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ABSTRACT

The Joint Department of Energy (DOE)-Electric Power Research Institute (EPRI) Program (Light Water Reactor Sustainability (LWRS) Program–Material Pathway–Concrete and Long-Term Operation (LTO) Program) and US Nuclear Regulatory Commission (NRC) research studies aim at understanding the most prominent degradation modes and their effects on the long-term operation of concrete structures to nuclear power generation. Based on the results of the Expanded Materials Degradation Analysis (EMDA), (NUREG/CR-7153, ORNL/TM-2011/545), irradiated concrete and alkali-silica reaction (ASR)-affected concrete structures are the two prioritized topics of on-going research. This report focuses specifically on the topic of irradiated concrete and summarizes the main accomplishments obtained by this joint program, but also provides an overview of current relevant activities domestically and internationally. Possible paths forward are also suggested to help near-future orientation of this program.

Significant progress was made during fiscal year 2014:

1. A thorough literature review has led to the formation of the largest irradiated concrete database ever collected. All mechanical properties shows a trend to decrease for fluence beyond 10^{19} n.cm^{-2} at varied energy cut-offs.
2. The literature analysis and the subsequent micromechanical modeling have emphasized the importance of aggregate-radiation-induced volumetric expansion (RIVE) as a major damage mechanism for irradiated concrete.
3. An International Committee on Irradiated Concrete (ICIC) has been created to facilitate information exchange and research coordination at an international level.
4. Concrete irradiation feasibility study has confirmed the difficulty to conduct experiments under conditions representative of light water reactors (LWRs).
5. A 1D-structural cylindrical model using the collected database to evaluate the extent of possible in-depth damage induced by irradiation and RIVE has been developed. This approach has the advantage of being computationally cost efficient for parametric studies.

Suggested research includes:

1. The development of more fundamental irradiation experiments; in particular, on mineral analogues to understand what type of aggregate may be most susceptible to RIVE.
2. The evaluation of the significance of irradiated concrete on structural performance of concrete biological shield (CBS) / reactor pressure vessel support structure (RPVSS): The long-term approach will require the development of appropriate simulation tools which embrace the complexity of the 3D problem, and the coupling, between several time-dependent mechanisms (moisture transport, heat transfer, irradiation transport, shrinkage, swelling, cracking, and relaxation).

1 INTRODUCTION

Concrete is the most common and predominant material used in construction of commercial LWRs. Concrete-based LWR structures provide functions including foundation, support, shielding, and containment [42]. Many of these structures are made of large and irreplaceable sections; therefore, the longevity of a specific plant could depend on the durability of these concrete structures. The ranking developed by the EMDA in NUREG/CR-7153 vol. 4 [18] target the most significant degradation modes for three categories of large-scale concrete structures in nuclear power plants (NPPs):

1. Concrete containment building (CCB), CBS and, reactor pressure vessel (RPV) support structures
    a. Research priorities:
        i. Radiation;
        ii. Alkali-Silica Reaction;
        iii. Creep and creep-fracture.
    b. Modes with available remediation/mitigation:
        i. Liner corrosion;
        ii. Corrosion of the post-tensioning system.
2. Spent fuel handling building (SFHB):
    a. Research priorities:
        i. Borated water attack.
3. Cooling towers (non-safety related structures)
    a. Corrosion;
    b. Alkali-Silica Reaction.

The LWRS program focuses on the effects of irradiation and ASR on safety-related concrete structures. Both programs are conducted in coordination with the U.S. NRC and EPRI representing the nuclear industry. Each program is summarized by a roadmap developed initially during Fall of 2013 and updated in May 2015. This report provides the status of the on-going effort on the subject of irradiated concrete.

2 JOINT EPRI-DOE-NRC ROADMAP ON IRRADIATED CONCRETE

A LWR-specific environmental factor, the effect of radiation on the microstructure and properties of concrete-based structures, requires further investigation [18] due to the limited understanding of the potential susceptibility – Mechanism 12 in Fig. 1. The extension of the operating lifetimes of commercial LWRs has reignited the study of radiation effects on concrete. Of particular interest are the expected radiation exposure (fluence or dose) on concrete structures in typical LWR configurations and the resulting changes in mechanical and physical properties, and the mechanisms for such changes.

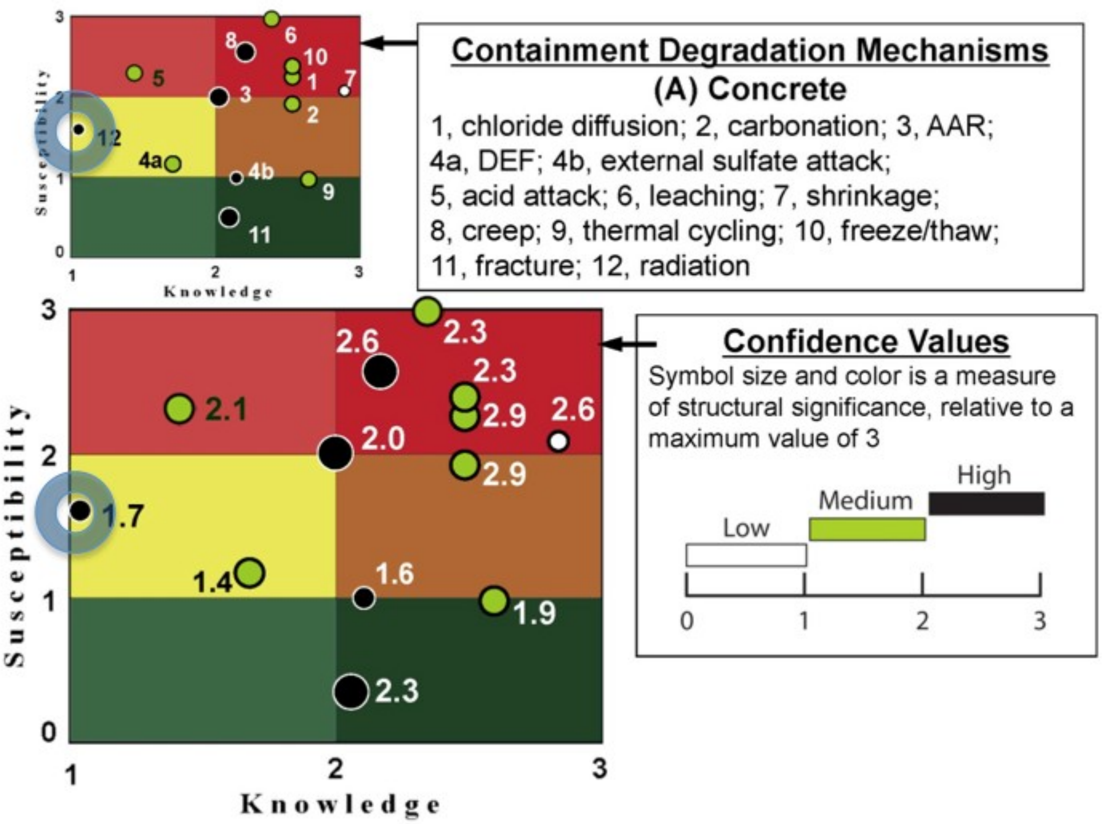

Fig. 1. EMDA chart for irradiated concrete. The circled point shows the knowledge and susceptibility index found using the PIRT exercise performed by an expert panel in 2011. A knowledge level of 1 indicates a "poor understanding, little and/or low confidence data." Susceptibility factors of 1 and 2 correspond, respectively, to a "conceptual basis for concern from data, or potential occurrence under unusual operating conditions", and, a "strong basis for concern or known but limited plant occurrence." Reproduced from Ref. 18.

To address these potential gaps in the knowledge base, the EPRI and DOE are working to study radiation damage as a degradation mechanism. The on-going program within this pathway includes:

1. The definition of the upper bound of the neutron and gamma dose levels expected in the biological shield concrete for extended operation (80 years of operation and beyond);
2. The determination of the effects of neutron and gamma irradiation as well as extended time at temperature on concrete;
3. The evaluation of opportunities to irradiate prototypical concrete under accelerated neutron and gamma dose levels to establish a conservative bound and share data obtained from different flux, temperature, and fluence levels;

4. The evaluation of opportunities to harvest and test irradiated concrete from international commercial NPPs;
5. The development of cooperative test programs to improve confidence in the results from the various concretes and research reactors;
6. The expansion of further understanding of the effects of radiation on concrete and;
7. The study of the structural significance of irradiation on CBSs and RPV support structures;
8. The establishment of an international collaborative research and information exchange effort to leverage capabilities and knowledge.

Note that this document is not intended to provide an extensive literature review of the effects of irradiation on concrete. We would like to refer the reader to the available open literature, e.g. Refs. 14 and 58, before reading this document. Significant knowledge improvements achieved, in particular, by the DOE-LWRS Program on irradiated concrete since the publication of Willam et al.'s report, are detailed in this document.

This joint coordination roadmap (Fig. 2a) has been developed initially with the objective to avoid duplication and to increase synergies between the EPRI LTO program and the DOE LWRS program. Each identified cell of the roadmap corresponds to an individual project sponsored either by EPRI (blue cells), DOE (green cells) or a third party, here, the Japan National Regulatory Agency (orange cells). The realization of the EPRI program relies on different research providers such as Lucius Pitkins Inc. (LPI) or the Nuclear Research Institute, Řež (NRI). ORNL is the primary research provider for the Material Pathway of the LWRS program. Mitsubishi Research Institute Corp. (MRI), Kajima Corporation and the University of Nagoya are the principal research organizations involved in the Japanese program. At DOE's initiative, a new international organization, the ICIC, has been formed to provide the framework for exchanging information on a broad set of topics related to the effects of irradiation on concrete. The purpose is to provide a forum for discussing issues that advance the state of knowledge of the effects of irradiation on structural concrete used in nuclear reactor facilities including storage sites. It is anticipated that the information exchange will leverage capabilities and knowledge, including developing cooperative test programs, to improve confidence in the results from the various concretes and research reactors. Although joint EPRI-DOE activities were initiated in 2012 on this subject, this particular roadmap was developed in October 2013 and is to be revised in 2015 (Fig. 2b).

The roadmap chart is organized in five general categories spanning from basic mechanistic comprehension to engineering applications:

1. Mechanisms understanding: Includes the basic theoretical and experimental science necessary to comprehend the effects of radiation on concrete constituents and their interactions;
2. Materials characterization: Aims at providing experimental characterization of concrete and concrete constituents properties and micro-structural evolution before and after irradiation;
3. Nondestructive evaluation and monitoring to assess and manage degradation;
4. Engineering validation: Aims at conducting validation testing and simulation on structural members (i.e., at an intermediate scale between the material and full-size structures);
5. Structural significance: Aims at evaluating the structural integrity of exposed nuclear reinforced concrete structures (biological shield and reactor pressure vessel support structures) by using numerical simulation tools.

Note that these five categories were introduced, not only for the irradiation program, but are also used generically for other degradation mechanisms, e.g. alkali-silica reaction.

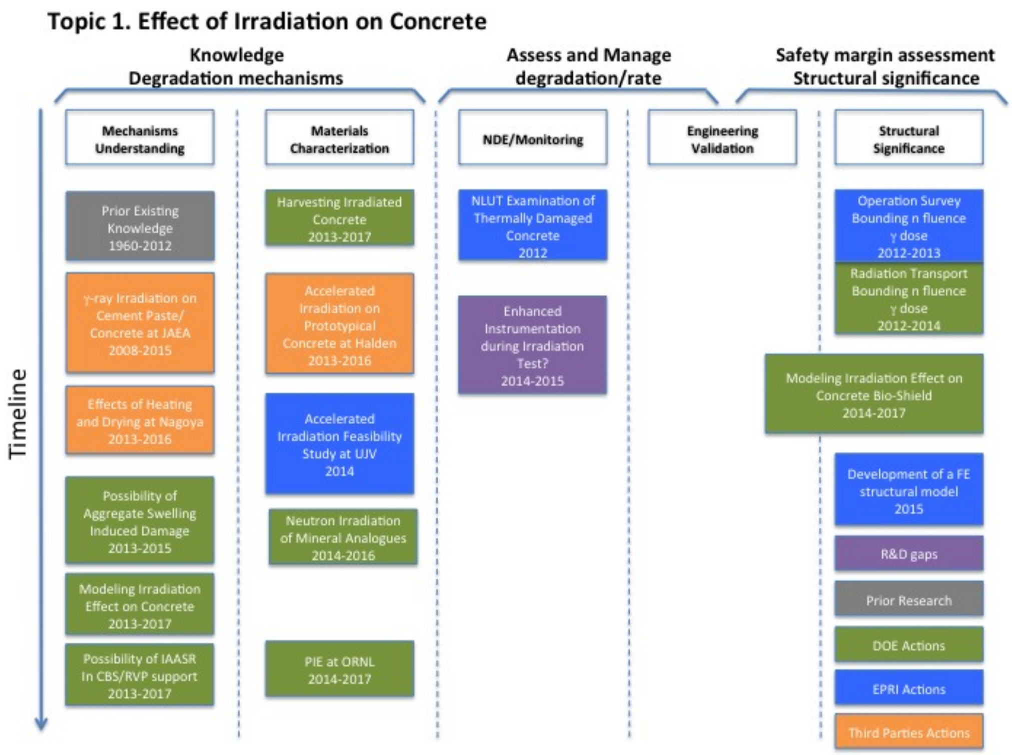

Fig. 2a. DOE-EPRI-NRC Research roadmap on irradiated concrete (October 2013).

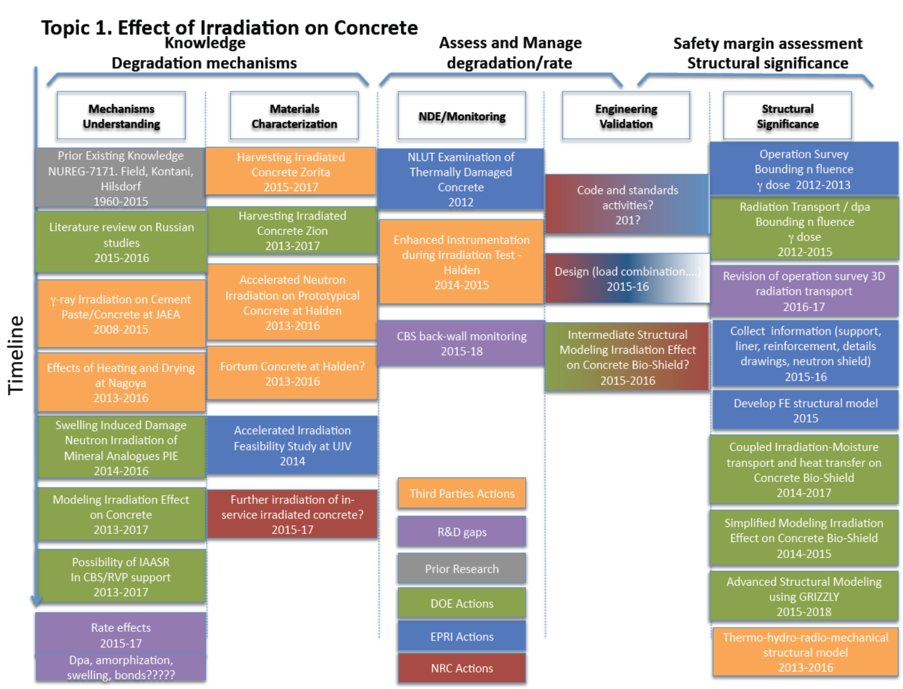

Fig 2b. Revised (May 2015) DOE-EPRI-NRC Research roadmap on irradiated concrete. (This revision occurred after the preparation of this report)

2.1 EPRI RESEARCH ACTIVITIES

EPRI initiated research (principal investigator (PI): LPI on irradiated concrete as early as 2011 and published its first report in 2012 [21]. The suggested path forward included:

1. The creation of an international consortium for testing irradiated concrete to collect and test cores of interest. This activity has been transferred to the LWRS program and separated in two tasks, namely: "Harvesting Irradiated Concrete" and "Irradiated Concrete International Committee" (see Section 2.4 for details).
2. The development of numerical modeling for irradiated concrete both at the atomic and subatomic levels to study the radiation damage, and at the macroscopic scale for the assessment of the materials damage. The modeling activity is being performed by the LWRS program (see Sections 2.4.2 and 2.4.3 for details).

2.1.1 Accelerated Irradiation Feasibility Study at NRI, Řež / ÚJV, Řež

EPRI has actively worked with NRI to evaluate the feasibility of irradiating concrete specimens at the LVR-15 research reactor. For example, a concrete sample was placed in the reactor and its vertical position varied during the experiment to study the effect of neutron and gamma flux on the sample temperature while the gas pressure was monitored at the core. Cooling was ensured by direct contact between the concrete specimen, the 1 mm –thick aluminum capsule and the primary circuit water (max. value at 8 MW: about 40°C). Maintaining the temperature of the core below 65°C (i.e., design value for LWRs) requires limiting the power of the reactor below 3 MW; maintaining it under 93°C (i.e., maximum value allowed locally for LWRs) can be achieved at a reactor power of about < 6 MW.

The absence of a concrete expansion space appeared inconsistent with the evaluation of post-irradiation swelling although it is clearly advantageous for cooling the specimens. The exact quantification of the actual mechanical constraints in the CBS are still not clearly evaluated but are not reflected either by free-expansion or fully-restrained conditions.

Maintaining a temperature at the center of the specimen lower than 65°C cannot be achieved without the installation of an additional cooling system which considerably increases in the experiment cost.

The temperature gradient between the surface and the center on the concrete specimen is estimated around 45°C. Note that the sample diameter was limited by design for the experiments sponsored by the Japanese group to avoid possible thermal-induced cracking [34].

The results of preliminary testing and studies conducted by NRI, LPI and ORNL question value of testing irradiated prototypical concrete under accelerated conditions until:

1. A better selection of the "critical" concrete mixtures has been made, i.e., finding materials both representative of plants potentially affected by high level of fluence and susceptible to significant damage.
2. A clear assessment of the actual moisture content, temperature, dose and mechanical confinement has been made.

2.1.2 Operation Survey on Neutron Fluence and Gamma Dose in LWRs

This activity was initiated by EPRI (PI: LPI), and co-funded by EPRI and the LWRS program. As summarized by Ref. 26: "Acknowledging the absence of flux monitors at, or in, the CBS, time and spatial extrapolation of the RPV surveillance data were used to determine the fluence at the inner diameter (ID) of the CBS at 80 years of commercial operation (92% capacity). The irradiation exposure (fluence level based on Esselman and Bruck's survey [12]): The estimated fluence at the CBS ID varies between about $> 1.0 \times 10^{19}$ and $< 7.0 \times 10^{19}$ n.cm^{-2} ($E > 0.1$ MeV) for pressurized water reactors (PWRs) at 80 years of operation. 4-loop PWRs are less susceptible to develop high neutron exposure ($< 4.0 \times 10^{19}$ n.cm^{-2}) compared to 2 or 3-loop PWRs. Boiling water reactors (BWRs) maximum fluence should barely exceed 1.0×10^{19} n.cm^{-2} at 80 years of operation. Hence, BWRs CBS should be relatively immune to irradiation effects since the effects of radiation on concrete mechanical and physical properties are observed for fluence [13] above 1.0×10^{19} n.cm^{-2}. The flux attenuation in ordinary concrete is about one order of magnitude per ≈ 12 to 15 cm. Hence, radiation-induced effects should be predominant primarily in the first 10 to 25 cm depending on the actual fluence [and neutron energy spectrum] at the CBS ID although constrained-RIVE could potentially develop detrimental stresses deeper in the CBS wall." Estimation of the induced elastic stresses is discussed in Section 2.4.9.

2.1.3 Nonlinear Ultrasonic Testing (NLUT) of Thermally Damaged Concrete

NLUT are gaining popularity for the assessment of damage of concrete induced by ASR [29;28], mechanical loading [53], and carbonation [5;25]. No specific attempt to use non linear acoustic technique on irradiated materials has been attempted. A study, sponsored by EPRI, of thermally damaged concrete using a nonlinear technique was conducted by Los Alamos National Laboratory (LANL). For all degradation mechanisms, it clearly appears that nonlinear acoustic techniques are extremely sensitive to any microstructural change like cracking and porosity change. It is likely that NLUT can potentially detect irradiation-induced damage. However, separating the effects of coupled degradation mechanisms, like moisture transport, temperature and irradiation, remains not trivial. Deployment limitations are to be expected regarding the difficulties to access the reactor cavity, and the belt-line region, in particular.

2.1.4 Structural Modeling

Because of the recent progress made in the comprehension of the neutron effects on concrete [13;27], the LWRS program has developed a 1-Dimensional cylindrical model [26] to provide a first assessment of the structural significance of irradiated concrete on CBSs in PWRs – see Section 2.4.9 for details. In parallel, EPRI is planning to develop a 2-dimensional structural model of a prototypical PWR. "These models will include a portion of the basemat, the biological shield, and an extent of the reactor support structure sufficient to capture all load paths associated with the reactor vessel and primary piping support." It will include the reinforcement details and the RPV support system to evaluate the transmission of the RPV load, and the development of stresses in concrete, in-service and also, during a seismic event. This model will serve as a reference to future simulation accounting for the effects of irradiation of the mechanical properties of reinforced concrete.

2.2 RESEARCH ACTIVITIES IN JAPAN

The Japanese research program on irradiated concrete, which is sponsored by the Japanese Nuclear Regulatory Authority (NRA) through the Japanese Aging Management Program on Systems and Structures (JAMPSS) and performed at Nagoya University, Kajima Corporation and managed by Mitsubishi Research Institute, is conducting a comprehensive on-going program on neutron, gamma, temperature and moisture transport effects on concrete, cement paste, and aggregate.

2.2.1 Gamma-Ray Irradiation on Concrete and Concrete Constituents

Gamma irradiation tests are conducted at Japan Atomic Energy Agency (JAEA) Takasaki Advanced Radiation Research Institute, on aggregate, cement paste and concrete. Preliminary planning was initiated in 2009. Most of the tests started late 2012 and will end during the Fall 2015 and are expected to reach a 20 MGy dose. Preliminary results were presented at the first ICIC meeting in Barcelona, Spain in March 2014. Per ICIC charter, these results cannot be displayed here without the explicit consent of their authors.

2.2.2 Accelerated Neutron Irradiation on Concrete and Concrete Constituents

Neutron experiments are conducted at the Institutt for Energiteknikk (IFE) JEEP II test reactor in Halden, Norway, on concrete, cement paste and aggregate. Neutron irradiation experiments started in September 2013 and are scheduled until August 2015. The maximum expected fluence after two years is 6.0×10^{19} $n.cm^{-2}$. The selection of JEEP II test reactor was based on the low gamma heating rate [34]. The expected temperature at the center of the concrete specimens is estimated around 75 to 80°C. The specimens diameter is limited to 40 mm to avoid thermal cracking induced by the radiation-induced thermal profile (the temperature increase between the outer diameter and the center axis is estimated at 17°C). The maximum aggregate diameter is limited to 13 mm to obtain a similar drying shrinkage damage pattern and dimensional change, and also failure mode under compression loading, as a reference ordinary concrete. This size is compatible with the 1:3 aggregate/diameter ratio recommended for mechanical testing of concrete. Five different aggregates containing varied proportion of quartz, feldspars and clay minerals were studied. The two containing the highest fractions of quartz because of their low shrinkage (limited clay content) exhibit high thermal expansion coefficients. These aggregates are also expected to be affected by neutrons (see DOE activities for technical explanations).

2.2.3 Effect of Heating and Drying

Heating and drying tests were conducted at the University of Nagoya and also at the Halden facility. Results have not been published yet. A comprehensive review of the effect of moisture content can be found in Refs. 32, 35, and 36.

2.3 FORTUM RESEARCH ACTIVITIES

Fortum is conducting neutron irradiation experiment of serpentinite concrete at IFE test reactor in Norway. The concrete mixture is representative of a Voda Voda Energo Reactor (VVER). Online measurements include two thermocouples, a gamma-thermometer, an elongation detector and the monitoring of pressure and gas release. Two capsules are still being irradiated. Four other capsules are currently stored for activity decay after reaching target exposure.

2.4 DOE RESEARCH ACTIVITIES

2.4.1 Expanded Literature Review and Possibility of Aggregate Swelling Induced Damage

Since Hilsdorf et al.'s work [20], several recent attempts were made to develop a more comprehensive review [14;16] of the effects of radiation on concrete properties. The database assembled by Field et al. [13] is, by far, the most extensive ever produced. The 307 compression strength data, 62 tensile strength data, 138 elastic modulus data and 114 linear expansion data collected in the open literature sheds a new light on the effects of neutron irradiation on concrete:

1. "Concrete irradiated with neutrons exhibited a marked decrease in compressive strength at fluence levels above 1.0×10^{19} $n.cm^{-2}$ with lower bounds at 50% of the reference concrete strength."
2. "Neutron irradiation of concrete has a greater impact on the tensile strength compared to the compressive strength. Loss of tensile strength occurs at fluence levels similar to those for compressive strength, but a 75% loss of tensile strength can occur compared to a 50% loss of compressive strength. As a result, the usual relationships (code or empirical formulae) used to derive the tensile strength in absence of measured compressive strength may not be applicable."
3. "The elastic modulus shows a gradual decrease under neutron irradiation with significant decreases observed above 1.0×10^{19} $n.cm^{-2}$, although data reported in this range were also conducted at high temperature, and the combined effect of neutrons and elevated temperature must be considered."

4. “The decrease in mechanical properties is attributed to many factors, but indications show that the RIVE is a first-order mechanism for loss of mechanical properties under neutron irradiation. Radiation tolerance is expected to be dependent on the aggregate type and a partitioning scheme for evaluating the data was presented. Data suggest siliceous aggregates present the highest risk for deleterious effects of both irradiation and elevated temperatures on concrete due to its susceptibility for low fluence amorphization and corresponding swelling and high thermal expansion coefficients.”
5. “The estimated fast neutron fluences (E > 0.1 MeV) in the biological shield during long-term operation (> 40 years) will reach the levels where the effect of RIVE and loss of mechanical properties are expected and cannot be ignored as a potential degradation.”

2.4.2 Unified Parameter for Characterization of Radiation Intended for Evaluation of Radiation-Induced Degradation of Concrete

The principal objective of this modeling, developed at ORNL by Remec [45], is to quantify the contribution of neutrons at different energies to the damage of simple crystalline systems (silicon, silica and quartz). The damage is quantified in terms of displacement per atom (dpa). While dpa is “the preferred irradiation parameter for characterization of radiation effects on metals,” this research is, to the best of our knowledge, the first study on minerals constitutive of concrete aggregate. It was found that the ≈ 95% of the total displacement damage is due to neutron at energies above 0.1 MeV, while only 20–25% for 2-loop PWRs, and less than 20% for a 3-loop PWR, of damage is due to neutrons with E > 1.0 MeV. These calculations were obtained assuming the energy spectrum of a 2-loop PWR. This result sheds a new light on the definition of the relevant neutron fields to be considered for the structural assessment of PWR CBS [47]. This work also provides a fundamental research contribution to the development of damage at the atomistic scale.

2.4.3 Modeling Irradiation Effects on Concrete at the Meso-Scale

Because concrete is a heterogeneous material and irradiation affects concrete constituents differently, modeling is necessary to understand and analyze irradiation coupled effects and interactions in concrete. It is also the only way to interpret comprehensively literature data derived from experiments conducted at varied exposure (temperature in particular) on varied mixtures. The proposed model is based on the homogenization theory of random media (micromechanics). Details and results are fully detailed in Le Pape et al. (2015) [27]. The main conclusions of this work are:

1. “A comparison with limited published experimental data highlights the importance of separating the irradiation effects in the aggregate and in the cement paste and understanding their interaction. The predominant role of the aggregate on damage and swelling is confirmed and quantified. Pre-existing damage in the cement paste is clearly aggravated by the aggregate expansion though the reduction of the elastic properties of the aggregate tends to reduce the expansion transfer to the paste.”
2. “Of the extensive literature review conducted and presented in Field et al.’s companion paper, only the data published by Kelly et al. [24] and Elleuch et al. [11] contains systematic information with pre- and post-irradiation characterization of the cement paste, the aggregate and concrete made with the same constituents. The mechanistic understanding of irradiation effects in concrete needs further experimental investigation in that spirit.”
3. “The broad classification of aggregate (i.e., limestone, silicate and miscellaneous/trap) used in our companion paper [13] provided a qualitative partitioning that led to the identification of the radiation-induced volumetric expansion, resulting primarily from silicate-based mineral amorphization. For quantitative analysis, this general classification might be inappropriate because different mineral compositions can affect an aggregate’s susceptibility to neutron radiation damage.”

2.4.4 Investigation of the Possibility of Irradiation-Assisted Alkali-Silica Reaction (IAASR)

The possibility of a coupling mechanism between irradiation and ASR was suggested first by Ichikawa and Koizumi [22]. The dissolution rate of the irradiated materials immersed in a 1 mol L^{-1} solution of sodium hydroxide was multiplied by more than 20× for α-quartz and approximately tripled for amorphous quartz. Hence, showing the increased reactivity of the material and its susceptibility to develop ASR. On-going effort sponsored by the Laboratory Directed Research and Development (LDRD) program at ORNL aims at pursuing the experimental effort initiated by Ichikawa and Koizumi. The dissolution rate of Ar-ion implanted pure quartz, calcite and mica is characterized by vertical scanning interferometry (VSI) technique. This research is performed in collaboration with University of California, Los Angeles (UCLA) and the University of Michigan. Preliminary results show that the dissolution rate of irradiated quartz is found to be two-orders of magnitude higher that pure α-quartz at pH between 10 to 14, confirming the initial findings of Ichikawa and Koizumi.

2.4.5 Fast-Flux Neutron Effects on Mineral Analogues

On-going research by Rosseel and Le Pape [48] is focusing on characterizing the effects of neutrons on mineral analogues, and cement paste. Specifically, "A a comprehensive review of the literature by Field et al. [13] has greatly expanded the database and confirmed the predominant role of radiation-induced volumetric expansion (RIVE)." "Moreover, the development of a specifically targeted micromechanical model using the available data from literature confirmed the predominant role of aggregates on the macroscopic expansion of irradiated concrete. In particular, ORNL studies [27] support the hypothesis formulated by Seeberger and Hilsdorf [52] concerning the role of silicate-bearing aggregates on irradiated concrete residual properties. Vanelstraete and Laermans [56] have shown that fast neutrons ($E > 0.1$ MeV) cause displacement cascades in quartz resulting in disordered regions of the crystal. For sufficiently high doses, these regions overlap, reducing long-range ordering and resulting in amorphization of the SiO_2 phase. The loss of ordering is observed as a reduction of density and increase in swelling of the quartz phase. Complete amorphization is thought to be reached at a neutron dose of > 2.0×10^{20} $n.cm^{-2}$." "Plans were developed for studying the effects of irradiation on mineral analogues and aggregate swelling using the Hydraulic Tube (HT) sample positions at the ORNL high flux isotope reactor (HFIR). Specifically, a series of short-term, high-flux irradiations of minerals at different fluence levels were performed at two temperatures. The purpose is to evaluate the evolution of aggregate and mineral amorphization through saturation. The HT irradiation positions at HFIR offered several advantages over other options at HFIR. These include:

1. Short duration experiments due to the higher flux that would simplify the task of irradiating the samples at a series of neutron fluences below swelling through amorphization and full swelling
2. A variety of capsule designs previously approved for use in HFIR
3. An option to simultaneously irradiate two capsules with similar flux and therefore fluence
4. An option for irradiating sealed capsules and perforated capsules. Sealed capsules would duplicate the conditions, including elevated temperature, of many of the experiments found in the literature. A perforated capsule, if feasible, would permit the samples to be irradiated at ≈ 50°C, which is similar to the temperature of the biological shield."

"Using Seeberger and Hilsdorf [52] as a guide, three common minerals found in concrete aggregates: quartz (SiO_2), dolomite ($CaMg(CO_3)_2$ and calcite ($CaCO_3$) as well as pure hydrated cement paste (HCP), prepared with triclinic (Ca_3SiO_5)", [w/c = 0.485], "were selected for the initial study." "The nominal fluences selected were 0.5, 4.0, and 20 × 10^{19} $n.cm^{-2}$ ($E > 0.1$ MeV)." "Four sets of 24–28 specimens (quartz, dolomite, calcite, and hydrated cement paste) were cut and polished, weighed, dimensions measured, and loaded (four each) into six capsules – three sealed and three perforated. The three pairs of capsules were inserted into the HFIR hydraulic tubes and irradiated to the prescribed nominal fluences. The irradiations were completed, transferred to the hot cells, where the samples were removed from the capsules and repackaged, and shipped to Low Activity Materials Design and Analysis (LAMDA) facility for physical, mechanical and microscopic characterization. On-going post-irradiation evaluation (PIE) includes: dimensional and mass measurements, X-ray diffraction, microscopy, and the evaluation of residual mechanical properties by nanoindentation.

2.4.6 Harvesting Irradiated Concrete

During the last fifteen years, several nuclear power plants in the United States and other countries have been decommissioned, are in the process of being decommissioned, or decommissioning will commence soon. Examples include Zion Nuclear Power Station Units 1 and 2, Milestone 1, Indian Point Unit 1, Crystal River 3, Zorita (Spain), nuclear power plant Krummel (Germany), and Barseback (Sweden). Harvesting of concrete cores from decommissioned nuclear power plants will provide an opportunity to generate data from concrete that has experienced typical radiation fields, while also providing guidance to accelerated irradiation studies. The coupling of accelerated or laboratory-irradiated concrete with harvested nuclear power plant cores is expected to facilitate the effort to develop an understanding of the damage mechanisms in irradiated concrete, including understanding potential effects of accelerated testing.

Possible Harvesting of Zion Concrete: In support of extended service of the U.S. nuclear reactor fleet, ORNL (through the LWRS Program) is coordinating and contracting with Zion Solutions, LLC (a subsidiary of Energy Solutions) the selective procurement of materials, structures, and components, including concrete from the decommissioned Zion reactors [49]. Physical acquisition of concrete cores will need, however, to be supplemented by extensive investigations into the operating history of the nuclear power plant, as well as the concrete composition and performance history. Information such as the material test reports for cement, admixtures, and aggregate; concrete mix design; and aggregate characterization, including type, petrographic analyses, and gradation will attempt to be collected. Other critical information might include concrete property test results such as the reference 28-day compressive strength and modulus of elasticity, results from any concrete strength testing over the life of the plant, and the American Society of Mechanical Engineering (ASME) inspection reports. It is anticipated that data from the concrete from the Zion nuclear power plant will be integrated with data from other decommissioned reactors and possibly with data from accelerated irradiation of well-characterized nuclear power plant-like concrete. As of June 2015, this effort will not proceed due to conflicts with the Zion decommissioning and demolition activities.

Possible Harvesting of Barseback Concrete: ORNL initiated discussions with its Concrete Containment Condition Status and Aging Examination System (CONSAFESYS) partners concerning harvesting concrete cores from Barseback NPP Units 1 and 2. Proposed locations would focus on regions of elevated radiation, elevated temperature, elevated radiation and temperature, and ambient conditions. This effort was terminated following notification in May 2015 that neither the utility not the Swedish government would approve it.

Possible Harvesting of Zorita Concrete: The Jose Cabrera NPP is a single-loop, Westinghouse-designed, PWR located near Zorita, Spain. The reactor, which was commissioned in 1968, operated until 2006 accumulating 26.5 Effective Full Power Years (EFPY) of operation. As described in T. M. Rosseel, "Status Report on Evaluation and Plan to Harvest Service-Irradiated Concrete from the Jose Cabrera (Zorita), NPP, Spain," ORNL/LTR-2015/52, (submitted to the NRC), ORNL has reviewed and evaluated three critical issues to assist the NRC in their decision whether to undertake an effort to harvest and characterize service irradiated concrete from the Jose Cabera (Zorita) NPP. First, the Zorita biological shield concrete was found to be similar to some concretes found in US NPPs. Second, the estimated fast neutron fluence ($E >$ 0.1 MeV) on the biological shield appears to be sufficient to produce microstructural changes in the cement paste and the onset of radiation-induced volumetric swelling of the aggregates. Moreover, the Zorita NPP has the highest fluence of any plant currently being decommissioned. Third, the aggregate, although rich in limestone, contains siliceous aggregates and is expected to exhibit the onset of radiation-induced damage at the estimated fluence.

Based on data provided by the Zorita Consortium and data obtained from the literature, the Jose Cabrera (Zorita) NPP provides a unique opportunity for the NRC to obtain critical information radiation damage on reactor cavity concrete. Specifically, confirmatory research could focus on: (1) validating predictive models, based on accelerated aging studies, with empirical data obtained from field-aged concrete in radiation and thermal environments, (2) evaluating concrete radiation gradients in the biological shield to investigate the changes in properties as a function of the level of radiation, and (3) irradiating the harvested cores to higher fluences to evaluate the changes in service irradiated concrete at extended lifetimes. Moreover, the Zorita Consortium invited the US NRC to participate in harvesting service-irradiated concrete for characterization.

For these reasons, harvesting and characterizing concrete from Zorita would be beneficial in evaluating the effect of radiation and temperature on the possible degradation of concrete in NPPs at extended lifetimes. As part of the NRC decision making process of evaluating the information provided, however, it is critical that the NRC obtain, review, and perform a detailed assessment of the probability of radiation-induced damage in the biological shield based on the final calculations of fluence and temperature. In August 2015, the US NRC decided not to proceed with efforts to harvest Zorita concrete.

2.4.7 Development of Post-Irradiation Evaluation at ORNL

In the perspective of receiving irradiated concrete samples obtained either from the harvesting campaign or accelerated testing, ORNL is developing a post-irradiation examination/testing protocol. While literature tends to focus on mechanical properties, obtaining a more descriptive characterization of irradiated concrete may provide additional information of the softening or the embrittlement of the materials. Seeberger and Hilsdorf (1982) [52] [Fig. 17 of the original paper] showed for example that while the tension-expansion response of non-irradiated granite is classically described by a quasi-brittle elastic, that of irradiated granite showed a non linear hardening behavior with increased ductility. In general, these behavior curves are not provided by the literature data because several different tests were performed to characterize each of the properties. In particular the elastic modulus is often derived from non destructive dynamic testing (resonance frequency method or pulse velocity). It is known that dynamic modulus technique provides a biased measurement of the quasi-static modulus and that the correction factors are quite empirical.

As noted in ACI 318, and other codes such as Eurocode 2, the design of reinforced and prestressed concrete structures relies on simplified representation (including safety factors) of the behavior (stress-strain curve) under quasi-static loading. The evaluation of the resistance of structural members is based on the integration of that simplified constitutive law (assuming a maximum allowable ductility) and the determination of concrete strength. If the very nature of irradiated concrete response to loading is modified, usual design rules would be improper for the re-assessment of the affected members.

Hence, it is suggested to develop a full characterization of the behavior of irradiated concrete under quasi-static uniaxial loading. The proposed testing is adapted from the ASTM historical standard:

- ASTM C39 / C39M-14 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [1]
- ASTM C469 / C469M-10 Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression [2]
- ASTM C496 / C496M-11 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens [3]

2.4.8 Radiation Transport Bounding Neutron Fluence and γ Dose

Rosseel et al. [50] provided a comprehensive summary of the work accomplished: "Coupled neutron and gamma transport calculations for one, three-loop and one, two-loop PWR were conducted recently at ORNL [46;47]. Neutron fluxes for all energies, except the thermal neutron flux, exhibit a monotonic decrease through the RPV, cavity, and inside the concrete shield. The rate of attenuation, however, varies depending on the material.

Several observations and conclusions from these radiation transport simulations of neutron and gamma fields are described as follows:

- Fast neutron (E > 1.0 MeV and E > 0.1 MeV) fluxes at the pressure vessel outer radius are 20 to 30% higher than the maximum fluxes in concrete. These fluxes, determined at maximum at the pressure vessel wall, are typically provided in RPV surveillance reports and could be used as conservative estimates for fluxes in the concrete shield or for screening purposes.
- The total neutron and gamma flux at the pressure vessel wall agree within 10% of the maximum values in concrete. Heating rates calculated at the pressure vessel maximum flux location also are 10 to 20% higher than the highest rates in concrete.
- It is not practically possible to renormalize results from fast neutron fluence (e.g., E > 0.1 MeV) to total neutron fluence or vice versa without knowing the details of the irradiation experiment."

2.4.9 Structural Significance of Irradiated Concrete

Modeling the structural significance of irradiation on CBSs or RPVSSs has been the subject of limited research [43;38;51]. Recent work was also conducted at ORNL to address the limitations of these models in terms of accounting for RIVE. Details can be found in Ref. 26: "Available structural models do not account for radiation-induced volumetric expansion, although it was found to develop important linear dimensional change of the order of 1%, and, can lead to significant concrete damage [27]. A 1D-cylindrical model of an unreinforced CBS accounting for temperature and irradiation effects is developed. Irradiated concrete properties are characterized probabilistically using the updated database collected by ORNL [13]." "The simplified cylindrical model of a prototypical PWR CBS geometry shows that radiation-induced volumetric expansion can result in the development of mechanical stresses, largely exceeding the strength of irradiated concrete. Because of the important attenuation of the neutron transport in concrete, differential expansion is predominant in the portion of the CBS located in the vicinity of the reactor. Differential RIVE induces high bi-axial compression stresses, mostly localized in the concrete cover near the reactor cavity, and widely spread circumferential tensile stresses toward the back of the CBS. The overstressed concrete depths (i.e., exceeding the strength of concrete) of a prototypical 1.5 m (5 ft.) CBS using a 40 MPa (5800 psi) compressive strength concrete were found equal, on average, to 8.6 cm ($3^{1/2}$ in.) in the compression zone and, to 1.08 m ($42^{1/2}$ in.) in the tension zone. These results are valid for a maximum neutron fluence on the concrete surface of $3.1 \times 10^{+19}$ n.cm^{-2} (E > 0.1 MeV), obtained after 80 years of operation." [26]

This research must be pursued, in particular, by considering the presence of reinforcement, and, the possibility of stress-relaxation induced by creep in the cement paste. The first question requires the use/development of simulation tools, such as finite element codes. On-going development of DOE code GRIZZLY [55] will provide that feature in the future. The second question is a materials issue: "The potential relaxation of the RIVE-induced stresses in the hardened cement paste is crucial to determining the extent of concrete damage at the CBS end-of-operation. Concrete creep depends primarily on the internal moisture content [60], and temperature, which results from coupled moisture–heat transport (see previous paragraph), but it seems also to depend on gamma irradiation [37]. While increased temperature amplifies concrete creep kinetics, lower moisture content and gamma-irradiation decreases creep amplitude and, hence, the possibility of stress relaxation in the cement paste."

2.4.10 Irradiated Concrete International Committee

Understanding the effects of radiation on concrete is important in determining long-term or extended operating performance of concrete structures in existing NPPs. Not surprisingly, this issue is being addressed by research organizations and utilities across the globe. Moreover, in the last two years, the

LWRS Program has been actively working to build international partnerships and collaborations in an effort to better define the issues, develop a sound approach to resolving the major questions, and maximizing resources. As part of that effort, an international meeting, entitled, "International Irradiated Concrete Information Exchange Framework Meeting," was proposed and organized by ORNL in cooperation with Professor Carmen Andrade, Consejo Superior de Investigaciones Científicas - CSIC (Spanish National Research Council). Nineteen researchers from five countries attended the meeting, which was held at the Hotel Colon in Barcelona, Spain, on March 12-14, 2014. The foundation for this meeting has been the understanding that international cooperation will provide the best opportunities to share resources, acquire valuable specimens from decommissioned NPPs, and build a systematic database to provide a framework for decisions concerning extended operation of nuclear power plants in a timely and efficient manner.

The purpose of this meeting was two-fold. First, to develop the framework for exchanging information on a broad set of topics related to the effects of irradiation on concrete used in NPPs by those who are actively pursuing research, were active in the field, or wish to contribute to the advancing the current state of knowledge. And second, to provide a forum for discussing issues that advance the state of knowledge of the effects of irradiation on structural concrete used in nuclear reactor facilities including storage sites.

The first portion of the meeting included presentations and discussions on past and current irradiated concrete research and / or issues related to irradiated concrete. The second portion of the meeting focused on establishing the framework for exchanging information. This included a discussion of the types of information that could be exchanged, the level of release, an organizational framework for cooperation including resource and data sharing, and the development of charter based on the International Group on Radiation Damage Mechanisms (IGRDM) in RPVs.

The final portion of the meeting focused on making a decision or commitment by attendees to participate in the information exchange. At the conclusion of the meeting, the participants reached a consensus to move forward with the ICIC and that a follow-up meeting should be held within six months to finalize its charter and elect an executive committee. Moreover, the participants endorsed a plan to determine the frequency and location of future ICIC meetings. It is anticipated that future meetings will be held on a rotating schedule in Europe, the US, and Japan.

The meeting concluded with the election of Dr. Thomas M. Rosseel, Acting Chair, and Dr. Carlos Castelao, Consejo de Seguridad Nuclear, (CSN), Acting Vice Chair, to lead the interim process. Information on the ICIC, the draft charter, and meeting agenda and presentations can be found on the ICIC web site.

A second ICIC meeting was hosted by FORTUM and Aalto University, Finland, early October 2014. Information accessible to members only can be found at:
http://web.ornl.gov/sci/physical_sciences_directorate/mst/ICICIEF/index.shtml.

Twenty-five attendees from 18 organizations and 7 countries attended the second ICIC Information Exchange Framework Meeting in Helsinki, Finland, on October 8-10, 2014. The purpose of the meeting, which was graciously hosted by the Fortum Corporation, was two-fold. First, to finalize the framework established at the first ICIC framework meeting in Barcelona for developing a technical organization whose goal is to exchange information on a broad set of topics related to the effects of irradiation on concrete used in nuclear power applications. And second, to provide a forum for broad technical interactions in research on the effects of irradiation on concrete used in nuclear applications, such as nuclear facilities, storage, and disposal sites, and which will contribute to advancing the current state of knowledge. Twenty-three technical papers on the latest results of neutron and gamma irradiation experiments, plans for harvesting service irradiated concrete, proposed irradiation experiments, modeling of past irradiation data that address first order affects, and numerical simulations were presented and vigorously discussed.

At the conclusion of the meeting, the participants approved the revised ICIC Charter with 19 of the participants and 16 organizations accepting membership in the duly constituted ICIC. The participants also selected four Technical Areas (TA) and corresponding Technical Area Coordinators (TAC). The main function of the TA and TAC is to facilitate and expedite progress by the membership in specified technical topics. The four TA and TAC selected by vote of the members are as follows:

1. Structural Performance and Mechanistic Understanding of the Effects of Irradiation on Concrete (Yann Le Pape – ORNL, USA)
2. Harvesting and Characterization of Service Irradiated Concrete (Manuel Ordonez, ENRESA, Spain)
3. Accelerated Irradiation Studies of Concrete and its Components (Michal Koleska, RC-Řež, Czech Republic)
4. Characterization of Irradiated Concrete (Carmen Andrade, CSIC, Spain)

Finally the participants elected Dr. Rosseel, ORNL, as Chairman, Prof. Maruyama, Nagoya University, as Vice Chairman, and Dr. Miguel Ferreira, VTT, as Secretary of the ICIC. The first General Meeting of the ICIC will be held in the Knoxville, Tennessee on November 3-5, 2015.

3 SUMMARY OF EXISTING KNOWLEDGE, GAP ANALYSIS AND PATH FORWARD

3.1 MECHANISTIC UNDERSTANDING OF THE DEGRADATION

3.1.1 Neutron-Irradiation Effects on Concrete

RIVE of silica-bearing aggregate has been confirmed as a potentially important degradation mechanism [52;27;13] for concrete under neutron irradiation: RIVE can develop important dimensional change, comparable or higher, to those observed for ASR-affected concrete. Neutron exposure, at high fluence, causes amorphization [4;8] (disordering of the atomic structure) and volumetric change [59;44;62;52] (change of density) of crystalline structures of aggregate. Neutrons at energies higher than 0.1 MeV produce about 95% of the calculated damage (dpa) in simple crystalline systems such as silica and calcite [45]. Amorphization results in a change of loss of elastic properties [15;52]. Volumetric change is prominent for quartz, but is not so marked for calcite [19;31] even at fluence reaching 1.0×10^{20} n.cm^{-2} ($E > 0.1$ MeV). Fast neutrons produce ion-vacancy-induced damage in calcite ionic-bonded structure. Damage can be absorbed by the lattice because of the mobility of the defects [61]. On the opposite, covalent bonds (like in quartz) are more susceptible to neutron-induced damage [6]. Other silicates, like zirconium and micas (muscovite, biotite), exhibit important density/volume change [52;6;7] under neutron irradiation above 1.0×10^{19} n.cm^{-2}. The integrity of irradiated granite at high fluence is questioned [52]. Seeberger and Hilsdorf [52] classified the minerals and rocks in three categories: (I) *"Serious irradiation damage up to destruction"*: mica (e.g. in granite); (II) *"Slight irradiation damage"*: quartz, olivine, baryte, serpentine; (III) *"No irradiation damage"*: calcite, dolomite, feldspar, pyroxene, hornblende, magnetite. On-going fast-flux testing of mineral-analogues at HFIR will bring more elements of comparison. Irradiation-induced amorphization results in a significant increase of the dissolution rate of quartz [22], leading to the possibly of IAASR [40], although operating conditions can limit greatly the presences of water necessary to the formation of gels.

3.1.2 γ-Irradiation Effects on Concrete

γ-irradiation causes microstructural change of the cement paste [30;57;39]. Literature on γ-irradiation effect on cement paste strength and the elastic modulus provides apparently contradictory information [24;11;20;54;23;39]. The analysis of test reactor data [24;11] by Le Pape et al. [27] showed that γ-irradiation effects, unlike RIVE, does not seem to produce a first-order effect on concrete swelling or damage for the specific set of studied experiments. Limited knowledge is available on γ-irradiation effects on shrinkage and creep properties [37]. The understanding of the effects of γ-rays on the nano- and micro-structures of cement hydrates requires more basic research.

3.1.3 Interaction Mechanisms at the Meso-Scale

RIVE of minerals affects the behavior of concrete aggregate. Because the mineralogy of aggregates is extremely complex, each aggregate will be affected by complex interaction between the most RIVE-susceptible phases and the least RIVE-susceptible phases, resulting in specific aggregate expansion. The stress-strain behavior of irradiated rock appears to remain quasi-brittle elastic [52] with a loss of tensile strength and elastic modulus. A notable exception to this general statement is an irradiated-granite sample, that presented a marked loss of elastic modulus compared to the pristine granite, followed by a gradual hardening. The generalization to other type of granites cannot be assessed by lack of additional data. RIVE of aggregates and shrinkage of the hardened cement paste (hcp) cause damage to the interfacial transition zone (ITZ) [33] and to the cement paste [27] by the development of large mechanical stress. In test reactor, the thermal expansion, at relatively high temperature (i.e. > 250°C), and possible pre-drying treatment [11], exacerbate the aggregate-expansion-induced damage to the hcp [27] and result in thermal damage – See Ref. 41 for a review. When the temperature is maintained under < 65°C, damage to the hcp [24] result in, at minimum, two mechanisms: (1) The neutron irradiation damage of aggregates result in decreasing elastic properties, and hence of the RIVE-induced stresses to the hcp; (2) The differential volumetric change between the hcp and the aggregate. The transposition of test reactor results to actual operation condition requires understanding several concomitant time-dependent processes: dose rate, moisture transport, paste shrinkage and creep.

The effects of testing reactor high-flux on concrete damage need to be assessed: The rapid aggregate expansion occurs at a rate that could prevent stress-relaxation in the paste. ORNL is developing advanced materials modeling tools, using **AMIE finite element code** [9;10;17] to account for varied time-dependent mechanisms and fracture propagation to accurately describe rate effects.

3.2 MATERIALS CHARACTERIZATION

The largest database ever collected on irradiated concrete has been assembled by a thorough literature review [13]. Concrete strength and elastic materials properties are affected beyond fluence level of 1.0×10^{19} $n.cm^{-2}$. Important dimensional change can be observed beyond the same level of fluence. Conducting irradiation experiments on concrete under conditions similar to operating conditions proved extremely difficult. Three exposure variables must be considered simultaneously because of their potential effects on concrete properties: irradiation, temperature and moisture content. Maintaining the samples below design temperature, in particular, (i.e., < 65°C) requires an additional embedded cooling system. The scheduled PIE associated with the irradiation program conducted by the Japanese group is limited to mass change, length change, and strength. Theoretical analysis [27] shows that the construction of a fully predictive irradiated concrete model would also require, for each constituent, the pre- and post-irradiation characterization of the elastic and fracture properties, creep properties, the thermal expansion coefficient, the thermal conductivity, the specific heat, the porosity, the desorption curve (and permeability) and the water content.

3.3 CONDITION ASSESSMENT AND MONITORING

No condition assessment is currently being performed on CBS. The RPV surveillance data, available publicly in the Agency wide Documents Access and Management System (ADAMS) database provides the only operation-related information. Moroever, accessibility to the reactor cavity is extremely limited: The gap between the RPV and the CBS is about 15 cm (6 in.) wide over a height of nearly 5 m (16 ft.) for a typical Westinghouse design. The estimated flux in the cavity (i.e., almost equivalent to the neutron fluxes at the outer boundary (1T) of the RPV) are of the order of $1.0 \times 10^{+10}$ $n.cm^{-2}$ s^{-1} requiring the use of automated in-service inspection device. EPRI is currently developing, in partnership with International Climbing Machine (ICM) and Southwest Research Institute (SwRI), a fully automated crawler capable of carrying nondestructive instruments for the inspection of concrete structures. The required payload led to a fairly massive robot that is designed for the inspection of easily accessible surface. The current size of most nondestructive devices is also hardly compatible with the dimensions of the reactor cavity. Remote visual (RV) inspection using endoscopy techniques could provide a potential pathway to examine the presence of RIVE-induced surface cracking, if any.

3.4 STRUCTURAL SIGNIFICANCE

The bounding neutron fluence for the U.S. fleet at 80 years of operation (92% capacity) [12] is estimated at 6.5×10^{19} $n.cm^{-2}$. Two-loop and three-loop reactors are more susceptible to high fluence than 4-loop reactors. BWRs maximum fluence are unlikely to produced significant damage. Radiation fields analysis shows the considerable attenuation [47] of the neutron and gamma-ray profiles within the first 20 to 40 cm of the CBS. Resulting materials properties and "free" dimensional changes also present extremely variable profiles [26]. Preliminary structural assessment [26] was developed on a 1D-cylindrical model of an unreinforced PWR CBS accounting for irradiation effects. As the result of structural constraints and RIVE, large circumferential tensile stresses exceeding the concrete strength develop .at the back of the CBS while biaxial compression stresses are created in the region subjected to the highest neutron exposure. Adequate numerical tools need to be developed to assess quantitatively the development of potential damage in the reinforced CBS accounting for temperature transfer, moisture and radiation transport. Idaho National Laboratory (INL) Multiphysics Object Oriented Simulation Environment (MOOSE) has been chosen to develop dedicated modeling to the simulation of irradiated CBS and other degradations in varied reinforced structures. This work will benefit from the development support, the quality assurance and the code maintenance provided by INL Interfacing (or coupling if required) with radiation transport tool must be evaluated.

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Note on References: Parts of this report have also been published elsewhere. In particular, some large portions of the report ORNL/TM-2014/247, entitled "Light Water Reactor Sustainability (LWRS): Material Pathway, Concrete Activities Status Report and State of Collaborations with Industry and Academic Partners, Opportunities and Challenges", are reproduced here.

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ACRONYMS

ADAMS Agencywide Documents Access and Management System

AMIE Automated Mechanics Integrated Environment

ASME American Society of Mechanical Engineering

ASR alkali-silica reaction

BWR boiling water reactor

CBS concrete biological shield

CCB concrete containment building

CONSAFESYS Concrete Containment Condition Status and Aging Examination System

DOE Department of Energy

EMDA Expanded Materials Degradation Analysis

EPRI Electric Power Research Institute

FEA finite element analysis

GaTech Georgia Institute of Technology

hcp hardened cement paste

HFIR high flux isotope reactor

IAASR irradiation-assisted alkali-silica reaction

ICIC International Committee on Irradiated Concrete

ICM International Climbing Machine

ID inner diameter

IFE Institutt for Energiteknikk

INL Idaho National Laboratory

ITZ interfacial transition zone

JAEA Japan Atomic Energy Agency

LANL Los Alamos National Laboratory

LDRD Laboratory Directed Research and Development

LPI Lucius Pitkins Inc.

LTO Long-Term Operation

LWR light water reactor

LWRS Light Water Reactor Sustainability

MOOSE Multiphysics Object Oriented Simulation Environment

MRI Mitsubishi Research Institute Corp.

NEUP Nuclear Energy University Program

NDE nondestructive evaluation

NIST National Institute of Standard and Technologies

NLUT non linear ultrasonic technique

NPP nuclear power plant

NRC nuclear regulatory commission

NRI Nuclear Research Institute, Řež

NSSS nuclear steam supply system

ORNL Oak Ridge National Laboratory

PI principal investigator

PIE post-irradiation evaluation

PIRT phenomena identification and ranking table

PWR pressurized water reactor

RC reinforced concrete

RIVE radiation-induced volumetric expansion

RPV reactor pressure vessel

RPVSS reactor pressure vessel support structure

RV remote visual

SFHB spent fuel handling building

SwRI Southwest Research Institute

UCLA University of California, Los Angeles

VSI vertical scanning interferometry

VVER Voda Voda Energo Reactor