NEW APPROACH TO DERIVE LINEAR POWER / BURNUP HISTORY INPUT FOR CANDU FUEL CODES

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Abstract

The fuel element linear power / burnup history is a required input for the ELESTRES code in order to simulate CANDU fuel behavior during normal operating conditions and also to provide input for the accident analysis codes ELOCA and SOURCE. The purpose of this paper is to present a new approach to derive "true", or at least more realistic linear power / burnup histories. Such an approach can be used to recreate any typical bundle power history if only a single pair of instantaneous values of bundle power and burnup, together with the position in the channel, are known. The histories obtained could be useful to perform more realistic simulations for safety analyses for cases where the reference (overpower) history is not appropriate.

1. INTRODUCTION

Traditionally, Gentilly-2 (G-2) safety analyses have assumed that a bundle's power history as a function of burnup has the same form as the reference overpower envelope (hereafter referred to as the "reference history"), i.e. it is obtained by subtracting (or adding) a constant value of power from (or to) the reference history, for all burnups. It is noted that the reference history for Gentilly-2 is not based on an actual power history for G-2, but is derived from the envelope of a series of snapshots of fuel bundle powers and burnups obtained from a fuel management simulation of the first 600 EFPD of operation. The question that was then raised is whether this method of deriving the power / burnup history is truly representative of what a given bundle actually undergoes during its period of residence in the reactor core.

Since the power / burnup history of a given fuel bundle depends both on its position in the channel and the fuelling sequence, its real history could conceivably have a different shape than the reference history. Furthermore, it is also clear that bundles that remain in the core for more than one refueling cycle, i.e. their position in the channel shifts from one refueling cycle to the next, cannot have such a continuously smooth history.

With the fuelling strategy practiced at Gentilly-2 ("8-bundle shift"), two history "types" exist, according to whether the bundle in question resides in the core for one or two refueling cycles. If the part of the history which corresponds to each refueling cycle is designated a "stage", then the histories comprise either one stage (Type 1) or two stages (Type 2). At any instant, therefore, the bundles in positions 1 to 8 in the core experience only a one-stage power / burnup history (Type 1) and the bundles in positions 9 to 12 experience two-stage power / burnup histories (Type 2).

In order to clarify these points, a study [1] was performed to investigate the real fuel power histories at Gentilly-2, covering many refueling cycles of normal operation at equilibrium core conditions and a wide range of channel powers.

Furthermore, it is important to know if this change in the approach would affect the values of the fission product releases from the safety analyses. So, the free inventory fission product releases derived using the standard approach is compared with the values obtained from this approach, using the ANS-5.4 methodology to determine the fission product releases.

2. DETERMINATION OF THE REAL HISTORY

First, actual bundle power / burnup histories were obtained from routine runs of the fuel management program SIMEX over the period of 755 to 1730 EFPD of G-2 operation.

In order to characterize the behavior of the bundle power as a function of burnup, twenty three channels were selected, based on maximizing the number of refueling cycles during the period in question and representative of all core zones. Also, the study has been done using only the corresponding external element powers and burnups, in order to limit the work load and because these values are representative of all bundle element rings. Any other element power / burnup history can be derived using the appropriate ring factors as required.

As an example, Figure 1 shows the outer element linear power histories of bundles (channel E-07) irradiated in position 4 for a period of time and then moved to position 12 for another period of time before being discharged from the core. As it can be seen, there is consistency in the linear power with burnup for the different cycles of refueling. Also, there is a slight spread of the data due to the different effects affecting the channel E-07, like the refueling of the surrounding channels, the liquid zone controller level changes, etc…

The different histories were averaged for each channel and for each bundle position in the channel, after some data processing (interpolation/extrapolation) to obtain the mean values for the same set of burnups. Figure 2 shows the effect of averaging the data shown in Figure 1. Figure 3 shows the average linear powers for the bundle staying in position 5 in the channel E-07 for only one cycle (a 'Type 1' history). An observation coming from the different histories is that the curves are similar for a specific position and a specific channel. The variability of the individual histories, over the various refueling cycles and for each specific channel and position, was characterized by an average standard deviation (of the individual linear powers relative to the average linear power for the channel and position) of 2.61%.

3. RELATION BETWEEN THE REAL AND THE REFERENCE HISTORIES

Proportionality

For all the 23 channels analyzed, the value of each outer element power at each burnup, was divided by the value of the reference history at the same burnup. Looking at the curves built from these ratios, it was apparent that the histories are effectively proportional to the reference history.

Thus, the most significant result from the study is that, for practical purposes, each stage of a real bundle history is in fact directly proportional to the Gentilly-2 reference history. That is, each stage can be characterized by a single parameter, namely the ratio "f_i" of the real power at any given burnup to the value of the reference history at the same burnup. The curves of average linear power for a given channel and position, when divided by the average associated characteristic ratio "f_i", are within ±2.61% (1σ) of the reference history, e.g. see Figures 2 and 3. This confirms the conclusion that the real histories are indeed proportional to the reference history.

Furthermore, for the bundles undergoing a two-stage history (i.e. Type 2, bundles 9 to 12), there is a linear correlation relating the parameter f_1 for the1st stage to the associated parameter f_2 for the 2nd stage. There is also a linear correlation relating the transition burnup ω_t (i.e. burnup at refueling, where the bundles from positions 1 to 4 are shifted to positions 9 to 12) to the 2nd stage parameter f_2. It is very interesting to see that there is a direct relation between the bundle powers in the two stages.

Correlations for the two-stage histories

As the power for the bundles in positions 9 to 12 is directly related to the power from the first stage (i.e. initially in positions 1 to 4), it is possible to determine either one by the characteristic factors proportional to the reference history and an appropriate correlation. Thus, the f_1 factors characterizing the linear power for the bundles in positions 1 to 4, and the transition burnups at refuelling, can each be determined by a linear relation as a function of the f_2 factor characterizing the second stage (in positions 9 to 12). The equation to determine the transition burnup is :

$$(1) \quad \omega_t = \omega_0 + k_\omega \bullet f_2$$

where ω_0 and k_ω are values obtained from the Gentilly-2 histories and are given in Table 1. The f_1 factor is given by :

$$(2) \quad f_1 = f_{1,0} + k_f \bullet f_2$$

where $f_{1,0}$ and k_f are values obtained from the Gentilly-2 histories and are given in Table 2.

Rebuilding a history

The correlations derived as described above can be used to rebuild (estimate) the complete history for a given fuel element based on instantaneous values of its linear power and burnup. Designating this pair of values of linear power and burnup as an "anchor point", the method used to derived the estimated history is as follows :

- For bundles in positions 1 to 8

  The element linear power from the "anchor point" divided by the value of the reference history gives the "f" factor, which is then used to derive the power for all burnups. That is, the reference history multiplied by this factor, gives the required element history.

- For bundles in positions 9 to 12

  That is, the "anchor point" is in the second stage. For these elements, the history is built in two steps, one for each stage. In the first step, the transition burnup is determined (see equation (1)) based on the "f_2" factor obtained as described above. For burnups below the transition burnup, the f_1 factor is calculated by the equation 2 above, and the first stage of the history is obtained by multiplying the reference history by this factor f_1. Above the transition burnup, the second stage of the history is obtained by multiplying the reference history by the factor f_2.

4. COMPARISON OF THE FREE INVENTORY FISSION PRODUCT RELEASES USING ANS-5.4 METHODOLOGY

It was interesting to assess the consequences of this approach on safety analyses. Note that in previous safety analyses for Gentilly-2, the free inventory fission product releases for a channel were all obtained for single-stage ('Type 1') power / burnup histories and at a burnup corresponding to the Pu peak (for all fuel elements). Using the ANS-5.4 methodology as implemented in the ELESIM code, a comparison of the free inventory fission product (FP) releases for an outer elements of 12 different bundles (a full channel) was done for the following two cases :

- the "constant burnup" approach which uses the same burnup for all the 12 bundles in a channel. This approach is similar to the standard approach used in the past, because the same burnup is assumed for all the bundles, but the element power history is proportional to the reference history instead of being "biased" by a constant value as was done previously.
- The new approach based on a distributed burnup corresponding to an equivalent time for all the bundles, and which also takes into account the two-stage 'realistic' history for bundles 9 to 12.

Table 3 gives the values of bundle powers and burnups used for the two cases.

Table 3 also gives the results of the FP releases obtained for both cases. Only results for the isotopes I-131, Cs-137 and Te-132 have been used for the comparison between the approaches. Due to the spread of their decay constants, they are considered to be representative of most of the fission products that could be released from an element.

As can be seen from Table 3, there is no significant difference in the total FP releases for the 12 bundles obtained using the two approaches. This is mainly due to the facts that: bundles located in the high power regions (position 5, 6, 7 & 8) produce 94.5 % of the FP releases, bundles in position 4 & 9 produce ~5 %, and bundles 1 to 3 & 10 to 12 produce less than 0.5 %. So, changes in the histories for bundles 1 to 4 and 9 to 12 have a minimal impact on the total releases, because they are located in the relatively low power region (see figure 4).

These results show that the fact that bundle power has a strong effect on the FP releases and burnup has a lesser impact, has a consequence that there is no significant difference between the two approaches.

5. CONCLUSION

The new approach has been demonstrated to be valid for Gentilly-2 fuel management procedures. It allows the reality of what a bundle is experiencing in the reactor core to be represented more closely. The most interesting result from this study is that the fuel element linear power history as a function of burnup is proportional to the reference history for Gentilly-2. This approach is different from the standard approach used in the past for the Gentilly-2 safety analyses.

Based on these observations and the correlations developed, this approach allows the fuel element linear power / burnup histories to be rebuilt for any bundle in the core, based on an instantaneous coupled power / burnup value.

However, for Gentilly-2 safety analyses, a comparison has shown that using the new approach, which increases significantly the work load to derive the required linear power / burnup histories, does not have a significant impact on the prediction of the free inventory fission product releases.

6. REFERENCE

1. T. L. Tang, "Historiques typiques de la puissance du combustible à Gentilly-2", Hydro-Québec Rapport Technique Interne, G2-RTI-1992-37000-21, novembre 2002, (*to be issued*).

TABLE 1 CORRELATION FACTORS USED TO DERIVE THE TRANSITION BURNUPS

Bundle Position	Slope (k_ω)	Ordinate at Origin (ω_0)
1-9	51.36	6.334
2-10	100.37	40.66
3-11	105.86	105.31
4-12	107.51	157.52

TABLE 2 CORRELATION FACTORS USED TO DERIVE THE F_1 FACTOR AS FUNCTION OF F_2

Bundle Position	Slope (k_f)	Ordinate at Origin ($f_{1,0}$)
1-9	0.3216	-0.0682
2-10	0.7436	-0.0542
3-11	1.1887	0.1083
4-12	2.6943	0.2596

TABLE 3 BUNDLE PARAMETER COMPARISONS BETWEEN THE DIFFERENT APPROACHES

BUNDLE NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	CHANNEL
BUNDLE POWER (KW) BOTH APPROACHES	168,4	391,2	581,2	745,0	872,9	935,1	935,1	874,0	713,7	558,6	365,8	166,1	7307
BUNDLE BURNUP (MWH/KGU) NEW APPROACH	9.11	21.1	31.2	39.9	46.69	50.0	50.0	46.75	87.06	138.2	173.3	189.1	-
BUNDLE BURNUP (MWH/KGU) "CONSTANT BURNUP" APPROACH	50	50	50	50	50	50	50	50	50	50	50	50	-
OUTER ELEMENT FP FREE INVENTORY (CURIES) NEW APPROACH	0,03	0,08	1,79	25,09	137,4	242,8	242,8	139,0	16,14	0,99	0,09	0,21	806,42
OUTER ELEMENT FP FREE INVENTORY (CURIES) "CONSTANT BURNUP" APPROACH	0,03	0,08	1,73	25,20	138,1	242,8	242,8	139,7	15,64	1,15	0,07	0,03	807,37

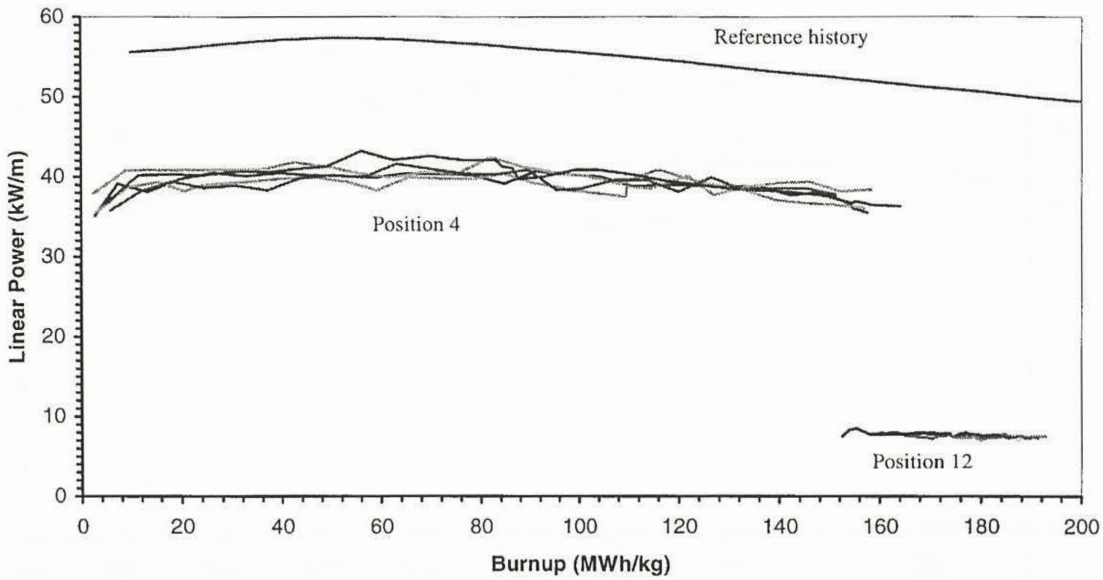

Figure 1: Element linear power history: raw data for channel E-07, obtained from fuel management calculations (bundle in position 4 for the first stage and shifted to position 12 for the second stage)

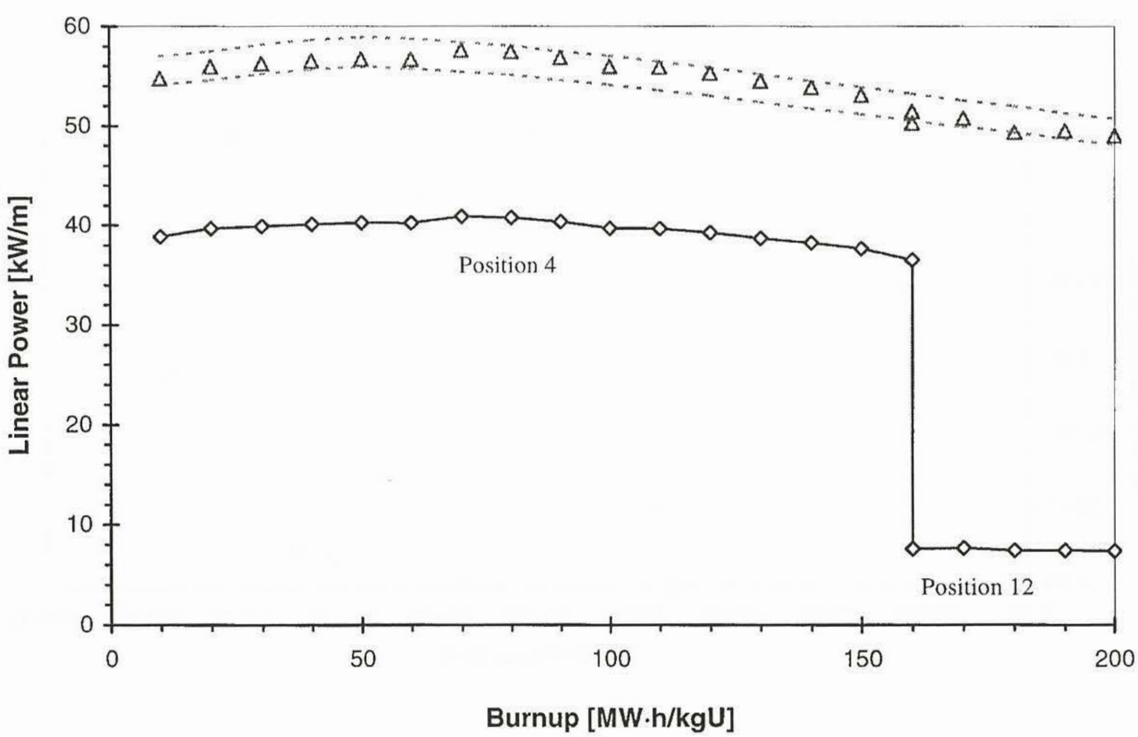

Figure 2: Element linear power history: averaged data for channel E-07 obtained from fuel management (bundle in position 4 for the first stage and shifted to position 12 for the second stage)

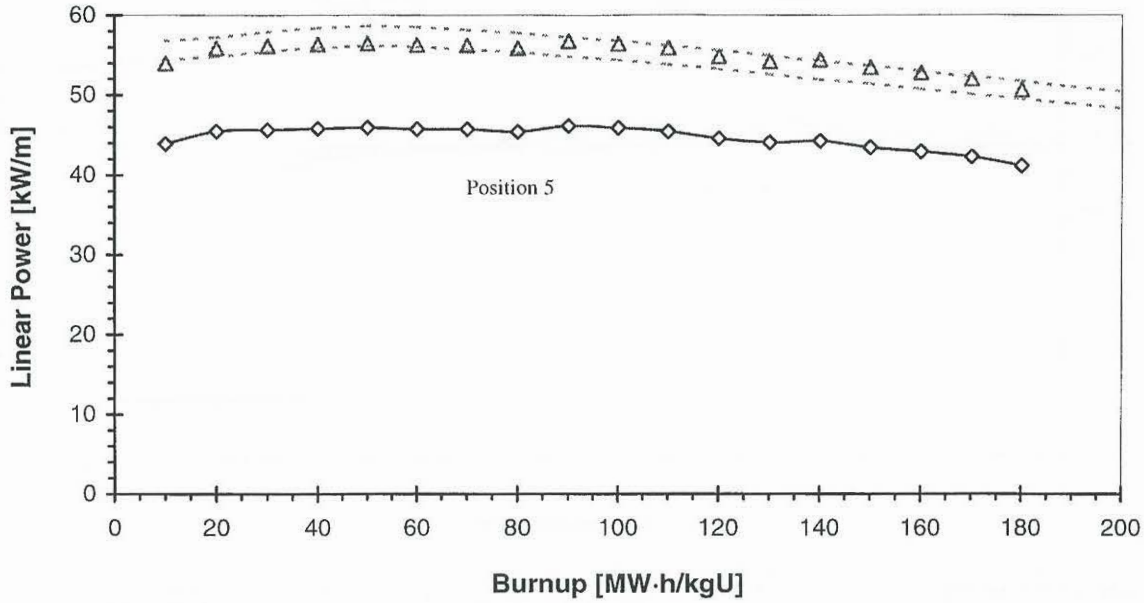

Figure 3: Element linear power history averaged data for channel E-07 obtained from fuel management (bundle in position 5 for the whole period of residence in the reactor)

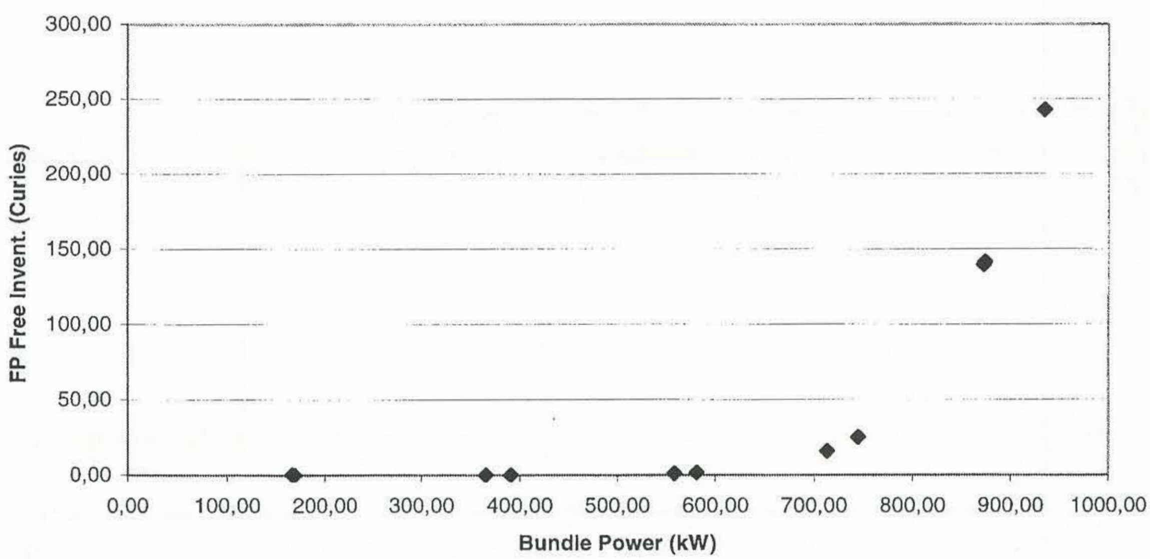

Figure 4: Fission product free inventory for the hottest element, as a function of bundle power