NUCLEAR DATA FOR ADVANCED FAST REACTORS

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ABSTRACT

Interest revives to fast reactors as the only proven technology obviously able of satisfying human energy needs for next millenium by using full energy content of both natural uranium resources and of vast stocks of depleted uranium. This interest stimulates revision and improvement of fast reactor ND. Progress in reactor calculations accuracy due to better codes and much faster computers also increases relative importance of the input data uncertainties, especially in case of small reactivity margin and fuels of equilibrium compositions. The main objects of corresponding R&D efforts should be minor actinides and heavy liquid metal coolant. Data error bands and covariance information also gains importance as necessary component of neutron physics calculations.

1. INTRODUCTION

After prolonged stagnation in nuclear power industry development which was triggered by TMI and Chernobyl accidents and resulted in postponement of the plans to start full scale introduction of fast reactors there are signs now of revived interest in FR technology. The interest is stimulated by gradual realization of following basic facts:

1. The mankind is consuming organic fuels million times faster than Nature was creating them. Peak production level of the most important one – conventional oil – may be reached in a few years and followed by decline so steadily growing demand could be met only by non-conventional oil at much higher prices. Recent signals from the oil market should not be misinterpreted.
2. The resources of natural uranium to be enriched and used in PWR type thermal reactors only could support nuclear power for less than a century even if spent nuclear fuel is recycled with full use of regenerated U and Pu.
3. Fast reactors are the only proven technology obviously able of satisfying human energy needs for next millenium by using full energy content of both natural uranium resources and of vast stocks of depleted uranium.
4. Fast reactors can burn minor actinides destroying the most hazardous component of radwaste and provide excess neutrons for transmutation of long-lived fission products so, in principle, radiation balance may be reached between excavated and buried radioactivity in long term closed nuclear fuel cycle.

Operating fast reactors were designed a few decades ago so nuclear data libraries should be revisited and critically analyzed to make fast neutron physics calculations of future advanced units more reliable. Some most prominent problems are discussed below.

2. BASIC PRINCIPLES AND CHALLENGES OF ADVANCED FAST REACTORS DESIGN

Following requirements to nuclear technologies of future large scale nuclear power industry may be formulated:

- higher safety level based primarily on natural laws, not on engineering barriers (natural safety);
- guaranteed fuel supply for thousands of years;
- proliferation resistance;
- competitiveness with organic fuels;
- solution of the problem of long-lived radwaste.

Physical and chemical principles of natural safety allowing to meet the above requirements:

- neutron rich cores with hard fast spectrum;
- reactivity effects of appropriate signs and values;
- breeding ratio slightly above unity without uranium blankets, producers of high grade Pu;
- inert, high-boiling, low activating coolant;
- closed NFC without Pu separation and with transmutation of long-lived radionuclides.

A set of engineering solutions for implementation of natural safety principles was proposed recently in Russia [1-2] and chosen by Minatom as focus of development efforts:

- dense mononitride fuel with equilibrium actinide composition;
- heavy liquid metal coolant (Pb);
- double circuit cooling;
- $BR \approx 1.05$ without uranium blankets;
- total reactivity margin within $\approx \beta_{eff}$ for the whole fuel life-time;
- fuel regeneration without U and Pu separation.

Possibility to apply the same principles (except the coolant choice, of course) for modification of Na-cooled BN-800 fast reactor design is now under intense investigation [3] and first results indicate that parameters close to those expected with Pb coolant may be achieved and the first BN-800 unit may incorporate the new features.

3. STATUS AND NEEDS IN THE SECTOR OF NUCLEAR DATA FOR FAST REACTORS

Recent progress in the accuracy of fast reactor neutron physics calculations is estimated in Table 1. Up to now final uncertainties were determined mainly by software algorithmic quality and by computers' speed but with their substantial progress the uncertainties of input nuclear data begin to show.

Table 1. Target and achieved accuracy of fast reactors neutronic calculations [4].

	Target Accuracy	Achieved Accuracy	
		1990	2000
K-eff	**0.5 %**	2.5 %	1.0 %
Void Reactivity Effect	**0.2 %Δk/k**	1.1 %Δk/k	0.4 %Δk/k
Doppler Effect	**10 %**	20 %	12 %
Power Release	**2 %**	5 %	3 %
Control Rods Efficiency	**5 %**	20 %	15 %
Breeding Gain	**0.02**	0.06	0.04

Following main directions of FR nuclear data improvements may be pointed out:

3.1 Minor actinides. FR equilibrium fuel itself contains MA with concentrations much higher than SNF of PWRs. If heterogeneous transmutation mode is applied MA concentrations in the target sub-assemblies will be still higher so needed data accuracy for MA should be close to the accuracy of traditional fuel nuclides. A list of achieved and target accuracies of minor actinides data aimed at transmutation needs and published recently [5] is given in Table 2.

Table 2. Actinides fast neutrons cross sections accuracy, achieved and needed, per cent [5].

	Capture		**Fission**		**Inelastic**	
	Achieved	**Target**	**Achieved**	**Target**	**Achieved**	**Target**
Np-237	15	5	7	5	30	10
U-238	5	3	3	3	10	10
Pu-238	25	10	10	5	40	
Pu-239	6	4	3	3	20	15
Pu-240	10	5	5		20	15
Pu-241	15	5	5	3	20	
Am-241	10	5	10	5	30	10
Am-242m	30	10	15	5	40	
Am-243	30	10	10	5	30	
Cm-242	50	10	15	5	30	
Cm-243	50	10	15	5	30	
Cm-244	50		10	5	30	

MA nuclear data are important not only for reactivity calculations but probably even more so for closed nuclear fuel cycle calculations because MA concentrations in the fuel to be reprocessed determine technology, safety and economy of the process as well as the level of irretrievable losses and radiotoxicity of final radwaste.

Dozens of specimens of actinide isotopes and isotopic mixtures were irradiated in BN-350 fast reactor [6]. Full time of irradiation was 781-797 days, fluence varied from 1.5 to $2.0\times10^{23}\text{cm}^{-2}$, full burn up from 9.3 to 23 per cent, principal isotope burn up from 11 to 35 per cent. Some results compared with calculated values are presented in Table 3. C/E ratio is considerably less than unity in most cases, the lowest value is below 50 per cent. Preliminary recommendations resulting from this analysis are: uncertainties pile up in long chains which probably indicates on correlation of the data used in calculations; fast neutron capture cross sections for some actinides are underestimated and should be increased (^{240}Pu by 8%, ^{241}Am by 10%, ^{242}Cm by 20%); covariation matrices of the uncertainties should be estimated.

Table 3. Accumulation of Am and Cm in actinide specimens irradiated in BN-350.

Nuclide	Cell 89	Cell 243
	C/E	C/E
^{242m}Am	1.11±0.02	-
^{243}Am	0.78±0.09	-
^{242}Cm	0.89±0.10	0.83±0.09
^{243}Cm	0.67±0.03	0.58±0.01
^{244}Cm	0.47±0.023	0.75±0.70

3.2. Burn-up credit. One of the well known problems in the reactor fuel cycle calculations is burn-up credit. It's important due to influencing the efficiency of SNF storage and transportation. PWR case is, in a sense, simpler: spent fuel unloaded from reactor is placed in the same environment – water - in "wet" storage. With fast reactors situation is different, and the difference is especially important for the fuels of equilibrium compositions. First, water moderating and reflecting properties are drastically different from those of liquid metal coolants. Second, small reactivity margin during the whole fuel life time in the core means that SNF practically maintains its criticality properties so, due to changing environment, burn up credit may turn into "burn up debit" which should be calculated carefully.

Extensive OECD/NEA benchmark activity on burn up credit in the nineties was summarized in a series of publications (see, for example, [7-9]). The status of some important data used in the calculations is illustrated by the tables 4-9. There is four-fold difference in Np-237 thermal cross section values used by different participants (see Table 4) which is obviously unacceptable. The discrepancies in the properties of important fission product absorbers (cumulative yields and capture cross sections, Tables 6-9) are also prominent.

The data presented in Tables 4-5 indicate that in fact uncertainties estimated in Table 2 as "achieved" in some cases still are to be achieved. One more example of this kind is presented in Fig.1. Controversial data on the fission cross section of Cm-243 hardly support 15% accuracy labeled as "achieved" in Table 2.

Table 4. Comparison of ^{243}Am thermal capture cross sections used in NEA benchmark.

Participant	Thermal cross section, b	Participant	Thermal cross section, b
AEA	68	BNFL	40
NUPEC/INS	51	ORNL-27g	52
ORNL-44g	40	PSI	74

Table 5. Comparison of ^{237}Np thermal capture cross sections.

Participant	Thermal cross section, b	Participant	Thermal cross section, b
AEA	159	BNFL	132
NUPEC/INS	38	ORNL-27g	77
ORNL-44g	89	PSI	89

Table 6. Comparison of ^{149}Sm thermal capture cross sections.

Participant	Thermal cross section, b	Participant	Thermal cross section, b
AEA	6.15E+04	BNFL	4.50E+04
NUPEC/INS	-	ORNL-27g	4.35E+04
ORNL-44g	4.70E+04	PSI	4.16E+04

Table 7. Comparison of ^{151}Sm thermal capture cross sections.

Participant	Thermal cross section, b	Participant	Thermal cross section, b
AEA	1.25E+04	BNFL	4.38E+03
NUPEC/INS	-	ORNL-27g	4.03E+03
ORNL-44g	3.93E+03	PSI	4.16E+04

Table 8. Cumulative fission yield data for ^{151}Sm.

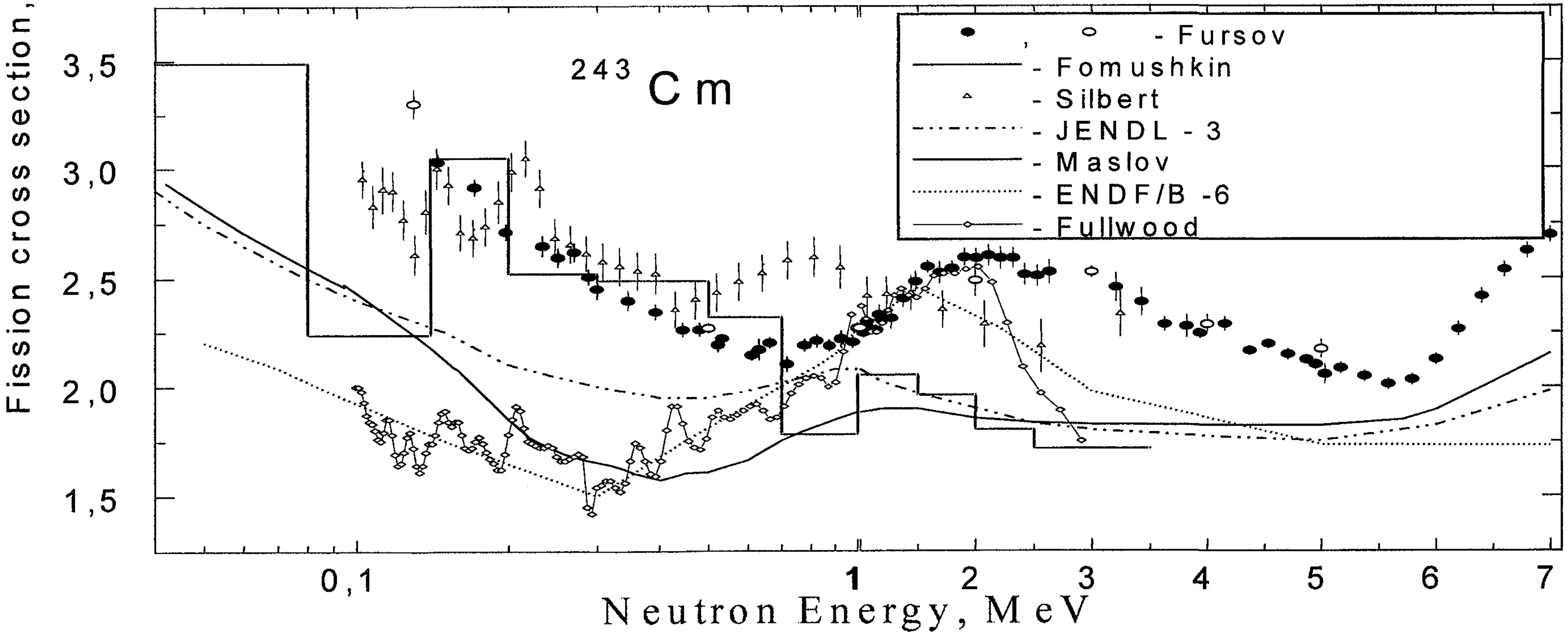
	AEA	CEA	BNFL
U-235	4.16E-03	4.16E-03	3.12E-03
U-238	8.09E-03	8.05E-03	3.31E-03
Pu-239	7.62E-03	7.55E-03	6.37E-03
Pu-241	8.55E-03	9.11E-03	7.33E-03

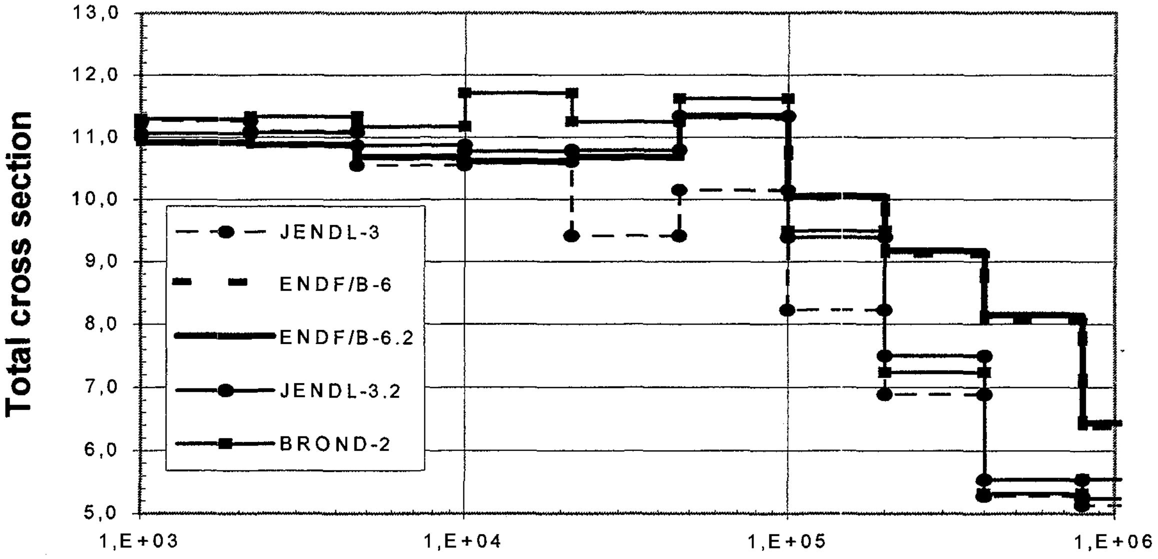
Table 9. Cumulative fission yield data for ^{149}Sm.

	AEA	CEA	BNFL
U-235	1.05E-02	1.07E-02	2.42E-03
U-238	1.66E-02	1.62E-02	1.04E-03
Pu-239	1.25E-02	1.23E-02	3.81E-03
Pu-241	1.46E-02	1.47E-02	5.63E-03

3.3. Heavy liquid metal coolant. Pure lead is rather neutron transparent substance. Its relative nuclear neutrality was probably the reason why Pb did not attract special attention of ND community until recently. The results of experiments and analysis presented in [4] indicate that there are considerable discrepancies between various nuclear data libraries on basic cross sections of lead. This situation is illustrated by Figs.2-5 and Table 10 below.

Fig.1. Experimental data on Cm-243 fission cross section.





ig. 2. Data on ^{nat}Pb total cross section taken from different ND libraries.

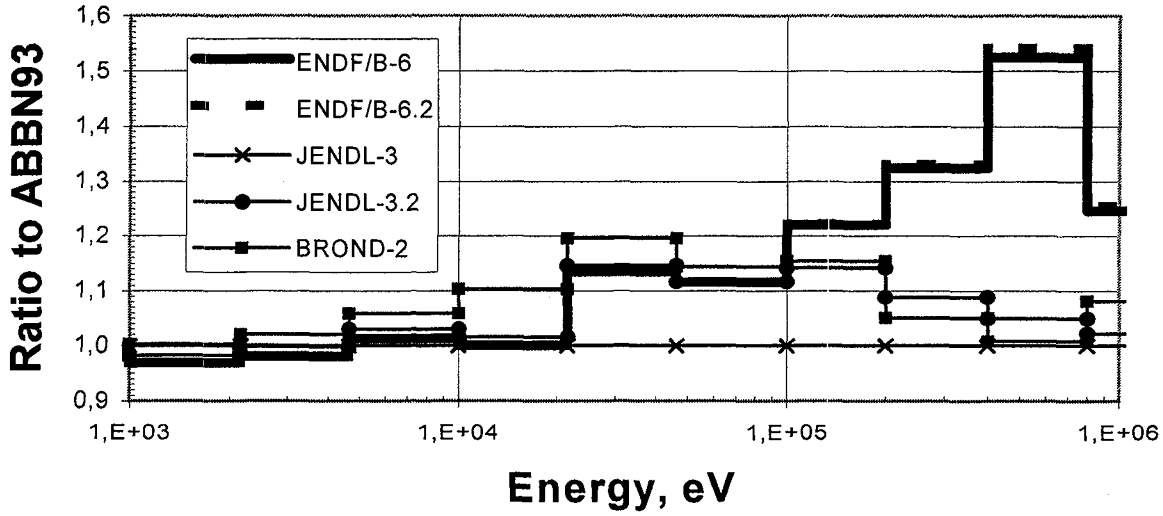


Fig. 3. The same as in previous Figure relative to ABBN93.

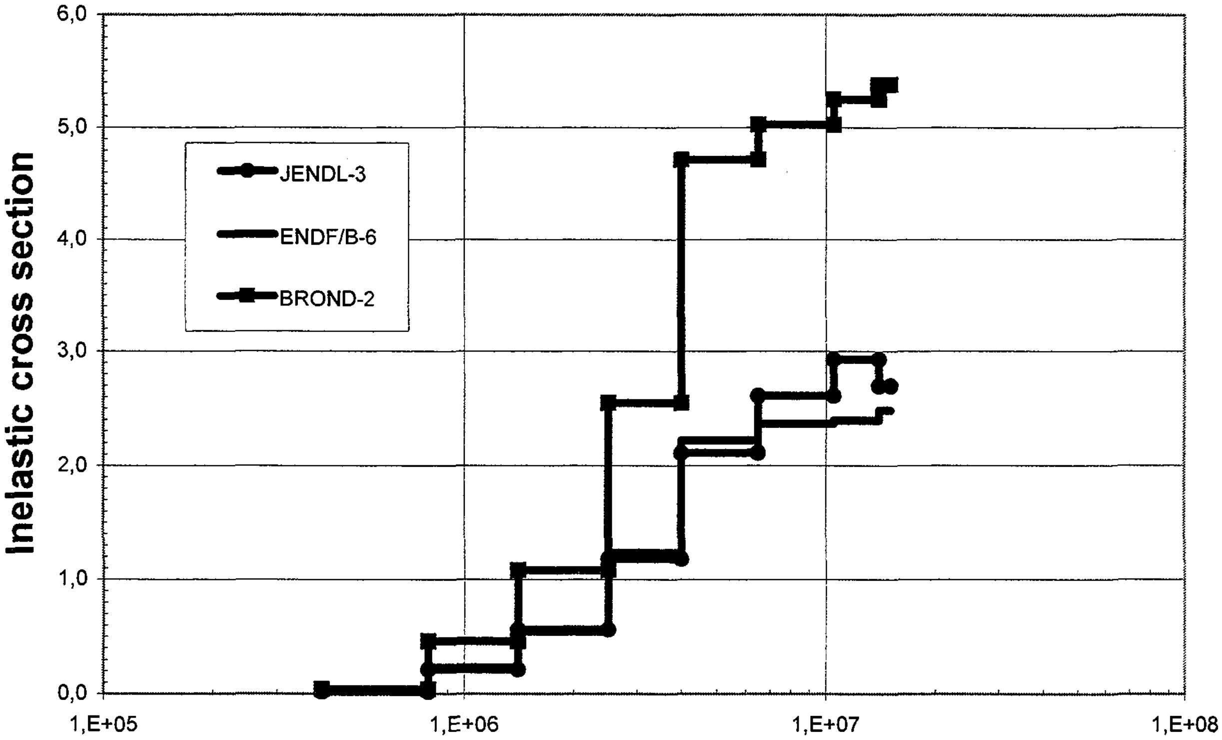


Fig. 4. Data on ^{nat}Pb inelastic cross section taken from different ND libraries.

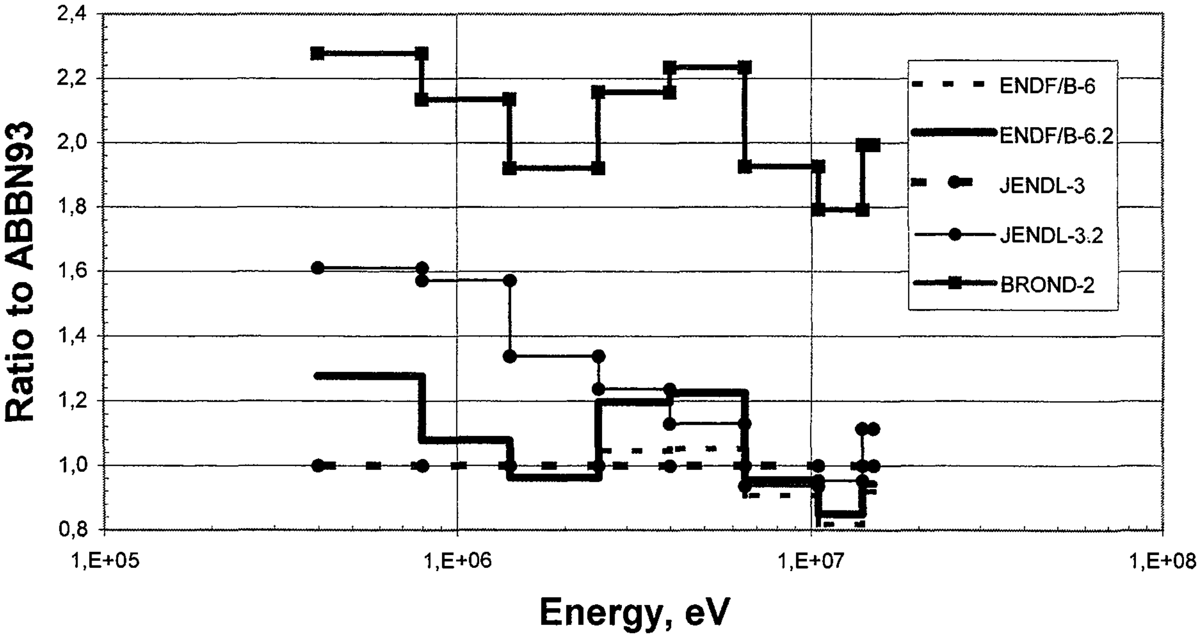


Fig. 5. The same as in previous Figure relative to ABBN93.

Table 10. C/E ratio of sigma remove for Pb^{nat} [4].

Data	**C / E**		
Library	***U^{238}(n,f)***	***Np^{237}(n,f)***	***Al^{27}(n,p)***
BROND-2	1.70	1.90	1.09
ENDF/B-6	1.07	1.19	0.99
ENDF/B-6.2	1.15	1.30	1.13
JENDL-3	***0.97***	***1.00***	***0.99***
JENDL-3.2	1.51	2.00	1.08

3.2. Error bands and covariances. The accuracy of calculated reactor parameters is of vital importance for safe and reliable operation of the units. The uncertainties of nuclear data used in those calculations are starting ground for any evaluation of calculations accuracy. At the same time it's widely known that standard statistical methods applied to generate error bands of evaluated ND from primary experimental information produce grossly underestimated values. This situation is probably best illustrated by comparison of purely statistical and expert evaluations of nuclear standard data [10] given in Table 11. One of the reasons of this discrepancy are highly correlated systematic errors of experimental data. The algorithms taking them into account are now being developed and there are some hopeful results both for error bands and for covariance matrices.

Table 1. The uncertainties of recommended standard cross sections. I – the results of purely statistical analysis of American Cross Section Evaluation Working Group (CSEWG). II – final expert evaluations by the members of the same Group.

$^{10}B(n,\alpha_0)^7Li$

Energy range, KeV	I, %	II, %	II/I
5 - 30	0.38	3	7.9
30 - 90	0.38	5	13.2
90 - 150	0.86	10	11.6
150 - 200	0.86	12	14.0
200 - 250	0.79	15	19.0

$^6Li(n,t)^4He$

Energy range, KeV	I, %	II, %	II/I
1 - 10	0.14	0.7	5.0
10 - 50	0.14	0.9	6.4
50 - 90	0.25	1.1	4.4
90 – 150	0.25	1.5	6.0
150 – 450	0.29	2.0	6.9

$^{197}Au(n,\gamma)^{198}Au$

Energy range, KeV	I, %	II, %	II/I
200 - 500	1.31	3.0	2.3
500 - 1000	2.10	3.5	1.7
1000 - 2500	2.00	4.5	2.3

^{235}U(n,f)

Energy range, KeV	I, %	II, %	II/I
150 - 600	0.19	1.5	7.9
600 - 1000	0.60	1.6	2.7
1000 - 3000	0.60	1.8	3.0
3000 - 6000	0.69	2.3	3.3
6000 – 10000	0.69	2.2	3.2
10000 - 12000	1.14	1.8	1.6
12000 - 14000	1.14	1.2	1.1
14000 - 14500	0.55	0.8	1.5
14500 - 15000	0.55	1.5	2.7
15000 - 16000	0.97	2.0	2.1

CONCLUSIONS

1. Revision and improvement of nuclear data for fast reactors are needed, progress in reactor calculations accuracy due to better codes and much faster computers increases relative importance of the input data uncertainties.
2. Better accuracy is especially important in the case of small reactivity margin and fuels of equilibrium compositions characteristic for the cores of enhanced safety and proliferation resistance.
3. The main objects of R&D efforts should be minor actinides and heavy liquid metal coolant where data discrepancies still are large.
4. Data error bands and covariance information also gains importance as necessary component of neutron physics calculations so adequate methods of their generation should be developed.

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