NUCLEAR DATA FOR ADVANCED FUEL CYCLES

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Within the Working Party on Evaluation Cooperation (WPEC) of the OECD Nuclear Energy Agency Nuclear Science Committee, a systematic approach has been developed to define data needs for advanced reactor and fuel cycle systems.

A sensitivity and uncertainty study has given the impact of neutron cross-section uncertainty on the integral parameters of the core and fuel cycle of a wide range of innovative systems that correspond to :

- Generation-IV
- Global Nuclear Energy Partnership (GNEP),
- Advanced Fuel Cycle Initiative (AFCI),
- Advanced fuel cycle and P&T studies in Japan and Europe.

Features of the Investigated Systems

System	Fuel	Coolant	TRU/(U+TRU)	MA[(a)]/(U+TRU)	Power (MWth)
ABTR	Metal	Na	0.162	~0	250
SFR	Metal	Na	0.605	0.106	840
EFR	MOX	Na	0.237	0.012	3600
GFR	Carbide	He	0.217	0.050	2400
LFR	Metal	Pb	0.233	0.024	900
ADMAB	Nitride	Pb-Bi	1.0	0.680	380

(a) Minor Actinides

Some Features of the SFR and ADMAB Systems

System	Fuel	Coolant	TRU/(U+TRU)	MA/(U+TRU)	Power (MWth)
SFR	Metal	Na	0.605	0.106	840
ADMAB-ADS	Nitride	Pb-Bi	1.0	0.680	380

Fast Neutron Systems with high MA content: Total Uncertainties (%)

Reactor	k_{eff}	Power Peak	Doppler	Void	Burnup [pcm]	Decay Heat	Dose	Neutron Source
SFR	1.82	0.4	5.6	17.1	272	0.4	0.3	1.0
ADMAB	2.94	21.4	-	15.5	1044	0.7	1.0	2.5

Uncertainties (%) due to Selected MA data

		SFR		ADMAB		
Isotope	Cross-Section	k_{eff}	Void	k_{eff}	Power Peak	Void
Am241	fission	0.08	0.4	0.83	5.8	3.3
Am242m	fission	0.73	3.7	0.14	1.1	0.3
Am243	fission	0.04	0.3	0.35	2.4	1.6
Cm244	fission	0.39	3.0	1.90	13.4	3.2
Cm245	fission	0.39	1.0	1.04	7.6	1.6

Uncertainties (%) due to some Pu Isotope data

		SFR		ADMAB		
Isotope	Cross-Section	k_{eff}	Void	k_{eff}	Power Peak	Void
Pu238	ν	0.34	0.4	0.13	0.9	0.2
	fission	0.53	2.9	0.21	1.5	0.4
Pu240	ν	0.39	2.2	0.14	1.0	0.2
	fission	0.44	2.6	0.16	1.2	0.2
	capture	0.31	1.8	0.08	0.6	0.3
Pu241	fission	0.96	4.1	1.04	7.6	2.0
Pu242	fission	0.36	2.5	0.15	1.1	0.3

ADMAB: Δn ($t_F - t_0$) Uncertainty (%)

		Pu241	Pu242	Am241	Am242m	Am243	Cm242	Cm244	Cm245	Cm246
Pu241	capture	2.18	4.42	0.01	-	-	-	-	-	-
	fission	9.18	0.27	0.05	-	-	-	-	-	-
Pu242	capture	-	5.80	-	-	1.03	-	-	-	-
	fission	-	3.72	-	-	0.01	-	-	-	-
Am241	capture	-	5.05	4.18	5.92	-	4.73	-	-	-
	fission	-	0.09	1.51	0.11	-	0.11	-	-	-
Am242m	capture	-	-	-	0.80	-	-	-	-	-
	fission	-	-	-	3.81	-	-	-	-	-
Am243	capture	-	-	-	-	4.27	-	9.40	1.93	0.03
	fission	-	-	-	-	1.17	-	0.11	0.02	-
Cm242	fission	-	-	-	-	-	0.54	-	-	-
Cm244	capture	-	-	-	-	-	-	3.93	57.10	1.38
	fission	-	-	-	-	-	-	15.13	2.96	0.05
Cm245	capture	-	-	-	-	-	-	-	3.78	12.08
	fission	-	-	-	-	-	-	-	90.97	2.21
Cm246	fission	-	-	-	-	-	-	-	-	1.39
Total		9.97	9.62	4.45	7.09	4.54	4.76	18.24	107.52	12.44

SFR: Δn ($t_F - t_0$) Uncertainty (%)

		Pu241	Pu242	Am241	Am242m	Am243	Cm242	Cm244	Cm245	Cm246
	capture	2.77	4.23	0.04	-	-	0.01	-	-	-
Pu241	fission	19.38	0.21	0.31	-	-	0.06	-	-	-
	capture	-	12.83	-	-	49.38	-	3.23	-	-
Pu242	fission	-	15.25	-	-	0.37	-	0.02	-	-
	capture	-	0.69	5.41	0.44	-	44.66	-	-	-
Am241	fission	-	0.01	2.99	0.01	-	0.84	-	-	-
	capture	-	-	-	2.15	14.13	0.04	-	-	-
Am242m	fission	-	-	-	10.65	0.58	0.22	-	-	-
	capture	-	-	-	-	14.46	-	38.66	0.21	-
Am243	fission	-	-	-	-	6.52	-	0.43	-	-
Cm242	fission	-	-	-	-	-	15.02	-	-	-
	capture	-	-	-	-	-	-	28.94	18.11	-
Cm244	fission	-	-	-	-	-	-	145.34	0.77	-
	capture	-	-	-	-	-	-	-	2.81	18.13
Cm245	fission	-	-	-	-	-	-	-	61.89	2.19
	capture	-	-	-	-	-	-	-	-	24.45
Cm246	fission	-	-	-	-	-	-	-	-	51.16
Total		24.61	20.39	6.20	10.88	53.76	47.18	153.19	64.55	59.57

SFR and ADMAB Target Accuracies (1σ)

Multiplication factor (BOL)	300 pcm
Power peak (BOL)	2%
Burnup reactivity swing	300 pcm
Reactivity coefficients (Coolant void and Doppler at BOL)	7%
Major nuclide density at end of irradiation cycle	2%
Other nuclide density at end of irradiation cycle	10%

The unknown uncertainty data requirements can be obtained by solving a minimization problem (the “inverse” problem) :

$$\sum_{i} \lambda_i / b_i'^2 = \min \qquad i = 1 \ldots I$$

$$\sum_{i} S_{Ri} b_i'^2 S_{Ri}^{+} + \sum_{i,j} S_{Ri} b_i' b_j' c_{ij} S_{Rj}^{+} < Q_R$$

The c_{ij} are the correlation coefficients of the original data covariance matrix, and the b_i' are the unknown variance values needed to meet the requirements .

The S_{Ri} are the sensitivity coefficients of integral parameter R to nuclear data i.

Q_R is the target accuracy on the integral parameter R, and λ_i are cost parameters.

SFR: MA Uncertainty Reduction Required to Meet Design Target Accuracies

Isotope	Cross-Section	Energy Range	Uncertainty (%)	
			Initial	Required
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
		1.35 - 0.498 MeV	19.0	3.5
Cm245	σ_{fiss}	183 - 67.4 keV	47.5	6.7

ADMAB: MA Uncertainty Reduction Required to Meet Design Target Accuracies

Isotope	Cross-Section	Energy Range	Uncertainty (%)	
			Initial	Required
Cm244	σ_{fiss}	6.07 - 2.23 MeV	31.3	3.0
		2.23 - 1.35 MeV	43.8	2.6
		1.35 - 0.498 MeV	50.0	1.5
Am243	σ_{inel}	1.35 - 0.498 MeV	42.2	2.3
		498 - 183 keV	41.0	3.6
		183 - 67.4 keV	79.5	3.7
Am241	σ_{fiss}	6.07 - 2.23 MeV	11.7	1.7
		2.23 - 1.35 MeV	9.8	1.4
		1.35 - 0.498 MeV	8.3	1.2
Cm245	σ_{fiss}	1.35 - 0.498 MeV	49.4	3.3
		498 - 183 keV	37.2	2.9
		183 - 67.4 keV	47.5	2.9
		67.4 - 24.8 keV	26.5	3.2
Am243	σ_{fiss}	6.07 - 2.23 MeV	11.0	2.3
		1.35 - 0.498 MeV	9.2	1.6
Cm244	ν	6.07 - 2.23 MeV	11.1	2.5
		1.35 - 0.498 MeV	5.5	1.3
Cm242	σ_{fiss}	6.07 - 2.23 MeV	52.6	26
		498 - 183 keV	66.0	28.4
Am242m	σ_{fiss}	498 - 183 keV	16.6	4.8
		183 - 67.4 keV	16.6	4.8

Other data needs

Some fuel cycle related data needs are implicitly accounted for since nuclide densities at the end of irradiation were included in the analysis.

However, a specific analysis should be made on the decay heat data needs (both in the reactor and at fuel discharge/storage) when a fuel highly loaded (e.g. ~50% HM) is considered or a FR with a low conversion ratio.

In fact, the relative contribution of heavy isotopes (and its breakdown by isotope) and fission products at different cooling times of the decay heat in a dedicated burner reactor with a highly MA loaded fuel and in SUPERPHENIX, are very different.

The data show the importance of the MA contribution and, as a consequence, they underline the need for high accuracy data.

Decay heat assessment with high accuracy is needed in safety case

Decay Heat—Relative Contribution of Heavy Isotopes and Fission Products at Different Cooling Times*

	Discharge[a]	500 s	1000 s	3000 s	1 h	12 h	1 day	10 days
Burner FR								
Heavy elements	23	46	50	57	58	74	77	86
Fission products	77	53	50	43	41	26	22	14
Superphenix								
Heavy elements	8.9	NA	20.2	22.3	22.5	32.3	34.5	22.8
Fission products	89.7	NA	74.6	72.6	72.3	63.7	62.1	73.2

*Relative contribution (%).
[a]EOL (2 yr).

Standard Pu fuel

High MA content in the fuel

Decay Heat—Heavy Element Breakdown by Isotope*

	Discharge[a]	500 s	1000 s	3000 s	1 h	12 h	1 day	10 days
U	7.63E+0[b]	7.62E+0	7.61E+0	7.59E+0	7.58E+0	7.29E+0	7.01E+0	3.71E+0
Np	3.05E+5	3.04E+5	3.04E+5	3.01E+5	3.01E+5	2.58E+5	2.19E+5	1.15E+4
Pu	9.59E+4	9.58E+4	9.56E+4	9.50E+4	9.49E+4	8.93E+4	8.81E+4	8.85E+4
Am	9.08E+5	7.73E+5	6.65E+5	4.08E+5	3.66E+5	1.73E+5	1.34E+5	7.83E+4
Cm	4.33E+6	4.33E+6	4.33E+6	4.33E+6	4.33E+6	4.33E+6	4.33E+6	4.20E+6
Bk	1.37E−3	1.35E−3	1.33E−3	1.26E−3	1.26E−3	7.09E−4	6.58E−4	6.41E−4
Cf	2.16E−4	2.16E−4	2.16E−4	2.16E−4	2.16E−4	2.17E−4	2.17E−4	2.22E−4
Total	5.64E+6	5.51E+6	5.40E+6	5.14E+6	5.09E+6	4.85E+6	4.77E+6	4.38E+6

*Decay heat (W).
[a]EOL (2 yr).
[b]Read as 7.63×10^0.

Decay heat dominated by MA
High accuracy decay data are needed

How to meet requirements.

- **The previous results indicate some very tight requirements for some MA isotopes (Cm-244, Am-243 etc), essentially for the fission cross section data.**

- **In order to meet these requirements and to obtain such tight accuracies, it is essential to use appropriate integral experiments and statistical nuclear data adjustment techniques.**

- **However, the available integral experiments are relatively limited and the present database should be expanded.**

1- Irradiation of small samples of separated isotopes in well-characterized spectral conditions.

An example is the PROFIL experiment program performed in PHENIX in the '70s

New series of experiments are underway in PHENIX: PROFIL-R and –M (i.e. with a modera surrounding the samples, to soften the spectrum), with a larger number of MA sampl

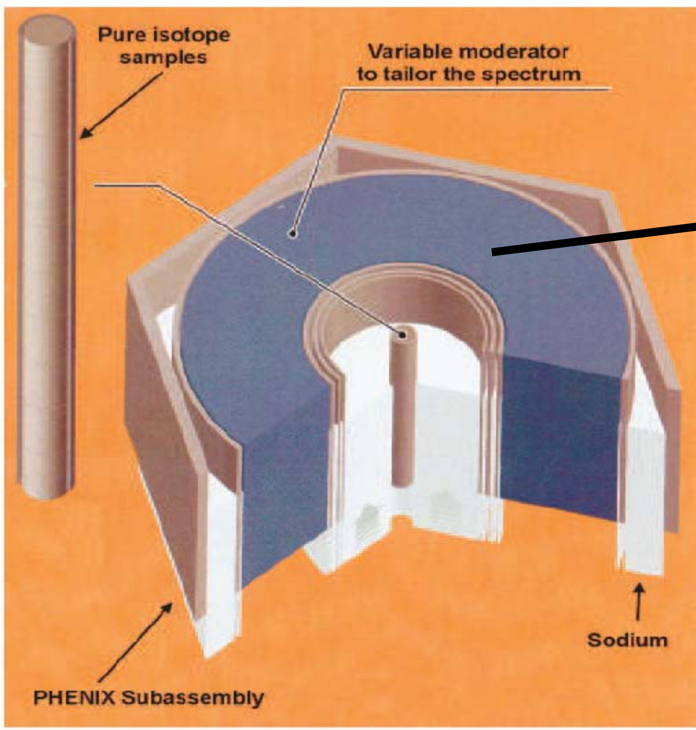
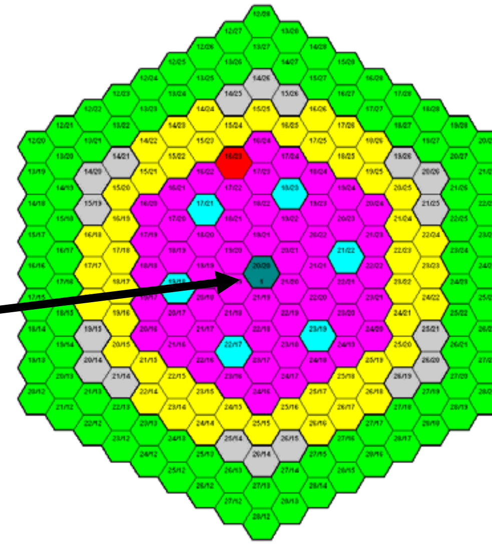
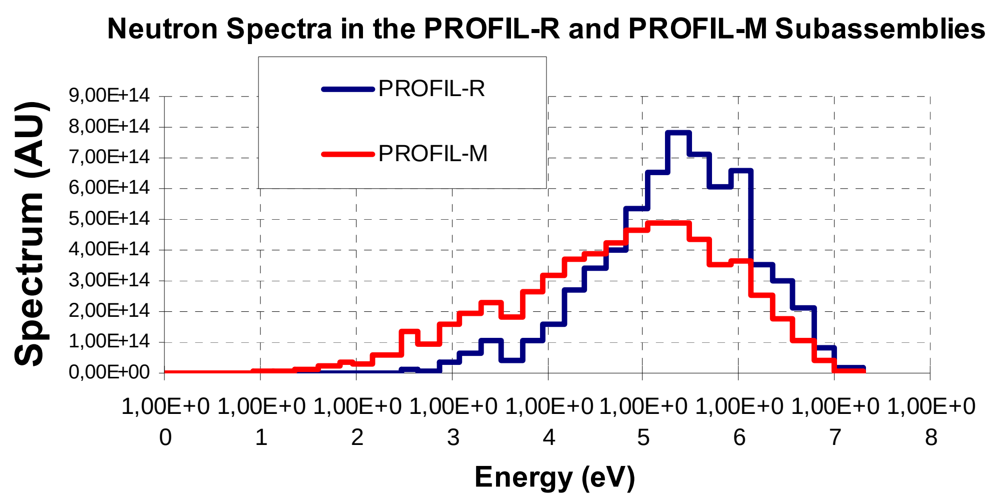


Figure 1. Transuranium pure sample irradiation in PHENIX in "Tailored" neutron spectra.





2- Fission rate measurements in critical assemblies.

- As for fission, a few experiments have been performed in the MASURCA critical facility with MA fission chambers (e.g. during the MUSE program).
- These experiments should be repeated with a *larger number of MA fission chambers*, and using variable moderators surrounding the fission chamber, to gain information on the fission cross section over a wide energy range.

3- Other critical experiments

Finally, a systematic integral experiment program has been performed at the FCA critical facility in the past, aiming to the reactivity assessment of selected MA in variable spectrum environments.

A possible frame and objectives for international collaboration

The need for MA high quality data should allow to envisage a long term international program:

- To consolidate target accuracy assessment, including an exhaustive analysis of fuel cycle data needs in this field. In particular target accuracies for MA inventories in a repository should be quantified.

- To define specific needs in the field of decay heat, both in the reactor and at fuel unloading (or storage)

- To support, expand and consolidate the effort for covariance data assessment and production.

- **To agree on a comprehensive integral data base, to be managed at the DataBank, that should include old, reliable and well documented experiments and new experiments**

- **To apply agreed methods and procedures for nuclear data adjustment. For this purpose, use should be made of a new Subgroup as proposed to the WPEC ("Methods and issues for the combined use of integral experiments and covariance data")**

The proposed project should be an "horizontal" type of project, since it is of interest for, at least, WPFC, WPEC and WPRS.

Conclusions

- **New covariance data allow to derive credible uncertainties on integral design parameters of cores loaded with significant amounts of MA**
- **To meet potential design requirements, MA data uncertainties should be definitely reduced**
- **The combined use of covariance and integral experiments is probably the best way to meet requirements**
- **An improved use of such powerful approach would imply the use of a wider integral data base as compared to the existing data base**
- **In this respect future initiatives aiming to the performance of well targeted integral experiment with high experimental accuracies, could be very welcome by a large international community**