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Generation and Performance of a Multigroup Coupled Neutron-Gamma Cross-Section Library for Deterministic and Monte Carlo Borehole Logging Analysis

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As part of the IRTMBA (Improved Radiation Transport Modelling for Borehole Applications) project of the EU community's 5th framework program a special purpose multigroup cross-section library was prepared for use in deterministic and Monte Carlo oil well logging particle transport calculations. This library is expected to improve the prediction of the neutron and gamma spectra at the detector positions of the logging tool, and their use for the interpretation of the neutron logging measurements was studied. Preparation and testing of this library is described.

KEYWORDS: cross-section library, multigroup, oil well logging

1. Introduction

Nuclear borehole logging is used for a variety of applications in the oil industry, for example, to locate hydrocarbons remaining behind a steel well casing after a field has been in production. The proper interpretation of the measured data requires extensive radiation transport calculations. As part of the IRTMBA (Improved Radiation Transport Modelling for Borehole Applications) project of the European Union's 5th framework program the calculation tools for this type of problem were studied, including deterministic as well as Monte Carlo methods, both direct and adjoint. These applications require the use of a multigroup cross-section library, which is better dedicated to the problem than the existing multigroup libraries produced mainly for reactor or shielding applications.

2. Borehole logging

A borehole logging tool generally consists of a 14 MeV pulsed neutron source and one or more neutron or photon detectors. In the latter case photons with discrete energies are generated in inelastic neutron scattering events or in neutron capture events, mostly after thermalization of the neutrons. The characteristic lines in the measured gamma spectrum indicate the presence of different nuclei. In borehole logging practice the photons produced by carbon and oxygen are of particular interest, since they indicate the presence of oil (CH_2) and water, respectively, in the pores of the formation around the borehole. As the photon detectors used in a logging tool do not have very good resolution in the relevant energy range, one detects the number of photons in a window around the primary carbon energy of 4.44 MeV and around the primary oxygen energy of 6.13 MeV.

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3. Cross-section library requirements

Due to the characteristics of a borehole logging calculation the multigroup library should provide cross-section data both for neutrons and photons, as well as for all photon generating processes due to neutron reactions. Moreover, sufficiently detailed energy description is required in the high energy range between about 1 and 15 MeV to represent properly the neutron source and the inelastic scattering reaction, as well as in the epithermal and thermal range due to the photon production from the neutron capture. As for the photon energy group structure it is important to cover adequately the carbon and oxygen windows in the range between ~3.2 and ~7 MeV. In addition the library should offer the possibility to take into account the self-shielding effects.

The currently available multigroup libraries intended primarily for nuclear reactor or shielding calculations do not fulfil these requirements.

4. Production of the library

A cross-section library specially dedicated for oil well logging applications with an optimized energy group structure as well as the appropriate weighting and self-shielding treatment was processed. To facilitate the comparison and validation against the existing libraries a group structure similar to one of the standard structures - VITAMIN-J - was selected. The library provides for 175 neutron and 45 gamma-ray energy groups. The neutron energy groups are the same as in the VITAMIN-J structure (175), including 12 groups below 5 eV as well as 3 up-scatter neutron groups. On the other hand several gamma groups were added in the MeV region to have a total of 45 gamma groups, with 9 gamma groups covering the range of the oxygen and carbon windows (the oxygen window is between 4.75 and 7.05 MeV; the carbon window between 3.21 and 4.75 MeV).

The library is based on the latest release of the ENDF/B-VI (revision 8) evaluated nuclear data files. P_0 to P_5 Legendre terms are included. The following nuclides, present in the formation material, in the cement used in the borehole and in the detector material, were included into the library: ^{1}H, ^{12}C, ^{16}O, ^{23}Na, ^{nat}Mg, ^{27}Al, ^{28,29,30}Si, ^{nat}S, ^{35,37}Cl, ^{nat}K, ^{nat}Ca, ^{54,56,57,58}Fe, ^{127}I, ^{nat}W. All those nuclides were processed by the NJOY99.81 code [1] to reconstruct the resonance cross-sections, if applicable, to evaluate the cross-sections at the room temperature of 300 K and to calculate group cross-sections in the selected energy group structure, both for neutrons and photons. The output format can be the MATXS or the GROUPR format. In the latter case some further processing from the NJOY output with the NSLINK code is necessary to convert to AMPX master format [2]. The TRANSX [3] code can be used to prepare the data for deterministic codes (like DORT-TORT [4]), and the CRSRD [5] code for the Monte Carlo code MCNP [6]. The TRANSX code takes into account the self-shielding effects for a specific configuration, and can produce the cross-section in a modified (reduced) energy group structure.

5. Processing problems with ^{35}Cl

Cross-sections for chlorine in the new ENDF/B-VI.8 evaluation are given for the two major isotopes (^{35}Cl and ^{37}Cl) [7], contrary to the older evaluations providing data for natural chlorine. Several problems were detected when processing the ^{35}Cl ENDF/B-VI.8 data. The gamma-ray production data from the many (n,γ) reactions (MT=102) contained negative terms. This turned out to be caused by a format error in the photon production data in the ENDF/B-VI.8 data. For this reaction type the part of the ENDF file describing the photon

production multiplicities and transition probability arrays (MF=12) specifies a number of 404 discrete photon energies. However, the photon angular distribution section (MF=14), which is only given to specify that all angular distributions are isotropic, specifies a number of 40 for the number of discrete photons. This number is apparently used by NJOY in processing the photon production data and it accepts this inconsistent value without any error message, resulting in partly negative photon production cross-sections. After correcting the wrong number the photon production group cross-section are correctly calculated. We checked that processing the ^{35}Cl data with the ACER module of NJOY for the continuous-energy cross-section library for the Monte Carlo code MCNP is not influenced by the format error.

Furthermore, processing the group cross-section data in the AMPX format requires the AJAX module of the AMPX system to combine data for different nuclides. This module gave a fatal error, which turned out to be due to an array boundary limitation for the number of reaction types of the neutron cross-section. For ^{35}Cl data evaluation this number is exceptionally high due a large number of different discrete level reactions for (n,p), (n,d), (n,t), and (n,α) reactions, in addition to the more usual reaction type data. After increasing the array boundary from 100 to 200, the problem was solved.

6. Application to a borehole logging case

A simplified but realistic borehole-logging geometry shown in Fig. 1 was used in the analysis. As the details of logging tools are kept confidential by the logging tool vendors, we used typical tool dimensions frequently used in this type of studies.

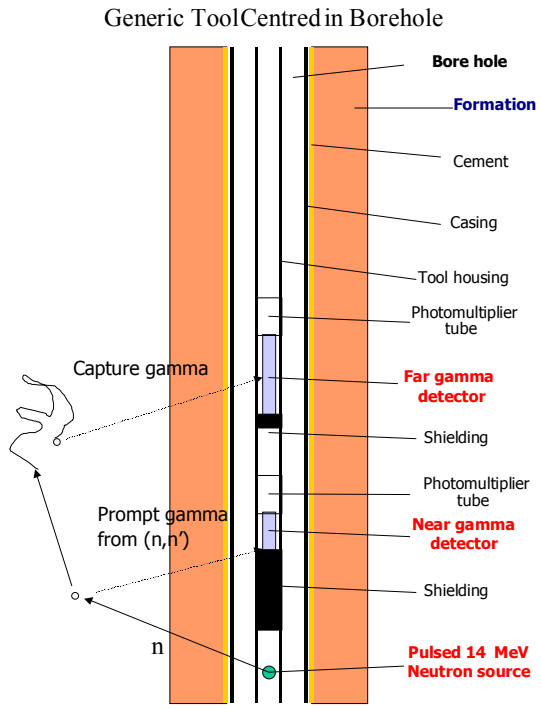

Fig. 1: Geometry for calculation

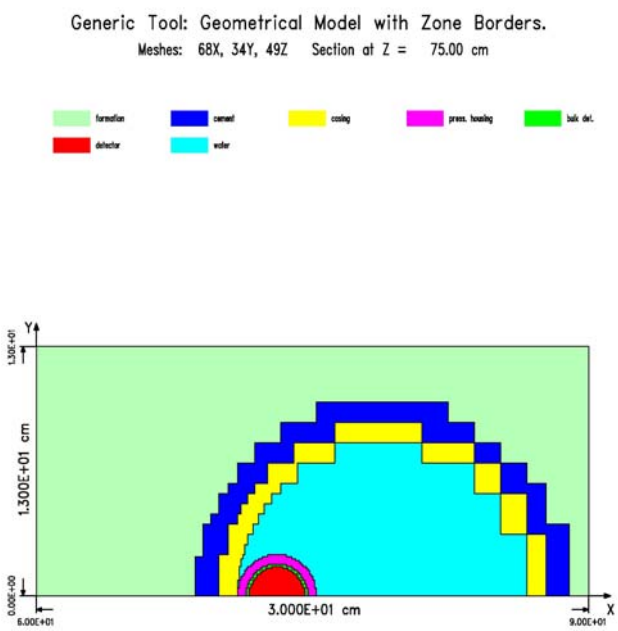

Fig. 2: Eccentered geometrical model used in the TORT code (X-Y plane view).

Transport calculations were performed with the discrete ordinates code system DORT-TORT [4], and Monte Carlo codes MCNP-4C and MCBEND. Tables 1 and 2 compare the results from both codes for the photon flux in the energy ranges 3.21-4.75 MeV (C-window)

and 4.75-7.05 MeV (O-window) for various values of porosity and saturation of the formation. The formation materials are sandstone (SiO_2) and limestone ($CaCO_3$).

Deterministic calculations were done using DORT in 2D *r-z* geometry for a centered tool and TORT in 3D *x-y-z* geometry with an eccentered logging tool in the borehole. The cylindrical form of the tool and borehole was approximated in *x-y-z* geometry by a ring of staggered rectangles. The BOT-3P [8] code was used to prepare the corresponding 3D geometry, and several degrees of approximation were studied, from the simplest square to the more precise description shown on Fig. 2. The standard S-8/P-5 approximations were used.

Monte Carlo calculations were performed with the MCNP4C3 code, in which the geometry can be modeled exactly.

7. The general radiation transport code MCBEND

Apart from calculations with the DORT, TORT and MCNP codes, we also tested the multigroup data library with the MCBEND code. As this code may not be generally known to a wider public, we give a short description of its characteristics.

MCBEND [9,10] is an established Monte Carlo code in the fields of shielding, dosimetry and general radiation transport. It can calculate neutron, gamma-ray and electron transport; coupling of the different radiation types is also possible. The code is the result of over 30 years' development and it is licensed and actively supported in use by the ANSWERS Software Service of Serco Assurance. The aim of the on-going development program continues to be the delivery of accurate, robust and fit for purpose techniques into the hands of the user. User support and easy to understand input data and documentation are designed to make the techniques easily accessible, even to the novice.

MCBEND provides sophisticated modeling capabilities comprising two major components:

- A geometry body-based system built around hierarchically structured collections of bodies of general orientation. The collections of bodies can have simple relationships (e.g. nested or arrays) or complete freedom of overlap. Particle tracking is performed using conventional ray tracing techniques.
- A system of ‘hole’ geometry options that provides detailed structure and repeating configurations within the body-based system. The particle tracking in this option is performed using Woodcock tracking, which allows for a considerable increase in modeling capability and efficiency.

In combination, these options provide almost unlimited modeling capability, yet retain the simplicity of concept of the originators. Major extensions to both options have taken place in the recent past to meet emerging customer needs.

Efficient and robust variance reduction is a key requirement of a Monte Carlo calculation. The standard method utilized by MCBEND is splitting/Russian roulette in space and energy together with source weighting. Both methods rely on a set of space/energy dependent importances. In MCBEND the importances are calculated using adjoint diffusion theory. The library of diffusion coefficients has been carefully adjusted so that the solution approaches that which a transport calculation would provide. For the purposes of variance reduction, this approach is sufficiently accurate. The importances are calculated in an orthogonal mesh ("splitting mesh") which overlays the problem geometry. The user simply has to define the mesh, the target response function and its location - the code does the rest. This facility has taken a lot of the difficulty out of efficient, robust variance reduction. Additional techniques, such as forced flight and revision of importances, are also available for difficult radiation streaming problems.

The standard techniques in MCBEND for scoring are by track length or collision density in regions. Fluxes and responses may be scored. Sensitivity of fluxes and responses to material cross-sections can be scored. Both first and second order sensitivities are available. These may be used to calculate uncertainties in the result due to data uncertainties or due to uncertainties or perturbations of physical parameters such as density, porosity, etc. Accurate prediction of detector response in terms of energy deposition requires the code to simulate the physical processes occurring in the detector. In MCBEND the raw energy deposition spectrum (pulse height distribution) is accurately recorded, even in the presence of events such as pair production and variance reduction which cause a number of fragments from the same sample to score.

Nuclear data libraries based on UKNDL, JEF2.2, ENDF/B-VI and JENDL3.2 data are currently available for MCBEND. For neutron calculations, the cross-sections are held in 13,193 ultrafine energy groups. Detailed treatment of thermal neutron transport is included using $S(\alpha,\beta)$ data or free gas treatment as appropriate. For special purposes a multigroup treatment is available, as used for the current research.

7.1 Library format conversion for the MCBEND code

As the format of the multigroup library for the MCBEND code is different from that for the MCNP code, a conversion program was written. As the MCBEND code requires angular data in the form of Legendre components, the best starting point for the conversion is the multigroup library in the AMPX format. Using the Legendre components MCBEND computes internally a probability table for cosines of the scattering angle for scattering from one group to another. This may cause differences with the way these data are calculated for the MCNP multigroup library. Also, slight differences in atomic mass numbers may cause small differences.

In both formats photons are dealt with by extending the number of particle groups. AMPX uses a compact format with so called magic words to indicate the range of groups from which transfer by scattering or photon production can take place to the group considered. As MCBEND considers transfer from a certain group to all other groups with a higher number (lower energy or photon groups), the transfer matrices have to be expanded with zero elements for the MCBEND format. MCBEND does not allow upscattering in multigroup mode. Therefore, possible neutron up-scattering matrix elements are added to the in-group matrix elements to conserve total scattering. Taking these differences into account, it was possible to produce a multigroup library for MCBEND with essentially the same cross-section data.

8. Numerical results

Using the DORT, TORT, MCNP and MCBEND codes, results were obtained for the photon flux in the carbon and oxygen energy window for the borehole logging problem. Both a centered and an eccentered logging tool was considered. Moreover, the calculations were done for two different formation materials and for two different values for the saturation of oil in the pores of the formation.

The results for the centered tool are shown in Table 1. Those for the eccentered tool in Table 2. Only gamma rays produced by inelastic scattering (neutron cut-off energy 0.64 MeV) are presented. The discrete ordinates codes DORT and TORT applied a S_8/P_5 approximation. The Monte Carlo MCNP calculations in multigroup mode used 80,000,000

Table 1 Comparison of the DORT, MCNP and MCBEND centered generic tool calculation using the 175n/45γ group library.

Centered tool Inelastic gammas		SiO_2			$CaCO_3$		
		19 % H_2O	19 % H_2O 150g NaCl	19 % CH_2	19 % H_2O	19 % H_2O 150g NaCl	19 % CH_2
	E (MeV)	Φ_γ	Φ_γ	Φ_γ	Φ_γ	Φ_γ	Φ_γ
DORT (r-z) (CPU ~10 min. on a 1,7 GHz PC)							
Det 1	3.21-4.75	6.94E-6	6.94E-06	7.01E-6	7.57E-06	7.56E-06	7.66E-06
	4.75-7.05	7.16E-6	7.15E-06	6.96E-6	6.62E-06	6.61E-06	6.42E-06
Ratio C/O		**0.970**	**0.972**	**1.007**	**1.144**	**1.144**	**1.193**
Det 2	3.21-4.75	6.37E-7	6.35E-07	6.47E-7	6.99E-07	6.95E-07	7.11E-07
	4.75-7.05	6.49E-7	6.45E-07	6.30E-7	5.86E-07	5.83E-07	5.66E-07
Ratio C/O		**0.981**	**0.984**	**1.027**	**1.192**	**1.192**	**1.257**
MCNP Multigroup (CPU ~4.5 h on a 677 MHz workstation)							
Det 1	3.21-4.75	7.00E-6 ±1.0%	7.00E-6 ±1.0%	7.07E-6 ±1.0%	7.58E-6 ±0.9%	7.55E-6 ±0.9%	7.62E-6 ±0.9%
	4.75-7.05	6.92E-6 ±1.0%	6.93E-6 ±1.0%	6.75E-06 ±1.0%	6.45E-06 ±1.0%	6.47E-6 ±1.0%	6.27E-06 ±1.0%
Ratio C/O		**1.011** ±1.4%	**1.010** ±1.4%	**1.047** ±1.4%	**1.174** ±1.3%	**1.167** ±1.3%	**1.216** ±1.3%
Det 2	3.21-4.75	5.65E-7 ±2.7%	5.60E-7 ±2.7%	5.84E-7 ±2.7	6.12E-7 ±2.7	6.01E-7 ±2.6	6.37E-7 ±2.5
	4.75-7.05	5.65E-7 ±2.7%	5.85E-7 ±2.7%	5.65E-7 ±2.8%	5.19E-7 ±2.9%	5.18E-7 ±2.9%	5.12E-7 ±2.9%
Ratio C/O		**1.000** ±3.8%	**0.958** ±3.8%	**1.033** ±3.9%	**1.179** ±3.9%	**1.162** ±3.9%	**1.243** ±3.8%
MCBEND Multigroup (CPU ~4h on a 2 GHz PC)							
Det 1	3.21-4.75	7.09E-6 ±1.0%	7.19E-6 ±1.0%	7.09E-6 ±1.1%	7.62E-6 ±0.9%	7.69E-6 ±1.0%	7.92E-6 ±0.9%
	4.75-7.05	6.93E-6 ±1.1%	6.89E-6 ±1.1%	6.87E-6 ±1.2%	6.58E-6 ±1.0%	6.53E-6 ±1.1%	6.32E-6 ±1.1%
Ratio C/O		**1.023** ±1.5%	**1.044** ±1.5%	**1.032** ±1.6%	**1.157** ±1.3%	**1.177** ±1.5%	**1.254** ±1.4%
Det 2	3.21-4.75	5.42E-7 ±2.9%	5.36E-7 ±3.0%	5.73E-7 ±3.0%	6.52E-7 ±2.6%	6.28E-7 ±2.6%	6.26E-7 ±2.6%
	4.75-7.05	5.93E-7 ±2.9%	5.85E-7 ±2.9%	5.52E-7 ±3.0%	5.13E-7 ±3.0%	5.05E-7 ±3.0%	5.26E-7 ±3.0%
Ratio C/O		**0.914** ±4.1%	**0.916** ±4.2%	**1.038** ±4.2%	**1.271** ±4.0%	**1.243** ±4.0%	**1.190** ±4.0%
MCNP Pointwise ENDF/B-VI.8 library [11]							
Det 1	3.21-4.75	6.63E-6 ±2.1%	6.63E-6 ±2.1%	6.69E-6 ±2.1%	7.37E-6 ±2.0%	7.31E-6 ±2.0%	7.53E-6 ±2.0%
	4.75-7.05	6.87E-6 ±2.4%	6.86E-6 ±2.4%	6.60E-6 ±2.4%	6.30E-6 ±2.5%	6.27E-6 ±2.5%	6.12E-6 ±2.5%
Ratio C/O		**0.966**±3.2%	**0.967**±3.2%	**1.014**±3.2%	**1.169**±3.2%	**1.166**±3.2%	**1.230**±3.2%
Det 2	3.21-4.75	5.46E-7 ±6.2%	5.49E-7 ±6.3%	5.67E-7 ±6.28%	6.34E-7 ±5.8%	6.22E-7 ±5.8%	6.30E-7 ±5.6%
	4.75-7.05	5.42E-7 ±6.9%	5.19E-7 ±7.0%	5.29E-7 ±6.9%	4.75E-7 ±7.5%	4.76E-7 ±7.4%	4.70E-7 ±9.4%
Ratio C/O		**1.008**±9.3%	**1.059**±9.4%	**1.072**±9.3%	**1.334**±9.5%	**1.307**±9.4%	**1.340**±9.4%

Table 2 Comparison of the TORT, MCNP and MCBEND eccentered generic tool calculation using the new library

Eccentered tool Inelastic gammas		SiO_2			$CaCO_3$		
		19 % H2O	19 % H2O 150 g NaCl	19 % CH2	19 % H2O	19 % H2O 150 g NaCl	19 % CH2
	E (MeV)	Φ_γ	Φ_γ	Φ_γ	Φ_γ	Φ_γ	Φ_γ
TORT (X-Y-Z) (CPU 200-300 min. on a 1,7 GHz PC)							
Det. 1	3.21-4.75	5.86E-6	5.86E-6	5.93E-6	6.40E-6	6.42E-6	6.49E-6
	4.75-7.05	6.13E-6	6.11E-6	5.94E-6	5.54E-6	5.54E-6	5.34E-6
Ratio C/O		**0.957**	**0.959**	**0.999**	**1.156**	**1.158**	**1.215**
Det. 2	3.21-4.75	4.93E-7	4.91E-7	5.03E-7	5.46E-7	5.44E-7	5.58E-7
	4.75-7.05	5.25E-7	5.20E-7	5.08E-7	4.61E-7	4.59E-7	4.42E-7
Ratio C/O		**0.940**	**0.944**	**0.992**	**1.184**	**1.186**	**1.262**
MCNP Multigroup (CPU ~4.5 h on a 677 MHz workstation)							
Det. 1	3.21-4.75	6.13E-6 ±1.0%	6.15E-6 ±1.0%	6.20E-6 ±1.0%	6.70E-6 ±1.0%	6.70E-6 ±1.0%	6.80E-6 ±1.0%
	4.75-7.05	6.00E-6 ±1.0%	6.01E-6 ±1.0%	5.77E-6 ±1.1%	5.54E-6 ±1.1%	5.53E-6 ±1.0%	5.39E-6 ±1.2%
Ratio C/O		**1.023** ±1.4%	**1.023** ±1.4%	**1.075** ±1.5%	**1.210** ±1.5%	**1.213** ±1.4%	**1.261** ±1.6%
Det. 2	3.21-4.75	4.56E-7 ±2.9%	4.53E-7 ±2.8%	4.65E-7 ±2.8%	5.03E-7 ±2.8%	5.03E-7 ±2.8%	5.09E-7 ±2.7%
	4.75-7.05	5.04E-7 ±2.8%	4.91E-7 ±2.8%	4.85E-7 ±2.9%	4.61E-7 ±3.0%	4.52E-7 ±3.0%	4.36E-7 ±3.2%
Ratio C/O		**0.904** ±4.0%	**0.924** ±4.0%	**0.957** ±4.0%	**1.089** ±4.1%	**1.114** ±4.1%	**1.169** ±4.2%
MCBEND Multigroup (CPU ~4 h on a 2 GHz PC)							
Det. 1	3.21-4.75	6.02E-6 ±1.2%	6.22E-6 ±1.2%	6.40E-6 ±1.1%	6.80E-6 ±1.0%	6.89E-6 ±1.0%	6.89E-6 ±1.0%
	4.75-7.05	6.12E-6 ±1.1%	6.09E-6 ±1.2%	5.98E-6 ±1.2%	5.55E-6 ±1.1%	5.54E-6 ±1.1%	5.43E-6 ±1.2%
Ratio C/O		**0.983** ±1.6%	**1.022** ±1.7%	**1.069** ±1.6%	**1.224** ±1.5%	**1.243** ±1.5%	**1.267** ±1.6%
Det. 2	3.21-4.75	4.81E-7 ±3.6%	4.90E-7 ±3.2%	4.78E-7 ±3.3%	5.05E-7 ±2.9%	5.23E-7 ±2.8%	5.37E-7 ±2.8%
	4.75-7.05	4.82E-7 ±3.2%	4.87E-7 ±3.2%	4.93E-7 ±3.2%	4.47E-7 ±3.8%	4.26E-7 ±3.3%	4.36E-7 ±3.3%
Ratio C/O		**0.999** ±4.8%	**1.007** ±4.5%	**0.969** ±4.6%	**1.131** ±4.8%	**1.230** ±4.3%	**1.233** ±4.3%

neutron histories for each case. This nearly coincides with the number of histories used in the MCBEND calculations, which were not set at a specific number, but were CPU-time limited. Small systematic differences may arise between the results of the different transport codes due to differences in atomic mass numbers used, or differences in abundances of isotopes of Si, Fe and Cl.

Table 3 compares the results of the DORT calculations performed using the chlorine cross-sections taken from different evaluated files, i.e. from ENDF/B-VI.3, ENDF/B-VI.8 (modified) and ENDF/B-VII (prerelease). Differences between the results using ENDF/B-VI.3 and /B-VI.8 are of the order of few %, and up to 5%. The results using ENDF/B-VI.8 and ENDF/B-VII are almost identical.

Table 3 Comparison of the DORT centered generic tool calculation using different chlorine evaluations for brine (19 % H_2O, 150 g NaCl)

Centered tool Inelastic + capture gammas		**SiO_2**			**$CaCO_3$**		
		ENDF/B-VI.3	**ENDF/B-VI.8rev.**	**ENDF/B-VII.prerel.**	**ENDF/B-VI.3**	**ENDF/B-VI.8rev.**	**ENDF/B-VII.prerel.**
	E (MeV)	Φ_γ	Φ_γ	Φ_γ	Φ_γ	Φ_γ	Φ_γ
DORT (r-z)							
Det. 1	3.21-4.75	1.68E-5	1.72E-5	1.72E-5	1.71E-5	1.74E-5	1.74E-5
	4.75-7.05	1.73E-5	1.73E-5	1.74E-5	1.66E-5	1.66E-5	1.66E-5
Ratio C/O		**0.969**	**0.993**	**0.992**	**1.028**	**1.050**	**1.049**
Det. 2	3.21-4.75	1.70E-6	1.79E-6	1.79E-6	1.66E-6	1.73E-6	1.73E-6
	4.75-7.05	1.90E-6	1.91E-6	1.91E-6	1.75E-6	1.76E-6	1.76E-6
Ratio C/O		**0.895**	**0.937**	**0.937**	**0.948**	**0.985**	**0.985**

9. FNS- Liquid Oxygen benchmark

The calculated carbon/oxygen ratios rely on a good knowledge on the oxygen and carbon cross-sections in particular. The recommended way to determine the quality and merit of the cross-sections data files, as well as of the calculational procedures is to test them against some well-defined benchmark experiments.

The Time-of-Flight Experiment on Liquid Oxygen Slab [12], performed at the JAERI/FNS facility, was found suitable for the validation of oxygen cross-sections for the purpose of the oil well logging applications. The experiment was performed at the 14 MeV D-T neutron source facility at the Fusion Neutronic Source (FNS) at JAERI. The angular neutron spectra leaking from a 20 cm slab of liquid oxygen were measured at the angles of 0, 12.2, 24.9, 41.8, and 66.8 degrees with respect to the source beam. The spectra in the energy range between 0.05 and 15 MeV were determined using the NE-213 scintillator. The cross-section sensitivity profiles of the typical oil well cases indicate that this neutron energy range is most relevant also for the oil well logging needs. The 14 MeV neutron source was used in the two cases.

The description of the FNS/JAERI Liquid Oxygen experiment is included in the SINBAD package [13] available from the OECD/NEA Data Bank and the RSICC. The compilation includes the calculational models for MCNP4C and DORT, as well as all the relevant reports in pdf format.

In order to determine the actual state of the art of nuclear data relevant for nuclear oil well logging, this benchmark was analyzed using the same code system as described before, i.e. the DORT code with the new cross-section library, as well as with the MCNP4C code and ENDF/B-VI.8 point-wise data. As shown on Fig. 3, good general agreement was found between the two calculations and the measured spectra. Both for DORT and MCNP the C/E values degrade with increasing angle, indicating possible problems in the description of the secondary angular distribution of the scattered neutrons.

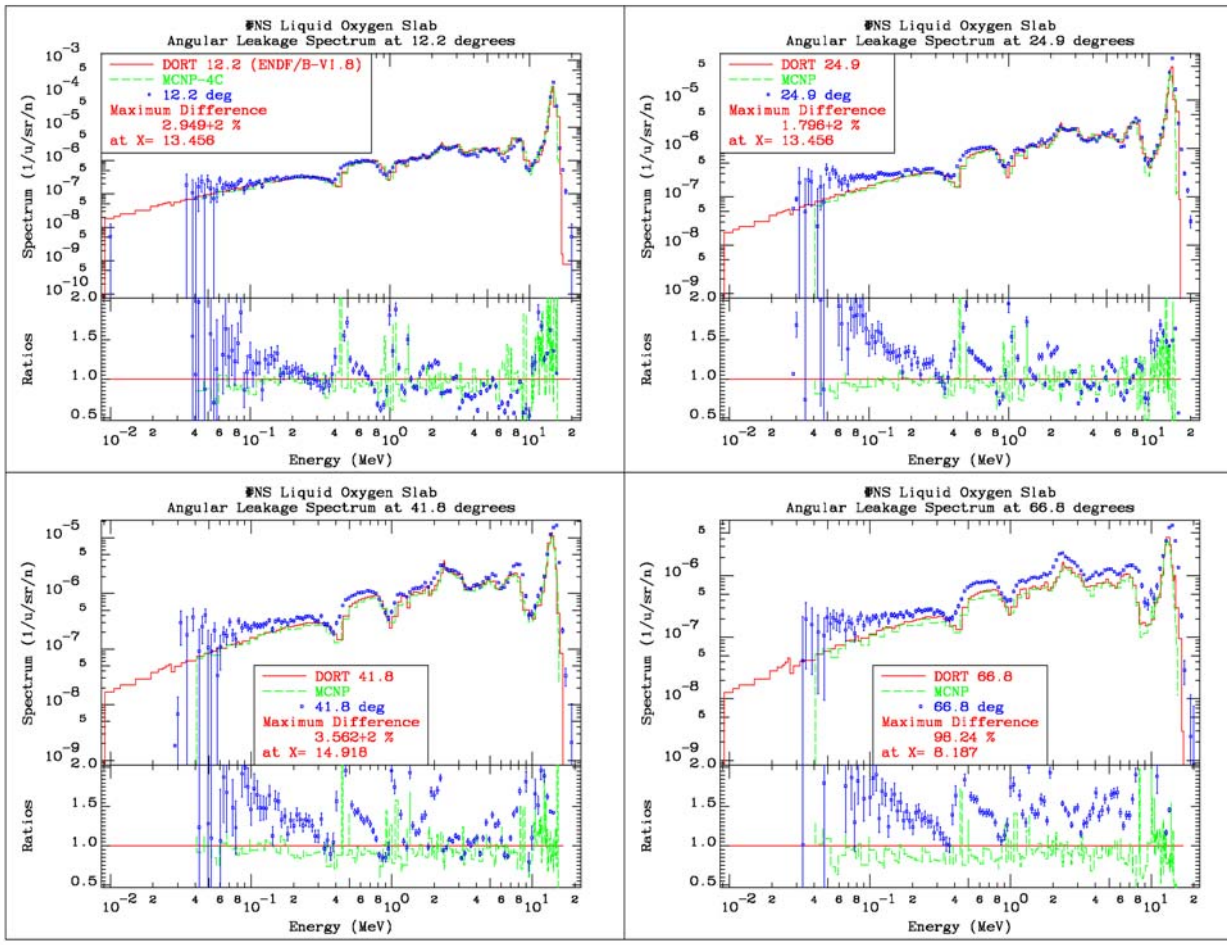

Fig. 3: Measured spectra from the FNS Liquid Oxygen Benchmark, compared to the calculated spectra obtained using the DORT and MCNP4C codes with multigroup and point-wise ENDF/B-VI.8 cross-sections, respectively.

10. Discussion and conclusions

A special-purpose multigroup cross-section library was derived from the latest ENDF/B-VI.8 evaluation. The energy group structure was selected in a way to take into account the requirements of the oil well logging applications. The library was used to compare the performances of the MCNP4C and DORT/TORT codes for the analysis of a typical oil well logging tool in the borehole with different formations and formation fluids.

The new library, in particular its oxygen cross-sections, was validated against the FNS/JAERI Liquid Oxygen Time-of-Flight benchmark experiment, demonstrating very good agreement with the measured neutron spectra.

A problem in the processing of the photon production data for ^{35}Cl was detected, which is of wider interest than this project. The results using the corrected ENDF/B-VI.8 file differ from those using the ENDF/B-VI.3 chlorine data by up to 5%, and are almost identical to those obtained using the chlorine from the pre-release of ENDF/B-VII.

Satisfactory agreement was found between corresponding cases treated with different transport codes.

The cross-section library will be available through the OECD/NEA Data Bank.

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