Attachment 1
Appendix K Decay Heat Standards

ATTACHMENT 1

# DECAY HEAT CHANGES TO 50.46 AND APPENDIX K

## 1. INTRODUCTION

In Reference 1, the staff recommended:

> "(A) changes to the technical requirements of the current 50.46 (Reference 2) related to acceptance criteria and evaluation model(s), and (B) development of a voluntary risk-informed alternative to the reliability requirements in 50.46."

Reference 1 identified implementation of a modern decay heat standard in the 50.46 best estimate option and Appendix K (Reference 3) as possible changes. This attachment describes an approach for implementation of the ANSI/ANS-5.1-1994 decay heat standard (Reference 4) in 50.46 and in particular Appendix K.

## 2. BACKGROUND REGARDING DECAY HEAT

Originally, 10CFR50.46 (Reference 2) allowed only one evaluation model option, which is described in Section I of Appendix K to 10CFR Part 50 (Reference 3). Section I of Appendix K describes about 40 required and acceptable features for ECCS evaluation models, including heat produced from decay of fission products based on the Draft ANS 1971 decay heat standard (Reference 5) and from the decay of actinides. The 1994 standard requires the user to specify more parameters than is the case for the 1971 draft standard. This attachment describes how for Appendix K analysis, a single "curve" can be developed using pre-determined selections from Reference 4. Those selections are discussed and evaluated in sections 3 and 4 of this attachment. Pre-determined selections would minimize the complexity of any model reviews.

Below is a description of the various ANS decay heat standards for comparison purposes.

_1971 Draft Standard (Reference 5)_ - The 1971 draft standard has three features relevant to Appendix K analysis:

1. A figure of Fraction of Operating Power vs. Time After Shutdown for infinite reactor operating time. For "convenience" a table of constants is provided for exponential decay equations to be used sequentially during four consecutive time periods. These equations provide a fit within the accuracy of the curve.
2. A table of uncertainties for the curve.
3. Two standard equations for the decay of two actinides ($^{239}U$ and $^{239}Np$).

This and subsequent standards apply only to thermal reactors initially loaded with $^{235}U$ and $^{238}U$ with modest enrichments and assumes the buildup of $^{239}Pu$ for such reactors.

Appendix K requires the use of the 1971 standard for infinite operation for decay heat but is silent on the use of the figure or the sequential equations. The Appendix K decay heat multiplier of 1.2 is the maximum positive value from the uncertainty table in Reference 5 for shutdown times less than $10^7$ seconds. Appendix K requires the consideration of actinide decay but does not refer to the 1971 draft for this purpose.

*1973 Draft Standard (Reference 6)* - The 1971 draft standard was re-issued in 1973 with one modification. The set of constants for the sequential equations was replaced by a table of Fraction of Operating Power vs. Time After Shutdown to better reflect the graphical curve. Comparison of the sequential equations in Reference 5 indicates discontinuities at the beginning and end of the time regimes.

*1979 Standard (Reference 7)* - The 1979 standard is a substantial technical advancement over previous standards. This was made possible by research programs initiated in 1974 by DOE (ERDA), NRC and EPRI. Specific models are now included for neutron capture. Shutdown times (cooling times) are extended from $10^7$ to $10^9$ seconds. Decay heat from three fissionable isotopes (thermal fissioning of $^{235}U$ and $^{239}Pu$ and fast fissioning of $^{238}U$) is considered explicitly. Analytical expressions are provided for decay heat power from a fission pulse and after a finite operating time. These expressions, which are the sum of exponential terms, are given for each of the three starting isotopes. Each analytical expression is the sum of 23 exponential terms. The constants for these exponential terms are provided in tables for the three fissionable isotopes. Two sets of tables for each of the fissionable isotopes are provided for shutdown times up to $10^9$ seconds by evaluating the analytical expressions for pulse fission and for operating times of $10^{13}$ seconds. For all six tables $1\sigma$ uncertainties are provided for each shutdown time calculated. Thus, the uncertainty is not a single value for all shutdown times as is the case in Appendix K.

Methods are provided for evaluating decay heat from operating histories that can be represented by a histogram of N time intervals at constant power. The basic equation for this procedure was also provided in the 1971 standard but no detail was provided concerning its derivation. The 1979 standard also provides methods for determining overall uncertainty. The equations for evaluating decay of actinides $^{239}U$ and $^{239}Np$ are virtually identical to the 1971 standard.

A simplified method is provided for determining decay heat power and its uncertainty. This method utilizes $^{235}U$ only over an infinite operating history at constant power. A $1\sigma$ uncertainty of 4% and an additional multiplier of 1.02 is proposed without explanation in the 1979 standard.. It appears that this simplified method is meant to simulate the type of conservatism specified in Appendix K but updated to incorporate new information.

*1994 Standard (Reference 4)* - The tables in the 1979 standard have been revised to reflect further improvement in data and uncertainties. A fourth fissionable isotope, $^{241}Pu$, has been added. The shutdown time range has been extended to $10^{10}$ seconds for all fissionable isotopes.

The simplified method is different from the one in the 1979 standard. The uncertainty methodology for the1994 simplified method is based on using the isotope with the largest uncertainty. For the first 200 seconds after shutdown this is the fast fissioning of $^{238}U$, even though this is not a very abundant source of fissioning. There are other questions about the uncertainty methodology in Reference 4 which are discussed in Appendix A. NRC staff and members of the ANS 5.1 decay heat subcommittee are reviewing the uncertainty methods and examples to determine the need for modification to Reference 4.

## 3. APPENDIX K DECAY HEAT IMPLEMENTATION BASED ON 1994 ANS STANDARD

From the above description it is obvious that the 1994 standard (Reference 4) is not a simple "curve" as is the case for the 1971 standard (Reference 5). However, by making conservative or even bounding selections of various tables, equations, parameters and uncertainty methods, the equivalent of a simple curve could be constructed along with a substantial reduction in conservatism. Also much of the conservative philosophy of Appendix K would still be retained. Following is a discussion of 6 categories of assumptions that must be made to implement the 1994 ANS standard. Recommendations are made for each category. Section 4 provides an evaluation of the effect of the recommendations. Selections are based on the equations, tables and methods in Reference 4 and Appendix A.

1. *Operating Time* - Infinite operating time is the simple choice in Appendix K. The 1994 standard describes a method for using a histogram approach to account for operating history. It is possible to develop a bounding histogram similar to that described in Example 1 of the standard. However, it is not expected to be significantly different from the infinite operating time assumption. It is therefore suggested that infinite operating time (T) be assumed for all equations where that is possible. That is, for exponential decay equations for fission products and actinides that have the term:

$$1.0 - \exp(-\lambda T),$$

it should be assumed that the term is equal to 1.0. This includes Equations 14 and 15 for actinide decay and the equations for F(t,T) that accompanies each table of $\alpha$ and $\lambda$ for exponential decay. Infinite operating time also results in the subtractive terms being deleted from Equations 8 and 10.

2. *Fission Fractions Per Isotope* - The 1971/73 standard assumed $^{235}U$ as the only fissioning isotope. Information for three additional isotopes is provided in the 1994 standard. Fission fractions vary with time and space. The 1994 standard states that the values chosen are user determined. Lattice physics calculations with appropriate enrichments, core geometry and burnup are needed to determine isotopic fission fractions. Fission fractions should also be evaluated along with recoverable fission energy. Evaluation of Reference 8 may provide insight as to how to assess this parameter in the context of the 1994 standard. In Section 4 several assumptions regarding fissioning fractions are evaluated. This included a fissioning mix of 90% $^{235}U$ and 10% $^{238}U$. Since $^{238}U$ has the highest uncertainty, this turns out to be more conservative than $^{235}U$

only. 10% fast fissioning of $^{238}U$ is a conservatively high value for LWRs. However, the analysis in Section 5 showed that the 90/10 assumption is only slightly conservative compared to 100% $^{235}U$. It is also conservative to assume that decay heat from other fissioning isotopes is bounded by the decay heat from $^{235}U$. Therefore it is recommended that fissioning is assumed to be 100% $^{235}U$.

3. _Neutron Capture_ - This effect is burnup dependent and was added to the 1979 and 1994 standards. The model in the standard appears to be conservative and adds to the decay heat. It is recommended that Equation 11 be used for the effect of neutron capture for shutdown times less than 10,000 seconds. Since Equation 11 has a term $T^{0.4}$, $T=\infty$ will not work. Thus $T=2.0X10^8$ seconds (~6.3 years) is conservatively chosen. In Equation 11, $\Psi$ is the fissions per initial fissile atom. A value of 1.0 is chosen which assumes a high plutonium production. Use Table 13 to account for neutron capture for shutdown times greater than or equal to 10,000 seconds. Table 13 always shows larger capture factors than Equation 11. These selections are evaluated in Section 4.

4. _Fission Energy_ - Each fissionable isotope has different recoverable fission energies, which are required by the standard. Values and uncertainties for fission energies are not specified in the standard. It is recommended that the total recoverable fission energy assumed should be 200 MeV/fission for all fissionable isotopes. This may be conservative by at least 2%. This assumption is assessed in Section 4.

5. _Actinide (Heavy Element) Decay_ - The same basic equations are presented in the 1971, 1979 and 1994 standards. However, the required $^{239}U$ fission yield is not specified and is burnup dependent. It is recommended that Equations 14 and 15 be used for actinide decay with the infinite operating assumption described above. A value of 0.7 is chosen for the $^{239}U$ yield factor, R. Example 1 in Reference 10 assumes 0.6. Informal curves from H. Richings in the 1970's assumed 0.7. The default value in RELAP5 (Reference 9) is 1.0. Actinides are further discussed in Section 4.

6. _Tabular Data_ - Three tables are provided for each of the four fissionable isotopes. One of the three tables provides constants for 23 exponential decay groups, which may be used in a calculation to determine the decay heat as a function of shutdown time for each fissionable isotope. The other two tables provide decay heat and uncertainty as a function of time. The first of these tables represents the decay heat power per fission following an instantaneous pulse of a significant number of fission events. The second of these two tables represents the decay heat power from fission products produced over an infinitely long operating period without neutron absorption in the fission products. The uncertainty values in these two tables are $1\sigma$ values. Use of the exponential decay equations for F(t,T) and the constants provided in the tables for 23 decay groups is suggested because the other two tables require interpolation.

7. _Decay Heat Uncertainty_ - Since 1973 it has been recognized that the Appendix K application of the 1971 standard has a degree of conservatism that exceeds the decay heat uncertainty. The uncertainty methods described in the 1994 standard do not appear to be nearly as large as the

1971 standard. Use of the 1994 standard with nominal inputs and uncertainties could result in a substantial reduction of overall conservatism in Appendix K analysis.

The current version of Appendix K makes no break size distinction concerning the application of the decay heat requirement. Longer transients, such as small breaks, would derive a larger benefit from a reduction in decay heat compared to faster large breaks. Among the required features of Appendix K, decay heat is the only one that has clear application to small breaks.

The following equation for overall uncertainty is derived in Appendix A and is evaluated in Section 4:

$$[\Delta F_T]^2 = [X_{235} * \Delta F_{235}]^2 + [X_{238} * \Delta F_{238}]^2 \qquad (1)$$

where:

$\Delta F_T$ = overall 1$\sigma$ uncertainty (MeV/fission)

$X_{235}$ = fraction of fissions attributable to $^{235}U$

$X_{238}$ = fraction of fissions attributable to $^{238}U$

$\Delta F_{235}$ = 1$\sigma$ uncertainty assigned to $^{235}U$ (MeV/fission)

$\Delta F_{238}$ = 1$\sigma$ uncertainty assigned to $^{238}U$ (MeV/fission)

RES is evaluating appropriate use of the uncertainty methods described in the 1979 and 1994 standards. We have contacted ANS about this issue. Thus, additional work may be needed to modify the standard. For use in 50.46, the 1994 standard could be partially adopted with choices that obviate the uncertainty issue as discussed in Section 6. Nonetheless, we suggest that the NRC work with the ANS to assure a proper uncertainty is used in the ANS standard. Appendix A discusses the four equations identified for possible re-evaluation.

To be consistent with the philosophy of References 3 and 10, an overall 2$\sigma$ value should be utilized. The multiplier (1.0+2$\sigma_T$) should be applied to the sum of fission product and actinide decay heat.

## 4. RESULTS OF PROPOSED APPENDIX K DECAY HEAT IMPLEMENTATION

This section compares decay power fractions as a function of shutdown time for the proposals described above and for other decay heat assumptions.

Two spread sheets were developed by PNL to evaluate Examples 1 and 4 in Reference 4 and provided to the NRC. One spread sheet was then substantially modified to reflect the assumptions described in Section 3 above. Two SAS2D/ORIGEN calculations were also performed. One calculation was for a 17X17 PWR assembly for 3 typical cycles. The other calculation was for a typical 10X10 BWR assembly The ORIGEN results were then compared to the results using the 1973 Standard (Reference 6) and the 1994 Standard (Reference 4). SAS2/ORIGEN calculates decay heat from first principles and fundamental data. Hence, these calculations provide a benchmark to values derived from the ANS standard.

Table 1 summarizes the assumptions for the calculations presented in Table 2.

**Table 1. Calculational Assumptions**

| Case No. | Model | Multiplier | Operating Time | Fiss. Fractions | Capture Time (sec.) | $\psi$ | Fiss. Ener. MeV/F. | Actinide Yield | Isotope Tables | Isotopic Uncertainties |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | *Current Appendix K* | | | | | | |
| 1 | ANS73 | 1.2 | ∞ | 100%235U | N/A | N/A | N/A | 0.7 | N/A | N/A |
| | | | | *Appendix K Proposals* | | | | | | |
| 2 | ANS94 | 2σ,add | ∞ | Note 3 | 2e8 | 1.0 | 200 | 0.7 | Note 7 | Note 8 |
| 3 | ANS94 | 2σ,RMS | ∞ | Note 3 | 2e8 | 1.0 | 200 | 0.7 | Note 7 | Note 8 |
| 3a | ANS94 | 2σ | ∞ | 100%$^{235}$U | 2e8 | 1.0 | 200 | 0.7 | Note 7 | Note 9 |
| 4 | ANS94 | mean | ∞ | Note 3 | 2e8 | 1.0 | 200 | 0.7 | Note 7 | N/A |
| | | | | *Best Estimate* | | | | | | |
| 5 | ORIGEN[1] | mean | Calc. | Calc. | Calc. | Calc. | Calc. | Calc. | Calc. | N/A |
| 6 | ANS94 | mean | ORIGEN[5] | Note 4 | 1.2e8[5] | 1.0 | ORIGEN[5] | .514[5] | Note 7 | N/A |
| 7 | ANS94 | mean | ORIGEN[6] | Note 4 | 1.2e8[6] | 1.0 | ORIGEN[6] | .508[6] | Note 7 | N/A |
| 8 | ORIGEN[2] | mean | Calc. | Calc. | Calc. | Calc. | Calc. | Calc. | Calc. | N/A |

Note 1 -17X17 PWR assembly
Note 2 - 10X10 BWR assembly
Note 3 -Assumes fissioning fractions are 90% $^{235}$U and 10% $^{238}$U as described in Section 3.
Note 4 -Cycle average values from ORIGEN for four isotopes.
Note 5 -From 17X17 ORIGEN calculation
Note 6 -From 10X10 ORIGEN calculation
Note 7 -23 group exponential fits as described in Assumption 6 in Section 3.
Note 8 -Used curve fit as provided in Equations A7 and A8 in Appendix A.
Note 9 -Used curve fit as provided in Equations A7.

Table 1 categorizes the cases into 3 groups. The first group contains only the current Appendix K case. The second group includes four different proposals that were evaluated. Including Case 3a, which is the preferred proposal. The third group comprises cases that are classified as "best estimate", which includes ORIGEN calculations or calculations using the 1994 ANS standard with inputs from the SAS2/ORIGEN calculations.

Table 2 presents comparative results up to 10,000 seconds for all nine cases.

## Table2. Comparison of Decay Heat Models

| -0- Shut-down Time (sec) | -1- ANS73 +Acti-nides X1.2 | -2- ANS94 @2$\sigma$ additive uncert. | -3- ANS94 @2$\sigma$ RMS uncert. | -3a- ANS94 2$\sigma$ 100% $^{235}U$ | -4- ANS94 @mean No uncert. | -5- ORIGEN 17X17 Assem-bly | -6- ANS94 @mean ORIGEN 17x17in | -7- ANS94 @mean ORIGEN 10x10in | -8- ORIGEN 10X10 Assem-bly |
|---|---|---|---|---|---|---|---|---|---|
| 1.0 | 0.07874 | 0.07124 | 0.07014 | 0.06896 | 0.06670 | 0.0557 | 0.05633 | 0.05648 | 0.05613 |
| 1.5 | 0.07646 | 0.06882 | 0.06783 | 0.06679 | 0.06470 | 0.0542 | 0.05480 | 0.05494 | 0.05464 |
| 2.0 | 0.07454 | 0.06690 | 0.06598 | 0.06506 | 0.06306 | 0.0530 | 0.05351 | 0.05365 | 0.05339 |
| 4.0 | 0.06998 | 0.06170 | 0.06094 | 0.06027 | 0.05845 | 0.0494 | 0.04982 | 0.04997 | 0.04981 |
| 6.0 | 0.06770 | 0.05836 | 0.05768 | 0.05715 | 0.05541 | 0.0470 | 0.04739 | 0.04753 | 0.04742 |
| 8.0 | 0.06518 | 0.05593 | 0.05529 | 0.05485 | 0.05317 | 0.0452 | 0.04559 | 0.04572 | 0.04566 |
| 10. | 0.06374 | 0.05403 | 0.05343 | 0.05305 | 0.05141 | 0.0438 | 0.04417 | 0.04430 | 0.04427 |
| 15. | 0.06013 | 0.05062 | 0.05008 | 0.04979 | 0.04824 | 0.0413 | 0.04165 | 0.04172 | 0.04177 |
| 20. | 0.05773 | 0.04826 | 0.04776 | 0.04753 | 0.04603 | 0.0396 | 0.03980 | 0.03991 | 0.04002 |
| 40. | 0.05123 | 0.04279 | 0.04237 | 0.04224 | 0.04089 | 0.0355 | 0.03551 | 0.03561 | 0.03590 |
| 60. | 0.04750 | 0.03969 | 0.03931 | 0.03923 | 0.03796 | 0.0331 | 0.03303 | 0.03312 | 0.03349 |
| 80. | 0.04519 | 0.03754 | 0.03719 | 0.03714 | 0.03593 | 0.0315 | 0.03129 | 0.03138 | 0.03181 |
| 100. | 0.04338 | 0.03594 | 0.03561 | 0.03558 | 0.03440 | 0.0303 | 0.02998 | 0.03006 | 0.03067 |
| 150. | 0.03961 | 0.03320 | 0.03290 | 0.03291 | 0.03180 | 0.0279 | 0.02772 | 0.02780 | 0.02833 |
| 200. | 0.03656 | 0.03140 | 0.03113 | 0.03115 | 0.03009 | 0.0264 | 0.02623 | 0.02631 | 0.02675 |
| 400. | 0.03160 | 0.02750 | 0.02727 | 0.02733 | 0.02638 | 0.0233 | 0.02295 | 0.02302 | 0.02357 |
| 600. | 0.02856 | 0.02533 | 0.02512 | 0.02520 | 0.02431 | 0.0214 | 0.02106 | 0.02113 | 0.02173 |
| 800. | 0.02663 | 0.02376 | 0.02357 | 0.02365 | 0.02281 | 0.0200 | 0.01968 | 0.01974 | 0.02039 |
| 1000. | 0.02518 | 0.02253 | 0.02235 | 0.02244 | 0.02162 | 0.0190 | 0.01859 | 0.01865 | 0.01933 |
| 1500. | 0.02275 | 0.02027 | 0.02010 | 0.02020 | 0.01944 | 0.0171 | 0.01656 | 0.01662 | 0.01730 |
| 2000 | 0.02134 | 0.01867 | 0.01852 | 0.01862 | 0.01790 | 0.0157 | 0.01513 | 0.01519 | 0.01598 |
| 4000 | 0.01739 | 0.01514 | 0.01502 | 0.01512 | 0.01449 | 0.0127 | 0.01203 | 0.01208 | 0.01294 |
| 6000 | 0.01531 | 0.01344 | 0.01333 | 0.01343 | 0.01285 | 0.0113 | 0.01057 | 0.01062 | 0.01151 |
| 8000 | 0.01436 | 0.01241 | 0.01230 | 0.01239 | 0.01185 | 0.0104 | .009714 | .009754 | 0.01072 |
| 10000 | 0.01331 | 0.01169 | 0.01159 | 0.01167 | 0.01115 | .00988 | .009128 | .009164 | 0.01014 |

The shutdown times in column 0 are chosen to correspond to Table 1 in the 1973 standard (Reference 6). Table 2 in this paper was limited to 10,000 seconds because this appears to bound the times considered for most Appendix K analyses. Column numbers in this table are the same as the case numbers in Table 1 and in Figures 1, 2 and 3. Figure 1 is a graphical comparison of the 9 calculations shown in Table 2. Figure 2 is an expanded plot for the last two time decades of Figure 1. In particular the expansion in Figure 2 indicates that the best estimate calculations using the 94 standard (curves 6 and 7) are non-conservative relative to comparable ORIGEN calculations (curves 5 and 8). Figure 3 is a graphical representation of the ratio of curves 2 through 8, each divided by the 1973 standard without the 1.2 multiplier. The difference between 1.2 and the values shown in Figure 3 is a measure of the reduction in conservatism that results from using the newer models. The ORIGEN calculations and the calculations using the ANS94 Standard with ORIGEN inputs (Cases 5-8) show that the decay heat curve using the ANS94 Standard and the choices explored in this report (Cases 2-4) has a sufficient amount conservatism relative to decay heat uncertainties. The close grouping of Cases 2, 3, 3a and 4 and the close grouping of Cases 5, 6, 7 and 8 indicates that the uncertainty is not as important as the user choices.

A second decay heat sensitivity study was performed to explore the effect of individual choices described in Section 3. This study is described in Appendix B. In particular, Appendix B describes a potential non-conservatism arising from the treatment of actinides in the ANS standard. However, it is not recommended that an actinide correction be applied at this time until further review by the ANS5.1 Decay Heat Subcommittee. Figures 1, 2 and 3 indicate that the model selections for Case 3a (the preferred proposal) contain enough conservatism to compensate for the actinide non-conservatism even up to 10,000 seconds.

It is suggested that a change in the decay heat requirement for Appendix K could be implemented based on the 1994 standard. The user choices and uncertainty methods described in Section 3 and used in Case 3a would be the preferred choice for use in Appendix K.

## 5. DECAY HEAT IMPLEMENTATION FOR THE REALISTIC OPTION IN 50.46

The 1988 revision to 50.46 provides an evaluation model alternative to Appendix K that allows use of realistic or "best-estimate" methods. Except for break spectrum requirements and a reference to GDC35, there are no specific technical requirements for best estimate evaluation models in 50.46. However, Regulatory Guide 1.157, "Best Estimate Calculations of ECCS Performance" (Reference 10) does provide an extensive description of models, correlations, procedures, and methods that are acceptable to the NRC staff for meeting the requirements for best-estimate calculations described in the 1988 revision to 50.46. Reference 10 includes modeling guidance for decay of actinides and fission product decay heat based on the 1979 ANS decay heat standard (Reference 7). Reference 10 states that the 1979 decay heat standard "is considered acceptable for calculating fission product decay heat." The guide also states that the effects of neutron capture should be included. The methodologies for decay heat are nearly identical in the 1979 standard (Reference 7) and the 1994 standard (Reference 4). It is recommended that the 1994 standard, with appropriate choices for user input and uncertainty methods, be considered acceptable for best estimate analysis. Any existing best estimate models that currently use the 1979 standard could easily change to the 1994 standard. As in the case for Appendix K analysis, consideration of all relevant actinides is important.

Actually, there is nothing that prevents a licensee/applicant/vendor from utilizing the 1994 standard for best estimate analysis right now. But making the modification to Reference 10 with some specific guidance would be a regulatory improvement.

## 5. CONCLUSIONS AND RECOMMENDATIONS

Changes to the decay heat model in Appendix K could be implemented as described in this report. If adopted the decay heat implementation for Appendix K could be as follows:

1. "Grandfather" the current Appendix K decay heat requirements.

2. Add an Appendix K option to use the 1994 ANS standard with the following pre-selected choices, which are equivalent to Case 3a in Figures 1, 2, and 3 and should be incorporated in a Regulatory Guide rather than the rule:

   1) Assume $^{235}U$ is the only fissioning isotope
   2) Assume infinite operating time
   3) Assume 200 MeV/fission recoverable fission energy
   4) Use Equation 11 in Reference 4 for neutron capture effect for shutdown times less than $10^4$ seconds. Use 2.e8 seconds operating time for this equation. Use 1.0 as the value for $\Psi$.
   5) Use Table 13 in Reference 4 for neutron capture for shutdown times greater than or equal to $10^4$ seconds.
   6) Apply Section 4 in Reference 4 for the decay heat contribution of $^{239}U$ and $^{239}Np$. Use a value of 0.7 for R.
   7) Use a $2\sigma$ value of uncertainty for $^{235}U$ based on the bounding curve of Figure A1 (Equation A7) in this paper. Along with choices 1) and 2), this obviates the need to consider methods to combine uncertainties.

3. Add another Appendix K option to allow use of a subsequent consensus standard and/or selection of user choices other than those shown above.

Regardless of the disposition of decay heat in Appendix K, it is recommended that the modification of Regulatory Guide 1.157 (Reference 10) as described in Section 5 be implemented.

## 7. REFERENCES

1. USNRC, "Status Report on Study of Risk-informed Changes to the Technical Requirements of 10 CFR Part 50 (Option 3) and Recommendations on Risk-informed Changes to 10 CFR 50.46 (ECCS Acceptance Criteria)," SECY-01-0133, July 23, 2001.

2. 10 CFR Part 50 §50.46, Acceptance Criteria for Emergency Core Cooling Systems for Light-water Nuclear Power Reactors, January 4, 1974, amended September 16, 1988.

3. 10 CFR Part 50, Appendix K to Part 50 - ECCS Evaluation Models, January 4, 1974, amended September 16, 1988.

4. American Nuclear Society, ANSI/ANS-5.1-1994, Decay Heat Power in Light Water Reactors, August 23, 1994.

5. American Nuclear Society, ANS-5 Standards Subcommittee, Proposed ANS Standard -Decay Energy Release Rates Following Shutdown of Uranium Fueled Thermal Reactors, October 1971.

6. American Nuclear Society, Draft ANS-5.1/N18.5, Decay Energy Release Rates Following Shutdown of Uranium Fueled Thermal Reactors, October 1973.

7. American Nuclear Society, ANSI/ANS-5.1-1979, Decay Heat Power in Light Water Reactors, August 29, 1979.

8. H. Tran and V. E. Schrock, "Decay Power Evaluation for Licensing Analysis," ANS Transactions, Volume 54, p. 246, 1987.

9. Scientech, Inc., RELAP5/MOD3 Code Manual, Volume II: Appendix A - Input Requirements, June 1999.

10. USNRC Regulatory Guide 1.157, Best Estimate Calculations of ECCS Performance, May 1988.

11. I. C. Gauld and C. V. Parks, "Standard Methods for Decay Heat Prediction," ORNL Information Paper W6479/IIR-02-01, February 18, 2002.

# APPENDIX A
# UNCERTAINTY EQUATIONS IN 1994 ANS STANDARD
# AND
# DERIVATION OF AN OVERALL UNCERTAINTY EQUATION

This appendix compares several uncertainty equations in the 1994 standard with similar RMS equation and describes the derivation of Equation 1 in Section 3.

## A1. Uncertainty Equation Comparisons

Following is a comparison of four equations in the 1994 standard.

1. Equation 5b in the 1994 Standard is a straight summation of uncertainties for each fissionable isotope. A statistical review suggests the use of an RMS summation, e.g.:

$$(\Delta P'_d)^2 = \sum_{i=1,4} (\Delta P'_{di})^2 \quad (1)$$

instead of:

$$|\Delta P'_d| = \sum_{i=1,4} |\Delta P'_{di}| \quad (1a)$$

where:

$\Delta P'_d$ = One standard deviation in total decay heat power uncorrected for neutron capture in fission products, MeV/sec

$\Delta P'_{di}$ = One standard deviation decay heat power for the ith fissionable nuclide, uncorrected for neutron capture in fission products, MeV/sec

2. It is also suggested that the summation symbol in the last term in Equation 9 in the 1994 Standard may need to be outside the brackets so that it too is converted to an RMS summation, e.g.:

$$[\Delta P'_{di}/P'_{di}]^2 = [\Delta Q_i/Q_i]^2 + \sum_{\alpha=1,N}[P_{ia}\Delta F_i(t_\alpha,T_\alpha)/(Q_i P'_{di})]^2 \quad (2)$$

instead of:

$$[\Delta P'_{di}/P'_{di}]^2 = [\Delta Q_i/Q_i]^2 + [\sum_{\alpha=1,N} P_{ia}\Delta F_i(t_\alpha,T_\alpha)/(Q_i P'_{di})]^2 \quad (2a)$$

where:

$P'_{di}$ = Decay heat power for the ith fissionable nuclide, uncorrected for neutron capture in fission products, MeV/sec

$\Delta Q_i$ = One standard deviation in $Q_i$, MeV/fission

$Q_i$ = Total recoverable energy associated with one fission of nuclide i, MeV/fission

$P_{ia}$ = Average power from fissioning of nuclide i during operation period $T_\alpha$, MeV/fission

$\Delta F_i(t_\alpha,T_\alpha)$ = One standard deviation in $F_i(t_\alpha,T_\alpha)$, (MeV/sec)/(fission/sec)

$F_i(t_\alpha,T_\alpha)$ = Decay heat power $t_\alpha$ seconds after an operating period of $T_\alpha$ sec at constant fission rate of nuclide i in the absence of neutron capture in fission products, (MeV/sec)/(fission/sec)

3. For Equation 10 in the 1994 Standard to be in RMS form, it should be:

$$\Delta F_i(t,T)^2 = \Delta F_i(t,\infty)^2 + \Delta F_i\,(t+T,\infty)^2 \qquad (3)$$

instead of:

$$\Delta F_i(t,T) = \Delta F_i(t,\infty) - \Delta F_i\,(t+T,\infty) \qquad (3a)$$

4. Several reviewers have suggested that the denominator in the last term in Equation 13 of the 1994 Standard should not be $Q^2$, but should be $(F_{max} - F_{min})^2$, so that Equation 13 is:

$$[\Delta P_d/P_d\,]^2 = [\Delta P_{max}/P_{max}\,]^2 + [(\Delta F_{max})^2 + (\Delta F_{min})^2]/(F_{max} - F_{min})^2 \qquad (4)$$

instead of:

$$[\Delta P_d/P_d\,]^2 = [\Delta P_{max}/P_{max}\,]^2 + [(\Delta F_{max})^2 + (\Delta F_{min})^2]/Q^2 \qquad (4a)$$

See Section 3.6 and Example 4 in the 1994 Standard (Reference 4) for an explanation of terms for the simplified method.

**A2. Alternate Overall Uncertainty Equation**

The derivation of Equation 1 in Section 3 results from the consideration of Equations 5, 9 and 10 in the 1994 Standard (Reference 4). In References 4 and 7 the uncertainties are defined as $\Delta F$, $\Delta P$, or $\Delta Q$. This Appendix will use that $\Delta$ terminology.

Assumption 1 in Section 3 assumes infinite operating time. Thus equation 3 or 3a in Section A1 becomes:

$$\Delta F_i(t,T) = \Delta F_i(t,\infty) \qquad (A1)$$

where:

$\Delta F_i\,(t,T)$ = one standard deviation in $F_i\,(t,T)$ (MeV/fission)

$F_i\,(t,T)$ = decay heat power t seconds after an operating period of T seconds of ith fissionable isotope uncorrected for neutron capture (MeV/fission)

t = shutdown time (seconds)

T = operating time (seconds)

Assuming no uncertainty in the recoverable energy per fission and only one infinitely long operating power interval, Equation 2 or 2a in Section A1 reduces to:

$$\Delta P'_{di} = P_i \, \Delta F_i(t,\infty)/Q_i \tag{A2}$$

where:

$\Delta P'_{di}$ = uncertainty in fission product decay heat power contribution by the ith fissionable isotope uncorrected for neutron capture (MeV/second)

$P_i$ = average power from fissioning of fissionable isotope i (MeV/second)

$Q_i$ = total recoverable energy with one fission of fissionable isotope i(MeV/fission)

For several test cases evaluated in Section 4, the two fissionable isotopes considered are $^{235}U$ and $^{238}U$. Denoting these isotopes by the subscripts 235 and 238, and substituting Equation A2, Equation 1 in Section A1 becomes:

$$[\Delta P'_d]^2 = [P_{235} \, \Delta F_{235}(t,\infty)/Q_{235}]^2 + [P_{238} \, \Delta F_{238}(t,\infty)/Q_{238}]^2 \tag{A3}$$

where:

$\Delta P'_d$ = total one $\sigma$ uncertainty in fission product decay heat power uncorrected for neutron capture (MEV/second)

The fraction of fission power attributable to $^{235}U$ is defined as:

$$X_{235} = P_{235}/P_T \tag{A4}$$

where:

$X_{235}$ = the fraction of fission power attributable to $^{235}U$

$P_T$ = total fission power (MeV/second)

Similarly for $^{238}U$, the fraction of fission power attributable to $^{238}U$ is defined as:

$$X_{238} = P_{238}/P_T \tag{A5}$$

Substituting A4 and A5 into A3 and including Assumption 4 in Section 3 that all recoverable fission energy is 200 MeV/fission, the result is the same as Equation 1 of Section 3:

$$[\Delta F_T]^2 = [200^* \Delta P'd/P_T]^2 = [X_{235} \, \Delta F_{235}(t,\infty)]^2 + [X_{238} \, \Delta F_{238}(t,\infty)]^2 \tag{A6}$$

where:

$\Delta F_T$ = overall 1$\sigma$ uncertainty (MeV/fission)

It should be noted that the term $\Delta P'd/P_T$ is the uncertainty as a fraction of full power.

Tabular values for $\Delta F_{235}$ and $\Delta F_{238}$ in Reference 4 are converted to analytical expressions for ease of use in computer codes. The expressions are:

$$\Delta F_{235} = 0.33*t^{-0.22925} \quad \text{(A7)}$$

and:

$$\Delta F_{238} = 1.33*t^{-0.28427} \quad \text{(A8)}$$

where: t = time after shutdown in seconds

The Case 3A recommendation to account for $^{235}U$ only, results in the elimination of the last term in Equation A6 and the total elimination of the need for Equation A8.

Figures A1 and A2 compare Equations A7 and A8 to the tabular uncertainties in Tables 5 and 7 in the 1994 Standard.

## APPENDIX B
## SENSITIVITY TO INDIVIDUAL CHOICES IN THE 1994 ANS STANDARD

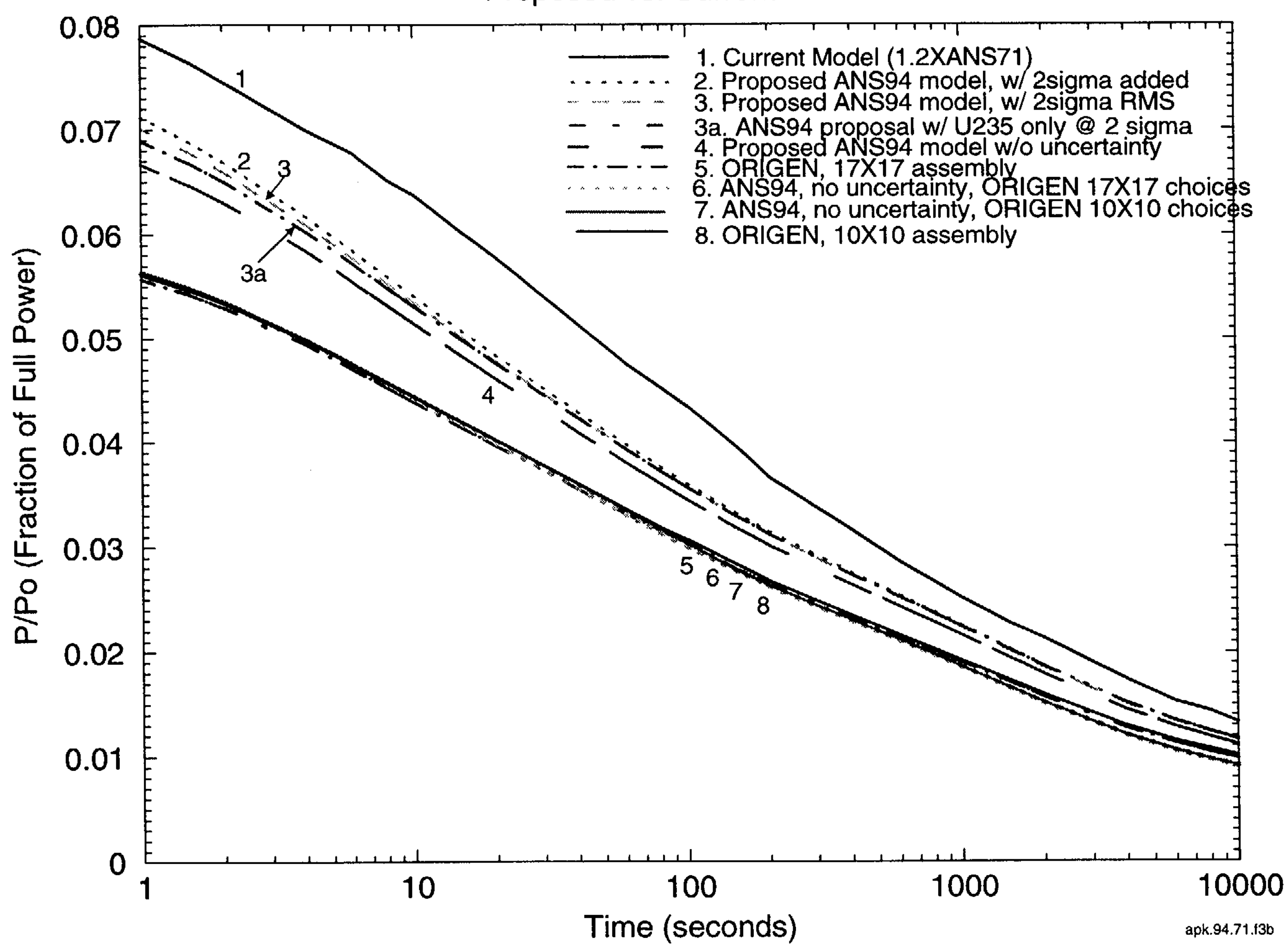
In this study, the base case (Case 0) was taken to be the PWR ORIGEN calculation, which was Case 5 in the Section 4 study. Case 1 in this study is the ANS94 calculation with the PWR ORIGEN input. This is the same as Case 6 in the previous study. Individual changes were then made sequentially to the Case 1 ANS94 calculation. The final calculation was the decay heat model recommended for Appendix K analysis, and is designated as Case 7 in this study and Case 3a in the previous study. Figures B1 and B2 are the graphical representation of results of this study, shown as fraction of full power as a function of shutdown time. Since cases 0 and 1 are repeats of Cases 5 and 3a in the previous study, the same non-conservatism of the 94 standard compared to ORIGEN are clearly indicated in Figure B2. Case 2 is a repeat of Case 1 with only the actinide yield factor, R, changed from the ORIGEN calculated value of 0.514 to a "conservative" value of 0.7. Case 3 is the same as Case 2 with the fission energy value of 200 MeV/ fission used in the Reference 10 examples in place of the values calculated with ORIGEN. In Case 4 the fraction of fissioning isotopes was taken to be 90% 235U and 10% 238U instead of the cycle averaged SAS2 values for the four isotopes as was used in Cases 1, 2 and 3. Case 5 assumes infinite irradiation (1.0e13 seconds). This is in place of the 1.18e8 seconds total fuel irradiation time assumed in case 4. Case 6 uses the infinite irradiation equations described in Assumption 1(Operating Time) in Section 3. As expected, there is virtually no difference between Cases 5 and 6. Case 7 is the recommended choice for Appendix K. There are two changes from Case 6 to Case 7, the change to 100% fissioning from 235U, and use of the $2\sigma$ adder for 235U instead of one of the combined uncertainties.

Figures B3 and B4 display the information in Figure B1 in ratio and difference mode for comparison purposes. In Figure B3 the various decay heat curves calculated using the 1994 standard are divided by the PWR ORIGEN calculation. In Figure B4 the individual changes from the previous ANS94 calculation divided by the ORIGEN value are plotted to show the magnitude of the particular change. Figures B3 and B4 clearly show the growing non-conservatism of the 1994 standard as a function of shutdown time due to the actinide effect.

Reference 11 provides an explanation of the non-conservatism of the 1994 ANS standard compared to ORIGEN as described above. In that paper it is shown that the actinide contribution grows significantly with shutdown time. Figure B5 is a reproduction of Figure 1 in Reference 11, which is a curve of actinide contribution (other than $^{239}U$ and $^{239}Pu$) as a function of shutdown time. The figure shows that at 10,000 seconds actinides other than $^{239}U$ and $^{239}Pu$ can contribute as much as 4% to the total decay heat. At 1000 seconds the contribution is nearly 3%. An analytical expression for a log log straight line conservative approximation is also shown in Figure B5. This added actinide contribution was applied in a spreadsheet to Case 1 in Figures B6 and B7. The new case was designated as Case 1A. Figures B6 and B7 provide comparisons of ORIGEN and ANS94 with ORIGEN input, with and without the actinide modification. As can be seen in Figure B7, the initial time of ANS94 non-conservatism shifts from 60 to 2000 seconds. Figure B7 also shows that at 10,000 seconds the non-conservatism is reduced from 7.3% to 2.7%. Thus, the contribution of other actinides should be considered for increasing shutdown times.

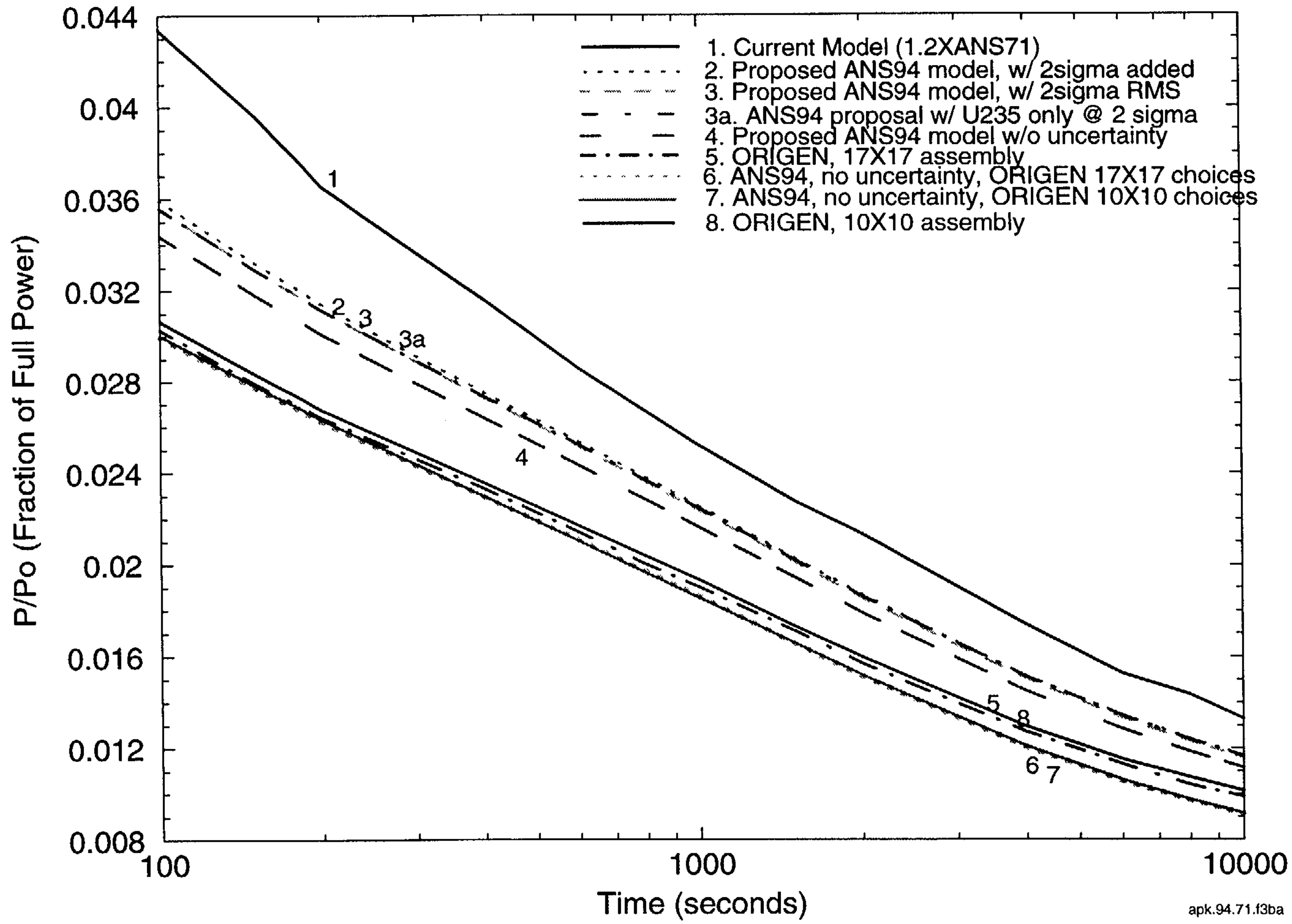
# Figure 1. Appendix K Decay Heat Comparison

Proposed vs. Current Models



# Figure 2. Appendix K Decay Heat Comparison

Proposed vs. Current Models



# Figure 3. Appendix K Decay Heat Comparison

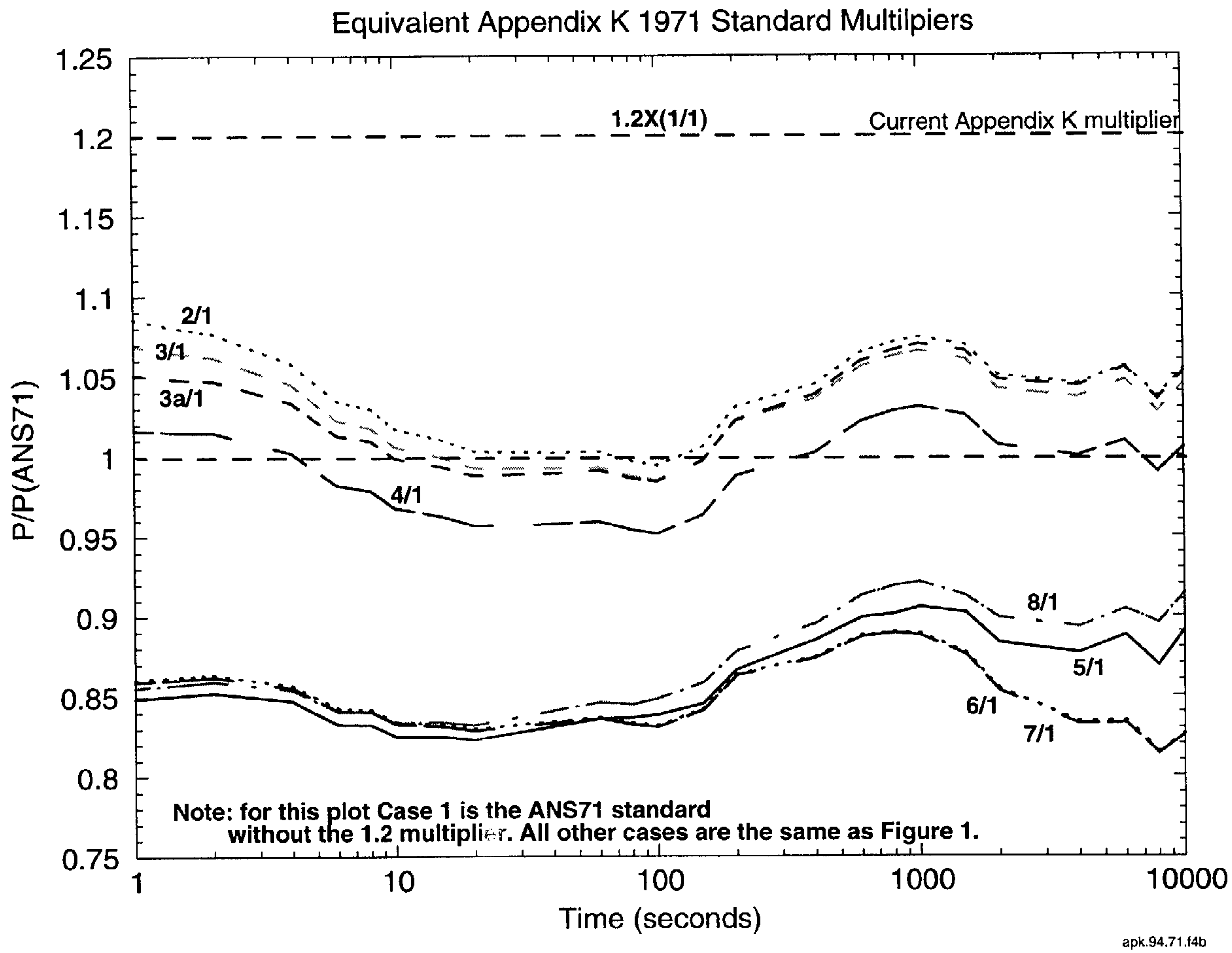
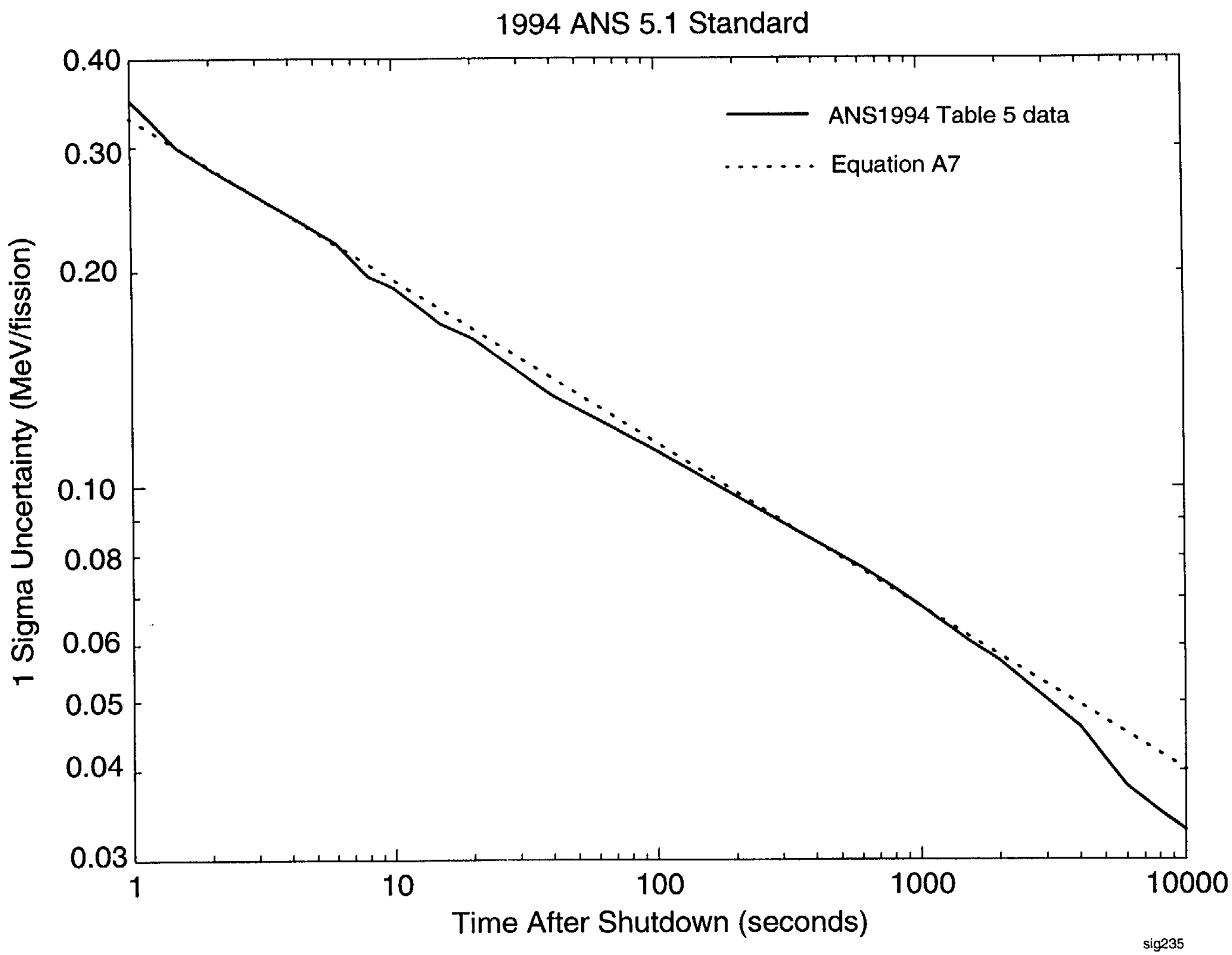


Figure A1. Uranium 235 Decay Heat Uncertainty



## Figure A2.  Uranium 238 Decay Heat Uncertainty

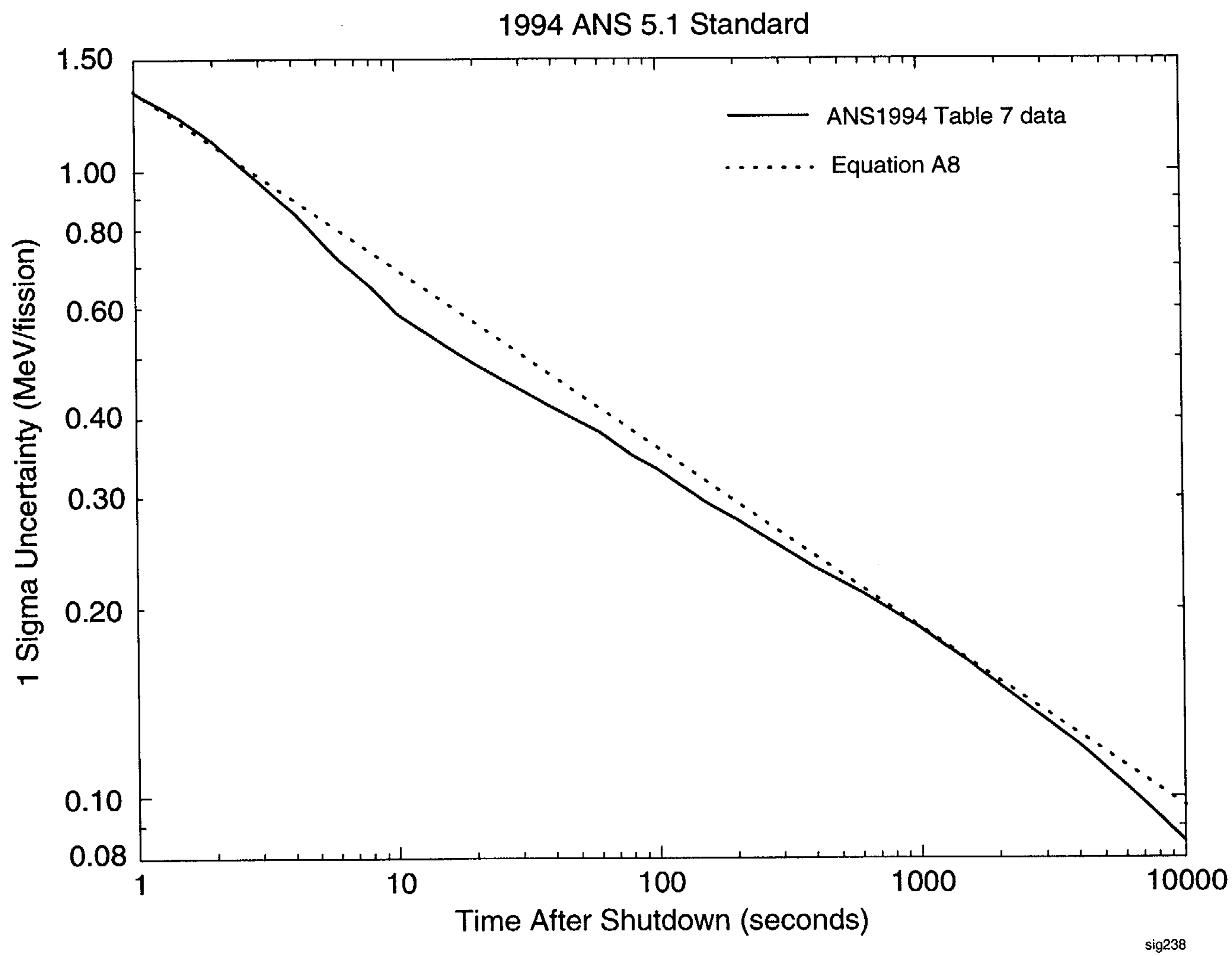
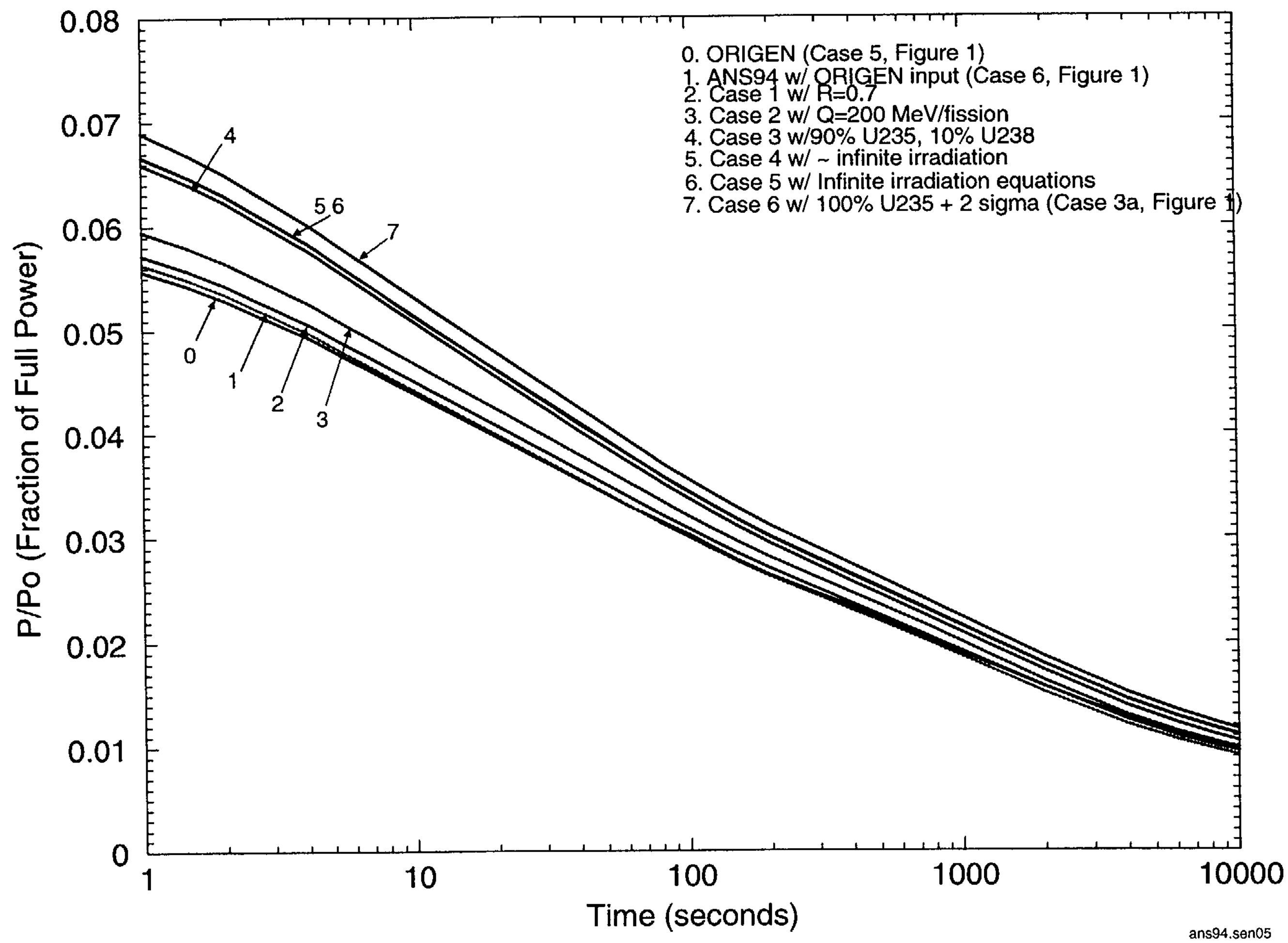
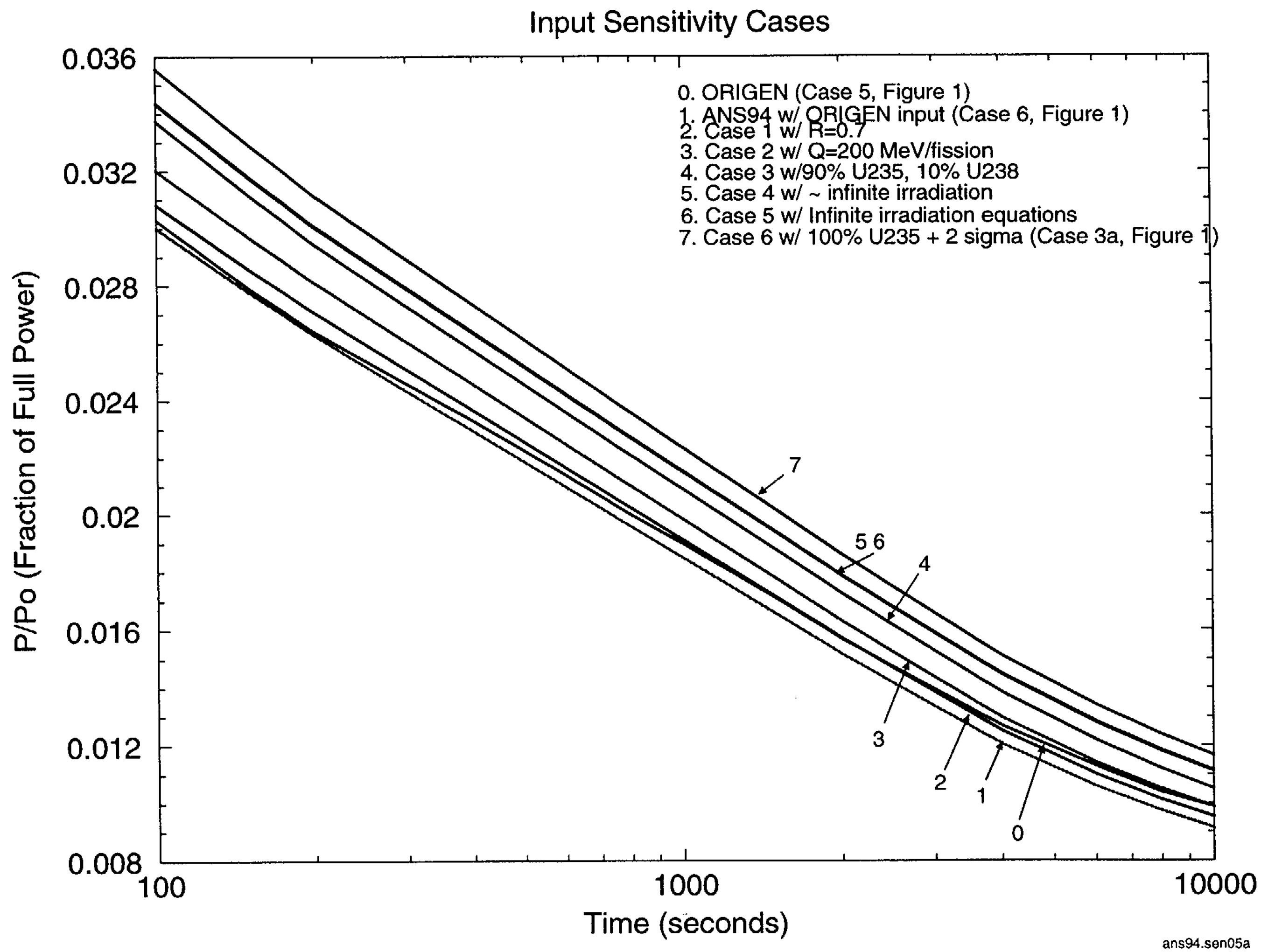


Figure B1. ANS94 and ORIGEN Decay Heat

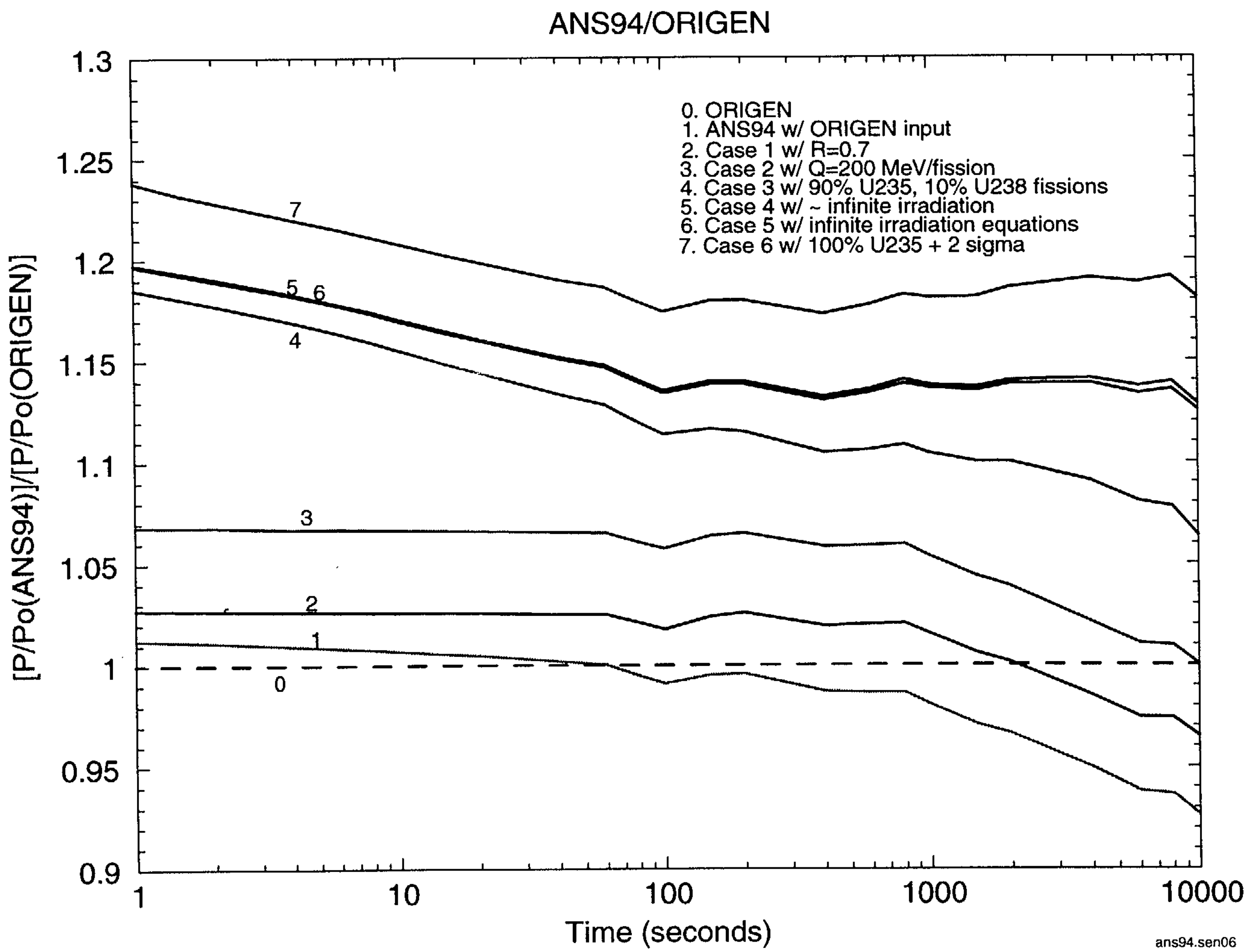
Input Sensitivity Cases



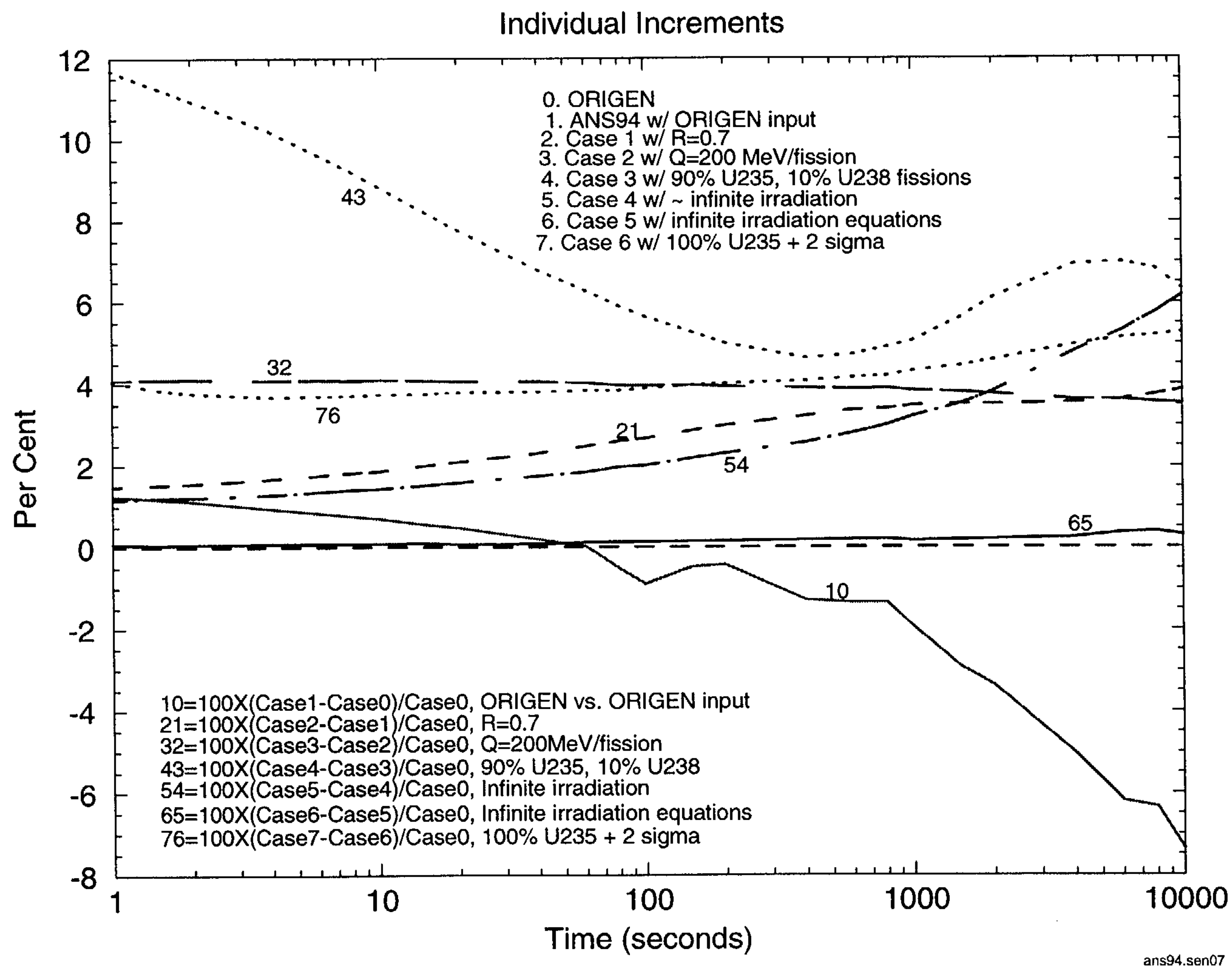
# Figure B2. ANS94 and ORIGEN Decay Heat



# Figure B3. Decay Heat Ratios

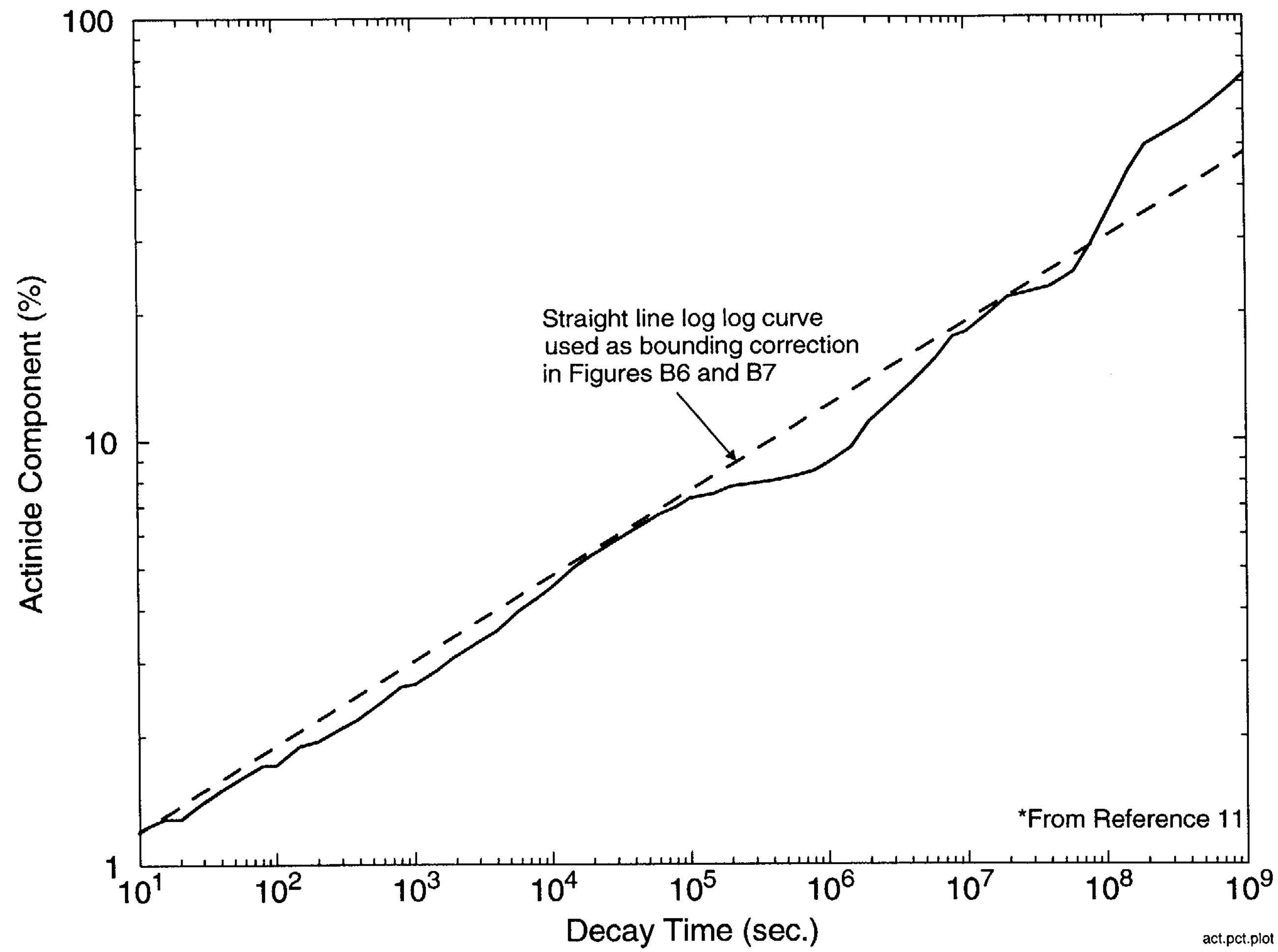


# Figure B4. ANS94 Decay Heat % Differences



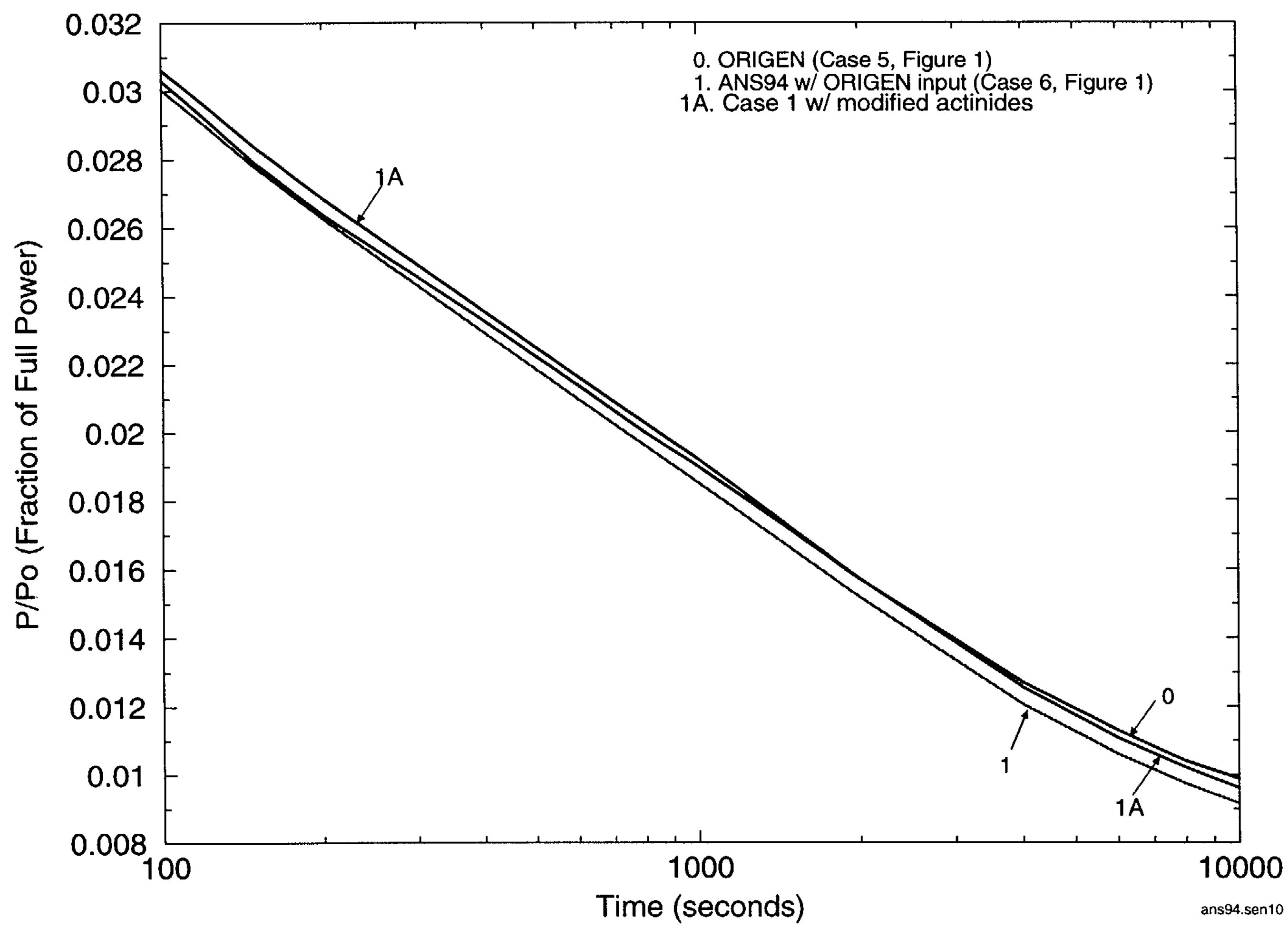
# Figure B5. % of Decay Heat from Actinides*

(Excluding U239 and Np239)



## Figure B6. ANS94 and ORIGEN Decay Heat

Actinide Cases



## Figure B7. ANS94 Decay Heat % Differences

Individual Increments for Actinide Cases