MINI-SMR-21 In Once-Through Long-Lived Fuel Cycle Feasibility Assessment

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INTRODUCTION

Small modular reactors (SMRs) can enhance the flexibility in deployment and operation. The most popular Small Modular Reactor (SMR) designs are derived from the well proven typical Pressurized Water Reactor (PWR) 4-Loop design. To reduce the reactor core size and total heat output, the most popular way is covert the PWR 4-Loop core design to One-Loop as in the typical SMRs design, such as, SMR-57 with 57 fuel assemblies (FA) and SMR-37 with 37 FA [1-3]. In addition to the SMR, DOE is pushing for the Micro-Nuclear Reactor (MNR) for DOD and the remoted area reliable power supply nuclear system [4]. However, there is a gap between SMR and MNR. In this work, we proposed a minimized core size SMR with 21 FA - Mini-SMR-21.

A Monte Carlo MCNP [5] coupling with ORIGEN-2 [6] burnup BASH script – MCOS [7, 8] was used to access the Mini-SMR-21 once-through long-life core sustainable operation cycle. Due to the core size reduction, the Mini-SMR-21 will have a higher neutron leakage core. To achieve a once-through long-life of 6-year full power operation with no refueling, we have to increase the ^{235}U enrichment of the Low Enrichment Uranium oxide (LEU). The higher the ^{235}U enrichment is, the undesired larger the initial K-eff will be. The proposed burnable absorber (BA) Gd_2O_3 loading pattern in this work cans effectively hold-down the initial large K-eff to a manageable range. In addition, the proposed BA can minimize the ΔK swing band versus burnup, and can provide an adequate excess reactivity at the discharged fuel burnup.

The developed Monte-Carlo fuel burnup code MCOS, was used to calculate the effective reactivity worth band and its controllability by the reactor control rods. The minimized SMR UO_2 fuel and the proposed new Gadolinia BA (U-GdO) rods loading pattern's achievable high burnup are evaluated with the 1/8th full core model in Section 4. Finally, the conclusion and recommendation are presented in Section 5.

Minimized SMR Core Model Description

The current Small Modular Reactor (SMR) designs are derived from the well proven typical Pressurized Water Reactor (PWR) 4-Loop design [6, 9] adapted with the well proven Fuel Assembly (FA) (17x17). The core is cooled and moderated by light water at a pressure of 2250 psia by the Reactor Coolant System. The chosen FA (17x17) model has 264 UO_2 fuel rods, 24 control tubes and one central guide tube. FA (17x17) in PWR 4-Loop design has a well-proven operation safety record for the past half-century.

The PWR and Mini-SMR fuel core effective outer diameter OD are 337 and 110 cm, respectively. The Mini-SMR-21 fuel pin lengths also decrease to 135 cm in this study. The Mini-SMR-21 core comprises multiple regions of 21 FA as shown in Figure 1. The detailed 1/8th Mini-SMR-21 core model has the two diagonal reflecting surfaces inter-sections make it to represent a whole core model. The Mini-SMR-21 1/8th core 3D Pin-by-Pin working model has 717 tally fuel pins.

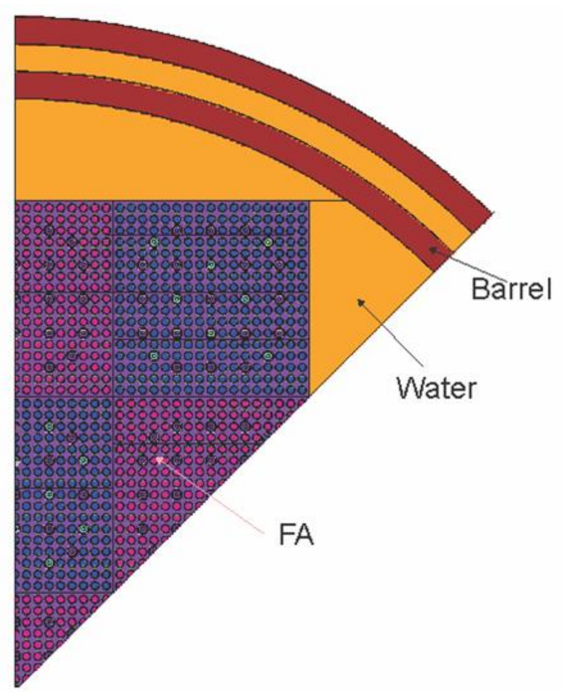

Fig .1. Mini-SMR-21 MCNP 3D detailed Pin-by-Pin1/8th core model.

Proposed New Burnable Absorber Gd_2O_3 Loading Pattern Description

To hold-down the initial excess reactivity and reduce the ΔK swing during the long-lived core operation for the increased ^{235}U enrichment in Mini-SMR-21 core, a new effective BA loading pattern design is needed. They most commonly used BA types in the Light Water Reactor (LWR) are, the Integral Fuel Burnable Absorber (IFBA) ZrB_2 type for 18-month refueling cycle, and the Gadolinia (Gd_2O_3) type for the longer 24-month fuel cycle. The integral BA UO2 + Gd_2O (UGdO) pins were chosen in this work for the once-through long-lived Mini-SMR-21 core feasibility study. Because the UGdO has extremely high thermal neutron absorption cross sections, which will depress the UGdO pin power. As a result, the depressed UGdO pins will increase the FA power peaking factor. To reduce this undesirable effect, an evenly distribution of the new 56 UGdO arrangement loading pattern is proposed as shown in Figure 2, which not only can reduce the power peaking factor, but also effectively hold-down the initial excess reactivity. In addition, due to the self-shielding, the lumped GdO in the 56 fuel-pin's effective neutron absorption cross-section will decrease. As a result, it can also reduce the reactivity swing verse burnup.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68
69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85
86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102
103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119
120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136
137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153
154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170
171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187
188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204
205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221
222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238
239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255
256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272
273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289

Fig. 2. Schematic Fuel Assembly (17x17) 56-UGdO BA pins arrangement configuration.

- 208 fuel pins (White)

- 24 guide-tubes and one instrument-tube (Green)

- 56 Burnable Absorbers (Red)

- Total 17 x 17 = 208 + 25 + 56 = 289 positions.

RESULTS AND DISCUSSION

A typical pressurized water reactor (PWR) is scheduled to reach the equilibrium core operation by 3-batch reshuffling high burnup fuel cycles strategy from its fresh core. However, the proposed Mini-SMR-21 in this work would like to achieve a sustainable once-through long-lived core operation cycle. In order to enhance core sustainable operability, the ^{235}U enrichment need be increased. Its performance related design requirements as well as meeting power maneuvering margin requirement were also need to be evaluated.

MCOS is a BASH shell script that couples the MCNP and ORIGEN-2 computer codes. It can update the nuclide neutron spectrum weighted XS at the beginning of each time step, automatically from the fuel cycle beginning of life to the end of life without the need for any manual interface. In this study, the Mini-SMR-21 1/8th core 3D Pin-by-Pin model will be used for the fuel and BA GdO fuel cycle burnup performance analysis.

Sensitivities studies by trial-and-error method were performed to determine the best ^{235}U enrichment, which can provide an adequate excess reactivity at the discharge burnup. The results of a series of ^{235}U enrichment sensitivity study, indicates that the ^{235}U 12.5% enrichment (Case-12.5%) can meet the design goal. MCOS-calculated K-eff and excess reactivity at the burnup of 80 GWd/t is plotted in Figure 3. It shows that the Case-12.5% has a desired excess reactivity of 68.0 mk at the discharged burnup of 80 GWd/t. However, the selected Case-12.5% has a quite large initial K-eff of 1.36. It requires the BA UGdO to hold down the initial excess K-eff and to reduce the excess reactivity swing.

From the fuel cycle reactivity control point of view, the Case with ^{235}U enrichment of 12.5% (Case-12.5%) has the best fuel cycle performance with an adequate excess reactivity (K-eff - 1) of 68.0 mk at the intend discharged burnup of 80 GWd/t. In this study, we assume the total core thermal output is 140 MW_{th}, which is equal to about 6.0 full power years. The Case-12.5% K-eff is monotonically decreased from 1.35 to 1.03. If the SMR core designer prefers a smaller excess reactivity at the discharged burnup, we can fine tuning the ^{235}U enrichment to meet the specific requirement.

The MCOS-calculated K-eff versus burnup is plotted in Figure 3. The heavier load is the content of Gadolinia in the fuel the smaller is the reactivity of the fresh fuel. For all 2-Case, GdO can hold-down the initial reactivity from 1.35 to less than 1.11. Because of the BA GdO decreases faster than the ^{235}U depletion rate initially, the K-eff versus burnup increase up to the burnup of 40 GWd/t. After that, then, all 2-case GdO K-eff decease to around 1.05.

The MCOS-calculated reactivity swings comparisons are tabulated in Table 7. The K-eff Max and K-eff Min in between the burnup range of 2 and 70 GWd/t are also tabulated in Table 7. For all cases the fluctuation of the ΔK band is less than 28 mk. At the discharged burnup of 80 GWd/t, all cases have an adequate excess reactivity large than 30 mk. In this work, we use the following three criteria to select a good BA GdO candidate. First, BA GdO cans effectively hold-down the initial K-eff less than 1.15. Second, hold the ΔK swing band as small as possible. And, the third, it can provide an adequate excess reactivity at the discharged fuel burnup. By method of trial-and-error, we found that the new BA GdO loading pattern with 11.5 wt% and 13.5 wt% 2-Case can meet the above mentioned three criteria.

The confirmation comparison of BA free fuel Case-12.5% and the selected UGdO BA 2-Case's K-eff versus burnup is plotted in Figure 3. The figure indicates that the selected UGdO BA 2-Case not only can reduce the ΔK swing, but also can provide the adequate excess reactivity at the discharge burnup of 80 GWd/t.

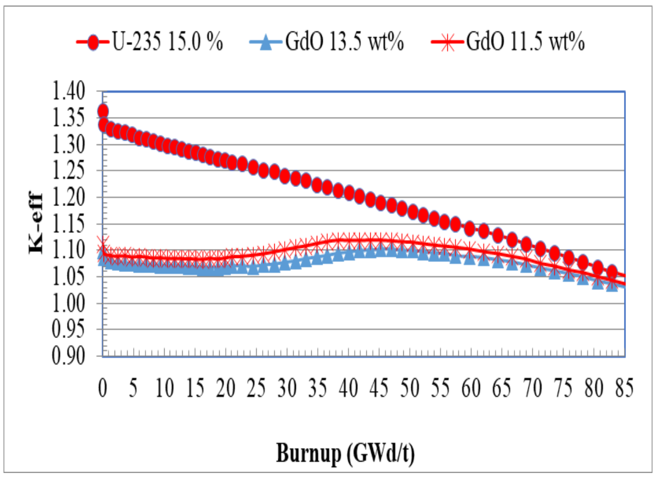

Fig. 3. The selected fuel ^{235}U enrichment 12.5% and UGdO BA 2-Case K-eff versus burnup comparison.

CONCLUSION

The built Mini-SMR-21 1/8th small core MCNP model has been successfully used in the selected fuel achievable discharged burnup validation analyses. The developed MCOS BASH script can provide accurate and stable fuel burnup calculations for the depleted fissionable materials and BA U vs. depletion time. In this work, we also demonstrate that MCOS-calculated results show that the BA UGdO cans effectively hold-down the initial excess reactivity from 1.36 to 1.08. It shows that the stability of MCOS algorithm can provide the new BA UGdO loading pattern performance assessment accurately. In addition, the Monte Carlo burnup script – MCOS using the continuous neutron cross library can update the nuclides resonance effect very well from depletion time-step to next time-step on the fly.

The developed MCOS fuel burnup analysis script has been effectively applied in the Mini-SMR-21 operation controllability validation. It has been well demonstrated that the excess reactivity swing can be adequately controlled by the proposed new U BA banks system. In this work, we have demonstrated that the ^{235}U with 12.5% enrichment can achieve the long-lived fuel burnup of 80 GWd/t. MCOS calculations also showed that a combination of UO_2 and new GdO loading pattern can have a good long-lived core excess reactivity control performance. Therefore, the proposed GdO Cases 11.5 wt% or 13.5 wt% are promising options for once-through long-lived cycle Mini-SMR-21 core. Nevertheless, this study is incomplete for neither has thermal-hydraulic nor thermo-mechanical analyses of these fuels. The developed MCNP working model will be improved towards a more detailed axially divided model for the xenon oscillation analysis validation. It is also absent any FA power peaking factor analysis regarding heavy UGdO loading. The proposed new GdO in the 56 fuel-pin's loading design can reduce the reactivity swing verse burnup, such that, it might be able to meet the Soluble-Boron-Free reactivity control requirements. The possibility in using the minor actinides - Np/Am/Cm as the alternative BA will be explored. These problems can be addressed in future works.

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