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Revision 1

Fission Battery Initiative

October 2022

Research and Development Plan

Vivek Agarwal, Youssef A. Ballout, and Jess C. Gehin
Idaho National Laboratory

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ABSTRACT

Idaho National Laboratory's (INL's) Nuclear Science and Technology Directorate established the Fission Battery Initiative to define, focus, and coordinate research and development of technologies that can *fully* achieve battery-like functionality for nuclear energy systems. The notion of a "fission battery" conveys a vision focused on realizing very simple "plug-and-play" nuclear systems that can be integrated into a variety of applications requiring affordable, reliable energy in the form of electricity and/or heat and function without operations and maintenance staff. In order to formalize the desired functionality, the initiative has adopted and plans to achieve the following key attributes: economic, standardized, installed, unattended, and reliable.

The initiative will conduct fundamental research and development (i.e., from Technology Readiness Level 1 [basic principles] through 5 [technology demonstration]) to innovate and demonstrate enabling technologies to achieve fission battery attributes.

This document introduces the Fission Battery Initiative's vision, fission battery attributes, priority research directions to support the research and development thrust areas and attributes, priority research directions, updated accomplishments, and the initial scope of targeted research and development planned through 2024.

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ACRONYMS

AI	artificial intelligence
CAES	Center for Advanced Energy Studies
CIE	cyber-informed engineering
DOE	Department of Energy
INL	Idaho National Laboratory
LDRD	Laboratory Directed Research and Development
M&S	modeling and simulation
MAGNET	Microreactor AGile Non-nuclear Experimental Testbed
MARVEL	Microreactor Application Research Validation and Evaluation
MIT	Massachusetts Institute of Technology
ML	machine learning
NE	nuclear energy
NRC	Nuclear Regulatory Commission
NRIC	National Reactor Innovation Center
NS&T	Nuclear Science and Technology
NUC	National University Consortium
POC	points of contact
PRA	probabilistic risk assessment
PRD	priority research direction
R&D	research and development
TREAT	Transient Reactor Test Facility
TRL	Technology Readiness Level
UQ	uncertainty quantification
V&V	validation and verification

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Fission Battery Initiative

1. INTRODUCTION

The term battery was first introduced by the American scientist and inventor Benjamin Franklin in 1749, followed by the invention of the first true battery in 1800 by Alessandro Volta. Today, batteries are a ubiquitous source of portable and reliable electric power across different applications. Batteries are widely used across a range of scales from consumer products to grid-scale energy storage. There are different types of batteries, but they can be broadly classified as chemical or electric batteries [1], atomic batteries, nuclear batteries, tritium batteries, or radioisotope generators [2, 3]. Atomic batteries, nuclear batteries, tritium batteries, and radioisotope generators have gained significant attention for applications requiring long-term power supply and high-power density, including the space power reactor [3, 4]. Battery-based systems are appealing for many applications because they allow straightforward deployment across a wide range of applications. Chemical batteries come in a range of standardized sizes that support many applications, from small electronic devices to grid-scale storage. They generally function on their own without need for extensive operations and maintenance.

The current operating nuclear systems are large reactors that require significant onsite infrastructure and a large operational staff. They provide clean, economic, and reliable power and have been a key energy source for the United States and the world. Recent trends in energy development have highlighted the benefits of distributed energy generation to provide power off-grid or through microgrids to fulfill remote, expansive, self-contained power needs. In order to support these needs, a number of reactor technologies, particularly microreactors, are currently under development. These and future reactor technologies exhibit the potential to achieve simple, secure, reliable, and affordable operation of a nuclear system that can readily integrate into a variety of applications to provide affordable and reliable electricity and/or heat. These systems provide technologies that can achieve functionality that would allow them to be used more like battery systems.

Idaho National Laboratory's (INL's) Nuclear Science and Technology (NS&T) Directorate [5] established the Fission Battery Initiative to define, focus, and coordinate the research and development (R&D) of technologies that can *fully* achieve battery-like functionality for nuclear energy systems. The notion of a "fission battery" conveys a vision focused on realizing very simple "plug-and-play" nuclear systems that can be integrated into a variety of applications requiring affordable, reliable energy in the form of electricity and/or heat and function without operations and maintenance staff. To formalize the desired functionality, the initiative has adopted and plans to achieve the following key attributes: economic, standardized, installed, unattended, and reliable (Figure 1).

The initiative will conduct fundamental R&D (i.e., from Technology Readiness Level [TRL] 1 [basic principles] through 5 [technology demonstration]) to innovate and demonstrate enabling technologies to achieve fission battery attributes. The R&D within this initiative is focused on developing technologies that support a range of modular and microreactor designs and concepts, rather than the development of new reactor concepts. This initiative is coordinated with INL's National University Consortium (NUC) [6], Center of Advanced Energy Studies Universities (CAES) [7], and other strategic university partnerships.

This document introduces the Fission Battery Initiative's vision, fission battery attributes, and the initial scope of targeted R&D planned through 2024. This document will be revised periodically to reflect updated priorities.

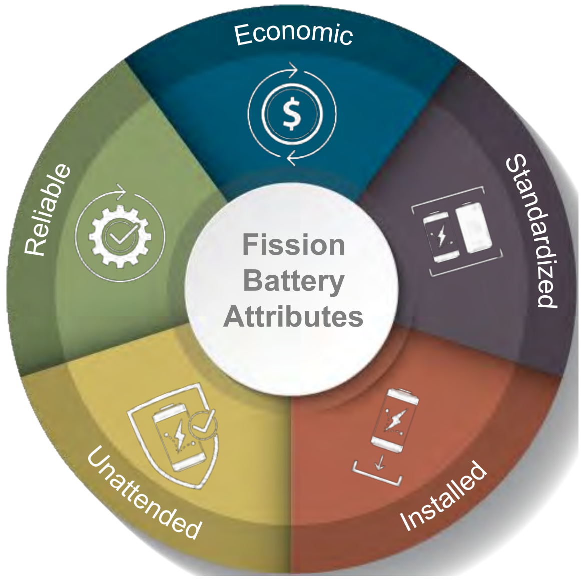

Figure 1. Fission battery attributes.

1.1 Initiative Vision

The initiative envisions developing technologies that enable nuclear reactor systems to function as batteries.

Elaborating on this vision with an example provides the context of what this initiative seeks to achieve. The vision is to achieve nuclear technology to enable the ability to produce reactors in factories with standardized designs that can be directly installed for applications at any location with no or limited site development. Scalability to achieve application needs can be achieved through use of multiple standardized units (similar to a wind farm). These reactors would be able to operate reliably on their own, without onsite personnel and operators, and autonomously adjust to application demand. When no longer needed or fully utilized, the reactors can be readily replaced or removed, and the used reactors can be centrally refurbished or dispositioned.

2. FISSION BATTERY ATTRIBUTES

The following attributes have been defined to support the Fission Battery Initiative's vision. R&D will be performed to enable fission batteries to be:

Economic—Cost competitive with other distributed energy sources (electricity and heat) used for a particular application in a particular domain. This will enable flexible deployment across many applications, integration with other energy sources, and use as distributed energy resources. Here cost refers to the overall lifecycle cost, including costs associated with manufacturing, transportation, deployment, operation, replacement, and decommissioning. To be cost competitive with other distributed energy sources, the costs of energy generation (electricity and heat) across many applications for fission batteries need to be defined.

Standardized—Developed in standardized sizes, power outputs, and manufacturing processes that enable universal use and factory production, thereby enabling low-cost and reliable systems with faster qualification and lower uncertainty for deployment. Standardization is expected to influence licensing, large volume transportation, and scalable manufacturing of fission batteries. Technical and regulatory requirements related to transportation and manufacturing need to be defined.

Installed—Readily and easily installed for application-specific use and removal after use. After use, fission batteries can be recycled by recharging with fresh fuel or responsibly dispositioned. Fission batteries must achieve prompt (within a few hours) installation and operation upon delivery, with no or minimal onsite construction, security, siting, and infrastructure requirements.

Unattended—Operated securely and safely in an unattended manner to provide demand-driven power. To ensure unattended operation of fission batteries, a resilient and secure autonomous system is required to operate, monitor, control, and guard them with no onsite human involvement.

Reliable—Equipped with systems and technologies that have a high level of reliability to support the mission life and enable deployment for all required applications. They must be robust, resilient, fault tolerant, and durable to achieve fail-safe operation. The ability to provide advance notification based on state of health is required to achieve 100% availability and timely replacement of fission batteries.

3. RESEARCH AND DEVELOPMENT PLAN

To achieve the Fission Battery Initiative's vision and attributes, disruptive innovation is required through cross-cutting R&D activities in four thrust areas: technology, data science, material science, and capabilities. The resulting innovation and advancements (ranging from TRL 1 through 5) will result in simplified nuclear systems and technologies that are beyond those considered in near-term plans for any currently proposed or existing reactor technologies [8]. The initiative R&D plan is focused through Fiscal Year (FY) 2024.

Figure 2 shows how the Fission Battery Initiative's R&D will extend nuclear reactor technologies to fully achieve the fission battery attributes.

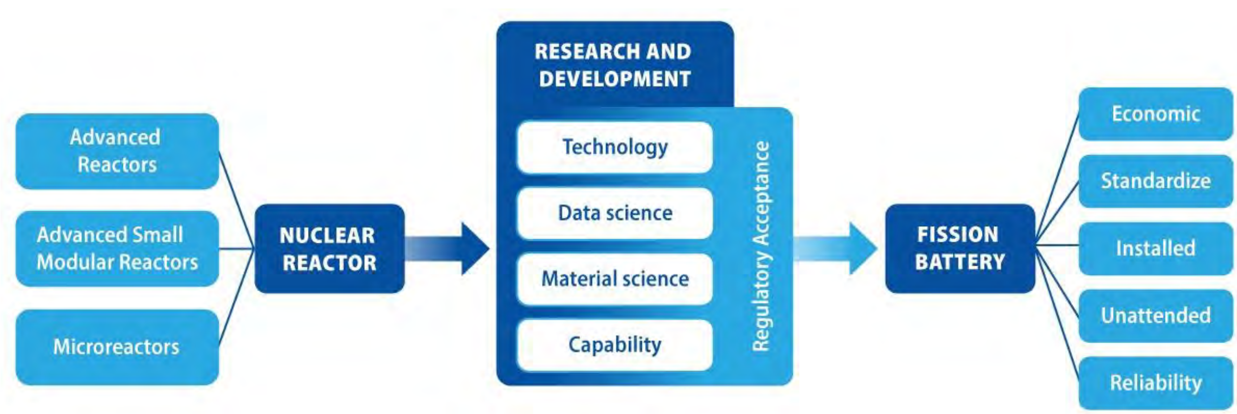

Figure 2. Fission Battery Initiative R&D to enable nuclear reactor technologies to achieve fission battery attributes.

Technology: The fundamental and proof-of-principle R&D performed will specifically develop and demonstrate technologies related to the identified fission battery attributes. These include digital instrumentation and sensors, autonomous or anticipatory controls, remote monitoring, transportation, siting, manufacturing, safeguards and security, reliability and resilience, and economics.

Data Science: The fundamental and proof-of-principle R&D performed will enable innovation in multiscale multiphysics modeling and simulation (M&S); big-data analytics; machine learning (ML) and artificial intelligence (AI); robustness, interpretability, and trustworthiness of ML/AI; data architecture; uncertainty quantification; and real-time risk and vulnerability assessment tools.

Capabilities: The prototypes developed as a result of technological advancements by integrated R&D in technology and data science need to be validated and verified using an experimental test bed. The data generated as a result of validation and verification (V&V) exercises will provide valuable evidence that can be used to advance the TRL of models, tools, and approaches. The initiative would support expansion of test beds needed to support V&V of the developed technologies. The V&V exercise will also enable the enhancement of these test beds for technological demonstration of fission battery attributes and a platform on which external collaborators can perform testing of their technologies.

Material Science: Fission batteries are expected to support multimodal transportation during their lifecycle. To ensure safe, secure, and reliable mobility and operation of fission batteries located at different sites, this initiative will coordinate R&D related to advanced materials, manufacturing, and qualification process with other programs within NS&T and, specifically, coordinate and perform innovative R&D in light-weight shielding and structural materials and their accelerated qualification process.

Regulatory Acceptance: The cross-cutting activities across the thrust areas should address regulatory risks linked to R&D outcomes as enabling technologies advance from basic principles through technology demonstration. Addressing regulatory risks at early stages of R&D is expected to enhance the possibility of acceptance and implementation of the technologies as they transition through higher TRLs and regulatory review.

3.1 R&D Thrust Areas

Technology

Innovation within several technology-thrust areas is required to achieve the fission battery attributes discussed in Section 2. Specifically, R&D is required in the following technology areas (Figure 3).

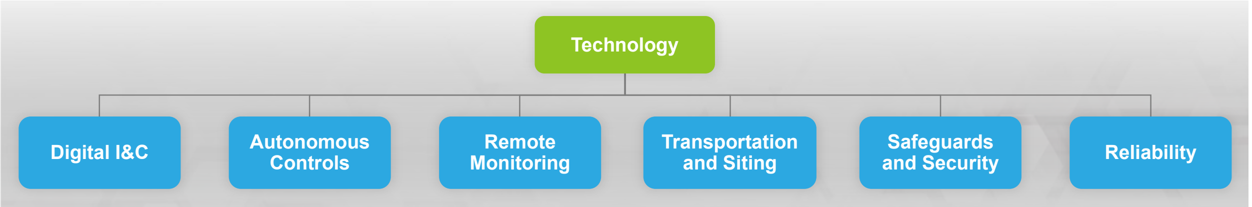

Figure 3. R&D in technology-thrust areas.

Digital instrumentation and sensors provide salient measurements that are essential for autonomous control, operation, security, and remote monitoring of fission batteries. Given the advancement in sensors and associated electronics, R&D is required to develop novel miniaturized sensors (single modal or multimodal) that could be installed or embedded at optimal locations (possibly as part of the physical structure of the reactor systems) and survive harsh operating environments. The potential to apply ML/AI integrated with M&S to enable the concept of virtual sensors is also required to provide necessary information in the absence of physical measurements and could potentially offset a physical sensor requirement.

Resilient and trustable autonomous controls utilizing salient measurements from digital instrumentation and sensors are required to achieve reliable and secure operation of fission batteries with no human in the loop under different operating conditions. The control algorithms to achieve autonomous operation must be able to gather information about their operational environment, learn, adapt, anticipate, and take informed control actions. Research challenges related to system engineering, design, computing, and optimal control actions need to be broadly considered for the development of fully autonomous fission batteries. To address these research challenges, knowledge gaps, and limitations, innovation in multiphysics and multiscale M&S, reduced-order methods, ML and AI, and digital twins is required.

The concept of remote monitoring of fission batteries is supported by intelligent automation and decision-making capabilities with minimal human intervention. Remote monitoring is envisioned to encompass complete state and situation awareness (in terms of state of health) from the time a fission battery is manufactured through transportation, installation, operation, and replacement or disposition. This requires advancements in data and communication architectures and innovations in ML/AI methodologies along with their interpretability, robustness, and trustworthiness.

Technological innovations are required to achieve multimodal transportation and multisite deployment of fission batteries. For multimodal transportation, R&D is required to address both domestic and international challenges. R&D covering sensors, onboard data analysis (edge computing), and requirements related to each mode of transportation (road, rail, air, water, and underwater) must be established. For multisite deployment, technologies that would enable site readiness of the manufactured fission battery are required. The technology developed should support a wide variety of above ground and underground deployment. To address both multimodal transportation and multisite deployment research challenges, M&S tools capturing the dynamic behavior of the fission battery coupled with environmental conditions, ground and soil interactions, and other external factors must be developed and analyzed.

Safeguards and security of fission batteries must ensure their usage does not raise any concerns related to domestic and international proliferation, cybersecurity, and physical security during transportation, deployment in remote locations, and unattended operation, thus ensuring the flow of electrons is not compromised. Development of safeguard and security technologies could include approaches that integrate the concept of safeguards-by-design and security-by-design and take advantage of INL's expertise in cyber-informed engineering (CIE) [9] and consequence-driven CIE (CCE) [10] to secure critical infrastructure. The U.S. Department of Energy (DOE), directed by the 2020 National Defense Authorization Act, Section 5726, is developing a DOE national CIE strategy. One of the pillars of that strategy will include recommendations for incorporating CIE into energy technology research. The developed technologies must be able to adapt their operation in response to or in anticipation of changing security postures.

Reliability aims to achieve fail-safe resilient autonomous operation and decision-making capabilities with 100% availability under different operating conditions. To achieve 100% availability, R&D in the areas of hardware, software, system integration, and operation reliabilities is required. Performing failure modes and effects analysis and phenomena identification and ranking table analysis of both hardware and software are required, including development of models that can handle both independent and dependent failures. To handle both types of failures, complete state of health awareness is necessary. Independent failures do not result in the occurrence of other faults while dependent failures result in secondary and in some cases tertiary faults, thereby resulting in cascading failures.

Data Science

Data science is a broad field that involves R&D activities from different science and engineering disciplines. It includes development of scientific models, methods, tools, and computing platforms that are used to extract meaningful information to enable intelligent automation and decision-making. For this initiative, R&D in the data-science thrust area (Figure 4) specifically focuses on addressing knowledge gaps in the areas of: big-data analytics; ML/AI; integration with multiscale, multiphysics M&S; robustness, interpretability, and trustworthiness of ML/AI; data and communication architectures; and real-time risk and vulnerability assessment tools.

Big data, ML, and AI R&D and their applications to extract, diagnose, and suggest prognoses and present relevant information and knowledge for decision-making are highly desired to achieve technological breakthroughs related to fission battery attributes. ML/AI applications are characterized according to their tasks, such as classification, regression, clustering, dimension reduction, unsupervised learning, semi-supervised learning, supervised learning, and reinforcement learning. All the types of ML/AI approaches simply rely on data (or big data). Fission battery R&D is focused on (1) achieving computationally light, efficient, and scalable ML/AI methodologies ensuring faster-than-real-time prediction and decision-making capabilities and (2) combining multiphysics and multiscale M&S with

ML/AI-based adaptivity to create a hybrid approach (i.e., digital twin) to capture both deterministic and stochastic behavior of a system of interest.

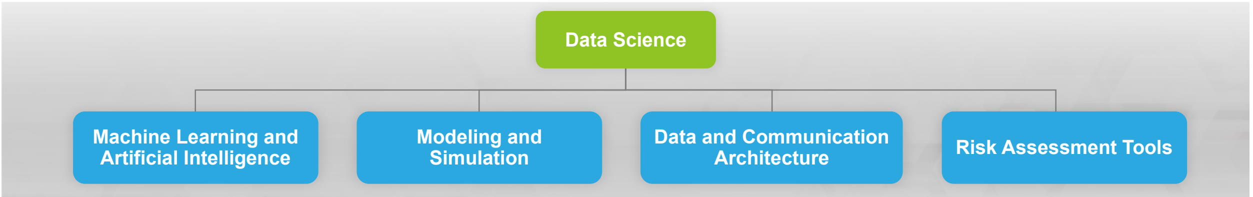

Figure 4. R&D in the data-science thrust area.

Multiphysics and multiscale M&S aim to enable technological advancements related to fission battery attributes by providing a computational platform able to understand nuclear system behavior under different operating scenarios. Fission battery R&D in M&S is focused on developing first-principle models and libraries that capture and estimate or predict the underlying physics related to chemical, thermal-mechanic, thermal-hydraulic, and neutronic aspects of fission batteries across different levels of systems and at different resolutions. Development and enhancement of existing M&S computation platforms would enable optimization of technological advancements related to fission battery attributes and reduce the timeline and costs of deploying simplified nuclear systems.

Data and communication architectures aim to achieve connected, scalable, and agile architectures to ensure the data required for autonomous control, operation, big-data analytics, ML/AI-based intelligent automation and decision-making, and remote monitoring are always available and synchronized.

Robustness, interpretability, and trustworthiness aim to achieve a level of scientific rigor with quantifiable uncertainties that would establish acceptance of ML/AI methodologies. Basic requirements include validation and limits on inputs, as well as verification of the basic algorithms to ensure they are capable of delivering known solutions. Though these issues are investigated and applied, more research is still needed, especially when normal and abnormal operating values are not defined for fission batteries. In many applications, information is extracted from high-dimensional data using complex models. Alternatively, to address computational complexity, reduced-order models are used to draw inferences from the information. This creates different scales of information, so it is essential to establish interpretability and trustworthiness of ML/AI methodologies to ensure timely, informed decision-making.

Real-time risk and vulnerability assessment aim to use ML/AI approaches to develop risk assessment tools capable of identifying, locating, and quantifying vulnerabilities across systems of systems. This would address existing limitations of probabilistic risk assessment (PRA) approaches that rely on humans to develop risk scenarios and system vulnerabilities and would enable transition from Boolean logic to a more continuous risk assessment approach.

Material Science

Significant research progress is ongoing in developing materials that can survive harsh environmental conditions (high temperature, high radiation, corrosion, and others) for existing and future reactors. For the Fission Battery Initiative, specific focus is on R&D related to light-weight materials and their manufacturing, testing, and qualification process (Figure 5). To advance light-weight materials R&D, leveraging advancements in material science and data science is necessary and supported by capabilities to perform separate and combined testing for radiation, thermal, and corrosion for qualification purposes.

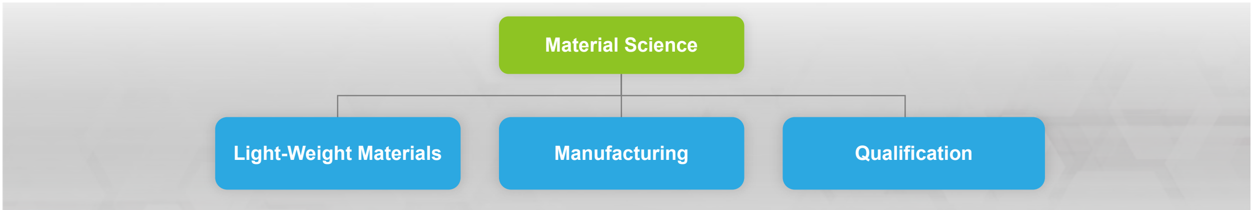

Figure 5. R&D in the material science thrust area.

Fission batteries are required to be mobile (from fabrication site to reactor operation site, between sites during their operational lifetime or after the completion of their mission or operational lifetime back to the manufacturing site) and ensure installation at different site locations with no or minimal onsite infrastructures (that could be onshore or offshore or co-sited with other distributed energy sources). To achieve mobility and siting vision of fission batteries, light-weight materials for shielding and structural applications are required. For shielding applications, the light-weight material must demonstrate high radiation (e.g., neutron and gamma ray) shielding, appropriate structural property when exposed to different operating conditions such as a wide range of operational temperatures and radiation doses and meet multimodal transportation needs. For structural applications (for example, reactor vessels and other passive structures), light-weight materials must demonstrate resilience when subjected to different operational, transportation, and external conditions (for example, shock, seismic vibrations, flooding, tsunami, fire, and other hazards).

Manufacturing for nuclear applications enables multiple benefits over conventional approaches. Flexibility in design and use of materials, complex geometry, cost-effectiveness, embedded sensing, hybrid materials, and others are some of the benefits of additive manufacturing. New and ongoing advancements in additive manufacturing could be beneficial to design and develop light-weight materials for shielding and structural applications of fission batteries. Beyond the manufacturing needs for light-weight materials, facilitating the expanded usage of standardized reactor components and scalable manufacturing infrastructure, that meet both technical and economical requirements to fully factory-fabricate reliable and durable fission battery systems, is required.

Fast-paced advancement in material design, development, and manufacturing must be matched with well-established qualification process before commercial usage. This requires ensuring materials reliability under different conditions such as knowing failure modes, failure mechanisms, performance analysis of failure, and others. Testing of material samples performed at an actual or sub-sample level must be scalable to field deployment size of components and operating conditions. Testing and the qualification process must include studying time-based singular and/or combined effects of temperature, radiation, corrosion, and other environmental conditions. These warrant developing capabilities to provide data to expedite the qualification process.

Capabilities

Some of the experimental test beds and facilities that are encouraged for proof-of-concept demonstration and V&V of developed technologies (Figure 6) include:

1. Microreactor AGile Non-nuclear Experimental Testbed (MAGNET) is a non-nuclear test bed. Initial operation of MAGNET is expected to be controlled by manual operators with some proportional-integral-derivative controllers. The instrumentation and sensors are defined for initial operation of MAGNET to support startup, steady-state, shutdown, and off-normal transient behavior in steady-state operation, transient operation, and load-following conditions. The MAGNET test bed provides a unique opportunity for development and demonstration of the minimal set of instrumentation and sensors, reliable autonomous operation, and dynamic risk calculation for different operating conditions of fission batteries supported by digital-twin technologies.

Figure 6. R&D in capabilities thrust area for V&V.

2. Microreactor Application Research Validation and Evaluation (MARVEL) provides an opportunity to establish and exercise key capabilities that support future reactor demonstrations. The MARVEL test bed will support the rapid development and demonstration of a small reactor system, including performing environmental assessments, developing and reviewing safety bases, and demonstrating autonomous controls with minimal sensor sets, data architecture and communications, secure unattended operations, and remote-monitoring capabilities.

3. Transient Reactor Test Facility (TREAT) is a graphite-based material test reactor with strong negative temperature feedback physics, a nimble transient-control drive, and an automatic control system, making it uniquely able to perform shaped-power excursions for nuclear fuel safety research and other transient science. This test bed can be used to demonstrate anticipatory controls, the impact of radiation on digital instrumentation and sensors, and the possible collection and transmission of data during a transient event.

4. The capabilities with INL's National and Homeland Security Directorate will be leveraged to V&V technologies developed to ensure safe and secure operation of fission batteries. In particular, capabilities with power and grid systems, control systems cybersecurity, infrastructure resiliency, nuclear nonproliferation, and wireless security will be leveraged.

5. Research reactors at the NUC, CAES, and other strategic universities offer complimentary resources to develop and demonstrate technologies associated with fission battery attributes. For example, the Massachusetts Institute of Technology (MIT) reactor could be used for digital instrumentation and sensor evaluation. The Ohio State University research reactor is used for a wide range of nuclear-related research and demonstration activities, such as the evaluation of radiation damage to electronic components and other materials.

3.2 Priority Research Directions

Between January and April 2021, the INL and NUC leads (see Appendix A) organized a series of workshops on five scoping areas:

- Markets 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.

Each workshop area had several embedded topics; experts from academia, industry, government, national laboratories, regulatory group, and other organizations were invited to present and discuss technological challenges, knowledge gaps, and limitations (research, development, demonstration, and deployment) in each of the respective topics/areas. Each workshop summarized research challenges, gaps, and potential research topics in individual workshop reports [11–15]. These reports are available on the Fission Battery Initiative website [16] along with presentations and video recordings.

The Fission Battery Initiative workshop series identified six priority research directions (PRDs) that strengthen the initiative attributes and address the challenges herein. Figure 7 illustrates PRDs that support the different R&D thrust areas in Section 3.1 (except for the material science area). The identified PRDs are not mutually exclusive but rather have significant dependency among each other. Embedded within each PRD is the research need to address the economic attribute of the initiative.

PRD 1. Fully reliable, secure, and resilient autonomous operation and controls. Full autonomy will differentiate fission batteries from other advanced reactor systems and represents a significant departure from the currently accepted operational paradigm. Achieving such goals requires investment in sensor and instrumentation, AI, communication, digital twin, advanced/anticipatory control, cybersecurity and physical security, online predictive M&S, and other emerging technologies. Additionally, these new and emerging technologies present significant integration challenges to enable holistic reactor monitoring capabilities, real-time risk-informed decision-making, and accounting for trustworthiness in algorithms and human-system interactions at remote-monitoring locations. This demands innovative research in hardware, software, networks, security, human factors, and their seamless integration and addresses economic benefits of autonomy by developing approaches that quantifiably reduce operation costs.

PRD 2. Sensor requirements and their optimization for complete situational awareness. Sensors are the primary source of real-time data and represent one of the driving challenges for achieving PRD 1. Sensors are broadly categorized into three types: active, passive, and virtual. In the context of fission batteries, the majority of sensors and instrumentation will be utilized throughout their lifecycles or reused for a new fission battery to (1) monitor salient in-core and ex-core parameters, (2) maintain situational awareness, and (3) provide a basis for informed decision-making. With the miniaturization and simplification of nuclear system design and preference to eliminate penetrations to power sensors and transfer data, installing extensive and redundant active sensing technologies is no longer feasible. This evolution warrants redefining sensor and associated instrumentation requirements while optimizing their selection and placements. In addition, to offset the extensive dependence on active and passive sensing technologies both in-core and ex-core, virtual sensing is expected to play a prominent role in the demonstration, deployment, and operation of fission batteries.

PRD 3. PRA tool for fission battery attributes. Fission batteries will employ new and emergent technologies enabling new operating, transportation, siting, manufacturing, safeguards, safety, licensing, and dispositioning concepts. U. S. Nuclear Regulatory Commission (NRC) uses PRA techniques across multiple levels (Level 1–Level 3 [17]) to determine risk and safety of nuclear reactors under a wide range of conditions (including normal, transient, and abnormal situations due to external natural and man-made hazards). To enable commercial deployment of fission batteries as a distributed energy source when connected to the load directly or as part of other distributed energy resources, new and advanced dynamic PRA tools supporting the fission battery attributes need to be developed. The fission battery PRA tools must be scalable and adaptive as they will be based on a set of unique, limited, and evolving data. In some cases, PRA tools could be an extension of legacy and current PRA tools developed for light-water and advanced reactors.

PRD 4. Decay heat removal to ensure safe and reliable operation and transportation. The decay heat removal presents challenges both at reactor installation sites and during transportation, as each require different functional safety requirements. With respect to fission battery siting, multiple scenarios are possible (on ground, over a mobile truck, underground in a vault, or over a body of water). Decay heat removal is critical in all scenarios. Based on peak allowable fission battery accident temperature limits, the fission battery emergency decay-heat removal system should have the ability to ensure immediate and long-term heat removal, ensuring safety from external events and malicious intents. Similarly, some of the challenges associated with transporting fission batteries after their usage and operational history include ensuring decay heat and dose rates are below allowable levels for transportation while developing/identifying light-weight materials with excellent shielding of neutrons, radiation absorption, and heat removal capabilities. Light-weight materials must demonstrate acceptable performance.

Figure 7. Fission Battery Initiative PRDs.

PRD 5. Validation, verification, and uncertainty quantification of models, methods, and tools. A wide range of methods, models, tools, and technologies to be developed and integrated to achieve fission battery attributes and regulatory acceptance will be new and/or a significant advancement of legacy approaches. Mathematically rigorous and detailed validation, verification, and uncertainty quantification (V&V+UQ) protocols are required. These V&V+UQ protocols should include different levels moving between different scales and from single physics to multiphysics M&S such as code verification for standalone codes, separate effects validation for single physics, verification of multiphysics coupling, integral effects validation for a coupled model, and uncertainty quantification/propagation supported through stochastic tools. Dedicated V&V+UQ protocols should be defined for fission battery technology. In addition, software quality assurance should be part of the V&V+UQ protocol.

PRD 6. Secure remote monitoring and communication infrastructure. Fission batteries will potentially be deployed in remote, harsh, and/or hostile environments either in isolation or in multiples such as those found in disaster relief areas or remote community. While local control of the fission battery will be addressed through autonomy, remote monitoring of fission batteries needs to address issues that evade the autonomous system, sabotage, and issues related to theft of nuclear material or the battery. Fission batteries could be reused, and therefore, transition from one usage application to another can be abused. A remote site is required to maintain secure monitoring of one or more fission batteries at various geo-locations. Research addressing cyber and physically secure remote-monitoring architecture with scalable and multi-band communication technologies with both domestic and international aspects is required.

3.3 Planned Annual R&D Activities and Outcomes

The Fission Battery Initiative's progress is defined by cross-cutting R&D and technological demonstration through FY 2024 (Table 1).

Table 1. Cross-cutting R&D activities through FY 2024.

Fiscal Year	**Activities**
2020	• Established the initiative. • Executed a special Laboratory Directed Research and Development (LDRD) call supporting unattended and reliable attributes. • Engaged NUC in planning a workshop series in FY 2021.
2021	• Issued the Fission Battery Initiative R&D plan. • Organized a virtual workshop series on the five scoping topics in Table A2 to inform the identification of PRDs. • Identified six PRDs to address gaps and challenges of the fission battery attributes. • Secured funding from National Nuclear Security Administration's International Nuclear Security Program (NA-21) on Cyber Digital Twins for Secure Autonomous Operation of Microreactors. • Performed an initial risk and reliability modeling of an autonomous control system to enable unattended operation of fission batteries.
2022	• Update the Fission Battery Initiative R&D plan. • Develop a light-weight materials research scope in coordination with other NS&T programs. • Publish research articles in the special issue *Innovations Addressing Technical Issues Posed by Fission Battery Attributes* in *Progress in Nuclear Energy*. • Achieve the digital twin of MAGNET testbed.
2023	• Coordinate with activities to achieve INL net-zero carbon emission. • Coordinate and align Fission Battery Research and Development activities within INL's Nuclear Reactor Sustainment and Expanded Deployment initiative with MIT's nuclear battery efforts.

	• Align the fission battery research effort with INL's Advanced Materials and Manufacturing for Extreme Environments initiative for manufacturing of light-weight materials and testing capabilities. • Organize a workshop to discuss gaps, challenges, desired outcomes, and resources required to develop a light-weight materials for shielding and structural applications of fission batteries. • Reach out to experts on establishing a technical basis for regulatory acceptance of the unattended operation of a nuclear system. • Identify research needs for smart materials to achieve situational awareness. • Identify research needs to enable transportation and flexible siting requirements. • Demonstrate autonomous and reliable operation of experiments/test articles using MAGNET with dynamic risk assessment capability. • Formulate a research scope to develop a technical basis to achieve total integrated autonomous operation of fission batteries.
2024	• Establish a sufficient set of sensors, including virtual sensing, to measure salient nuclear system parameters and demonstrate it in MAGNET/MARVEL/TREAT. • Develop a proof-of-concept for technologies enabling manufacturing of light-weight materials. • Invest in developing capabilities for testing light-weight materials. • A methodology to enable optimal sparse sensing and sparse learning of nuclear digital twins (for example, a MAGNET digital twin). • Collaborate with National Reactor Innovation Center (NRIC) to support the inclusion of fission battery attributes with integrated energy systems.

Through cross-cutting R&D and technological demonstration, the Fission Battery Initiative by 2024 would:

- Advance R&D with enabling technologies targeted to fission battery attributes
- Establish an understanding of fission batteries' overall lifecycle costs for different potential markets
- Establish an understanding of fission batteries' security and reliability under possible operating environments
- Assess, analyze, and establish an approach to understand implications of domestic regulatory structures related to enabling technologies associated with fission battery attributes to enable broad deployment while minimizing the associated risk
- Attract collaboration and partnership from the U.S. DOE, Office of Nuclear Energy (NE), the U.S. Department of Defense, the National Aeronautics and Space Administration, the National Nuclear Security Administration, the U.S. NRC, and private industries in area of unattended operation of fission batteries.

3.4 Initiative Accomplishments

The accomplishments of the initiative to date include (1) three peer-reviewed conference papers in the American Nuclear Society Virtual Winter Meeting, November 16–19, 2020, (2) seven active LDRD projects with total investment of $1,365,000 in FY 2022 (see Appendix B), (3) a workshop series in collaboration with NUC schools to identify PRDs associated with the fission battery attributes, and (4) secured funding to perform preliminary assessment of potential vulnerabilities of autonomous operation using cyber-digital twins from National Nuclear Security Administration's International Nuclear Security Program.

4. EXECUTION STRATEGY

To ensure success of the initiative, the following execution strategies are currently planned:

1. **Cross-Directorate and Cross-Initiative R&D:** There is a wide range of expertise, infrastructure, and resources, along with separate initiatives, across directorates within INL that need to be coordinated and connected through R&D. In this effort, synergetic collaboration will be identified between different directorate capabilities and initiatives to advance fission battery attributes. The collaboration will be mutually beneficial in maximizing cross-cutting R&D and demonstration. The following cross-directorate and cross-initiative collaborations are of particular interest: (1) NS&T Directorate and the National and Homeland Security Directorate on topics related to safeguards and security and data resilience; (2) NS&T and the Energy Environmental Science and Technology Directorate on topics related to integrated energy systems, data integration, and controls; and (3) NS&T's Fission Battery Initiative and the Nuclear Material Discovery and Qualification Initiative on topics related to materials research and manufacturing.

2. **University Partnerships:** Collaborate with INL's NUC, CAES, and other strategic universities to identify expertise, resources, and infrastructures that are unique, complementary to INL capabilities and would directly benefit the R&D and technological demonstration of fission battery attributes. This collaboration can also be established through the DOE-NE's Nuclear Energy University Program. These collaborations also lay the foundation for future talent pipeline development via internships, graduate fellowships, and joint appointments.

3. **Engaging the Department of Energy:** Understanding R&D activities performed in key DOE-NE programs—such as Advanced Reactor Development, Nuclear Energy Enabling Technologies, Nuclear Energy Advanced M&S, along with NRIC, Gateway for Accelerated Innovation in Nuclear, and Advanced Research Projects Agency–Energy—is critical in identifying technical and knowledge gaps. In addition, R&D performed by the DOE, Office of Science, needs to be understood and expanded to achieve fission battery attributes.

4. **Engaging Regulators, Industries, and other DOE Laboratories:** The initiative's vision will be shared with the U.S. NRC, advanced reactor developers and stakeholders, and other DOE national laboratories. In the FY 2021, this engagement will be established via an INL- and NUC-organized workshop series on the initiative. The workshop details are in Appendix A.

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Appendix A

Workshop Point of Contacts

Table A1. INL points of contact (POCs) for the fission-battery workshop.

Scoping Area	INL POC	Email
Markets and Economic Requirements for Fission Batteries and Other Nuclear System	Andrew W. Foss	andrew.foss@inl.gov
Technology Innovations for Fission Batteries	Vivek Agarwal	vivek.agarwal@inl.gov
Transportation and Siting for Fission Batteries	Elmar F. Eidelpes	elmar.eidelpes@inl.gov
International Safeguards and Security of Fission Batteries	Gustavo A. Reyes	gustavo.reyes@inl.gov
Safety and Licensing of Fission Batteries	Jason A. Christensen	jason.christensen@inl.gov

Table A2. NUC POCs for the fission-battery workshop.

Scoping Area	NUC POC	Email
Markets and Economic Requirements for Fission Batteries and Other Nuclear System	Charles W. Forsberg (MIT)	cforsber@mit.edu
Technology Innovations for Fission Batteries	Izabela Gutowska and Marcum Wade (Oregon State University) and Cassiano Ricardo (University of New Mexico)	izabela.gutowska@oregonstate.edu; wade.marcum@oregonstate.edu; cassiano@unm.edu
Transportation and Siting for Fission Batteries	Abhinav Gupta (North Carolina State University) and Abdollah Shafieezade (The Ohio State University)	agupta1@ncsu.edu; shafieezadeh.1@osu.edu
International Safeguards and Security of Fission Batteries	Carol Smidts (The Ohio State University) and Cassiano Ricardo (University of New Mexico)	smidts.1@osu.edu; cassiano@unm.edu
Safety and Licensing of Fission Batteries	Maria Avramova (North Carolina State University) and Dean Wang (The Ohio State University)	mnavramo@ncsu.edu; wang.12239@osu.edu

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Appendix B

Current Research Projects

Table B1. List of current projects addressing fission battery attributes.

Fiscal Year	Project Title	Principal Investigator
2020	Unattended Operation through Digital Twin Innovations	Jeren M. Browning
	Quantitative Reliability Analysis for Unattended Operation of Fission Batteries	Steven R. Prescott
2021	Promoting Optimal Sparse Sensing and Sparse Learning for Nuclear Digital Twins	Mohammad G. Abdo
2022	Resilient Remote Operation of Microreactors and Fission Batteries	Joseph E. Oncken
	Integrated Reactor Shield-Structures for Fission Batteries	Samuel E. Bays
	Development of Light-weight Structural Materials with Improved Mechanical Properties for Fission Batteries Application	Rongjie Song
	A Causal Approach to Model Validation and Calibration	Diego Mandelli