Secondary source reconfiguration for a Westinghouse four-loop plant

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Abstract. An approach is described for estimating the excore source range detector count rate for several secondary neutron source configurations. A case in which a Westinghouse four-loop plant considered relocating the secondary source fuel assemblies and switching from secondary source fuel assemblies with six secondary source rods to assemblies with two or four secondary source rods is presented. The excore detector count rate is first estimated computationally, by modeling the secondary source fuel assemblies and excore detectors in MCNP and predicting the detector count rate based on detector sensitivity in cps/nv listed in the detector manual. Since the excore detector response can vary greatly from cycle to cycle even for equilibrium loading patterns due to variations in detector response, benchmarking to actual excore source range detector count rates is presented. A correction factor for each individual source range detector is determined from the benchmark, then applied in the prediction of excore source range detector count rate for the proposed two or four secondary source rod configurations. The approach presented in this paper could also be used to perform an engineering evaluation on the feasibility of elimination of secondary sources.

1 Introduction

Most US-designed pressurized water reactors (PWRs) have a requirement that the excore source range detectors maintain a minimum count rate in counts per second (cps) to demonstrate detector functionality during initial and reload core loading per Reference [1] or the plant-specific Updated Final Safety Analysis Report (UFSAR). Depending on the plant design and excore source range detector types, the minimum count rate could be 2 cps, 0.5 cps, or 0.2 cps. During a core reload, the first two fuel assemblies loaded contain secondary neutron sources to ensure this minimum detector count rate criterion is met. Some plants are investigating the possibility of altering their existing secondary neutron source loading strategy, either to accommodate different fuel assembly types in the traditional secondary source fuel assembly (SSA) locations, or as a cost reduction measure by incorporating fewer secondary source rods.

A Westinghouse four-loop plant investigated relocating SSAs from their traditional locations. Relocating SSAs could cause multiple issues during the core loading process,

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one of which is that the excore detector count rate may not meet the minimum count rate requirement. The secondary source under consideration is an antimony-beryllium (Sb-Be) source. Before being used as secondary source, the Sb-Be is "charged" during the previous cycle. The antimony becomes activated, producing Sb-124, which decays via gamma emission. Those gammas produce photoneutrons in Be-9. The purpose of this evaluation is to determine the excore detector count rate for the new proposed SSA locations. The predicted excore detector count rates will inform the decision about where to relocate the SSAs. The source range detector minimum count rate criterion for this plant is 0.2 cps, based on the plant's UFSAR and the lower range of the detector used (Gamma-metrics fission chamber), which is 0.1 cps.

2 Determining Source Range Detector Count Rate

The MCNP three-dimensional Monte Carlo transport code [2] is used to perform the neutron detector response calculations assessing the source range detector count rates for different core loading configurations. MCNP is a general-purpose, continuous-energy, generalized geometry, time-dependent, coupled neutron-photon-electron, Monte Carlo transport code system. MCNP treats an arbitrary three-dimensional configuration of materials in geometric cells bounded by first- and second-degree surfaces and some special fourth-degree surfaces. Point-wise continuous-energy cross section data are used. For neutrons, all reactions in a particular cross section evaluation are accounted for. The MCNP calculations were run using fixed source to a statistical error of approximately 7% on thermal flux and 5% on fast flux. Due to the proximity of the source to the detectors, no variance reduction techniques were required.

The analysis consists of two phases: benchmarking to measurement data, and analyzing proposed reloading configurations

The benchmarking phase is important because detector response cannot be accurately predicted computationally. Benchmarking is performed by modeling a previously operated cycle (Cycle N) and comparing the calculated detector count rates to the measured detector count rates. This comparison results in an adjustment factor that is then used when analyzing the proposed reloading configurations.

The overall core layout is shown in Figure 1. Source range detector N31 is located at 180°, nearest Row 1, and source range detector N32 is located at 0°, nearest Row 15.

To correlate the energy-dependent neutron flux calculated by MCNP to a detector count rate, it is necessary to know the energy-dependent detector response. According to the detector manual, the expected response is:

Thermal: 4 cps/nv
Fast: 2 cps/nv

No uncertainty is listed in the detector manual. The thermal energy range is defined as E < 0.5 eV, while the fast energy range is defined as E > 0.5 eV by convention. The term *nv* is a flux shorthand unit meaning 1 n/cm^{2}s produced by multiplying the neutron density *n* (n/cm^3) with neutron velocity *v* (cm/s).

2.1 Benchmarking

The first step of the analysis is to model Cycle N, and benchmark the measured source range detector count rate to the calculated detector count rate. It was not deemed necessary to model the entire loading sequence. Modeling the first nine loading steps validates the ability of the calculational model to calculate the effect of fuel assemblies without secondary sources loaded around SSAs and, most importantly, yields a detector-specific adjustment factor for each source range detector (N31 and N32) when SSAs are loaded in the core periphery.

Fuel-assembly-specific isotopic content was modeled on a quarter-assembly basis. An overview of the MCNP model after the first nine loading steps (i.e., loading the first nine assemblies) is shown in Figure 2.

The calculated detector count rate for each of the nine loading steps is provided in Table 1 for source range detector N31 and in Table 2 for source range detector N32. Applying the detector responses to the calculated thermal and fast neutron flux at the detector yields the calculated detector count rate. Comparing this calculated count rate to the measured count rate yields the detector-specific adjustment factor. The measured, calculated, and adjusted count rates at each assembly loading step for each source range detector is shown in Figure 3. This adjustment factor varies significantly based on the performance of the individual detector. The calculated initial response for each detector is ~10 cps; however, detector N31 registers an initial count rate less than half that of detector N32 (3.1 cps vs 7.7 cps). This variation in performance of the same detector model is not unusual across the fleet and can be accounted for using the detector-specific adjustment factor.

The count rate of source range detector N31 does not change after the initial loading step, because no more assemblies are loaded in the vicinity of that detector during Steps 2 through 9. There is no reported count rate for source range detector N32 for Step 1, because there are no assemblies loaded in the vicinity of that detector during Step 1. The calculated adjustment factor for source range detector N32 remains consistent as more assemblies are loaded. The adjustment factors calculated would not remain applicable if the secondary source were relocated to a location in the interior of the core.

Measured initial count rate of source range detector N31 for Cycles N-6 through Cycle N is provided in Table 3. These count rates were used to determine an additional correction factor to account for cycle-to-cycle variability in detector response. Cycles N-6 through Cycle N are equilibrium fuel cycles; i.e., each cycle follows the same loading pattern, and the first fuel assemblies loaded have enrichment and burnup characteristics such that the expected count rate on the detector(s) after the first and second step would be essentially the same (see the calculated response for detector N31 for Step 1 and for detector N32 for Step 2, which differ by <1%). The variability in detector response across cycles in Table 3 is attributed to the detectors themselves rather than to variation in neutrons reaching the detectors. The standard deviation of these count rates is found to be 22.9%. Therefore, a 1-σ correction of 0.77 will be applied to the predicted count rates to account for cycle-to-cycle variability in detector response.

2.2 Proposed Reloading Configuration

The proposed reloading scheme differs from the current reloading scheme in two key ways:

1. The SSAs will contain either two secondary source rods or four secondary source rods each (as opposed to six secondary source rods typically used).
2. The SSAs will initially be loaded into core location E15 or G15 (or an equivalent to E15 or G15), as opposed to K1.

As with the benchmark, fuel-assembly-specific isotopic content was modeled on a quarter-assembly basis. The isotopics for the proposed reloading scheme are modeled considering a 30-day and 120-day outage, and considering a low peripheral burnup range ("SW" for short window) and a high peripheral burnup range ("LW" for long window). The outage length primarily impacts the secondary source strength due to decay of Sb-124, which has a half-life of 60.2 days. The burnup range impacts the isotopics of the fuel assemblies - higher burnup leads to more fission product poisons in the fuel and less reactivity for each assembly, though this is a minor impact compared to the secondary source strength and variation in detector response. Secondary source strength is considered an input to this evaluation; it was calculated using ANC 8.11.10 and PARAGON 1.4.0.

The calculated detector count rate for each of the proposed loading configurations is provided in Table 4 for secondary sources with a 120-day outage and in Table 5 for secondary sources with a 30-day outage. In these tables, the thermal and fast neutron flux at the source range detector is provided. Applying the energy-dependent detector responses yields the calculated count rate. The detector-specific adjustment factor from Tables 1 and 2 is then applied to each detector (N31 and N32), along with the detector response variability 1-σ correction factor shown in Table 3. In addition, a factor of 0.75 is applied due to the uncertainty of the methodology; this factor has no formal basis but represents a source of conservatism given the small analytical uncertainties in the MCNP calculations and the other adjustment factors applied. The result is the predicted count rate for each detector under each proposed loading configuration. In cases where this predicted count rate is less than the 0.2 cps criterion, the predicted count rate is shown in red text and italics.

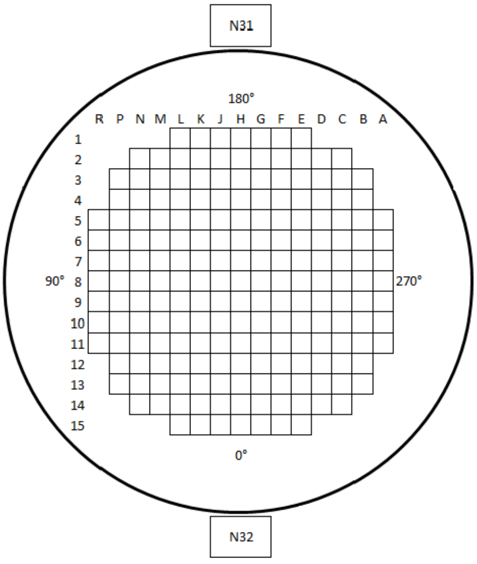

Fig. 1. Core layout with source range detectors.

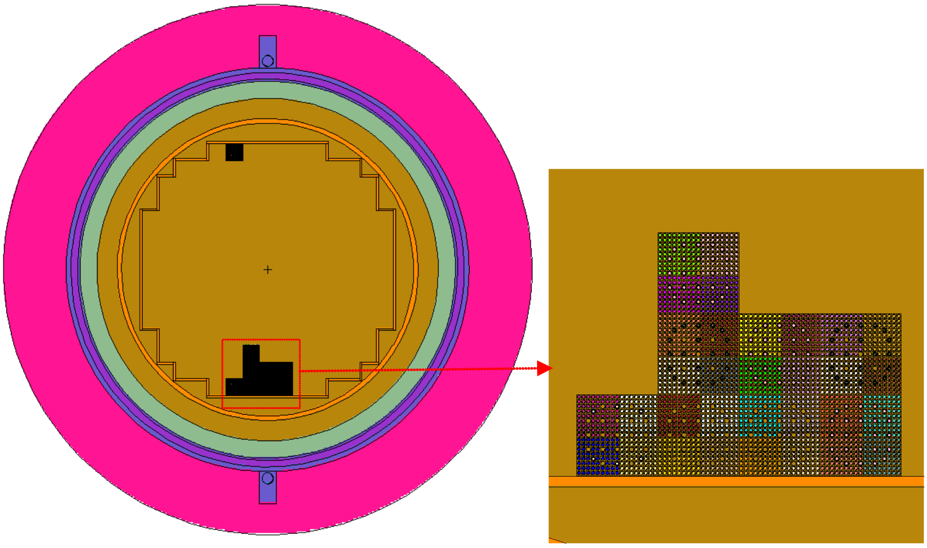

Fig. 2. MCNP Model of Cycle N after Loading Step 9, Overview (left) and Closeup of Eight Assemblies near Source Range Detector N32 (right).

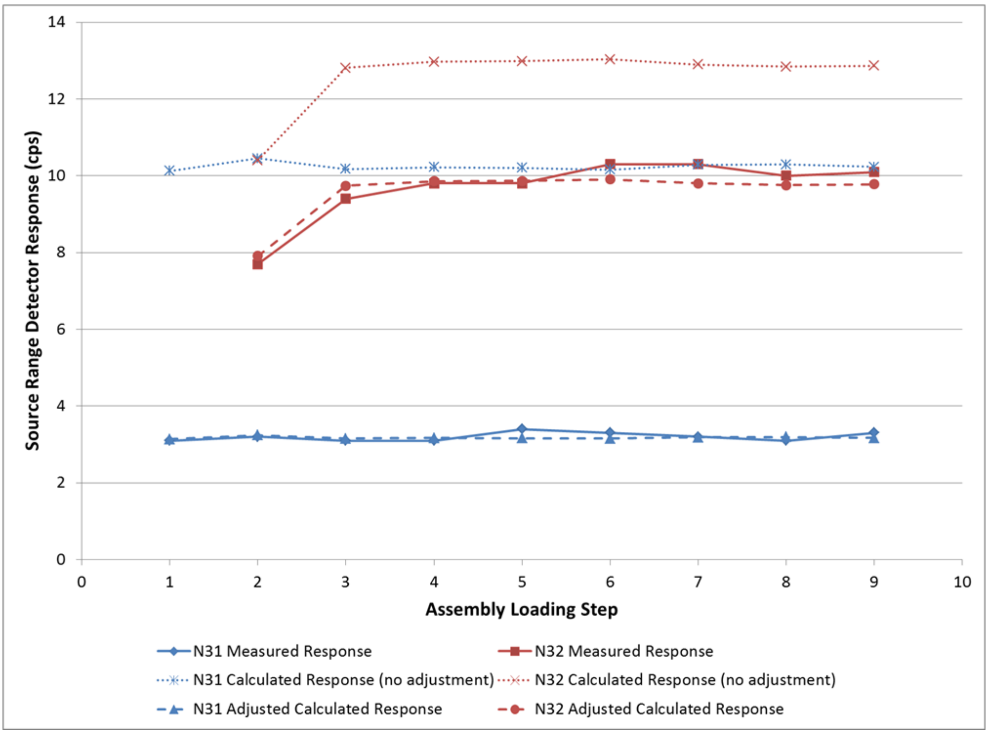

Fig. 3. Source Range Detectors (N31 and N32) Responses during Core Loading.

Table 1. Source Range Detector N31 Calculated and Measured Response during Cycle N Loading.

Parameter	Loading Step (Location)								
	1 (K1)	**2 (K15)**	**3 (J15)**	**4 (H15)**	**5 (G15)**	**6 (J14)**	**7 (H14)**	**8 (G14)**	**9 (J13)**
Thermal neutron flux at detector [n/cm^{2}s]	1.03	1.14	1.12	1.12	1.12	1.11	1.13	1.13	1.12
Fast neutron flux at detector [n/cm^{2}s]	3.01	2.95	2.86	2.87	2.86	2.86	2.89	2.89	2.88
Calculated Detector Response [cps]	10.12	10.45	10.18	10.22	10.20	10.16	10.28	10.29	10.23
Measured Detector Response [cps]	3.1	3.2	3.1	3.1	3.4	3.3	3.2	3.1	3.3
Adjustment factor (Measured / Calculated)	0.31	0.31	0.30	0.30	0.33	0.32	0.31	0.30	0.32
Average adjustment factor (Measured / Calculated)	0.31								

Table 2. Source Range Detector N32 Calculated and Measured Response during Cycle N Loading.

Parameter	Loading Step (Location)								
	1 (K1)	**2 (K15)**	**3 (J15)**	**4 (H15)**	**5 (G15)**	**6 (J14)**	**7 (H14)**	**8 (G14)**	**9 (J13)**
Thermal neutron flux at detector [n/cm^{2}s]	-	1.17	1.37	1.38	1.39	1.41	1.36	1.36	1.34
Fast neutron flux at detector [n/cm^{2}s]	-	2.87	3.66	3.73	3.72	3.69	3.72	3.70	3.76
Calculated Detector Response [cps]	-	10.41	12.81	12.97	12.98	13.03	12.90	12.84	12.87
Measured Detector Response [cps]	-	7.7	9.4	9.8	9.8	10.3	10.3	10.0	10.1
Adjustment factor (Measured / Calculated)	-	0.74	0.73	0.76	0.75	0.79	0.80	0.78	0.78
Average adjustment factor (Measured / Calculated)	0.76								

Table 3. Source Range Detector N31 Initial Response across Cycles.

Cycle	Response (cps)	Cycle	Response (cps)	Cycle	Response (cps)
N-6	3.4	N-3	4.4	N-1	4.9
N-5	4.7	N-2	5.6	N	2.8
N-4	3.7				
Average	4.2 (Std Dev 22.9 %)				

3 Results and Conclusions

Several potential SSA loading configurations were evaluated to determine the count rate of source range detectors N31 and N32. One of the variables considered when evaluating the proposed loading configurations was the peripheral burnup range, either high (LW) or low (SW). The variation in peripheral burnup affects the fuel assembly isotopics and has a minimal impact on predicted detector response. The predicted source range detector count rates with LW burnups are slightly lower than those with SW burnups due to the decreased reactivity of the fuel assemblies, consistent with expectations. As the fuel is burned, active fuel is depleted and fission product poisons are produced, reducing reactivity of the assembly. Therefore, assemblies with lower burnup (SW) would be expected to produce more neutrons in the presence of a secondary source, and cause a stronger detector response, than assemblies with higher burnup (LW). Outage time has a far bigger impact on predicted source range detector response. Predicted source range detector count rate for a given SSA configuration is a factor of 2.8 higher for a 30-day outage than for a 120-day outage.

All the proposed SSA configurations meet the 0.2 cps criterion when assuming a 30-day outage. However, assuming the more conservative 120-day outage, neither of the 2-secondary-source-rod SSA configurations (Location E15 and G15) meets the 0.2 cps criterion for both detectors. With the 120-day outage, of the 4-secondary-source-rod SSA configurations only Location G15 meets the 0.2 cps criterion for both detectors. For this reason, of the options presented, the design configuration of a 4-secondary-source-rod SSA at location G15 is the preferred option from a detector functionality standpoint.

The approach outlined in this paper can be used to analyze SSA configurations in a plant- and detector-specific manner. By incorporating available measured source range detector responses from a specific plant, it is possible to alter the existing secondary neutron source loading strategy, either to accommodate different fuel assembly types in the traditional secondary source fuel assembly locations, or as a cost reduction measure by incorporating fewer secondary source rods. This approach can be extended to cases with no secondary source rods. By incorporating available plant-specific source range detector responses, the need for secondary source rods can be evaluated based on the specific plant's expected outage duration.

Table 4. Predicted Source Range Detector Response with 120-day Outage for Proposed Reloading Configuration.

Peripheral burnup range	**LW**				**SW**			
Secondary source rods per SSA	**2**		**4**		**2**		**4**	
SSA Location	**E15**	**G15**	**E15**	**G15**	**E15**	**G15**	**E15**	**G15**
Thermal neutron flux at detector [n/cm^{2}s]	0.060	0.068	0.112	0.128	0.068	0.081	0.124	0.122
Fast neutron flux at detector [n/cm^{2}s]	0.135	0.247	0.240	0.394	0.148	0.270	0.254	0.414
Calculated Detector Response [cps]	0.51	0.77	0.93	1.30	0.57	0.86	1.00	1.32
Detector N31 Adjustment Factor	0.31							
Detector N32 Adjustment Factor	0.76							
Response Variation Factor (N31 & N32)	0.77							
Predicted N31 Detector Response [cps]	*0.09*	*0.14*	*0.17*	0.23	*0.10*	*0.15*	*0.18*	0.24
Predicted N32 Detector Response [cps]	0.22	0.34	0.41	0.57	0.25	0.38	0.44	0.58

Table 5. Predicted Source Range Detector Response with 30-day Outage for Proposed Reloading Configuration.

Peripheral burnup range	**LW**				**SW**			
Secondary source rods per SSA	**2**		**4**		**2**		**4**	
SSA Location	**E15**	**G15**	**E15**	**G15**	**E15**	**G15**	**E15**	**G15**
Thermal neutron flux at detector [n/cm^{2}s]	0.168	0.190	0.315	0.361	0.195	0.228	0.348	0.352
Fast neutron flux at detector [n/cm^{2}s]	0.383	0.700	0.662	1.107	0.415	0.759	0.720	1.166
Calculated Detector Response [cps]	1.44	2.16	2.59	3.66	1.61	2.43	2.83	3.74
Detector N31 Adjustment Factor	0.31							
Detector N32 Adjustment Factor	0.76							
Response Variation Factor (N31 & N32)	0.77							
Predicted N31 Detector Response [cps]	0.26	0.39	0.46	0.66	0.29	0.43	0.51	0.67
Predicted N32 Detector Response [cps]	0.63	0.95	1.14	1.61	0.71	1.07	1.24	1.64

References

1. Regulatory Guide 1.68, Revision 4, *Initial Test Programs for Water-Cooled Nuclear Power Plants*, U. S. Nuclear Regulatory Commission, June 2013
2. RSICC Code Package CCC-740, *MCNP5/MCNPX: Monte Carlo N–Particle Transport Code System Including MCNP5-1.60 and MCNPX-2.7.0 and Data Libraries*, Los Alamos National Laboratory, June 2011