Development of Limiting Decay Heat Values

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1. Introduction

A number of tools are used in the assessment of decay heat during an outage of the CANDU-6. Currently, the technical basis for all of these tools is "CANDU Channel Decay Power", Reference 1. The methods used in that document were limited to channel decay powers. However, for most outage support analysis, decay heat limits are based on bundle heats. Since the production of that document in 1977, new versions of codes, and updates of general-purpose and CANDU-specific libraries have become available. These tools and libraries have both a more formal technical basis than Reference 1, and also a more formal validation base. Using these tools it is now possible to derive decay heat with more specific input parameters, such as fuel composition, heat per unit of fuel, and irradiation history, and to assign systematically derived uncertainty allowances to such decay heat values. In particular, we sought to examine a broad range of likely bundle histories, and thus establish a set of limiting bundle decay heat values, that could serve as a bounding envelope for use in Nuclear Safety Analysis.

2. Summary of the validation of the code and nuclear data libraries

2.1. Validation of the code

The ORIGEN-S code, Ref. 2, as a part of the SCALE computational sequence, Ref. 3, has been extensively validated and verified through years of international experience with the code in various applications including analysis of measurements and benchmarks, and code comparison studies.

Recently, a series of benchmark calculations using the ORIGEN-S code has been performed at AECL-WRL and the report has been presented. These calculations were intended to assess the performance and the accuracy of the code and nuclear data libraries for use in applications within the Canadian nuclear industry. The report documented a series of both experimental and numerical benchmarks aimed at demonstrating code verification and validation, as required by CAN/CSA N286.7. The verification studies compared the ORIGEN-S results with a wide array of the codes that use similar numerical methods, and codes that use independent methods (analytical solutions). Validation was performed with benchmarks involving validated standards, experimental measurements, or other validated codes.

The results of verification indicated that the ORIGEN-S methods are accurate, and produce results that are within the range of other code predictions.

The validation benchmarks demonstrated that the ORIGEN-S accurately predicts results over a wide range of applications including a broad class of problems to which the code is routinely applied by the Canadian nuclear industry.

The report also serves as a baseline verification and validation document for nuclear data libraries associated with the ORIGEN-S code.

2.2. Validation of the cross-section libraries

Validation of the CANDU cross-section libraries was performed at AECL by comparing a series of decay heat predictions against measured decay heat from the Douglas Point reactor fuel bundles, and the ANSI/ANS-5.1-1979 Standard.

Calculations of the Douglas Point decay heat values are generally within the experimental uncertainty of the measurements. The average ratio of calculated to measured results has a small positive bias and standard deviation. These data characterise the accuracy of the cross section library for fuel with cooling times ranging from about one month to six years.

The ORIGEN-S decay heat results are within the range established by the ANS 5.1 – 1979 decay heat standard in the range of cooling time from discharge to about 30 years.

As mentioned by the library developers, the CANDU cross section libraries were generated under certain assumptions regarding operating power, but real bundle power histories may be significantly different from what was assumed. The error associated with this assumption was estimated to be insignificant.

3. Determination of limiting bundle cases

In order to generate a limiting decay-power curve, ORIGEN-S was used in a parametric study of decay-power fraction versus exit power, burnup, and power history, with a basis set of bundle data. A decay heat fraction curve that enveloped the highest fraction would then be extracted for use in Safety Analysis, where needed.

This section describes a range of bundle histories selected so that it encompasses the full spectrum of normal reactor conditions, including bundle power, burnup, and history. Because of differences in terminology, care is taken to ensure that the definitions of items such as thermal power, and fission power are consistent between code and plant interpretation.

3.1. Selection of a basis set of bundle data

Total number of burnup histories considered was 64. Simulated histories include all 5 types of bundle shifts existing in the 8 bundle shift scheme, namely,

- bundle shift from position 1 to 9,
- bundle shift from 2 to 10,
- bundle shift from 3 to 11,
- bundle shift from 4 to 12, and
- bundle residing in positions 5-8.

Examples of simulated burnup histories are shown in the figures 1 - 2. For example, in Figure 1, three bundle shifts from position 3 to position 11 are shown, each shift occurring at a different burnup.

Pre-shift bundle residence time was a variable parameter. The time and, accordingly, the burnup have been calculated using correlations from Reference 4, which relate the ratio of the bundle power before shifting to the power for the nominal power-burnup envelope and the bundle burnup at which the shift occurs. Variation of these parameters was managed so that

a) its range covers operating conditions, but
b) correlation formulae are kept valid.

Curve '3→11 230', see Figure 1, illustrates a violation of the condition b). Here, the bundle shift 3 → 11 occurred at burnup of 230 MW*h/kgU, which is considered within the operational envelope, but the character of power change (it should drop, but it increased instead) indicates that the correlation formula is not valid for that burnup. However, this curve was used as it still may correspond to some operating conditions.

3.2. Simulation of bundle burnup history

Note that previous generations of the decay heat calculations, namely, ANS-5.1-1979 Standard, Reference 5, and AECL-5704, Reference 1, assume that bundle was kept at constant power throughout the operating period. This is an approximation. Consequently, an additional source of uncertainty appeared and the magnitude of uncertainty was to be evaluated. In the current study, a set of realistic power-burnup histories is considered. Simulation of bundle burnup history includes up to 90 time steps. Selection of the total number of steps used and their arrangements is consistent with the approach used at AECL-WRL for generation of CANDU cross section libraries. The CANDU libraries were each created for eight burnup intervals, which may be required for high accuracy isotopic studies. The eight intervals maintain a micro cross section change of less than 1% over any given interval. In current study, each burnup/time interval is split into ten, where new isotopic concentrations are re-calculated, thereby maintaining equal accuracy of macro cross sections over all eighty time steps, i.e. over the burnup range from 0 to 276.5 MW*h/kgU. When an exit burnup is higher than upper limit of this range, additional 10 time steps are included into simulation of burnup history.

The power histories are based on pro-ratings of the nominal power/burnup envelope. The bundle power before and after shifting, bundle burnup at which the shift occurs were calculated using the correlation formulae (see Reference 4):

$$F_1 = f_1(A, B, F_2, F_{\lim}, \sigma_F)$$
$$\omega = f_2(C, F_2, D, \sigma_\omega)$$

where:

F1	is the ratio between the bundle power before shifting and the power for the nominal power-burnup envelope,
F2	is the ratio between the bundle power after shifting and the power for the nominal power-burnup envelope,
Flim	is the maximum allowable value of F1 and F2, which corresponds to a power that would be 960 kW at the plutonium peak,
ω	is the bundle burnup at which the shift occurs,
A, B, C, D	are correlation coefficients,
σ_F, σ_w	are uncertainty corrections.

In order to generate required power-burnup histories, two auxiliary FORTRAN programs were developed and used. There was always exact match between the actual exit burnup calculated by ORIGEN-S using generated power history and the target exit burnup used as input in auxiliary FORTRAN codes. The match confirms that FORTRAN codes indeed produce power-burnup histories as required.

3.3. Calculation of bundle decay heat

Each decay heat curve was generated using four ORIGEN-S runs that cover four consecutive decay intervals over a range from 0.36 seconds to 120 days at 40 time steps. A similar curve presented in Reference 1 seems to be based on decay heat calculations at six times.

The total number of burnup histories considered was 64. Simulated histories include all five types of bundle shifts existing in the eight bundle shift scheme. Pre-shift bundle residence time was a variable parameter.

An exit bundle power, that is a power at shut down, varied over a wide range. Minimum exit power was 117 kW, maximum exit power was 934.7 kW. Exit bundle burnup was in the range from 12.65 MW*h/kgU to 400 MW*h/kgU. Bundle residence time was in the range from 11.35 days to 790 days

Simulation of bundle burnup history included up to 90 time steps. Selection of total number of steps and their arrangements is based on an approach used for generation of CANDU cross section libraries. The CANDU libraries were each created with eight intervals, which may be required for high accuracy isotopic studies. The eight intervals maintain a micro cross section change of less than 1% over any given interval. In current study, each interval was split into 10 steps, where new isotopic concentrations were re-calculated, thereby maintaining equal accuracy of macro cross section over all eight intervals, i.e. over the burnup range from 0 to 276.5 MW*h/kgU. When an exit burnup to be simulated was higher than upper limit of this range, additional 10 time steps were included into simulation of burnup history.

4. Results

A set of high power bundles was simulated as a part of decay heat study, and that included simulation of un-shifted bundles with a maximum power ranging from 600 kW to 935 kW. All essential aspects of the simulation were the same as those described in previous sections. A part of the study included simulation of un-shifted bundle with maximum power of 935 kW. The bundle burnup was a variable parameter changing over the range 12.65 – 400 MW*h/kgU, see Table 1. This range covers all typical operating conditions, it also encompasses such cases as premature unloading of defective bundle or abnormally long operation due to, say, unavailability of refuelling machine. As seen from Figure 3, corresponding decay heat fractions are very close to each other, thus confirming the fact that the ratio of post-shut down decay heat to pre-shut down thermal power, P/P0, is a stable parameter over a wide variety of bundle histories.

Table 1. Parametric Study of High Power Bundle Histories

Bundle History Identification	Exit Bundle Power, kW	Exit Burn up, MW*day /bundle	Exit Burn up, MW*h /kgU
935-9	632.84	327.50	400.0
935-8	736.77	226.38	276.5
935-7	781.91	188.64	230.4
935-6	820.82	150.90	184.3
935-5	863.88	131.15	138.2
935-4	910.37	75.46	92.16
935-3	934.69	37.748	46.1
935-2	927.35	18.834	23.0
935-1	918.01	10.358	12.65

Note that despite of wide variation of exit burnup, decay heat fractions are close to each other and very well inside the established envelope. Two known facts are confirmed using these results. First, curves of this family have the same maximum in a short decay time range because its magnitude is mainly determined by the maximum bundle power,

Figure 1. **Power/burn up histories**

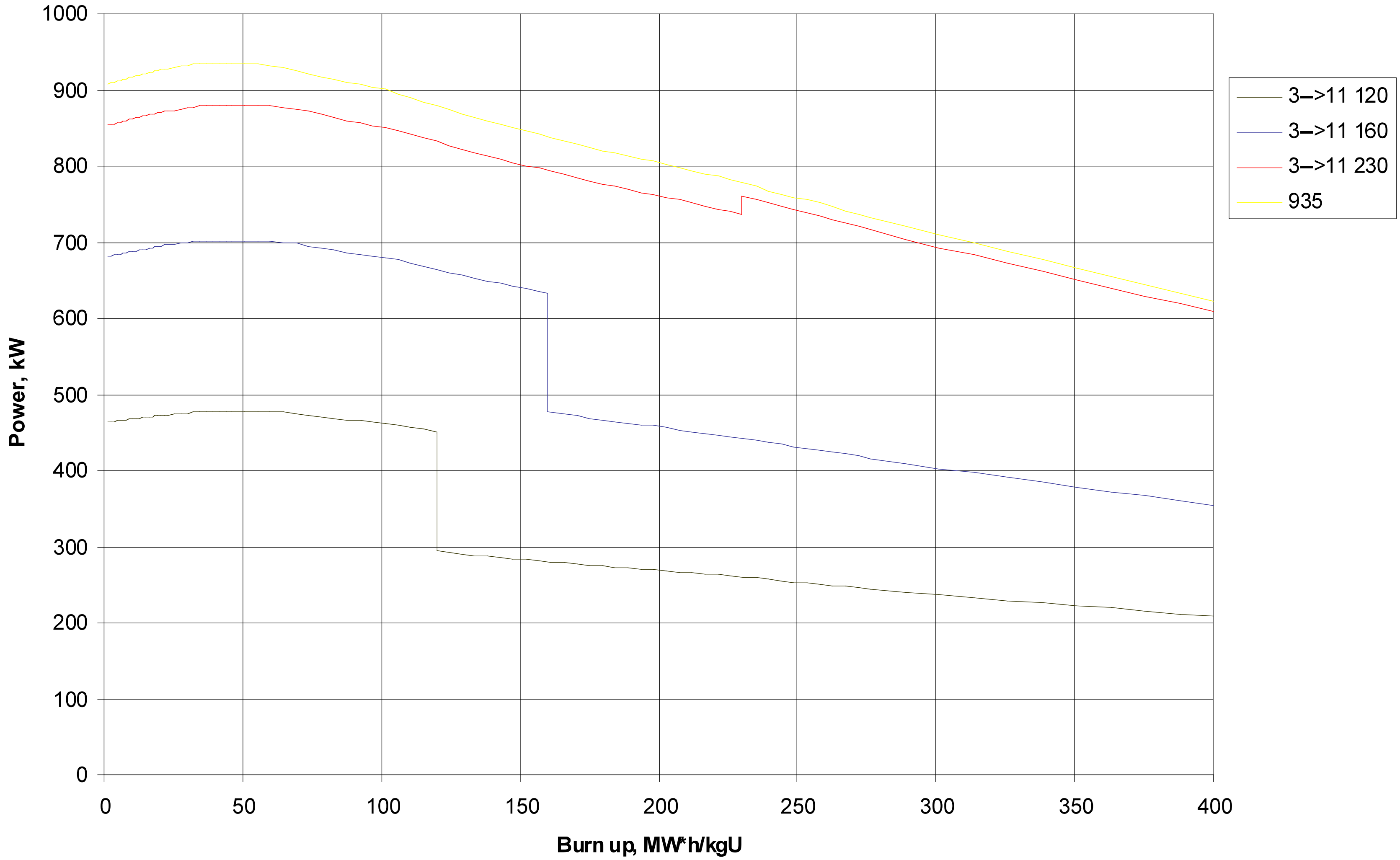


Figure 2. Power/burnup histories

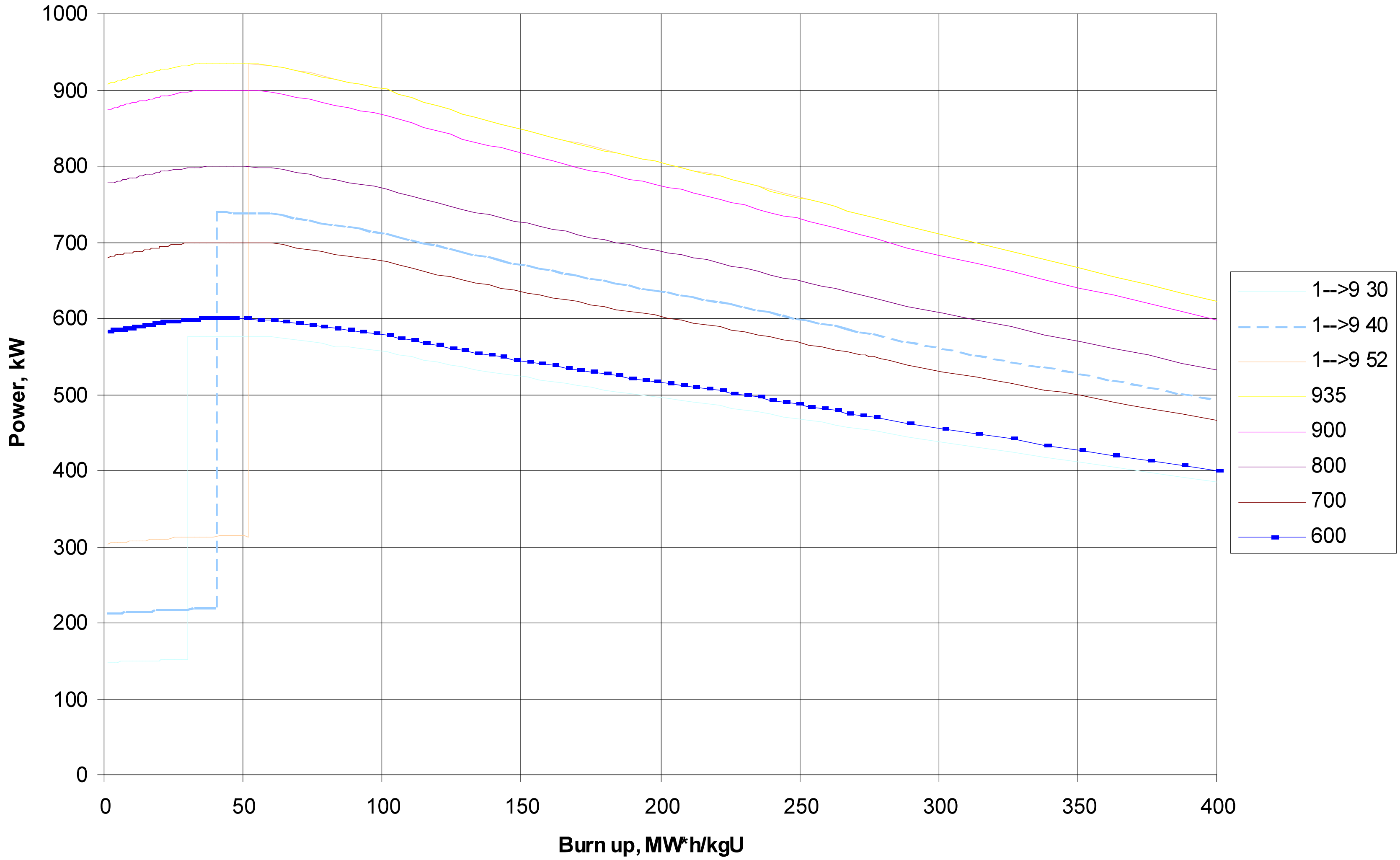


Figure 3. Dependance of Bundle Decay Heat on Burnup for P(max)=935 kW

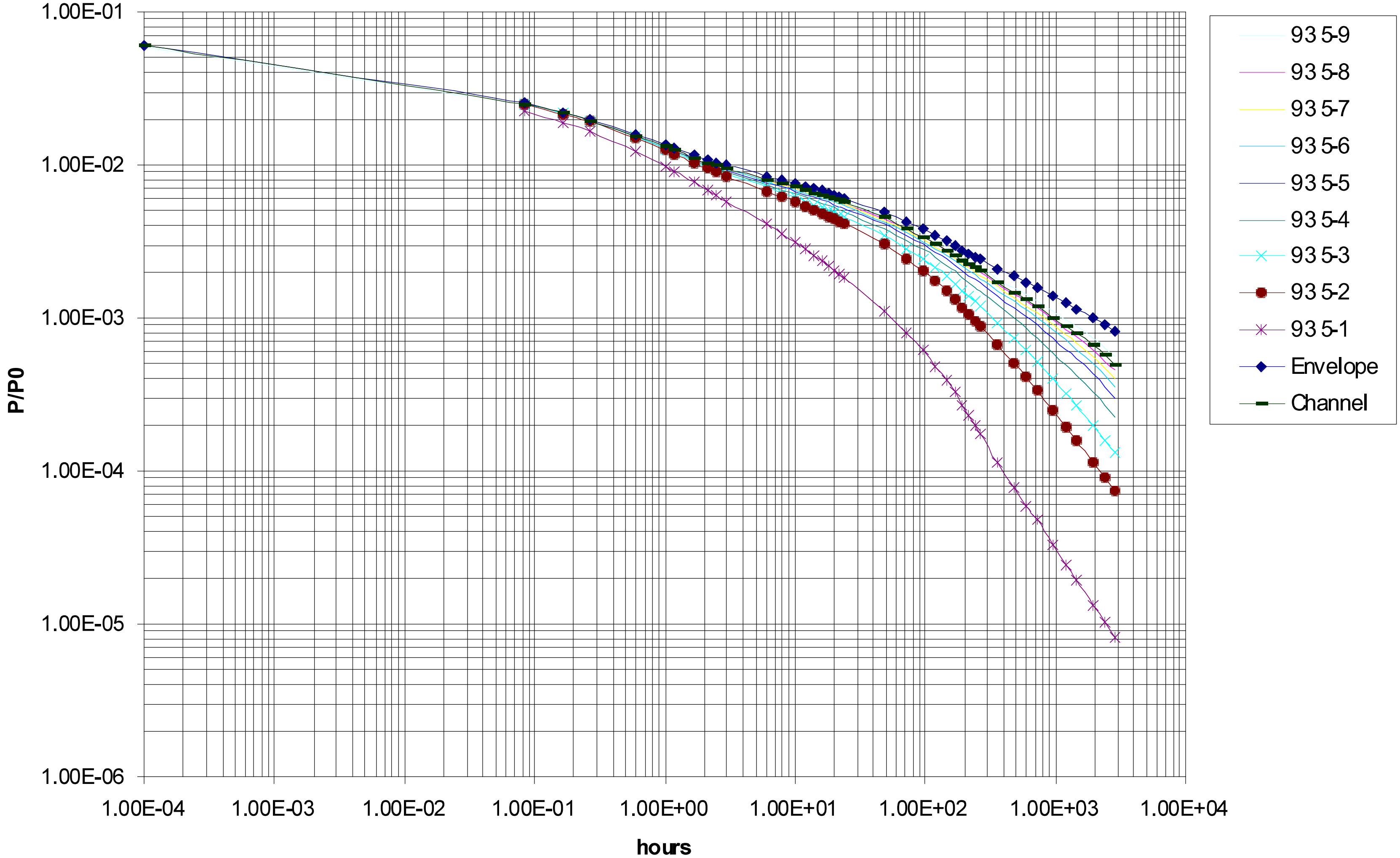
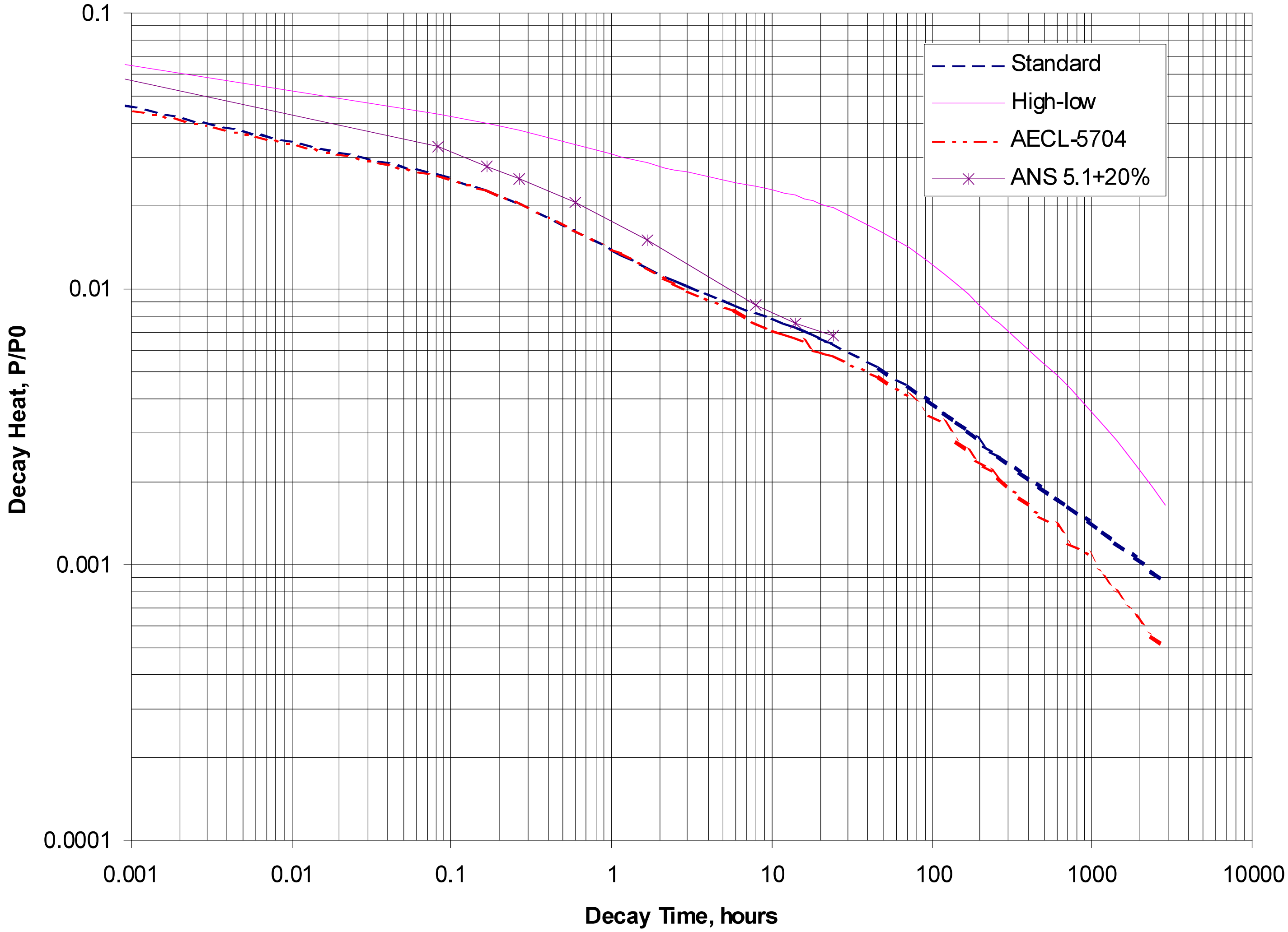


Figure 4. Comparison of Decay Heat Curves



which is the same in all cases. Second, in a longer decay time range, the higher the bundle burnup - the higher the heat decay curve.

The limiting heat decay curve for a CANDU 37-element fuel bundle gives the variation with time of the ratio of bundle decay heat after reactor shut down to bundle power before shut down. It was found not practical to use a single curve for decay heat characterisation; thus, two curves were produced, as shown in Figure 4. The first curve is applicable to wide range of bundle histories including un-shifted bundles, bundles that have been shifted from lower power position to higher power position, and bundles that have been shifted to lower power position in at least 50 MW*h/kgU prior to reactor shut-down. In a short cooling time range, this curve is very close to that presented in Reference 1 . However, in a long cooling time range (until 120 days), the new curve is somewhat higher mainly because a very high fuel burnup (up to 400 MW*h/kgU) was included in the simulation. The second curve was generated for bundles that have been shifted from higher power to lower power position shortly before the reactor shut-down. This curve is higher than the channel heat decay curve (Reference 1) because decay heat up is controlled by pre-shift bundle power.

5. Summary

Limiting decay heat values for a CANDU 37-element fuel bundles have been developed. New features of this development incorporate

- The latest version of calculation tools and nuclear data files, that have both a more formal technical basis and a more formal validation base.
- The use of more specific input parameters, such as fuel composition, heat per unit of fuel
- The use of a set of realistic power-burnup bundle histories instead of an assumption of constant power operation.
- A wider fuel burnup range.
- A greater degree of detail in the description of irradiation history and cooling time.

It was found that

- Currently used channel decay powers are close to newly generated bundle limiting decay heat values for un-shifted bundles and for bundles that have been shifted from lower power position to higher power position.
- However, channel decay powers cannot be applied for decay heat assessment of bundles that have been shifted to lower power position in at least 50 MW*h/kgU prior to reactor shut-down.

6. References

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2. O.W. Hermann and R.M. Westfall, "ORIGEN-S - SCALE System Module to Calculate Fuel Depletion, Actinide Transmutation, Fission Product Buildup and Decay, and Associated Radiation Source Terms", NUREG/CR-0200, Rev.5 (ORNL/NUREG/CSD-2/V2/R5), Vol 2, Section F7.

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5. American National Standard for Decay Heat Power in Light Water Reactors, ANSI/ANS-5.1 – 1979, American Nuclear Society, Lagrange Park, Illinois (1979).