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Modeling Doubly Heterogeneous Systems in SCALE

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INTRODUCTION

Several proposed advanced reactor concepts require methods to address double-heterogeneity effects. In doubly heterogeneous systems, heterogeneous fuel particles in a moderator matrix form the fuel region of the fuel element and thus constitute the first level of heterogeneity. Fuel elements themselves are also heterogeneous with fuel and moderator or reflector regions. The fuel elements may also form regular or irregular lattices.

The SCALE [1] analytical sequences that use NITAWL [1] to process the cross sections in the resolved energy range do not have the geometry options to accurately model a doubly heterogeneous fuel lump. NITAWL, which uses the Nordheim Integral Treatment Method, assumes the flux in the surrounding moderator is spatially flat with an asymptotic spectrum in the epithermal range and Maxwellian in the thermal. The lattice geometry effects are accounted for through the use of Dancoff factors. For accurate results, correct Dancoff factors must be calculated and used.

Alternatively, CENTRM [1] and PMC [1] modules of the SCALE code system can be used to perform the resonance self-shielding correction of the cross sections. CENTRM calculates fluxes using point-wise (PW) cross sections in the one-dimensional transport equation, and PMC generates flux-weighted multigroup cross sections for final analysis. PMC can optionally generate cell-weighted cross sections. However, the SCALE sequences that use these modules did not support modeling of doubly heterogeneous systems.

METHOD

A new capability to model doubly heterogeneous systems has been added to the SCALE system. [1] This feature is included in the control sequences CSAS and CSAS6 that utilize the Monte Carlo codes KENO V.a [1] and KENO-VI, [1] respectively, for three-dimensional analyses; and in the TRITON [1] sequence that uses the two-dimensional lattice physics code NEWT. [1]

A new doubly heterogeneous unit cell type that uses CENTRM and PMC modules, as well as new additional modules, has been created to generate problem-dependent multigroup cross sections in SCALE. When the new unit cell type is selected, first the PW flux disadvantage factors in the fuel grains (coated particles) are calculated. Then, these PW flux disadvantage factors are used to generate the cell-weighted PW cross sections for the homogenized fuel region in the fuel pebble. Finally, these spatially averaged PW cross sections are used to calculate the flux distribution in the fuel element, which is then used in PMC to generate the multigroup problem-dependent cross sections. As with many other features in SCALE, this process is transparent to the user and has been automated in the control sequences.

APPLICATION TO PEBBLE BED REACTOR FUEL

High-temperature reactors (HTR) utilize graphite-moderated fuel forms and helium gas as a coolant. There are two main forms of the HTR fuels: pebbles are used in the pebble bed high temperature reactor (PBR), and rods are used in the modular high temperature gas cooled reactor (MHTGR). In PBRs, the fuel elements are 6-cm-diameter spheres. In MHTGRs, the fuel elements are graphite rods that are inserted into graphite hexagonal blocks. In this study, only the pebble-type fuels have been analyzed.

The pebble bed fuel element is a graphite ball with an outside diameter of 6 cm, as shown in Fig. 1. Each fuel element contains fissionable elements in the oxide form inside small coated particles called Triso particles. These coated Triso particles (~1.0 mm in diameter) are embedded in a graphite matrix, which forms the inner fuel region of the fuel element. The spherical fuel elements have a 0.5-cm-thick outer layer of graphite. These spherical fuel elements are placed in the reactor vessel along with graphite moderator balls and absorber balls of the same size (absorber balls are similar to fuel balls except that the absorber region is made of homogeneous absorber matrix material). This randomly placed combination of fuel, moderator, and absorber balls in the reactor vessel is referred to as the "pebble bed" of the reactor. A core load consists of thousands of fuel, moderator, and absorber spheres, depending on the power level and the design of the reactor. Fuel and moderator balls are added from the top, while used balls (the balls that have been in the reactor) are discharged from the bottom. After inspection, fuel balls that haven't reached the desired burnup are placed back into the reactor.

The fuel element consists of a double-layered geometry: (1) the small fuel particles within a single fuel sphere or "pebble" and (2) the fuel pebbles within the reactor core. This double heterogeneity must be explicitly handled because the fuel particles are closely packed and the interactions between the fuel particles, as well as the

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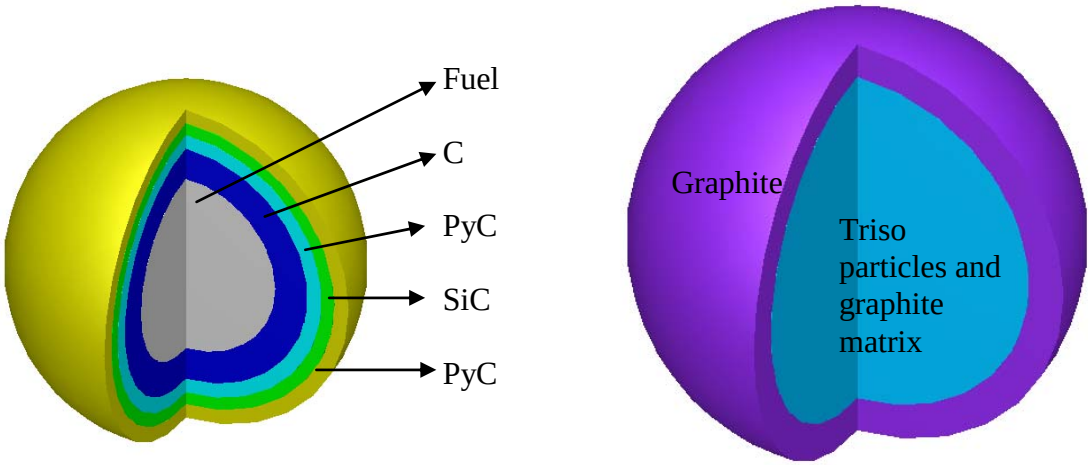

Fig. 1. Triso particle and fuel pebble.

slowing down within the fuel particles, cannot be ignored (a fuel particle 0.5 mm in diameter surrounded by a moderator shell 0.25 mm thick). This double heterogeneity in the fuel lattice cannot be modeled directly in the resonance processing codes that rely on the collision probability technique. Instead, one must use either the Dancoff factor approach or another method that does not rely on a collision probability technique to account for the lattice effects.

ANALYSIS

The new cell type has been tested using the benchmark definitions [2] provided by the Organization for Economic Cooperation and Development, Nuclear Energy Agency (OECD NEA), Nuclear Science Committee, Working Party on the Physics of Plutonium Fuels and Innovative Fuel Cycles. The analyses have been performed for UO_2– and PuO_2–fueled pebbles. UO_2–fueled pebbles contain 0.091-cm outer diameter (OD) Triso particles with 8.2% enriched uranium. PuO_2–fueled pebbles contain 0.066-cm OD Triso particles. The plutonium vector for these Triso particles is 2.59/53.85/23.66/13.13/6.77 percent, which corresponds to the plutonium isotopes $^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$, respectively.

The results of the calculations are listed in Table I. Analysis of the results shows that resonance shielding is considerable for the UO_2– and PuO_2–fueled pebbles. Properly shielded cases calculate 8 and 20% higher for UO_2 and PuO_2 systems, respectively. For all cases, KENO V.a and KENO VI results show excellent agreement. This is expected since both codes use the same resonance-shielded cross sections. For UO_2–fueled pebbles, KENO V.a and KENO VI eigenvalue results agree with MONK9 [3] results with ~0.7% difference. For PuO_2–fueled pebbles, the difference between KENO V.a and KENO VI results and MONK9 results is less than 1.7%.

CONCLUSIONS

Doubly heterogeneous systems can now be modeled with SCALE using automated, easy-to-use, and user-friendly sequences CSAS, CSAS6, and TRITON. The KENO V.a and KENO VI results agree well with each other. The agreement with MONK9 is not as good. This, however, could be due to the difference in the cross-section sets rather than to the accuracy of the resonance-shielding methodology. This remains to be investigated. Further benchmarking and validation work is necessary.

TABLE I. Effect of double heterogeneity in various systems.

Problem	Definition	Method	KENO V.a		KENOVI	
			k_{eff}	σ	k_{eff}	σ
1	Infinite array of UO_2–fueled pebbles	Homogenized	1.39943	0.00044	1.39965	0.00043
		Doubly heterogeneous	1.51132	0.00037	1.51059	0.00045
		% difference	8	--	8	--
2	Infinite array of PuO_2–fueled pebbles	Homogenized	1.19762	0.00042	1.19820	0.00039
		Doubly heterogeneous	1.44087	0.00039	1.44107	0.00036
		% difference	20	--	20	--

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