Radiation Effects on Concrete Structures: Structural Performance and Material Degradation

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NRC Regulatory Information Conference – March 15, 2018

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

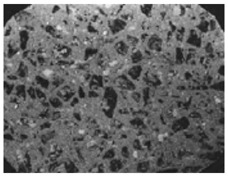
- **Concrete structures in vicinity of reactor pressure vessel (RPV) experience highest radiation fields**
  - Neutron and gamma in conjunction with related heating effects
  - RPV support and shielding
- **Subsequent license renewal (SLR) from 60 to 80 years raises questions**
  - Potential cumulative concrete radiation exposure exceeds damage levels
  - Expanded Material Degradation Assessment Report (NUREG/CR-7153 Vol. 4)
    - 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



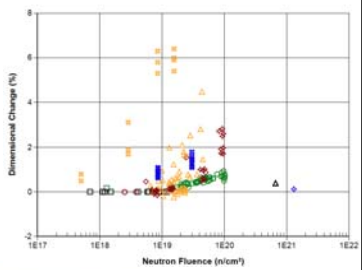
- **Aggregates**
  - Two common categories
    - Siliceous (e.g., quartzite, granite, and flint; crystalline structure)
    - Calcareous (e.g., limestone and dolomite; amorphous structure)
  - Expected that local quarries were used at time of construction
    - Too expensive to truck in aggregates with 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 1×10^{19} cm^2



Gamma Radiation Levels and Impacts

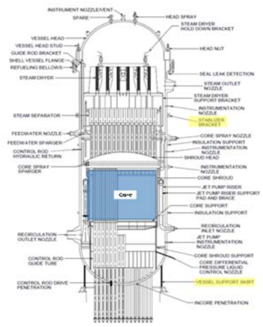
- **Gamma dose could potentially exceed 1×10^{10} rad at the face of the bioshield wall after 80 years of PWR operation**
- **Contributes heating effect**
  - Estimated maximum 20^{o}F temperature increase over ambient (outside the bioshield) due to gamma radiation about 0.75 ft into the bioshield
  - Estimated highest temperature in the bioshield would be about 158^{o}F given a reactor cavity temperature of 150^{o}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 MeV)

- **Starting point is 60-year end-of-life fluence at the clad-base metal interface (0T position) for neutrons (E > 1.0 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 MeV fluence estimates to E > 0.1 MeV fluence**
  - Use of empirical curve fit (ratio of >0.1 MeV to >1.0M 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 1×10^{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



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PWR Concrete Support Structure Summary

- Neutron fluence levels (E > 0.1 MeV) after 80-years of operation are estimated to exceed 1×10^{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 6×10^{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 uparates)
    - Reactor-specific cavity dosimetry
- Need neutron fluence estimates for the region beyond the active core
  - Area where supporting bioshield could exceed 1×10^{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

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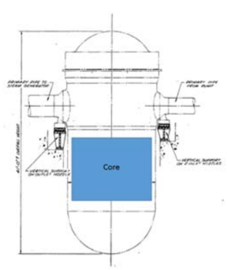
80-Year Neutron Fluence at PWR Supports

- 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



Example of a 2-Loop PWR vessel supported under 2 inlet and 1 outlet nozzles

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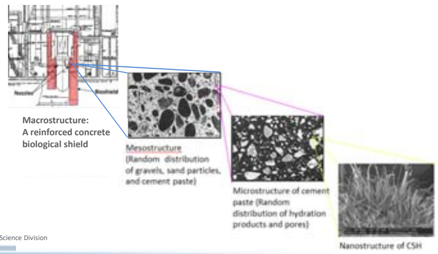
End Game – Structural Performance

- **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