Impact of thermal spectrum small modular reactors on performance of once-through nuclear fuel cycles with low-enriched uranium

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ABSTRACT

Small modular reactors (SMRs) may offer potential benefits relative to large light water reactors, such as enhanced flexibility in deployment and operation. 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 neutronics and fuel cycle analyses conducted in support of the US Department of Energy, Office of Nuclear Energy, Fuel Cycle Options Campaign. The hypothetical light water SMR example case considered in these preliminary scoping studies is a “cartridge type” one-batch core with slightly less than 5.0% enrichment.

The high-level issues identified and preliminary scoping calculations in this paper are intended to inform decision makers regarding potential fuel cycle impacts of one-batch thermal-spectrum SMRs. In particular, this paper highlights the impact of increased neutron leakage and a reduced number of batches on the achievable burnup of the reactor. Fuel cycle performance metrics for the simplified example SMR analyzed herein are compared with those for a conventional three-batch light water reactor (LWR) in the following areas: nuclear waste management, environmental impact,

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and resource utilization. The metrics performance for such 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.

Finally, it is noted that the features of some SMR designs impact three main aspects of fuel cycle performance: (1) small cores, which mean high leakage (there is a radial and an axial component); (2) a lack of boron, which means a heterogeneous core and extensive use of control rods and burnable poisons; and (3) single-batch cores. But not all SMR designs have all of these traits. The approach used in this study is therefore a bounding case, and not all SMRs may be affected to the same extent.

Key Words: small modular reactor; fuel cycle performance; evaluation and screening; neutron leakage.

1. Introduction

One objective of this paper is a qualitative identification of issues related to the impacts on fuel cycle performance of thermal spectrum light water-cooled SMRs. In addition, the paper documents preliminary neutronics analyses conducted in support of the US Department of Energy Office of Nuclear Energy (DOE-NE) Fuel Cycle Options Campaign study of modularity impacts.

The DOE-NE Fuel Cycle Evaluation and Screening (E&S) identified nuclear fuel cycle options with significant potential benefits relative to the present once-through fuel cycle in thermal spectrum LWRs in the United States (Wigeland et al. 2014a). The E&S evaluated possible fuel cycles with respect to nine high-level criteria, including natural resource utilization and nuclear

waste management. Analysis examples for each fuel cycle in the E&S were evaluated based on peer-reviewed reactor physics and inventory analyses to quantitatively document performance. These analysis examples were evaluated based on 25 metrics that correspond to the nine high-level criteria. The metric values were placed in alphabetized bins to accommodate uncertainties. The bins used in the E&S represent performance, with “A” representing the highest-performing bin and “F” representing the least-performing bin.

The E&S and follow-on studies have yielded several contributions in the literature. One important contribution is a review of the impact of various nuclear fuel cycles on the E&S nuclear waste management metrics (Stauff et al. 2015). Stauff et al. (2015) overviews the nuclear waste management metrics performance of each of the fuel cycles in the E&S, as well as the nuclear waste management metric definitions, which are relevant to the present paper. Other literature related to the E&S has explored performance trade-offs in various sustainable fuel cycles by examining the impact of technology choices (Brown et al. 2015) and the performance of externally driven systems versus critical reactors in uranium fuel cycles (Heidet et al. 2015) and thorium fuel cycles (Brown et al. 2016a). Similar to the present paper, Brown et al. (2015), Heidet et al. (2015), and Brown et al. (2016a) explore the relative performance of fuel cycle options or technology choices and the underlying physics reasons the performance is different. Additional studies have examined the potential transition from the present once-through fuel cycle to a promising future fuel cycle (Feng et al. 2016, Brown et al. 2016b).

The analysis example for the reference fuel cycle in the E&S was based on a large pressurized water reactor (PWR) with 4.21% enrichment, 3% neutron leakage, and 50 GWd/t discharge burnup. SMRs will have different fuel cycle performance compared with large LWRs because of differences

in enrichment variation in the assemblies and because of neutron leakage, which will impact the achievable discharge burnup for a given average enrichment and fuel batch loading.

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 LWRs. Some key differences that have the potential to impact the fuel cycle performance of SMRs versus large LWRs are fuel design information, reactivity control approaches, and core loading and design. Specific issues identified in each of these areas are outlined below.

1.1 SMR reactivity control impacts on fuel cycle performance

Some SMR design concepts, for example the mPower and Holtec designs, do not use boron in the coolant for global reactivity control (Worrall 2014). The aim of this design is to reduce capital cost and reduce the amount of waste consisting of boron chemistry resins. However, using control rod insertion to control the reactor means stronger axial and radial power variations, which again will yield more heterogeneous fuel assembly designs. Additionally, concepts without boron will have a more negative moderator temperature coefficient of reactivity. This will impact the shutdown margin and impact the axial power distribution for those designs with a large temperature change in the core.

1.2 SMR fuel assembly design impacts on fuel cycle performance

SMR core designs typically use fewer fuel assemblies (Vujić et al. 2012), which makes core design more challenging, as there are fewer degrees of freedom. Worrall (2014) provides a comprehensive overview of some of the challenges associated with core design in SMRs. Typically, SMRs have somewhere between 37 and 89 assemblies (Liu and Fan 2014; Worrall 2014); whereas a

large generation III+ PWR, for example, the Westinghouse AP1000 (Westinghouse 2009), has 157 assemblies.

SMR fuel assembly designs use shorter assemblies than designs in large LWRs (Haugh and Mohamed 2012; Liu and Fan 2014; Worrall 2014), 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 compared with LWRs. Another potential approach is more enrichment zoning in the reactor core. This design characteristic is more relevant to those designs with no critical boron and hence uses burnable poisons and, in particular, control rod clusters for global reactivity control. These design characteristics yield a more heterogeneous reactor core. Additionally, because the maximum enrichment is 5%, and SMR designs may leverage varying enrichments to control power peaking, the average enrichment may be less than in a large LWR core; this will yield lower discharge fuel burnup.

1.3 SMR core loading impacts on fuel cycle performance

Some SMR concepts are focused on single-batch reloads and “cartridge” fuel loadings. Although single-batch cores limit the number of degrees of freedom (in particular, burnup distribution), which can make the core design more challenging, it does simplify the core design process in the long term, as the same design can be used repeatedly. Additionally, extended cycles of 3–4 years have the potential to reduce outages compared with a large LWR. Assuming a 3-year refueling cycle (versus 1.5 years for a large LWR), a 1-month outage duration, and a 60-year reactor

lifetime, the reduction in outages equates to approximately 600 more full-power days over the reactor lifetime. However, single-batch core loadings do not use the fuel as efficiently as multi-batch loadings (Driscoll, Downar, and Pilat 1990). In terms of the results of the E&S study, core loadings with enhanced complexity impact the technology readiness of SMRs and the development and deployment risks of the fuel, the reactor, and the spent fuel disposition.

1.4 Summary of potential SMR impact on fuel cycle performance

SMRs would impact a variety of assumptions made in the E&S analysis of the reference LWR once-through fuel cycle with low-enrichment uranium fuel. These include assumed enrichments, discharge burnup, core neutron leakage, and spectral effects due to heterogeneous heavy burnable absorber loadings. The effects of neutron leakage, single-batch cores, and heavy burnable absorber loadings will impact uranium utilization. The hardened spectrum due to heavy burnable absorber loading and heavy control rod insertion will result in differences in plutonium ingrowth, as well as plutonium isotopics. The harder spectrum may also impact the reactor vessel and core barrel lifetime. However, the fast fluence experienced by the vessel will also be impacted by the fact that some SMR designs feature linear power that is de-rated by approximately 50% versus large LWRs (Haugh and Mohamed 2012). Each of these factors will impact the discharged isotopics and therefore the decay heat, radioactivity, and radiotoxicity per unit of energy generation.

Fuel assembly designs with greater heterogeneity may reduce the fuel plant throughput, and may have increased quality assurance and quality control requirements, which could increase fuel costs. Since there is the possibility of co-locating more than one reactor at a single site (Locatelli, Bingham, and Mancini 2014), the spent fuel pool may be shared by several units and may be a more challenging optimization problem; but sharing the spent fuel across a number of reactor cores could

provide some benefit in terms of optimized utilization of irradiated fuel. Additionally, the different fuel assembly designs and discharge isotopics may impact the potential recycling of spent fuel.

SMRs will also have environmental impacts, including footprint, water use, surface-to-volume ratio effects on building volume per unit of electricity generation, and reduced amounts of waste from resins during operation for no-boron cores. In addition, decommissioning and disposal will be affected by building volumes and the number of components and associated volumes per unit of electricity generation.

A summary of each of the issues identified in this elicitation is shown in Table 1. It also shows the E&S criteria that each parameter and identified issue is expected to impact.

Table 1. SMR fuel cycle performance issues identified and criteria affected

Category	Parameter	Criteria affected
Fuel	# Assemblies	Nuclear waste management Environment impact Resource utilization
	Fuel dimensions, including height	Nuclear waste management Environment impact Resource utilization
	Neutron leakage	Nuclear waste management Environment impact Resource utilization
	Burnable poison loadings	Nuclear waste management Environment impact Resource utilization
	Assembly burnups	Nuclear waste management Environment impact

		Resource utilization
	Heterogeneous fuels	Financial risk and economics Institutional issues
Reactivity control	Boron-free coolant	Nuclear waste management Environment impact Resource utilization
		Nuclear waste management Environment impact Resource utilization Financial risk and economics
	Heavy control rod insertion	Nuclear waste management Environment impact Resource utilization Financial risk and economics
		Nuclear waste management Environment impact Resource utilization Financial risk and economics
Core loading	Single vs. multibatch	Nuclear waste management Environment impact Resource utilization Financial risk and economics
		Nuclear waste management Environment impact Resource utilization Financial risk and economics
Other	Technology readiness: fuel (fresh and irradiated) and reactor	Development and deployment risk Institutional issues
	Irradiated fuel management across reactors	Development and deployment risk Institutional issues
	Water and land use	Environment impact
	Decommissioning and disposal volumes	Nuclear waste management
	Specific power density	Development and deployment risk Nuclear waste management

2. Scoping 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 slightly less than 5% enrichment. Some core parameters, such as the size of the reactor and the general assembly layout, are similar to published information about the NuScale

PWR concept (Haugh and Mohamed 2012). The calculations in this paper 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 concepts (Brown et al. 2014); the version studied has a reduced core height and reduced core radius. The SCALE lattice physics tool TRITON/NEWT was used to generate two-group constants (DeHart and Bowman 2011). A conventional two-step approach was recently shown to be adequate for The PARCS core simulator (Downar et al. 2002) 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).

2.1 Review of a simplified reference 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 a standard Westinghouse ZrB_2 coating (Simmons et al. 1988), referred to as integral fuel burnable absorbers (IFBAs). 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 (Brown et al. 2014).

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 ^{235}U 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 during power operations). 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 ZrB_2 IFBAs 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 slightly less than 5% 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.

Note that the core design used in this study for the large PWR is an out-in loading pattern (fresh fuel on the outside of the core, moved more toward the center in subsequent reloads). Therefore, this form of loading pattern has higher radial neutron leakage than modern low-leakage-loading patterns that purposefully put more burned fuel on the periphery of the core to reduce leakage and peak pin burnup. This form of loading pattern was chosen to be a simplified bounding case for the large PWRs against which the SMR results can be compared.

Fig. 2. Equilibrium one-eighth core power and burnup distribution for a large PWR with UO₂ fuel (Brown et al. 2014).

2.2 Development of a simplified thermal spectrum SMR model

The NuScale SMR concept (Haugh and Mohamed 2012) 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 by 17 Westinghouse assembly with a reduced radial and axial core size and one-batch fuel. The relative radial core sizes are shown in Fig. 3 and other key parameters in Table 2. Two reactor heat outputs were selected for the SMR calculations, which are intended to span the parameter space of potential SMR designs. The layout of control rod clusters in the SMR model is shown in Fig. 4. In the core models, 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. It is noted that the loading pattern shown in Fig. 3

loads twice burnt fuel assemblies in the center of the core, this would slightly exceed peak pin burnup limits and perhaps exceed fuel performance limits as well (due to a high linear heat rate at high burnup). This simplified loading pattern is intended to inform on physics behavior on a scoping basis, not directly represent a realistic commercial PWR core design.

Fig. 3. Comparison of radial core size and layout for three-batch large PWR (left) and one-batch SMR (right). Each colored “box” is a fuel assembly.

Table 2. Large PWR vs. SMR core parameters (differences are bolded)

Parameter	Large PWR	SMR
Reactor core heat output, MW(th)	3400	160 or 400
System pressure, nominal, MPa	15.51	15.51
Nominal inlet coolant temperature, °C	279.4	279.4
Fuel assembly design	17×17	17×17
Active fuel height, cm	426.7	213.35
Number of fuel assemblies	157	37
Fuel assembly pitch, cm	21.44	21.44
Uranium rods per assembly	264	264

Number of control clusters	53	16
Control rod material	Ag-In-Cd	Ag-In-Cd
Number of fuel batches	3	1

Fig. 4. Control rod bank configuration, one-quarter core (Haugh and Mohamed 2012).

Key simplifications versus the NuScale reference design (Haugh and Mohamed 2012) included the following:

- Only one enrichment zone: NuScale does not report the exact enrichment scheme used, only that the maximum enrichment is slightly less than 5% (Haugh and Mohamed 2012; Worrall 2014).
- Simplified reactor and reflector geometry: NuScale does not report the exact reactor geometry, only the radial layout (37 assemblies), assembly layout (17 by 17), and other general information.

- ZrB_2 is used for reactivity control instead of Gd_2O_3 : NuScale does not report the exact intra-assembly burnable absorber configurations.
- Assembly height is assumed to be half of AP1000, and axial depleted uranium blankets are neglected: NuScale does not report the exact active core height but does state that the height is approximately half that 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 slightly less than 5% (including near the periphery) and the omission of axial depleted uranium blankets. Although the model developed in this study is simplified, reasonable agreement was achieved between the reported NuScale design value of hot zero power (HZIP) critical boron concentration (1303 ppm) and the calculated HZIP boron concentration using the simplified model employed here (1456 ppm).

3. Fuel cycle performance results and analysis

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 MWt, and the lower heat generation rate (NuScale) corresponds to a reactor thermal power of 160 MWt. The EOC axial and radial power distributions are shown in Fig. 5 and Fig. 6, respectively. The corresponding radial burnup distributions are also shown in Fig. 6. 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 (Mart, Klein, and Soldatov 2014).

Fig. 5. EOC axial power distribution for the simplified SMR: AP1000 linear power and NuScale linear power

Fig. 6. EOC one-eighth radial power and burnup distribution for the simplified SMR: 5.72 kW/ft (left) and 2.28 kW/ft (right).

The average discharge burnup at a linear power of 5.72 kW/ft was 30.5 GWd/t and at 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 was apparent. The cycle length was approximately 24 months with 4.9% ^{235}U enrichment and a 5.72 kW/ft linear power, and approximately 48 months with 4.9% ^{235}U enrichment and a 2.28 kW/ft linear power. The discharge burnup was consistent with estimates in the literature for cores of similar size (Mart, Klein, and Soldatov 2014).

The reduced discharge burnup versus the reference large LWR once-through fuel cycle using uranium dioxide fuel (referred to as the EG01 analysis example) cascaded throughout all of the E&S metrics and negatively impacted fuel cycle performance. The E&S metrics (Wigeland et al. 2014b) are compared with the reference once-through fuel cycle with low-enrichment uranium in LWRs in Table 3. The metric values in

Table 3 were calculated using the Monte Carlo neutronics tool Serpent (Leppänen et al. 2015) for a single reflected fuel assembly assuming 3% leakage using the linear reactivity model. The assumptions for the metrics calculations for the large LWR in

Table 3 are consistent with the assumptions made for EG01 in the E&S. In the E&S, the WIMS code and ORIGEN-2 were utilized by ANL to calculate the metrics for EG01. A comparison was conducted which showed that the metrics derived from the Serpent calculation are in good agreement with those from the E&S. A detailed discussion of the E&S metrics is outside the scope of this

paper. More information about the metric calculations is found in Wigeland et al. (2014b) and Stauff et al. (2015).

Table 3. One-batch SMR scoping impact on E&S metrics (metrics where bin boundaries were crossed are in bold typeface). The letters after the slash (“/”) denote the alphabetized bins from the E&S study.

Criterion	Metrics	Large LWR	SMR	
			5.72 kW/ft	2.28 kW/ft
Nuclear waste management	Mass of spent nuclear fuel and high-level waste disposed of, t/GWe-year	22.13/E	36.28/F	34.16/E
	Activity of spent nuclear fuel and high-level waste (@100 years), MCi/GWe-year	1.34/C	1.40/C	1.35/C
	Activity of spent nuclear fuel and high-level waste (@100,000 years), 10 ⁻⁴ MCi/GWe-year	15.1/C	16.9/C	16.9/C
	Mass of depleted and recovered uranium disposed of, t/GWe-year	167.98/E	329.67/F	310.34/F
	Volume of low-level waste, m ³ /GWe-year	399.6/C	470.6/C	462.04/C
Environmental impact	Land use per energy generated, km ² /GWe-year	0.175/B	0.263/C	0.251/C
	Water use per energy generated, ML/GWe-year	23893/B	24067/B	24046/B
	Carbon emissions—CO ₂ released per energy generated, kt CO ₂ /GWe-year	44.4/B	72.4/C	68.8/C
	Radiological exposure, Sv/GWe-year	B	B	B
Re-source utilization	Natural uranium required per energy generated, t/GWe-year	190.16/D	366.04/D	344.58/D

Natural thorium required per energy generated, t/GWe-year	0/A	0/A	0/A
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The uranium natural resource utilization was significantly worse in the simplified SMR (~345 t/GWe-year) than in the EG01 (~190 t/GWe-year) analysis example and was lower than in the least-performing evaluation groups in the E&S (~305 t/GWe-year). The mass of DU+RU+RTh was higher than in any analysis example in the E&S. The performance of all metric values was degraded. As noted in the introduction, the E&S used alphabetized bins to gauge the relative performance of fuel cycles and accommodate uncertainties. 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. Although neither the large PWR nor the SMR core design was optimized (either pin/assembly powers or cycle length), doing so would change the results marginally but would not change the overall observations and conclusions. However, a more efficient loading pattern design (using a split batch approach to a single batch core) may marginally increase discharge burnup versus this simplified example.

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. 7 throughout the burnup cycle. Fig. 7 also shows the representative core leakage from a three-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. 7 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.

Fig. 7. Neutron leakage (%) from 3-dimensional core models for a one-batch SMR and three-batch large PWR.

4. Parametric study of core size, neutron leakage, and single-batch discharge burnup

It is well understood that multi-batch fuel loading yields better fuel utilization (Driscoll, Downar, and Pilat 1990), and the best fuel utilization is achieved in a continuously refueled system (Wigeland 2014c). 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. 8 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. 9.

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 GWd/t, significantly less than the three-batch large LWR example (50 GWd/t at 4.2% enrichment). This discharge burnup corresponds to a minimum natural resource requirement of 254 t/GWe-year versus the large LWR example value of 190 t/GWe-year.

Fig. 8. Impact of one-batch core size on neutron leakage and achievable discharge burnup.

Fig. 9. Discharge burnup and uranium resource required as a function of radial core size.

5. Summary

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; that will impact the buildup of transuranic isotopes, including the production of additional plutonium, which could increase the cycle length slightly. 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 an example scoping calculation, many metric values from the DOE-NE Fuel Cycle E&S study were negatively impacted. The E&S metrics negatively impacted in SMRs include the mass of depleted and recovered uranium disposed of per energy generated, the mass of spent nuclear fuel and high-level waste disposed of per energy generated, and the natural uranium required per energy generated. This impact is due to single-batch fuel loadings and increased neutron leakage from the reactor core, both of which act to reduce the discharge burnup of an SMR. In addition, environmental metrics will be impacted, including land use, water use, and carbon emissions.

Finally, note that some SMR designs impact three main aspects of fuel cycle performance: (1) small cores, which mean high leakage (there is a radial and an axial component); (2) the lack of boron, which means a heterogeneous core and extensive use of control rods and burnable poisons; and

(3) single-batch cores. But not all of the SMR designs have all of these traits. The approach used in this study is therefore a bounding case, and not all SMRs may be affected to the same extent.

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