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# Fuel Burnup Improvement in a HIGA-Based Soluble-Boron-Free i-SMR Core through an Alternating Fuel Loading Scheme

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## 1. Introduction

The innovative Small Modular Reactor (i-SMR) is designed for soluble-boron-free (SBF) operation with a 24-month operating cycle. Kim et al. proposed the Highly Intensive and Discrete Gadolinia/Alumina Burnable Absorber (HIGA) and developed an i-SMR core using HIGA together with integral gadolinia burnable absorber (IGD) rods for excess-reactivity control [1].

The i-SMR core contains 69 fuel assemblies. In the fixed 36-feed reference case, 72 fresh assemblies are loaded over two cycles, resulting in the discharge of three once-burned assemblies. This early discharge lowers the average discharge burnup. To remove this mismatch, an alternating 33/36 fresh-fuel loading scheme is assessed in this study. The scheme loads exactly 69 fresh assemblies over two cycles and eliminates the discharge of once-burned fuel assemblies.

The alternating scheme is the primary fuel-management modification. The use of 10 wt% $Gd_2O_3$ IGD and a burnable absorber loading optimization (BAO) are then assessed as additional modifications. Their effects on discharge burnup, excess reactivity, cycle performance, and power peaking are evaluated separately from the effect of the alternating loading scheme.

## 2. Analysis model and design changes

### *2.1. Core model and calculation setup*

The core model follows the HIGA-based SBF i-SMR design in Ref. [1]. The major design features used in the present assessment are summarized in Table I. The same core model and KARMA/ASTRA code system are used for REF and all modified cases.

HIGA and IGD are both gadolinia burnable absorbers, but they have different depletion characteristics. HIGA is a discrete $Gd_2O_3$-$Al_2O_3$ absorber and provides a relatively long-lived negative reactivity. IGD is a $UO_2$-$Gd_2O_3$ fuel rod, and its absorber effect decreases as gadolinium is depleted. The reference HIGA core uses the two absorber types together [1].

Table I: Major design features of i-SMR [1].

| Parameter | Value |
|---|---|
| Core thermal power | 520 MWth |
| Fuel assembly | $UO_2$, 17×17 square pitch |
| Number of fuel assemblies | 69 |
| Fuel enrichment | < 5 wt% $^{235}U$ |
| Active fuel height | 240 cm |
| Nominal fuel management | Two-batch / 24 months |
| Burnable absorbers | HIGA + IGD |
| Radial reflector | Stainless steel |
| Control-rod configuration | 24-finger; S, R1-R4 banks |
| EOC criterion | R4 position at 80% core height |

The reference case was recalculated because Ref. [1] used ENDF/B-VI.8, whereas the present calculations use ENDF/B-VII.1. Previous calculations for the same HIGA-based i-SMR showed non-negligible differences between different ENDF/B nuclear data libraries [2]. Therefore, REF and all modified cases were calculated using the same ENDF/B-VII.1 nuclear data library for a consistent comparison.

### *2.2. Alternating 33/36 fresh-fuel loading scheme*

Table II compares the fixed 32- and 36-fresh-fuel loading schemes with the proposed alternating 33/36 loading scheme. With 32 fresh fuel assemblies per cycle, the discharge of once-burned fuel can be avoided, but the cycle length becomes too short for the 24-month operating cycle. With 36 fresh fuel assemblies per cycle, the required cycle length can be maintained, but three once-burned assemblies are discharged because 72 fresh assemblies are loaded over two cycles.

In contrast, the alternating 33/36 scheme loads exactly 69 fresh fuel assemblies over two cycles. It therefore removes the two-cycle fuel-balance mismatch while maintaining a cycle length comparable to REF. The fixed 36-feed reference case is denoted REF, and the alternating 33/36 case is denoted ALT (alternating loading).

Table II: Comparison of fresh-fuel loading schemes for the 69-assembly core.

| Item | Fixed 32 | Fixed 36 (REF) | Alternating 33/36 |
|---|---|---|---|
| Fresh fuel assemblies per cycle | 32 | 36 | 33 / 36 |
| Fresh fuel assemblies over two cycles | 64 | 72 | 69 |
| Two-cycle difference from 69 assemblies | -5 | +3 | 0 |
| Once-burned assemblies discharged | 0 | 3 | 0 |
| Cycle-length characteristic | Shorter | Reference | Comparable to REF |

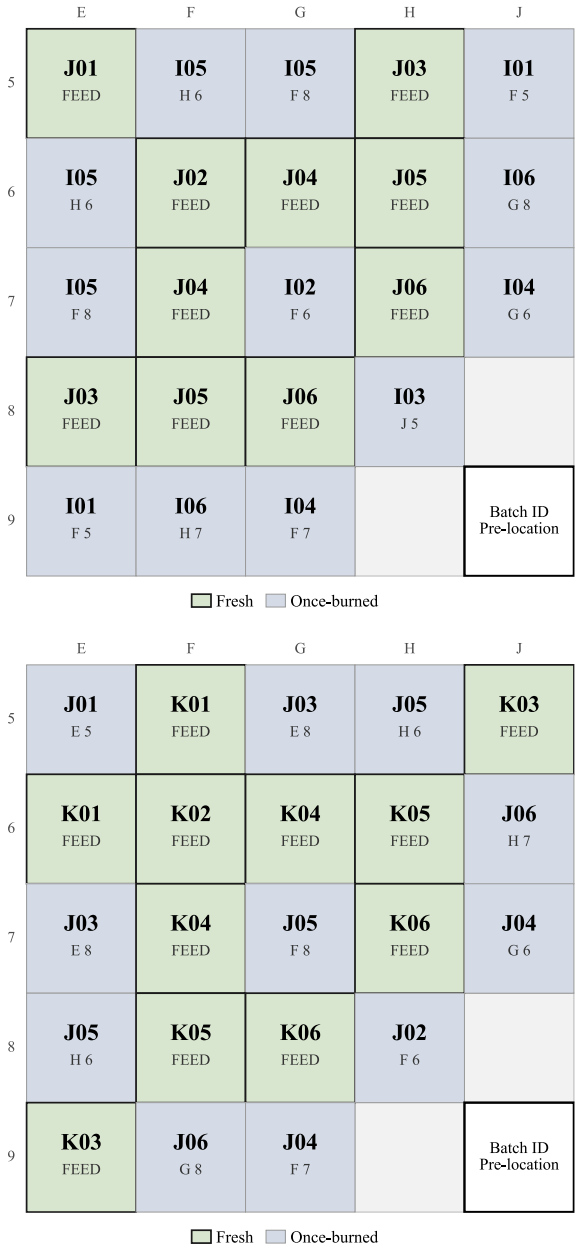



Fig. 1. Representative quarter-core loading patterns: (a) 33-feed even-numbered cycles and (b) 36-feed odd-numbered cycles. Green and blue denote fresh and once-burned fuel, respectively.

Because the core inventory is fixed at 69 assemblies, a 33-feed cycle discharges 36 assemblies, whereas a 36-feed cycle discharges 33 assemblies. The two-cycle assembly-weighted average discharge burnup is therefore calculated from the sizes of the discharged batches, not from the feed labels: $B_{pair} = (33\ B_{d,33} + 36\ B_{d,36})/69$. Here, $B_{d,33}$ and $B_{d,36}$ are the average burnups of the 33- and 36-assembly discharge batches, which occur in the 36-feed and 33-feed cycles, respectively.

The representative quarter-core loading patterns are shown in Fig. 1. The same assembly IDs and assembly positions are used for ALT, ALT-10Gd, and ALT-10Gd-BAO. The later cases differ in burnable-absorber specifications rather than in the basic 33/36 assembly arrangement.

### *2.3. Use of 10 wt% $Gd_2O_3$ IGD*

The reference HIGA core uses IGD rods with $Gd_2O_3$ contents up to 8 wt% [1]. In the ALT-10Gd case, the maximum IGD content is increased to 10 wt% to increase the contribution of IGD to excess-reactivity control. The higher gadolinia content gives the IGD rods greater absorber worth, allowing IGD to take a larger share of the reactivity-control function and reducing the required HIGA loading. Therefore, the 10 wt% IGD is not introduced as a direct means of extending the cycle, but as a means of changing the relative contributions of IGD and HIGA to core reactivity control.

An important feature of the ALT-10Gd design is the use of HIGA-free fuel assemblies at selected core locations. The fresh fuel assemblies at the H7 and G8 positions in Fig. 1 are HIGA-free and use 10 wt% IGD as the burnable absorber. In the ALT-10Gd case containing these HIGA-free assemblies, the maximum ARO excess reactivity is lower than in ALT, while the calculated remains within the range of the assessed cases. This result shows that IGD can take over part of the reactivity-control function of HIGA at selected locations while maintaining the evaluated core reactivity and power-peaking behavior.

Fuel assemblies containing 10 wt% gadolinia rods have been loaded in commercial reactors [3]. In addition, an NRC safety evaluation for AREVA methods includes $UO_2$ fuel with gadolinium contents up to 10 wt% in its application range [4]. Therefore, 10 wt% $Gd_2O_3$ is treated here as a practical extension of existing gadolinia-fuel technology for the present neutronic assessment.

### *2.4. Burnable absorber loading optimization (BAO)*

After the ALT-10Gd case was established, the relative use of 10 wt% IGD and HIGA was further adjusted while the alternating 33/36 assembly arrangement was kept unchanged. The 10 wt% IGD distribution was adjusted using the assembly power-peaking distribution at an intermediate cycle burnup of

approximately 12 GWd/MTU. This point was used as an intermediate-burnup checkpoint for the core power distribution.

The HIGA concentration was then reduced step by step using the power-peaking distribution near EOC. Assemblies with relatively low peaking factors were preferentially selected for HIGA reduction because they had more room for the local power increase caused by a lower absorber loading. The objective was to reduce the HIGA negative reactivity remaining late in the cycle while limiting the local power increase caused by the HIGA reduction. The selected case is denoted ALT-10Gd-BAO, where BAO denotes burnable absorber loading optimization.

Table III summarizes the burnable-absorber redistribution in the fresh fuel of the repeated 33/36 pair. The number of fresh assemblies containing 10 wt% IGD increases from zero in ALT to 16 in ALT-10Gd and to 48 in ALT-10Gd-BAO. At the same time, the axial-weighted HIGA loading decreases to about 85% and 79% of the ALT value, respectively. These changes show that 10 wt% IGD is used to take over part of the absorber role that was previously assigned to HIGA.

Table III: Burnable-absorber changes in the alternating loading cases.

| Case | Max. IGD $Gd_2O_3$ | 10 wt% IGD FAs in 33/36 pair* | Relative HIGA loading* |
|---|---|---|---|
| ALT | 8 wt% | 0 | 100% |
| ALT-10Gd | 10 wt% | 16 | 85.4% |
| ALT-10Gd-BAO | 10 wt% | 48 | 79.4% |

* Values are based on the fresh fuel loaded over one repeated 33/36 pair, corresponding to 69 fresh fuel assemblies over two cycles. The relative HIGA loading is based on the axially weighted HIGA loading and is normalized to ALT.

## 3. Results and discussion

### *3.1. Effect of alternating loading on discharge burnup*

In REF, 33 twice-burned fuel assemblies are discharged at an average burnup of 37.43 GWd/MTU, while three once-burned assemblies are discharged at only 18.86 GWd/MTU. The average discharge burnup of the REF discharge batch is therefore 35.89 GWd/MTU. The three low-burnup assemblies directly lower fuel utilization.

ALT eliminates the discharge of once-burned assemblies. In the representative 33-feed cycle, 36 assemblies are discharged at an average burnup of 36.61 GWd/MTU. In the 36-feed cycle, 33 assemblies are discharged at 38.42 GWd/MTU. The two-cycle average discharge burnup is 37.48 GWd/MTU. Thus, the alternating loading scheme alone increases the average discharge burnup by 1.59 GWd/MTU, or 4.4%, compared with REF.

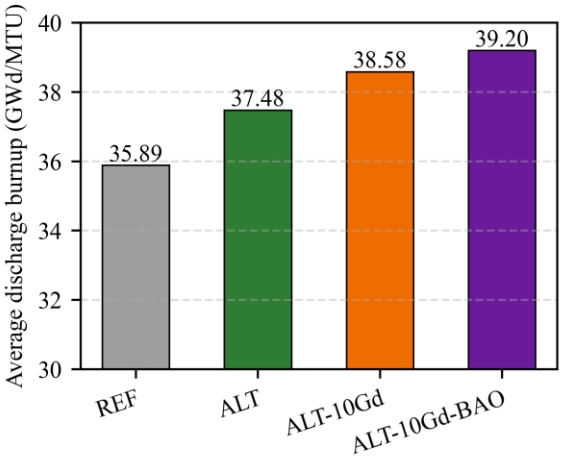



Fig. 2. Average discharge burnup for REF and the modified fuel-management cases.

The subsequent burnable-absorber modifications provide additional improvement. The two-cycle average discharge burnup increases to 38.58 GWd/MTU in ALT-10Gd and to 39.20 GWd/MTU in ALT-10Gd-BAO, as shown in Fig. 2. The final value is 3.31 GWd/MTU, or 9.2%, higher than REF. The first 4.4% improvement is attributed to the fuel-management change itself, whereas the additional gain is associated with the redistribution of IGD and HIGA loading.

### *3.2. Core reactivity, cycle length, and power peaking*

Table IV summarizes representative cycle results. REF has a maximum ARO excess reactivity of 1583.7 pcm and a cycle length of 707.8 EFPD. The ALT 33-feed and 36-feed cycles have maximum ARO values of 1569.4 and 1590.8 pcm, respectively, with cycle lengths of 714.4 and 704.2 EFPD. These values remain close to REF. This indicates that ALT mainly improves fuel utilization by eliminating the discharge of once-burned fuel assemblies, rather than by directly suppressing core excess reactivity.

Table IV: Representative core neutronic results.

| Case (feed) | Max. ARO excess reactivity (pcm) | Max. Fq | EFPD | Cycle burnup (GWd/MTU) |
|---|---|---|---|---|
| REF (36) | 1583.7 | 2.147 | 707.8 | 18.74 |
| ALT (33) | 1569.4 | 2.246 | 714.4 | 18.87 |
| ALT (36) | 1590.8 | 2.313 | 704.2 | 18.60 |
| ALT-10Gd (33) | 1448.6 | 2.203 | 735.1 | 19.30 |
| ALT-10Gd (36) | 1424.4 | 2.357 | 731.2 | 19.20 |
| ALT-10Gd-BAO (33) | 1245.6 | 2.122 | 739.5 | 19.40 |
| ALT-10Gd-BAO (36) | 1176.1 | 2.463 | 753.4 | 19.77 |

With the 10 wt% IGD option and the associated absorber redistribution, the maximum ARO excess reactivity decreases to 1448.6 pcm in the 33-feed cycle and 1424.4 pcm in the 36-feed cycle. BAO lowers the maximum further to 1245.6 and 1176.1 pcm. At the same time, cycle burnup increases, reaching 19.40

GWd/MTU in the ALT-10Gd-BAO 33-feed cycle and 19.77 GWd/MTU in the ALT-10Gd-BAO 36-feed cycle.

The core ARO curves in Fig. 3 show that the effect of 10 wt% IGD is not a uniform reduction in excess reactivity at every burnup point. In the 33-feed cycle, the relative ordering of ALT and ALT-10Gd changes with burnup. These results suggest that 10 wt% IGD can provide additional flexibility in controlling excess reactivity over the cycle. The use of 10 wt% IGD also permits more of the absorber role to be assigned to fueled IGD rods, which enables the subsequent reduction of HIGA loading.

The maximum Fq among all assessed calculations is 2.463, occurring in the ALT-10Gd-BAO 36-feed cycle. The calculated values are used here as comparative power-peaking indicators among the assessed cases.

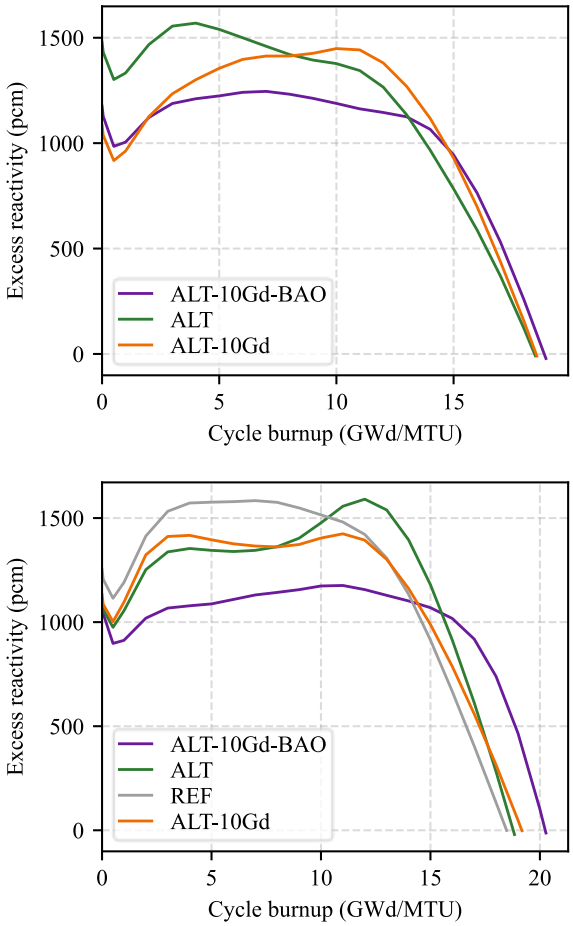



Fig. 3. Core ARO excess reactivity as a function of cycle burnup, evaluated at each burnup step under HFP conditions with equilibrium xenon for the representative (a) 33-feed and (b) 36-feed cycles.

### *3.3. Distinct contributions of the design changes*

The two modifications improve fuel utilization through different mechanisms. ALT eliminates the discharge of once-burned fuel assemblies while maintaining cycle performance close to REF. The subsequent IGD/HIGA adjustment increases the contribution of IGD to reactivity control and reduces HIGA loading, which decreases the residual negative reactivity near EOC and allows a higher cycle burnup. Thus, ALT provides the primary fuel-management improvement, while the burnable-absorber adjustment provides an additional gain.

## 4. Conclusions

An alternating 33/36 fresh-fuel loading scheme was assessed for the 69-assembly HIGA-based SBF i-SMR core. The scheme eliminates the discharge of once-burned fuel assemblies and increases the average discharge burnup from 35.89 to 37.48 GWd/MTU, corresponding to a 4.4% improvement over REF.

The subsequent use of 10 wt% IGD further increases the average discharge burnup to 38.58 GWd/MTU while increasing the contribution of IGD to excess-reactivity control. The BAO case further reduces the HIGA loading and increases the final average discharge burnup to 39.20 GWd/MTU, which is 9.2% higher than REF. These results show that the alternating loading scheme provides the primary fuel-utilization improvement, while the burnable-absorber modifications provide additional gains.

## Acknowledgments

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