Application Evaluation of Vanadium Fixed-incore Detector

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1. Introduction

Reliable and accurate detection of neutron flux inside of reactor is an important part for reactor operation as well as safety protection. Incore neutron detector is major component of nuclear instrumentation. There are two types of incore detectors; movable detector and fixed incore detector. Fixed incore detector used in OPR1000 plants showed good stability and linearity[1]. The most common material used in fixed detector are listed in Table I.

TABLE 1. Materials for Fixed Incore Detector

Material	Burnup rate (%/month)	Cross section (barn)
Rh	0.39	145
V	0.012	4.9
Co	0.094	37
HfO2	0.3	115
Ag	0.16	64.8
Pt	0.03	24

Rhodium(Rh) is composed of one isotopes, Rh-103 which absorb neutrons by (n,β) reaction. Rh has the largest capture cross section among the materials shown in table above, which induces largest depletion rate. It results more radioactive wastes, higher replacement cost and higher worker's irradiation dose. Therefore, it is more favorable to develop a fixed incore detector which can operate longer period.
On the other hand vanadium(V) is selected because of its low depletion rate and easier signal processing technique. Vanadium capture neutrons by (n,β) reaction as rhodium and has two isotopes in nature; 99.75% of vanadium-51 and 0.25% of vanadium-50.

In this paper, analysis of vanadium detector will be done. First, MCNP calculation for vanadium detector is done to set up a reference. Then vanadium detector model for KARMA[2], a transport code that generates pin flux and power distribution, is verified by MCNP results. Vanadium detector analysis is done by KARMA depletion. KARMA generates cross section and heterogeneous form function file for ASTRA[3], 3-D neutron transport code using SANM. After calculating vanadium depletion by ASTRA, the results of ASTRA code are compared with those of KARMA code.

2. KARMA Model Determination

To set up a vanadium detector analysis, following reference test assemblies are adopted to MCNP modeling. PLUS7 assemblies are selected to reference. Table 2 and Figure 1 show geometries and conditions for reference calculation model.

TABLE 2. Reference PLUS7 assemblies

No.	U-235 enrichment (w/o)	Temperature(K)			Boron Con. (PPM)	BP	CR
		Fuel	Clad	Mod			
ICI-72	5.0/4.5	900	600	600	500	0	0
ICI-90	5.0/4.5	900	600	600	500	8	0
ICI-99	5.0/4.5	900	600	600	500	16	0

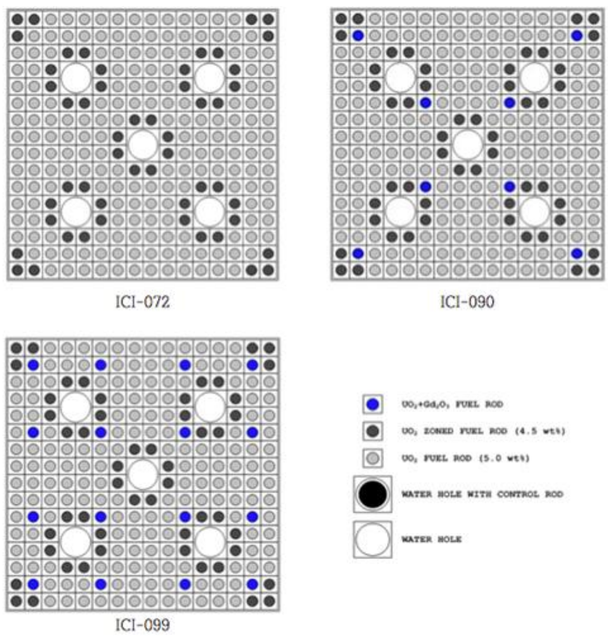

Fig 1. Reference PLUS7 assemblies

With following test assemblies, Vanadium detector model for MCNP is set up. Detailed specification of vanadium model is as same as a real vanadium detector. Figure 2 shows the model of vanadium detector.

Three dimensional MCNP calculations are done with 100,000 particle, 250 active cycle and 50 inactive cycle condition. Reflective boundary condition is applied to radial boundary and infinitely boundary condition is applied to axial boundary. Table 3 shows the results of reaction rate of vanadium-50 and vanadium-51. It is a basis for reference for vanadium detector modeling verification.

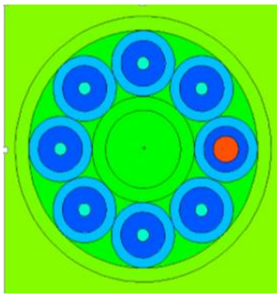

Fig 2. MCNP modeling of vanadium detector

Table 3. Reaction rate of Vanadium isotopes

NO	V-50	V-51
ICI-72	1.0233E-08	3.4426E-07
ICI-90	9.6410E-09	3.3101E-07
ICI-99	9.8469E-09	3.3102E-07
ICI-90 (5% V-51 depletion)	4.9739E-09	3.1652E-07
ICI-90 (9% V-51 depletion)	1.0129E-09	3.0707E-07

Unit: (#/cm^2)

KARMA is a transport code that calculates 2 group cross section, eigenvalue and distribution of flux and power. KARMA uses 47-group cross section based on ENDF/B-VI.R8 except vanadium; cross section of vanadium is based on ENDF/B-VII.R1 library.
Detector model for KARMA consists of several rings as shown in Figure 3. Air gap located at the center is adjusted to make the same reaction rate with results from MCNP. Reaction rate of KARMA is calculated according to Eq. (1).

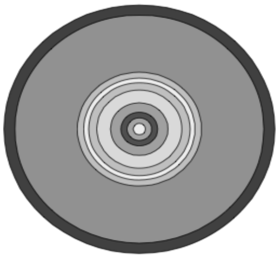

Fig. 3. Vanadium detector model of KARMA

$$R_{x,i} = AN_i \sum_{g=1}^{2} \sigma_{x,i,g} \phi_g \qquad (1)$$

where

$R_{x,i}$: Reaction rate of reaction x, nuclide i
A: Area of assembly
N_i: Number density of nuclide i
$\sigma_{x,i,g}$: Microscopic cross section of reaction x, nuclide i, and group g
ϕ_g: Neutron flux of group g

Effect of air gap size to the model is shown in Table 4 and Figure 4. Test assembly number is ICI-90. It shows that vanadium-51 reaction rate is almost same as MCNP's result at 0.06cm of air gap.

TABLE 4. Relative reaction rate of vanadium detector

Air gap(cm)	Reaction rate	
	V-50	V-51
MCNP	9.64100E-09	3.31010E-07
0.0	9.90503E-09 (102.7%)	3.29306E-07 (99.5%)
0.06	9.93953E-09 (103.1%)	3.30688E-07 (99.9%)
0.1	9.96927E-09 (103.4%)	3.32046E-07 (100.3%)

Unit: (#/cm^2)

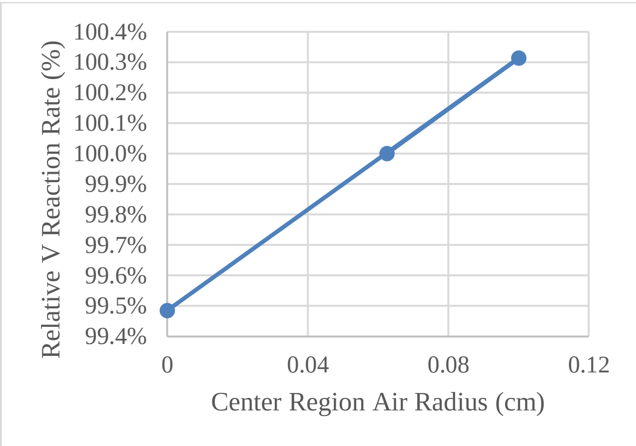

Fig. 4. Relative vanadium reaction rate according to center gap

Therefore, KARMA calculation has been done with 0.06cm air gap. Reaction rates between MCNP and KARMA in reference assemblies are listed in Table 5.
MCNP calculation that assuming only vanadium is depleted in ICI-90 problem has done to depletion effect of vanadium. This results are listed in Table 6. Table 5 and 6 show that relative reaction rates of vanadium-51 between MCNP and KARMA is less than 0.8 %.

TABLE 5. Relative vanadium reaction rate between MCNP and KARMA

No		V-50	V-51
72	MCNP	1.02330E-08	3.44260E-07
	KARMA	1.02866E-08	3.45561E-07
	Relative RR	100.5%	100.4%
90	MCNP	9.64100E-09	3.31010E-07
	KARMA	9.93953E-09	3.30688E-07
	Relative RR	103.1%	99.9%
99	MCNP	9.84690E-09	3.31020E-07
	KARMA	9.98151E-09	3.31826E-07
	Relative RR	101.4%	100.2%

Unit: (#/cm^2)

TABLE 6. Relative vanadium reaction rate between MCNP and KARMA (Depleted case, ICI-90)

Vanadium depletion		V-50	V-51
95%	MCNP	4.97390E-09	3.16520E-07
	KARMA	5.27829E-09	3.14066E-07
	Relative RR	106.1%	99.2%
91%	MCNP	1.01287E-09	3.07074E-07
	KARMA	1.10316E-09	3.06676E-07
	Relative RR	108.9%	99.9%

Unit: (#/cm^2)

3. Vanadium Detector Analysis

3.1 Vanadium Detector Analysis by KARMA

Vanadium detector depletion calculation at ICI-99 is done by KARMA to check characteristic of vanadium detector. Figure 5 and 6 show the reaction rate of each vanadium isotopes versus burnup. Both reaction rate of vanadium-50 and vanadium-51 are increased because fissile materials are decreased during burnup.

Figure 7 shows the remaining fraction of vanadium-50 and vanadium-51. Remaining fraction of vanadium-50 is about 78% at 60,000MWD/MTU and that of vanadium-51 is about 98% at 60,000MWD/MTU. It shows that vanadium-51 has small absorption cross section than that of vanadium-50. Also, vanadium-51 has nearly small depleted, it is assume that vanadium-51 is a good material for long-term fixed incore detector.

Figure 8 shows relative portion of vanadium-50 reaction rate. It decreases because of vanadium-50 depletion. As shown in Figure 8, about 0.03% of reaction rate is effect to reaction rate of vanadium-51. Depletion calculation with vanadium-50 and without vanadium-50 has done to find effect of vanadium-50. The result are shown at Figure 9.

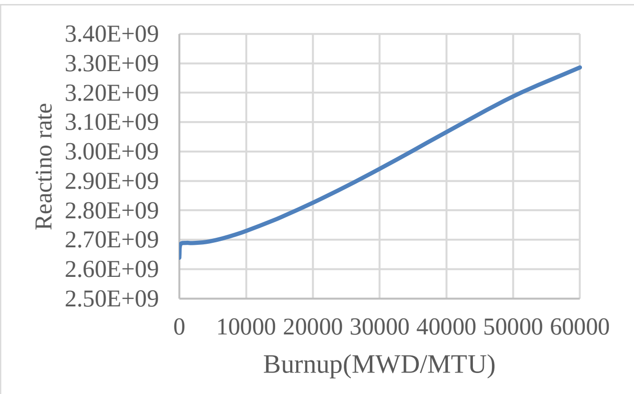

Fig. 5. Reaction rate of vanadium-50 vs. burnup

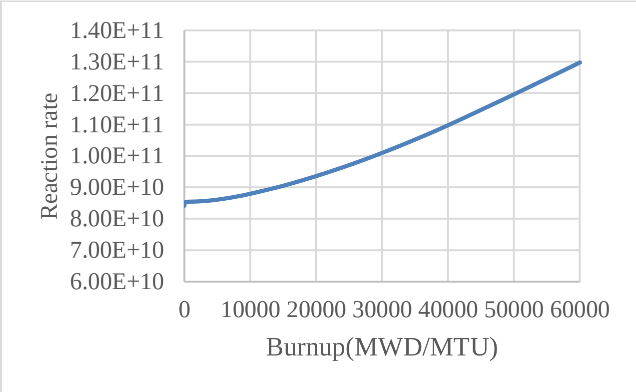

Fig. 6. Reaction rate of vanadium-51 vs. burnup

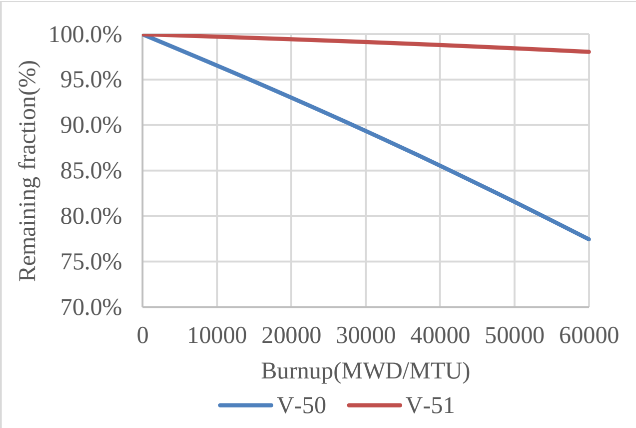

Fig. 7. Remaining fraction of vanadium-50 and vanadium-51 vs. burnup

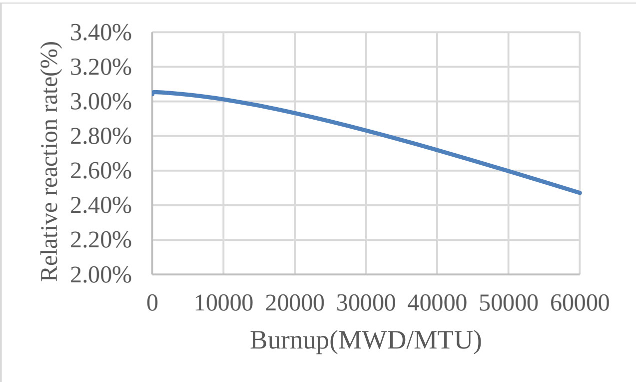

Fig. 8. Relative reaction rate of vanadium-50 vs. burnup

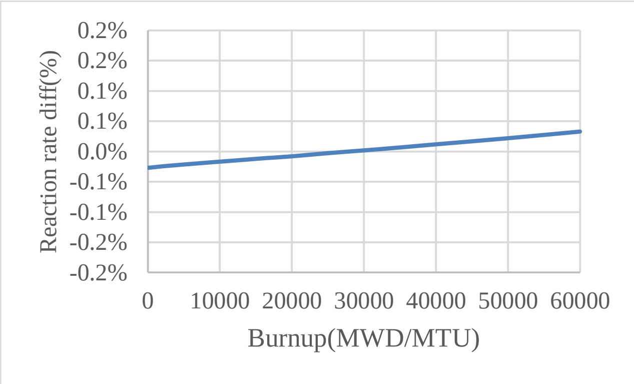

Fig. 9. Effect of V-50 on of V-51 reaction rate

3.2. Vanadium Detector Analysis by ASTRA

ASTRA code was modified to analysis vanadium detector. ASTRA code was modified to analyze vanadium detector. Reference test assemblies were calculated with 0-D model of ASTRA to compare with result from KARMA. Figures 10 to 12 show the differences of the reaction rate of KARMA and ASTRA during burnup. These figures show that both vanadium-50 and vanadium-51's reaction rates of ASTRA are matched within 1% with those of KARMA at 0MWD/MTU. The difference of reaction rates between ASTRA and KARMA is slightly increased during depletion because the burnup chain model of both codes is different.

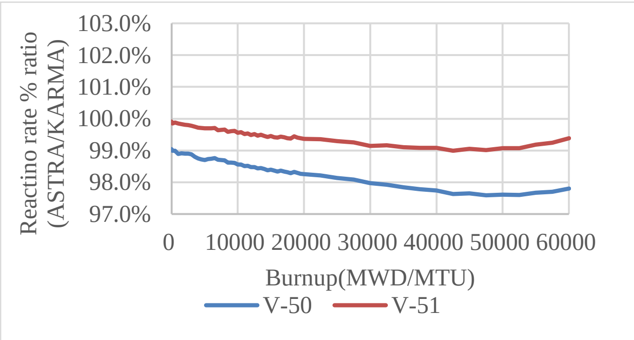

Fig. 10. Reaction rate Comparison between ASTRA and KARMA (ICI-72)

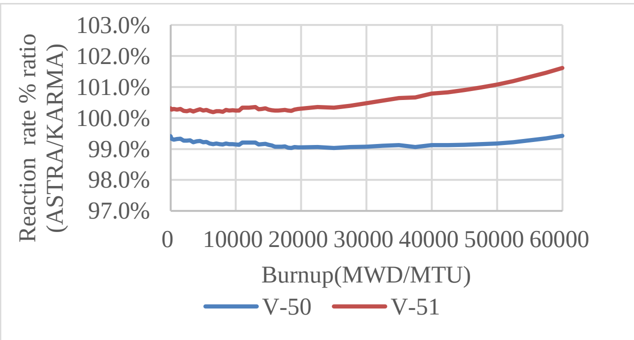

Fig. 11. Reaction rate Comparison between ASTRA and KARMA (ICI-90)

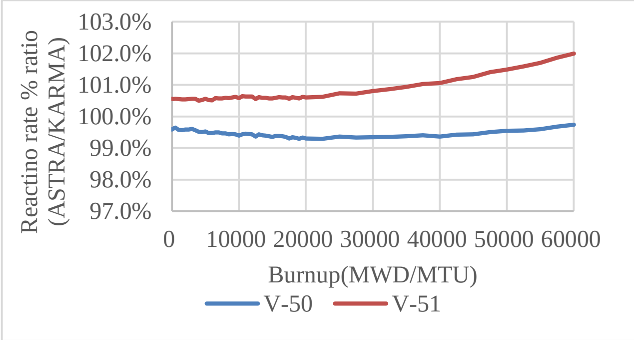

Fig. 12. Reaction rate Comparison between ASTRA and KARMA (ICI-99)

4. Conclusion

A fixed incore detector to be operable during longer period is needed to extend detector maintenance cycle. Vanadium has good potential for this because of slower burnup rate compared with existing detector with rhodium. As a reference calculation model, a detail MCNP model is used. After proper model adjustment of air gap size in KARMA model, calculation results agreed well with capture reaction rate from MCNP.

Vanadium detector depletion done by KARMA show that remaining fraction of vanadium-51 is almost 98% at 60,000MWD/MTU. It shows that vanadium is good material for long-term fixed incore detector. Also contribution extent of reaction rate of vanadium-50 is about 0.03% at 60,000MWD/MTU.

ASTRA 0-D calculations are done to verify the same tendency of KARMA's results. The results show that reaction rate between KARMA and ASTRA is matched within 1%. ASTRA's results are validated since KARMA calculation results are well matched to MCNP calculation.

Acknowledgements

This work was supported by the Optimization of Long-lived In-core Detector and Development of COLSS Algorithm of the Korea Hydro & Nuclear Power.

References

1. TODT SR. WILLIAM. H, "Characteristics of self-powered neutron detectors used in power reactors," *Proc. of a Specialists' Meeting on In-core Inst. and Reactor Core Assessment*, NEA Nuclear Science Committee (1996).
2. "KARMA User's Manual", KNF-TR-CDT-13021 Rev.01, (2014)
3. "ASTRA User's Manual", KNF-TR-CDT-12030 Rev.04, (2014)