The Water Ingress Effects on the Reactivity Change of the Conceptual Designed Reactor at NIST

Zeyun Wu[1, 2]* and Robert E. Williams[1]

[1]NIST Center for Neutron Research, 100 Bureau Drive, Mail Stop 6101, Gaithersburg, MD 20899 USA
[2]Department of Materials Science and Engineering, University of Maryland, College Park, MD 20742 USA
*Corresponding author: zeyun.wu@nist.gov

INTRODUCTION

The conceptual research reactor design with a split core for a replacement reactor project at the NIST (National Institute of Standards and Technology) Center for Neutron Research is underway. [1, 2] The reactor core is cooled and moderated by light water and reflected by heavy water in a reflector tank. The reactor core is immersed in light water, which is isolated from heavy water with a slightly pressurized boundary box made of zirconium alloy. The heavy water is contained in a large size cylindrical tank which also provides ample space to accommodate neutron beam tubes, cold sources and other irradiation equipment. The reflector tank is placed in the center of a large light water pool, which provides thermal and biological shielding to the reactor.

Light water and heavy water have distinct physical properties in regard to neutron moderation. Light water is generally known to have greater moderating power and absorption cross-sections, while heavy water has a higher moderating ratio. Table I summarizes common moderating characteristics of light water and heavy water with the interaction of 2200 m/s neutrons [3].

Table I. LW and HW Neutron Moderating Characteristics

Moderator	**H_2O**	**D_2O**
ρ (g/cc)	1.0	1.1
σ_a (barn)	0.66	0.001
σ_s (barn)	103	13.6
Σ_a (cm^{-1})	0.0221	3.31E-5
Σ_s (cm^{-1})	3.4429	0.4498
ξ	0.948	0.57
$\xi\Sigma_s$ (cm^{-1})	3.264	0.256
$\xi\Sigma_s/\Sigma_a$	148	7752

ξ – Neutron average lethargy gain (or average logarithmic energy loss) per collision.
$\xi\Sigma_s$ – Neutron moderating power or slowing down power
$\xi\Sigma_s/\Sigma_a$ – Neutron moderating ratio

Due to these differences in properties, the accidental mixing of light water and heavy water in either direction will inevitably affect the reactivity of the reactor. Moreover, since the neutron flux spectrum at different locations of the reactor will have significantly different characteristics (for example, the spectrum at the heavy tank should be much softer than that at the core center region), the effect of reactivity changes becomes complicated and will depend on the water mixing locations. From the reactor safety analysis perspective, the water ingress reactivity change is one of the required design base reactivity accidents that must be evaluated in the final safety analysis report.

Given these concerns, neutronics calculations have been performed to determine the effect and trend of the reactivity changes due to water ingress in different scenarios by purposely mixing the waters at three representative places in the reactor: the reflector area, the center coolant area and the peripheral coolant area (see Fig. 1). These three places were selected for the study because of their uniqueness in the flux spectrum (as shown in the results section). Simple static neutronics calculations were performed using MCNP6 [4] to examine the reactivity effects due to water ingress. It should be noted that all calculations performed in this study assume homogeneous water mixing in the area of interest; therefore, the local effect of the mixing situation would possibly be missed by this study.

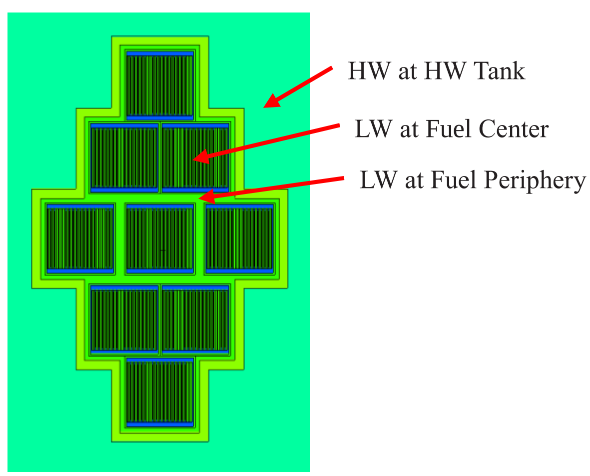

Fig. 1. The water at different locations of the reactor in one half of the split core.

REACTIVITY EFFECTS

Light Water Ingress in the Heavy Water Tank

The reflector tank is filled with D_2O that is assumed to be volumetrically 99.97% pure with 0.03% H_2O. The reactor core, which is slightly pressurized and surrounded by the heavy water reflector, is cooled and moderated by light water. The outside of the reflector tank is surrounded by a large light water pool. Thus it is possible that the light water coolant could leak into reflector and contaminate the D_2O. To assess the reactivity effect due to the non-purity of heavy water in the reflector tank, the volumetric fraction of the D_2O in the reflector is reduced in several cases; each case has 2% less D_2O, while the H_2O fraction for each case is increased accordingly to preserve the total volume of water in the reflector. The k_{eff} results for each perturbed case are shown in Fig. 2 in terms of k_{eff} vs. the amount of H_2O impurity for each case. The original case with H_2O% ~0 is at the critical status (k_{eff} = 0.99838 ± 0.00012). The end of cycle (EOC) equilibrium core is used for the perturbation in this study.

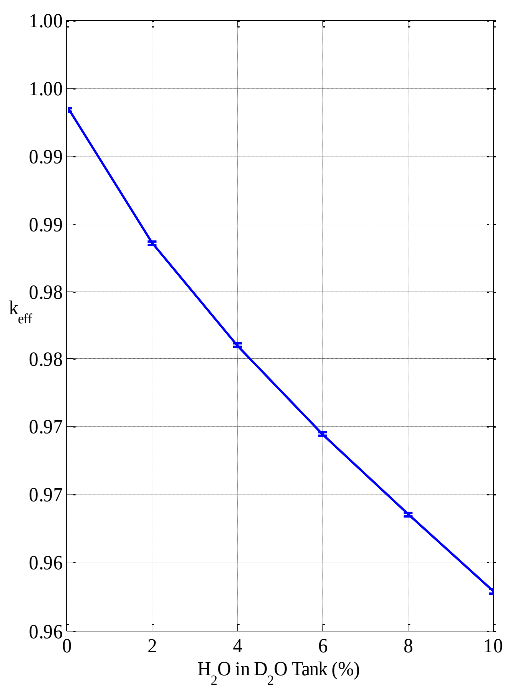

Fig. 2. Reactivity change with the light water ingress in the heavy water tank.

As shown in Fig. 2, any amount of light water contamination would have a negative effect on the reactivity to the reactor. A nearly linear decreasing trend on reactivity is observed with the amount of H_2O ingress in the heavy water.

Heavy Water Ingress in the Light Water Region

A similar approach is applied to assess the reactivity effect due to the heavy water ingress in the light water region. The main focus here is on those cases for which heavy water leaks into the core region (rather than to the light water pool region) because this is the place where fission occurs and makes large contributions to the reactivity. The heavy water will probably not be able to leak into the fuel center area unless it passes through the core peripheral area. Distinct effects on the reactivity were observed by researchers when they performed similar water mixing analysis on the 6 MWth plate-type HEU fueled MIT reactor [5]. Therefore, this study is bisected here to examine the water mixing at two different locations in the core; one is the flowing coolant region between the fuel plates (fuel center), the other is the stationary coolant region between the fuel elements (fuel periphery). Again, since the perturbation to the water composition is uniform throughout these locations, the local effect of the water mixing remains unknown in this study. To understand the combined effects, the perturbation in both locations is also performed. The results of this study are all shown in Fig. 3.

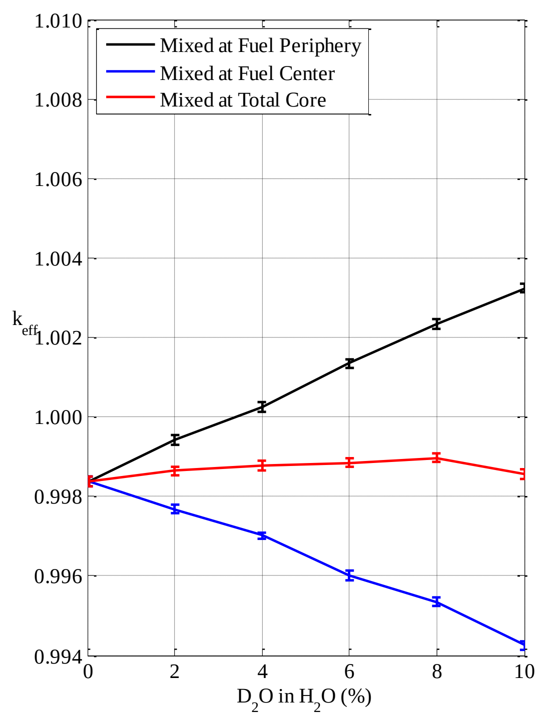

Fig. 3. Reactivity changes with the heavy water ingress in different locations of the light water regions.

As can be seen in Fig. 3, the water mixing in the fuel center provides a negative effect on the reactivity, whereas the water mixing the fuel periphery renders a positive effect on the reactivity. The combined effect of water mixing in the light water coolant has slightly positive effect under the EOC split core configuration. These are rather interesting results, and the water mixing analysis on the MITR core demonstrated a similar trend on the reactivity effects in this regard [5]. However, since the core box is slightly pressurized and has higher pressure than the heavy water tank, it is unlikely that the heavy water will leak into the fuel periphery region as assumed in this study.

DISCUSSION

The reactivity is a highly integral parameter that is affected by many components. As far as light water and heavy water are concerned, the absorption and scattering (moderating) effects on the neutrons are competing with each other all the time. The competition is complicated by the consideration of the distinct characteristics of light water and heavy water as shown in Table I. The flux spectra at those three locations of interest in this study are shown in Fig. 4. It can be seen the spectra indeed exhibit significant differences in those locations, particularly in the epithermal and fast neutron range. Since the effects of neutron absorption and scattering are intimately related to the flux spectrum, we believe the effect of the reactivity due to water mixings is more or less influenced by the flux spectrum.

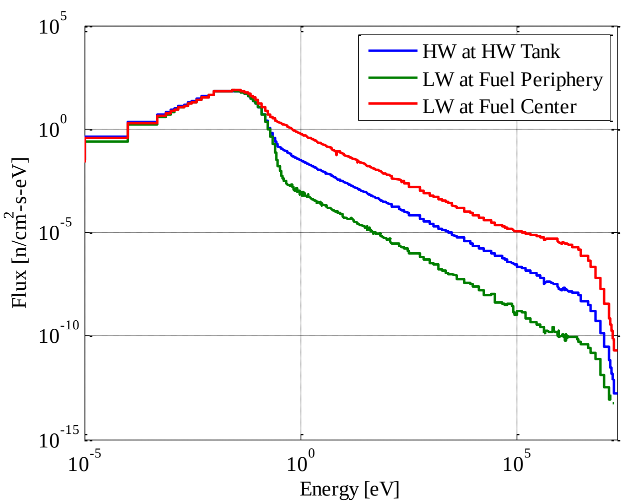

Fig. 4. Neutron flux spectrum at different locations.

CONCLUSION

The split core design employs a ‘tank-in-pool’ design pattern, in which the cores are immersed in a cylindrical heavy water tank and the tank is surrounded by a light water pool. The core itself is moderated and cooled by light water. Water mixing scenarios may occur during any accidental or malfunctioned conditions of the reactor operation. The effect on reactivity due to the water mixing in either direction is studied in this paper. The results show that the light water ingress in the heavy water tank would always cause negative reactivity, whereas the heavy water ingress in core coolant region is more complicated; heavy water ingress in the coolant at the fuel center provides negative effects, whereas heavy water ingress in the coolant at the fuel periphery renders positive effects, which results a slightly positive effect on the reactivity in the combined case. These reactivity effects will be taken into account when designing the primary and reflector cooling systems.

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