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Nuclear Physics and Related Computational Science R&D for Advanced Fuel Cycle Workshop

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Advanced fuel cycles and R&D needs in the nuclear data field

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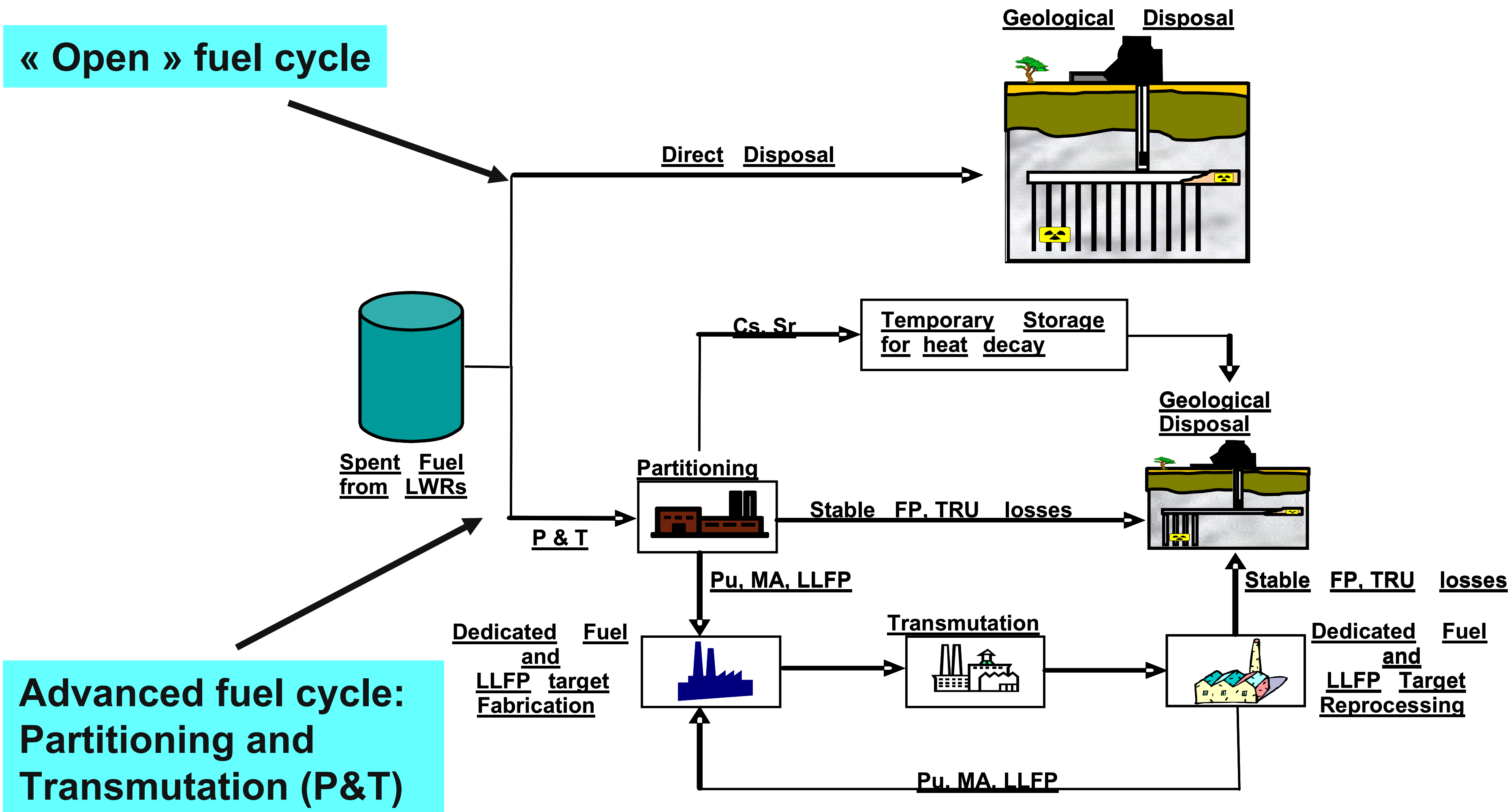
Summary

- Advanced fuel cycles: new requirements and role of nuclear physics
- Interlude: the relevance of nuclear data in the industry perspective
- How to assess requirements and priorities
- An example: from nuclear data uncertainties to required accuracies. The case of Gen-IV systems
- Neutron cross sections and beyond
- How to meet requirements: a common R&D challenge for nuclear and reactor physicists and nuclear system designers
- Conclusions and perspectives

Innovative Reactors and Fuel Cycles

Advanced fuel cycles allow sustainability, a drastic reduction of the burden on a geological disposal and offer enhanced non-proliferation characteristics.



Innovative Reactor and Fuel Cycles: R&D needs

The new requirements (closed fuel cycle, full TRU recycling, enhanced proliferation resistance, enhanced safety and economy) require a relevant R&D effort, from basic research to engineering implementation:

1- Design, Safety and System integration

2- Data and Computational methods improvement and validation

Reactor Physics „at large“: from nuclear physics to thermo hydraulics (multiscale physics)

3- Innovative fuels

Fuel and Material Sciences: basic properties, fabrication, irradiation…

…and modeling from „first principles“

4- Materials, Components and System Technology

Material Science: characterization, irradiation, mechanical behavior…

…and modeling from „first principles“

5- Fuel cycle (separation, reprocessing, waste forms)

Chemistry of actinides: partitioning, chemical processes…

…and modeling

Physics issues and validation needs for innovative Fast Reactors and associated fuel cycles as foreseen in GNEP and Gen-IV

For the validation of system safety and performance, the following fundamental characteristics will need enhanced nuclear data for the viability assessment of innovative fast reactors and their associated fuel cycles:

a) Presence of a high content of transuranium elements (i.e. high fissile/fertile isotope ratio, in the order of ~30%) in the fuel (related to the waste minimisation objective) and in the fuel cycle (Am, Cm etc.)

b) Need of an effective evaluation of a) the power distributions (and their evolution with time) in the core and close to interfaces (e.g. reflectors) , b) the reactivity effects due to innovative control rod system and to core perturbations (e.g. coolant void effect).

c) Moreover, the use of non-standard materials (e.g. new fuel constituents and reflector materials), will need specific validation.

Nuclear physics plays a crucial role

Industry has recognized the relevance of nuclear data. As an example, statement made by S.Ion, former Director of research at British Nuclear Fuel Ltd, for present reactor systems:

FRONT END OF THE CYCLE (mining, conversion, enrichment, fuel fabrication)

Good nuclear data does have the potential for significant impact in fuel fabrication. Based on a pessimistic world nuclear capacity of 400 GWe, the capital cost allocation for fuel fabrication is estimated at $250m/year. A saving of just 1% attributable to better nuclear data would equate to a benefit of several million $/y.

REACTORS

Based on an assessment of operating margins to cover uncertainties, better nuclear data could have the potential to allow at least a 2% uprating in the current generation of LWRs. This equates to a potential increase in generation worth $3bn/year for 400 GWe capacity

BACK-END OF THE FUEL CYCLE (reprocessing, waste management)

The total value of the back-end services for a 400 GWe programme is ~$5-10bn per year. A 1% saving in capital and operating costs attributable to improved nuclear data, amounts to a benefit of $50-100m per year.

Besides its economical value, nuclear data have an important defensive role to play: issues of regulatory and public acceptance are especially dependent on being able to present a sound technical case with the minimum of uncertainty.

The approach to evaluate the impact of nuclear cross-section uncertainties and needs for improvement

- **Sensitivity analysis** is performed, e.g. via GPT (Generalized Perturbation Theory), on performance parameters (core, fuel cycle) of representative models of the systems of interest.
- **Uncertainty (e.g. nuclear data covariance)** propagation and assessment

Once the **sensitivity coefficient matrix *S*** and the **covariance matrix *D*** are available, the uncertainty on the integral parameter can be evaluated:

$$\Delta R_0^2 = S_R^+ D S_R$$

- **Impact** on design and **target accuracy requirements** can then be specified as a successive step.

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An exemple (to give the flavor…) for Generation-IV systems. Nuclear data uncertainty impact evaluated on:

Reactor parameters….

- Criticality (multiplication factor)
- Doppler Reactivity Coefficient
- Coolant Void Reactivity Coefficient
- Reactivity Loss during Irradiation
- Transmutation Potential (i.e. nuclide concentration at the end of irradiation)
- Peak Power Value

….and fuel cycle parameters:

- MA Decay Heat in a Repository
- Radiation Source at Fuel Discharge
- Radiotoxicity in a Repository

In a preliminary study, performed at ANL, "educated" guesses for nuclear data uncertainties and partial energy correlations were used.

SFR (Burner: CR = 0.25)

840 MW_{th} – Na Cooled

U-TRU-Zr Metallic Alloy Fuel

SS Reflector

Pu content: 56%

MA: 10%

Irradiation Cycle: 155 d

EFR

3600 MW_{th} – Na Cooled

U-TRU Oxide Fuel

U - Blanket

Pu content : 22.7%

MA: 1%

Irradiation Cycle: 1700 d

"GNEP type"

GFR

2400 MWe – He Cooled

SiC – (U-TRU)C Fuel

Zr_3Si_2 Reflector

Pu content : 17%

MA: 5%

Irradiation Cycle: 415 d

LFR

900 MW_{th} – Pb Cooled

U-TRU-Zr Metallic Alloy Fuel

Pb Reflector

Pu content : 21%

MA: 2%

Irradiation Cycle: 310 d

VHTR

TRISO Fuel

U235 Enrichment: 14%

Burnup: 90 GWd/Kg

The systems which have been investigated

Results of preliminary analysis: Fast Reactors

Total 1σ Uncertainties (%)

Reactor		K_{eff}	Power Peak	Doppler coeff	Void coeff	Burnup $\Delta\rho$ (10^{-5} $\Delta k/k$)	Decay Heat	Dose	Neutron Source
GFR	No Correlation	±1.21	±1.2	±4.4	±5.2	±238	±0.3	±0.4	±1.2
	PEC	1.92	1.8	6.8	7.7	381	0.5	0.6	1.8
LFR	PEC	2.26	1.0	9.1	13.6	251	0.6	0.5	1.2
SFR	PEC	1.75	0.5	7.7	19.5	217	0.4	0.2	0.9
EFR	PEC	1.74	1.1	6.7	11.8	979	2.3	1.7	6.0

PEC: Partial Energy Correlations

SFR

Uncertainties (%) PEC – Breakdown by Isotope (Major Contributions)

Isotope	K_{eff}	Doppler	Void	Burnup [10^{-5} $\Delta k/k$]
U238	±0.21	±0.8	±1.9	±15
Pu238	0.34	1.1	3.8	53
Pu239	0.88	2.5	5.5	99
Pu240	0.52	1.3	4.4	45
Pu241	0.51	1.7	4.3	109
Pu242	0.23	0.6	1.6	21
Am241	0.13	0.8	1.2	7
Am242m	0.64	1.9	4.1	89
Cm242	0.04	0.1	0.3	15
Cm244	0.36	1.1	2.8	58
Cm245	0.37	1.2	3.0	64
Fe56	0.62	2.9	8.3	45
Na23	0.34	2.4	18.7	30

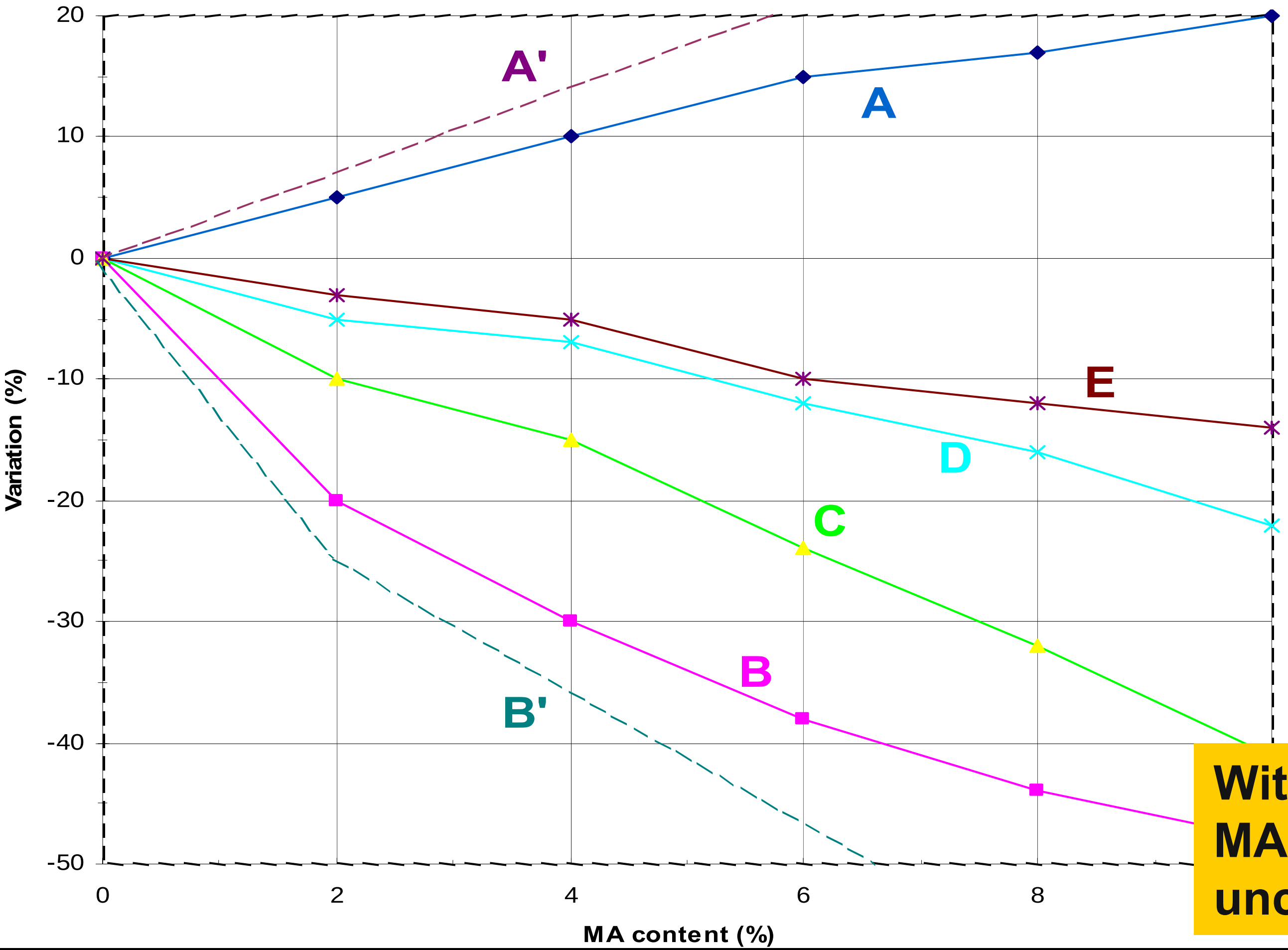
SFR

K_{eff} Uncertainties. Energy breakdown [10^{-5} $\Delta k/k$]

Gr.	Energy	Pu^{238} σ_{fiss}	Pu^{239} σ_{fiss}	Pu^{240} σ_{fiss}	Pu^{241} σ_{fiss}	Am^{242m} σ_{fiss}	Cm^{244} σ_{fiss}	Fe^{56} σ_{in}	Na^{23} σ_{in}
1	19.6 MeV	±4	±7	±9	±6	±3	±8	±30	±9
2	6.07 MeV	36	76	81	59	39	75	111	51
3	2.23 MeV	40	87	89	37	38	75	114	42
4	1.35 MeV	113	261	185	109	138	189	242	238
5	498 KeV	94	351	42	180	262	33	0	1
6	183 KeV	50	293	18	183	258	9	0	0
7	67.4 KeV	90	148	10	111	152	5	0	0
8	24.8 KeV	80	118	6	101	70	4	0	0
9	9.12 KeV	35	43	3	43	29	1	0	0
10	2.03 KeV	64	44	8	65	47	2	0	0
11	454 eV	11	13	0	17	11	0	0	0
12	22.6 eV	0	1	0	3	1	0	0	0
13	4.00 eV	0	0	0	0	1	0	0	0
14	0.54 eV	0	0	0	0	0	0	0	0
15	0.10 eV	0	0	0	0	0	0	0	0
Total [pcm]		217	575	227	334	434	220	291	247

IMPACT OF UNCERTAINTIES ON DESIGN

Variation of integral parameters as a function of MA content. Case of a large Na-cooled FR with homogeneous recycling of MA. Impact of uncertainties on max. amount of MA in the fuel?



A - Na-Void coefficient

B - Doppler coefficient

C – Δρ cycle

D - Control rod worth

E - Beta effective

A' - Upper limit of Na void coefficient variation (including uncertainty)

B' - Lower limit of Doppler coefficient variation (including uncertainty)

With nominal values, max MA content is ~4%. With uncertainties: ~3%!!

Results of preliminary analysis: VHTR

Total 1σ Uncertainties (%)

	K_{eff} BOC	K_{eff} EOC	Peak Power BOC	Peak Power EOC	Doppler BOC	Doppler EOC	Burnup [10^{-5} $\Delta k/k$]	Decay Heat	Dose	Neutron Source
PEC	*0.58*	*1.07*	*1.9*	*2.1*	*3.1*	*6.1*	*1749*	*3.1*	*2.6*	*14.3*

BOC: Beginning Of irradiation Cycle
EOC: End Of irradiation Cycle

VHTR

Uncertainties (%) PEC – Breakdown by Isotope (Major Contributions)

Isotope	Keff		Doppler		Burnup [$10^{-5}\Delta k/k$]	Neutron Source
	BOC	EOC	BOC	EOC		
U235	±0.36	±0.25	±1.3	±0.6	±171	±0.02
U238	0.43	0.55	2.7	2.2	150	2.61
Pu239	0.00	0.57	0.0	3.0	624	2.26
Pu240	0.00	0.63	0.0	3.9	1313	2.60
Pu241	0.00	0.17	0.0	0.3	222	2.33
Pu242	0.00	0.02	0.0	0.1	36	3.95
Am243	0.00	0.02	0.0	0.1	27	12.60
Cm244	0.00	0.00	0.0	0.0	3	2.30

To consolidate uncertainties and impact on design, uncertainties should evolve from „educated“ guesses, to scientifically sound covariance data.

- Needed: Systematic approach to provide covariance data with evaluated nuclear data files.
- Close interplay between experiments and nuclear models needed.
- A possible approach: Propagate model parameter uncertainties to cross section uncertainties with Monte Carlo
- Random sampling of model parameters
- Full covariance file produced.
- Other approaches used at LANL, ORNL, BNL (see later in the Workshop)

The next step:

To establish priorities and target accuracies on data uncertainty reduction, a formal approach can be adopted: define design-oriented target accuracies Q_n^T on integral parameters and find out required accuracy on nuclear data.

The unknown uncertainty data requirements d_i can be obtained solving the following minimization problem:

$$\sum_i \lambda_i / d_i^2 = \min \quad \text{with the following constraints :} \quad \sum_i S_{ni}^2 d_i^2 < Q_n^T$$

i = 1 ... I

n = 1 ... N

S_{ni} are sensitivity coefficients for integral parameter Q_n, and Q_n^T are the target accuracies on the N integral parameters, as defined by designers.

λ_i are "cost" parameters related to each σ_i proportional to the difficulty of improving that parameter with an appropriate experiment.

Fast Reactors Performance Target Accuracies (1σ)
(as defined within an international working group of the OECD-NEA)

PARAMETER	Q_n^T TARGET ACCURACY (1σ)
Multiplication factor (BOL)	0.3% Δk/k
Peak power (BOL)	2%
Power distribution	3%
Control rod worth (element)	5%
Control rod worth (total)	2%
Burn-up reactivity swing	0.3% Δk/k
Breeding gain	0.02
Coolant void reactivity coefficient (BOL)	7%
Doppler reactivity coefficient (BOL)	7%
Beta effective	5%
Major nuclide density at end of irradiation cycle	2%
Other nuclide density at end of irradiation cycle	10%

Results of the Target Accuracy Analysis

GFR

Isotope	Cross Section	Energy Range	Uncertainty % Initial	Uncertainty % Required
Pu239	σ_{capt}	183 KeV-67.4 KeV	15	8.1
		24.8 KeV-9.12 KeV	10	6
		9.12 KeV-2.03 KeV	5	4.1
		2.03 KeV-454 eV	5	4.5
	σ_{fiss}	6.07 MeV-2.23 MeV	5	3.3
		2.23 MeV-1.35 MeV	5	3.2
		1.35 MeV-498 KeV	5	2
		498 KeV-183 KeV	5	2
		183 KeV-67.4 KeV	5	1.8
		67.4 KeV-24.8 KeV	5	2
		24.8 KeV-9.12 KeV	5	2.2
		9.12 KeV-2.03 KeV	5	1.9
		2.03 KeV-454 eV	3	2.3

SFR

Isotope	Cross Section	Energy Range	Uncertainty % Initial	Uncertainty % Required
Pu239	σ_{capt}	498 KeV-183 KeV	15	9.4
		183 KeV-67.4 KeV	15	8.1
		67.4 KeV-24.8 KeV	10	9
		24.8 KeV-9.12 KeV	10	7.7
	σ_{fiss}	6.07 MeV-2.23 MeV	5	3.9
		2.23 MeV-1.35 MeV	5	3.6
		1.35 MeV-498 KeV	5	2.1
		498 KeV-183 KeV	5	1.8
		183 KeV-67.4 KeV	5	2
		67.4 KeV-24.8 KeV	5	2.8
		24.8 KeV-9.12 KeV	5	3.1

EFR

Isotope	Cross Section	Energy Range	Uncertainty % Initial	Uncertainty % Required
Pu239	σ_{capt}	1.35 MeV-498 KeV	15	12
		498 KeV-183 KeV	15	7.1
		183 KeV-67.4 KeV	15	5.3
		67.4 KeV-24.8 KeV	10	5
		24.8 KeV-9.12 KeV	10	4.4
		9.12 KeV-2.03 KeV	5	4.1
		2.03 KeV-454 eV	5	3.4
	σ_{fiss}	6.07 MeV-2.23 MeV	5	3.4
		2.23 MeV-1.35 MeV	5	3.4
		1.35 MeV-498 KeV	5	1.9
		498 KeV-183 KeV	5	1.8
		183 KeV-67.4 KeV	5	1.7
		67.4 KeV-24.8 KeV	5	2
		24.8 KeV-9.12 KeV	5	2.3
		9.12 KeV-2.03 KeV	5	2.7
		2.03 KeV-454 eV	3	2.2
	$\sigma_{n,2n}$	19.6 MeV-6.07 MeV	50	32.4

The case of Pu-239 data…..

Results of the Target Accuracy Analysis

GFR

Isotope	Cross Section	Energy Range	Uncertainty %	
			Initial	Required
Pu241	σ_{fiss}	6.07 MeV-2.23 MeV	20	8.4
		1.35 MeV-498 KeV	10	5
		498 KeV-183 KeV	10	4.5
		183 KeV-67.4 KeV	10	3.7
		67.4 KeV-24.8 KeV	10	3.7
		24.8 KeV-9.12 KeV	10	3.8
		9.12 KeV-2.03 KeV	10	3.2
		2.03 KeV-454 eV	10	4

SFR

Isotope	Cross Section	Energy Range	Uncertainty %	
			Initial	Required
Pu241	σ_{fiss}	6.07 MeV-2.23 MeV	20	8.8
		2.23 MeV-1.35 MeV	10	7.8
		1.35 MeV-498 KeV	10	4.6
		498 KeV-183 KeV	10	3.6
		183 KeV-67.4 KeV	10	3.5
		67.4 KeV-24.8 KeV	10	4.5
		24.8 KeV-9.12 KeV	10	4.7
		9.12 KeV-2.03 KeV	10	7.3
		2.03 KeV-454 eV	10	6

EFR

Isotope	Cross Section	Energy Range	Uncertainty %	
			Initial	Required
Pu241	σ_{capt}	24.8 KeV-9.12 KeV	20	14.5
		9.12 KeV-2.03 KeV	20	15.3
		2.03 KeV-454 eV	20	13
	σ_{fiss}	6.07 MeV-2.23 MeV	20	10.6
		2.23 MeV-1.35 MeV	10	9.9
		1.35 MeV-498 KeV	10	5.7
		498 KeV-183 KeV	10	4.5
		183 KeV-67.4 KeV	10	3.8
		67.4 KeV-24.8 KeV	10	4.1
		24.8 KeV-9.12 KeV	10	4.3
		9.12 KeV-2.03 KeV	10	4.8
		2.03 KeV-454 eV	10	4.3

….the case of Pu-241….

Results of the Target Accuracy Analysis

GFR				
Isotope	Cross Section	Energy Range	Uncertainty % Initial	Uncertainty % Required
Am241	σ_{capt}	183 KeV-67.4 KeV	10	5.1
		67.4 KeV-24.8 KeV	10	4.9
		24.8 KeV-9.12 KeV	10	5
		9.12 KeV-2.03 KeV	10	4.2
		2.03 KeV-454 eV	10	4.8
	σ_{fiss}	6.07 MeV-2.23 MeV	10	4.7
		2.23 MeV-1.35 MeV	10	4.7
		1.35 MeV-498 KeV	10	4.4

EFR				
Isotope	Cross Section	Energy Range	Uncertainty % Initial	Uncertainty % Required
Am241	σcapt	183 KeV-67.4 KeV	10	9.8
Am242m	σcapt	183 KeV-67.4 KeV	40	32.7
	σ_{fiss}	183 KeV-67.4 KeV	20	19.4
		67.4 KeV-24.8 KeV	20	19.2

SFR				
Isotope	Cross Section	Energy Range	Uncertainty % Initial	Uncertainty % Required
Am241	σ_{capt}	498 KeV-183 KeV	10	9.2
		183 KeV-67.4 KeV	10	8.3
	σ_{fiss}	6.07 MeV-2.23 MeV	10	9.3
		2.23 MeV-1.35 MeV	10	8.7
		1.35 MeV-498 KeV	10	7.9
Am242m	σ_{capt}	498 KeV-183 KeV	40	19.8
		183 KeV-67.4 KeV	40	15.7
	σ_{fiss}	6.07 MeV-2.23 MeV	20	11.1
		2.23 MeV-1.35 MeV	20	11.3
		1.35 MeV-498 KeV	20	5.8
		498 KeV-183 KeV	20	4.2
		183 KeV-67.4 KeV	20	4.2
		67.4 KeV-24.8 KeV	20	5.5
		24.8 KeV-9.12 KeV	10	5.7
		9.12 KeV-2.03 KeV	10	8.8
		2.03 KeV-454 eV	10	7

….and the case of higher mass Actinides.

Remember: GFR: 5% MA EFR: 1% MA SFR: 10% MA

Uncertainty Requirements for UO_2- and PuO_2-fuelled HTR's

Parameter	Q_n^T Target accuracy (1 sigma)
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 concentration of irradiated fuel)
Burn-up (cycle length)	0.5-1% (⇒ ~ 500 MWd/t)
Doppler coefficient	20%
Moderator temperature coefficient	1 pcm/°C
Beta-eff	10%
Prompt neutron lifetime	10%
Control rod worth: Integral Differential	10% 15% (locally)
Nuclide inventories at EOL: Main fissile isotopes Fertile isotopes MAs and FPs	4% 5% 20%
Poisons	< 3% (capture)
Shutdown margins	10%
Fuel decay heat	30% (20% on radio-nuclide concentrations + 10% on decay half-lives and energies)

Case of a VHTR: required cross-section uncertainties to meet design target accuracies (e.g. ≤ 0.5% Δk/k on the reactivity loss/cycle)

Isotope	Cross Section	Energy Range	Uncertainty %	
			Initial	Required
U236	σ_{capt}	22.6 eV-4.00 eV	8	7.1
U238	σ_{capt}	454 eV-22.6 eV	3	1.9
		22.6 eV-4.00 eV	3	1.4
Pu239	σ_{capt}	0.54 eV-0.10 eV	3	1.1
	σ_{fiss}	0.54 eV-0.10 eV	2	1
Pu240	σ_{capt}	454 eV-22.6 eV	10	9.6
		4.00 eV-0.54 eV	7	1.1

Isotope	Cross Section	Energy Range	Uncertainty %	
			Initial	Required
Pu241	σ_{fiss}	454 eV-22.6 eV	10	8.1
		22.6 eV-4.00 eV	10	5.5
		0.54 eV-0.10 eV	2	1.9
Am241	σ_{capt}	0.54 eV-0.10 eV	10	9.4
Am243	σ_{capt}	4.00 eV-0.54 eV	20	12.4
C	σ_{scatt}	6.07 MeV-2.23 MeV	35	12.3

A general "message": a few, very high accuracy new measurements can be needed, in particular (still!!) for major actinides and for selected minor actinides, often at the limit of the performances of present experimental techniques!!

Beyond neutron cross-sections…

In the different stages of development, the assessment of advanced nuclear systems requires improved data not only for neutron reaction data but also for other nuclear parameters.

A few examples:

- **The decay and fission yield data**
- **The effective fraction of delayed neutrons/fission**
- **Thermal scattering data**
- **Gamma production data**
- **…and method approximations.**

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

Burner FR 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

Decay Data Evaluations

- The measured data for some isotope is incomplete, and for some there are no measured values.
- In some cases integral decay properties have been measured (mean beta and gamma energies).
- Theoretical estimates have been made and these could be included in the absence of measured data.
- Adjustment of data to fit the integral measurements is another possibility.
- How is the balance to be struck between including only "good quality" data, based on an evaluation of the measurements, and completeness?

Fission Product Yield Evaluations

- The ensemble of the measured data have been adjusted, within the uncertainties, to satisfy conservation laws. However, the uncertainties assumed for some key fission monitors isotopes in the adjustment process were too large, or that these yields should be constrained in some way.
- The evaluation methodology has been improved. E.g. improvements have been made (and are still in progress) to the data base of measured values, the decay data used to calculate isomeric splitting and cumulative yields and uncertainties.

Delayed neutron fraction β for selected nuclides

Nuclide	β
^{238}U	0.0158
^{235}U	0.00680
^{237}Np	0.00437
^{239}Pu	0.00215
^{240}Pu	0.00310
^{241}Pu	0.00515
^{242}Pu	0.00720
^{241}Am	0.00138
^{243}Am	0.00230
^{242}Cm	0.00033

The presence in the fuel of a high content of MA lowers the effective delayed neutron fraction, making the reactor control more delicate.

Higher accuracy data are needed.

Thermal Scattering Data

- Scattering dynamics models for H in H_2O, D in D_2O, C in graphite, Be in beryllium and H in polyethylene at a range of temperatures have been used to produce S(a,b) data on a fine mesh. Extensive comparisons were made with experiment.
- Recently, thermal scattering data for H in ZrH and H in CaH_2 have also been produced. These are of interest in connection with studies using **moderated assemblies for actinide incineration in fast reactors.**
- However, changes in microstructure e.g. of graphite during irradiation, can affect thermal scattering (e.g. via phonon distribution).
- **This can affect spectrum in a VHTR and have impact on safety and performance parameters.**

Gamma production data

- Gamma production data are of relevance for **power distribution assessment in particular at interfaces (e.g. core/reflector) of innovative burner reactors**. Improved evaluation and possibly experiments, are still needed

Investigations of Method Approximations

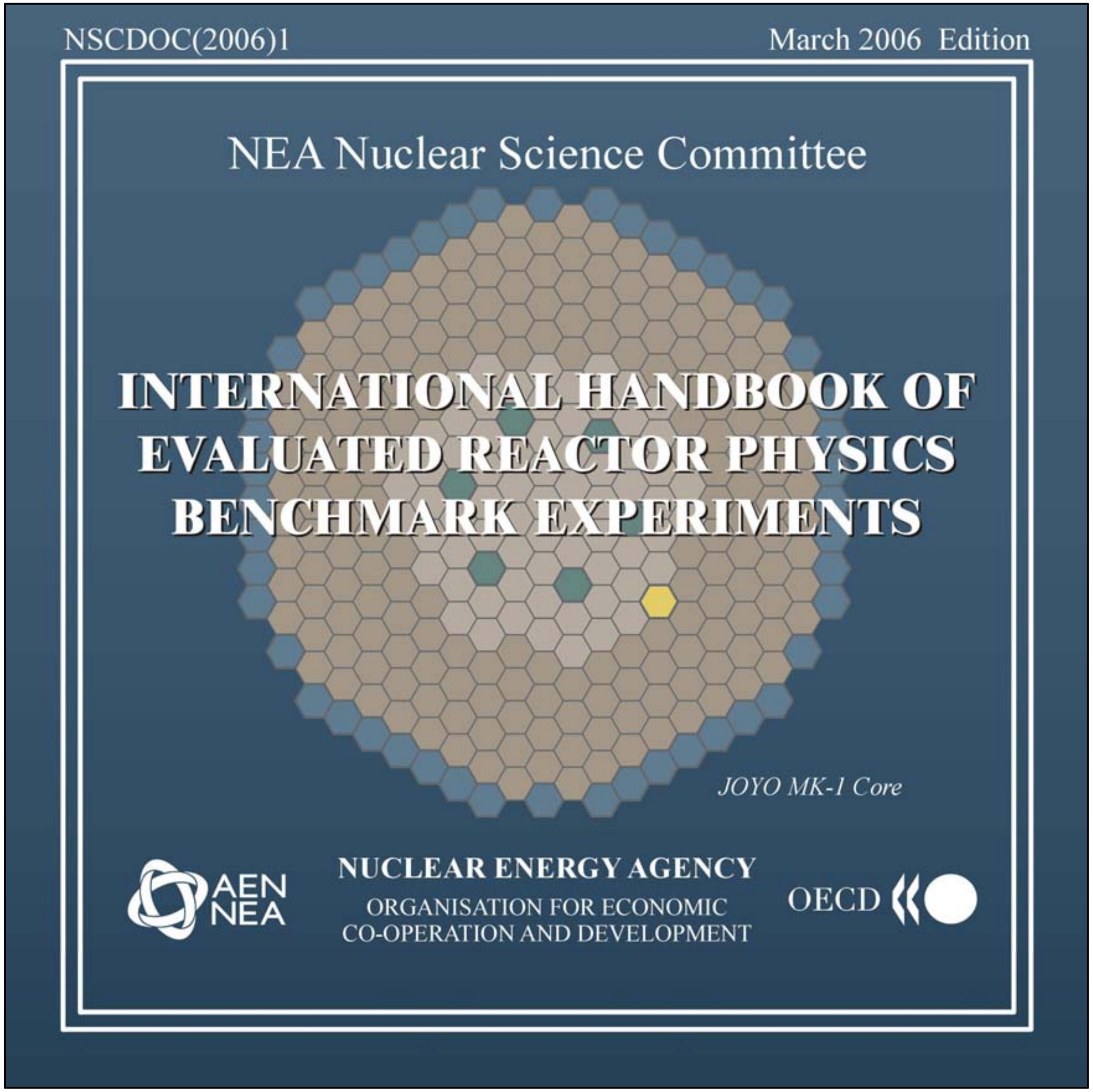
- There are still some approximations in the treatment of temperature effects which should be given consideration: secondary energy distributions in resonances and the influence of solid state effects are only treated approximately and there could be other approximations which require further study.

How to meet requirements…

- **The task to assess credible requirements requires a tight co-operation of nuclear physicists, reactor physicists and reactor system designers. A major challenge: the nuclear data covariance assessment.**

- **Moreover, in view of the high accuracy requirements, as shown previously, innovative experiments, experimental techniques and certainly theoretical developments (in order to allow as far as possible simulation starting from "first principles"), are needed.**

- **"Nuclear physics" experiments and "integral" (i.e. reactor physics oriented) experiments should play a complementary role, and should be well understood by both communities.**



A large number of integral experiments have been performed worldwide in the past, and are been collected and documented at OECD NEA

1 DVD
17 evaluations
Several hundred configurations

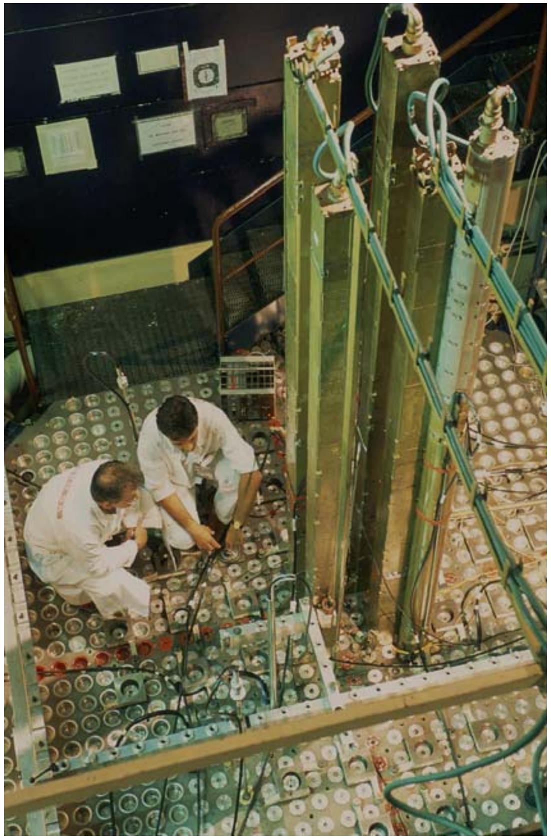
1st Edition

Selected new integral experiments should be carefully defined to meet well specified objectives and performed in the frame of large international collaborations.

MASURCA FACILITY (CEA-CADARACHE):

BOTTOM VIEW

TOP VIEW



Imagination should be at work to plan for innovative integral experiments...

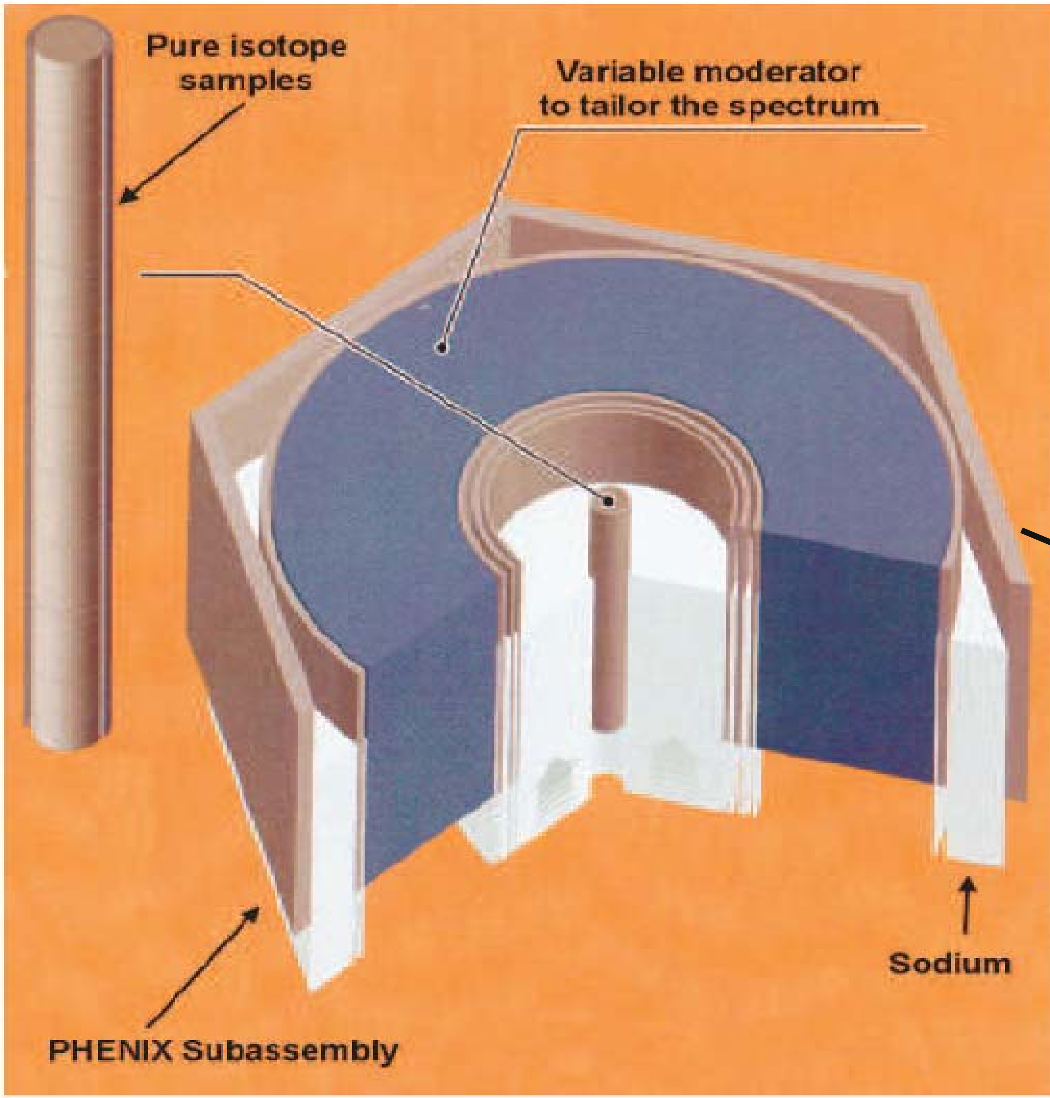
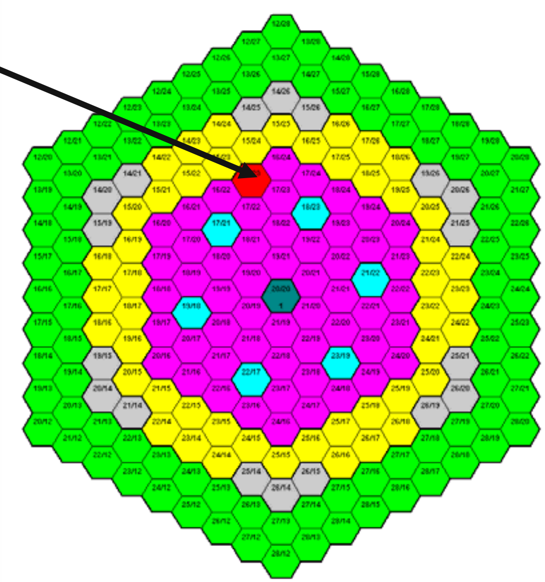


Figure 1. Transuranium pure sample irradiation in PHENIX in "Tailored" neutron spectra.



...and innovative techniques should be explored:

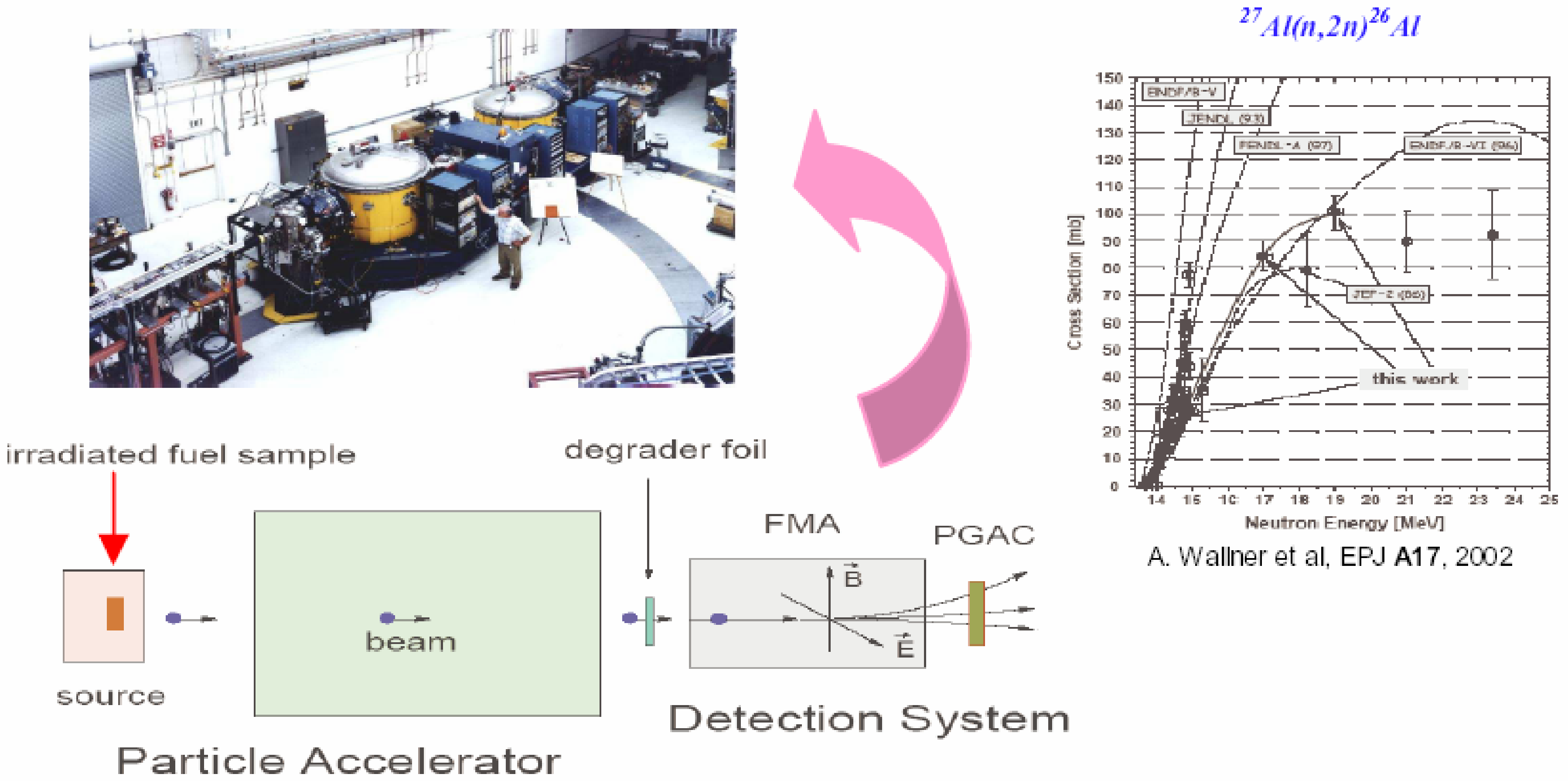


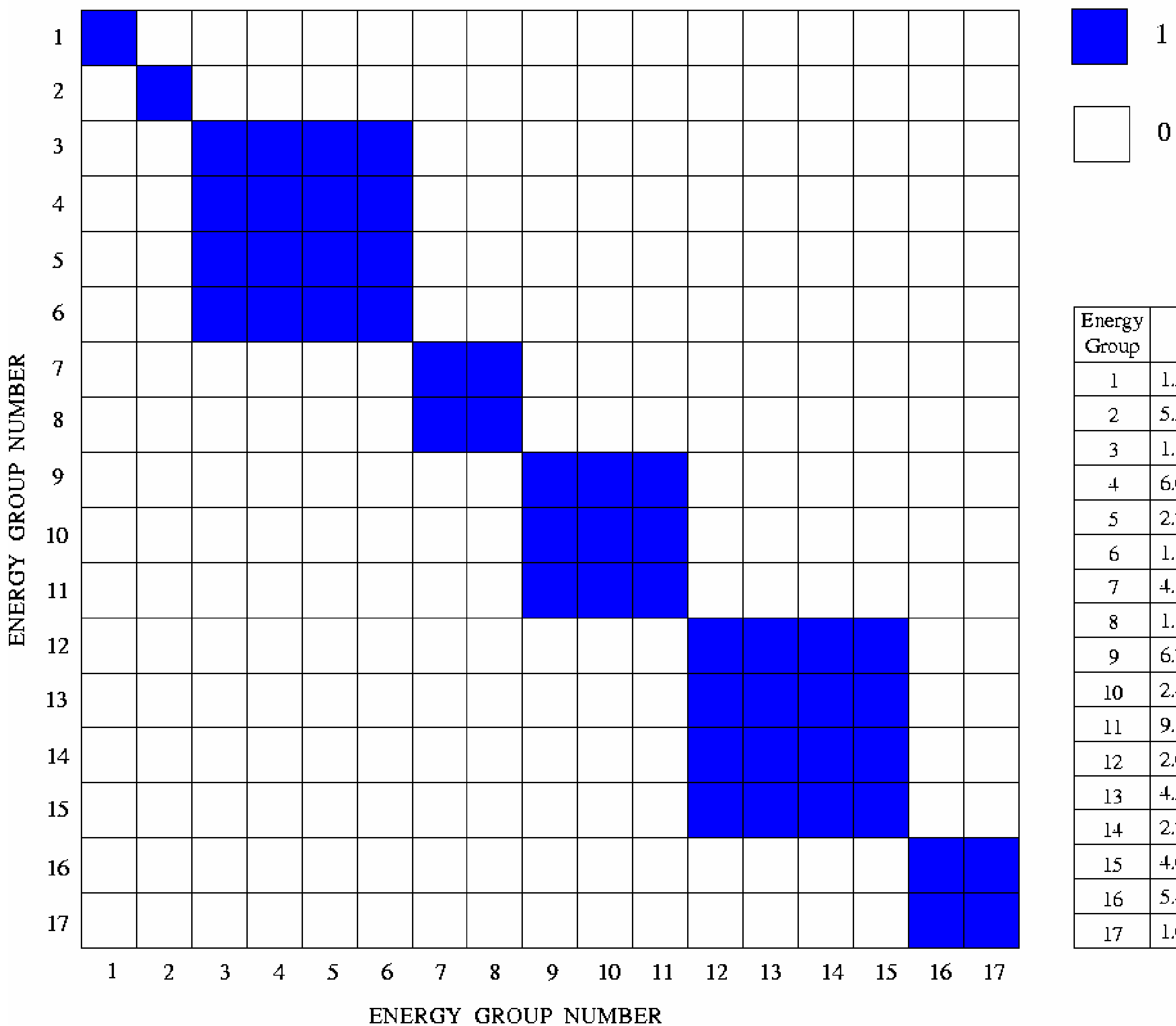
Figure 2. Accelerator Mass Spectrometry for TRU data measurements.

Conclusions and perspectives

- Nuclear reactors have been designed and operated rather successfully during five decades.
- Fundamental physics was at the heart of the early developments (Fermi, Seaborg, Wigner, Feynman…).
- Successively, heuristic and engineering approaches were mainly used in a wide industrial deployment. Global experimental mock-ups often prevailed over fundamental understanding and specific analytical experiments
- Today, we are probably at a turning point in view of the new requirements and challenges which go under the label „advanced fuel cycles“
- The early days tight interconnection of basic sciences, applied physics, engineering (and industry) has to be reconstructed to meet the new requirements and challenges
- A similar need is felt elsewhere in the world (e.g. in Europe) and the boundary conditions to start this endeavor look favorable

BACK-UP

Energy group structure and proposed partial energy correlation.



Energy Group	MeV
1	1.50000E+2
2	5.51820E+1
3	1.96403E+1
4	6.06531E+0
5	2.23130E+0
6	1.35335E+0
7	4.97871E–1
8	1.83156E–1
9	6.73795E–2
10	2.47875E–2
11	9.11882E–3
12	2.03468E–3
13	4.53999E–4
14	2.26033E–5
15	4.00000E–6
16	5.40000E–7
17	1.00000E–7