HEDL-7202

A COMPARISON OF MEASURED AND CALCULATED DECAY HEAT FOR SPENT FUEL NEAR 2.5 YEARS COOLING TIME

Hanford Engineering Development Laboratory

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Operated by Westinghouse Hanford Company
P.O. Box 1970 Richland, WA 99352
A Subsidiary of Westinghouse Electric Corporation
Prepared for the U.S. Department of Energy
under Contract No. DE-AC06-76FF02170
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I. Summary

A comparison of calculated and measured decay heat values for four Turkey Point Unit 3 Region 4 spent fuel assemblies was made. In most cases excellent agreement was obtained and provides additional confidence in the prediction of spent fuel performance.

Measured values were obtained from a HEDL calorimeter at the Engine Maintenance Assembly and Disassembly (EMAD) facility located in Nevada. Calculated values were obtained with ORIGEN2[1], an updated version of the Oak Ridge National Laboratory code, ORIGEN[2].

The four measurements were made between April 1, and July 9, 1980 and include decay times between 864 and 963 days after reactor discharge. For three of the assemblies, D34, D15, and D22, calculated values were within 6% of the measured values. A larger difference of 12.3% for assembly D04 may be a consequence of experimental difficulties. These differences can be compared with an experimental uncertainty of 5% and a calculational uncertainty of 8.6% (one-sigma). The comparison also indicates that the ORIGEN2 code gives better values than the older ORIGEN code which gave values nearly 8% higher, at least near the 2.5 year cooling times studied here.

Finally, the need for a proper modeling of the burnup history was re-emphasized. However, it is demonstrated that detailed power fluctuations are of little concern.

II. Introduction

This report compares the measured and calculated decay heat for several commercial light water reactor spent fuel assemblies. This activity is in support of programs managed by the Office of Nuclear Waste Isolation (ONWI) for the Department of Energy to demonstrate the safe disposal of commercial spent fuel. The Westinghouse Hanford Company (WHC) is conducting analytic studies and experimental tests to provide information on the performance of spent fuel in geologic disposal. The capability to predict decay heat accurately at various times in the disposal cycle is necessary for understanding spent fuel performance and for efficient design of waste disposal repositories.

Decay heat calculations such as those performed by the ORIGEN[1,2] code have been improved greatly in recent years. Some uncertainties in these calculations still exist, however, due to nuclear data uncertainties, reactor operating histories, and modeling approximations. Therefore experimental validation is desirable.

WHC's capability to measure decay heat from an intact spent fuel assembly stems from the recent installation of a calorimeter, designed by the Pacific Northwest Laboratory (PNL), at the Engine Maintenance Assembly and Disassembly (EMAD) facility located within the Nevada Test Site. EMAD is operated for the Department of Energy (DOE) by Westinghouse AESD. The calorimetry performed on four Turkey Point Unit 3 spent fuel assemblies destined for emplacement into the CLIMAX-Spent Fuel Test was the first opportunity for a comparison between calculated and measured decay heat. These comparisons provide a direct validation of calculations of decay heat for complete spent fuel assemblies.

III. Experimental and Analytical Decay Heat Assessments

A. Calorimetric Measurement of Decay Heat

The design configuration of the spent fuel calorimeter is illustrated in Figure 1. The calorimeter was designed to measure single PWR or BWR fuel assembly decay heat rates in the range of 0.1 to 2.5 kW. The expected accuracy for assemblies with a total decay heat greater than 1.0 kW is $\pm 5\%$; maximum decay heat measurement errors are estimated to be $\pm 10\%$ at 0.1 kW. The equipment is contained within the Engine Maintenance Assembly and Disassembly (EMAD) facility hot bay located on the Nevada Test Site.

The calorimeter is comprised of a double walled stainless steel vessel approximately 18 feet in length. The inner wall, or vessel, supports lead shielding which serves to capture and account for assembly decay heat resulting from escaping gamma radiation. Figure 1 identifies the system's major components: the vessels, lead shielding, steam condenser and condensate collection system mounted on a precision weigh scale. A data acquisition system controls, monitors, and records the equipment operational parameters needed to determine equilibrium conditions. The system measures decay heat by evaluating differential steam condensate collection rates. The system is first filled with water and brought to boiling equilibrium via heat input from a precision internal vessel heater. After a reference (i.e., constant) equilibrium steam condensate collection rate is established under

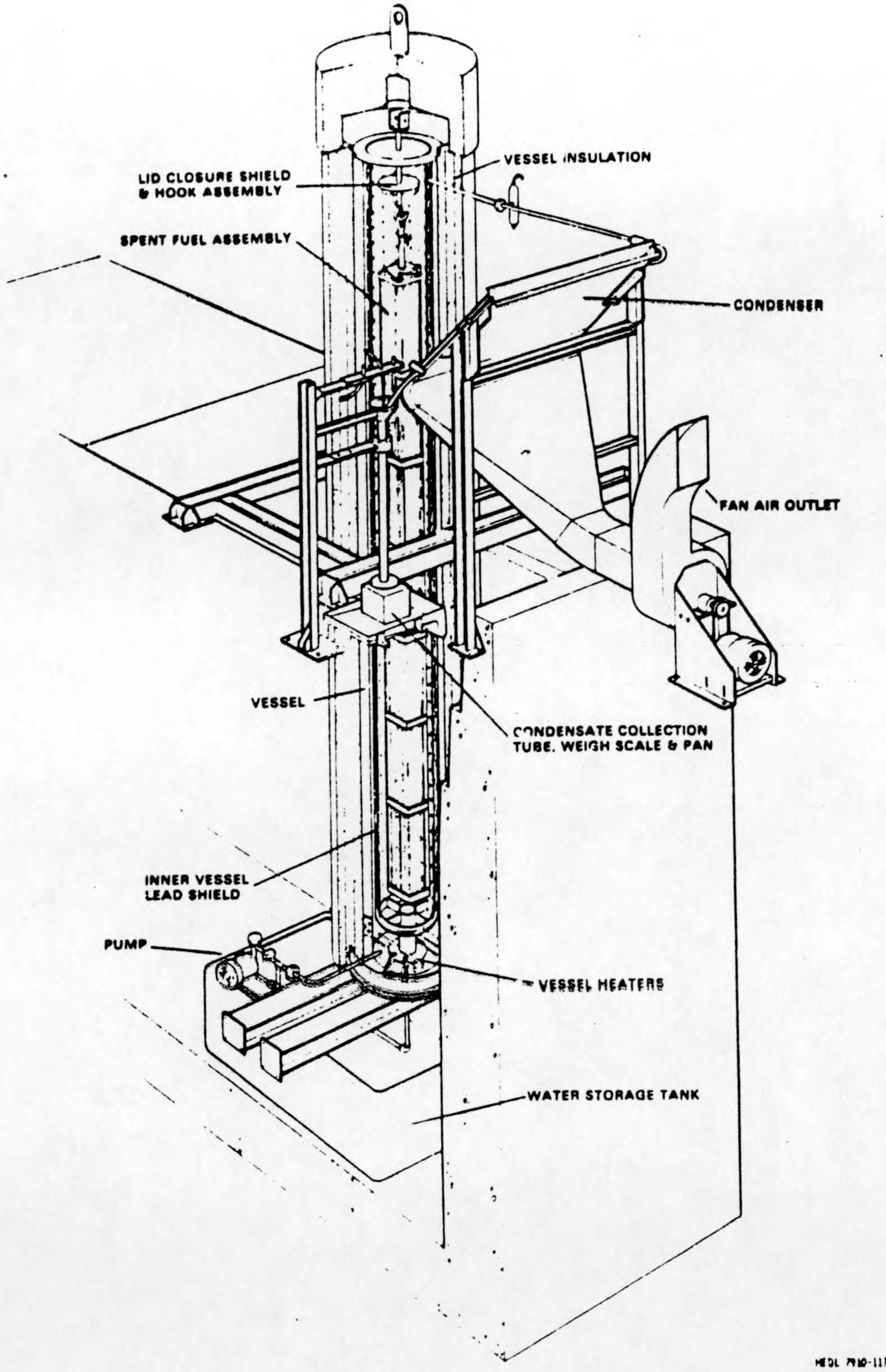

Figure 1. Spent Fuel Calorimeter

controlled hot cell ambient conditions, the spent fuel is placed within the calorimeter vessel. Boiling equilibrium is re-established with the combined heat inputs of the assembly and the constant heat value of the precision vessel heater. The differential condensate collection rate between the reference equilibrium state and the final equilibrium state directly measures the total decay heat contribution due to the addition of spent fuel to the calorimeter.

The calorimeter performed without any major problems during decay heat measurements for the four Turkey Point spent fuel assemblies D34, D04, D15, and D22. Some improvements were made during the measurements as experience was gained with the equipment. For example, additional equipment was developed to minimize contamination of the EMAD hot cell during fuel emplacement into the calorimeter vessel. Procedures evolved to allow the calorimeter to achieve thermal equilibrium the day prior to fuel insertion. Also, the condensate collection weigh scale was improved. Finally, experience was obtained to distinguish the desired true equilibrium from non-equilibrium conditions.

B. Decay Heat Calculations

Decay heat calculations (often called summation calculations) have been studied extensively going back to the classic paper[3] by Way and Wigner in 1946. In recent years, an extensive effort was expended to validate these calculations for short cooling times[4]. In some respects, these calculations are easier for long cooling times where only a relatively few nuclides with well known decay properties contribute significantly to decay heat, especially for the cooling times near 2.5 years addressed here. Nevertheless, there are few if any supporting measurements at these longer times and none directly for an intact commercial spent fuel assembly. One of the longer cooling time small-sample measurements[5] extends to only 4500 hours.

A recent analysis[6] of the uncertainties in decay heat calculations indicates that in spite of the relatively accurate nuclear data libraries that are now available, appreciable decay heat uncertainties still arise from uncertainties in the reactor and assembly operating history (thermal power, e.g.), uncertainties in the reactor spectrum, and uncertainties in the basic nuclear cross section and decay data. It was found that with relatively large uncertainties of 6% assigned to the assembly power and its irradiation time, the expected calculational decay heat uncertainty was nearly 13% (one-sigma). Moreover, over half of this uncertainty arose from the power and operating history. For the present work, additional documentation of the reactor power was obtained, and these uncertainties are reduced.

This study compares experimental and calculated decay heat values for four Turkey Point Unit 3, Region 4 assemblies, D34, D04, D15 and D22. Data extracted from these references and used for decay heat calculations are tabulated in Table B.I of Appendix B.

All calculations were made with ORIGEN2 code[1] and its associated libraries, a recently revised version of the Oak Ridge National Laboratory ORIGEN[2] code. ORIGEN2 allows a choice of reactor dependent cross section sets, and the PWR ^{235}U-enriched set was used. As noted in Table B.I, the four assemblies studied here all had a common residence time (1073 days), the same number of Effective Full Power Days (851 days), and an equal uranium loading (457.0 kg). They differed mainly in burnup although their cycle-to-cycle history varied slightly. The three cycle burnup history was modeled by assuming three irradiation periods at full power of 284 days, 284 days, and 283 days separated by two shutdown periods of 111 days. Finally, the assembly powers given in Table B.I were deduced from:

$$\text{Power} = \frac{(\text{Burnup})\text{X}(\text{Uranium mass})}{\text{Total Effective Full Power Days}} .$$

Before discussing the results, a review of calculational uncertainties is in order. As noted above, the reactor operating history is a potentially large source of calculational uncertainty. Based on information available, a decay heat uncertainty of 5.7% is attributed to operating parameters. As discussed in Appendix A, this value includes power, irradiation time, and burnup considerations. The 5.7% uncertainty is then added quadratically to an uncertainty of 6.3% that accrues from other sources[6] (nuclear data and calculational methods) to give a combined one-sigma uncertainty of 8.5%. A small reduction in uncertainty relative to the study in Ref. 6 was allowed for due to more consistent values for the ^{133}Cs capture cross section used in the new ORIGEN2 library.

One additional source of uncertainty associated with the reactor power history was considered. There is some indication that the fuel assemblies had a lower specific power near the end of their irradiation. In Appendix B, it is demonstrated the small power variations are relatively unimportant as long as the overall burnup is maintained. Nevertheless, one supporting calculation was made where the power was increased by 5% in the first cycle and decreased by 5% in the last cycle. The effect was less than 1.5% for cooling times near 2.5 years and completely negligible for longer cooling times beyond 10 years. A final uncertainty of 8.6% (one-sigma) is assigned to the calculation.

IV. Results

Table I, below, gives the comparison between calculated and measured decay heat values for the four Turkey Point spent fuel assemblies D34, D04, D15, and D22. Except for assembly D04, the agreement is excellent with respect to the 8.6% calculational uncertainty and provides a strong confirmation of these decay heat calculations. Decay heat measurements are expected to be within the design uncertainties for assemblies D34, D15, and D22. Equilibrium was clearly established and cell ambient conditions were stable. However, based on the analysis of later reference and measurement data, thermal equilibrium was not established during the measurement of assembly D04. The calculated values are taken directly from the more complete tabulations in Appendix B (log-log interpolation was used and introduces negligible errors).

Some background on these calculations is appropriate, particularly since they were completed during the course of the measurements and not before. First, it must be emphasized that these calculations are absolute. There are no parameters that were adjusted to fit the measurements. Nevertheless preliminary experimental/calculational comparisons prompted a closer study of early calculations. E.g., an initial calculation was about 20% high because the shutdown periods between cycles in the irradiation history were neglected. A second calculation was also high because an outdated ORIGEN library was used. In particular, this outdated library contained average decay energies and a ^{133}Cs cross section that were known to be in error. Once these values were corrected, the experimental and calculated values were still slightly discrepant but not seriously. Even so, these intermediate calculations which were made with the older ORIGEN code were about 7.7% above the values reported here. This would boost the D34 discrepancy (the worst case, excluding D04) from 5.8 to 13.5%, a value only marginally consistent with a combined experimental and calculational one sigma uncertainty of $\sqrt{(5.0)^2 + (8.5)^2} = 9.9\%$. Under the hypothesis that the true distribution of variations is given by 9.9%, the probability of a 13.4% difference is 0.18 (i.e., about one chance in six). Agreement is better for the other assemblies.

The values reported here were obtained with the newer ORIGEN2 code and its associated library. Over half of the difference between the results of the older ORIGEN code with its corrected nuclear data and the newer ORIGEN2 code was traced to ^{134}Cs. The ^{133}Cs capture cross section which leads to ^{134}Cs has a large epithermal cross section and is particularly sensitive to the neutron spectrum. It was previously identified(6) as one of the largest sources of uncertainty in decay heat calculations near 2.4 years. The remaining discrepancy accumulated from a variety of small differences.

The differences between the updated older ORIGEN code and the newer ORIGEN2 code are near the limit of what was expected based on sensitivity studies. Moreover, since the parameters used in the older code were chosen with some care, there was no prior expectation that the newer code would give substantially better results. However, the results of the present comparison do indicate a clear choice for the newer code and its nuclear data library.

Table I. Comparison of calculated and measured decay heat for four Turkey Point fuel assemblies.

Assembly Identification	Burnup MWD/MTU	Date of Measurement	Cooling Time (days)	Decay Heat (kW) Measured[a]	Decay Heat (kW) Calculated[b]	$\frac{C-E}{E} \times 100$
D34	27,863	April 1,'80	864	1.550	1.640	+5.8%
D04*	28,430	May 20, '80	913	1.385**	1.555*	+12.3%
D15	28,430	July 8, '80	962	1.423	1.491	+4.8%
D22	26,485	July 9, '80	963	1.284	1.357	+5.7%

* Calculated value is reduced by 213/217 to account for the removal of four fuel pins.

a Measurement uncertainty is 5%.

b Calculational uncertainty is 8.6%.

** Low confidence (see text).

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Appendix A: Burnup as a Constraint on Decay Heat Uncertainties

Decay heat calculations are sensitive to reactor power and operating history. In Ref. 6 it was demonstrated that the sensitivity of decay heat near a cooling time of 2.4 years was 1.4 for the power P and 0.9 for the operating period T. For example a 1% increase in P gives a 1.4% increase in the decay heat D. To first order, we express this relation by

$$\frac{\Delta D}{D} = \left(\alpha_P \frac{\Delta P}{P}\right)\left(\alpha_T \frac{\Delta T}{T}\right) , \qquad \text{(A.1)}$$

where $\alpha_P = 1.4$ and $\alpha_T = 0.9$ are the power and irradiation time sensitivities.

Assigning uncertainties to P and T are difficult for two reasons. First the documentation is meagre, and secondly the operating statistics are not separately detailed as power and time. For this study the burnup is given for each assembly along with the number of effective full power days (EFPD). The number of EFPD, although closely related to the true irradiation time and used as such here, is an artificial time which assumes the reactor operates at full power. There is no attempt to model the detailed power fluctuations here, and both the power and irradiation time used in the calculations could be off by as much as 10%. However the burnup

$$B = P\,T \qquad \text{(A.2)}$$

is known more accurately since the power variations are included in deducing the actual burnup. The accuracy of the total assembly burnup depends on an assessment of the total reactor thermal power, the relative assembly power, and accurate records of the plant capacity factor. Although detailed uncertainties are not readily obtained, information available indicates that a 4% (one-sigma) burnup uncertainty is conservative. Moreover, the burnup values are corroborated by preliminary destructive burnup analyses.

Based on Eqs. (A.1) and (A.2), and using methods from the theory of constrained least-squares, the following result was obtained for the fractional decay heat uncertainty r_D:

$$r_D^2 = (r_P^2 + r_T^2 + r_B^2)^{-1} \left[r_P^2 r_T^2 (\alpha_P - \alpha_T)^2 + r_B^2 (\alpha_P^2 r_P^2 + \alpha_T^2 r_T^2) \right] , \qquad \text{(A.3)}$$

where r_P, r_T, and r_B denote fractional uncertainties for power, time, and burnup respectively. For equal power and time uncertainties, $r_P = r_T = r_0$.

this result simplifies to

$$(r_D / r_o)^2 = (2 + X_B^2)^{-1} \left[(\alpha_p - \alpha_T)^2 + X_B^2 (\alpha_p^2 + \alpha_T^2) \right], \qquad \text{(A.4)}$$

where the ratio r_B / r_o is denoted by X_B. With the values given above, Eq. (A.4) gives $r_D = 5.7\%$ for the decay heat uncertainty due to uncertainties in the power and operating history of the fuel assembly.

Appendix B. Decay Heat Calculations for Turkey Point, Unit 3, Region 2 and Region 4 Fuel Assemblies.

This Appendix gives decay heat values for Turkey Point Unit 3, Region 2 and Region 4 assemblies based on ORIGEN2[1] calculations. These assemblies were obtained for the Spent Fuel Handling and Package Program Demonstration and the CLIMAX-Spent Fuel Test.

Region 4 D-Assemblies

Table B.I lists the operating parameters for the Region 4 D-assemblies. The operating history was modeled by three full power periods of 284 d, 284 d, and 283 d separated by two shutdown periods of 111 days.

Table B.I Turkey Point Unit 3, Region 4 Fuel Assembly Data.

Beginning of Irradiation	Dec. 12, 1974
Discharge	Nov. 19, 1977
Residence Time	1073 days
Total Effective Full Power Days	851 days
Initial Uranium Loading per Assembly	457 kg

Assembly Identification	Burnup, MWD/MTU	Power, kW
D09, D16, D18, D34	27,863	14.06
D01, D15, D35, D47 D04, D06, D40, D46	28,430	15.27
D22	26,485	14.22

Table B.II gives computed decay heat values for the Region 4 D-assemblies up to 10 years decay time. Figure B.1 gives a graphical representation. In order to assist the conversion between cooling time measured from discharge and calendar time, Table B.III is included for convenience.

Region 2 B-Assemblies

Table B.IV lists the operating parameters for the Region 2 B-assemblies. The operating history was modeled by three full power periods of 259 d, 284 d, and 284 d separated by two shutdown periods of 111 days for a total time of 1049. The additional residence time was assumed to be at low power immediately after loading.

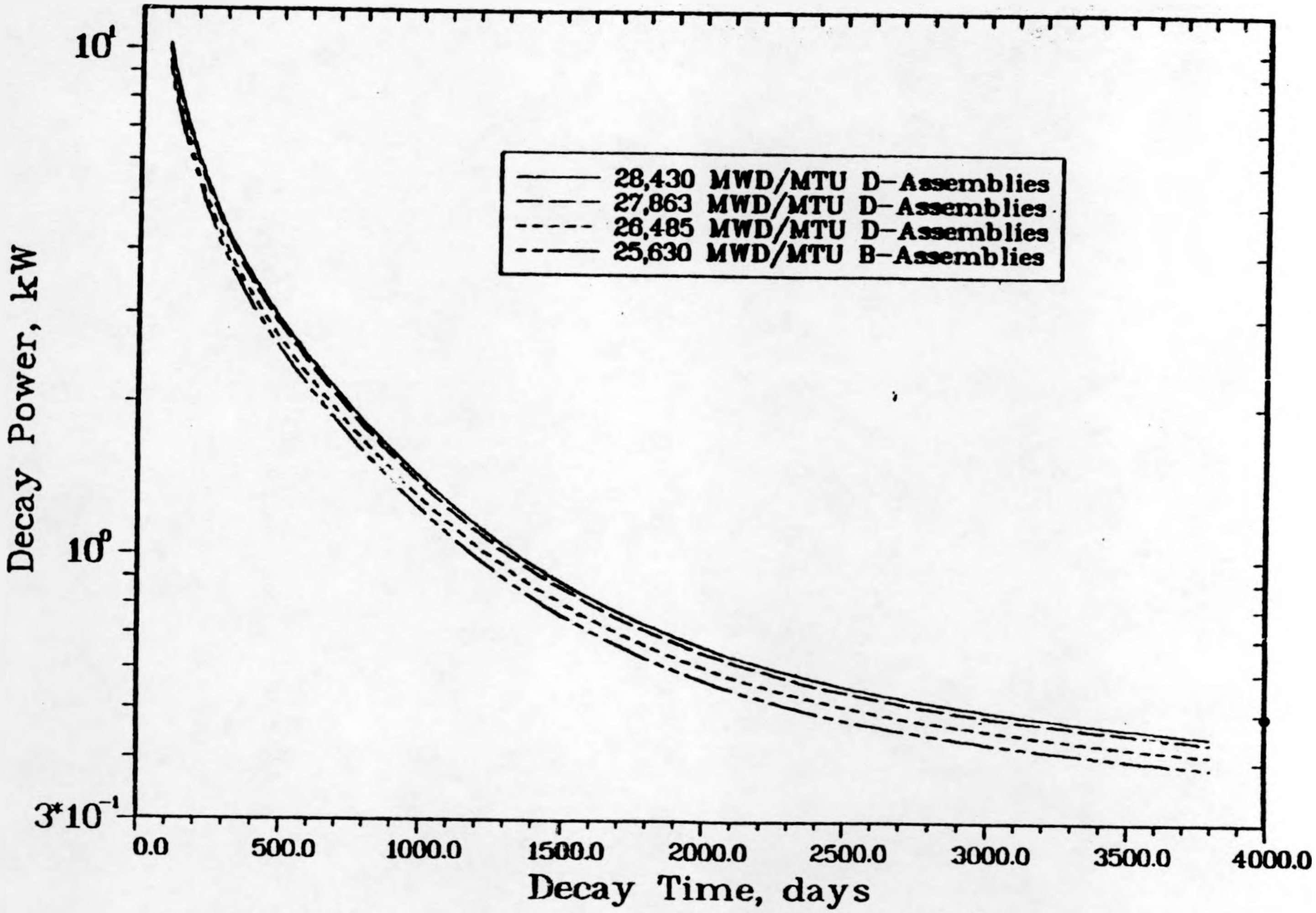
Table B.II. Calculated Decay Heat for Turkey Point Unit 3 Fuel Assemblies.

Assembly Identification	D09, D16, D18, D34	D01, D15, D35, D47, D04, D06, D40, D46	D22	B02, B03, B17, B41, B43
Burnup, MWd/MTU	27,863	28,430	26,485	25,630*
Cooling Time (days)	Decay Heat Power, kW			
0	878.5	896.3	836.0	805.2
100	10.00	10.22	9.484	9.157
110	9.418	9.626	8.924	8.613
120	8.894	9.092	8.425	8.128
130	8.422	8.611	7.975	7.691
150	7.607	7.779	7.197	6.935
160	7.252	7.418	6.858	6.606
180	6.628	6.782	6.264	6.029
200	6.101	6.244	5.761	5.541
220	5.651	5.786	5.333	5.125
240	5.264	5.391	4.965	4.768
260	4.930	5.050	4.646	4.460
290	4.505	4.616	4.242	4.068
310	4.262	4.369	4.012	3.846
340	3.948	4.047	3.713	3.557
380	3.597	3.689	3.381	3.236
420	3.305	3.390	3.105	2.969
460	3.056	3.135	2.869	2.742
500	2.840	2.914	2.665	2.545
550	2.604	2.673	2.443	2.331
610	2.362	2.424	2.214	2.111
670	2.153	2.210	2.018	1.922
740	1.943	1.995	1.820	1.733
810	1.763	1.811	1.651	1.570
900	1.567	1.610	1.467	1.394
1000	1.388	1.426	1.299	1.233
1100	1.240	1.275	1.160	1.100
1200	1.119	1.150	1.047	0.9915
1300	1.018	1.046	0.9524	0.9015
1500	0.8648	0.8887	0.8089	0.7646
1600	0.8062	0.8284	0.7541	0.7124
1800	0.7147	0.7344	0.6689	0.6313

Table B.II. (Continued)

Assembly Identification	D09, D16, D18, D34	D01, D15, D35, D47, D04, D06, D40, D46	D22	B02, B03, B17, B41, B43
Burnup, MWd/MTU	27,863	28,430	26,485	25,630*
Cooling Time (days)	Decay Heat Power, kW			
2000	0.6483	0.660	0.6071	0.5727
2200	0.5990	0.6151	0.5612	0.5293
2400	0.5614	0.5764	0.5264	0.4963
2600	0.5321	0.5462	0.4992	0.4707
2900	0.4987	0.5118	0.4683	0.4417
3100	0.4813	0.4938	0.4522	0.4265
3400	0.4601	0.4719	0.4326	0.4081
3800	0.4381	0.4492	0.4121	0.3889

* Assemblies B02, B03, B17, and B41 have a burnup of 25,665 MWd/MTU while B43 has a burnup of 25,595 MWd/MTU. These values differ trivially (less than 0.15%) from the average value used here.



B.1. Calculated Decay Heat for Turkey Point Unit 3 Fuel Assemblies.

Table B.III. Calendar Time vs. Cooling Time Measured from Discharge.

Calendar Time (Discharge Date)	Decay time (days) B-Assemblies Oct. 25, 1975	Decay time (days) D-Assemblies Nov. 19, 1977
1. Jan. 1, 1980	1529	773
2. Feb. 1, 1980	1560	804
3. Mar. 1, 1980	1589	833
4. Apr. 1, 1980	1620	864
5. May 1, 1980	1650	894
6. June 1, 1980	1681	925
7. July 1, 1980	1711	955
8. Aug. 1, 1980	1742	986
9. Sept. 1, 1980	1773	1017
10. Oct. 1, 1980	1803	1047
11. Nov. 1, 1980	1834	1078
12. Dec. 1, 1980	1864	1108
13. Jan. 1, 1981	1895	1139
14. Jan. 1, 1982	2260	1504
15. Jan. 1, 1983	2625	1869
16. Jan. 1, 1984	2990	2234
17. Jan. 1, 1985	3356	2600
18. Jan. 1, 1986	3721	2965
19. Jan. 1, 1987	4086	3330
20. Jan. 1, 1988	4451	3695
21. Jan. 1, 1989	4817	4061
22. Jan. 1, 1990	5182	4426

Table B.IV. Turkey Point Unit 3, Region 2 Fuel Assembly Data.

Beginning of Irradiation	Jan. 12, 1972
Discharge	Oct. 25, 1975
Residence Time	1382 days
Total Effective Full Power Days	827 days
Initial Uranium Loading per Assembly	448 kg

Assembly Identification	Burnup MWD/MTU	Power, kW
B02, B03, B17, B41	25,665	13.90
B43	25,595	13.87

These assemblies are two-cycle assemblies. The division into three full-power periods is an artifact to more realistically spread the full-power operating periods over the residence time. Calculated decay heat values for the Region 2 B-assemblies are given in Table B.II and Fig. B.1 along with the D-assembly values.

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