Journal of the Korean Nuclear Society
Volume 21, Number 1, March, 1989

Estimation of Decay Heat Generated from Long-Term Management of Spent Fuel

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(Received September 4, 1988)

장기관리 핵연료로부터 방출되는 붕괴열량 추정

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(1988. 9. 4. 접수)

Abstract

In this study, simple functional forms which could predict decay heat are referred to and modified in order to analyse more easily long-term behavior of decay heat generated from domestic PWR and CANDU spent fuel. To reduce the difference between the predicted data by functional forms and ORIGEN 2 results and to predict the decay heat under the important parameter(s), sensitivity analysis is performed. By introducing the identified key parameter, burnup, into the functional forms, the decay heat of spent fuels within a limited rangs of cooling time(3~500 years) becomes predictable for various burnup rates. The predicted decay heat of spent fuels with representative burnup rates such as 33, 37 and 40 GWD/MTU by the functional forms is in so good agreement with ORIGEN 2 results within ±10% difference over the cooling time from 1 to 10^5 years that the functional forms presented here may be used for engineeering purposes such as the thermal design and assessment of the facilities associated with spent fuel management.

요 약

본 논고에서는 국내의 PWR 및 CANDU 사용후핵연료로 부터 발생하는 붕괴열의 장기적인 거동을 보다 손쉽게 분석하기 위하여 붕괴열을 추정할 수 있는 간단한 근사식을 도출하였다. 근사식의 장기적인 붕괴열 추정에서 ORIGEN 2코드 결과와의 차이를 줄이고 중요한 변수 조건하에서도 붕괴열을 추정 할 수 있도록 하기 위하여 민감도 분석을 수행하였다. 그 결과로서 얻어진 근사식은 사용후핵연료의 이력자료중 중요변수인 연도를 포함함으로써 3~500년정도의 냉각시간 범위내에서는 임의의 연소도를 가진 사용후핵연료의 붕괴열이라도 추정할 수 있게 되었다. 그리고 대표적으로 30, 37 및 40 GWD/MTU등의 연소도를 갖는 사용후핵연료의 붕괴열 추정에 있어서는 1년부터 10^5년까지의 냉각시간에 따라 ORIGEN2 코드의 결과와 ±10%이내의 차이를 보이고 있어 사용후핵연료 관리를 위한 관련시설의 열적설계 및 평가 등과 같은 공학적 목적에 유용하게 사용될 수 있을 것이다.

1. Introduction

Decay heat generated by spent fuel is an important factor in designing and/or assessing the related systems and facilities of spent fuel managemet. Particularly, in the time period from 0 to 100 years after discharge, decay heat is important for the design and assessment of transportation and interim stoage of spent fuels. Considering longer periods time from 10^3 to 10^5 years, decay heat is also thought to be an important factor for the engineering and environmental evaluation of various geological disposal schemes.

The decay heat of spent fuel may be calculated by ORIGEN 2, a radionuclide generation and depletion computer code, incorporating various data of spent fuel in watt per unit mass of uranium[1]. To verify the accuracy of ORIGEN 2, a few decay heat measurements have been carried out at Hanford Engineering Development Lab., Pacific national Lab, etc [2,3]. Though the experimental data cover only a limited number of cooling times and fuel burnups, the review of these values and ORIGEN 2 results falls within $\pm 10\%$ [2,4].

It could be expected that any simple functional form fitted with ORIGEN 2 results might be useful for the purposes of engineering applications, and avoiding inconvenient, time-consuming and expensive usage of computer code. However, the practical usage of this functional form requires that the difference between the predicted data and ORIGEN 2 results be as small as possible and the decay heat be predicted easily under various conditions of important parameter(s).

A standard published in 1979 by the American Nuclear Society provides analytical expressions for predicting the decay heat from fissionproducts, U-239 and Np-239 in LWR fuel for the first 30 years after discharge [5]. Although this has been applied to LWR safety analysis, it is not suitable for spent fuel management over mid-long term periods of time, because the calculation errors increase from the time when actinides become a dominant factor to the decay heat.

Malbrain et. al [6] and Jordi [7] presented simple functional forms to predict the decay heat of spent fuel over long term period of cooling time. However, it is thought that they may not be suitable to the long-term management of spent fuel, since the decay heat predicted by them agree with ORIGEN 2 results for cooling times 〈1000 years, but for times〉 1000 years, tyey tend to deviate too high (by〉 $\pm 10\%$ difference) to be useful.

In this paper, simple functional forms which could could predict the decay heat are referred to and modified in order to more easily analyse long-term behavior of decay heat generted from domestic PWR and CANDU spent fuel. Although some parameters required for predicting the decay heat are given, the functional forms which have presented does not follow the decreasing tendency of decay heat during the time of long-term management of spent fuel. Thus, in this case, to have a good fit with ORIGEN 2 results within $\pm 10\%$ difference, the entire cooling period of spent fuel is divided into several interals. The coefficients of functional forms are determined by least squares method for divided cooling times. However the functional forms and their coefficient become invalid when primary parameter(s) is (are) varied. An effort is made to overcome this restriction within an important range of cooling time (up to seveal hundred years) by incorporating a correction factor, which is derived from sensitivity analysis, into the functional forms.

2. Decay Heat Calculation

Decay heat data used in this paper were obtained using ORIGEN 2 computer code for several inputs of fuel enrichment and discharge burnup, as listed in Table 1. For PWR fuels, 17×17 PWR fuel assembly used at Youngkwang unit-1 and 2 is taken as a representative of all types of dometic PWR fuels discharged and CANDU fuel bundle is taken for PHWR fuels used at Wolsung unit-1.

The decay heat generated by spent fuel decreases exponentially with the decay of fission products and actinides built up in spent fuel materials. To predict the decreasing trend of decay heat which could agree

with ORIGEN 2 data, two functional forms are quoted as follows [6];

$$Q(t)=C_1 \text{ Exp } [C_2+C_3\ t]^{-1} \quad (1)$$

$$Q(t)=D_1\ t^{-D2}[1+\frac{D_3}{1+(t/D_4)}] \quad (2)$$

where, Q(t) is the decay heat (or decay power, W/MTU) in given cooling time t which is the time (years) after discharge.

and energies which already have been tested and documented [8] and it is reported that the effect of power history (capacity factor), specfic power and fuel enrichment on the decay heat is very small [6]. In this study, only fuel burnup and enrichment are taken into consideration to investigate the sensitivites of decay heat to those parameters.

Sensitivity could be defined by the fractional change in decay heat,($\triangle D/D$) relative to the fractional change in the selected parameter($\triangle X/X$) [3], which is expressed as follows;

Table.1: **Input Parameters for Decay Heat Calculation of PWR and CANDU spent Fuel.**

I T E M S	P W R	CANDU
Electric Power, Mwe	900	600
Average Specific Power, MW/MTU	41.78	25.57
Average Discharge Burnup,	33.00	7.50
GWD/MTU	37.00	
	37.00	
	40.00	
Fuel ennichment, wt.% of U-235	*	Natural U.
Fuel Type, Rod Array	17×17	37 Elements

* PWR Fuel enrichment is considered with 3 cases as follows,
i) 3.2wt. % of U-235
ii) 3.4wt. % of U-235
iii) 3.6wt. % of U-235

In practice, either functional form (1) or (2) does not follow all the decreasing tendency of total decay heat shown in Fig. 1. Thus the entire cooling period of spent is divided, as listed in Table 3, into 3 intervals for PWR and 5 intervals for CANDU fuel.

The calculation of decay heat with ORIGEN 2 requires many input parameters such as spent fuel ages, nuclide decay half-lives, decay energies, power history, fuel burnup, enrichment, etc. It is desirable to know which parameter(s) among them is (are) of primary importance. Thus, the simple functional form may be expressed as the function of primary parameters to predict the decay heat more easily by varying the parameters. Eq.(1) and (2), being functions of cooling time(t), are applicable to several known conditions of parameters, whereas they become useless when primary parameter(s) is (are) varied.

ORIGEN 2 code has a library of nuclide hale-lives

$$\text{Sensitivity}=\frac{X}{D}\ \frac{\triangle D}{\triangle X} \quad (3)$$

The decay heat of PWR spent fuel irradiated with the burnup of 33 GWD/MTU is taken for the data. The sentivities of decay heat are studied with the burnup increased gradually from 27 to 40 GWD/MTU and the enrichment increased from 3.2 to 3.6 wt.% of U-235, which are practical values in korea.[9]

3. Results and Discussions

The decreasing trends of decay heat along with the entire cooling period are so similar regardless of fuel enrichment or burnup that only the decay heat of PWR fuel of 3.2wt.% U-235 irradiated with 33 GWD/MTU and CANDU fuel of natural uranium irradiated with 7.5 GWD/MTU are illustrated in Fig.1.

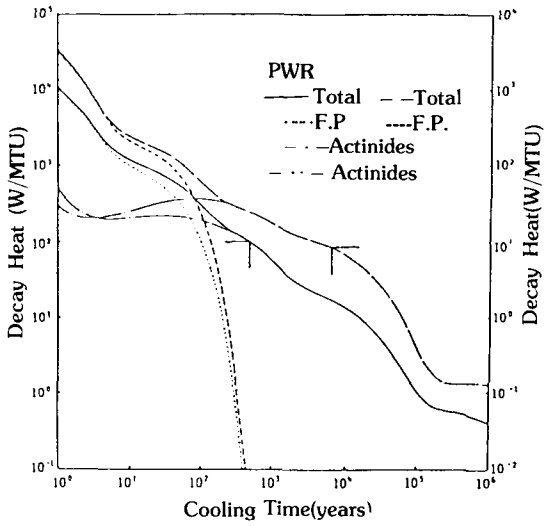

Fig 1. Decay Heat Generated by 1 Metric Ton of Uranium in 3.2 wt.% U-235 PWR of 33,000 MWD/MTU and CANDU Fuel of 7,500 MWD/MTU

The calculation results show that the contribution of the activation products to total decay heat is about 2% for early stage of cooling time and in the time period from 1 to 30 years after discharge that of fission products decreases from 96 to 70 %, especially Y-90, Ba-137m and Cs-137 being major contributors. Following the decay of fission products for 60 to 70years, the decay heat of fission products becomes equivalent with of actinides and contributes 1% or less after around 300 years. The decay heat of spent fuel beyond 350 years almost depends on actinides such as Pu-239, Pu-240 and Am-241.

The calculation results indicate also that decay heat shows a certain trend with respect to fuel enrichment and burnup. As shown in Table 2, the sensitivity of decay heat to burnup is near unity within a restricted range of cooling period ($3 \leq t < 500$), i.e., decay heat varies with burnup at almost same rate in this period. The sentivity of decay hecay heat to enrichment is found to be negligible and rather negative. Decay heat decreases with enrichment because increased enrichment reduces neutron flux for the same specific power. Thus, primary parameters are found to be burnup and cooling time of spent fuel.

Decay heat calculated by ORIGEN 2 would make nearly constant difference with discharge burnup such

Table 2. Sensitivities of the Decay heat to the Related Parameters

Cooling Times (Years)	Base[a] Decay Heat	Sensitivities					
		Burnup (MWD/MTU)[b]				Enrichment of U-235[c]	
		27,000	30,000	37,000	40,000	3.4wt.%	3.6wt.%
1	1.093+4	0.7664	0.7548	0.7624	0.7591	−0.1025	−0.2049
3	3.371+3	1.0262	2.0509	1.0695	1.0852	−0.1222	−0.2520
5	1.806+3	1.1542	1.1816	1.2425	1.2765	−0.1019	−0.2038
7	1.350+3	1.1733	1.2059	1.2833	1.3235	−0.0770	−0.1541
10	1.116+3	1.1513	1.1838	1.2567	1.2969	−0.0609	−0.1219
30	7.222+2	1.1012	1.1241	1.1720	1.1985	−0.0681	−0.1363
50	5.245+2	1.0979	1.1157	1.1467	1.1613	−0.0946	−0.1891
70	3.976+2	1.1503	1.1205	1.1391	1.1442	−0.2535	−0.2535
100	3.976+2	1.1182	1.1298	1.1375	1.1342	−0.1745	−0.3489
500	9.371+1	0.9719	0.9637	0.8971	0.8648	−0.5327	−0.5336
1000	5.474+1	0.8842	0.8681	0.7900	0.7605	−0.2368	−0.4735
10000	1.352+1	0.5573	0.5288	0.4637	0.4428	−0.2485	−0.2485
10000	1.3	0.5119	0.5209	0.5479	0.5536	−0.0154	−0.0154

a) Decay heat generated from PWR spent fuel(3.2wt.% of U-235) irradiated with burnup of 33,000 MWD/MTU

b) Minimum, average and Maximum discharge burnup of PWR spent fuel discharged from KORI 3,4~YOUNGKWANG 1,2

c) Average and maximum fuel enrichment used at KORI 1,2~YOUNGKWANG 1,2

Table 3. The Correlation Coefficients for the Prediction of Decay Heat with Cooling Time

CORRELATION COEFFICIENTS			$Q(t)=C_1\ EXP\ (C_2+C_3\,t)^{-1}$ $1 \leqq t < 30$ Years			$Q(t)=D_1\ \bar{t}^{D2}\ [\ 1+D_3/\{\ 1+(t/D_4)\}]$ $30 \leqq t < 5000$ Years				$Q(t)=C_1\ EXP(C_2+C_3)t^{-1}$ $5000 \leqq t \leqq 1000000$ Years		
			C_1	C_2	C_3	D_1	D_2	D_3	D_4	C_1	C_2	C_3
P W R	3.2[a]	33[b]	5.82640+2[c]	2.11603−1	1.26171−1	9.39860+3	7.45470−1	9.18850−1	1.07630−2	3.29169−1	2.23299−1	4.99772−6
		37	6.60535+2	2.22605−1	1.21736−1	1.09440+4	7.51150−1	1.7247	4.56450−1	3.62940−1	2.25992−1	5.09577−6
		40	7.20758+2	2.31280−1	1.18135−1	1.22780+4	7.57430−1	1.81600−2	5.27020−2	3.87280−1	2.28184−1	5.13415−6
	3.4	33	5.78149+2	2.13313−1	1.26047−1	9.62940+3	7.55030−1	9.9770	1.94200−1	3.23104−1	2.24313−1	4.88326−6
		37	6.55239+2	2.23616−1	1.22055−1	1.10550+4	7.56740−1	3.4331	1.5036	3.57771−1	2.26929−1	5.01002−6
		40	7.14948+2	2.31624−1	1.18827−1	1.23620+4	7.62020−1	2.93750−4	6.2416	3.61930−1	2.35940−1	3.96083−6
	3.6	33	5.73514+2	2.15195−1	1.25782−1	9.85510+3	7.64240−1	7.10690−4	6.9842	3.17203−1	2.25243−1	4.77594−6
		37	6.50171+2	2.24715−1	1.22321−1	1.12170+4	7.63540−1	3.3809	3.1411	3.52574−1	2.27723−1	4.92995−6
		40	7.09255+2	2.32350−1	1.19306−1	1.24560+4	7.66840−1	1.28400−3	1.3261	3.78377−1	2.29904−1	5.00196−6

CORRELATION COEFFICIENTS		$Q(t)=C_1\ EXP\ (C_2+C_3\,t)^{-1}$ $1 \leqq t < 5$ Years			$5 \leqq t \leqq 30$ Years			$Q(t)=D_1\ \bar{t}^{D2}\ [\ 1+D_3/\{\ 1+(t/D_4)\}]$ $30 < t < 5000$ Years			
		C_1	C_2	C_3	C_1	C_2	C_3	D_1	D_2	D_3	D_4
CANDU	7.5	2.33527+1	1.60842−1	3.88619−2	1.14027+2	3.43620−1	1.04312−1	9.74670+4	1.7133	3.8309	7.7979

CORRELATION COEEFICENTS		$Q(t)=D_1\ \bar{t}^{D2}\ [\ 1+D_3/\{\ 1+(t/D_4)\}]$ $5000 \leqq t \leqq 50000$ Years				$Q(t)=C_1\ EXP\ (C_2+C_3\,t)^{-1}$ $50000 < t < 1000000$ Years		
		D_1	D_2	D_3	D_4	C_1	C_2	C_3
CANDU	7.5	3.74500+3	6.99060+1	3.28180−2	1.11410−1	1.28293−1	−1.42019	3.19078−5

1.42019 −1

a : Intial enrichment of spent fuel, wt. % of U-235 Initial

b : Average discharged burnup of spent fuel, GWD/MTU

c : 5.83640+2 is equavalent to 5.83640×10^2

as 27, 30, 33, 37 and 40 GWD/MTU. For instance, decay heat increases by a factor of 1.14 as burnup increases by 12.1 % from 33 GWD/MTU to 37 GWD/MTU and increases by a factor of 1.25 as burnup increaes by 21.2% from 33 GWD/MTU to 40 GWD/MTU under the same enrichment (3.2, 3.4, 3.6, wt.% of U-235), implying that decay heat varies linearly with burnup wihin a range of cooling periods ($3 \leq t < 500$)

From the analysis of calculation results by ORIGEN 2 and sensitivites of the decayheat to fuel rurnup, some insight could be obtained. By introducing the decreasing or increasing ratio of decay heat with burnup in given cooling time (correction factor), eq.(1) and (2) could be re-expressed with the same intervals of cooling time as follows;

Table 4 The Coefficients of Correction Factor

COEFF	$CF(t)=K_1+K_2t+K_3t^2$			Burnup Ratio
FUEL BURNUP	K_1	K_2	K_3	B/33000
33,000 MWD/MTU	1.0	0.0	0.0	1.0
37,000 MWD/MTU	1.13923+0[b]	-1.20164-5	1.99538-10	1.12121+0
40,000 MWD/MTU	1.24787+0	-2.25267-5	3.77033-10	1.21212+0

a : CF(t) is the time-dependent correction factor in given cooling time,t years.

b : 1.13923 + 0 is equavalent to 1.13923×10^0

$$Q(t)=C_1 \text{ Exp } [C_2+C_3 t]^{-1} CF(t) \quad (1)$$

$$Q(t)=D_1 t^{D2} [1+\frac{1)_3}{1+(t/D_4)}] CF(t) \quad (5)$$

$$CF(5)=K_1+K_2 t+K_3T^2 \quad (6)$$

where CF(t) is the time-dependent correction factor in given cooling time(t) and expressed in the form of 2nd order polynomials.

The coefficients of eq.(4),(5) and (6) are determined by least squares method as given in Table 3 and 4, respectively. In particular, from Table 4, it is observed that K_1 of eq.(6) is almost equivalent to the burnup ratio, B/33000. For cooling times 1000 years, K_2 and K_3 of eq.(6) could be negligible since their effect on the correction factor is very small in this period. Therefore, it is found that the burnup ratio, B/33000, could take the place of CF(t). Thus, for a rang eof cooling times 3 to 500 years regarded as relatively important from a point-view of long term management of spent fuel, the decay heat of PWR spent fuel irradiated with any burnup could be predicted by means of eq.(4), (5) and (6).

Table 5 Comparison of ORIGEN 2 with the Decay Heat Predicted by ANSI-Method, Reference and Functional Forms Presented in this Study (3.2 wt.% U-235, 33,000 MWD/MTU)

Cooling Times	ORIGEN2 DATA(W/MTU)	ANSI-METHOD[a] W/MTU	% Diff	REFERENCE[b] W/MTU	% Diff	THIS STUDY W/MTU	% Diff
	1.093+4	1.110+4	1.555	1.042+4	-4.670	1.125+4	2.927
2	5.545+3	6.118+3	10.334	4.905+3	-11.54	5.031+3	-9.269
5	1.806+3	2.100+3	16.287	1.896+3	5.000	1.910+3	5.758
10	1.116+3	1.234+3	10.578	1.127+3	0.987	1.149+3	2.957
30	7.222+2	7.838+2	8.530	7.189+2	-0.460	7.439+2	3.004
50	5.245+2	5.814+2	10.848	5.024+2	-4.214	5.082+2	-3.108
70	3.976+2	4.494+2	13.028	3.905+2	-1.786	3.955+2	-0.528
100	2.843+2	3.302+2	16.145	2.990+2	5.170	3.031+2	6.612
500	9.371+1	-	-	8.955+1	-4.440	9.127+1	-2.603
1000	5.474+1	-	-	5.328+1	-2.680	5.443+1	-0.566
5000	1.880+1	-	-	1.596+1	-15.03	1.847+1	-1.755
10000	1.352+1	-	-	9.497+0	-29.76	1.278+1	-5.473

a : Decay heat data by ANSI-method [10]

b : Reference data [6]

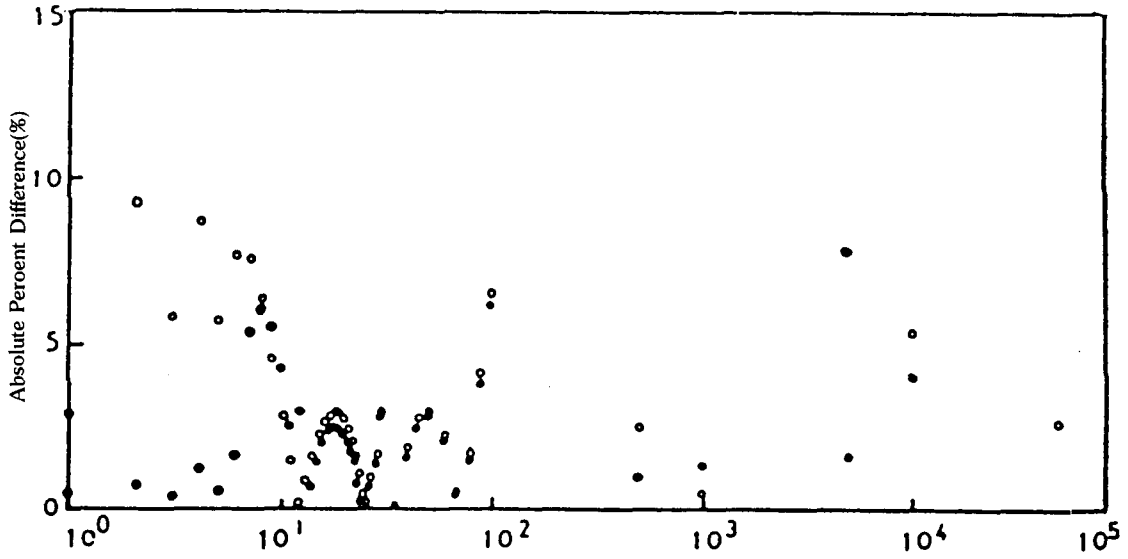

Fig 2. Absolute Percent Difference in Decay Heat between ORIGEN2 Calculation and Predicted Data(3.2 wt.% U-235 PWR S pent Fuel of 33,000 MWD/MTU, CANDU Spent Fuel of 7,500 MWD/MTU)

The decay heat calculated by ORIGEN 2 is compared with the predicted data by eq. (4) and (5), and also with the data referred from Ref.[6] data by eq. (4) and (5), and also with the data referred from Ref. [6] and [10], as shown in Table 5 and Fig. 2. From Table 5, it appears that ANST method over-estimates ORIGEN 2 data by an average of 13% and the percet difference between them tends to increase after 30 years of cooling time, which could be understood with by Ref.[6] are good at least for times 〈1000 years after discharge, they are biased high by 15~30% for times〉 1000 years. However, as shown in Fig.2 and Tab.5, the decay heat predicted by eq.(4) and (5) are found to be excellent within ±10% over long term period of cooling times.

4. Conclusions

From the results of sensitivity analysis, the key parameters are found to be burnup rates and cooling time of spent fuel, and in the time period from 3 to 500 years, the decay heat of spent fuel varies with burnup at almost same rate. Therefore, by introducing the burnup factor into the functional forms the decay heat of spent fuels within a limited range of colling time (3~500 years) becomes predictiable for various burnup rates. The predicted decay heat of spent fuels with representative burnup rates such as 33, 37 and 40 GWD/MTU by the functional forms is in so good agreement with ORIGEN 2 data within ±10% deff-erence over the cooling time from 1 to 10^5 years that the functional forms presented here may be used for engineering purposes such as the thermal design and assessment of the facilities associated with spent fuel mangement.

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