FLASHPOINT – A Tool to Routinely Calculate the Heat Load in the Irradiated Fuel Bays

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Abstract

At the recommendation of the World Association of Nuclear Operators (WANO), a tool was developed as an enhancement of NuFLASH (Nuclear Fuel Location and Storage History) in order to routinely calculate the Irradiated Fuel Bay (IFB) heat load. It uses information stored in NuFLASH regarding the location and details of spent fuel bundle properties to calculate the decay power on a bundle by bundle basis and then sum the decay powers of all bundles in a particular IFB.

FLASHPOINT employs a two-step approximation of the bundle irradiation history based on the record of the life cycle for each individual fuel bundle. The primary parameter affecting the decay power of any individual irradiated CANDU fuel bundle following its discharge from core is the period of time elapsed since the bundle last operated at power within the reactor. The remaining factors influencing the decay power of an individual fuel bundle concern the irradiation history of that bundle while in core.

The accuracy of the FLASHPOINT methodology has been assessed primarily through comparison of results obtained using the two step history representation implemented in FLASHPOINT against results from a more detailed ORIGEN-S calculation of the decay heat based on the SORO power history for a randomly selected sample of bundles. The results for individual bundles and the aggregate group are presented and the accuracy of the two-step approximation is demonstrated to be acceptable.

Introduction

During the Fukushima incident, it was reported that the water level in the spent fuel pool in Unit 4 may have been reduced by boiling to the point where the spent fuel was uncovered. As a result, fire engines, water cannons and helicopters were brought in to attempt to replenish the water inventory in the spent fuel pools to prevent fuel damage. Later analysis determined that the irradiated fuel was never uncovered; however the reduction in the water levels may have caused higher radiation levels in the area [1].

As a result of this incident, WANO recommended that the time for the irradiated fuel bays to boil be established and if the time was less than 72 hours that controls be established to ensure decay heat removal and coolant inventory control [2]. The ability to accurately and routinely calculate the total decay power in a specific irradiated fuel bay is therefore a required first step in order to comply with WANO's recommendations.

Given the irradiation history of a specific fuel bundle, tools such as the ORIGEN-S isotope generation and depletion code [3], DP-THOT [4] and other methods using the ANSI/ANS-5.1 standard [5] have been developed and demonstrated to accurately calculate the decay heat load at a specified cooling time.

However, in order to calculate the total heat load in a specified irradiated fuel bay, it is necessary to calculate the contribution from each irradiated fuel bundle. For the irradiated fuel bays in stations, such as Darlington, there are already over 200 000 fuel bundles. The required computation time using existing tools would be excessive for a calculation that is expected to be carried out for monitoring purpose on a regular basis.

Objective

The overall objective of FLASHPOINT development is to provide the capability to routinely and accurately calculate and output the total heat load in each of the IFBs at the OPG and Bruce Power nuclear generating stations. This capability was developed on the basis of the existing NuFLASH tool, which maintains a record of the life cycle of each individual fuel bundle, from the time it is first received from the manufacture as fresh fuel at the station, through its loading and irradiation in core, then discharge to the irradiated fuel bay (IFB), and subsequent transfer to dry storage.

The overall methodology for the calculation of the IFB heat load can be described as follows:

1) On a bundle by bundle basis for all bundles identified as present in the subject IFB, extract the relevant information from NuFLASH.
2) On the basis of the NuFLASH data, determine the values of all the variables required by the two-step irradiation representation (and not directly provided by NuFLASH).
3) Using pre-calculated tables, look up the decay heat value for the bundle at the applicable cooling time.
4) Sum the heat contributions for all bundles in the IFB.

The accuracy of the FLASHPOINT methodology was assessed primarily through comparison of results obtained against results from a more detailed ORIGEN-S calculation of the decay heat based on the SORO power history for a randomly selected sample of bundles.

NuFLASH

The NuFLASH (Nuclear Fuel Location and Storage History) fuel accounting system is a multi-user on-line transaction processing system designed to track fuel bundles throughout their lifetime at all OPG and Bruce Power nuclear generating stations. NuFLASH accounts for every bundle at the station from the time received to the time it is (potentially) shipped off-site. Specifically the following information related to the irradiation history is available; the total burnup for the fuel bundle, the thermal power of the fuel bundle prior to being discharged from the core, the bundle specific mass of uranium and the calendar dates when the fuel bundle was loaded into the core, when the fuel bundle was shifted into its final position before being discharged and when the fuel bundle was discharged from the core.

Bundle Irradiation History

Unlike most other commercial reactor types where each fuel assembly in-core operates at relatively constant power between infrequent refuelling outages, the CANDU reactor system makes use of on-power refuelling. Every bundle experiences a unique irradiation history reflecting its shift pattern within a fuel channel. The changing irradiation conditions for an individual bundle throughout its time in-core, due to fuel burnup and fuel movement, as well as potential variation in operating power for the reactor as a whole, pose a unique challenge (specifically applicable to CANDU reactor types) in prescribing a means to adequately specify the decay power of a given fuel bundle over the entire post-discharge period.

Figure 1 illustrates a commonly used convention for depicting power history in the form of a histogram, whereby the x-axis is used to denote elapsed time, and the y-axis indicates the applicable power level at any time. (Note that convention used in this generalized figure for numbering of irradiation periods is the reverse of that used elsewhere in this document describing the two-step irradiation representation.) The area of any "block" defined by a power level extending over a specified time interval thus represents a quantity proportional to the burnup increment accrued over that duration.

The decay power resulting from a series of sequential blocks of irradiation can be expressed as the sum of the decay power contributions arising from each step of the irradiation, provided that the decay time in each case correctly reflects the elapsed time since the end of that block-period of irradiation.

Two Step Approximation

Optimal use must be made of the available information for each individual bundle, and so the following factors have been considered in arriving at a standardized representation of each bundle's history

1) The calendar date when the bundle was discharged from the core represents the best available datum for the end of the irradiation and the beginning of the cooling period.
2) Even though the discharge burnup has less influence at shorter cooling times, it is necessary that in any representation this parameter be conserved because it directly controls the bundle decay heat at long cooling times.
3) The final operating power and the length of time spent at this power must be explicitly represented since these parameters have the greatest influence on the decay heat immediately following discharge.
4) The early stage of a bundle's residence in core has the least influence on decay power after discharge, so it is adequate to preserve the overall period over which the irradiation takes place and to conserve burnup.

Based on this, the following two-step approximation has been developed as illustrated in Figure 2.

The three date stamps available in NuFLASH; the initial loading into the core, the calendar date the bundle was moved into the final position and the calendar date the bundle is discharged are taken to be the dates defining the two steps in the irradiation period called the ante-pre-discharge and pre-discharge periods. The discharge bundle power is assumed to be constant over the entire pre-discharge period.

The effects of the two stages of irradiation on the decay power of a bundle after it has spent an amount of time cooling are considered separately. The quantity D_R (t, P, B) is used to denote the decay power of a fuel bundle at decay time t following irradiation at constant fission power P from zero burnup to an end burnup of B. The quantity D_S (t, P, T), on the other hand, is used to denote the decay power of a fuel bundle at decay time *t* following irradiation at constant fission power *P* from zero burnup for a period of *T*.

Considering only the ante-pre-discharge period, the corresponding decay power contribution (denoted by D_a) is a function of the burnup, B, the bundle fission power, P, and the cooling time, t , i.e.,

$$D_a = D_R(t = \Delta_2 + \Delta_3, P = P_1, B = B_1)$$

Since the pre-discharge period starts with a burnup of B_1, the corresponding decay power contribution D_b represents the decay power due to operating at power P_2 for a burnup increment from B_1 to B_2 which can be calculated as follows:

$$D_b = D_S(t = \Delta_3, P = P_2, T = \Delta_e + \Delta_2) - D_S(t = \Delta_2 + \Delta_3, P = P_2, T = \Delta_e)$$

Where Δ_e is the effective time period that the fuel bundle would be required to spend at power P_2 to reach a burnup B_1.

Decay Heat Lookup Tables

Generation of the decay heat values needed to populate the lookup tables was carried out using the ORIGEN-S code, where each ORIGEN-S calculation simulates constant irradiation of a single fuel bundle for a given time, yielding a given combination of two parameters (*P* and *B* for D_R tables, or *P* and *T* for D_S tables). Each ORIGEN-S case generates decay power results for the entire range of cooling times required, spanning < 2 hours to ~ 30 years.

Conceptually, the resulting tables can be considered organized as a 2-dimensional array of values in a single “worksheet”, with each sheet representing a particular decay time, and the whole set of sheets spanning all required decay times comprising a “workbook” for either D_R or D_S. Any lookup for a particular decay time thus involves consulting only the sheet for the nearest available decay time less than the subject time, and the sheet for nearest available time greater than the subject time. Discretization for each of the two variables comprising each 2-dimensional table has been optimized such that, linear interpolation between adjacent values in each dimension yields acceptable accuracy. Finally, exponential interpolation of decay power over the time variable is applied between the two time-ordered results from the previous step.

Accuracy

Using the detailed SORO power history as input for ORIGEN-S SCALE 5.1 is considered a more accurate method of obtaining the decay heat for an individual fuel bundle, so it was used to quantify the potential errors introduced by the two-step methodology.

Samples of 550 bundles were randomly selected from the east and west irradiated fuel bays at Darlington for a total sample size of 1100. The bundles in this randomly selected sample were simulated at a pre-determined set of decay times using the two step methodology designed for FLASHPOINT. Using the detailed power history for the same 1100 bundles extracted from DPTHOT-UI [4], the decay heat for each bundle at a pre-determined set of decay times was again calculated, this time with ORIGEN-S.

In comparing the results between the two approaches on a bundle-by-bundle basis, the average relative differences, median relative difference as well as the 68th percentile about the median for the specific decay times selected are provided in Table 1. In general, while the average and median differences remained within ±2%, the distribution of differences was not Gaussian, precluding the possibility of assigning a confidence level to the results. For a comparison of the distribution of differences to a comparable Gaussian distribution for a decay time of 1 day, see Figure 4. Similar behaviour is seen at all cooling times in the pre-determined set.

To accurately assess the impact these errors would have on the overall heat load in an IFB, the IFB inventory of bundles is grouped by decay time interval yielding each interval's fractional contribution to the overall heat load. Using the latter as a weighting on each time interval's relative difference between the two-step and detailed methodology, the weighted difference between the two methodologies is estimated. On this basis, it is concluded that the two-step methodology underestimates the overall heat load in Darlington IFBs by 0.21%. These results are summarized in Table 2.

The Darlington IFBs are somewhat unique in that each of the East and West bays holds bundles with cooling times roughly evenly spanning a range of cooling times from freshly discharged up to about 15 years. The rate of bundle addition to each of the IFBs at Darlington is also approximately balanced by the rate of removal into dry storage.

This situation contrasts with the arrangement at some other OPG stations, specifically Pickering A, and at Bruce Power plants where storage of spent fuel in IFBs is typically apportioned between primary bays and secondary bays, dependent on the cooling time of the fuel. The current analysis, however, can be extended to assess the impact of such an arrangement. As an example, the error introduced by the two step methodology is used in conjunction with average bundle flows between bays at Bruce B. Sensitivity is examined by assuming that bundles are shifted from the primary to the secondary bay after a 1 year or alternatively a 3 year period. The results are summarized in Table 3 and 4 in a similar manner to the results for Darlington.

Conclusion

Concerns surrounding the safety of fuel stored in the irradiated fuel bays during Fukushima led to WANO recommending that irradiated fuel bays be managed such that the time to boil be maintained at greater than 72 hours. The first step therefore, was developing the capability to routinely and accurately calculate the IFB heat load as an input to estimating time to boil. FLASHPOINT is a unique tool that has been developed specifically to address this need, demonstrating the capability of calculating the total decay heat load in a specified irradiated fuel bay with a reasonable calculation time and to within 0.5% when compared to a more accurate methodology using ORIGEN-S.

References

[1] “Special Report on the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station”, INPO 11-005, November 2011.

[2] “Fukushima Daiichi Nuclear Station Spent Fuel Pool/Pond Loss of Cooling and Makeup”, WANO SOER 2011-03, August 2011.

[3] American Nuclear Society Proposed Standard, ANS 5.1 “Decay Energy Release Rates Following Shutdown of Uranium-Fueled Thermal Reactors”, October 1971, revised October 1973.

[4] S. Johnston, C.A. Morrison and H. Albasha, “DP-THOT – A Calculation tool for Bundle Specific Decay Power based on Actual Irradiation History”, presented at Canadian Nuclear Society Annual Conference, 2005

[5] ANSI/ANS-5.1 – 1994, “American National Standard for Decay Heat Power in Light Water Reactors”, published by American Nuclear Society, approved by American National Standards Institute, August 1994.

Figure 1: Typical representation of an irradiation history for the purpose of calculating decay power in the post-irradiation period.

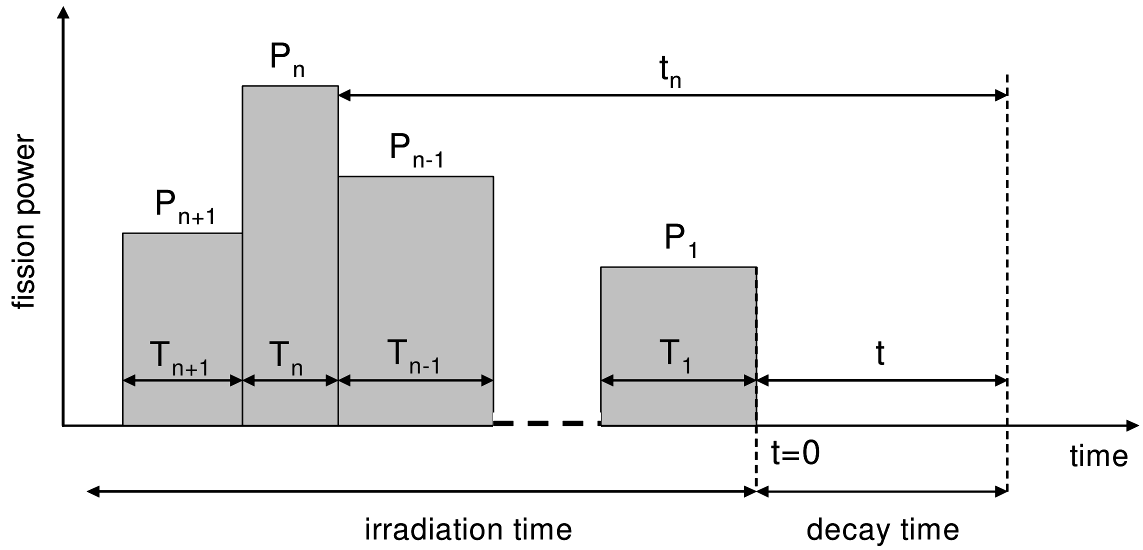

Figure 2: Overall timeframe and terminology for a fuel bundle irradiation history.

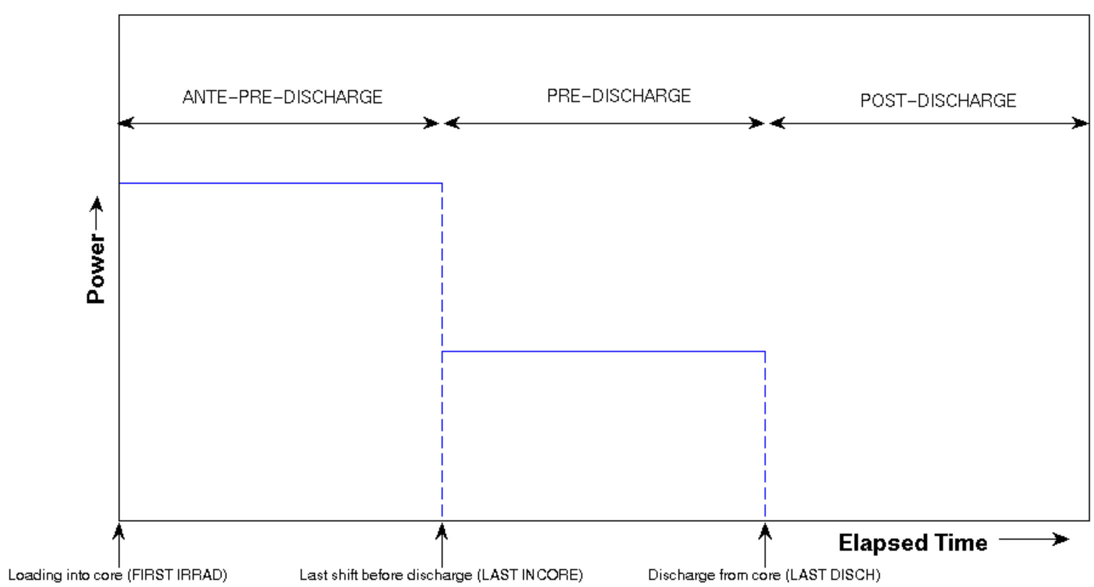

Figure 3: Decay heat calculation terminology for the ante-pre-discharge time period.

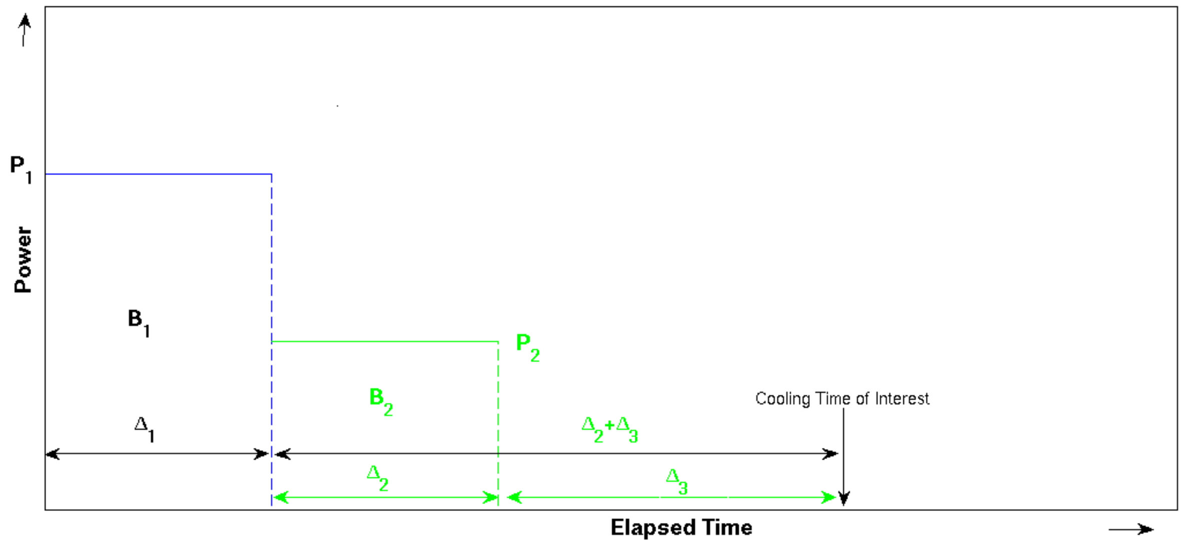

Figure 4: Cumulative Distribution Function for Differences Between FLASHPOINT Methodology and Detailed Power History Calculation, Decay Time = 1 day

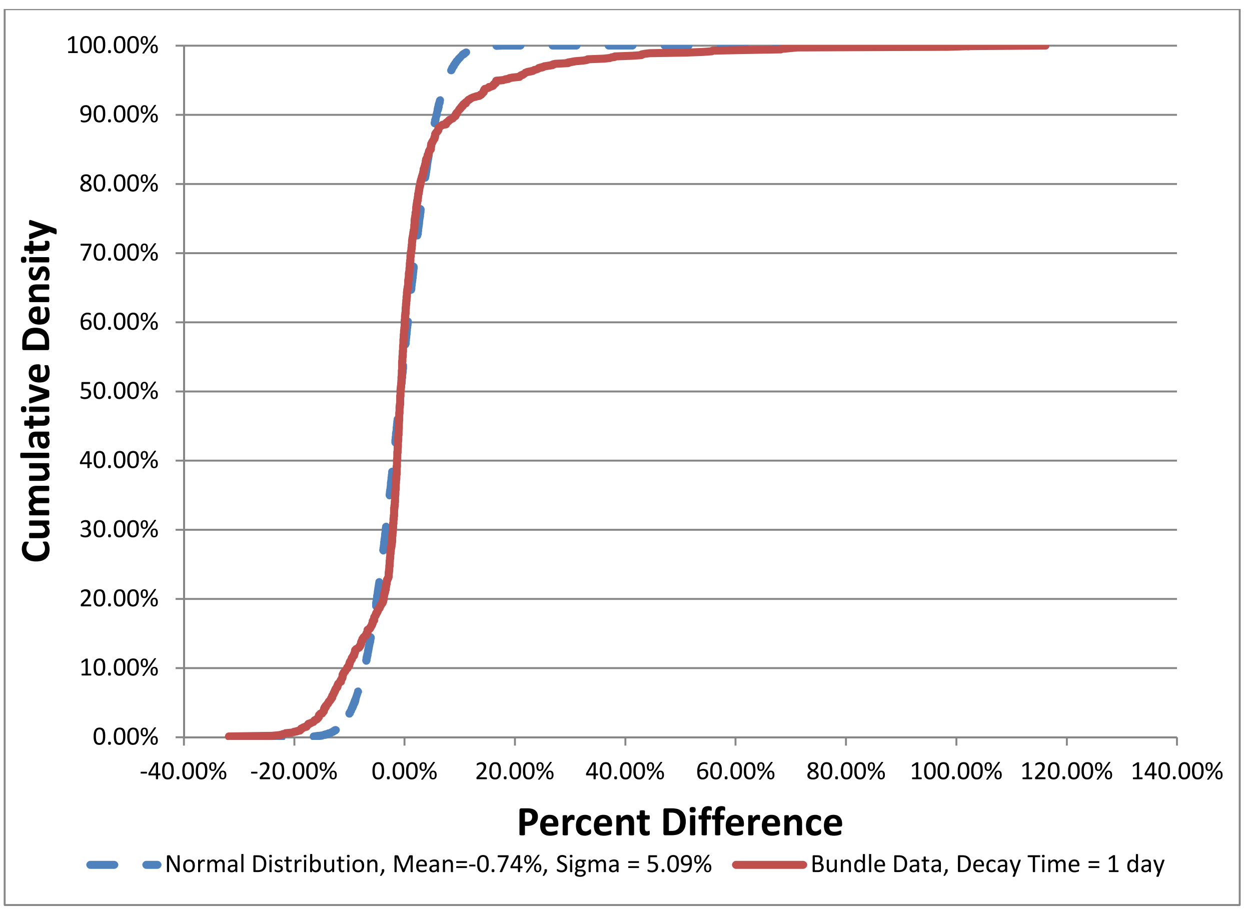

Table 1: Differences between FLASHPOINT Methodology and Detailed Power History Calculation for Individual Bundles[1]

	Cooling Time (days)									
	1	7	15	30	61	122	183	365	1095	3650
Mean	1.25%	0.98%	0.50%	-0.18%	-0.21%	-0.88%	-0.79%	-0.72%	-0.34%	0.94%
Median	-0.74%	-1.41%	-1.74%	-2.02%	-1.50%	-1.77%	-1.37%	-0.73%	-0.26%	0.86%
68^{th} %	5.09%	7.43%	8.70%	9.33%	9.29%	8.19%	7.07%	4.77%	2.86%	1.09%

Table 2: Irradiated Fuel Bay Decay Heat Contribution Breakdown - Darlington

Cooling Interval (days)	Relative Contribution to Total IFB Head Load	Relative Difference Between Detailed and Two-Step Methodology[1]	Weighted Relative Difference
0 ⇒ 1	1.67%	1.25%	0.02%
1 ⇒ 7	5.75%	1.25%	0.07%
7 ⇒ 15	4.54%	0.98%	0.04%
15 ⇒ 30	6.03%	0.50%	0.03%
30 ⇒ 61	8.58%	-0.18%	-0.02%
61 ⇒ 122	11.36%	-0.21%	-0.02%
122 ⇒ 183	7.61%	-0.88%	-0.07%
183 ⇒ 365	13.62%	-0.79%	-0.11%
365 ⇒ 1095	20.56%	-0.72%	-0.15%
1095 ⇒ 3650	15.88%	-0.34%	-0.05%
3650 ⇒ 10950	4.40%	0.94%	0.04%
		Derived Relative Difference Between ORIGEN and Two-Step Methodology for the Entire IFB	**-0.21%**

[1] Calculated as $\frac{\text{(FLASHPOINT Calculation)} - \text{(Detailed ORIGEN-S Calculation)}}{\text{(Detailed ORIGEN-S Calculation)}}$

Table 3: Irradiated Fuel Bay Decay Heat Contribution Breakdown – Bruce B Bundles Assumed Transferred 1 Year after Discharge

Cooling Interval (days)			Relative Difference Between Detailed and 2-Step Methodology	Primary Fuel Bay		Secondary Fuel Bay	
				Relative Contribution to Total IFB Heat Load	Weighted Relative Difference	Relative Contribution to Total IFB Heat Load	Weighted Relative Difference
0	⇒	1	1.25%	2.82%	0.04%	0.00%	0.00%
1	⇒	7	1.25%	9.71%	0.12%	0.00%	0.00%
7	⇒	15	0.98%	7.67%	0.08%	0.00%	0.00%
15	⇒	30	0.50%	10.19%	0.05%	0.00%	0.00%
30	⇒	61	-0.18%	14.51%	-0.03%	0.00%	0.00%
61	⇒	122	-0.21%	19.20%	-0.04%	0.00%	0.00%
122	⇒	183	-0.88%	12.86%	-0.11%	0.00%	0.00%
183	⇒	365	-0.79%	23.03%	-0.18%	0.00%	0.00%
365	⇒	1095	-0.72%	0.00%	0.00%	51.80%	-0.37%
1095	⇒	3650	-0.34%	0.00%	0.00%	40.00%	-0.14%
3650	⇒	10950	0.94%	0.00%	0.00%	8.20%	0.08%
Weighted Difference Between ORIGEN-S and Two-Step Methodology for Entire IFB					**-0.08%**		**-0.43%**

Table 4: Irradiated Fuel Bay Decay Heat Contribution Breakdown – Bruce B Bundles Assumed Transferred 3 Years after Discharge

Cooling Time Range (days)			Relative Difference Between Detailed and 2-Step Methodology	Primary Fuel Bay		Secondary Fuel Bay	
				Relative Contribution to Total IFB Heat Load	Weighted Relative Difference	Relative Contribution to Total IFB Heat Load	Weighted Relative Difference
0	⇒	1	1.25%	2.09%	0.03%	0.00%	0.00%
1	⇒	7	1.25%	7.21%	0.09%	0.00%	0.00%
7	⇒	15	0.98%	5.69%	0.06%	0.00%	0.00%
15	⇒	30	0.50%	7.56%	0.04%	0.00%	0.00%
30	⇒	61	-0.18%	10.77%	-0.02%	0.00%	0.00%
61	⇒	122	-0.21%	14.25%	-0.03%	0.00%	0.00%
122	⇒	183	-0.88%	9.55%	-0.08%	0.00%	0.00%
183	⇒	365	-0.79%	17.09%	-0.13%	0.00%	0.00%
365	⇒	1095	-0.72%	25.79%	-0.19%	0.00%	0.00%
1095	⇒	3650	-0.34%	0.00%	0.00%	73.82%	-0.25%
3650	⇒	10950	0.94%	0.00%	0.00%	26.18%	0.25%
Weighted Difference Between ORIGEN-S and Two-Step Methodology for Entire IFB					**-0.24%**		**0.00%**