Chapter 8

SHIELDING VALIDATION STUDIES

Introduction

The present review first provides a summary of comparisons which have been made in shielding benchmark situations, i.e. where neutron reaction rates have been measured at various distances from a well-characterised fission neutron source within single material regions or simple mixtures (water, graphite, iron and the JANUS arrays of iron/stainless steel, iron/sodium with borated steel regions and iron/water). The benchmark configurations studied are those relevant to fission reactor calculations. In fact these benchmarks are all shielding arrays measured in the ASPIS facility of the NESTOR reactor at Winfrith. These benchmarks do not include those that are more relevant to fusion reactor studies, such as those having a 14 MeV neutron source. Secondly, the results of a comparison of TRIPOLI-4 calculations with measurements made in the shield of the PWR Saint Laurent B1 are summarised.

If useful conclusions are to be drawn from the benchmarks on the accuracy of the material cross-sections, then the uncertainties in the ratio of calculation to measurement (Calculation/Experiment, or C/E) due to the estimated uncertainties in those cross-sections must be greater than those arising from other sources. At short penetrations the sensitivities of calculations to the material cross-sections are small so that the comparisons at these positions are indicators of the accuracies of other factors such as the source normalisation, the detector cross-sections and the calibration of the detectors. The sensitivities to the material cross-sections increase with penetration, so that it is the comparisons at positions remote from the source which usually provide the most relevant tests of the accuracy of these data. It should be kept in mind, however, that other uncertainties can increase with penetration which may counterbalance this effect. The measurements become less reliable when the counting rates for the detectors become small. The contribution from uncertainty in the fission spectrum rises if the dominant source energy moves to higher values with penetration, and the uncertainties due to the detector cross-sections can increase if the neutron spectrum changes with penetration to give larger contributions from an energy range where the cross-section is less well known. The contributors to the uncertainties on the values of C/E are considered later in this chapter.

Water

In the water benchmark, described in JEF/DOC-443 [1], the reaction rates for $^{32}S(n,p)^{32}P$ were measured at distances of 10.16 cm to 46.52 from ^{252}Cf sources. This detector is sensitive to neutrons with energies greater than 2 MeV. The calculations, which were performed with the MCBEND code and data in 8 220 groups, gave C/E values in the range 1.0 to 1.20. Apart from the results at the nearest position the ratio is effectively constant, which demonstrates that the attenuation is accurately predicted over this range. The reaction rates for $^{32}S(n,p)^{32}P$ were calculated by multiplying the neutron fluxes by cross-sections taken from IRDF-85. Subsequent unpublished calculations with IRDF-90 data gave an improved agreement where the C/E values for the results in the plane of the source were between 0.98 and 1.04, which gave discrepancies less than the estimated standard deviation of 7%.

The latter is mainly due to the measurement (6%) and the detector cross-section (4%). The fractional sensitivity of the reaction rate R to the cross-section σ, $\frac{\partial R}{\partial \sigma} \cdot \frac{\sigma}{R}$, is calculated by MCBEND to be -3.77 for hydrogen and -1.16 for oxygen at a penetration of 50.8 cm. The benchmark is not a very demanding test of the accuracy of the oxygen total cross-section, but it does suggest that errors in the energy range 4 MeV to 8 MeV are less than 5%.

Iron

JEF-2.2 data has been applied to the calculation of neutron attenuation in iron in JEF/DOC-420 (CEA Saclay) [2], JEF/DOC-421 (Winfrith) [3], JEF/DOC-447 (CEA Saclay) [4], JEF/DOC-612 (CEA Cadarache [5], and also the thesis of E. Lefevre [6]) and JEF/DOC-790 (Winfrith). There are effectively three independent studies, and revised Winfrith results in JEF/DOC-790. Two of the documents, JEF/DOC-447 and JEF/DOC-612, compared the calculations with the measurements made in ASPIS in 1975, whilst the third, JEF/DOC-421, was for the later Iron 88 benchmark. The first two are similar with the latter one, having an enriched fission plate located further from the NESTOR core. The calculations reported in JEF/DOC-421 and JEF/DOC-612 were performed with the Monte Carlo code MCBEND hyperfine the DICE group data. The results which are considered in this review are those which were obtained with shielded cross-sections, i.e. the cross-sections were weighted by the inverse total cross-section when being averaged over the energy groups. In JEF/DOC-447 the method was again Monte Carlo, the code in this case being TRIPOLI-3. Three different representations of the data were employed with TRIPOLI; the results with 3 857 energy groups were taken as being the reference values, and it is these that are considered in this review. The cross-sections were averaged with a fission spectrum weighting above 1 MeV and $1/E^*\Sigma_T$ at energies below this. The third set of calculations was carried out with the discrete ordinates code BISTRO, the ECCO/JEF-2.2 library in 1 968 groups (plus probability table data to represent the within fine group energy structure) being condensed into 175 groups for the BISTRO calculation using a procedure specially adapted for the treatment of shielding regions. The measurements considered in all three cases were the reaction rates for $^{32}S(n,p)^{32}P$, $^{115}In(n,n')^{115m}In$, and $^{103}Rh(n,n')^{103m}Rh$. In addition, the $^{27}Al(n,\alpha)^{24}Na$ and $^{197}Au(n,\gamma)^{198}Au$ reaction rates were compared for the Iron 88 benchmark. The results are examined for each detector in turn.

It should be noted that the ^{56}Fe evaluation includes an unresolved resonance region above the inelastic scattering threshold, and the method used to treat this in the different code systems could be different.

$^{32}S(n,p)^{32}P$

The reaction rates for $^{32}S(n,p)^{32}P$ were measured over a thickness of 62.86 cm and 66.9 cm, respectively, in the two experiments, which represented an attenuation by a factor of 5×10^5. It is thus a very sensitive measurement for assessing the accuracy of the cross-sections at high energies with a fractional sensitivity of 10.0 for inelastic scatter in the range 1.35-10.0 MeV. The results from MCBEND in 421 show C/E values which rise from 0.9 at 0.0 cm to 1.14 after 56.69 cm. (These values are changed to 0.84-1.08 in the later results obtained when IRDF-90 cross-sections are used in place of IRDF-85 for the detector response.) The TRIPOLI results (using IRDF-85 detector cross-sections) give C/E values which rise from 1.01 to 1.34 over a penetration of 57.15 cm. It is difficult to understand why the two calculations with IRDF-85 cross-sections differ by 10% close to the source. However both suggest that the cross-sections for iron are too low at these energies. In contrast the BISTRO results show C/E values which vary between 0.88 and 0.95 for the first 50 cm and then

decrease to a value of 0.77 at 68.58 cm. However, only the final points are outside the uncertainty range of the measurements. The differences between the results obtained using different methods illustrate the difficulty of separating the effects of errors in the data library and approximations in processing and representing the nuclear data in the codes. The two different approaches lead to different conclusions.

At 61.8 cm the fractional sensitivities for the calculated reaction rates are -6.0 for the inelastic cross-section and -0.36 for the elastic, making it is the former which mainly determines the rate of attenuation. The increase in the inelastic scatter cross-section would thus have to be about 4% to decrease the reaction rate by 25%. This is equivalent to one standard deviation since ±4% is the accuracy typically quoted for the inelastic scatter cross-section at these energies. There would be a constraint on changes to the two cross-sections which would be imposed by the uncertainty on the total cross-section.

$^{115}In(n,n')^{115m}In$

The results for the indium detector are broadly similar for all three comparisons. MCBEND gives C/E values which fall from 0.93 to 0.70 over a penetration of 46.44 cm iron. With TRIPOLI the decrease is from 1.05 to 0.71 over 57.15 cm, whilst BISTRO gives a corresponding change from 1.03 to 0.8 over the same distance. The indium reaction rate is mostly sensitive to cross-sections in the range 0.58 MeV to 4.4 MeV (see JEF/DOC-421 [3]) with fractional sensitivities at 61.8 cm being -1.78 for the inelastic scatter and -2.41 for the elastic cross-section. This would imply a decrease in both cross-sections of 7% to bring the calculations into agreement with measurement. The uncertainties on the cross-sections are typically 3-5% in this energy range so that the required reduction would be significantly greater than a single standard deviation. Changes from IRDF-85 to IRDF-90 do not significantly alter the results.

$^{103}Rh(n,n')^{103m}Rh$

For the rhodium reaction MCBEND gives C/E values which lie between 0.95 and 0.92 for the first 36 cm and then decrease slightly to 0.87 at a thickness of 61.81 cm iron. The results from TRIPOLI give C/E values which lie between 0.89 and 0.96 for the first 68.58 cm and then fall to 0.74 after 108.58 cm of iron. BISTRO C/Es show a steady rise from 0.88 to 1.12 over the first 85.72 cm with subsequent values of 1.04 at 97.15 cm and 1.1 at 108.58 cm. The TRIPOLI and MCBEND results give broadly the same conclusion that over the initial region the agreement is good with up to 10% random underestimation of the measured values. The TRIPOLI results show that this deteriorates, giving more serious underestimation at penetrations beyond 85 cm of iron. This conflicts with the BISTRO indication that there is a rise in C/E with penetration, thus suggesting that the cross-sections are too small. The sensitivity calculations with MCBEND show that at a penetration of 61.8 cm the reaction rate is mainly influenced by the elastic scatter cross-section of iron in the energy range 0.1 MeV to 1.35 MeV. Again the results are changed by only a few per cent if IRDF-90 data are used instead of IRDF-85. However at deep penetrations the uncertainty on the calculation increases due to the cross-sections for rhodium having standard deviations as high as 18% in the range 0.21 MeV to 0.37 MeV and 31% at energies below this. The contributions from these energies rise with penetration, providing 70% of the reaction rate at 61.8 cm and leading to an uncertainty of 13% in the calculation. The results for rhodium do not show the same degree of underestimation as those for indium, which suggests that the neutron fluxes are predicted more accurately in the energy range below 0.37 MeV where there is little contribution to the indium reaction rate. It is not possible, however, to draw conclusions from the rhodium results because of the uncertainty on the detector cross-section.

$^{27}Al(n,\alpha)^{24}Na$

The measurements with the $^{27}Al(n,\alpha)^{24}Na$ detector which were made in the Iron 88 benchmark extended to a penetration of only 25.64 cm over which the attenuation was a factor of 2.3×10^2. Calculations were performed with MCBEND, giving C/E values that decreased monotonically from 1.09 to 0.89. No sensitivities are reported for this reaction, with its threshold at 6 MeV, but the comparison suggests that the effective attenuation cross-section at these high energies is too high by about 3%.

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

Measurements with gold foils encased in cadmium were made in the Iron 88 benchmark. They show an attenuation of only a factor of 25 over the 66.99 cm depth of the measurement. C/E values were calculated with MCBEND using a suppressed cross-section to allow for self-shielding in the gold foils. (The foils themselves were not modelled in the MCBEND calculation for the benchmark.) The C/E values ranged between 0.93 and 1.09 except for one point, at which the value was 1.23. The comparisons with measurements at these low energies, with little attenuation, are mostly tests of the calculation of the slowing down spectrum and they suggest that the errors are small in the context of shielding.

Summary for iron

The results obtained with the Monte Carlo codes MONK and TRIPOLI-3 are broadly consistent for the two iron benchmarks. They suggest that the inelastic scattering cross-section is about 4% too low in the energy range 2.0 MeV to 6.0 MeV and the inelastic and elastic scattering cross-sections are 7% too high in the range 0.58 MeV to 2.0 MeV. In addition, the Iron 88 results indicate that the cross-sections are too high by 3% at energies above 6 MeV. In calculations of the attenuation of neutrons the possibility of streaming in "windows" at energies where the cross-sections are small emphasises the importance of resonance data and the treatment of these by the transport code. It should be noted, however, that conflicting results are obtained with the ECCO/BISTRO code system, whereas for the JANUS-1 experiment excellent agreement was found between the results of this method and TRIPOLI-4.

Discussion has concentrated on possible errors in the cross-sections, but deficiencies in other data (i.e. angular distribution of scatter and the energy loss laws) could be contributing to the discrepancies. The sensitivities to these parameters have not yet been studied for the shielding benchmarks.

Calculations have been made using the new JEFF-3T evaluation for ^{56}Fe based on recent high resolution transmission and inelastic scattering measurements made at IRMM Geel (JEF/DOC 790 [7]). The sulphur, indium and rhodium reaction rates have been recalculated using MCBEND. For sulphur the results are similar to those obtained using JEF-2.2, increasing from 0.83 to 1.11. The indium results are much improved, being approximately constant through the shield at an average value of 0.96. For rhodium the C/E values increase from 0.96 to 1.11 through the shield, in contrast to the decrease from 0.94 to 0.87 obtained when using JEF-2.2.

Graphite

Comparisons of calculations with measurements for neutron attenuation in graphite are presented in JEF/DOC-476 [8]. Reaction rates were measured through a thickness of 70 cm of graphite.

The detectors were $^{32}S(n,p)^{32}P$, $^{115}In(n,n')^{115m}In$ and $^{103}Rh(n,n')^{103m}Rh$. Calculations were performed using MCBEND with cross-section data in 8 220 groups and response cross-sections from IRDF-85. For the sulphur detector the C/E values were almost constant at 1.02. For indium they decreased with penetration from 1.02 to 0.91 over the first 50 cm with values of 0.79 and 0.73 respectively at 60 cm and 70 cm. For rhodium they fell from 1.08 to 0.88 over the first 50 cm with values of 0.79 and 0.63 at 60 cm and 70 cm. The differences between the measured and calculated rates of attenuation thus deteriorated markedly in the last 20 cm of graphite. For the UKNDL data the corresponding ranges of C/E over 50 cm were 0.98 to 0.96 for indium and 1.04 to 0.92 for rhodium, with values of 0.89 at both 60 cm and 70 cm for indium and 0.90 and 0.73 at 60 cm and 70 cm respectively for rhodium. The agreement with UKNDL over 50 cm is thus to within 4% for indium and 8% for rhodium, which is significantly better than that obtained with JEF-2.2 data. The sulphur results suggest that there are no significant errors in the cross-sections in the range 3.0 MeV to 8.0 MeV, whilst those for indium and rhodium indicate that the cross-sections are too high between 0.5 MeV and 3.0 MeV. For indium the measured decrease over 70 cm is 2.3×10^3 so that the attenuation cross-section would need to be decreased by 4%, whilst for rhodium the corresponding numbers are 1.8×10^3 and 7%. It is difficult to reconcile these discrepancies with the high accuracies, typically a standard deviation of less than 1%, which are claimed for the elastic scatter cross-section of carbon at these energies. It would be helpful to have other benchmark data to check these conclusions. If the reasons for the discrepancies have to be sought outside of the scatter cross-sections then one possibility might be that there is a need to treat the angular distribution of scatter in more detail at the energies of resonances. Investigations are needed to determine whether these effects would be significant.

The JANUS iron/stainless steel/sodium series of benchmarks

The JANUS series of shielding benchmarks was designed to validate methods used to calculate fast reactor shields consisting of mild steel, stainless steel and sodium, and including boron absorber in some configurations. The source was the fission plate in the ASPIS facility and the detectors were $^{32}S(n,p)^{32}P$, $^{103}Rh(n,n')^{103m}Rh$, $^{55}Mn(n,\gamma)^{56}Mn/Cd$ and $^{197}Au(n,\gamma)^{198}Au/Cd$.

Comparisons of measurement and calculation for the JANUS Phase 1 to 6 benchmarks are reported in an internal CEA Technical Note [9]. The calculations were made using the ERANOS system. The 1 968 fine group cross-sections plus probability table within group data in the ECCO code are condensed to 175 groups (for a number of sub-regions of the shield) using a procedure which has been developed for use in shielding calculations. The ECCO flux calculation assumes an exponential spatial variation associated with a source. The bucklings for the assumed exponential variation are obtained by iteration between ECCO and the S_n code BISTRO which is used to calculate the flux (in 175 groups) through the shield. The procedure has been validated by making comparisons with TRIPOLI-4 Monte Carlo calculations for the sulphur and indium reaction rate distributions in JANUS-1 (iron/stainless steel) and JANUS-2 (iron/stainless steel/sodium). Agreement is within the statistical uncertainty of the Monte Carlo calculations, about 2% (although some of the Monte Carlo values show a larger fluctuation from point to point).

The JANUS Phase 1 array consisted of 17.78 cm mild steel, followed by 40.41 cm stainless steel, and a further 44.7 cm of mild steel backed by concrete. The Phase 2 array contained 17.9 cm mild steel, 22.4 cm stainless steel, and 91.4 cm sodium followed by mild steel. The subsequent phases had different materials in the intermediate zone, which in Phase 2 contained the 22.4 cm of stainless steel. The constitution of the intermediate zones is summarised in Table 8.1.

Table 8.1. Constitution of the intermediate zones

Phase 2	22.4 cm JANUS stainless steel.
Phase 3	25.0 cm JASON stainless steel.
Phase 4	8.9 cm stainless steel, 5.0 cm B_4C/stainless steel, 9.0 cm stainless steel
Phase 5	13.5 cm stainless steel, 5.0 cm B_4C/stainless steel, 4.5 cm stainless steel
Phase 6	8.9 cm stainless steel, 10.0 cm B_4C/stainless steel, 4.5 cm stainless steel

All of these intermediate zones are preceded by 17.9 cm of mild steel and followed by 91.4 cm of sodium.

In the calculations the cross-sections of sulphur and rhodium were adopted from IRDF-90. However, for manganese and gold the ECCO JEF-2.2 cross-sections were used because a collision probability transport theory calculation must be made to treat the self-shielding effects in the environment of the detector.

A simplification is made in modelling the shield. The void gaps between blocks cannot be treated in the calculation scheme and so the voids are smeared into neighbouring regions.

Concerning the C/E values for the different detectors at the position adjacent to the fission plate, for sulphur the value is about 0.9 in JANUS-1 and is in the range 0.95 to 1.0 in the other phases. For rhodium, gold and manganese the values are all above unity, being in the range 1.0 to 1.2 (and perhaps 1.3 for manganese in JANUS-4).

The C/E values vary smoothly except for the gold and manganese detectors in the B_4C regions, where there are very large peaks, the values reaching 1.8 for Mn in JANUS-4 and JANUS-6. This could be because of an inadequate treatment of the self-shielding effects for the detectors in these regions.

Sulphur

The C/E values for the sulphur detector increase by about 15% through the mild steel region, being in the range 0.9 to 1.1. The C/E values then decrease in the first few centimetres of the stainless steel region and then increase again by about 15% in going through the thicker stainless steel zone of JASON-1. The values also increase in the thinner stainless steel zones of JASON-2 and JASON-3. The values remain in the range 0.9 to 1.2. The C/E values in the sodium region are approximately constant in JANUS-2 and JANUS-3, although they do show fluctuations. In JANUS-6 the three measured points show a strong increase in the C/E values but the activation is small in these cases.

Rhodium

The C/E values adjacent to the fission plate are in the range 1.05 (JANUS-1) to 1.2 (JANUS-6). The C/E values increase initially by about 10% in the first 10 cm, then flatten out and decrease through the stainless steel region, the decrease being about 20% in the case of the thick stainless steel region in JANUS-1. There is then a further decrease through the mild steel region of JANUS-1. Again the variation through the sodium region is approximately flat, after an initial decrease. The values at the final points, particularly in the phases that include the boron steel zones, are less accurate and the deviations are probably not significant.

Gold

In the case of JANUS-1 the C/E values are approximately constant, ranging from about 1.2 to 1.3 down to 1.0 through the steel regions. However, for the penetration through sodium in JANUS-2 and JANUS-3 there is a strong decrease, from about 1.2 down to about 0.5. When the boron region is present there is a strong reduction in C/E when it goes through this region.

Manganese

In this case there is a 20% increase in C/E through the mild steel region followed by a flatter variation through the stainless steel and sodium. In the case of the phases which include a boron zone, one again sees a strong reduction in C/E on going through the zone.

Conclusions reached by the authors

On the basis of the analysis, limits can be put on the uncertainties in calculations. It is also concluded that there would be a significant improvement if the new sodium evaluation (based on the IRMM, Geel and ORNL measurements) were to be used.

Iron/water array

JEF/DOC-476 [8] includes a summary of the results of calculations for the NESDIP-2 benchmark. This was a simulation of the radial shield of a PWR with 12.1 cm water, a 6.3 cm stainless steel slab to reproduce a thermal shield, a further 13.1 cm water, and a 22.8 cm thick region of mild steel to represent the pressure vessel. A gap outside this array simulating the external cavity was backed by another water tank. The experiment was performed in the ASPIS facility with its fission plate source and measurements were made with $^{103}Rh(n,n')^{103m}Rh$ detectors throughout the shield supplemented by $^{32}S(n,p)^{32}P$ and $^{115}In(n,n')^{115m}In$ in the regions representing the pressure vessel and the cavity.

Calculations were performed with MCBEND using the 8 220 group data for the materials and IRDF-85 for the detector cross-sections. For rhodium the C/E values in the water were between 0.87 and 0.97 at the twelve measuring positions. The values in the second water region tended to be lower than those in the first with a mean of 0.89 compared with 0.92. In the pressure vessel the C/Es for rhodium rose to 0.99 but then dropped to 0.84 in the cavity. For sulphur the C/E ratios were 0.95, 1.02, 1.04 and 1.02 within the simulated vessel region and 1.05 in the cavity. Corresponding values for the indium comparisons were 0.89, 0.91, 0.92, 0.90 in the vessel and 0.84 in the cavity. The results suggest that the attenuation through the array is calculated accurately, with the slowing down spectrum giving discrepancies of some 10% in the fluxes in the energy range 0.5 MeV to 2.0 MeV.

The 900 MWe PWR Saint Laurent B1

In the measurements the reactor was partially fuelled with MOX fuel assemblies, the objective being to compare TRIPOLI-4 continuous energy Monte Carlo calculations with measurements made of the fluence at the position of the containment. Calculations using the multi-group plus probability table Monte Carlo code TRIPOLI-3.4 were also compared with the TRIPOLI-4 results. Measurements

were made in a capsule situated radially in the interior of the pressure vessel and also in an external cavity. The detectors used were ^{54}Fe(n,p), ^{58}Ni(n,p), ^{63}Cu(n,a), ^{93}Nb(n,n′), ^{238}U(n,f)/Cd and ^{237}Nd(n,f)/Cd. The comparison between TRIPOLI-3.4 and TRIPOLI-4 showed a tendency for TRIPOLI-3.4 to underestimate the values calculated for the capsule by a few per cent (-9% to +6%) relative to TRIPOLI-4. For the cavity there is an average underestimation by about 5% but the differences are at about the 1 s.d. level. Concerning the comparison with experiment, the calculations for the capsule show an underestimation in the range -3% for ^{58}Ni(n,p) to -16% for ^{238}U(n,f)/Cd. For the cavity the calculations overestimate the reaction rates by between 2% and 20%.

It is concluded that TRIPOLI-3.4 and TRIPOLI-4 are in satisfactory agreement when the same library of cross-section data is used. Secondly, the calculations underestimate the internal values (capsule) and overestimate the external values (cavity). It is noted that these are the same trends as those observed in the REPLICA and NESDIP benchmarks and concluded that the problem is probably associated with the cross-sections of water.

Uncertainties

Uncertainties in C/E values arise from a number of sources. Systematic errors which affect all the measurements for a given detector in a similar way are those due to the source strength and the calibration of the detectors. Random uncertainties arise from the counting statistics for the detectors, positioning of the detectors and the scoring statistics in the Monte Carlo calculations, although in the latter there will be some correlation between reaction rates scored at different positions in the same computer run. Measurements made with a fission plate source will also be subject to uncertainties from the subtraction of the background contributions to the reaction rates. Other uncertainties due to the detector cross-sections and the source spectrum will vary with position when the neutron spectrum and the source energies contributing to the reaction rates are found to change with penetration. Finally, there are possible uncertainties arising from approximations in modelling the configuration of the experiment or in representing the nuclear data. In an ideal benchmark these uncertainties would be very small so that the comparisons would give an unambiguous indication of errors due to the cross-sections of the materials being studied. The uncertainties are estimated in most of the comparisons that have been considered above.

The uncertainties in the source calibration are typically ±3.5% to ±5.0% for the fission plates and 0.5% for the californium. The calibration of the counting systems for the detectors have uncertainties of 1.5% for Mn, 0.9% for Au, 3.0% for Rh, 1.9% for In, 5.0% for S and 2.2 % for Al. (All of the benchmark experiments considered above were performed at AEA Technology, Winfrith so that errors are systematic across the complete set of comparisons.) The random uncertainties due to counting statistics vary, being typically 1% or less close to the source where counting rates are high, but increasing to 6% at deeper penetrations. (For sulphur at the deepest penetration in the Iron 88 benchmark the uncertainty exceeds this with counting statistics of ±20%.) The Monte Carlo statistics are similar to those from counting, ranging from 1% at short penetrations to 5% after attenuation through the benchmark. The uncertainties due to the subtraction of the background vary from benchmark to benchmark but are close to 1%. The estimated uncertainties in the fission spectrum are most significant for the high energy detectors at deep penetrations. For ^{27}Al(n,α) they can rise to 7.7% and for ^{32}S(n,p) to 5%, whilst for the other detectors they are negligible in the iron benchmarks and less than 5% in graphite and in NESDIP2. Uncertainties due to the detector cross-sections based on IRDF-90 are typically 2% for Al, 5-7% for S, 2-4% for In and 3-13% for Rh. The large uncertainties for rhodium arise at deep penetrations in iron where the spectrum gives large contributions to the reaction rate from neutrons with energies close to the threshold. The uncertainties for the Au and Mn detectors under cadmium are expected to be large because of the difficulty experienced in taking

account of the self-shielding, but no standard deviations are quoted for these data for the shielded cross-sections. The largest uncertainty due to specification of the configuration of the benchmark is 3% for the sulphur measurements in NESDIP2 due to bowing of the water tank. For the other detectors in NESDIP2 and for all detectors in the other benchmarks the contributions from uncertainties in material configurations were less than 1.1%. Positional errors did not arise when detectors were located between slabs of material, as in the iron benchmark, or in specially prepared slots, as in the graphite. However they were present in the water benchmark where a 6% uncertainty was estimated from the reproducibility of the results. (This will include a small contribution from the counting statistics in addition to the major effect arising from the positioning of the detectors.) In the water in NESDIP2 the uncertainty due to positioning of the detectors was estimated to be ±1 mm which translates into ±2% in the reaction rate when it is combined with the measured rate of attenuation.

The uncertainties in the C/E values due to the contributions summarised above should be comparable with or less than those arising from the material cross-sections if the uncertainties assigned to the latter are to be confirmed or reduced. At short penetrations the reaction rates are not very sensitive to the material cross-sections so that the comparisons at these positions provide information which is mostly relevant to checking the systematic uncertainties. At deep penetrations the situation changes, and for nearly all of the measurements considered above the sensitivity to the material cross-sections is sufficiently large and the uncertainties from other sources sufficiently small for useful conclusions to be drawn on the accuracy of the material cross-section data. The exceptions are the measurements made with rhodium in the iron benchmark where the large uncertainty in the detector cross-section greatly reduces their value when assessing the accuracy of the cross-sections for iron.

Adjustments

Reviews of the validation of JEF-2.2 data for structural materials have been presented in JEF/DOC-412, JEF/DOC-422 and JEF/DOC-477. Results for these materials are also included in JEF/DOC-440 and JEF/DOC-478. The approach adopted is to use a statistical adjustment of the microscopic cross-section data. This procedure is described in Part III, which also summarises the results. The adjustments are based on a large number of benchmark comparisons involving integral data on critical masses, bucklings, null reactivity measurements and spectral indices in addition to the shielding benchmarks.

The conclusions which are presented in Part III are as follows:

^{56}Fe	σ(n,n′)	Slight increase for E > 2 MeV, decrease by ~20%±7% for threshold energy < E < 2 MeV.
^{58}Ni	σ(n,abs)	Decrease by 10%±7%.

For iron it can be seen that the simplified consideration of the discrepancies in the iron benchmark suggested changes which are broadly consistent with the results of the least squares analysis with its detailed treatment of the full range of benchmarks with their sensitivities to the cross-sections. The previous indications were for an increase of 4% in the attenuation cross-section (mainly due to σ(n,n′)) at energies above 2 MeV together with a decrease of 7% in elastic scatter in the range 0.5 MeV to 2 MeV. The suggestion that the cross-section at high energies (E > 6 MeV) should be decreased by 3% is not confirmed by the adjustments.

A simple examination of the results for stainless steel cannot identify errors in individual isotopes, but a decrease in the absorption cross-section of nickel does not appear to be consistent with the overestimation of the $^{197}Au(n,\gamma)$ reaction in the stainless steel benchmark.

The adjustment of the cross-sections gives an improved overall agreement (the discrepancy could however increase at an individual point) between measurements and calculations for the collection of benchmarks which have been included in the process. The adjusted cross-sections can be expected to provide improved accuracies in other situations only if the changes are in effect removing errors which were present in the original data file. The likelihood that the adjustments have this physical significance is increased when they are based on a large number of comparisons in a range of configurations. However, the possibility that the adjustments could be compensating for approximations in the processing of the data or in the method of calculation has already been recognised. Furthermore, in the context of shielding calculations, data such as the angular distributions of scattered neutrons and the energy loss laws are important. These are not included in the adjustment procedure, which would instead attempt to correct for the effects of errors in such data by making changes to the cross-sections. Assessments of the accuracies of shielding calculations can be made on the basis of the co-variance data and the consistency of the standard deviations that they give for the predictions of benchmark reaction rates and the observed discrepancies between measurements and calculations.

Summary

The benchmark considered here cover the penetration of neutrons in water, iron, stainless steel, graphite and sodium. In general they show that the attenuation of high energy neutrons (E > 2 MeV) is predicted satisfactorily. Measurements made with the indium and rhodium detectors suggest that the fluxes at energies between 0.5 MeV and 2 MeV are underestimated by some 30% at deep penetrations in iron, graphite and stainless steel. Problems have been encountered in interpreting the measurements of the low energy fluxes made with gold and manganese detectors, which may be due to the difficulties in treating the effects of self-shielding in the foils.

In the case of the iron benchmark studies, differences have been noted between the results of the MONK and TRIPOLI-3 Monte Carlo calculations and the ECCO/BISTRO discrete ordinates calculations. An excellent agreement, however, is found between TRIPOLI-4 and ECCO/BISTRO for the JANUS experiment for mild steel and stainless steel.

The discrepancies in the comparisons for the indium reaction rates are difficult to explain, particularly in graphite where the cross-sections are expected to be known to a high accuracy. It is suggested that the importance of the changes in the angular distribution of scatter at the energies of resonances should be investigated.

E. Fort, *et al*. have included the results from the shielding benchmarks together with those from reactor physics and criticality experiments in a comprehensive adjustment procedure which employs maximum likelihood principles to derive cross-section changes that would improve the agreement between measurements and calculations. These studies indicate the need for changes to the iron and nickel cross-sections which are consistent with the trends of recent measurements.

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Annex

List of JEF Documents Related to Shielding Validation Studies

JEF/DOC-412 Validation of JEF-2.2 Structural Material Data; E. Fort.

JEF/DOC-420 Validation of ENDF/B-VI and JEF-2 Iron Cross-Sections by Sensitivity and Adjustment Analysis; I.A. Kodeli.

JEF/DOC-421 Analysis of the Winfrith Iron 88 Benchmark Experiment; G.A. Wright and M.J. Grimstone.

JEF/DOC-422 Validation of Iron and Structural Materials Data of JEF-2, Provisional Conclusions on the 14/6/1993; E. Fort.

JEF/DOC-440 JEF-2 Validation, Global Analysis – Problems Encountered; E. Fort.

JEF/DOC-443 Benchmark Testing of JEF-2.2 Data for Shielding Applications: Analysis of the Winfrith Water Benchmark Experiment; H.F. Lock and G.A. Wright.

JEF/DOC-447 Qualification and Improvement of Iron ENDF/B-VI and JEF-2 Evaluations by Interpretation of the ASPIS Benchmark; S.H. Zeng, I. Kodeli, C. Raepsaet, C.M. Diop, J.C. Nimal, A. Monnier.

JEF/DOC-476 Benchmarking of the JEF-2.2 Data Library for Shielding Applications; G.A. Wright, A.F. Avery, M.J. Grimstone, H.F. Locke, S. Newbon.

JEF/DOC-477 Validation of Iron and Structural Materials Data of JEF-2 – Status; E. Fort, K. Dietze

JEF/DOC-478 JEF-2 Validation Methodology – Present Results, Future Plans; E. Fort. M. Salvatores.

JEF/DOC-612 The ERANOS System Applied to Shielding Calculations with Validation on JANUS Experiments; G. Rimpault, E. Lefevre.

JEF/DOC-790 Application of JEFF-3T Data to the Winfrith Iron Benchmark; S.J. Chucas, C.J. Dean, R.J. Perry, W.V. Wright.