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Design of a Mixed-Spectrum Reactor With Improved Proliferation Resistance for Long-Lived Applications

Abdalla Abou-Jaoude[1,2*], Anna Erickson[1], and Nicolas Stauff[3]

[1]*Georgia Institute of Technology, North Ave., Atlanta, GA 30332, USA*

[2]*Idaho National Laboratory, 2525 Fremont Ave, Idaho Falls, ID 83402, USA*

[3]*Argonne National Laboratory, 9700 Cass Ave., Lemont, IL 60439, USA*

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Long-lived Small Modular Reactors are being promoted as an innovative way of catering to emerging markets and isolated regions. They can be operated continuously for decades without requiring additional fuel. A novel configuration of long-lived reactor core employs a mixed neutron spectrum, providing an improvement in nonproliferation metrics and in safety characteristics. Starting with a base sodium reactor design, moderating material is inserted in outer core assemblies to modify the fast spectrum. The assemblies are shuffled once during core lifetime to ensure that every fuel rod is exposed to the thermalized spectrum. The Mixed Spectrum Reactor is able to maintain a core lifetime over two decades while ensuring the plutonium it breeds is below the weapon-grade limit at the fuel discharge. The main drawbacks of the design are higher front-end fuel cycle costs and a 58% increase in core volume, although it is alleviated to some extent by a 48% higher power output.

Keywords: Mixed-spectrum, Reactor physics, Neutron transport simulation, Nonproliferation, Long-lived reactor

*Corresponding Author.
Abdalla Abou-Jaoude, Idaho National Laboratory, E-mail: abdalla.aboujaoude@inl.gov, Tel: +1-208-526-3578

ORCID

Abdalla Abou-Jaoude	http://orcid.org/0000-0003-3022-8463	Anna Erickson	http://orcid.org/0000-0002-3276-4414
Nicolas Stauff	http://orcid.org/0000-0001-6167-9326		

1. Introduction

The potential demand in emerging markets for nuclear energy has led researchers to propose a novel type of Small Modular Reactor (SMR) that can better cater to their needs by operating continuously for decades and without relying on an external fuel feed. These 'long-lived' or 'battery-type' reactors are envisaged to be built at centralized facilities and shipped to areas of need, including isolated and remote ones. The long-lived SMR would be operated continuously by the host nation and shipped back to the central facility at the end of its lifetime for decommissioning. This 'hub-spoke' model, is touted as a way of reducing the risks of proliferation by providing newcomer countries with access to nuclear energy, without the need to develop enrichment or reprocessing capabilities [1]. Nevertheless, critics have argued that the reactors themselves may become the weakest link in the proliferation regime due to the high quality and quantity of plutonium they breed within their core [2]. Addressing some of these concerns is becoming increasingly important in light of the nascent private sector interest in developing such reactor concepts (e.g. Toshiba 4S, Gen4 Power, Oklo, General Atomics).

One potential approach to improve the proliferation resistance of these reactors is to rely on mixed-spectrum configurations. Mixed spectrum reactors have been studied in the past for a wide range of applications. The dual neutron spectra inside the same core, offers more design flexibility and allows the reactor to be more versatile. Mixed-spectra systems were first proposed by Avery as a means to improve controllability of fast reactors [3]. A study was then commissioned in the 1970s between MIT and Brookhaven National Laboratory, to study an equilibrium gas-cooled configuration that only required natural uranium for fuel feed after the start [4, 5]. More recently, adding moderating material within a fast reactor was proposed as a way to reduce plutonium quality within blanket region, to improve reactivity coefficients, or to provide both fast and thermal irradiation testing within the same reactor [6-8]. In this paper, previous research on both mixed-spectrum and long-lived designs are leveraged to develop a concept that can maintain a long core lifetime while reducing the plutonium attractiveness in all of its core regions.

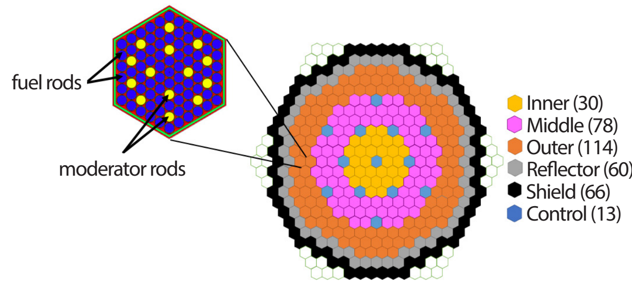

Fig. 1. Layout of the proposed MXR core design. Outer core assemblies (orange) contain moderating rods mixed among the fuel rods.

2. Design Characteristics

The proposed Mixed-Spectrum Reactor (MXR) is illustrated in Fig. 1, with detailed design specifications outlined in Table 1. Outer assemblies (orange) contain moderating material that is dispersed within the fuel rods. The moderating material selected was $ZrH_{1.6}$. The starting point for the design is a long-lived fast reactor developed by Argonne National Lab, the AFR-100 [9]. A model based on the AFR-100 specifications was developed and is termed the Long-Lived Reactor (LLR). It will represent a typical battery-type reactor and will be employed for comparative analysis to the MXR. The LLR is a U-Zr fueled, Na-cooled fast reactor designed to operate without additional fuel feed for up to 30 years. This is achieved by operating at a lower power density (64.3 kW·m^{-1}), along with a conversion ratio close to unity. Fuel enrichment is both radially and axially graded to flatten the power distribution. Three radial zones (inner/mid/outer) each containing three axial zones (bottom/center/top) are used, resulting in a total of six enrichment zones. The main modification in the MXR relative to the LLR is the addition of moderating material in the core

Table 1. Design Specifications of the proposed Mixed-Spectrum Reactor (MXR)

Parameter	LLR	MXR
Thermal/Electrical power	250 MW_{th} / 100 MW_e	370 MW_{th} / 148 MW_e
Reactor lifetime	< 34 years	25 years
Refueling interval	N/A	13 years
Fuel/Moderator/Coolant/Structure	U-Zr/N/A/Na/HT9	U-Zr/ZrH/Na/HT9
Coolant T_{in} / T_{out}	395 / 550℃	395 / 550℃
Active core height	110 cm	132 cm
Assembly pitch	16.5 cm	16.5 cm
Fuel pin diameter	1.49 cm	1.49 cm
Fuel/moderator pins per assembly	91/0	77/144
Heavy metal inventory	24.6 t	37.0 t
Power density	58.3 $kW \cdot l^{-1}$	48.6 $kW \cdot l^{-1}$
Average burnup	125.9 GWd/MTU	92.3 GWd/MTU
Fuel enrichment: - Inner region - Middle region - Outer region	upper-mid-lower: - 18-8.0-18% - 18-10.5-18% - 15-14.5-15%	upper-mid-lower: - 18-8.0-18% - 18-14.5-18% - 18-14.5-18%

periphery. The average enrichment is also increased from 13.5% to 15.1%, the active core length is 20% higher, and two additional rings of fuel assemblies are added. The majority of other specifications are kept the same as the LLR.

In order to expose all assemblies to the moderated spectrum, the outer and central ones are shuffled once during the lifecycle of the core. As illustrated in Fig. 2, moderating material is removed from the outer assemblies and placed within inner and mid assemblies. A mechanism similar to the one used in PWR control rod spiders is proposed to move the moderating material during the shuffling. Then, outer and inner/mid assemblies are shuffled to their respective locations. A wide range of different approaches can achieve this objective. One option envisages the moderating rods being contained above the core level; they would be inserted into the active region once the assemblies are shuffled. Alternatively, they could be attached to an interchangeable core handling region at the top of the assembly

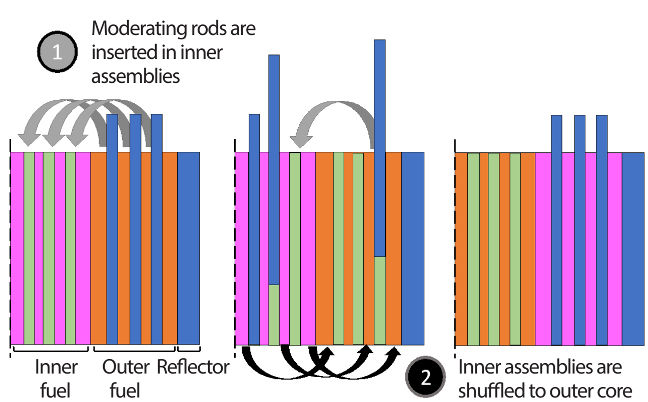

Fig. 2. Schematic of assembly shuffling with removal of moderating material (blue). The core x-z section is shown here.

for the outer regions, while those in the center do not have any moderating material whatsoever. During shuffling, the assembly tops are switched before moving the assemblies around. These examples are meant to be illustrative of the variety of options available, a detailed design of the mechanism is considered beyond the scope of this analysis. Because the shuffling takes place only once throughout the core lifetime, it is not expected to limit the original objective of providing energy to isolated grids.

3. Simulation and Evaluation

3.1 Long-lived application

Neutron Transport simulations were conducted with MCNP6 (ENDF/B-VII.0 library) to model the reactor performance [10]. Sensitivity studies determined that a total of 5×10^6 virtual particles (25,000 particles, 50 inactive cycles, and 150 active cycles) were sufficient to obtain acceptable statistical uncertainties of less than 25 per cent mile (pcm). Fig. 3 highlights the effect of spectral softening by the addition of moderating material in the outer core region. This demonstrates how two near-distinct neutron spectra can be obtained in the same core to increase design versatility. The ratio of energy bin between 0.11 and 0.18 MeV to the energy bin between 0.75 and 1.23 keV drops from 70 the inner region to 6 in the outer.

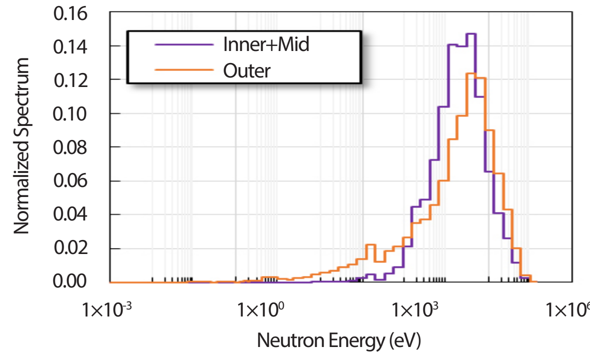

Fig. 3. Spectral softening at the outer core region of the MXR due to the addition of moderating material. Standard deviations of the total tallied fluxes were lower than 0.1%.

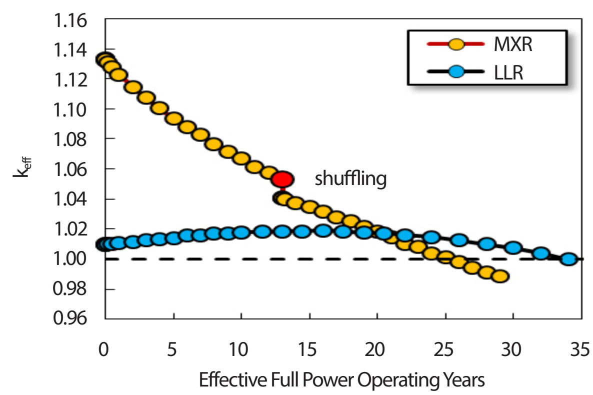

Fig. 4. Evolution of k_{eff} in the MXR and LLR designs. Shuffling occurs in the MXR after 13 years and a lifetime of 25 years can be achieved. The average Monte Carlo standard deviation is 28 pcm.

Depletion simulations were then conducted using the CINDER90 module of MCNP6 with the implicit predictor/corrector scheme. Fig. 4 shows the eigenvalue evolution over time for both the LLR and MXR. The excess reactivity will need to be mitigated in both designs by partial control rod insertions, as will be discussed later on. The results highlight how a long core lifetime can be maintained with a k_{eff} above unity for up to 25 years. While the LLR can remain critical for over 30 years, its lifetime was found to be limited to around 25 years due to material limits such as cladding fast fluence [11]. The results validate the MXR for long-lived application.

One notable drawback relative to the LLR is the large burnup reactivity swing, which can be alleviated by partial control rod insertion. However, doing so could also impact total control rod lifetime and must be carefully accounted for in the MXR design. Because of this, the estimated 25-year lifespan of the design is in fact conservative. Reducing the excess reactivity at Beginning-of-Life (BOL) would result in a slower depletion of fissile material, ultimately leading to an extension of total core lifetime, provided other design limitations are not reached (e.g. fluence limits).

3.2 Proliferation resistance

A primary design objective for the MXR is to reduce the attractiveness of nuclear material in its fuel cycle. The first step is ensuring that uranium enrichment is kept below 20%. The main criticism of typical long-lived reactors centers on the premise that plutonium remains of very high purity throughout the core lifetime, and single-assembly diversions can provide enough material for one Significant Quantity (SQ, 8 kg as defined by the IAEA) of weapon-grade material [2]. The objective of the MXR design is to alleviate plutonium quality and quantity concerns while still maintaining a core lifetime in the decades-range.

Fig. 5 highlights the evolution of the ratio in plutonium fissile isotopes within each core region. As shown, regions with a softer spectrum witness a much steeper drop in plutonium quality. This is the case for the outer region prior to shuffling, and for inner and mid regions after shuffling has occurred. The more thermalized neutron spectrum leads to an increase in the capture-to-fission cross-section ratio of ^{239}Pu, resulting in the reduction in the fissile plutonium ratio. By the End-of-Life (EOL), all regions have an average plutonium quality that is below the weapon-grade limit (taken to be 93.5% fissile isotopes), as summarized in Table 2. Reducing the attractiveness of the material disincentivizes a potential proliferator from misusing this particular core for plutonium production. Since large numbers of these type of long-lived cores are envisaged for global distribution, this could be an important feature.

Analysis was conducted to study the plutonium mass within the core as well. Fig. 6 highlights the average plutonium content per assembly in each core region. Most assemblies never reach 1 SQ, thus improving the proliferation resistance of the core. This can be mainly attributed to lower volume fraction of fuel inside of each assembly (to accommodate moderating rods). Potential proliferators will need to divert more assemblies with less attractive material than for a typical fast-spectrum long-lived reactor design.

3.3 Safety considerations

The next stage in the design evaluation is to ensure the reactor operates within acceptable safety bounds.

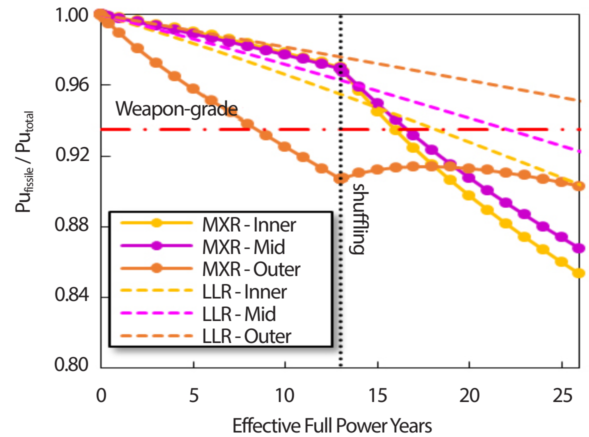

Fig. 5. Ratio of fissile to total plutonium isotopes. Results are grouped for different core regions corresponding to those in Fig. 1. Note that the location of assembly groupings for the MXR are flipped after shuffling occurs.

Table 2. Plutonium vector at discharge for the whole core of the MXR and LLR.

	MXR	LLR
^{238}Pu	1.00%	0.47%
^{239}Pu	87.46%	92.57%
^{240}Pu	10.05%	6.67%
^{241}Pu	1.36%	0.27%
^{242}Pu	0.13%	0.02%

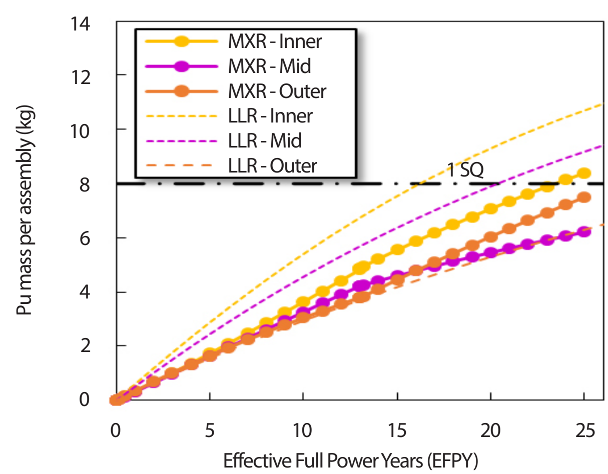

Fig. 6. Average mass of plutonium per assembly in each core region for the MXR and LLR. Only a few assemblies in the inner core of the MXR reach 1 SQ of plutonium (8 kg) during the reactor lifetime.

Table 3. Reactivity feedback coefficients for the MXR and LLR at the beginning and end-of life (BOL and EOL)

	MXR		LLR	
Coefficient	BOL	EOL	BOL	EOL
β-eff	0.0069 ± 0.0002	0.0051 ± 0.0002	0.0071 ± 0.0002	0.0045 ± 0.0002
Radial expansion (cent/C)	-0.0548 ± 0.0038	-0.1092 ± 0.0065	-0.0860 ± 0.0042	-0.1487 ± 0.0078
Axial expansion (cent/C)	-0.0218 ± 0.0035	-0.0363 ± 0.0054	-0.0016 ± 0.0032	-0.0352 ± 0.0053
Na void worth ($)	+0.0367 ± 0.0221	+1.6948 ± 0.0636	+0.0496 ± 0.0215	+2.6738 ± 0.0899
Doppler (cent/C)	-0.1235 ± 0.0081	-0.1149 ± 0.0102	-0.0470 ± 0.0068	-0.0539 ± 0.0107
Moderator (cent/C)	+0.0008 ± 0.0157	+0.0338 ± 0.0239	N/A	N/A

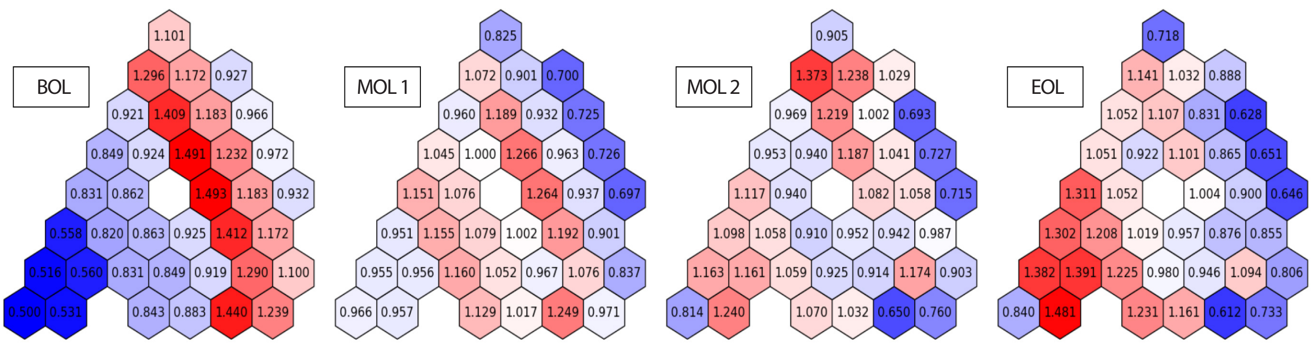

Fig. 7. Assembly power peaking factors in the MXR at beginning, middle and end of life (BOL, MOL and EOL). MOL results are shown before (MOL1) and after shuffling (MOL2). Illustration is for 1/6th core symmetry.

Reactivity coefficients were calculated for the MXR and are summarized in Table 3 for beginning and end-of-life (BOL and EOL). To reach the required level of accuracy, the total number of particles was increased to 50,000 for these simulations, and the number of inactive cycles to 400. The results are generally comparable to those observed in the LLR, with the exception of the Doppler and void coefficients, which see notable improvements. The epithermal spectrum inside the outer core region accentuates the Doppler broadening effect, while sodium scatter in that region now contributes to a net positive reactivity effect by thermalizing the spectrum further. It is worth noting that the moderator temperature appears to have little effect on overall core reactivity.

Another important metric to consider is power peaking within the core. Fig. 7 shows the radial peaking factor within a 1/6th model. The resulting outline at BOL is nonconventional for a sodium reactor; the most pronounced peaking appears at the fast-thermal interface at the edge of the core, not at the core center. Power generation can be seen to progressively transfer to the more centralized regions with burnup. After shuffling of assemblies, inner and mid assemblies (that are now in the outer regions) show a higher peaking factor. The maximum value observed throughout the core lifetime is 1.493. This is higher than in a typical sodium-cooled fast reactor but is considered to be manageable in light of the lower power density (48 $kW \cdot l^{-1}$ against 258 $kW \cdot l^{-1}$ for the Advanced Burner Test

Table 4. Comparison of fuel cycle metrics (based on the ones defined by the Fuel Cycle Evaluation and Screening Campaign). Values for metric tons of uranium (MTU), spent nuclear fuel (SNF), and resources consumptions are summarized here.

Fuel Cycle Metric	PWR	LLR*	MXR*
Fissile inventory (t-^{235}U/ GW$_e$-yr)	1.0	1.3	1.5
Heavy Metal consumption (MTU/GW$_e$-yr)	22.4	9.9	10.0
Nat U consumption (MTU/GW$_e$-yr)	200.0	269.5	307.1
SWU (t/GW$_e$-yr)	164.3	274.6	316.9
Av. discharge burnup (GW.d/MTU)	49.1	92.6	91.2
Mass of SNF (t/GW$_e$-yr)	25.5	11.0	11.1
Mass of depleted U (t/GW$_e$-yr)	117.5	259.7	297.1
SNF activity @ 100 yr (kCi/GW$_e$-yr)	497.34	172.68	201.58
SNF activity @ 100,000 yr (kCi/GW$_e$-yr)	0.88	0.56	0.56
Land use (km^2/ GW$_e$-yr)	0.182	0.189	0.204
Water use (m^3/ GW$_e$-yr)	2.4×10^7	2.1×10^7	2.2×10^7
Carbon emitted (t-CO$_2$/ GW$_e$-yr)	41.6	43.7	47.7

* A total core lifetime of 25 years was assumed for both the LLR and MXR.

Reactor, for instance) [12]. Modifying the inlet orifices of specific assemblies to adjust the coolant flow rate can help reduce peak temperatures. Future work will also investigate rod-level peaking factors to ensure they are within acceptable bounds for a sodium-cooled reactor.

3.4 Fuel Cycle Metrics & Design Limitations

Fuel cycle metrics were evaluated for the MXR and summarized in Table 4. They are based on those developed as part of the Fuel Cycle Evaluation and Screening Campaign [13]. Estimates for resource consumption, land usage, carbon emissions, and waste generation were calculated using the appropriate multipliers (in inverse units of metric tons of uranium, SWU, or GW$_e$-year). Multiplier constants are available for the front, reactor, and back-end of the fuel cycle. For instance, the water consumption multiplier for fuel mining operations is 850 m^3/MTU. Resulting values in Table 4 are normalized per total electricity generated. The results are compared between the MXR, a typical PWR, and the LLR design based on the Argonne National Laboratory concept [9]. Most metrics are estimated using approximations and are conservative. Reactor water consumption was assumed to be proportional to thermal efficiency losses and was modified correspondingly.

The results show how the long-lived concepts (LLR and MXR) have a higher resource requirement than a typical PWR but can reduce total quantity and activity of waste generated. Land use and CO_2 emissions see a slight increase, mostly in light of the higher front-end activities, while water consumption is lower due to higher thermal efficiencies. Compared to the LLR, the MXR performs slightly less favorably on the different fronts, but not to an extent that is deemed prohibitive. This is mostly attributed to the need for a slightly higher fissile inventory to sustain core lifetime.

Additional design tradeoffs of the MXR include the larger core volume. Core radius is increased by 14.7% relative to the LLR, and core height by 20%. This is somewhat alleviated by the 48% increase in total energy production within the core, maintaining the same power density. Another design challenge comes from the increase in operational complexity associated with forcing shutdown of the core once in its lifetime to shuffle assemblies and insert/remove moderating rods. This is not expected to be limiting however, since it only needs to occur once in the core lifetime and could be coordinated with required maintenance.

4. Conclusion

A Mixed-Spectrum Reactor (MXR) is proposed to improve the proliferation resistance of long-lived core designs. Moderating material is inserted within assemblies to soften the neutron spectrum in localized zones. Neutron transport simulations showed that the concept can maintain criticality for at least 25 years, while reducing bred plutonium quality and quantity within each assembly.

The MXR design displayed improved Doppler and void reactivity coefficients within the core, while maintaining power peaking within acceptable bounds of a typical sodium-fast reactor. The main design drawback was higher resource consumption at the front-end of the fuel cycle; mostly due to the higher average enrichment within the core relative to comparable fast designs. The overall core volume was increased to account for the added moderator (and empty channel) rods within the core. However, this allowed for an increase in core output by 48%, somewhat alleviating the higher volume limitation. Lastly, the need to interrupt operations for assembly shuffling could potentially add to operational complexities, especially in remote areas. This is not expected to be prohibitive since it only occurs once. Future work will investigate some safety aspects of the MXR in more detail.

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