Regulatory Perspective on CANDU Feeder Pipe Degradation due to FAC and IGSCC

John C. Jin, Specialist
Raoul Awad ,
Director,
Canadian Nuclear Safety Commission
Commission canadienne de surete nucleaire

IAEA Workshop
April 21-23, 2009, Moscow

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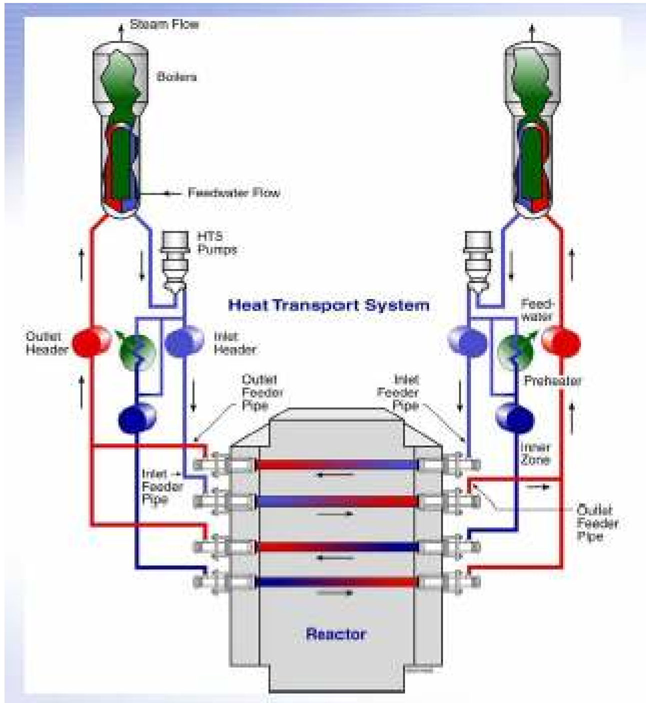
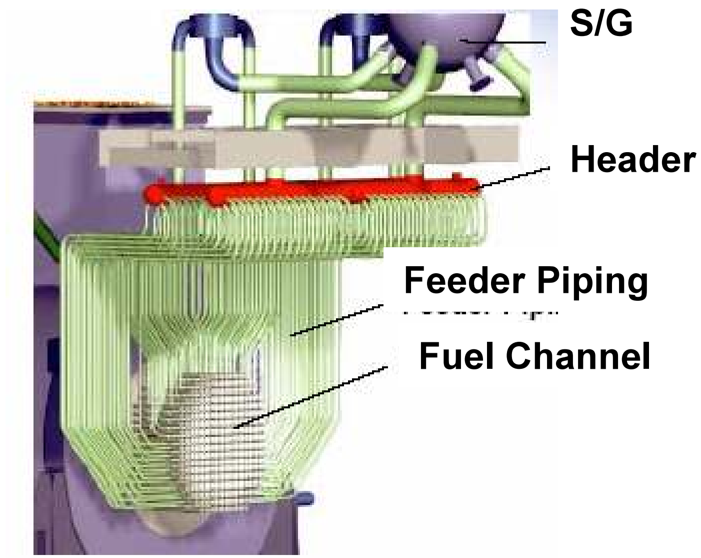
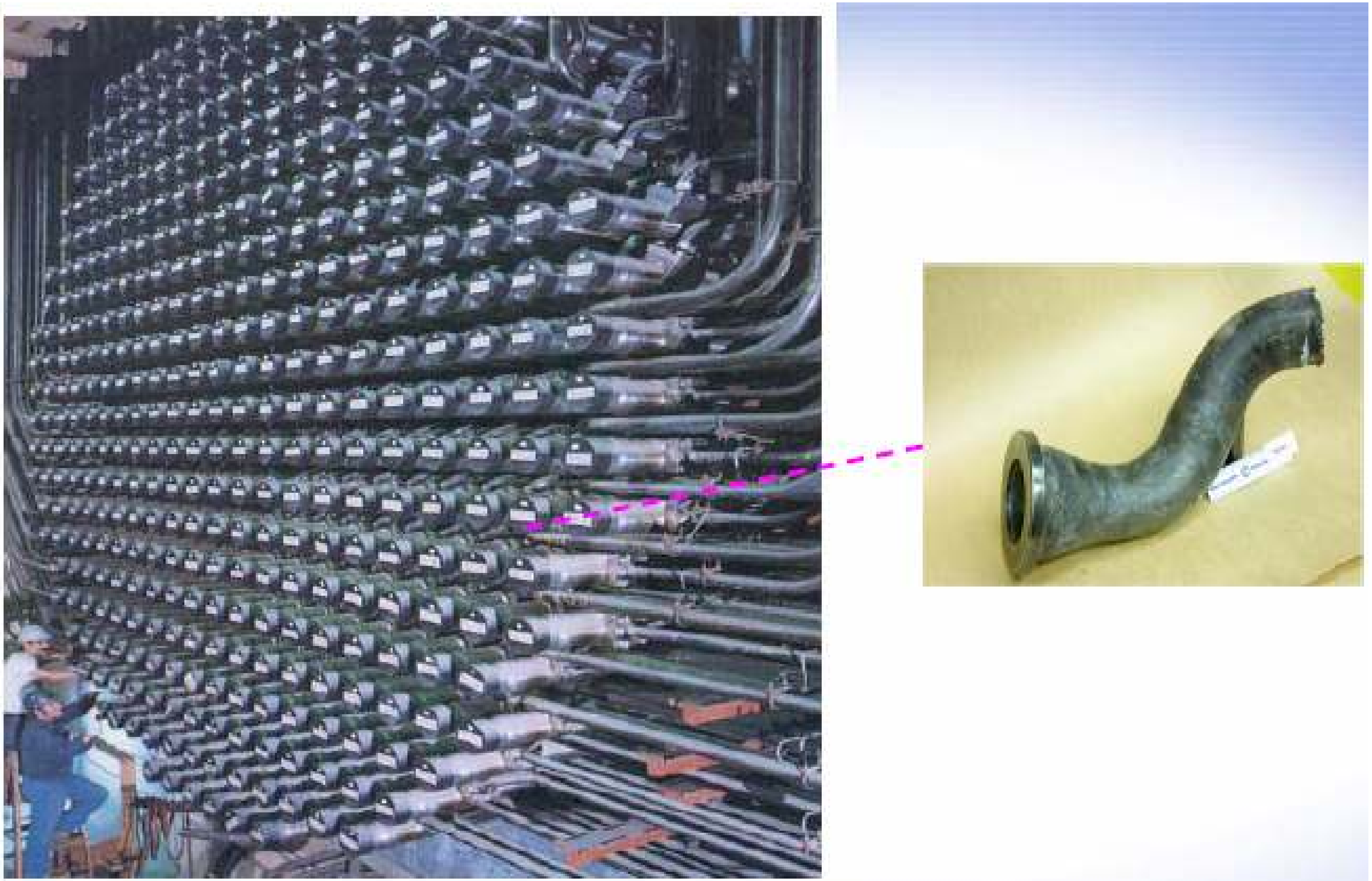


Schematics of CANDU



*Conceptual - Property of the AECL



Specifications of CANDU Feeder Piping

- Number of Outlet Feeder Piping: 380~480 per reactor
- Nuclear Class 1 piping
- Size: 1.5 ~ 3.5 NPS 80 (mostly 2”and 2.5”)
- Material: Carbon Steel, SA-106, Gr.B
- Elbow: Bend or Fitting
- Pressure: 1475 ~ 1550 Psig
- Temp: 515 ~ 585 oF

Operating CANDUs in Canada

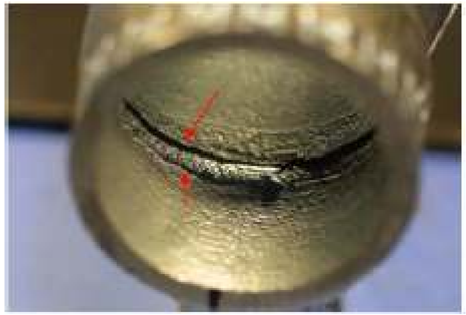
	Reactor		Capacity (MWe)	First Criticality
1	Pickering A	Unit 1	542	Feb. 1971
2		Unit 4	542	May 1973
3	Bruce A	Unit 3	904	Nov. 1977
4		Unit 4	904	Dec. 1978
5	Gentilly-2		675	Sep. 1982
6	Point Lepreau		680	Jul. 1982
7	Pickering B	Unit 5	540	Oct. 1982
8		Unit 6	540	Oct. 1983
9		Unit 7	540	Oct. 1984
10		Unit 8	540	Dec. 1985
11	Bruce B	Unit 5	915	Nov. 1984
12		Unit 6	915	May 1984
13		Unit 7	915	Jan. 1987
14		Unit 8	915	Feb. 1987
15	Darlington	Unit 1	935	Oct. 1990
16		Unit 2	935	Nov. 1989
17		Unit 3	935	Nov. 1992
18		Unit 4	935	Mar. 1993

II. Degradation Mechanisms in Feeder Piping

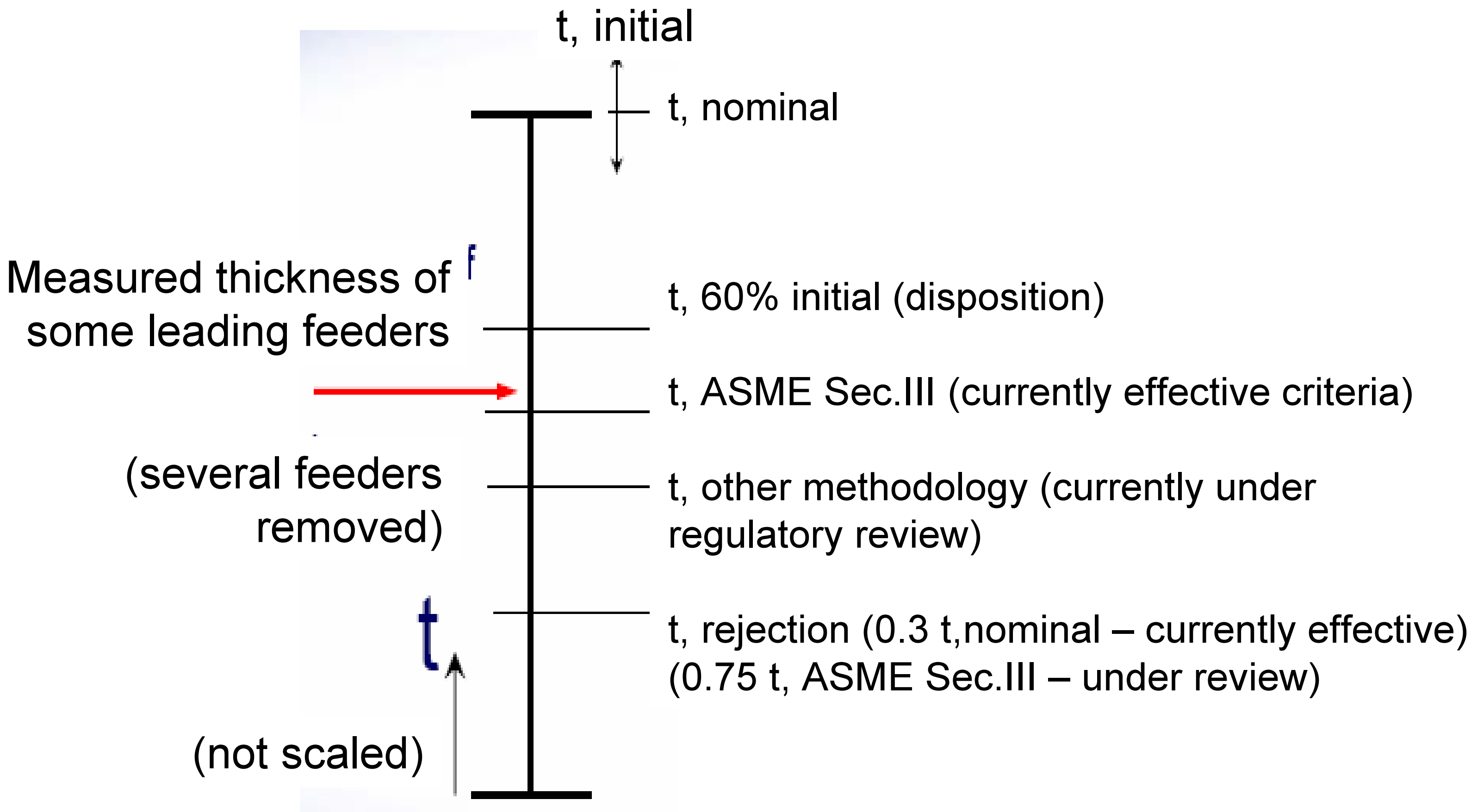
Degradation Mechanism	Susceptible Area	Affected Plants
Pipe wall thinning due to Flow Accelerated Corrosion (FAC)	– Bends –Welds	All CANDUs
Service induced cracking – Inter-Granular Stress Corrosion Cracking (IGSCC) – Low Temperature Creep Cracking (LTCC)	– Bend ID & OD	PLGS (under refurbishment)
	– Repaired welds	G-2 (to be refurbished soon)

II.1 Wall thinning due to FAC

- Extent -All outlet feeder pipes at all CANDU plants are experiencing pipe wall thinning due to the FAC at a rate much higher than design allowance.
  - General and local thinning at bends
  - Local and blunt flaw near weld
  - thinning rate: 0.05 ~ 0.2 mm/yr (linear)
- Failure History
  - Several feeders have been replaced, but no pipe failures occurred during operation



Thickness criteria



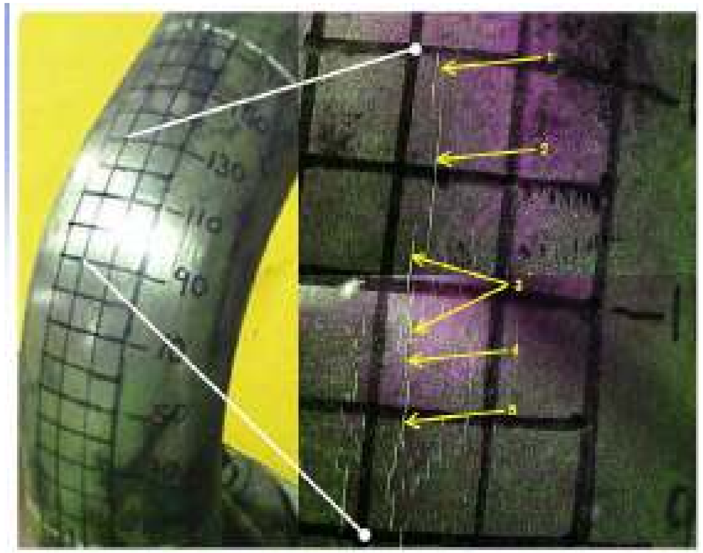
II. 2 Feeder Cracking

Feeder Cracking History at PLGS

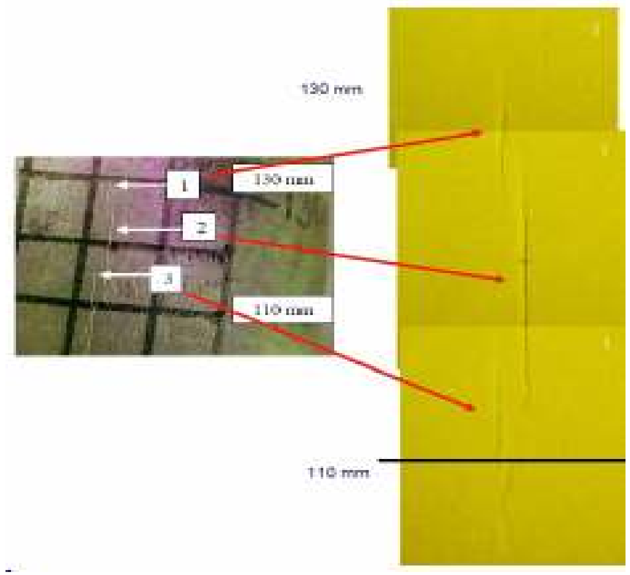
Year	Feeder	Location	Inside/Outside Surface	Length (mm)	Depth (mm)	
1997	S08a	1st Bend	Inside	63	7.0	Leaking
2001	K16a	1st Bend	Inside	55	7.3	Leaking
	U15c	1st Bend	Inside	30	5.7	
	Q08a	1st Bend	Inside	50	3.6	
2003	C13a	1st Bend	Inside	38	5.8	
	P09a	1st Bend	Inside	15	3.7	
	N19a	2nd Bend	Inside	66	6.9	
			Outside	40	4.8	
2004	N11a	1st Bend	Inside	18	2.8	
2005	D14a	2nd Bend	Inside	19	2.5	
			Outside	15	2.7	
2006	H12a	2nd Bend	Outside	17	3.2	
	N16c	1st Bend	Inside	28	3.3	

* All PLGS feeders were replaced in 2008 for refurbishment

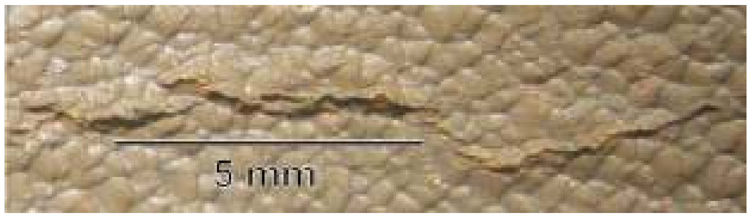
Characteristics of Feeder Cracking

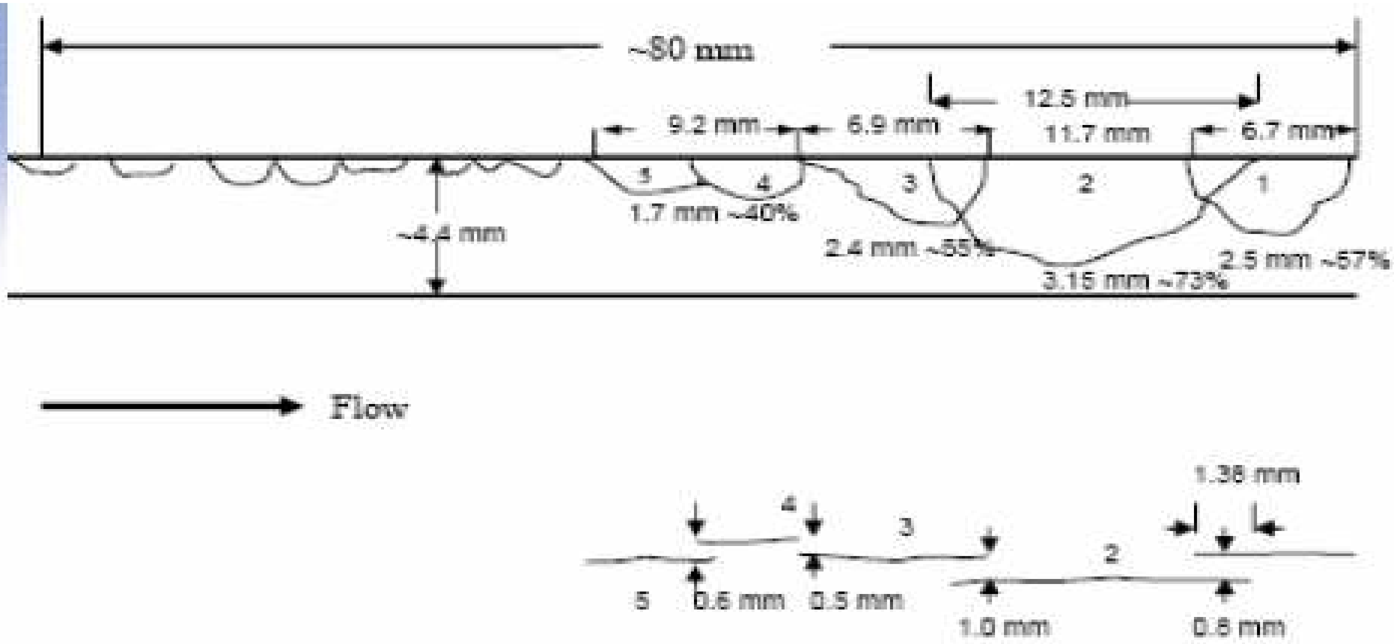


Crack Field Measured by Magnetic Particle Inspection



Magnetic Rubber Replicas




~80 mm
12.5 mm
9.2 mm
6.9 mm
11.7 mm
6.7 mm
5
4
3
2
1
1.7 mm ~40%
~4.4 mm
2.4 mm ~55%
3.15 mm ~73%
2.5 mm ~57%
Flow
1.38 mm
0.6 mm
0.5 mm
1.0 mm
0.8 mm


#5
#4
#3
#2
#1

Physical Characteristics

- At high residual stress region (cold bend)
- Entirely Intergranular (environmental effect)
- Axial in direction (hoop stress)
- Multiple (coalescence)
- Crack Shape
  - Semi-elliptical shape with an aspect ratio of less than 6
  - As crack develops, aspect ratio increases
  - Abrupt increase of aspect ratio can be resulted from coalescence
    - Inspection capability
    - Structural Integrity during the last operating cycle
    - Invalidate conventional LBB argument

Cracking Mechanisms

No conclusive mechanistic understanding. Most likely mechanisms are:

- Inside surface crack: Oxidant-driven stress corrosion cracking
- Outside surface crack: Low temperature creep cracking assisted by hydrogen flux through the pipe wall from flow accelerated corrosion

Key factors

	Primary	Secondary
Stress	Residual Stress	Operating Stress
Material	Cold work	Ovality and impurities
Environmental	Temperature	Hydrogen generated by FAC Oxidizing species

- Currently there are no feeders with active cracking mechanism, but cold worked bends at some stations are considered susceptible

III. Regulatory Perspective

Regulatory concerns about FAC

- Unique aspects of CANDU feeders
  - A large number
  - Small diameter carbon steel
  - Class 1 piping
- Uncertainties
  - caused by limited understanding of degradation (epistemic)
    - susceptible location
    - degradation rate
  - inspection capability
- No practical mitigating method except replacement with FAC resistance material –higher chrome content

Regulatory concerns about FAC

- Failure mode could be a rupture of Class 1 piping without adequate prior warning by leakage in the absence of a proper management program
- Continued service is allowed based on the argument that FAC is relatively slow and predictable process which can be manageable by
- – Comprehensive inspection
- – Conservative engineering evaluation
- Adequacy of the methodology, procedures and acceptance criteria to assess the fitness for continued service

  > Demonstration by testing required

Regulatory concerns about Cracking

- Currently no feeders with active cracking but considered susceptible particularly cold worked feeder bends.
- No practicable mitigation
- Uncertainties
  - caused by limited understanding of degradation
    - uncertain crack initiation rate
      - possible large population of bends with incipient cracks
    - uncertain crack propagation rate
      - a crack grew from undetectable size to 73% through wall in one year operation at PLGS
  - inspection capability
    - detection limit
    - probability of detection

Bases for continued operation

- Continued service based deterministic assessment
  - Detect and remove partial through-wall cracks before they challenge structural integrity
  - Full scope inspection of all susceptible areas
  - Engineering assessment for postulated cracks for feeder population
- Challenges
  - Deepest undetected crack of 2.7mm while min. acceptable thickness is 3.25mm (2.5” feeder)
  - LBB was not valid (from a conventional perspective)
    - low fracture toughness measurement at extrados
    - Possible long surface crack
    - tight crack morphology

> **Probabilistic Assessment combined with Burst Test**

- Quantify the nuclear safety risk and provide a basis for safe operation

Probabilistic Safety Evaluation (PSE)

Probabilistic Safety Evaluation

- provided an insight into the degree of impact of feeder cracking on overall plant risk
  - quantified the risk reduction provided by mitigation activities
  - needs improvement in input parameters such as:
    - crack initiation and growth modeling
    - crack detection modeling by ISI
    - crack stability modeling
  - Acceptance criteria is currently under development

Probabilistic Safety Evaluation (PSE)

- Increase in severe core damage frequency (ΔSCDF) associated with feeder rupture frequency
  - 3.3e-7 per year, given the 100% UT inspection of all outlet tight radius bends until Spring 2008 (1e-6 per year proposed to be acceptable provided there is no indication that the overall SCDF is above 1e-4 per year)
- Quantify the risk reduction provided by various management activities
  - Reducing the inspection scope and/or interval from 100% of the high risk locations every year would increase the frequency of SBLOCA by one or two orders of magnitude
    - Primary strategy of extensive frequent inspection was the most effective risk reduction strategy to manage feeder cracking

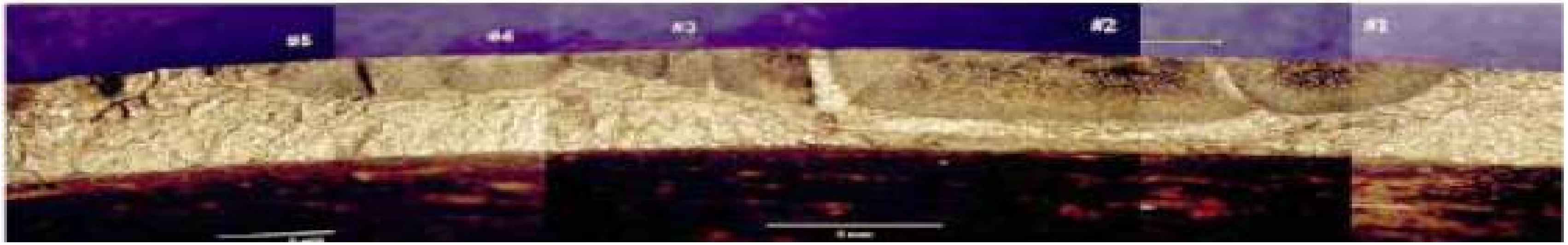
IV. Tests performed by Industry

1. Burst pressure tests on ex-service cracked feeders
   - To demonstrate fitness for service of the cracked feeder during the past operating period
   - For input to probabilistic safety assessment
   - To address a material property issue

2. Burst pressure tests on ex-service FAC wall thinned feeders and specimen
   - to validate methodologies for calculating minimum required thickness

- Funded by CANDU Owner's Group (COG) and conducted by Atomic Energy of Canada Limited (AECL)

Burst Test on cracked feeders



Failure Site after Pressure Test

- Results

Feeder	Wall Thickness	Crack Length	Crack Depth	Test Temp.	Failure Pressure	Apparent Toughness
D14a	4.6mm	12.7mm	59% tw	90oC	70.3 MPa	94 KJ/m2
H12a	4.31mm	10.0mm	73% tw	90oC	51.1 MPa	65 KJ/m2

- Predicted failure pressures for H12a
  - 28 MPa (lower bound material properties)
  - 40 MPa (upper bound material properties)
    - More feeder bend tests with artificial defects and other loading conditions were carried out

AECL's Feeder bend testing for FAC

- Objectives
  - to support engineering evaluation methodologies by demonstrating existence of sufficient safety margin to burst and a fully ductile failure mode of failure of the wall thinned feeder pipe due to FAC
- Performed for ex-serviced, archived and fabricated bends under various loading conditions

AECL’s Feeder bend testing – ex-service feeders

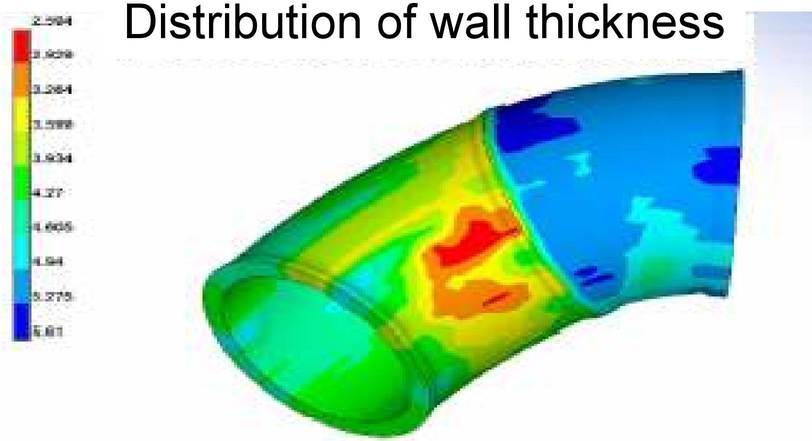
- **OPG Ex-Service Test**

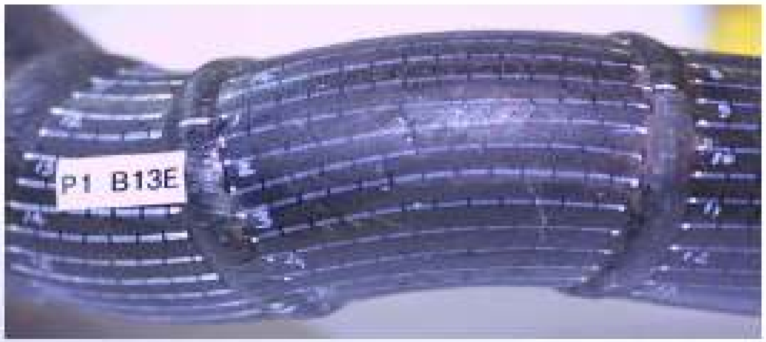
- P1 B13E removed in 2005 and tested in 2006
- 90°C
- 50 cycles under 10.7 MPa internal pressure and 0-4 kN·m bending moment
- Failure pressure 65 MPa, and Bending moment 0.9 kN·m

AECL’s Feeder bend testing – ex-service feeders

Wall Thickness Measurements

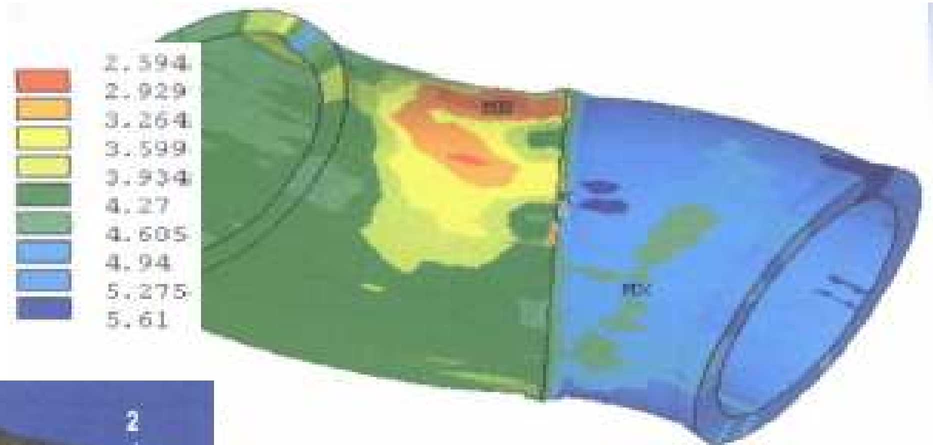
Distribution of wall thickness





AECL's Feeder bend testing – ex-service feeders

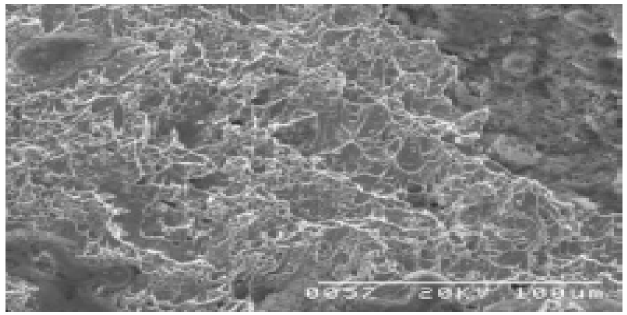
More Wall Thickness Measurements



Another evidence of local wall thinning at the intrados.

AECL's Feeder bend testing – ex-service feeders

Post-test Met Examination



- Internal Pressure
  – Measured failure pressure of 64.1 MPa
  – Predicted failure pressure of 51.4 MPa
  – Design Pressure ~ 10.7 MPa
  – Level C Pressure ~ 12.4 MPa

AECL's Feeder bend testing – for specimen

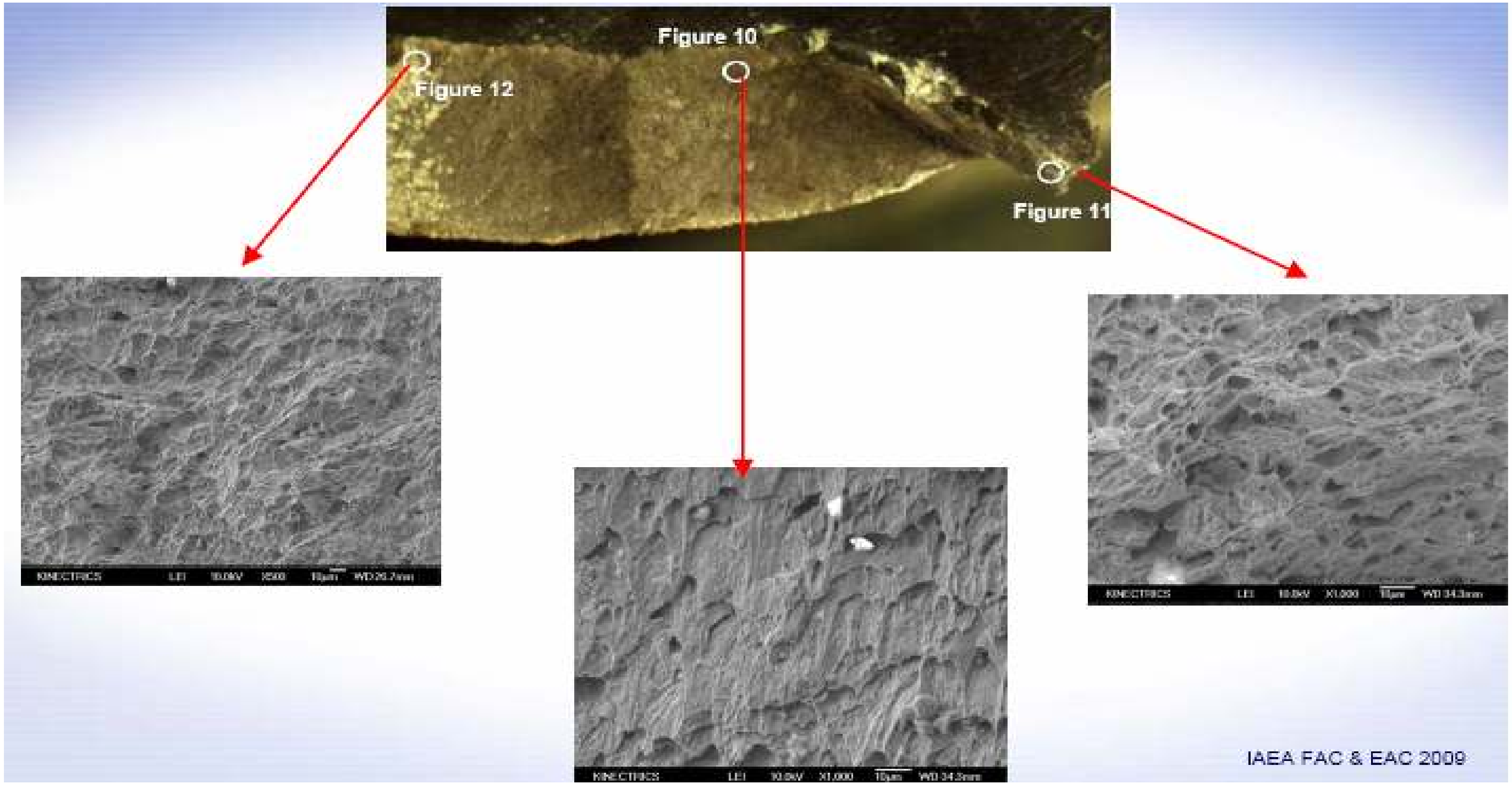
Test Conditions

- NPS2½ or NPS2 Schedule 80 SA-106 Gr.B
- 300°C (265°C in Phase 1&2)
- General thinning: 40%t_{nom}
- Internal pressure 10.3 MPa
- Large bending moment (cyclic & monotonic)
- Local thinning flaw
  - 70%t_{min} wall thickness (2.3mm for NPS2½)
  - 45o or 90o circumferential extent
  - 12 mm axial length

AECL's Feeder bend testing – Phase III for FAC

AECL's Feeder bend testing – Phase III for FAC

Ductile Mode of Failure



Ductile Mode of Failure

- Continued operation of feeder pipes experiencing FAC wall thinning is based on
  - Comprehensive inspection whose scope and frequency are determined by risk insight based on mechanistic understanding
  - Conservative engineering evaluation for acceptance criteria for thickness
    - sufficient safety margin should be maintained to account for various uncertainties
    - evaluation methodologies should be validated by supporting tests.

V. Conclusions
Regulatory Expectations - Cracking

- Any feeder with detected crack should be replaced –not allowed for disposition
- Continued operation of feeder pipes susceptible to cracking should be based on
  - Comprehensive inspection whose scope and frequency are determined by risk insight based on mechanistic understanding
  - Probabilistic assessment, as a complementary, of safety impact
  - Demonstration of LBB as a defence-in-depth (LBB will become a requirement for feeders with active cracking mechanism)