Incorporation of Resonance Upscattering and Intra-Pellet Power Profile in Direct Whole Core Calculation

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1. Introduction

It was generally known that the Doppler feedback effect computed by most industrial reactor analysis codes is underestimated than the actual values[1]. Part of the underestimation was attributed to the neglect of the resonance upscattering during the slowing down calculation[2]. On the contrary, the edge peaked power profile noted in burned fuel pins due to more plutonium buildup at the periphery of fuel pellets might lead to smaller power defects than the predicted values obtained with a flat profile[1]. This work is to mitigate these problems with a direct whole core calculation code nTRACER[3] which is capable of handling ringwise depletion as well as incorporating nonuniform power profiles inside a fuel pellet.

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2. Methods for Better Doppler Feedback Prediction

Two approaches are taken to improve the Doppler feedback prediction in nTRACER. The first one is to employ the resonance upscattering during the slowing down calculation to determine the resonance subgroup parameters and the other is to incorporate nonuniform power profiles in the fuel temperature calculation.

2.1 Incorporation of Resonance Upscattering

With a little fixes in the McCARD Monte Carlo code [4] incorporating the Doppler broadening rejection correction (DBRC) method[5], it became possible to incorporate the influence of thermal motion of the target nucleus into the scattered neutron, enabling the consideration of resonance upscattering. Note that the Doppler effect is enhanced by the inclusion of the resonance upscattering of U-238 because the upscattering brings a neutron back into the resonance energy range. The updated McCARD was used in the nTRACER cross section generation procedure that involves the determination of the resonance subgroup parameters by solving a least square problem to minimize the error in the effective cross sections defined as:

$$F(\mathbf{w}) = \sum_{k=1}^{K} \left(1 - \frac{\sigma_k^{SG}}{\sigma_k^{\text{Ref}}} \right)^2 \qquad (1)$$

where k is the index for different dilution cases and σ_k^{SG} is the effective cross section reconstructed by the subgroup parameters and σ_k^{Ref} is the reference effective cross section obtained by the slowing down code. By using the McCARD generated reference effective cross sections, the subgroup parameters were generated such that the new sets enhance resonance absorption. The upscattering correction has a significant impact on the U-238 resonance absorption for low energy resonances as identified by following figure.

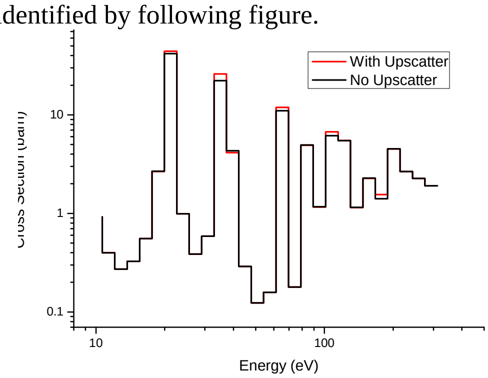

Fig. 1. Effective absorption cross section of U-238 at 2000K with different treatment of resonance upscattering

2.2 Non-uniform Heat source Profile

Because of spatial self-shielding due to U-238 resonance absorption, more fissile plutonium isotopes are built at the periphery of a fuel pellet as the fuel depletes. This would lead to a higher heat generation rate at the rim for burned fuels, namely, the rim effect. This edge-peaked, intra-heat source shape should be reflected in the fuel heat conduction calculation. In the nTRACER calculation, a non-uniform power profile such as the one shown below can be readily incorporated. The resulting temperature distribution in Fig.2 shows a lower average temperature as well as the lower centerline temperature for the same linear heat generation rate of the rod.

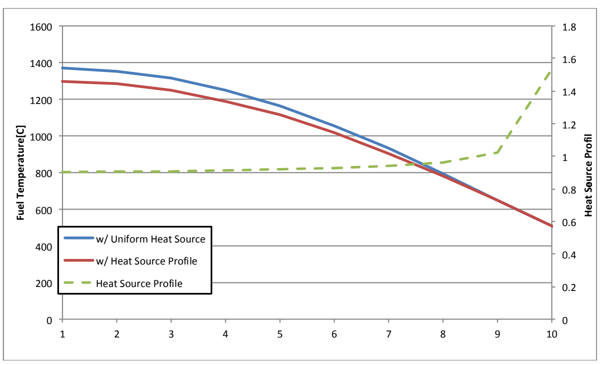

Fig. 2. Temperature profile with uniform and edge peaked power profiles at 30 GWD/T

Since the cross sections are evaluated ringwise in nTRACER, the power profile effect can be incorporated in nTRACER.

3. Effect of Improved Doppler Treatment

In order to examine the effect of improved Doppler treatment, nTRACER calculations were performed for a UO_2 pin, an assembly and for a full core problem of the OPR1000 core.

3.1 Resonance Upscattering Effect

Tables 1 and 2 show the results for the pin and assembly problems. The exact scattering model increases the fuel temperature coefficients (FTC) by about 10% compared to the conventional asymptotic model.

Table 1. FTCs for a 3 w/o UO_2 pin

Asymptotic Model			Exact Model		
Temp (K)	**keff**	**FTC (pcm/K)**	**Temp (K)**	**keff**	**FTC (pcm/K)**
700	1.32591		700	1.32491	
		-2.02			-2.28
1100	1.31184		1100	1.30908	
		-1.69			-1.90
2000	1.28625		2000	1.28044	

Table 2. FTCs for OPR 1000 Assembly Type B

Asymptotic Model			Exact Model		
Temp (K)	**keff**	**FTC (pcm/K)**	**Temp (K)**	**keff**	**FTC (pcm/K)**
700	1.32914		700	1.32738	
		-1.73			-1.94
1100	1.32307		1100	1.32057	
		-1.68			-1.88
2000	1.31432		2000	1.31079	

The increase in FTC by the exact scattering model is also observed in the core problem as identified in Table 3. About 15% larger FTCs are noted with the exact model.

Table 3. FTCs for an OPR 1000 core

Asymptotic Model			Exact Model		
Temp (K)	**keff**	**FTC (pcm/K)**	**Temp (K)**	**keff**	**FTC (pcm/K)**
708.3	1.42507	-2.44	708.3	1.42369	-2.82
846.4	1.41849	-2.32	846.4	1.41610	-2.69
999.8	1.41126	-2.33	999.8	1.40779	-2.65
1168.0	1.40342	-2.18	1168.0	1.39893	-2.48

3.2 Power Profile Effect

Since the average fuel temperature is reduced with an edge-peaked heat source profile, it is expected that the power coefficients will be reduced by incorporating the power profile effect. This expectation is confirmed by the following figure which shows the reactivity variation with power level for a pin at different burnups.

It is shown in this figure that more power defect reduction is observed at higher burnup because of the increased rim effect.

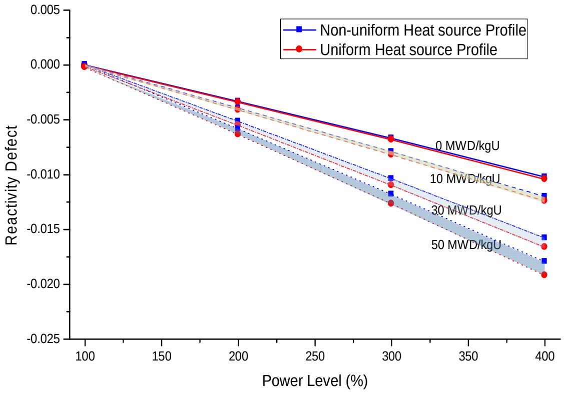

Fig. 3. Uniform heat source profile (Left) and Non-uniform heat source profile (Right)

4. Conclusions

The exact scattering model based subgroup resonance parameters and the non-uniform heat source profile effects were incorporated into the nTRACER direct whole core calculation code. The exact scattering model employed in the McCARD code results in subgroup parameters that enhance resonance absorption through resonance upscattering that eventually increases the FTC of the core by more than 10% which can compensate the current underprediction of power coefficients particularly at BOCs. The incorporation of the nonuniform temperature, however, brings the opposite effect at EOCs. At any rate, it is possible now with nTRACER to predict the FTCs and power coefficients more accurate than the conventional two-step codes at various burnup states.

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