Nuclear Characteristics of SPNDs and Preliminary Calculation of Hybrid Fixed Incore Detector with Monte Carlo Code

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1. Introduction

Recently, an innovative In-Core Instrumentation (ICI) system has been suggested (and developed) to expand the applicability of conventional Self-Powered Neutron Detectors (SPND). By introducing a hybrid fixed in-core detector composed of a neutron sensitive emitter and a number of gamma sensitive emitters, core protection and monitoring are possible. Gamma sensitive materials generate prompt signals without a time-delay and a neutron sensitive emitter is used to calibrate the prompt signals.

In this paper, the basic nuclear characteristics of major emitter materials were surveyed. In addition, preliminary calculations of Cobalt-Vanadium fixed incore detector were performed using the Monte Carlo code[1]. Calculational results were cross-checked by KARMA[2]. KARMA is a two-dimensional multi-group transport theory code developed by the KAERI and approved by Korean regularity agency to be employed as a nuclear design tool for a Korean commercial pressurizer water reactor.

2. Methods and Results

2.1 Nuclear Characteristics of SPNDs

The SPND consists of three main parts, i.e., an emitter, insulator, and a collector, arranged in a coaxial geometry. During operation, there is a thermal neutron interaction with the emitter, which results in the emission of high-energy electrons generating a current directly proportional to the neutron flux. For power reactor applications, the typical emitter materials used in SPNDs include Rhodium, Vanadium, Cobalt, and Platinum. Table 1 shows an overview of some of the important characteristics of SPND emitters used in power reactor application.

Rhodium (^{103}Rh) has a (n,β) interaction with a 146 barn cross-section(XS) for thermal neutrons and a resonance at 1.25eV. The burnup rate is 0.39% per month in a thermal neutron flux of 10^{13} $n/cm^2\text{-}sec$. An SPND with a rhodium emitter has a relatively high sensitivity, high burnup rate, perturbs the local power density, and has a (two-fold) delayed signal.

Vanadium (^{51}V) has a (n,β) interaction with a thermal neutron XS of 4.9 barns featuring a *1/v* characteristic without resonances in the energy of thermal/epithermal neutrons. The burnup rate is 0.012%/month in at thermal neutron flux of 10^{13} $n/cm^2\text{-}sec$. Ninety-nine percent of the signal has a half-life of 3.76 minutes, and 1% of the signal is prompt. A vanadium SPND emitter has a relatively low sensitivity, low burnup rate, and minimal perturbation of the local power density, but has a very long delayed signal.

Cobalt (^{59}Co) has a (n,γ) interaction with a 37 barn thermal neutron XS and a parallel gamma-photon reaction. The signal is prompt, but requires long term compensation owing to a build-up of radioactive isotopes ^{60}Co and ^{61}Co. The cobalt emitter has a relatively low sensitivity, moderate burn-up rate, and a prompt signal.

Platinum (^{195}Pt) has a (n, γ) interaction with a 24 barn thermal neutron XS and a parallel gamma-photon reaction. A platinum emitter is sensitive to both gamma and neutron. A platinum emitter has a relatively low sensitivity, low burn-up rate and a prompt signal.

The characteristics of self-powered detectors most commonly used in nuclear power plants are summarized in Table 2.

Table 1. SPND emitter materials characteristics

Emitter	Delayed (n, β)	Prompt (n, γ,e)	Prompt (γ,e)	Applications
^{59}Co	S	P	S	LWR Flux mapping LWR control Local core protection
^{195}Pt	S	P	P	LWR control HWR control
^{103}Rh	P	-	-	LWR flux mapping
^{51}V	P	P	S	HWR flux mapping LWR flux mapping

a) P : Primary interaction, S : Secondary interaction

Table 2. Nuclear characteristics of selected emitter materials

Emitter	Stable isotope	Compo. (%)	XS (barns)	Result nuclide	Half-life
^{59}Co	^{59}Co	100	37	^{60}Co	5.27 yr
^{195}Pt	^{192}Pt	0.78	14	^{193m}Pt	4.3 day
	^{194}Pt	32.90	2	^{195m} Pt	4.1 day
	^{195}Pt	33.80	24	^{196}Pt	stable
	^{196}Pt	25.30	1	^{197m} Pt	1.3 hr
	^{198}Pt	7.22	4	^{199}Pt	30.8 min
^{103}Rh	^{103}Rh	100	11(8%)	^{104m} Rh	4.4 min
			135(92%)	^{104}Rh	42 sec
^{50}V	^{50}V	0.24	100	^{51}V	stable
	^{51}V	99.76	4.9	^{52}V	3.76 min

2.2 Hybrid ICI System

An innovative ICI system has recently been developed to enhance (or expand) the applicability of conventional incore detectors, not only a control function but *also* protection capability[3].

The core power surveillance of Siemens PWRs combines two complementary in-core instrumentation systems, i.e., an Aeroball system and a Power Density Detector (PDD) system. The Aeroball system is a movable flux mapping system and the PDD system continuously monitors the core using fixed in-core prompt responding detectors. A SENTINEL protection system was realized by introducing a hybrid fixed in-core detector composed of a neutron sensitive vanadium emitter and a number of gamma sensitive platinum emitters.

In Korea, the Central Research Institute of KHNP suggested the MAPSSEL system using vanadium-platinum hybrid detector[4]. Its functionality and nuclear characteristics are similar with the SENTINEL system except for the detector configuration.

2.3 Modeling of Co-V Hybrid ICI Assembly

A set of reference fuel assemblies, PLUS-7, was selected and a Co-V hybrid ICI assembly was modeled. Each fuel assembly is made up of a 16×16 array of normal UO_2 fuel rods, gadolinia-bearing UO_2 fuel rods and four guide tubes and a central instrumentation tube. Normal fuel rods are enriched with 5.0/4.5 wt% U^{235} and gadolinia-bearing fuel rods are loaded with 8.0/6.0 wt% Gd_2O_3 admixed in 0.711wt% UO_2. The four guide tubes can be filled with B_4C as a neutron absorber.

For all of the problems, the reflective boundary condition for the radial direction and infinite condition for the axial direction (i.e. zero axial buckling) are assumed. In the KARMA calculation, the default ray option was used. An ENDF/B-VII library was used in the KARMA and MCNP calculations. Figure 1 shows a modeled fuel assembly (ici-72 type) and Co-V ICI assembly composed of Cobalt, Vanadium, and background detectors.

The MCNP results were regarded as a reference solution, and the eigenvalue and pin-by-pin fission power distributions were compared. Table 3 shows eigenvalue differences between MCNP and KARMA for each calculation. The results of the two codes show good agreement within ~0.003 delta-k. Figure 2 shows the pin-by-pin fission power distributions, and the maximum difference is not greater than 0.5%.

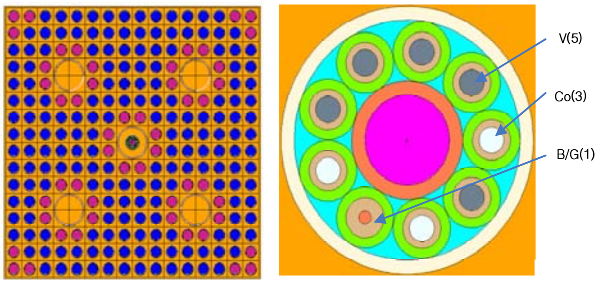
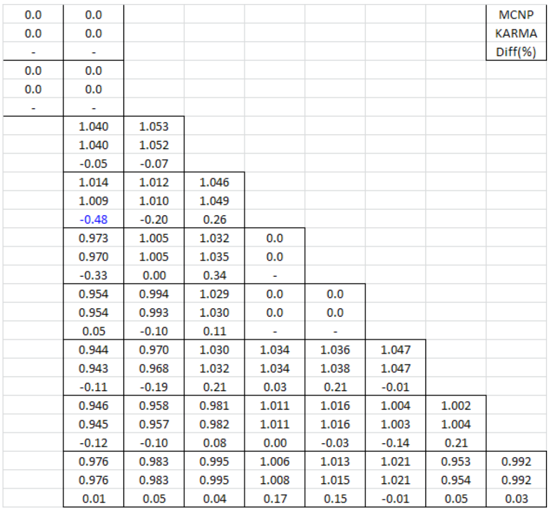


Fig. 1. Modeled 16×16 fuel assembly and Co-V hybrid ICI assembly

Table 3. k-infinitive comparison between KARMA and MCNP code for reference fuel assemblies (*ICI uninstalled*)

Case ID	KARMA	MCNP	delta_k	Description
ici-72	1.37327	1.37695	-0.00368	0-BP/0-CR
ici-90	1.26725	1.27066	-0.00341	8-BP/0-CR
ici-99	1.17872	1.18118	-0.00246	16-BP/0-CR
ici1-35	1.11578	1.11391	0.00187	0-BP/4-CR
ici1-44	1.03820	1.03608	0.00212	8-BP/4-CR

a) 8-BP : gadolinia rod (8w/o Gd_2O_3+0.711w/o U^{235})
b) 16-BP : gadolinia rod (6w/o Gd_2O_3+0.711w/o U^{235})
c) CR : B_4C control rod



0.0 0.0 -	0.0 0.0 -							MCNP KARMA Diff(%)
0.0 0.0 -	0.0 0.0 -							
	1.040 1.040 -0.05	1.053 1.052 -0.07						
	1.014 1.009 -0.48	1.012 1.010 -0.20	1.046 1.049 0.26					
	0.973 0.970 -0.33	1.005 1.005 0.00	1.032 1.035 0.34	0.0 0.0 -				
	0.954 0.954 0.05	0.994 0.993 -0.10	1.029 1.030 0.11	0.0 0.0 -	0.0 0.0 -			
	0.944 0.943 -0.11	0.970 0.968 -0.19	1.030 1.032 0.21	1.034 1.034 0.03	1.036 1.038 0.21	1.047 1.047 -0.01		
	0.946 0.945 -0.12	0.958 0.957 -0.10	0.981 0.982 0.08	1.011 1.011 0.00	1.016 1.016 -0.03	1.004 1.003 -0.14	1.002 1.004 0.21	
	0.976 0.976 0.01	0.983 0.983 0.05	0.995 0.995 0.04	1.006 1.008 0.17	1.013 1.015 0.15	1.021 1.021 -0.01	0.953 0.954 0.05	0.992 0.992 0.03

Fig. 2. Fission power difference between KARMA and MCNP code *(ici-72 type, ICI uninstalled)*

3. Conclusions and Future Work

The nuclear characteristics of the major emitter materials were surveyed, and preliminary calculations of the hybrid fixed incore detector were performed with the MCNP code. The eigenvalue and pin-by-pin fission power distributions were calculated and showed good agreement with the KARMA calculation results.

As future work, gamma power distributions as well as several types of XS of the emitter, insulator, and collector regions for a Co-V ICI assembly will be evaluated and compared.

REFERENCES

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