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# The activation system EASY-2007

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ABSTRACT

Safety and waste management of materials for ITER, IFMIF and future power plants require knowledge of the activation caused by irradiation with neutrons, or in the case of IFMIF, deuterons. The European Activation System has been developed for such calculations and a new version was released earlier this year. This contains a large amount of nuclear data in the European Activation File covering neutron-, deuteron- and proton-induced cross sections. These data are input to the FISPACT code for activation calculations. EASY-2007 is being validated using integral and differential measurements. However, only a minority of reactions have experimental support and a statistical method is described that can test the complete library. Importance diagrams are useful in finding the dominant nuclides formed following irradiation and the reactions responsible for their production. These diagrams now cover energies above 20 MeV and examples of new dominant nuclides and reactions relevant to IFMIF are given.



## 1. Introduction

Planning for the safety and waste management of materials for ITER, IFMIF and future power plants require detailed knowledge of the activation caused by irradiation with neutrons or charged particles. The European Activation System (EASY) has been developed for such calculations and a new version (EASY-2007) [1] was released earlier this year. This contains a large amount of nuclear data in the European Activation File (EAF-2007) covering neutron-, deuteron- and proton-induced cross sections (about 200 000 reactions have data extending up to 60 MeV), decay data (2231 nuclides) and subsidiary data for, e.g., biological hazards. These data are input to the FISPACT inventory code [2] used to calculate the activation.

The EAF library production and validation is carried out with the developer tool SAFEPAQ-II [3] and this has been extended so that deuteron- and proton-induced reactions can be handled. The validation and testing consists of comparison with cross sections measured at particular energies and activation measurements in well-defined neutron spectra. Both of these differential and integral comparisons require measurements and these are only available for a small minority of the reactions. Testing of the majority of the reactions is done by a statistical method termed SACS [4].

It has been determined that while a large number of reactions are required in a library for completeness (65 565 in the case of neutron-induced data for EAF-2007) only a small number of these are responsible for the activation properties. An efficient method of identifying these reactions involves importance diagrams [5].

## 2. EASY-2007

The current version, EASY-2007 contains the nuclear data EAF, the inventory code (FISPACT), the library development tool (SAFEPAQ-II) and documentation.

### 2.1. EAF-2007

EAF contains all the nuclear data required for activation calculations. Cross sections for neutron-, deuteron- and proton-induced reactions are available for energies up to 60 MeV. As well as the point-wise data various multi-group files are available for a range of applications. The neutron data [6] covers 65 565 reactions and for each of these uncertainty data are included with between two and four variance values. Decay data for all relevant nuclides (2231) and subsidiary data such as biological hazards complete EAF-2007.

### 2.2. FISPACT-2007

The activation code included in EASY is FISPACT [2]. This is a mature code which as well as standard inventory calculations is able to identify the pathways for the production of radionuclides and give uncertainties for quantities such as activity.

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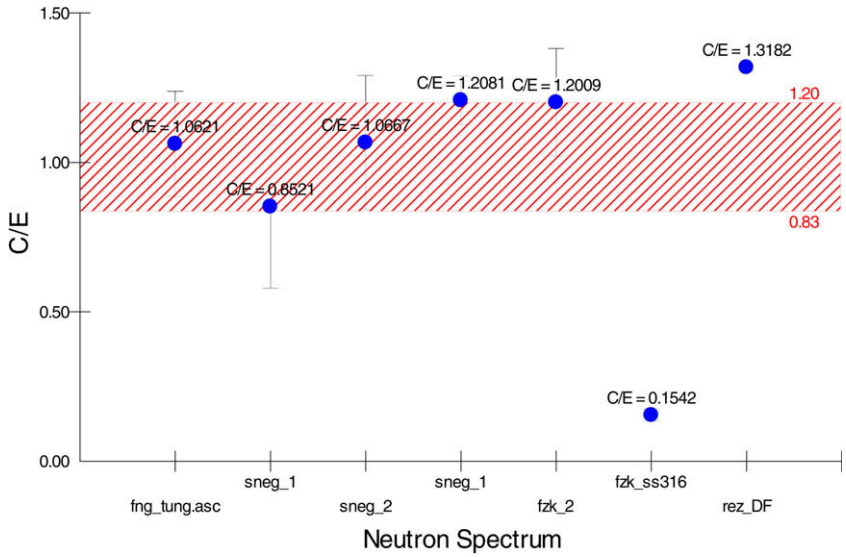


**Fig. 1.** *C*/*E* data for the $^{182}$W(n,p)$^{182}$Ta reaction, the band indicates the EAF-2007 uncertainty and the experimental uncertainties are shown by the error bars.

### 2.3. SAFEPAQ-II

EAF libraries are built using data from many data sources (in the case of the EAF-2007 neutron data more than 50) and it is necessary to be able to consistently merge and then modify these data for the final library. SAFEPAQ-II [3] has been developed for this objective; all data are held in relational databases so that selection and modification can be carried out efficiently. The visualisation options allow comparison of data from many sources with experiments and the validation and testing methods described below are all integrated into SAFEPAQ-II for ease of use.

## 3. Validation

Validation of an EAF library is an important task following library production. This is necessary to confirm that the data can be trusted and where discrepancies are found indicates where the data can be improved. Measurements have been made in fusion relevant neutron spectra and a wide range of materials have been studied. Many of these measurements are part of the European fusion technology programme, although other measurements made worldwide have also been used as available. Validation reports have been produced for several EAF libraries; with the number of reactions studied increasing for each version. The report for EAF-2001 covered 65 reactions, for EAF-2003 287 reactions and for EAF-2005 [7] 448 reactions. Currently the report for EAF-2007 is being produced. The activities of a set of radionuclides are measured ($E$) and compared with calculated activities ($C$) using the EAF data. The results can be presented as C/E for each nuclide but the value of the comparison is enhanced if the results are shown as $C/E$ values for the effective cross section of the reaction responsible for the production of the nuclide. This is done using the pathways calculated using FISPACT and although trivial for a single production pathway the method can be extended for parallel pathways. Fig. 1 shows preliminary data for the $^{182}$W(n,p)$^{182}$Ta reaction, the error bars for the first five points overlap the error band, while for the final point the stated experimental error may be unphysically small. In conjunction with the integral data the available differential data are also compared to the EAF data and only when there is adequate agreement with both types of experiments is the reaction 'validated'. Note that at present no reactions have integral and differential data covering the entire energy range so even for validated reactions further measurements at higher energies are very desirable.

## 4. SACS

A large data file like the neutron-induced cross sections in EAF-2007 covers many reactions. However, only a small minority (~1700) are supported by any experimental measurements. A method of testing the data that does not rely on measurements is required. The statistical analysis of cross sections (SACS) method [4] has been developed to address this need. It considers various statistics such as the maximum cross section ($\sigma_{max}$), the energy at which the maximum occurs ($E_{max}$) and the width of the curve at half maximum ($\Delta_{½}$) and plots these against the mass number ($A$) or asymmetry ($s = (N - Z)/A$) of the target as a scatter plot. Good correlations are usually seen and points significantly deviating from the trend line represent reactions whose data should be investigated and improved. This process was used extensively to improve the first EAF data file extending above 20 MeV (EAF-2005 [8]) to produce EAF-2007. Fig. 2 shows data for $\sigma_{max}(s)$ of the (n,n′α) reactions in EAF-2007, a trend line to guide the eye has been added and the points for the $^{57}$Ni and $^{58}$Ni targets are distinguished as (red[1]) triangles. Overall there is a reasonably small spread about the trend although the two Ni targets are discrepant and on different sides of the trend line. These reactions need to be investigated further.

## 5. Importance diagrams

Importance diagrams answer two needs of activation calculations; firstly investigation of any device typically involves many runs each of which produces large numbers of results, and a pictorial 'summary' of this would be useful. Secondly importance diagrams allow the important nuclides and reactions to be identified and it therefore possible to focus on just a few of the many reactions in a library such as EAF-2007 for improvement. Fig. 3 shows the activity diagram for cobalt calculated with EAF-2007. A difference from previously published diagrams [5,9] is that the diagram now includes

[1] For interpretation of colour in Fig. 2, the reader is referred to the web version of this article.

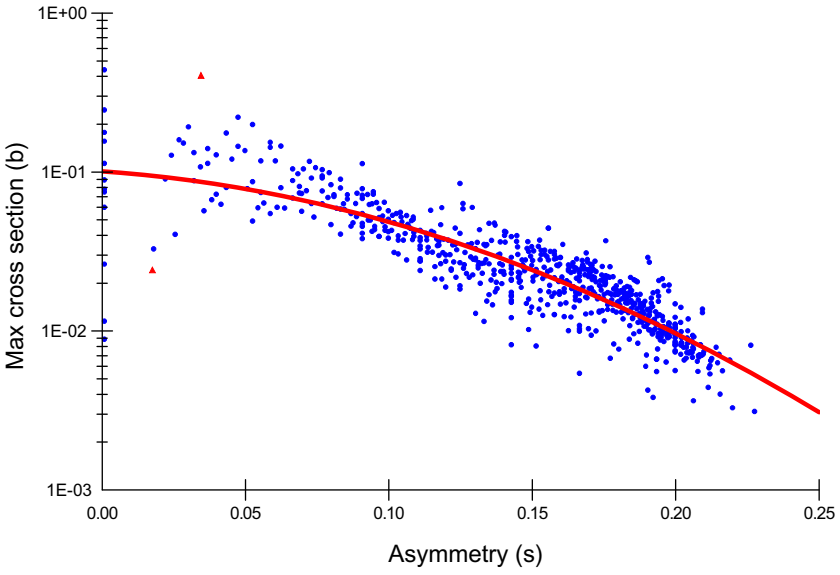


**Fig. 2.** $\sigma_{max}(s)$ for (n,n′α) reactions in EAF-2007 targets with $A < 20$ and $A > 84$ are excluded.

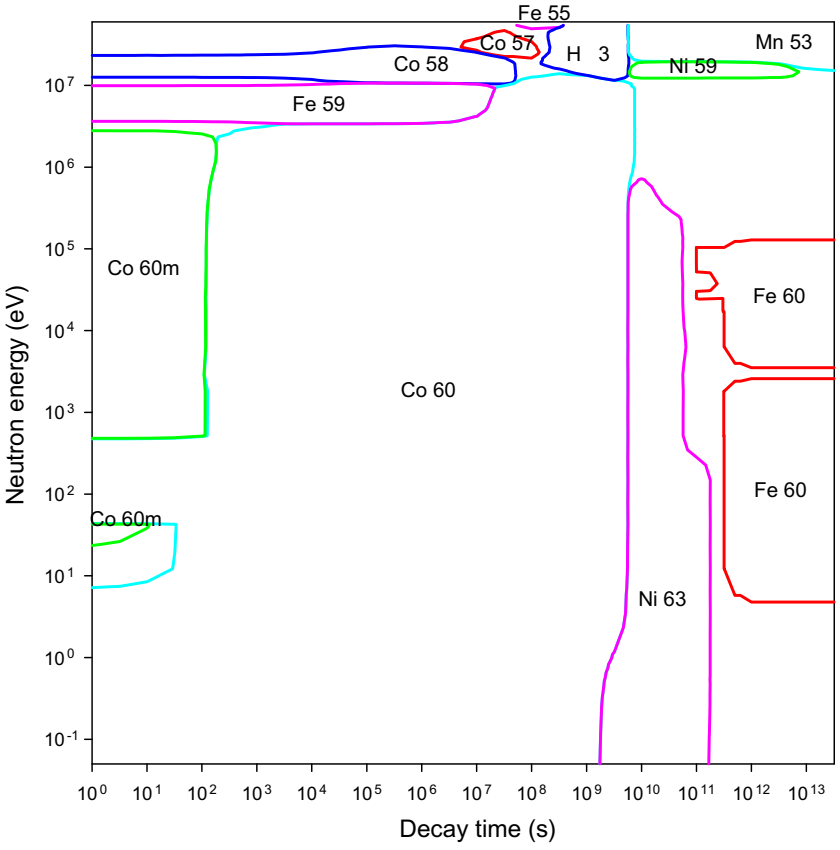


**Fig. 3.** Activity importance diagram for cobalt calculated with EASY-2007.

energies above 20 MeV, hence making the results relevant to IFMIF. Above 20 MeV there are two new nuclides for cobalt: $^{57}$Co and $^{55}$Fe, there are also some minor changes in the shape of the regions below 20 MeV compared to the one calculated with EASY-2003 [10] but the nuclides remain the same.

The main pathways for the production of $^{57}$Co at 14.7 MeV are $^{59}$Co(n,2n)$^{58}$Co(n,2n)$^{57}$Co (31.5%) and $^{59}$Co(n,2n)$^{58}$Co(IT)$^{58}$m-Co(n,2n)$^{57}$Co(67.6%), while at 50 MeV the production is almost exclusively by $^{59}$Co(n,3n)$^{57}$Co (99.7%). The (n,3n) reaction with a threshold of 19.35 MeV can only contribute at higher energies and is an example of a new important reaction.

The main pathway for the production of $^{55}$Fe at 14.7 MeV is $^{59}$Co(n,α)$^{56}$Co(β$^-$)$^{56}$Fe(n,2n)$^{55}$Fe (94.0%), while at 50 MeV it is mostly produced by $^{59}$Co(n,2nt)$^{55}$Fe (71.1%). The (n,2nt) reaction is an example of an 'exotic' reaction not present in earlier EAF libraries. The cross section in EAF-2007 for this reaction has no experimental support and is produced by model calculations.

The analysis of the importance diagrams for all the stable elements using EASY-2007 is underway, but it can already be seen that many new dominant nuclides occur above 20 MeV, for the elements H–Xe there are 15 new nuclides such as $^{7}$Be and $^{11}$C appearing on the importance diagrams while for the elements H–Co a total of 1042 reactions are needed in the pathways, each of which contributes at least 1% of the dominant nuclides. At the completion of this study general conclusions about the numbers of nuclides and reactions along with the data needs will be presented as was done for EASY-2003 in Refs. [11,12].

## 6. Conclusions

EASY-2007 is a complete code and data package for activation calculations. Details of its components are given and methods of validation and testing by means of integral data and SACS are described. The nuclear data library EAF-2007 contains data above 20 MeV and cross section data for neutron-, deuteron- and proton-induced reactions, hence making it relevant to both ITER and IFMIF calculations. Identifying the most important reactions is a major task so that scarce resources can be focussed on data improvement. Importance diagrams show the dominant nuclides and help in identifying the reactions that produce them.

## Acknowledgements

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