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Preliminary Evaluation of Fuel Management Strategies for the Versatile Test Reactor

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INTRODUCTION

The US Department of Energy (DOE) is currently considering the deployment of a Versatile Test Reactor (VTR) to provide a fast neutron irradiation source. This 300 MW_{th} reactor is envisaged to contain 66 fuel assemblies containing metallic U-20Pu-10Zr fuel (5% enriched U, 72% fissile Pu). It will be sodium cooled, and able to provide a peak fast flux above 4.0×10^{15} n/cm^2-s.

Different fuel management approaches are being investigated for the VTR. This preliminary evaluation compares a range of loading strategies and compares their merits and limitations. The main design variables are the number of batches, the number of unique orifice zones, the target fuel average discharge burnup (i.e. fuel utilization), and the loading pattern within the core. The design objectives are maximizing the fast flux at the centermost position, minimizing the peak assembly power, and minimizing the fuel consumption for a given fissile enrichment. Design constraints are mainly driven by the maximum assembly power, the peak fuel burnup, and operating conditions (e.g. clad temperature).

The preliminary study was performed before a reference VTR core design was established. The main objective was to inform about various potential options. Some of the options considered are non-starters due to the desired operation mode of the VTR, but still provide useful insight. The impact of the number of different approaches with unique orifice zones, and varying number of batches is presented in this paper.

STUDY ASSUMPTIONS

For the purpose of this analysis, cold dimensions of the VTR core were used, and no irradiation swelling was assumed. Instrumented testing locations are modeled as empty sodium channels (i.e. no experiments). The results are mainly intended to be used for comparative purposes and are not necessarily indicative of the actual VTR configuration. More detailed evaluation of the core will rely on ongoing efforts within the wider program. Any considered fuel management strategy will have to ensure it can abide by the following preliminary criteria:

- Peak clad temperature shall not exceed 650°C [1].
- Average core temperature rise shall be 150°C.
- Coolant velocity shall not exceed 12 m/s in an assembly [2].
- Peak fuel burnup shall not exceed 10% FIMA.
- Normal operation peak linear power shall not exceed 450 W/cm (to avoid incipient fuel melting).

ZONE ORIFICING AND FUEL SHUFFLING

The first part of the study consisted in quantifying the impact of having different numbers of unique orifice zones. The working assumption is that fuel shuffling is allowed between assemblies having the same orifice. Three zoning cases were considered: (a) a single orifice zone (whereby assemblies can be shuffled freely within the core), (b) three unique orifice zones (assemblies can only be shuffled within their zone), and (c) five unique orifice zones (due to the 1/12th core azimuthal symmetry of the model used, resulting in no fuel being shuffled). Figure 1 shows an illustrative breakdown of the core for the 3-orifice zones design (case b). Regional boundaries for case (a) are determined by the fuel residence time in the core as seen in Fig. 2. The 5-orifice zone boundaries are determined by each hexagonal ring of the VTR core. A six-batch strategy is assumed in this section, meaning 1/6th of the fuel assemblies (11 in total) are replaced every cycle. The cycle length was set to 120 days, 100 of which are active.

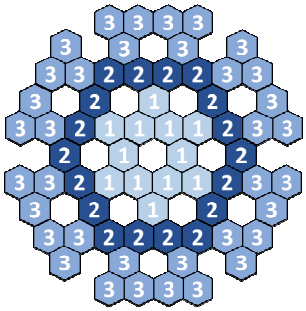

Fig. 1. Illustrative fuel assemblies divided into three separate orifice regions.

While no shuffling scheme can be implemented in the 5-orifice zones case, the single orifice zone case allows assemblies to be progressively shuffled from the periphery to the center of the core as they are burned (see Fig. 2). In the 3-orifice zones case, this can only be replicated within each zone. Fuel loadings in each assembly were explicitly modeled using the REBUS fuel

cycle code [3]. The code was used to generate burnup and power values in each assembly location as a function of time. Values at equilibrium conditions were then used to calculate the required coolant mass flow, the corresponding velocities, and the peak inner cladding temperature using a simple analytical model.

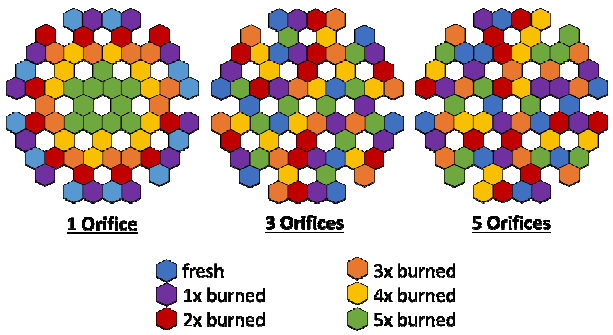

Fig. 2. Diagram of the fuel management layout at equilibrium (after cycle 6) for the three cases considered.

The results in Table I show that thermal limits can be met in all three cases. Fuel shuffling contributes to a reduction in peak assembly power (and therefore maximum required mass flow rate), but the results in the 3 and 5 orifice zones cases can be improved further by a more optimized selection of the zone boundaries. In addition, the higher peak power corresponds to an increase in peak fast flux which may be desirable for certain experiment configurations. Overall, shuffling is found to provide only limited benefit relative to the added operational requirements (a bigger concern for a test reactor). Moving forward, a combination of the 3 and 5-zone approach was selected for the study: three orifice zones will be used, but assemblies will not be shuffled within each zone.

TABLE I. Summary of the assembly-level thermal analysis conducted for the three orifice strategies to reach the same peak clad temperature margins, and core temperature rise. The reported fast flux is in the center test location. Only nominal values are reported.

# of orifice zones:	**1**	**3**	**5**
peak power (MW)	5.8	6.3	6.8
max/min flow rate (kg/s)	24/24	27/22	30/23
peak sodium velocity (m/s)	7.4	8.2	9.1
peak clad temperature (°C)	589	590	590
peak fast flux ($\times 10^{15}$ n/cm^2-s)	4.2	4.3	4.4

FLEXIBLE ASSEMBLY RESIDENCE TIME

Building on the 3-orifice zones layout without fuel shuffling, the next step is to consider variable batch numbers in each region. The total fuel residence time in each of zone is adjusted to compare cases with different average fuel discharge burnup (innermost assemblies stay less time as they accumulate burnup faster; outermost assemblies stay for more cycles as they accumulate burnup slower). Such an approach would ensure a similar discharge burnup in each zone. It should be noted that increasing fuel burnup will likely require an increase in fuel enrichment or a decrease in active cycle length. These compromises are not investigated at the current stage of this exploratory study. The three configurations considered were termed '5-6-8', '5-6-6', and '6-6-6' as summarized in Table II, with the inner, middle and outer zones corresponding to those shown in Figure 1. The 6-6-6 layout is equivalent to the 5-orifice zone case discussed in the previous section (6 batches throughout each of the three zones with no shuffling).

TABLE II. Number of batches in each of the 3 zones.

	Inner	**Mid**	**Outer**
5-6-8	5	6	8
5-6-6	5	6	6
6-6-6	6	6	6

REBUS calculations were repeated for the new loading schemes. The main objective is to estimate the variation in assembly discharge burnup and asses the corresponding power distribution within the core. A Python script was devised to post-process the REBUS outputs and evaluate average discharge burnups at each cycle. The results are shown in Fig. 3.

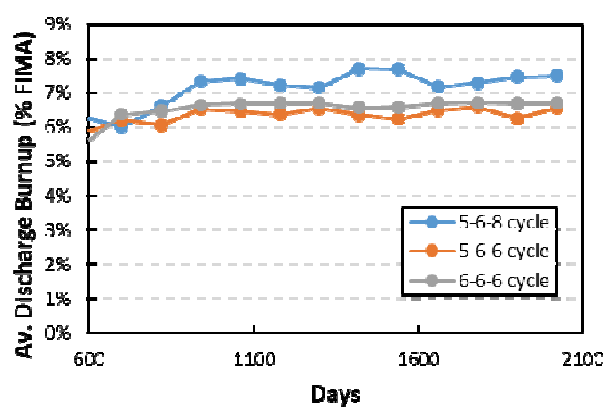

Fig. 3. Core average discharge burnup, after semi-equilibrium is reached, for the three cases considered.

The results demonstrate the improvement in fuel utilization for the 5-6-8 case (translating to less assemblies fabricated). The number of cycles in this approach were tailored according to the general power distribution within the VTR. In its current form, the increase in burnup comes with a correspondingly higher power peaking factor as highlighted in Fig. 4. This can be mostly attributed to the longer residence time of assemblies in the outermost region. The higher burnup at the edge of the core shifts the power towards the center

resulting in a more peaked profile. Careful selection of the zone boundaries in future studies can help overcome this issue and achieve higher burnup with a more limited increase in power peaking. On the other hand, a more homogenous shuffling strategy like 6-6-6, provides a less variable discharge burnup between cycles and a reduced maximum peaking factor.

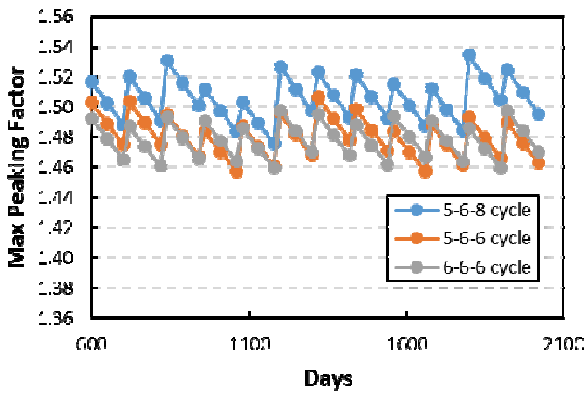

Fig. 4. Maximum assembly radial peaking factor for each of the three fuel loading strategies.

It should be noted that the higher power peaking tends to be associated with higher fast flux at the center of the core, as shown in Fig. 5. The peak fast flux at a startup core with 66 fresh fuel assemblies is 4.3×10^{15} n/cm^2-s. Comparing the three cases considered, 5-6-8 appears to have improved fuel utilization and peak fast flux for irradiation testing, but at a cost of higher power peaking values within its assemblies. However, as demonstrated in the previous section, this can be mitigated by increasing mass flow rate within the innermost orifice zone. The simple analytical models used in Table I estimate that an increase in velocity to 9.4 m/s can provide the same margins in peak clad temperature. This is below the 12 m/s criteria stated in the Introduction.

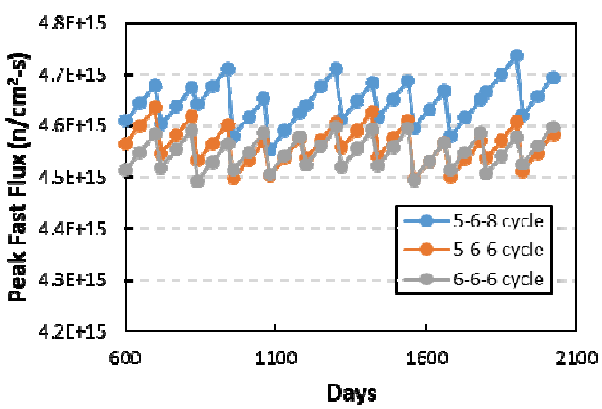

Fig. 5. Peak fast flux in the core of each of the three loading strategies considered in this section.

CONCLUSION

Preliminary fuel loading strategies were explored for an early version of the VTR core. The analysis explored various approaches for fuel management inside the VTR. Some allowed for shuffling, while others for variable orifice diameter and assembly residence time in different core regions. The characteristics of the VTR core provided enough flexibility to ensure all safety criteria can be met in each of the considered cases. Moving forward, it is envisaged that the fuel management strategy will not involve any shuffling to limit operational complexities. A 3-orifice zone layout was found to provide sufficient flexibility to ensure thermal hydraulic limits are met. Within these three zones, assemblies can have variable residence time to improve operating parameters of the VTR such as fuel utilization and peak fast flux. Future work will further improve on the general management strategy based on these guiding principles. The boundary of the 3-orifice zone will be considered more carefully, and the number of batches in each region will be optimized to maximize fuel burnup while minimizing power peaking. Future design iterations will also consider a more up-to-date model of the VTR that accounts for geometric expansion effects.

ACKNOWLEDGMENTS

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