ORNL/TM-2024/3326

Considerations for Improving the Technoeconomic Viability of Heat Pipe Microreactors by Employing a Functional Containment Approach

A. J. Huning
A. Abou Jaoude
R. G. de Oliveira

March 2024

OAK RIDGE National Laboratory

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

ORNL/TM-2024/3326

Nuclear Energy and Fuel Cycle Division

CONSIDERATIONS FOR IMPROVING THE TECHNOECONOMIC VIABILITY OF HEAT PIPE MICROREACTORS BY EMPLOYING A FUNCTIONAL CONTAINMENT APPROACH

Alexander J. Huning (ORNL)
Abdalla Abou Jaoude (INL)
Rodrigo G. de Oliveira (INL)

February 2024

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The economic cost of a microreactor is being investigated by leveraging MARVEL cost information in conjunction with some simplified design and analysis activities to present a hypothetical, yet feasible, option for investigation. This bottom-up cost estimate for a hypothetical commercial microreactor will be used to provide guidance to the industry and research communities regarding where priorities should be set to improve the viability of broad microreactor deployment. To support the design and analysis activities required to present a feasible option, some understanding of maximum accidental radionuclide releases and consequences is needed to provide bounding estimates on containment or confinement systems for radionuclide retention.

To estimate fission product barrier and retention performance, a gaussian plume dose and dispersion model is employed, with isotopic inventories being propagated between barriers assuming conservative fractional release rates. Demonstrably conservative meteorological assumptions are also assumed. Standard reference release rates are assumed where safety requirements could be easily and economically employed. Results are provided in units of total effective dose equivalent as a function of distance from the release (i.e., the reactor). Initial results indicate that the hypothetical microreactor will likely need to credit the fuel cladding and at least one other barrier, or combination of barriers, to ensure public health and safety as required during a postulated accident. This approach is referred to as "functional containment," since no single barrier will be relied upon for satisfying regulatory requirements and fundamental safety functions for radionuclide retention. Finally, a set of barrier options are provided so that future economic analyses can select the most viable design path.

1. INTRODUCTION

The US Department of Energy (DOE) Microreactor Program (MRP) vision is to enable broad deployment of microreactor technology by supporting cross-cutting research and development and technology demonstration by

- achieving technological breakthroughs for key features of microreactors,
- identifying and addressing technology solutions to improve the economic viability and licensing readiness of microreactors, and
- enabling successful demonstrations of multiple domestic commercial microreactors.

Microreactors are fission-based nuclear reactors that generate significantly less power than typical commercial facilities, around 1–20 MW as compared with ~1000 MW. Because of this reduced power, the physical size and complexity of systems is also significantly reduced. This is not a novel concept, as low-power systems were among the first to be developed and operate today primarily as research reactors across the globe. The uniqueness of microreactors lies principally in their operation, fuel and supporting technology, planned sites, manufacturing operations, and transportability. These new paradigms present new safety questions and potential licensing challenges that differ from those posed by traditional large light water reactors (LWRs) and other advanced and small modular reactors (A/SMRs), which are expected to be licensed under traditional pathways. The DOE's MRP has supported research into several of these areas, which are documented in several reports; examples include the following:

- regulatory analysis of the transportation of a factory-manufactured microreactor [1],
- assessment of safety analysis challenges and recommendations for MELCOR and BlueCRAB microreactor applications [2][3],
- microreactor opportunities and licensing challenges [4][5], and,
- emergency planning challenges for transportable microreactors [6].

At an early design stage, vendors need assurance that their reactor concepts and deployment strategies can satisfy required regulatory safety requirements without fundamental alteration to the core technology and/or business approach. This is especially true for situations that envision new commercial nuclear deployment scenarios where microreactors can replace diesel generators [7] or be sited in densely populated areas [8].

Although there are many safety requirements an applicant must satisfy, those related to accidental releases may have the largest impact on siting, operations, barrier design, and radionuclide retention strategies. Fundamental alteration of any of these during licensing could significantly impact a vendor's deployment timeline, licensing, development costs, and/or site selection. At an early design stage, top-level regulatory requirements for ensuring acceptable public health and safety during an accident may include

1. 10 CFR 50.34(a),
2. Nuclear Regulatory Commission (NRC) Quantitative Health Objectives (QHOs), and,
3. US Environmental Protection Agency (EPA) Protective Action Guides (PAGs).

For item (1), there are two principal requirements: (1) any design-basis accident (DBA) shall not result in a fission product release that exceeds 25 rem-total effective dose equivalent (TEDE) during a 2 hour period at the exclusion area boundary (EAB), and (2) any DBA shall not result in a fission product release that exceeds 25 rem-TEDE over the entire release period at the low-population-zone boundary.

Item (2) is defined in the *Safety Goals for the Operation of Nuclear Power Plants* [9]. Essentially, QHOs are desirable attributes for nuclear power plants (NPPs) that reflect acceptable societal risks at the time of the safety goals statement. Practically, QHOs can be translated into dose limits for any accident, including beyond-design-basis accidents (BDBAs). However, there are conflicting technical opinions as to the translation of these limits into dose (i.e., cancer rates in large populations due to low levels of radiation exposure), and the applicability of QHOs as policy, as opposed to strict regulatory requirements. Unless a microreactor developer is planning on applying for a license, certification, or approval following the newly proposed 10 CFR Part 53 [10], QHOs are unlikely to be significant design-stage requirements.

Item (3) also comprises several requirements, the most pertinent of which are (1) early-phase sheltering-in-place or evacuation of the public if the projected dose over 4 days is to exceed 1 rem and (2) relocation of the public if the projected dose over the first year is to exceed 2 rem in the first year and 0.5 rem per year in the second and subsequent years [11]. From a design perspective, these requirements translate to ensuring accidental releases do not exceed 1 rem for the first year and 0.5 rem for subsequent years. Demonstrating that this requirement could be met for any DBA could alleviate and simplify the licensing review of emergency planning actions by the applicant/developer.

Demonstrating that all safety requirements are met necessitates that a significant fraction of the final design be complete, with most data gaps and uncertainties addressed during a licensing review.[1] Achieving this status also requires a significant investment in engineering and development. A functional containment evaluation of planned or anticipated barriers to radionuclide release can aid in providing some conservative assurances that there are no inherent obstacles to meeting all safety requirements and that typical engineering design activities can go forward without obvious licensing risk.

Broadly, functional containment refers to the set of barriers that, when taken together, effectively limit the physical transport of radioactive materials to the environment [12]. The NRC has recently accepted the functional containment concept as an approach to be used for advanced non-LWRs in lieu of large pressure-retaining structures to provide the ultimate prevention of radionuclide release to the environment [13]. This concept has also been included in the draft Part 53 rule and associated guidance. Functional containment was first promulgated through various modular high-temperature gas-cooled reactor programs that employed tristructural isotropic (TRISO) fuels [14]. It has since been utilized in the Next Generation Nuclear Plant (NGNP) program [15], Transformational Challenge Reactor program [16], and various commercial conceptual designs.

Figure 1 illustrates how functional containment performance criteria can be applied to physical buildings, as needed for specific events.

[1] For a non-operating licensing (e.g., design certification, standard design approval, manufacturing licensing). An operating licensing would require a complete final design with all essential data gaps and uncertainties addressed to achieve commission approval and fuel loading.

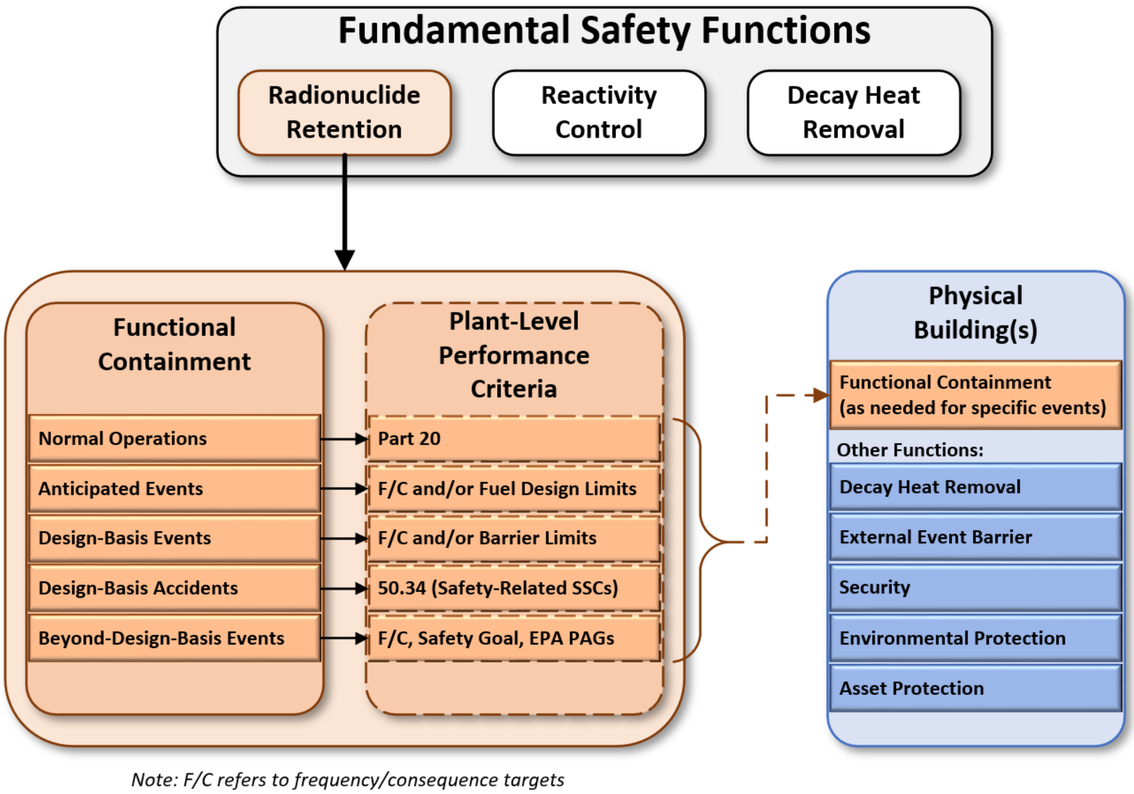


Figure 1. Functional containment performance criteria (adopted from Ref. [12]).

Functional containment evaluations can also help inform early design decisions regarding what barriers may be required and what the economic trade-offs are. A few assessments were performed for generic 1 MWt gas-cooled and molten salt reactors and documented in a 2022 MRP report [17]. A similar approach is followed in this report to help inform decisions regarding what barriers are needed for a generic heat pipe microreactor.

The goal of this report is to present a conservative assessment of the performance of some expected barriers to radionuclide release for a generic heat pipe microreactor. This generic heat pipe microreactor is expected to be described in more detail in another report to be published as an MRP report, along with more economic viability and cost discussions later this year (at the end of FY 2024). Therefore, only a few barriers are considered now, with recommendations provided at the end of this report for additional barriers or perhaps more data to support clad and fuel fission product retention.

2. FUNCTIONAL CONTAINMENT EVALUATION

Source terms for DBAs have been considered since the early days of commercial nuclear power. To support dose consequence evaluations for siting (i.e., 10 CFR Part 100), source terms for a "maximum credible" accident were initially estimated in a report from 1962 referred to as TID 14844 [18]. These reference release fractions into containment for a pressurized water reactor (PWR) are shown in Table 2.

Table 1. TID 14844 release rates into reactor building.[2]

Nuclide group	Release fraction
Noble gases	1.0
Halogens	0.50
Solids	0.01

These source term release rates have been used extensively by the current operating fleet for many design-basis applications. Since the TID 14844 report was published, there have been extensive advances in the understanding of LWR severe accidents, which have led to new guidance called "alternative source term," or AST, which is documented in Regulatory Guide (RG) 1.183 [19]. Table 2 shows the AST release fractions into containment by accident phase for a PWR.[3]

Table 2. RG 1.183 PWR release rates into containment by accident phase.

Nuclide group	Gap release	Early in-vessel	Ex-vessel	Late in-vessel
Noble gases	0.05	0.95	—	–
Halogens	0.05	0.35	0.25	0.10
Alkali metals	0.05	0.25	0.35	0.10
Te group	0	0.05	0.25	0.005
Ba, Sr group	0	0.02	0.10	0
Noble metals	0	0.0025	0.0025	0
Ce group	0	0.0005	0.005	0
Lanthanides	0	0.0002	0.002	0
Phase duration (h)	0.5	1.3	2.0	10.0

The AST phases roughly correspond to a large loss-of-coolant accident without emergency core cooling. It is unlikely that either TID 14844 or RG 1.183 would be applicable for any A/SMR concept, especially those with a strong reliance on passive heat removal for safety. For example, under the DOE Advanced Gas Reactor program [20], TRISO fuel has been demonstrated to have fractional release rates several orders below LWR AST values [21] for most radionuclides. However, both TID 14844 and AST RG 1.183 values can serve as references as unmitigated, baseline hazards against which to make comparisons when selecting or designing barriers for radionuclide retention.

For functional containment evaluation, fission product retention factors can be allocated to various barriers or systems to achieve regulatory or safety thresholds, like those described in the previous section.

[2] Since these were intended for both power and test reactors, the generic "reactor building" terminology is used rather than "containment." Later guidance uses the term "containment" rather than "reactor building."
[3] The only substantial differences between PWR and BWRs are 0.25 and 0.20 for boiling water reactor halogens and alkali metals, respectively, for the early-in-vessel phase.

This evaluation approach was utilized during the NGNP program [15] and can inform the design at an early stage with regard to safety and licensing uncertainty of different sites and applications where it would be necessary to know minimum distances to EABs and population centers. Alternatively, if a desired site and application have already been selected, then functional containment evaluations can drive data and experiment requirements to achieve a specified level of certainty around the different barriers for fission product retention. For this report, the former use case is assumed where different fission product retention factors are postulated and the required minimum EAB is estimated for some maximum credible accident (i.e., BDBA). Figure 2 illustrates the functional containment evaluation approach.

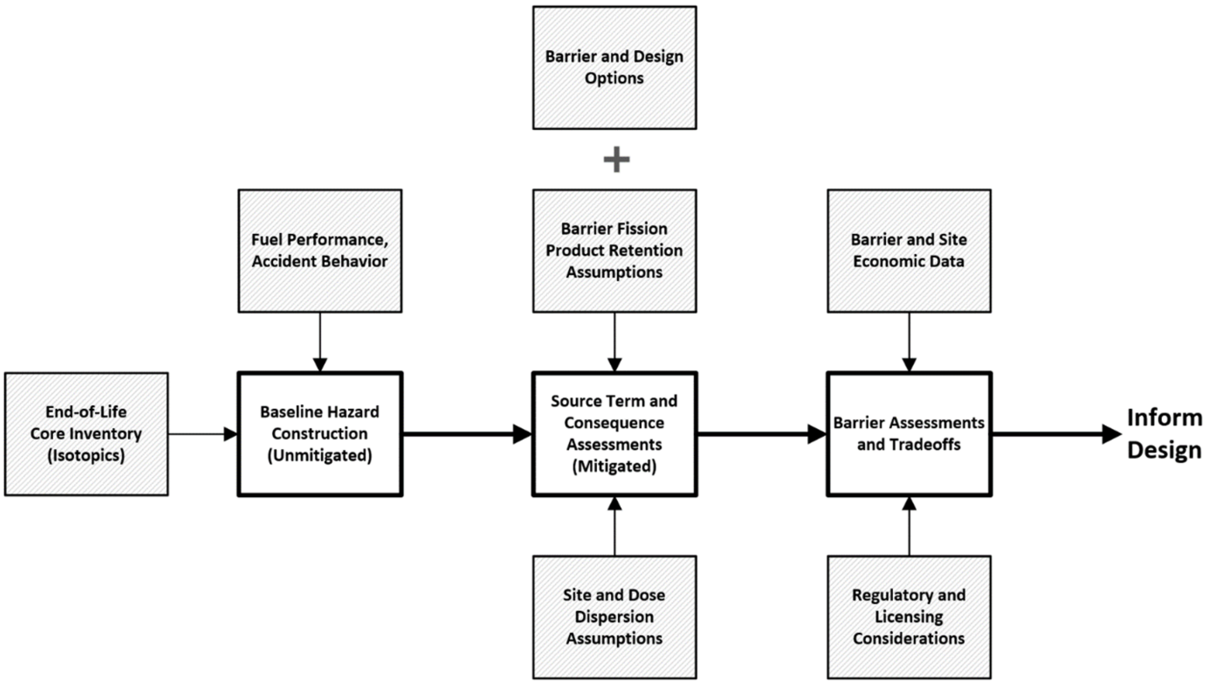


Figure 2. Functional containment approach for barrier assessment and risk-informed design.

Each bold white box in the center of Figure 2 represents a key step in the functional containment evaluation approach. Each gray box represents a key input and/or where assumptions are necessary. Each of the three key steps is described in the next sections for the hypothetical generic microreactor under investigation.

2.1 REFERENCE DESIGN AND BASELINE HAZARD ESTIMATE

The goal of this report is to provide input for the cost estimation of a hypothetical microreactor and obtain an understanding of the barriers likely be needed which is as realistic as is possible without directly modeling an existing commercial concept. To initiate this economic assessment, a 20 MWt, heat pipe microreactor with MARVEL-like fuel and design features was assumed. Although MARVEL is NaK cooled, most components are or would be sufficiently like that of other microreactors. This assumption allowed for cost information from the MARVEL project [22] to be employed without divulging any commercial or proprietary data.

At the end-of-life, roughly at a core burnup of 80 MWd/kg, Table 3 shows the reference core inventory for several key dose-contributing radionuclides. One important assumption is that this list is not fully comprehensive of the fission product inventory and is condensed as a trade-off between estimating a realistic maximum dose consequence and efficiency in computation and analysis of results. If there is a substantial gap in the identified list, additional nuclides could be added for further barrier design and economic estimations.

Table 3. Key dose contributing radionuclides and reference core inventories.

Key radionuclide	Activity (Ci)	Key radionuclide	Activity (Ci)
I-130	6.44E+03	Xe-133	1.51E+06
I-131	6.84E+05	Xe-135	5.33E+05
I-132	1.00E+06	Sr-89	9.64E+05
I-135	1.40E+06	Sr-90	5.61E+04
Cs-134	7.74E+04	Ba-140	1.36E+06
Cs-136	2.61E+04	Ce-141	1.30E+06
Cs-137	6.25E+04	Ce-143	1.25E+06
Te-127m	4.60E+03	Ce-144	1.02E+06
Te-129m	2.35E+04	Pu-238	8.76E+02
Te-132	9.94E+05	Pu-239	1.33E+02
Ru-103	8.81E+05	Pu-240	1.04E+02
Ru-105	4.39E+05	Pu-241	3.90E+04
Ru-106	1.60E+05	Np-239	6.48E+06
Rh-105	1.76E+09	Nb-95	1.53E+06
Mo-99	1.38E+06	La-140	1.42E+06
Tc-99m	2.54E+09	H-1	1.92E+08
Kr-85	7.01E+03		

From this inventory, an initial baseline hazard was constructed against which different barriers could be evaluated. The approach to generating an individual's total effective dose (TED) at various distances from the source (i.e., the reactor) is to use a standard gaussian plume dispersion model with moderately conservative weather conditions. For this assessment, the Lawrence Livermore National Laboratory, DOE toolbox code [23], HotSpot (V 3.1.1) [24] was employed. The following parameters were assumed:

- 1 m wind speed of 1.0 m/s,
- atmospheric stability "F,"
- 0 m release height (ground release),
- 10 min sample time,
- FGR11 dose conversion factor library,
- $3.33 \cdot 10^{-4}$ m^3/s breathing rate,
- standard rural terrain, and,
- no ground shine or resuspension.

Figure 3 shows the unmitigated dose hazard for three different approaches. A full-core unmitigated release is assumed using the core inventory listed in Table 3 with no retention in the fuel. Then, TID 14844 and RG 1.183 assume LWR-like release fractions like those described earlier. Although these approaches are not directly employable for non-LWRs, they demonstrate a level of mitigation between the totally unmitigated case and a traditional LWR source term analysis. Then, when additional fission product barrier retention is added (e.g., enhanced non-LWR fuel fission product retention, containment) a clear margin can be observed and is expected for A/SMRs.

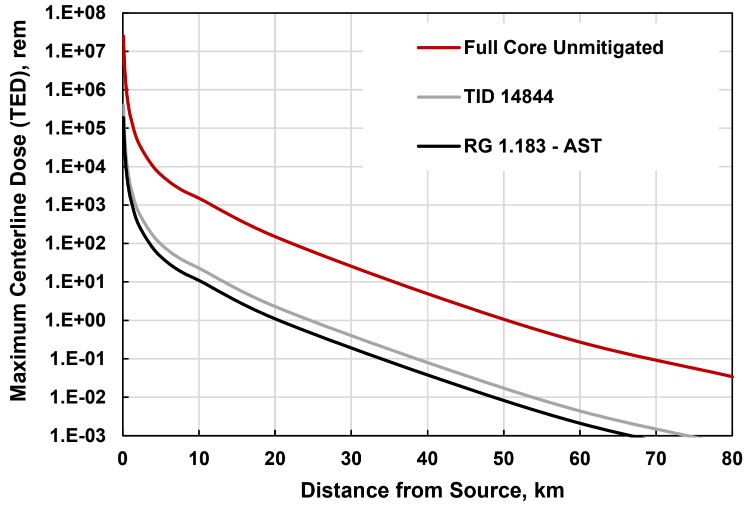


Figure 3. Unmitigated dose hazard.

Assuming the microreactor EAB would be less than about 50 km, from Figure 3, it is evident that some fission product retention would be required; and typical commercial NPP safety functions would be needed to ensure all EPA and NRC offsite accidental release requirements could be met.

2.2 SOURCE TERM AND CONSEQUENCE ASSESSMENTS

To allow for siting the microreactor at a reasonable distance from the public (e.g., a few kilometers or less), some barriers for fission product retention will be required. Five cases are presented in this report; however additional cases could be investigated, depending on the design and what specific systems, structures, and components (SSCs) are being considered. These cases include the following:

1. AST from RG 1.183,
2. Maximum credible accident (MCA)—with no cladding but no fuel relocation (i.e., fuel melt),
3. MCA—95% of fuel cladding remains intact, 5% gap release and no fuel relocation,
4. MCA—same as above, but with additional 50% retention by reactor building/containment,
5. MCA—same as above, but with 95% retention by reactor building/containment.

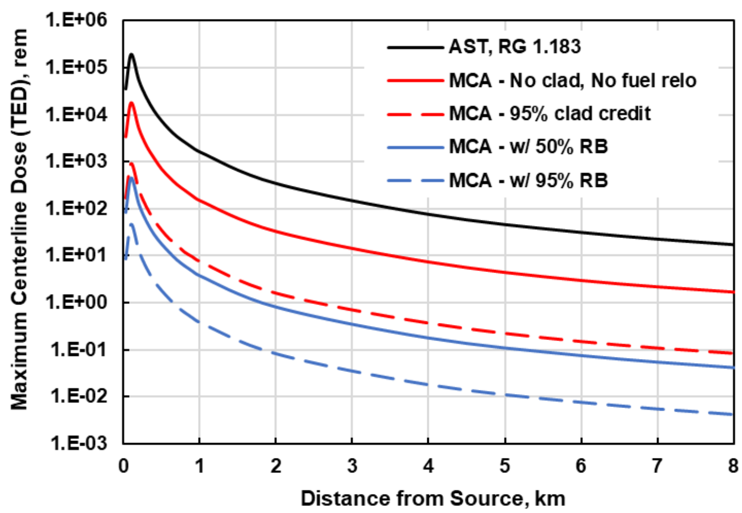
For case 1, the AST is presented again as a reference hazard if the microreactor is a traditional PWR with no generation III+ or accident-tolerant fuel safety features, and for a leak-tight containment design and analysis.

For case 2, the MCA is not defined with respect to accident progression or initiating event. Additionally, the MCA is not representative of any specific licensing approach, as this cost estimate task will not explicitly consider differences between an MCA, maximum hypothetical accident (MHA), traditional DBA, or other approach for safety analysis development. For the MCA presented herein, the fission product release corresponds only to the “gap release” from the AST. This amounts to 5% of the total core inventory of noble gases, halogens, and alkali metals. For the purposes of this microreactor assessment, it is assumed that passive core safety features and A/SMR safety design would be employed to preclude any accidental fuel melt and relocation. However, no credit is given to clad integrity, so fission products in the gap would be mobile and, under MCA conditions, directly released to the environment.

For case 3, the MCA now credits 95% of fuel cladding. Under this accident scenario, most of the core would remain or peak at temperatures well below clad rupture conditions. Specific temperatures or clad rupture conditions are not considered herein.

For cases 4 and 5, 95% of fuel cladding is credited but an additional containment/confinement or reactor building is employed, either of which would contribute to either 50% or 95% retention of fission products entering that system. This containment/confinement/reactor building would likely exist regardless of any radionuclide retention safety functions. Additionally, its primary purpose could be for security, for environmental protection, or for supporting other fundamental safety functions. However, if it exists, it may be reasonable, through performance testing and design, to credit some amount of fission product retention. The 50% retention case is typical for a normally “leaky” building with no active filtration. The 95% retention case would be consistent with a moderate confinement structure, like that of a research reactor.

Figure 4 shows the expected maximum dose (TED) for an individual as a function of distance from the source for these five cases.



Distance to [km]		
	25 rem	1 rem
AST	6.75	n/a
MCA - No clad	2.34	20
MCA - 95% clad	0.58	2.42
MCA - w/ 50% RB	0.48	1.85
MCA - w/ 95% RB	0.16	0.71

Figure 4. Mitigated dose alternatives.

From Figure 4, as anticipated, only including a gap release significantly lowers the estimated dose, illustrating the benefit of passive safety and preventing fuel melt and relocation under MCA conditions. However, not including any credit for the clad or other barriers may result in EAB distances too far (2.34 km to 25 rem) to be economical. If the safety design can credit some clad integrity, this approach would significantly lower the distance to key dose limits. The trade-off is that for any credit given to the clad or other barrier, that barrier must then have supporting quality data at prototypic conditions to demonstrate a high confidence value in the assumed performance. Generally, it may be easier and less costly from a development perspective to acquire quality data outside of a high-radiation, high-temperature environment.

2.3 BARRIER ASSESSMENTS AND TRADE-OFFS

In terms of land use, the US Department of Agriculture estimates the national average value of farmland to be at or around $3,800 (in 2022) per acre [25]. Even though most NPPs are sited in remote areas and often surrounded by farmland, this average land value could represent a lower bound, as the land quality required for building an NPP is expected to be higher than that of typical or average farmland. Also, this estimate does not factor in costs that might vary between sites for additional site preparation and characterization. Using this average cost, the costs of the amounts of land required to meet the minimum distances from a dose limit perspective are shown in Table 4.

Table 4. Lower-bound land cost estimates for 25 rem and 1 rem offsite dose limits.

	25 rem dose limit distance			**1 rem dose limit distance**		
	Distance [km]	**Area [acre]**	**Cost [$M]**	**Distance [km]**	**Area [acre]**	**Cost [$M]**
AST	6.75	35370	134	–	–	–
MCA – No clad	2.34	4251	16.2	20.0	310,521	1,180
MCA – 95% clad	0.58	261	0.99	2.42	4,546	17.3
MCA – w/ 50% RB	0.48	179	0.68	1.85	2,657	10.1
MCA – w/ 95% RB	0.16	20	0.08	0.71	391	1.49

Based on Table 4, several trade-offs and observations can be made. First, the AST and MCA–No clad cases are unlikely to be feasible with such lower-bound estimates for the land costs associated with the minimum distances required to meet dose limits. Using the 25 rem dose limit, a partially credited clad case could be feasible, but the trade-off then is between acquiring quality data for cladding fission product retention to lower the MCA offsite dose to less than 1 rem, versus implementing emergency planning actions and enlisting offsite emergency services.

Second, the 25 rem dose limit represents a minimum distance to meet 10 CFR 50.34(a) requirements. Depending on the licensing approach, MCA cases presented may not be relevant to compare against this requirement if a more realistic, less restrictive, DBA can be identified. However, the 1 rem EPA PAG dose limit could potentially include BDBAs and those events which are less realistic and more akin to an MCA or MHA. Therefore, to meet this condition, a land area of at least 100 acres would likely be required for any configuration of fission product barriers.

Finally, for the conservative MCA selected in this analysis, it is apparent that some reactor building, confinement, or containment, fission product retention should be credited or pursued because such a structure would likely exist to perform other functions and, with modest data collection and performance verification under MCA conditions, could be credited. Addition conclusions and recommendations are presented in Section 3.

3. CONCLUSIONS

Initial results from a fission product retention/barrier assessment indicate that for a hypothetical 20 MWt, heat pipe reactor, some partial fuel cladding (e.g., 95%) and at least one other barrier will be needed to ensure public health and safety as required during a worst-case (maximum credible) postulated accident. The other barrier recommended is a reactor building that would likely exist to support other functions such as environmental protection and SSC housing. Crediting some moderate fission product retention (e.g., 50%) would not add substantial development cost but could significantly reduce the size of the EAB and complexity of emergency planning actions. In this MCA scenario, no credit for fission product retention would necessarily be needed by the vessel, piping, heat pipes, or other core structures beyond the fuel cladding.

An MCA scenario was investigated, as it is both flexible—not requiring a significant amount of design information—and demonstrably conservative. To estimate fission product barrier and retention performance, a gaussian plume dose and dispersion model (HotSpot V3.1.1) is employed, with isotopic inventories being propagated between barriers, assuming conservative fractional release rates. This analysis approach is akin to that documented in another microreactor program report from 2022 [17]. Results are provided in units of TEDE as a function of distance from the release (i.e., the reactor). Finally, using these required distances, land cost estimates can help inform the selection of minimum required barriers and performance expectations for radionuclide retention.

This hypothetical microreactor and its barriers for fission product release are being investigated to support a bottom-up cost estimate for a generic microreactor. This cost estimate, and its constituents, can then help inform research and development priorities to aid in the broad deployment of novel nuclear technologies to support climate net-zero and other national energy and infrastructure goals.

The specific selection of barriers and other design features is not critically relevant to developers or other stakeholders. The goal is to generate a point-design that leverages real data from the MARVEL project to present one accurate estimate for a microreactor. While estimates of other commercial concepts are likely to be less than what is identified through this effort, none are expected to provide equally robust economic data with more certainty than this effort.

One result of this effort is the demonstration of functional containment and source-term assessments as an early influence on the safety design and economic viability of the A/SMR or microreactor. The approach is adaptable and can be applied to many different design concepts, regulatory approaches, and applications. Functional containment and source term assessments are not the focus of this report, but they can also play a role in the early design of protection features, security-by-design, and safety-security-safeguards (i.e., 3S) integration. Other functional containment and source term applications could include the following:

- inform the design of off-gas, cover gas, or other primary coolant cleaning systems to reduce noble gas and other highly volatile fission product consequences,
- inform vessel and primary system piping qualifications,
- inform containment/confinement performance requirements,
- inform fuel qualification and fuel performance testing requirements to meet regulatory/licensing objectives,

- inform spent fuel and waste management efforts that may be included in the inventory for accidental releases for emergency planning distances,

- support site selection,

- support regulatory activities where hazard assessment and consequence-based approaches could reduce and/or streamline safety reviews, and,

- provide assurance to investors and other stakeholders regarding feasibility and reduce uncertainties surrounding the safety performance of novel technologies.

Were this a commercial endeavor, significant safety analysis development would be needed to properly derive a set of credible accidents. However, using this conservative approach, an upper bound on the consequences can begin to form to support those applications listed.

In terms of economic cost discovery, the next step would be to assess a typical reactor building structure for the hypothetical microreactor without any specific controls for radionuclide retention. Then, moderate controls could be added, such as ventilation, filters, dampers, and conventional fire and sodium fire suppression systems. No leak-tight containment would be anticipated, which would significantly reduce the cost as compared with a moderately controlled reactor building. However, for regions with higher land costs, and areas where the population would be near the reactor building, a leak-tight containment system could be compared; it would further reduce the 25 rem and 1 rem maximum consequence distances. For a commercial endeavor, these trade-offs would need to be evaluated holistically, as development and site application costs, in addition to the physical SSC costs, could play a factor in the business case. For this activity, identifying and quantifying specific trade-offs will be greatly beneficial to the nuclear development community and aid in setting research priorities for broad microreactor deployment.

4. REFERENCES

[1] Christensen, J., and A. Huning, *Regulatory Analysis of the Transportation of a Factor Manufactured Microreactor,* Idaho National Laboratory, INL/RPT-22-66051, Rev. 0 (September 2022).

[2] Huning, A. J., *Assessment of Microreactor Safety Analysis Challenges and Recommendations for Utilization of the Comprehensive Reactor Analysis Bundle,* Oak Ridge National Laboratory, ORNL/TM-2023/3147 (September 2023).

[3] Behne, P., M. K. Jaradat, N. Choi, S. Terlizzi, and V. M. Laboure, *Development of a BlueCRAB/MELCOR Framework for Supporting Realistic Mechanistic Source Term Calculations in Microreactors,* Idaho National Laboratory, INL/RPT-23-74793 (September 2023).

[4] Huning A. J., S. A. Arndt, and J. A. Christensen, "An introduction to microreactor licensing basis events," *Trans. of the American Nuclear Society* **128** (1), pp. 516-519 (June 2023).

[5] Huning A. J., D. E. Shropshire, and E. Kurt, *Risk-Informed Opportunities and Challenges for Microreactors,* 2023 International Probabilistic Safety Assessment Conference, July 16–20, 2023, Knoxville, TN (July 2023).

[6] Maheras, S. J., S. A. Foss, and R. E. Reed, *Microreactor Transportation Emergency Planning Challenges,* Pacific Northwest National Laboratory, PNNL-34816 (September 2023).

[7] Blain, L., "Radiant aims to replace diesel generators with small nuclear reactors," *New Atlas*, website, accessed February 19, 2024 (October 2021). https://newatlas.com/energy/radiant-portable-advanced-nuclear/

[8] The University of Illinois Urbana-Champaign, *Regulatory Engagement Plan for Submittal and Approval of an Application to Construct a New Research Reactor,* NRC ADAMS Accession No. ML23178A261 (June 2023).

[9] Nuclear Regulatory Commission, S*afety Goals for Nuclear Power Plant Operation,* NUREG-0880, Rev. 1 (May 1983).

[10] U.S. Nuclear Regulatory Commission, *Risk-Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors, Enclosure 1 – Proposed Rule Federal Register Notice,* SECY-23-0021, ADAMS Accession No. ML21162A102 (March 2023).

[11] Environmental Protection Agency, *PAG Manual: Protective Action Guides and Planning Guidance for Radiological Incidents,* EPA-400/R-17/001 (January 2017).

[12] U.S. Nuclear Regulatory Commission, *Functional Containment Performance Criteria for Non-Light Water Reactors,* SECY-18-0096, ADAMS Accession No. ML18115A546 (October 2018).

[13] U.S. Nuclear Regulatory Commission, *Staff Requirements – SECY-18-0096 – Functional Containment Performance Criteria for Non-Light Water Reactors,* SRM-SECY-18-0096, ADAMS Accession No. ML18338A502 (December 2018).

[14] U.S., Nuclear Regulatory Commission, *Draft Preapplication Safety Evaluation Report for the Modular High-Temperature Gas-Cooled Reactor,* NUREG-1338 (March 1989).

[15] Naidoo D., and K. Fleming, *Next Generation Nuclear Plant: Plant Level Assessments Leading to Fission Product Retention Allocations*, NGNP-PLD-GEN-RPT-N-00007_Rev0, Westinghouse Electric Company LLC (2009).

[16] Huning A. J., W. M. Kirkland, and K. A. Terrani, Transformational challenge reactor safety design and radionuclide retention strategy, *Nuclear Science and Engineering* **196** (12) (November 2021).
https://doi.org/10.1080/00295639.2021.1989237

[17] Shropshire D., E. Kurt, and A. Huning, *Cost Efficient-by-Design Microreactors,* Idaho National Laboratory, INL/RPT-23-03080 (December 2022).

[18] U.S. Atomic Energy Commission, *Calculation of Distance Factors for Power and Test Reactor Sites,* TID 14844, ADAMS Accession No. ML021750625 (March 1962).

[19] U.S. Nuclear Regulatory Commission, *Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors,* Regulatory Guide 1.183 (July 2000).

[20] U.S. Department of Energy, "Advanced Gas Reactor Fuel Program's TRISO Particle Fuel Sets a New World Record for Irradiation Performance," press release dated November 16, 2009. website, accessed March 3, 2024 (November 2009).
https://www.energy.gov/ne/articles/advanced-gas-reactor-fuel-programs-triso-particle-fuel-sets-new-world-record

[21] Electric Power Research Institute, *Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance,* EPR-AR-1 (NP), Product ID: 3002015750 (May 2019).

[22] Abou-Joude, A., C. Bolisetti, Y. Arafat, B. Naseif, and H. B. Hanna, *Assessing the Impact of Mass Production on Microreactor Costs,* Idaho National Laboratory, INL/CON-23-73253-Rev. 0 (November 2023).

[23] U.S. Department of Energy, *Safety Software Quality Assurance – Central Registry,* website, accessed March 6, 2024 (March 2024).
https://www.energy.gov/ehss/safety-software-quality-assurance-central-registry

[24] Homann, S. G., and F. Aluzzi, *HotSpot Health Physics Codes Version 3.0 User's Guide,* Lawrence Livermore National Laboratory, LLNL-SM-63647 (August 2014).

[25] U.S. Department of Agriculture, *Land Values 2022 Summary*, ISSN: 1949–1867 (August 2022).