Potential Areas of Enhancements for Concrete Containment and Other Structures

Julia Tcherner, Specialist Civil Engineer. AtkinsRéalis, Canada

Workshop on LTO Beyond 60 Years. February 2024, NRG, Petten

AtkinsRéalis

- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Outline

- Nuclear Civil Structures
- Understanding Ageing
- Detection and Maintenance
- Conclusions and Lessons Learned
- Areas for Enhancements

- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Nuclear Civil Structures

- Nuclear civil structures are essentially passive under normal operating conditions, but play a key role in mitigating the impact of extreme/abnormal operating and environmental events
- Structural components are somewhat plant specific, may be subjected to aggressive environment, may be difficult to inspect and repair and typically can not be replaced
- Structures are subject to time-dependent changes that may impact their ability to withstand various demands from operation, the environment, and accident conditions
  - *excessive degradation can lead to failure*
  - *failure often affects serviceability, not safety*
- Operating Experience (OPEX) indicates that nuclear civil structures have a history of reliability and durability, but there have been occurrences of degradation

- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Multi – Unit CANDU

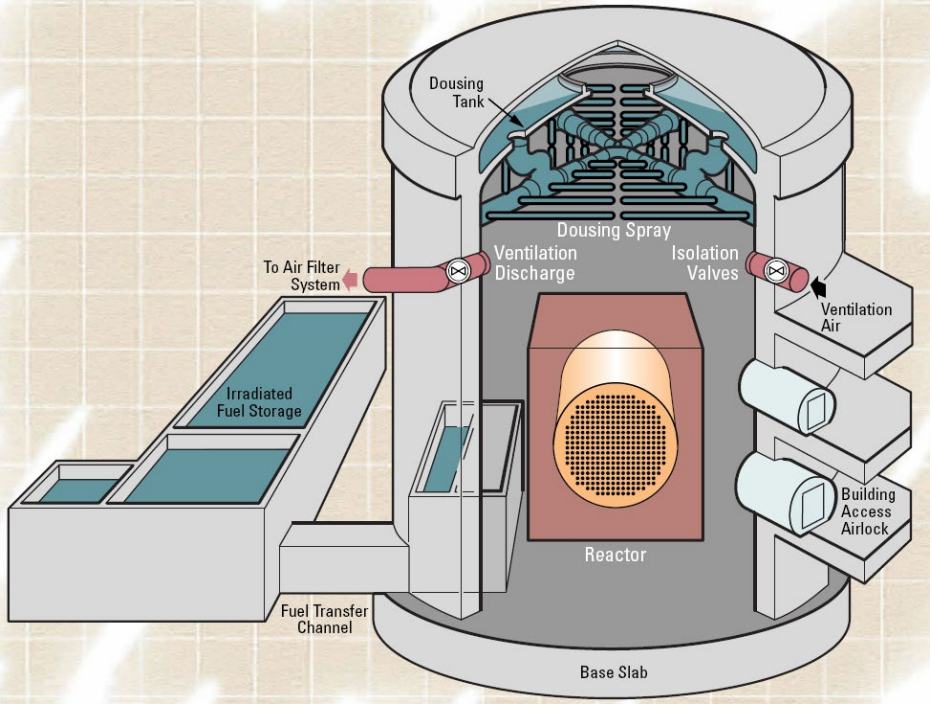
- 18 operating units at 3 sites in Ontario, Canada
  - ✓ Darlington
  - ✓ Bruce
  - ✓ Pickering
- Typically, several Reactor Buildings are connected by pressure relief duct to the same vacuum building

- Oldest
  - ✓ Pickering A (1971)
- Most Recent
  - ✓ Darlington (1993)
- Original Design Life
  - ✓ 30-40 years

- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

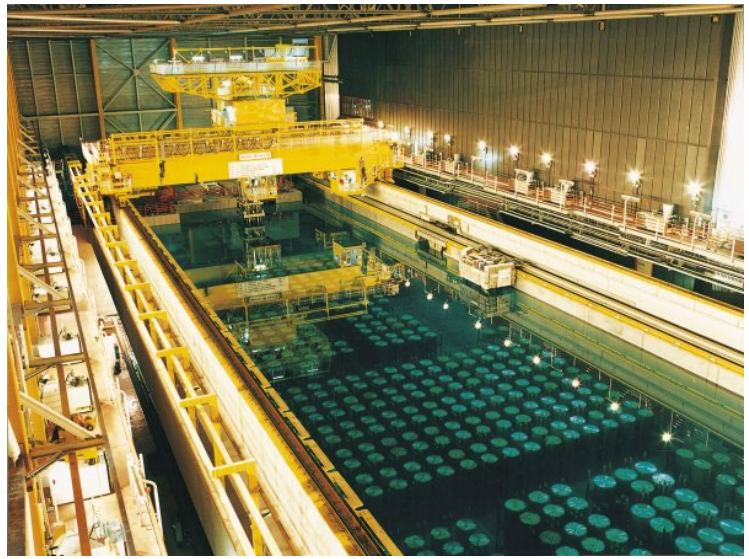
CANDU 6

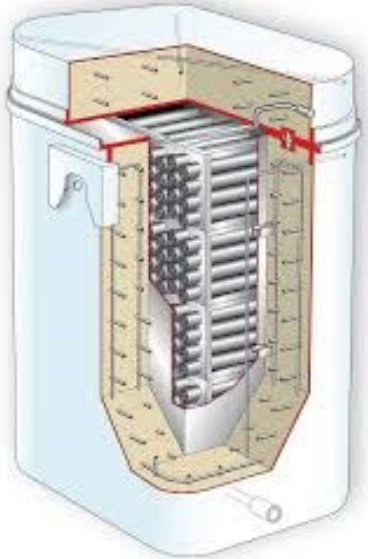
- 9 CANDU 6 Operating Reactors
- 1 in Canada, 8 around the world
  - ✓ Argentina
  - ✓ China
  - ✓ Korea
  - ✓ Romania



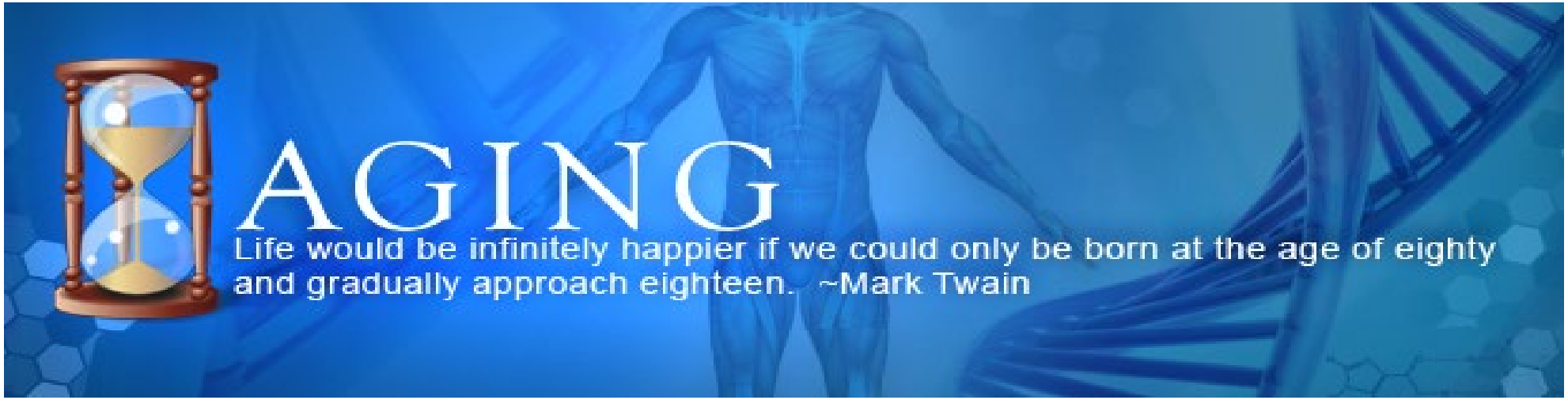
- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Other Nuclear Structures, e.g. Waste Storage

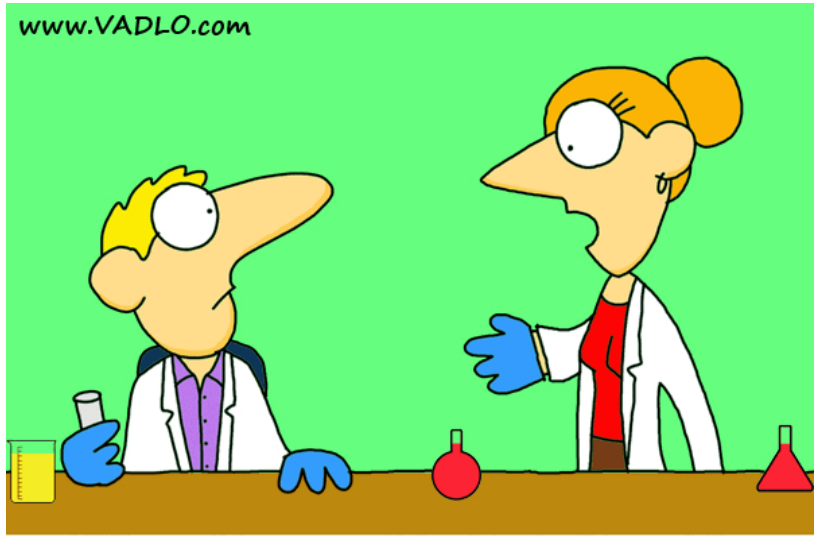




- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.



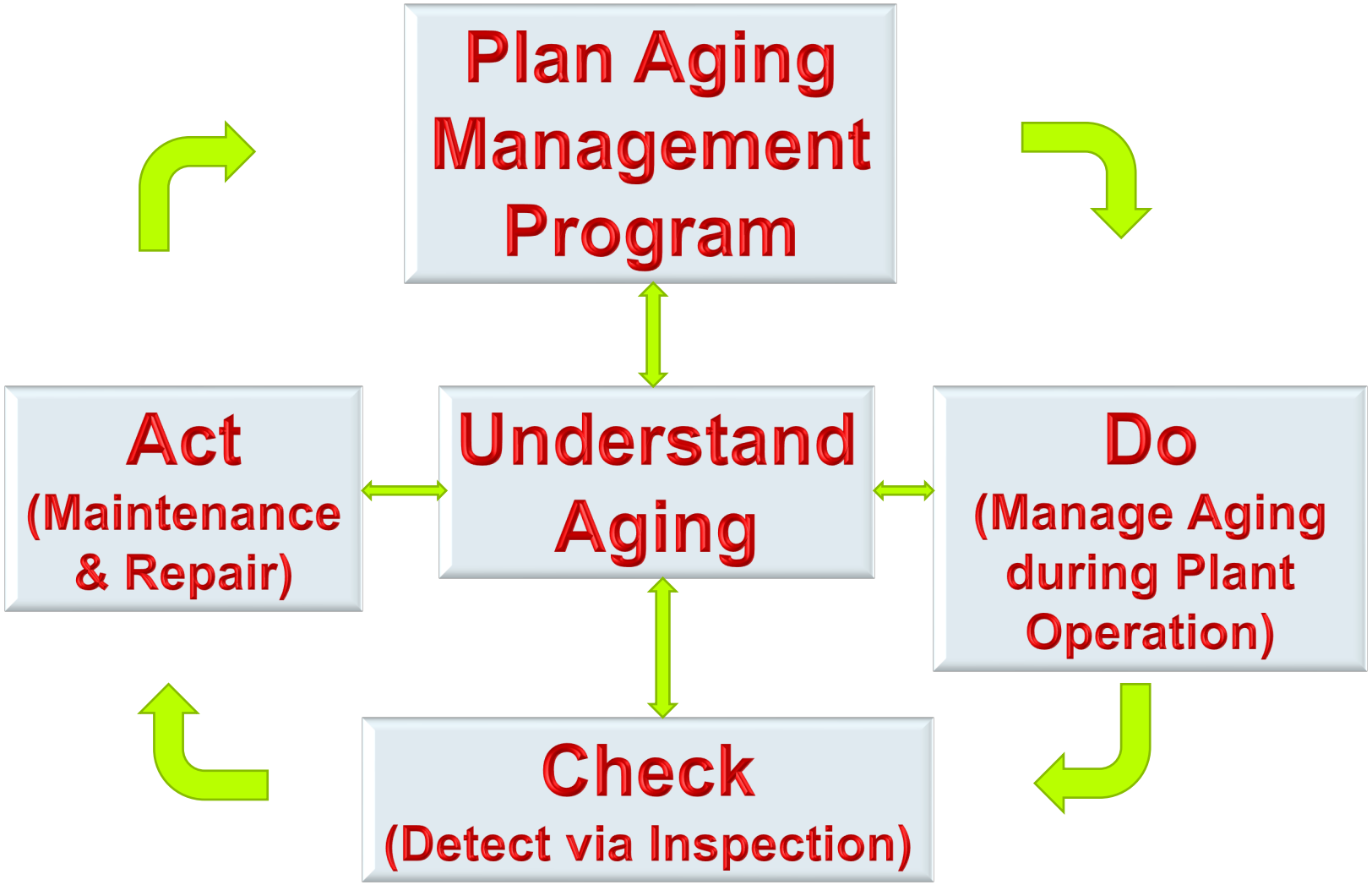
Aging – the process of change in the properties of a material occurring over a period of time, either spontaneously or through deliberate action



"All my colleagues are doing "Ageing Research",
I am simply ageing!"

- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Aging Management Model



- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Aging Management

Definition

Engineering, operations, inspection, and maintenance actions to control, within acceptable limits, the effects of physical aging and obsolescence of a structure.

Purpose

To ensure that structures satisfy their functional and performance requirements in all different phases of their life cycle including design, construction, commissioning, operation (including long-term operation and extended shutdown), and decommissioning.

Understanding the relevant aging mechanisms and their potential impact on structures is the key to effective AM.

This includes an understanding of:

- ✓ design
- ✓ material properties,
- ✓ methods of construction,
- ✓ structure models,
- ✓ stressors,
- ✓ operating conditions,
- ✓ aging mechanisms,
- ✓ sites of degradation,
- ✓ consequences of degradation,
- ✓ relevant R&D,
- ✓ relevant OPEX,
- ✓ maintenance history,
- ✓ mitigation measures,
- ✓ and current structure status.

- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Aging Related Degradation Mechanisms (ARDMs)

CONCRETE

- Leaching and Efflorescence
- Sulphate Attack / Delayed Ettringite Formation (DEF)
- Acid / Base Attack
- Alkali Aggregate Reaction (AAR)
- Carbonation
- Salt Crystallization
- Freeze Thaw Attack
- Fatigue
- Abrasion / Erosion / Cavitation
- Moisture content changes, material incompatibility due to different thermal expansion values
- Aggregate Expansion, hydrolysis
- Differential Settlement

 - Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Aging Related Degradation Mechanisms (ARDMs)

REINFORCEING/ PRESTRESSING STEEL

- Corrosion
- Microcrystalline changes due to high temperature exposure
- Microstructural changes due to irradiation
- Fatigue
- Stress relaxation / creep and shrinkage of concrete

 - Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Aging Related Degradation Mechanisms (ARDMs)

CARBON STEEL

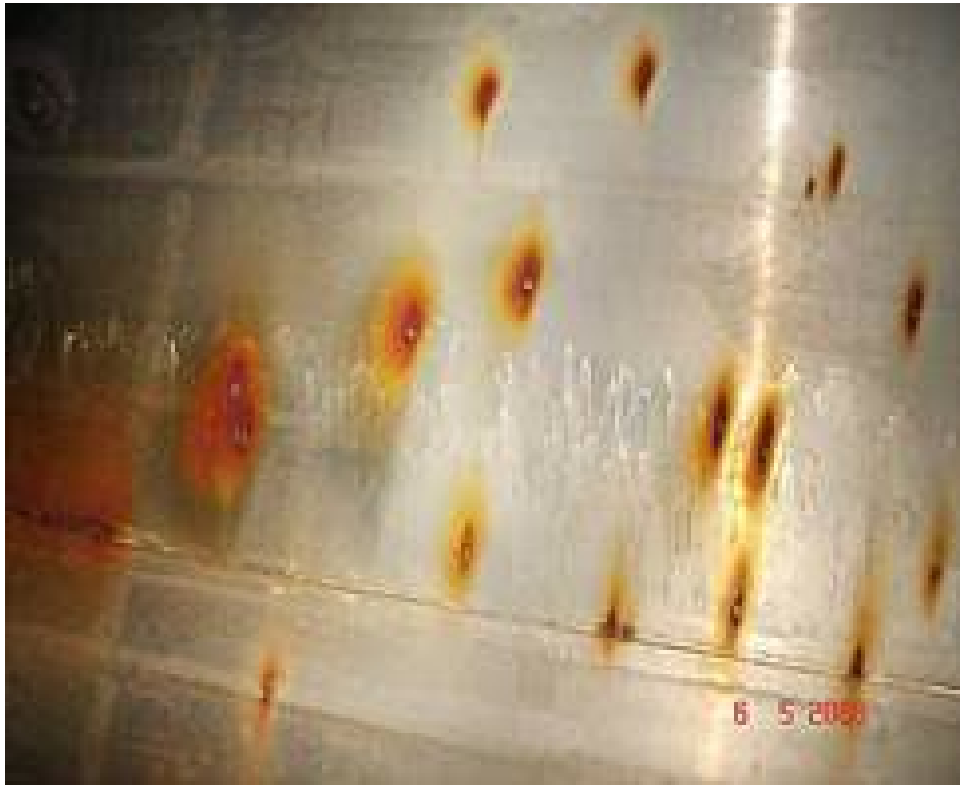
- General Corrosion
- Flow Accelerated Corrosion (FAC)
- Galvanic Corrosion
- Atmospheric Corrosion / weathering
- Pitting
- Microbially Influenced Corrosion (MIC)
- Stress Corrosion Cracking (SCC)
- Hydrogen Embrittlement
- Neutron Embirttlement

 - Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Aging Related Degradation Mechanisms (ARDMs)

STAINLESS STEEL

- Stress Corrosion Cracking (SCC)
- Pitting
- Microbially Influenced Corrosion (MIC)
- Flow Accelerated Corrosion (FAC)
- Galvanic Corrosion
- Neutron Embrittlement
- Thermal Embrittlement

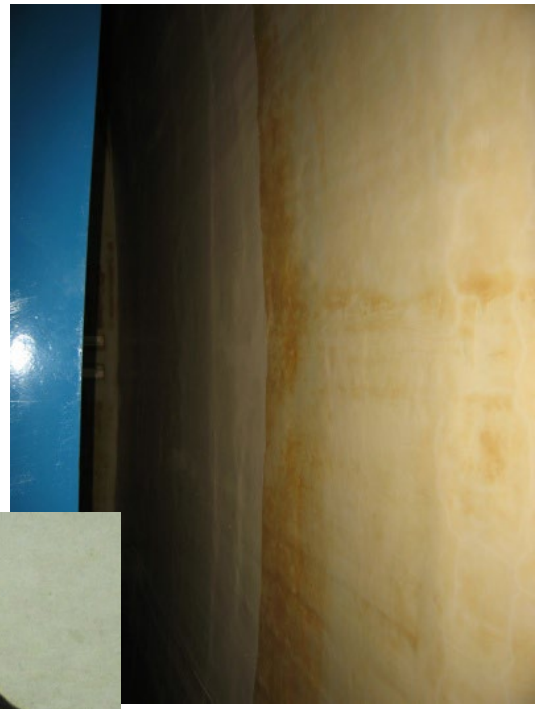


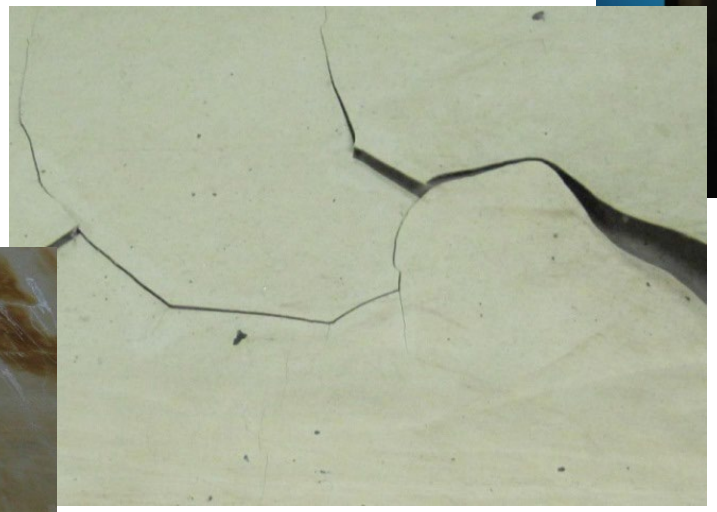
 - Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

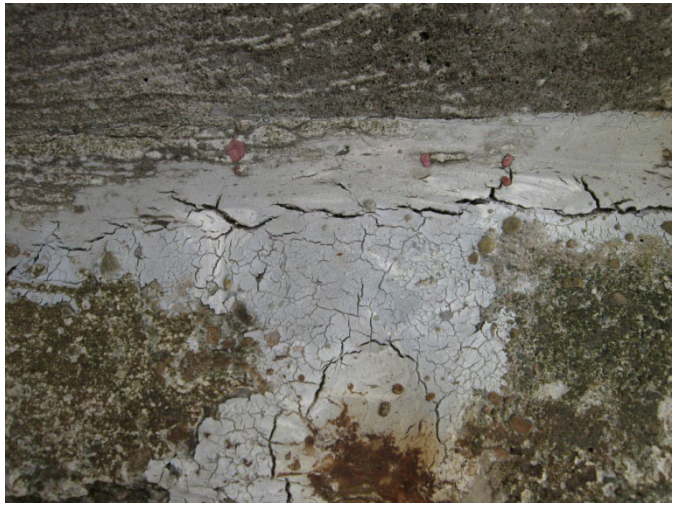
Aging Related Degradation Mechanisms (ARDMs)

NON-METALLIC COMPONENTS

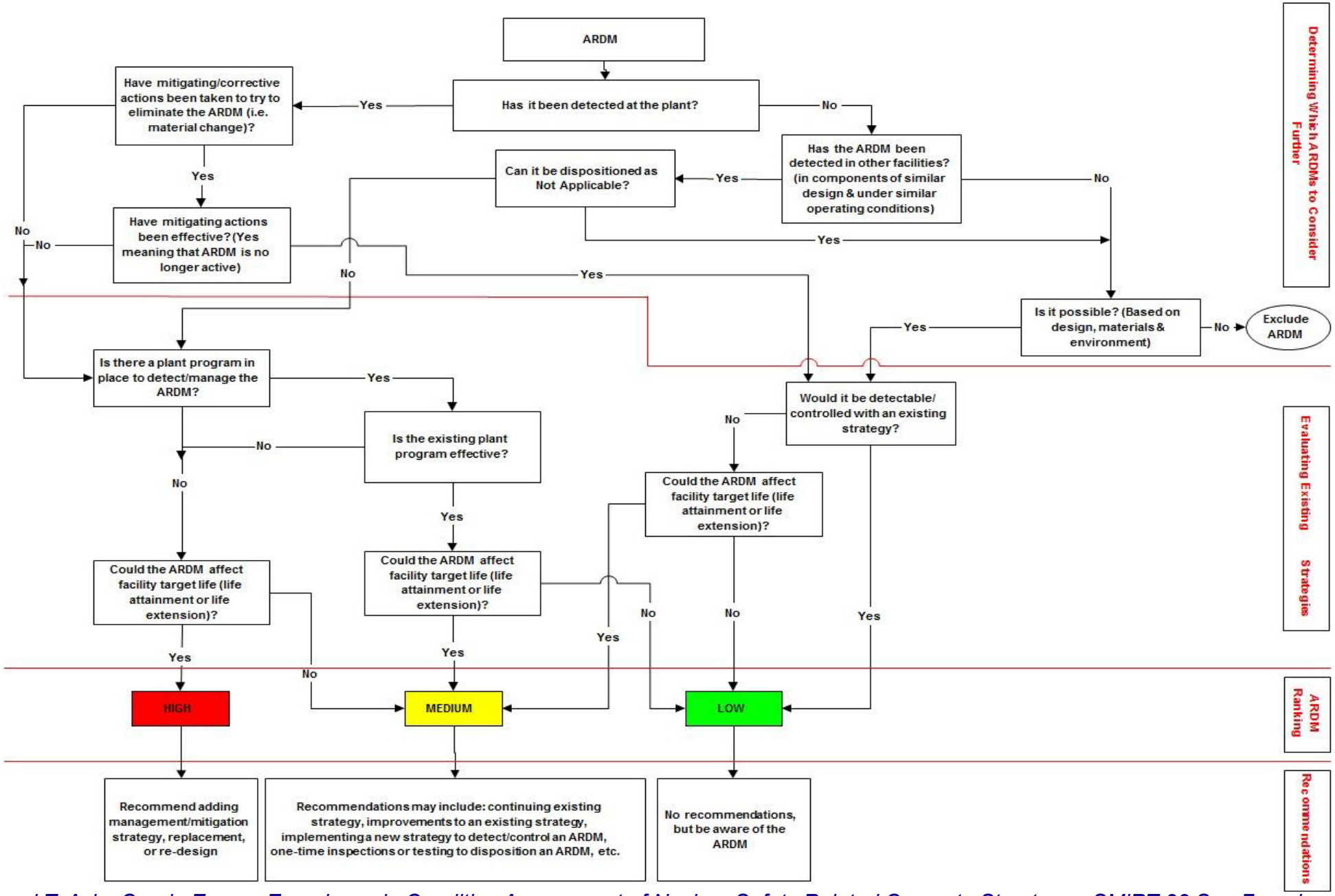
- Increased cross linking, etc. due to Irradiation
- Thermal embrittlement
- Wear / weathering
- Delamination







 - Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.



Source: J. Tcherner and T. Aziz, Candu Energy Experience in Condition Assessment of Nuclear Safety Related Concrete Structures. SMiRT 22 San Francisco, USA. 2013.

 - Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

ARDM Matrix Example

	Leaching and Efflorescence	Sulphate Attack	Acid/Base Attack	Alkali-Aggregate Reactions	Carbonation	Crystallization of Chlorides & Other Salts	Freeze-Thaw Attack	Abrasion/Erosion/Cavitation	Elevated Temperature/Thermal Cycling	Irradiation	Fatigue/Vibration	Settlement	Creep/Shrinkage	General Corrosion	Weathering	Loss of Prestressing Force	Wear	Stress Corrosion Cracking	Hydrogen Embrittlement	Delamination
Concrete	M			M					L				M							
Reinforcing Steel														M						
Embedded Parts														M						
Joint Sealant									M	M					M		M			
Non-metallic Liner									M	L					L		L			M

Source: J. Tcherner, et.al. Effective Aging Management of NPP Concrete Structures. Journal of Advanced Concrete Technology. Vol. 15, pp 1-9, 2017

 - Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Coupled Degradation Mechanisms

- More than one ARDM may contribute to degradation
- Necessary to consider effects of interaction of various stressors
- Evaluation of the effect of relevant coupled degradation mechanisms is required to understand visual manifestation, effects of combined mechanisms (adding? competing?), etc.

Coupled degradation mechanism	Damage to concrete (based on measure of resistance)	Positive and negative effects on concrete durability	Additional comments
Freeze-Thaw and Chloride Exposure	Increase	Negative: Micro cracks from FT enhanced the permeability of concrete to chloride ions. Positive: Chloride ions can lower the freezing point of water	• Usage of multiple measure of resistances resulted in % increase in damage from less than 10% to over 200% • Scarce SCM studies • Lack of air entrainment

Additional Information: Coupled Effects of Environmental Loads on Concrete Nuclear Structures: A Review. SMiRT 27, Yokohama, Japan. 2024.

 - Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Outline

- ✓ Nuclear Civil Structures
- ✓ Understanding Ageing
- ❑ Detection and Maintenance
- ❑ Conclusions and Lessons Learned
- ❑ Areas for Enhancements

- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Methods for Detecting Degradation

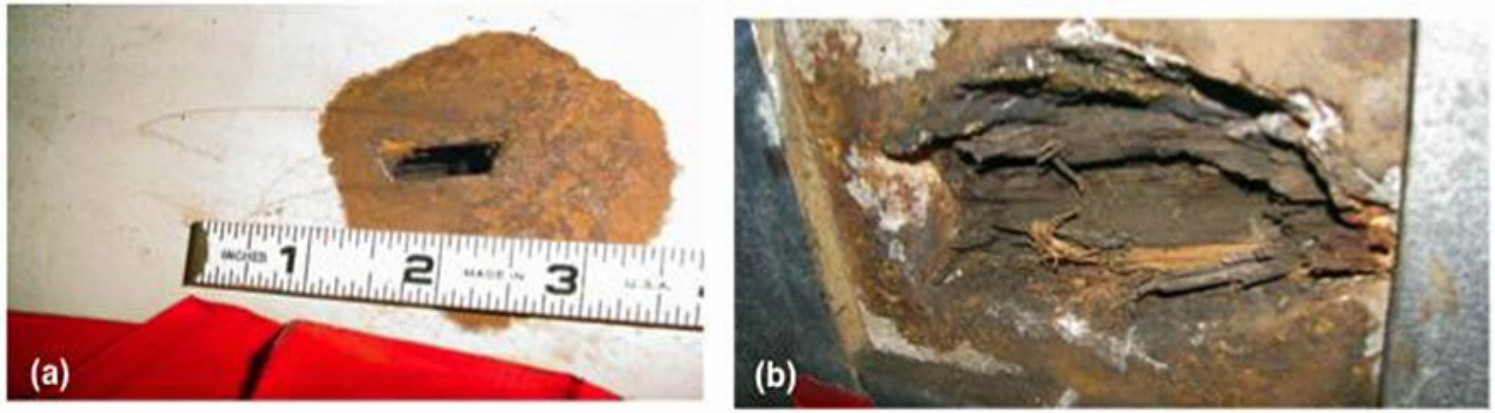
Visual Inspection

NDT

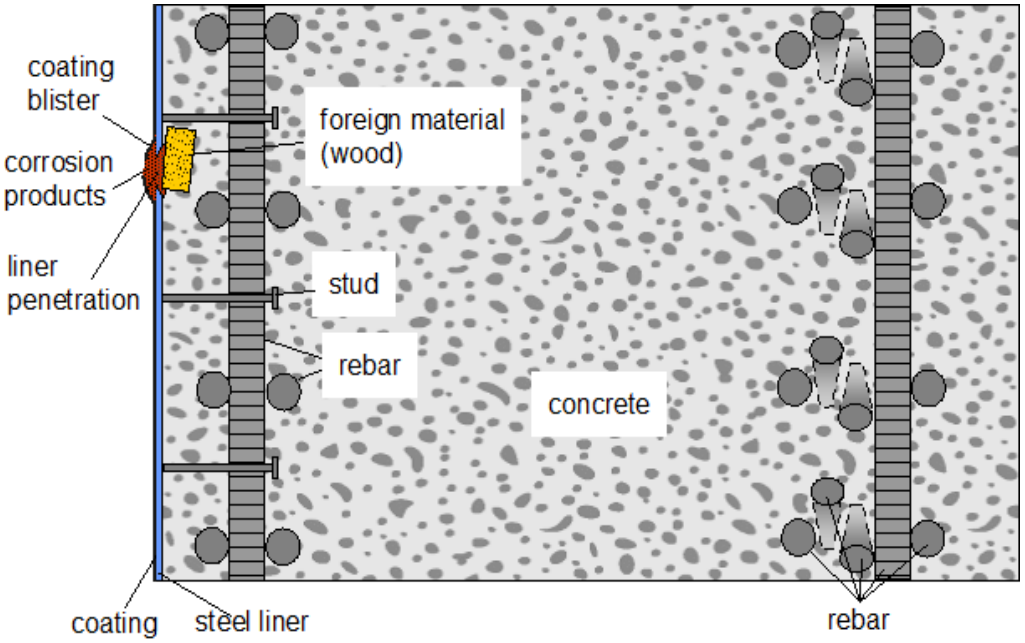
Destructive Testing, Lab Analysis

 - Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Degradation of Steel Lined Concrete Structures



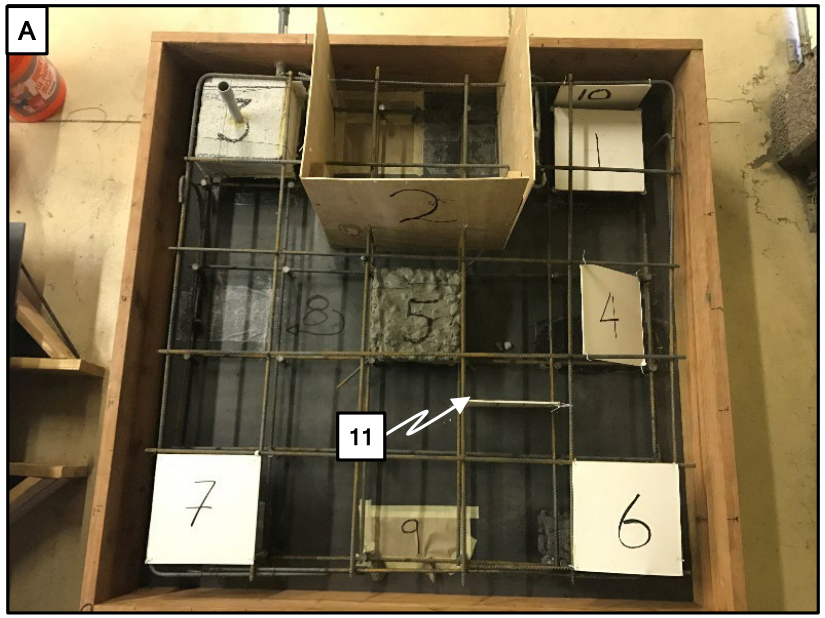
Source: First Energy, 2009

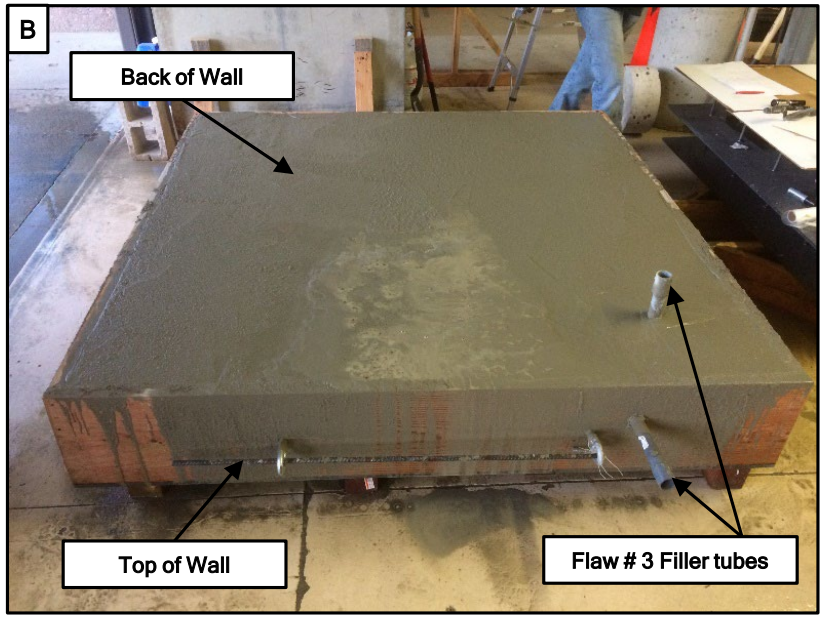


Source: Dunn, D., Pulvirenti, A., and Klein, P. US Nuclear Regulatory Commission ML112140119, Containment Liner Corrosion.

- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

NDT - Concrete Behind Steel Liner





Sources:

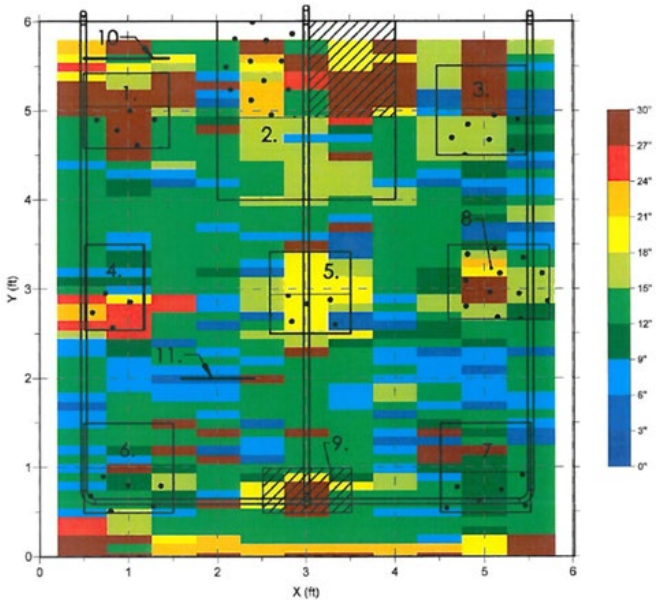
J. Tcherner, L. Olson, D. Sack, P. Miller. Non-Destructive Evaluation Techniques for Evaluation of Nuclear Concrete Structures with Limited Accessibility. SMiRT 25, Charlotte, NC, USA, 2019

L. Olson, D. Sack and J. Tcherner. NDE NucCon 2023 - International Conference on Non-destructive Evaluation of Concrete in Nuclear Applications. Espoo, Finland, 2023

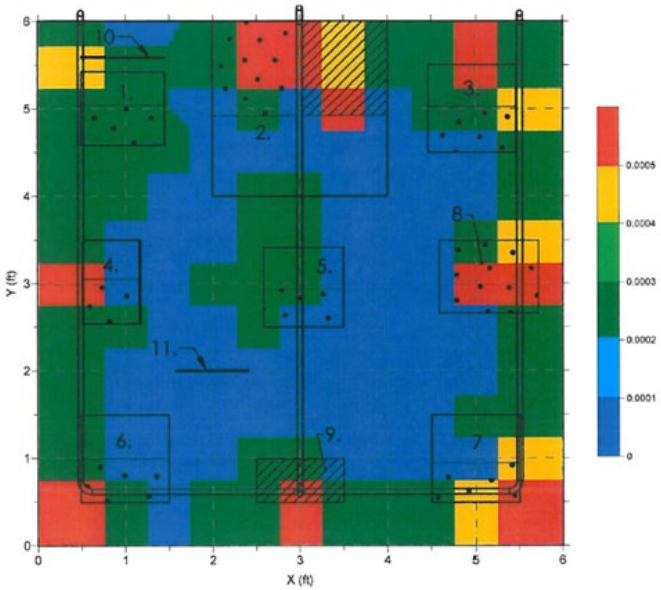
- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

NDT - Concrete Behind Steel Liner

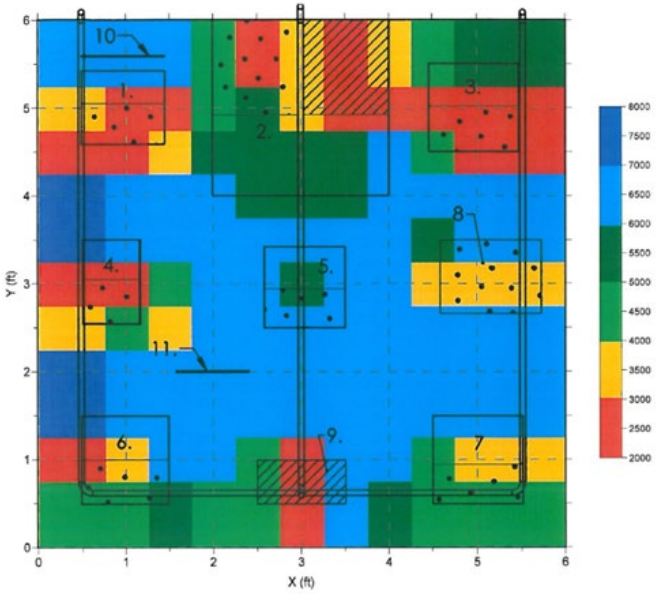
Impact Echo Scanning



Slab Impulse Response



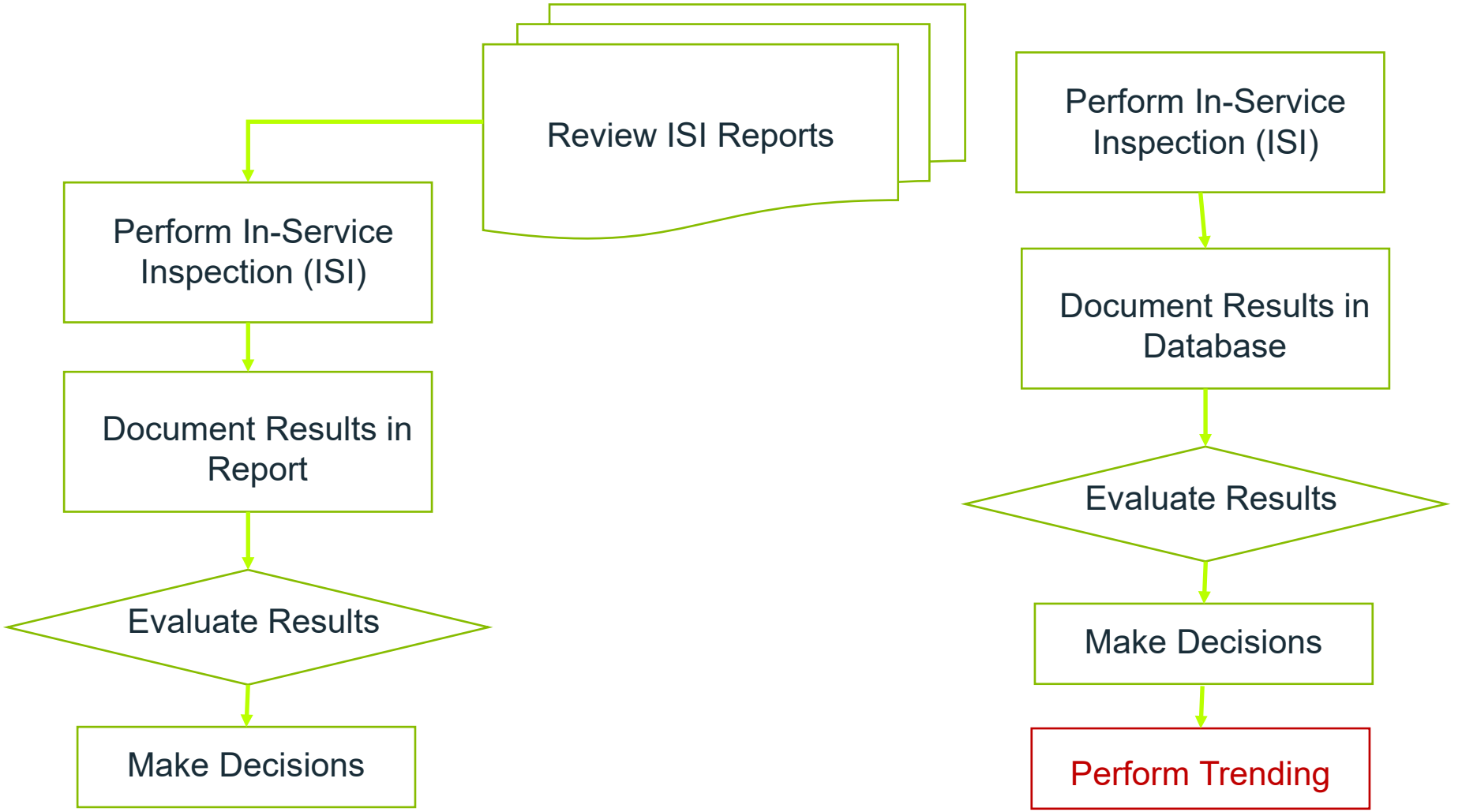
Spectral Analysis of Surface Waves



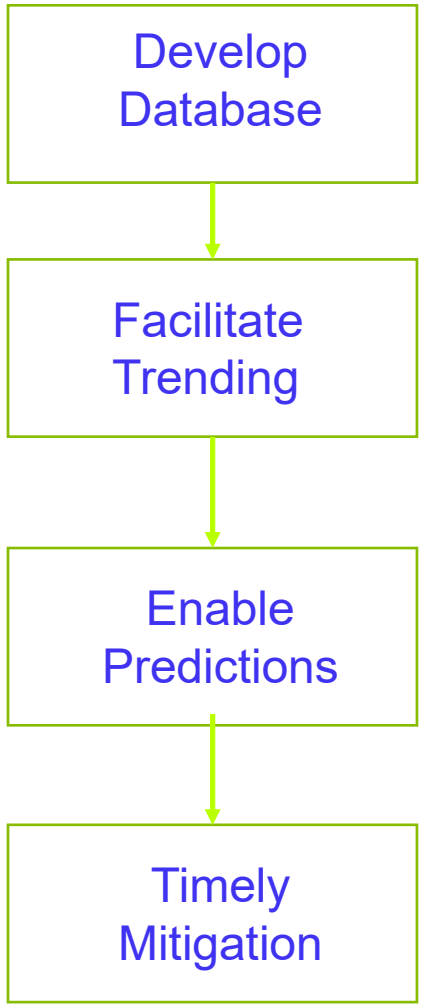
- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Managing Results of In-Service Inspection

Problem Statement



Solution



Additional Information: Database for In-Service Inspection Results' for NPP Structures. SMiRT 27, Yokohama, Japan. 2024.

- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Prerequisites for Repair

Activities to be undertaken for design of successful repair:

- Evaluate degradation
- Establish the cause of distress and assess possibility of eliminating or controlling it, as applicable
- Establish prognosis for mitigation of degradation, i.e. if repair can be implemented and if it will be long-lasting and economical
- Select appropriate repair methodology
- Confirm the methodology by qualification tests and mock-up tests as applicable
- Prepare adequate Technical Specification

- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Technical Specification

Performance Requirements

Prescriptive Requirements

INPUTS

- repair considerations
- governing mode(s) of deterioration
- exposure environment
- possible transfer mechanisms

- Materials and mixes
- Repair installation techniques

OUTPUTS

- Specify limiting values in relation to inputs
- Provide clear procedures for non-compliance (e.g. possible remediation)

- Clearly prescribe limitations on materials, repair installation process, etc.
- Provide suitable guiding narrative

Pre-qualification Tests

Verification Tests

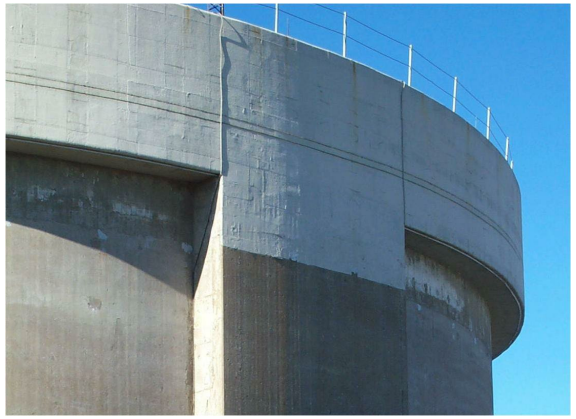
Source: J. Tcherner, Waterproofing of Nuclear Concrete Structures, SMiRT 23, Manchester, UK 2015

- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Maintenance – Protection and Repairs

- ✓ Assessing root cause
- ✓ Designing repair
- ✓ Ensuring materials qualification
- ✓ Ensuring long term field performance
- ✓ Field support of implementation
- ✓ QC/QA

Long Lasting Repair Solutions



- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Conclusions and Lessons Learned

1. Requirements on nuclear civil structures are increasing beyond what was originally envisaged, due to plant life extensions, security, and evolving safety requirements.
2. OPEX indicates that properly designed and constructed nuclear civil structures typically have good field performance well beyond their original design life although there have been some occurrences of degradation
3. As operating experience increases, more “surprises” should be expected.
4. As structures age, environmental stressors have increased potential for impacting functionality and durability of structures
5. Degree of degradation depends on:
   - ✓ quality of the structure as constructed
   - ✓ aggressiveness of the environment
6. Understanding ageing and operating environment and accounting for it during design, as well as considering the possibilities for inspections and maintenance as applicable, together with the enhanced quality control during construction, would improve the quality of new structures of NPPs
7. Properly prepared and executed AMP is paramount to ensure continuous integrity of civil structures throughout all phases of plant’s lifecycle including design, construction, commissioning, operation (including long-term operation and extended shutdown), and decommissioning.

- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

Areas of Enhancements

1. Enhancing considerations for aging management during design and construction
2. In addition to assessing all possible degradation mechanisms coupled degradation mechanisms should be considered
3. Enhancing means for detecting degradation (visual inspections, NDTs)
4. Facilitate periodic inspections (develop tools / database to enable trending and facilitate decision making)
5. Enhancing protection and repairs:
   - ✓ Incorporating better understanding of aging in addressing the root cause
   - ✓ Incorporating advancements in repair techniques and materials
   - ✓ Taking advantage of previously performed repairs with good field performance
   - ✓ Documenting repairs

 - Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.

THANK YOU

Julia.Tcherner@atkinsrealis.ca

AtkinsRéalis

- Copyright -: ©2024 AtkinsRéalis. All rights reserved. Unauthorized use or reproduction is prohibited.