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Online Monitoring of Concrete Structures in Nuclear Power Plants: Interim Report

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Online Monitoring of Concrete Structures in Nuclear Power Plants: Interim Report

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ABSTRACT

The existing fleet of nuclear power plants in the United States have initial operating licenses of 40 years, and many of these plants have applied for and received license extensions. As plant structures, systems, and components age, their useful life—considering both structural integrity and performance—is reduced as a result of deterioration of the materials. Assessment and management of aging concrete structures in nuclear plants require a more systematic approach than simple reliance on existing code-based design margins of safety. Structural health monitoring is required to produce actionable information regarding structural integrity that supports operational and maintenance decisions.

The online monitoring of concrete structures project conducted under the Advanced Instrumentation, Information, and Control Technologies Pathway of the Light Water Reactor Sustainability program at Idaho National Laboratory is seeking to develop and demonstrate capabilities for concrete structures health monitoring. Through this research project, several national laboratories and Vanderbilt University propose to develop a framework of research activities for the health monitoring of nuclear power plant concrete structures that includes the integration of four elements—damage modeling, monitoring, data analytics, and uncertainty quantification.

This report briefly discusses activities in this project during October-December, 2014. The most significant activity during this period was the organizing of a two-day workshop on research needs in online monitoring of concrete structures, hosted by Vanderbilt University in November 2014. Thirty invitees from academia, industry and government participated in the workshop. The presentations and discussions at the workshop surveyed current activities related to concrete structures deterioration modeling and monitoring, and identified the challenges, knowledge gaps, and opportunities for advancing the state of the art; these discussions are summarized in this report

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EXECUTIVE SUMMARY

The U.S. Department of Energy's Office of Nuclear Energy funds the Light Water Reactor Sustainability (LWRS) Program to develop the scientific basis for extending the operation of commercial light water reactors beyond the current 60-year license period. The LWRS Program has three pathways. This project integrates the research activities performed by the Advanced Instrumentation, Information, and Control Technologies and Material Aging and Degradation Pathways.

A unique challenge to light water reactor sustainability concerns aging of passive structures (materials). As nuclear power plants (NPPs) continue to age and their structures degrade, it is important to understand the degradation condition, enhance monitoring and predictive data analytics techniques and be able to quantify the uncertainty introduced at various stages. This can be achieved by developing a structural health monitoring (SHM) framework to assess and manage aging structures. The SHM research needs to produce actionable information regarding structural integrity that supports operational and maintenance decisions. This critical information is individualized for a given structure and its performance objectives. Among different materials of interest, concrete is investigated in this research project.

Under the LWRS Program, several national laboratories and Vanderbilt University have begun to develop a framework of research activities for the health monitoring of NPP concrete structures. A systematic approach to assess and manage aging concrete structures requires an integrated framework that includes the following four elements:

- Damage modeling
- Monitoring
- Data analytics
- Uncertainty quantification.

A workshop was organized during November 5-6, 2014 at Vanderbilt University, with thirty invited participants from academia, government and the industry, to discuss research needs and plans with respect to online monitoring of concrete structures in nuclear power plants. The specific objectives of the workshop were: (1) to survey the current knowledge and ongoing national/international research efforts in concrete damage modeling, damage diagnosis and prognosis, data analytics, and uncertainty quantification techniques; (2) to develop ideas for future research directions; and (3) to explore applications to concrete structures in nuclear power plants. The capabilities of current monitoring techniques for damage diagnosis (detection, localization, and quantification) and capabilities of current modeling techniques for prognosis were addressed, and future research needs and promising directions were discussed.

The presentations and discussions during the workshop identified critical challenges that need to be addressed in future research, in each of the aforementioned four elements. In damage modeling, key challenges relate to interaction between multiple damage mechanisms, connection of modeling to monitoring to facilitate inference, and design and conducting of accelerated aging tests. In monitoring, key challenges relate to the applicability of available NDE techniques to PHM of actual structures, modeling and distinction of signatures of different damage mechanisms, and characterization of the state and activity level of damage. Key challenges in data analytics include fusion of heterogeneous information, handling of large volumes of image data (big data), and sparse information about the structural history and the environment. Key challenges in uncertainty quantification relate to uncertainty in the models, measurements and past history, and developing information to support decision-making under uncertainty. The workshop also identified opportunities for collaboration with other ongoing research efforts around the country with respect to concrete structures health monitoring and modeling.

ACKNOWLEDGMENTS

This report was made possible through funding by the U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program. We are grateful to Richard Reister of the DOE, and Bruce Hallbert and Kathryn McCarthy of the Idaho National Laboratory (INL) for championing this effort. We also thank Charity Hasty and David Koester at Vanderbilt University for administrative and organizational support of the workshop.

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ACRONYMS

AE	Acoustic Emission
ASR	Alkali-Silica Reaction
CBP	Cementitious Barriers Partnership
CNDE	Center of Non-Destructive Evaluation
COSTAR	Concrete Structures Aging Reference
EPRI	Electric Power Research Institute
FW-PHM	Fleet-Wide Prognostics and Health Management
GPR	Ground Penetration Radar
II&C	Instrumentation, Information and Control systems technologies
LEAF	Leaching Environmental Assessment Framework
LWRS	Light Water Reactor Sustainability
MAAD	Materials Aging and Degradation
MOOSE	Multiphysics Object-Oriented Simulation Environment
mTFM	modified Total Focusing Method
NDE	Non-Destructive Evaluation
NIST	National Institute of Standards and Technology
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PHM	Prognostics and Health Management
RISMC	Risk-Informed Safety Margin Characterization
RSG	Resistive Strain Gauges
RUL	Remaining Useful Life
SHM	Structural Health Monitoring
USNRC	United States Nuclear Regulatory Commission

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1. INTRODUCTION

As many existing nuclear power plants (NPPs) continue to operate beyond their license life, plant structures, systems, and components suffer deterioration that affects their structural integrity and performance. Health monitoring is essential technology for insuring that the current and future state of a NPP will meet performance requirements. This project focuses on concrete structures. Concrete structures are present in all NPPs and are grouped into four categories: primary containment, containment internal structures, secondary containment/reactor buildings, and other structures such as used fuel pools, dry storage casks, and cooling towers. These concrete structures are affected by a variety of chemical, physical and mechanical degradation mechanisms such as chloride penetration, sulfate attack, carbonation, alkali-silica reaction, freeze-thaw cycles, shrinkage, irradiation, and mechanical loading. The age-related deterioration of concrete results in continuing microstructural changes (slow hydration, crystallization of amorphous constituents, reactions between cement paste and aggregates, etc.). Such changes must be measured, monitored, and analyzed to best support long-term operation and maintenance decisions.

Vanderbilt University, in collaboration with INL and ORNL personnel, is developing a framework for health diagnosis and prognosis of aging concrete structures in nuclear power plants subject to physical, chemical, and mechanical degradation, by integrating modeling, monitoring, data analytics, and uncertainty quantification techniques. Current knowledge and ongoing national/international research efforts in individual directions are sought to be leveraged and synthesized in order to advance the state of the art in full-field, multi-physics assessment of concrete structures.

The framework for the health monitoring of NPP concrete structures will include four technical elements: (1) Damage modeling, (2) Monitoring, (3) Data analytics, and (4) Uncertainty quantification. The framework will enable plant operators to make risk-informed decisions on the structural integrity, remaining useful life, and performance of concrete structures. The framework will be generalizable to a variety of aging passive components in nuclear power plants.

2. MOTIVATION

Structural health monitoring is required to produce actionable information regarding structural integrity that supports long-term and operational and maintenance decision making. Information is conveyed to the decision-maker in a manner that is suitable for risk management with respect to structural integrity and performance. The methods and technologies employed include the assessment of the critical measurements, monitoring and the analysis of aging. The risk management decisions include sustainment decisions regarding inspection, maintenance and repair, as well as operational decisions regarding the mission demand limits for the system and its operating conditions. In all engineering systems, such decisions are made in the presence of uncertainty that arises from multiple sources. The various types of uncertainty include natural variability (in loads, material properties, structural geometry, and boundary conditions), data uncertainty (e.g., sparse data, imprecise data, missing data, qualitative data, and measurement and processing errors), and model uncertainty (due to approximations and simplifying assumptions made in diagnosis and prognosis models and their computer implementation). An important challenge is to aggregate the uncertainty arising from multiple sources in a manner that provides quantitative information to the decision-maker relative to the future risks for structural integrity and performance, as well as the risk reduction offered by various risk management activities, thus facilitating quantitative risk-informed cost vs. benefit decisions.

The information available in structural health monitoring is quite heterogeneous, with the information amassed from a variety of sources in a variety of formats. These heterogeneous sources include mathematical models, experimental data, operational data, literature data, product reliability databases, and expert opinion. In addition to the specific system being monitored, information may also be available for similar or nominally identical systems in a fleet, as well as legacy systems. Even within the system being monitored, information may be available in different formats (e.g., numerical, text, image). It is also worth noting that information about different quantities may be available at different levels of fidelity and resolution. Information gathered is individualized for a given structure and its performance objectives and compiled into an effective Prognostics and Health Management (PHM) framework. An important challenge in data analytics for PHM is information integration, i.e., fusion of heterogeneous information available from multiple sources and activities.

An effective framework for health diagnosis and prognosis of aging reinforced concrete structures needs to make use of all the available information through damage modeling, monitoring, data analytics, and uncertainty quantification techniques (Mahadevan et al, 2014). The long-term research objective of this project is to produce actionable information regarding structural integrity that supports operational and maintenance decision making, which is individualized for a given structure and its performance goals. The project will support the research objectives of the Material Aging and Degradation Pathway and the Advanced II&C Technologies Pathway under the LWRS Program.

The ongoing research is seeking to develop a probabilistic framework for health diagnosis and prognosis of aging concrete subjected to physical, chemical, environmental, and mechanical degradation, by integrating modeling, monitoring, data analytics, and uncertainty quantification techniques. Current knowledge and ongoing national/international research efforts in individual directions will be leveraged and synthesized in order to advance the state-of-the-art in full field, multi-physics assessment of concrete structures.

In the first year of the project, INL, ORNL and Vanderbilt are reviewing existing non-destructive monitoring techniques and degradation mechanisms. It is observed that alkali-silica reaction (ASR) is currently of interest among the nuclear utilities. Several monitoring techniques are under investigation to identify and monitor ASR degradation in concrete structures.

A workshop was organized during November 5-6, 2014 at Vanderbilt University, with thirty invited participants from academia, government and the industry, to discuss research needs and plans with respect to online monitoring of concrete structures in nuclear power plants. Section 3 provides a report of this workshop.

3. WORKSHOP REPORT

3.1 Workshop goals

The ultimate goal in structural health monitoring is to produce actionable information regarding structural integrity that supports operational and maintenance decision making, which is individualized for a given structure and its performance objectives. A two-day workshop was hosted by Vanderbilt University with thirty invited researchers from the industry, government and academia on health monitoring of concrete structures. An effective health monitoring framework needs to integrate damage modeling, monitoring techniques, and data analytics, and systematically quantify the uncertainties in each step, in order to provide meaningful decision support. Therefore the goal of the workshop was to identify needed advances in concrete structural health monitoring that will facilitate risk management decisions with respect to structural integrity and sustainment. The specific objectives of the workshop were: (1) to survey the current knowledge and ongoing national/international research efforts in concrete damage modeling, damage diagnosis and prognosis, data analytics, and uncertainty quantification techniques; (2) to develop ideas for future research directions; and (3) to explore applications to concrete structures in nuclear power plants. The capabilities of current monitoring techniques for damage diagnosis (detection, localization, and quantification) and current modeling techniques for prognosis were addressed, and future research needs and promising directions were discussed.

The two-day workshop featured six sessions – an opening session to set the context and goals, then four sessions to address the four components of PHM (damage modeling, monitoring, data analytics, and uncertainty quantification), and a final session on the integration of various methodologies. Each session featured 3 or 4 presentations, followed by discussion by all the participants regarding the current state of the art, key challenges and gaps in each domain, and future research needs. The detailed agenda is attached in Appendix A. The following subsections summarize the presentations and discussions in each session and the identified challenges and gaps.

3.2 Session 1. Workshop objectives and challenges

3.2.1 Session Summary

This opening session introduced the approaches and challenges in developing an integrated health monitoring framework for concrete structures in nuclear power plants (NPPs) and set the context for the rest of the workshop. Four components of a health monitoring framework were outlined, namely, damage modeling, monitoring, data analytics and uncertainty quantification.

The goals and scope of the Light Water Reactor Sustainability (LWRS) program, and the need for modern digital II&C technologies were discussed. The development of a roadmap to modernize II&C was discussed, and the development of a probabilistic (Prognosis and Health Monitoring) PHM framework for active and passive NPP structures were discussed. Some common aging concerns regarding NPP concrete structures were introduced.

Current status and future planned upgrades of the Fleet-wide Prognostics and Health Management (FW-PHM) tool suite (EPRI, 2011) were discussed. The FW-PHM suite consists of diagnostic advisor, asset fault signature database, remaining life advisor and remaining useful life (RUL) database. The addition of fault signature master database and RUL master database is planned for release in 2015. The Concrete Structures Aging Reference (COSTAR) (Gregor and Carey, 2001) is a valuable resource in this regard.

Ongoing activities related to concrete in two groups at NRC, one with respect to NPP structures, and the other with respect to nuclear waste, were discussed. Case studies of concrete damage modeling in several hydraulic structures operated by the U.S. Army Corps of Engineers, especially the Center Hill Dam and the Chickamauga Lock (post-tensioned anchors) were surveyed. The discussion included finite element modeling of ASR damage growth rate.

3.2.2 Key Challenges and Gaps

Efforts within the LWRS program have resulted in the development of a PHM framework for active NPP components. The next challenge is in developing a PHM framework for passive components, especially concrete structures. The utilities' engagement in LWRS is an important factor in identifying and overcoming implementation challenges.

Overall challenges and gaps were identified in each of the four elements of a PHM framework, as below:

- A research roadmap is needed for online monitoring until 2025, similar to other research topics (human performance, outage safety/efficiency, integrated operations, automated plan, and hybrid control room). Currently plans are available until 2018 for online monitoring.
- Damage modeling: Modeling of interactions between damage mechanisms is difficult; current state of the art mostly considers individual mechanisms.
- Monitoring: Combination of multiple NDE techniques for concrete PHM needs to be investigated; currently only individual techniques have been investigated.
- Data analytics: PHM implementation for NPP structures, with multiple NDE techniques, will produce large volumes of heterogeneous data; the HADOOP framework needs to be explored to handle big data.
- Uncertainty quantification: Integration of multiple aleatory and epistemic uncertainty sources across multiple physics to quantify the overall uncertainty in PHM results is an important challenge.
- Pilot projects that demonstrate research in plant settings and develop the use of digital technologies are needed. The results need to be made available to the Utility Working Group and the industry, and need to address uncertainty (technical, experience, and regulatory).

3.3 Session 2. Concrete Damage Modeling

3.3.1 Session Summary

Activities at ORNL regarding the modeling of concrete aging and degradation within the Materials Aging and Degradation (MAAD) pathway of the LWRS program were presented. Potential degradation mechanisms, in particular the simulation of irradiation effects (similar to temperature effects) and structural restraining effects on ASR swelling, and the evaluation of structural integrity were discussed. An overview of the Cementitious Barriers Partnership (CBP) project led by Vanderbilt University, supported by DOE and in collaboration with several government and industry partners was presented. The project is developing tools to predict the structural, hydraulic and chemical performance of cementititious barriers used in nuclear waste applications over extended time frames. The project is trying to answer key questions such as: what is the rate of release for radionuclides and contaminants under a range of scenarios, and what is the structure's service life. A CBP toolbox composed using GoldSim, STADIUM and LeachXS/ORCHESTRA, has been developed for thermodynamic modeling of degradation mechanisms such as chloride penetration, sulfate attack, and carbonation. The LEAF (Leaching Environmental Assessment Framework) decision support system for beneficial use and disposal decisions regarding leaching behavior of a wide range of materials and scenarios was presented. The characterization of cementitious materials, and probabilistic analysis of cement grout, considering both deterministic and stochastic parameters, were discussed. Advection and combined tank closure analyses were illustrated using the CBP toolbox.

3.3.2 Key Challenges and Gaps

The presentations and discussions in this session identified the following challenges and gaps in knowledge:

- Advanced modeling is needed to understand the interactions between different damage mechanisms, to isolate the contribution of each mechanism when multiple mechanisms are concurrently active, and to de-convolve different effects (temperature, shrinkage, irradiation).
- Modeling approaches need to be connected to monitoring techniques and data, in order to facilitate damage inference.
- Advances in modeling the feedback connections between mechanical damage and its effect on transport phenomena are needed. Currently available methods are phenomenological, not mechanistic.
- Research is needed on quantitative validation of the damage models and design of validation tests.
- Many uncertainty sources are present in reactive transport modeling (chemical speciation and thermodynamics, presence/evolution/influence of cracks, coupling of changes in mineral phases with damage, and data sets from field and lab studies). It is not clear what a reasonable time-frame for periodic observations is.
- The design of accelerated aging tests, and the connection of acceleration factor to actual damage evolution under different mechanisms needs deeper investigation, considering the complexity of concrete material and the damage mechanisms, and expected time frames for degradation.
- The models need to be connected to important issues related to safety, economics, and conservatism in structural assessment and decision-making.

3.4 Session 3: Monitoring Techniques

3.4.1 Session Summary

This session began with an overview of NDE techniques investigated at ORNL for suitability in NPP concrete structures. In 2012, an LWRS concrete NDE workshop held at ORNL identified four general research and development areas. In 2013, five NDE techniques were examined: shear-wave ultrasound, ground penetrating radar, air-coupled impact echo, air-coupled ultrasonic surface wave and semi-coupled ultrasonic tomography. In FY 2014, two advanced signal processing tools were investigated with a thick test specimen. Two signal processing applications were explained with examples: (1) frequency band extraction using wavelet packet decomposition and reconstruction; and (2) modified total focusing method (mTFM).

Experience with a variety of additional NDE techniques, such as SAFT-B (Synthetic Aperture), frequency banding, harmonic imaging, acoustic emission (AE), ground penetration radar (GPR), Ultrasonic pulse-scho, fiber bragg grating, thermography, and novel smart sensors was discussed.

An NDE method being investigated at the Center of Non-Destructive Evaluation (CNDE) for monitoring concrete meso-structures was discussesd. In NPP structures, immense amount of reinforced steels and complex structures is of concern, and the need for collaboration of NDE and SHM techniques was highlighted.

Wireless monitoring systems were discussed, to overcome the accessibility challenges posed by reinforced concrete structures. Real time or quasi-real time data can be obtained with appropriate data acquisition techniques. The Jindo Bridge was shown as an example of wireless monitoring. Reliability of data aggregation and monitoring system were also discussed.

The use of sensing skin for NDE was introduced. The bio-inspired flexible membrane is inexpensive, easy to install, and robust. Background technology and fabrication process were discussed, as well as potential for application in large-scale monitoring.

3.4.2 Key Challenges and Gaps

Challenges and gaps were identified in the monitoring element of a PHM framework, as below:

- The combination of multiple NDE techniques for effective online monitoring of concrete structures needs to be investigated. Past work has only examined individual techniques.
- Many damage mechanisms have similar signatures (spalling, cracking, delamination, debonding etc.), thus isolating the damage mechanism based on damage signature is challenging. A combination of detecting techniques from different disciplines (chemical, electrical and mechanical) need to be investigated.
- Techniques for in-situ characterization of stress concentrations, and for inferring the activity status of damage.
- Practical implementation of the available NDE techniques to actual NPP structures considering access on the structure for monitoring is a challenge.
- The suitability of FW-PHM for concrete structures needs to be investigated, since the damage evolution time scales in concrete are very long.

3.5 Session 4: Data Analytics

3.5.1 Session Summary

This session began with a review of the fleet-wide prognostics and health management (FW-PHM) suite developed by EPRI for active components in nuclear power plants. Core elements of fault signatures and procedures to collect and store them in the FW-PHM suite were discussed. Data visualization techniques and tools, as well as techniques to handle big data, were introduced. The connections of these techniques to the four elements of PHM (modeling, monitoring, data analytics, and uncertainty quantification) were discussed.

Big data analytics and machine learning methods were discussed at length. The availability of large quantities of image data from different monitoring techniques creates the motivation for big data analytics, considering the large volume and heterogeneity of collected data. Relational, NoSQL, and NewSQL databases were introduced. For big data problems, MapReduce applied with Hadoop is a solution. For machine learning methods, a python package called Scikit-learn was discussed with some classification examples. The use of data-parallel and graph-parallel techniques for big data machine learning was discussed.

3.5.2 Key Challenges and Gaps

The following challenges and gaps were identified with respect to data analytics:

- The type of information available is heterogeneous, when multiple techniques are used. The fusion of heterogeneous information and use in damage diagnosis is challenging.
- Additional information is needed on the concrete material, the operating environment, and the operational history of the structure. Such information is not easily available, thus creating uncertainty in the data analytics and inference.
- Forensic studies of core samples from decommissioned NPPs need to be undertaken in order to understand the operational history, and this data needs to be fused with online monitoring, to aid the inference.
- The large amounts of full-field monitoring data need to organized and managed in an effective manner. The application of recent big data analytic frameworks (e.g., Hadoop) to online monitoring of NPP concrete structures needs to be investigated.

3.6 Session 5: Uncertainty and Risk Quantification

3.6.1 Session Summary

Uncertainty quantification for decision making was reviewed. Various sources of uncertainty (natural variability, data uncertainty and model uncertainty) were discussed. The Bayesian Network approach to integrate heterogeneous information from multiple sources for uncertainty integration and management was explained with several examples. Techniques to quantify model uncertainty (calibration, verification and validation) were explained. The challenges in quantifying extrapolation confidence and in decision making under uncertainty were reviewed.

Probabilistic analysis of cementitious materials under degradation and aging mechanisms was discussed. Three application examples specific to probabilistic evaluation in reactive transport modeling were shown: sulfate attack, percolation with radio diffusion and carbonation. The sulfate attack analysis includes the modeling of diffusion, chemical reaction, and mechanical damage progression. Bayesian calibration was used to quantify the uncertainty in model parameters, and the uncertainty was propagated for probabilistic estimation of durability. Validation and sensitivity analysis of a dual regime model were discussed next. Third, carbonation modeling of concrete in a representative high-level waste tank was introduced, and augmented with probabilistic analysis. The use of Goldsim to integrate various models within the Cementitious Barriers Partnership (CBP) software toolbox and perform probabilistic performance analysis was reviewed.

Risk-Informed Safety Margin Characterization (RISMC), one of the pathways in the LWRS program, was discussed. The goal of RISMC is to integrate information generated from the other pathways to estimate risk and inform decision making. It provides a technical approach to understand and manage decision margins. Using RISMC, the analyst can obtain enhanced decisions, integrated assessment, realistic evaluation of uncertainties, and identify cliff edge effects. The RISMC toolkit brings together probabilistic and mechanistic modeling. An application example was shown and future plans were discussed.

3.6.2 Key Challenges and Gaps

The following challenges and gaps were identified with respect to uncertainty and risk quantification:

- The characterization of material properties and constituents is affected by several uncertainty sources, including measurement error, material complexity and inhomogeneity, and mineral diversity.
- The modeling of damage mechanisms is affected by both model form uncertainty and solution approximation errors.
- Model parameters have significant uncertainty due to the availability of limited data.
- The data on past history is sparse, creating a large source of uncertainty in the inference of past history and therefore damage diagnosis and prognosis.
- The quantification of overall uncertainty in diagnosis and prognosis in the presence of the above uncertainty sources needs to be investigated.
- The integration of multiple sources of aleatory and epistemic uncertainty sources, and quantification of their individual contributions to the overall diagnosis and prognosis uncertainty, need to be investigated.
- The uncertainty quantification results need to be connected to risk management and decision-making under uncertainty.

3.7 Session 6: Integration of PHM Elements

3.7.1 Session Summary

This was a discussion session by all participants, synthesizing the insights gained in the previous sessions. The exploration of possible collaboration with the USNRC-NIST ASR project was suggested. This is a three-year project with three proposed tasks: construction of test beams with and without ASR, investigation of bond strength in anchors, investigation of beam behavior under loading. Leveraging the knowledge gained from tests at University of Texas at Austin was suggested.
The results of the four-component PHM framework need to be connected to the characterization of the risk margins in the RISMC pathway.
For empirical tests, a formal methodology needs to be developed for collecting core samples to validate models. The availability of core samples from the U.S. Army Corps of Engineers, and from DOE sites should be explored, in order to learn about the transport properties of concrete and the capabilities of the NDE techniques.

Local materials and suppliers affect concrete properties and damage evolution. Therefore the PHM framework needs a systematic approach to account for these factors.

The integrated PHM framework needs to consider the coupling of mechanisms (e.g., coupling of ASR expansion and moisture shrinkage). The knowledge being gained through ongoing efforts by other researchers need to be leveraged. For example, ongoing experiments and modeling of nano-concrete for dry casks being studied at Vanderbilt could be leveraged.

NDE techniques are limited by how deep they can detect damage. Some techniques only provide surface characterization. Ultrasonic techniques can detect damage up to 24 inches, but are very localized. Multiple techniques should be integrated in a manner that could progressively narrow the area of investigation before applying highly localized techniques.

Online implementation issues and challenges should be considered while developing the PHM framework.

4. CONCLUSION AND FUTURE PLANS

A two-day workshop was organized at Vanderbilt University during November 5-6, 2014, in order to survey the state of the art and outline research directions for concrete structures prognostics and health management (PHM). The workshop was attended by thirty invited participants from the industry, government and academia, and featured focused presentations and engaged discussions related to research progress and needs for the PHM of concrete structures in nuclear power plants (NPPs). Synergistic activities undertaken by other organizations were also identified.

The next activity in this project is to develop a pilot problem in order to demonstrate the integration of the four components of the PHM framework (namely, modeling, monitoring, data analytics and uncertainty quantification). Concrete slabs with and without damage will be modeled using recently developed modeling techniques, and several types of monitoring techniques (e.g., digital image correlation, infra-red thermal imaging, and ultrasonics) will be investigated and combined for effective reference. The Hadoop® framework and image processing techniques will be investigated for data analytics. A Bayesian network approach will be investigated for uncertainty quantification and fusion of heterogeneous information. Details and results of the pilot problem will be provided in the next milestone report.

In the short term (next 90 days), the following activities will be pursued:

1. Detailed investigation of the pilot problem
2. Investigation of the MOOSE framework to implement damage modeling that supports online monitoring and damage inference.
3. Pursuit of synergy with other ongoing activities related to concrete deterioration modeling and health monitoring (e.g., ORNL, EPRI, NRC, NIST)

In the longer term (for the duration of the project), this research will investigate monitoring of chemical-mechanical coupled degradation in concrete via full-field imaging techniques (thermal, optical, and vibratory) and acoustic measurements. Possible full-field techniques include infrared imaging, digital image correlation, and velocimetry. Effective combinations of full-field techniques need to be identified for different types of concrete structures. Dynamic operating conditions (cycle loading, pressure variations, humidity, etc.) may lead to coupled chemical-mechanical degradation such as alkali-silica, reaction, fracture, corrosion, and internal swelling. The forward analysis of the evolution of concrete degradation is a challenging task in itself, which requires the combination of reactive transport modeling with mechanical degradation models. The inverse problem of damage inference in the presence of multiple damage mechanisms is even more challenging, and requires development of damage signatures that have to be effectively connected to monitoring data.

Overall, this research focuses on data analysis and development of uncertainty-quantified diagnostic and prognostics models that will support continuous assessment of concrete performance. The resulting comprehensive approach will facilitate the development of a quantitative, risk-informed framework that would be generalizable for a variety of concrete structures and can be adapted for other passive structures.

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Appendix A

Workshop Agenda

Wednesday, November 5

7:30 a.m. - 8:00 a.m. Registration, Breakfast

8:00 a.m. - 9:10 a.m. Session 1: Workshop Objectives and Challenges

- Sankaran Mahadevan, Vanderbilt University
- Bruce Hallbert, INL
- Richard Rusaw, EPRI
- Britt Henderson, U.S. Army Corps of Engineers

9:10 a.m. – 9:30 a.m. Break

9:30 a.m.- 11:30 a.m. Session 2: Concrete Damage Modeling (Chair: David Kosson)

- David Kosson, Vanderbilt University
- Jeremy Busby, ORNL
- Kevin Brown, Vanderbilt University
- Group discussion (60 min)

11:30 p.m. - 1:00 p.m. Lunch (LASIR Lab Tour, Douglas Adams, Vanderbilt University)

1:00 a.m.-3:30 p.m. Session 3: Monitoring Techniques (Chair: Dwight Clayton)

- Dwight Clayton, ORNL
- Paul Ziehl, University of South Carolina
- David Eisenmann, Iowa State University
- Simon Laflamme, Iowa State University
- Lauren Linderman, University of Minnesota
- Group discussion (60 min)

3:30 pm – 3:45 pm Break

3:45 pm – 5:30 pm Session 4: Data Analytics (Chair: Vivek Agarwal, INL)

- Daniel Fabbri, Vanderbilt University
- Vivek Agarwal, INL

- Group discussion (60 min)

Thursday, November 6

7:30 a.m. – 8:00 a.m. Breakfast

8:00 a.m. – 10:00 a.m. Session 5: Uncertainty and Risk Quantification (Chair: Sankaran Mahadevan)

- Sankaran Mahadevan, Vanderbilt
- Kevin Brown, Vanderbilt
- Curtis Smith, INL
- Group discussion (60 min)

10:00 a.m. – 10:15 a.m. Break

10:15 a.m. – 11:45 p.m. Session 6: Integration of Modeling, Monitoring, Data Analytics, and Uncertainty/Risk Quantification (Chair: Bruce Hallbert)

- Group discussion (90 min)

11:45 p.m. - 12:00 noon Wrap-up and Adjourn

Appendix B

List of Workshop Participants

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