International Conference on Nuclear Data for Science and Technology 2007
DOI: 10.1051/ndata:07297

The role of differential and integral experiments to meet requirements for improved nuclear data

M. Salvatores[1,2], G. Aliberti[1], and G. Palmiotti[1]

[1] Argonne National Laboratory, Argonne, IL 60439, USA
[2] CEA Cadarache, 13108 Saint-Paul-lez-Durance, France

1 Introduction

A formal procedure can be used to assess the nuclear data uncertainty reductions needed in order to meet target accuracies on crucial design integral parameters, if target uncertainties have been agreed on these design parameters.

In the present paper, we used the covariance information and the resulting uncertainties on advanced reactor systems, both described in ref. [1] as part of the activity of the OECD-NEA WPEC Subgroup 26, to investigate data target accuracies and possible approaches to meet them.

2 Data target accuracies

Within Subgroup 26, a preliminary list of design target accuracies for fast reactor systems (at first, independently of the coolant or the fuel type) has been agreed upon, see table 1, for high burn-up PWRs, see table 2, and for (V)HTRs, see table 3. These target accuracies reflect the perceived status of the art, even if they are not the result of a systematic analysis, which should necessarily involve industrial partners. Moreover, it has to be kept in mind that no well defined "images" for any of the Gen-IV exist at present. This means that the target accuracies shown in particular in table 1 reflect the current thinking of systems with innovative fuels and core configurations described in ref. [1], i.e. the Na-cooled systems (burners with different fuel types as the SFR and ABTR, or self-sustaining as the EFR), gas-cooled GFR and lead-cooled LFR. The case of the (V)HTR is somewhat different, since the target accuracies shown in table 3 were suggested by a major industry (AREVA).

Table 1. Fast reactor target accuracies (1σ).

Multiplication factor (BOL)	300 pcm
Peak power (BOL)	2%
Burn-up reactivity swing	300 pcm
Reactivity coefficients (coolant void and Doppler - BOL)	7%
Major nuclide density at end of irradiation cycle	2%
Other nuclide density at end of irradiation cycle	10%

Table 2. PWR target accuracies (1σ).

k_{eff}	Temperature reactivity coefficient	Burn-up $\Delta\rho$	Transmutation
0.5%	10%	500 pcm	5%

Table 3. Target accuracy (1σ) for UO_2- and PuO_2-fuelled HTR's (Source: AREVA-NP, reproduced with permission for WPEC SG26).

Criticality	300 pcm (operation); 500 pcm (safety)
Local power (in fuel compact)	6% (2% in pin-wise fission rate of fresh fuel; 4% in main fissile isotope conc. of irradiated fuel)
Burn-up (cycle length)	1% (.⇒ ~ 500 MWd/t)
Doppler coefficient	20%
Moderator temperature coeff.	1 pcm/°C
Nuclide inventories at EOL Main fissile isotopes Fertile isotopes MAs and FPs	4% 5% 20%

Once the design target accuracies have been defined, the formal procedure to obtain the unknown uncertainty nuclear data requirements d_i implies solving the following minimization problem with constraints (see, e.g., ref. [2]):

$$\sum_i \lambda_i / d_i^2 = min \quad i = 1 \ldots I. \tag{1}$$

$$\sum_i S_{ni}^2 d_i^2 \leq \left(Q_n^T\right)^2 n = 1 \ldots N \tag{2}$$

(where I is the number of nuclear data, N is the number of integral parameters, S_{ni} are the sensitivity coefficients for the integral parameter Q_n, and Q_n^T are the target accuracies on the N integral parameters), the λ_i which are "cost" parameters related to each σ_i, can be used to give a relative figure of merit of the difficulty of improving that parameter (e.g., with a differential experiment).

As already done in previous work [2], we used at first a constant value of one for all λ. The results given in table 4 are relevant to the ABTR.

©2008 CEA, published by EDP Sciences

Article available at http://nd2007.edpsciences.org or http://dx.doi.org/10.1051/ndata:07297

Table 4. ABTR: Uncertainty reduction requirements needed to meet integral parameter target accuracies.

Isotope	Cross-Section	Energy Range	Uncertainty (%)		
			Initial	Required	
				$\lambda = 1$	$\lambda \neq 1$ [(a)]
U238	σ_{inel}	6.07 - 2.23 MeV	19.8	3.3	5.8
		2.23 - 1.35 MeV	20.6	3.6	6.3
		1.35 - 0.498 MeV	11.6	6.5	11.4
U238	σ_{capt}	24.8 - 9.12 keV	9.4	2.9	1.6
Pu239	σ_{capt}	498 - 183 keV	11.6	5.7	3.2
		183 - 67.4 keV	9.0	5.0	2.8
		67.4 - 24.8 keV	10.1	5.8	3.2
		9.12 - 2.04 keV	15.5	7.4	4.1
Pu241	σ_{fiss}	183 - 67.4 keV	19.9	8.8	7.0
Fe56	σ_{inel}	2.23 - 1.35 MeV	25.4	5.6	9.9
		1.35 - 0.498 MeV	16.1	7.5	13.1
Na23	σ_{inel}	1.35 - 0.498 MeV	28.0	10.1	17.7

(a) $\lambda_{\text{inel}} = 10$; $\lambda_{\text{el}} = 1$; $\lambda_{\text{capt,fiss},\nu}$(U235, U238, Pu239) = 1; $\lambda_{\text{capt,fiss},\nu}$ (other fissiles) = 2; λ_{capt}(structural) = 1.

Table 5. Summary target accuracies for fast reactors.

		Energy Range	Current Accuracy (%)	Target Accuracy (%)
U238	σ_{inel}	6.07 ÷ 0.498 MeV	10 ÷ 20	2 ÷ 3
	σ_{capt}	24.8 ÷ 2.04 keV	3 ÷ 9	1.5 ÷ 2
Pu241	σ_{fiss}	1.35 MeV ÷ 454 eV	8 ÷ 20	2 ÷ 3 (SFR,GFR, LFR) 5 ÷ 8 (ABTR,EFR)
Pu239	σ_{capt}	498 ÷ 2.04 keV	7 ÷ 15	4 ÷ 7
Pu240	σ_{fiss}	1.35 ÷ 0.498 MeV	6	1.5 ÷ 2
	ν	1.35 ÷ 0.498 MeV	4	1 ÷ 3
Pu242	σ_{fiss}	2.23 ÷ 0.498 MeV	19 ÷ 21	3 ÷ 5
Pu238	σ_{fiss}	1.35 ÷ 0.183 MeV	17	3 ÷ 5
Am242m	σ_{fiss}	1.35 MeV ÷ 67.4 keV	17	3 ÷ 4
Am241	σ_{fiss}	6.07 ÷ 2.23 MeV	12	3
Cm244	σ_{fiss}	1.35 ÷ 0.498 MeV	50	5
Cm245	σ_{fiss}	183 ÷ 67.4 keV	47	7
textbfFe56	σ_{inel}	2.23 ÷ 0.498 MeV	16 ÷ 25	3 ÷ 6
Na23	σ_{inel}	1.35 ÷ 0.498 MeV	28	4 ÷ 10
Pb206	σ_{inel}	2.23 ÷ 1.35 MeV	14	3
Pb207	σ_{inel}	1.35 ÷ 0.498 MeV	11	3
Si28	σ_{inel}	6.07 ÷ 1.35 MeV	14 ÷ 50	3 ÷ 6
	σ_{capt}	19.6 ÷ 6.07 MeV	53	6

To have a first indication of the impact of the choice of the λ_i parameters, related to achievable experimental uncertainties for σ_{fiss}, σ_{capt}, σ_{inel} measurements for actinide and structural materials, a different set of λ values was used (as indicated in table 4), with the purpose to stress, as an example, the difficulty to improve σ_{inel}, with respect to σ_{fiss}. The results show that, if we relax the accuracy requirement on σ_{inel}, a higher accuracy on σ_{capt} and σ_{fiss} is required. In absence of a systematic experimental study, we used $\lambda = 1$ to obtain a first comprehensive set of data accuracy requirements.

In order to quantify specific nuclear data target accuracies, we considered the design parameters for which design target accuracies were available (see tables 1, 2 and 3). The procedure indicated above was applied to all nuclear data whose uncertainty gave a contribution to the integral parameter uncertainty above a pre-defined threshold.

Table 6. SFR: Uncertainty reduction requirements needed to meet integral parameter target accuracies.

Isotope	Cross-Section	Energy Range	Uncertainty (%)	
			Initial	Required (λ=1)
Pu241	σ_{fiss}	1.35 - 0.498 MeV	16.6	3.4
		498 - 183 keV	13.5	2.6
		183 - 67.4 keV	19.9	2.6
		24.8 - 9.12 keV	11.3	3.5
		2.04 - 0.454 keV	12.7	4.4
Fe56	σ_{inel}	2.23 - 1.35 MeV	25.4	3.3
		1.35 - 0.498 MeV	16.1	3.2
Na23	σ_{inel}	1.35 - 0.498 MeV	28.0	4.0
Cm244	σ_{fiss}	1.35 - 0.498 MeV	50.0	5.1
Am242m	σ_{fiss}	1.35 - 0.498 MeV	16.5	4.2
		498 - 183 keV	16.6	3.1
		183 - 67.4 keV	16.6	3.1
		67.4 - 24.8 keV	14.4	4.0
		24.8 - 9.12 keV	11.8	4.2
		2.04 - 0.454 keV	12.2	5.1
Pu240	σ_{fiss}	1.35 - 0.498 MeV	5.8	1.8
Pu240	ν	1.35 - 0.498 MeV	3.7	1.5
Pu238	σ_{fiss}	2.23 - 1.35 MeV	33.8	5.6
		1.35 - 0.498 MeV	17.1	3.3
		498 - 183 keV	17.1	3.6
Pu238	ν	1.35 - 0.498 MeV	7.0	2.7
Pu242	σ_{fiss}	2.23 - 1.35 MeV	21.4	4.9
		1.35 - 0.498 MeV	19.0	3.5
Cm245	σ_{fiss}	183 - 67.4 keV	47.5	6.7
Pu242	σ_{capt}	24.8 - 9.12 keV	38.6	8.4
U238	σ_{capt}	24.8 - 9.12 keV	9.4	4.3
Fe56	σ_{capt}	2.04 - 0.454 keV	11.2	5.3

Table 5 shows a summary of the results obtained over the whole set of fast reactors. Values are given as uncertainty ranges within selected energy intervals and only the most significant values are shown.

Several significant features can be pointed out. As expected from the results of the uncertainty analysis (see ref. [2]), very tight requirements are shown for the σ_{inel} of U-238 (2–3%), Fe-56 (3–6%), Na-23 (4–10%) and even for Pb isotopes. The required accuracies are probably beyond achievable limits with current techniques. As previously discussed, there are little margins to relax the requirements on σ_{inel} if one does not want to produce comparably difficult requirements on some Pu isotope σ_{fiss} and σ_{capt}.

In any case, the accuracy requirements for Pu isotopes are very tight (very often <2–3%).

As for σ_{capt}, the requirements for U-238 and Pu-239 aim to cut by more then a factor of 2 the current uncertainties.

In the case of minor actinides (MA), uncertainties improvements are in some cases are very significant. However, as we will see later on, this is the case when MA play an important role in the critical balance, and this is the case only for MA dedicated burner with a fuel heavily loaded with MA. For these very specific cases, the accuracy requirement for σ_{fiss} of selected MA isotopes can go from 3 to 7%.

Table 7. EFR: Uncertainty reduction requirements needed to meet integral parameter target accuracies.

Isotope	Cross-Section	Energy Range	Uncertainty (%)	
			Initial	Required (λ=1)
U238	σ_{inel}	6.07 - 2.23 MeV	19.8	3.7
		2.23 - 1.35 MeV	20.6	4.0
		1.35 - 0.498 MeV	11.6	5.0
U238	σ_{capt}	24.8 - 9.12 keV	9.4	2.9
O16	σ_{abs}	19.6 - 6.07 MeV	100.0	14.2
		6.07 - 2.23 MeV	100.0	10.9
Fe56	σ_{inel}	2.23 - 1.35 MeV	25.4	6.6
		1.35 - 0.498 MeV	16.1	8.4
Pu241	σ_{fiss}	1.35 - 0.498 MeV	16.6	8.0
		498 - 183 keV	13.5	6.7
		183 - 67.4 keV	19.9	5.7
		67.4 - 24.8 keV	8.7	6.2
		24.8 - 9.12 keV	11.3	6.8
		9.12 - 2.04 keV	10.4	7.6
		2.04 - 0.454 keV	12.7	6.9
Pu240	σ_{fiss}	1.35 - 0.498 MeV	5.8	3.5
Pu239	σ_{capt}	183 - 67.4 keV	9.0	7.0
		67.4 - 24.8 keV	10.1	6.7
		24.8 - 9.12 keV	7.4	6.1
		9.12 - 2.04 keV	15.5	5.6
Na23	σ_{inel}	1.35 - 0.498 MeV	28.0	7.9
Pu240	σ_{capt}	498 - 183 keV	14.3	8.9
		183 - 67.4 keV	13.8	6.7
		67.4 - 24.8 keV	11.3	6.1
		24.8 - 9.12 keV	10.2	6.5

Tables 6 to 9 give the details for each fast system (data for the ABTR were already summarized in table 4). Again, only the most significant data are shown.

In general, the priority is for U-238 (inelastic), Pu-239 (capture), Fe-56 and Na-23 σ_{inel} uncertainty reduction. The high content of Pu in the fuel and the relatively clean Pu vector are at the origin of this trend. The requirement for improved accuracy of the higher Pu isotopes, and in particular the fission of Pu-241, becomes more stringent for the EFR, GFR and LFR cases. As indicated above, the requirements for improved MA data, are limited to the SFR case and only for selected isotopes and reactions. A few specific requirements are shown according to specificities of some cores, e.g. Si data requirements for the GFR and Pb data for the LFR.

Tables 10 and 11 give a summary of the main data requirements related to the thermal neutron systems, i.e., the VHTR (table 10) and the extended burn-up PWR (table 11). The present analysis indicates few significant requirements. In the case of the VHTR, it is required to improve Pu-241 σ_{fiss} below ~400 eV. Pu-239 and Pu-241 very tight σ_{capt} requirement below ~0.5 eV are also shown, together with C data improvements (both capture and inelastic) with respect to current uncertainty estimates. For the PWR with extended burn-up, we find the requirement to improve Pu-241 and some O data.

The required accuracies are such that the design target accuracies are fulfilled in most cases. Table 12 gives a summary of the uncertainties of selected design parameters both with the original and with the required uncertainties, as obtained with the minimization procedure indicated above. In few cases only the residual uncertainties are slightly beyond the pre-defined target accuracies.

Table 8. GFR: Uncertainty reduction requirements needed to meet integral parameter target accuracies.

Isotope	Cross-Section	Energy Range	Uncertainty (%)	
			Initial	Required (λ=1)
U238	σ_{inel}	6.07 - 2.23 MeV	19.8	1.6
		2.23 - 1.35 MeV	20.6	1.8
		1.35 - 0.498 MeV	11.6	2.4
U238	σ_{capt}	24.8 - 9.12 keV	9.4	1.6
		9.12 - 2.04 keV	3.1	1.4
Pu241	σ_{fiss}	1.35 - 0.498 MeV	16.6	3.5
		498 - 183 keV	13.5	3.1
		183 - 67.4 keV	19.9	2.5
		67.4 - 24.8 keV	8.7	2.5
		24.8 - 9.12 keV	11.3	2.6
		9.12 - 2.04 keV	10.4	2.2
		2.04 - 0.454 keV	12.7	2.8
Pu239	σ_{capt}	9.12 - 2.04 keV	15.5	2.8
Si28	σ_{capt}	19.6 - 6.07 MeV	52.9	5.6
Si28	σ_{inel}	6.07 - 2.23 MeV	13.5	3.0
		2.23 - 1.35 MeV	50.0	5.8
C	σ_{el}	1.35 - 0.498 MeV	5.0	1.7
Pu242	σ_{fiss}	1.35 - 0.498 MeV	19.0	4.0
Pu240	σ_{fiss}	1.35 - 0.498 MeV	5.8	2.2
Am241	σ_{fiss}	6.07 - 2.23 MeV	11.7	3.3

Table 9. LFR: Uncertainty reduction requirements needed to meet integral parameter target accuracies.

Isotope	Cross-Section	Energy Range	Uncertainty (%)	
			Initial	Required (λ=1)
U238	σ_{inel}	6.07 - 2.23 MeV	19.8	2.8
		2.23 - 1.35 MeV	20.6	2.3
		1.35 - 0.498 MeV	11.6	2.1
Pu241	σ_{fiss}	1.35 - 0.498 MeV	16.6	3.7
		498 - 183 keV	13.5	2.6
		183 - 67.4 keV	19.9	2.6
B10	σ_{capt}	498 - 183 keV	15.0	2.4
		183 - 67.4 keV	10.0	2.3
		67.4 - 24.8 keV	10.0	2.7
U238	σ_{capt}	24.8 - 9.12 keV	9.4	2.0
Pu240	σ_{fiss}	1.35 - 0.498 MeV	5.8	1.6
Pu240	ν	1.35 - 0.498 MeV	3.7	1.3
Pu238	σ_{fiss}	1.35 - 0.498 MeV	17.1	3.3
		498 - 183 keV	17.1	3.4
Fe56	σ_{inel}	2.23 - 1.35 MeV	25.4	4.2
		1.35 - 0.498 MeV	16.1	3.6
Pb206	σ_{inel}	2.23 - 1.35 MeV	14.2	3.3
Pb207	σ_{inel}	1.35 - 0.498 MeV	11.3	3.0
Pu242	σ_{fiss}	1.35 - 0.498 MeV	19.0	3.9
Cm244	σ_{fiss}	1.35 - 0.498 MeV	50.0	6.4

3 Complementary use of experiments

The very tight uncertainty requirements, discussed in the previous paragraph, suggest the complementary use of

Table 10. VHTR: Uncertainty reduction requirements needed to meet integral parameter target accuracies.

Isotope	Cross-Section	Energy Range	Uncertainty (%) Initial	Uncertainty (%) Required (λ=1)
U238	σ_{capt}	454 - 22.6 eV	1.7	1.2
C	σ_{scat}	19.6 - 6.07 MeV	30.0	7.1
C	σ_{abs}	19.6 - 6.07 MeV	20.0	7.1
		4 - 0.54 eV	20.0	5.0
Pu239	σ_{capt}	0.54eV - 0.1 eV	1.4	0.9
Pu241	σ_{fiss}	454 - 22.6 eV	19.4	6.4
		4 - 0.54 eV	26.8	9.4
		0.54eV - 0.1 eV	2.9	1.5
Pu241	σ_{capt}	0.54eV - 0.1eV	6.8	2.4

Table 11. PWR: Uncertainty reduction requirements needed to meet integral parameter target accuracies.

Isotope	Cross-Section	Energy Range	Uncertainty (%) Initial	Uncertainty (%) Required (λ=1)
O	σ_{abs}	19.6 - 6.07 MeV	100.0	12.1
		6.07 - 2.23 MeV	100.0	9.9
Pu241	σ_{fiss}	454 - 22.6 eV	19.4	4.7
		4 - 0.54 eV	26.8	7.7
		0.54eV - 0.1eV	2.9	1.7
		0.1eV - thermal	3.3	1.9
Pu239	σ_{capt}	0.54eV - 0.1eV	1.4	1.0
U238	σ_{capt}	24.8 - 9.12 keV	9.4	4.6
		454 - 22.6 eV	1.7	1.4
U238	σ_{inel}	6.07 - 2.23 MeV	14.6	5.1
Pu241	σ_{capt}	0.54eV - 0.1eV	6.8	3.0
Pu240	σ_{capt}	0.1eV - thermal	4.8	3.1
O	σ_{scat}	6.07 - 2.23 MeV	54.9	12.6
		19.6 - 6.07 MeV	84.6	15.6

Table 12. Integral parameter uncertainties (%) with initial and required cross section uncertainties.

		ABTR	SFR	EFR	GFR	LFR	VHTR	PWR
k_{eff} BOC	**initial**	0.62	1.04	0.79	1.24	0.88	0.37	0.36
	final	0.31	0.32	0.37	0.33	0.33	0.31	0.27
k_{eff} EOC	**initial**	-	-	-	-	-	0.41	0.64
	final	-	-	-	-	-	0.31	0.37
Void	**initial**	5.11	15.66	6.68	5.46	4.97	-	-
	final	3.07	4.06	3.26	3.12	1.88	-	-
Burn-up [pcm]	**initial**	37.4	152.1	584.9	254.2	127.7	487.0	684.6
	final	19.1	47.0	297.9	105.8	49.8	366.3	504.2

differential and integral experiments in order to meet design target accuracies.

At first, a realistic assessment of the potential role of experimental techniques at existing experimental facilities, could help to streamline and prioritize new differential measurements. This effort should be as far as possible coordinated at an international level. In parallel, the use of integral experiments should be envisaged, to provide complementary information. In fact, a powerful strategy has been developed and recently generalized and applied to Na-cooled fast reactors [3]. This strategy allows to reduce current uncertainties on design parameters, using integral experiments as much as possible "representative" of the corresponding integral parameters for the "reference" design.

In particular, in ref. [3] it is shown that in the case of ABTR, the use of appropriate integral experiments allows to reduce the uncertainty on the k_{eff} from 2.02% to 0.36%. In the case of the SFR the reduction is significant but smaller (from 1.77% to 1.13%), due to the fact that the chosen integral experiments are not sensitive enough to MA data.

4 Summary and conclusions

When reliable design target accuracies and nuclear data uncertainties are available, quantitative indications can be defined on priority needs for data uncertainty reductions. Requirements can obviously differ between fast and thermal neutron systems. The present status of nuclear data uncertainties, and in particular the very low values for U-235, U-238 and Pu-239 fission and capture uncertainties, allows to underline specific priority needs for fast systems. The present study indicates a priority requirement for a drastic uncertainty reduction for some σ_{inel} (in particular for U-238), for the σ_{fiss} of Pu-241 (between ~1–500 keV) and of σ_{capt} of Pu-239 (~1–500 keV). These indications are valid for all the fast reactors considered in this work, and which are representative of the current priorities of the Gen-IV and GNEP initiatives. Other requirements are of course associated to specific systems (as Si data for the GFR or Pb in the case of LFR).

We have also investigated a method to tune the accuracy requirements on different cross-section types (e.g., inelastic and fission) according to the relative difficulty to achieve high accuracies in different types of measurement and more investigations in this field can be fruitful.

Since many of the requirements are very tight and difficult to be met within a reasonable time horizon, it seems that a strategy of combined use of integral and differential measurements should be pursued.

Finally, it should be stressed the essential role played by the recent effort in several laboratories to assess credible uncertainty data, which help to define a sound strategy for nuclear data improvements to meet the needs of future reactors and their associated fuel cycles.

References

1. M. Salvatores et al., *Nuclear Data Needs for Advanced Reactor Systems. A NEA Nuclear Science Committee Initiative* (these proceedings).
2. G. Aliberti et al., *Nuclear data sensitivity, uncertainty and target accuracy assessment for future nuclear systems*, Ann. Nucl. Energy **33**, 700 (2006).
3. M. Salvatores, G. Aliberti, G. Palmiotti, *Nuclear data validation and design performances uncertainty reduction*, to be presented at ANS meeting (Boston, USA, June 2007).