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Equilibrium Core Design of a U-TRU-Zr Fueled SFR for TRU Loading Maximization within Design Limits

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1. Introduction

The Prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR) has been designed as a burner reactor [1]. Its purpose is to consume the transuranium (TRU) elements recovered from spent nuclear fuel of pressurized water reactors (PWRs). The initial core is loaded with U-Zr fuel. As the core goes through successive refueling cycles, the fuel is gradually replaced with U-TRU-Zr fuel. However, experimental data for TRU-bearing metallic fuel are still lacking. This makes it difficult to define the associated computational uncertainties. In this study, therefore, a U-TRU-Zr equilibrium core was designed to serve as a basis for evaluating such uncertainties. The objective was to maximize the TRU loading while satisfying the design limits on the cladding. The neutronic performance of such U-TRU fueled cores has been compared with that of HALEU fueled cores in a companion study [8]. Nine candidate cores were generated here by varying the cycle length, the radial zoning, and the number of stages. For each core, the coolant flow was allocated and the cladding integrity was evaluated. This paper presents the overall design process and the selected core.

2. Calculation Scheme

2.1. Computational Codes

The neutronics calculations were performed using the ARC (Argonne Reactor Computation) code system developed at Argonne National Laboratory (ANL). Within this system, MC^2-3 was used to generate multigroup cross sections [2], DIF3D for the flux solution [3], REBUS-3 for the equilibrium fuel cycle search [4], and RCT for pin power reconstruction [5]. The subchannel coolant flow characteristics were analyzed with the SLTHEN code [6]. The fuel performance, from which the cladding cumulative damage fraction (CDF) and the thermal strain were obtained, was evaluated with the LIFE-METAL code [7]. The three codes were linked in a one-way multiphysics coupling scheme.

2.2. Core Model and Design Limits

The present core is based on the PGSFR, with an electrical output of 150 MWe and a thermal output of 392.2 MWth. The fuel is U-TRU-RE-10Zr, in which rare earth (RE) elements are inevitably recovered together with TRU during the pyroprocessing of spent PWR fuel. A TRU-to-RE ratio of 6:1 was therefore imposed. The U-235 enrichment of the carrier uranium was fixed at 0.687 wt.%, so that the TRU content is the only variable that determines the reactivity of the charged fuel. The main specifications are summarized in Table I. An example of core configuration is shown in Fig. 1.

Table I: Core design specifications

Parameter	Value
Electrical output (MWe)	150
Thermal output (MWth)	392.2
Active core height (cm)	90
Fuel type	U-TRU-RE-10Zr
Fuel inventory (ton)	5.57
U-235 enrichment (wt.%)	0.687
TRU:RE ratio	6:1
Coolant inlet temperature (°C)	360
Coolant outlet temperature (°C)	510
Total coolant flowrate (kg/s)	1877.32
Cycle length (EFPD)	Various
TRU content (wt.%) in U-TRU	Various
Inner/Middle/Outer cores	Various

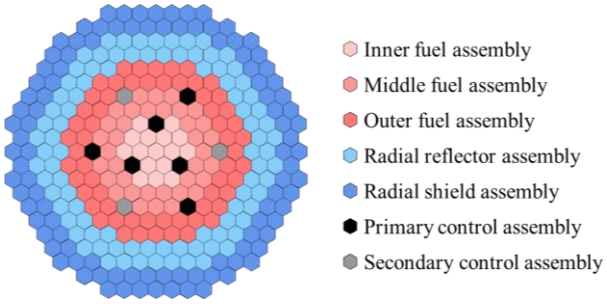


Fig. 1. An example of core configuration. The fuel assembly configuration varies depending on nine different cases.

The design limits imposed on the cladding are a CDF below 0.05 and a thermal strain below 1.0%. A core is regarded as acceptable only when every fuel assembly satisfies both limits.

2.3. One-way Coupling Scheme

The calculation proceeds through two iterations. In the first iteration, the assembly specification, the core layout, and the enrichment zoning are given as input, and the TRU content is searched so that the target cycle length is

attained at equilibrium. This iteration yields the charged fuel composition and the assembly-wise burnup, flux, and power distributions. In the second iteration, the coolant flow is allocated and grouped on the basis of the power distribution, and the resulting flow rates are passed to the fuel performance calculation. In the flow grouping, assemblies whose flow rates differ by less than 3% were assigned to the same group. The CDF and the strain margin are then flattened across each flow group.

2.4. Power History Reflecting the Stage Power Factor

REBUS-3 divides one cycle into four equal intervals, providing the power distribution at five time nodes. Since the equilibrium core is a stage-averaged representation, this one-cycle distribution is used directly in SLTHEN, and the resulting flow rates are fixed for the whole irradiation. An individual assembly, however, experiences a different power level at each stage of its residence. REBUS-3 provides this deviation as a stage power factor for each fuel node, which is shown in Fig. 2. Multiplying the one-cycle power distribution by the stage power factor therefore reproduces the power history over the entire residence time of the assembly, which is the number of time nodes multiplied by the number of stages, shown in Fig. 3. This history was used as the LIFE-METAL input, so that the flow rate is fixed at the stage-averaged value while the power varies along the actual life of each assembly. An amount of Pu equivalent to the TRU content was substituted in the input of LIFE-METAL. One of the major differences between U-Zr and U-TRU-Zr fuel is the irradiation-induced fuel growth, which decreases from 8% to 4% for U-TRU-Zr fuel.

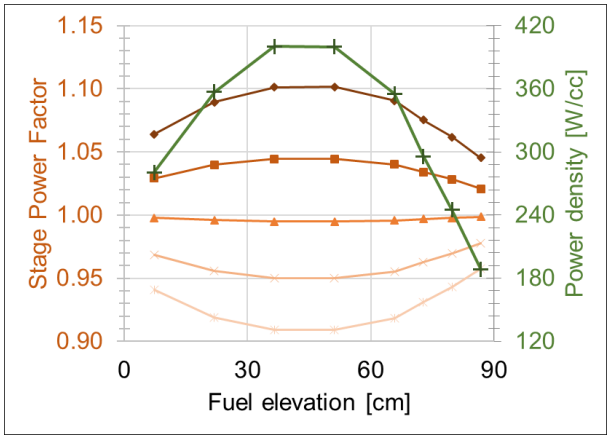


Fig. 2. Five stage power factors and power profile in a sample fuel assembly at 0 EFPD of each cycle.

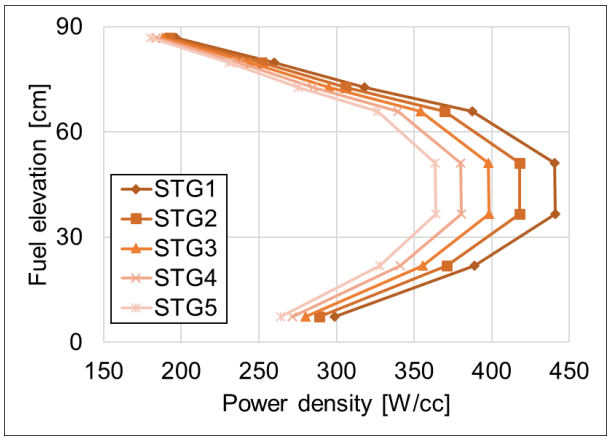


Fig. 3. Power profiles reflecting stage power factors in a sample fuel assembly at 0 EFPD of each cycle.

Table II: Test cases and equilibrium cycle results

Case	Cycle length [EFPD]	Inner/Middle/Outer-Core Configuration				Excess Δρ [pcm]	Charged U-TRU-RE-10Zr		
		# of Rings	# of FA	Stages	Avg. BU [GWd/tHM]		TRU/HM	TRU[wt.%]	RE[wt.%]
1	330	5/0/2	52/0/60	4/0/5	87/0/63	2,327	0.22	19.20	3.24
2	330	5/0/2	52/0/60	5/0/6	108/0/77	2,422	0.23	19.87	3.32
3	330	3/2/2	16/36/60	4/5/6	100/101/76	2,416	0.23	19.64	3.24
4	330	5/0/2	52/0/60	4/0/6	87/0/75	2,375	0.22	19.37	3.26
5	330	4/2/1	34/48/30	4/5/6	93/80/64	2,374	0.22	19.38	3.27
6	330	5/0/2	52/0/60	5/0/7	109/0/87	2,465	0.23	20.03	3.30
7	330	4/2/1	34/48/30	5/6/7	116/97/76	2,464	0.23	20.06	3.31
8	420	5/0/2	52/0/60	4/0/6	111/0/96	3,209	0.24	20.44	3.44
9	330	4/2/1	34/48/30	5/8/10	119/128/106	2,619	0.24	20.71	3.46

3. Results

3.1. Test Cases and Equilibrium Cycle Results

Nine cases were generated by varying the cycle length, the number of rings assigned to the inner, middle, and outer cores, and the number of stages in each region. The case definitions and the equilibrium cycle results are listed in Table II. The number of stages determines how long an assembly resides in the core. Because the outer assemblies operate at a lower power, assigning more stages to the outer core lets them accumulate a discharge burnup comparable to that of the inner core, which flattens the burnup distribution.

The TRU content required to sustain the target cycle length increases as the cycle length is extended and as more stages are assigned. Cases 4 and 8 share the same radial configuration and stage assignment, and differ only in the cycle length. Extending the cycle from 330 to 420 EFPD raises the required TRU content from 19.37 to 20.44 wt.% and the discharge burnup from 87/75 to 111/96 GWd/tHM in the inner and outer cores. Case 9 attains the highest TRU content of 20.71 wt.%, obtained by assigning up to ten stages to the outer core.

3.2. Fuel Performance and Core Selection

The fuel performance was evaluated for every fuel assembly of each candidate core. Case 9, despite having

the largest TRU loading, does not satisfy the design limits: the CDF exceeds 0.05 in all 38 assemblies, reaching a maximum of 0.185, and the thermal strain exceeds 1.0% in two assemblies. The long residence time of up to ten stages accumulates excessive cladding damage.

Case 8, whose core configuration is depicted in Fig. 4, satisfies both limits with a margin. Flowrate distribution is given in Fig. 5. The maximum CDF is 0.0217 and the maximum thermal strain is 0.434%, as shown in Fig. 6 and Fig. 7, respectively. Its TRU content of 20.44 wt.% is the highest among the cores that meet the design limits, and it is therefore selected as the final core. In this core the inner region consists of 52 assemblies with four stages and the outer region of 60 assemblies with six stages, giving discharge burnups of 111 and 96 GWd/tHM. Both assembly counts are exactly divisible by the corresponding number of stages, which simplifies the construction of a heterogeneous core model.

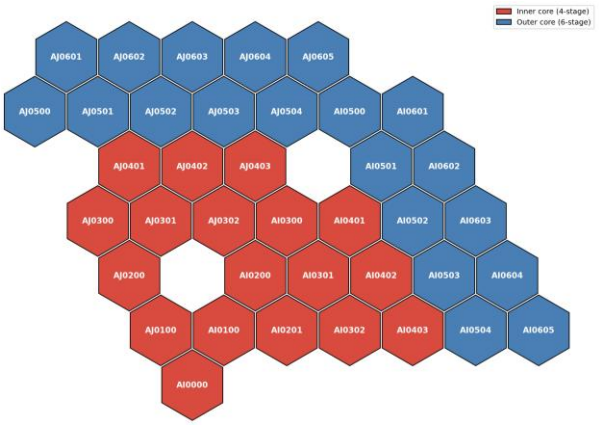


Fig. 4. One-third core configuration of the Case 8 core.

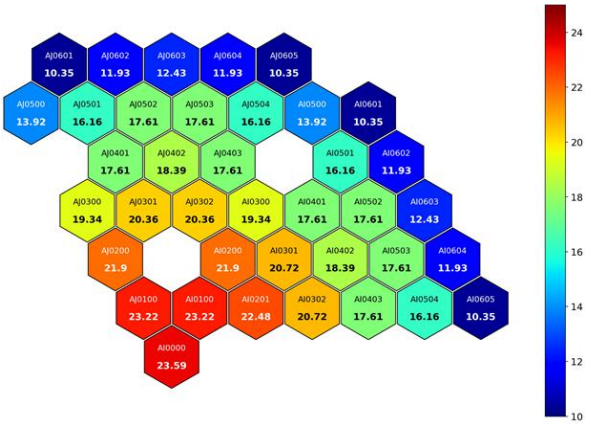


Fig. 5. Flowrate (kg/s) distributions of the Case 8 Core.

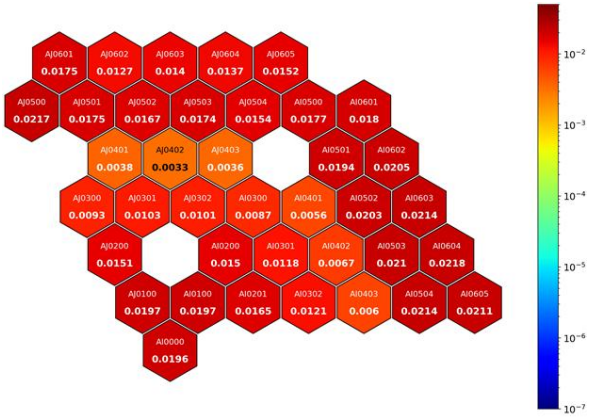


Fig. 6. CDF distributions of the Case 8 core.

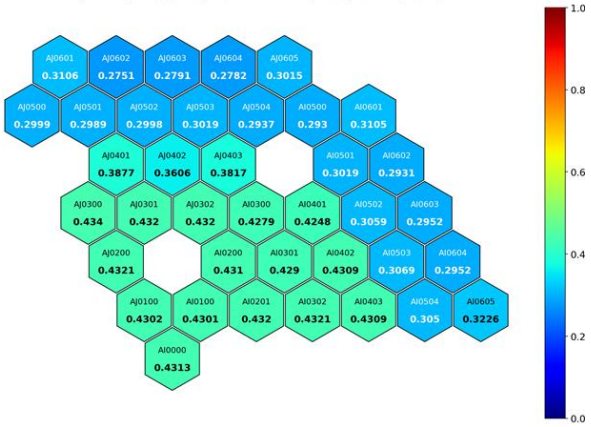


Fig. 7. Thermal strain (%) distributions of the Case 8 core.

4. Conclusions

A U-TRU-Zr equilibrium core was designed to maximize the TRU loading within the design limits. Nine candidate cores were generated by varying the cycle length, the radial zoning, and the number of stages, and each was evaluated through a one-way coupling of ARC, SLTHEN, and LIFE-METAL. The power history of every assembly was reconstructed by applying the stage power factor over its whole residence time. The selected core, Case 8, charges 20.44 wt.% TRU over a 420 EFPD cycle and satisfies both design limits, with a maximum CDF of 0.0217 against the limit of 0.05 and a maximum thermal strain of 0.434% against the limit of 1.0%. This core will be used as a basis for the uncertainty evaluation of TRU-loaded cores and for the improvement of the fuel performance analysis code.

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