Reactivity Coefficient Calculation for a Low-Power LEU Research Reactor

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INTRODUCTION

Core design studies on a 20-MW thermal power low enriched uranium (LEU) fueled research reactor are underway at the NIST Center for Neutron Research (NCNR) with the primary purpose of providing quality neutron beams for scientific research. [1, 2] The 'tank-in-pool' design pattern is adopted for the new reactor: A compact core composed of two horizontally split halves are surrounded by a cylindrical D_2O reflector tank, and the tank is itself surrounded by a large H_2O pool, which functions as thermal and biological shielding. The split core consists of 18 MTR-type fuel elements which are evenly distributed into two regions. The LEU fuel used in the study is the U_3Si_2-Al dispersion fuel with U-235 enrichment of 19.75%, the only NRC certified LEU fuel in the U.S. The core is cooled and moderated by H_2O, and separated from D_2O by zircaloy core boxes. Hafnium control blades are utilized as both criticality and safety control elements for the reactor. They are controlled by a mechanical driver located at the bottom of the core but with the fully withdrawn positions at the top of the core. A configurational description of the new reactor design can be found in Ref. 2, and will not be reiterated here.

In a standard reactor calculation, it is necessary to evaluate the reactivity coefficient with respect to some physical parameters such as fuel or moderator temperature. For nearly all reactor designs, negative reactivity coefficients are required for safety. As a light-water cooled thermal reactor, the new reactor is designed to work in an under-moderated mode with the most achievable reactivity. The core is required to have negative reactivity coefficients under any normal or abnormal circumstances such as over power transient, loss of coolant or reflector, etc. Therefore the reactivity coefficient addresses reactor safety concerns as well as provides valuable quantitative parameters for reactor safety analyses.

In this summary, three typical reactivity coefficients for the low-power LEU core are calculated using the Monte-Carlo code MCNP-6: the moderator temperature coefficient (MTC), the fuel temperature coefficient (FTC), and the void coefficient (VC). A direct perturbation methodology is applied to calculate all these coefficients. The perturbed case is produced by manually perturbing a single physical property with respect to the reference case (the one with normal operational conditions), as the multiplication factor (i.e. k_{eff}) of the perturbed case is calculated by MCNP. The corresponding reactivity coefficient is thereby determined by dividing the reactivity change over the associated parameter changes.

REACTIVITY COEFFICIENTS

Moderator Temperature Coefficient (MTC)

The moderator temperature coefficient accounts for the reactivity change when the temperature of the moderator varies. The underlying mechanism of MTC is due to the moderator density changes because of thermal expansion or contraction. MTC is the main factor that contributes to the *temperature defect* of reactivity [3], which is the change of reactivity that occurs in the reactor core from the fuel-loading temperature to the operating temperature.

The temperature of the moderator is reflected in MCNP in three ways. One is through the specification of the density of the moderator and the other one is through the cross section file that specifies a temperature dependent thermal neutron scattering kernel, S(α,β), for the moderator. For higher energy scattering, the physical temperature is entered on the TMP card for every cell. The density of the moderator is a user input so it can be changed in a continuous manner for the purpose of examining the MTC at different temperatures.

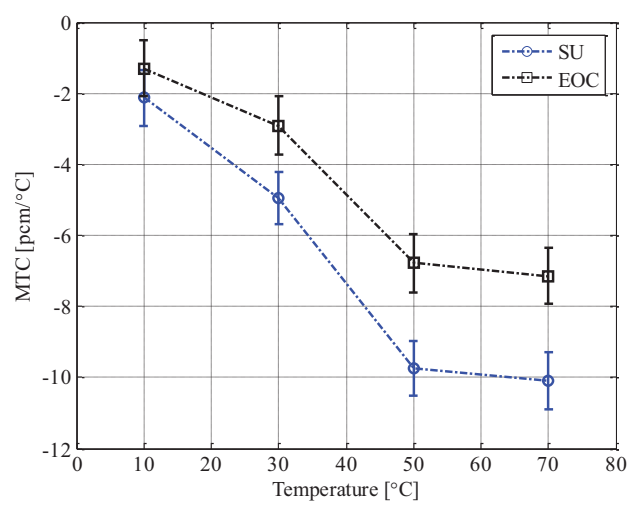

Fig. 1. The MTC curves at SU and EOC.

The reactivity coefficients at both the startup (SU) and the end of cycle (EOC) status of an equilibrium core cycle were calculated to examine the variations of the coefficients at different state of the cycle. The fuel compositions for SU and EOC were determined using an iterative search procedure introduced by Hanson and Diamond [4]. The reference cases were selected with operating conditions in which the light water is assumed to be 43 °C with the density 0.9914 g/cm^3. To calculate the MTC, the water density is modified with a series of values associated with temperature from 0 °C to 80 °C in 20 °C increments. The TMP card for the coolant cells are also changed correspondingly whereas the scattering kernel remains unchanged due to the limited data in MCNP ENDF-B7.1 libraries. The kernel at room temperature (20 °C) is used for this calculation. The k_{eff} for each perturbed case is calculated and the corresponding MTC (dρ/dT with units of pcm/°C) is evaluated by dividing the reactivity change by the temperature difference. Fig. 1 illustrates the results. As can be seen, for both SU and EOC, the MTC has negative effect on the reactivity and has a magnitude of only few pcm (per cent mille) per Celsius, but its absolute value has an *increasing* trend as the temperature rises.

Fuel Temperature Coefficient (FTC)

The fuel temperature coefficient accounts for the reactivity change due to the fuel heat up or cool down. The primary physics that dominates FTC is the Doppler broadening of the resonance peaks of the U-238 in the fuel. The FTC would have negligible effect on high enriched uranium (HEU) fuel as weight percentage of U-238 in HEU is very small, but the large amount of U-238 in the LEU core may result in significant FTC effect. FTC is a significant factor that contributes to the *power defect* of reactivity [3], which is defined to be the change in reactivity taking place between zero power and full power.

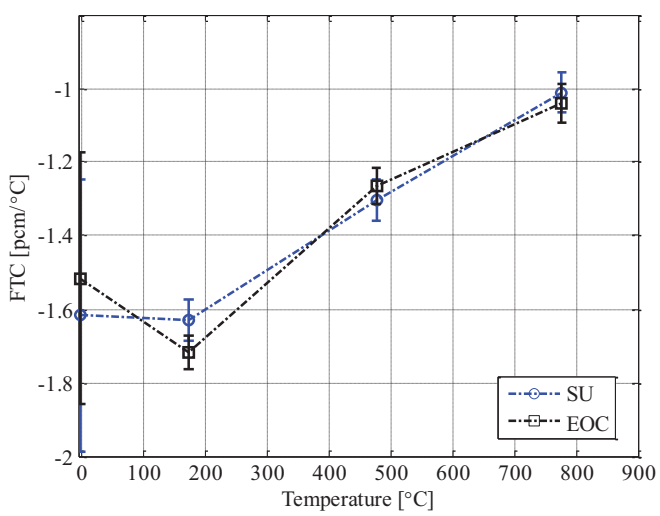

Fig. 2. The FTC curves at SU and EOC.

To calculate the FTC for the LEU core, the same SU and EOC model were used by modifying only the fuel temperature and Doppler-broadened cross-section to determine the reactivity changes in the perturbed cases. With the available data in MCNP6, a set of ENDF-B7.1 libraries generated for 250 K (.86c), 293.75 K (.80c), 600 K (.81c), 900 K (82.c), and 1200 K (.83c) are used for the perturbation. The TMP card for fuel is modified accordingly whereas the thermal expansion is neglected in the calculation due to the compact nature of the core. The k_{eff} for each fuel cross-section perturbed case is calculated and the corresponding FTC (dρ/dT with units of pcm/°C) is determined by dividing the reactivity change by the temperature difference. The results are illustrated in Fig. 2. It can be seen the FTC for both SU and EOC have a very slight negative effect on the reactivity (~1-2 pcm/°C), but it has an insignificant *decreasing* trend with the fuel temperature increases.

Void Coefficient (VC)

The void coefficient accounts for the reactivity change due to voiding in coolant, moderator, or reflector. Voiding could take place in the coolant channel, for example, through boiling because of flow blockage, or in the heavy water reflector tank through leakage. A negative void coefficient is definitely needed to ensure negative feedback to the power level.

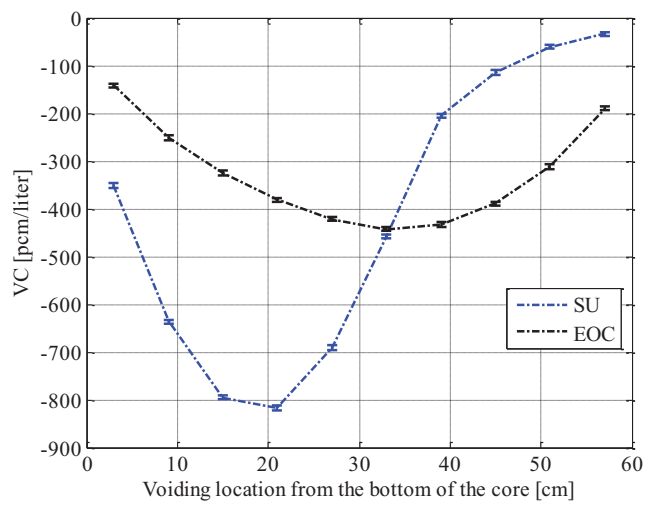

Fig. 3. The VC curves at SU and EOC.

Because the neutrons in different areas of the core exhibit different importance to the criticality, the void reactivity coefficient has an apparent spatial dependence as well. In order to examine the spatial characteristic of the coolant void coefficient, a series of perturbed cases are generated with voids created at different axial zoning of the coolant channels. The voiding height of each zone is 6 cm. The reactivity change is calculated for each voided case,

and the corresponding VC is determined by dividing the reactivity change by the volume of void.

Fig. 3 depicts the corresponding VC (dρ/dV with units of pcm/liter) estimated based on reactivity change of each perturbed case. The k_{eff} for the reference case is 1.00293 ± 0.00011 for SU and 0.99856 ± 0.00011 for EOC. As can be seen, the VC at any axial voiding zone shows a negative effect on the reactivity, and has a magnitude of few hundred pcm per liter of coolant volume for both SU and EOC. The axial dependence of the VC, however, has demonstrated appreciable difference from SU to EOC. The coefficient for the SU has higher values at the bottom half of the core. This is because most of the power is concentrated in the bottom half of the core and neutrons at the bottom half have more importance at the startup state of the core. The peak in the VC curve is gradually shifted to top half of the core is also due to the neutron importance variation, which is caused by the control rod movement (withdrawal out of the active core) in the operation cycle.

NEGATIVE REACTIVITY EFFECTS

Table I summaries the global reactivity effect at different specific scenarios for the core. The 1-σ deviation of all reactivity changes are about ~15 pcm. Among them, the moderator temperature effect is treated with two alternative ways: one only considers the density changes from operating temperature 42 °C to the higher temperature 76 °C (Case #1), another considers the scattering kernel changes from 42 °C to 76 °C (Case #2). The overall moderator temperature effect would need to combine both of their contributions (Case #3). The fuel temperature effect considers the LEU fuel cross-section changes from 293.75 K (.80c) to 900 K (82.c). The void effect considers the voids completely occupy the following elements or areas, respectively: (a) the stationary light water between fuel elements (Case #5); (b) the flowing light water coolant inside the fuel element (Case #6); (3) the heavy water reflector tank (Case #7).

As can be seen in Table I, negative reactivity variation is achieved for every hypothetical case. The increase of moderator and fuel temperature both have negative effect on reactivity, each of which can contribute up to a few hundred pcm. Voiding light water inside the core can provide significant negative feedback to the reactivity, particularly when the voids occur in the coolant channels. Thus water boiling that may take place in the coolant channel will have an overwhelming influence to the reactivity when the reactor is operating. The reactivity effect from voiding the heavy water reflector is also enormous as shown in Table I. This is as expected since the heavy water reflector serves as a moderator as well. Because of this significant negative effect, drainage of heavy water tank can be considered as a secondary shutdown mechanism for the reactor.

Table I. Negative Reactivity Effect of the Core.

		Δρ (pcm)	
#	**CASE**	**SU**	**EOC**
1	**Moderator density changed**	-309	-267
2	**Moderator S(α,β) changed**	-43	-92
3	**Combine 1 & 2 effects**	-352	-359
4	**Fuel temperature changed**	-391	-379
5	**Water between FEs voided**	-3841	-2478
6	**Water within FEs voided**	-32904	-27013
7	**Heavy water tank voided**	-36306	-35112

CONCLUSION

Core design studies are underway at NIST to develop a low-power LEU fueled beam reactor to advance the neutron source capability at NCNR for the next century. The reactivity effect caused by moderator temperature, fuel temperature and void is investigated though a direct perturbation approach using the MCNP code. The MTC, FTC, and VC for a representative startup core is obtained and the negative effect characteristics of these coefficients are observed. The reactivity effects under several postulated abnormal scenarios are also investigated. The overall negative feedback to the reactivity at each situation is confirmed.

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