



Canadian Nuclear
Safety Commission

Commission canadienne
de sûreté nucléaire

Steam Generator Ageing Management in Canada - current practices and related issues

J. Riznic

Operational Engineering Assessment Division
IAEA Consultancy Meeting on Ageing Management of Steam
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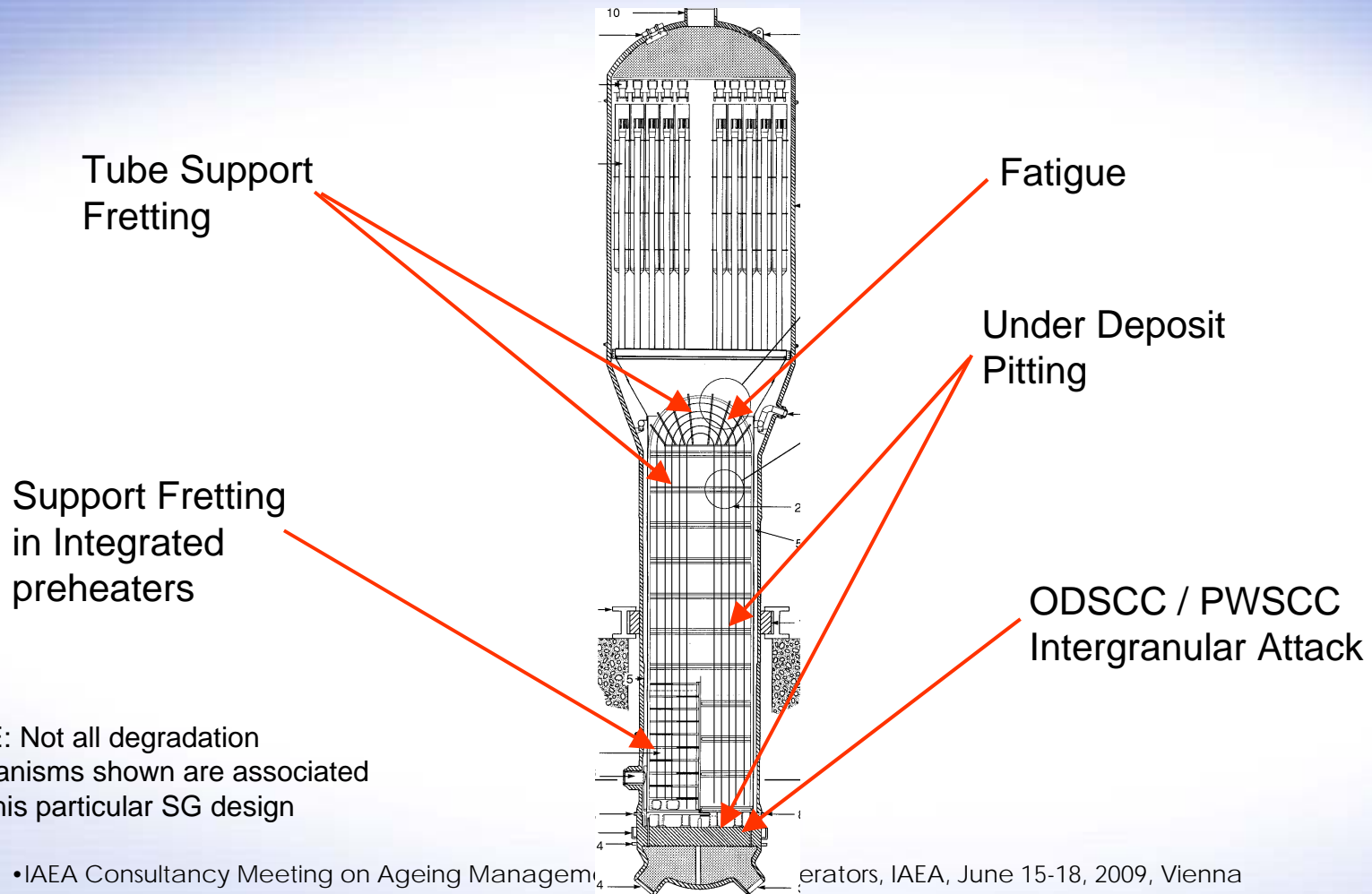


Presentation Overview

- Overview of CANDU Steam Generators
- CNSC Regulatory Approach
- Observed SG Degradation Mechanisms
- SG Inspection practices
- Ageing Management



Observed Tube Degradation





CANDU SGs in Canada

Station (In Service)	Units	SGs per Unit	Total Tubes	Separate Preheater	Tube Material
Bruce A (1976-79)	4 (750 MW)	8	134,400	Yes	I-600
Bruce B (1984-87)	4 (750 MW)	8	134,400	Yes	I-600
Gentilly-2 (1983)	1 (675 MW)	4	14,200	No	I-800
Pt. Lepreau (1983)	1 (680 MW)	4	14,200	No	I-800
Darlington (1989-92)	4 (880 MW)	4	76,400 (15.9 mm)	No	I-800
Pickering A (1971 -73)	4 (542 MW)	12	124,800	No	I-400
Pickering B (1982-86)	4 (540 MW)	12	124,800	No	I-400

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CNSCs Regulatory Approach

- **Regulations**
 - Nuclear Safety and Control Act / Regulations / Licences and Licence Conditions / Regulatory Documents / Regulatory Programs
 - CNSC assesses its regulatory framework against an expanding and evolving industry
 - Technical, organizational and administrative requirements
- **Inspection and oversight**
 - With focus on the licensees competence and capabilities to maintain safe operation
- **Compliance verification and research**
 - To support CNSC inspection and oversight activities and keep staff competence

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Regulatory Objectives for SGs

- Ensure radiation doses from any steam generator (SG) tube leak during normal operation and postulated accident conditions will not exceed the effective dose limits set out in the regulations
- This condition is met by ensuring:
 - a low probability of spontaneous tube rupture under normal operating conditions
 - a very low probability of tube rupture under design basis accident conditions

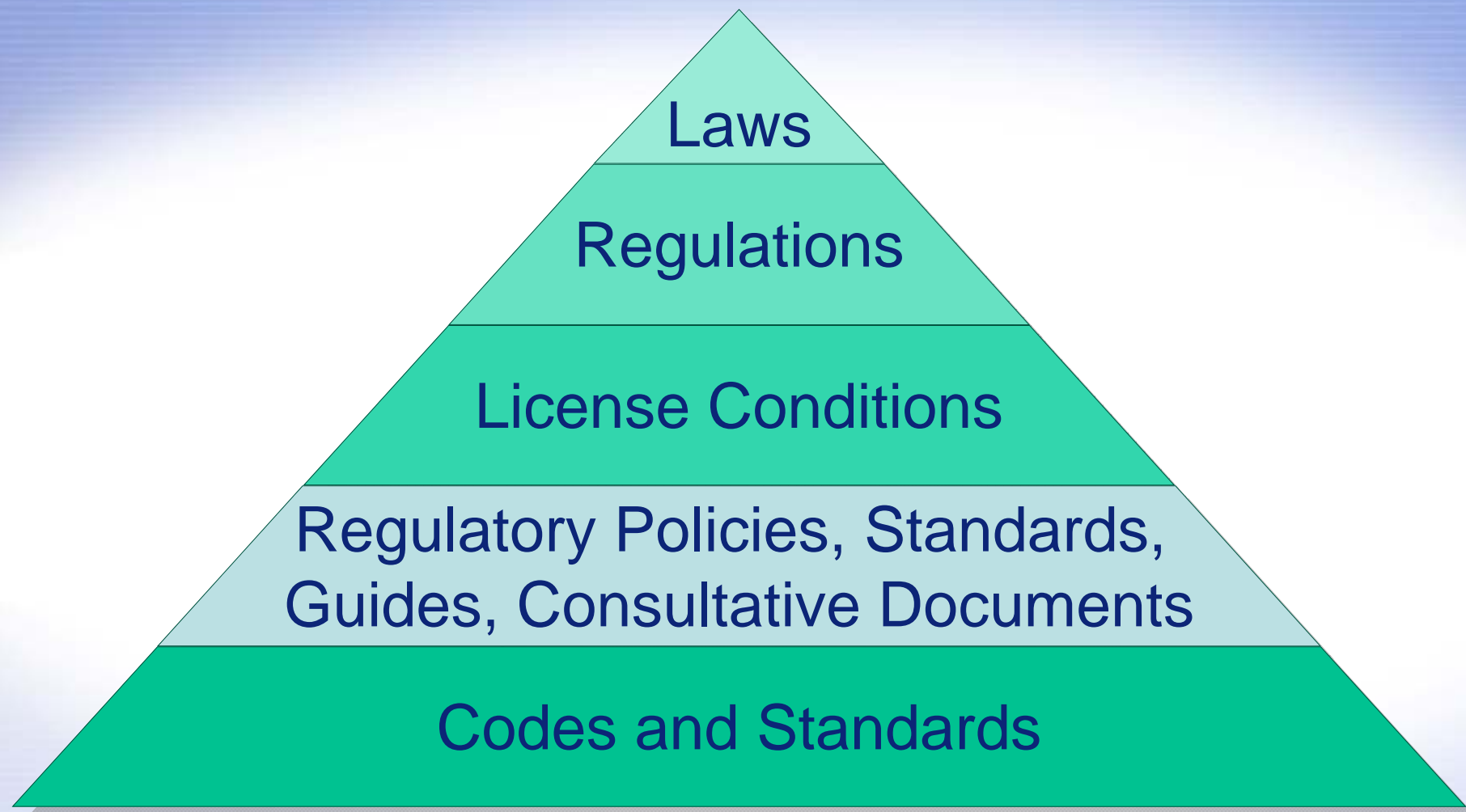


Regulatory Control for SGs

- Main Regulatory Controls:
 - Licence conditions
 - Inspection requirements
 - Limits on SG tube leakages
 - Requirement for reporting of pressure boundary integrity
 - Requirement for flaw disposition



Canadian Regulatory Framework



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New Regulatory Standards

- CNSC is preparing / has prepared new Regulatory “Standards” (Guiding documents) for inclusion in operating licences. These standards will be added to licences for new facilities or licences for existing facilities as they come up for renewal
- Documents intended to be technology neutral
- Examples include ;
 - S-98, “Reliability Programs for Nuclear Power Plants”, 2005.
 - S-294, “Probabilistic Safety Analysis for Nuclear Power Plants”, 2005.
 - S-210, “Maintenance Programs for Nuclear Power Plants, 2007”.
 - RD-360, “Life Extension of Nuclear Power Plants”, 2008.
 - RD-310, “Safety Analysis for Nuclear Power Plants”, 2008.
 - RD-337, “Design of New Nuclear Power Plants”, 2008

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CSA N285.4-05

- CSA N285.4-05, “Periodic Inspection of CANDU Nuclear Power Plant Components”
- Outlines requirements for Periodic Inspection Program (PIP) and In-service Inspection (ISI)
- General intentions of changes in 05 Edition
 - Time and budget expenditures should be focused where required to ensure plant safety
 - Requirements evaluated on a plant by plant basis
 - Still maintains a set of minimum prescriptive requirements to monitor plant performance



CSA N285.4-05 Changes in 2005 Edition (Clause 14)

- Notable changes in Clause 14 between 1994 and 2005 Editions
- Lead Unit Concept
 - Concept of lead unit for a multi-unit power plant removed (PIP now applies to all units of a multi-unit power plant)
 - In practice, lead unit concept was not used by Licensees in Canada
- PIP Sample Requirements
 - Previously PIP could be applied using tubes from a single SG
 - Clause 14.2.2.4 now requires that all SGs be inspected under the PIP by the end of the fourth inspection interval
 - In practice, inspection of all SGs is carried out using shorter intervals than minimum required

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Practical Implementation of Inspection Programs

- Recognized by CNSC and Licensees that the minimum requirements of CSA N285.4 cannot address all operational and safety issues associated with SG in-service degradation
- Licensees have generally divided inspection programs into two elements
 - In-Service Inspection Program
 - Periodic Inspection Program
- These elements comprise key components of the Life Cycle Management Plan (LCMP)



Life Cycle Management Plans

- LCMPs satisfy the requirements of CSA N285.4 Clause 3.6(a)
- LCMPs outline the process the licensee intends to follow to ensure reliable long-term operation of a plant's SGs (i.e. for a 10 year period)
- LCMPs are revised as necessary to address new findings which impact the long-term plan
- LCMPs (and revisions) are submitted to the CNSC for review and approval



Observed Material Degradation / Primary Side Issues

- Primary header divider plates
 - No major safety impacts, but can lead to loss of thermal efficiency
- Tube plugs
- SG tube ID magnetite build-up
 - Thermal efficiency
 - Possible safety related impact on inspection capabilities
- Foreign materials



Divider Plate Degradation

- Degradation permits hot Reactor Outlet Header fluid to by-pass tube bundle
- Increase in Reactor Inlet Header Temperature (RIHT) observed
- Two designs considered in this presentation
 - Segmented / lap joint design
 - Welded floating plate design



Segmented / Lap Joint Divider Plate

- Plate segments bolted to each other, the tubesheet and the primary side bowl
- Subject to leakage
 - Around periphery between plate segments and seat bars
 - Between plate segments
 - Through bolt holes
 - Around corner filler blocks



Welded Floating Divider Plate

- Welded construction, no bolted lap joints
- Eliminates leakage at bolted lap joints
- Leakage still possible around periphery of plate
- Geometry issues and magnetite in primary water may lead to flow assisted corrosion (FAC) in carbon steel elements at periphery of plates
 - No significant degradation of this nature experienced to date



Divider Plate Leakage Mitigation

- Inconel overlays (“skin fixes”)
 - Applied to segmented / lap joint divider plates on hot leg side
 - Notable drop in RIHT observed



Tube Plug Leaks

- General practice to visually inspect HL and CL tube plug during outages
- Leaking tube plug welds have been identified during inspections
- Tubes with poor plug welds could become pressurized and fail due to tube degradation if it progressed
- Contribute to primary to secondary leakage if tube contained a leaking defect
- Assessment indicated that leaks due to poor initial weld quality and not in-service degradation



Tube ID Fouling

- Decrease in solubility of magnetite from PHT in D_2O with decreased temperature
 - Magnetite deposits in SG tubes
- From a thermal performance perspective, increases in RIHT occur
- From an inspection/safety perspective, deposits can impact tube inspection capabilities
 - Tubes may become obstructed preventing tool passage
 - Magnetite deposits may affect ET flaw detectability and sizing by increasing NDE signal noise



Foreign Materials

- Foreign materials left in primary side of SGs could introduce scratches on ID of tubes
 - Possible initiation sites for in-service degradation
- Possible damage to other primary side SG internals
- Materials could be transported through PHTS and into reactor



Foreign Materials Exclusion (FME)

- FME programs required to ensure all materials entering SGs accounted for before restart
 - Occasional failures of FME programs observed and improvements expected
 - Important to educate all employees and contractors of importance
- Any materials unaccounted for must be disposition prior to reactor restart
 - Consideration given to SG and entire PHTS operation



Secondary Side Issues / Degradation

- Tube support degradation
- Secondary side deposits and sludge piles
- Foreign materials
- Tube degradation mechanisms



Carbon Steel Support Degradation

- Tube supports made of carbon steel have been subject to a variety of degradation mechanisms
 - Under deposit corrosion and cracking of U-bend scallop bar supports
 - Scallop bar stack growth in U-bend region
 - Corrosion of tube support plates leading to tube denting and loss of tube support
 - Debris fretting can occur if pieces of support plate break free
 - Tube fretting at supports due to increased clearances

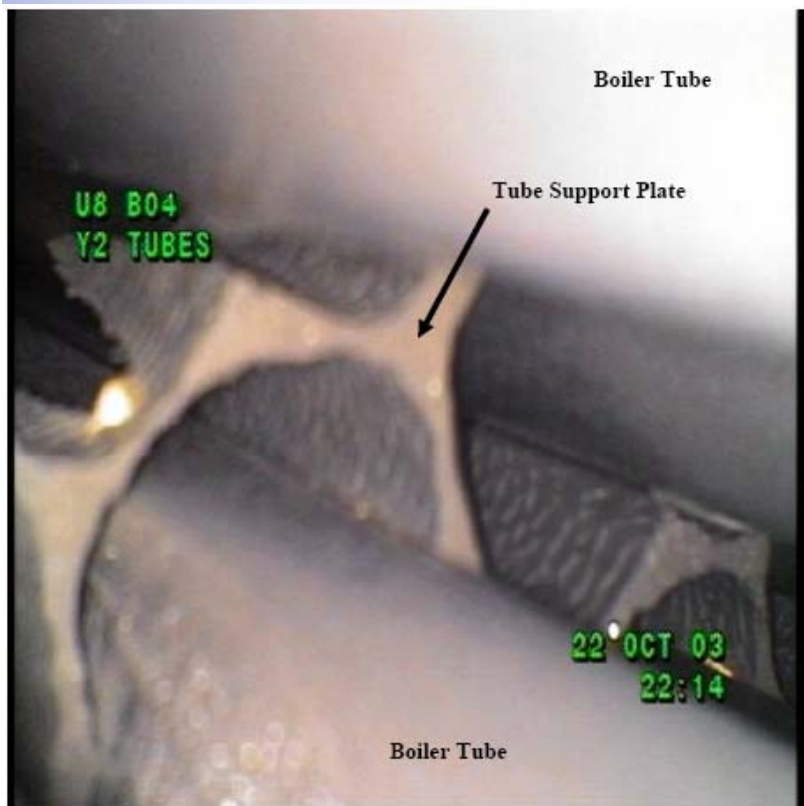


Scallop Bar Stack Growth

- Considered to be a contributing factor to U-bend SCC in I-600 tubes
- Corrosion products between carbon steel plates have higher volume than steel
- Causes the stack to grow, imposing uneven loading on tubes

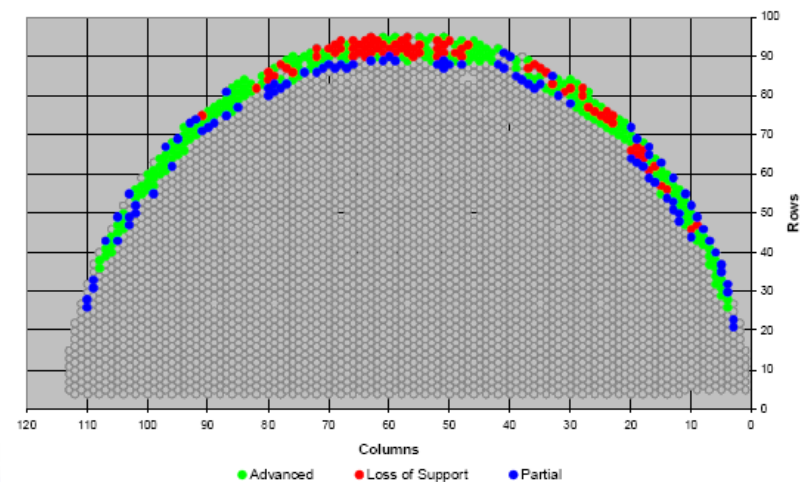
FAC of Support Plates

- FAC observed in carbon steel supports



- May contribute to tube fretting
- Concerns regarding additional loading applied to tubes and pinching if support plates bend

2003 Unit 8 SG8 H07 Support Plate Damage Comparisons (Analysed To Nov. 12)



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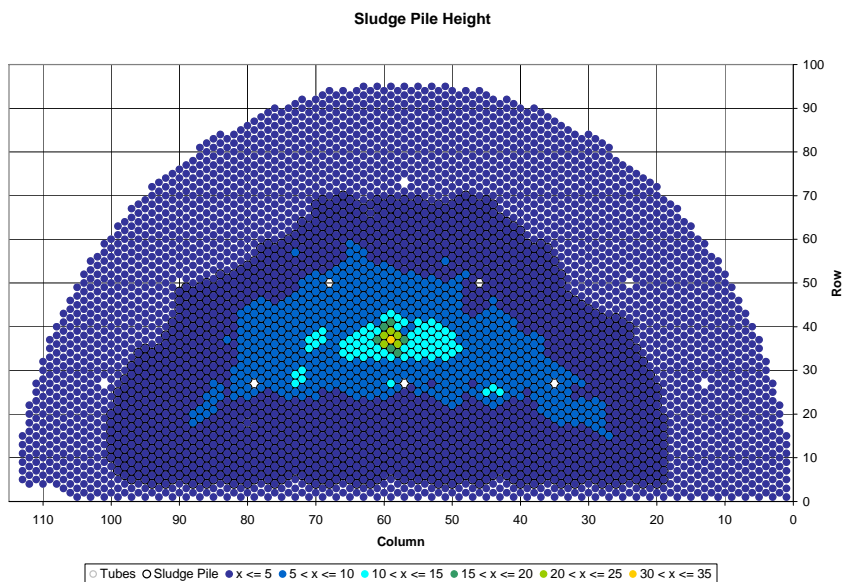


Secondary Side Deposits

- Generally pitting at supports or along straight legs has been associated with secondary side deposits
- Deposits contain higher concentrations of impurities than secondary side water and form crevices
- Pitting has been observed at tube supports in I-800 tubes
- Mitigation strategies include
 - Secondary side chemistry control
 - Secondary side chemical cleaning
 - Waterlancing

Sludge Pile

- Pitting and ODSCC have been attributed to the top of tubesheet sludge pile region
- Sludge piles can be extensive



- Mitigation strategies include
 - Waterlancing (hard sludge may be difficult to remove)
 - Monitoring sludge pile growth and expansion of area-at-risk as required
 - 100% HL and partial CL TTS inspection during outages as required

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Foreign Materials – Debris Fretting

- Forced outages from leaks due to debris fretting have occurred
- Sources of debris identified include
 - Welding electrodes
 - Wire
 - Screws
 - Gasket material
- It is anticipated that some materials have been left behind during construction
- Gasket material may break off and fall into SGs when access ports are opened



Foreign Materials – Other Issues

- Lead blanket left in an SG lead to significant ODSCC and eventual plant shutdown
 - Importance of effective FME programs and proper education of workers



Observed Tube Degradation I-600 and I-800

- Several degradation mechanisms have affected CANDU SGs with I-600 and I-800 tubes
- I-600 Tubes
 - Fatigue
 - Stress corrosion cracking (SCC) / Intergranular attack (IGA)
 - Pitting
 - Fretting



Observed Tube Degradation

- I-800 Tubes
 - Fretting
 - Pitting
- To date, I-800 tubing has generally performed better, but cumulative service life of Canadian plants is slightly shorter than plants with I-600 tubes
- CNSC and Canadian Licensees monitoring recent findings of SCC in I-800 tubes in German pressurized water reactor SGs
 - Operating temperatures and pressures lower in CANDU SGs, but may just be a matter of time before cracking observed



Fatigue (I-600)

- Cracking in U-bend region lead to early failures of I-600 tubes
- Initiated at fretting flaws or SCC
- Attributed to high cycle fatigue due to flow induced vibration (FIV)
- Located in hot leg (HL) at upper support plate or near the 40° U-bend support in large radius U-bends



Fatigue (I-600)

- Installation of anti-vibration bars (AVBs) appears to have improved situation
 - Recent inspections indicate that AVBs are effective
- Recognized that tight fatigue cracks are difficult to detect



U-bend SCC (I-600)

- Attributed to combination of stresses due to tube deformation and aggressive under-deposit chemistry in HL U-bend region
- Scallop bar supports comprised of a stack of carbon steel plates
- As carbon steel corrodes “stack growth” observed due to increased volume of corrosion products
 - Applies stresses to adjacent tubes
 - Corrosion of flow holes in carbon steel support plates leads to tube deformation and tensile stresses
 - Additional stresses and chemical environment contribute to crack initiation



TTS SCC / IGA (I-600)

- SCC / IGA mechanism has attributed to tube degradation and leaks at the top of tubesheet (TTS) region
- Associated with HL TTS sludge pile region
- OD initiated at the top transition of the upper expansion joint
- ID primary water SCC (PWSCC) also identified on tubes pulled to examine OD indications
- May be primarily a result of chemistry during lay-up
 - Yet to be fully confirmed

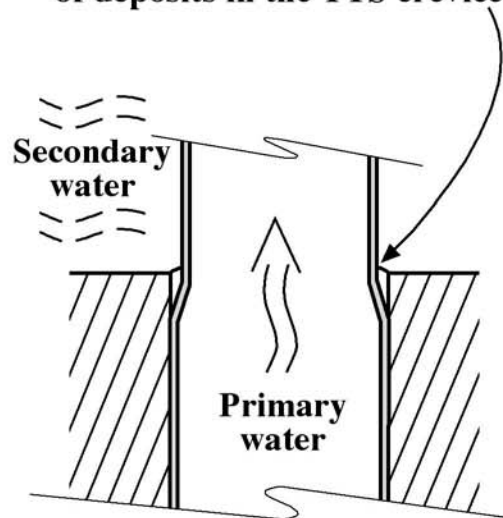


TTS SCC / IGA (I-600)

(a)

Top of Tubesheet (TTS)

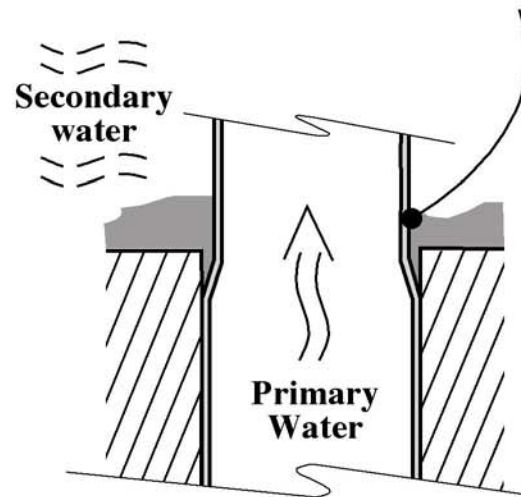
Concentration of chemicals increases with accumulation of deposits in the TTS crevice



(b)

Sludge

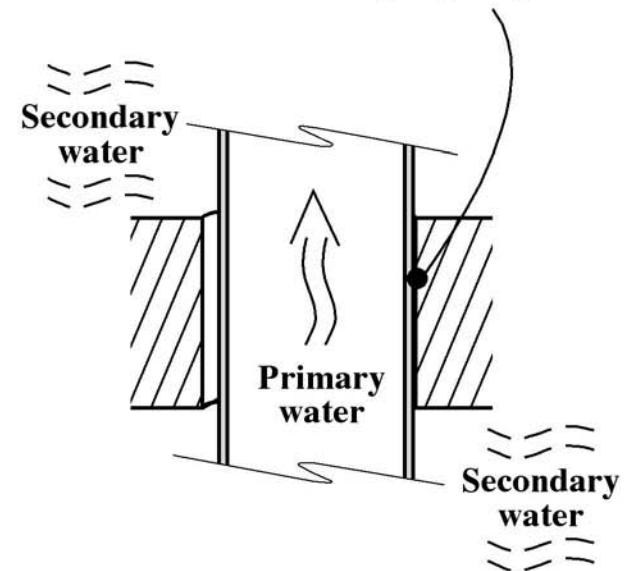
Concentration of chemicals at sludge/metal interface increases with accumulation of sludge on TTS surface



(c)

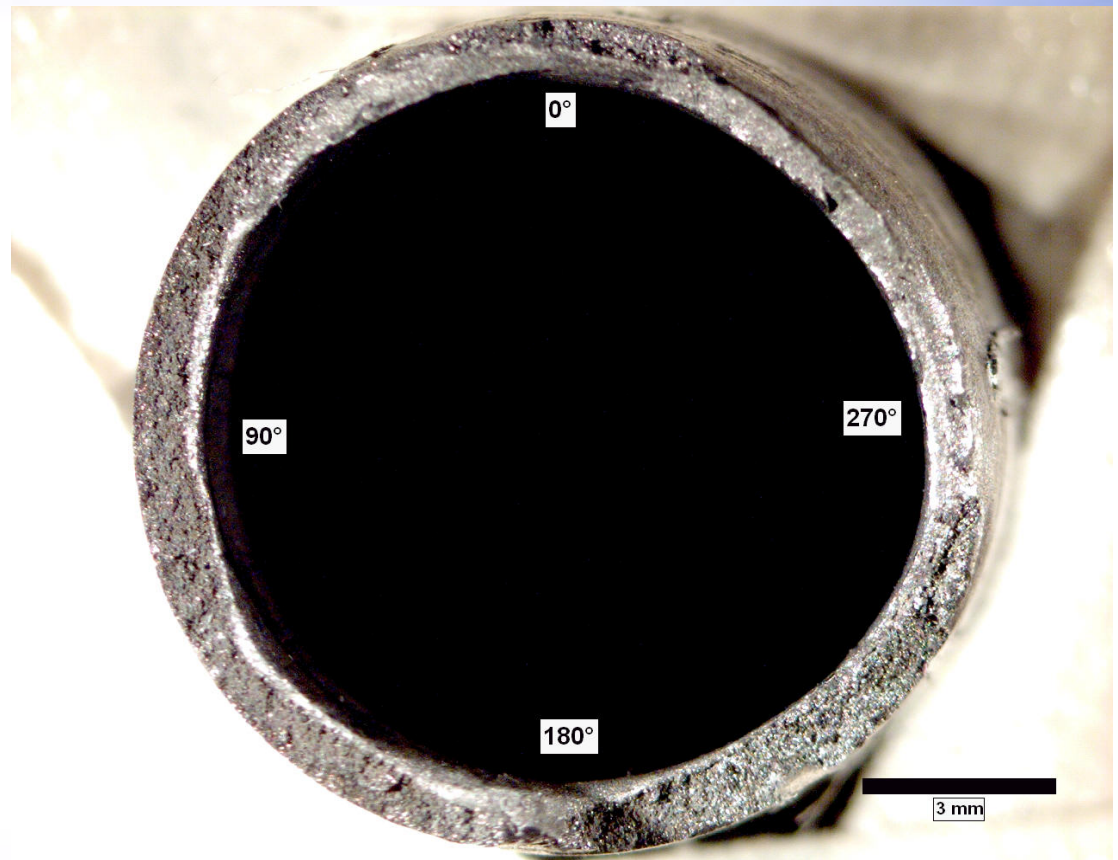
Tube Support (TSP)

Initial concentration of chemicals on contacting side. Concentration of chemicals increases as deposits accumulate around periphery.



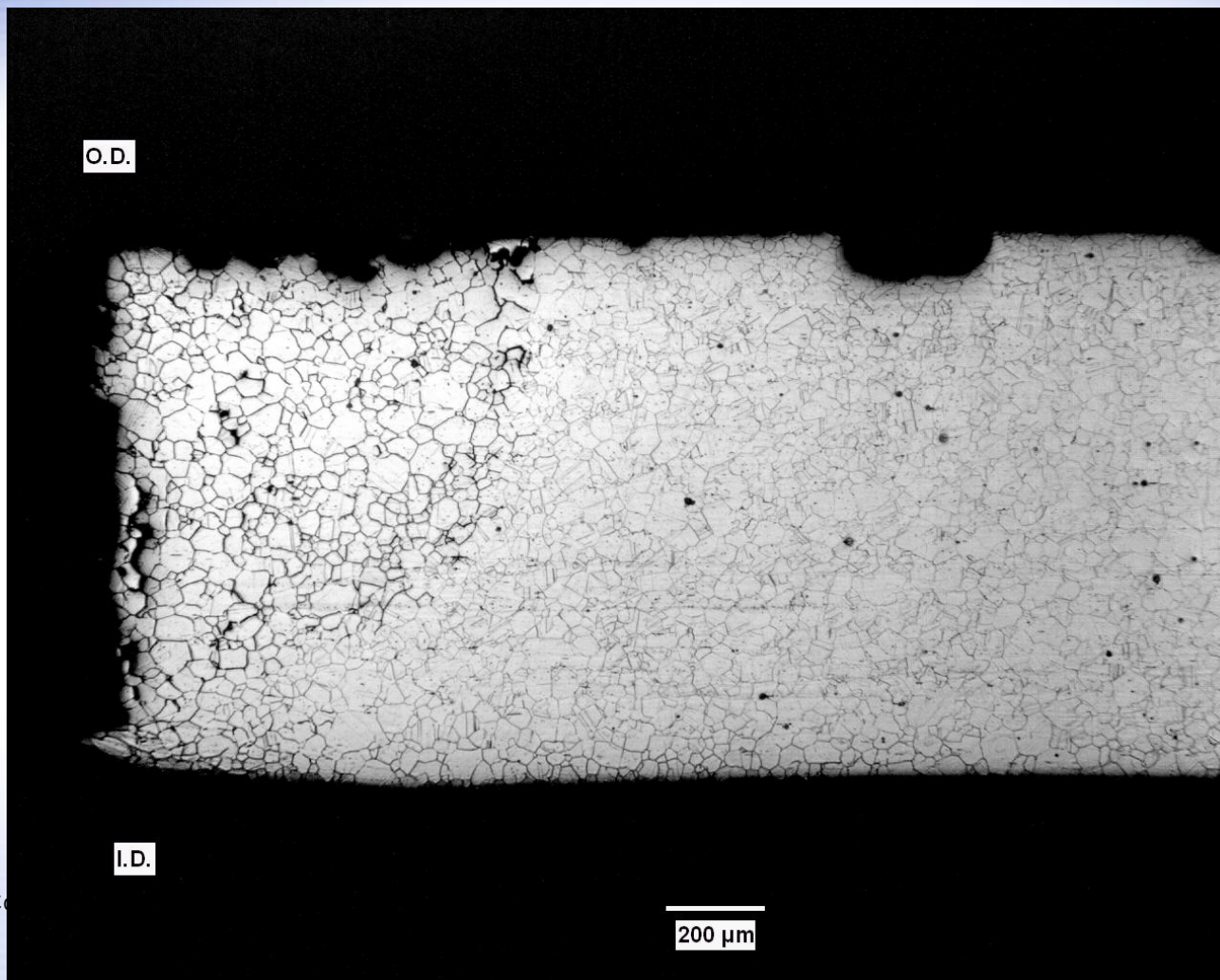
TTS SCC / IGA (I-600)

- Rough surfaces in-service degradation
- Smooth surfaces remaining ligament of tube wall



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TTS SCC / IGA (I-600)



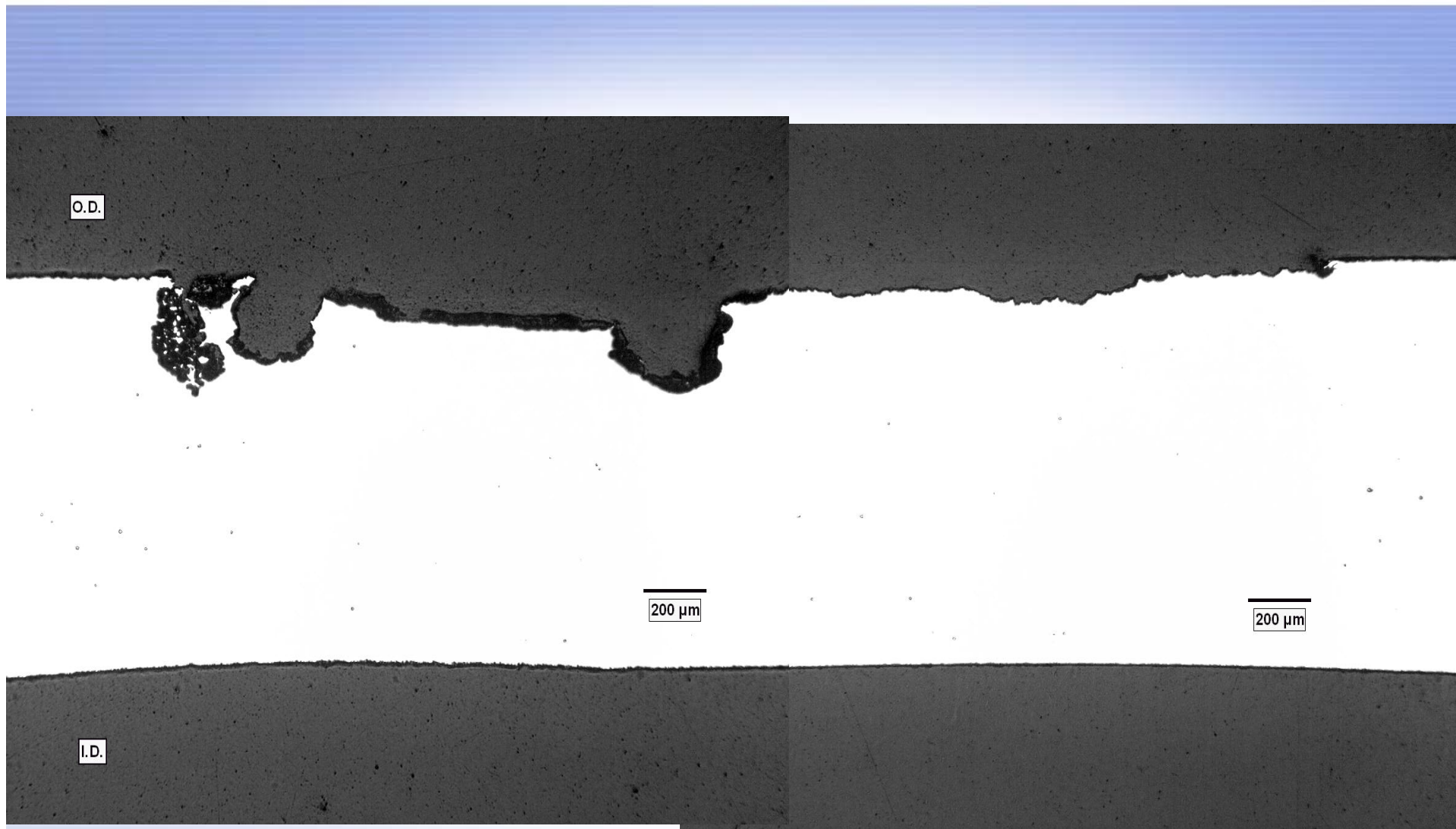
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Pitting (I-600)

- Following lay-up of some SGs with I-600 tubes, pitting was detected at the HL TTS between the top of the upper expansion and top of sludge pile
- Appears to be primarily associated with chemistry during lay-up
- Limited number of new pits and limited growth detected during in-service inspection following return to service

Pitting (I-600)



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Fretting (I-600)

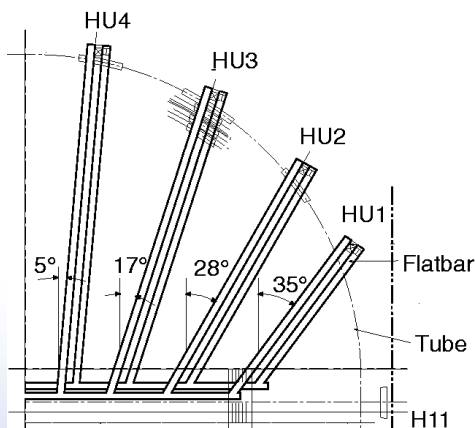
- Majority of SG fretting observed in periphery tubes
- Primarily the associated with scallop bars in U-bend
 - Fretting also possible at straight leg support plates and support forks at U-bend scallop bars
- New AVBs installed which appear to reduce fretting growth rates
- One leak attributed to U-bend support fret
- Scallop bar support frets have been observed in separate preheaters (PH)
 - One leak attributed to PH tube fretting

Fretting (I-800)

- High fret growth rates associated with U-bend region flat bar and fan bar supports have been observed in some SGs



D1 Met Exam
(2004)



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Fretting (I-800)

- Auxiliary AVBs installed
- Preliminary findings from inspections conducted shortly after installation of auxiliary AVBs suggest initiation and growth rates reduced
 - Some fretting has been observed at auxiliary AVB locations and will be monitored
- Findings will be confirmed with results from future inspection outages



Pitting (I-800)

- Recent inspections of I-800 tubes have identified shallow OD under-deposit pitting at the middle bundle at tube supports
 - Not yet determined if there may be a contribution due to secondary water flow (i.e. possible erosion process involved)



Mitigation Measures

- A summary of the actions taken to address observed degradation provided below
- I-600 Tubes
 - Installation of AVBs in U-bend to reduce potential for fatigue and fretting
 - Improved chemistry control requirements during lay-up
- I-800 Tubes
 - Installation of AVBs in U-bend region to reduce fretting initiation and growth rates
 - Secondary side cleaning programs to address under-deposit pitting

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SG Tube Inspection Programs

- Inspections programs typically planned on intervals of 10 years or more
 - Outlined in Life Cycle Management Plans (LCMPs)
 - Modified as required based upon findings
 - Comprised of In-Service Inspection (ISI) programs and Periodic Inspection (PIP) programs
 - PIP program requirements often incorporated as subset of ISI programs

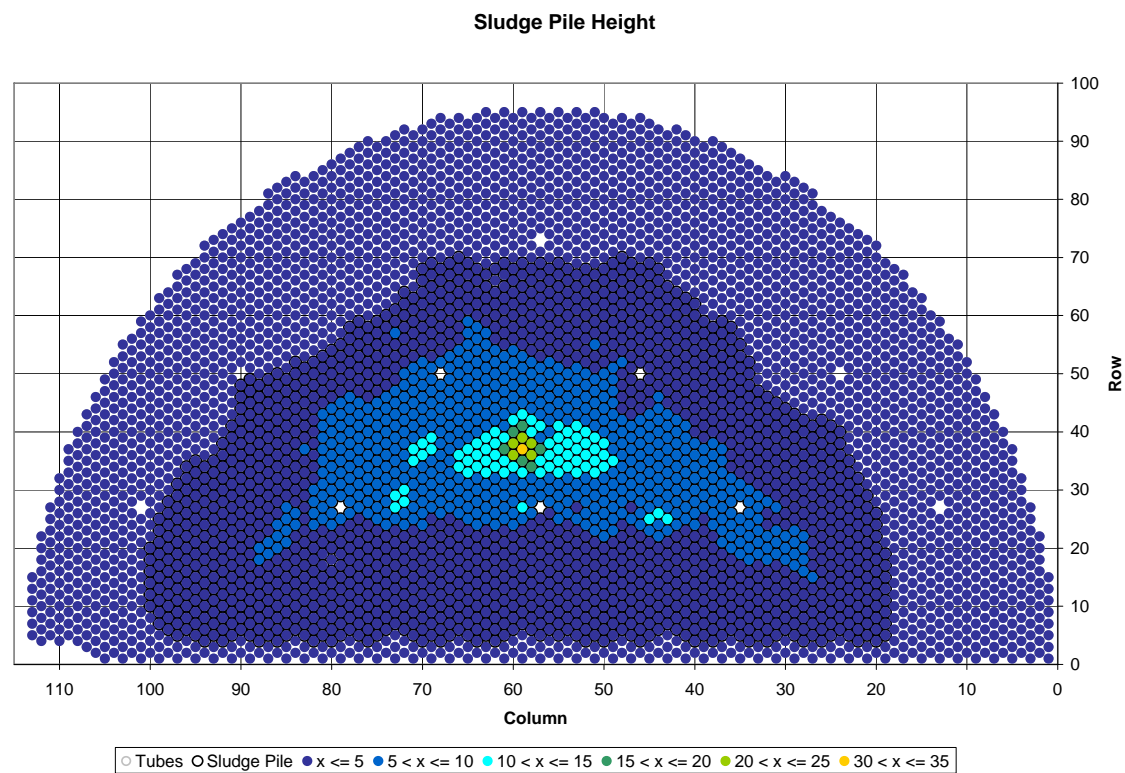


Area-at-Risk (AAR)

- For known degradation mechanisms AARs defined
- Typical AARs include
 - Fatigue: Large radius U-bend and upper TSPs
 - Fretting: U-bend region and upper TSPs
 - ODS/IGA: HL TTS under the sludge pile, HL U-bend region
 - Pitting: HL TTS under sludge pile, TSPs with significant deposit build-up

Area-At-Risk (AAR)

- Example: AAR defined as HL sludge pile region for TTS degradation



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Outage Inspection Scope (Tubes)

- Inspection of a sample of tubes in the Not-Area-at-Risk (NAR)
 - Identification of unanticipated degradation
 - Possible results may lead to expansion of AAR
- Process leads to 100% inspection of all tubes in defined AAR and sample of tubes in NAR over the course of two outages
 - Typical duration ranges from 1 year to 6 years (outages between 6 months and 3 years apart)
- Scope also defined to meet CSA N285.4 PIP requirements

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Fitness-for-Service

- SG LCMP require reasonable assurance:
 - tube structural integrity is maintained during evaluation period
 - there are adequate margins between estimated accumulated dose and applicable site dose limits based on a consequential leak assessment
- Achieved through the development of Fitness-for-Service (FFS) guidelines



Fitness-for-Service

- CAN/CSA-N285.4 calls for fitness-for-service assessment for indications exceeding 40% of wall thickness prior to next inspection
- FFS Guidelines provide evaluation procedures and acceptance criteria
- Technical Basis for FFS
 - Not fully developed by industry
 - Work in progress
 - Similar practices used by licensees, but methods not universally applied



Ageing Degradation - Traditional Regulatory Approach



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Meeting the Challenges - Enhancing the Regulatory Framework

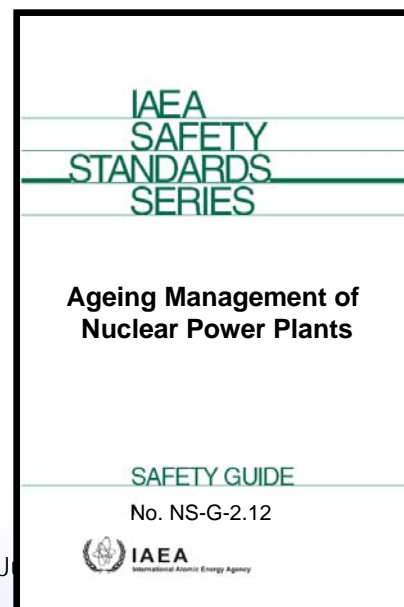
- New Regulatory Document on Ageing Management (RD-334)
- Strengthen role of proactive ageing management for Existing Plants and New Builds
- National and International R&D programs
- Sharing / exchange of OPEX



Development of RD-334

- Will represent the CNSC's adoption and adaptation, consistent with the Canadian regulatory framework, of the guidance established in new IAEA draft safety guide

IAEA NS-G-2.12 Ageing Management of Nuclear Power Plants (2009)



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RD-334

- SSC Specific AMP Development

- SSC Specific AM strategies should cover the 9 elements for effective ageing management program:



GENERIC ATTRIBUTES OF AN EFFECTIVE **SSC AMP**



<i>Attribute</i>
1. Scope of the ageing management program based on understanding ageing
2. Preventive actions to minimize and control ageing degradation
3. Detection of ageing effects
4. Monitoring and trending of ageing effects
5. Mitigating ageing effects
6. Acceptance criteria
7. Corrective actions
8. Operating experience feedback and feedback of R&D results
9. Quality management



CNSC Research Initiatives

- **CANTIA (CANdu Tube Inspection Assessment)**
 - Probabilistic Methodology for Assessing Steam Generator Tube Inspections, in 1997.
- CNSC staff is currently working on updating the methodology
- There are no plans to impose or rely on CANTIA in inspection dispositions
 - Intended for use as an independent checking tool



CNSC Research Initiatives

- CNSC research program brought forth an alternative methodology
 - Constrained expected likelihood estimates (CELE), Example: Grubb's estimators
 - Bias in data identified
 - Standard deviations estimated for each data set separately
 - Very useful for tool error evaluation if comparing data from two inspection tools (i.e. ET vs. UT)
 - Has been used in oil and gas pipeline industry in North America for estimating inspection tool errors



Conclusions

- The CNSC is taking an active approach to ensure the knowledge base and tools required to ageing challenges for NPP:
 - Strengthening the regulatory framework for life extension and proactive management of materials degradation / ageing issues,
 - participating in R&D initiatives with industry, international organizations and standards committees,
 - ensuring effective coordination and exchange of R&D and OPEX.



6th International Steam Generator Conference

- November 8-11, 2009
- Hilton Toronto, Toronto, Ontario, Canada
- Call for Papers is out
- Submission of Abstracts – June 19th 2009
- www.cns-snc.ca



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