Validation of Decay Heat Estimation Capability of BESNA

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1. Introduction

The operation of nuclear power reactor leads to the accumulation of radioactive nuclides, which can release a considerable amount of heat during their decay. To ensure the safety of spent nuclear fuel during long-term management or transportation, the estimation of decay heat in the fuel is necessary from view point of cooling. The decay heat in spent fuel is calculated using the decay heat recoverable for each nuclide and the nuclide-wise compositions which can be obtained by depletion calculation. However, the validation study should be performed to ensure the reliability of the decay heat calculation results.

In this work, the decay heat calculation capability of BESNA (Bateman Equation Solver for Nuclear Applications) code that has been recently developed by Hanyang University through the supports from NRF and KINS is validated against measured data of the Ringhals 3 PWR fuel assemblies. The rest of this paper presents the measured data as well as shortly describes the data used in decay heat calculation in BESNA. The decay heat calculations are also performed by SCALE/ORIGEN [1] for comparisons.

2. Calculation methods

2.1 Cross-section generation for BESNA depletion calculation

This section presents the cross-section (XS) library used in depletion calculation with BESNA. **Fig. 1** presents the 17x17 fuel assembly model with MCNP6 [2] for generating the effective one group XS for BESNA at difference burnups. The fuel assembly was considered without burnable poison rods and the reflective boundaries are applied to all sides of the model. The depletion calculation with MCNP6 was performed with constant power of 0.015 MW/cm up to burnup of 56 GWd/tHM, and diluted boron in coolant was not considered. The effective one-group cross-sections were calculated by using reaction rates and fluxes at difference burnups for the reactions: $(n,\gamma),(n,2n),(n,\alpha),(n,p),(n,d),(n,t)$, $(n,3n)$ and $(n,fission)$. The cross-section for (n,γ), $(n,2n)$ reactions which result in nuclide production in isomer state were calculated by combining the 63-group fluxes from MCNP6 at various burnups with the branching ratios calculated from CINDER [3] library, where the 63-group XSs are provided for those reactions. Those one-group effective XSs are stored in the BESNA library format (i.e., PWR17.lib) and the effective one-group XSs in each depletion step of BESNA can be interpolated from those data.

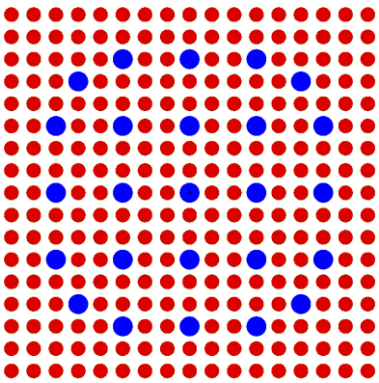

Fig. 1. Fuel assembly model using in effective one-group XS generation.

2.2. Decay heat calculation in BESNA

The point depletion code BESNA which uses burnup-dependent effective one-group XS has been developed by Hanyang University for various purposes such as isotopic predictions and source terms estimation. The BESNA code uses the Chebyshev rational approximation method (CRAM) [4,5] in depletion calculation coupled with the use of the constant extrapolation – constant midpoint (CE/CM) scheme related to the predictor-corrector calculation [6]. The decay heat from each nuclide is calculated by multiplying the decay heat recoverable (Q_i) per decay with the nuclide number density (N_i) and the decay constant (λ_i) as shown in the following equation:

$$H = \sum_i N_i \lambda_i Q_i , \quad (1)$$

where subscript i represents each unstable nuclide in the mixture. The total recoverable energy per decay (Q_i) was not accounted for the spontaneous fissions, which is considered as one type of decay in the code. In our calculation, an energy of 200 MeV is considered as the recoverable energy per fission, and the contribution of spontaneous fission to the decay heat was calculated by multiplying to the spontaneous fission branching ratio.

2.3. Decay heat calculation in SCALE

The decay heat calculation in SCALE 6.2 can be performed through module ORIGEN in SCALE. The ORIGEN family of modules include the following four modules: COUPLE module for creation of ORIGEN libraries, ARP module for creation of an ORIGEN library from existing libraries, ORIGEN module for solving depletion problems and OPUS module for post processing.

In this work, the decay heat calculations are performed using two modules, ARP and ORIGEN. The ARP module was used to create library for depletion calculations from **w17x17_ofa** libraries in SCALE. The **w17x17_ofa** libraries include seven libraries for different initial ^{235}U enrichments ranged from 0.5 to 6.0 wt % and discharged burnups up to 70 GWd/tHM. The ARP module then uses these libraries to create new library using in depletion calculations with ORIGEN. The ORIGEN module also calculates decay heat using Eq. (1) with the decay data based on ENDF/B-VII.1 library.

3. Validation of decay heat estimated with BESNA

3.1 Validation problem

This sub-section presents the decay heat benchmark data used in our validation study. The decay heat measurement data for sixteen 17x17 fuel assemblies of Ringhals 3 reactor [7], which were carried out by Swedish interim storage facility, CLAB, are considered for the validation of the decay heat calculated with BESNA. These fuel assemblies have the initial enrichments ranged from 2.1 wt% to 3.4 wt%, with the discharged burnups from 19.7 to 47.3 GWd/tHM and cooling time from 12 to 20 years. The ID, final discharged burnups and cooling times of each assembly are summarized in **Table. I** while the details on burnup and boron concentration, as well as fuel assembly information are provided in the benchmark documentation [7]. Among these FAs, the ones with the ID 5A3 were measured five times and the decay heat measurement data reported the average value for three measurements conducted in 2003, and the average of two last measurements in 2004.

Table I. Ringhals 3 fuel assemblies decay heat measurement data.

Assembly ID	Enrichment (wt.%)	Burnup (GWd/tHM)	Decay time (days)
2A5	2.1	20.11	7297
5A3	2.1	19.70	6972-7304
0C9	3.1	38.44	6551
1C2	3.1	33.32	6559
1C5	3.1	38.48	6593
2C2	3.1	36.58	6550
3C1	3.1	36.57	6545
3C4	3.1	38.45	6544
3C5	3.1	38.37	6543
3C9	3.1	36.56	6552
4C4	3.1	33.33	6572
4C7	3.1	38.37	6549

0E2	3.1	41.63	5823
0E6	3.1	35.99	5829
1E5	3.1	34.64	5818
5F2	3.4	47.31	4724

3.1 Validation results

The decay heat calculations in BESNA are performed with consideration of the operation data described in the benchmark documentation using the effective one-group XS library generated by MCNP6 for different enrichments and burnups. The decay heat estimated by BESNA are compared with the measured decay heat data in **Table II**, where the relative and absolute differences of BESNA calculated values compared to the measurement results are presented. The measurement uncertainties in **Table II** are obtained by linear interpolation from the measurement uncertainties at 250 W and 900 W, which were reported in the benchmark documentation. The relative differences of decay heat calculation by BESNA compared to the measured data are about 2%, which may be explained by the library generated by MCN6 without consideration of detail boron concentration in each cycle.

Table II. Decay heat measurement and calculation results of BESNA for Ringhals 3, PWR assemblies.

ID	Measured decay heat (W)	Measurement uncertainty (W)	Calculation decay heat (W)	C/E - 1 (%)	$\|C - E\|$ (W)
2A5	233.8	8.96	234.79	0.42	0.99
5A3*	239.3	9.04	232.93	-2.66	6.37
5A3**	230.6	8.91	229.38	-0.53	1.22
0C9	491.2	12.76	490.63	-0.12	0.57
1C2	417.7	11.68	414.69	-0.74	3.01
1C5	499.2	12.88	490.57	-1.73	8.63
2C2	466.5	12.4	463.97	-0.54	2.53
3C1	470.2	12.45	462.94	-1.54	7.26
3C4	497.3	12.85	491.20	-1.23	6.10
3C5	501.4	12.91	491.10	-2.05	10.30
3C9	468.4	12.43	463.31	-1.09	5.09
4C4	422.0	11.74	414.69	-1.73	7.31
4C7	498.7	12.87	490.25	-1.70	8.45
0E2	587.9	14.19	575.61	-2.09	12.29
0E6	487.8	12.71	479.91	-1.62	7.89
1E5	468.8	12.43	461.30	-1.60	7.50
5F2	714.1	16.05	712.69	0.20	1.41

*) measured in 2003, **) measured in 2004

Additionally, the decay heat calculation results of BESNA are compared with those from SCALE/ORIGEN. The comparison results are presented in Fig. 2, where the BESNA and ORIGEN results showed the similar level of differences compared to the measured results, which means that the decay heat results of BESNA are comparable with those from SCALE/ORIGEN and the differences of BESNA results are within the uncertainties for all the considered FAs. From these results, it can be concluded that the BESNA code gives very reliable decay heat for realistic PWR spent fuel assemblies.

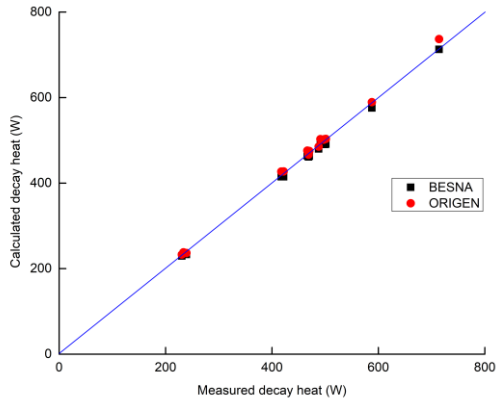

Fig. 2. Calculated vs. measured decay heat for Ringhals 3 PWR.

4. Conclusions

In this paper, the decay heat calculation capability of our point depletion code BESNA, which has been developed for estimating spent fuel compositions as well as the source terms was validated. The decay heat from 16 fuel assemblies in Ringhals 3 PWR with the fuel enrichment from 2.1 wt% to 3.4 wt% and the burnup ranged from 19.7 to 47.3 GWd/tHM are calculated by BESNA, and the results are compared with those calculated by SCALE/ORIGEN as well as the measurement data given in CLAB benchmark documentation. The decay heat calculations in BESNA showed a good agreement with those from SCALE, and the differences compared to measured data are within the measurement uncertainties, which demonstrate the reliability of BESNA in decay heat prediction. The decay heat validation for other benchmark data with difference initial enrichments and discharged burnups will be considered in our future work.

Acknowledgments

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