AGING MANAGEMENT OF NUCLEAR CIVIL STRUCTURES – POTENTIAL AREAS FOR ENHANCEMENTS

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What Research for Beyond 80 Years for Civil Structures
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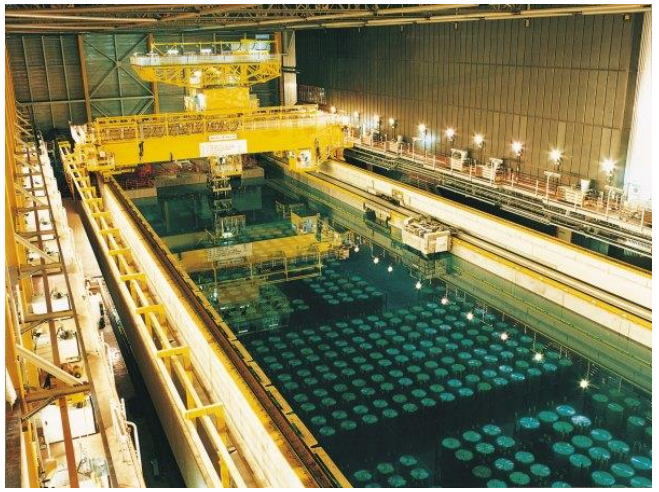
Outline

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

Nuclear Concrete Structures

- Nuclear concrete 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 elements 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 concrete structures have a history of reliability and durability, but there have been occurrences of degradation

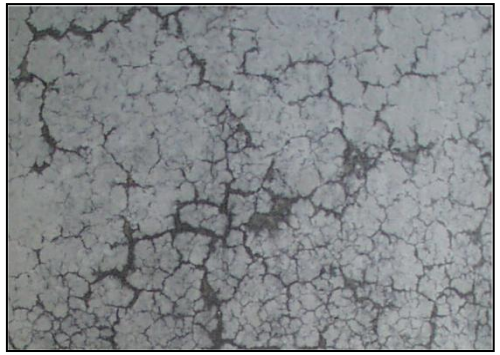


Degradation Occurrences

Underground Structure
Leaching and Efflorescence

Reinforcing
Steel Corrosion

Fill Concrete
Degradation



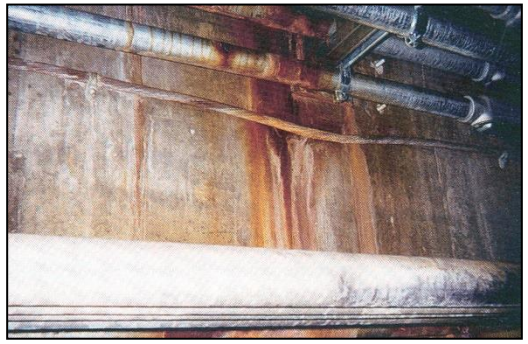
Waste Storage Structure
Map Cracking

Concrete Wall
Alkali Silica Reaction

Concrete Cracking
Outside Containment Wall

Spent Fuel Pool
Leakage

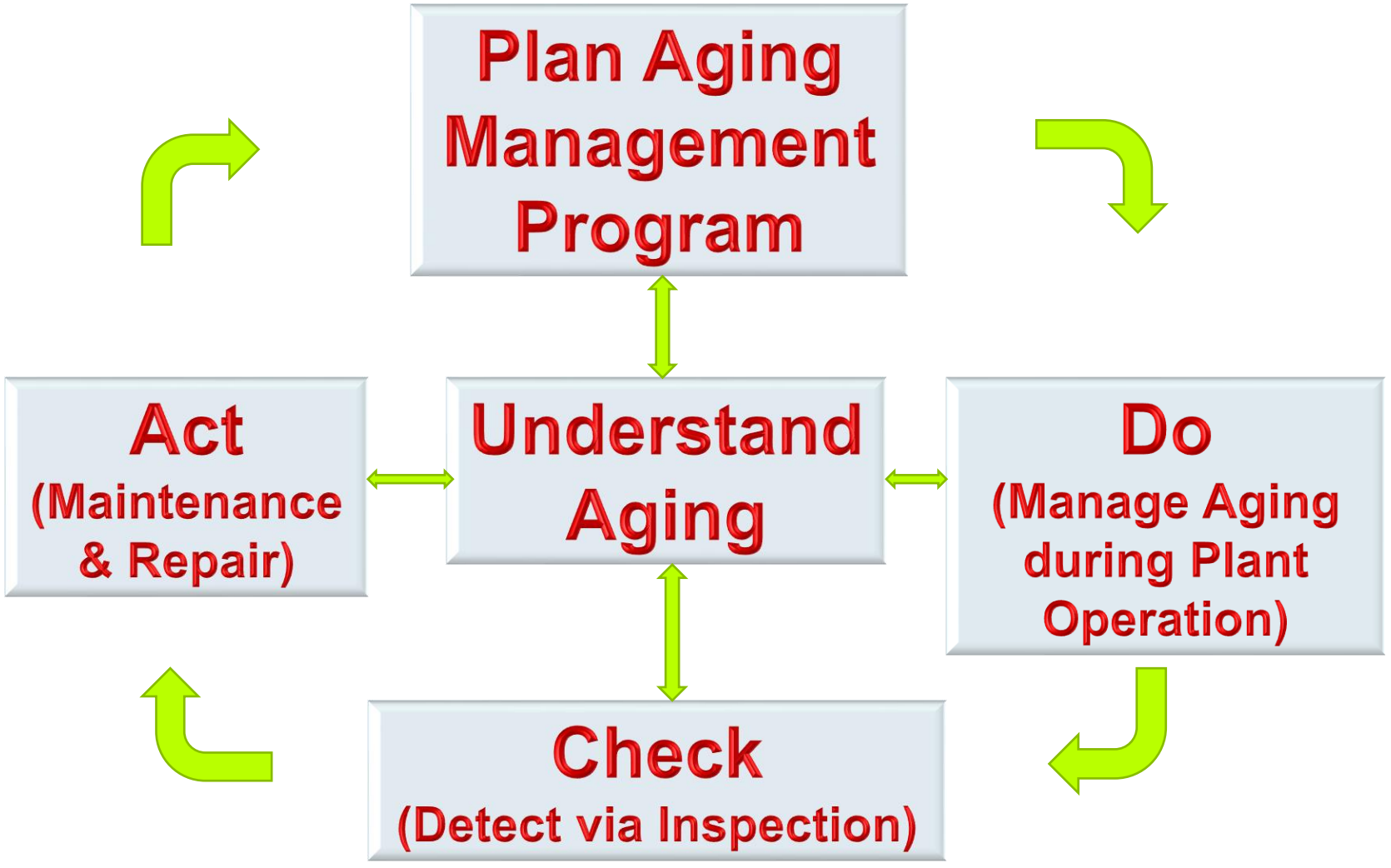
Containment Dome
Delamination

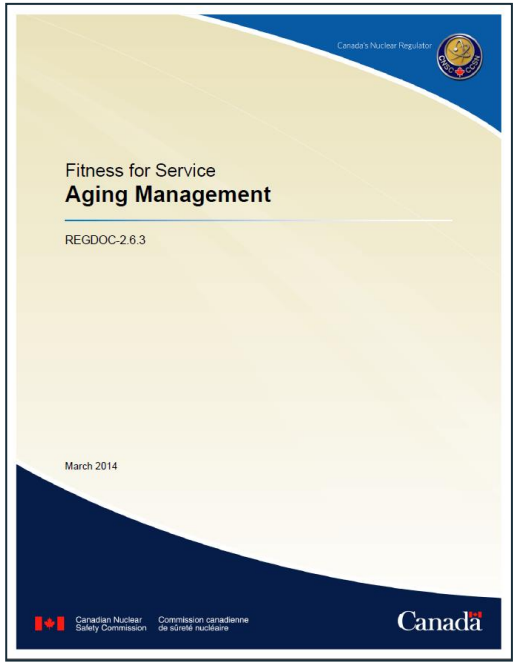


Concrete Wall
Water Infiltration

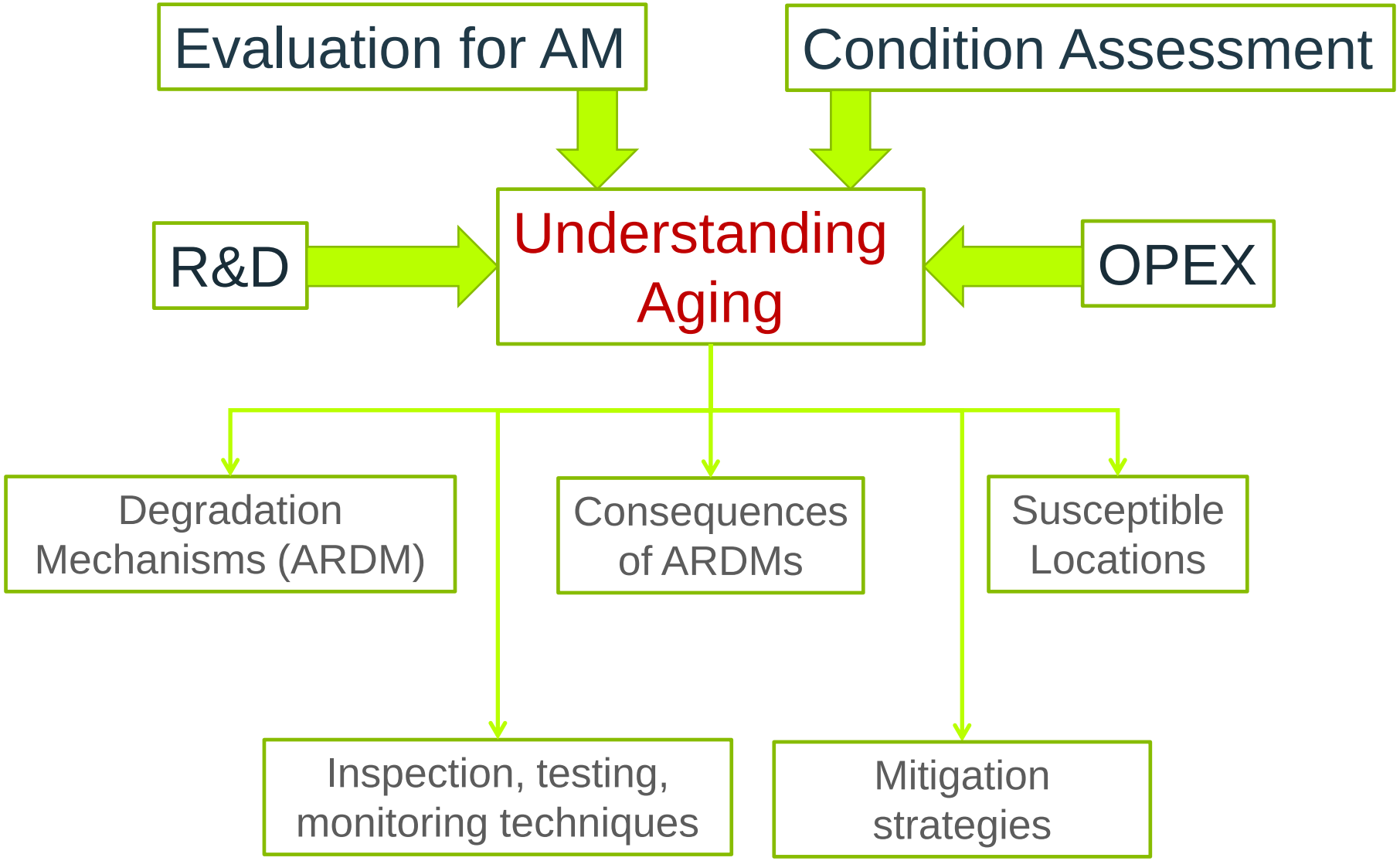
Water Intake Structure
Rebar Corrosion

Aging Management Model





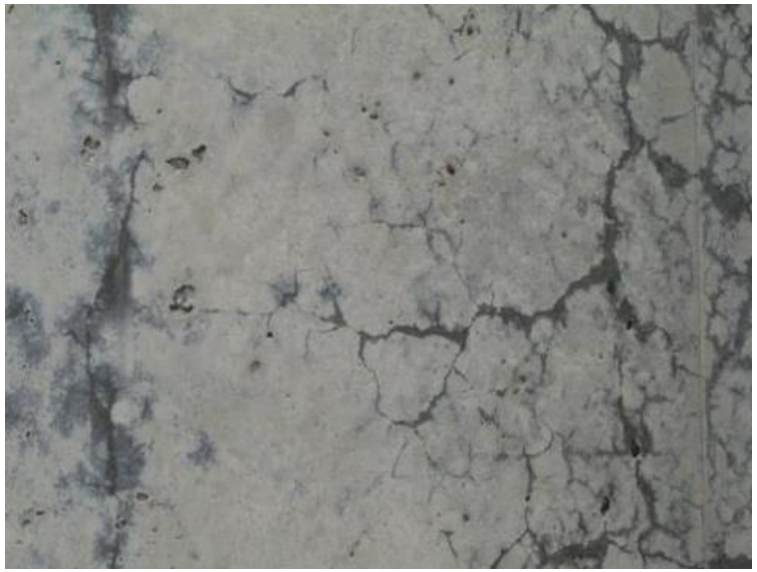
Understanding Aging



Aging Related Degradation Mechanisms (ARDMs)

CONCRETE

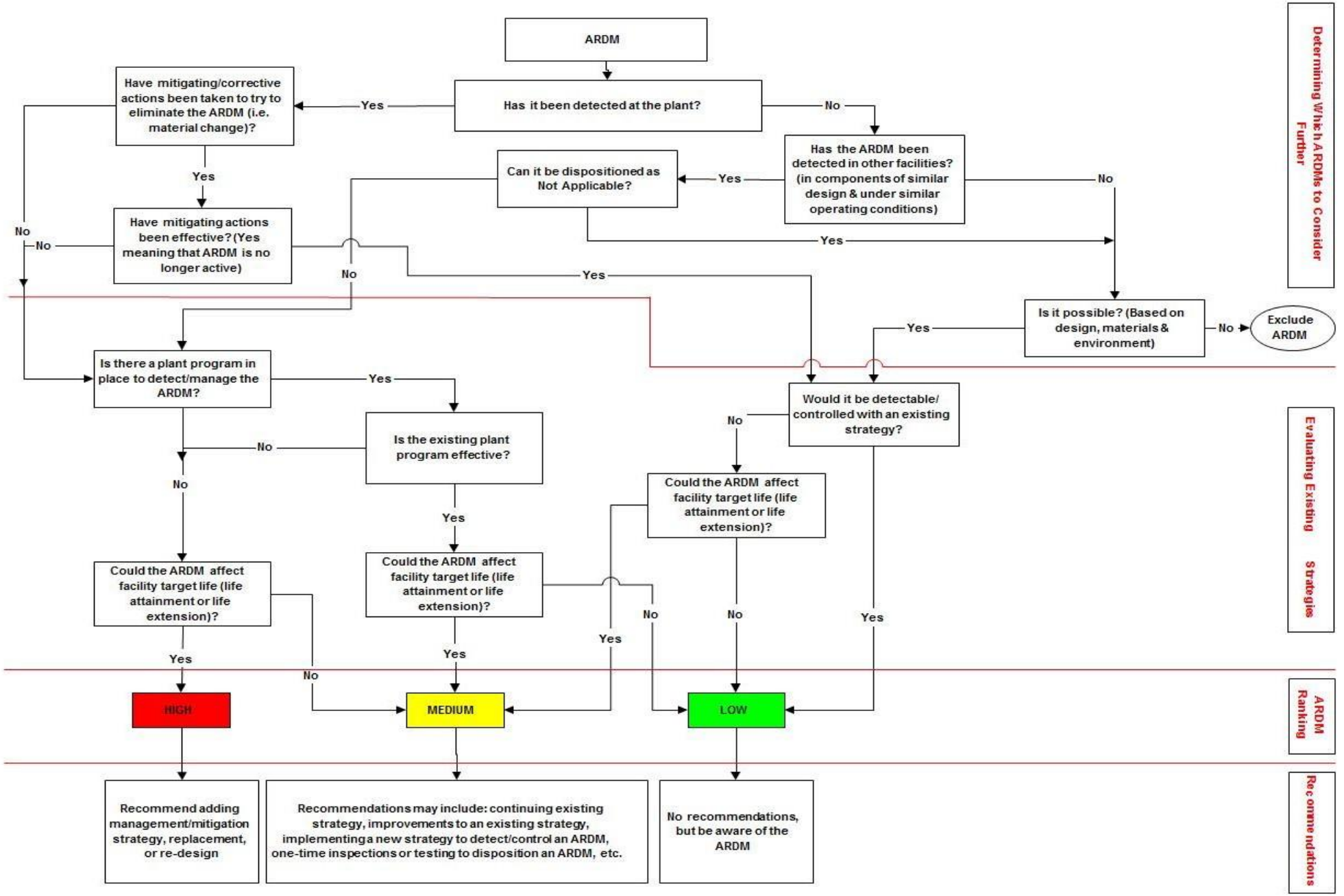
- Leaching and Efflorescence
- Sulphate Attack / Delayed Ettringite Formation (DEF)
- Acid / Base Attack
- Alkali Aggregate Reaction (AAR)
- Carbonation
- Salt Crystallization
- Freeze Thaw Attack
- Fatigue
- Abrasion / Erosion / Cavitation
- Moisture content changes, material incompatibility due to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



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



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

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

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

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

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- ✓ Nuclear Civil Structures
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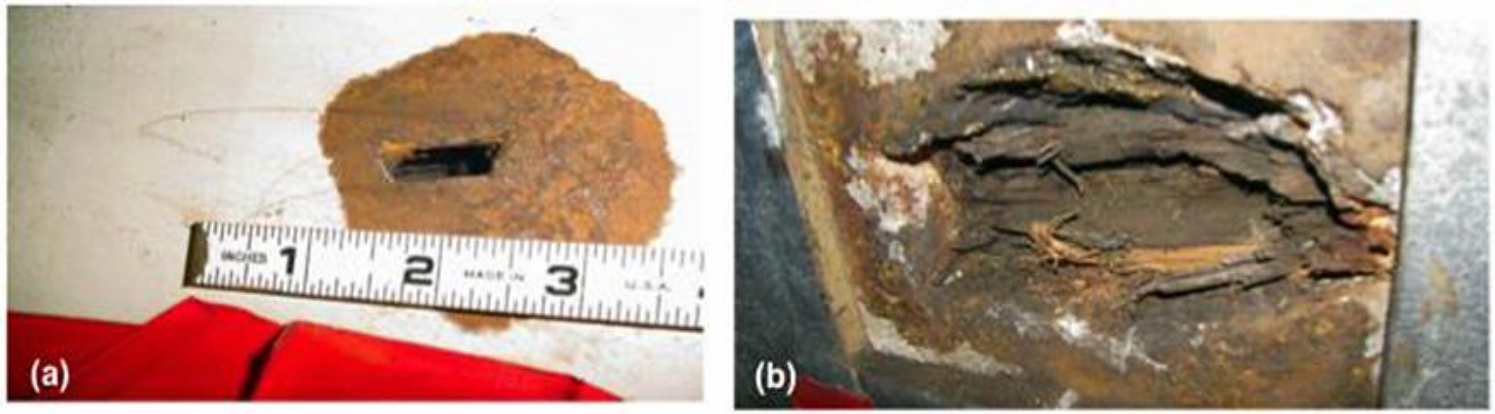
Methods for Detecting Degradation

Visual Inspection

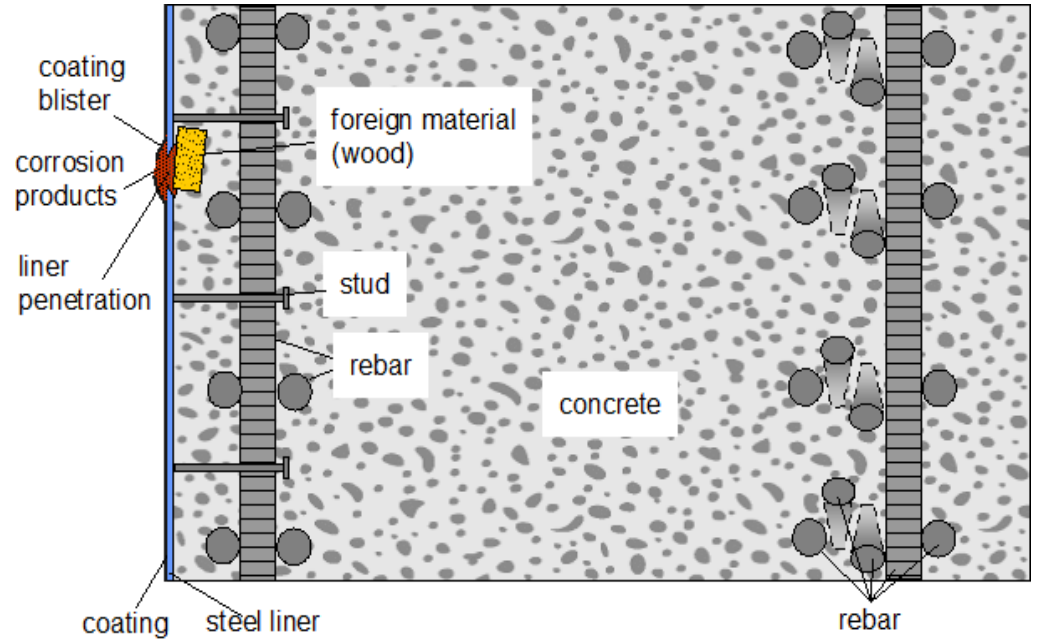
NDT

Destructive Testing, Lab Analysis

Degradation of Steel Lined Concrete Structures

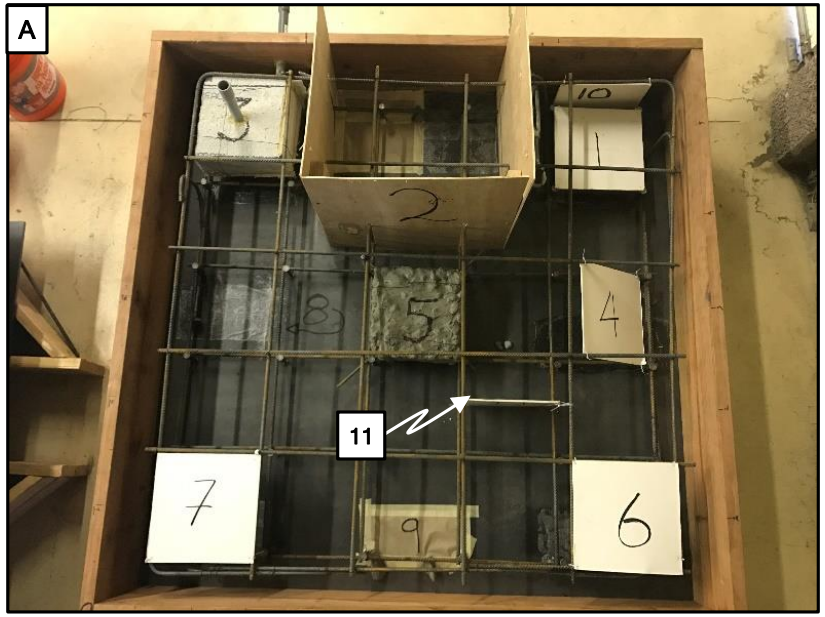


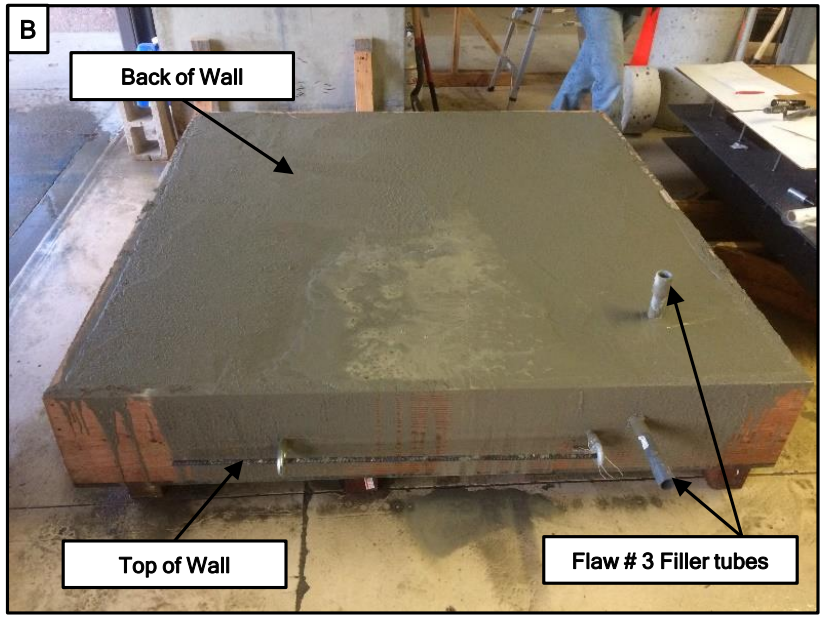
Source: First Energy, 2009



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

NDT - Concrete Behind Steel Liner





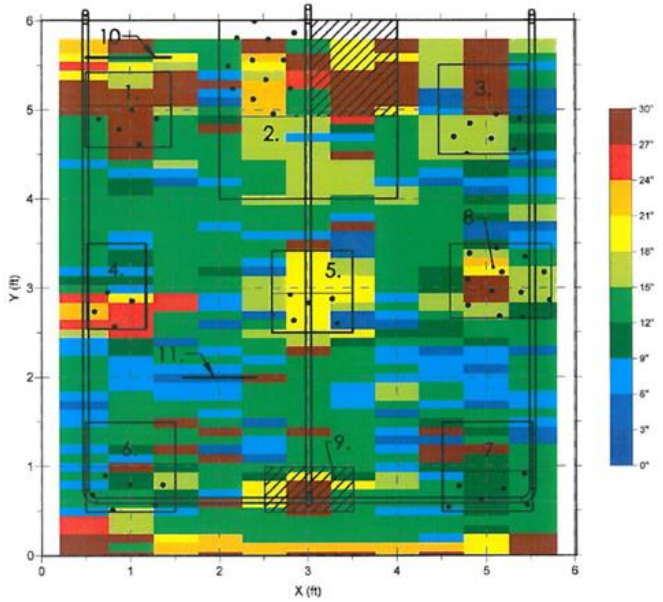
Sources:

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

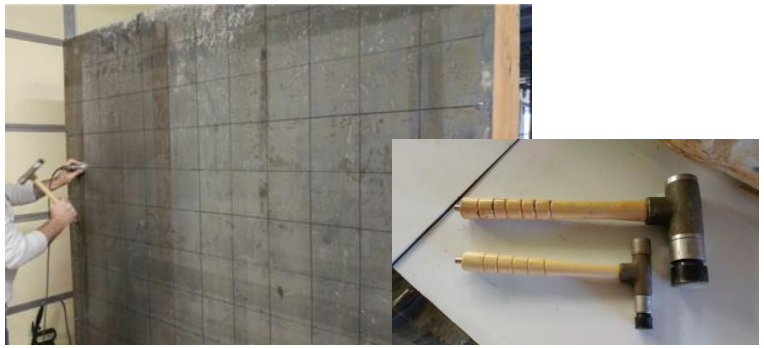
L. Olson, D. Sack and J. Tcherner. NDE NucCon 2023 - International Conference on Non-destructive Evaluation of Concrete in Nuclear Applications. Espoo, Finland, 2023

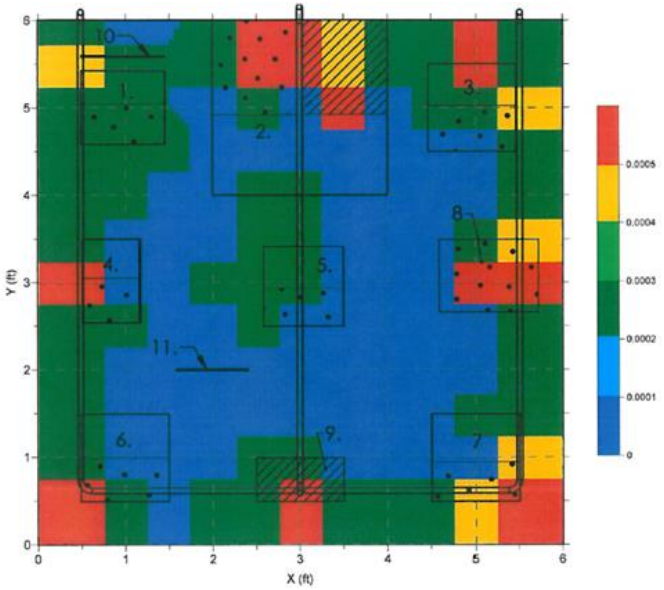
NDT - Concrete Behind Steel Liner

Impact Echo Scanning

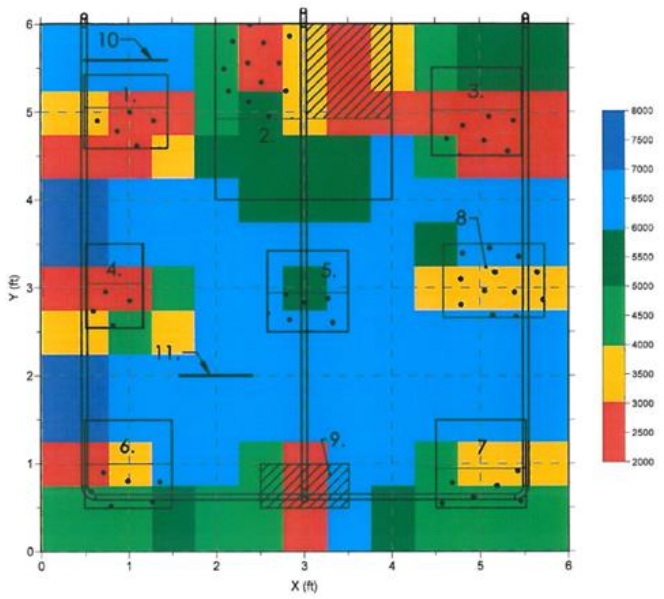


Slab Impulse Response





Spectral Analysis of Surface Waves



Managing Results of In-Service Inspection

Review ISI Reports

Perform In-Service Inspection (ISI)

Document Results in Report

Evaluate Results

Make Decisions

Perform In-Service Inspection (ISI)

Document Results in Database

Evaluate Results

Make Decisions

Perform Trending

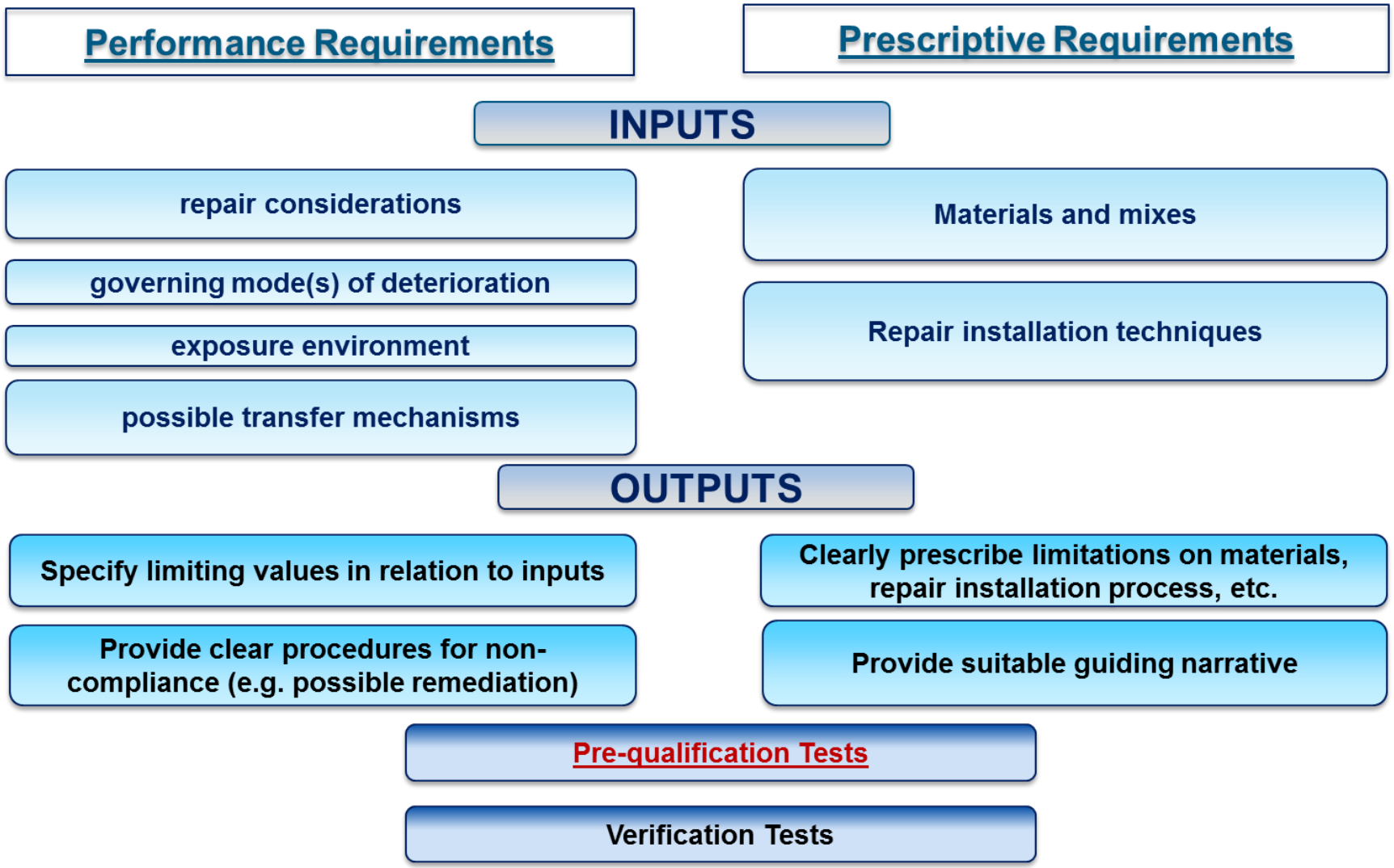
Source: Database for In-Service Inspection Results' for NPP Structures. SMiRT 27, Yokohama, Japan. 2024.

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

Technical Specification



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

Mitigation of Degradation – Protection and Repairs

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

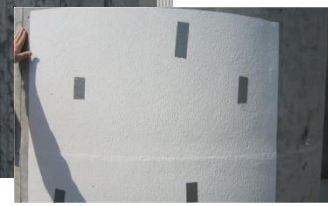
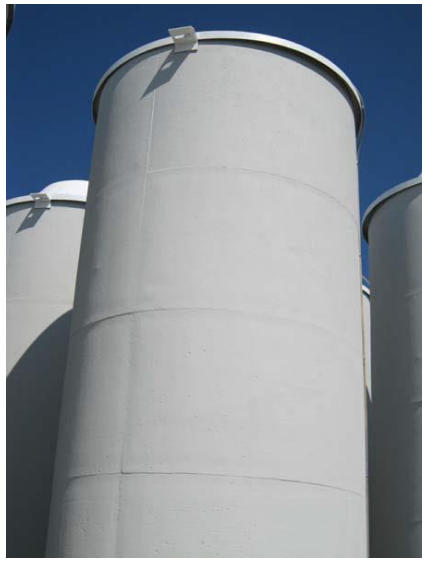
Long Lasting Repair Solutions









Conclusions and Lessons Learned

1. Requirements on nuclear concrete 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 concrete structures typically have good field performance well beyond their original design life although there have been some occurrences of degradation
3. As structures age, environmental stressors have increased potential for impacting functionality and durability of structures
4. Degree of degradation depends on:
   - ✓ quality of the structure as constructed
   - ✓ aggressiveness of the environment
5. 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 concrete construction including repairs and modifications
6. Effective AMP is paramount to ensure continuous integrity of nuclear concrete structures throughout all phases of the lifecycle including design, construction, commissioning, operation (including long-term operation and extended shutdown), and decommissioning.

Potential Areas of Enhancements

1. Enhancing considerations for aging management during design and construction (including repair and modification projects)
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. Facilitating periodic inspections (developing tools / database to enable trending and to 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 proven field performance
   - ✓ Documenting repairs

THANK YOU

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