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Effect of Annular Fuel Rod Designs on the Sodium Void Worth in the KALIMER-600 TRU Burner

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1. Introduction

For an efficient transition between the KALIMER-600 breakeven and TRU burner fast reactors without a sufficient change in the core and subassembly layouts, annular fuel design concepts with a central region of a variable diameter consisting of B_4C, Nb, V, W, void, etc. were proposed and investigated[1]. The core performance analysis showed that the annular fuel designs with central void and vanadium rods are encouraging. However, the impact of these design concepts on the sodium void worth, which is one of the most important safety parameters in the TRU burner, has not yet been clearly clarified. Thus, a careful analysis of the void worth in accordance with each fuel rod design in the TRU burner is required for further optimization of the passive safety design of the core.

A perturbation analysis is performed here to elucidate the effect of annular fuel designs with central void and vanadium rods on the sodium void worth in the TRU burner in relation to the reference breakeven and TRU burner cores with variable cladding thicknesses. The scenarios of total sodium voiding at the beginning and end of the equilibrium cycle (BOEC and EOEC) in the TRU burner are examined. The calculation tool is the DIF3D-based perturbation code, PERT-K, which can provide a resolution down to the region-, isotope-, and reaction-wise reactivity components in a fast reactor [2-4].

2. Methods and Results

2.1 Calculation Model and Method

The KALIMER-600 breakeven core shown in Fig. 1 is loaded with a ternary metallic fuel (TRU-U-10Zr) of a single enrichment, and has a rated thermal power of 1,523 MWt. The radial layouts of the fuel rods in the breakeven and TRU burners with variable cladding thicknesses and central void/vanadium rods are represented in Figs. 2 and 3.

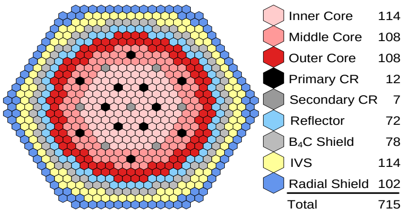

Fig. 1. Reference breakeven core layout

The Tri-Z geometry of the cores is applied with 54 triangles per hexagonal fuel assembly. The neutron microscopic cross-sections for 150 energy groups based on the ENDF/B-VI.6 library are collapsed into those for 25 groups using the TRANSX and TWODANT to generate the microscopic cross-section files (ISOTXS) for use in DIF3D and PERT-K runs. The exact perturbation formula in PERT-K for calculating the reactivity of the region-wise isotope k shown in Eq. (1) is used for the analysis of whole-core voiding scenarios at BOEC and EOEC in the breakeven and the TRU burner[4]. The voided regions include the active core (inner, middle, and outer cores), the sodium bond, and the gas plenum.

$$\rho_{exack.k} = \frac{\frac{1}{k_{eff}^{p}}\sum_l V_l \sum_g \Phi^*_{gl}\chi^p_{gk}\sum_{g'}\Delta(\nu\Sigma_f)_{g'lk}\Phi^p_{g'l} + \sum_l V_l \sum_g \Phi^*_{gl}\sum_{g'\neq g}\Delta\Sigma_{g'\to g/g\to g'k}\Phi^p_{g'/gl} - \sum_l V_l \sum_g \Phi^*_{gl}\Delta\Sigma_{rglk}\Phi^p_{gl} + \sum_l V_l \sum_g \nabla\Phi^*_{gl}\Delta\tilde{D}_{glk}\nabla\Phi^p_{gl}}{\sum_l V_l \sum_g \Phi^*_{gl}\chi_g \sum_{g'}\Delta(\nu\Sigma_f)_{g'l}\Phi^p_{g'l}} \quad (1)$$

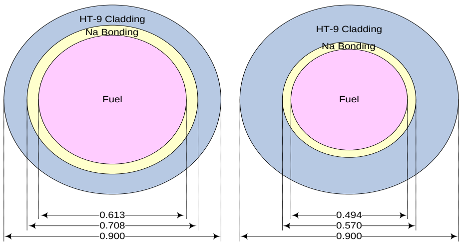

Fig. 2. Fuel rod designs with variable cladding thicknesses for the reference breakeven (left) and TRU burner (right) cores

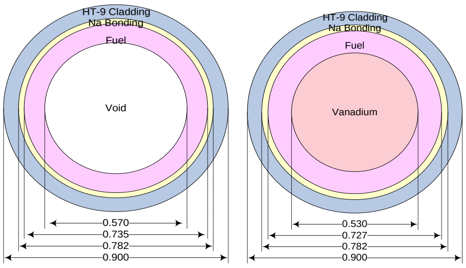

Fig. 3. Annular fuel rod designs with central void (left) and vanadium (right) rods for the TRU burner

2.2 Analysis of sodium void worth in the TRU burner

The results calculated by PERT-K shown in Table I indicate that the voided regions mostly contributed to the global reactivity. A much higher scattering component in the sodium bond and a much lower increased leakage through the gas plenum in the reference TRU burner with variable cladding thicknesses with respect to other cases mainly caused the global reactivity in this core too much positive (~8.5$ or 2668 pcm) and beyond the design safety limit of 8$. Case c shows a much higher leakage through the gas plenum compared to the other ones, and therefore exhibits the least positive void worth of ~5$ (1593 pcm). The softer neutron spectrum in the burner with central vanadium rods (Case d) and the higher leakage in the burner with central void rods (Case c) suggest that an appropriate combination of these two fuel designs may lead to an optimal fuel design in regard to reducing the void worth in the case that the use of vanadium in the annular fuel design is to be realized. It should be noted that the use of vanadium in annular fuels is favorable owing to its high melting point of 1910°C, and hence acting as a solid replacement for sodium.

Table I: Region-wise void reactivity and components (pcm)

100% whole core void at BOEC/EOEC					
Reactivity	ρ_{fiss}	ρ_{abso}	ρ_{scat}	ρ_{leak}	ρ_{total}
Reference breakeven (case a)					
Inner core	48.2/48.1	118.6/117.4	2183.9/2216.2	-464.1/-467.5	1886.6/1914.1
Middle core	26.4/26.1	68.9/67.5	1378.8/1379.9	-383.9/-381.7	1090.3/1091.9
Outer core	9.7/9.6	26.6/26.0	498.3/495.5	-421.8/-416.7	112.8/114.5
Sodium bond	0.0/0.0	8.2/8.1	163.1/166.3	-427.3/-429.6	-256.0/-255.2
Gas plenum	0.0/0.0	3.9/3.9	108.5/109.8	-312.1/-313.0	-199.6/-199.3
Whole core	84.4/83.8	226.0/222.7	4335.6/4370.9	-2010.6/-2009.9	2635.4/2667.4
TRU burner, variable cladding thicknesses (case b)					
Inner core	58.9/60.3	107.4/110.1	2090.3/2147.1	-511.2/-512.4	1745.4/1805.1
Middle core	34.1/35.7	63.1/66.0	1303.1/1363.4	-378.5/-387.0	1021.7/1078.1
Outer core	19.1/20.2	31.1/32.8	583.2/619.1	-539.3/-559.7	94.0/112.4
Sodium bond	0.0/0.0	11.2/11.5	239.7/248.6	-461.9/-478.1	-211.0/-218.0
Gas plenum	0.0/0.0	3.0/3.1	125.2/129.6	-235.8/-243.5	-107.6/-110.8
Whole core	112.1/116.3	215.2/223.0	4347.3/4513.9	-2131.2/-2185.5	2543.4/2667.7
TRU burner, annular fuels with central void rods (case c)					
Inner core	65.7/67.7	97.0/100.6	2135.5/2216.7	-738.7/-750.7	1559.5/1634.3
Middle core	42.5/44.4	63.3/66.3	1432.7/1509.9	-601.2/-614.5	937.2/1006.1
Outer core	21.7/23.1	31.8/33.7	658.5/701.6	-761.2/-790.3	-49.2/-31.9
Sodium bond	0.0/0.0	5.5/5.7	150.0/156.0	-474.7/-493.9	-319.3/-332.1
Gas plenum	0.0/0.0	9.3/9.7	280.8/292.1	-956.2/-992.9	-666.1/-691.1
Whole core	130.1/135.4	206.9/215.9	4670.1/4889.7	-3537.5/-3648.2	1469.5/1592.8
TRU burner, annular fuels with central vanadium rods (case d)					
Inner core	81.8/83.1	176.4/179.4	1665.1/1714.5	-413.8/-415.1	1509.5/1561.9
Middle core	54.0/56.0	113.6/117.7	1118.7/1170.5	-309.2/-315.9	977.1/1028.3
Outer core	30.3/32.0	52.5/54.9	528.3/560.1	-474.3/-490.4	136.8/156.6
Sodium bond	0.0/0.0	4.0/4.1	104.1/108.0	-288.2/-298.9	-180.2/-186.8
Gas plenum	0.0/0.0	5.3/5.5	150.3/155.9	-487.8/-505.0	-332.2/-343.6
Whole core	166.0/171.0	350.8/360.6	3576.5/3719.5	-1974.9/-2027.0	2118.4/2224.1

Comparing Tables I and II signifies that just a few isotopes in the sodium voided regions were the main contributors to the global reactivity. Sodium-23, on the whole, largely enhanced the global positive reactivity of at most ~2500 pcm (Cases a, b) and of at least ~1500 pcm (Case c). The use of vanadium in annular fuels directly inserted a small positive reactivity of ~80 pcm. Among the fissionable isotopes in the TRU burners, the neutron capture of uranium-238 and the fission processes of plutonium-239 and plutonium-240 were the most sensitive to the change in sodium densities.

3. Conclusions

Valuable details on the effect of annular fuel designs with central void and vanadium rods, for a smooth transition between the KALIMER-600 breakeven and TRU burner, on the void worth were revealed. In particular, just a few isotopes in the voided regions were found to mostly contribute to the global reactivity. Also, annular fuels with central void or vanadium rods showed either higher leakage or softer neutron spectrum relative to the reference TRU burner with variable cladding thicknesses. As a result, it was suggested that a hybrid annular fuel design using void and vanadium rods, e.g., central vanadium rods with pin holes, is promising with regard to reducing the void worth.

Acknowledgement

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Table II: Isotope-wise void reactivity and components (pcm)

100% whole core void at BOEC/EOEC					
Reactivity	ρ_{fiss}	ρ_{abso}	ρ_{scat}	ρ_{leak}	ρ_{total}
Reference breakeven (case a)					
U-238	0.3/0.3	97.6/94.4	30.7/30.1	-1.2/-1.1	127.5/123.6
PU239	55.8/55.2	-9.3/-9.1	0.7/0.8	-0.1/-0.1	47.2/46.8
FE	0.0/0.0	28.2/28.1	94.1/95.0	-161.7/-162.2	-39.4/-39.1
NA23	0.0/0.0	114.3/113.8	4189.9/4224.9	-1839.0/-1838.0	2465.2/2500.7
TRU burner, variable cladding thicknesses (case b)					
U-238	0.6/0.7	51.7/52.8	21.3/21.6	-0.5/-0.5	73.1/74.6
PU239	64.8/67.3	-7.4/-7.5	0.8/0.8	-0.1/-0.1	58.2/60.5
PU240	33.1/34.2	-16.0/-16.2	1.6/1.6	-0.1/-0.1	18.6/19.6
FE	0.0/0.0	46.3/48.0	179.9/186.5	-252.2/-258.9	-26.0/-24.3
NA23	0.0/0.0	133.9/138.6	4109.0/4267.4	-1861.9/-1909.0	2380.9/2497.0
TRU burner, annular fuels with central void rods (case c)					
U-238	3.7/3.8	58.5/60.2	31.3/32.1	-0.4/-0.4	93.1/95.6
PU239	53.1/55.4	-10.0/-10.2	1.5/1.4	-0.1/-0.1	44.5/46.6
PU240	43.7/45.4	-15.7/-15.8	2.4/2.4	0.0/0.0	30.5/32.0
FE	0.0/0.0	41.4/43.2	138.2/144.4	-330.4/-341.6	-150.9/-154.0
NA23	0.0/0.0	134.6/139.9	4455.9/4666.7	-3186.9/-3285.5	1403.6/1521.2
TRU burner, annular fuels with central vanadium rods (case d)					
U-238	0.7/0.8	111.6/113.4	23.1/23.6	-0.8/-0.8	134.6/136.9
PU239	111.2/114.2	9.8/9.8	1.5/1.5	-0.1/-0.2	122.4/125.3
PU240	58.4/60.6	-23.3/-23.6	1.8/1.9	-0.2/-0.2	36.8/38.8
V	0.0/0.0	7.6/7.9	84.0/87.7	-11.8/-12.1	79.8/83.5
FE	0.0/0.0	16.8/17.7	64.1/67.1	-142.1/-146.4	-61.2/-61.5
NA23	0.0/0.0	213.2/220.4	3383.9/3518.0	-1812.1/-1859.4	1785.0/1879.0