NEANDC(UK)174A
NEACRP-A-400
INDC(UK)-34/G

An Assessment of the Accuracy Requirements on Higher Actinide Nuclear Data for Fast Reactors

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1. INTRODUCTION

Any assessment of the accuracy requirements on higher actinide nuclear data is very much dependent on the type of reactor, the details of the fuel cycle and the ground rules specifying the acceptable uncertainties in parameters to be predicted by calculation. This inevitably leads to limitations in the scope of any study since no single one can be expected to cover all possible aspects. Furthermore, these restrictions result in corresponding limitations in the conclusions. However, even a limited study produces firm conclusions for the particular case in question and, in addition, it provides a starting point for further discussions on wider aspects.

The aim of this paper is to assess the adequacy of the nuclear data needed for fast reactor calculations of the arisings of minor actinides, the α-contribution to decay heat of irradiated fuel and the neutron output from fuel, for a sub-assembly under typical irradiation conditions. The calculated quantities are usually obtained using an inventory code such as FISPIN[1]. Although the details depend upon the code and the data library used therein, the usual method employed is to follow the changes in the number density of each isotope resulting from fission, neutron capture, (n,2n) reactions and radioactive decay, through a specified irradiation. The other parameters of interest are then derived from the computed values of the number densities.

The FISPIN code was used in the calculations along with a one group fast reactor library. Although the data contained in this library no longer constitute the recommended set, it was used for convenience (the most up-to-date library was not then available on the Harwell computer) and it was proved that this resulted in no significant errors. The decay data contained in the library are those due to Sidebotham[2].

The FISPIN code takes account of all significant paths leading to the production or destruction of each isotope; e.g. the production of Pu-238 can occur by the following routes (a) neutron capture in Np-237 followed by the decay of the product nucleus Np-238, (b) decay of

Cm-242 and (c) (n,2n) reactions in Pu-239. The uncertainty in the production or destruction of a given isotope depends on the accuracy of the relevant nuclear data and also on the importance of each pathway. This latter quantity is normally taken into account using sensitivity coefficients.

The method employed in the present study is to find the important sensitivity coefficients for a particular quantity of reactor interest and to compound these with the nuclear data uncertainties in order to arrive at a total uncertainty which is the net result of inaccuracies in the actinide nuclear data. The uncertainties arrived at in this way can then be compared with requested accuracies to identify satisfactory situations or ones where further experimental work is required.

2. METHOD OF ASSESSING THE EFFECT OF ERRORS IN DATA

Let us suppose that the uncertainty in some quantity R is required; R could be, for instance, the neutron output from fuel or the arisings of Am-241. Then, if k isotopes are being followed in the calculation of R and each of these has i items of nuclear data (x_{ki}) included in the data library, the perturbation, ΔR, produced by changes Δx_{ki} in the data is given by

$$\Delta R \doteq \sum_k \sum_i \frac{R}{x_{ki}} \Delta x_{ki} \qquad (1)$$

If the sensitivity coefficient U_{rki} is defined as

$$U_{rki} = \frac{\partial R}{\partial x_{ki}} \cdot \frac{x_{ki}}{R} \qquad (2)$$

then it can be shown that the variance in R ($VAR(R) = \langle \Delta R^2 \rangle$) due to errors in nuclear data is given by

$$\frac{VAR(R)}{R^2} = \sum_k \sum_i U_{Rki}^2 \frac{VAR(x_{ki})}{x_{ki}^2} + \sum_k \sum_i \sum_{\substack{j \\ j \neq i}} U_{Rki}\, U_{Rkj} \frac{COV(x_{ki}, x_{kj})}{x_{ki}\, x_{kj}}$$

$$+ \sum_k \sum_i \sum_{\substack{j \\ j \neq k}} \sum_l U_{Rki}\, U_{Rjl} \frac{COV(x_{ki}, x_{jl})}{x_{ki}\, x_{jl}} \qquad (3)$$

where $COV(x_{ki}, x_{jl})$ is the covariance of x_{ki} and x_{jl}. The second term on the right hand side is the sum of the covariances between the different items of nuclear data for isotope k weighted by the appropriate sensitivity coefficients and summed over all isotopes. The third term in the expression takes account of the covariances between the data types for different isotopes. In the absence of any correlations in the nuclear data, the covariance terms are zero and the expression for $VAR(R)/R^2$ reduces to the sum of the squares of the fractional errors weighted by the sensitivity coefficients. When correlations are present, the expression for VAR(R) shows the importance of taking account of covariances, as VAR(R) can be larger or smaller than the value derived solely from the variances in the nuclear data, depending on the signs of the covariances and the sensitivity coefficients.

The calculation of VAR(R) therefore demands a knowledge of

(a) the sensitivity coefficients,

(b) the standard deviations (or variances) of the nuclear data,

(c) the covariances of the nuclear data (it will be indicated later that the magnitudes of the covariances are small compared with the variances and can therefore be neglected in this study).

The sensitivity coefficients depend on the details of the irradiations and were obtained by running FISPIN for a standard case, followed by a number of other cases in each of which one cross-section or half-life value was altered. The sensitivity coefficient U_{Rki} is then given by

$$U_{Rki} = \frac{\dfrac{R_{ki} - R'_{ki}}{R'_{ki}}}{\dfrac{x_{ki} - x'_{ki}}{x'_{ki}}}$$

where R'_{ki} and R_{ki} are the values of the parameter R calculated for the standard case and when the nuclear datum i of element k is changed from its standard value x'_{ki} to x_{ki}. The difference $(x_{ki} - x'_{ki})$ was generally taken to be approximately equal to the assumed standard deviation of x'_{ki}.

The standard case, based on one adopted by Baker and Phillips(3) consisted of a CDFR outer core sub-assembly, containing a mass of mixed oxide in the core region of 57.4 kg and AGR plutonium as a fraction, 0.296, of the heavy element content. The isotopic composition is given in Table 1. The fuel was assumed to have been stored for four years before 'irradiation' began. In the calculation, the irradiation was done in eight equal time-steps, the total time being 3.118×10^7 s. To allow for the increase in the power generated in the breeder regions of the sub-assembly as the irradiation progressed, the power in the core region was reduced for each time-step in accordance with the values given by Baker and Phillips. At the end of the irradiation, the burn-up was 8.26% and the fuel was then assumed to begin a cooling period. The parameters of interest were followed at various times up to a maximum cooling period of 10 years. Figure 1 shows the variation with time of the number density of actinide atoms; also given at the start of the cooling step is the activity in curies for each isotope. From this figure it is possible to understand the changes of $\Delta R/R$* as a function of time calculated later in the paper. It should be noted that, in order to minimise the computational effort, the calculations were performed only for the core region of the sub-assembly.

It is not reasonable or desirable to include in this paper all the information generated in this study and some selectivity is necessary. Accordingly the sensitivity coefficients and the uncertainties in the following parameters are presented, these being the quantities of greatest interest.

(a) Production of Pu-236,
(b) Production of Pu-238,
(c) Production of Am-241,
(d) Production of Am-243,
(e) Production of Cm-242,
(f) Production of Cm-244,

*From this point onwards, $\Delta R/R$ is used to represent $\sqrt{VAR(R)/R^2}$

(g) α-contribution to decay heat,

(h) Total heat generation,

(i) Neutron output from spontaneous fission,

(j) Neutron output from (α,n) reactions,

(k) Total neutron output.

Table 2 contains a list of the nuclear data altered to obtain the sensitivity coefficients. As expected, many of the sensitivity coefficients are found to be zero or very small and, generally speaking, only those cases which contribute significantly to the overall uncertainty have been included in the results given in Section 4.

3. POINTS RELATING TO THE FISPIN CALCULATIONS AND PRESENTATION OF THE RESULTS

The list of quantities altered (Table 2) in the assessment of the sensitivity coefficients contains all the important cross-sections together with certain half-lives. An examination of the current accuracy of half-life data shows (Table 3) that only those for Pu-241, Am-242m and Cm-243 have uncertainties in excess of 1%, the information being taken from Nichols and James(4). Even if a parameter of interest has a high sensitivity coefficient (e.g. 1.0) with respect to one of the other half-lives, the contribution to the overall uncertainty will be negligible because of the high accuracy of the half-life value. This explains the selection of half-lives included in Table 2.

The data contained in the one-group fast reactor library used in our FISPIN calculations, are on the whole fairly close to the values which are recommended at the present time. To check the effect of using a different data set, the half-life of Pu-241 was varied from its currently accepted value of 14.6y to 13.2y and a series of calculations carried out with this revised value as the standard case. It was found that the sensitivity coefficients thus obtained were almost identical to those already calculated, showing that the coefficients are not sensitive to the absolute values of the data input.

The sensitivity coefficients of many of the cross-sections listed in Table 2 are so small that they make a negligible contribution to the total uncertainty in the particular parameter of interest. Hence, it is unnecessary to consider the uncertainties in these cross-sections. The uncertainties* adopted for the cross-sections of importance and the sources from which these were taken are given in Table 4. At this stage, only differential data were taken into account in assessing the uncertainties.

The absence of the capture and fission cross-sections of the major isotopes (U-238, Pu-239 and Pu-240) from the list in Table 4 does not mean that the reactor parameters are insensitive to these quantities. The uncertainties in these cross-sections have been significantly reduced in the adjustment procedure in which differential and integral measurements are taken into account and it would not be correct therefore to assign uncertainties from differential data only. Changes to these cross-sections can also affect reactor properties such as reactivity and burn-up which make the interpretation of the sensitivity coefficients difficult. Fortunately, it can be shown that this is not a problem. If we assign uncertainties of 3% to the capture and fission cross-sections of the three major isotopes and combine these with the sensitivity coefficients, we find that the uncertainties in all of the parameters studied are negligible compared with those arising from inaccuracies in the cross-sections and half-lives of the minor actinides. It is to be emphasised that the actual uncertainty on the major isotope cross-sections is probably significantly less than 3% which makes it even safer to neglect their contribution to the overall uncertainties.

The estimation of the covariance terms in equation (3) is difficult. Some of the terms, particularly those involving two fission cross-sections, are undoubtedly non-zero due to the frequent use of the U-235 fission cross-section as a standard. However, the uncertainty in this cross-section in the fast region is ~3% and the covariance terms are expected to be small compared to the largest variances. It was therefore felt reasonable to neglect the covariance contributions.

*Throughout this paper, uncertainties are given as one standard deviation, except where stated.

In the FISPIN calculations, the parameters of interest were followed for cooling times ranging from 10^3s to 10y after the irradiation. The results for a selection of four cooling times, 2×10^7s (0.63y), 3×10^7s (0.95y), 6×10^7s (1.90y) and 1.6×10^8s (5.07y), are given in this paper, but others can be made available with little effort.

4. RESULTS

The results of the calculations will now be given for the parameters (a) - (k) listed in Section 2. In each case only the most important contributions will be included. For simplicity, the suffices R, i and j (equation (3)) have been omitted in the headings of the tables.

(a) Production of Pu-236

Table 5 shows the results relating to Pu-236 arisings. It is immediately clear that the overall uncertainty is completely dominated at all cooling times by the uncertainty in the Np-237 (n,2n) cross-section. This reaction leads to two states in Np-236, a short-lived one ($T_{\frac{1}{2}}$ = 22h) and a long-lived one ($T_{\frac{1}{2}} = 1.15 \times 10^5$y). These are generally taken to be the ground state and an isomeric state respectively but, in the latest evaluation(8) from the Nuclear Data Project, the assignments are reversed. Fortunately, this uncertainty does not affect our calculations. The long-lived state has only a relatively weak β^- decay branch (8.9%) leading to Pu-236 compared to the short-lived state (β^- branch 48%) and the production of Pu-236 arises essentially entirely through the formation of Np-236 in its short-lived state. The cross-section required for the FISPIN calculation is therefore that to produce Pu-236 and not the full (n,2n) cross-section.

There are only a few measurements of the Np-237 (n,2n) cross-section leading to Pu-236 and these are generally in the region of 14 MeV. The full (n,2n) cross-section is often derived from systematics, such as those of Pearlstein(9), and the values obtained do not agree very well with the measurements that exist. If we restrict the argument to differential data then one is forced to conclude that the uncertainty in the cross-section for Pu-236 production is very large and 100% is not unreasonable. However, Paulson and Hennelly(10), in an integral experiment, obtained a value of 63 ± 6mb for the Np-237 (n,2n) cross-section leading to Np-236 in its short-lived state, averaged over the U-235 fission spectrum above a neutron energy of 6.8 MeV. They conclude that this value is consistent with Pearlstein's systematics, assuming that the ratio of the formation of Np-236 in its two states has the value measured by Landrum et al(11) using neutrons from thermonuclear devices. The result of Paulson and Hennelly, when used in calculations of Pu-236/Pu-238 ratios in various thermal reactor spectra, gives good agreement with measurement, leading to the conclusion that the integral data are accurate and that the appropriate Np-237 (n,2n) cross-section uncertainty is closer to 10% than 100%. However, it is clear that further measurements are needed to remove the discrepancies between the differential and integral data.

(b) Production of Pu-238

The results of combining the sensitivity coefficients with the uncertainties in the nuclear data involved in the production of Pu-238 are shown in Table 6. The calculations indicate that the uncertainty in the Pu-238 arisings lies between 8 and 9% as a result of nuclear data uncertainties. Almost 80% of the estimated uncertainty stems from that in the Am-241 capture cross-section leading to the ground state of Am-242.

(c) Production of Am-241

The results relating to the production of Am-241 are contained in Table 7. The overall uncertainty varies from 6.3% for a cooling time of 0.63y, falling to 4.4% after a cooling period of 5 years. At short cooling times, most of the uncertainty arises from inaccuracies in the Am-241 capture cross-section to the ground state of Am-242 but at long cooling times, the uncertainty arising from errors in the Pu-241 half-life makes a comparable contribution.

(d) Production of Am-243

Table 8 contains the results of the calculations for Am-243 arisings, showing that the uncertainty is about 10% for the range of cooling times investigated. In this case the dominant contribution arises from the uncertainty in the Pu-242 capture cross-section.

(e) Production of Cm-242

The overall uncertainty and the contributions to the Cm-242 arisings are shown in Table 9. Up to cooling times of ~2 years, the dominant contribution to the uncertainty comes from inaccuracies in the Am-241 capture cross-section leading to the Am-242 ground state but by cooling times of 5 years, the major contribution stems from the capture cross-section to the isomeric state. This situation arises from the Cm-242 half-life of 162.8d; for cooling periods of this order or less, the Cm-242 production is through Am-242g ($T_{\frac{1}{2}}$ = 16h) but for very much longer cooling periods, the route is through the longer lived Am-242m ($T_{\frac{1}{2}}$ = 152y). The calculations indicate that the uncertainty in Cm-242 production due to errors in the nuclear data is typically ~16%.

(f) Production of Cm-244

The results for Cm-244 are shown in Table 10. Over the range of cooling times considered, the total uncertainty due to nuclear data errors is about 22%. The capture cross-section of Am-243 is the major contributor, with the capture cross-section of Pu-242 being the only other significant contribution.

(g) α-Contribution to Decay Heat

The total uncertainty and its various components for the α-contribution to decay heat are given in Table 11. The results show that as a result of data uncertainties, the uncertainty on the α-decay heat falls from ~15% at cooling times of 0.6y to ~4% at 5y. At the short times, the major contribution arises from the Am-241 capture cross-section leading to Am-242g while at the long times, the uncertainty in the Am-243 capture cross-section becomes significant. For cooling times $\lesssim$0.5y, Cm-242 is the dominant source of α-decay heat, while at long cooling times ($\sim$5y), Pu-238, Pu-240, Am-241 and Cm-244 make significant contributions.

Examination of a recent report by Nichols(12) on the current status of evaluated heavy element decay data for reactor calculations indicates that the uncertainties on the important α-particle energies and branching ratios are small compared with the other contributions to the total uncertainty in the α-decay heat and can therefore be safely neglected.

(h) Total Heat Generation

The results for the uncertainty on the total heat generation due to errors in actinide cross-section and decay data are contained in Table 12. The uncertainty is a little less than 6% at the short cooling times, falling to just over 2% after 5 years' cooling. The major contribution at the short cooling times arises from the capture cross-section of Am-241 to Am-242g, while at the long cooling times, the Am-243 capture cross-section begins to play a significant part.

At short cooling times, the total decay heat arises predominantly from fission fragments. Since the uncertainty due to these has not been included in the present study, the overall uncertainty on total decay heat will be considerably larger than indicated in Table 12.

No account has been taken of decay heat arising from activation of the cladding and wrapper materials. This contribution is small compared to that from the fission products, for cooling times up to at least 10^8s (Baker and Phillips(3)).

(i) Neutron Output from Spontaneous Fission

The results of compounding the sensitivity coefficients with the data uncertainties to obtain the total uncertainty on the neutron output from spontaneous fission are shown in Table 13. The uncertainties arising from errors in spontaneous fission branching ratios and $\bar{\nu}$ values are included. The spontaneous fission neutron output originates almost entirely from Cm-242 and Cm-244. Because of the relatively short Cm-242 half life of 162.8d, this isotope, which dominates at short times, is less important for cooling times of longer than $\sim$1y. If we accept the data (and errors) for the spontaneous fission branching ratios given for Cm-242 by Ellis and Haese[13] and for Cm-244 by Schmorak[14] and for $\bar{\nu}_{sp}$ in BNL 325 3rd Edition, Vol.1, then we find that the uncertainties on the neutron emission rates are $\pm$ 10.4% and $\pm$ 0.5% for Cm-242 and Cm-244 respectively. It can be seen from the table that the total uncertainty varies between 14% and 20%. The dominant contribution at times up to $\sim$1y comes from the Am-241 capture cross-section feeding the ground state of Am-242 with significant contributions coming from the Cm-242 spontaneous fission data and Am-243 capture cross-section data. At longer times the Am-243 contribution dominates.

(j) Neutron Output from (α,n) Reactions

The results of the study on the neutron output from (α,n) reactions are shown in Table 14. Included in the table is a 10% allowance for the uncertainty of the (α,n) yield, this figure being arrived at from information supplied by West[15]. At short cooling times, the largest contribution to the overall uncertainty arises from the capture cross-section of Am-241 feeding the ground state of Am-242. However, the uncertainty in the (α,n) yield is also significant and at long cooling times it becomes the dominant effect.

(k) Total Neutron Output

The total neutron output is given by the sum of the spontaneous fission and (α,n) components but because of correlations the uncertainty is not that obtained by summing in quadrature the uncertainties of the two contributions. Table 15 gives the necessary details showing that the error varies from 13.8% to 19.2% depending upon the cooling time. In this particular case calculations have been done for cooling times of less than 2 x 10^7s because the neutrons from irradiated fuel are of importance for reactivity monitoring following a reactor shut down.

5. ASSESSMENT OF RESULTS

The results of the calculations must be compared with the accuracy requirements for the quantities of interest to ascertain whether or not these are met. The requirements for the current stage of the fast reactor programme have been outlined by Baker(16) and these will be used here, without questioning their validity.

Baker suggests that it is desirable to calculate the arisings in waste of Am-241, Am-243, Cm-242 and Cm-244 to a two-sigma accuracy of a factor of two. The results in Tables 7-10 show that the largest standard deviation is ~22% (for Cm-244) so that the required accuracy is very comfortably met so far as uncertainties in nuclear data are concerned.

An important contribution to the neutron output of fresh fuel arises from (α,n) reactions due to the α-decay of Pu-238. Baker states a need to estimate Pu-238 arisings with a standard error of $\pm$ 20% and Table 6 indicates that this requirement is met.

In some circumstances, there is a need to produce Pu-238 with as little Pu-236 contamination as possible to minimise the number of hard γ-rays emitted. For these cases, it would be useful to calculate the quantity of Pu-236 produced to a two-sigma accuracy of a factor of two. Because of the discrepancy between the differential and integral data for Np-237 (n,2n) (Section 4(a)) and the 100% sensitivity of Pu-236 production to this cross-section, this requirement is not yet satisfied (Table 5) and further work is required to remove the discrepancy.

It is hoped that by improving fission product data the total decay heat of spent fuel can be predicted eventually to an accuracy of $\pm$5%. The contribution from uncertainties in actinide data must therefore be small compared to this value. The results in Table 12 show that this is not the case, except for cooling times in excess of 2 years. The total uncertainties given in Table 12 arise almost entirely from the uncertainties in α-decay heat shown in Table 11. An improvement in the knowledge of the Am-241 capture cross-section leading to Am-242g would do most towards meeting the decay heat accuracy requirements.

The neutron output of spent fuel is important for shielding assessments and for reactivity monitoring and Baker suggests standard error requirements of 20% and 10% respectively. The results in Table 15 show that the shielding needs are possibly met whilst those for reactivity monitoring are never met. To improve the accuracy of prediction at short times improved data on the Am-241 capture cross-section to the ground state of Am-242, the Cm-242 fission cross-section and the spontaneous fission branching ratio of Cm-242 are required. At long times the capture cross-sections of Am-243 and Pu-242 become the most important. Since measurements of the Cm-242 fission cross-section are essentially impossible due to its short half-life of 162.8 days, improved data can only become available by improving the accuracy of calculated cross-sections. This requires the making of cross-section measurements on as many higher actinides as possible to improve our understanding of the neutron reaction mechanism of the actinides. Because of current measurement programmes the errors in the (α,n) data have recently decreased to the value of 10% assumed in this study and now do not make a major contribution to the errors in the total neutron production. However, they make a larger contribution for unirradiated fuel; for a 10% uncertainty in the (α,n) yield the resulting errors in the total neutron production are $\pm$ 3.3% and $\pm$ 3.8% at the start and end of the 4 year storage period used in this study.

From the data discussed above it is possible to deduce the quantities which need to be measured in order that the needs specified by Baker can be achieved. These are listed in Table 16 together with their required accuracies. The quantities contained in the table can be considered to be the requirements of the highest priority.

6. LIMITATIONS OF THIS STUDY, AND CONCLUSIONS

The scope of this paper has been limited to assessing the effects of uncertainties in the cross-section and half-life data of the actinides, with some account being taken of the contribution from errors in spontaneous fission $\bar{\nu}$ and spontaneous fission branching ratios, where these are important. The accuracies of neutron-induced $\bar{\nu}$ data, α-particle energies and decay branching ratios are sufficiently high that these sources contribute negligibly to the overall uncertainties. The work has also been restricted to the study of a particular sub-assembly of a given fuel composition irradiated for a specific period at a defined power level. The results will therefore not necessarily apply to other situations, such as a different initial fuel composition or higher burn-up. It is anticipated that in the long term higher accuracies than those suggested by Baker will be required. For instance one cannot imagine that accuracies of $\pm 50\%$ in the arisings will be acceptable once a large scale fast reactor programme has been initiated.

It must also be remembered that if the requirements, as laid down by Baker, are to be interpreted as total overall uncertainties then errors arising from sources other than nuclear data must be taken into account. It is likely that there will be uncertainties associated with following the precise irradiation history for each sub-assembly due to, for example, control rod movements and other spatial effects. This again suggests that the nuclear data requirements must be correspondingly tightened.

The estimates of the cross-section errors given in Table 4 are also subject to uncertainty. It should be noted that most of them have not been obtained from proper evaluations. In many cases there are few measurements and experience tells us that sometimes new measurements produce large and significant changes far outside the previously assessed accuracy. This is difficult to allow for statistically but again it points to the need for a reduction in the errors of required data. It also brings out the importance of confirmatory measurements where few data exist.

The foregoing arguments point to a need for higher accuracy requirements than given in Table 16 - which as stated before gives our list of requirements of the highest priority. The improvement necessary is a matter for discussion.

Finally, Table 17 summarises the accuracies in the calculated quantities that can be achieved for the particular case discussed in the paper using the data errors specified in Table 4 and in the text.

The last column gives an indication of the main contributors to the uncertainties and it can be used to identify the less important data requests.

ACKNOWLEDGEMENTS

The authors are grateful to Drs. J.E. Lynn, M.S. Coates and A.R. Baker for useful discussions and suggestions..

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TABLE 1

Pu and U Composition of Sub-Assembly

(a) Pu Composition

Isotope	% Composition	No. of Atoms
Pu-238	0.8	3.027×10^{23}
Pu-239	49.5	1.873×10^{25}
Pu-240	33.3	1.260×10^{25}
Pu-241	10.8	4.086×10^{24}
Pu-242	5.6	2.119×10^{24}

(b) U Composition

Isotope	% Composition	No. of Atoms
U-234	0.0031	2.790×10^{21}
U-235	0.4	3.599×10^{23}
U-238	99.5969	8.961×10^{25}

TABLE 2

The Quantities Altered in the Assessment of the Sensitivity Coefficients

Quantity	
U-233	$\sigma_{n\gamma}$
U-233	σ_{nf}
U-234	$\sigma_{n\gamma}$
U-234	σ_{nf}
U-235	$\sigma_{n\gamma}$
U-235	σ_{nf}
U-236	$\sigma_{n\gamma}$
U-236	σ_{nf}
U-238	$\sigma_{n\gamma}$
U-238	σ_{nf}
U-238	σ_{n2n}
Np-237	$\sigma_{n\gamma}$
Np-237	σ_{nf}
Np-237	σ_{n2n}
Pu-236	$\sigma_{n\gamma}$
Pu-236	σ_{nf}
Pu-238	$\sigma_{n\gamma}$
Pu-238	σ_{nf}
Pu-239	$\sigma_{n\gamma}$
Pu-239	σ_{nf}
Pu-239	σ_{n2n}
Pu-240	$\sigma_{n\gamma}$
Pu-240	σ_{nf}
Pu-241	$\sigma_{n\gamma}$
Pu-241	σ_{nf}
Pu-241	$T_{\frac{1}{2}}$
Pu-242	$\sigma_{n\gamma}$
Pu-242	σ_{nf}
Pu-242	σ_{n2n}

Quantity	
*Am-241	$\sigma^{g}_{n\gamma}$
**Am-241	$\sigma^{m}_{n\gamma}$
Am-241	σ_{nf}
Am-242g	$\sigma_{n\gamma}$
Am-242g	σ_{nf}
Am-242m	$\sigma_{n\gamma}$
Am-242m	σ_{nf}
Am-242m	$T_{\frac{1}{2}}$
Am-243	$\sigma_{n\gamma}$
Am-243	σ_{nf}
Cm-242	$\sigma_{n\gamma}$
Cm-242	σ_{nf}
Cm-243	$\sigma_{n\gamma}$
Cm-243	σ_{nf}
Cm-243	$T_{\frac{1}{2}}$
Cm-244	$\sigma_{n\gamma}$
Cm-244	σ_{nf}

*Am-241 $\sigma^{g}_{n\gamma}$ means the Am-241 $\sigma_{n\gamma}$ to the ground state of Am-242.

**Am-241 $\sigma^{m}_{n\gamma}$ means the Am-241 $\sigma_{n\gamma}$ to the metastable state of Am-242.

TABLE 3

Half-Lives and Uncertainties

Nuclide	$T_{\frac{1}{2}}$	$\Delta T_{\frac{1}{2}}$	$\Delta T_{\frac{1}{2}}/T_{\frac{1}{2}}$ (%)
U-233	1.5925×10^5y	0.004×10^5y	0.25
U-234	2.446×10^5y	0.007×10^5y	0.29
U-235	7.038×10^8y	0.005×10^8y	0.07
U-236	2.3416×10^7y	0.0039×10^7y	0.17
U-238	4.468×10^9y	0.010×10^9y	0.22
Np-237	2.14×10^6y	0.01×10^6y	0.47
Pu-236	2.851y	0.008y	0.28
Pu-238	87.7y	0.2y	0.23
Pu-239	24115y	80y	0.33
Pu-240	6537y	10y	0.15
Pu-241	14.6y	0.5y	3.42
Pu-242	3.76×10^5y	0.03×10^5y	0.80
Am-241	432y	2y	0.46
Am-242g	16.02h	0.04h	0.25
Am-242m	152y	7y	4.61
Am-243	7380y	40y	0.54
Am-244	10.1h	0.1h	0.99
Cm-242	162.8d	0.5d	0.31
Cm-243	30y	2y	6.67
Cm-244	18.11y	0.02y	0.11

TABLE 4

Adopted Values of Cross-Section Uncertainties and Their Sources

Isotope	Quantity	Uncertainty (%)	Source
U-236	$\sigma_{n\gamma}$	25	Estimated from plot in BNL325, 3rd edition
U-238	σ_{n2n}	20	Guess
Np-237	$\sigma_{n\gamma}$	25	Estimated from plot in BNL325, 3rd edition
	σ_{nf}	10	" " " "
	σ_{n2n}	100	Guess
Pu-236	$\sigma_{n\gamma}$	50	Guess
	σ_{nf}	50	"
Pu-238	$\sigma_{n\gamma}$	50	Estimated from plot in BNL325, 3rd edition
	σ_{nf}	20	" " " "
Pu-239	σ_{n2n}	100	" " " "
Pu-241	$\sigma_{n\gamma}$	20	Patrick[5]
	σ_{nf}	5	"
Pu-242	$\sigma_{n\gamma}$	10	"
	σ_{nf}	5	"
Am-241	$\sigma^{g}_{n\gamma}$	20	Lynn et al[6]
	$\sigma^{m}_{n\gamma}$	20	"
	σ_{nf}	10	"
Am-243	$\sigma_{n\gamma}$	25	Patrick[5]
	σ_{nf}	10	"
Cm-242	$\sigma_{n\gamma}$	50	Guess
	σ_{nf}	50	"
Cm-244	$\sigma_{n\gamma}$	50	Caner and Yiftah[7]
	σ_{nf}	20	" " "

TABLE 5

Uncertainties in Pu-236 Arisings, from Sensitivity Coefficients and Data Uncertainties

Cooling Time		2×10^7s (0.63y)		3×10^7s (0.95y)		6×10^7s (1.90y)		1.6×10^8s (5.07y)	
Sensitivity To	Fractional Uncertainty in Data (i.e. $\Delta x/x$)	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$
U-236 $\sigma_{n\gamma}$	0.25	0.059	2.18×10^{-4}	0.059	2.18×10^{-4}	0.058	2.10×10^{-4}	0.059	2.18×10^{-4}
U-238 σ_{n2n}	0.20	0.78	2.43×10^{-2}	0.78	2.43×10^{-2}	0.78	2.43×10^{-2}	0.77	2.37×10^{-2}
Np-237 $\sigma_{n\gamma}$	0.25	-0.133	1.11×10^{-3}	-0.132	1.09×10^{-3}	-0.134	1.12×10^{-3}	-0.133	1.11×10^{-3}
Np-237 σ_{nf}	0.10	-0.024	5.76×10^{-6}	-0.023	5.29×10^{-6}	-0.025	6.25×10^{-6}	-0.024	5.76×10^{-6}
Np-237 σ_{n2n}	1.0	1.0	1.00	1.0	1.00	1.0	1.00	1.0	1.00
Pu-236 $\sigma_{n\gamma}$	0.50	-0.036	3.24×10^{-4}	-0.036	3.24×10^{-4}	-0.036	3.24×10^{-4}	-0.036	3.24×10^{-4}
Pu-236 σ_{nf}	0.50	-0.028	1.96×10^{-4}	-0.029	2.10×10^{-4}	-0.029	2.10×10^{-4}	-0.028	1.96×10^{-4}
Pu-241 $\sigma_{n\gamma}$	0.20	0.011	4.84×10^{-6}	0.013	6.76×10^{-6}	0.013	6.76×10^{-6}	0.012	5.76×10^{-6}
Pu-241 σ_{nf}	0.05	0.064	1.02×10^{-5}	0.063	9.92×10^{-6}	0.065	1.06×10^{-5}	0.063	9.92×10^{-6}
Pu-241 $T_{\frac{1}{2}}$	0.035	-0.170	3.54×10^{-5}	-0.176	3.79×10^{-5}	-0.169	3.50×10^{-5}	-0.183	4.10×10^{-5}
$\Sigma(U.\Delta x/x)^2$			1.03		1.03		1.03		1.03
$\Delta R/R$			1.01		1.01		1.01		1.01

TABLE 6

Uncertainties in Pu-238 Arisings, from Sensitivity Coefficients and Data Uncertainties

Cooling Time		2 x 10^7s (0.63y)		3 x 10^7s (0.95y)		6 x 10^7s (1.90y)		1.6 x 10^8s (5.07y)	
Sensitivity To	Fractional Uncertainty in Data (i.e. $\Delta x/x$)	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$
Np-237 $\sigma_{n\gamma}$	0.25	0.012	9.00 x 10^{-6}	0.011	7.56 x 10^{-6}	0.013	1.06 x 10^{-5}	0.011	7.56 x 10^{-6}
Pu-238 $\sigma_{n\gamma}$	0.50	-0.063	9.92 x 10^{-4}	-0.061	9.30 x 10^{-4}	-0.058	8.41 x 10^{-4}	-0.058	8.41 x 10^{-4}
Pu-238 σ_{nf}	0.20	-0.167	1.12 x 10^{-3}	-0.159	1.01 x 10^{-3}	-0.153	9.36 x 10^{-4}	-0.150	9.00 x 10^{-4}
Pu-239 σ_{n2n}	1.0	0.002	4.00 x 10^{-6}	0.002	4.00 x 10^{-6}	0.002	4.00 x 10^{-6}	0.002	4.00 x 10^{-6}
Pu-241 $T_{\frac{1}{2}}$	0.035	-0.32	1.25 x 10^{-4}	-0.32	1.25 x 10^{-4}	-0.36	1.59 x 10^{-4}	-0.36	1.59 x 10^{-4}
Am-241 $\sigma^g_{n\gamma}$	0.20	0.32	4.10 x 10^{-3}	0.34	4.62 x 10^{-3}	0.36	5.18 x 10^{-3}	0.36	5.18 x 10^{-3}
Am-241 σ_{nf}	0.10	-0.015	2.25 x 10^{-6}	-0.017	2.89 x 10^{-6}	-0.016	2.56 x 10^{-6}	-0.019	3.61 x 10^{-6}
Cm-242 $\sigma_{n\gamma}$	0.50	-0.013	4.23 x 10^{-5}	-0.013	4.23 x 10^{-5}	-0.014	4.90 x 10^{-5}	-0.014	4.90 x 10^{-5}
Cm-242 σ_{nf}	0.50	-0.032	2.56 x 10^{-4}	-0.033	2.72 x 10^{-4}	-0.035	3.06 x 10^{-4}	-0.035	3.06 x 10^{-4}
$\Sigma(U.\Delta x/x)^2$			6.64 x 10^{-3}		7.02 x 10^{-3}		7.49 x 10^{-3}		7.45 x 10^{-3}
$\Delta R/R$			8.2 x 10^{-2}		8.4 x 10^{-2}		8.7 x 10^{-2}		8.6 x 10^{-2}

TABLE 7

Uncertainties in Am-241 Arisings, from Sensitivity Coefficients and Data Uncertainties

Cooling Time		2×10^7s (0.63y)		3×10^7s (0.95y)		6×10^7s (1.90y)		1.6×10^8s (5.07y)	
Sensitivity To	Fractional Uncertainty in Data (i.e. $\Delta x/x$)	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$
Pu-241 $\sigma_{n\gamma}$	0.20	-0.025	2.50×10^{-5}	-0.030	3.60×10^{-5}	-0.040	6.40×10^{-5}	-0.058	1.35×10^{-4}
Pu-241 σ_{nf}	0.05	-0.115	3.31×10^{-5}	-0.136	4.62×10^{-5}	-0.179	8.01×10^{-5}	-0.25	1.56×10^{-4}
Pu-241 $T_{\frac{1}{2}}$	0.035	-0.85	8.85×10^{-4}	-0.85	8.85×10^{-4}	-0.84	8.64×10^{-4}	-0.77	7.26×10^{-4}
Am-241 $\sigma^{g}_{n\gamma}$	0.20	-0.27	2.92×10^{-3}	-0.26	2.70×10^{-3}	-0.22	1.94×10^{-3}	-0.149	8.88×10^{-4}
Am-241 $\sigma^{m}_{n\gamma}$	0.20	-0.040	6.40×10^{-5}	-0.039	6.08×10^{-5}	-0.032	4.10×10^{-5}	-0.025	2.50×10^{-5}
Am-241 σ_{nf}	0.10	-0.067	4.49×10^{-5}	-0.065	4.23×10^{-5}	-0.055	3.03×10^{-5}	-0.033	1.09×10^{-5}
$\Sigma(U.\Delta x/x)^2$			3.97×10^{-3}		3.77×10^{-3}		3.02×10^{-3}		1.94×10^{-3}
$\Delta R/R$			6.3×10^{-2}		6.1×10^{-2}		5.5×10^{-2}		4.4×10^{-2}

TABLE 8

Uncertainties in Am-243 Arisings, from Sensitivity Coefficients and Data Uncertainties

Cooling Time		2×10^7s (0.63y)		3×10^7s (0.95y)		6×10^7s (1.90y)		1.6×10^8s (5.07y)	
Sensitivity To	Fractional Uncertainty in Data (i.e. $\Delta x/x$)	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$
Pu-241 $\sigma_{n\gamma}$	0.20	0.089	3.17×10^{-4}	0.089	3.17×10^{-4}	0.093	3.46×10^{-4}	0.093	3.46×10^{-4}
Pu-241 σ_{nf}	0.05	0.014	4.90×10^{-7}	0.014	4.90×10^{-7}	0.027	1.82×10^{-6}	0.014	4.90×10^{-7}
Pu-241 $T_{\frac{1}{2}}$	0.035	-0.020	4.90×10^{-7}	-0.020	4.90×10^{-7}	-0.020	4.90×10^{-7}	0	0
Pu-242 $\sigma_{n\gamma}$	0.10	0.95	9.03×10^{-3}	0.95	9.03×10^{-3}	0.96	9.22×10^{-3}	0.95	9.03×10^{-3}
Pu-242 σ_{nf}	0.05	-0.040	4.00×10^{-6}	-0.040	4.00×10^{-6}	-0.027	1.82×10^{-6}	-0.027	1.82×10^{-6}
Am-243 $\sigma_{n\gamma}$	0.25	-0.145	1.31×10^{-3}	-0.145	1.31×10^{-3}	-0.143	1.28×10^{-3}	-0.146	1.33×10^{-3}
Am-243 σ_{nf}	0.10	-0.020	4.00×10^{-6}	-0.020	4.00×10^{-6}	-0.014	1.96×10^{-6}	-0.020	4.00×10^{-6}
$\Sigma(U.\Delta x/x)^2$			1.07×10^{-2}		1.07×10^{-2}		1.08×10^{-2}		1.07×10^{-2}
$\Delta R/R$			10.3×10^{-2}		10.3×10^{-2}		10.4×10^{-2}		10.3×10^{-2}

TABLE 9

Uncertainties in Cm-242 Arisings, from Sensitivity Coefficients and Data Uncertainties

Cooling Time		2×10^7s (0.63y)		3×10^7s (0.95y)		6×10^7s (1.90y)		1.6×10^8s (5.07y)	
Sensitivity To	Fractional Uncertainty in Data (i.e. $\Delta x/x$)	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$
Pu-241 $T_{\frac{1}{2}}$	0.035	-0.87	9.27×10^{-4}	-0.87	9.27×10^{-4}	-0.88	9.49×10^{-4}	-0.88	9.49×10^{-4}
Am-241 $\sigma^g_{n\gamma}$	0.20	0.77	2.37×10^{-2}	0.77	2.37×10^{-2}	0.76	2.31×10^{-2}	0.164	1.08×10^{-3}
Am-241 $\sigma^m_{n\gamma}$	0.20	-0.027	2.92×10^{-5}	-0.025	2.50×10^{-5}	-0.017	1.16×10^{-5}	0.61	1.49×10^{-2}
Am-241 σ_{nf}	0.10	-0.049	2.40×10^{-5}	-0.050	2.50×10^{-5}	-0.050	2.50×10^{-5}	-0.046	2.12×10^{-5}
Am-242m $T_{\frac{1}{2}}$	0.05	0	0	0	0	-0.009	2.03×10^{-7}	-0.41	4.20×10^{-4}
Cm-242 $\sigma_{n\gamma}$	0.50	-0.039	3.80×10^{-4}	-0.038	3.61×10^{-4}	-0.039	3.80×10^{-4}	-0.014	4.90×10^{-5}
Cm-242 σ_{nf}	0.50	-0.097	2.35×10^{-3}	-0.099	2.45×10^{-3}	-0.097	2.35×10^{-3}	-0.035	3.06×10^{-4}
$\Sigma(U.\Delta x/x)^2$			2.74×10^{-2}		2.75×10^{-2}		2.68×10^{-2}		1.77×10^{-2}*
$\Delta R/R$			16.6×10^{-2}		16.6×10^{-2}		16.4×10^{-2}		13.3×10^{-2}*

*If the errors in the capture cross-sections of Am-241 to the metastable and ground states of Am-242 were 100% correlated the values of $\Sigma(U.\Delta x/x)^2$ and $\Delta R/R$ would be 2.57×10^{-2} and 16.0×10^{-2} respectively.

TABLE 10

Uncertainties in Cm-244 Arisings, from Sensitivity Coefficients and Data Uncertainties

Cooling Time		2×10^7s (0.63y)		3×10^7s (0.95y)		6×10^7s (1.90y)		1.6×10^8s (5.07y)	
Sensitivity To	Fractional Uncertainty in Data (i.e. $\Delta x/x$)	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$
Pu-241 $\sigma_{n\gamma}$	0.20	0.074	2.19×10^{-4}	0.075	2.25×10^{-4}	0.073	2.13×10^{-4}	0.074	2.19×10^{-4}
Pu-241 σ_{nf}	0.05	0.064	1.02×10^{-5}	0.065	1.06×10^{-5}	0.067	1.12×10^{-5}	0.067	1.12×10^{-5}
Pu-241 $T_{\frac{1}{2}}$	0.035	-0.034	1.42×10^{-6}	-0.034	1.42×10^{-6}	-0.036	1.59×10^{-6}	-0.041	2.06×10^{-6}
Pu-242 $\sigma_{n\gamma}$	0.10	0.97	9.41×10^{-3}	0.97	9.41×10^{-3}	0.97	9.41×10^{-3}	0.97	9.41×10^{-3}
Pu-242 σ_{nf}	0.05	-0.016	6.40×10^{-7}	-0.016	6.40×10^{-7}	-0.016	6.40×10^{-7}	-0.019	9.03×10^{-7}
Am-243 $\sigma_{n\gamma}$	0.25	0.76	3.61×10^{-2}	0.76	3.61×10^{-2}	0.76	3.61×10^{-2}	0.76	3.61×10^{-2}
Am-243 σ_{nf}	0.10	-0.012	1.44×10^{-6}	-0.012	1.44×10^{-6}	-0.012	1.44×10^{-6}	-0.014	1.96×10^{-6}
Cm-244 $\sigma_{n\gamma}$	0.50	-0.032	2.56×10^{-4}	-0.032	2.56×10^{-4}	-0.034	2.89×10^{-4}	-0.034	2.89×10^{-4}
Cm-244 σ_{nf}	0.50	-0.036	3.24×10^{-4}	-0.036	3.24×10^{-4}	-0.038	3.61×10^{-4}	-0.038	3.61×10^{-4}
$\Sigma(U.\Delta x/x)^2$			4.63×10^{-2}		4.63×10^{-2}		4.64×10^{-2}		4.64×10^{-2}
$\Delta R/R$			21.5×10^{-2}		21.5×10^{-2}		21.5×10^{-2}		21.5×10^{-2}

TABLE 11

Uncertainties in α-Contribution to Decay Heat, from Sensitivity Coefficients and Data Uncertainties

Cooling Time		2×10^{7}s (0.63y)		3×10^{7}s (0.95y)		6×10^{7}s (1.90y)		1.6×10^{8}s (5.07y)	
Sensitivity To	Fractional Uncertainty in Data (i.e. $\Delta x/x$)	U	$(U\Delta x/x)^2$	U	$(U\Delta x/x)^2$	U	$(U\Delta x/x)^2$	U	$(U\Delta x/x)^2$
Pu-238 $\sigma_{n\gamma}$	0.50	-0.003	2.25×10^{-6}	-0.004	4.00×10^{-6}	-0.012	3.60×10^{-5}	-0.023	1.32×10^{-4}
Pu-238 σ_{nf}	0.20	-0.007	1.96×10^{-6}	-0.011	4.84×10^{-6}	-0.030	3.60×10^{-5}	-0.059	1.39×10^{-4}
Pu-241 σ_{nf}	0.05	0.005	6.25×10^{-8}	0.004	4.00×10^{-8}	-0.008	1.60×10^{-7}	-0.057	8.12×10^{-6}
Pu-241 $T_{\frac{1}{2}}$	0.035	-0.81	8.04×10^{-4}	-0.78	7.45×10^{-4}	-0.61	4.56×10^{-4}	-0.36	1.59×10^{-4}
Pu-242 $\sigma_{n\gamma}$	0.10	0.016	2.56×10^{-6}	0.024	5.76×10^{-6}	0.065	4.23×10^{-5}	0.115	1.32×10^{-4}
Am-241 $\sigma^{g}_{n\gamma}$	0.20	0.70	1.96×10^{-2}	0.66	1.74×10^{-2}	0.46	8.46×10^{-3}	0.119	5.66×10^{-4}
Am-241 σ_{nf}	0.10	-0.047	2.21×10^{-5}	-0.045	2.03×10^{-5}	-0.035	1.23×10^{-5}	-0.018	3.24×10^{-6}
Am-243 $\sigma_{n\gamma}$	0.25	0.012	9.00×10^{-6}	0.019	2.26×10^{-5}	0.050	1.56×10^{-4}	0.088	4.84×10^{-4}
Cm-242 $\sigma_{n\gamma}$	0.50	-0.034	2.89×10^{-4}	-0.031	2.40×10^{-4}	-0.016	6.40×10^{-5}	0.075	1.23×10^{-5}
Cm-242 σ_{nf}	0.50	-0.090	2.03×10^{-3}	-0.085	1.81×10^{-3}	-0.060	9.00×10^{-4}	-0.016	6.40×10^{-5}
$\Sigma(U\Delta x/x)^2$			2.28×10^{-2}		2.03×10^{-2}		1.02×10^{-2}		1.70×10^{-3}
$\Delta R/R$			15.1×10^{-2}		14.2×10^{-2}		10.1×10^{-2}		4.1×10^{-2}

TABLE 12

Uncertainties in Total Heat Generation, from Sensitivity Coefficients and Data Uncertainties

Cooling Time		2×10^7s (0.63y)		3×10^7s (0.95y)		6×10^7s (1.90y)		1.6×10^8s (5.07y)	
Sensitivity To	Fractional Uncertainty in Data (i.e. $\Delta x/x$)	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$
Pu-238 $\sigma_{n\gamma}$	0.50	-0.001	2.50×10^{-7}	-0.002	1.00×10^{-6}	-0.004	4.00×10^{-6}	-0.012	3.60×10^{-5}
Pu-238 σ_{nf}	0.20	-0.003	3.60×10^{-7}	-0.004	6.40×10^{-7}	-0.009	3.24×10^{-6}	-0.032	4.10×10^{-5}
Pu-241 σ_{nf}	0.05	0.001	2.50×10^{-9}	0	0	-0.023	1.32×10^{-6}	-0.036	3.24×10^{-6}
Pu-241 $T_{\frac{1}{2}}$	0.035	-0.29	1.03×10^{-4}	-0.27	8.93×10^{-5}	-0.18	3.97×10^{-5}	-0.20	4.90×10^{-5}
Pu-242 $\sigma_{n\gamma}$	0.10	0.006	3.60×10^{-7}	0.009	8.10×10^{-7}	0.022	4.84×10^{-6}	0.062	3.84×10^{-5}
Am-241 $\sigma^{g}_{n\gamma}$	0.20	0.26	2.70×10^{-3}	0.24	2.30×10^{-3}	0.14	7.84×10^{-4}	0.064	1.64×10^{-4}
Am-241 $\sigma^{m}_{n\gamma}$	0.20	-0.009	3.24×10^{-6}	-0.008	2.56×10^{-6}	-0.003	3.60×10^{-7}	+0.003	3.60×10^{-7}
Am-241 σ_{nf}	0.10	-0.017	2.89×10^{-6}	-0.016	2.56×10^{-6}	-0.011	1.21×10^{-6}	-0.010	6.25×10^{-6}
Am-243 $\sigma_{n\gamma}$	0.25	0.005	1.56×10^{-6}	0.007	3.06×10^{-6}	0.015	1.41×10^{-5}	0.048	1.44×10^{-4}
Cm-242 $\sigma_{n\gamma}$	0.50	-0.013	4.23×10^{-5}	-0.011	3.03×10^{-5}	-0.005	6.25×10^{-6}	+0.004	4.00×10^{-6}
Cm-242 σ_{nf}	0.50	-0.034	2.89×10^{-4}	-0.031	2.40×10^{-4}	-0.018	8.10×10^{-5}	-0.009	2.03×10^{-5}
$\sum(U.\Delta x/x)^2$			3.15×10^{-3}		2.67×10^{-3}		9.40×10^{-4}		5.06×10^{-4}
$\Delta R/R$			5.6×10^{-2}		5.2×10^{-2}		3.1×10^{-2}		2.3×10^{-2}

TABLE 13

Uncertainties in Spontaneous Fission Neutron Output, from Sensitivity Coefficients and Data Uncertainties

Cooling Time		2×10^7 s (0.63y)		3×10^7 s (0.95y)		6×10^7 s (1.90y)		1.6×10^8 s (5.07y)	
Sensitivity To	Fractional Uncertainty in Data (i.e. $\Delta x/x$)	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$
Pu-241 $\sigma_{n\gamma}$	0.20	0.023	2.12×10^{-5}	0.030	3.60×10^{-5}	0.054	1.17×10^{-4}	0.070	1.96×10^{-4}
Pu-241 σ_{nf}	0.05	0.023	1.32×10^{-6}	0.029	2.10×10^{-6}	0.046	5.29×10^{-6}	0.058	8.41×10^{-6}
Pu-241 $T_{\frac{1}{2}}$	0.035	-0.60	4.41×10^{-4}	-0.60	4.41×10^{-4}	-0.60	4.41×10^{-4}	-0.60	4.41×10^{-4}
Pu-242 $\sigma_{n\gamma}$	0.10	0.29	8.41×10^{-4}	0.39	1.52×10^{-3}	0.69	4.76×10^{-3}	0.90	8.10×10^{-3}
Am-241 $\sigma^{g}_{n\gamma}$	0.20	0.53	1.12×10^{-2}	0.44	7.74×10^{-3}	0.19	1.44×10^{-3}	0.007	1.96×10^{-6}
Am-241 σ_{nf}	0.10	0.034	1.16×10^{-5}	0.029	8.41×10^{-6}	0.012	1.44×10^{-6}	0	0
Am-243 $\sigma_{n\gamma}$	0.25	0.224	3.14×10^{-3}	0.30	5.63×10^{-3}	0.54	1.82×10^{-2}	0.71	3.15×10^{-2}
Cm-242 $\sigma_{n\gamma}$	0.50	-0.027	1.82×10^{-4}	-0.022	1.21×10^{-4}	-0.008	1.60×10^{-5}	+0.001	2.50×10^{-7}
Cm-242 σ_{nf}	0.50	-0.068	1.16×10^{-3}	-0.057	8.12×10^{-4}	-0.024	1.44×10^{-4}	0	0
Cm-244 $\sigma_{n\gamma}$	0.50	-0.010	2.50×10^{-5}	-0.013	4.23×10^{-5}	-0.024	1.44×10^{-4}	-0.031	2.40×10^{-4}
Cm-244 σ_{nf}	0.20	-0.011	4.84×10^{-6}	-0.015	9.00×10^{-6}	-0.027	2.92×10^{-5}	-0.036	5.18×10^{-5}
Cm-242* spon. fiss.	0.10	0.730	5.33×10^{-3}	0.620	3.84×10^{-3}	0.260	6.76×10^{-4}	0.050	2.50×10^{-5}
$\Sigma(U.\Delta x/x)^2$			2.24×10^{-2}		2.02×10^{-2}		2.60×10^{-2}		4.05×10^{-2}
$\Delta R/R$			15.0×10^{-2}		14.2×10^{-2}		16.1×10^{-2}		20.1×10^{-2}

*Error due to $\bar{\nu}$ and branching ratio data - primarily for Cm-242.

TABLE 14

Uncertainties in Neutron Output from (α,n) Reactions, from Sensitivity Coefficients and Data Uncertainties

Cooling Time		2×10^7s (0.63y)		3×10^7s (0.95y)		6×10^7s (1.90y)		1.6×10^8s (5.07y)	
Sensitivity To	Fractional Uncertainty in Data (i.e. $\Delta x/x$)	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$
Pu-238 $\sigma_{n\gamma}$	0.50	-0.002	1.00×10^{-6}	-0.003	2.25×10^{-6}	-0.009	2.03×10^{-5}	-0.023	1.32×10^{-4}
Pu-238 σ_{nf}	0.20	-0.005	1.00×10^{-6}	-0.008	2.56×10^{-6}	-0.024	2.30×10^{-5}	-0.060	1.44×10^{-4}
Pu-241 σ_{nf}	0.20	0.006	1.44×10^{-6}	0.005	1.00×10^{-6}	0.004	6.40×10^{-7}	0.056	1.25×10^{-4}
Pu-241 $T_{\frac{1}{2}}$	0.035	-0.83	8.44×10^{-4}	-0.81	8.04×10^{-4}	-0.67	5.50×10^{-4}	-0.38	1.77×10^{-4}
Pu-242 $\sigma_{n\gamma}$	0.10	0.013	1.69×10^{-6}	0.021	4.41×10^{-6}	0.062	3.84×10^{-5}	0.138	1.90×10^{-4}
Am-241 $\sigma^{g}_{n\gamma}$	0.20	0.72	2.07×10^{-2}	0.69	1.90×10^{-2}	0.53	1.12×10^{-2}	0.124	6.15×10^{-4}
Am-241 $\sigma^{m}_{n\gamma}$	0.20	-0.027	2.92×10^{-5}	-0.025	2.50×10^{-5}	-0.014	7.84×10^{-6}	+0.010	4.00×10^{-6}
Am-241 σ_{nf}	0.10	-0.048	2.30×10^{-5}	-0.047	2.21×10^{-5}	-0.038	1.44×10^{-5}	-0.018	3.24×10^{-6}
Am-243 $\sigma_{n\gamma}$	0.25	0.010	6.25×10^{-6}	0.016	1.60×10^{-5}	0.048	1.44×10^{-4}	0.107	7.16×10^{-4}
Cm-242 $\sigma_{n\gamma}$	0.50	-0.035	3.06×10^{-4}	-0.033	2.72×10^{-4}	-0.020	1.00×10^{-4}	+0.008	1.60×10^{-5}
Cm-242 σ_{nf}	0.50	-0.093	2.16×10^{-3}	-0.089	1.98×10^{-3}	-0.068	1.16×10^{-3}	-0.017	7.23×10^{-5}
(α,n) Yield	0.10	1.0	1.00×10^{-2}	1.0	1.00×10^{-2}	1.0	1.00×10^{-2}	1.0	1.00×10^{-2}
$\sum(U.\Delta x/x)^2$			3.41×10^{-2}		3.22×10^{-2}		2.33×10^{-2}		1.22×10^{-2}
$\Delta R/R$			18.5×10^{-2}		17.9×10^{-2}		15.3×10^{-2}		11.0×10^{-2}

TABLE 15

Uncertainties in Total Neutron Production

Cooling Time		1 x 10^3 s(16.7m)		1 x 10^6 s(11.6d)		2 x 10^7 s(0.63y)		3 x 10^7 s(0.95y)		6 x 10^7 s(1.90y)		1.6 x 10^8 s(5.07y)	
Sensitivity To	Fractional Uncertainty in Data (i.e. $\Delta x/x$)	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$	U	$(U.\Delta x/x)^2$
Pu-238 $\sigma_{n\gamma}$	0.50	0.0	0	0.0	0	0.0	0	0.0	0	-0.001	2.50 x 10^{-7}	-0.002	1.00 x 10^{-6}
Pu-238 σ_{nf}	0.20	0.0	0	0.0	0	0.0	0	0.0	0	-0.002	1.60 x 10^{-7}	-0.003	3.60 x 10^{-7}
Pu-241 $\sigma_{n\gamma}$	0.20	0.009	3.24 x 10^{-6}	0.009	3.24 x 10^{-6}	0.019	1.44 x 10^{-5}	0.026	2.70 x 10^{-5}	0.049	9.60 x 10^{-5}	0.066	1.74 x 10^{-4}
Pu-241 σ_{nf}	0.05	0.013	4.23 x 10^{-7}	0.013	4.23 x 10^{-7}	0.020	1.00 x 10^{-6}	0.025	1.56 x 10^{-6}	0.041	4.20 x 10^{-6}	0.051	6.50 x 10^{-6}
Pu-241 $T_{\frac{1}{2}}$	0.035	-0.77	7.26 x 10^{-4}	-0.76	7.08 x 10^{-4}	-0.64	5.02 x 10^{-4}	-0.55	3.71 x 10^{-4}	-0.27	8.93 x 10^{-5}	-0.059	4.26 x 10^{-6}
Pu-242 $\sigma_{n\gamma}$	0.10	0.111	1.23 x 10^{-4}	0.115	1.32 x 10^{-4}	0.241	5.81 x 10^{-4}	0.333	1.11 x 10^{-3}	0.632	3.99 x 10^{-3}	0.857	7.34 x 10^{-3}
Am-241 $\sigma^g_{n\gamma}$	0.20	0.68	1.85 x 10^{-2}	0.67	1.80 x 10^{-2}	0.56	1.25 x 10^{-2}	0.48	9.22 x 10^{-3}	0.22	1.94 x 10^{-3}	0.136	7.40 x 10^{-4}
Am-241 $\sigma^m_{n\gamma}$	0.20	-0.025	2.50 x 10^{-5}	-0.025	2.50 x 10^{-5}	-0.020	1.60 x 10^{-5}	-0.016	1.02 x 10^{-5}	-0.004	6.40 x 10^{-7}	-0.006	1.44 x 10^{-6}
Am-241 σ_{nf}	0.10	-0.044	1.94 x 10^{-5}	-0.044	1.94 x 10^{-5}	-0.037	1.37 x 10^{-5}	-0.031	9.61 x 10^{-6}	-0.014	1.96 x 10^{-6}	-0.001	1.00 x 10^{-8}
Am-243 $\sigma_{n\gamma}$	0.25	0.087	4.73 x 10^{-4}	0.090	5.06 x 10^{-4}	0.189	2.23 x 10^{-3}	0.261	4.26 x 10^{-3}	0.496	1.54 x 10^{-2}	0.673	2.83 x 10^{-2}
Cm-242 $\sigma_{n\gamma}$	0.50	-0.034	2.89 x 10^{-4}	-0.034	2.89 x 10^{-4}	-0.028	1.96 x 10^{-4}	-0.024	1.44 x 10^{-4}	-0.010	2.50 x 10^{-5}	-0.002	1.00 x 10^{-6}
Cm-242 σ_{nf}	0.50	-0.086	1.85 x 10^{-3}	-0.086	1.85 x 10^{-3}	-0.072	1.30 x 10^{-3}	-0.062	9.61 x 10^{-4}	-0.028	1.96 x 10^{-4}	-0.001	2.50 x 10^{-7}
Cm-244 $\sigma_{n\gamma}$	0.50	-0.004	4.00 x 10^{-6}	-0.004	4.00 x 10^{-6}	-0.008	1.60 x 10^{-5}	-0.011	3.03 x 10^{-5}	-0.022	1.21 x 10^{-4}	-0.030	2.25 x 10^{-4}
Cm-244 σ_{nf}	0.20	-0.004	6.40 x 10^{-7}	-0.005	1.00 x 10^{-6}	-0.010	4.00 x 10^{-6}	-0.013	6.76 x 10^{-6}	-0.025	2.50 x 10^{-5}	-0.034	4.62 x 10^{-5}
(α,n) Yield*	0.10	0.190	3.61 x 10^{-4}	0.189	3.57 x 10^{-4}	0.166	2.76 x 10^{-4}	0.149	2.22 x 10^{-4}	0.094	8.84 x 10^{-5}	0.058	3.36 x 10^{-5}
Spon.Fiss**	0.10	0.728	5.30 x 10^{-3}	0.728	5.30 x 10^{-3}	0.595	3.54 x 10^{-3}	0.509	2.59 x 10^{-3}	0.226	5.14 x 10^{-4}	0.045	2.03 x 10^{-5}
$\Sigma(U.\Delta x/x)^2$			2.767 x 10^{-2}		2.715 x 10^{-2}		2.123 x 10^{-2}		1.895 x 10^{-2}		2.246 x 10^{-2}		3.690 x 10^{-2}
$\Delta R/R$			16.6 x 10^{-2}		16.5 x 10^{-2}		14.6 x 10^{-2}		13.8 x 10^{-2}		15.0 x 10^{-2}		19.2 x 10^{-2}

*U values obtained as neuts. from (α,n) reactions/total neuts.

**Error due to $\bar{\nu}$ and branching ratio data - primarily for Cm-242.

TABLE 16

Nuclear Data Requirements of Highest Priority

Quantity	Present Accuracy (%)	New Required Accuracy (%)	Purpose
Np-237 σ_{n2n}	100	25	Production of Pu-236
Am-241 $\sigma^{g}_{n\gamma}$	20	8 10	Total heat generation Total neutron production
Am-243 $\sigma_{n\gamma}$	25	10	Total neutron production
Cm-242 spontaneous fission branching ratio	10	5	Total neutron production
(α,n) yield	30	10*	Total neutron production

*This value has been used in the calculations in this paper. It therefore anticipates the measurements of West[15] which need to be completed to achieve the required accuracy.

TABLE 17

Summary of Achieved Accuracies and Requirements

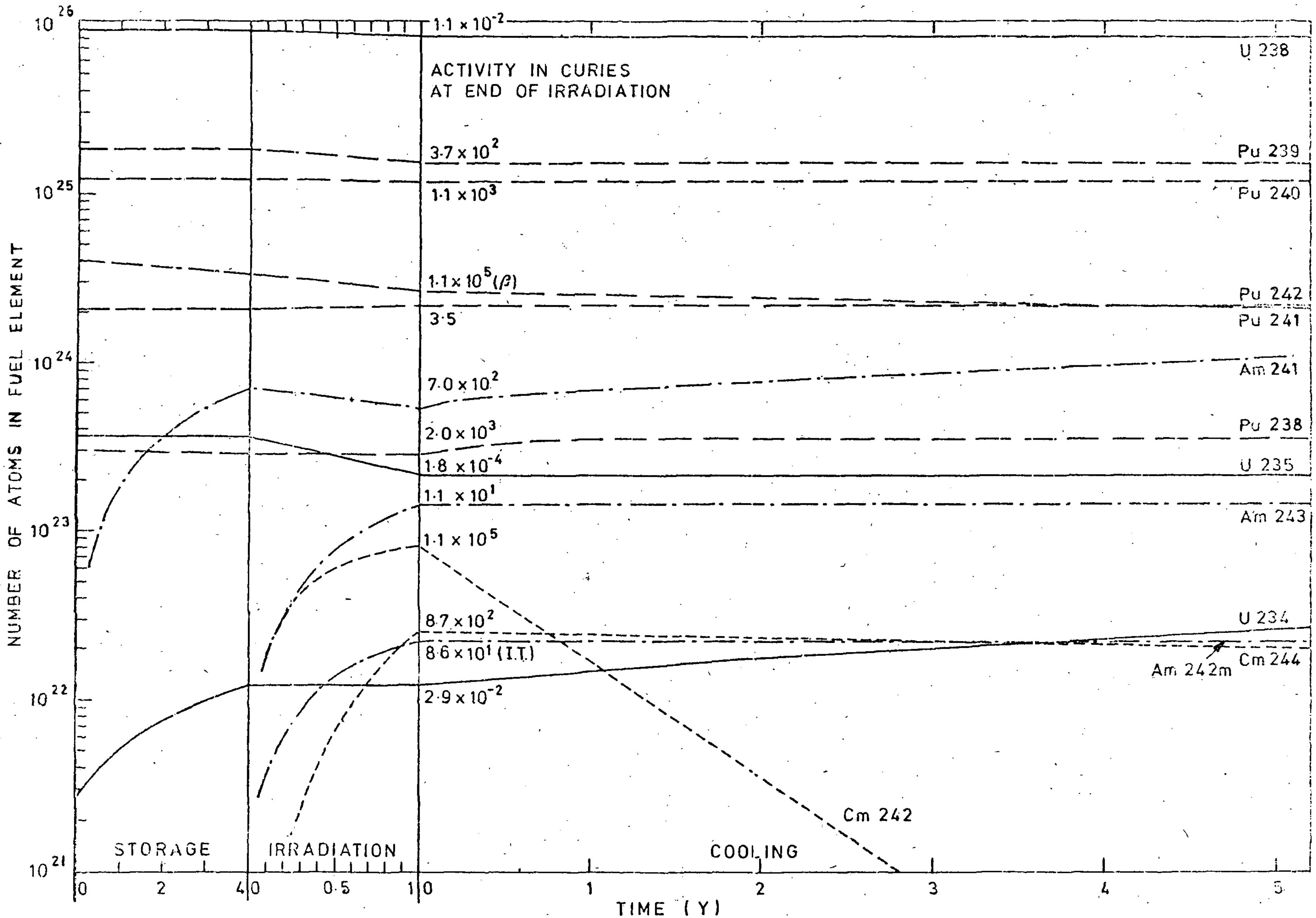
Quantity	Currently Requested Accuracy* (%)	Uncertainty Due to Errors in Actinide Data (%)	Most Important Data Needing Improvement to Achieve Higher Accuracy**
Production of Pu-236	100(2σ)	100	Np-237 σ_{n2n} [100%]
Production of Pu-238	20	8.5	Am-241 $\sigma^{g}_{n\gamma}$[6.5%], Pu-238 σ_{nf}[3.5%], Pu-238 $\sigma_{n\gamma}$[3%]
Production of Am-241	100(2σ)	6.3 - 4.4	Am-241 $\sigma^{g}_{n\gamma}$[5%], Pu-241 $T_{\frac{1}{2}}$[3%]
Production of Am-243	100(2σ)	10	Pu-242 $\sigma_{n\gamma}$[9.5%], Am-243 $\sigma_{n\gamma}$[3.5%]
Production of Cm-242	100(2σ)	17 - 13	Am-241 $\sigma^{g}_{n\gamma}$[15%], Am-241 $\sigma^{m}_{n\gamma}$[12%], Cm-242 σ_{nf}[5%]
Production of Cm-244	100(2σ)	22	Am-243 $\sigma_{n\gamma}$[19%], Pu-242 $\sigma_{n\gamma}$[10%]
α-decay heat	«5	15 - 4	Am-241 $\sigma^{g}_{n\gamma}$[13%], Cm-242 σ_{nf}[4%], Pu-241 $T_{\frac{1}{2}}$[3%]
Total heat generation	5***	5.6 - 2.3****	Am-241 $\sigma^{g}_{n\gamma}$[5%], Cm-242 σ_{nf}[1.5%]
Spontaneous fission neutrons		14 - 20	Am-241 $\sigma^{g}_{n\gamma}$[10%], Am-243 $\sigma_{n\gamma}$[10%], Pu-242 $\sigma_{n\gamma}$[8%]
(α,n) neutrons		19 - 11	Am-241 $\sigma^{g}_{n\gamma}$[14%], (α,n) yield [10%], Cm-242 σ_{nf}[4%]
Total neutron production	10 (reactivity) 20 (shielding)	14 - 20	Am-243 $\sigma_{n\gamma}$[14%], Am-241 $\sigma^{g}_{n\gamma}$[10%], Pu-242 $\sigma_{n\gamma}$[6%], Cm-242 spont. fis. [5%]

* Values are given as 1σ except where stated.

** The numbers in brackets are an indication of the contributions of the important nuclear data to the overall uncertainty. Since the contributions can vary significantly as a function of cooling time, the values quoted here are only a rough guide and the individual tables should be consulted for a more accurate picture. The contributions are to be summed in quadrature (along with other less important contributions) to obtain the overall uncertainty.

*** Including uncertainties arising from fission product decay.

****These uncertainties take no account of inaccuracies in fission product data which are very important in the total heat generation, particularly at short cooling times.



VARIATION OF NUMBER OF ATOMS IN FUEL ELEMENT AS A FUNCTION OF TIME.

FIG. 1.

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