Decay Heat Calculation Program Development adopting state-of-the-art Standard, ANS-2014

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1. Introduction

Although decay heat can be calculated explicitly by the definition of itself, it is very difficult to calculate the decay power from the core after accident because that isotope inventory will change roughly exponentially. And we have so many isotopes-almost 1600 isotopes are dealt with in the ORIGEN code-to analyze. The American Nuclear Society (ANS) recognized this problem early in 1970 and raised issue on decay heat calculation. The first version officially approved by American National Standard Institute (ANSI) in 1979 through long discussion from original draft which was suggested and submitted in 1971 and 1973.

By considering that almost 50 years passed after first version was proposed, still 1979 version is being used every field in the nuclear industry [1]. But recent revision in 2014 includes many changes such as Cs134 consideration for neutron capture effect of fission product, propose of a factor for neutron capture effect of fission product from isotopes except for Cs134, use of nuclear data library of ENDF/B-VII.1 version, addition of actinides decay heat from U239 and Np239 and analytic uncertainty calculation on decay heat of fission product neutron capture [2].

In this study, a program which can reflect changes in ANS 2014 standard is developed and its results were compared with the results from ANS 2014 for verification of the decay heat calculation program development. This program followed same approach, assumption and equations used in ANSI/ANS-5.1-2014 to reproduce same result. By doing this, this program can be applied in the severe accident areas and other safety analysis so that make it easier to utilize.

2. History of ANS Code Development

After original draft which was submitted in 1971, 5 times revisions were made until now. Those revisions include their unique features and it will be a problem that using the oldest ANS 1979 version until now [2]. For example, in the severe accident research field still ANS 1979 is being used for every sub area.

It is true that most of the changes are made in 1979 version. But Pu241 contribution is added in 1994 and cooling time is extended from 10^9 second to 10^{10} second in 1994. ENDF/B-VI version is used and user defined model is allowed in 2005. In 2014 version, several meaningful changes which can change the decay power after early times in cooling process. In the below table, arranged revision history of the ANS decay heat calculation and major content of change for corresponding revision are presented.

Table I: Revision History of ANS Decay Heat Standard and Their Major Contents

Version	Major Contents
ANSI/ANS-5.1-1971, ANSI/ANS-5.1-1973	-Draft -Single Curve for Decay Heat Expression -It is not an official version -Ambiguous uncertainty
ANSI/ANS-5.1-1979	-Consideration of neutron capture of fission product is possible -Decay curves for isotopes of U235, U238, Pu239 -Statistical uncertainly is provided (standard deviation of normal distribution is introduced) -ENDF/B-IV version is used -Calculation results is only used for U238 data production -Release energy for a fission reaction is considered as constant
ANSI/ANS-5.1-1994	-Reevaluation of existing decay heat curved (U235, U238, Pu239) -New decay curve is added for isotope Pu241 -Experimental results is used for U238 data production additionally -Cooling time is extended from 10^9 second to 10^{10} second
ANSI/ANS-5.1-2005	-JENDL library usage is verified that the result lies in the uncertainty boundary -ENDF/B-VI version is used -User defined model can be used for simplified calculation -Appendix D is introduced for simplified, conservative calculation method
ANSI/ANS-5.1-2014	-Cs134 is included newly for neutron capture effect of fission product -A factor is introduced for neutron capture effect of fission product except for Cs134 -Actinides except for U239 and Np239 contributions for decay heat is added -ENDF/B-VII.1 version is used -Analytic uncertainly calculation is now possible for neutron capture effect of fission product

One thing which should be reminded is that this ANS standard is not an absolute standard for every reactor. This standard aims at Pressurized Water Reactor (PWR) applications including Light Water Reactor (LWR), Boiling Water Reactor (BWR), Pressurized Heavy Water Reactor (PHWR). Also, this standard doesn't guarantee any legal responsibility against usage of this standard for any field.

For information supply purpose, below table for computer code list for decay heat is also introduced as well.

Table II: Summary of Computer Codes which are used for decay heat calculation commonly

Code	Country	Organization	Solution Type
ORIGEN	United States	ORNL	Numerical
CINDER	United States	LANL	Analytical
FISPIN	United Kingdom	UKNNL	Numerical
KORIGEN	Germany	KFK	Numerical
PEPIN	France	CEA	Analytical
INVENT	Sweden	Studsvik	Analytical
DCHAIN	Japan	JAEA	Analytical
AFPA	Russia	MEPHI	Analytical

3. Verification Problem

By the addition of Pu241 for decay heat calculation, contributions from 4 isotopes should be provided explicitly. In addition, power history such as Fig. 1 which provides additional explanation about Fig. 2 can be reflected as well.

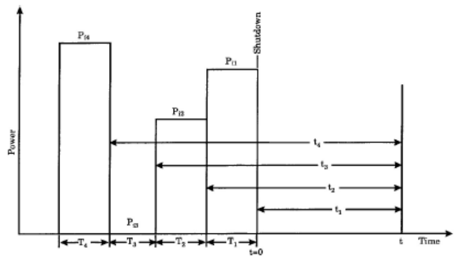

Fig. 1. Example of a Reactor Power History

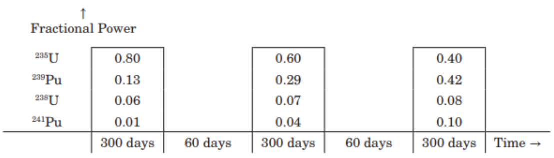

Fig. 2. Fractional Powers of Each Isotopes for Number of Operation Periods

Fraction power from each isotope is proposed in below figure which explains verification problem. In Fig. 2, it can be observed that U235 contribution for operational power is decreasing, naturally while contributions for the other isotopes are increasing. User defined inputs for decay heat calculation are given as following table.

Table III: User Defined Input for Verification Problem

Parameter	User Defined Value
Enrichment	4.2wt%
Burnup	40,000MWD/tonU
Fission Energy	$Qi=Q_{eff}$=200MeV/fission
ψ	1.00 (number of fission per atom of initial fissile material)
Uncertainty of Fission Energy	0 (assumption)
Uncertainty of Operational Power	0 (assumption)

By following the contents which was provided by ANS 2014, isotope-wise decay heat power fraction compared with operational power can be obtainable as following tables. Also, total decay heat fraction compared with operational power can be calculated as following table and it is confirmed that newly developed program result is exactly consistent with the ANS 2014 solution, even for uncertainties.

Table IV: Isotope Wise Decay Heat Fraction Results

Time after shutdown (s)	^{235}U		^{239}Pu		^{238}U		^{241}Pu	
	P'_d/P	1 σ (%)	P'_d/P	1 σ (%)	P'_d/P	1 σ (%)	P'_d/P	1 σ (%)
1	2.453E-02[1)]	3.2	2.129E-02	5.5	5.881E-03	9.8	5.994E-03	6.3
10	1.877E-02	2.1	1.704E-02	3.9	4.108E-03	6.1	4.500E-03	5.0
10^2	1.218E-02	1.9	1.167E-02	3.7	2.510E-03	5.5	2.824E-03	5.6
10^3	7.371E-03	1.9	7.113E-03	3.9	1.440E-03	5.2	1.648E-03	7.0
10^4	3.596E-03	1.8	3.355E-03	5.0	6.767E-04	4.9	7.533E-04	10.4
10^5	1.718E-03	2.0	1.708E-03	5.2	3.281E-04	3.9	3.837E-04	10.4
10^6	8.823E-04	2.0	8.032E-04	5.0	1.564E-04	3.8	1.811E-04	10.0
10^7	2.750E-04	2.0	2.357E-04	5.0	4.497E-05	4.2	5.370E-05	10.0
10^8	3.029E-05	2.0	2.146E-05	5.1	4.134E-06	5.1	5.069E-06	10.0
10^9	9.264E-06	2.1	2.928E-06	5.0	8.002E-07	4.5	4.860E-07	10.0

Table V: Total Decay Heat Fraction Results

Time after shutdown (s)	Total					
	P'_d/P	1 σ (%)	P_{dC}/P	P_{dHE}/P	P_{dA}/P	P_T/P
1	5.770E-02	5.0	2.817E-04	2.594E-03	4.633E-04	6.104E-02
10	4.441E-02	3.4	2.172E-04	2.588E-03	4.632E-04	4.768E-02
10^2	2.918E-02	3.3	1.447E-04	2.529E-03	4.584E-04	3.231E-02
10^3	1.757E-02	3.5	9.964E-05	2.057E-03	4.503E-04	2.018E-02
10^4	8.382E-03	4.1	1.070E-04	1.192E-03	4.194E-04	1.010E-02
10^5	4.138E-03	4.3	3.563E-04	8.704E-04	3.251E-04	5.690E-03
10^6	2.023E-03	4.1	1.911E-04	4.063E-05	2.299E-04	2.485E-03
10^7	6.094E-04	4.0	5.717E-05		1.250E-04	7.915E-04
10^8	6.095E-05	4.0	1.947E-05		1.760E-05	9.803E-05
10^9	1.348E-05	3.2	1.494E-07		1.071E-05	2.433E-05

Because the results were perfectly match with each other (almost more than 7-8 significant figures), supplementary explanations such as graph, comparison of calculated values and so on are omitted in this paper.

4. Conclusions

In this study, new fortran program is developed which can reflect revision contents of state-of-the-art ANS 2014 standard. Its result is compared with sample problem which was suggested in the ANS 2014 and it is verified that newly developed program is fully consistent with ANS 2014 standard and sample problem. This program can replace old ANS 1979 related studies and may be applied for new generation reactors such as Molten Salt Reactor (MSR) and Small Modular Reactor (SMR).

Isotope-wise contributions for decay heat should be clarified more clearly in the future. Adding assembly wise calculation option may be also installed for further advancement of this code in the future.

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