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Fission Battery Initiative

July 2021

Technology Innovation Workshop Report

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ABSTRACT

Idaho National Laboratory and National University Consortium virtually organized the Technology Innovation for Fission Battery workshops in January and February 2021. The workshops' topics were aimed to understand technological challenges, knowledge gaps, and limitations that must be addressed to achieve the unattended attribute of the fission battery concept.

Achieving secure, reliable, and resilient fully autonomous controls and operation of fission batteries is a foundational technology that defines the unattended attribute. Many enablers likely play a vital role in achieving autonomous operation. These include, but are not limited to, modeling and simulation, artificial intelligence, machine learning, reduced-order methods, sensors, advanced materials, and digital twins.

The workshops' outcomes identified five thrust areas that will require extensive research and development. These include:

Thrust Area 1: Heterogeneous sensors requirements and optimization to achieve complete state awareness

Thrust Area 2: New innovations required to achieve online modeling and simulation

Thrust Area 3: Establishing trustworthiness in autonomous controls and decision-making

Thrust Area 4: Smart materials using additive manufacturing

Thrust Area 5: Holistic approach to integrating hardware and software and implementing both on a platform.

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ACRONYMS

AI	Artificial Intelligence
IIoT	Industrial Internet of Things
M&S	Modeling and Simulation
ML	Machine Learning
MOOSE	Multiphysics Object-Oriented Simulation Environment
NRC	U.S. Nuclear Regulatory Commission
R&D	Research and Development
SAE	Society of Automotive Engineers
TIA	Totally Integrated Automation
TRL	Technology Readiness Level

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Fission Battery Initiative

1. INTRODUCTION

The current operating commercial nuclear fleet consists of large (~1,000MWe) reactors that require significant onsite infrastructure and a sizeable operational staff. Reactors in this class provide clean, economic, reliable power and have been a key energy source for the U.S. and the world. Recent trends in energy development highlight the benefits of distributed energy generation to provide power off-grid or through microgrids to fulfill remote, expansive, and self-contained power needs. To support these needs, several reactor technologies, particularly microreactors, are currently under development [1]. The fission battery initiative [2] envisions developing technologies that enable nuclear reactor systems to function as batteries. Fission batteries are intended to be integrated into a variety of applications, as "plug-and-play" nuclear systems providing affordable and reliable energy in the form of heat and/or electricity and function without operations and maintenance staff.

The fission battery initiative [2] is focused on conducting fundamental research and development (R&D) to address the challenges related to five attributes: economic, standardized, installed, unattended, and reliable. Innovative R&D utilizing three interdependent areas—technology, data science, and capabilities—are required to achieve deployable fission batteries beyond those considered in near-term plans for any currently proposed or existing reactor technologies. As R&D progresses through the technology readiness levels (TRLs), lessons learned will be used to inform and/or develop new regulatory guidelines, policies, and technical measures with the aim of achieving domestic and international regulatory acceptance to support successful deployment and operation of fission batteries.

The fission battery attributes are intended to drive technological innovation and development. Though the specific innovations for each fission battery attribute are expected to be different, they will inform the innovation and development needs of other attributes. For example, one technological advancement pursued is fully autonomous operation and controls with no onsite human required. This directly drives the innovation associated with the unattended attribute and informs the innovation needs of attributes like economic, standardize, and reliable. With these considerations, it is important to understand the current state of the art of technologies under development related to fully autonomous operation and controls with the nuclear industry. This will allow the initiative to clearly identify the challenges, gaps, and limitations to prioritizes the R&D needed.

Idaho National Laboratory, in collaboration with its National University Consortium, identified five scoping areas and organized a workshop series to drive discussion on the technological R&D required to achieve the fission battery attributes. These scoping areas include:

- Market and economic requirements for fission batteries and other nuclear systems
- Technology innovation for fission batteries
- Transportation and siting for fission batteries
- International safeguards and security of fission batteries
- Safety and licensing of fission batteries.

The discussions held during the workshop series promoted fundamental rethinking of developing, demonstrating, and deploying technological solutions that would address issues related to sensors; secure data storage and communication; manufacturing; siting; multi-modal transportation; installation site readiness; policies around international safeguards; regulatory policies and guidelines related to transportation (before and after use of fission batteries); fuel storage; physical security; and so on.

1.1 Technology Innovation Workshop Series Purpose

Within the technology innovation for fission batteries scoping, three virtual workshops focused on the following topics:

- Autonomous Controls and Operation on January 20, 2021
- Modeling & Simulation and Soft & Virtual Sensors on February 10, 2021
- Advanced Manufacturing on February 24, 2021.

The workshop topics were aimed to *understand technological challenges, knowledge gaps, and limitations that must be addressed to achieve the unattended attribute of the fission battery*. Achieving secure, reliable, and resilient fully autonomous controls and operation of fission batteries is one of the key technologies that defines the unattended attribute. Many enablers may play a vital role in achieving the autonomous operation. These include, but are not limited to, modeling and simulation (M&S), artificial intelligence (AI), and machine learning (ML), reduced-order methods, sensors, advanced materials, and digital twins.

A recording of each workshop is available on the fission battery initiative website with workshop agendas and presentations [3]. These agendas, presentations, and speaker information are summarized in Appendix A, B, and C respectively.

1.2 Report Outline

The report is organized as follows:

- Section 2 presents the summary of challenges and gaps discussed during the technology innovation for fission batteries workshop
- Section 3 describes the research direction in fully autonomous controls and operation with emphasis on automation levels
- Section 4 describes the research thrust areas that were identified during the three workshops and are required to achieve a fully autonomous, operating fission battery
- Section 5 presents the outcomes and impacts expected due to technological advancements in identified thrust areas.

2. CHALLENGES AND GAPS

- Current high-fidelity nuclear reactor M&S tools and techniques that capture the fundamental behavior of a reactor system would benefit from an "online" predictive capability. The current M&S environment is defined by input files, boundary and initial conditions, governing equations, and other parametric values to simulate desired application-specific solution outcomes. There is a need for M&S tools to have a feedback loop enabling them to modify or adapt simulations in response to real-time changes in a reactor system.
- Integrating M&S with AI and ML needs to minimize the dependency on high-performance computing architectures and must be computationally light to enable faster-than-real-time prediction capability.
- Advancements in AI and ML approaches are significant but their application in nuclear is limited because challenges like explainability and trustworthiness have not yet sufficiently been resolved. AI/ML explainability required solutions that are simple and generally understandable to users.
- Physical sensors are sources of data. Large numbers and varieties of physical sensor types are installed in-core, in-vessel, and ex-vessel to record salient measurements to achieve complete state awareness of a reactor. However, fission batteries will not have the luxury of supporting the installation of large numbers and varieties of physical sensor types. This creates a challenge of

optimizing the number of physical sensor types and their placement to achieve complete state awareness. In addition, virtual sensing has a critical role to play in optimizing the measurement space (physical and virtual sensors).

- The development of "smart materials" with embedded sensors that are designed to survive different operating and design limits (e.g., high-temperature, corrosive molten salt, and radiation environments).
- Material development using additive manufacturing requires a long and tedious qualification process. There is a need to accelerate the qualification process of developing smart materials and their manufacturing.

3. AUTONOMOUS CONTROLS AND OPERATION

The priority research direction targeted during the technology innovation workshops is R&D required to achieve secure, reliable, and resilient fully autonomous controls and operation of fission batteries, by linking data, M&S, AI/ML, and demonstration under steady-state and extreme limits capabilities.

There are automation levels identified for the existing commercial reactor fleet. However, the degree of automation required for fission batteries is beyond the currently envisioned automation levels (semi-autonomous operation) for both the existing commercial fleet and advanced reactor technologies. To make the transition from semi-autonomous operation and controls to full autonomy, it is important to clearly understand automation requirements and develop a roadmap to ensure a paradigm transition is possible through transformational R&D.

Central to the fission battery initiative is enabling "unattended" reactor operations. Achieving a state of autonomy to address operation and maintenance costs for advanced reactor designs has been the focus of previous and ongoing studies among advanced reactor stakeholders. For example, Wood et.al. [4] introduced the current state of reactor autonomy for small-modular rectors as well as potential benefits and challenges to achieve additional autonomy. However, full autonomy of reactor systems presents a significant departure from the currently accepted operational paradigm of the existing reactor fleet. Automation in the current reactor fleet is recognized by the U.S. Nuclear Regulatory Commission (NRC) and outlined automation levels in the NUREG-0700 [5]. There is no guidance for fully automatic systems [5]. Table 1 shows the levels of automation currently acceptable in operating nuclear power plants. Due to the inherent complexity of the existing U.S reactor fleet, a system (or subsystem) may be characterized by varying levels of automation under different operating conditions.

To achieve unattended operation, the automation levels in Table 1 are insufficient and need to be revised at a minimum. Drawing parallels from the automotive industry within the context of self-driving cars could provide insights on automation level requirements for fission batteries (even for advanced reactors). The Society of Automotive Engineers (SAE) has recently outlined levels of automation supporting fully autonomous (i.e., without human operator) vehicles (Table 2) [6] [7]. At Levels 4 and 5, a paradigm shift in the vehicles' design is expected. Here, vehicles are sufficiently automated, so the requirement for a driver seat with pedals and a steering wheel is no longer required and overall cabin design can be radically revisited. It can be referred to as the "tipping point" in vehicle automation. Automation levels are also outlined by other industries but are beyond the scope of this report and workshop series.

First, recognizing the SAE automation levels better represent the end goal of achieving an engineered system not reliant on a human-in-the-loop, we set out to combine concepts of SAE automation levels with NUREG-0700 (Table 3). Table 4 details these efforts in terms of reactor characteristics, reactor class, as well as the location and responsibility of operators.

Table 1. Current NRC approved automation levels as per NUREG-0700.

Level		**Human/Machine Interoperability**	**LWR Example** [8]
1	Manual Operation	Manual control, operator makes all decisions and actions.	--
2	Shared Operation	Some tasks are operated automatically; some are manual.	Drywell cooling system (ESBWR)
3	Operation by Consent	Automatic performance when prescribed. Operator closely monitors and may intervene with supervisory commands.	Steam generator water level control (US-APWR)
4	Operation by Exception	Operators approve critical decisions and may intervene if specific circumstances are encountered.	Feedwater control system. (AP1000)
5	Autonomous Operation	Operators monitor performance and perform backup operations. Actions not normally able to be disabled but may be started manually.	Reactor trip

Table 2. Current SAE approved automation levels for self-driving vehicles as per SAE-J3016 [7].

Level		**Human/Machine Interoperability**	**Example**
0	Do-Driving Automation	Manual control. Active safety systems present, but driver performs all decisions and actions.	Automatic emergency braking; blind spot warning.
1	Driver Assistance	Single system automation. Either lateral or longitudinal motion are controlled.	Adaptive cruise control **or** lane centering.
2	Partial-Driving Automation	Multiple system automation. Both lateral and longitudinal motion are controlled.	Adaptive cruise control **and** lane centering.
3	Conditional-Driving Automation	Vehicle automation under specific conditions. Driver must be present to resume controls if requested by automation system.	Traffic jam chauffer. Human **must** drive if requested.
4	High-Driving Automation	Vehicle automation under limited conditions. No expectation of driver intervention.	Local driverless taxi. Pedals/steering wheel may not be installed.
5	Full-Driving Automation	Sustained and unconditional performance by automation system. No expectation of driver intervention.	Vehicle can drive everywhere in all conditions without human intervention.

Table 3. Automation levels for fission battery.

Level		Human/Machine Interoperability	Reactor Class
0	No automation	Manual control, operator makes all decisions and actions.	Current fleet capabilities (Generation 2 commercial designs).
1	Operator assistance	Some tasks are operated automatically; some are manual.	
2	Operation by consent	Automatic performance when prescribed. Operator closely monitors and may intervene with supervisory commands.	Generation 3/3+ LWRs, small-modular reactors, and microreactors.
3	Operation by exception	System automation under specific conditions. Operators monitor performance and perform backup operations circumstances are encountered or requested.	
4	High automation	System automation under normal/limited operating conditions. Operators offsite and optional. System will not operate unless specific conditions are all met.	Fission battery
5	Full automation	Sustained and unconditional performance by automation system. No expectation of operator intervention.	

Table 4. Operator location and responsibilities corresponding to automation levels of Table 3.

	Level 0 & 1	Level 2	Level 3	Level 4	Level 5
Where is the operator located?	Onsite.			Offsite/remote.	No operator required.
What does the operator do?	Is in full control of reactor and must always remain engaged.	Constant monitoring not required. There to act under abnormal operating conditions.		Operators offsite and optional for single unit. Based on system feedback, can manually override.	If necessary, a remote operator could monitor a fleet of units.

As in Table 2, we highlight the "tipping point" in fission battery automation at Levels 4 and 5. At these levels, reactor operations, overall plant design, construction, and installation fundamentally change. Here the reactor system is sufficiently automated, so there is no longer a requirement for operations staff onsite. At Level 4, the operations staff can safely be shifted to a remote location and are no longer required to carefully monitor a reactor system. At Level 5, automation is sustained under all foreseen operating conditions without any intervention of a licensed operator. At this point, the fission battery becomes a true "plug-and-play" system completely independent of licensed operators and can be safely operated by the layperson.

Achieving Levels 4 and 5 autonomy is not trivial. Significant R&D investments will be required in sensor development; AI; online predictive M&S; physical-/cyber-security; secure remote communications; integrated automation systems; reliability and resilience to external physical/cyber stressors; and algorithms that account for uncertainty and exhibit human interpretability and trustworthiness. Some of these topics were discussed during the three workshops and form the basis for the thrust areas to be discussed in Section 4.

4. RESEARCH THRUST AREAS

4.1 Thrust Area 1: Heterogeneous Sensor Requirements and Optimization to Achieve Complete State Awareness

The data from different sensor modalities are used for a variety of purposes and applications to make informed decisions and inferences. For instance, the information from different sensors and their locations can be used to maintain situational awareness and assess the health conditions and the operation status of reactor systems and the reactor itself. Today, this is used to inform the decision-making capability of the operator in the loop. For fission batteries, this information needs to be used to design, develop, and deploy autonomous operation and controls with no human-in-the-loop for onsite decision-making. This will require new technologies relying on advancements in sensors, communication, ML, and AI to be utilized in an integrated manner. Sensors are a critical part of the entire autonomous requirements as they are the source of all data required for non-human decision making.

In fission batteries, due to the potential compact size and the need for rapid portability, installation (installable), and operation, it is not possible to install many sensors and data processing instrumentation connected to them. The sensor modalities used in-core, in-vessel, and ex-vessel need to be revisited across different TRLs to understand the sensor requirements for fission batteries. This will inform the research needed to achieve optimization of sensor modalities and their placement with no loss in reliability nor in informing the communication architecture that is resilient, safe, and secure.

Different types of sensors are used in-core, in-vessel, and ex-vessel. They can be broadly categorized into physical sensors and virtual sensors. Physical sensors in turn can be further divided into active sensors and passive sensors (Figure 1). The concept of virtual sensing is not new, but its application has been very limited in critical industries, like nuclear. Within the nuclear industry, they are sometimes used for a short duration as a replacement for a faulty sensor. As R&D is required to establish sensor technology requirements for fission batteries, the entire sensor space (physical and virtual sensing) must be considered holistically. R&D is required to address the following challenges:

- Different forms of data obtained from simulations, experiments, technical specifications, set points, and action (part of decision-making) are expected to be available on a continuous basis. These data will be collected at different spatial and temporal resolutions at different readiness levels using different sensor modalities at different locations (i.e., in-core, in-vessel, and ex-vessel). Therefore, R&D is required to streamline data collection, storage, and sharing via a datahub for monitoring and analysis.
- Fission batteries are expected to operate independently and without any form of maintenance for the duration of mission/designed life (i.e., time duration for which fission batteries are required to provide heat/electricity to meet a specific, desired application needs). Therefore, different in-core, in-vessel, and ex-vessel sensors must be 100% reliable for the fission batteries' operation period. This requires R&D to develop fail-safe sensors ensuring complete state awareness.
- Optimizing the number of fail-safe heterogeneous sensors and their placement needs to be achieved to provide salient data for different purposes, ranging from remote monitoring, real-time condition of fission batteries, maintain autonomous control and operation, structural health monitoring, and so on. This requires R&D to solve a multi-objective and multiple constraint cost function that would the number of sensors (physical and virtual) and their placement.

- Smart sensors are a category of sensors with the ability to process data onboard and make decisions in real-time. The advancements in edge computing and related science are required to enable smart sensors development with 100% reliability.

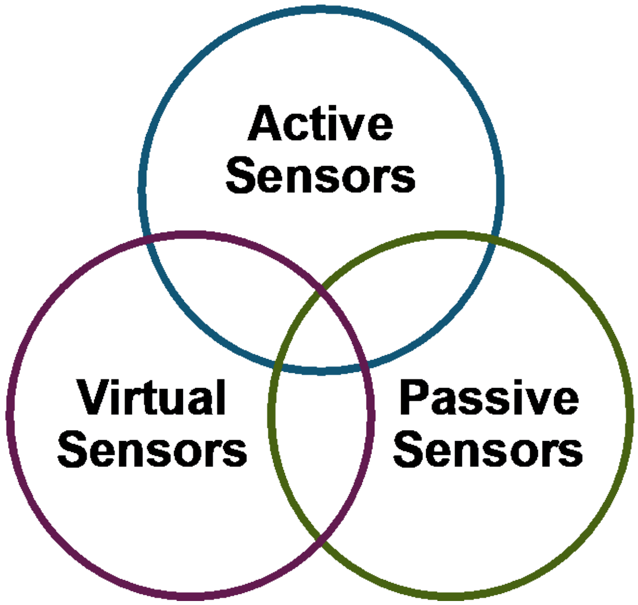

Figure 1. Integration of active, passive, and virtual sensors.

4.2 Thrust Area 2: New Innovations Required to Achieve Online Modeling and Simulation

M&S is one of the mechanisms for supplementing measurements from physical sensors and enables a holistic view of the physical system of interest based on first principles calculations. Over the past decade, there has been significant progress in M&S. Despite these advancements, there are gaps and challenges yet to be addressed. The following research needs were identified during the M&S workshop to facilitate the online M&S tools and applications.

- Balance the need for engineering and high-fidelity scale M&S tools.

  The model predictive capability should provide a realistic and accurate characterization of the system parameters and dynamic responses for a variety of operating scenarios. This requires combination of high- and low-fidelity models to achieve a balance between M&S data quality, reliability, and execution performance. When developing physics models for different reactor types and across levels of subsystems to understand their characteristics, there are a lot of different directions one can take. There are several existing M&S tools used to model phenomena not previously accounted for in the legacy codes, and often new tools are developed to accommodate new phenomena. In addition, there will be a need for M&S tools to interact with each other to perform multiphysics simulations. Thus, an agile M&S architecture where one can mix and match different codes to achieve different application needs is clearly needed (for example, Multiphysics Object-Oriented Simulation Environment's [MOOSE's] MultiApp System). To achieve an adaptable system that addresses different types of reactors, operational scenarios, and physics computations at a spectrum of fidelity scales remains a topic of research.

- Integrate M&S, AI, and ML tools to develop faster than real-time predictive capabilities and better understand dynamic reactor conditions.

The nuclear industry has pioneered the use of M&S tools to design, build, optimize, and assess the safety of nuclear reactors. However, the existing multiphysics M&S tools (for instance MOOSE, VERA, or commercial codes such as those developed by Studsvik) do not have built-in online predictive capabilities.

Autonomous operation based on the online decision-making process relies on faster-than-real-time distributed simulations. A real-time model converges at a pace that allows updates to the control systems and operator console identical to the real plant. Faster-than-real-time simulation means the elapsed computational time is smaller than the physical (real) time of the modeled phenomena. The predictive results coming from simulations should provide feedback to the physical system that will allow for system adjustments before undesirable occurrences. While M&S coupled with AI and ML technologies create numerous opportunities for predictive monitoring and managing of the nuclear systems, the task of tools integration remains a challenge.

Developing new M&S tools or refurbishing the existing codes to employ online predictive modeling capabilities, and the challenge of addressing multiscale temporal (femtoseconds to years) and spatial (atom scale to kilometers) phenomena remains imperative.

- Validation of multiphysics tools

  Incorporating predictive models into multiphysics codes is a multistep, complex process composed of problem definition and data inspection, model specification, estimation, performance, predictive analytics, validation, and presentation steps [9]. Assessing model performance and capability to predict future outcomes via model validation is a critical step, necessary to determine accuracy, reproducibility, and generalizability applied to different conditions. Thacker et al. defines validation as "*the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model* [9]" Validation aims to quantify the model's predictive accuracy by comparing simulation outcomes with experimental data [10]. Progress towards establishing multiphysics tools' online predictive capabilities requires establishing a comprehensive validation database for all possible scenarios of fission battery operations.

- Minimizing or eliminating user effects

  The effectiveness of the M&S process relies on the engineer/user who builds the models. In standard M&S tools development and application processes, the user takes the lead on defining the model's operational envelope, execution, and postprocessing of the results. While the user effect on simulation uncertainties propagates between and within different multiphysics codes and models, it becomes almost impossible to quantify this impact. Moreover, the more dependent the model is on user inputs, the more limited its predictive capability becomes at enabling autonomous operation. The need to understand and quantify the user's effect on the propagation of uncertainties in the model's setup and execution, along with the associated sensitivities, is imperative to the decision-making process.

- Adequacy of establishing computing resources to perform real-time reduced-order multiphysics simulations

  The hardware, technical, and functional requirements for computing resources needed to perform online predictive multiphysics simulations remain unknown. Access and availability of computing resources adequate to perform real-time reduced-order multiphysics simulations are imperative to the successful implementation and execution of the reactor autonomous control and operation.

4.3 Thrust Area 3: Establishing Trustworthiness in Autonomous Controls and Decision-making

Modern AI methodologies span many fields of science and engineering and provide opportunities to holistically integrate real-time sensor data, online M&S, and inform decisions of value. However, typical off-the-shelf applications of AI, such as neural networks, suffer from the classical "black-box" phenomenon. Though proven powerful algorithms in classifying large, complex, nonlinear data sets, and neural networks are inherently complex, and their results can be difficult to interpret. To leverage the potential of AI systems to advance automation levels, ensure regulatory acceptance, and provide resilient and robust digital architectures, it is essential that AI technologies developed for nuclear applications be "trustworthy."

Trustworthy AI is a multilevel and multifaceted concept, as shown in Figure 2, which leverages the potential of AI while maintaining human interpretability, security, self-awareness, resilience, and reliability. In the context of nuclear systems, discussions were held during the "Autonomous Controls and Operation" workshop focusing primarily on resilient data, resilient systems, and resilient models [11].

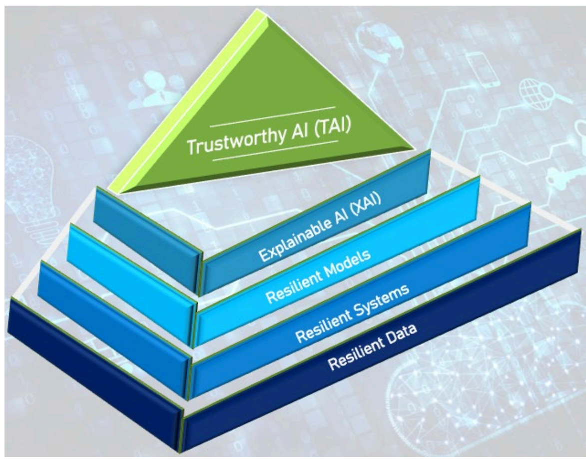

Figure 2. Multilevel representation to achieve trustworthy AI [11].

R&D activities are required to address all three areas as they are foundational layers to achieve trustworthiness (Figure 2). Some of the specific concerns include:

- Data poisoning accounts for unwarranted data perturbation
- System corruption by maliciously reprogramming AI algorithms, reward hacking (applicable to automated controls via reinforcement learning), and exploiting software dependencies
- Model corruption, reconstruction of outputs, model misspecification, and model stealing.

Besides these R&D open topics related to trustworthiness, there are several known unknowns and unknown unknowns. A few are discussed below:

- How trustworthy AI (including data, model, systems, and explainability) can be used to establish trustworthy digital twins and minimize uncertainties?
- There are different types of digital twins across different system hierarchies. Establishing trust across different types of digital twins needs to be addressed.
- Fission batteries need to operate despite sensor failure or malfunctioning. This leads to the question: how can resilience be designed into deployed sensors, and can trust/confidence be maintained in abnormal operating conditions?

4.4 Thrust Area 4: Smart Materials Using Additive Manufacturing

Structural health monitoring is another key factor that must be taken into consideration during manufacturing, transportation, installation, operation, and disposition stages of fission batteries. R&D is required to develop smart materials (i.e., materials with embedded sensors). However, material qualification time of such new materials has been identified as a potential deployment barrier. If smart materials are to be developed and qualified for use in fission batteries to enable structural health monitoring, additive manufacturing has a potentially large role in streamlining new material qualifications, sensor selection, digital twins, and in-process monitoring.

This is also essential to support automation Levels 4 and 5 (Table 3), as a variety of real-time data generation is key to fission battery operation. Smart materials also have application in detecting and averting outsider threats. In concert with virtual sensors, it is believed fission batteries can benefit from the combination of additive manufacturing and embedded active sensors to create and achieve "smart materials" [12] [13] [14]. The purpose of these materials would be to enable both in-core and ex-core real-time sensor data in previously infeasible locations (e.g., internal to structures/components). In theory, these aspects would enable online component quality verification, remote inspection, emerging defect identification (e.g., because of prolonged irradiation or an off-normal event), predictive system management via integration with online M&S and AI, to potentially provide physical sensor security to external stressors. This new class of sensor/material integration and the benefits provided may prove particularly useful for critical components. However, several knowledge gaps and resulting research questions have been identified as follows:

1. How to integrate/account for radiation damage effects (for both the sensor and material)?
2. How is data from these sensors retrieved? Physically wired penetrations? Wireless technology?
    a. If the latter, how can data streams be protected from external attack (e.g., sensor/data manipulation and stealing data)?
3. Can data from embedded sensors be used for specific component inspection/qualification/lifetime extension in real-time?
    a. If so, which materials are required to achieve this technology?
4. How can the qualification process for new sensor-material combinations be expedited?
    a. Identifying appropriate sensor embedding techniques.
    b. Ensuring long-term sensor/material operation for in-core applications (resistance to high-temperature, corrosive, and radiation environments).
    c. How to verify and validate that a particular sensor is operating correctly under normal and abnormal (as required or outlined in the reactor final safety analysis report) reactor conditions?
    d. What would the regulatory framework around embedded sensor technology look like?
5. How are traditional sensor properties affected by being embedded within materials?
    a. Material swelling applying physical stress on sensors.
    b. How can sensors be calibrated with no physical access? Can they be recalibrated?

4.5 Thrust Area 5: Holistic Approach to Integrating Hardware and Software and Implementing Both on a Platform

The holistic systems integration approach, often called the totally integrated automation (TIA), requires the complete integration of hardware, software, services, or networks (Figure 3) and consolidation of information and operational technologies (IT, OT) [15]. Software requirements pertain to specifics of the programs, procedures, routines, codes, and data associated with the operation of computer systems. In contrast, hardware requirements, are comprised of the technical details of physical components installed in nuclear power plants. Applying the industrial internet of things (IIoT) solutions to enable autonomous control and operation of fission batteries is unavoidable and remote connectivity of TIA components will become critical. To enable the TIA and application of the IIoT solution for fission batteries, the following questions should be addressed:

- What are the technical requirements for the IIoT platform and integration of hardware, software, and services that enable the TIA?
- What are the challenges associated with data flow, collection, transfer, management, storage, and security?

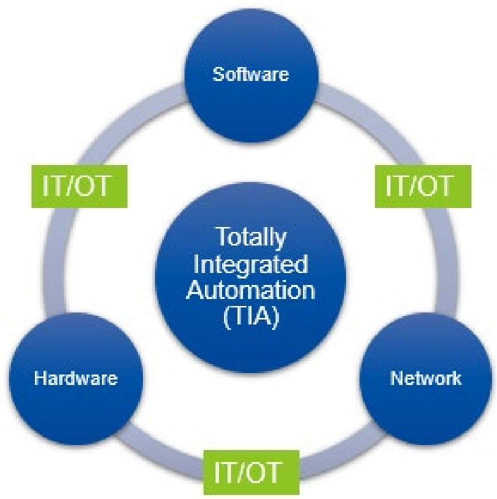

Figure 3. TIA diagram [15].

5. OUTCOMES AND IMPACTS

The ongoing digital transformation and Industry 4.0 innovations and practices are impacting how future nuclear reactor designs will be implemented and executed. The thrust areas outlined in this workshop report present the major technological challenges that needs to be addressed to advance autonomous controls and enable reactor systems to operate as batteries. The listed thrust areas also aim to reveal the key research directions to address the shortcomings of implementing new digital (or “smart”) technologies, predictive M&S, virtual sensing, ML, and AI to achieve fission battery attributes.

Exploring these thrusts will ultimately result in:

- An optimized portfolio of active, passive, and virtual sensors that enable complete nuclear reactor state awareness (Thrust Area 1)
- An integrated M&S, AI, and ML toolset with faster than real-time predictive capabilities (Thrust Area 2)
- A trustworthy and resilient nuclear reactor digital enterprise (Thrust Area 3)
- A framework for real-time nuclear reactor structural components monitoring (smart materials) and predictive maintenance (Thrust Area 4)

- A demonstration of hardware, software, and network integration that advances the system capability of autonomous control and operation (Thrust Area 5).

Establishing and catalyzing innovative research that successfully addresses the described technological thrusts will have a positive impact on nuclear reactor economics (predictive management and no human-in-the-loop/operational staff), broaden the nuclear reactor application spectrum, simplify design (significantly reduced infrastructure), and enhance safety characteristics (well-trained digital enterprise that reacts to abnormal signals faster than real-time).

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Appendix A
Autonomous Controls and Operation

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A.1 Technology Innovation for Fission Batteries: Autonomous Controls and Operation

Moderator: Youssef Ballout

Wednesday, January 20, 2021
11:00 a.m.–3:00 p.m. (Eastern Time)

The initiative envisions *developing technologies that enable nuclear reactor systems to function as batteries and to be referred as fission batteries*.

Autonomous controls and operation are one of the required technologies to achieve the initiative vision and to ensure expanded deployment of fission batteries to meet clean energy demands across broader applications and markets.

The aim of this *workshop* is to:

- Understand technological challenges, knowledge gaps, and limitations (development, demonstration, and deployment) associated with autonomous controls and operation of fission batteries.
- Role of multiphysics and multiscale modeling and simulation, reduced-order methods, machine learning, artificial intelligence, and digital twins in achieving autonomous controls and operation of fission batteries.

The expected outcome of this workshop is to identify technological goals that autonomous controls and operation of a fission battery must achieve. Concurrently, the workshop will enable a broad discussion on the potential of the new technologies and facilitate the creation of research paths and networks.

A.2 Agenda

Time	Workshop	Presenter
11:00–11:15 a.m.	Fission Battery Initiative and Workshop Overview	Youssef Ballout Director, Reactor Systems Design and Analysis Division Idaho National Laboratory
11:15–11:40 a.m.	Challenges in Achieving Autonomy in Advanced Reactors	Nam Dinh/Linyu Lin Professor, Nuclear Engineering/Researcher North Carolina State University
11:40 a.m.–12:05 p.m.	R&D Opportunities to Achieve Autonomous Operation for Fission Batteries	Yasir Arafat Technical Lead, Microreactor Idaho National Laboratory
12:05–12:30 p.m.	Covert Cognizance (C2): Novel Modeling and Monitoring Paradigm for Critical Systems	Abdel-Khalik Hany Associate Professor, Nuclear Engineering Purdue University
12:30–12:45 p.m.	Break	
12:45–1:10 p.m.	Dispatchable, Base-Load Nuclear: The Case for a Fission Thermal Battery	Anthonie Cilliers Senior Manager, Instrumentation, Controls, & Electrical Kairos Power
1:10–1:35 p.m.	Failures in AI and ML: Insights and Mitigations	Charmaine Cecilia Sample Cybersecurity Research Officer Idaho National Laboratory
1:35–2:00 p.m.	Resilient Fission Battery Control: Challenges & Opportunities	Michael W. Sievers Senior Systems Engineer JPL/NASA
2:00–3:00 p.m.	Panel Session	

A.3. Speaker Information

Youssef Ballout, Ph.D.
Director, Reactor Systems Design and Analysis Division
Idaho National Laboratory

Anthonie Cilliers, Ph.D.
Senior Manager, Instrumentation, Controls, and Electrical
Kairos Power

Professor Nam Dinh, Ph.D.
Professor, Nuclear Engineering
North Carolina State University

Charmaine Cecilia Sample, Ph.D.
Senior Cybersecurity Research Officer
Idaho National Laboratory

Yasir Arafat
Technical Lead, Microreactor
Idaho National Laboratory

Michael W. Sievers, Ph.D.
Senior Systems Engineer
JPL/NASA

Abdel-Khalik Hany, Ph.D.
Associate Professor, School of Nuclear Engineering
Purdue University

Linyu Lin, Ph.D.
Post-Doctoral Research Scholar
North Carolina State University

Appendix B
Modeling & Simulation and Soft & Virtual Sensors

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B.1 Technology Innovation for Fission Batteries: Modeling & Simulation and Soft & Virtual Sensors

Moderator: Izabela Gutowska, Ph.D.

Wednesday, February 10, 2021
11:00 a.m.–3:00 p.m. (Eastern Time)

The initiative envisions *developing technologies that enable nuclear reactor systems to function as batteries and to be referred as fission batteries.*

Autonomous controls and operation are one of the required technologies to achieve the initiative vision and to ensure expanded deployment of fission batteries to meet clean energy demands across broader applications and markets.

The aim of this *workshop* is to:

- Understand technological challenges, knowledge gaps, and limitations (development, demonstration, and deployment) associated with autonomous controls and operation of fission batteries.
- Role of multiphysics and multiscale modeling and simulation, reduced-order methods, machine learning, artificial intelligence, and digital twins in achieving autonomous controls and operation of fission batteries.

The expected outcome of this workshop is to identify technological goals that autonomous controls and operation of a fission battery must achieve. Concurrently, the workshop will enable a broad discussion on the potential of the new technologies and facilitate the creation of research paths and networks.

B.2 Agenda

Time	Workshop	Presenter
11:00–11:15 a.m.	Fission Battery Initiative and Workshop Overview	Vivek Agarwal Senior Research Scientist Idaho National Laboratory
11:15–11:40 a.m.	Adaptable Multiphysics Simulation	Derek Gaston Idaho National Laboratory
11:40 a.m.–12:05 p.m.	Connecting M&S Tools for Fission Battery & Microreactor Performance	Phil Sharpe Studsvik Scandpower, Inc.
12:05–12:30 p.m.	Advancing Fission Battery Deployment through Modeling and Simulation	David Pointer Oak Ridge National Laboratory
12:30–12:45 p.m.	Break	
12:45–1:10 p.m.	How Advanced Modeling and Simulation with Multi-Physics Could Help Advance Fission Battery Systems	Brandon Haugh Kairos Power
1:10–1:35 p.m.	Measurement Systems for Autonomous Operation of Nuclear Reactor	Pattrick Calderoni/Richard Vilim Idaho National Laboratory/Argonne National Laboratory
1:35–2:00 p.m.	Perovskite Retinomorphic Sensors	John Labram Oregon State University
2:00–3:00 p.m.	Panel Session	

B.3. Speaker Information

Vivek Agarwal, Ph.D.
Senior Research Scientist,
Instrumentation, Controls, and Data Science
Idaho National Laboratory

Derek Gaston, Ph.D.
Computational Frameworks
Idaho National Laboratory

Phil Sharpe, Ph.D.
Vice President for Innovation and Special Projects
Studsvik Scandpower, Inc.

W. David Pointer, Ph.D.
Head, Advanced Reactor Engineering and Development
Nuclear Energy and Fuel Cycle Division
Oak Ridge National Laboratory

Brandon Haugh
Director, Modeling and Simulation
Kairos Power

Pattrick Calderoni, Ph.D.
Director, Advanced Sensors and Instrumentation
Manager, Measurement Science Department
Idaho National Laboratory

Richard Vilim, Ph.D.
Senior Nuclear Engineer
Department Manager, Plant Analysis & Control & Sensors
Nuclear Science and Engineering Division, Argonne National Laboratory

John Labram, Ph.D.
Assistant Professor
Electrical & Computer Engineering
Oregon State University

Appendix C
Advanced Manufacturing

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C.1 Technology Innovation for Fission Batteries: Advanced Manufacturing

Moderator: Vivek Agarwal, Ph.D.

Wednesday, February 24, 2021
11:00 a.m.–3:00 p.m. (Eastern Time)

The initiative envisions *developing technologies that enable nuclear reactor systems to function as batteries and to be referred as fission batteries*.

Additive manufacturing is one of the required technologies to achieve the initiative vision and to ensure expanded deployment of fission batteries to meet clean energy demands across broader applications and markets.

The aim of this *workshop* is to:

- Understand technological challenges, knowledge gaps, and limitations (development, demonstration, and deployment) associated with additive manufacturing and advanced materials for fission batteries.
- Role of multiphysics and multiscale modeling and simulation, machine learning, artificial intelligence, and digital twins would play in addressing technological challenges and knowledge gaps.

The expected outcome of this workshop is to identify technological goals that additive manufacturing approaches must achieve to standardize attribute of the fission battery initiative. Concurrently, the workshop will enable a broad discussion on the potential of the new technologies and facilitate the creation of research paths and networks.

C.2 Agenda

Time	Workshop	Presenter
11:00–11:15 a.m.	Fission Battery Initiative and Workshop Overview	Vivek Agarwal Senior Research Scientist Idaho National Laboratory
11:15–11:40 a.m.	Qualification Challenges for Additively Manufactured High Temperature Nuclear Components	Michael McMurtrey Idaho National Laboratory
11:40 a.m.–12:05 p.m.	Industrialization of Metal AM: Progress and Future Vision	Ed Herderick The Ohio State University
12:05–12:30 p.m.	Advanced Materials for Microreactors	Derick Botha NuScale Power
12:30–12:45 p.m.	Break	
12:45–1:10 p.m.	Design for “_________”	Slade Gardner Big Metal Additive
1:10–1:35 p.m.	A Paradigm Shift in Manufacturing as Opportunity for Fission Battery Success	Isabella J. van Rooyen Idaho National Laboratory
1:35–2:00 p.m.	Perspectives on Materials Degradation Challenges for Fission Battery Deployment	Samuel Briggs Oregon State University
2:00–3:00 p.m.	Panel Session	

C.3. Speaker Information

INL & Guest Presenters

Vivek Agarwal, Ph.D.
Senior Research Scientist,
Instrumentation, Controls, and Data Science
Idaho National Laboratory

Michael McMurtrey
Idaho National Laboratory

Edward D. Herderick, Ph.D.
Director, Additive Manufacturing
College of Engineering CDME
The Ohio State University

Derick Botha
Innovation Manager
NuScale Power

Slade Gardner:
President and Founder
Big Metal Additive

Isabella J. van Rooyen, Ph.D., MBA
National Technical Director: DOE – NE
Advanced Methods for Manufacturing
INL Distinguished Staff Scientist
Reactor Systems Design and Analysis Division
Idaho National Laboratory

Samuel Briggs, Ph.D.
Assistant Professor
School of Nuclear Science & Engineering
Oregon State University