Chapter 6

FAST REACTOR VALIDATION STUDIES

Introduction

Studies have mainly been carried by SPRC/LEPh, CEA Cadarache. The measurements which have been analysed include those made at the start-up of the SUPERPHENIX reactor (and associated measurements made in the critical facility MASURCA). A wide range of measurements made in MASURCA and other critical facilities have also been analysed, including core properties and reaction rate distributions in blanket and shielding regions. The analysis of the results of measurements, of transmutation of actinide samples made in the PROFIL sample irradiation programme in PHENIX gives information, in particular, on capture and (n,2n) cross-sections. Analyses have also been made of the measurements of the reactivity worths of fission product samples made in the STEK facility at Petten and in the RRR/SEG facility at Rossendorf, Dresden. Spectrum averaged capture cross-section measurements have also been made for fission product isotopes in the PROFIL irradiation measurements.

The analyses carried out at Cadarache were made using the ERANOS system. The JEF-2.2 cross-section library is first processed to the form used by the ECCO cell code. The cross-sections are in 1 968 fine groups, with the energy structure of the cross-sections within these fine groups being treated using subgroup or probability table methods. ECCO calculations are made for regions of the reactor (the basic cells, or macrocells) and the cross-sections are condensed to fewer energy groups, normally 33, for use in the whole reactor calculations. These calculations are then made in three dimensions using either diffusion theory or transport theory methods. When considered advisable these methods are compared with continuous energy Monte Carlo calculations made using the TRIPOLI-4 code.

The standard ECCO library in 1 968 groups treats anisotropy using P_0 and P_1 scattering matrices only. For calculations which require a higher order of anisotropic scattering to be represented the SHIVA library in 172 groups is used. This treats scattering anisotropy up to order P_5. For calculations of transmission through shields the 175 group P_3 ASPILIB2 library is used. This also uses probability table data to treat within group structure, the data having been obtained by condensation from the 1 968 group library.

A cross-section adjustment study has been carried out at Cadarache and an adjusted ECCO library, ERALIB1, produced. The procedure used and the main results of the adjustment study are described in Part III. Some reanalyses made using the adjusted library are relevant to the assessment of some items of JEF-2.2 data because the adjustments can affect the calculated neutron energy spectrum (and importance spectrum) and hence, for example, the values of C/E for fission product isotope reactivity worths and the spectrum-averaged capture cross-sections of the minor actinides, isotopes for which the cross-sections have not been adjusted.

The studies have highlighted the need to revise the cross-sections of sodium above the inelastic scattering cross-section threshold at 440 keV. A new evaluation has been produced based on recent measurements made at IRMM Geel and at ORNL. This has been used in some of the analyses.

Studies have also been made intercomparing JEF-2.2, JENDL-3.2 and ENDF/B-VI calculations of k_{eff} for fast systems. Certain of the evaluations have common features between the three libraries and so the overall level of agreement is not surprising.

A note of caution concerning the ^{239}Pu data should be made. The evaluation includes fission spectra for both the total fission (MT = 18) and for the partial fission cross-sections (MT = 19, etc.) and these are markedly different. The MT = 18 spectrum is the one recommended by the evaluator. However, unless care is taken NJOY will process the MT = 19, etc. spectra, this being the default procedure. It should also be noted that in the codes used in France a corrected version of the ^{239}Pu data in the unresolved resonance region (1 to 30 keV) has been used.

Results for the unreflected spheres, GODIVA and JEZEBEL, and associated reflected spheres

Calculations have been made by a number of contributors for these benchmarks and the results summarised in a JEF report (see JEF/DOC-792). There are some significant differences between the results obtained using different methods. The values of k_{eff} are calculated to be about 420-520 pcm low for GODIVA and about 350 pcm low for JEZEBEL (MT = 18 fission spectrum). The C/E values for the spectral indices are consistent between GODIVA and JEZEBEL when the ^{239}Pu MT = 18 fission spectrum is used. The ^{239}Pu/^{235}U fission ratio is about 1% low, the ^{233}U/^{235}U, ^{238}U/^{235}U and the ^{237}Np/^{235}U fission ratios are about 3% low, and the ^{197}Au capture/^{235}U fission ratio is about 5% low.

W. Bernnat, *et al*. have presented the results of calculations of k_{eff} using JENDL-3.2, ENDF/B-V and VI, and JEF-2.2 [1]. The k_{eff} value (calculated using MCNP and JEF-2.2) for JEZEBEL is in closer agreement with experiment than the JEF/DOC-792 results, the value of (C-E) being -220 ± 30 pcm. This difference could be due to the use of a different specification for the core (i.e. Handbook of Evaluated Criticality Safety Benchmark Experiments, rather than the CSEWG benchmark book). For GODIVA the JENDL-3.2 k_{eff} value is in agreement with experiment and the fission ratio, ^{238}U/^{235}U is in better agreement. However, for JEZEBEL the JENDL-3.2 agreement is less good.

H. Takano has reported calculations of k_{eff} made using the MVP Monte Carlo code for Los Alamos criticals [2]. There is a surprising difference between the results for the bare cores, GODIVA and JEZEBEL, and the uranium reflected cores, FLATTOP-25 and FLATTOP-Pu. H. Takeda points out the very large effect of the differences between the ^{238}U inelastic scattering secondary energy distributions in JENDL-3.2 and ENDF/B-VI. One also can note the very poor JEF-2.2 result for the ^{233}U fuelled core, JEZEBEL-23. Table 6.1 gives the C/E values for k_{eff}, with the uncertainties of calculation ( )%

Analyses of k_{eff} and spectral index measurements for a large number of fast critical assemblies

Calculations have been made by G. Rimpault, *et al*. for a large number of critical assemblies and the results have been used in a cross-section adjustment study carried out by E. Fort, *et al*. [3]. Most of the assemblies are those built in the MASURCA facility at Cadarache but measurements made in SNEAK (Karlsruhe) and ZEBRA (Winfrith) are also included.

Table 6.1. C/E values for k_{eff}, with the uncertainties of calculation ( )%

Core	Characteristics	JENDL-3.2	ENDF/B-VI.2	JEF-2.2	Exp. Error
JEZEBEL	Bare Pu sphere	0.9973 (0.026)%	0.9972 (0.041)%	0.9970 (0.025)%	(0.20)%
JEZEBEL-Pu	Bare sphere of Pu (20% ^{240}Pu)	1.0018 (0.041)%	0.9987 (0.039)%	0.9990 (0.041)%	(0.20)%
FLATTOP-Pu	U-reflected Pu sphere	0.9918 (0.078)%	1.0041 (0.066)%	0.9889 (0.065)%	(0.14)%
THOR	Th-reflected Pu sphere	1.0060 (0.048)%	1.0059 (0.044)%	0.9800 (0.033)%	(0.10)%
GODIVA	Bare sphere of highly enriched U	1.0025 (0.026)%	0.9965 (0.039)%	0.9953 (0.026)%	(0.10)%
FLATTOP-25	U-reflected highly enriched U sphere	0.9985 (0.076)%	1.0037 (0.053)%	0.9917 (0.055)%	(0.10)%
BIGTEN	U-reflected core of 10% enriched U	1.0005 (0.080)%	1.0190 (0.051)%	1.0084 (0.061)%	(0.20)%
JEZEBEL-23	Bare sphere of ^{233}U	1.0131 (0.023)%	0.9933 (0.040)%	0.9641 (0.024)%	(0.10)%
FLATTOP-23	U-reflected ^{233}U sphere	1.0057 (0.059)%	1.0028 (0.044)%	0.9710 (0.054)%	(0.14)%

Calculations have also been made by S. Pelloni (JEF/DOC-634) for the MASURCA CIRANO programme cores ZONA-2A, -2A3 and -2B comparing different calculation methods. The difference between the three cores is the replacement of the radial blanket of core 2A with the sodium and steel reflector of core 2A3 and then the replacement of the axial blanket region also by a sodium and steel region in 2B. MCNP-4A results are compared with deterministic methods. There is a trend for the calculated values of k_{eff} to increase by about 850 pcm, in going from 2A to 2A3 to 2B, in the MCNP calculations for simplified models of the cores.

k_{eff} calculations

Concerning the start-up critical mass of SUPERPHENIX, core CMP, the reserve of reactivity is 3 710 ± 520 pcm. The value calculated using ERANOS/JEF-2.2 is 3 142 pcm, an underestimate of 568 ± 520 pcm.

It is interesting to note that the “pin-plate discrepancy” which was a problem in the past is no longer present. The problem was a discrepancy between calculations made for two versions of the ZEBRA core CADENZA, one built with plate geometry cells and the other with pin geometry cells. The discrepancy found originally was about 750 pcm. Using ECCO, with its improved treatment of cell geometry and anisotropic effects, together with JEF-2.2 data, the discrepancy between the calculated k_{eff} values for the two critical cores is only about 44 pcm, within the uncertainties of measurement, the values of k_{eff} being underestimated by 940 pcm for the pin geometry core and 984 pcm for the plate geometry core.

For five uranium fuelled cores studied k_{eff} is overestimated by about 500 pcm. For the plutonium fuelled cores the discrepancy range is much wider, ±1%, the mean discrepancy being an underestimation by about 300 pcm. For the cases with mixed (U + Pu) fuel there is an average

underestimation of about 250 pcm. A similar tendency is noted for k_{eff} of uranium fuelled systems to be overestimated in the calculations made by H. Takano, Akie and Kaneko [2,4] for the FCA-IX critical experiments. These seven uranium fuelled cores (FCA-9-1 to FCA-9-7) covered a wide range of spectra and the C/E values for k_{eff} are in the range 1.011 to 1.039 with uncertainties of about 0.07%.

Measurements have been made on a number of zero leakage test zones, designed to have $k_{\infty} = 1.0$. The calculations for these have a discrepancy range of ±1.7%.

Infinite medium calculations corresponding to buckling measurements also show a wide variation, with a tendency to overestimate k_{eff} by up to 2.4%. If one compares the discrepancy with that for the calculation of the critical core in which the buckling measurement was made one finds a systematic trend of a relative difference of about 1.2%, with the k_{eff} calculation for the measured buckling being higher than that for the critical core by about this amount. It has also been observed that there is a trend for the discrepancy to increase as the buckling increases. It raises the question whether the (implied) calculated reflector savings of blanket regions could be in error by this amount, or whether there could be an error in the procedure used to derive measured bucklings.

Spectral indices

Fission ratios

F49/F25

The ratio of ^{239}Pu fission to ^{235}U fission varies very little with fast reactor spectrum, from about 1.1 in hard spectrum systems down to 0.9 in soft spectrum systems, and so it is fairly insensitive to uncertainties in the calculated reactor spectrum. The discrepancy in calculated values is expected to be very small, perhaps only 1-2%, which is comparable with the measurement accuracy, typically 1.8%. It is only when there are a number of measurements using different techniques that one can expect to get useful information relevant to the nuclear data. (Fission ratio measurements through heterogeneous regions can also be useful for checking calculations of flux fine structure.) Differences between measured and calculated values of 3% or 4% indicate measurement errors. There is a tendency for calculated values to be about 1% low, on average.

F41/F25

The calculated value of this ratio varies by an even smaller amount, from about 1.31 to 1.34, and so it is not sensitive to spectrum uncertainties. The average overestimation is about 1.4% but the standard deviation of the measurements is 3 to 4%.

F-28/F-25

The values range from about 0.020 to 0.048 in the series of fast critical assemblies in which the fuel is diluted with materials such as sodium and steel. The agreement between measurement and calculation is sensitive to the accuracy of the spectrum calculation. The discrepancies range from an overestimation of about 6% to an underestimation of about 8%, the standard deviation of the measurements typically being ±2%. One sees a different tendency in the four SNEAK cores (average

underestimation by 2%) to that in the MASURCA cores (overestimation, on average, by about 1%) suggesting that the systematic errors in the measurements made in a particular core could be significant.

Fission in ^{240}Pu and ^{242}Pu

These show a similar variation to the ^{238}U fission. The variation in the discrepancies can be reduced by converting the measurements to be in terms of ^{240}Pu/^{238}U and ^{242}Pu/^{240}Pu. When this is done one sees for ^{240}Pu/^{238}U an average overestimation of 3% (and a range of about 3%). For ^{242}Pu/^{240}Pu there is a range of about 5% relative to a very small overestimation.

Capture in ^{238}U

There are 35 measured values of C-28/F-25 and these range from about 0.11 to 0.14. The average discrepancy is an underestimation of about 2% and a range of about 4%(in contrast to an average overestimation of about 2% of the C-28/F-49 ratio measured in six ZEBRA cores). Systematic errors could again be affecting the averages. There are independent measurements made in the PROFIL sample irradiation programme carried out in the PHENIX reactor. The C/E values for the measurements of C-28/F-25 are 0.98 ± 2.3% in PROFIL 1 and 0.99 ± 2.3% in PROFIL 2. The full set of measurements in the PROFIL programme are summarised in a later section.

Spectral index measurements in the CIRANO programme

Fission ratio measurements made in the recently completed CIRANO programme carried out in the MASURCA facility have been analysed by G. Rimpault, *et al*. Measurements were made in six versions (some of the fission ratios were measured in only four or five of the cores). The average indications are approximately as follows:

	Mean (E-C)/C	**Measurement s.d.**	**Range**
^{239}Pu/^{235}U	+1.2%	1.5%	1.5%
^{238}U/^{235}U	+1.5%	2.3%	3.0%
^{237}Np/^{235}U	+6%	2.3%	4.0%
^{240}Pu/^{235}U	-4%	4%	2%
^{241}Pu/^{235}U	+1%	4%	4%
^{242}Pu/^{235}U	-1%	4.5%	3%
^{241}Am/^{235}U	-4%	4%	2%
^{243}Am/^{235}U	-4%	4%	2%

When the calculations are made using the adjusted cross-section set there are modifications to the calculated reactor spectrum which can affect the values by about 1%.

Spectral index measurements in the FCA-9 programme of uranium fuelled cores

Measurements for a number of fission ratios have been made in these cores and analysed by H. Takano, *et al*. The values of (E-C)/C can be summarised as in the following table.

	Mean (E-C)/C
$^{237}Np/^{239}Pu$	+5%
$^{241}Am/^{239}Pu$	+10%
$^{243}Am/^{239}Pu$	+3%
$^{244}Cm/^{239}Pu$	-4%

It will be seen that the trends observed for $^{241,243}Am$ in these experiments are different from those observed in the CIRANO measurements.

Irradiations of isotopic samples and analyses of irradiated fuel pins

Two types of irradiation experiment have been carried out in the PHENIX reactor: fuel rod irradiations (the TRAPU experiment) and irradiations of pure isotopic samples (the PROFIL-1 and -2 experiments). Irradiation experiments are particularly valuable in giving information concerning the capture and (n,2n) cross-sections which in many cases cannot be measured in zero power critical facilities.

The TRAPU experiment was a six cycle irradiation of mixed oxide fuel pins containing plutonium of three different isotopic compositions, in particular with TRAPU-3 containing a higher proportion of $^{240,241,242}Pu$. TRAPU-1 and TRAPU-2 are more similar in isotopic composition.

Table 6.2. Plutonium isotopic compositions of the three TRAPU pins

	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
TRAPU-1	0.1	73.3	21.9	4.0	0.7
TRAPU-2	0.8	71.4	18.5	7.4	1.9
TRAPU-3	0.2	34.0	49.4	10.0	6.4

In PROFIL-1 the isotopes irradiated were:

- $^{235,238}U$.
- $^{238,239,240,241,242}Pu$.
- ^{241}Am.

In PROFIL-2 the isotopes irradiated were:

- ^{232}Th.
- $^{233,234,235,238}U$.
- ^{237}Np.
- $^{238,239,240,241,242}Pu$.
- $^{241,243}Am$.
- ^{244}Cm.

The analyses have been carried out by R. Soule and E. Fort using the ERANOS system. They obtain the C/E values listed in Table 6.3 for the final compositions of the TRAPU fuel samples (relative to the ^{238}U content).

Table 6.3. Values of C/E and percentage uncertainties for the TRAPU isotopic compositions following irradiation

Relative to ^{238}U	TRAPU-1	TRAPU-2	TRAPU-3
^{234}U	0.98 ± 2.5%	1.00 ± 1.3%	1.04 ± 1.0%
^{235}U	1.01 ± 0.3%	1.03 ± 0.2%	1.03 ± 0.2%
^{236}U	0.91 ± 0.5%	0.93 ± 0.4%	0.93 ± 0.3%
^{237}Np	0.78 ± 6.8%	0.77 ± 3.3%	0.75 ± 3.2%
^{238}Pu	0.99 ± 0.9%	1.01 ± 0.4%	1.01 ± 0.4%
^{239}Pu	1.02 ± 0.4%	1.00 ± 0.3%	1.00 ± 0.3%
^{240}Pu	0.99 ± 0.4%	0.97 ± 0.3%	0.99 ± 0.3%
^{241}Pu	1.04 ± 0.4%	1.01 ± 0.3%	1.03 ± 0.3%
^{242}Pu	1.11 ± 0.5%	1.05 ± 0.4%	1.03 ± 0.3%
^{241}Am	0.98 ± 3.0%	0.98 ± 3.6%	0.98 ± 2.1%
^{242}Am	1.03 ± 3.6%	1.06 ± 4.0%	1.02 ± 2.5%
^{243}Am	1.07 ± 3.6%	1.03 ± 4.0%	1.06 ± 2.5%
^{242}Cm	1.02 ± 2.4%	0.99 ± 2.6%	0.99 ± 2.1%
^{243}Cm		0.71 ± 2.7%	0.70 ± 2.6%
^{244}Cm	0.98 ± 2.0%	1.09 ± 2.2%	1.10 ± 1.7%

The results of the PROFIL measurements have been analysed by R. Soule and E. Fort to obtain values for the spectrum averaged cross-sections. The C/E values obtained in the analysis are presented in the Table 6.4.

One notes, in particular, the need for a ~7% increase in the capture cross-sections of ^{233}U and ^{235}U and for reductions of ~10% in ^{240}Pu capture, ~18% in ^{241}Pu capture and ~13% in ^{242}Pu capture. The discrepancies in the (n,2n) values could be due to errors in calculations of the high energy component of the spectrum, although the agreement found for ^{235}U and ^{241}Pu suggests that the discrepancies found for ^{239}Pu and ^{237}Np are significant.

Sodium voiding reactivity effects

A large number of sodium voiding measurements have been made in the MASURCA critical facility and the methods of analysis have been progressively refined. As an example of the current status we refer to JEF/DOC-725 in which G. Rimpault, *et al*. describe analyses of sodium voiding measurements made in MASURCA as part of the CIRANO programme [5]. In addition to the analysis made using the JEF-2.2 library the adjusted library, ERALIB1 was used, and also ERALIB1 together with a new evaluation for sodium based on recent measurements of total and inelastic scattering cross-sections made at ORNL and IRMM Geel.

Measurements are made for different zones of the reactor thus having different contributions from the leakage and non-leakage terms to the total sodium voiding reactivity effect. It is usual to interpret the results in terms of factors to be applied to the non-leakage and the axial and radial

Table 6.4. C/E Values for the PROFIL experiments

Cross-section	PROFIL-1	PROFIL-2	Average
^{233}U (n,γ)		0.93 ± 3.0%	0.93 ± 3.0%
^{234}U (n,γ)		0.99 ± 3.0%	0.99 ± 3.0%
^{235}U (n,γ)	0.93 ± 1.7%	0.92 ± 1.7%	0.93 ± 1.2%
^{235}U (n,2n)	0.95 ± 5.0%	0.96 ± 5.0%	0.96 ± 3.5%
^{238}U (n,γ)	0.98 ± 2.3%	0.99 ± 2.3%	0.99 ± 1.6%
^{238}U (n,f)	1.00 ± 1.4%		1.00 ± 1.4%
^{238}Pu (n,γ)	0.97 ± 4.0%	0.99 ± 4.0%	0.98 ± 2.8%
^{239}Pu (n,γ)	0.96 ± 3.0%	0.96 ± 3.0%	0.96 ± 2.2%
^{239}Pu (n,2n)	0.63 ± 15.0%	0.58 ± 15.0%	0.61 ± 10.6%
^{240}Pu (n,γ)	1.10 ± 2.2%	1.13 ± 2.2%	1.11 ± 1.6%
^{240}Pu (n,2n)	1.13 ± 20.0%	0.88 ± 20.0%	1.00 ± 14.1%
^{241}Pu (n,γ)	1.24 ± 4.1%	1.18 ± 5.9%	1.22 ± 3.6%
^{241}Pu (n,f)	0.98 ± 3.3%		0.98 ± 3.3%
^{241}Pu (n,2n)	1.04 ± 4.1%		1.04 ± 4.1%
^{242}Pu (n,γ)	1.18 ± 3.5%	1.12 ± 4.3%	1.15 ± 2.8%
^{242}Pu (n,f)	0.94 ± 8.6%		0.94 ± 8.6%
^{241}Am (n,γ)	1.03 ± 1.7%	1.03 ± 1.7%	1.03 ± 1.2%
^{243}Am (n,γ)	0.96 ± 5.0%		0.96 ± 5.0%
^{237}Np (n,γ)		0.97 ± 3.6%	0.97 ± 3.6%
^{237}Np (n,2n)		1.20 ± 4.7%	1.20 ± 4.7%

Table 6.5. E/C values for the non-leakage and axial and radial leakage terms, and the corresponding values of chi-squared

JEF-2.2 results

	Non-leakage	Axial leakage	Radial leakage	Chi-squared
ZONA-2A	0.966	1.058	1.007	4.60
ZONA-1/R1	0.911	1.061	1.002	4.30

Table 6.6. E/C results for ERALIB1 plus the new evaluation for sodium

	Non-leakage	Axial leakage	Radial leakage	Chi-squared
ZONA-2A	1.025	1.017	0.994	0.68
ZONA-1/R1	0.959	1.018	0.986	1.14

leakage terms. However, the factor to be applied to the non-leakage term can be strongly dependent on the accuracy of the adjoint flux calculation and can vary with the core composition. Results for two different cores, ZONA-2A and ZONA-1/R1 (8% ^{240}Pu) illustrate the effects. The factors are those that give a best fit to the E/C values measured for the different voided zones of a particular core, a measure of the goodness of fit being the chi-squared value.

One sees that the E/C values are closer to unity and that the chi-squared values indicate a much better consistency in the fit. Using ERALIB1 without the new sodium evaluation does not show a marked improvement relative to JEF-2.2 for sodium voiding effects.

K. Sugino and G. Rimpault have analysed sodium voiding measurements made in the ZPPR-9 assembly of the JUPITER programme [6]. They conclude that to reproduce the measured results it is necessary to apply bias factors to the non-leakage and leakage terms, the factors being 0.941 and 1.008 respectively. This gives an indication of the accuracy to be attained.

Control rod reactivity worth measurements

These are particularly dependent on the calculation method used and also on the calculated delayed neutron fraction relative to which the measurements are usually made. For the measurements made in ZPPR-9, K. Sugino and G. Rimpault find C/E values in the approximate range 0.94-0.96 [7]. A more comprehensive series of analyses has been made for the SUPERPHENIX measurements but most of these have used the Cadarache adjusted version of JEF-2.2, ERALIB1. Agreement with measurement is good.

Reaction rate distributions in core regions

Analyses made for the inner and outer core region of ZPPR-9 show that the reaction rate distributions for fission in ^{235}U, ^{238}U and ^{239}Pu and for capture in ^{238}U are well reproduced, there being no marked radial trend. There are some fluctuations about the average, the range of values being about 3% for fission in ^{235}U and ^{239}Pu and capture in ^{238}U, and a range of about 7% for ^{238}U fission.

Reaction rate distributions in reflected cores

In the CIRANO programme in MASURCA studies were made for cores without radial breeder blanket regions, the sodium/steel shield region being adjacent to the core. Three versions were studied, the first without internal fuel storage facilities, the second with these facilities and the third with the storage protected using B_4C. The method of calculation uses the ERANOS system of codes. For the shield region calculation the 1 968 fine groups (plus within fine group probability table data) of the ECCO library are condensed to the 175 group ASPILIB2 structure for application in the BISTRO S_8 P_3 whole reactor flux calculation. The method of condensation used in ECCO for the shield regions requires the bucklings which characterise the exponential decrease in the flux to be provided. These are obtained by iteration with the whole reactor calculation (an initial guess followed by one iteration).

The reaction rates measured are for rhodium, fission in ^{237}Np, ^{235}U, ^{239}Pu, capture in boron, manganese and gold. We note that in the reference version, SIREF, the values of C/E decrease markedly with distance through the shield. A similar pattern of results is found for the other cores.

Doppler effect calculations

Calculations have been made using the ECCO/ERANOS system for the SEFOR Doppler effect measurements and for the measurement made in SUPERPHENIX (G. Rimpault, V. Colacioppo and J. Rowlands, JEF/DOC-378 [8]).

The South-West Experimental Fast Oxide Reactor (SEFOR) was specially designed to measure Doppler effects representative of an LMFBR. In order to obtain high fuel centre temperatures at a low power the reactor used large diameter fuel pins, these being composed of 20% enriched U-Pu oxide fuel. The reactor was built in two versions, SEFOR-1 and SEFOR-2, having different fast reactor spectra. In SEFOR-1 beryllium rods were introduced to soften the spectrum while in SEFOR-2 these were replaced by steel rods. The experiments included static, oscillation and transient tests, the Doppler constants measured in the different tests being consistent. The fuel temperature increases from 677 K (the mean temperature of the sodium coolant) to 1 365 ± 100 K.

It is important to treat the fuel rod, fuel assembly and control rod heterogeneity effects and this has been done using ECCO. The measurements were made relative to the effective delayed neutron fraction which has been recalculated using JEF-2.2 data. It is necessary to treat the structural material Doppler effects as well as those of the fuel isotopes. Consideration must also be given to the influence of solid state effects which alter the effective temperatures for resonance Doppler broadening calculated using the gas model.

The values of C/E are as follows:

SEFOR-1	C/E = 0.96 ± 0.15
SEFOR-2	C/E = 1.05 ± 0.15

The calculated values are within the uncertainties of the measurements.

A value for the Doppler coefficient can be deduced from the isothermal temperature coefficient measured in the SUPERPHENIX start-up measurement programme. The change of reactivity is measured when the temperature of the coolant is increased at low power, from 453 K to 673 K. Again the measurements are relative to the delayed neutron scale. The temperature coefficient is separated into two components, one being the linearly dependent thermal expansion effect and the other the Doppler effect, which is logarithmic in the effective temperature. Again care must be taken over the treatment of solid state effects in the determination of effective temperature and in the treatment of structural material Doppler effects. The value of C/E derived in this study is:

SUPERPHENIX	C/E = 1.00 ± 0.11

Thus we observe satisfactory agreement with experiment, within the uncertainties of the measurements.

The ZPPR-9 Sample Doppler reactivity measurement has been calculated by K. Sugino and G. Rimpault [9]. Measurements were made in the temperature range 298 K to 1 087 K and comparisons made at intermediate temperatures. The C/E values are in the range 0.90 to 0.95, with the overall temperature change effect having a C/E of about 0.95. The experimental uncertainty is quoted as being 1-3%.

Variation of reactivity with burn-up

During the start-up phase of SUPERPHENIX (phase CMP) measurements were made of the variation of reactivity with burn-up for a period of 83 full power days equivalent. The results were analysed by P. Smith and G. Rimpault [10]. The part of the variation due to ^{241}Pu decay to ^{241}Am

(C_2 = 0.77 ± 18% (1 σ) pcm/day) has been subtracted from the measured variation. The remaining part is C_1 = 5.76 pcm per equivalent full power day, with an uncertainty of ± 13% (1 σ). In addition there are the uncertainties associated with the delayed neutron reactivity scale and the calibration of the control rods (the S-curve) relative to which the reactivity variation is measured. The contribution of the burn-up of fuel isotopes to the reactivity variation is ~30% of the total variation in SUPERPHENIX (compared with ~75% in PHENIX) the remaining ~70% being due to the build-up of fission product isotopes. In the interpretation account must be taken of the fraction of gaseous and volatile fission products which escape from the fuel and also the time dependent effects of fission product decay and transmutation. There are some uncertainties associated with the estimation of the migration effects.

The ECCO/ERANOS calculation with an allowance for migration of gaseous fission products gives C/E values of 0.83 for the burn-up dependent term, C_1, and 0.81 for the ^{241}Pu decay term, C_2. Using adjusted cross-sections for the principal isotopes improves the value of C/E for C_1 to 0.94.

Fission product validation studies

Analysis of the sample reactivity worth measurements made in STEK

Reactivity worth measurements were made for samples of fission product isotopes, structural material samples and standards materials, such as H, ^{10}B, ^{235}U and ^{239}Pu, in the fast reactor zone of the fast-thermal coupled critical facility STEK at Petten. Measurements were made in five different versions of the fast zone, STEK-4000, -3000, 2000, 1000, and 500, these having spectra of differing hardness. An analysis of the measurements was made using JEF-2.2 by A. Meister (JEF/DOC-746) [11]. Particular care has been taken in treating the sample size effects – that is, resonance shielding and flux perturbation effects.

The reactivity of natural boron is used for normalisation. Agreement is within the experimental uncertainties of about ±5% for the reference materials:

H, C, O, Al, ^{133}Cs, ^{235}U and ^{239}Pu

For most isotopes the accuracy is about ±10% and the agreement is within this accuracy for the following materials:

Nb, Mo, ^{99}Tc, ^{103}Rh, Pd, ^{105,106,,107}Pd, In, ^{127}I, ^{135}Cs, ^{150}Sm, Eu, Pb

There are significant discrepancies, greater than 20%, for the following isotopes:

^{90,93,96}Zr, ^{95,97,98,100}Mo, ^{102,104}Ru, ^{111}Cd, ^{139}La, ^{141}Pr, ^{143,145,148}Nd, ^{147}Pm, ^{147,149}Sm, ^{157}Gd, Hf

Analysis of sample reactivity worth measurements made in the RRR/SEG facility

Two core configurations in which measurements were made in the Rossendorf facility, RRR/SEG-4 and SEG-5, were characterised by energy independent adjoint spectra, and so the worth measurements can be more directly related to the spectrum averaged capture cross-sections, scattering

effects being very small. The SEG-5 measurements have been analysed by K. Dietz and G. Rimpault and a preliminary analysis made for SEG-4 (JEF/DOC-491) [12]. The measurements are normalised to the ^{10}B values. The uncertainties are in the range 7% to 20%. The elements for which measurements have been made are:

Ta, Mo, Mn, Cd, Nb, Cu, Zr, W, Fe, Cr, Ni, Co

There are significant discrepancies only for Cd in SEG-5, with a C/E value of $1.215 \pm 9\%$, whereas the preliminary C/E value for SEG-4 is $1.046 \pm 10\%$.

The isotopes for which measurements have been made are:

$^{95,97,98,100}Mo$, ^{103}Rh, ^{105}Pd, ^{109}Ag, ^{133}Cs, $^{143,145}Nd$, ^{149}Sm, ^{153}Eu

The discrepancies are larger than 1 s.d. in SEG-5 for ^{95}Mo, C/E = $1.133 \pm 10\%$, ^{103}Rh, C/E = $0.901 \pm 7\%$, and ^{149}Sm, C/E = $1.191 \pm 9\%$. However, these isotopes are not discrepant in the preliminary SEG-4 analysis, instead the discrepancies are underestimates for $^{98,100}Mo$, which have C/E values of about $0.8 \pm 13\%$.

Measurements made for fission product isotopes in the PHENIX PROFIL irradiation experiments

The analyses for these measurements are being made by G. Rimpault and are at present only preliminary. These measurements have the advantage of giving direct information on the spectrum averaged capture cross-section whereas the reactivity measurements have a contribution from scattering effects.

The isotopes for which measurements have been made are:

$^{95,96,97}Mo$, ^{101}Ru, $^{105,106,107}Pd$, $^{133,134}Cs$, $^{147,148,149,150,151}Sm$, $^{143,144,145}Nd$, $^{153,154}Eu$

The accuracy of the measurements is in most cases better than ±5% but only ±20% for ^{96}Mo. Measurements for six of the isotopes have been made in both PROFIL 1 and 2. The consistency of the results in the two series of measurements is good for ^{133}Cs, ^{149}Sm and ^{145}Nd but poor for ^{106}Pd and ^{151}Sm.

Intercomparison of the PROFIL and RRR/SEG measurements with the STEK measurements

Table 6.7 compares the values of (C-E)/E for PROFIL and RRR/SEG with the corresponding values for STEK. For the complete set of results for STEK reference should be made to the CEA Cadarache document by A. Meister.

Intercomparison of fission product cross-sections in different nuclear data libraries

An intercomparison of fast reactor spectrum averaged pseudo fission product data has been organised by the NEA International Working Party on Evaluation Co-operation and carried out by Subgroup 17 [13]. In particular JEF-2.2, JENDL-3.2 and the Russian data sets FOND-2.1 and ADL-3

Table 6.7. A comparison of values of (C-E)/E for PROFIL, RRR/SEG and STEK

Isotope	STEK	PROFIL1	PROFIL2	SEG5	SEG4
^{95}Mo	(14 to 25)% ± 4%	7.6% ± 3.8%		13.3% ± 10%	-8.7% ± 10%
^{96}Mo	Discrepant	-2.6% ± 20.0%			
^{97}Mo	(22 to 27)% ± 4%	-0.6% ± 4.4%		-4.6% ± 10%	-4.8% ± 9%
^{98}Mo	Discrepant			6.1% ± 15%	-22.7% ± 12%
^{100}Mo	Discrepant			-11.2% ± 16%	-19.7% ± 13%
^{101}Ru	(7 to 11)% ± 4%	10.1% ± 3.6%			
^{103}Rh	(-2 to 9)% ± 3%			-9.9% ± 7%	5.6% ± 12%
^{105}Pd	(5 to 12)% ± 4%	-9.7% ± 4.0%		6.4% ± 7%	-11.8% ± 19%
^{106}Pd	(2 to 13)% ± 8%	-62.4% ± 9.0%	-3.0%		
^{107}Pd	(6 to 16)% ± 3%		14.8%		
^{109}Ag	(5 to 24)% ± 4%			-7.1% ± 8%	-19.1% ± 12%
^{133}Cs	(-2 to +2)% ± 3%	3.7% ± 4.7%		-7.4% ± 13%	3.8% ± 13%
^{134}Cs		-3.5% ± 6.6%			
^{143}Nd	(11 to 99)% ± (4 to 17)%		18.9%	-10.4% ± 9%	
^{144}Nd	Dispersed		2.0%		
^{145}Nd	(10 to 74)% ± (4 to 11)%	22.1% ± 3.8%	13.5%	6.6% ± 9%	
^{147}Sm	(18 to 23)% ± 4%		19.0%		
^{148}Sm			46.4%		
^{149}Sm	(19 to 24)% ±3%	11.1% ± 3.1%	7.3%	19.1% ± 9%	9.4% ± 9%
^{150}Sm	(6 to 15)% ± 4%	-7.5% ± 3.3%			
^{151}Sm	(13 to 29)% ± 4%	-8.3% ± 4.0%	27.1%		
^{153}Eu	(11 to 15)% ± 3%		5.1%	9.1% ± 10%	10.8% ± 10%
^{154}Eu			-6.5%		

have been compared. The difference in the pseudo fission product effect is very small, about 5%, despite some very large differences for individual fission products. Capture and scattering effects are separately compared and conclusions drawn about the impact of the use of different theoretical methods on the data. Theory must be used to a large extent to obtain the data for fission product isotopes and tested for those materials for which measured data are available. The STEK analyses are playing an important role in this assessment work.

Analyses of measurements for ^{232}Th and ^{233}U

Measurements have been carried out in two cores, 11 and 12, studied in the PROTEUS/GCFR programme at PSI Villigen of capture and fission in ^{232}Th and fission in ^{233}U in a fast reactor spectrum (JEF/DOC-677 by S. Pelloni, G. Youinou and P. Wydler [14]). The ^{232}Th capture rate is well predicted using JEF-2.2 data but the fission rate is underestimated, with the JENDL-3.2 data being in better agreement with the measurements in the two cores for the fission rate but less good agreement for the capture. The ^{233}U fission rate (analysed in Core 11 only) is well predicted using JEF-2.2 data. However, we note the poor results obtained for the sphere of ^{233}U, JEZEBEL-23, using JEF-2.2, as described earlier.

Intercomparisons of calculations made using different nuclear data libraries

Calculations have been made by S. Pelloni intercomparing the results of calculations made using different nuclear data libraries. In JEF/DOC-524 calculations of sodium void coefficients in advanced fast reactors are intercompared and in JEF/DOC-546 the effects of the choice of Fe and actinide data on calculated parameters are calculated [15,16]. These show some very large differences.

Analysis of thick sample transmission measurements for ^{238}U

F. Froehner (JEF/DOC-326 and JEF/DOC-345 [17,18]) has analysed thick sample transmission measurements made for ^{238}U in the unresolved resonance region. These have confirmed the validity of the JEF-2.2 data. A similar study has also been made by M. Uematsu and J. Rowlands (JEF/DOC-379 [19]), analysing measurements made in Japan.

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Annex

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