Concrete Materials and Structures - Aging and Life Beyond 40 Years, 60 Years, •••

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Concrete (Originally Based on Lime Hardened by Atmospheric Carbonation) has been Utilized as a Construction Material for Several Thousand Years

Why did these structures survive?
- Careful materials selection
- Mild climatic conditions
- Lack of steel reinforcement
- Construction method

These structures were not fabricated using current “hydraulic portland cement” (circa 1824)
NPP Safety-Related Concrete Structures are Composed of Several Constituents that, In Concert, Perform Multiple Functions

Concrete
- coarse aggregate
- water
- chemical admixture
- sand
- mineral admixture

Mild Steel Reinforcement
- Steel Rebar
- Anchor
- Liner Plate

Post-tensioning tendons

Steel Liner Plate
The Longevity (or Long-Term Performance) of Concrete Structures is a Function of their Durability or Propensity to Withstand the Potential Effects of Degradation

Concrete degradation can result from adverse performance of its cement-paste matrix or aggregate materials

<table>
<thead>
<tr>
<th>Degradation Factor</th>
<th>Primary Manifestation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical Processes</strong></td>
<td></td>
</tr>
<tr>
<td>Cracking</td>
<td>Reduced durability</td>
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<tr>
<td>Salt crystallization</td>
<td>Cracking/loss of material</td>
</tr>
<tr>
<td>Freezing and thawing</td>
<td>Cracking/scaling/disintegration</td>
</tr>
<tr>
<td>Abrasion/erosion/cavitation</td>
<td>Section loss</td>
</tr>
<tr>
<td>Thermal exposure/thermal cycling</td>
<td>Cracking/spalling/strength &amp; modulus loss</td>
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<tr>
<td>Irradiation</td>
<td>Volume change/cracking</td>
</tr>
<tr>
<td>Fatigue/vibration</td>
<td>Cracking</td>
</tr>
<tr>
<td>Settlement</td>
<td>Cracking/spalling/misalignment</td>
</tr>
<tr>
<td><strong>Chemical Processes</strong></td>
<td></td>
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<tr>
<td>Efflorescence/leaching</td>
<td>Increased porosity</td>
</tr>
<tr>
<td>Sulfate attack</td>
<td>Volume change/cracking</td>
</tr>
<tr>
<td>Delayed ettringite formation</td>
<td>Volume change/cracking</td>
</tr>
<tr>
<td>Acids/bases</td>
<td>Disintegration/spalling/leaching</td>
</tr>
<tr>
<td>Alkali-aggregate reactions</td>
<td>Disintegration/cracking</td>
</tr>
<tr>
<td>Aggressive water</td>
<td>Disintegration/loss of material</td>
</tr>
<tr>
<td>Phosphate</td>
<td>Surface deposits</td>
</tr>
<tr>
<td>Biological attack</td>
<td>Increased porosity/erosion</td>
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</table>
Working Life of a Concrete Structure may be Reduced or Extensive Maintenance Required as a Result of Material Deterioration

Aging also includes changes to embedded steel as well as its interaction with concrete

<table>
<thead>
<tr>
<th>Material System</th>
<th>Degradation Factor</th>
<th>Primary Manifestation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel reinforcement</td>
<td>Corrosion, Elevated temperature, Irradiation, Fatigue</td>
<td>Concrete spalling/cracking/section loss, Reduced strength, Reduced ductility, Bond loss</td>
</tr>
<tr>
<td>Post-tensioning system</td>
<td>Corrosion, Elevated temperature, Irradiation, Fatigue, Stress relaxation/end effects</td>
<td>Strength loss/reduced ductility, Reduced strength, Reduced ductility, Concrete cracking, Prestress force loss</td>
</tr>
<tr>
<td>Liner/structural steel</td>
<td>Corrosion, Elevated temperature, Irradiation, Fatigue</td>
<td>Section loss, Reduced strength, Reduced ductility, Cracking</td>
</tr>
</tbody>
</table>

Ref: NUREG/CR-6927
All NPPs Contain Concrete Structures Whose Performance and Function are Necessary to Protect the Safety of Plant Operating Personnel and General Public

- 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 components are somewhat plant specific, may be difficult to inspect, and usually 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.

Trojan NPP

Steel Reinforcement In Wall Near Base
Overall NPP Concrete Structures have a History of Reliability and Durability, but There have been Instances of Degradation

Concrete Cracking Outside Containment Wall
Exterior Concrete Wall Cracks and Spalling
Concrete Wall Water Infiltration
Corrosion of Grease Cap

Grease Leakage Outside Containment Wall
Anchor Head Failure
Containment Dome Delamination Repair
Water Intake Structure Rebar Corrosion
Several Activities have Contributed to a Knowledge Base to Provide Evidence that Capability of Concrete Structures to Mitigate Extreme Events has not Deteriorated Unacceptably Due to Either Aging or Environmental Effects
Data and Information Developed on Time Variation of Material Properties Under the Influence of Pertinent Environmental Stressors and Aging Factors
Long-Term Test Results Generally Show an Increase in Concrete Compressive Strength with Time

Decommissioning and plant modifications provide opportunities to obtain samples for use in aging assessments
Transformations and Reactions Occur when Portland Cement Concrete is Heated that Affect Mechanical and Physical Properties

What are the effects of long-term thermal loadings at moderate temperature levels?

Source: R. Blundell, C. Diamond, and R.G. Browne, Technical Note No. 9, Concrete Society, 1976

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>General Effect</th>
</tr>
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<tbody>
<tr>
<td>20-200</td>
<td>Some strength loss</td>
</tr>
<tr>
<td>120-300</td>
<td>Strength gain</td>
</tr>
<tr>
<td>200-250</td>
<td>Strength approx. const.</td>
</tr>
<tr>
<td>&gt;350</td>
<td>Decrease strength</td>
</tr>
</tbody>
</table>

(NUREG/CR-6900)
Prolonged Exposure of Concrete to Irradiation can Result in Decreases in Tensile and Compressive Strengths and Modulus of Elasticity

- Concrete is an effective shield as gamma rays are absorbed by high-density aggregate materials and neutrons attenuated by hydrogen atoms in cement paste.
- Shielding effectiveness can be reduced by elevated temperature exposure as drying reduces hydrogen content or cracking occurs.
- Changes in properties of concrete appear to primarily depend on behavior of coarse aggregate material.
- Data on effects of radiation on concrete properties are somewhat limited due to difficulties in conducting experiments.
- Difficult to separate radiation from thermal effects and to compare results from different researchers because of concrete composition and test method differences.

For operation >40 years, are radiation levels sufficient to affect concrete shielding effectiveness and load-bearing capacity?

Source: H.K. Hilsdorf, ACI SP-55, American Concrete Institute, 1978.
Guidance has been Developed to Assist in Selection, Assessment, and Repair of Structural Components

Component Classification
- Identify Safety-Focused or Category I Structures and Divided into Subelements and Material Constituents
- Identify Component Classification Values for Each Subelement
- Evaluate Influence and Determine Grading for Degradation Factors
- Combine/Apply Weighting Factors to Compute Subelement and Structure Rank

Degradation Assessment Methodology
- Subelement Importance
- Safety Significance
- Environmental Exposure
- Time Rate of Deterioration
- Impactability and Early Detection
- Reparability
- Ultimate Impact

Develop Listing of Critical Subelements/Structures

In-Service Inspection

Remedial Measures

Corrosion Repair Example: Not NPP Application

Periodic Inspection and Maintenance are Key Elements in Managing Aging of NPP Concrete Structures
Inspection of NPP RC Structures Presents Challenges Different from Conventional Civil Engineering Structures

- Wall thickness can be in excess of one meter
- Structures often have increased steel reinforcement density with more complex detailing
- Can be a number of penetrations or cast-in-place items
- Accessibility may be limited due to presence of liners or other components, harsh environments, or structures may be located below ground
- Experience with NDE of NPP concrete structures is relatively limited
- NDE of concrete structures is often based on equipment developed for other materials or technologies
Primary Manifestations of Distress that can Occur in Concrete Materials Include Cracking, Chemical Deterioration, Delaminations, and Strength Loss

As Concrete Structures Age, NDE is Likely to Gain An Increasingly Important Role In Their Aging Management, Improved Quantification of the Capabilities is Required
Inspection Methods for Thick, Heavily-Reinforced Concrete Sections and Basemats Require Development

- Noninvasive techniques to provide additional assurances of continued structural integrity are desirable
  - As-built or current structural features
  - Flaw detection and characterization
  - Honeycomb and embedded items
  - Voids adjacent to liner

- CONMOD Project indicates that coupling of finite-element-analysis methods with in-situ nondestructive testing may provide improved approach to aging management

- Acoustic, radar, and radiography techniques appear to have greatest potential

- Inspection of basemats based on indirect approach (i.e., environmental qualification)

Test Block (4 x 4 x 0.8 m³) Containing Flaws at Force Institute (Brøndby, Sweden)
Assessments of Steel Reinforcing Materials are Primarily Related to Determining Characteristics and Occurrence of Corrosion

- NDE techniques are available for corrosion monitoring
- Trends from examinations of post-tensioning systems at specified intervals provide indications that system characteristics are acceptable until next scheduled inspection
For Prestressed Concrete Containments, Maintaining the Post-Tensioning System Components in Good Working Order is Essential

- Current examination programs adequate for determining condition of PT tendon materials and evaluating effects of conventional degradation
- Conventional material degradation has not been a significant aging concern, but isolated incidences of wire failure due to corrosion have occurred
- Leakage of tendon sheathing filler (except for loss of corrosion protection) appears to be primarily an aesthetic problem
- Tendon forces at most plants are acceptable by a significant margin, but excessive loss of force has occurred in few older plants
- What is exact relationship between end-anchorage force measured by lift-off test and change in mean force along length of tendon?
- Estimation of time-dependent loss of prestressing force is based on limited duration relaxation tests (e.g., 1000 h) and concrete creep results (e.g., 6 m). What is validity of extrapolation of these results by time factors of ~500 and 120 (60 yr. life)?
Inspection Methods for Inaccessible Portions of the Metallic Pressure Boundary Components Require Development

- Conventional ultrasonics
- Electromagnetic acoustic transducers
- Magnetostrictive sensors
- Multimode guided plate waves

Liners of Concrete Containments

Steel Containments
Evaluation Methods for NPP Structures Generally Fall Into Three Categories

• Visual Examinations
  – Many of manifestations of concrete degradation appear at the surfaces as visible indications or discontinuities
  – Scope of investigations should include all exposed concrete surfaces, joint and joint material, interfacing structures and materials, and attached components
  – Aggressiveness of local operating environment and condition of surrounding structures (e.g., settlement)

• Destructive and nondestructive testing
  – Structure-specific
  – Environment-specific

• Analytical reassessment
  – Reevaluate behavior/resistance of structures (e.g., structural margins)
  – Finite-element and ultimate strength design

Knowledge of Future Performance of RC Structures can be Enhanced through Advanced Characterization of Service Environments and Understanding of Degradation Mechanisms (Damage Models), and Development of Improved Acceptance Standards
Repair Objectives are to Restore a Component’s Integrity, Arrest the Mechanism(s) Producing Distress, and Ensure (As Far As Possible) Causes of Distress will not Reoccur

Repair Process

Techniques well Established

Data on Performance of Repair Materials and Techniques is Desirable
Since Time-Dependent Changes to Structures and Potential Future Challenges are Random, Structural Reliability Theory is Useful for Safety Evaluations

- Assure minimum accepted performance requirements are exceeded
- Estimate ongoing rate of component degradation and project “end-of-life”
- Investigate ISI and maintenance strategies (e.g., maintain failure probability lower than target value)
- Assess continued-service risk for plants with degraded components
Probabilistic Modeling of Component Performance Used to Investigate How Aging Affects Structural Capacity

- Structural reliability theory provides basis for uncertainty analysis
- Fragility modeling depicts role of uncertainties in response of structures to specified challenges
  - Identify sources of uncertainty
  - Perform numerical experiments using FEA methods to evaluate structural response
  - Establish limit states
  - Propagate uncertainties to develop fragilities
  - Compare degraded and undegraded response to determine if whether observed change is likely to impact safety

Continue Development of Approach to help Provide Risk-Based Criteria to Evaluate Existing Structures to Achieve a Desired Performance Level when Subjected to Uncertain Demands
General Conclusions

- Performance of structures in NPPs has generally been good, with the majority of identified problems initiating during construction and corrected at that time; however, as structures age and the scope of inspection programs has increased, increasing incidences of degradation are likely to occur.

- Methods for conduct of condition assessments are fairly well established and generally start with a visual examination of the structure’s exposed surfaces.

- Techniques for detecting the effects of environmental stressors are sufficiently developed to provide qualitative data.

- Techniques for repair of structures are well established and when properly selected and applied are effective.

- A reliability-based methodology has been developed that can be used to facilitate quantitative assessments of current and future reliability and performance of NPP structures.
Concrete Materials and Structures Activities to Help Ensure Continued Safe and Reliable NPP Operation Beyond 40 Years, 60 Years, •••

- Compilation of material property data
  - Long-term performance and trending
  - Effects of elevated temperature
  - Potential radiation effects
  - Assessment and validation of NDE methods

- Evaluation of effects of moderate long-term thermal loadings on concrete materials and structures
  - Physical and mechanical properties
  - Constitutive models and analytical methods for nonlinear structural response of reinforced concrete structures

- Improved damage models and acceptance criteria for current and future condition assessments
Concrete Materials and Structures Activities to Help Ensure Continued Safe and Reliable NPP Operation Beyond 40 Years, 60 Years, ••• (cont.)

- Inspection methods for thick, heavily-reinforced concrete sections and basemats
- Global inspection methods for metallic pressure boundary components including inaccessible areas and backside of liner
- Longer duration relaxation and creep data for use in estimating prestressing force losses for extended service lives and acoustic methods for monitoring tendon wires for failure
- Data on application and performance (e.g., durability) of repair materials and techniques
- Extend basis for risk-informed assessment of future safety margins of existing structures to demonstrate a desired performance level when subjected to uncertain demands
Backup Information
Additional Information on Candidate Research Topics Related to Aging Management of Concrete Materials and Structures for Continued Service

• Objective - Establish models, methodologies, and tools for an improved aging management program to help provide additional assurances of safe and reliable continued service

• Primary Tasks
  – Data base on performance of concrete and concrete-related materials
  – Prediction of remaining service life of concrete structures
  – Structural component inspection, assessment, and remediation
  – Assessment of thick, heavily-reinforced concrete sections
  – Inspection of inaccessible portions metallic pressure boundaries
Data base on performance of concrete and concrete-related materials

- **Objective** - Obtain and test samples to help quantify aging and environmental affects on current and future performance of concrete and concrete-related materials

- **Primary Tasks**
  - Develop procedures and conduct “baseline” assessment of candidate NPP and civil engineering structures emphasizing parameters of time, elevated temperature, and irradiation
  - Removal and testing of samples
  - Develop data base management system and incorporate results
  - Evaluate effects of aging factors and environmental stressors on material properties and potential effect on structural margins
  - Utilize results to validate existing models or develop improved models for estimating future performance
Prediction of remaining service life of concrete structures

- Objective - Develop and evaluate improved quantitative models for predicting failure probability of a degraded concrete structure, either at present or at some future point in time

- Primary Tasks
  - Characterization of service environments
  - Identification of pertinent degradation mechanisms
  - Development and validation of advanced service life (damage) models including synergistic effects
  - Development of guidelines on use and standards for acceptance of service life predictions
  - Refinement and application of time-dependent reliability methodology for optimization of ISI/maintenance strategies and evaluating current and future performance of degraded structures
Structural component inspection, assessment, and remediation

• Objective - Develop improved guidelines for inspection, assessment, and repair for use in demonstrating that structures are safe and reliable for continued use

• Primary Tasks
  – Identification of candidate destructive and nondestructive inspection methods and methodologies for their application
  – Develop improved guidelines and criteria to aid in the interpretation of condition assessment results
  – Assess durability characteristics of candidate repair materials and techniques and provide improved guidelines on application of repair strategies
Assessment of thick, heavily-reinforced concrete sections

- Objective - Develop non-invasive techniques for use in conduct of condition assessments of thick, heavily-reinforced concrete sections

- Primary Tasks
  - Assess prior research activities and select “most-promising” technique(s)
  - Conduct preliminary modeling and laboratory experiments to study dependence, dispersion, and propagation of waves under realistic conditions
  - Fabricate representative structural features component(s) containing defects of interest (e.g., cracks, delaminations, voids)
  - Evaluate candidate techniques
  - Demonstrate “most-promising” technique in field under representative conditions
Inspection of inaccessible portions metallic pressure boundaries

- **Objective** - Develop nondestructive testing technique that can be utilized to detect, locate, and quantify any general or pitting corrosion in inaccessible regions of the metallic pressure boundary that can affect structural or leaktight integrity (global method desirable)

- **Primary Tasks**
  - Assess prior research activities and select “most-promising” technique(s)
  - Conduct preliminary modeling and laboratory experiments to study dependence, dispersion, and propagation of waves under realistic conditions
  - Fabricate representative structural features component(s) containing defects of interest (e.g., size, orientation, shape)
  - Optimize sensor (or probe) design, develop data acquisition and analysis system, establish system parameters
  - Demonstrate and validate technique in field under representative conditions
Several Programs have Addressed the Integrity and Aging of NPP Concrete Materials and Structures

- NRC Structural Aging (SAG) Program
- OECD/NEA CSNI
- IAEA
- International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM)
OECD/NEA has Sponsored Workshops and Prepared Reports Addressing Aging of NPP Concrete Structures

- “Workshop on Development Priorities for NDE of Concrete Structures in Nuclear Plants (NEA/CSNI/R(97)28)”
- “Workshop on Finite-Element Analysis of Degraded Concrete Structures (NEA/CSNI/R(1999)1)”
- ”Proceedings of the Workshop on Instrumentation and Monitoring of Concrete Structures (NEA/CSNI/R(2000)15”

http://WWW.nea.fr/html/nsd/docs
IAEA has Published A Report that Addresses Assessment and Management of Aging of NPP Concrete Containment Buildings

Assessment and management of ageing of major nuclear power plant components important to safety: Concrete containment buildings

IAEA-TECDOC-1025

Framework Developed for AMP for Concrete Containment Buildings
RILEM TC Has Sponsored Workshops and Prepared a Report on Aging Management of NPP Concrete Structures