International Journal of Energy, Information and Communications
Vol.13, No.1 (2022), pp.1-12
http://dx.doi.org/10.21742/ijeic.2022.13.1.01

A Limited-Scope Probabilistic Risk Assessment Model for the Transportation of Fission Batteries

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Abstract

Advanced reactor designs are currently in the spotlight as a future nuclear energy source amid climate change challenges. A worldwide effort is currently underway toward scaling back in size large nuclear power plant designs to reduce the capital cost. In this trend, the idea of a fission battery emerged. The fission battery initiative established by Idaho National Laboratory (INL) is envisioning to enable the installed deployment of nuclear energy to unlicensed users with the concept of "plug-and-play" without operations and maintenance staff alike the use of chemical batteries. Safe transportation is one of the key challenges for fission batteries that would have to be fully assembled at the manufacturing factories, deployed to users, and decommissioned. To this end, this study was conducted to evaluate the safety of fission battery transportation using Probabilistic Risk Assessment (PRA) techniques. PRA is a comprehensive methodology to evaluate the safety of complex systems by answering three questions: what can go wrong, how likely it is to go wrong, and if it does go wrong, what are the consequences? To quantify the likelihood of what can go wrong, the United States Nuclear Regulatory Commission's Radioactive Material Transport (NRC-RADTRAN) computer code was used to evaluate scenarios with end states, such as incident-free transportation, loss of shielding accident without and with the release of radioactive materials. To determine the fission products inventories of fission batteries for various design and operational configurations, the Oak Ridge Isotope Generation (ORIGEN) computer code was used assuming 3 months, 6 months, and 1 year of operation with 100% power operation at 10 MWth and 20 MWth. To showcase the approach, we developed a scenario involving the transportation by rail of one fission battery right after shutdown through urban areas from Maine Yankee to the Oak Ridge National Laboratory (ORNL) site. The results of our study revealed that the individual dose during incident-free transportation was at a maximum of 5.36E-04 mrem, which is significantly smaller than 10 mrem of radiation dose from a chest X-ray. Also, the maximum dose rate at 2 meters to an emergency responder during the loss of shielding accidents was between 42.9 mrem/h and 717 mrem/h, under the regulatory dose rate of 1000 mrem/h under the hypothetical accident condition. Finally, the individual dose risk to the public resulting from the release of radioactive materials following the loss of shielding accidents was between 1.30E-13 rem and 1.70E-14 rem. For additional insights, a discussion is provided to compare the risk of fission battery transportation with the risk of spent nuclear fuel transportation from current light water reactors assuming the same packaging design requirements. Under these assumptions, we demonstrated that fission

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Article history:
Received (September 20, 2022), Review Result (October 28, 2022), Accepted (November 21, 2022)

battery transportation is as safe as the current spent nuclear fuel transportation. The significance of this study is the transportation of fission batteries can be achieved with existing technology safely, at cost, and on time, which is needed to enable the upcoming energy transformation.

Keywords: *Fission battery, Probabilistic risk assessment, Transportation*

1. Introduction

Entering the era of climate change, nuclear energy is currently recognized as a net-zero energy source and a sustainable energy source to be deployed worldwide. Historically, however, the misfortune of the development of nuclear weapons using nuclear energy and nuclear accidents, such as Chernobyl and Fukushima, have dented the public's trust in nuclear energy and instilled public fear of future adoption and expansion. Moreover, the high capital cost of construction projects for large nuclear power plants and the weakening of nuclear supply chains have further restricted the worldwide adoption of nuclear power. Therefore, the latest efforts in designing the next generation of nuclear power plants have been aimed at the miniaturization of reactor designs. Accordingly, small modular reactors and microreactors are currently under development using either light water or non-light water technologies.

One step further, taking the idea from a chemical battery, Idaho National Laboratory (INL) has established the fission battery initiative to achieve the vision that nuclear energy could be used by ordinary people with the concept of "plug-and-play" without any on-site operators [1]. To be widely deployable to a wide range of target markets, such as isolated grids, fission batteries must meet the economic, standardized, installed, unattended, and reliable attributes [1]. Fission batteries will have cost competitiveness, compared to energy sources that operate only on a specific platform, through a wide range of use and multiple deployments. Fission batteries will be developed in standardized sizes, power outputs, and manufacturing processes for extensive use, and will be fully assembled in the factory to ensure low-cost and quality assurance. Fission batteries will be ready for deployment to implement "plug-and-play". Fission batteries will be operated without the need for on-site operators based on a resilient and autonomous system. Fission batteries will have high reliability during their lifetime based on a robust, resilient, fault-tolerant, and durable system to achieve fail-safe operation. Fission batteries are expected to be manufactured to be used for less than 1 year with an output of less than 25 MWth to meet midsize customer energy demands [2].

A design example of a fission battery currently under development by Westinghouse is the eVinci autonomous microreactor [3]. The most important safety feature of this design, just like any other design, is that it relies on active and passive safety features for reactivity control, heat removal, and containment for redundancy and diversity [4]. Additional designs are under development by BWX Technologies (BWXT) and X-energy with initial funding from the United States (U.S.) Department of Defense (DOD) [5]. The U.S. DOD selected BWXT's microreactor design for its Project Pele full-scape transportable prototype using high-temperature gas-cooled technology that will be able to produce between 1 MWe and 5 MWe. Under DOD's specifications, the transportable design will consist of multiple modules that contain the microreactor's components in 20-foot-long, ISO-compliant CONEX shipping containers. In addition, the microreactor will be designed to be safely and rapidly moved by road, rail, sea, or air. The entire microreactor system will be designed to be assembled on-site and operational within 72 hours. The shutdown, cool down, disconnection, and removal of the microreactor for transport will be designed to occur in less than seven days [6].

The typical fission battery deployment phases, which are expected to be fully installed in a factory and deployed to the target market like other batteries, are as follows: 1) moving fresh fuel to manufacture factories, 2) deploying fully assembled fission batteries to users, 3) transferring fission battery's location after use including irradiated and irradiated fuel to a different user or for decommissioning [7]. Therefore, the safe transportation of fission batteries is one of the key factors to realizing the vision that fission batteries could be extensively used by the public at any site.

The main research gap when it comes to the transportation of fission batteries is if it can be achieved with existing technology safely, at cost, and on time, which is needed to enable the upcoming energy transformation. In the U.S., the Nuclear Regulatory Commission (NRC) and the Department of Transportation (DOT) are co-regulating the transportation of radioactive materials. They are requiring that radioactive materials must be packaged with appropriate packaging types and the packages must meet various radiation dose limits. Also, security provisions must be in place such that the outside of a package must remain intact and have not been opened by unauthorized people during transportation [8]. Each packaging type that has its fundamental safety features is classified by the quantities of radioactive materials. The detailed regulations are shown in [Table 1] [9] and [Table 2] [6], [7].

Table 1. Classification of packaging type

Packaging Type Industrial	Packaging Type Type A	Packaging Type Type B
Low hazard	Small quantities of radioactive materials	Large quantities of radioactive materials
(e.g., contaminated clothing)	(e.g., medical use)	(e.g., spent nuclear fuel)

The cask used for Type B packaging, which handles the most hazardous radioactive materials, guarantees safety through multiple layers of defense systems to prevent the release of radioactive materials even in accident conditions. Given the third phase of fission battery deployment, which is the transfer of the fission battery's location after use including irradiated and unirradiated fuel to a different user or for decommissioning, fission batteries must be transported with the spent fuel encapsulated. Therefore, if fission batteries will use type B packaging, the fission battery transportation is expected to meet the current regulations if the radiation dose limit specified in [Table 2] is observed during the transportation under all conditions [12].

Table 2. Regulated radiation dose rate limit for packages

Source	Contents
10 CFR Part 71.47	2 mSv/h on the external surface package mSv/h at any point 2 meters from the outer lateral surfaces of the vehicle
10 CFR Part 71.51	10 mSv/h at 1 meter from the external surface of the package on the HYPOTHETICAL ACCIDENT CONDITION (HAC)

In line with this, the purpose of the study was to investigate if the transportation of fission batteries can be achieved with existing technology safely, at cost, and on time by imposing Type B packaging requirements for the reactor core module of the fission batteries. To this end, this study used Probabilistic Risk Assessment (PRA) techniques as described in the methodology section to generate the frequencies and consequences of transportation scenarios of interest given in the results section. Lastly, the discussion section covers the significance of this study to fill the research gap highlighted on the transportation of fission batteries.

2. Limited-Scope Fission Battery Transportation PRA Methodology

The U.S. NRC, which is responsible for regulating the use of nuclear energy in the U.S., published NUREG-2125's "Spent Fuel Transportation Risk Assessment" [13] study using PRA techniques. PRA is a comprehensive methodology to evaluate the safety of complex systems by answering three questions: what can go wrong, how likely it is to go wrong, and if it does go wrong, what are the consequences? Therefore, we leveraged the analysis and results of NUREG-2125 to assess the risk of fission battery transportation. To quantify the likelihood of what can go wrong, the NRC's Radioactive Material Transport (NRC-RADTRAN) code [14] was used to evaluate scenarios with end states, such as incident-free transportation, loss of shielding accident, and release of radioactive materials. To determine the fission products inventories of fission batteries for various design and operational configurations, the Oak Ridge Isotope Generation (ORIGEN) [15] code was used assuming 3 months, 6 months, and 1 year of operation with 100% power operation at 10 MWth and 20 MWth. To showcase the approach, we developed a scenario involving the transportation by rail of one fission battery right after shutdown through urban areas from Maine Yankee to the Oak Ridge National Laboratory (ORNL) site. Lastly, this study was conducted to numerically evaluate the safety of fission battery transportation under current regulations and compare it with the safety of current spent nuclear fuel transportation. The transportation PRA methodology used in this study was implemented using the process shown in [Figure 1] for the transportation of fission batteries.

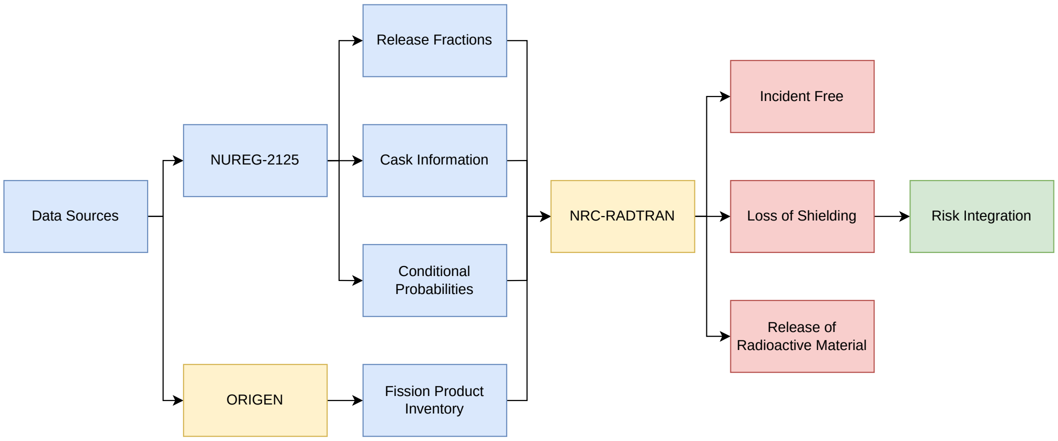

Figure 1. The transportation PRA process followed in this study

2.1. Data sources

The data required for this study, such as Type B cask information, the conditional probability of severe accidents, and release fraction of radionuclides of light water reactor spent nuclear fuel, were obtained from NUREG-2125 "Spent Fuel Transportation Risk Assessment". The U.S. NRC is responsible for issuing regulations for the packaging of spent nuclear fuel transportation. Historically, the U.S. NRC published NUREG-0170 "Final environmental statement on the transportation of radioactive material by air and other modes" [16] to assess the adequacy of stipulated regulations. After that, Sandia National Laboratory published the reexamined document NUREG-6672 "Reexamination of spent fuel shipment risk estimates"[17] reviewed by the U.S. NRC, which considers four generic Type B casks. Finally, the U.S. NRC issued NUREG-2125 [13], conducting an advanced study on the risk of spent nuclear fuel transportation by extensively studying the safety performance of three NRC-certified Type B casks of HI-STAR 100 Rail-Steel cask, NAC-STC Rail-Lead cask, and GA-4 Truck-DU cask. The important result was that when transporting uncanistered spent nuclear fuel using rail-lead cask (NAC-STC), radioactive materials were released following the loss of lead-shielded cask accidents.

Also, the ORIGEN code was used to generate fission product inventories of fission batteries obtained with assumed input parameters of power output, fuel enrichment, and operation time.

2.2. Fission battery transportation scenarios

Following the result from NUREG-2125, this study created a hypothetical model that one fission battery packaged by NAC-STC (i.e., rail-lead cask) would be transported using railroad only through an urban area on the route from Maine Yankee to ORNL described in NUREG-2125 right after the shutdown. In this hypothetical model, five assumptions were made:

- Subcritical is maintained during transportation.
- The safety structure of fission battery packages is the same as spent nuclear fuel packages (i.e., safety features of fission batteries, such as their containment system, are not considered explicitly in the study).
- Radionuclides and their release fractions for fission batteries are the same as light water reactor spent nuclear fuel.
- The standardized size of fission batteries is 5 meters.
- Risks related to security and safeguards during transportation are not considered.

2.2.1. Incident-free transportation

The incident-free transportation analysis provided in NRC-RADTRAN was modeled using the conceptual cask design from the NRC-RADTRAN technical manual [18]. When a receptor is located farther than the critical dimension, NRC-RADTRAN models the dose to the receptor as proportional to $1/r^2$ and $1/r$ otherwise [13]. NRC-RADTRAN computes the maximum individual dose during incident-free transportation using the following steps.

1. Calculate the dose rate at 1 meter from the cask, DR_{1m}, also known as transport index (TI) using equation. It should be noted that since the dose rate at 2 meters from the cask (DR_{2m}) of fission batteries is not known, the regulatory dose limit (0.1 mSv/h) at 2 meters specified in 10 CFR 71.47 [10] was used. Also, d_e denotes the effective dimension of the shipment vehicle.

$$DR_{1m} = DR_{2m} \times \frac{2 + 0.5\ d_e}{1 + 0.5\ d_e} \tag{1}$$

2. Obtain maximum individual dose by calculating total individual dose absorbed at x, $D(x)$. Equation is performed in RADTRAN by use of a Gaussian quadrature, GAUS8, which is a Sandia National Laboratories' math routine [18], where $B(r)$ indicates buildup factor, k_0 point-source package shape factor (m^2), V rail speed (km/h), and μ attenuation coefficient (m^{-1}).

$$D(x) = I(x) \times \frac{2k_0 \times DR_{1m}}{V} \tag{2}$$

$$I(x) = \int_{x}^{\infty} \frac{e^{-\mu r} \times B(r)}{r \times (r^2 - x^2)^{1/2}} dr \tag{3}$$

2.2.2. Loss of shielding accident without releases of radioactive materials

Loss of shielding accidents occurs when the packaging structures used for radiation shielding are damaged during severe accidents. According to NUREG-2125 [13], a loss of shielding accident occurs only in the case of using a rail-lead cask that is relatively soft and low melt temperature. The dose risk resulting from the loss of shielding accidents when using a rail-lead cask (i.e., NAC-STC) can be calculated with the following steps.

1. Obtain conditional probabilities of loss of shielding accidents using the event tree in [13] shows the conditional probabilities of loss of shielding accidents and their respective slumped fraction analyzed in NUREG-2125, which are directly used as NRC-RADTRAN input parameters.
2. Apply shielding factor from 0 (100% shielding) to 1 (no shielding) to emergency responders during the loss of shielding accidents. In this study, a shielding factor of 0.1, which is derived from protective equipment using lead [19], was applied.
3. Calculate the dose rate at 1 meter and 2 meters using in NRC-RADTRAN and compare the consequences with the regulatory dose rate. Each term denotes: S_L source photon emission rate per unit length of the source, $R(E_0)$ dose response function, and $B\left(E_0, \mu_{pb} x_{pb}\right)$ buildup factor for photons in lead, while SS denotes stainless steel. All the parameters are described in the NRC-RADTRAN technical manual [18].

$$\begin{aligned} D_{Los}(z) &= S_L \times R(E_0) \times \\ &\times \int_{z_{min}}^{z_{max}} \frac{B\left(E_0, \mu_{pb} x_{pb}\right) \times \exp\left[-\mu_{pb}(E_0)\, x_{pb}(z, z') - \mu_{ss}(E_0) x_{ss}(z, z')\right]}{4\pi r^2} dz \end{aligned} \tag{4}$$

4. Calculate individual dose risk resulting from loss of shielding accidents using equation (5). Each term denotes: $\gamma_{j,L}$: Accident probability, D_{LOS} : Dose consequences, AR_L: Accident rate, $SV_{j,L}$: Conditional probability, $DIST_L$: Route length (161 km [13]). The accident rate of 1.27E-06/km is derived from the U.S. DOT for the period from 2006 to 2017 [20].

$$Risk = \sum_{j=1}^{6} \gamma_{j,L} \times D_{LOS} = AR_L \times SV_{j,L} \times DIST_L \times D_{LOS} \tag{5}$$

2.2.3. Loss of shielding accident with releases of radioactive materials

As mentioned above, the release of radioactive materials following the loss of shielding accidents only occurs when transporting uncanistered fuel using a rail-lead cask. The degree of release is determined by the radionuclide inventory of fission batteries. We determined it using the ORIGEN code that computes isotopic compositions for light water reactor assemblies containing uranium dioxide (UO_2) fuel [21] as a conservative assumption for TRISO fuel particles packed in graphite pebbles or rods. The input parameters required were the uranium enrichment, thermal output, and operation time. We simulated 3 months, 6 months, and 1 year of operation with 100% power operation at 10 MWth and 20 MWth. Also, uranium enrichment was assumed to be 19.75% according to eVinci-like special-purpose reactors [22]. Finally, the dose risk resulting from the release of radioactive materials was calculated using the following steps.

1. Determine fission product inventories of fission batteries right after shutdown [23]. Since ORIGEN produces the mass of fission products in grams, conversion to Curie was required. Each term denotes; M: Mass of fission products, N_A: Avogadro constant, λ: Decay constant, A: Atomic mass of fission products.

$$Activity\ (Ci) = \frac{M \times N_A \times \lambda}{A} \times \frac{1(Ci)}{(3.7E+10)(Bq)} \tag{6}$$

2. Calculate population dose from inhalation, cloud-shine, resuspension, and ground-shine.

$$D_{p-tot-u} = D_{p-inh-u} + D_{p-res-u} + D_{p-cld-u} + D_{p-gnd-u} \tag{7}$$

3. Calculate the population total dose risk, also known as collective dose risk.

$$Risk_{p-tot-u} = \gamma_{j,L} \times D_{p-tot-u} \tag{8}$$

4. Calculate route-independent individual dose risk, where PD_L denotes population density on the route. Table 8 shows the result of individual dose risk.

$$Individual\ Dose\ Risk = \frac{Risk_{p-tot-u}}{DIST_L \times PD_L} \tag{9}$$

The significance of this study to the safety and cost of fission battery transportation can be better understood by comparing the results in terms of objective performance criteria. Thus, the dose consequences and risks computed in incident-free transportation, loss of shielding accidents, and release of radioactive materials were compared to chest X-ray dose in ordinary life [24], the regulatory dose rate of 10 CFR 71.47 [10] and 71.51 [11], and dose risk of spent nuclear fuel transportation from NUREG-2125, respectively.

3. Limited-Scope Fission Battery Transportation PRA Results

The likelihoods and consequences of the scenarios with end states, such as incident-free transportation, loss of shielding accident, and release of radioactive materials were evaluated and given below.

3.1. Incident-Free Transportation Results

Following the above steps, the maximum individual in transit dose was computed, as seen in [Table 4] using the NRC-RADTRAN input parameters shown in [Table 3].

Table 3. NRC-RADTRAN incident-free input parameters

Input Parameters	d_e (CD)	DR_{1m} (TI)	Vehicle Speed	Number of shipments
Value	5 meters	13 mrem/h	64 kph	1
Source	Assumption	Equation	Manual [14]	Scenario

Table 4. Comparison of the maximum individual in transit dose with a radiation dose of chest X-ray

The maximum individual in transit dose (mrem)	The radiation dose of chest X-ray (mrem)
5.36E-04	10 [24]

As seen in [Table 4] the maximum individual dose is significantly small compared to the radiation dose of chest X-ray.

3.2. Loss of shielding accident without releases of radioactive materials results

[Table 5] shows the calculated average and maximum individual dose rate during the loss of shielding accidents. It should be noted that the dose rate from loss of shielding accidents should be compared with the regulatory dose rate under the Hypothetical Accident Condition (HAC). As can be seen, no cases exceed the regulatory dose limit.

Table 5. Average and maximum individual dose rate during the loss of shielding accidents

Slumped Fraction	Average Individual Dose Rate (mrem/h)		Maximum Individual Dose Rate (mrem/h)
	1 meter	2 meters	
0.0725	425	190	717
0.017	80	35.9	169
0.0634	364	163	627
0.0234	115	51.7	232
0.00316	12.5	5.65	32
0.00426	17.1	7.72	42.9
Regulatory Dose Rate	1000 mrem/h on the HAC (10 CFR 71.51 [11])	10 mrem/h (10 CFR 71.47 [10])	

The individual dose risk resulting from loss of shielding accidents without the release of radioactive materials is shown in [Table 6] together with the maximum individual dose risk when one fission battery is being transported through the urban area from Maine Yankee to ORNL is 4.45E-11 mrem/h at 2 meters from the cask.

Table 6. Individual dose risk resulted from the loss of shielding accidents

Conditional Probability	Slumped Fraction	Average Individual Dose Risk at 1 meter (mrem/h)	Average Individual Dose Risk at 2 meters (mrem/h)	Maximum Individual Dose Risk at 2 meters (mrem/h)
5.96E-12	0.0725	5.17E-13	2.31E-13	8.72E-13
1.13E-10	0.017	1.84E-12	8.28E-13	3.9E-12
3.57E-11	0.0634	2.65E-12	1.19E-12	4.57E-12
6.79E-10	0.0234	1.59E-11	7.16E-12	3.21E-11
1.79E-11	0.00316	4.56E-14	2.06E-14	1.17E-13
3.4E-10	0.00426	1.19E-12	5.35E-13	2.98E-12
Total Dose Risk		2.21E-11	9.96E-12	4.45E-11

3.3. Loss of shielding accident with releases of radioactive materials results

We simulated using ORIGEN 10 MWth and 20 MWth fission batteries with 3 months, 6 months, and 1 year operating at 100% power fueled by 19.75% enriched uranium to obtain the fission product inventories given in [Table 7].

Table 7. Summary of fission product inventories

Fission Products	Form	Activity (Ci)					
		10 MWth			20 MWth		
		3 months	6 months	1 year	3 months	6 months	1 year
^{3}H	Gas	1.27E+01	2.51E+01	5.02E+01	2.53E+01	5.02E+01	1.00E+02
^{10}Be	Particle	8.034E-08	1.61E-07	3.27E-07	1.61E-07	3.22E-07	6.52E-07
^{14}C	Gas	3.24E-06	6.44E-06	1.32E-05	6.48E-06	1.30E-05	2.63E-05
^{156}Eu	Volatile	1.12E+03	1.17E+03	1.20E+03	2.26E+03	2.40E+03	2.53E+03
^{153}Gd	Particle	6.46E-06	8.53E-05	1.21E-03	5.02E-05	6.71E-04	9.44E-03
^{160}Tb	Particle	2.79E-03	6.11E-03	1.35E-02	7.99E-03	2.00E-02	4.90E-02
^{166m}Ho	Particle	4.49E-09	9.11E-09	1.90E-08	9.11E-09	1.87E-08	4.02E-08

The individual dose risk resulting from loss of shielding accidents without the release of radioactive materials is shown in [Table 8]. This individual dose risk to the public is between 1.30E-13 rem and 3.96E-13 rem.

Table 8. Individual dose risk resulted from the release of radioactive materials (rem)

Dose Risk (rem)	10 MWth			20 MWth		
	3 months	6 months	1 year	3 months	6 months	1 year
Individual Dose Risk	1.30E-13	1.69E-13	1.98E-13	2.61E-13	3.37E-13	3.96E-13

To get a better understanding of the risk of fission battery transportation during the loss of shielding accident with releases of radioactive materials, a comparison to that of NUREG-2125 was conducted. Since this study used more recent data on accident rates, it is reasonable to use conditional individual dose risk excluding accident rate for an objective comparison. As seen in [Table 9], the result was between 1.02E-07 rem and 3.12E-07 rem.

Table 9. Comparison of conditional individual dose risk with that of spent nuclear fuel from NUREG-2125 (rem)

Dose Risk (rem)	Fission Battery 10 MWth			Fission Battery 20 MWth			Spent Nuclear Fuel
	3 months	6 months	1 year	3 months	6 months	1 year	
Conditional Individual Dose Risk	1.02E-07	1.33E-07	1.56E-07	2.05E-07	2.65E-07	3.12E-07	1.29E-07

The individual risk results, which are shown in [Table 9] and plotted in [Figure 2], show that fission battery transportation would be as safe as spent nuclear fuel transportation under the assumptions used in this study. The limitations and significance of these results are discussed in the next section.

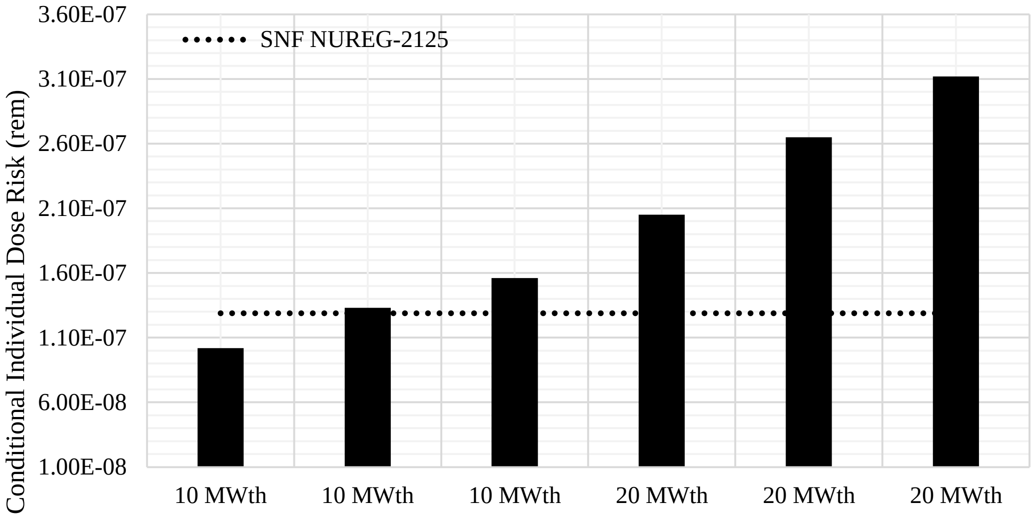

Figure 2. Comparison of fission battery conditional individual dose risk with that of SNF from NUREG-2125

4. Discussion of the Limited-Study Fission Battery Transportation PRA Results

The results indicate that dose consequences, and associated risks, of fission battery transportation during incident-free transportation, and loss of shielding accidents without and with the release of radioactive materials are significantly lower when compared to chest X-ray, regulatory dose limit, and spent nuclear fuel transportation, respectively.

For this study, the regulatory dose limit at 2 meters was used as a radiation dose of fission batteries conservatively to calculate the transport index. Despite this assumption, the consequences were significantly small, which means the transport index of fission batteries with enhanced safety features is expected to be much lower, and subsequently, the dose consequences will be also smaller than shown here. Also, in case of loss of shielding accidents, comparison with regulatory dose rate at 1 meter on the hypothetical accident condition and 2 meters on the normal condition. Considering the severity of loss of shielding accidents, it is reasonable to compare it with the hypothetical accident condition. Therefore, it was demonstrated that all possible situations were under the regulatory dose limit, which means fission battery transportation would be safe even in the loss of shielding accident. Finally, the risk to the public resulting from the release of radioactive material showed that fission battery transportation is as safe as current light water reactor spent nuclear fuel transportation, which means safe fission battery transportation is possible even at present.

In this study, the ORIGEN code was used to determine fission product inventories of fission batteries under the assumption that the TRISO fuel using uranium dioxide (UO_2) currently in use would be the main fuel of fission batteries. However, there is a limitation that it does not reflect the enhanced safety performance of the TRISO fuel coated with three layers. As a result, research should be conducted by reflecting on the enhanced safety features of fission batteries. Moreover, since fission batteries are equipped with their defense-in-depth strategies, such as radiation shielding and containment system, stipulating the use of Type B packaging should be re-evaluated being recognized to be potentially an excessive safety measure and uneconomical. Therefore, it is necessary to carry out a study on the development of dedicated packaging for fission batteries and figure out which one is more appropriate to use in terms of cost and safety benefits.

5. Conclusions

The primary objective of this research was to evaluate the safety of fission battery transportation under current regulations utilizing the general theory of PRA to support the feasibility of the installed idea supporting the "plug-and-play" feature of fission batteries. In this study, a PRA model was developed for multiple scenarios, such as incident-free transportation, and loss of shielding accidents without and with the release of radioactive materials. To verify the safety under current regulations, we used regulatory dose limit conservatively as input parameters since the fission battery designs are under development. Depending on the characteristics of fission batteries that may be transported with spent fuel inside, we mainly cited NUREG-2125, which includes research on Type B packaging, and assumed most of the model parameters conservatively.

The fission batteries are envisioned to be widely deployed and operated without the need for licensed operators. To accomplish this vision, the fission batteries should be factory installed and safely delivered to users under any conditions. This study showed that the risk of fission battery transportation is comparable to the risk of light water reactor spent nuclear fuel transportation packaged with Type B. This study implies that fission battery transportation is sufficiently safe and possible at cost and on time using the current state of technology even without applying the characteristics of the fission battery that are expected to be equipped with more advanced safety technologies, which are needed to enable the upcoming energy transformation.

Author Contributions

Conceptualization, Mihai A. Diaconeasa; Formal analysis, DaeHo Lee; Methodology, DaeHo Lee and Mihai A. Diaconeasa; Supervision, Mihai A. Diaconeasa; Validation, Mihai A. Diaconeasa; Writing – original draft, DaeHo Lee and Mihai A. Diaconeasa. All authors have read and agreed to the published version of the manuscript.

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