

## An Introduction to Microreactor Licensing Basis Events

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### INTRODUCTION

Microreactors, which are reactors that generally have a rated power of less than 20 MW, may employ fuel, primary core cooling, electric conversion, or other physical system characteristics similar to those used in larger reactor designs. Compared with these larger designs, microreactors have significantly different operation, construction, transportation, and decommissioning strategies. Smaller physical systems enable unique opportunities for nuclear energy growth. However, these new and unique opportunities may challenge some traditional nuclear safety norms, such as

- siting commercial nuclear facilities away from densely populated areas,
- having large footprints and exclusion areas,
- having a large human operator and security force presence,
- having large-volume leak-tight containment structures,
- having multiple redundant active safety systems, and,
- requiring backup electric power sources.

Although changing these deep-rooted norms may seem like a far-off possibility, regulations are evolving. Many examples of the US Nuclear Regulatory Commission (NRC) granting approval for items such as smaller emergency planning zones [1], not requiring Class 1E diesel generators [2], and employing the concept of functional containment over strictly requiring large leak-tight containments [3] have occurred.

For any licensing pathway, reactors must submit a safety analysis report (SAR), which evaluates the design against regulatory dose limits for postulated accidents. The NRC then evaluates the accidents evaluated in the SAR via a safety evaluation report (SER) and classifies the accidents as licensing basis events (LBEs). LBEs include design basis events (DBEs) and any beyond DBEs (BDBEs) or other accidents evaluated as part of the licensing process.

LBEs may be selected through either a deterministic process or a risk-informed process (e.g., using a probabilistic risk assessment [PRA] in addition to any deterministically selected events). Because of the unique microreactor operational, transportation, and other aspects, the types of

LBEs may be significantly different from larger conventional reactor designs. The potential consequences associated with each LBE will also vary significantly. The most potentially consequential events that could reasonably occur within the life of the facility are assessed as design basis accidents (DBAs), which are a subset of LBEs.

Conservative assumptions are employed when uncertainties exist in the DBA analysis. As our understanding and knowledge of light-water reactor (LWR) DBAs have evolved, best-estimate tools and calculations have replaced many conservatisms, enabling more efficient operations. The 10 CFR 50.69 process is one example in which systems and components may have been originally designated as safety related, but new information and risk-informed calculations now show that the classification may be unnecessary for some specific system or component.

For any new reactor design without decades of operational experience (e.g., LWRs), a trade-off exists in the decision to collect either quality data to help assess DBAs with best-estimate tools or to employ conservative assumptions that might not introduce restrictive requirements on plant design and system requirements.

Strong motivation may exist for microreactors, especially first-of-a-kind facilities, to opt for a more conservative approach because the cost of collecting these data for more realistic analyses of DBAs would be proportionally greater than for larger reactor designs. Successive microreactors of the same design would then be better suited to collect the necessary data and perform best-estimate calculations, which could result in immediate improvements for *n*th-of-a-kind facilities, as well as retrofit improvements for the first-of-a-kind facility that relied on overly conservative assumptions.

Additionally, with lower power levels, the total radionuclide inventory and associated radiological hazards at the time of an accident would also be lower. Because of the inherently increased safety margin, a more conservative assessment of DBAs might not introduce any potentially restrictive requirements on the plant or specific systems. However, this safety margin would likely be offset because of the more integrated microreactor operations and higher proximity to the public.

This trade-off is not unique to microreactors, and it still requires a comprehensive search for initiating events and an

assessment of their potential effects regardless of whether a risk-informed or purely deterministic approach is used to select LBEs.

This paper reviews some commercial microreactor types and design features, as well as some potential LBEs. To help construct these potential LBEs, some background and historical information is provided. Finally, recommended next steps for selecting and constructing a set of LBEs are provided for microreactor developers.

## BACKGROUND AND HISTORICAL LBEs

The requirements to analyze postulated accidents and submit a preliminary SAR, as well as to include an explanation of the design basis in the final SAR, was added to 10 CFR 50.34 in December 1968 [4]. Before December 1968, more than 18 commercial US nuclear plants entered operation. Many test and experimental reactors were also brought into operation, most of which have since been shut down and decommissioned.

The Atomic Energy Commission (AEC)—which licensed nuclear reactors until the NRC assumed this responsibility in accordance with the Atomic Energy Act (AEA) of 1954—included a group that reviewed the safety of and licensed nuclear reactors. Until 1962, this included only early prototype reactors, but by the late 1960s, larger commercial size reactors were being reviewed. From the late 1950s until the late 1960s, the AEC licensing group was developing the regulatory framework for and licensing these reactors.

Since its inception, the AEC struggled with technical uncertainties and limited operating experience in trying to define acceptable risk. At first, this necessitated case-by-case technical judgments of the ability of the proposed reactor to be constructed and operated without undue risk to the health and safety of the public. Meanwhile, reactor designs were expanding their use of engineered safety systems and formalizing the concept of multiple layers of defense, particularly for containment. In 1967, an Oak Ridge National Laboratory report [5] highlighted certain accidents that could cause a breach of containment, which fully integrated the importance of engineered safety features into regulatory reviews.

During this time, the AEC and national standard organizations began formalizing the licensing review process by developing the review infrastructure that would become 10 CFR 50.34, the standard review plan (NUREG-75/087, later NUREG-0800) [6], and Regulatory Guide (RG) 1.70 [7]. This guidance began as several AEC Licensing and safety guides. In 1962, the AEC issued *AEC Licensing Guide, Purpose, Organizations and Contents of Hazards Summary Reports for Power Reactors* [8]. This guide provided applicants with information on what was needed in a preliminary hazards summary report—which would eventually be called a *preliminary SAR*—and would later become 10 CFR 50.34 and RG 1.70. At this point, the

concept of developing DBEs was articulated as an “analytical test of the summation of safeguards available should be made to ascertain the consequences of accidents and should include discussion of an accident having consequences not expected to be exceeded by any other accident arising out of any other credible circumstances”. Little guidance was available as to which accidents should be included other than whether they should include a short list of specific events.

By the time 10 CFR 50.34 was first issued in 1968, the case-by-case analysis of a range of situations from common to highly unlikely failures was formalized into three classes according to radiological consequences:

- Class 1: Events leading to no radioactive release at the exclusion radius
- Class 2: Events leading to small to moderate radioactive release at the exclusion radius
- Class 3: DBAs

Class 3 events were to be accidents of “very low probability, postulated in evaluating the design and performance of the plant and the acceptability of the site” [6]. These events were to be evaluated using very conservative assumptions, conservative methods of evaluation, and conservative calculations of potential offsite doses. The choice of these DBAs was to be justified as part of the SAR. By this time, a list of 29 representative types of transient and accidents to be evaluated had been developed.

## NRC RESEARCH AND TEST REACTORS

Commercial LWR DBAs are described in RG 1.70 and NUREG-0800. NRC-licensed nonpower research and test reactors also followed commercial reactor guidance until the publication of NUREG-1537 [9] in 1996. Under paragraph 104 of the AEA, these reactors qualify for being regulated with the “minimum extent consistent with protecting the health and safety of the public and promoting the common defense and security.” NUREG-1537 was developed to alleviate review challenges associated with applying RG 1.70 and NUREG-0800 to the wide array of test and research reactor designs and hazards while staying cognizant of paragraph 104.

The basis for paragraph 104 of the AEA is partly because of the recognition that research and test reactors have thermal power levels several orders of magnitude less than the commercial designs of that time, and therefore the accumulated fission products are proportionally less. This logic can be applied to microreactors, but it is unclear whether there is sufficient political motivation to amend the AEA that would enable their inclusion under paragraph 104. Regardless, an approach for identifying and assessing DBAs for microreactors may benefit from investigating approaches used by research and test reactors.

Per NUREG-1537, the limiting accident is the maximum hypothetical accident (MHA). Some MHAs are suggested for research and test reactors, but applicants are ultimately

responsible for determining their specific MHA. One difference between MHAs and other types of accidents or design basis events is that the MHA “scenario need not be entirely credible”. This difference implies a degree of conservatism above and beyond what would normally be assumed for a DBA. However, this is not overly constraining because of the reduced power level and hazard that most research and test reactors employ. Although this might be true for some microreactor concepts, the barriers and technology differences between commercial microreactors and other research reactors (e.g., pool-type configurations) may necessitate a less conservative best-estimate approach.

A slightly less conservative approach is the maximum credible accident (MCA) as the limiting accident. The difference between the MHA and MCA is that the MCA originates from the set of “credible accidents” and is the accident with the greatest or maximum consequence and thus is bounding. MCAs have been proposed during the time of the AEC for Elk River Station (Elk River, Minnesota), Vallecitos Nuclear Center (Alameda County, California), Enrico Fermi Nuclear Generating Station (Frenchtown Charter Township, Michigan), Experimental Breeder Reactor II (Idaho), and others [10, 11]. Recently, Oklo submitted its license application and followed an MCA approach for Aurora Powerhouse [12].

Following an MCA or MHA approach for microreactors may offer significant benefits. Specifically, the MHA and MCA

- do not require a PRA for event sequence quantification and accident frequency assessment;
- are bounding and are not expected to change in definition over the life of the facility, and;
- are proven methodologies with which the NRC has experience and familiarity.

However, following an MCA or MHA approach also has significant drawbacks that may motivate an advanced reactor developer to follow a more risk-informed approach, such as the approach documented in NEI 18-04 [13]. Principally, any highly conservative approach may could be particularly challenging for microreactors because many are being planned to be sited within population centers and to be mobile and/or transportable with very small emergency planning zones. Given the wide array of microreactors being developed, the level of acceptable conservatism will depend on the specific microreactor concept and desired operational characteristics.

## POTENTIAL MICROREACTOR LBES

Many different microreactor concepts are being proposed for many different and unique applications. A select few of these concepts are listed in Table I.

TABLE I. Select Summary of Microreactor Technologies\*

| Developer          | Name             | Type                                       | Power    |
|--------------------|------------------|--------------------------------------------|----------|
| BWXT               | BANR             | High-temperature gas-cooled reactor (HTGR) | 50 MWt   |
| Radiant Nuclear    | Kaleidos Battery | HTGR                                       | 1.2 MWe  |
| Ultra Safe Nuclear | MMR              | HTGR                                       | 15 MWt   |
| X-energy           | Xe-Mobile        | HTGR                                       | 20 MWt   |
| LeadCold           | SEALER           | Liquid metal reactor (LMR)                 | 3–10 MWe |
| NuScale Power      | NuScale Micro.   | LMR/heat pipe                              | <10 MWe  |
| Oklo               | Aurora           | Sodium-cooled fast reactor/heat pipe       | 1.5 MWe  |
| Westinghouse       | eVinci           | Heat pipe                                  | 1–5 MWe  |

\*Publicly available information

LBES for microreactors will depend on the reactor type (i.e., the combination of coolant type, fuel structure, and neutron spectrum). Anticipated operational occurrences (AOOs) and transients are similar between reactor types and may include events such as turbine or balance-of-plant fault/trip, loss of heat sink, pump trip or loss of flow, or reactor scram. Excluding AOOs and minor transients, DBEs and BDBEs could have significant phenomenological differences between reactor types.

HTGRs generally use He gas as the coolant and tristructural-isotropic (TRISO) fuel. The matrix material and specific core structure may change from design to design. The most consequential DBEs and BDBEs generally include depressurized loss-of-flow (D-LOFC) scenarios [14]. For molten salt reactors (MSRs), the most consequential scenarios are “salt spill” accidents [15]. LMRs include both liquid Na- and Pb-type reactors, and like MSRs, loss of coolant should be considered for LMRs. However, loss of coolant could be eliminated with a pool-type design and other barriers, such as a guard vessel. Transient overpower or other accidents may be more “credible” and consequential for LMR microreactors. For heat pipe reactors that use liquid metal, loss of coolant and transient overpower cases could be assessed. However, some unique DBEs and BDBEs may also be present. For TRISO-fueled designs, loss of heat sink may be like a D-LOFC for HTGRs.

Example microreactor LBES are presented in Table II, although not all event classes may be represented. The table provides as a starting point and introduction to the expected types or classes of events that would be documented in an

SAR. For all LBEs presented, the LBE type and reactor applicability may be different for certain microreactors. Any reactor design will be expected to perform a systematic search and identification of events.

TABLE II. Example Microreactor LBEs

| Event                                    | LBE Type     | Reactor Type |
|------------------------------------------|--------------|--------------|
| Negative reactivity insertion (scram)    | AOO          | All          |
| Positive reactivity insertion            | AOO—DBE      | All          |
| Loss of offsite power                    | AOO—DBE      | All          |
| Heat pipe failure (single)               | DBE          | Heat pipe    |
| Loss of flow                             | DBE          | All          |
| Overcooling                              | DBE          | All          |
| Seismic and other external hazards       | DBE          | All          |
| Station blackout                         | DBE          | All          |
| Transportation accidents (preoperation)  | DBE          | All          |
| Transportation accidents (postoperation) | DBE          | All          |
| D-LOFC                                   | DBE—<br>BDBE | HTGR         |
| Heat pipe failure (multiple)             | DBE—<br>BDBE | Heat pipe    |
| Salt spill                               | DBE—<br>BDBE | MSR          |

## CONCLUSION

This paper presents an introduction to microreactor LBEs and discusses some DBEs and BDBEs for different reactor types. Any of the example LBEs listed in Table II may be a candidate as the MCA for those concepts that pursue a more deterministic safety analysis approach. If an MHA approach is followed, then the accident scenario need not be credible, and any event could form the basis for the MHA. If a risk-informed safety approach is followed, then the LBEs are expected to be identified through the PRA, as well as any deterministically identified DBAs.

Although some microreactor concepts are expected to have power levels similar to current research reactors, their applications are expected to be significantly different. Considering the required changes that are moving away from traditional large LWR safety norms, microreactors may benefit in regulatory discussions that have a more mechanistic and best-estimate treatment of potential accidents. Alternatively, first-of-a-kind microreactors may be built with significant conservatism that could be alleviated with *n*th-of-a-kind deployments after successful safety performance demonstration.

## REFERENCES

1. US NUCLEAR REGULATORY COMMISSION, “Early Site Permit – Clinch River Site”, ADAMS Accession No. ML19009A286 (2019)
2. US NUCLEAR REGULATORY COMMISSION, “Letter to NuScale Transmitting Final SER for Electrical Topical Report,” ADAMS Accession No. ML17339A9533 (2017).
3. US NUCLEAR REGULATORY COMMISSION, “Functional Containment Performance Criteria for Non-Light-Water-Reactors,” ADAMS Accession No. ML18114A546 (2018).
4. FEDERAL REGISTER, “Title 10 – Atomic Energy,” 33 FR 18612 (1968).
5. J. S. WALKER, T. R. WELLOCK, “A Short History of Nuclear Regulation, 1946 - 2009,” NUREG-BR-0175, US Nuclear Regulatory Commission (2010).
6. ATOMIC ENERGY COMMISSION, “Regulatory Guide 1.70 Revision 0, Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants,” ADAMS Accession No. ML 13350A353 (1972).
7. ATOMIC ENERGY COMMISSION, NUREG-75/087, “Standard Review Plan, Revision 0,” ADAMS Accession No. ML042080088 (1975).
8. ATOMIC ENERGY COMMISSION, “AEC Licensing Guide, Purpose, Organizations and Contents of Hazards Summary Reports for Power Reactors,” ADAMS Accession No. ML021750324 (1962).
9. US NUCLEAR REGULATORY COMMISSION, “Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors” NUREG-1537, (1996).
10. G. T. MAZUZAN, S. WALKER, “Controlling the Atom: The beginnings of nuclear regulation, 1946 – 1962,” NUREG-1610, US Nuclear Regulatory Commission (1984).
11. US NUCLEAR REGULATORY COMMISSION, “Maximum Credible Accidents for Reactors,” ADAMS Accession No. ML021430236 (2002).
12. OKLO Inc., “Maximum Credible Accident Methodology,” ADAMS Accession No. ML21184A002 (2021).
13. NUCLEAR ENERGY INSTITUTE, “Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development,” NEI 18-04, Revision 1 (2019).
14. A. J. HUNING, S. CHANDRASEKARAN, S. GARIMELLA, “A Review of Recent Advances in HTGR CFD and Thermal Fluid Analysis,” *Nuclear Engineering and Design*, 373, 111013 (2021). <https://doi.org/10.1016/j.nucengdes.2020.111013>.
15. D. E. HOLCOMB et al., “Molten Salt Reactor Fundamental Safety Function PIRT,” ORNL/TM-2021/2176, Oak Ridge National Laboratory (2021).