LWRS
LIGHT WATER REACTOR SUSTAINABILITY

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Stakeholder Engagement Review Meeting

The U.S. Department of Energy (DOE)-sponsored Light Water Reactor Sustainability (LWRS) Program Stakeholder Engagement Review Meeting was held on January 17 and 18, 2019, in Rockville, Maryland. The purpose of the meeting was to provide information on the accomplishments and plans of the LWRS Program and obtain input from stakeholders on priorities in order to identify needs for future research and development

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Panelists: (from left to right) Brad Adams, Robert Coward, Paul Harden, and Scot Greenlee. Moderator: Jack Cadogan

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U.S. DEPARTMENT OF ENERGY

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(R&D) activities. More than 130 individuals from over 41 organizations were represented at the meeting, including representatives from the U.S. commercial nuclear power industry, vendors and suppliers, regulators, and research organizations.

Shane Johnson, Deputy Assistant Secretary for Reactor Fleet and Advanced Reactor Deployment, Office of Nuclear Energy, Department of Energy, welcomed meeting participants. He was followed by an Industry Overview and Direction presentation given by Tim O'Connor, Senior Vice President and Chief Nuclear Officer, Xcel Energy. Tim provided compelling remarks on reinventing and repurposing nuclear plants to ensure their competitiveness as the key to their long-term sustainability. He presented a roadmap for transformation that is tied to Xcel's plans for its nuclear fleet going forward.

Bruce Hallbert, LWRS Program Technical Integration Office Director, described the LWRS Program accomplishments and plans. Kate Jackson, formerly Westinghouse, Chief Technology Officer, Senior Vice President, now Director, Energy and Technology Consulting at Key Source, reported on the results of a recent LWRS Program external review.

A panel discussion entitled, "Industry Challenges and Perspectives for Long-Term Operation," was then moderated by Jack Cadogan, Senior Vice President of Site Operations, Arizona Public Services, Palo Verde Generating Station. The panel consisted of the following leaders in nuclear energy:

- Scot Greenlee, Senior Vice President, Engineering and Technical Support at Exelon Nuclear
- Paul Harden, Senior Vice President/Chief Operating Officer at FirstEnergy Nuclear Operating Company
- Brad Adams, Vice President Engineering at Southern Nuclear
- Robert Coward, Principal Officer at MPR Associates.

The panelists shared their perspectives on industry challenges for the long-term operation of the existing nuclear fleet. Panelists noted that the best outcomes for industry from the LWRS Program's R&D are: (1) digitization of the entire plant; (2) risk-informed approaches that have been accepted by the U.S. Nuclear Regulatory Commission (NRC) and the Institute of Nuclear Power Operations (INPO); (3) continued long-term R&D, such as in the areas of Materials, as well as executing near-term results; and (4) research in the areas of physical and cybersecurity.

After the panel discussion, Doug True, Senior Vice President and Chief Nuclear Officer of the Nuclear Energy Institute, gave a presentation regarding the current Industry Initiatives to Sustain the Existing LWR Fleet. Doug's presentation highlighted the value of nuclear energy and some recent performance achievements of the industry. He described NEI's targeted outcomes to achieve meaningful cost reductions and described a call to action in the near term to ensure the viability of the existing nuclear fleet.

During the afternoon, attendees met in parallel sessions that were conducted to address the gaps and

Bruce Hallbert, Alison Hahn, Heather Feldman (EPRI), and Jack Cadogan.

opportunities for LWRS R&D to enable improved plant performance and address industry needs in the following areas:

- Plant Modernization, Craig Primer, Plant Modernization Pathway Lead
- Materials Research, Keith Leonard, Materials Research Pathway Lead
- Risk-Informed Systems Analysis, Curtis Smith, RISA Pathway Lead
- Integrated Energy Systems, Richard Boardman, Research Lead
- Physical Security, Mitch McCrory, Research Lead.

Meeting participants highlighted the needs, opportunities, and provided fresh perspectives on needed timeframes for results that are needed to have the type of impacts required to sustain and achieve improved performance by the existing U.S. fleet.

Raymond Fursteneau, NRC Director of Nuclear Regulatory Research, gave a presentation during the meeting. In summary, he noted that the NRC will continue to: (1) collaborate with DOE and the Electric Power Research Institute (EPRI) on aging management research to reduce regulatory uncertainty; (2) build on the successful cooperation that has established the technical basis for long-term operation of nuclear power plants; and (3) conduct regulatory research supporting operational safety to support the revision of aging management guidance and associated aging management plans.

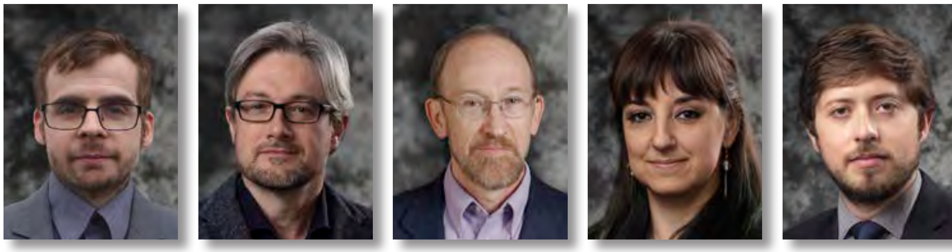
In the closing comments, Brad Adams, Vice President Engineering, Southern Nuclear, noted that the nation's nuclear plants are valuable national assets and encouraged those of us in the industry to believe in what we do and be proud of it. He provided a positive outlook on the construction progress of Vogtle Units 3 and 4 and optimism of their future operation, shared his perspectives that current plants will bridge to next generation plants, and that we will get next generation plants with advanced designs built and get them operating in the future. He said that some in the industry may be skeptical of those plans, but that we should maintain a positive attitude because attitude makes a difference.

Alison Hahn, Federal Program Manager, Department of Energy, thanked the meeting participants for providing valuable information and contributions during the presentations and parallel sessions. The meeting and discussions emphasized opportunities to increase LWRS Program engagement with the U.S. commercial nuclear power industry, vendors and suppliers, research organizations, and the regulator focusing on issues of sustainability, safety, and enhanced economic performance of the light water reactor industry.

The presentations from the conference can be downloaded at the following link: (https://lwrs.inl.gov/Meetings/2019 Meetings/01-17 Stakeholder Engagement/Presentations). A meeting summary report is being prepared and will be posted on the LWRS Program website at Technical Integration Office Reports.

Ray Fursteneau, Director of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission

Simulating the Effects of Neutron Irradiation on Concrete with the MOSAIC Software



Alain B. Giorla, Yann Le Pape, Thomas M. Rosseel, Elena Tajuelo Rodriguez, and Jose D. Arregui-Mena
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In nuclear power plants, the concrete biological shield is used to contain neutron and gamma radiation emitted by the reactor. Depending on the design and operating condition, the inner surface of the concrete biological shield may be exposed to high fluences. Within the framework of aging management and subsequent license renewal of U.S. nuclear power plants, it becomes critical to understand the effects of irradiation on the concrete and other materials over extended periods of operation.

The primary degradation mechanism in irradiated concrete is radiation-induced volumetric expansion (RIVE). It is caused by the amorphization of certain mineral phases contained in concrete aggregates (e.g., sand, crushed rocks, gravels). These mineral phases expand during the amorphization process, while the cement paste that binds the aggregates together remains mostly unaffected by the irradiation. This causes the concrete to swell and opens micro-cracks due to differential strains between the different mineral phases and the cement paste. Experimentally, this is measured as an increase in dimension and a loss of mechanical properties, such as Young's modulus, and tensile or compressive strength.

The effects of neutron radiation vary significantly from one concrete to another resulting in unusually large scatter of experimental data on irradiated concrete. This is caused by the fact that different minerals have a different susceptibility to neutron irradiation. Generally, quartz and silicate-bearing minerals swell much more than limestone and carbonate-bearing minerals, while some vitreous minerals, such as opal, may even shrink instead of swell.

This indicates that radiation susceptibility of a given concrete depends on the mineral composition of the rocks used as aggregates, which is typically not reported at the time of construction. For this reason, the Materials Research Pathway is developing the Microstructure-Oriented Scientific Analysis of Irradiated Concrete (MOSAIC) software. MOSAIC is a tool to assess the susceptibility to neutron irradiation of concrete based on an analysis of an actual concrete specimen (e.g., a core from a concrete structure).

The first step in the analysis is determining the microstructure and mineral composition of the specimen. This requires two experimental characterization techniques: micro-X-ray fluorescence (XRF) and two-modulator generalized ellipsometry microscopy (2MGEM). Micro-XRF provides a map of the chemical composition across the specimen surface, while 2MGEM provides a map of the optical properties of the surface. Both techniques require the same simple specimen preparation and can thus be combined to identify the minerals present in the specimen. Notably, the optical information is used to distinguish between minerals that have the same chemical composition (such as quartz and opal) but different crystal structures (and thus, different irradiation susceptibility). By using appropriate thresholds on the chemical composition, the cement paste and porosity can also be identified in the specimen.

The second step in the analysis is to perform a numerical simulation on the microstructure obtained above. Since the data from the micro-XRF and 2MGEM is presented on regular grids, the Fast Fourier Transform (FFT) method is ideal to compute the mechanical response of the material. The mechanical behavior of concrete under irradiation is controlled by the following three factors:

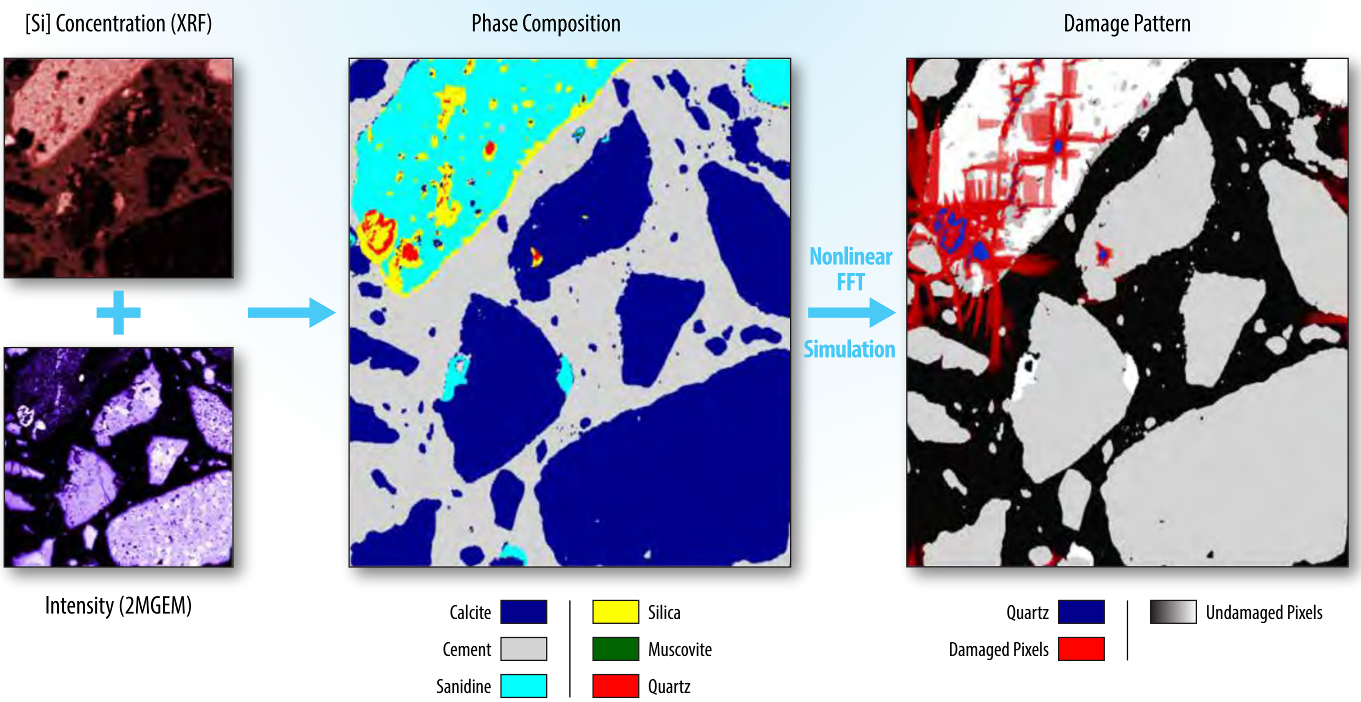
- The RIVE of the minerals present in the concrete. MOSAIC uses the Irradiated Minerals, Aggregates, and Concrete (IMAC) database, which contains a large collection of experimental results from the literature and uses these results to calibrate theoretical models for the RIVE of each mineral as a function of the neutron fluence and temperature.
- The brittle behavior of both the minerals and the cement paste. MOSAIC uses a sequential nonlinear solver to compute the spread of damage in the microstructure. The damage algorithm is nonlocal to limit spurious oscillations arising from the FFT calculations and reduce the sensitivity of the method to the spatial discretization.
- The viscoelastic behavior of the cement paste. This is critical to assess the long-term performance of irradiated concrete as creep can delay the onset of damage caused by irradiation. In MOSAIC, this is accounted for using a finite difference scheme, which is automatically combined with the sequential nonlinear solver to resolve the coupled creep-damage-expansion problem.

The numerical specimen can be subject to various boundary conditions in terms of macroscopic strain or stress, temperature, and fluence, thus allowing for the simulation of either experimental conditions, or conditions representative of long-term operations, including mechanical restraints induced by the unirradiated section of the biological shield.

This two-step process is illustrated in Figure 1, in which the micro-XRF and 2MGEM maps are combined to identify the cement paste and minerals in a concrete specimen, after which an irradiation simulation is carried out under free mechanical boundary conditions (corresponding to an accelerated experiment in a test reactor).

With this tool, concrete specimens extracted from nuclear power plants could be analyzed to estimate their susceptibility to neutron irradiation in conditions that are representative of the long-term operations of the reactor.

Figure 1: MOSAIC flowchart. The micro-XRF and 2MGEM images of the same specimen (left) are analyzed to obtain the phase composition (middle), which is then used as an input for the nonlinear FFT solver that computes the strain, stress, and damage in the microstructure (right).



Risk and Cost Analysis of Utilizing FLEX Equipment for Efficient Maintenance in Nuclear Power Plants

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This article describes an innovative framework of reducing operation and maintenance (O&M) costs at nuclear power plants by utilizing the onsite FLEX equipment. FLEX strategies were postulated by the U.S. NRC in the wake of the Fukushima Daiichi accident to address beyond-design-basis accidents and improve plant flexibility. Onsite FLEX includes equipment such as portable pumps, generators, batteries, compressors, and other supporting equipment or tools stored in a dedicated and secure building designed to withstand external hazards. In the past few years, many nuclear power plants have invested in procuring and maintaining onsite FLEX assets that are unused for most of the time. Recently there have been active efforts to develop strategies through which nuclear power plants can take credit for this FLEX equipment. The LWRS program is conducting research on identifying areas where FLEX equipment can be utilized during normal plant operation and develop a framework that would aide in the reduction of O&M costs without impacting plant safety. The research explores two areas that have the potential to utilize portable FLEX equipment: (1) technical specification-required shutdown due to component failure; and (2) scheduled maintenance during a refueling outage.

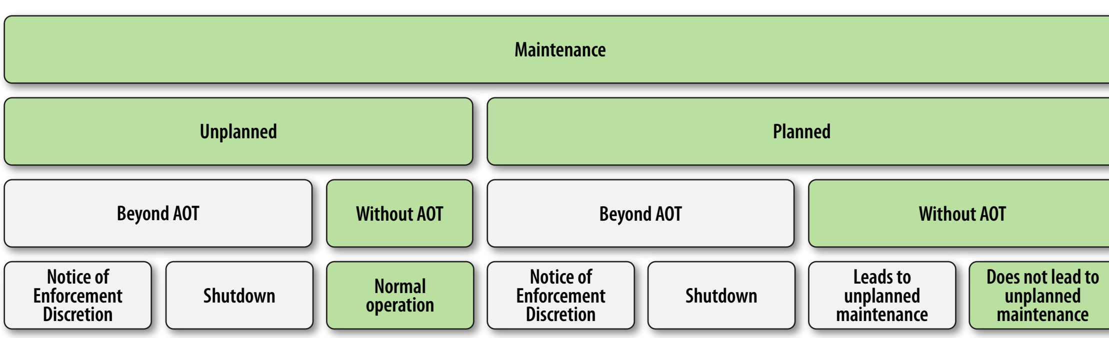
A risk- and cost-analysis framework has been developed for technical specification-required shutdowns due to component failure. The NRC's licensee event report (LER) database shows that commercial nuclear power plants in the U.S. reported 86 technical specification required shutdowns since 2010. When a component failure or unavailability leads to a technical specification-required shutdown, the nuclear power plants have additional costs, both direct costs in terms of revenue loss arising from the loss of generation and indirect costs in the form of reporting and inspection performed by the NRC.

The ongoing research has developed the following five-step framework to utilize FLEX equipment when a component failure could potentially lead to a technical specification-required shutdown.

Step 1. Identify the components, the failure or unavailability of which would result in a 10 CFR 50.73(a)(2)(i)A-reportability requirement, postulated by the NRC for technical specification-required shutdown to be reported in NRC's LER database.

Step 2. Identify the FLEX equipment that may be utilized as a standby to the failed component.

Figure 2. Possible maintenance scenarios.



Step 3. Develop a model that incorporates the FLEX equipment in an existing plant Probabilistic Risk Assessment (PRA) model.

Step 4. Perform calculations using the FLEX equipment model and the plant-specific PRA to study change in core damage frequency and change in risk-informed allowable outage time.

Step 5. Perform a cost-benefit analysis to determine the economic feasibility of implementing the FLEX equipment in the suggested manner.

Figure 2 shows the possible scenarios that may occur during maintenance activities [1]. Maintenance may be planned or unplanned due to unpredicted faults discovered during routine testing or online monitoring. Both scenarios may require a completion time exceeding allowable outage time (AOT). When this happens, licensees either file a notice of enforcement discretion to the NRC or shut down the plant. Both options incur costs or a loss of revenue. These O&M costs may be averted by extending AOT using FLEX equipment. Furthermore, the extended AOT may permit maintenance activities to be conducted thoroughly, with better resulting quality. Figure 3 illustrates the AOT extension framework when a component failure increases the plant's Core Damage Frequency (CDF) from CDF1 to CDF2. Taking credit of FLEX equipment reduces the CDF to CDF3 while also enabling extension in AOT.

An example of a cost analysis employs the premise that using FLEX equipment can maintain or reduce CDF such that an NRC inspection is avoided. This is based on recent NRC estimates that the hourly cost of a staff professional to conduct an inspection or conduct testing at a nuclear power plant facility is $275/hour [2]. Given the inspection event possibilities [3], inspection costs could range from a low of $36,000 per event to $667,000. In July 2018, the Energy Information Administration reports the average retail sales price of electricity across all user types was ¢11.02/kWh [4]. This equates to $110.2/MWh. Suppose a nuclear power plant is shut down for a 24-hour period. The amount of the opportunity cost and the foregone revenue depends on the size of the facility. At this rate, in terms of $/MWh, a plant with a capacity of 800 MWe loses $2.1 million per day. For a plant that is 1,000 MWe, it rises to $2.6 million per day and reaches $3.7 million per day for a plant that is 1,400 MWe. Adding the opportunity cost to the direct cost results in significant cost savings that might be avoided through the implementation of FLEX equipment to avoid technical specification-required shutdown.

This ongoing research is currently in Step 3 of incorporating a portable FLEX pump in the plant PRA model in a candidate system PRA model of a participating U.S. utility. The modeling efforts of Step 3 and the calculations of change in CDF (Step 4) are expected to be completed in May 2019. The comprehensive cost-benefit analysis and the economic feasibility study (Step 5) is expected to be completed in July 2019. Implementing the framework developed in this work would enable commercial nuclear power plants to reduce the economic impact of component failures, avoid unscheduled plant shut downs, perform efficient maintenance, and maximize generation.

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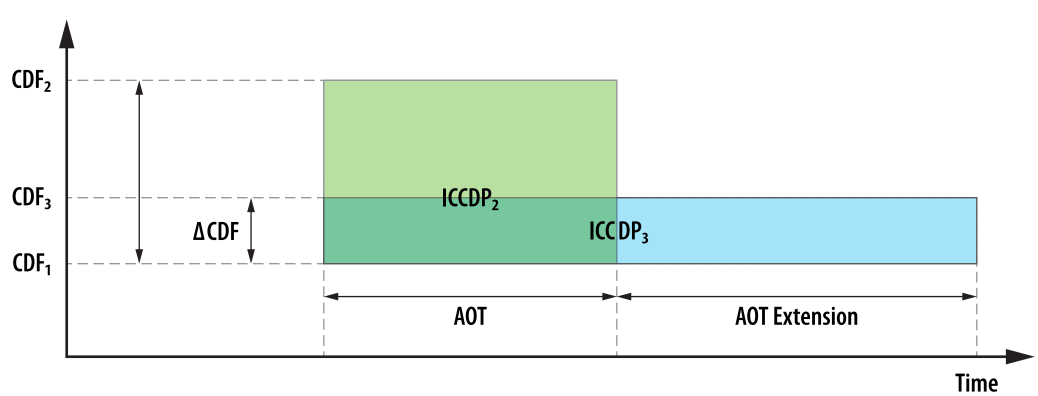
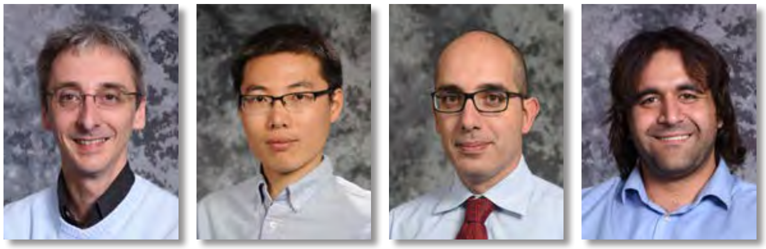
Figure 3. AOT extension in compliance with allowed risk acceptance guideline.



Integration of Classical PRA models into Dynamic PRA



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Risk-Informed Systems Analysis Pathway

Since the 1970s, the U.S. nuclear industry and the U.S. NRC have developed probabilistic risk assessment (PRA) models to evaluate the safety risk associated with nuclear power plants. These PRA models, termed "Classical PRA," are based on two classes of models: Fault-Trees (FTs) and Event-Trees (ETs). FTs are used to determine under which condition a plant system (e.g., low pressure injection system) can fail provided the status of its components (e.g., pumps and valves) through a series of logic gates (e.g., AND, OR). ETs are instead used to model accident progression provided the status of the plant systems for a specific initiating event (e.g., transient, loss-of-offsite power, loss-of-coolant-accident) using a tree structure. Traditionally, two outcomes are possible for each ET sequence: OK (i.e., reactor in a safe and stable state) or core damage.

Dynamic PRA models have been under development since the early 1990s as an evolution from Classical PRA models. Instead of employing ETs and FTs, they are based on two items: (1) a set of system simulator(s) to represent plant physical phenomena; and (2) a stochastic code to represent probabilistic variation found within off-normal scenarios. The stochastic codes are used to determine timing and sequencing of events that are either stochastically (through a Monte-Carlo sampling algorithm) or deterministically (because of something occurring in a scenario). System simulators are used to model accident progression provided the timing and sequencing of events generated by the stochastic results.

The Risk-Informed Systems Analysis (RISA) Pathway has developed methods to integrate important portions of Classical PRA models into a Dynamic PRA, thus creating a "hybrid" PRA. We have shown how this integration can be performed within the open source Risk Analysis Virtual ENvironment (RAVEN) statistical software that has been created by LWRS Program researchers. As part of this research, we developed unique capabilities including:

1. Implementing the ability to import Classical PRA models (e.g., ETs and FTs) into RAVEN.
2. Integrating the imported Classical PRA models to a system simulation code approach.
3. Comparing Classical and Dynamic PRA quantitative results for comparison and validation purposes.

Capability 1 allows RAVEN to read ET and FT structures from files in the OpenPSA format (a widely used format in the nuclear industry) and creates a RAVEN model that mimics such structures. In addition, RAVEN can import two other common Classical PRA models: Markov models and Reliability Block Diagrams (RBDs). In Dynamic PRA, time is explicitly considered in the analysis while Classical PRA is based on Boolean logic, not time. This implies that a Dynamic PRA considers not only if something has failed or not, but also when it fails.

Capability 2 uses RAVEN to identify input/output connections between different Classical PRA models in order to properly run these models. Note that proper execution of all the connected models is important because a model may be dependent on one of the outcomes of a previously executed model (e.g., an ET may depend on a FT).

Capability 3 creates a data-mining post-processor in RAVEN that can be used to match the ET or FT output to the data generated by a Dynamic PRA. This data classifier associates a label to each simulation generated by the Dynamic PRA – this label is created by understanding what systems have failed or are successful as a part of the simulation.

Representative Test Case

In order to test the methods proposed here, several simple analytical test cases based on classical reliability configurations were generated. For all these simple cases, the results matched the predicted analytical results. In addition, a more thorough benchmark testing was developed between our approach (using RAVEN/RELAP5-3D) and the Classical PRA approach. The more relevant test case was for a large break loss-of-coolant accident (LB-LOCA) where depressurization of the reactor occurs very quickly (due to the large break) and a large amount of water inventory is lost. In this situation, several systems are called upon to respond to the LOCA, including the accumulator (ACC), the low-pressure injection (LPI), and the low pressure recirculation (LPR) system.

The overall LB-LOCA model (see the right portion of Figure 3) was created by: (1) importing the three FTs into RAVEN; (2) developing the RELAP5-3D models for LB-LOCA cases (4", 8", 10", and double guillotine break); and (3) creating a RAVEN model that links the three FT models to the RELAP5-3D model. Then, 10,000 simulation runs were generated using RAVEN/RELAP5-3D on high-performance computing system. The scope of this exercise is not only to show how FTs can be effectively linked to a simulation run, but also to perform a comparison between the outcome prediction of the ET sequences and the set of RELAP5-3D simulation runs as shown in Figure 3. This comparison was performed by associating each transient simulated by RELAP5-3D to a specific branch of the ET.

From Figure 4, Classical and Dynamic PRA results match for Branches 1 through 3 while the simulations contained in Branch 4 saw outcomes that resulted in OK part of the time and core damage part of the time. This inconsistency was observed for all four LB-LOCA cases (6", 8", 10", and 2A), which implied that the classical PRA model was, in this case, conservative. The successful outcome of this research has shown how to take the investment in classical PRA models and integrate them into Dynamic PRA in order to reduce conservatisms found in the traditional models. Further, by integrating the Classical PRA models using RAVEN, we can bring in a large body of engineering knowledge found in those models (e.g., how systems operate under off-normal conditions) into our risk analysis approaches.

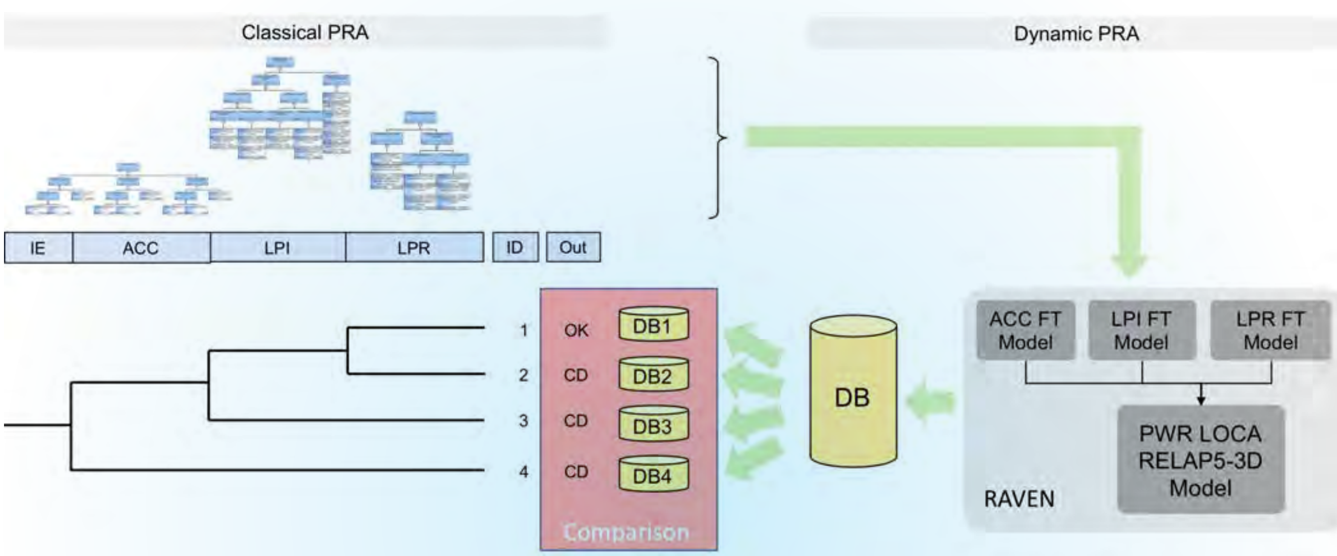

Figure 3. Scheme of the Classical and Dynamic PRA integration for the LB-LOCA test case.

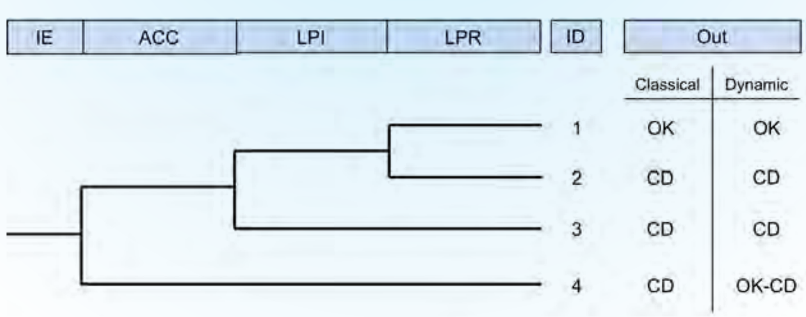

Figure 4. Comparison of Classical and Dynamic PRA results.

Toward a Predictive Model for Cabling Failure: An interdisciplinary, collaborative effort between the University of Minnesota–Duluth and the Materials Research Pathway

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Medium- and low-voltage cables are used in nuclear power plants to deliver power to pumps and to control and power a variety of equipment. In many instances, the cables are unpowered and turned on only in backup/emergency scenarios. Having confidence that these power cables will operate when called upon is necessary for many applications, especially if they serve a safety function. The power cables are exposed to conditions that are known to degrade power cables, such as water immersion, cleaning chemicals, high temperatures, and other damaging stressors common to an industrial environment. Cable failures (see Figure 5) in submerged environments has been a growing problem, with an increasing number of reported failures for medium-voltage cables that have failed in the 20 to 40-year operational range [1].

A research team led by the University of Minnesota–Duluth (UMD), partnered with the LWRS Program, are in the second year of a three-year project supported by a U.S. Department of Energy (DOE) Nuclear Energy University Program (NEUP). The goal of the collaborative effort is to develop a mechanistic understanding of the degradation process to confidently predict functional properties and safety margins for dielectric breakdown in submerged

Figure 5. Water-related catastrophic failure of a power cable is important safety concern in various locations and applications for utilities (http://mydocs.epri.com/docs/PublicMeetingMaterials/1202/epri/05.pdf).

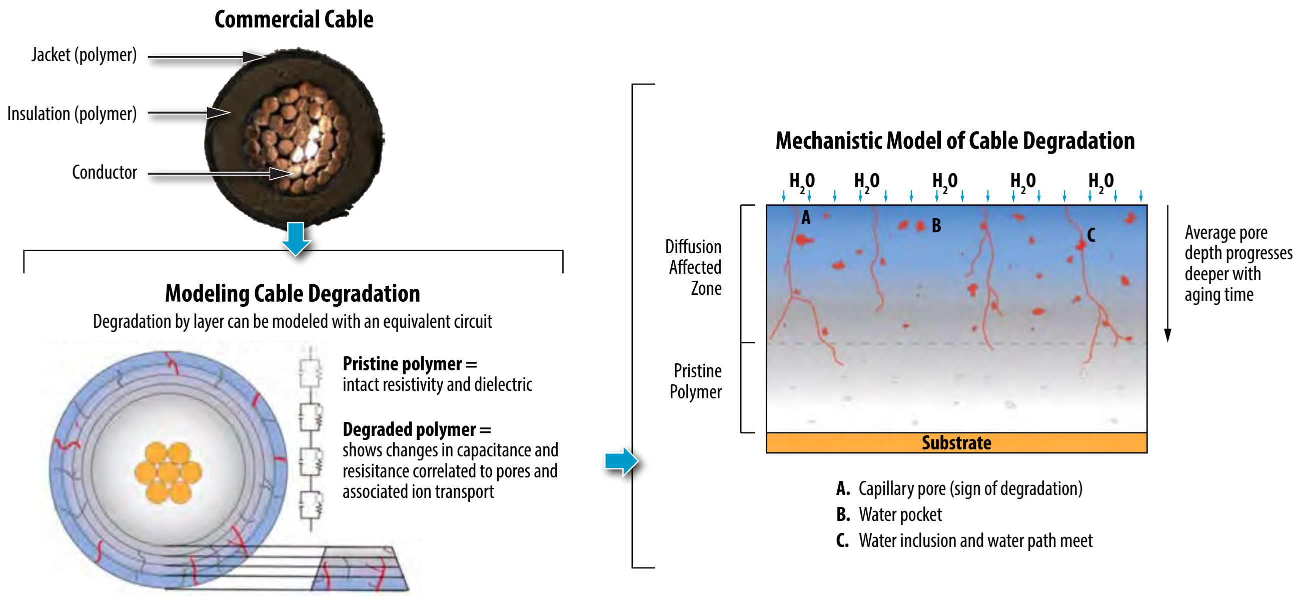

Figure 6. Mechanistic model to describe the degradation of the cables by water intrusion.

cables over extended nuclear power plant operational lifetimes. The research will result in an analytical, predictive aging model (see Figure 6) developed to estimate the accelerated rate of degradation of nuclear power plant electrical cables under various environmental stress conditions that include: temperature, cyclic aqueous immersion exposure, and oxygen concentration. As an example of recent work, electrochemical impedance spectroscopy was used to evaluate pore advancement, one mechanism leading to failures, into the cable insulation at various temperatures and with various electrolytes that are used to predict the time-to-failure at service environment temperature. Charged gold nanoparticle-based imaging methods are being used to help image the water pore structures of the degraded polymer samples.

This NEUP project has involved researchers and graduate and undergraduate students from three different departments at UMD and has offered a significant opportunity for student participation, through directly supported activities or providing a project opportunity through volunteering, the University of Minnesota Undergraduate Research Experience Program, graduate teaching assistantships, and as a project for a Senior Capstone Project. Furthermore, students from UMD have traveled to Oak Ridge National Laboratory during summer sessions, as shown in Figure 7, giving an opportunity to be involved in research at a national laboratory.

The mechanistic model of cable degradation rates in various locations in the nuclear power plant will help nuclear utilities make better informed decision on when expensive electrical cable replacements are needed. The value of this work also extends beyond the nuclear industry, as buried power cables from windmills have been found to be subjected to aqueous environments in underground conduits and fail in a similar fashion.

Figure 7. Tana O'Keefe (left) and Tayler Hebner (right) during their appointments at Oak Ridge National Laboratory in summer 2017.

Compact Digital Modernization – Enabling Nuclear Power Plant Operations and Maintenance Cost Benefits

Kenneth D. Thomas
Plant Modernization Pathway

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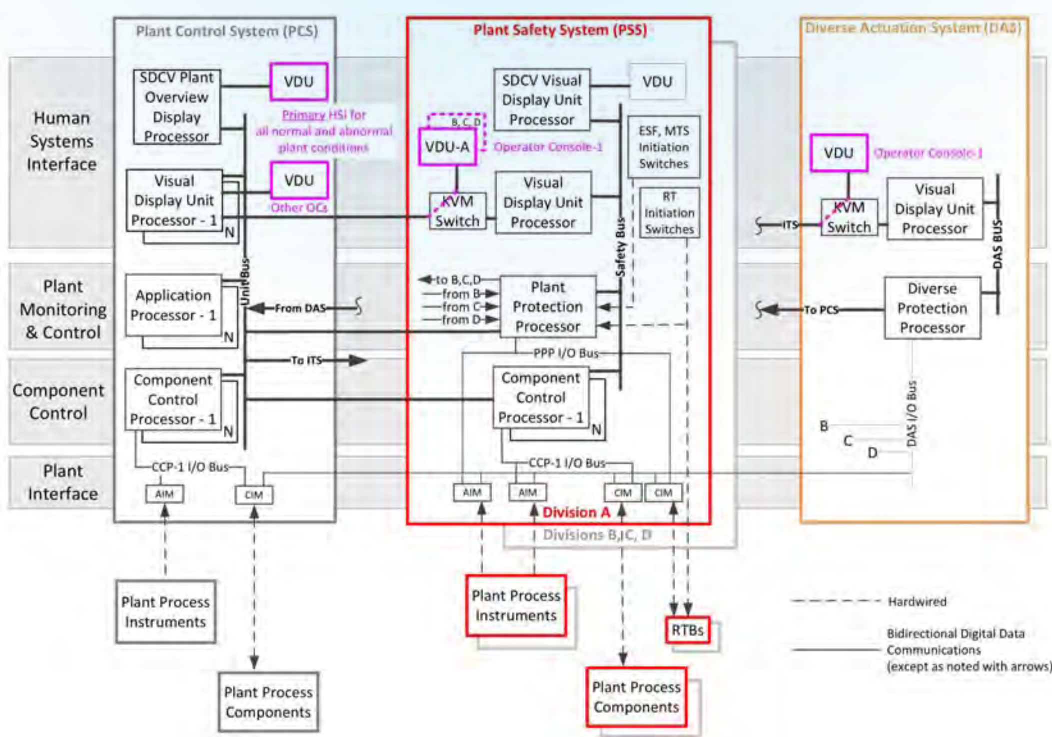
Nuclear operating companies are challenged with growing obsolescence concerns with their legacy instrumentation and control (I&C) systems. They have not been able to overcome the technical, regulatory, and business case barriers to enable wide-scale modernization of these systems. Moreover, there has not been a viable cost-effective migration path to take the current fragmented array of I&C systems of today's nuclear power plants, along with the conventional control rooms based on hundreds of discrete analog devices, to a modern digital architecture and control room. There is an urgent need to address these current operational issues and, at the same time, transform these systems to enable the types of business efficiencies that all other energy and industrial sectors are achieving with modern digital technology.

The Plant Modernization Pathway is conducting research on an optimal digital I&C system and control room architecture, which is termed "compact control room digital modernization" or CDM. This highly integrated I&C configuration minimizes the quantity of I&C equipment, and maximizes the use of modern self-tested digital data processing, communication and video human systems interfaces (HSI), to achieve an efficient I&C architecture that provides substantial performance and cost-reduction benefits.

With the CDM, the complexity of the current I&C systems is reduced to just three systems with two diverse digital platforms: (1) the plant control system; (2) the plant safety system; and (3) the diverse actuation system, as shown in Figure 8. Each of these systems encompasses HSI, plant and system level monitoring and control, and component level control. Functions are integrated within and between systems, and among redundant safety divisions, while meeting all design and regulatory criteria for independence

Figure 8. The CDM I&C configuration.



– electrical, physical, communication and functional. High availability and prevention of erroneous control actions are achieved without adding redundancy that is not needed for single failure criterion compliance. The diverse actuation system is a novel design with no input/output modules of its own, providing a cost-effective means to cope with digital common cause failure in the plant safety system.

The CDM also encompasses control room modernization, taking full advantage of digital technology to integrate the plant I&C systems into an advanced set of operator displays and control consoles as shown in Figure 9. This results in a fully-modernized control room similar to new nuclear power plants, with all of the electrical component controls, analog meters, recorders, controllers and hand-switches removed.

In addition to addressing I&C obsolescence, the CDM is specifically designed to enable significant reductions in nuclear power plant operating costs. This is based on detailed analysis of plant operating and support costs (testing, maintenance, etc.) that are driven by the I&C architecture, and the inclusion of new features that either preclude the need for these activities or reduce the effort to achieve them. Other costs are reduced by the simplicity of the system, minimizing the amount of hardware, software, and communication systems that are needed. The resulting cost reductions include:

- Reduction in operating staff requirements.
- Significant reduction in maintenance and testing staff for I&C systems due to self-testing and diagnostic features.
- Elimination of 80% of field-located control logic components (i.e., relays, timers, and switches) and associated cables, saving related testing, maintenance, and engineering work requirements.
- Elimination of the engineering and procurement support costs to constantly deal with obsolescence and lack of parts and vendor support for legacy analog I&C systems and components.
- Elimination of certain operational events (reactor trips and transients) due to modern digital reliability.

In summary, the CDM provides a comprehensive solution for these urgent needs for operating nuclear power plants – to address critical technological obsolescence of their I&C systems while enabling these plants to shift to a modern technology base that enables long-term, cost-effective operations. Ongoing efforts include the development of a CDM requirements specification that nuclear power plant owners can use for the design and procurement of these replacement systems. The Pathway is working with several first-mover utilities to incorporate these requirements into their I&C modernization and control room modernization projects. The Pathway is also working with nuclear operating companies to develop concepts for modernized control rooms based on the CDM concept.

Figure 9. Modernized CDM control room

Increasing the Value of the U.S. Nuclear Reactor Fleet

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LWRS Integrated Energy Systems Leads

It is becoming increasingly challenging for operating light water reactors (LWRs) to compete with natural gas combined-cycle power plants in deregulated wholesale electricity markets due to the historically low cost of natural gas. In addition, in areas where wind and solar power generation is being built up, the selling price of electricity is periodically less than the cost of operating nuclear power plants. Consequently, some LWR plants operate at a profit loss during certain periods. A new operating paradigm will benefit the profitability and sustainability of these plants. This new operating paradigm incorporates direct integration with industrial manufacturing processes that help diversify the products and thereby the revenue of LWR plants.

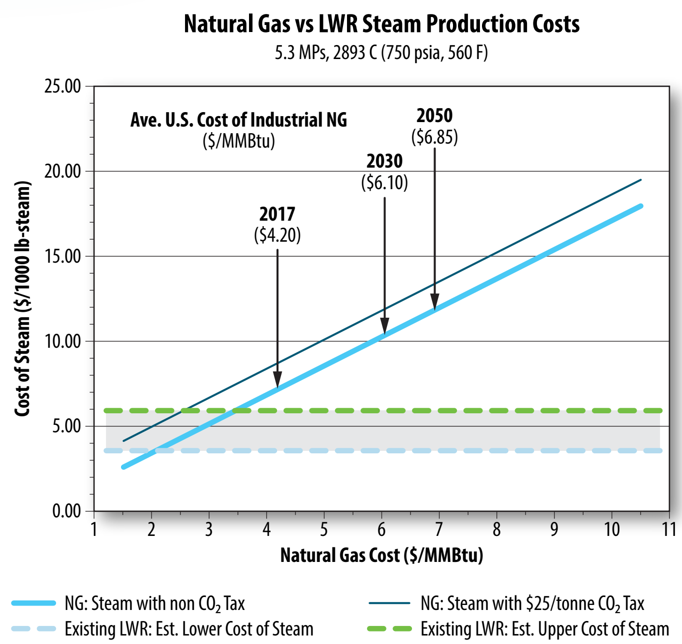
Existing nuclear power plants can provide a reliable and cost-competitive supply of steam and electricity for industrial process use for decades to come.

[1,2] A recent evaluation of the U.S. manufacturing industry indicated nuclear power plants can provide upwards to 75% of the electricity and heat currently produced by industry combined heat and power systems and fossil-fired steam boilers. [3] In addition, energy carriers, such as hydrogen, can be produced with LWRs for energy storage, petroleum refineries, production of fertilizers, chemicals, reduction of iron ore for steel manufacturing, and hydrogen fuel cell vehicles. [4] A comparison of the cost of producing high pressure steam using a natural gas-fired package boiler versus the cost of producing the same quality and quantity of steam using a LWR is illustrated in Figure 10. The cost of steam production by the existing U.S. fleet of LWRs will remain competitive, even accounting for plant upgrades to accomodate a future license extension.

The LWRS Program is evaluating the value proposition and technical challenges of integrating nuclear plants with industrial processes, leveraging interactions and advancements stemming from other DOE-sponsored programs, to enable potential near-term demonstrations and deployments of candidate technologies. In some cases, operating plants could dispatch energy for electricity generation or to a heat application to maximize the profit of these plants. The benefits of LWR integration with industry may include:

- Providing low-emissions energy to the industrial manufacturing and transportation sectors
- Maintaining the stability, reliability, and resiliency of the grid as renewable energy and distributed power generation become more prevalent
- Transitioning a classical baseload supplier into a more flexible operator allowing a higher level of penetration of variable low-cost, renewable energy
- Enabling expansion of variable, low-cost renewable energy by coupling nuclear reactors to energy storage and thermal energy users

Figure 10. Cost of High-Pressure Steam Production Using Natural Gas and Nuclear Energy (Arrows indicate U.S. DOE Energy Information Agency cost projections for natural gas).



- Ensuring U.S. competitiveness by domestically producing more of the most energy-intensive products and services.

Technical and economic assessments of participating operating plants and candidate integrated energy systems are now being conducted. Case studies depend on factors such as electric grid and market conditions and industry process possibilities near the nuclear plant. Process engineering models are being used to design the equipment and control systems that will transfer electricity, steam, or heat from the nuclear plant to the industrial process. Figure 11 illustrates how the heat, steam, and electricity that is produced by an operating plant can be used by all major U.S. industrial processes. Hydrogen and syngas (synthesis gas comprised of chemical building blocks like carbon monoxide and hydrogen) can be produced as intermediate product streams that are used in industrial processes.

Hydrogen production and use by industry is being evaluated for early movers of integrated energy systems. A first case study is evaluating the benefits of dynamically dispatching power to the grid when a profit can be made or for hydrogen production when the price of electricity falls to the point that competitively priced hydrogen can be produced. Initial calculations indicate hydrogen can currently be produced with emerging electrolysis technology for less than DOE's goal of $2/kg-$H_2$ for fuel cell vehicles. As LWR operators push the operational cost of energy production lower, the value of producing large volumes of hydrogen at the industrial processe scale looks promising.

In addition to technical and economic assessments, LWRS Program Integrated Energy Systems (IES) program activities focus on enabling the R&D that will help accelerate integrated energy system pilot projects at a currently operating LWR plant. This work builds on the significant investment in modeling and simulation capabilities developed by the Crosscutting Technologies Nuclear-Renewable Hybrid Energy Systems Program since 2014. The challenges of tying into the electrical and thermal delivery systems of a nuclear reactor are being identified through the engagement of LWR plant operators, hydrogen production technology providers, and other stakeholders. This research will help address the necessary technical and deployment aspects of near-term integrated energy system technologies.

In summary, the LWRS Program is undertaking IES research, development, and pilot project activities to address emerging issues associated with expanding the use of LWR power plants. Initial efforts are underway to evaluate the value proposition both generally and for specific applications that can be implemented in the near term to help diversify the products and the potential role of LWR plants in U.S. industry. Technical and economic assessments provide decision makers with information for moving forward on initial candidate technologies. Collaborative partnerships will be key to the execution of the first LWR integrated energy system.

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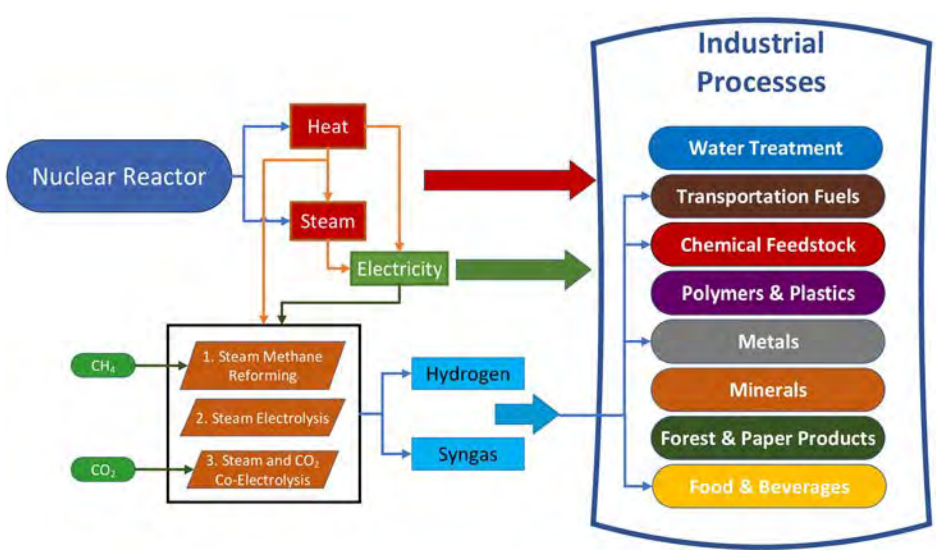
Figure 11. Integration of LWR plants with major U.S. industry processes.



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