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Fission Battery Initiative

September 2021

Safety and Licensing Workshop Report

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ABSTRACT

Idaho National Laboratory and National University Consortium organized the Safety and Licensing for Fission Battery (FB) workshop (virtual) on April 16, 2021. The workshop's topics were aimed at understanding safety and licensing aspects of fission batteries. The safety and licensing aspects are of high importance since many of the technologies needed to develop fission batteries will be disruptive and are expected to have new capabilities that will need to be addressed. The new safety analysis and licensing aspects should consider the main attributes of the fission batteries, such as simplified design to be mass produced in factories with standardized sizes, reliable performance with remote monitoring technologies, secure and safe unattended operation, and readily and easily installed for use and removal after use.

The objectives of this Safety and Licensing for Fission Battery workshop were to:

- Discuss computational and validation tools needed for fission battery safety analysis and confirmatory regulatory evaluations.
- Discuss approaches for preparing fission battery safety analysis reports.
- Discuss development of fission battery initial license applications.
- Discuss implementation of design control practice defined in ASME-NQA-1 to fission battery safety analysis and report.

The expected outcomes of this workshop were to:

- Identify research and development required to perform fission battery safety analyses and evaluations.
- Propose graded preparation approach and content of the fission battery safety analysis report.
- Establish the technical bases for licensing and operation based on unique fission battery attributes.
- Establish and implement processes to control the design and design changes of items that are subject to the quality assurance requirements.

The workshop's outcomes identified four thrust areas that will require extensive research and development. These areas, which were discussed in dedicated workshop sessions, include:

- Thrust Area 1: Modeling and Simulation of FB Safety.
- Thrust Area 2: Safety Design Basis and Strategy for FB.
- Thrust Area 3: Licensing and Regulatory Research for FB.
- Thrust Area 4: Design Control of the Design-Basis Envelope for FB and Support for DOE's Authorization Process.

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ACRONYMS

AI	Artificial Intelligence
ALARA	As Low As Reasonably Achievable
ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
BEPU	Best Estimate Plus Uncertainties
BWXT	BWX Technologies
CRAB	Comprehensive Reactor Analysis Bundle
DOE	Department Of Energy
DT	Digital Twin
FB	Fission Battery
HTGR	High Temperature Gas Reactor
INL	Idaho National Laboratory
LBEs	Licensing Basis Events
LMP	Licensing Modernization Project
LWR	Light Water Reactor
MIT	Massachusetts Institute of Technology
ML	Machine Learning
MR	Micro Reactor
M&S	Modeling and Simulation
NLWR	Non-Light Water Reactor
NQA-1	Nuclear Quality Assurance
NRC	Nuclear Regulatory Commission
NUC	National University Consortium
OSU	Ohio State University
PCMM	Predictive Capability Maturity Model
PIRT	Phenomena Identification and Ranking Table
PRA	Probabilistic Risk Assessment
PRDs	Priority Research Directions
QA	Quality Assistance
R&D	Research and Development
RTA	Research Thrust Areas
SER	Safety Evaluation Report
SQA	Software Quality Assurance
TRLs	Technology Readiness Levels
VVUQ	Verification, Validation, and Uncertainty Quantification

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Fission Battery Initiative

Safety and Licensing Workshop Report

1. INTRODUCTION

Nuclear power is an important part of United States (U.S.) energy portfolio and the most reliable and efficient way to produce carbon-free electricity. The current commercial nuclear power technology is based on Light Water Reactors (LWRs) consisting of large (~1,000MWe) reactors in terms of significant onsite infrastructure and a sizeable operational staff. LWRs are recognized as playing a critical role in our nation's transition to a carbon-free grid. At present, it is the only carbon-free technology capable of providing scalable, zero-emission baseload power around the clock. The next generation of nuclear reactors are based on a fundamentally different design philosophy than their LWR-based predecessors. They are not only safer and more efficient than LWRs but are also defined by their small size and modularity, which enables them to meet varying load demands. In another major departure from current LWR designs, the new advanced small modular reactors and microreactors are designed to be installed rather than constructed on site. This dramatically reduces the lead time to first power as well as the costs associated with the reactor. The small size, inherent safety, and modularity of these advanced reactor designs mean they can be deployed in situations that would have been impossible for LWRs. 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 [1-2]. The Fission Battery (FB) initiative [3] has been established by Idaho National Laboratory's (INL) to define, focus, and coordinate research and development (R&D) of technologies that enable microreactors to function as batteries. The vision and general concept of FBs is 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 FB initiative has adopted the following key attributes to be achieved: economic, standardized, installed, unattended, and reliable.

The FB initiative [4] is focused on conducting fundamental R&D to address the challenges related to the above listed five key attributes. This initiative is coordinated with INL's National University Consortium (NUC) [5]. 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. This will allow the initiative to clearly identify the challenges, gaps, and limitations to prioritizes the R&D needed.

Idaho National Laboratory (INL), 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 FBs attributes. These scoping areas include:

- Market and economic requirements for FBs and other nuclear systems.
- Technology innovation for FBs.
- Transportation and siting for FBs.
- International safeguards and security of FBs.

- Safety and licensing of FBs.

The discussions held during the workshop series promoted fundamental rethinking of developing, demonstrating, and deploying technological solutions that would address issues related to the above scoping areas. Safety and licensing aspects of FBs are very important since many of the technologies would be disruptive and is expected to have new features to be addressed in safety analysis and licensing process such as simplified design to be mass produced in factories with standardized sizes, reliable performance, autonomous controls and unattended operation, remote monitoring technologies etc. This report summarizes the outcomes of the Safety and Licensing workshop, which identify R&D required to perform fission battery safety analyses and evaluations; propose graded preparation approach and content of the FB safety analysis report; establish the technical bases for licensing and operation of unique FB features; and establish and implement processes to control the design and design changes of items that are subject to the quality assurance requirements.

1.1 Safety and Licensing Workshop Purpose

Within the FB safety and licensing technology scoping, the virtual workshop on April 16, 2021, focused on the following topics:

- Modeling and Simulation of FB Safety.
- Safety Design Basis and Strategy for FB.
- Licensing and Regulatory Research for FB.
- Design Control of the Design-Basis Envelope for FB and Support for DOE's Authorization Process.

The workshop's topics were aimed at understanding safety and licensing aspects of FBs. These safety and licensing aspects are of high importance since many of the technologies needed to develop FBs will be disruptive and are expected to have new capabilities that will need to be addressed. The new safety analysis and licensing aspects should consider attributes of the FBs, such as simplified design to be mass produced in factories with standardized sizes, reliable performance with remote monitoring technologies, secure and safe unattended operation, and readily and easily installed for use and removal after use.

A recording of the workshop is available on the FB initiative website with workshop agendas and presentations [6]. These agenda, presentation, and speaker information are summarized in Appendix A.

1.2 Report Outline

The report is organized as follows:

- Section 2 presents the summary of highlights, challenges, and gaps discussed during the FB safety and licensing workshop.
- Section 3 describes the research direction in Validation, Verification, and Uncertainty Quantification (VVUQ).
- Section 4 describes the research thrust areas that were identified during the workshop and are required to achieve a safe and licensable FB.
- Section 5 presents the outcomes and impacts expected in identifying research and development required to perform FB safety analyses and evaluations and to establish the technical bases for FB licensing.

2. HIGHLIGHTS, CHALLENGES AND GAPS

The Safety and Licensing Workshop topics covered corresponded to the titles of workshop sessions.

Session 1/Topic 1: Modeling and Simulation (M&S) of FB Safety

Session 1 focused on modeling and simulation tools required to analyze and understand the performance and behavior of FB safety. The objective was to identify a validated and verified, tightly integrated group of multi-physics modeling and simulation codes for FB safety analyses and evaluations. See Appendix A for presentation details.

Session 2/Topic 2: Safety Design Basis and Strategy for FB

Session 2 focused on comparing deterministic versus risk-informed and performance-based approaches. The objective was to compare these approaches and to focus on the graded approach, which encourages the preparation of safety analyses that justify the selection of event sequences, the level of analysis detail, and scope of documentation from a combination of risk- and performance-based evidence. In this context, the content of the FB safety analysis report was discussed. See Appendix A for presentation details.

Session 3/Topic 3: Licensing and Regulatory Research for FB

Session 3 discussed how to develop technical information, data, and knowledge that can support both industry and the regulators for an initial license application. The objective was to establish the technical bases for licensing and operation of unique FB features including control systems and strategies for autonomous and semi-autonomous FB control. See Appendix A for presentation details.

Session 4/Topic 4: Design Control of the Design-Basis Envelope for FB and Support for DOE's Authorization Process

Session 4 addressed the design control practice defined in ASME-NQA-1, where it is common to distinguish documents prepared for a nuclear facility safety case. The objective was to satisfy the DOE Quality Assurance (QA) Requirements as well as to establish and implement processes to control the design and design changes of items that are subject to the QA requirements. The U.S. NRC and DOE criteria and guidance for developing the overall safety basis, leading to the preparation of a documented safety analysis report for FB were discussed along with providing guidelines for performing those analyses necessary to identify the major facility hazards and associated critical safety functions. See Appendix A for presentation details.

2.1 Highlights of the Workshop

Highlights that support FB initiatives were identified from the above-described workshop sessions based on recent publications and rulemakings relevant to the safety and licensing of FBs:

Highlight 1: The relative newness of everything related to FB attributes presents several M&S challenges [6-9]:

- Safety case preparation.
- Knowledge of design-specific processes.
- Analysis fidelity.
- Data for VVUQ, risk measures, ALARA (As Low As Reasonably Achievable) methods.
- Consensus-building for technology readiness metrics.

Highlight 2: To fill safety case evidence gaps, there is a need for low-power FB prototype(s) [6, 10]:

- Data to support M&S applications and evaluation model validation.
- Some separate-effects testing may still be necessary.
- Low power, defined based on a deterministic radiological consequence analysis?

Highlight 3: Many (technology-dependent) paths can lead to the same destination, but we must all get there safely. From existing technologies those which guarantee high-level of safety will be selected [6].

Highlight 4: Wide variety of tools needed for design, licensing, deployment, and operation of advanced nuclear energy systems [6-9]:

- Includes conceptual design, production, reference, and R&D.

Highlight 5: Existing (ready for deployment) M&S tools are needed for design and deployment on short schedule [6-9]:

- Must take advantage of existing tools that are already available.
- Requirements include usability, robustness, efficiency, support, QA, and validation.

Highlight 6: In addition to standard validation of M&S tools for applications to microreactor design and safety a specific focused validation activities are required for the envisioned FB attributes as an economical, standardized, installed, unattended, and reliable microreactor [6].

Highlight 7: M&S capabilities for microreactors including FBs, must include high-fidelity high-resolution multi-physics and full core/reactor analysis and this would relatively efficient and affordable with current high-performance computing because of small size of the problem [6-9, 14].

Highlight 8: Can we skip demonstration steps for FB (Micro Reactor – MR) deployment [6, 14]?

- Previous operated High Temperature Gas Reactor (HTGR) demos/reactors could be used as demos.
- Heat-pipe FB/MR may need performance demonstration.

Highlight 9: There are several software stacks available based on Multiphysics Object Oriented Simulation Environment (MOOSE) for FB M&S [6, 9, 14].

- Heat-pipe cooled micro-reactors: DireWolf.
- Gas-cooled micro-reactors: Sabertooth.
- Generic: Comprehensive Reactor Analysis Bundle (CRAB).

Highlight 10: U.S. NRC has regulatory authority over the unattended operation attribute [6].

- In the absence of rulemaking to establish a new category of reactors that would not require licensed operators, exemptions from existing regulations would be necessary.

Highlight 11: 10 CFR 53. Milestone schedule (with an estimated date of October 2024) to publish the final rule and key guidance showing that FBs can be licensed under 10 CFR 53 [6, 11-13].

Highlight 12: We can enable the resilience, or at least reliability, using Probabilistic Risk Assessment (PRA) [6, 13].

- Monitoring system compares actual performance with "expected" performance given by a Digital Twin during normal operation conditions.
- Monitoring system compares actual performance with "expected" performance given by the PRA event sequences during abnormal conditions.

Highlight 13: Meeting LWR or non-LWR PRA standard requirements including performance of peer reviews is a key element to assure technical adequacy of PRA for both Licensing Modernization Project (LMP) and alternative safety case approaches [6].

Highlight 14: Definition of a Digital Twin and its purpose in future nuclear licensing activities [6].

- Ongoing research and development activities for Digital Twins.
- Potential applications for Digital Twins in Fission Batteries.

Highlight 15: Licensing Modernization Plan (LMP) approach and its role in the U.S. NRC licensing process [6, 11-13].

- History of event selection and the selection of Licensing Basis Events (LBEs) in the LMP approach for licensing today.

- Applying the future 10 CFR Part 53 to Fission Batteries.

Highlight 16: Potential FB regulation pathways with a focus on DOE authorization [6].

- Fundamental similarities and differences between the NRC and DOE regulation.
- Allowances and limitations associated with DOE regulation of emerging reactor concepts including FB.
- The role of the LMP approach in the DOE authorization process.

Highlight 17: Safety document development process within DOE authorization [6].

- Approach for integrating safety into the design of FB systems.
- Functioning of this approach within the DOE authorization process for efficiently establishing and protecting safety requirements within the design phase.

Highlight 18: Internal processes in DOE to accommodate and push forward new reactors and nuclear facilities to support the nation's energy and testing needs [6].

- DOE adaptable regulatory process for the design and operation of new nuclear facilities including its key features and process flow.

2.2 Challenges and Gaps

Based on the presentations and follow up discussions on the presented highlights in the workshop's sessions the following challenges and gaps that relate to the FB attributes were identified:

Challenge/Gap 1: All M&S software requires validation, which may not be available for all FB concepts:

- Need to define validation gaps for each FB prototype.
- Validation of multi-physics models is a concern for all prototypes.

Challenge/Gap 2: Low-power demonstration plants may be required.

Challenge/Gap 3: To shorten development time, "ready-use" codes should be used when available.

- No time to develop new software stacks.

Challenge/Gap 4: Software must include usability, robustness, efficiency, support, QA, and validation.

Challenge/Gap 5: Depending on the business model, with whom does the regulator interact on issues concerning safety or security?

Challenge/Gap 6: Is the current Generic Environmental Impact Statement (GEIS) similar to the GEIS for advanced reactors needed for FBs?

Challenge/Gap 7: How would a Reactor Oversight Program work for FBs?

Challenge/Gap 8: Do we need a full prototype, or can the design be done (and licensed) using separate effects tests combined with analysis?

- Unless the design uses bounding analysis, a full scope PRA will be critical to a safe and cost-effective design.

Challenge/Gap 9: What is the purpose of the use of PRA?

- Early introduction of the PRA can support optimization of designs and reduce the needs for costly backfits.

Challenge/Gap 10: Is there a reactor size that justifies skipping the PRA?

- There is no standard on maximum credible accident (MCA). One can only "bound" the accidents that one has considered and to make this robust one needs a comprehensive enumeration of the event sequences.

Challenge/Gap 11: What is the role of the LMP approach?

- Appropriate balance of deterministic and probabilistic inputs to risk-informed decisions involved in design, operations, programs, and licensing.

3. VERIFICATION, VALIDATION AND UNCERTAINTY QUANTIFICATION

Safety and licensing aspects of FBs are critical as many of the technologies will be disruptive and are expected to have new features to be addressed in safety analysis and licensing process. For this reason, it is important to identify research and development required to perform FB safety analyses and evaluations including computational and validation tools needed for FB safety analysis and confirmatory regulatory evaluations. The following topics were discussed as research needed:

- M&S tools for safety and licensing.
- Data requirements.
- Integration of modeling and simulation capabilities for FB applications (i.e., adapting existing capabilities if applicable with development of missing parts).
- Development of a validation, verification, and uncertainty quantification protocol of digital twins developed for different FBs.

The associated M&S activities supporting the envisioned FB safety-in-design concepts consist of two tiers: safety evaluation models (Phenomena Identification and Ranking Table (PIRT)-based, VVUQ-emphasized) and audit evaluation models (audit/confirmatory calculations to examine selected safety related events). The associated challenges include: (1) adopting the most efficient in terms of time and resources involved development approach while addressing needed analysis fidelity and target accuracy and uncertainty requirements for M&S capabilities for safety and licensing; (2) developing consistent and comprehensive VVUQ protocols for both safety/confirmatory analysis and Digital Twins (DT); (3) formulating data, quality assurance, NQA-1 compliance, and licensing application requirements for modeling and simulation capabilities for fission battery applications. Relative newness of everything associated with FBs requires to address the lack of data needed to support M&S applications and evaluation model VVUQ. To fill safety case evidence gaps, there is a need for low-power prototype(s). In addition, some separate-effects testing may still be necessary.

The following research and development activities are needed to address the above-described challenges:

Integration of modeling and simulation capabilities for FB safety analysis and licensing

Since the accident scenarios for FBs may not perfectly overlap with stationary reactors, lists of possible accident scenarios need to be developed first for different FB designs, followed by evaluation of existing M&S tools are sufficient to establish safety and enable licensing of these designs. M&S capabilities must include multi-physics and full core/reactor analysis. An efficient approach, in terms of time and resources involved, would include integration of modeling and simulation capabilities for FB applications (i.e., adapting existing capabilities if applicable with development of missing parts). First, the gaps and needs in individual physics models (e.g., thermal hydraulics, materials, neutronics, source terms, etc.) should be identified followed by the identification of gaps in multi-physics modeling, which will depend on the FB concept. To reduce development time, "ready-use" codes should be used when available. There is limited time to develop new software stacks and ready-now tools needed for design and deployment on short schedule should be identified and evaluated. This process would be focused on addressing needed analysis fidelity and target accuracy and uncertainty requirements for M&S tools for safety and licensing. The final objective is to have a tightly integrated group of multi-physics M&S codes for FB safety/confirmatory analyses and evaluations. Because a wide variety of types of tools are needed for design, licensing, deployment, and operation it is important to take advantage of existing tools that are already available, such as exploring the coupling of DOE and industry tools for FB applications. Other potential research topic could be developing "best-practice" guidelines with respect to data transfer between physics and improving the robustness/speed of tightly coupled algorithms.

Formulation of data, quality assurance, NQA-1 compliance, and licensing application requirements for FB M&S.

The first step in this activity is to determine which additional data may be missing. There remain a few major gaps with the current generation of high-fidelity modeling and simulation. Unlike the prior generations, the investment in validation data has been broadly outpaced by development of analytical capability. Data from both separate and integral systems is desperately needed to confirm the adequacy of the results in a manner compliant with U.S. NRC regulations. Included in this effort is the characterization of process and phenomenological uncertainties and sensitivities. Data is needed to support M&S development/integration and evaluation model VVUQ. Multi-physics and multi-scale nature of the FBs and lack of UQ grade data further complicates the situation. Sufficient cases should be defined to cover the field of application. Some separate-effects testing may still be necessary and should be identified. To fill safety case evidence gaps, there is a need for low-power prototype(s). A plan for research lower power FB facility for obtaining validation data should be developed.

The integrated/developed software must include usability, robustness, efficiency, support, QA, and validation. A "Code VVUQ plan" must be developed including Software Quality Assurance (SQA). This should be supplemented by "Application VVUQ plan". In the case of multi-physics safety-related application the "Application VVUQ plan" should include a series of Application Progression Problems starting from single-physics problems, then moving to two-physics problems, three-physics problems, etc. The "Application VVUQ plan" includes developing a PIRT, a building validation pyramid to decompose the problem and assign work, and UQ studies.

It is important to realize that codes are licensed for specific applications that are safety related. Licensing is achieved by submittal of a Topical Report and the approval comes in the form of a Safety Evaluation Report (SER) from the US NRC.

The integrated/developed software framework should be consistent with NQA-1 requirements (useful for Commercial Grade Dedication) as well as be able to perform safety analyses of FBs that can be customized to the specific licensing strategy that is being pursued (conservative or Best Estimate Plus Uncertainties (BEPU)), depending on margin requirements. The end-product should be ready for audit/confirmatory analyses and to be used in safety/licensing analyses.

Development of VVUQ protocols for FB M&S and DTs.

Typical evaluation models rely on VVUQ protocols which should be developed for FB M&S. These protocols include devising a VVUQ strategy including support data and benchmarks. All M&S software requires validation, which may not be available for all FB concepts. Some FB concepts are more mature than others. First, validation gaps for each FB concept should need to be defined. Further, FB single-physics and multi-physic benchmarks should be defined including comprehensive and consistent uncertainty quantification and propagation through multi-physics multi-scale M&S of FB concepts. Machine Learning (ML) techniques and Artificial Intelligence (AI) should be involved in the M&S and VVUQ of FB concepts. Since the validation of multi-physics models is a concern for all concepts hierarchical multi-physics multi-scale VVUQ protocols should be developed. These protocols should include different levels moving between different scales and from single physics to multi-physics M&S such as code verification for standalone codes, separate effects validation for single physics, verification of multi-physic coupling, integral effects validation for coupled model, and uncertainty quantification/propagation supported through stochastic tool module. Dedicated VVUQ protocols should be defined for each FB technology and scenario considered.

Validation strategy is required for the envisioned FB attributes as an economical, standardized, installed, unattended and reliable microreactor. Therefore, a systematic approach to assess predictive capability maturity of analysis methodologies should be established. This approach should be based on systematic treatment of different uncertainty sources related to model development and code VVUQ plan combined with application VVUQ plan. The assessment process should be guided by the two qualitative frameworks, i.e., PIRT and Predictive Capability Maturity Model (PCMM). The capability and credibility of codes (individual and coupled simulation codes) should be evaluated. Capability refers to evidence of required functionality for capturing phenomena of interest while credibility refers to the evidence that provides confidence in the calculated results. For this assessment, each safety case defines a set of phenomenological requirements (based on PIRT) against which the software should be evaluated. This approach should enable the focused assessment of only those capabilities that are relevant to the safety case. The credibility assessment using PCMM should be based on different decision attributes that encompass VVUQ of the codes. For each attribute, a maturity score from zero to three should be assigned to ascertain the acquired maturity level of the codes with respect to the safety case of interest. Credibility in the assessment should be established by mapping relevant evidence obtained from VVUQ of codes to the corresponding PCMM attribute.

Research and development activities for digital twins (DTs) are going on with potential applications of DTs in FBs. One of these applications is for the purpose of future nuclear licensing activities. The most likely applications of DTs discussed above are all either high value or safety critical. It is therefore very important to be able to trust the predictions of the digital twin. This requirement means that there must also be trust in the data, trust in the model, and trust in the updating procedure. Trust requires verification and validation procedures. A further complication is that the existence of uncertainty means that validation (comparison with reality) needs to be treated as a statistical process. Uncertainty evaluation also gives a better understanding of how much trust can be placed in the model results. This trust is particularly important for models that include parameters that cannot be determined independently. These models are precisely the cases when the digital twin concept is so useful: it allows you to estimate what you cannot measure directly and thus improve your model. Therefore, it is very important to develop a VVUQ protocol for DTs using data-based methods.

In summary, research proposals are sought for integrating needed model/capability developments/improvements with utilizing available multi-physics M&S tools to develop a comprehensive and consistent multi-physics predictive M&S of different FB concepts. These proposals should address both computational tools and validation data needed for FB safety analysis and for audit/ confirmatory regulatory evaluations. Other proposals are sought on developing efficient VVUQ strategy including validation protocols, benchmarks, and support data for the envisioned attributes of each FB concept. Finally, proposals are sought for development and utilization of digital twins for FB applications including demonstrating the trustworthiness of AI/ML techniques and developing DT validation protocols.

4. RESEARCH THRUST AREAS

Based on the analysis of identified challenges and gaps, Priority Research Directions (PRDs) in safety and licensing of FBs have been formulated and aligned with the FB attributes. Further these PRDs have interconnected/coordinated with the other FB workshops. The performed scoping analysis of the proposed PRDs resulted in identifying research topics to achieve FB attributes. Each of the above defined topics define a Research Thrust Areas (RTA).

4.1 Research Thrust Area 1: Comprehensive and consistent multi-physics predictive M&S of different FB concepts along with its VVUQ strategy

This Research Thrust Area 1 (RTA 1) is focused on integrating/utilizing available multi-physics M&S tools with efficient VVUQ strategy with support data for the envisioned attributes of each FB concept including:

- Identifying validation gaps for each FB concept.
- Planning for research lower power FB facility for obtaining validation data.
- Developing FB multi-physic benchmarks.
- Utilizing state-of-the-art uncertainty and sensitivity analysis techniques for comprehensive and consistent uncertainty quantification and propagation through multi-physics multi-scale M&S of FB concepts.
- Integrating machine learning techniques and artificial intelligence in the M&S and VVUQ of FB concepts.

In summary, the M&S and VVUQ RTA will consist of the following activities: identifying gaps and needs in individual physics models (e.g., thermal hydraulics, materials, neutronics, source terms, etc.), identifying gaps in multi-physics modeling, which will depend on FB concept, and developing VVUQ strategy including support data and benchmarks.

4.2 Research Thrust Area 2: Integration of safety in the FB design process

The RTA 2 addresses the following issues needed to integrate safety in the FB design process:

- LMP approach and the PRA guides and standards are generic (e.g., independent of reactor power level) but have been demonstrated only for stationary reactors.
- Research and testing required to validate analytical tools for plant transient and mechanistic source term development.
- Limitations of tools such as MAACS to evaluate radiological doses close to the reactor.
- Gaps in suitable codes and standards to support design and special treatment requirements for non-LWRs.
- Unique challenges for recycling or storage of radioactive waste.
- Lack of experience in carrying the safety and licensing case to completion, especially under 10 CFR 53.
- Continued application of the NRC endorsed Licensing Modernization Project approach including the use of Frequency-Consequence Target curves and Licensing Basis Event Selection.

4.3 Research Thrust Area 3: R&D to drive digital twin development and use in fission batteries

The Digital Twin (DT) development and application have many potential advantages for the licensing of fission batteries. The RTA 3 focuses on development and utilization of digital twins including demonstrating the trustworthiness of AI/ML techniques.

4.4 Research Thrust Area 4: Design Control of the Design-Basis Envelope for FB and Support for DOE's Authorization Process

There are two sub-areas in RTA 4. The first one is focused on the improvement of DOE authorization process through the further regulatory development oriented towards advanced reactor concepts such as FB. The second sub-area is concerned with the design specific safety functions with the purpose of ensuring inherent safety design features are engineered and proper design and operating margins are well maintained.

FB regulation pathways are highly desired with a focus on DOE authorization provided identified limitations associated with the current regulation of emerging reactor concept (including FB).

By integrating safety into the design process, it is recommended to allocate resources to advance the following fundamental safety functions of FB: reactivity control, heat removal, preservation of radioactive material boundaries, and shielding.

5. OUTCOMES AND IMPACTS

The Safety and Licensing Workshop outcomes outlined the goals of mostly the following two FB attributes:

- Unattended – Operated securely and safely in an unattended manner to provide demand-driven power.
- 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 Workshop's outcomes are envisioned as:

- Identifying the research and development required to perform fission battery safety analyses and evaluations.
- Proposing graded preparation approach and content of the fission battery safety analysis report.
- Establishing the technical bases for licensing and operation of fission batteries, processes to control the design and design changes of items that are subject to the quality assurance requirements.

These outcomes enabled understanding of the challenges and gaps that exist in developing:

- Computational and validation tools needed for fission battery safety analysis and confirmatory regulatory evaluations.
- Approaches for preparing fission battery safety analysis reports and initial license applications.
- Implementation of design control practice defined in ASME-NQA-1 to fission battery safety analysis and report.

These outcomes not only support but also accelerate regulatory acceptance.

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Appendix A
Safety and Licensing Workshop

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A.1 Fission Battery Initiative Workshop Series: Safety and Licensing

Friday, April 16, 2021
10:00 a.m.–4:00 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*.

Safety and licensing aspects of fission batteries are very important since many of the technologies would be disruptive and is expected to have new features to be addressed in safety analysis and licensing process such as simplified design to be mass produced in factories with standardized sizes, reliable performance, autonomous controls and unattended operation, remote monitoring technologies etc.

The objectives of this Workshop are to:

- Discuss computational and validation tools needed for fission battery safety analysis and confirmatory regulatory evaluations.
- Discuss approaches for preparing fission battery Safety Analysis Reports.
- Discuss development of fission battery initial license applications.
- Discuss implementation of design control practice defined in ASME-NQA-1 to fission battery safety analysis and report.

The expected outcomes of this workshop are to identify research and development required to perform fission battery safety analyses and evaluations; to propose graded preparation approach and content of the fission battery safety analysis report; to establish the technical bases for licensing and operation of unique fission battery features; and to establish and implement processes to control the design and design changes of items that are subject to the quality assurance requirements.

A.2 Agenda

Opening Session
(Moderator: M. Avramova, NCSU)

10:00-10:20 Opening Statement and Introduction ....Vivek Agarwal
Idaho National Laboratory

Session 1: Modeling and Simulation of FB Safety
(Moderator: S. Palmtag, NCSU)

10:20-11:35 Evaluation Model Content for New Reactor Licensing ....Robert P. Martin
BWX Technologies, Inc.

Industry Approaches for Microreactor Modeling and Simulation

.... Bradley T. Rearden
X-energy

Transient Modeling and Safety Issues of Fission Battery Reactors..T.K. Kim
Argonne National Laboratory

Highlights on MOOSE Capabilities for Safety Analyses of FB.Nicolas Martin
Idaho National Laboratory

11:35-11:45 Break ....10 Minutes

Session 2: Safety Design Basis and Strategy for FB. Content of FB Safety Analysis
(Moderator: M. A. Diaconeasa, NCSU)

11:45-1:15 NRC Perspectives on the Safety and Licensing of Fission Batteries

.... Jan Mazza & Martin Stutzke
U.S. Nuclear Regulatory Commission

Licensing Issues for Fission Batteries: Working INSIDE the Box
....Ronald Ballinger
Massachusetts Institute of Technology

Perspectives on the Role of PRA in Fission Battery Development ..Karl Fleming
KNF Consulting Services LLC

1:15-1:45 Lunch Break..30 Minutes

Session 3: Licensing and Regulatory Research for FB

(Moderator: J. Christensen, INL)

1:45-2:35 Developments in Digital Twins: Applications to the Future of Fission Batteries
....Christopher Chwasz
Idaho National Laboratory

Proposed Licensing Basis for Fission Battery Reactors - Three Critical Issues
.... Richard Denning
The Ohio State University

2:35-2:45 Break ....10 Minutes

Session 4: Design Control of the Design-Basis Envelope for FB and Support for DOE's Authorization Process

(Moderator: J. Hou, NCSU)

2:45-3:50 Overview of U.S. DOE Authorization Pathways....................... Thomas Sowinski
U.S. Department of Energy, Office of Nuclear Energy

Preparation of Safety Basis Documents for DOE Authorization of FB
.... Jason Andrus
Idaho National Laboratory

DOE Safety Authorization Process for New Reactors ....Charles Maggart
U.S. Department of Energy, Office of Nuclear Energy

3:50-4:00 **Outcomes & Closing Remarks**..Jason Christensen
Idaho National Laboratory

A.3. Organizer Information

INL & NUC POC:

Jason Christensen
Idaho National Laboratory

Maria Avramova
North Carolina State University

Dean Wang
The Ohio State University

Local Organizers:

Scott Palmtag
North Carolina State University

Mihai A. Diaconeasa
North Carolina State University

Jason Hou
North Carolina State University