FUEL CYCLE PERFORMANCE OF THERMAL SPECMR SMALL MODULAR REACTORS

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Small modular reactors (SMRs) offer potential benefits, such as enhanced operational flexibility. However, it is vital to understand the holistic impact of SMRs on nuclear fuel cycle performance. The focus of this paper is the fuel cycle impacts of light water SMRs in a once-through fuel cycle with low-enriched uranium fuel. A key objective of this paper is to describe preliminary reactor core physics and fuel cycle analyses conducted in support of the U.S. Department of Energy, Office of Nuclear Energy, Fuel Cycle Options Campaign. The hypothetical light water SMR considered in these preliminary scoping studies is a “cartridge type” one-batch core with 4.9% enrichment. Challenges associated with SMRs include increased neutron leakage, fewer assemblies in the core (and therefore fewer degrees of freedom in the core design), complex enrichment and burnable absorber loadings, full power operation with inserted control rods, the potential for frequent load-following operation, and shortened core height. Each of these will impact the achievable discharge burnup in the reactor and the fuel cycle performance. This paper summarizes a list of the factors relevant to SMR fuel, core, and operation that will impact fuel cycle performance.

The high-level issues identified and preliminary scoping calculations in this paper are intended to inform regarding potential fuel cycle impacts of one-batch thermal spectrum SMRs. In particular, this paper highlights the impact of increased neutron leakage and reduced number of batches on the achievable burnup of the reactor. Fuel cycle performance metrics for an SMR are compared with those for a conventional three-batch light water reactor in the following areas: nuclear waste management, environmental impact, and resource utilization. The metrics performance for an SMR is degraded for the mass of spent nuclear fuel and high-level waste disposed of, mass of depleted uranium disposed of, land use per energy generated, and carbon emissions per energy generated.

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I. INTRODUCTION

This paper has several objectives, including qualitative identification of issues related to fuel cycle performance impacts of thermal spectrum water-cooled small modular reactors (SMRs). In addition, the paper documents preliminary reactor core physics analyses conducted in support of the U.S. Department of Energy Office of Nuclear Energy (DOE–NE) Fuel Cycle Options Campaign study of modularity impacts.

I.A. Fuel Cycle Issues Associated with Thermal SMRs

A scoping expert elicitation was performed to identify SMR characteristics that may impact fuel cycle performance. These issues included identifying differences in SMRs compared with larger conventional light water reactors (LWRs). Some key differences that have the potential to impact the fuel cycle performance of SMRs versus LWRs include fuel design information, reactivity control approaches, and core loading and design. Specific issues identified in each of these areas are outlined below.
I.A.1. SMR Fuel Assembly Design Impacts on Fuel Cycle Performance

SMR core designs use fewer fuel assemblies, which makes core design more challenging, as there are fewer degrees of freedom. Typically, SMRs have somewhere between 37 and 89 assemblies; whereas a large Generation III+ pressurized water reactor (PWR), for example, the Westinghouse AP1000, has 157 assemblies.

Typically, fuel assembly designs in SMRs feature shorter assemblies than designs in large LWRs. SMR designs typically feature fuel that is roughly half the height (6.5–8 feet) of the assembly for a typical large LWR (12–14 feet). A smaller axial and radial core will yield significantly increased neutron leakage versus a large core, resulting in lower fuel utilization. One of the objectives of this paper is to quantify this impact.

The small core size of SMRs and resultant increase in neutron leakage means there may be a need to control power peaking via heavier burnable poison loadings versus large LWRs. Another potential approach is more enrichment zoning for inter- and intra-fuel assemblies. These design characteristics yield a more heterogeneous reactor core. Additionally, because the maximum enrichment is 5 wt%, and SMR designs may leverage varying enrichments to control power peaking, the average enrichment may be less than in a large LWR core and it will yield lower discharge fuel burnup.

I.A.2. SMR Reactivity Control Impacts on Fuel Cycle Performance

Some SMR design concepts do not use boron in the coolant for global reactivity control. The aim is to reduce capital cost and reduce the amount of waste produced from boron chemistry resins. However, using control rod insertion to control the reactor means stronger axial and radial power variations. Additionally, concepts without boron will have a more negative moderator temperature coefficient of reactivity.

I.A.3. SMR Core Loading Impacts on Fuel Cycle Performance

Some SMR concepts are focused on single-batch reloads and “cartridge” fuel loadings. These simplify core design, as each core is the same. Additionally, extended cycles of 3–4 years have the potential to reduce outages by approximately 50% versus the AP1000; the reduction in outages equates to ~750 more full power days over the core lifetime. However, single-batch core loadings do not use the fuel as efficiently as multi-batch loadings.

I.B. Example Fuel Cycle Performance Calculations

The qualitative identification of potential fuel cycle performance impacts of SMRs was used to inform an example quantitative study. The calculations in this paper focus on thermal spectrum light water SMRs. The SMR considered in these preliminary scoping studies is a “cartridge type” one-batch core with 4.9% enrichment. Some core parameters, such as the size of the reactor and general assembly layout, are similar to published information about the NuScale PWR concept1. The calculations in this document are intended only to provide information on potential fuel cycle impacts of one-batch thermal spectrum SMRs. In particular, these calculations highlight the impact of the reduced number of batches on the achievable burnup and on the metrics performance.

The SMR model developed here is based on a modified (reduced-size) version of a generic PWR model developed in support of the DOE–NE Advanced Fuels Campaign’s evaluation of the reactor performance and safety characteristics of advanced fuel concepts2; the version studied has a reduced core height and reduced core radius. The SCALE lattice physics tool TRITON/NEWT was used for the generation of two-group constants3. The PARCS regulatory-grade core simulator4 was used with two-group parameters to calculate full-core performance. The calculations of SMR performance in this document assume the following:

• Nodal neutron diffusion using a hybrid analytical nodal method and nodal expansion method solver.
• Reactivity feedback for fuel temperature, moderator temperature, moderator density, boron concentration, and control rods using thermal and hydraulic models appropriate for PWR core analysis.
• A 17 by 17 Westinghouse PWR assembly model for the generation of few-group parameters.
• A generic cross section set for reflector regions representative of a large Westinghouse PWR (not necessarily an SMR).

II. REVIEW OF REFERENCE EQUILIBRIUM CORE MODEL FOR A LARGE PWR

The large PWR core configuration used as a starting point for development of the SMR model was calculated with a single burnable poison configuration in a multi-cycle calculation. An identical burnable absorber configuration was used for all fuel assemblies. The burnable poison used, in all but one case, was standard Westinghouse ZrB2 coating5, e.g. integral fuel burnable absorbers (IFBA). The assembly geometry used in the generation of the few-group parameters is shown in Fig. 1.
Fig. 1. One-quarter-assembly geometry used for generation of the few-group parameters for the reactor core model.

The reference three-batch core model of a large PWR was developed using PARCS. The PARCS multi-cycle capability was used to calculate equilibrium cores with a discharge burnup convergence criterion of 0.1 GWd/t and a fixed fuel management scheme.

In each cycle, the relevant fuel assemblies were shuffled according to a prescribed fuel management scheme. In general, the fresh assemblies were located near the periphery of the core and the once- and twice-burned assemblies, throughout the central core region. The fuel management scheme was octant symmetric. Only one fuel type was used in this simplified core model; in reality, multiple fuel types with varying 235U enrichments and burnable poison content would be used in a reactor core. Soluble boron was used for reactivity control throughout the cycle (e.g., control rods were not used throughout the cycle). The critical soluble boron concentration was calculated iteratively within each burnup step. As the fuel depleted, the core simulator calculated the boron letdown curve for the core configuration. Within the fuel assemblies, 112 of the fuel pins used ZrB2 integral fuel burnable absorbers for reactivity control.

The equilibrium core search was performed using a prescribed fuel management scheme with fuel temperature, moderator density and temperature, and soluble boron feedback. The enrichment was 4.9% and the average discharge burnup was 53 GWd/t. The equilibrium core search convergence criterion (0.1 GWd/t) was the difference between the maximum end-of-cycle (EOC) burnup in the current cycle versus maximum EOC burnup from the previous cycle. The beginning-of-cycle and EOC core power and burnup distributions are shown in Fig. 2.

Fig. 2. Equilibrium quarter-core power and burnup distribution for a large PWR with UO2 fuel (the periphery of the core is at the top of the Figure).

III. DEVELOPMENT OF A SIMPLIFIED THERMAL SPECTRUM SMR CORE MODEL

The NuScale SMR concept1 was used as a general guiding concept in the development of the SMR scoping model. The same assembly configuration was assumed to be a 17 x 17 Westinghouse assembly with a reduced radial and axial core size and 1-batch fuel. The relative radial core sizes are shown in Fig. 3 and other key parameters in TABLE 1. The layout of control rod clusters in the SMR model is shown in Fig. 4. In the SMR model, the assembly pitch was 21.44 cm with four x-direction and y-direction mesh points per assembly. There were 20 axial meshes of 10.675 cm in the fuel region and two axial meshes in the reflector regions, each 21.44 cm.

Fig. 3. Comparison of radial core size and layout for 3-batch large PWR (left) and one-batch SMR (right). Each colored “box” is a fuel assembly.
TABLE 1. Large PWR vs. SMR core parameters (differences are bolded)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Large PWR</th>
<th>SMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor core heat output, MW(th)</td>
<td>3400</td>
<td>160 or 400</td>
</tr>
<tr>
<td>System pressure, nominal, MPa</td>
<td>15.51</td>
<td>15.51</td>
</tr>
<tr>
<td>Nominal inlet coolant temperature, °C</td>
<td>279.4</td>
<td>279.4</td>
</tr>
<tr>
<td>Fuel assembly design</td>
<td>17×17</td>
<td>17×17</td>
</tr>
<tr>
<td>Active fuel height, cm</td>
<td>426.7</td>
<td>213.35</td>
</tr>
<tr>
<td>Number of fuel assemblies</td>
<td>157</td>
<td>37</td>
</tr>
<tr>
<td>Fuel assembly pitch, cm</td>
<td>21.44</td>
<td>21.44</td>
</tr>
<tr>
<td>Uranium rods per assembly</td>
<td>264</td>
<td>264</td>
</tr>
<tr>
<td>Number of control clusters</td>
<td>53-RCCA</td>
<td>16-RCCA</td>
</tr>
<tr>
<td>Control rod material</td>
<td>Ag-In-Cd</td>
<td>Ag-In-Cd</td>
</tr>
<tr>
<td>Fuel enrichment (weight %)</td>
<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td>Number of fuel batches</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

- Simplified reactor and reflector geometry: NuScale does not report the exact reactor geometry, only the radial layout (37 assemblies), assembly layout (17 x 17), and other general information.
- ZrB2 used for reactivity control instead of Gd2O3: NuScale does not report the exact intra-assembly burnable absorber configurations.
- Assembly height assumed to be half of AP1000 and axial depleted uranium blankets neglected: NuScale does not report the exact active core height but does state that the height is approximately half of a large PWR.

The core calculations in this document are expected to yield conservative (high) estimates of neutron leakage from fuel regions due to a uniform enrichment of 4.9% (including near the periphery) and omission of axial depleted uranium blankets. Although the model developed here is simplified, reasonable agreement was achieved between the reported NuScale design value of hot zero power (HZP) critical boron concentration (1,303 ppm) and the calculated HZP boron concentration using the simplified model employed here (1,456 ppm).

IV. FUEL CYCLE PERFORMANCE IMPACTS OF A ONE-BATCH THERMAL SPECTRUM SMR IN A ONCE-THROUGH FUEL CYCLE

The one-batch discharge burnups in the 37 fuel assemblies are reported for two assembly average powers. One assembly power corresponds to the AP1000 average linear power (5.72 kW/ft) and the other to the NuScale average linear power (2.28 kW/ft). The higher heat generation rate (AP1000) corresponds to a reactor thermal power of 400 MWe, and the lower heat generation rate (NuScale) corresponds to a reactor thermal power of 160 MWe. The EOC axial and radial power distributions are shown in Fig. 5 and Fig. 6, respectively. The corresponding radial burnup distributions are shown in Fig. 7. In the radial distributions, each “box” represents a fuel assembly. Note that the AP1000 average linear power is consistent with some recent scoping analyses of SMRs.

Key simplifications versus the NuScale reference design included the following:

- Only one enrichment zone (4.9%): NuScale does not report the exact enrichment scheme used, only that the maximum enrichment is 4.9%.

![Control rod bank configuration](image-url)
The average discharge burnup at a linear power of 5.72 kW/ft was 30.5 GWD/t and at the 2.28 kW/ft linear power was 32.4 GWD/t. The key driver of the difference was the different amounts of buildup of fission product poisons, particularly xenon and samarium, associated with the different flux levels in the two cores. The difference in burnup between the central fuel assemblies and the peripheral fuel assemblies is apparent. The cycle length was approximately 24 months with 4.9% \(^{235}\text{U}\) enrichment and a 5.72 kW/ft linear power, and approximately 48 months with 4.9% \(^{235}\text{U}\) enrichment and a 2.28 kW/ft linear power. The discharge burnup was consistent with estimates in the literature for similarly sized cores.

The reduced discharge burnup versus the reference large LWR once-through fuel cycle (referred to as the EG01 analysis example)\(^7\) cascaded throughout all of the evaluation and screening (E&S) metrics and negatively impacted fuel cycle performance. The E&S metrics are compared with the reference EG01 case\(^8\) in TABLE 2. The uranium natural resource utilization was significantly worse in the simplified SMR (~ 345 t/GWe-yr) than in the EG01 (~189 t/GWe-yr) analysis example and was lower than in the least-performing evaluation groups in the E&S (~305 t/GWe-yr). The mass of DU+RU+RTh was lower than in any analysis example in the E&S. The performance of all metric values was degraded. The metrics where bin boundaries were crossed included mass of SNF+HLW disposed of, mass of DU+RU+RTh disposed of, land use per energy generated, and carbon emissions per energy generated.

The overall reduced performance of the thermal spectrum SMR was driven by the higher core neutron leakage and the reduced number of fuel batches. The leakage from the 3-dimensional core model is shown in Fig. 8 throughout the burnup cycle. Fig. 8 also shows a representative core leakage from a 3-batch large PWR.
core model. Although this is not an entirely consistent comparison, it provides an indication of the overall impact of neutron leakage on neutron economy in the SMR versus that in a large PWR. Fig. 8 also illustrates the need for full-core calculations of thermal spectrum SMR reactor physics: the leakage from the fuel region was considerable and it varied significantly throughout the burnup cycle. The activity normalized per GWe-yr as a function of decay time is shown in Fig. 9.

### TABLE 2. One-batch SMR scoping impact on E&S metrics (metrics where bin boundaries were crossed are in bold typeface)

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Metrics</th>
<th>Large LWR</th>
<th>SMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear waste management</td>
<td>Mass of SNF+HLW disposed of, t/GWe-year</td>
<td>21.92/E</td>
<td><strong>36.28/F</strong></td>
</tr>
<tr>
<td></td>
<td>Activity of SNF+HLW (@100 years), MCi/GWe-year</td>
<td>1.34/C</td>
<td>1.40/C</td>
</tr>
<tr>
<td></td>
<td>Activity of SNF+HLW (@100,000 years), 10^4 MCi/GWe-year</td>
<td>16.5/C</td>
<td>16.9/C</td>
</tr>
<tr>
<td></td>
<td>Mass of DU+RU+RTh disposed of, t/GWe-year</td>
<td>166.67/E</td>
<td><strong>329.67/F</strong></td>
</tr>
<tr>
<td>Environmental impact</td>
<td>Volume of low-level waste, m^3/GWe-year</td>
<td>398.8/C</td>
<td>470.6/C</td>
</tr>
<tr>
<td></td>
<td>Land use per energy generated, km^2/GWe-year</td>
<td>0.175/B</td>
<td><strong>0.263/C</strong></td>
</tr>
<tr>
<td></td>
<td>Water use per energy generated, ML/GWe-year</td>
<td>23891/B</td>
<td>24067/B</td>
</tr>
<tr>
<td></td>
<td>Carbon emission—CO₂ released per energy generated, kt CO₂/GWe-year</td>
<td>44.1/B</td>
<td><strong>72.4/C</strong></td>
</tr>
<tr>
<td></td>
<td>Radiological exposure, Sv/GWe-year</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Resource utilization</td>
<td>Natural uranium required per energy generated, t/GWe-year</td>
<td>188.63/D</td>
<td>366.04/D</td>
</tr>
<tr>
<td></td>
<td>Natural thorium required per energy generated, t/GWe-year</td>
<td>0/A</td>
<td>0/A</td>
</tr>
</tbody>
</table>

Fig. 8. Neutron leakage (%) from 3-dimensional core models for a one-batch SMR and three-batch large PWR.

Fig. 9. Energy-normalized activity as a function of decay time after discharge for one-batch SMR and three-batch PWR (EG01 analysis example).
V. PARAMETRIC STUDY OF ONE-BATCH LWR SMRS AS A FUNCTION OF CORE SIZE

It is well understood that multi-batch fuel loading yields better fuel utilization\(^6\), and the best fuel utilization is achieved in a continuously refueled system\(^3\). However, it is useful to quantify the relationship between one-batch core size and resource utilization in the context of this study. This relationship shows the impact of leakage on achievable burnup in a one-batch LWR SMR. The calculated leakage and discharge burnup are shown in Fig. 10 for light water SMRs as a function of increasing core size. These calculations were performed as a scoping study. This simplified parametric study shows one-batch SMR discharge burnup for radial core sizes of 12, 21, 32, 45, 60, and 77 assemblies. The calculated discharge burnup and uranium resource requirement are shown for the radial cores sizes in Fig. 11.

Also calculated was the maximum discharge burnup for a one-batch LWR with less than 5% enrichment and infinitely reflected with no leakage. This value is approximately 44.35 GWd/t, significantly less than the three-batch EG01 analysis example (50 GWd/t at 4.2% enrichment). This discharge burnup corresponds to a minimum natural resource requirement of 253.73 t/GWe-year versus the EG01 analysis example value of 188.63 t/GWe-year.

VI. CONCLUSIONS

The discharge burnup of SMRs will be different from that of large LWRs because of varying enrichments, especially in single-batch cores. The effects of neutron leakage, single-batch cores, and heavy burnable poison loadings will affect uranium utilization.

Heavy use of control rods and burnable absorbers will harden the neutron energy spectrum, which may impact the buildup of transuranic isotopes. In addition, the harder spectrum could limit vessel/barrel lifetime. Fuel costs per bundle will be higher because of increased complexity due to the additional radial and axial heterogeneity.

Discharged isotopic vectors will be different from those in large LWRs, especially for single-batch cores and those that use heavy burnable absorbers and control rods. This difference will impact decay heat, toxicity, and radioactivity. In addition, environmental metrics will be impacted, including land use, water use, and carbon emissions.

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REFERENCES


