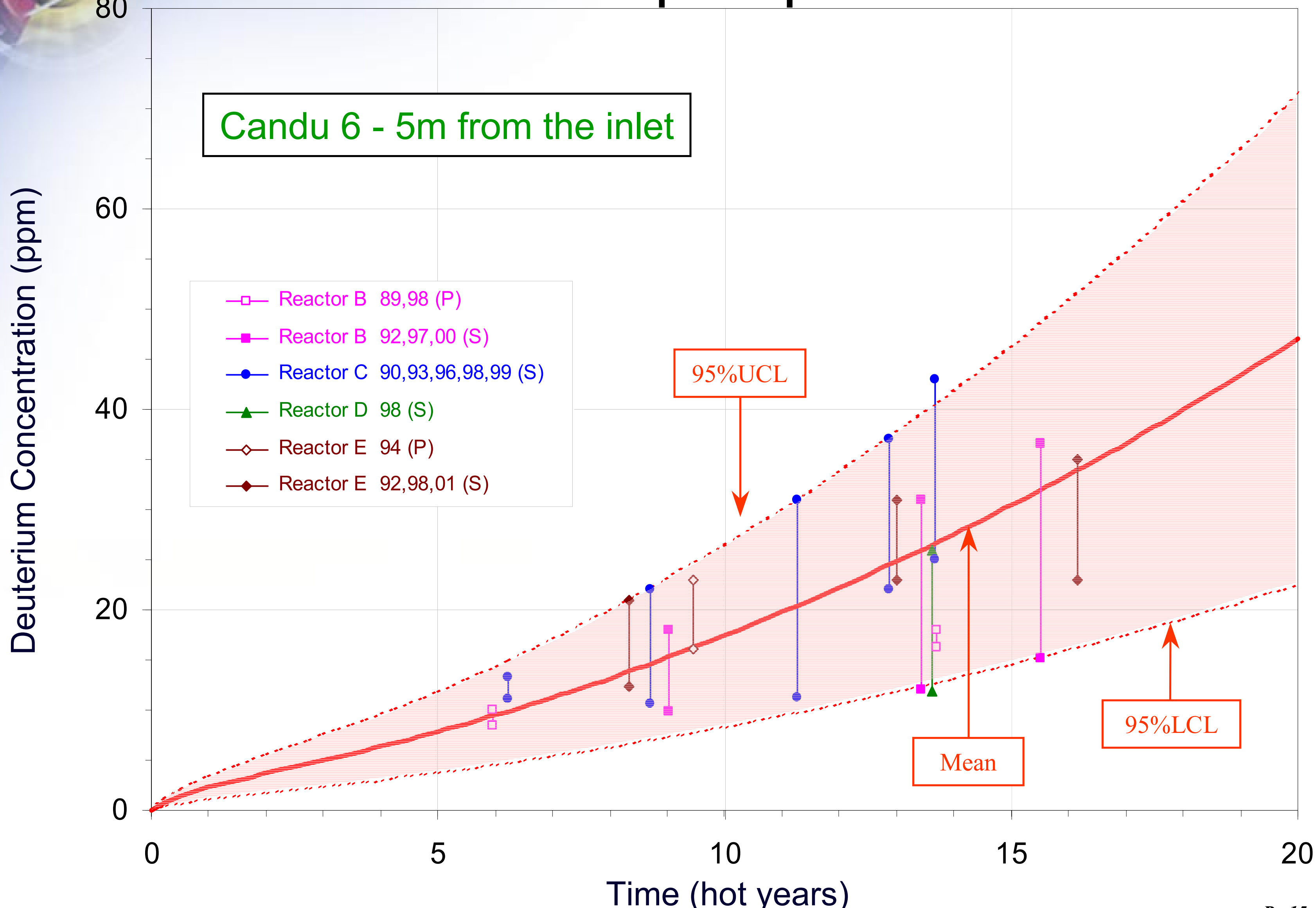


- Corrosion Reaction:
  $Zr + 2H_2O \rightarrow ZrO_2 + 4H$
- fraction of hydrogen absorbed by base metal
- hydrides present when Terminal Solid Solubility (TSS) exceeded
- hydrides can potentially lead to fracture issues
- ensure hydrides are not present during reactor operation at power

CANDU Experience

- **Pressure tubes corrode to produce hydrogen, some of which enters the tube**
  - **In current CANDU reactors, maximum waterside oxide thickness is 20 to 30 μm after 20 years operation**
  - **Maximum hydrogen pickup is approximately 20 ppm H (as D) after 20 years of operation except near rolled joints which exhibit higher hydrogen pickup**
  - **Empirical models of corrosion and hydrogen pickup, based on experimental programs, produce predictions consistent with observations from surveillance tubes**
    - **Models include rolled joint region and main body of the tube**

Measured Deuterium Pickup Compared to Model Predictions



Pressure Tube Leak-before-Break

- **Defense-in-depth for normal operation**
- **Gas circulated through the annuli between pressure tubes and calandria tubes is continuously monitored for moisture content**
- **Fracture toughness and crack growth rates of the pressure tube material remain at a level at which any tube, that could potentially develop a crack, would leak allowing time for leak detection, response and safe shutdown before the crack becomes unstable**
- **LBB is demonstrated by a sequence-of-events analysis using conservative assumptions**

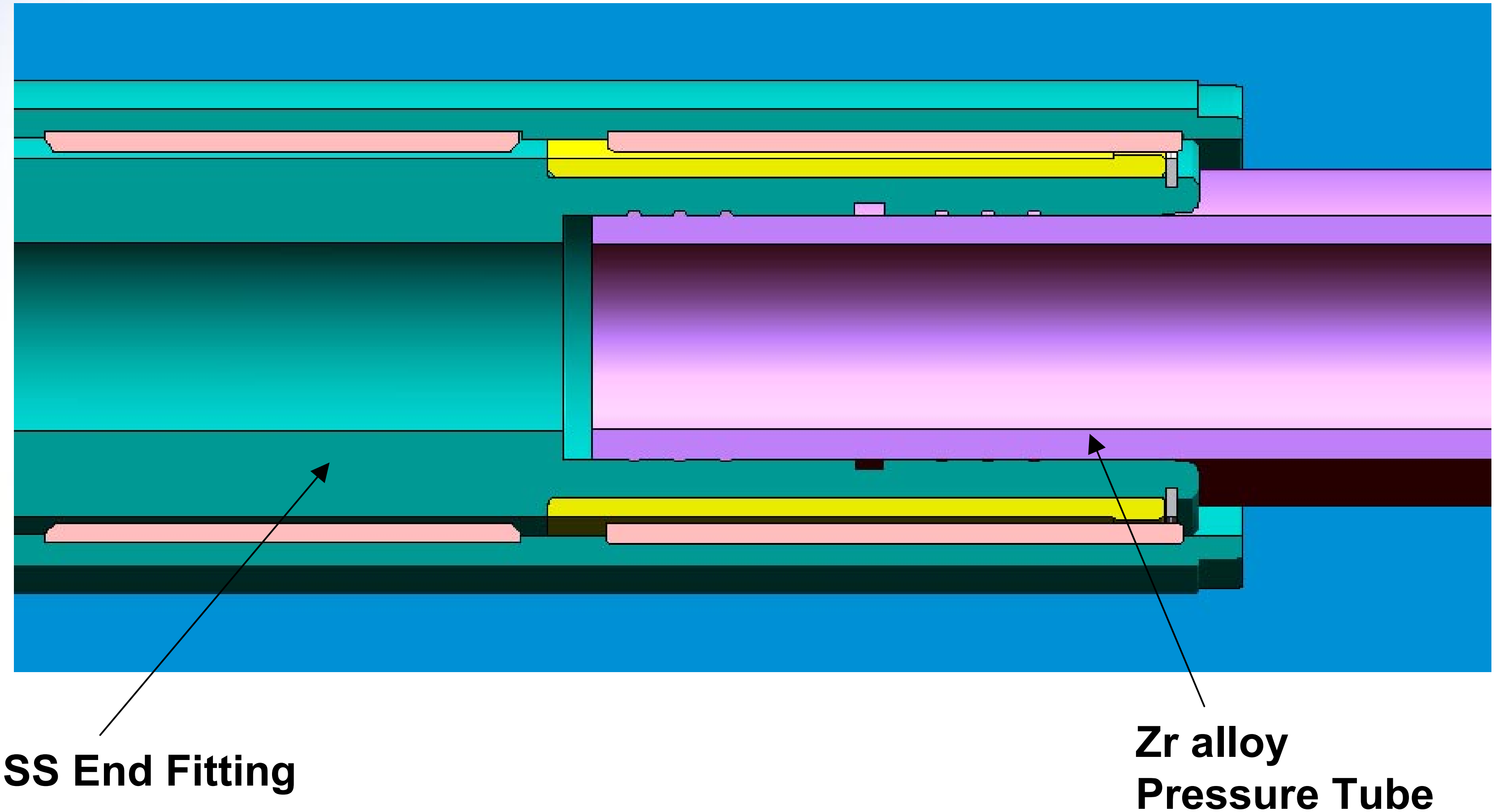
Fuel Channel Standards

- **Pressure tube**
  - Pressure tubes are designed to CAN/CSA N285.2 Standard
  - Tubes meet CAN/CSA N285.6 Standard and additional AECL Technical Specifications for material
  - Zr-2.5%Nb is an ASTM Standard B353 (UNS R60901) material
  - ASME – type criteria apply for allowable design stress levels
  - Tubes are a consistent, high quality product
  - Current production tubes have improved properties compared to earlier production achieved by improved material specifications and production methods – especially with respect to fracture toughness properties after irradiation – a result of R&D programs in fracture area

Fuel Channel Standards

- **Rolled joint**
  - Rolled joints will meet CAN/CSA N285.2
  - Designed to ASME Section III NB-3200 – "Design by Analysis"
  - Reliable, strong, mechanical joint suitable for zirconium alloy to stainless steel connection – able to withstand 3x design-condition axial load including pressure
  - Qualification is carried out on production-grade joints
  - Each reactor joint checked for designed pressure tube wall reduction and leak rate on installation

Pressure Tube to End Fitting Joints



Fuel Channel Standards

- **End Fitting**
  - Designed to CAN/CSA N285.2 and ASME Section III NB-3200
  - Material specified by CAN/CSA N285.6
    - Each end fitting made from a single forging
    - Modified 403 martensitic SS
      - High strength and corrosion resistance with acceptable fracture toughness
  - Excellent operating experience in CANDU – no identified issues from operation

Fuel Channel Standards

- **Channel Closures**
  - Channel closures are removable pressure boundary components at the outboard end of an end fitting required to permit on-power fueling
  - Satisfy ASME Class 1 design rules
  - Satisfy the following requirements specified by CAN/CSA N285.2:
    - Closure shall be locked in place to prevent inadvertent removal
    - Closures shall be leak tested each time they are installed prior to removal of the fuelling machine
  - CAN/CSA N285.2 requires interlocks to prevent fueling machine from disengaging before closure is in place

Fuel Channel Standards

- Periodic Inspection Programs for CANDU fuel channels are designed to monitor for any generic degradation and are defined by CAN/CSA N285.4
- Single channels removed for material surveillance purposes from “lead” reactor units
  - Source of fracture toughness, corrosion, hydrogen isotope pick up and DHC growth rate data after irradiation

Summary

- **CANDU fuel channels are a proven technology licensed in five jurisdictions including Korea**
- **An extensive technology base supports the design**

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