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ADVANCED CONSTRUCTION TECHNOLOGY INITIATIVE (ACTI)

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Changing the World's Energy Future

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ADVANCED CONSTRUCTION TECHNOLOGY INITIATIVE (ACTI)
Program Status and Perspectives on Potential Technologies for Nuclear Energy
National Reactor Innovation Center (NRIC)

Luke Voss

Abstract

The National Reactor Innovation Center (NRIC) Advanced Construction Technology Initiative (ACTI) supports a transformation in nuclear energy construction, management, and deployment costs, enabling nuclear energy to make important contributions to the energy systems of the future. This transformation will increase the confidence of investors, energy system planners, policymakers, and ultimately consumers in the capability of nuclear energy to meet future needs; thus, it represents a critical element of advanced nuclear energy system demonstration. Development and/or demonstration project(s) will consider regulatory requirements for commercial nuclear implementation and will incorporate strategies to develop regulator experience and review of the technology.

There are many activities that have, or could have, significant cost and productivity impacts on the design, permits, construction, and operation of a nuclear facility. The primary mission of the NRIC ACTI program is to identify these areas and develop approaches and technologies that will have a major impact.

1. INTRODUCTION

Advanced reactor technologies have attracted considerable financial support, catalysing innovation in the nuclear energy landscape. These next generation reactors are designed with enhanced passive safety systems and the potential for cost reductions. As these advanced reactors approach technological maturity, their commercial success also requires focused examination and essential support. Economic assessments in the nuclear energy sector often emphasize construction costs and the risk of scheduling delays as primary contributors to deployment expenditures. Various nuclear energy economic studies have identified the major role of construction costs and schedule risks in driving up nuclear power plant cost [1], [2], [3]. Traditionally, vital elements of nuclear energy deployment including civil/structural engineering, design sophistication and automation have been either undervalued or postponed in the development cycles. Additionally, the nuclear industry's collective experience in nuclear project execution has diminished over the past several decades due to the infrequency of new plant constructions. Hence, The NRIC ACTI program aims to reduce cost overruns and schedule slippages that have plagued the construction of nuclear power plant projects. With this initiative, NRIC is facilitating the development of advanced nuclear plant construction technologies and approaches through partnerships that would provide game-changing benefits to the construction of advanced nuclear power plants.

2. CURRENT EFFORT WITH GEH

In 2021, NRIC awarded a cost-shared, multi-year project to GE-Hitachi Nuclear Energy (GEH) and other key stakeholders on the first project of the ACTI Program. The goal of this cost-shared public-private partnership is to help demonstrate several technologies that, when combined, could reduce the construction costs of building new reactors by more than 10% and significantly lower the scheduling risks and uncertainties associated with them. Included in this work are two key technologies – fabricated steel/concrete modular wall systems and real time monitoring and digital twins.

Modular wall systems have several advantages over traditional steel-composite techniques and could significantly reduce the amount of labor required on site. Steel casings can be rapidly produced in factories during excavation (site preparation) and then shipped to the site for faster installation. This allows developers to significantly compress schedules by initiating wall construction in parallel with excavation. In addition, these systems have potential to dramatically improve quality of construction as wall frames are built in a controlled environment, and they result in a significant decrease in required site work.

Advanced inspection techniques will be used to provide an "as-built" 3-D model of the structure. The team will then use embedded sensors, 3-D structural and geotechnical models, and software services that interact with the physical structure to create a virtual representation known as a digital twin. By combining the digital twin with seismic and stress-strain sensors, the group can actively monitor the structure during and after construction to better understand the buildings structural integrity. This can help solve or anticipate construction issues before they happen and allow for active monitoring of the facility throughout the lifetime of the facility.

The GEH ACTI project was broken up into two phases. Phase 1 included a detailed, site-specific design of a demonstration reactor containment building, utilizing the proposed technologies. To support the design, this first phase also included the fabrication and testing of steel-concrete composite specimens to validate the calculations, models, and assumptions used for the design of the containment structure using steel-concrete composites. Furthermore, included in this first phase was the development of an implementation plan for the proposed Phase 2 demonstration as well as identifying non destructive examination techniques that can be deployed on a concrete composite structure during construction. At the completion of Phase 1, GEH is to propose the demonstration structure design, project cost, and projected construction schedule to NRIC to potentially receive additional funding to move into Phase 2. The second Phase of this project (if awarded) would be to construct a demonstration reactor building structure.

In Phase 1, GEH is utilizing a steel/concrete composite walling system design called diaphragm plate steel composite (DPSC) for the reactor building and containment walling system. The DPSC design greatly reduces weld volume and helps solve fit up issues as compared to other composite walling system designs. The DPSC system is composed of two continuous face plates connected by filet welded diaphragm plates (Figure 1). The fillet weld is designed to develop the capacity of the plates, similar to a full penetration weld in a composite walling system such as SteelBricks™; however, the welding process (automated robotic arms) and associated inspection is much easier to achieve than a full penetration weld. The inspection of the DPSC diaphragm fillet weld is classified as a Category H weld and only requires visual inspection which can be achieved by attaching a camera to the robotic welding arm, as opposed to extensive NDE for full penetration welds.

A DPSC module system, consists of multiple components arranged and welded together to form a module. The DPSC modules are spliced together to form structural walls, floors, or mat foundation sections. The DPSC system offers strength and stiffness similar to other similar composite walling system designs but addresses the limitations of other composite walling system designs with advantages such as a major reduction in weld volume and associated NDE, no bending/forming and post-forming heat treatment, simplified fit-up, more cost effective, and industry experience with a similar walling design in the AP1000®.

GEH is currently in the process of fabricating DPSC test specimens which are being sent to Purdue University for structural testing under various loading scenarios to represent accidental pressure and loading conditions, accidental thermal conditions, thermal cycling, and seismic conditions (Figure 2). This will validate their performance against models and confirm calculations used for analysis and design. This testing will assess and improve the constructability and feasibility of the DPSC system design when applying it to actual construction projects. The testing will also develop relevant experimental results for accelerating regulatory review of reactor building containment designs using the DPSC system. A total of 9 DPSC prototype specimens are being tested.

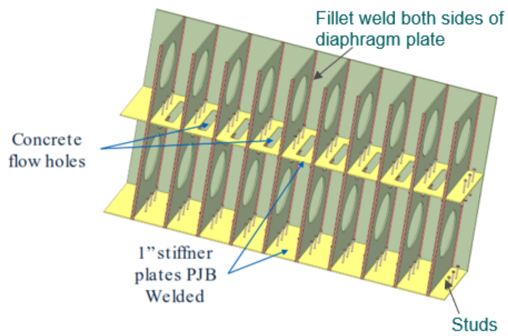

Figure 1. DPSC Diagram

Figure 2. Purdue Testing Rig

GEH has finalized the design of the demonstration structure and is working to provide a cost proposal to NRIC for the building and demonstrating of that structure using DPSC technology. For the Phase 2 demonstration design, due to the funding levels, GEH has proposed a minimum viable structure that will demonstrate all the key construction techniques, critical connections, concrete application, and other various aspects of using DPSC for a cylindrical reactor containment building. With additional funding and an extended project time frame, a larger scale reactor building could be built to demonstrate this DPSC technology for an entire facility. The figure below shows a digital representation of the proposed minimum viable reactor building structure using a DPSC system with a basemat, containment building wall, outer reactor building wall, critical basemat to wall connections, second level mezzanine, and inner passageway walls.

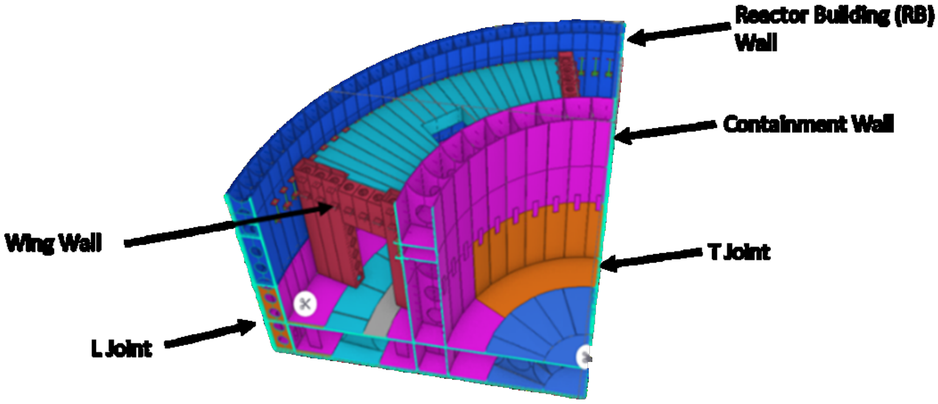

Figure 3. Digital Representation of DPSC System Demonstration Structure

This NRIC ACTI project is important to GEH because the primary purpose is to demonstrate advanced construction, deployment technologies, processes, and approaches that will have major impacts and reduce risk on nuclear energy construction costs. Phase 1 results have already created more confidence for GEH customers in constructability of this design. Phase 2 will further reduce risk items with DPSC as the preferred technology. Many lessons have already been learned by the DPSC manufacturers and many more lessons will be learned during the fabrication of the DPSC demonstration structure.

Furthermore, this ACTI project with GEH benefits the entire nuclear industry because it has the potential to be used by numerous SMR and Advanced Reactor US based companies. This project will help benefit the nuclear industry by establishing and improving supply chain capabilities for deployment to the nuclear industry, employing automated welding techniques to prove a reduction in construction time and improved quality for DPSC fabrication, demonstrating fabrication of DPSC submodules and field erection of the critical joint and section types, demonstrating non-destructive test methods for the DPSC composite walling design, and enabling more accurate estimations of timelines for new plant construction.

Results of this work should sufficiently demonstrate the viability, expected cost savings, regulatory implications, and interface conditions of the construction/deployment technologies, processes, or approaches. The intent of the work is to demonstrate that the systems and technologies can be subsequently used in nuclear energy projects to reduce costs, improve schedule reliability, and accelerate schedules.

3. ADVANCED CONSTRUCTION TECHNOLOGY DEVELOPMENT AND DEMONSTRATION

While the current ACTI project will greatly benefit the nuclear industry, it is only one project, and much more could be done. Several technologies provide potential to greatly improve schedule and economics of nuclear builds. NRIC has identified seven areas that could be addressed to help enable nuclear energy to economically compete with other energy forms. These seven topic areas are listed below as additional, potential projects:

- Improved implementation of the graded approach to nuclear quality assurance requirements
- Digital Twins for developing and deploying advanced nuclear facilities.
- Construction and testing of structural elements using high temperature concrete.
- Diaphragm wall construction testing and demonstration.
- Testing of robotic and 3-D printing of reinforced concrete techniques.
- Deployment of pre-cast concrete in nuclear construction.
- Techno-economic analysis of nuclear construction.

4. TOPIC NO. 1: IMPROVED IMPLEMENTATION OF THE GRADED APPROACH TO NUCLEAR QUALITY ASSURANCE REQUIREMENTS

Current practices for over-implementation of nuclear quality assurance requirements (e.g., 10CFR50 Appendix B, NQA-1) pose significant challenges for deployment of advanced reactors. These high costs of materials and construction due to over-implementation of quality assurance requirements are particularly problematic for advanced nuclear reactors. Unlike traditional large light-water reactors (LWR), many advanced designs inherently mitigate many of the safety concerns that challenge LWRs. While they are still subjected to the same safety focused nuclear quality assurance regulations (e.g., 10CFR50 Appendix B) and design criteria (e.g., N690, ASME Section III) as their predecessors, they are subject to different safety challenges than their LWR counterparts. This delta in designated safety systems warrants a review of civil/structural engineer/procure/construct (EPC) practices for improved efficiency as it relates to application of quality assurance requirements and practices. Given that the largest risk for new nuclear reactor deployment is cost, not safety, focusing on research and development (R&D) towards cost reduction is imperative.

Substantial cost efficiencies may be realized through improved implementation of engineering, procurement, and construction requirements defined in existing codes and standards (e.g., ASME Section III Div. 5, ASME NQA-1). While these structures are important to overall safety, the current mis-application of nuclear quality assurance (NQA) requirements significantly increases cost (by about two times). Nearly 75% of the civil/structural driven cost deltas vs. commercial construction can be attributed to a default to procurement solely from NQA-1 / Appendix B sources in lieu of exercising existing NQA-1 defined processes (e.g., commercial grade dedication) for procurement from commercial sources of steel and concrete. The U.S. Nuclear Regulatory Commission (NRC) has been actively engaged in shaping a framework that is technology-inclusive, risk-informed, and performance-based (TI-RIPB)[5]. Still, there remains a need to conclusively demonstrate how this evolving regulatory paradigm can be effectively applied to the design, licensing, and construction of nuclear structures, potentially unlocking economic benefits while maintaining the safety and reliability. NRIC recommends that further investments are needed to improve application of quality requirements found in current codes and standards for developing requirements for nuclear civil structures tailored to the specifics of advanced nuclear reactors, which would substantially accelerate advanced reactor deployment.

5. TOPIC NO. 2: DIGITAL TWINS FOR DEVELOPING AND DEPLOYING ADVANCED NUCLEAR FACILITIES

Recent advances in artificial intelligence (AI), machine learning (ML), computing power, and data management have introduced new capabilities that could be leveraged in the nuclear energy sector. The combination of these capabilities, coined the "digital twin" has already been successfully demonstrated to address challenges associated with energy asset operations and nuclear non-proliferation, providing predictive maintenance and diversion detection capabilities. However, this technology also has the potential to change the way the nuclear industry develops and deploys new infrastructure.

Accompanied with traditional systems engineering methodologies, digital twins could increase design productivity by automatically transferring information between applications, eliminating tedious, manual rework when replicating data in different engineering domains. Digital twins could also optimize designs digitally enabling systems engineering approaches to accommodate a wider range of simulations, analyses, and verification in the early stages of design. Finally, digital twins could help reduce errors by providing a robust digital thread of information maintained throughout the project lifecycle to ensure data are not "lost," the impact of change is well understood before it is implemented, and the as-built asset in the physical world is continuously tied back to the as-designed asset in the digital space.

One of the challenges associated with leveraging digital twins is that each are built separately from the ground up at firewalled institutions, with a unique architecture and methodology. NRIC suggests a project to build an open-source, project-agnostic, plug-and-play digital twin backbone that could benefit the nuclear energy industry. Actions would include developing a Technology Readiness Level (TRL) 7 open-source "digital engineering for nuclear" ecosystem, demonstrate the use and operation of the ecosystem in the design of a nuclear facility, and begin the NQA-1 qualification of the digital engineering ecosystem.

6. TOPIC NO. 3: CONSTRUCTION AND TESTING OF STRUCTURAL ELEMENTS USING HIGH TEMPERATURE CONCRETE

The current knowledge base, experience, applications, codes, and standards within the nuclear industry have been centred around LWR technologies, which operate at lower temperatures compared to high-temperature reactors. Unlike an LWR, a high temperature reactor could experience a risk of reduced structural integrity due to a severe thermal cycle that could potentially compromise the entire reactor plant investment without necessarily posing immediate environmental or public safety risks.

Conversely, the capability of advanced reactors to operate at higher temperatures can be considered as an asset. This is especially relevant and important in discussions around commercializing the heat at close by industrial facilities, thereby expanding the utility beyond power generation. Recent innovations in high-temperature applications, such as the development of thermal batteries that utilize high-temperature concrete, have the potential to further enhance the profitability and attractiveness of investing in the advanced reactor domain. Thus, a comprehensive understanding of high-temperature environments in the nuclear energy domain is essential; not only to safeguard long-term investments but also to explore and examine the compatibility and adoption to nuclear energy domain that can yield additional revenue avenues for the industry.

Several nuclear research projects have been conducted to investigate the behaviour of reinforced concrete structures at elevated temperature; however, the overall level of effort has not been sufficient for establishment of widely accepted elevated-temperature concrete design procedures for advanced nuclear applications.

7. TOPIC NO. 4: DIAPHRAGM WALL CONSTRUCTION TESTING AND DEMONSTRATION

The vertical wall technique is a flexible type of wall construction. A reinforced structural diaphragm wall is constructed using a continuous vertical trench excavated in ground and supported by a light mud fluid (typically bentonite or polymer mud) until the mud is systematically replaced by concrete, after the reinforcing steel cage installation as shown in Figure 4 below. Use of these types of systems can significantly reduce excavation for subsurface nuclear facilities when compared to the common practice of bathtub excavation. The walls can create a leak tight facility with spaces, or cells, that could be used for reactor operations, fuel storage, hot cell work, or other radiological activities. The steelwork could be completed in modules in a factory setting. The spaces can be sized and configured to suit the project needs and can be expanded in a modular fashion as future needs arise to install more capacity. The successful transfer of this method from non-nuclear industries to nuclear requires special knowledge of calculation, design, concrete technology, formation of joints and construction suited to meet nuclear regulatory requirements. A baseline demonstration of the technology could be utilized in conjunction with one or more reactors to provide proof of concept of the speed of construction.

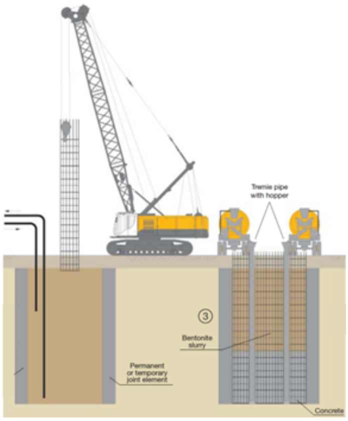

Figure 4. Diaphragm wall construction. Generalized process, not project specific.

NRIC proposes developing a detailed conceptual design with supporting analysis of a demonstration facility that would allow for the collection of requirements, development of alternate architectures, and provide simple design concepts to help define facility variants and options. This would provide a basis of understanding for cost and performance models for the technique, process, and scheduling timelines.

8. TOPIC NO 5: TESTING OF ROBOTIC AND 3-D PRINTING OF REINFORCED CONCRETE TECHNIQUES

Adopting 3D printing technology in constructing small nuclear reactor buildings and reactor pits represents a significant step change in construction timelines and associated costs. This advancement fundamentally alters the traditional stick-built approach to automated rapid construction, offering numerous benefits such as time reduction, cost efficiency, enhanced structural integrity, faster operational readiness, and increased worker safety.

The following video shows this technology in action: https://www.youtube.com/watch?v=69HrqNnrfh4

Taking this technology into a nuclear application space presents unique challenges, such as the temperature ranges and seismic loads the structures must withstand. With that said, there is already interest from advanced nuclear companies, such as Aalo, to begin exploring how 3D printing concrete can expedite nuclear construction and save cost. NRIC would like to pursue continued development with the eventual aim of a <1-month construction framework for microreactors and small modular reactors. To do this, immediate development work is needed in concrete formulation development, existing technology assessment for printing techniques, testing standards development, regulatory engagement, and test site development.

9. TOPIC NO. 6: DEPLOYMENT OF PRE-CAST CONCRETE IN NUCLEAR CONSTRUCTION

To achieve the United States' decarbonization goals (per DOE Advanced Nuclear Liftoff Report [6]), we need to construct 40+ 300 MWe advanced reactors every year. A mature construction supply chain is needed to meet this need. Modular precast reinforced concrete construction has been widely deployed for several decades in US non-nuclear construction sectors to build mission-critical infrastructure. A robust supply chain, including factories, infrastructure, trained labor, and proven transportation already exists for precast concrete. The US needs to adopt construction methods that maximize the factory production of standardized modules that can be quickly assembled on site by a small, trained workforce, avoiding the need to place on-site large volumes of concrete that are needed for currently used cast-in-place construction. Precast concrete has a long- established pedigree and has been successfully deployed in nuclear-scale megaprojects around the world, for mission-critical infrastructure of the size of nuclear power plants, in seismically active regions. ~~An example of US heavy civil construction shown in the image below: a precast reinforced concrete base for a 100+m tall chemical process tower, erected and completed in 3 weeks~~.

Precast reinforced concrete is at TRL 9 in the non-nuclear construction sectors but lags in the US nuclear sector. US standards and guidance have been available and used to design and deploy precast construction for 20+ years, with successful use documented at the scale (physical size and throughput) needed by the US nuclear industry. To accelerate the use of precast concrete in the US nuclear industry, maximize the benefits of pre-casting a nuclear power plant, and drastically reduce construction cost and schedule, a multi-pronged demonstration project is proposed to provide a pathway to deployment, using an archetype reactor building as an example. This project will quickly add a proven, modular construction option to the toolbox that is currently limited to cast-in-place concrete and steel composite construction. While no experimental testing is needed, NRIC proposes the following program to further the readiness of precast concrete in nuclear construction to TRL 9:

- Demonstration of an archetype reactor building in (a) full precast concrete and (b) combination of precast and cast-in-place concrete with differing percentage of precast, to judge impact on construction cost and schedule
- Webinars and workshops on the available US standards and guidance for precast concrete for delivery to consultants, contractors, EPCs, and DOE and NRC regulators and technical staff,
- Active engagement of the NRC in all aspects of the NRIC demonstration project.

10. TOPIC NO. 7: TECHNO-ECONOMIC ANALYSIS OF NUCLEAR CONSTRUCTION

In the past decade and more, researchers have performed techno-economic analysis of nuclear construction to diagnose the reasons behind nuclear cost and schedule overruns. These studies resulted in several insights, including the significance of construction management and practices as a cost driver, which this report addresses through the demonstration of advanced construction technologies. Given the large gap in nuclear construction in the United States, most of these studies use decades old construction cost data that may not be pertinent for today's challenges, including higher labor and material costs, and newer NRC regulations.

The NRIC advanced construction demonstration programs including ACTI, microreactor demonstration testbeds such as DOME and LOTUS, as well as the technology demonstration projects proposed here, offer a unique opportunity to collect and analyze construction cost and schedule data. INL (and partners, ANL and MIT), have been developing tools [7], [8] that can analyze this cost and schedule data and perform techno-economic analysis in such a way that they can be 'sanitized' to remove proprietary information, and compared across construction projects despite being of different scale and involving different technologies. Insights and lessons learned from these techno-economic analysis of these data can (a) provide a more objective comparison of the effectiveness of these advanced construction technologies in terms of cost and schedule, (b) model the application of these technologies in real nuclear power plant construction to estimate their contribution to potential capital cost construction risk reduction, and (c) translate the experience from these construction projects into learning that can be applied to advanced nuclear construction. NRIC proposes an advanced construction techno-economic analysis program that involves collecting cost and schedule data from demonstration projects, assembling the costs for each project using the generalized nuclear code of accounts (GN-COA) system that enables a technology and project neutral comparison of costs across different projects, and performing a detailed techno-economic analysis of the costs to understand the effectiveness of each technology in terms of measurable figures of merit such as reduction in capital costs and schedule, and construction risk reduction.

11. SUMMARY

Nuclear construction is difficult and costly with substantial risk of schedule and cost overruns. While NRIC's ACTI aims to tackle construction challenges in advanced nuclear and holds significant promise, the current project represents a first step in a much larger needed effort. The myriad of potential solutions, spanning technologies like risk-informed regulations, digital twins, high-temperature concrete, and 3D printing, demands a comprehensive prioritization strategy and systematic approach. A formal study, analyzing the impact and cost-effectiveness of each option, is crucial to ensure efficient allocation of resources. With this program, NRIC envisions paving the way for a streamlined, cost-effective nuclear construction process, ultimately accelerating the clean energy transition and unlocking the future of reliable, low-carbon nuclear energy.

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