Technology Base for the ACR: FUEL CHANNELS

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Presented to US Nuclear Regulatory Commission

Office of Nuclear Reactor Regulation

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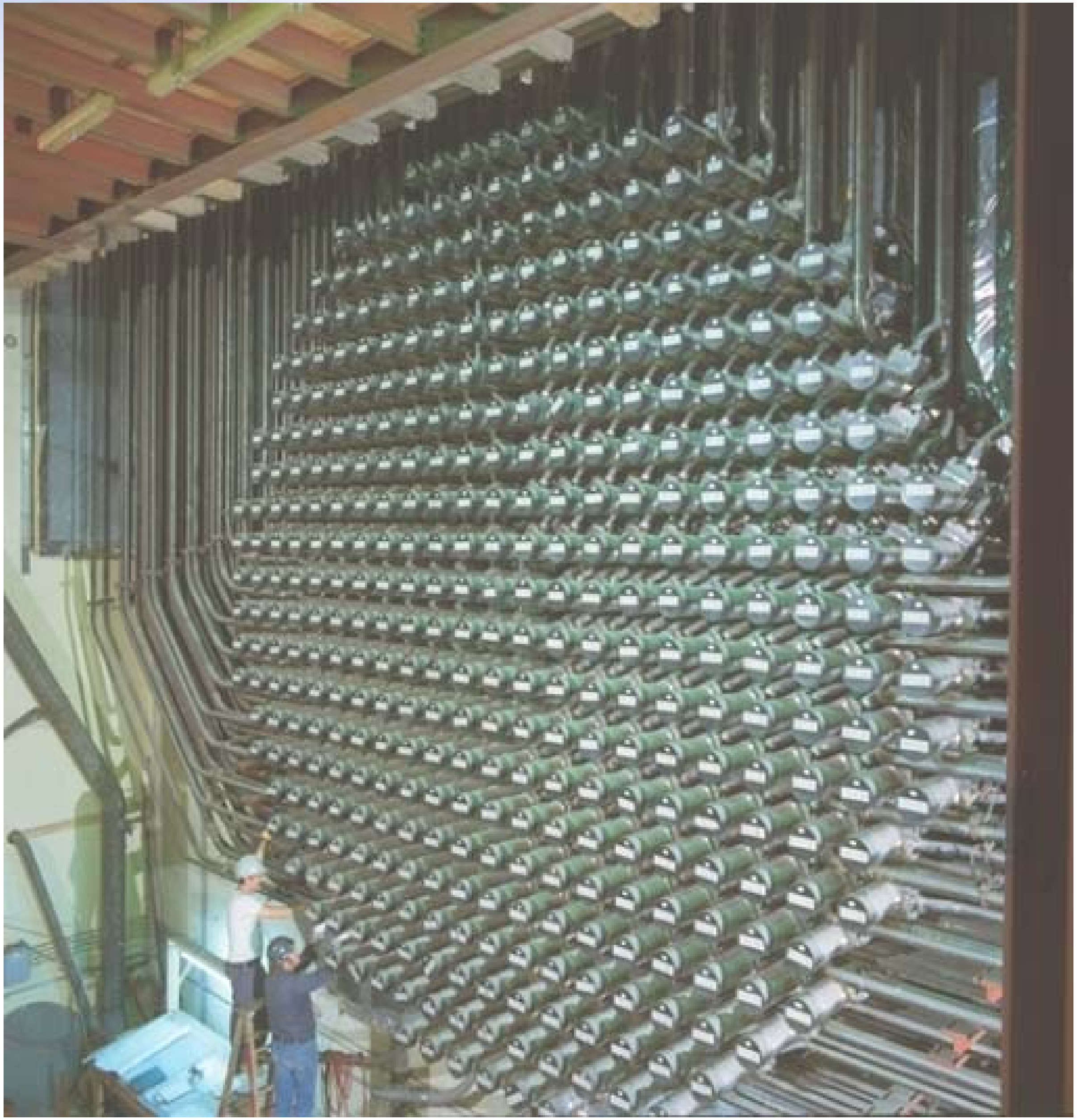
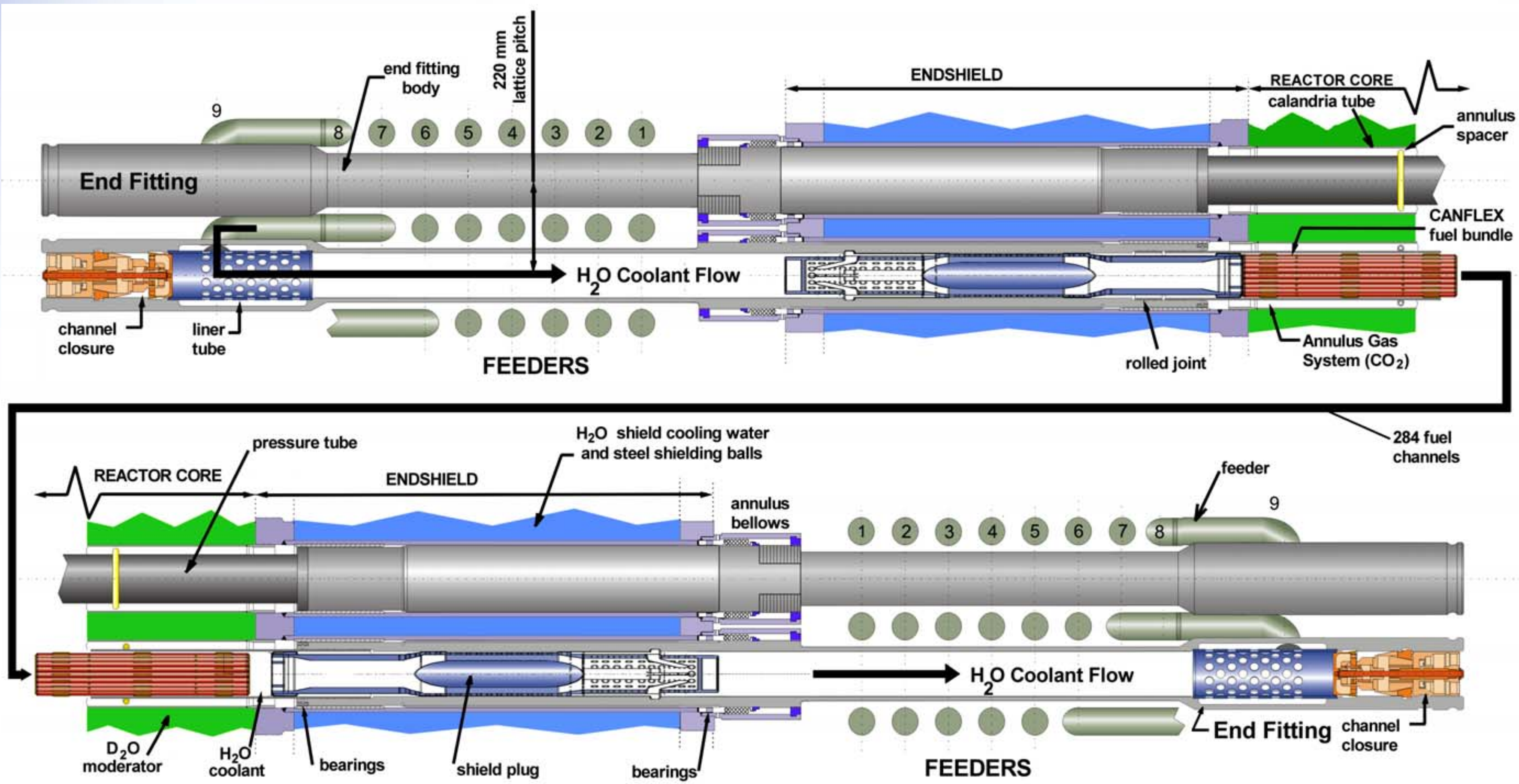
AECL

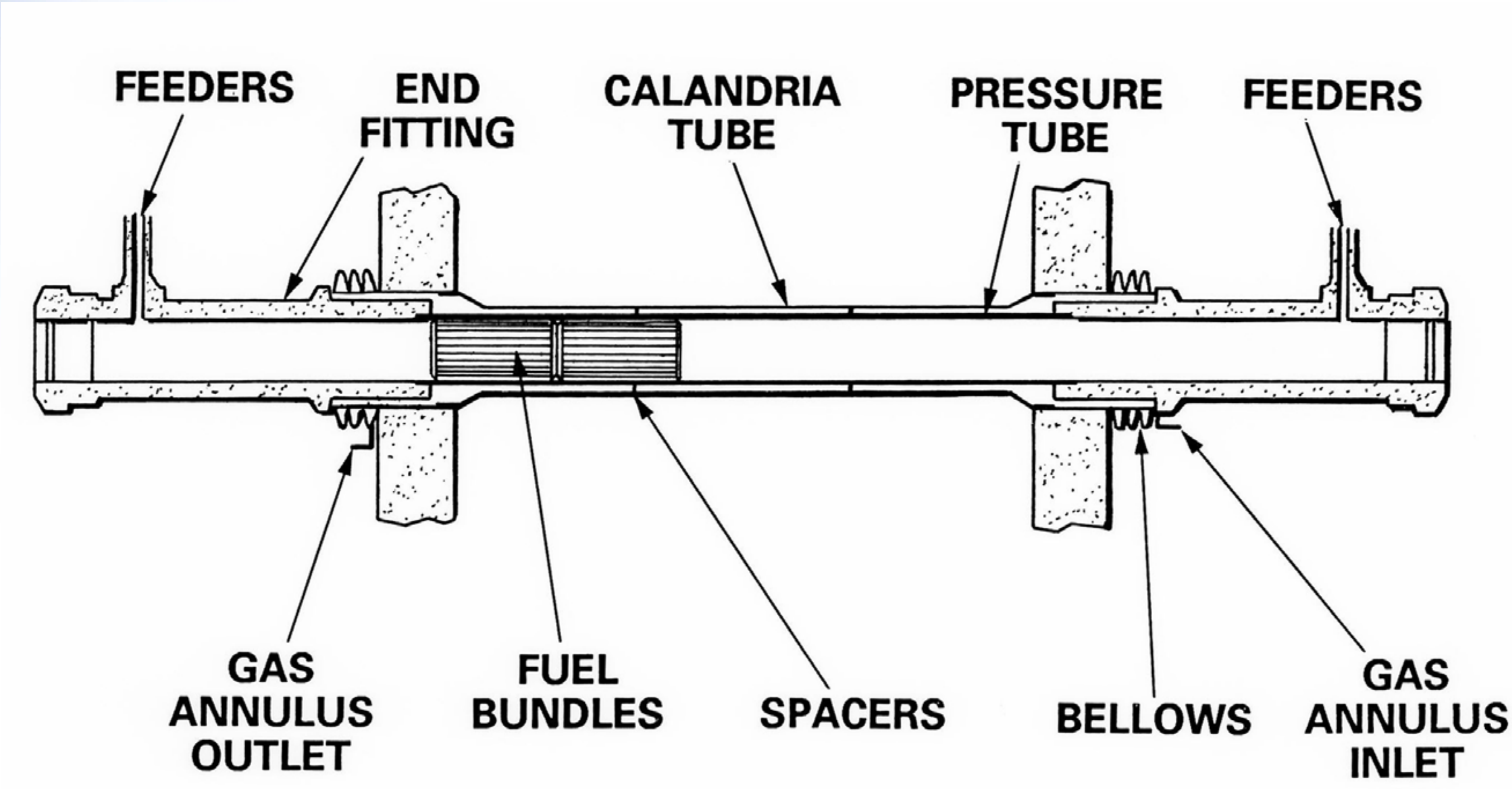
TECHNOLOGIES INC.



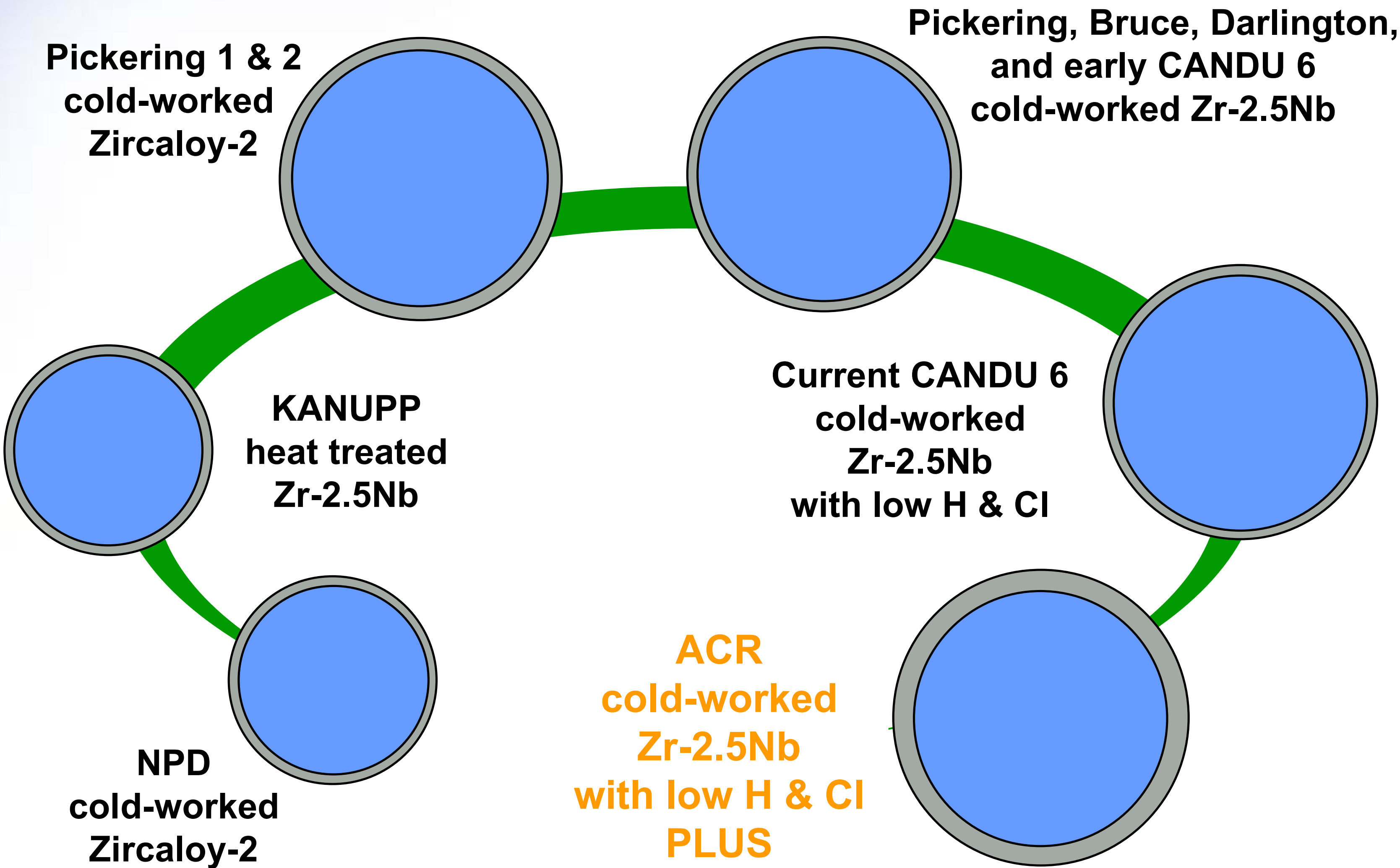
ACR FUEL CHANNEL DESIGN



FUEL CHANNEL COMPONENTS



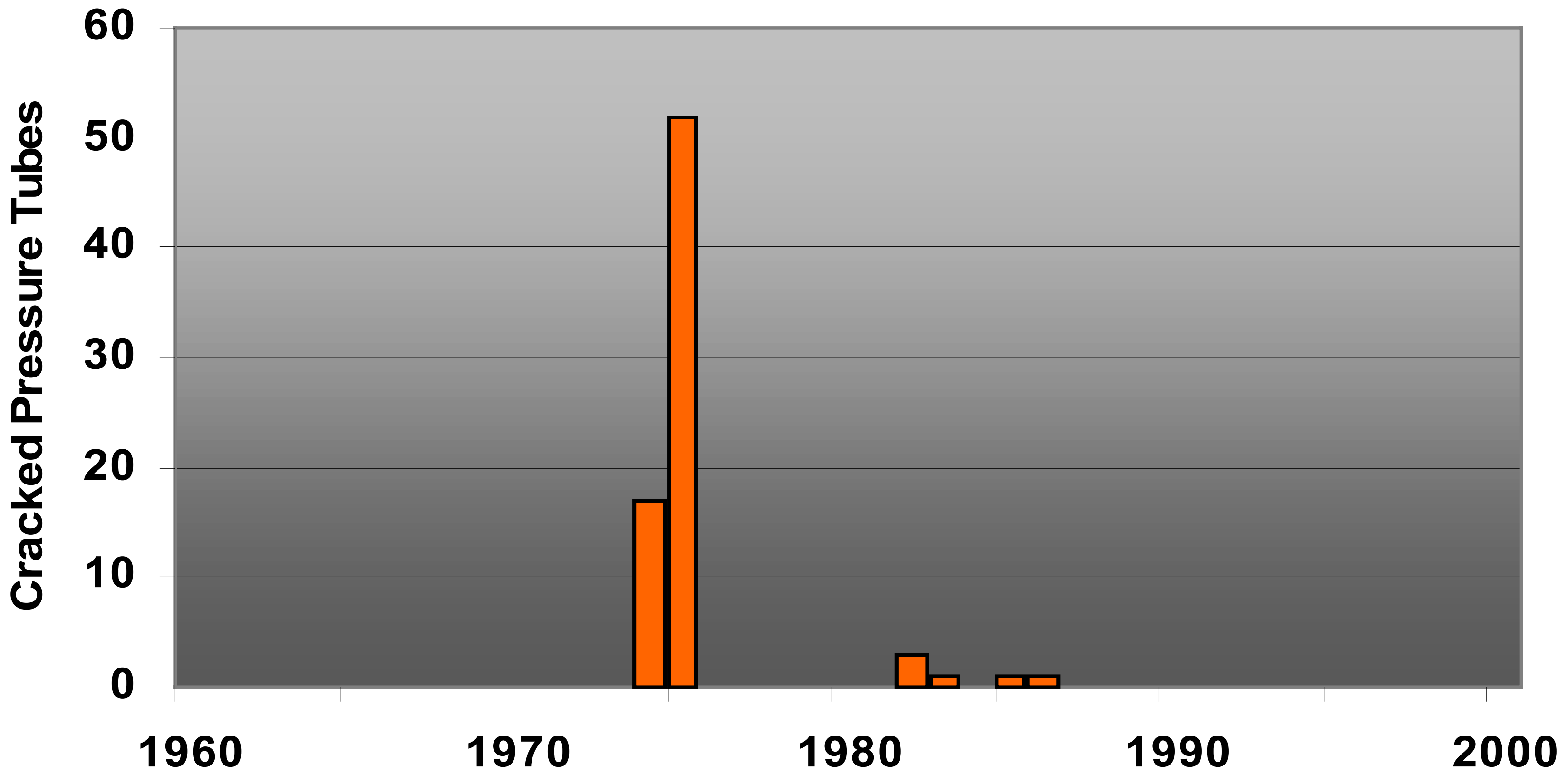
PRESSURE TUBE EVOLUTION



FUEL CHANNEL PERFORMANCE

- 31 CANDU reactors in 6 countries
- 208 to 480 pressure tubes per reactor
- More than 150,000 pressure tube years of equivalent full-power operation
- Only 2 pressure tube ruptures
- Less than 1 rupture per 75 thousand tube years of operation

PERFORMANCE STATISTICS



FUEL CHANNEL TECHNOLOGY

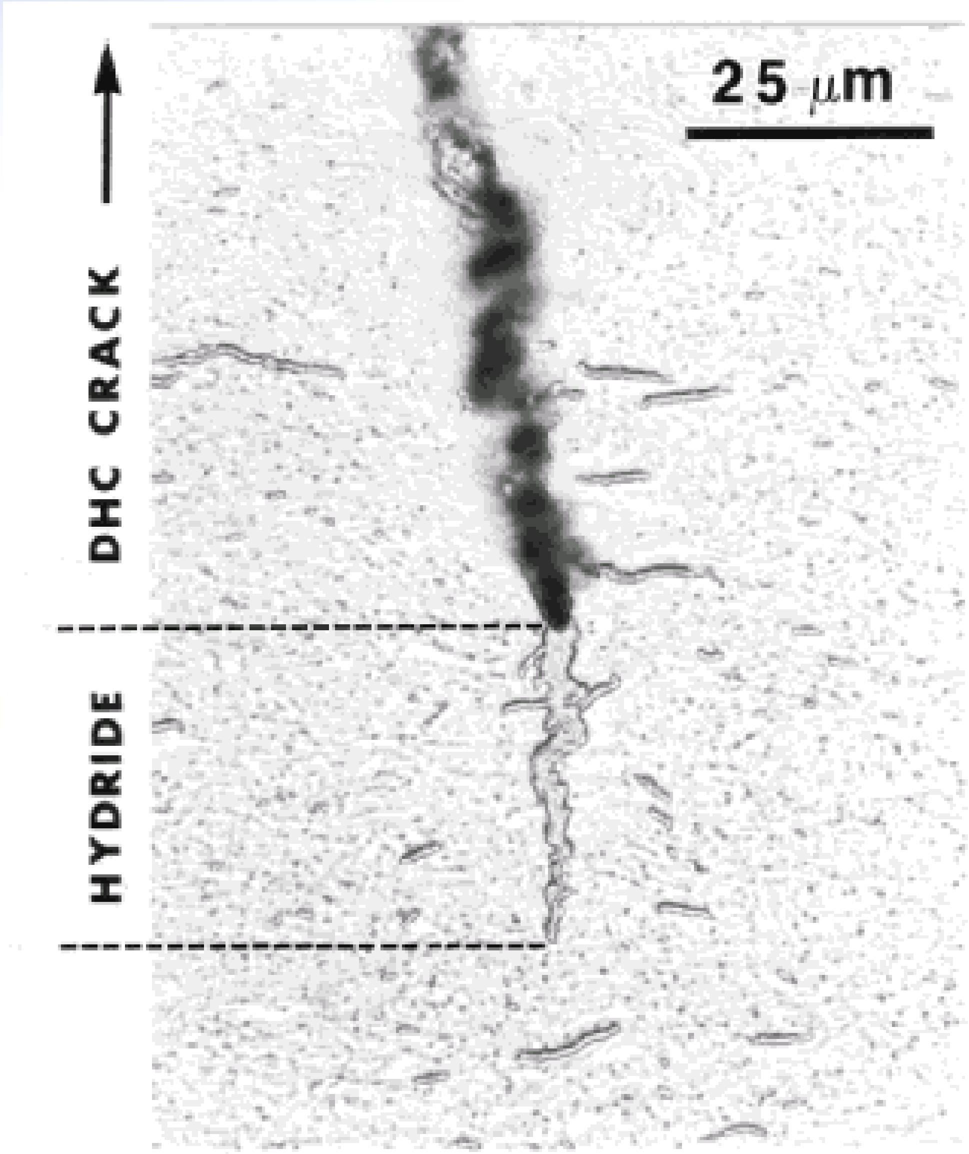
- Aging Mechanisms
- Reactor Experience
- R&D and Engineering

AGING MECHANISMS

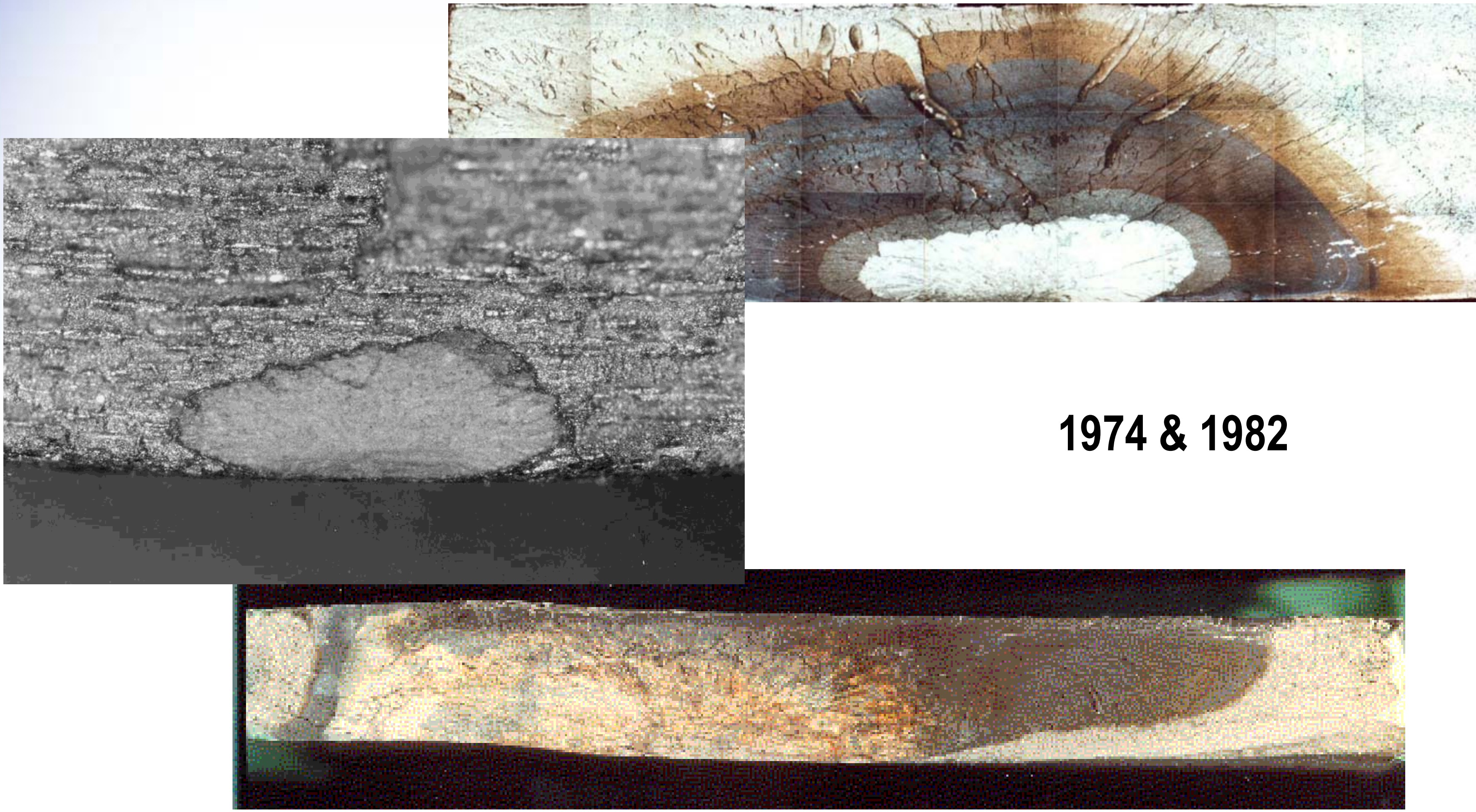
- Delayed Hydride Cracking
- Corrosion and Hydrogen Ingress
- Dimensional Changes
- Mechanical Properties

DELAYED HYDRIDE CRACKING

- Zirconium alloys can be susceptible
- Sufficient hydrogen in the metal must be available
- Need a driving force for diffusion, e.g. a stress gradient
- Anisotropic behavior
- When conditions are met, there is the potential for Delayed Hydride Cracking (DHC)

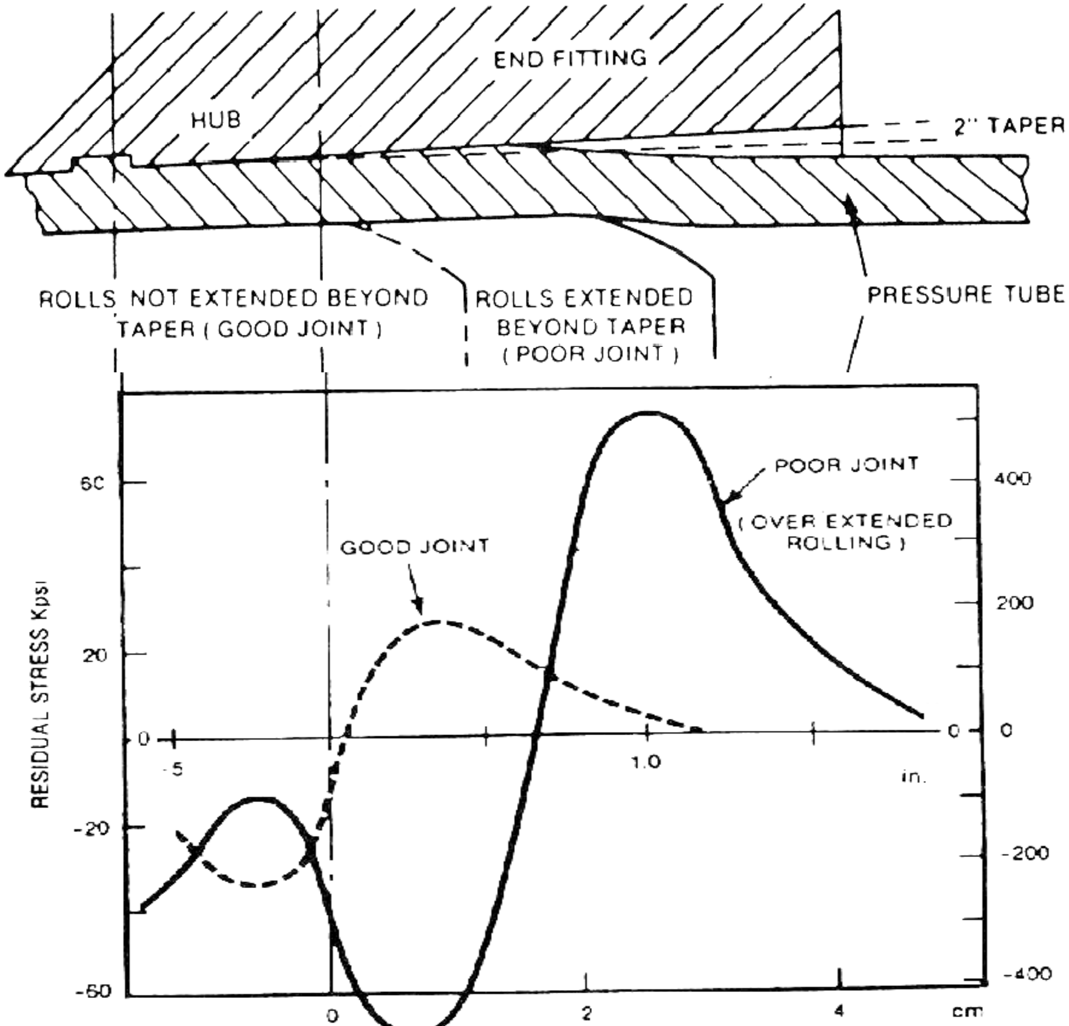

25 μm
DHC CRACK
HYDRIDE

IN-REACTOR EXPERIENCE



1974 & 1982

FABRICATION STRESSES



LEAK-BEFORE-BREAK DEMONSTRATED

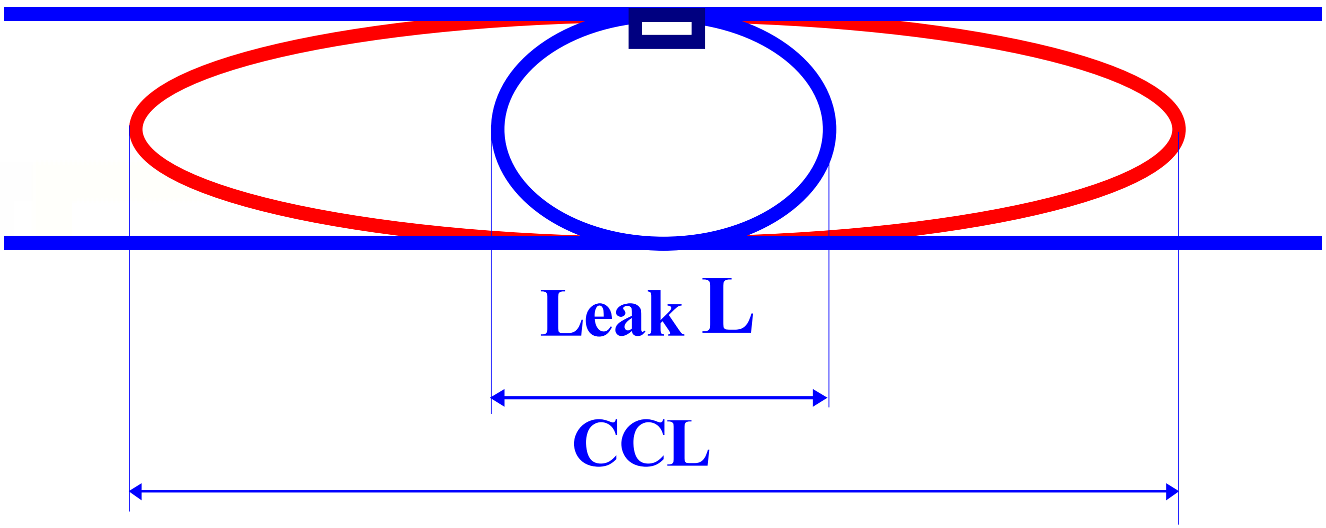
- High residual stresses from over-rolling
- Delayed Hydride Cracking during reactor shutdowns only
- Leakage and detection
- Safe shutdown
- Replacement of pressure tubes

SOLUTIONS

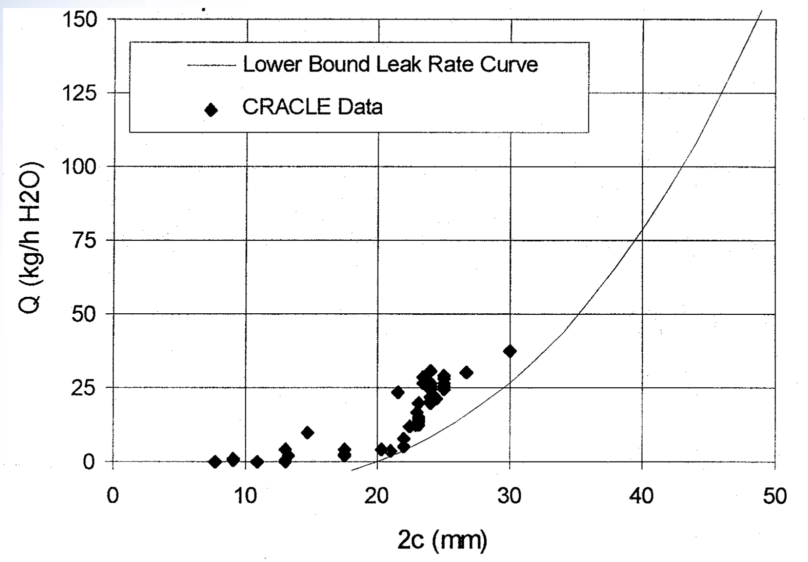
- Replace cracked pressure tubes
- Stress relieve other reactors with over-rolled pressure tube joints
- Development of zero-clearance rolled joint with lower residual stresses
- Implemented in subsequent reactor constructions, e.g. all CANDU 6 reactors

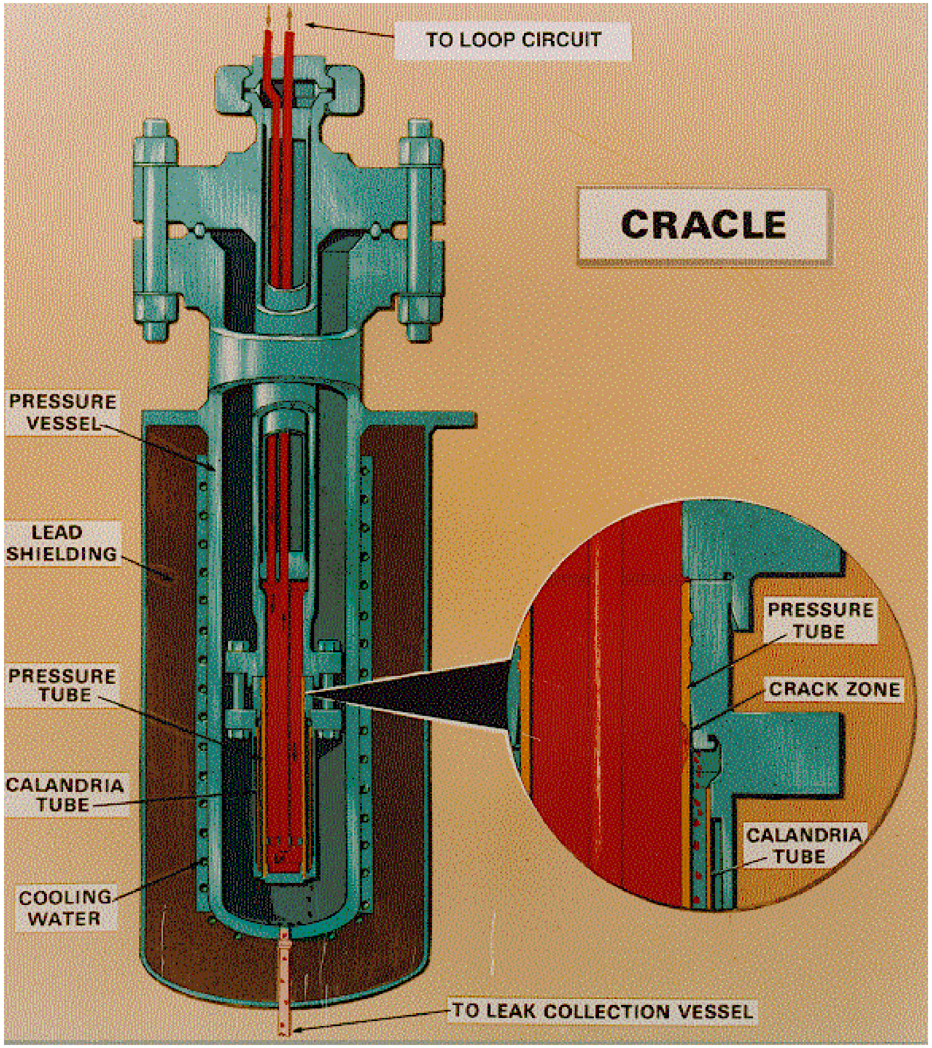
LEAK-BEFORE-BREAK

$$t = (CCL - Leak\ L)/(2xV_{axial})$$



LEAKAGE EXPERIMENTS

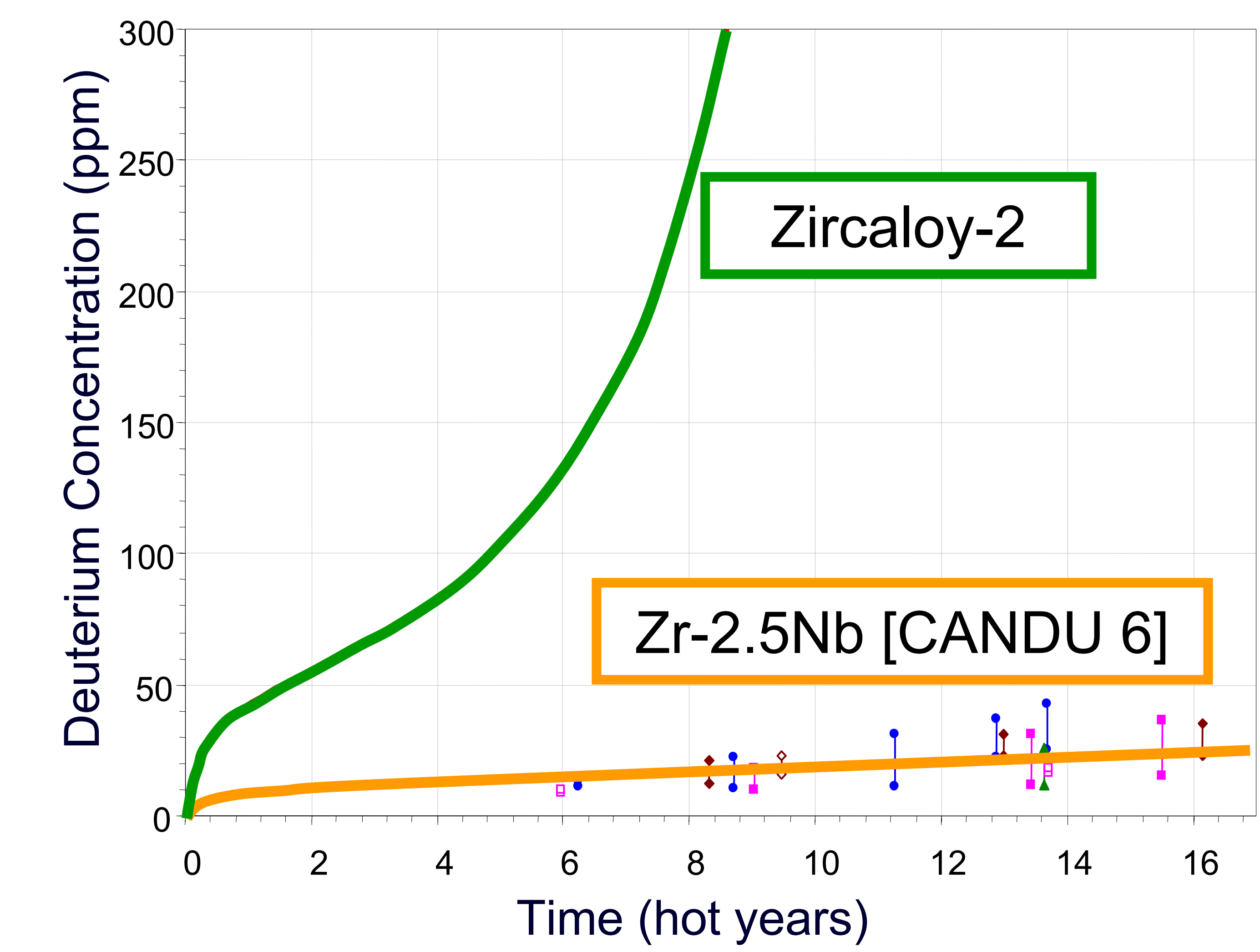




CORROSION & HYDROGEN INGRESS

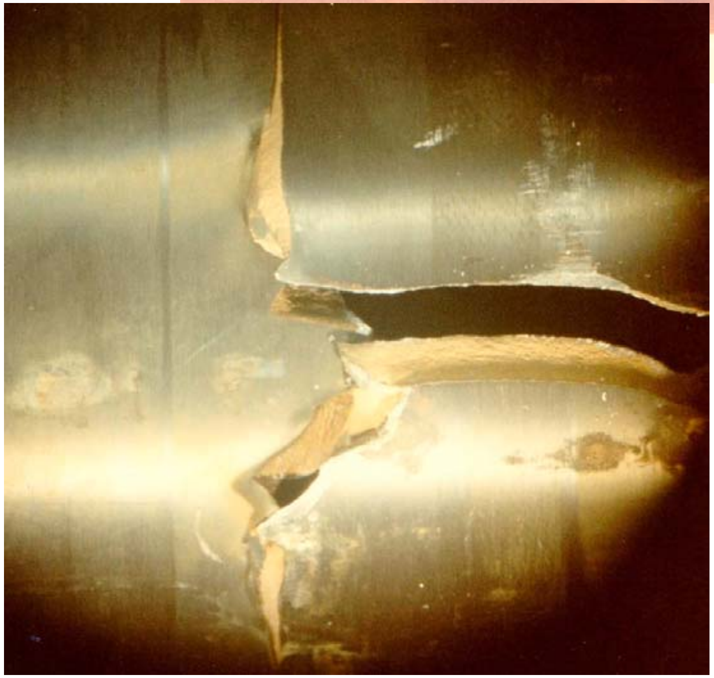
- Interaction of hot coolant with zirconium
- Limited corrosion and hydrogen ingress
- Solubility limit for hydrogen in zirconium
- When the solubility limited is exceeded, there is the possibility of Delayed Hydride Cracking and changes in material properties

CORROSION & HYDROGEN INGRESS



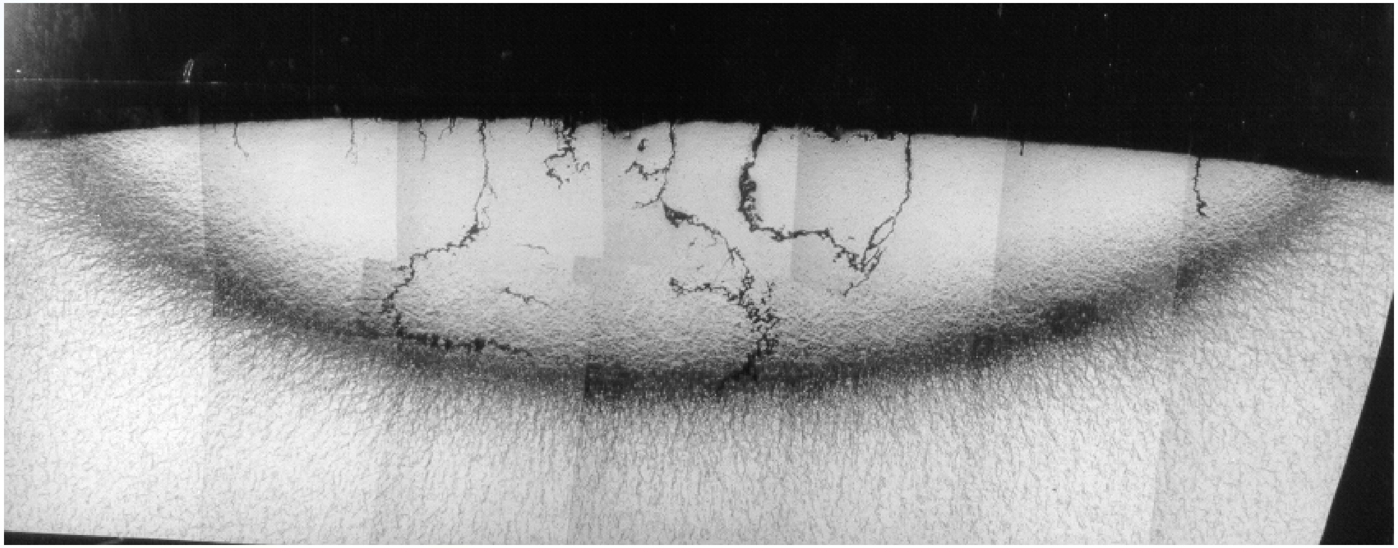
BLISTERS

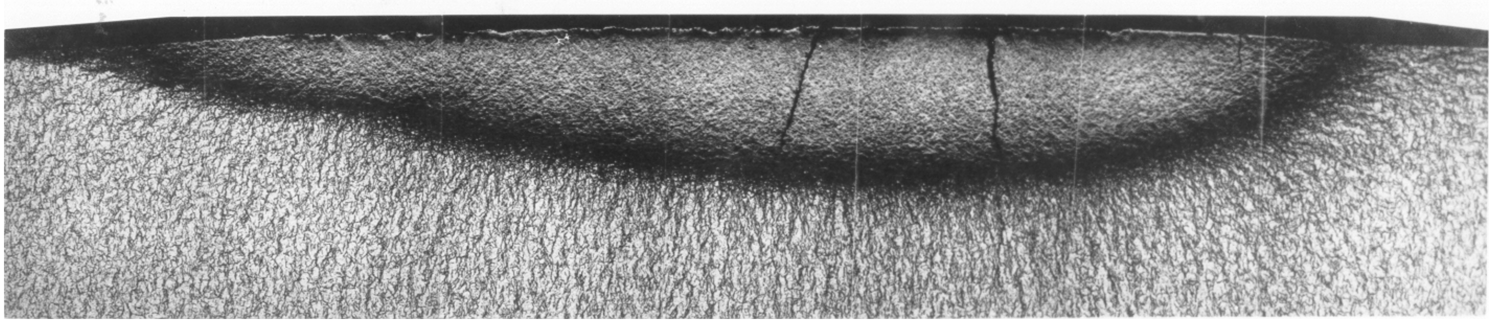
1983



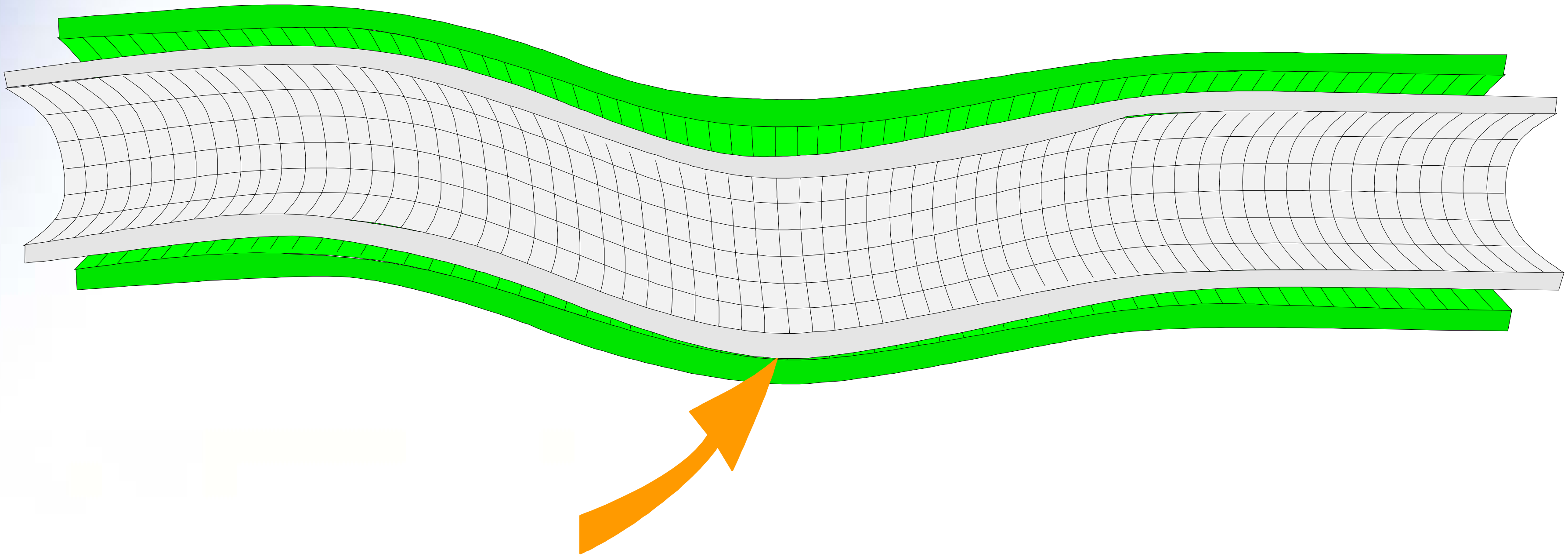
BLISTER FRACTURE

BLISTERS





CONTACT



Without support from spacers, the pressure tube can sag into contact with the calandria tube

PRESSURE TUBE CONTACT

- Spacer movement (2 spacers)
- High deuterium pick-up in Zircaloy-2
- Pressure tube sagged into contact with the calandria tube creating local “cold” spots
- Hydrogen diffusion and hydride blister formation
- Cracking of several brittle blisters
- Rupture of the pressure tube
- Shutdown and replacement of the pressure tube

SOLUTIONS

High Hydrogen:

- Re-tube Zircaloy-2 reactors with Zr-2.5Nb

Spacer Movement:

- In-reactor inspections for spacer locations and hydride blisters
- Reposition spacers in operating reactors
- Assessment methodologies
- Install 4 tight-fitting spacers in new reactors

DIMENSIONAL CHANGES

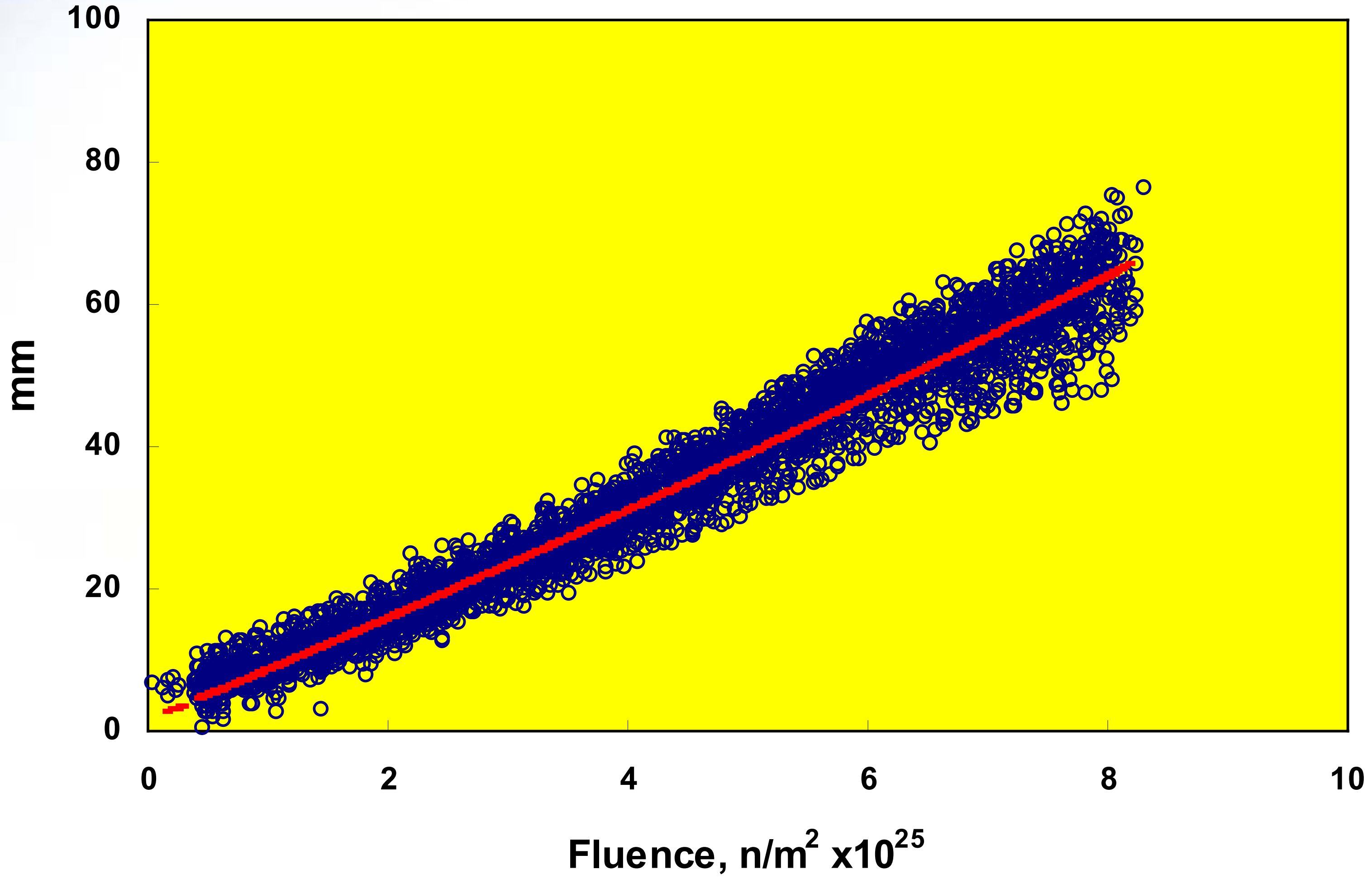
Response of fuel channel to:

- Temperature
- Stress
- Neutron Flux/fluence

Change in shape:

- Length
- Diameter
- Sag

ELONGATION



FUEL CHANNEL REPLACEMENTS

Long history for Single Fuel Channel Replacements (SFCR):

- Early 1960's at Douglas Point
- 1967 at NPD

Motivations

- Single fuel channel issue
- Material Surveillance
- PLIM / PLEX

LARGE-SCALE FUEL CHANNEL REPLACEMENTS

Pickering Units 1 and 2

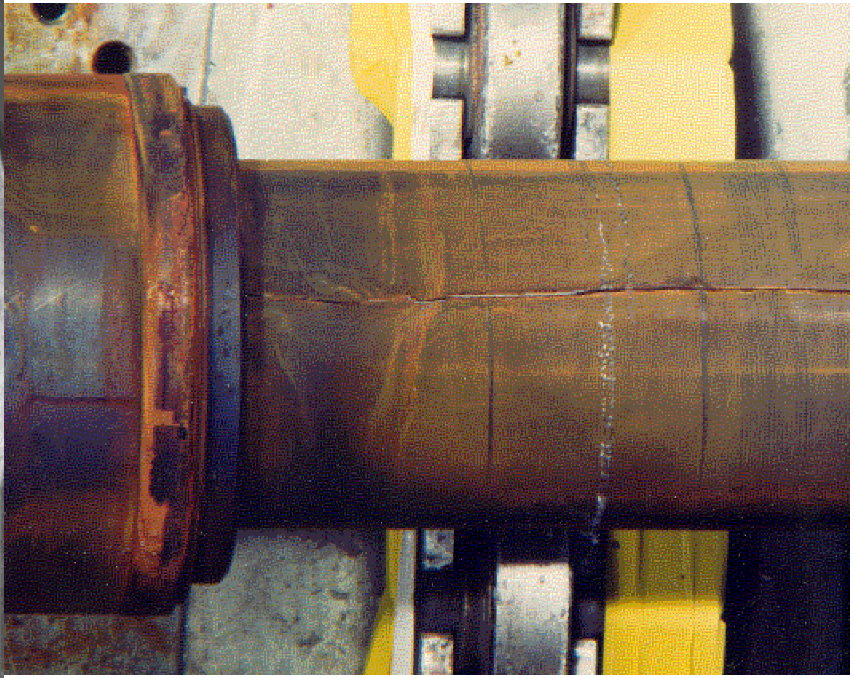
- Replace Zircaloy-2 with Zr-2.5Nb
- Install 4 spacers
- Avoid high hydrogen pickup, pressure tube contact with calandria tube, and possibility of blisters

Pickering Units 3 and 4

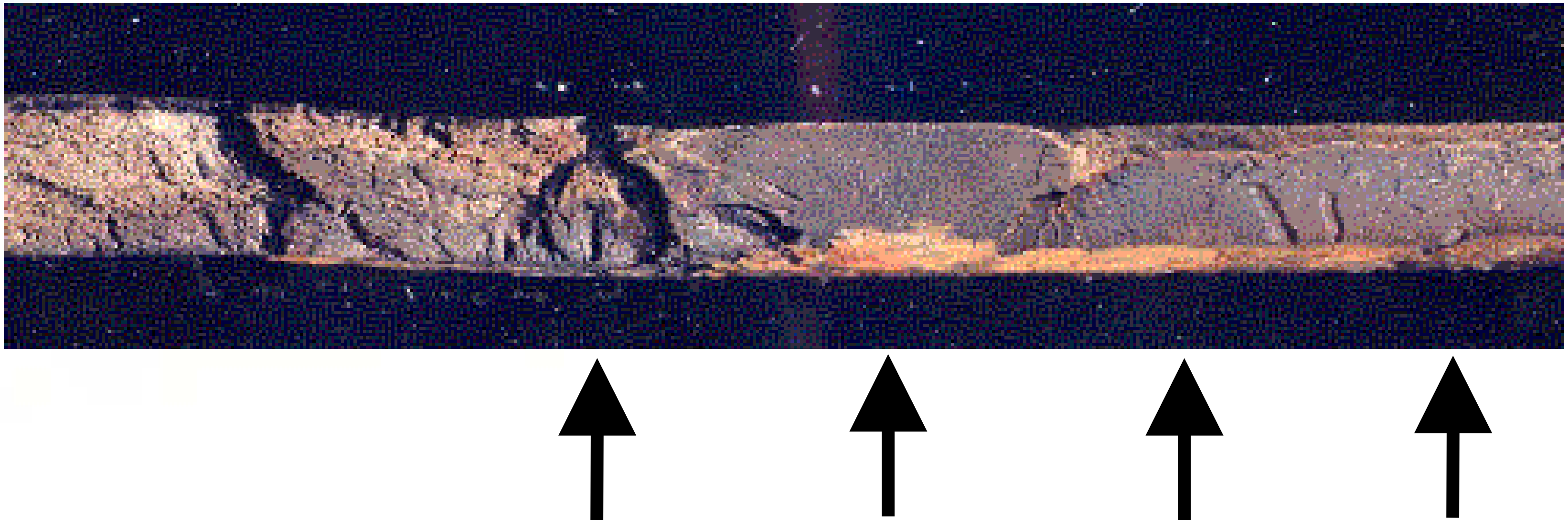
- Replace Zr-2.5Nb with Zr-2.5Nb
- Install 4 spacers
- Avoid pressure tube contact with calandria tube and possibility of blisters
- Allow for greater pressure tube elongation

MANUFACTURING FLAW

1985



DELAYED HYDRIDE CRACKING



LEAK-BEFORE-BREAK DEMONSTRATED

- Residual stresses from over-rolling
- Manufacturing Flaw
- Delayed Hydride Cracking with multiple initiation sites
- Leakage and detection
- Safe shutdown

SOLUTIONS

- Replace cracked pressure tube and ruptured calandria tube
- Inspect archive material for similar manufacturing flaws
- Inspect selected tubes in operating reactors
- Adjusted manufacturing process for all subsequent reactor constructions

IN-REACTOR INSPECTION

- Non-destructive
- Volumetric inspections required by CSA Standard
- Flaw detection
- Spacer locations
- Dimensional inspection – diameter and sag

INSPECTION TOOLING

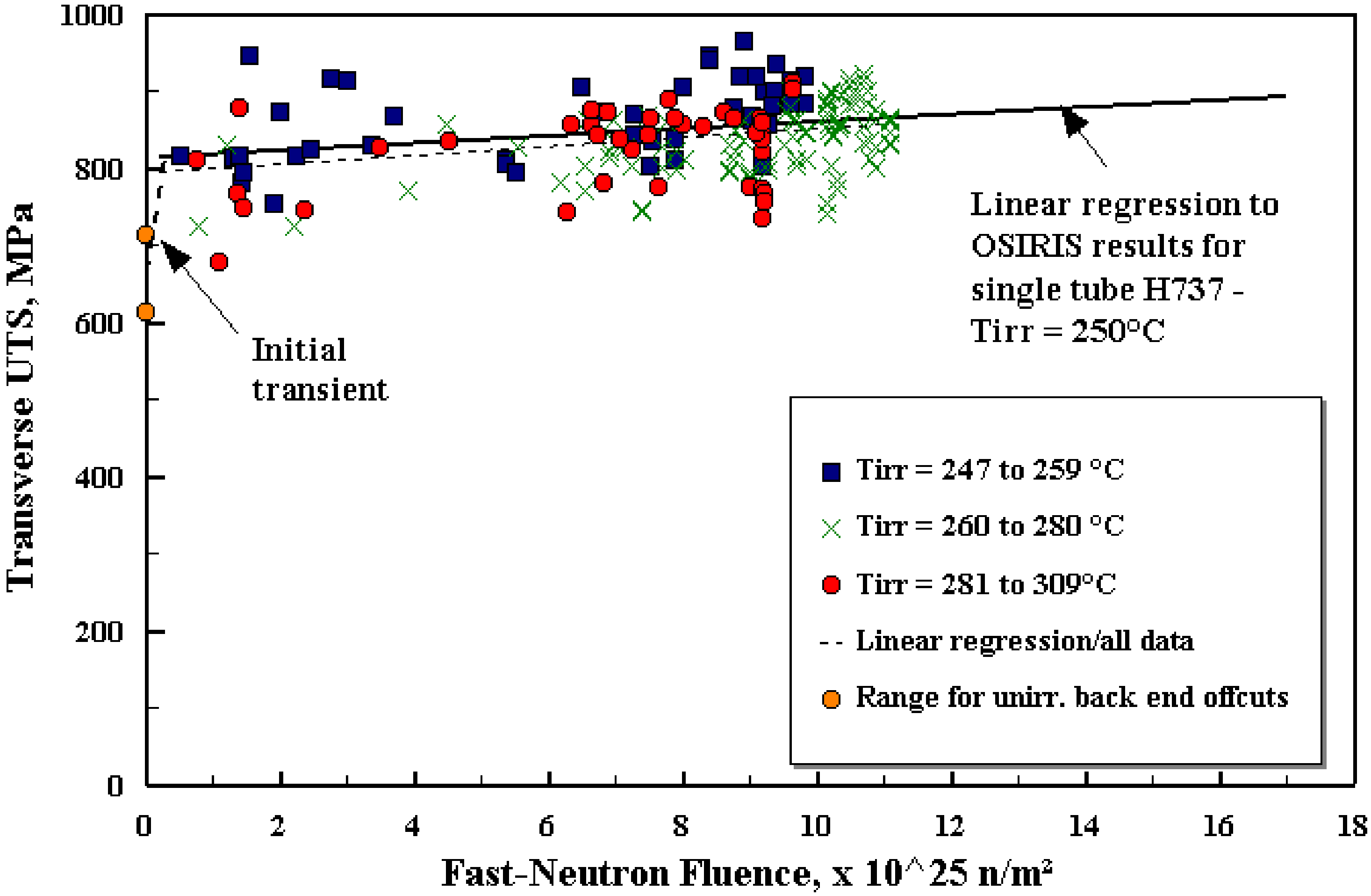
MOCK-UP TESTING

MATERIAL PROPERTIES

Changes in response to:

- Operating temperature
- Flux/Fluence
- Hydrogen Ingress
- Time

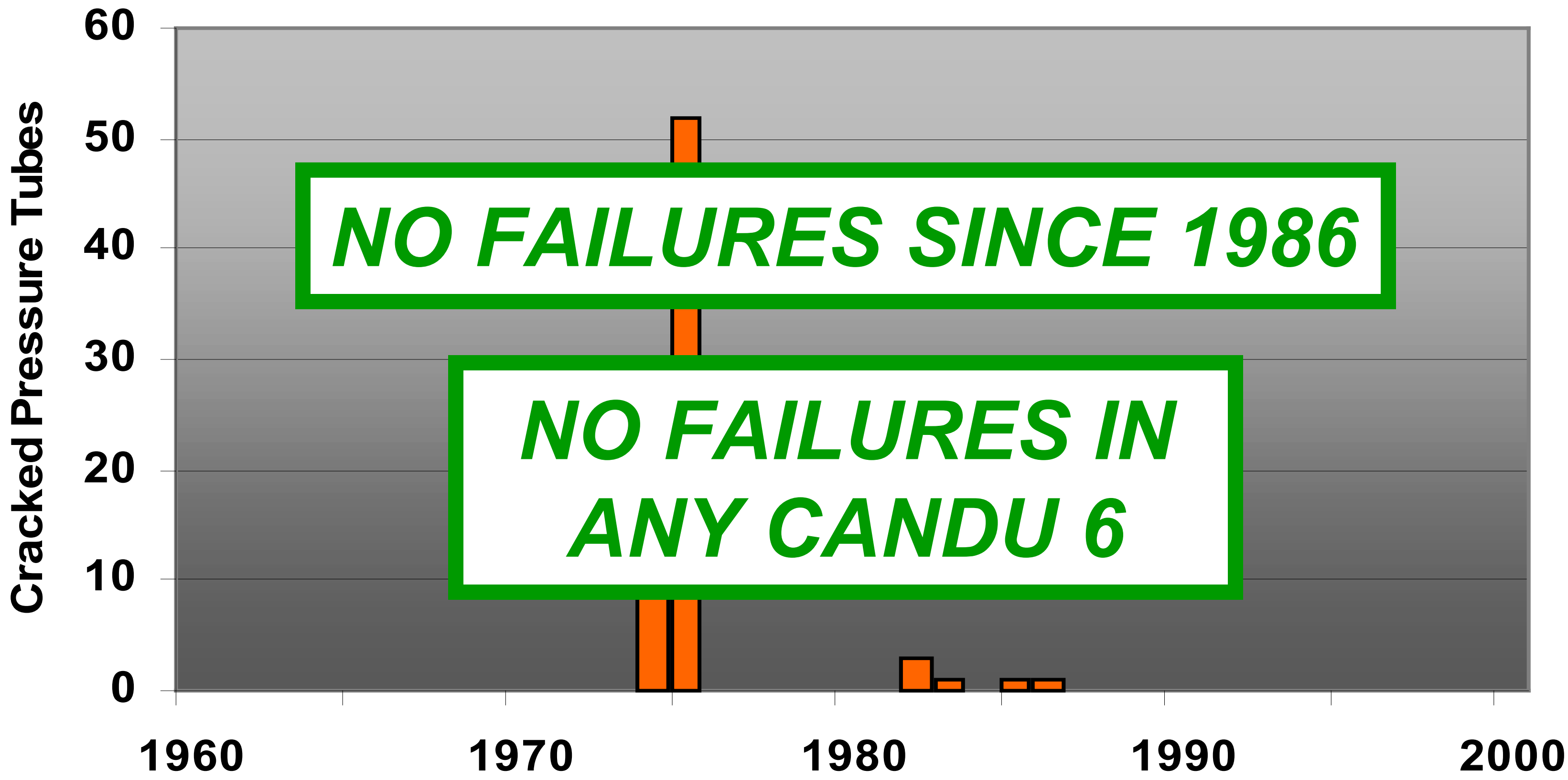
MATERIAL PROPERTIES



KEYS TO HIGH PEFORMANCE

- High-Quality Manufacturing
- Material Surveillance
- In-Depth Knowledge and Understanding
- In-Reactor Inspections
- Assessment Methodologies

PERFORMANCE STATISTICS



ACR-Specific R&D

– Anticipatory R&D

ACR Design

OPERATING CONDITIONS

- Slightly higher temperature
- Slightly higher internal pressure
- Slightly higher neutron flux

than CANDU 6 reactors

FUEL CHANNEL DESIGN

- Thicker pressure tube

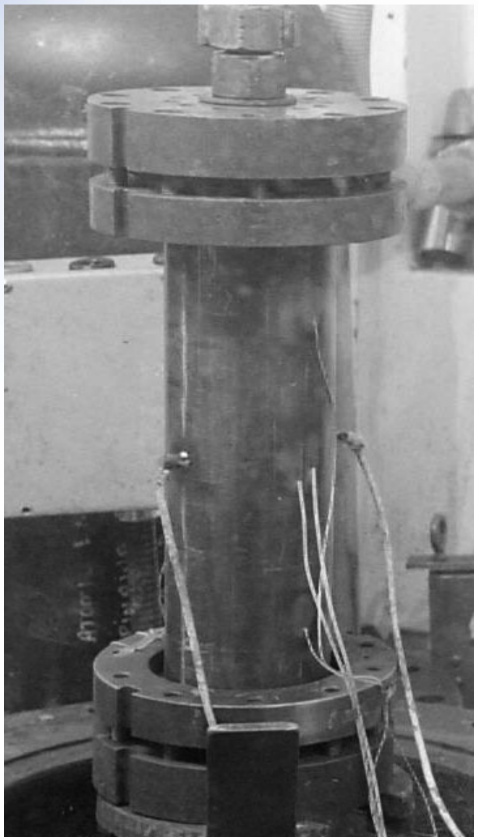
  and
- Thicker calandria tube

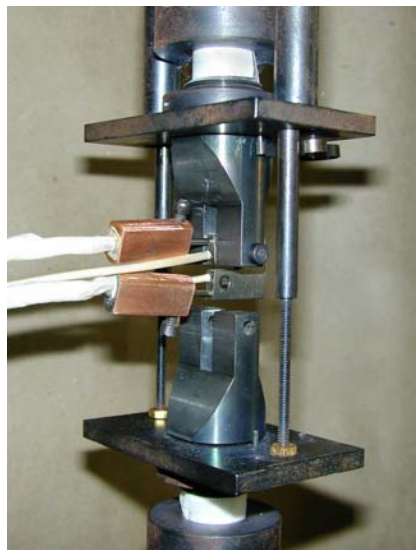
ACR-SPECIFIC ANTICIPATORY R&D

- **Fracture and Leak-Before-Break**
- **Deformation**
- **Corrosion and Hydrogen Ingress**
- **Calandria Tubes**
- **Core Integrity**

Confirmation of expected behavior

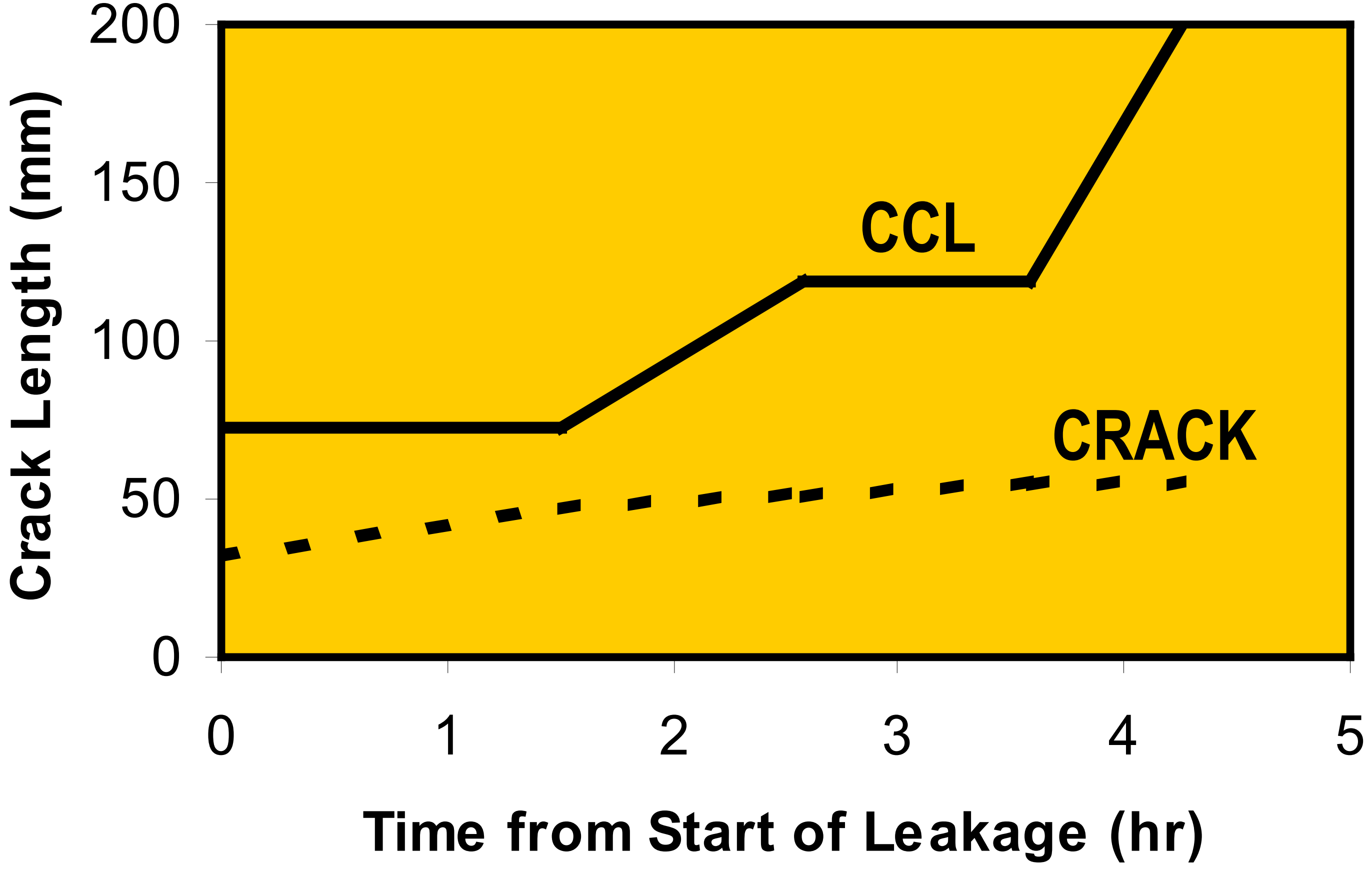
ACR R&D – FRACTURE & LBB





- **Material Property data:**
  - K_{IH}
  - Crack velocity
  - Penetration length
  - Leak rates
  - Critical crack length
  - Strength
- **Extension of Databases:**
  - Temperature
  - Irradiation
  - ACR specification

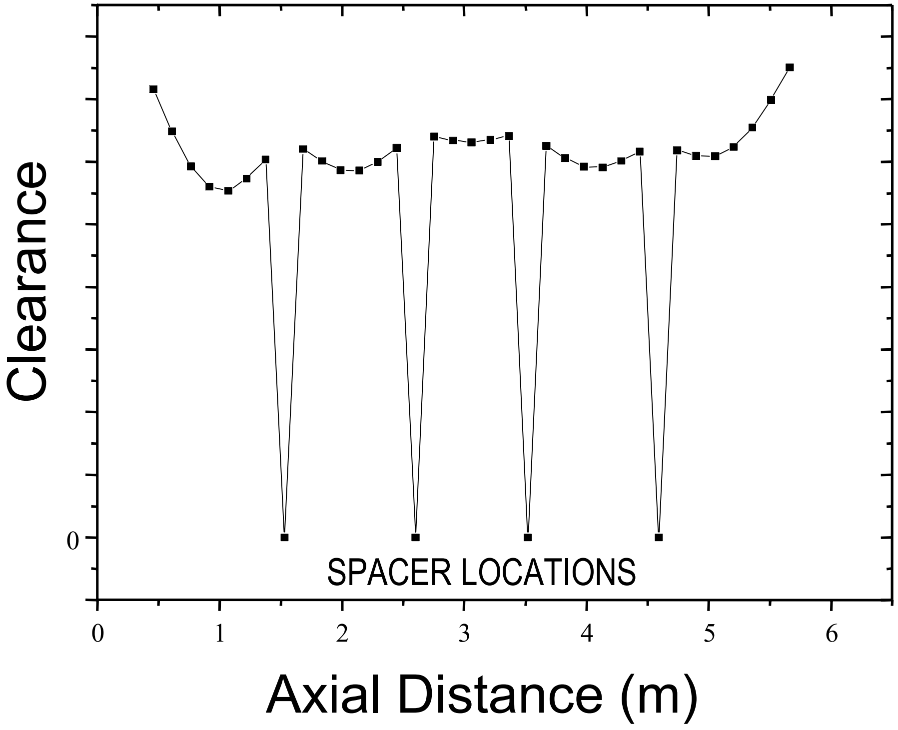
TYPICAL LBB ASSESSMENT



ACR R&D - DEFORMATION

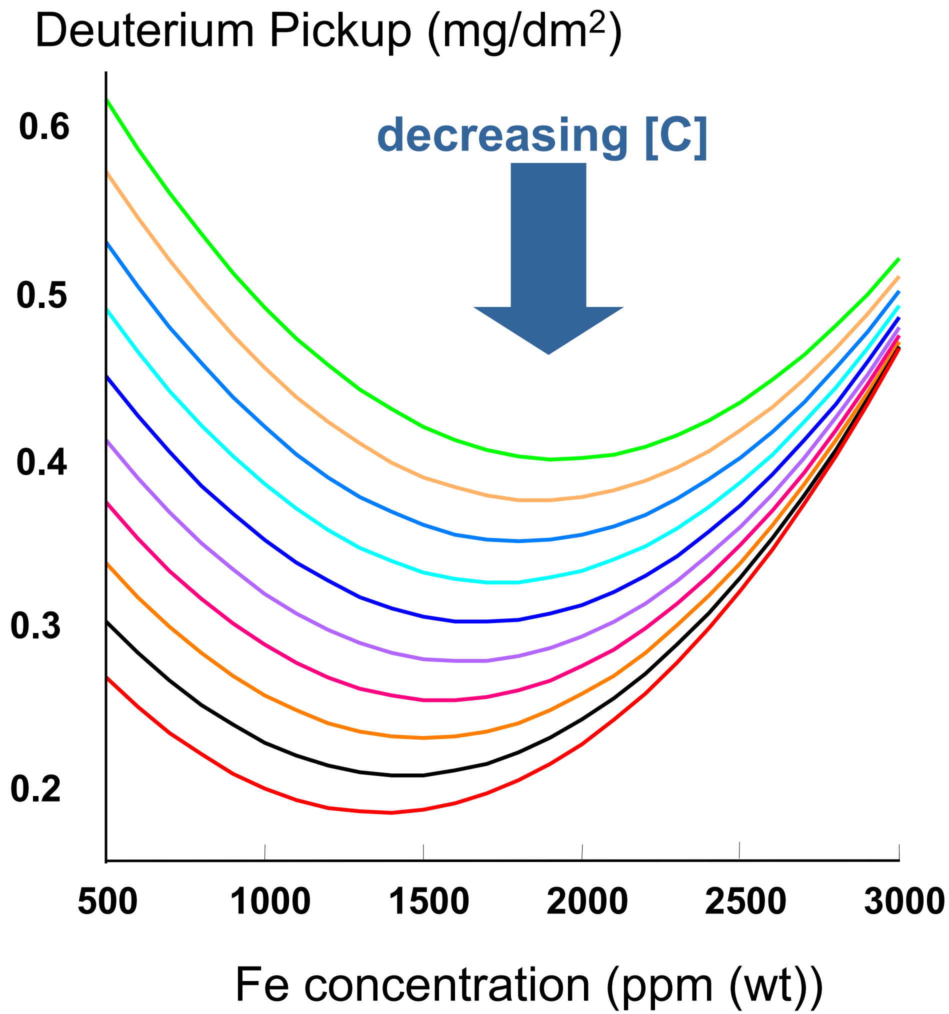
- **Material Property data:**
  - Creep and growth
  - Microstructure

- **Extension of databases:**
  - Temperature
  - Irradiation
  - ACR specification

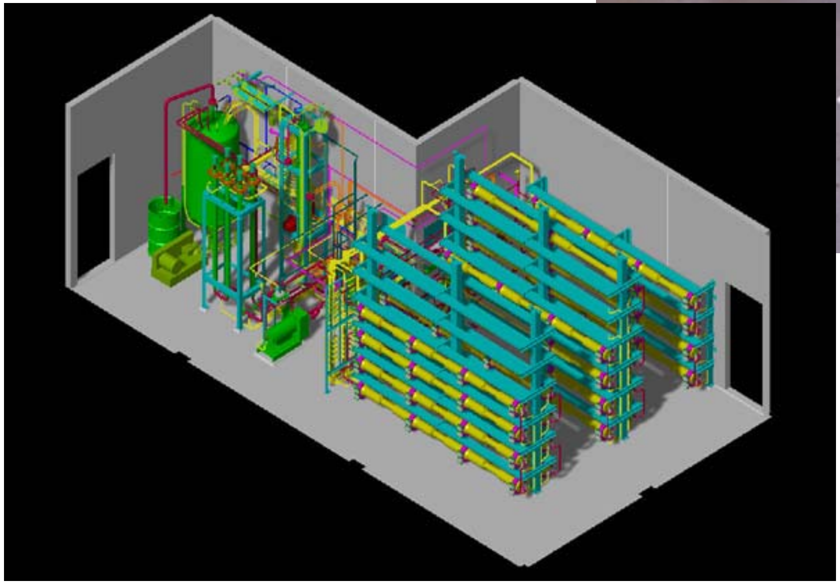


ACR R&D - CORROSION

- **Material Property data:**
  - Oxidation
  - Hydrogen pick-up
  - Hydrogen vs. Deuterium
- **Extension of Databases:**
  - Temperature
  - Irradiation
  - Microstructure
  - ACR specification



CTL-1 ROLLED JOINT TESTING



ACR R&D – CALANDRIA TUBES

Confirmation for:

- Manufacturing of thicker calandria tubes
- Mechanical properties of ACR calandria tubes
- Postulated accident performance properties

ACR FUEL CHANNEL

Assessments for 30 years:

- **Based on:**
  - Extrapolations of current knowledge
  - Conservative estimates of improvement benefits
- **All behaviors will be acceptable:**
  - DHC & Leak-Before-Break
  - Deformation, and
  - Corrosion and Hydrogen Ingress.

ANTICIPATORY R&D TO CONFIRM EXPECTATIONS

FUEL CHANNEL SUMMARY

- Well-Established R&D Program
  - Established for over 40 years – more than 2000 person-years
  - Cooperation between AECL, CANDU utilities, and others
- Proven Excellent Fuel Channel Performance
  - 2 ruptures in >150,000 pressure tube years
  - No fractures since 1986
- Extension of Existing R&D Programs for ACR
  - Temperature and pressure
  - ACR specification

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