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REACTIVITY STUDIES ON THE ADVANCED NEUTRON SOURCE

John M. Ryskamp, Everett L. Redmond II, and C. D. Fletcher

Idaho National Engineering Laboratory
EG&G Idaho, Inc.
P. O. Box 1625
Idaho Falls, ID 83415

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An Advanced Neutron Source (ANS) with a peak thermal neutron flux of about 8.5 x 10^{19} $m^{-2}s^{-1}$ is being designed for condensed matter physics, materials science, isotope production, and fundamental physics research. The ANS is a new reactor-based research facility being planned by Oak Ridge National Laboratory (ORNL) to meet the need for an intense steady-state source of neutrons.(1,2) The design effort is currently in the conceptual phase. A reference reactor design has been selected in order to examine the safety, performance, and costs associated with this one design.(3) The ANS Project has an established, documented safety philosophy, and safety-related design criteria are currently being established.(4)

The purpose of this paper is to present analyses of safety aspects of the reference reactor design that are related to core reactivity events. These analyses include control rod worth, shutdown rod worth, heavy water voiding, neutron beam tube flooding, light water ingress, and single fuel element criticality. Understanding these safety aspects will allow us to make design modifications that improve the reactor safety and achieve the safety related design criteria.

Reactor physics analyses were performed with ENDF/B-V cross section data. Many of the methods we used are well documented.(5) Primarily, some of the reactor physics calculations were performed with PDQ-7 (6) using two-dimensional, four-energy-group, diffusion theory models. Other calculations were performed with MCNP-3B (7) using three-dimensional, continuous-energy, Monte Carlo theory models. The MCNP calculations are generally much more accurate, as well as much more expensive, than the PDQ calculations. The MCNP models were used in cases where three dimensions are required (such as for beam tubes or control rods) or where diffusion theory is inadequate (such as for large voids). PDQ models were used for the remaining cases and when the reactivity changes are very small, since the statistical nature of Monte Carlo prohibits examining small differences.

Thermal hydraulic analyses were required to determine the movement of a light water front through the heavy water reactor. These calculations were performed with RELAP-5.(8) RELAP-5 was also used to compute a large break loss-of-coolant accident simulation, which is representative of core voiding, and therefore coolant density response, during depressurization accidents.

Four hafnium control rods in the central hole are represented explicitly in the three-dimensional MCNP model. They are smeared in the central hole of the PDQ r-z model. MCNP also accurately models the eight reflector shutdown rods surrounding the reactor. Table 1 presents the core multiplication factors for different central control rod bank and reflector shutdown rod bank positions. These results indicate that the current configuration of four control rods in the central hole is adequate to shut down the reactor. The control rods also have negligible reactivity effect when in the fully withdrawn position. The reactor is near critical when the control rod bank is at the core midplane. The reflector shutdown rods are capable of safely bringing the ANS to a subcritical state even with the control rods fully withdrawn. The control rod bank worths computed with PDQ are reasonably accurate even though they are smeared in a two-dimensional model. The agreement of the reactivity differences is achieved even though diffusion theory overestimates each core multiplication factor.

MCNP and PDQ were used to determine the effects of voiding heavy water regions on the core multiplication factor. Table 2 lists the results of these calculations. Diffusion theory does not give accurate answers when the volume of the voided region is large. However, it can identify the general magnitude and the sign of the reactivity changes, as shown when comparing the first two rows of numbers.

For example, voiding all coolant channels significantly shifts the flux spectrum in the fuel, making it harder. This changes the U-235 cross sections that are used in the MCNP model. However, the PDQ runs used the

TABLE 1. CENTRAL CONTROL ROD BANK WORTH AND REFLECTOR SHUTDOWN ROD BANK WORTH AT BEGINNING OF CYCLE

Description	Core Multiplication Factor	
	PDQ	MCNP[a]
Base Case - No control rods	1.1608	1.1205 ± 0.0045
Control rods fully withdrawn (100 mm above top element)		1.1162 ± 0.0040
Control rods fully inserted	0.9373	0.9014 ± 0.0032
Control rods inserted to core midplane	1.0301	1.0036 ± 0.0040
Reflector shutdown rods fully inserted with no control rods		0.8568 ± 0.0030

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[a] The statistical uncertainties reported with all MCNP calculations represent one standard deviation.

TABLE 2. EFFECTS of D_2O VOIDING ON THE CORE REACTIVITY

Voided Region	Change in Core Multiplication Factor (Δk)	
	MCNP[a]	PDQ
Coolant channels	-0.054	-0.032
Plenum above lower fuel element	-0.024	-0.034
Plenum below upper fuel element		-0.006
50 mm of void above upper fuel element		-0.003
Central hole with control rods at midplane	-0.058	
Central hole without control rods		-0.038
Central hole below midplane with control rods at midplane		-0.037
Coolant bypass annulus		+0.003
10% void in entire reflector tank		-0.021

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[a] The statistical uncertainties of the MCNP calculations are typically ±0.004 for one standard deviation.

same U-235 cross sections as the base case with heavy water. MCNP can automatically account for cross section changes and also treat neutron streaming through voids properly.

The core reactivity drops with voiding everywhere except in the coolant bypass annulus, where there is a small positive reactivity insertion. Voiding the coolant channels is negative because the fuel elements are very undermoderated. Voiding at the coolant exits in the upper plenum are also negative, so the most likely cause of voiding, steam generated in the fuel elements, has a negative effect on core reactivity. Voiding in the central hole is negative, even with control rods inserted to core midplane. Thus, the flux spectrum does not shift enough to significantly reduce the worth of the control rods. This may be partially because the hafnium nuclides in the rods have high epithermal cross sections as well as high thermal cross sections. The rods are very black over a wide neutron energy range.

Void coefficients were computed from the information presented in Table 2. These have been used as input to the RELAP-5 model of the ANS. The rod worths and void coefficients are being used in RELAP-5 to analyze several accident scenarios.

The core reactivity depends on the type of moderator present. Light water moderates neutrons much faster and in a much shorter distance than heavy water. However, light water also absorbs more neutrons than heavy water. The ANS was designed specifically to take advantage of the properties of heavy water. The reactor is cooled and moderated by heavy water and sits in a large tank of heavy water surrounded by a light water pool. Light water ingress into the reactor or heavy water tank is possible for some accident scenarios. The reactivity impact of light water ingress has been examined.

Table 3 shows the reactivity impact of substituting H_2O for D_2O in different regions inside the core pressure boundary tube. Light water ingress reduces the core reactivity for most scenarios. One safety

TABLE 3. REACTIVITY IMPACT OF LIGHT WATER INGRESS IN THE ADVANCED NEUTRON SOURCE AT BEGINNING OF CYCLE

Regions with H_2O inside CPBT[a]	Core Multiplication Factor (k)[b]	Reactivity Impact (%Δk/k)
None (base case)	1.3118	--
All regions	1.0261	-24.6
All regions except D_2O in central hole	1.2350	- 6.0
Fuel regions (coolant channels)	1.4521	10.2

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[a] These are the regions inside the core pressure boundary tube where D_2O has been replaced by H_2O. All models have D_2O in the reflector tank. There is no boron or hafnium anywhere.

[b] Peak thermal neutron flux in the reflector multiplied by k.

concern is that of an isolated slug or two of light water entering the fuel region with heavy water above and below the slugs. If two optimally shaped slugs that are offset axially enter each fuel element at the same time and displace all of the heavy water in the coolant channels, about 15 $ worth of reactivity would be inserted within 0.02 seconds, assuming a coolant flow of 27 m/s. However, this worst-case scenario certainly seems incredible. The two slugs in the separate flow paths would most likely be aligned axially and not of optimum shape. Uniform insertion of light water decreases core reactivity because more neutrons get absorbed in the light water adjacent to the fuel elements. We are currently investigating a more credible scenario of a front of light water as it enters the core from the cold leg during full-power operation and progresses through the core. RELAP-5 was used to compute the profile of this light-water/heavy-water boundary as a function of time.

Other reactivity accident scenarios have also been investigated and will be discussed in the full paper, such as the sudden flooding a beam tube in the reflector with heavy water, causing a positive reactivity insertion of about \$0.25.

In summary, several events related to the reactivity of the Advanced Neutron Source have been analyzed. Some of this information is being input to the RELAP-5 safety models of the ANS. These calculations are being used to make design modifications that improve reactor safety.

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