Comparison of Detector Signals for the Homogenization of a Self-Powered Neutron Detector Using STREAM and MCS

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1. Introduction

Self-Powered Neutron Detectors (SPNDs) are widely used to monitor power distribution within a reactor core. Among the various SPND emitters, Rh-based SPNDs are commonly employed due to their strong signal generation via the (n, β) reaction, which produces a large number of electrons [1]. However, the delayed response caused by the 42-second half-life of Rh-104 poses a limitation for real-time power monitoring. In contrast, Co-based SPNDs operate through the (n, γ, e) reaction, which minimizes response delay. This makes them a suitable alternative for applications that require rapid power distribution measurements [1].

South Korea is currently developing the innovative Small Modular Reactor (i-SMR), which differs from traditional reactors by eliminating the use of boric acid for reactivity control. Instead, i-SMR core relies on burnable poisons, such as enriched gadolinia, and control rods to regulate reactivity [2]. Moreover, i-SMR core is designed to support load-following operations, necessitating precise monitoring of power distribution changes. As control rods are inserted from the top to the bottom of the core, the power distribution shifts toward the lower regions. To ensure real-time core safety assessment under these dynamic conditions, the use of Co-based SPNDs is being considered due to their rapid response characteristics.

Monte Carlo-based codes have been employed to calculate SPND signals [3]. While these codes offer high accuracy, they require extensive computation time and a significant number of neutron histories to obtain reliable results in the relatively small SPND region compared to the entire reactor core. To address these challenges, this study utilizes a homogenized SPND model with STREAM, a neutron transport analysis code developed at Ulsan National Institute of Science and Technology (UNIST) [4]. The SPND signals calculated by STREAM are then compared with results obtained from MCS, a Monte Carlo-based code also developed at UNIST [5]. This approach aims to improve computational efficiency while maintaining accuracy in SPND signal prediction.

2. Modeling

In this section, the actual SPND model, the homogenized SPND model, and the fuel assembly model with an inserted SPND are described.

2.1 Actual SPND Model

Fig. 1 shows the configuration of the In-Core Instrument (ICI) on the left and the SPND on the right. Additionally, Table I presents the geometric structure of the SPND.

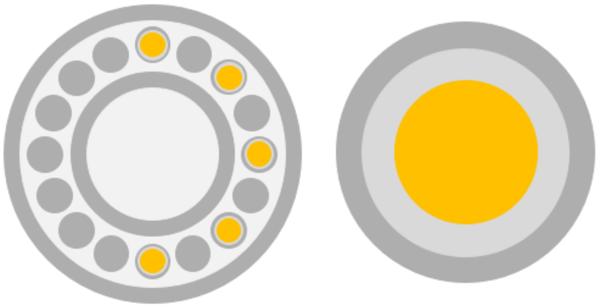

Fig. 1. Configuration of ICI (left) and SPND (right)

Table I: Geometric structure of SPND

Region Number	Part of SPND	Material
1	Emitter	Rh or Co
2	Insulator	Al_2O_3
3	Collector	INC600

As shown in Fig. 1 and Table I, the SPND consists of three main components: an emitter, an insulator, and a collector. The emitter plays a crucial role in neutron detection by interacting with incoming neutrons through (n, β), (n, γ, e), or (γ, e) reactions that generate electrons. These electrons are then transmitted through the insulator. The insulator serves to electrically isolate the emitter from the collector, preventing any unintended interference. Finally, the collector receives the generated electrons and transmits the signal for further processing and measurement, enabling accurate neutron flux monitoring.

2.2 Homogenized SPND Model

A lattice physics code, such as STREAM, can generally model only concentric structures. This makes it difficult to simulate the actual SPND model, which has a non-concentric structure. To address this issue, a homogenized SPND models with a concentric structure are constructed, as shown in Fig. 2.

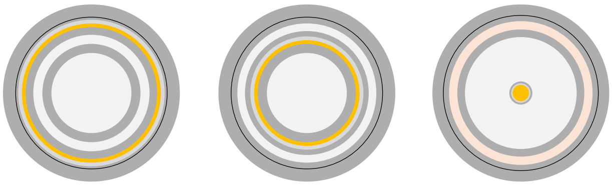

Fig. 2. Homogenized SPND models

The SV_OUT model and SV_IN model convert the emitter, insulator, and collector regions of the SPND into a concentric structure while preserving their original volumes. The CEN model places a single SPND at the center while homogenizing the remaining four SPNDs with other materials at their original locations.

2.3 Fuel Assembly Model with an Inserted SPND

Fig. 3 shows the fuel assembly used for the detector signal calculation. The fuel enrichment of the normal fuel pin and the zoned fuel pin are 3.64 wt.% and 3.14 wt.%, respectively. The gadolinia content in the gadolinia pin is 8.0 wt.%, and the fuel enrichment is 2.0 wt.%. At the center of the fuel assembly, there is a single instrument tube, into which the ICI is inserted.

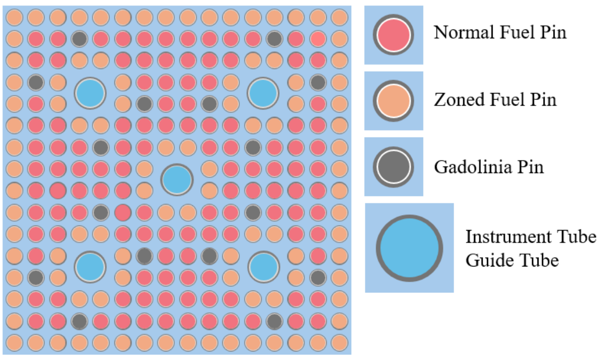

Fig. 3. Fuel assembly model with an inserted SPND

3. Results

In this section, the calculation method for the detector signal is briefly explained [3]. Additionally, the detector signal results obtained using MCS-MCNP for the actual SPND model and the homogenized SPND models are compared to identify an appropriate homogenized SPND model. Finally, the detector signal results calculated using STREAM-MCNP and MCS-MCNP for the selected homogenized SPND model are compared.

3.1 Detector Signal Calculation Method

Among the various types of nuclear reactor core analysis codes, only a few can simulate electron transport. In this study, MCNP, developed by Los Alamos National Laboratory in the United States, is used to model and analyze electron transport [6]. Performing core simulations and detector signal calculations using MCNP requires a significant amount of computational time. Therefore, core analysis is first conducted using MCS or STREAM. From this analysis, the neutron flux spectrum, photon flux spectrum, and absorption reaction rate in the emitter region are tallied and provided to MCNP. MCNP then analyzes only the ICI or SPND and performs the electron transport calculation.

3.2 Searching for an Appropriate Homogenized SPND Model using MCS-MCNP

Table II presents the k_{inf} calculated using MCS when each of the various SPND models containing a Co emitter is inserted into the instrument tube.

Table II: k_{inf} of a fuel assembly with an inserted SPND containing a Co emitter using MCS

Model	k_{inf} (Std. Dev. [pcm])	Diff. [pcm]
Actual (Ref)	1.10867 (1)	
SV_OUT	1.10858 (2)	-9
SV_IN	1.10860 (1)	-7
CEN	1.10860 (2)	-7

As shown in Table II, the k_{inf} difference for all homogenized SPND models is less than 10 pcm.

Fig. 4 and Table III present the detector signals calculated using each homogenized SPND model containing a Co emitter.

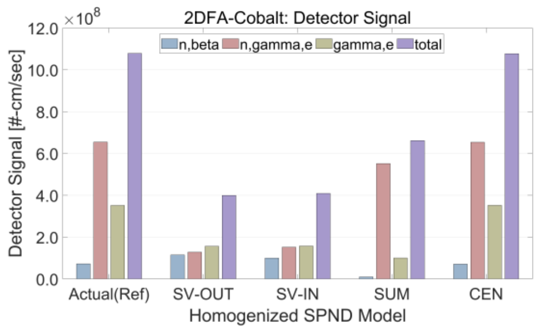

Fig. 4. Detector signals of a fuel assembly with an inserted SPND containing a Co emitter using MCS-MCNP

As shown in Fig. 4 and Table III, when the CEN model is used, the detector signal closely resembles that of the actual SPND model.

Table IV presents the k_{inf} calculated using MCS when each of the various SPND models containing a Rh emitter is inserted into the instrument tube.

Table IV: k_{inf} of a fuel assembly with an inserted SPND containing a Rh emitter using MCS

Model	k_{inf} (Std. Dev. [pcm])	Diff. [pcm]
Actual (Ref)	1.10714 (2)	
SV_OUT	1.10631 (1)	-83
SV_IN	1.10655 (2)	-59
CEN	1.10637 (2)	-77

As shown in Table IV, the k_{inf} difference for all homogenized SPND models is less than 100 pcm. This difference is based on the results from a single fuel assembly. In a real reactor core, since ICIs are not inserted into all fuel assemblies, the difference would likely be smaller.

Fig. 5 and Table V show the detector signals calculated using each homogenized SPND model containing a Rh emitter.

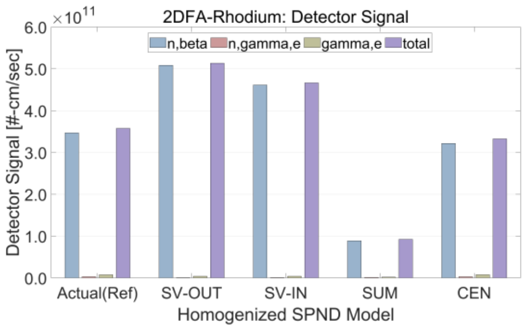

Fig. 5. Detector signals of a fuel assembly with an inserted SPND containing a Rh emitter using MCS-MCNP

As shown in Fig. 5 and Table V, when the CEN model is used, the detector signal closely resembles that of the actual SPND model.

In conclusion, the detector signal calculated using MCS-MCNP for the actual SPND model and the CEN SPND model shows a 0.16% difference for the Co emitter and a 6.99% difference for the Rh emitter. Finally, it is necessary to analyze the CEN SPND model using STREAM-MCNP.

3.3 Comparison of STREAM-MCNP and MCS-MCNP Calculation Results for a Homogenized SPND Model

Table VI and Table VII show the k_{inf} calculated using MCS and STREAM for the fuel assembly with the CEN model containing the Co emitter and the Rh emitter, respectively.

Table VI: k_{inf} of a fuel assembly with an inserted SPND (CEN model) containing a Co emitter

Model	k_{inf} (Std. Dev. [pcm]_	Diff. [pcm]
MCS	1.10860 (2)	-
STREAM	1.10903	43

Table VII: k_{inf} of a fuel assembly with an inserted SPND (CEN model) containing a Rh emitter

Model	k_{inf} (Std. Dev. [pcm]_	Diff. [pcm]
MCS	1.10637 (2)	-
STREAM	1.10693	56

As previously explained, the neutron flux spectrum, photon flux spectrum, and absorption reaction rate in the emitter region should be calculated using MCS or STREAM and then provided to MCNP.

Fig. 6 - Fig. 8 show the comparison results of the neutron flux spectrum, photon flux spectrum, and absorption reaction rate in the emitter region, respectively, for the CEN model containing the Co emitter, calculated using MCS and STREAM.

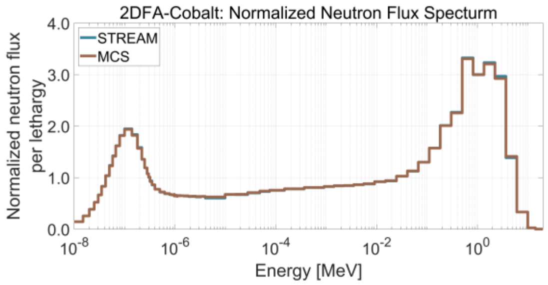

Fig. 6. Neutron flux spectrum of a fuel assembly with an inserted SPND (CEN model) containing a Co emitter

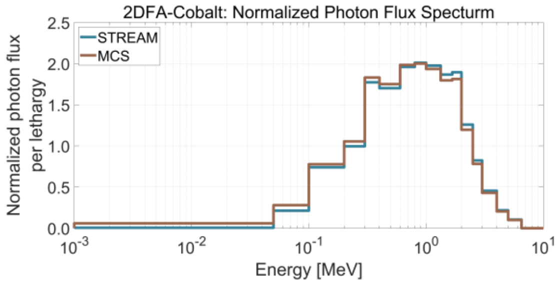

Fig. 7. Photon flux spectrum of a fuel assembly with an inserted SPND (CEN model) containing a Co emitter

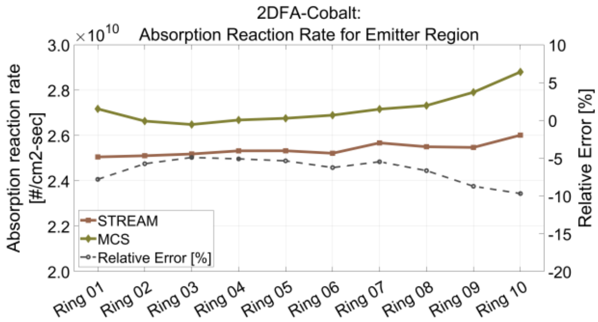

Fig. 8. Absorption reaction rate in the emitter region of a fuel assembly with an inserted SPND (CEN model) containing a Co emitter

As shown in Fig. 8, the absorption reaction rate in the Co emitter region calculated using MCS and STREAM exhibits a relative error of approximately -10 to -5%. Consequently, as seen in Table VIII, the (n, β) reaction signal calculated using MCS-MCNP and STREAM-MCNP shows a difference of about -6.97%. As presented in Table VIII, the total detector signal for the SPND containing the Co emitter, calculated using MCS-MCNP and STREAM-MCNP, shows a difference of approximately 0.06%.

Fig. 9 - Fig. 11 show the comparison results of the neutron flux spectrum, photon flux spectrum, and absorption reaction rate in the emitter region, respectively, for the CEN model containing the Rh emitter, calculated using MCS and STREAM.

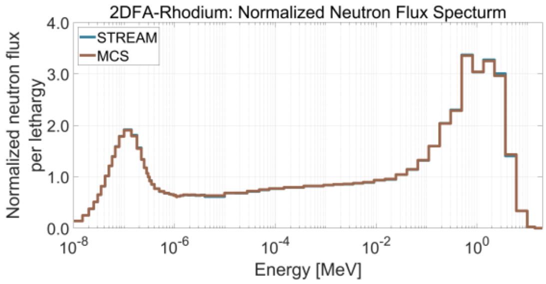

Fig. 9. Neutron flux spectrum of a fuel assembly with an inserted SPND (CEN model) containing a Rh emitter

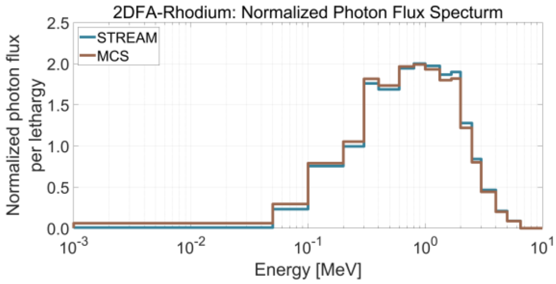

Fig. 10. Photon flux spectrum of a fuel assembly with an inserted SPND (CEN model) containing a Rh emitter

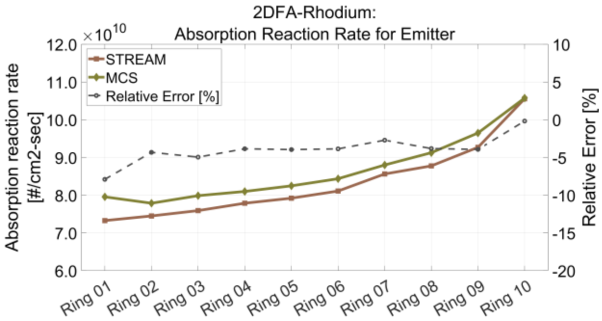

Fig. 11. Absorption reaction rate in the emitter region of a fuel assembly with an inserted SPND (CEN model) containing a Rh emitter

As shown in Fig. 11, the absorption reaction rate in the Rh emitter region calculated using MCS and STREAM exhibits a relative error of approximately -7% to 0%. Notably, as the absorption reaction rate increases (i.e., as the ring number increases), the relative error decreases. Consequently, as presented in Table IX, the (n, β) reaction signal calculated using MCS-MCNP and STREAM-MCNP shows a difference of about 3.35%. Finally, for the SPND containing the Rh emitter, the total detector signal calculated using MCS-MCNP and STREAM-MCNP shows a difference of approximately 3.20%.

4. Conclusions

This study investigates a method to replace the calculation of detector signals, previously obtained using a Monte Carlo-based core analysis code, with a neutron transport analysis code. Since neutron transport analysis codes such as STREAM generally model only concentric structures, this study explores a properly homogenized model that represents the non-concentric structures of ICI and SPND as concentric ones. Among the three homogenized SPND models examined (SV_OUT, SV_IN, and CEN), the CEN model demonstrated the highest accuracy in reproducing the detector signals obtained from the actual SPND model. The k_{inf} differences between the CEN model and the actual model were within an acceptable range for both Co-based and Rh-based SPNDs. Furthermore, the detector signals calculated using MCS-MCNP and STREAM-MCNP for the CEN model differed by 0.06% for Co emitters and 3.20% for Rh emitters. These results indicate that STREAM can be a viable alternative for SPND signal calculations.

Future work will involve comparing the detector signal results calculated using MCS-MCNP and STREAM-MCNP for the whole core, as well as analyzing the detector signal behavior over burnup simulations.

Acknowledgments

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Table III: Detector signals of a fuel assembly with an inserted SPND containing a Co emitter using MCS-MCNP

Model		(n, β)	(n, γ, e)	(γ, e)	total
Acutal (Reference)	electrons [#/s]	7.25113E+07	6.54655E+08	3.51694E+08	1.07886E+09
	rate [%]	6.72	60.68	32.60	-
SV_OUT	electrons [#/s]	1.15024E+08	1.28263E+08	1.56372E+08	3.37072E+09
	rate [%]	28.78	32.09	39.13	-
	diff. with ref [%]	58.63	-80.41	-55.54	212.43
SV_IN	electrons [#/s]	9.98695E+07	1.52078E+08	1.57310E+08	3.39816E+09
	rate [%]	24.40	37.16	38.44	-
	diff. with ref [%]	37.73	-76.77	-55.27	214.98
CEN	electrons [#/s]	7.11453E+07	6.53853E+08	3.52125E+08	1.07712E+09
	rate [%]	6.61	60.70	32.69	-
	diff. with ref [%]	-1.88	-0.12	0.12	-0.16

Table V: Detector signals of a fuel assembly with an inserted SPND containing a Rh emitter using MCS-MCNP

Model		(n, β)	(n, γ, e)	(γ, e)	total
Acutal (Reference)	electrons [#/s]	3.46912E+11	3.01632E+09	7.71438E+09	3.57642E+11
	rate [%]	97.00	0.84	2.16	-
SV_OUT	electrons [#/s]	5.08457E+11	8.52560E+08	4.14859E+09	5.13459E+11
	rate [%]	99.03	0.17	0.81	-
	diff. with ref [%]	46.57	-71.74	-46.22	43.57
SV_IN	electrons [#/s]	4.61438E+11	9.44074E+08	4.03167E+09	4.66414E+11
	rate [%]	98.93	0.20	0.86	-
	diff. with ref [%]	33.01	-68.70	-47.74	30.41
CEN	electrons [#/s]	3.21801E+11	3.06604E+09	7.78136E+09	3.32649E+11
	rate [%]	96.74	0.92	2.34	-
	diff. with ref [%]	-7.24	1.65	0.87	-6.99

Table VIII: Detector signals of a fuel assembly with an inserted SPND (CEN model) containing a Co emitter

Model		(n, β)	(n, γ, e)	(γ, e)	total
MCS-MCNP	electrons [#/s]	7.11453E+07	6.53853E+08	3.52125E+08	1.07712E+09
	rate [%]	6.61	60.70	32.69	-
STREAM-MCNP	electrons [#/s]	6.61842E+07	6.47335E+08	3.64293E+08	1.07781E+09
	rate [%]	6.14	60.06	33.80	-
	diff. with ref [%]	-6.97	-1.00	3.46	0.06

Table IX: Detector signals of a fuel assembly with an inserted SPND (CEN model) containing a Rh emitter

Model		(n, β)	(n, γ, e)	(γ, e)	total
MCS-MCNP	electrons [#/s]	3.21801E+11	3.06604E+09	7.78136E+09	3.32649E+11
	rate [%]	96.74	0.92	2.34	-
STREAM-MCNP	electrons [#/s]	3.11015E+11	2.95201E+09	8.04038E+09	3.22008E+11
	rate [%]	96.59	0.92	2.50	-
	diff. with ref [%]	-3.35	-3.72	3.33	-3.20