Assessment of the Back End of Advanced Nuclear Reactors for Developing Stable Waste Forms – 23452

Evaristo J. Bonano*, Laura L. Price**, and David Sassani**
* NAC International, Inc., Peachtree Corners, GA USA
** Sandia National Laboratories, Albuquerque, NM USA

ABSTRACT

As of 2021, there were nearly 140 advanced reactor (AR) designs around the world in different stages of conceptualization, development, and demonstration [1]. In the United States (US) an AR is defined, by legislation, as "a nuclear fission reactor with significant improvements over the most recent generation of nuclear fission reactors or a reactor using nuclear fusion."[a] Such reactors include light-water reactor (LWR) designs that are far smaller than existing reactors, as well as concepts that would use different moderators, coolants, and types of fuel, and are also commonly referred as Generation IV reactors. These ARs will generate spent nuclear fuel (SNF) and other waste streams that will require appropriate and acceptable management and disposition strategies. However, at present a complete picture of how the waste to be generated by ARs will be managed does not exist. This is an issue that needs prompt attention because nuclear waste issues may have implications for the planned deployment of ARs. A solid back-end integration strategy will not only provide sustainable waste confidence to help ARs succeed but will also minimize potential future liabilities. ARs based on non-LWR technologies can produce a large variety of different waste streams, with each waste stream potentially having both favorable and unfavorable characteristics with respect to storage, transport, and disposal. Most ARs will rely on high-assay, low enriched uranium (HALEU) as fuel, which could have higher decay heat, higher specific activity, and higher degradation of cladding materials compared to typical LWR fuels. In addition, the waste streams expected to be generated by different AR designs point to a wide range of values for key waste streams characteristics such as burnup, power density, SNF mass and volume per Gigawatt-year of electric power (GW-ye), fuel type, water reactivity, physical form, chemical form, potential for gas generation, etc. Other factors such as the potential attractiveness of these fuels and waste stream for non-peaceful uses, result in uncertainty regarding the design and capacity of the storage, transportation and disposal infrastructure that will be needed to manage the SNF and other wastes streams from ARs. Therefore, standardization of the back end can be a major challenge. This paper proposes a methodology that uses available information on waste streams from ARs to evaluate different options for treating these waste streams with the objective of identifying stable waste forms fit for storage, transportation, and disposal. The methodology takes into consideration existing information, identifies key information gaps, and considers different criteria such as safeguards requirements, storage, transportation, and disposal canister specifications, economics, and scalability to evaluate different treatment options for AR waste streams.

INTRODUCTION

To date, the focus of the AR development efforts in many countries, including the US seems to be on the front end of the fuel cycle with considerations of the back end perhaps being limited to onsite SNF management. ARs are expected to generate SNF and other waste streams that will require appropriate and acceptable management and disposition strategies. Recent studies [1,2] have concluded that at present a complete picture of the waste generation from ARs does not exist, and therefore it is an issue that needs prompt attention as they may have implications for the planned deployment of ARs. The International Atomic Energy Agency (IAEA) concludes that aspects of AR design and operation should be evaluated, in the context of an integrated waste management strategy, to identify "optimal" opportunities for reducing the future impact of generated wastes [2]. A solid back-end integration

[a] *Nuclear Energy Innovation Capabilities Act of 2017* (Public Law 115-248), signed into law in September 2018.

strategy that examines storage, transportation, and disposal is needed, not only to provide sustainable waste confidence to help ARs succeed, but also to minimize potential future liabilities.

ARs based on LWR technologies may not present significant technical challenges when it comes to SNF management; there may be differences in terms of physical dimensions (e.g., size of fuel assemblies), volumes and burnups, but other characteristics may be similar to those of SNF generated by conventional LWRs, and it could be argued that technical solutions exist for the management and disposition of the SNF from LWR-based ARs. Non-LWR-based ARs, on the other hand, may present a bigger SNF-management challenge because they can produce a large variety of different waste streams that are significantly different than the wastes generated by the current fleet of LWRs.

In the U.S., addressing the back end by establishing a comprehensive strategy to manage the waste from the existing fleet of reactors as well as from future ones, including ARs, has been closely linked to the successful and sustainable deployment of ARs [1,3]. A technical fellow at TerraPower noted that … *[t]he greatest challenge for us [TerraPower] and other reactor developers is that there is no permanent repository* [1]. The same is true in other countries [2,4]. For the deployment of nuclear reactors to … *be accepted by politicians, regulators and the public, the developers must be able to show that there is a credible strategy leading to safe radioactive waste disposal* [4].

CURRENT STATUS OF THE BACK END OF THE NUCLEAR FUEL CYCLE FOR ADVANCED REACTORS

As stated earlier, the focus of AR programs in many countries, including the U.S., has been on reactor design, development, and demonstration with apparently little attention to date paid to the back end. This is not to say that there have been no efforts related to the back end for ARs. Comprehensive reviews have been conducted [1,2] that provide excellent summaries of different ARs types and their respective different fuel types, waste streams and characteristics, and possible fuel cycles, treatments, and disposition paths.

In the US there have been studies focused on the factors that may affect the disposal of the SNF from ARs [5,6,7] under the Department of Energy (DOE) Office of Nuclear Energy's Spent Fuel and Waste Science and Technology Program. One study [7] used characteristics information from three existing DOE-managed SNF wastes streams (TRI-structural ISOtropic or TRISO particle fuel, metallic fuel, and molten-salt reactor SNF) as a reference point for initial feasibility assessment of the direct disposal of AR SNF. That study [7] compared the characteristics of these waste streams to SNF and waste forms priorly analyzed under a DOE-funded disposal options study [8] to develop a strategy that would identify information gaps and future research and development (R&D) efforts.

There are an ongoing R&D efforts under ARPA-E (Advanced Research Projects Agency-Energy) – an agency within DOE -- focused on minimizing the generation of spent fuel (**O**ptimizing **N**uclear **W**aste and **A**dvanced **R**eactor **D**isposal **S**ystems or ONWARDS)[b] and on developing innovative separations technologies, materials accountability, online monitoring technologies, and designs for reprocessing facilities (**C**onverting **U**NF **R**adioisotopes **I**nto **E**nergy or CURIE)[c]. ARPA-E has funded a total of 23 projects: 11 under ONWARDS and 12 under CURIE.

Innovation such as the efforts mentioned are a very significant, positive development, but considerably more work is still needed in the US and internationally to develop national integrated strategies for the

[b] ARPA-E ONWARDS Program ONWARDS | arpa-e.energy.gov

[c] ARPA-E CURIE Program CURIE | arpa-e.energy.gov

management of waste streams from ARs. It will be important to understand how these and future innovations will fit in the context of a national strategy for managing the back end of ARs.

INTEGRATED NUCLEAR WASTE MANAGEMENT STRATEGY FOR ARS – SOME CHALLENGES

Developing and implementing an integrated nuclear waste management strategy for ARs in the US will be challenging, but it will be necessary to make the deployment of ARs a reality. The challenges presented by ARs in terms of an integrated nuclear waste management strategy need to be recognized and addressed as a matter of high priority. The challenges are of technical, regulatory and policy nature [1,2,9]. However, this paper focuses primarily on technical issues, such as (1) Storage, Transportation and Disposal; (2) Waste-Stream Treatment; (3) Reprocessing; and (4) Safeguards.

Storage, Transportation and Disposal

For most of the historical and existing fleet of reactors and associated fuel cycles - whether open or closed - there is a good understanding of the types and inventories of nuclear waste that are being generated and their technical and regulatory storage, transport, and disposal paths. The case for ARs is expected to be very different due to the large variety of reactor classes, designs and materials, and fuels currently in some stage of development, which will lead to a large heterogeneity of waste streams. While there is general knowledge of the characteristics of the waste as a function of general AR design [1,2], for non-LWR ARs there is a considerable lack of quantified data regarding fuel forms, fissile material contents, burnup at discharge, isotopic content and compositions, radioactive composition, etc. [9]. Data are needed to provide a technical basis for designing storage, transportation, and disposal systems for waste expected to be produced by ARs.

The use of HALEU as fuel in these ARs may have impacts on the systems that are currently used for wet and dry storage, transportation, and disposal of SNF. Spent HALEU fuel could have higher decay heat, higher specific activity, and increased degradation of cladding materials. These conditions could impact, for example, dry-storage cask systems as well as waste acceptance criteria for geologic disposal.

The U.S. has experience addressing unique waste streams because the current DOE SNF inventory includes waste with properties similar to those that may be generated from some ARs, such as the TRISO fuels from the Fort St. Vrain reactor. These unique waste streams currently exist in very small volumes relative to the total U.S. inventory of commercial and DOE-managed SNF and high-level radioactive waste. For that reason, in the past these waste streams have been treated using conservative assumptions with respect to disposal in a deep geologic repository with no discernable impact on the results of postclosure performance assessment analyses [8,10]. In the future, depending on the number and types of ARs that are eventually deployed in the U.S., treating their waste streams using conservative assumptions may not be an acceptable approach because of their potential larger volumes.

There is uncertainty regarding the design and capacity of the storage, transportation and disposal infrastructure that will be needed to manage the SNF and other wastes streams from ARs, and near-term technical information will be needed to get a better understanding of the impact of waste streams from ARs on the back end of the fuel cycle [9].

Waste-Stream Treatment

Not all waste streams from ARs will be ready for storage, transportation and disposal and will therefore require treatment to render them acceptable. For example, sodium-bonded SNF is highly reactive to water; fluoride-based salts from molten salt reactors can be highly corrosive, undergo radiolytic decomposition, and result in gas generation; and lead coolants can be highly toxic and corrosive. Calcine radioactive waste, which exits in a powdery form, can be treated by hot isostatic pressing resulting in smaller, more condensed waste forms which are easier and more economical to handle, such as Synroc or "synthetic rock."[d]

For some ARs, designs such as molten salt reactors, there are large uncertainties on waste stream characteristics due to a considerable dearth of data. At present, it is unclear what treatment method(s) will be needed for AR waste streams to produce stable waste forms. There is a need for a comprehensive effort to identify waste streams from ARs that will require treatment; evaluate the possible treatment options, attendant economics, development, and deployment risks at commercial scales (including the supporting infrastructure); and quantify the characteristics of the resulting waste forms [9].

Reprocessing

It is important to note that "reprocessing" and "treatment" are different ways of rendering waste forms for transportation, storage and disposal. "Treatment" (see above) is intended to change the characteristics of a waste stream to make it suitable for storage, transportation, or disposal, whereas "reprocessing" is intended to remove particular constituents from the waste to decrease the volume of SNF produced per unit of energy generated, reduce major actinide content in the SNF, or reduce the decay heat of the resulting radioactive waste stream if fission products are separated.

Over the past decades there have been multiple international and US-based studies on advanced fuel cycles that have examined reprocessing as an option [11,12]. These studies concluded that, while alternative fuel cycles can reduce volume, they are unlikely to have an impact on either geologic disposal repository thermal load management without century-long aging of the fission products or on long-term repository performance due to the dominance of long-lived mobile fission products in the dose estimates. If reprocessing can result in long-lived, stable waste forms, there is the potential for positive impacts on performance depending on the disposal concept [7,12].

Closing the back end of the nuclear fuel cycle by reprocessing or recycling has been proposed as a means of significantly reducing the volume of SNF that will require disposal in a deep geologic repository. The main concerns with reprocessing in the US have been the potentially high operational costs vs. benefits [13] and the proliferation risk due to the separated plutonium being an attractive material for diversion for non-peaceful uses [1].

Some ARs are designed to operate with a closed fuel cycle. Developers of such ARs point out that these will be innovative reprocessing facilities unlike large-scale reprocessing facilities such as La Hague and that they would be cost-effective and reduce proliferation risks [1]. These assertions will need to be evaluated and a compelling argument developed if such ARs are to be deployed in a timeframe similar to that of ARs that can operate with an open fuel cycle.

Safeguards[e]

Another potentially significant uncertainty associated with the back end for ARs is a lack of understanding about the proliferation risks that may be associated with some of the waste streams that could be generated. This uncertainty has been discussed from the perspective of international safeguards obligations for countries that have signed comprehensive safeguards agreements and additional applicable protocols with the IAEA [1]. These obligations would impact U.S.-based AR developers that plan to deploy their designs in non-weapon states that are subject to the IAEA regulations.

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[d] https://www.ansto.gov.au/products/ansto-synroc

[e] It is recognized that safeguards considerations include, not only Material Control and Accounting, but also physical protection and cybersecurity. This paper focuses on Material Control and Accounting.

Applying material control and accounting (MC&A) considerations to the existing fleet of LWR-reactors is relatively straightforward. SNF assemblies are discrete items with unique identifiers that facilitate their counting, monitoring, and traceability as they moved through the fuel cycle all the way through final disposition. ARs without fixed fuel assemblies may not be amenable to the application of existing conventional MC&A methods, inspections, and monitoring techniques. Consider, for example, molten-salt reactors in which the fuel could be mixed with the salt coolant as well as fission products and actinides and could operate with continuous fueling and salt removal. In this case, identifying and tracking the attractive fuel components is not likely to be straightforward.

Recognizing this need, DOE's Office of Nuclear Energy established the Advanced Reactor Safeguards Program[f] for the purpose of supporting the … *domestic deployment of advanced nuclear reactors by mitigating safeguards and security roadblocks. The program applies laboratory research and development to address near-term challenges advanced reactor vendors face in meeting Physical Protection System (PPS) and Material Control and Accounting (MC&A) requirements for U.S. construction.*

Some AR designs may include built-in safeguards technologies commonly known as safeguards by design (SBD). If AR designs can have embedded SBD features this could lessen the burden of safeguards verification for the back end by taking advantage of "Continuity of Knowledge" (CoK). It is uncertain whether embedded SBD features would be sufficient to address safeguards considerations for the back end of ARs. Novel accounting and control techniques, including development of new equipment, could be required for some types of fuels such as TRISO and molten salt reactor liquids, suggesting that effective, acceptable accounting techniques could be highly dependent on the physical nature of the waste stream and how it is packaged for disposal. It could be that AR waste streams may first need to be treated to produce stable waste forms before applying materials accountability and controls techniques.

ASSESSMENT OF THE BACK END OF ARS FOR DEVELOPING STABLE WASTE FORMS

There are many outstanding issues related to the back end of the fuel cycle for ARs in need of resolution. "Standardization" through developing a manageable set of stable waste forms fit for storage, transportation and disposal may be the key to addressing many of the outstanding issues. Developing stable waste forms could require treating many of the AR waste streams. If treatment becomes necessary, there may be different treatment options for each waste stream. Assessing the treatment options will be necessary to inform decisions on an integrated nuclear waste management system for ARs.

A methodology for evaluating treatment options for developing stable waste forms is proposed. Fig. 1 shows the sets of activities that will be undertaken to develop and test the methodology.

Phase 1 – Information Gathering and Stakeholder Engagement

- Identify Target Audience and Stakeholders and Consult with Stakeholders- It would be critically important to the success of the project that it be socialized with key stakeholders (such as Congress, DOE, U.S. Nuclear Regulatory Commission [NRC,] professional societies, industry groups, reactor designers, vendors, etc.) and that these stakeholders (1) see the value of the study and (2) are willing to participate. Through these engagements, information will be gathered that would shape the scope of the study and increase the likelihood that, when completed, the study will be of utility to key policy decision-makers.
- Establish an Information Baseline on ARs Waste Streams and Consult with AR Vendors – As discussed, there have been comprehensive studies that have identified issues related to the back end of ARs. Information from DOE-managed SNF waste streams will be used as a supplement to information from AR vendors in this study. It is recognized that DOE-managed SNF waste streams are not identical to

[f] Advanced Reactor Safeguards: Sandia Energy

AR waste streams, but they have similar characteristics, and that may suffice for the purpose of developing the methodology discussed in this paper. Currently, Idaho National Laboratory maintains a library of about 250 different spent fuel types, some in inventory, with characteristics similar to those expected from ARs.[g] There are also a number of ongoing R&D studies addressing specific aspects of the back end of ARs. This phase would help establish a baseline of available information to identify information gaps that would need to be filled eventually and will complement the work by Sassani et al. 2022 [5].

- Identify External Drivers – Information on external drivers, such as MC&A requirements; storage, transportation, and disposal canisters design specifications; waste acceptance criteria for different disposal concepts (e.g., mined repositories and deep boreholes) in different geologies; and technology readiness levels, economics, and industrial scalability will be identified and evaluated because these factors may constrain the evaluation of waste stream treatment options.
- Identify Plausible Treatment Options – For a selected sample of waste streams, identify treatment options to be considered. Ongoing R&D projects in programs such as those under the DOE Office of Nuclear Energy's SFWS&T, and ARPA-E's ONWARDS and CURIE Programs will be leveraged.

[g] Nuclear Fuels & Materials Library - NSUF (inl.gov)

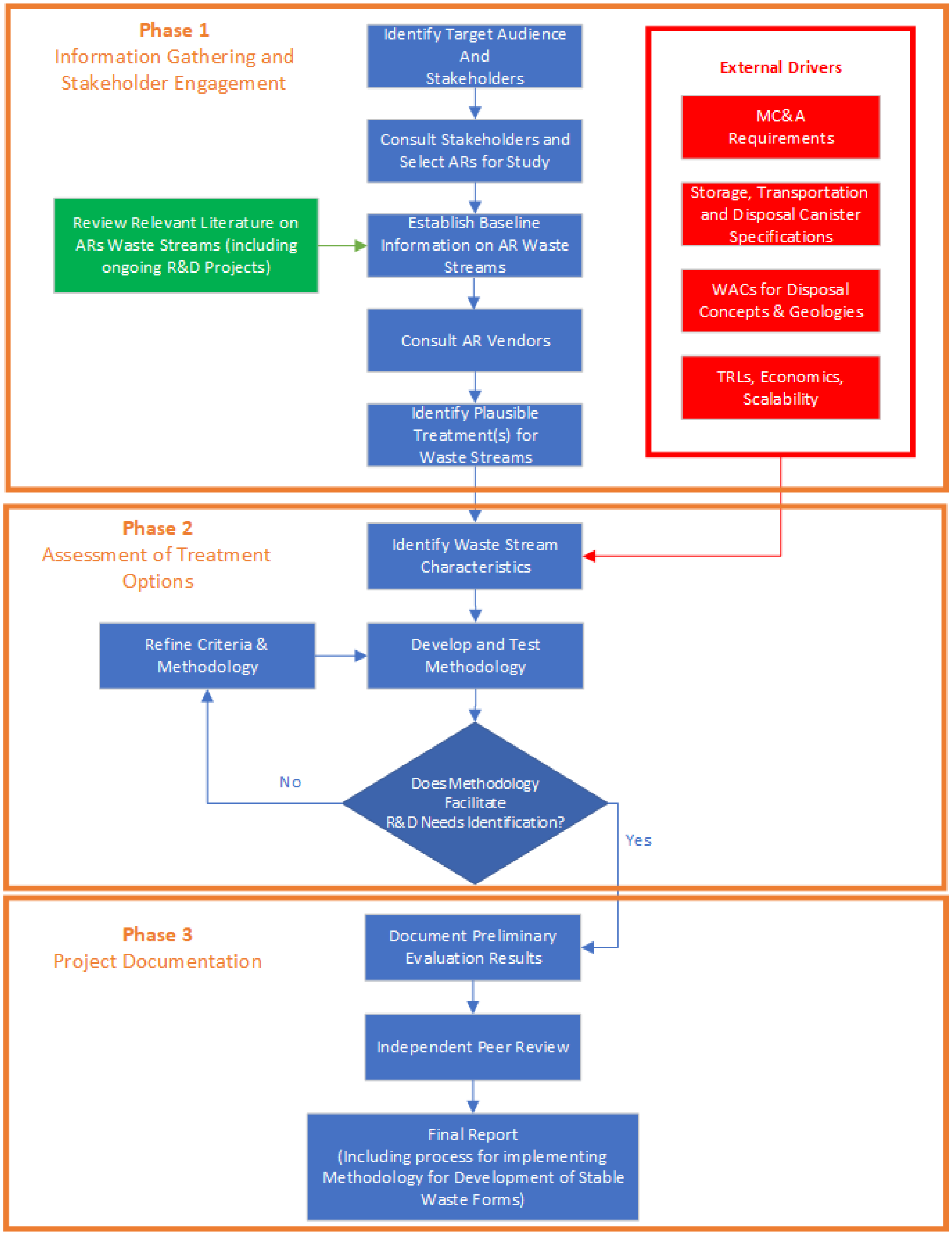

Fig. 1. Development of Methodology for Evaluating Treatment Options of Waste Streams from Advanced Reactors

Phase 2 –Assessment of Treatment Options for Developing Stable Waste Forms

- Identify waste stream characteristics – Based on the information gathered during Phase 1 of the study, a set of relevant waste stream characteristics will be identified that will hopefully be sufficiently discriminatory to increase the likelihood that salient differences between treatment options can be discerned and the pros and cons of each option identified.

- Develop Methodology - Past studies [1,14] will be considered in developing the assessment methodology.
- Preliminary Testing of Methodology – The assessment methodology will be exercised using available information. In areas in which data may not be available, informal expert opinions will be sought out and used to supplement the existing information baseline. As part of this activity, a qualitative sensitivity analysis of the results of exercising the methodology will be performed to rank the waste characteristics, from highest to lowest impact on treatment challenges, based on their on the results of the assessment.
- Testing of Methodology – Based on the outcome of the qualitative sensitivity analysis, the applicability of the methodology will be established to identify needed R&D on AR waste characteristics.
- Refinement of Assessment Methodology and Repeated Execution of Methodology – If needed, the methodology will be refined to the extent practicable given the available information, and the execution of the methodology will be repeated.

Phase 3 – Project Documentation

- Prepare Draft Report – An initial draft report will be prepared documenting the study.
- Conduct Independent Peer Review - Stakeholders that expressed interesting in the study will be asked to serve as peer reviewers of the draft report.
- Prepare Final Report – A final report will be prepared based on review comments. The final report will include guidance on how to implement the methodology as well as existing gaps in information that should be addressed through future R&D efforts.

CONCLUSIONS

The focus, to date, of ARs programs in many countries, including the U.S, seems to be on the front end of the fuel cycle with considerations of the back end perhaps being limited to onsite SNF management and some specific R&D efforts. At some point, the back end of the fuel cycle for ARs will need to be addressed from a systems perspective. A solid back-end integration strategy not only provides sustainable waste confidence to help ARs succeed but also minimizes potential future liabilities.

ARs are expected to generate SNF and other waste streams that will require appropriate and acceptable management and disposition strategies. At present a complete picture of the waste generation from ARs does not exist and therefore it is an issue that needs prompt attention. Some recent studies have concluded that the backend needs to be addressed now because it may have implications for the planned deployment of ARs. Others state that aspects of AR design and operation should be evaluated, in the context of an integrated waste management strategy, to identify "optimal" opportunities for reducing the future impact of generated wastes.

"Standardization" of the back end has been identified as a major challenge posed by ARs. Using available information on waste streams from ARs, this paper proposes a methodology for a systems study to evaluate different options for treating waste streams from generic ARs to develop stable waste forms fit for storage, transportation, and disposal. The methodology would take into consideration existing information; identify key information gaps; and consider different criteria such as safeguards requirements; storage, transportation, and disposal canister specifications; economics; and scalability to evaluate different treatment options for AR waste streams. In addition, the methodology could serve as a roadmap for the development of an integrated national strategy for addressing the back end of the nuclear fuel cycle for ARs.

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