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Fission Battery Initiative

August 2021

Siting and Transportation Workshop Report

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SUMMARY

This document is a summary report on the Fission Battery (FB) Initiative Siting and Transportation Workshop held on March 15, 2021. The workshop was developed by Idaho National Laboratory in collaboration with its National University Consortium. One goal of this workshop was to initiate a conversation between various stakeholders on FBs, focusing on FB transportation and siting. Other goals included sharing the current understanding of the FB concept among the shareholders, identifying technical gaps to inform research and development needs, and fostering community building. This report summarizes the presentations and conversations held by subject-matter experts and discusses the key findings and conclusions. Further, it provides intermediate recommendations to support research and development in successful FB transportation and siting.

The expertise presented in this workshop led to the conclusion that there are significant amounts of acceleration data available that could be used for the design of a FB transportation packaging. Such a design could be similar to the design of spent nuclear fuel transportation packaging. We identified ensuring criticality safety under hypothetical accident conditions during transport and meeting regulatory dose rate limits and thermal safety goals for system components during transportation as potential technical challenges. From a regulatory perspective, a modernized framework could support FB development and deployment through the consideration of FB-specific characteristics, such as a limited source term or transportability. Lastly, we discussed flexible siting principles and the potential of state-of-the-art visual sensing technologies for FB monitoring.

Workshop follow-up meetings provided opportunities to define priority research directions. These directions identified as part of the FB Siting and Transportation Workshop outcomes include the following development needs: (i) modeling and simulation tools to allow for efficient FB transportation shell design, (ii) strategies and technologies for FB transportation after very short cooldown periods, (iii) investigations in innovative shielding materials, (iv) remote handling operations considering limited site development and equipment availability, (iv) fail-proof criticality control mechanisms, and (v) methods and strategies for FB monitoring and self-testing capabilities during and after transport to ensure a structurally sound system.

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ACRONYMS

CFR	Code of Federal Regulations
DOE	Department of Energy
DOT	Department of Transportation
FB	fission battery
INL	Idaho National Laboratory
ISG	interim staff guidance
NCSU	North Caroline State University
NCT	normal conditions of transport
NRC	Nuclear Regulatory Commission
Q&A	question and answer
R&D	research and development
SNF	spent nuclear fuel
SME	subject-matter expert
SMR	small modular reactor
TTCI	Transportation Technology Center, Inc.

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Fission Battery Initiative – Siting and Transportation Workshop Report

1. INTRODUCTION

This document is a summary report on the Fission Battery (FB) Initiative Siting and Transportation Workshop held virtually on March 15, 2021. The workshop was developed by Idaho National Laboratory (INL) in collaboration with INL's National University Consortium. One of goals of this workshop was to initiate a conversation between various stakeholders on FBs, focusing on FB transportation and siting. Other workshop goals were sharing the current understanding of the FB concept among the shareholders, identifying FB research and development (R&D) needs, and fostering community building.

The workshop organizers invited speakers from the U.S. nuclear industry, regulators, academia, and the national laboratory complex to hold technical presentations on matters that relate to FB siting and transportation. Subsequently, a panel discussion took place, initiating a discussion among the participating subject-matter experts (SMEs).

Attendance of the workshop was open to the public. Question and answer (Q&A) sessions provided opportunities for interaction between registered workshop participants and the SMEs.

This report summarizes the workshop discussion, presentation, and outcomes within the context of INL's FB Initiative, specific to transportation and siting. We will describe the workshop agenda, provide brief summaries on the technical presentations, and discuss the key conclusions of the workshop organizers. Finally, we will suggest a path forward and potential action items to support safe and reliable FB transportation.

2. OVERVIEW – FISSION BATTERY INITIATIVE

INL's FB Initiative envisions developing technologies that enable nuclear reactor systems to function as batteries. The desired concept characteristics include the ability to produce FBs with standardized designs in factories, which could be directly installed for applications at any location with limited (and possibly zero) site development. The use of multiple standardized units would provide unprecedented scalability. These FBs would be able to operate without onsite personnel or operators and could provide power reliably and on demand. When their mission life is over, the FBs could be readily replaced or removed, and the used FBs could be centrally refurbished or dispositioned.

To formalize the desired functionality, the FB initiative has outlined the following attributes:

- *Economic:* Cost competitive with other distributed energy sources (electricity and heat) used for a particular application in a particular domain. This will enable distributed energy resources through flexible deployment across many applications and integration with other energy sources.
- *Standardized:* Developed in standardized sizes and power outputs with a manufacturing process that enables universal use and factory production. This will lower costs and produce more reliable systems that achieve faster qualification.
- *Installed:* Readily and easily installed for use and removal after use. After use they can be recycled by recharging with fresh fuel or responsibly dispositioned.
- *Unattended:* Operate securely and safely while unattended to provide demand-driven power.
- *Reliable:* Systems and technologies must have a high level of reliability to provide a long life and enable widescale deployment for applications. To support the concept of remote monitoring, they must be robust, resilient, fault tolerant, and durable and provide advance notification when replacement is needed.

2.1 Workshop Series

Within the FB Initiative, INL hosted a virtual workshop series. Each workshop in the series was focused on one of the following topics:

- Markets and economic requirements for FBs and other nuclear systems
- Technology innovations for FBs
- Transportation and siting for FBs
- Safeguards and siting for FBs
- Safety and licensing for FBs.

The workshop series was developed to drive forward the FB development. Due being at an early stage in the development process of this concept, the structure of the workshops was designed to provoke thoughts, initiate conversations, support community building, and help identify the FB technology R&D potential.

2.1.1 Siting and Transportation Workshop

This report summarizes the Siting and Transportation Workshop, which was held on March 15, 2021 in virtual format. Due to the conceptual and unique characteristics of FBs, the organizers invited SMEs to hold technical presentations on topics potentially closely related to FB transportation and siting. The speakers represented stakeholders such as the U.S. regulators, national laboratory complex, and nuclear industry. Subsequently, a moderated panel discussion took place to initiate a conversation on potential R&D needs and key takeaways.

2.1.1.1 Workshop Goals

A review of the lessons learned about spent nuclear fuel (SNF) transportation and storage was the starting point to initiate conversations focused on questions such as:

- How can the current SNF management experience and know-how be translated and utilized for FB transportation and siting technology development?
- What are the technical challenges for the safe transportation and siting of FBs?
- How and to what extent does the current regulatory framework cover FB siting and transportation?
- What are the current developments in the regulatory space to meet advanced reactor needs?
- What are the critical regulatory challenges for successful FB transportation and siting?

The goal of this webinar was to promote the identification of R&D needs to support FB siting and transportation. It was intended to foster community building and to define a consensus of what the individual stakeholders would like to achieve.

2.1.1.2 Workshop Agenda, Presentations and Recording

The workshop duration was approximately five hours. After an introduction session, there were three technical sessions, with two to three presentations each. These technical sessions were followed by a panel discussion, and the workshop concluded with closing statements.

The agendas, presentations and the recordings of the Siting and Transportation Workshop and all other workshops within the FB Initiative Workshop series can be downloaded from the FB Initiative website, accessible under the following hyperlink:
https://nuc1.inl.gov/SitePages/Fission%20Battery%20Initiative%20Workshops.aspx

Lists of workshop speakers, panelists, organizers, and details on the audience are provided in the appendix of this report.

3. SUMMARY

This section includes the presentations and discussion held by the SMEs, summarizes the covered scientific challenges and gaps, and presents the main conclusions.

3.1 Session 1 – Lessons Learned from SNF Waste Management

3.1.1 Discussion: Session 1 – Lessons Learned from Waste Management

Within this session, participants provided insights into SNF management, transportation, and siting processes and established their connection to FB siting and transportation. Acceleration and strain data, recorded during a multi-modal SNF transportation cask test, were presented that showed the potential to be used in the design process of a FB transportation package. Further, a set of FB transportation issues, such as criticality control under hypothetical accident conditions (HAC) of transport, were identified.

3.1.1.1 Department of Energy Nuclear Waste Management Transportation and Handling Tests by Sylvia Saltzstein (Sandia National Laboratory)

This technical talk held by Sylvia Saltzstein introduced the DOE Nuclear Waste Management Transportation and Handling Tests conducted between Summer 2017 and May 2020 to the audience. These test included the Multi-Modal Transportation Test (i.e., the transportation of an SNF cask, including surrogate SNF assemblies) instrumented with accelerometers and strain gauges, by truck, ship, and train, from Spain via Belgium to the U.S. Subsequently, the SNF cask was subjected to higher-than-normal railcar speeds, accelerations, and handling shocks at the Transportation Technology Center, Inc. (TTCI) in Colorado, U.S.

The goal of the Multi-Modal Transportation Test campaign was to simulate the normal conditions of transport (NCT) and to record strain and acceleration data of the surrogate SNF rods and the equipment (such as the railcar, cask cradle, or cask). Besides the Multi-Modal Transportation Test campaign, acceleration and strain data were recorded in a simulated 30-cm drop test of an instrumented Equipos Nucleares S.A. ENUN 32P cask (1:3 scale) (December 2018), a 30-cm drop test of a full-scale dummy SNF assembly (June 2019), and a 30-cm dull-scale surrogate assembly (May 2020). All these data logging efforts, including subsequent analyses, were part of the DOE Nuclear Waste Management Transportation and Handling Tests.

The presenter concluded that significant safety margins exist with regard to the structural integrity of SNF package components under NCT. The data of the conducted tests are publicly available on request, and there is the potential that they could be used in the design process of FB transportation packaging. Further, a similar test regime could be executed to experimentally test an FB transportation packaging for structural reliability under NCT.

The analyses of the data recorded in the Multi-Modal Transportation Test campaign suggest that the excitations generated at TTCI caused bounding, upper-limit accelerations, and strains in the SNF packaging components for the investigated transportation modes (i.e., truck, ship, and rail). Thus, testing an FB under NCT could potentially be limited to tests executed at the TTCI and would likely produce bonding accelerations for the desired FB transportation modes.

3.1.1.2 Transportation Issues – Fission Batteries by Alan Wells (Private Consultant)

Dr. Alan Wells' technical presentation addressed a variety of potential regulatory and technical issues that need to be considered when planning for FB transportation, while using SNF transportation in Type

B packagings as a base case. One of the discussed issues was FB criticality control. Current U.S. regulations require an effective neutron multiplication factor k_{eff} below 0.95 (a k_{eff} of 1.0 or above indicates a critical system). Criticality control in Type B SNF packages is typically achieved through the configuration control of the package content; thus, structural integrity requirements only permit insignificant permanent deformations of package components under the harshest credible transportation conditions, such as accidental package drops and impacts. Unlike an SNF transportation package, the content of an FB transportation package (i.e., the FB reactor) could be designed to reach criticality. This could lead to technical challenges when designing a system that needs to ensure criticality control under transportation loading. Other concerns voiced by Wells were the integrity of neutron absorbers, which are a common tool for criticality control SNF packages but are not considered structural materials, or the possibility of moderator exclusion, which is a commonly used regulatory exemption in double-sealed, Type B SNF transportation packages.

In preparation for transportation, after the temporary or permanent shut down of an FB, a potential exceedance of regulatory dose rate limits for transportation packages could be addressed by longer pre-transportation FB cooldown phases, due to the fast decay of short-lived radio isotopes in a nuclear reactor. However, the expected dose rate will be dependent on the source term, the design of the nuclear reactor, the burnup of the nuclear fuel, the shielding capability of the FB, and the transportation packaging, among other factors.

Other issues that need to be addressed in the design process of a Type-B-like FB transportation packaging are the package integrity when exposed to a fully engulfing fire (i. e., 800°C for 30 minutes), the permitted packaging leak rate (new release fractions for new FB fuel types may need to be evaluated), and handling concerns of radioactive components without the availability of the shielding effect of a spent fuel pool. Furthermore, remote FB siting locations may be only accessible by unimproved roads, which could lead to higher-than-normal transportation package excitations and, thus, affect the risk profile of a FB transportation campaign. Lastly, the speaker elaborated on the potential of crediting the FB reactor vessel as a transportation containment system.

3.1.2 Discussion: Session 2 – Regulatory Perspective

Within this session, the perspective of the U.S. regulator on FB transportation and siting were addressed. This included detailed discussions of the current regulatory framework applicable to transportation of radioactive material, as well as ongoing efforts of the U.S. Nuclear Regulatory Commission (NRC) to modernize the current regulatory framework to support advanced reactor siting.

3.1.2.1 Transportation of Radioactive Material by David Pstrak (U.S. NRC)

David Pstrak's presentation provided an overview of U.S. transportation regulations for the domestic transport of radioactive materials. In fact, the transportation is coregulated by the U.S. NRC and the U.S. Department of Transportation (DOT). The two sets of regulations are well aligned, and an agreement memorandum was signed between the two agencies in 1979 that delineates the responsibilities of each agency in the context of the transportation of radioactive material.

Different transportation packaging types exist, and, depending on the activity, quantity, and form of the transported material, a specific packaging type is required. For instance, a Type B packaging is required for the transportation of radioactive material in quantities exceeds an A_1 quantity and information on whether it is of special form or normal form. Another example would be a normal, solid material in a quantity between 0.001 and 1.0 A_2, which could be transported in Type A packaging. Special highway route control is required for large quantities or highly radioactive materials.

The fundamental philosophy governing the packaging and transportation emphasizes three distinct aspects. These are: (i) shielding to limit the external radiation dose rate, (ii) containment to limit the release of radioactive material, and (iii) subcriticality to prevent a criticality accident during transportation. The U.S. NRC reviews, evaluates, and approves packaging designs based on these three fundamental aspects. The assessments consider two different types of hypothetical conditions used to evaluate the transportation loads for land based transport (i.e., NCT and HAC). The NCT include package exposure to thermal loads, pressures, vibrations, and water spray; drop tests from a height of 4 feet or less; corner drops tests; compression tests; and penetration tests through a drop on a vertical steel cylinder. The package assessments for HAC include a 30-foot drop test, 40-inch drop puncture test, exposure to a fully engulfing fire at 800 °C for 30 minutes, and an immersion test. The regulations for the air transport of fissile material have additional requirements. In addition, specific regulations exist for the air transport of plutonium.

In short, the presentation provided a comprehensive discussion on SNF transportation regulations, which could likely govern FB transport as well. It is important to note that the source term for an FB will change throughout its service life. Consequently, the packaging requirements could change too, due to the buildup of highly active fission products during reactor operations.

3.1.2.2 Modernizing the Regulatory Framework for Advanced Reactor Siting by Robert Schaaf (U.S. NRC)

The presentation by Robert Schaaf provided an overview on the current regulatory framework for reactor siting and summarized the efforts being undertaken by the U.S. NRC to modernize and extend this framework to make it applicable for advanced reactor siting. Further, the presentation discussed the safety-focused mission of the U.S. NRC in the context of reactor siting for the civilian use of nuclear energy and the traditional regulatory approach to siting.

These discussions provided an opening for a review of the purpose of the U.S. NRC's siting review, which is to ensure both safety and security, to evaluate emergency planning, and to assess the environmental effects of a nuclear power reactor project. The safety aspects are evaluated considering natural and manmade hazards, such as seismic, flooding, hurricanes, tornadoes, among others. The implications of hazards due to manmade infrastructure, such as rail roads or pipelines, are considered as well.

While siting safety evaluations for traditional, large-sized nuclear power plants are largely governed by natural hazards, in particular seismic hazards, the smaller footprint and robustness of an FB should eliminate or significantly reduce this dependency. However, security and emergency planning aspects could get into the focus of the siting review process. These aspects overlap with other workshops in this FB Initiative Workshop series.

Another important objective of siting reviews by the regulator is the evaluation of the effects of a nuclear reactor on the natural and human environment. In particular, the regulator assesses the potential impacts on water quality, human health, ecology, and socioeconomic conditions, among others. Within this review process, the regulators also consider the potential advantages or disadvantages of alternative sites.

Bob Schaaf presented in detail the historical development of NRC modernization efforts of the regulatory framework with a focus on advanced reactor siting. While initial policy statements reach back as far as 1986, the current vision and strategy was developed in 2016, and an implementation action plan was developed in 2017. Recently, a program status report has been issued. This led to work being conducted by the NRC to establish a new part of the Code of Federal Regulations (CFR) under Title 10. 10 CFR Part 53 was developed to regulate the siting of advanced reactors. Other NRC regulatory modernization efforts focused on advanced reactor technologies include the development of new interim staff guidance (ISG) for light-water small modular reactors (COL/ESP-ISG-027) and microreactors (COL/ESP-ISG-029), as well as the development of a generic environmental impact statement. Outside of the advanced reactor space, the NRC has proposed a modernization of the 10 CFR 51 siting review process.

The NRC frequently holds public meetings on their efforts to modernize the regulatory framework and encourages the public and stakeholders to provide comments throughout the process.

3.1.3 Discussion: Session 3 – Industry and Other Stakeholder Perspective

This session focused on the perspectives of industry and other stakeholder representatives on FB transportation and siting and questions related to advanced reactor development and licensing. This included discussion on flexible siting principles (i.e., a robust design and minimal site dependencies) used by Oklo, Inc. to achieve licensing of their advanced reactor design Aurora, an overview on the potential of visual sensing technology to support FB siting and transportation, and a broader conversation on issues related to commercial reactor siting.

3.1.3.1 Flexible Siting by Emma Redfoot (Oklo, Inc.)

The presentation by Emma Redfoot provided an overview of Oklo's siting approach for Aurora. Currently, this design is among the closest to the FB concept. The presentation covered Oklo's identification process of some of the site-specific information for the Aurora design, specifically those to be included in license applications to ensure the reasonable protection of public health and safety and the environment.

Oklo's approach to flexible siting includes two objectives: (i) a robust design and (ii) minimal operations and resource requirements. A robust design addresses concerns on external hazards that could challenge reactor safety. Minimal operations and resource requirements led to an Aurora design that requires neither water for reactor cooling nor a large number of staff for operating and maintaining the reactors. Therefore, this design provides significant siting flexibility for Aurora. These design features allow communities to select preferred siting locations, relinquish the need for extensive site characterization efforts, and improve the overall cost-effectiveness of Aurora.

Oklo's external hazards methodology considers 36 external hazards. An analysis of these hazards identifies individual hazards that require site-dependent commitments. Event families are defined and bounding analyses are executed to identify event family site commitments. Oklo provided an exemplary demonstration for the hazard of intense precipitation, which can pose a threat to the reactor by causing flooding and, consequently, a loss of powerhouse structural integrity. Bounding analyses for this hazard included assumptions of the entire building being flooded followed by a collapse of the building. Bounding analyses indicated that Aurora's safety is not challenged by these events. Consequently, no flooding event family site commitment and no powerhouse collapse event family site commitment are required for the Aurora design.

For those hazards that have the potential to require a site-specific analysis, the flexible siting process establishes a set of site commitments. These commitments form a generic site envelop (i.e., a list of site characteristics that could impact Aurora's safety case). An important point relevant to the FB concept is that the envelop is "design specific" and not "site specific." The envelop can be used to identify locations where Aurora can be sited without the need to have extensive site-specific analyses by defining conditions and requirements for site-specific analyses. In sum, the presentation argued that, to achieve significant flexibility in reactor siting, the reactor design needs to be able to demonstrate that it is robust and resilient to many external hazards and, furthermore, does not require significant site resources.

3.1.3.2 Technological Innovations in Management of Transportation – Advances in Visual Sensing by Abhinav Gupta (North Carolina State University)

Dr. Abhinav Gupta presented on advances in visual sensing as they relate to the management of transportation systems and potential applications for FB transportation. Sensor arrays (e.g., cameras, thermal sensors, LiDAR, and radars) are being used in self-driving cars. Many devices are equipped with internal accelerometers that reliably measure device acceleration. Visual sensors allow for measuring the vibration responses of vehicles, including cargo, when traveling on roads or other modes of transportation. These sensors can be used to characterize impact vibrations too. Abhinav Gupta presented example applications for vibration response measurements of structures in the field, such as bridges.

Another application of visual sensing technology that Abhinav Gupta discussed is the dynamic monitoring of the progress of construction sites. Through periodic environment scanning, 3D models (i.e., digital twins) of the progression of the construction can be developed. This capability also allows for the analysis of alignment and tolerances through the virtual fitting of a piece of equipment at a site before the equipment is shipped.

Further, the generated 3D building information models can be used to develop structural models to analyze the effects of an impact or other loads on the structural health of a system. Target-based (using quick response codes to track the movement of a certain target on the monitored component) or target-less (tracking certain key-points of a component) visual equipment sensing methods are being developed to allow for different levels of acceleration resolution.

In summary, visual sensing technology advances rapidly, shows a strong potential to support the monitoring of FB vibrations in various phases and modes of shipping, and assists with the modular construction of these batteries.

3.1.3.3 Issues in Commercial Reactor Siting by George Griffith (INL)

The presentation by Dr. George Griffith focused on siting issues for current commercial nuclear power plant designs and identified parallels to FB siting. Siting issues were categorized into two groups: (i) the impacts of the environment on the reactor and (ii) the impacts of the reactor on the environment. Safety must be ensured considering both categories of issues. For conventional reactors, compelling arguments are needed to receive exceptions by the NRC from the existing requirements.

The presentation included a brief history of nuclear reactor R&D at INL. Note that INL has established a process for siting reactors on its grounds and has successfully applied it many times in the past. For instance, INL offers a site permit to vendors to install and test their reactor systems on INL grounds, and INL will provide the required resources, such as security, water, and power, among others, to these locations. The advanced reactor ventures NuScale and Oklo are currently working with INL for placing their reactors in INL's desert site west of Idaho Falls, ID. In support of these activities, the electric grid is being upgraded, and INL is performing Senior Seismic Hazard Analysis Committee seismic and volcanic studies of these locations, among other extensive, time-consuming, and cost-intense investigations. An FB concept design would demonstrate a robustness and resilience to external hazards to limit the need for similarly exhaustive site characterization studies as conducted for the NuScale and Oklo advanced reactor ventures.

George Griffith discussed some key administrative requirements to receive permission to site a reactor in the U.S., which include U.S. ownership of the nuclear power plant and demonstration of sufficient financial resources to complete the lifecycle of the reactor. The information needed to submit a U.S. NRC license application as well as preferred site characteristics were also reviewed. Since the advanced reactors developed by NuScale and Oklo appear to be robust and contain limited source terms, the space required for the exclusion zone could be relatively small compared to the exclusion zones typically established for large nuclear power plants. A small exclusion zone is desirable, because it allows for FBs to be placed closer to the locations where power is needed.

DOE has a similar set of requirements for nuclear reactor sites to the NRC. In order for NRC requirements to be suspended and DOE requirements to be applied, the reactor under discussion must be operated by DOE. Commercial entities can partner with DOE in multiple ways for that purpose.

Lastly, additional siting requirements were discussed, such as the NRC Environmental Standard Review Plan, the National Environmental Protection Act, or the radiological emergency-response plan, among others. Analyses of major external hazards that could pose a threat to reactor safety were briefly reviewed, although a successful (i.e., safe) FB design could lead to an exemption of some of the review requirements. In sum, careful planning and thoughtful choices are critical for a safe and cost-effective design and siting process of nuclear reactors, such as FBs.

3.1.4 Panel Discussion

The goal of the panel discussion was to facilitate a conversation between technical and regulatory experts involved in the siting and transportation of nuclear reactors and nuclear material and contemplate the path forward to make fission batteries a reality. The following panelists were chosen to represent the state of practice in the technical and regulatory aspects most related to siting and transportation:

- Emma Redfoot
- Alan Wells
- Bernie White
- George Griffith

The panel discussion started with a brief introduction of the panelists and description of the goals and format of the discussion, six questions to the panelists that served as starting points to specific areas of discussion, and a Q&A session with the audience. The panel discussion is summarized below.

3.1.4.1 Regulatory and Technical Challenges in Fission Battery Transportation

Bernie White indicated that 10 CFR 71, which is used to license the transportation of nuclear material, is very inclusive and that there is a potential to use it for the licensing of FBs. However, the challenge would be to develop an FB design, along with the methods of transportation and operation, and to ensure they are economically feasible. Alan Wells concurred with Bernie White that current regulations are inclusive. Further, he emphasized that timely communication with the NRC and the development of an appropriate and economically feasible FB design is very important. When asked by the moderator if additional rule making is needed, Bernie White said that, at the time of the workshop, the NRC hasn't been approached for licensing transportable reactors, and therefore, there is currently no data to determine if additional rulemaking is needed. He also added that a downside for additional rulemaking is that we may create a class of transportation packagings that are not International Atomic Energy Agency (IAEA) compatible[a] and therefore could not be shipped overseas, even though they could be shipped inside the U.S. through NRC and DOT regulations.

Alan Wells opined that, while there may not be large technical challenges, it is likely that there will be several smaller challenges, one of which being the design and demonstration of criticality control during transportation, which should preferably be addressed right from the beginning of the FB design

[a] Current NRC and IAEA regulations for transporting nuclear material are essentially equivalent, and therefore, changing NRC regulations might disrupt this equivalency.

process. Additionally, it is unclear how criticality control can be demonstrated before transportation. Criticality events during transportation can have dramatic consequences and are unacceptable. Therefore, applicants will have to strongly demonstrate safety, thereby leading to conservatisms in design. Bernie White argued that the FB containment can be an issue given the several inlet and outlet ports needed for an FB reactor system, especially considering transporting and shipping the FB to different sites. Abhinav Gupta added that, as hundreds of FBs are transported around the country, there is a need for high confidence in the determination process of transportation loads used for the FB and FB transportation packaging design.

3.1.4.2 Regulatory and Technical Challenges in Fission Battery Siting

George Griffith started by mentioning that the lifecycle of FBs is different from anything built before—involving its manufacturing, transportation to site, operation, transportation to another site, re-operating, and dispositioning. This is a completely new environment, especially when manufacturing an FB at one location and siting it at another[b]. This has not been done before, and the design and licensing of such a system is likely very challenging. In this context, Emma Redfoot opined that, although this is a novel situation, FBs are likely to be much smaller in terms of their source term, compared to current commercial nuclear power plants. Therefore, in the future, we should be able to use design approaches that are based on the actual risk presented, which will be much lower than larger advanced reactors or current commercial light-water reactors. For FB siting, Abhinav Gupta also added that, under the current regulatory framework, the siting of a reactor in an urban environment could become extremely challenging.

In the context of technical challenges, Emma Redfoot indicated that, for FBs, which are small and likely to pose a low risk to the public, a more important challenge might be to achieve asset protection and reliable operation in a cost-effective manner and not safety itself. It might therefore be worth examining non-nuclear construction and adopting their best practices, such as seismic isolation, to enable the cost-effective manufacturing, deployment, and operation of fission batteries.

3.1.4.3 Role of INL and National University Consortium in Fission Battery Research

While Emma Redfoot indicated that INL and universities can help identify markets for FBs, Bernie White opinioned that U.S. national laboratories and universities should undertake research that private industry cannot. Alan Wells suggested that INL is an ideal location for the demonstration and testing of FBs.

3.1.4.4 Panelist Key Takeaways from the Workshop

Alan Wells suggested that coordination with the regulator is important for the deployment of FBs. Specifically, if international markets are being aimed for, conforming to NRC regulations will almost certainly ensure conformance with IAEA regulations, since their transportation regulations are almost equivalent. Bernie White concurred with Alan Wells and added that the success of an FB design might come down to the cost of building and transporting them within the current regulations and the question of whether these costs are low enough. He also added that radio-isotope generators, which have been licensed in the past, are a good starting point for a design. Emma Redfoot reiterated that identifying market and design characteristics that make FBs a good product is essential for the success of FBs.

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[b] Currently operating reactors are all built and operated at the same site.

3.1.4.5 Responses to Questions from the Audience

- *Fission Battery transportation under U.S. Department of Defense or U.S. NRC regulations:* This comes down to if the FB has an NRC license. If not, they are not regulated by the NRC or DOT but could be licensed using Department of Defense regulations.
- *Transportation of fuel and the FB reactor separately, with the fuel in a Type B packaging and the rest of the reactor being in a Type A packaging:* This could be a possibility. In fact, if it is determined that there is no (or very little) residual radioactive material in the reactor after removing the fuel, it can even be shipped under normal DOT regulations.
- *Analytical demonstration of drop tests and other accident conditions:* Analytical methods are still not ideal for large deformations, which are introduced during drops. The NRC has approved packagings through analytical safety demonstrations, but these models have been benchmarked and validated with scaled models. While there is significant experience in large displacement problems, they can still be challenging and introduce uncertainties. Another potential complication here is the introduction of high-frequency vibrations (e.g., >20 Hz) from impacts that interfere with electronic control systems and affect their reliability. This has been observed in the electrical relays in the North Anna plant during the 2011 Mineral, VA earthquake. Not much data exists to validate analytical models, and more research needs to be done. Additionally, certain material behavior under high strain rates is also not well defined and could add to the uncertainties in purely analytical solutions.
- *Inspection of FBs after transportation and before installation:* Current inspection requirements for new fuel are quite extensive, and, from a transportation perspective, these requirements are pretty low. For new fuel in large reactors, the purpose of inspections is mainly to ensure that the fuel has not been damaged during transportation. But the inspection of the fuel during FB operation, or during FB relocation after the FB has been operated, could be challenging.

4. CONCLUSIONS

Based on the information provided by the speakers and discussions throughout the Siting and Transportation Workshop, the following conclusions were drawn with regard to the siting and transportation of FBs:

- Past evaluations of NCT and HAC indicate structurally reliable SNF transportation packaging designs with large safety margins. Similar packagings could be developed for FBs. Current transportation regulations follow a graded approach, and the requirements on packaging sturdiness correspond to the activity of the transported source term. Thus, to identify the correct packaging type (e.g., Type A or Type B), information on the FB source term activity is needed. Additional highway routing controls could be imposed on packages of large quantities or highly active material. Bounding source term evaluations considering the expected operational histories of FBs are needed to enable investigations into the feasibility of flexible FB transportation and independent siting.
- A great amount of acceleration data (collected in the Multi-Modal Transportation Test) for various modes of SNF transportation (i.e., truck, ship, and train) is available that could be used in the design process of FB transportation packaging. These tests are needed to validate analytical evaluations, such as computer simulations, of a package under NCT or HAC. The available data also indicate that a similar FB transportation packaging test campaign limited to tests conducted at the Transportation Technology Center, Inc. could be sufficient to cause upper-limit accelerations of a transportation packages under NCT. However, the FB transportation on

unimproved roads (e.g., to remote siting locations), ships, or aircrafts may require more specific evaluations.

- Ensuring criticality safety during FB transportation could be a challenging task in the FB design process. The reactor in an FB will be designed to achieve criticality. This is different from the content of an SNF transportation cask, which is configured to remain subcritical under the most credible HAC. In contrast, common reactor criticality control methods are not necessarily designed to function under HAC of transport.

  Another commonly used tool to demonstrate criticality safety to the NRC includes the exclusion of the moderator intrusion into a transportation package, but it could be challenging to meet applicable regulatory requirements for this exclusion.

  FB fuel handling, or the handling of irradiated components, could include challenging operations due to the absence of a fuel pool at the FB deployment location.
- Meeting regulatory dose rate limits for FB transportation packages may require a prolonged cooldown period after reactor shutdown. The external dose rate recorded in vicinity of a transportation packaging will be directly dependent on the FB source term activity and composition, as well as on the shielding capability of the transportation packaging.
- The decay heat removal of shut-down FBs could be challenging and may require a prolonged cooldown period before FB handling and transportation, to prevent reactor core damage.
- The current regulatory framework could be applicable to regulate FB siting and transportation. Nevertheless, under the given framework, the regulatory approval process could become complex and tedious. One issue is the lack of comparable historical examples that the regulators (i.e., the U.S. NRC) could use as a safety base case. Further, current regulations have evolved for large reactors with large source terms. An FB, however, will likely contain a much smaller source term, and thus, will pose a much smaller risk to the public than large reactors, among other unique FB-specific characteristics.

  Current siting regulations require evaluations of the environmental impacts of a nuclear reactor project according to the National Environmental Protection Act. These evaluations can be very complex and resource demanding; although, categorical exclusions can be used when no significant impacts on the safety case are anticipated from a decision. These categorical exclusions could be used for small-scale projects, such as FBs. The key to keep FB licensing efforts in check is demonstrate a robust design. Further, successful licensing requires extensive and continuous communications with the U.S. regulators.

  Although FB licensing appears possible under the current regulatory framework, a significant challenge may be to design and operate FBs in a cost-effective manner under current regulations. For example, currently, the siting of a reactor in an urban environment is extremely challenging and might even be impossible within a reasonable cost.

  These examples support the conclusions that a modernized regulatory framework will be crucial for large-scale FB licensing and deployment. There needs to be a development of a design paradigm that conforms to regulations as well as is suitable for small reactors with small source terms. The current U.S. NRC efforts to modernize regulations for the licensing of advanced reactors with its public meetings are a window of opportunity for providing input on regulatory needs and recommendations.
- Flexible FB siting will be governed by two principles. First, it requires a robust design to sustain any external hazard at any given siting location under consideration. Second, the FB needs to minimally rely on site-specific characteristics. Both principles will allow for minimal requirements on site characterization data in FB license applications.

  Bounding analyses could be performed to identify site commitments for a specific FB design. These commitments could be summarized in generic site envelopes that describe site characteristics that could impact an FB safety case. These envelopes could be used to develop indicators that trigger site-specific analyses. For the ease of NRC licensing and independent of

FB design robustness, it is advisable to deploy FBs at locations with favorable characteristics, such as locations more than 1 mile from any commercial rail line; 5 miles from any surface faults, capable tectonic structures, or hazardous sites; and 10 miles from any airport. Furthermore, the FB deployment locations should be outside of wetlands and 100-year flood plains, away from population centers of more than 25,000 people, and free from peak ground accelerations of 0.5 g or above.

- Transportation loads potentially dominate the FB structural design bases. The integrity of the FB reactor core, including auxiliary components, need to be monitored to ensure their integrity under NCT and accident conditions. This includes self-testing capabilities after transportation before reactor operation and the use of state-of-the-art monitoring technology. For instance, visual sensing could be used to monitor FB vibrations and impacts during transportation. Three dimensional building information models in combination with visual sensing systems could inform a digital twin of an FB. This digital twin would allow for evaluations of the structural health of an FB and to support stakeholders in the decision-making process.

In subsequent close-out meetings, participated in by the organizers of the workshop series, the following additional conclusions related to FB siting and transportation were drawn:

- Transportation packagings for FBs need to be made of lightweight materials to allow for flexible transportation modes, such as transportation using legal-weight trucks. Further, they need allow for sufficient heat removal and radiological protection from a shut-down FB.
- Due to the high (neutron) radiation level, it is expected that FB above a certain power level cannot remain within the transportation shell during operation to prevent the neutron activation of the shell components. Consequently, remote handling procedures may be required to move the FB into additional packaging when preparing for transportation.
- Thermal issues to consider are potential changes in FB orientation during transportation and their effects on the natural convection needed for cooling, as well as the detachment of the shut-down FB from the decay removal system used during operation (which could be a silo or a vault).
- Under a more suitable regulatory environment for FBs, the asset protection and reliability of FBs might become a more challenging task than achieving licensing and safety.

5. PATH FORWARD

During workshop follow-up discussions, priority research directions were defined to support FB technology development and deployment. These include the following:

- Modeling and simulation tools should be developed to allow for an efficient FB transportation shell design. These tools need to consider the post-operational FB vessel decay heat removal and external radiation dose levels, as well as the structural loads FB contents and containments might experience during normal or accidental conditions of transport.
- Strategies and technologies for FB transportation after very short cooldown periods need to be developed. Some unforeseen scenarios in FB applications may require swift FB transportation, such as a military base under attack or a disaster response mission in which worsening conditions require an FB evacuation. It is conceivable that these applications will limit the power rating of the FB and its burnup history to allow safe transport within short periods after shutdown.
- Investigations into innovative shielding materials are requested. These materials need to be lightweight, strong, and provide sufficient shielding. Ideally, these materials should undergo minimal neutron activation and radiation-induced embrittlement to allow for the largest possible FB power level before unloading from the transportation shell is required.

- Remote handling operations considering limited site development and equipment availability should be investigated.
- Fail-proof criticality control mechanisms need to be developed, especially for a partially burnt FB. These mechanisms need to be able to withstand NCT and HAC of transport typically not considered in stationary nuclear reactor design.
- Methods and strategies for FB monitoring and self-testing capabilities during and after transport need to be developed to ensure a structurally sound and reliably operating system.

The constrains and requirements to be considered within these investigations include:

- Regulatory weight and geometrical limitations to allow for a variety of FB transportation modes, such as legal-weight truck or airplane.
- Regulatory external dose rate limits to allow for the safe handling of the FB and loaded transportation packaging.
- Regulatory NCT and HAC of transportation of radioactive material.
- Potential FB transportation routes to remote locations, such as unimproved roads, sea lanes, or flight routes.
- Installation and handling operations executable at minimally developed sites and with limited handling equipment availability.
- Realistic source term compositions and reactor histories.
- Safety aspects important for transportation, such as packaging surface temperatures and heat dissipation, among others.

There are several additional recommendations for research thrust areas based on the subject matter addressed during the workshop:

- Investigations into the technical and regulatory feasibility of moderator exclusion for criticality control are needed to identify the potential for application in FB transportation packaging licensing.
- Recommendations for NRC regulation advancements could be identified to address FB regulatory needs. These would allow for the development of a regulatory framework that is optimized for effective FB siting. A regulatory framework that is more inclusive of FBs (and considers the potentially lower risk such system poses to the public and the environment) will also enable a cost-effective design and operation of FBs that is critical for their success.
- Investigations in preliminary source term compositions of FBs could allow for dose rate evaluations, FB transportation packaging shielding requirements, estimations on pre-transportation FB cooldown duration and highway routing-control requirements, and the environmental impact of a FB.

APPENDIX

Workshop Speakers and Panelists

The Siting and Transportation Workshop speakers and panelists included:

- Dr. Vivek Agarwal (INL)
- Sylvia Saltzstein (Sandia National Laboratory)
- Dr. Alan Wells (Private Consultant)
- David Pstrak (U.S. NRC)
- Bob Schaaf (U.S. NRC)
- Emma Redfoot (Oklo, Inc.)
- Dr. Abhinav Gupta (North Carolina State University)
- Dr. George Griffith (INL)
- Bernie White (U.S. NRC)

Workshop Organizers

The Siting and Transportation Workshop organizers included:

- Dr. Elmar Eidelpes (INL)
- Dr. Abhinav Gupta (North Carolina State University)
- Dr. Abdollah Shafieezadeh (Ohio State University)
- Dr. Chandrakanth Bolisetti (INL)

Further, the Siting and Transportation Workshop organization was supported by:

- Vivek Agarwal (INL) (technical lead of the FB Initiative)
- Dr. Dayna Daubaras (INL) (general support)
- Erik Schuster (INL) (technical support)

Workshop Audience

The target audience of this webinar was the researcher community from U.S. research institutions and academia and representatives from U.S. regulators and industry. This webinar was announced publicly and was open to the public to attend. During peak times, more than 100 people participated in the workshop.