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Revision 0

Fission Battery Initiative

January 2021

Research and Development Plan

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

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ABSTRACT

The Fission Battery Initiative has been established by Idaho National Laboratory's (INL's) Nuclear Science and Technology Directorate 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 the following key attributes to be achieved: 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, and the initial scope of targeted R&D planned through 2024.

ACKNOWLEDGEMENTS

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ACRONYMS

AI	artificial intelligence
CAES	Center for Advanced Energy Studies
ML	machine learning
MAGNET	Microreactor AGile Non-nuclear Experimental Testbed (MAGNET)
MARVEL	Microreactor Application Research Validation and Evaluation
M&S	modeling and simulation
NUC	National University Consortium
R&D	research and development
TREAT	Transient Reactor Test Facility
TRL	Technology Readiness Level
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, 4]. 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 [4, 5]. 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.

Currently operating nuclear system 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 U.S. 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.

The Fission Battery Initiative has been established by Idaho National Laboratory's (INL's) Nuclear Science and Technology Directorate [6] to define, focus, and coordinate 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 the following key attributes to be achieved: 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 micro-reactor designs and concepts, rather than development of new reactor concepts. This initiative is coordinated with INL's National University Consortium (NUC) [7], Center of Advanced Energy Studies Universities (CAES) [8], 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.

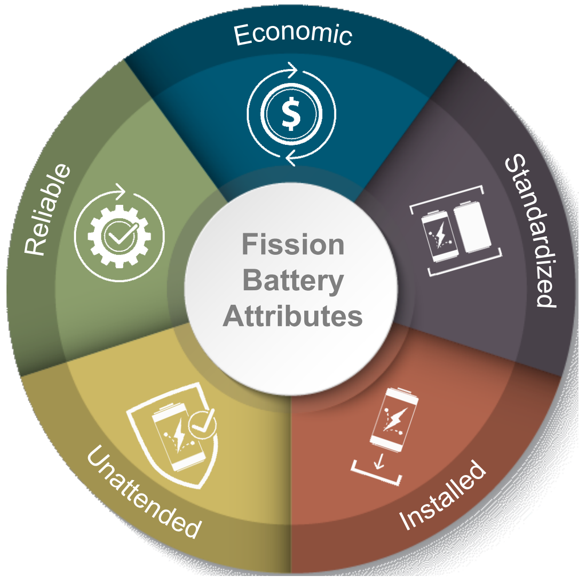

Figure 1. Fission battery attributes.

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 life-cycle 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 three thrust areas: technology, data 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 [9]. 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.

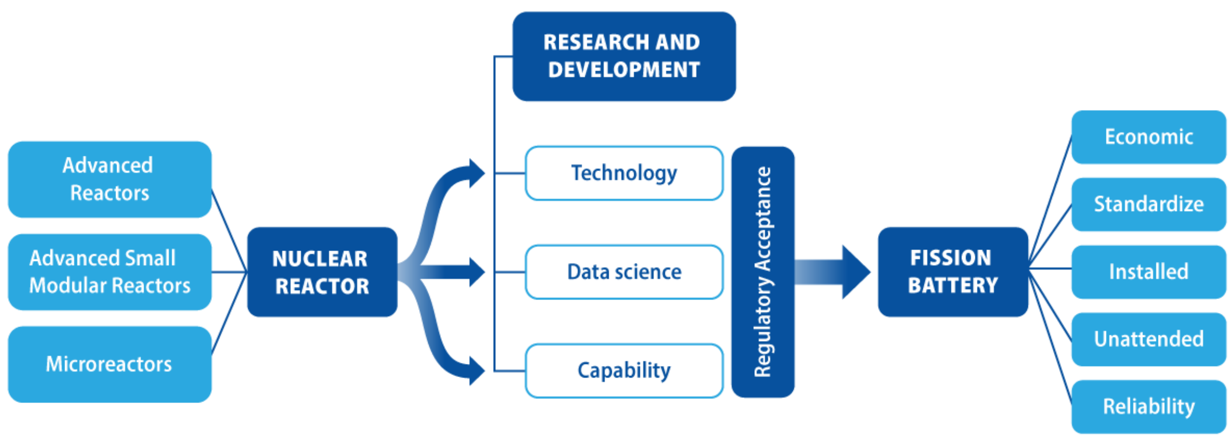

Figure 2. Fission Battery Initiative R&D to enable nuclear reactor technologies to achieve fission battery attributes.

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.

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

3.1.1 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).

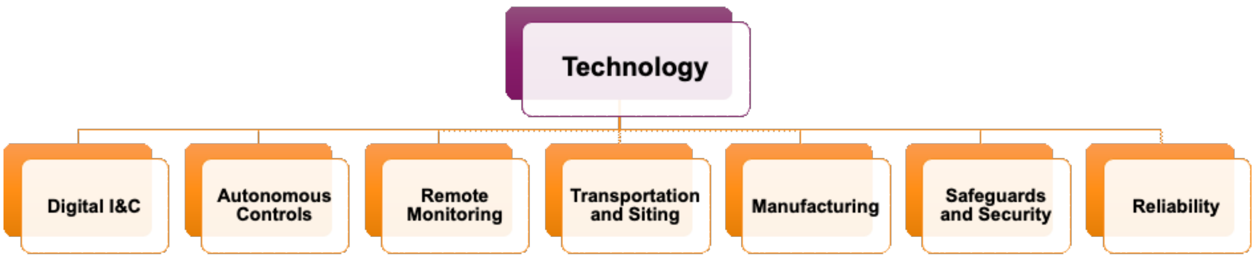

Figure 3. R&D in technology-thrust areas.

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- or multi-modal) 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 is 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 are 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- 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.

To facilitate expanded usage of standardized reactor components, scalable manufacturing infrastructure is required for assembly and fabrication. This requires advanced manufacturing methods to leverage M&S and ML/AI techniques to evaluate already qualified materials that meet both technical and economical requirements to fully factory-fabricate reliable and durable fission-battery systems.

Safeguards and security of fission batteries must ensure their usage does not raise any concerns related to domestic and international proliferation, cybersecurity, or 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 consequence-driven, cyber-informed engineering to secure critical infrastructure. 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.

3.1.2 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, 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.

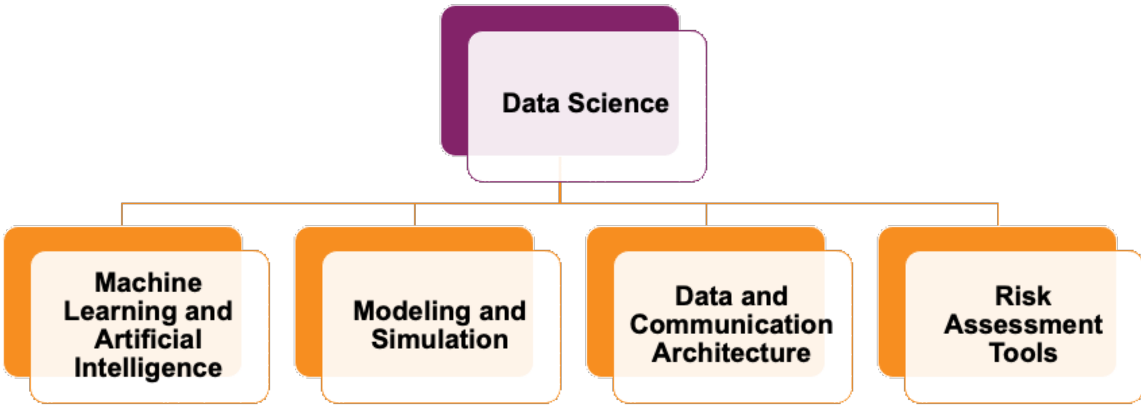

Figure 4. R&D in the data-science thrust area.

Multiphysics and multiscale modeling and simulation 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 deployment of 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 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.

3.1.3 Capabilities

Some of the experimental test beds and facilities that are encouraged for proof-of-concept demonstration and V&V of developed technologies (Figure 5), 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

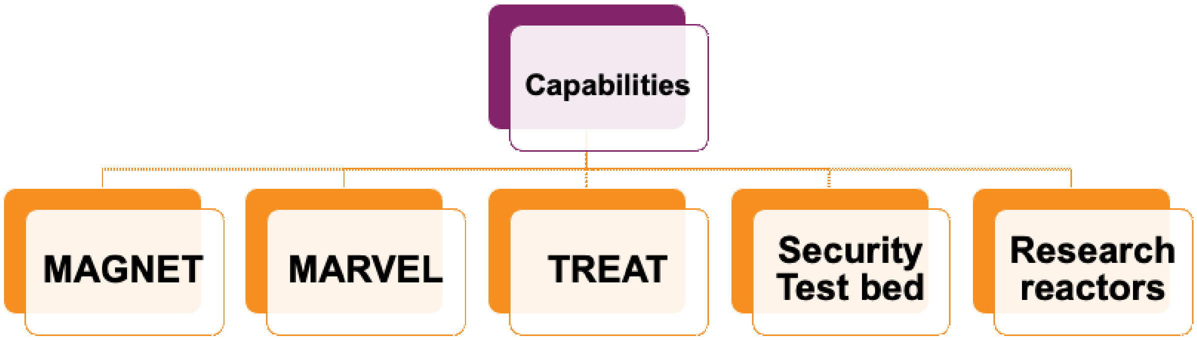

Figure 5. R&D in capabilities thrust area for V&V.

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.

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, impact of radiation on digital instrumentation and sensors and 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 reactor (MIT) 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 evaluation of radiation damage to electronic components and other materials.

3.2 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	• The initiative was established • A special Laboratory Directed Research and Development call supporting unattended and reliable attributes was executed • NUC was engaged to coordinate workshop series in FY 2021
2021	• Complete Fission Battery Initiative R&D plan • Demonstrate initial autonomous and reliable operation of experiments/test articles using MAGNET • Develop digital instrumentation, sensing (virtual sensing), and security technologies to achieve unattended operation • Develop integrated approach to address costs and/or risk linked to R&D outcomes in the unattended operation • Organize a series of workshops to update goals of fission-battery attributes and update the initiative R&D plan based on workshop series outcomes
2022	• Achieve autonomous operation of experiments/test articles using MAGNET through digital-twin technology • Develop technologies to standardize data and secure communication architectures for unattended and remote monitoring • Develop technologies to secure unattended operation of fission batteries
2023	• Demonstrate autonomous and reliable operation of experiments/test articles using MAGNET with dynamic risk assessment capability • Establish technical basis to achieve regulatory acceptability associated with autonomous controls and operation of a nuclear system • Develop technologies to demonstrate explain ability and trustworthiness of autonomous controls and operation
2024	• Establish a sufficient set of sensors, including virtual sensing, to measure salient nuclear system parameters and demonstrate it in MAGNET/MARVEL/TREAT • Develop technologies enabling scalable manufacturing process to achieve full factory fabrication of nuclear systems achieving goals of various fission-battery attributes • Collaborate with National Reactor Innovation Center (NRIC) to support inclusion of fission-battery attributes with integrated energy systems

Through cross-cutting R&D and technological demonstration, the initiative will, by 2024,

- Advance R&D in enabling technologies targeted to fission-battery attributes
- Establish an understanding of overall life-cycle costs of fission batteries for different potential markets
- Establish an understanding of the security and reliability of fission batteries 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. Department of Energy (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. Nuclear Regulatory Commission, and private industries in area of unattended operation of fission batteries.

3.3 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) two LDRD projects (see Appendix B); and (3) planning of a workshop series in collaboration with NUC schools.

4. EXECUTION STRATEGY

To ensure success of the initiative, the following execution strategies are planned to be carried out:

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) Nuclear Science and Technology (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 U.S. Department of Energy Office of Nuclear Energy's (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 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 Modeling and Simulation, 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. Nuclear Regulatory Commission, 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
Economic	Andrew W. Foss	andrew.foss@inl.gov
Technology	Vivek Agarwal	vivek.agarwal@inl.gov
Transportation and Siting	Elmar F. Eidelpes	elmar.eidelpes@inl.gov
Safeguards and Security	Gustavo A. Reyes	gustavo.reyes@inl.gov
Safety and Licensing	Jason A. Christensen	jason.christensen@inl.gov

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

Scoping Area	NUC POC	Email
Economic	Charles W. Forsberg (MIT)	cforsber@mit.edu
Technology	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	Abhinav Gupta (North Carolina State University) and Abdollah Shafieezade (The Ohio State University)	agupta1@ncsu.edu; shafieezadeh.1@osu.edu
Safeguards and Security	Carol Smidts (The Ohio State University); Cassiano Ricardo (University of New Mexico)	smidts.1@osu.edu; cassiano@unm.edu
Safety and Licensing	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