Radiation Effects on Concrete Structures: Structural Performance and Material Degradation
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Overview

- Concrete irradiation impacts relative to Subsequent License Renewal
- Concrete degradation in a radiation field (experimental results)
  - Concrete composition
  - Neutron interaction and impacts
  - Gamma interaction and impacts
- 80-year end-of-life radiation levels
  - Neutron / gamma
  - BWRs / PWRs
- Concrete Bioshield and Reactor Support
  - BWRs / PWRs
- Summary / Path Forward

Potential Radiation Impacts

- Concrete structures in vicinity of reactor pressure vessel (RPV) experience highest radiation fields
  - Neutron and gamma in conjunction with related heating effects
  - RPV support and shielding
- Subsequent license renewal (SLR) from 60 to 80 years raises questions
  - Potential cumulative concrete radiation exposure exceeds damage levels
    - Concrete plays significant role
    - SLR concrete degradation due to irradiation effects need investigation
Irradiation Impact Evaluation

- Reviewed existing literature
  - Extracted data relevant to LWR operation
- Need to understand separate and combined effects
  - Concrete composition
    - Cement paste vs aggregate vs concrete
    - Water-to-cement ratio
    - Aggregate type and fraction in concrete
    - Bond strength between steel and concrete (metal reinforcement and metal support embedment/anchorage)
  - Stressors
    - Neutron
    - Gamma
    - Temperature
    - Carbonization
    - ASR

Concrete Composition

- Aggregates in a cement paste matrix
  - The two phases have different hygroscopic, thermal, and mechanical properties
  - Bioshield formulations followed industry standard recommendations at the time of construction
- Aggregates
  - Two common categories
    - Siliceous (e.g., quartzite, granite, and flint; crystalline structure)
    - Calcareous (e.g., limestone and dolomite; amorphous structure)
  - Expected that local quarries were used at time of construction
    - Too expensive to truck in aggregates with better shielding properties (e.g., barite)

Concrete Composition (cont.)

- Cement Paste
  - Formed by hydration reaction of Portland cement with water
  - Primarily calcium silicate hydrate (amorphous) with some calcium hydroxide and ettringite (both crystalline)
  - Three types of water in cement paste
    - Capillary (free) – water in capillary pores, evaporable under air dry, drying shrinkage results from loss
    - Interlayer – between solid layers of calcium silicate hydrate – immobile under air dry but mobile under vacuum or low relative humidity, loss results in excessive shrinkage
    - Chemically combined – loss under high temperature (dehydration) results in major strength reduction
Neutron Induced Concrete Dimensional Change

- Concrete dimension / volume changes as a function of neutron fluence
  - Provides fundamental explanation for many changes in concrete properties
  - Temperature control (unirradiated) samples had changes < 0.15%

- Aggregate expansion
  - Disruption of crystalline structure
  - Siliceous aggregates show most change

- Cement paste shrinkage
  - From minor water loss

- Onset at about a fluence of $1 \times 10^{20} \text{ cm}^2$

Gamma Radiation Levels and Impacts

- Gamma dose could potentially exceed $1 \times 10^{10} \text{ rad}$ at the face of the bioshield wall after 80 years of PWR operation

- Contributes heating effect
  - Estimated maximum 20°F temperature increase over ambient (outside the bioshield) due to gamma radiation about 0.75 ft into the bioshield
  - Estimated highest temperature in the bioshield would be about 158°F given a reactor cavity temperature of 150°F
  - Some variation in reactor cavity temperature both within the cavity and among NPPs

- Radiolysis of water
  - Responsible for cement paste water loss and subsequent shrinkage
  - Results in cement paste micro-cracking and bond mismatch with aggregate

Preliminary 80-Year End-of-Life Neutron Fluence ($E > 0.1 \text{ MeV}$)

- Starting point is 60-year end-of-life fluence at the clad-base metal interface (0T position) for neutrons ($E > 1.0 \text{ MeV}$)
  - Primarily taken from license renewal applications (license extension to 60 yrs)
  - Based on capsule surveillance reports

- Estimate attenuation of fluence through the reactor wall (change from 0T to 1T position)
  - Uses methodology from Regulatory Guide 1.99 (Radiation Embrittlement of Reactor Vessel Materials)

- Linear scaling to 80-year fluence levels
  - First approximation, ignores past /future operating parameters

- Convert $E > 1.0 \text{ MeV}$ fluence estimates to $E > 0.1 \text{ MeV}$ fluence
  - Use of empirical curve fit (ratio of $0.1 \text{ MeV}$ to $1.0 \text{ MeV}$ as function of RPV thickness)
BWR Concrete Support Structure Summary

- Expected 80-year neutron fluence level ($E > 0.1$ MeV) for maximum case at the core belt line is $1 \times 10^{19}$ n/cm$^2$
- Nearest concrete support structures are the anchorage points for the lateral stabilizer brackets and the foundation for the RPV support skirt
- Large distances from the reactor core and significant amounts of shielding material in the intervening spaces serve to attenuate the radiation
- Plant-specific review still necessary due to design variations

PWR Concrete Support Structure Summary

- Neutron fluence levels ($E > 0.1$ MeV) after 80-years of operation are estimated to exceed $1 \times 10^{19}$ n/cm$^2$ at the RPV outside face for all PWRs
  - Estimates are for the core belt line region
  - Highest estimated fluence level is over $6 \times 10^{19}$ n/cm$^2$
  - Uncertainties are related to:
    - Attenuation of radiation passing through the reactor vessel shell
    - Conversion of $E > 1.0$ MeV to $E > 0.1$ MeV fluence
    - Extrapolation to 80-years of operation
  - Variabilities include:
    - Reactor-specific capacity factors
    - Changes to loading patterns and fuel configurations
    - Plant modifications (e.g. fuel spacers)
    - Reactor-specific cavity dosimetry

- Need neutron fluence estimates for the region beyond the active core
  - Area where supporting bioshield could exceed $1 \times 10^{19}$ n/cm$^2$ in some cases
  - Recent studies by ORNL suggest higher than expected fluence due to scattering and streaming

- Long-term elevated operating temperatures could contribute to concrete degradation in conjunction with neutron and gamma radiation

80-Year Neutron Fluence at PWR Supports

- Concrete supports near active core region most at risk (only inches from RPV)
- Lesser risk to reactors supported on a neutron shield tank
- Metal support columns resting on the concrete basemat in most cases are tied to the concrete bioshield and need investigation
- Streaming effects could increase neutron fluence in reactor cavity
- Effects of cavity liner or formwork to be investigated
End Game - Structural Performance

- Need to translate radiation damage at the nano-scale to the (structural) macro-scale
- Review of nano-/micro-mechanical models to provide basis for coupling to standard engineering analyses under design basis conditions
  - Four relevant degradation models proposed within the last 3 years

Path Forward

- Analyze select NPPs for performance against design basis criteria using degraded concrete properties and microstructural changes
  - Currently performing limited review to evaluate the susceptibility of individual reactor support designs
  - Account for embedded metal (e.g., rebar, support anchorage)
  - Select NPP(s) with available data (LOCA and seismic design data for supports)
- Complete analyses of neutron and gamma radiation data on concrete
  - Neutron and gamma data analyzed
  - Currently trying to understand combined effects (i.e., determine contributions from various stressors [e.g., neutron, gamma, thermal] to overall degradation mechanism)
- Verify predictive numerical models
  - Expansion of aggregate at different neutron fluences (nano-scale)
  - Degradation of aggregate & cement paste under high-T (nano- and micro-scale)
  - Interactions of aggregate and cement paste components (micro-scale)
  - Prediction of neutron distribution in concrete structures (multi-scale)
  - Metal – concrete bond strength