UK fusion technology experimental activities at the ASP 14 MeV neutron irradiation facility

L W Packer[a], M Gilbert[a], S Hughes[b], S Lilley[a], R Pampin[a], J-C Sublet[a]

[a]*EURATOM/CCFE Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, U.K.*
[b]*AWE Aldermaston, Reading, Berkshire, RG7 4PR, U.K.*

In support of the technological requirements for fusion, the UK fusion technology programme is conducting several experiments using the ASP DT neutron irradiation facility at AWE Aldermaston. The present experimental programme covers two key areas of technology development: improving the quality of nuclear cross-section data required for fusion-related materials; and benchmarking fusion nuclear analysis tools such as the shutdown activation dose system MC-R2S. The first of these areas is the focus of this paper.

The work presented here gives a technical overview of the ASP facility, including the accelerator, the irradiation cell, the recently re-commissioned fast sample extraction system and ancillary radiation metrology equipment. Results from preliminary activation experiments using high purity elemental- and fusion-relevant material foils, are presented. These include measurements of short-lived activation products conducted via gamma spectrometry methods.

Keywords: EAF, Nuclear Data, Activation

1. Introduction

One of the most important technology research areas for the development of fusion power is the study of material behavior under intense, high energy neutron irradiation. This is required for tokamak devices such as DEMO—a conceptual demonstration fusion power plant [1], but also for the ITER experimental fusion device. Within these devices it is important to know where neutrons are transported to and how they interact with and transmute the materials present. Since more than 10^{20} high energy neutrons per second are expected to be generated in these devices it is necessary to assess quantities such as neutron and photon flux, nuclear heating, neutron damage and activation via simulation over the range of materials used. These calculated quantities may then be used to iterate designs and support engineering decisions on, for example, cooling systems, or on the selection and placement of materials.

There are currently no facilities which can irradiate materials or components with the necessary intensity and spectrum, although some have been proposed, such as the International Fusion Materials Irradiation Facility (IFMIF) [2] or the Component Testing Facility (CTF) [3]. Until such facilities exist, high quality activation cross-section data obtained from experiments using existing neutron facilities or from nuclear interaction modelling codes, and used with the FISPACT inventory code, are crucial to the development of fusion nuclear technology. The completeness and accuracy of activation cross-section and decay nuclear data, such as those in the European Activation File nuclear data libraries [4-6], are fundamental to the assurance of the resulting calculation output. However, at the moment some of the underlying cross-section data have large uncertainties due to a lack of supporting experimental data; and in many cases data must be derived from nuclear interaction modelling codes, such as the European code TALYS [7].

Because of the importance of nuclear data to the development of future nuclear technologies, the UK fusion technology programme has recently initiated an experimental programme using the ASP DT neutron irradiation facility located at Aldermaston. This paper provides details of the ASP facility and the initial steps carried out towards the first aim of the programme: to improve the quality of nuclear cross-section data required for fusion-related materials.

2. Description of the ASP DT neutron irradiation facility

The ASP facility is based at AWE Aldermaston and provides the UK national measurement standard for DT neutrons around 14 MeV. A detailed description of the facility can be found in [8]. The ASP system operates at a 50 kV extract potential and can produce an ion current of up to 15 mA[1]. The ionised gas is deflected in a magnetic field which allows angular separation of the pure ion beam based on its radial trajectory. The ion beam then enters a solenoid focusing lens that precedes the main accelerating tube. A high voltage generator provides up to 300 kV of linear electric potential to the accelerating tube that consists of a series of alternate ceramic insulators and aluminium accelerating electrodes. Following the series of collimators, a focused beam of deuterons of about 1 cm diameter impacts the tritium-loaded target at the end of the drift tube. Several target attachments may be used at the facility allowing a range of neutron fluences. With fully-loaded tritium targets, a DT neutron output of up to 2.5 x 10^{11} s^{-1} is achievable. The resulting neutron emission from the target is essentially isotropic with a small energy-angular variation.

[1] Lower currents than this have been applied in this work in order to reduce charge-space effects, which can lead to beam defocusing.

author's email: lee.packer@ccfe.ac.uk

Neutron fluence measurements may be determined via the associated α-particle monitoring technique (AAPM). To achieve this, a drift tube with extension arms has been designed and can be attached to the high vacuum chamber. Neutron fluences can also be monitored via ^{238}U-based fission counters positioned either side of the target or via standard foil irradiations. The realisation of a neutron fluence standard is underpinned by the National Physical Laboratory in the UK who provide a periodic quality assurance check using ^{56}Fe(n,p)^{56}Mn and ^{27}Al(n,α)^{24}Na measurements via 4π beta/gamma coincidence counting as a transfer standard.

The ASP facility have recently re-commissioned a fast sample extract 'rabbit' system which has been used in this work to extract samples via a transfer capsule from the irradiation field to the measurement area, allowing for the measurement of radiation from short-lived reaction products. The current system is able to extract samples in about 4-6 seconds to the measurement area.

Figure 1 shows an image of the ASP facility irradiation cell. The sample positioning mount is shown along with the two fission counters, which are located either side of a target attachment.

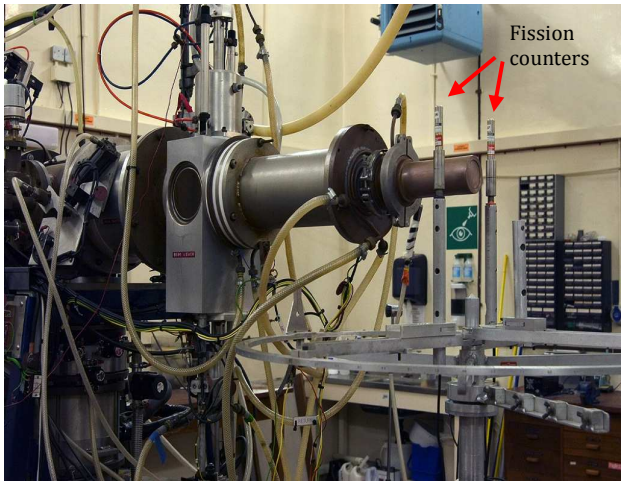

Fig. 1. ASP facility irradiation cell (kindly provided by AWE).

Some supporting radiation transport simulations have been carried out with an ASP facility model [9] using the MCNP5 code [10] and FENDL-2.1 nuclear data. This has been used to provide a simulated neutron spectrum for two irradiation positions of interest, as shown in Figure 2.

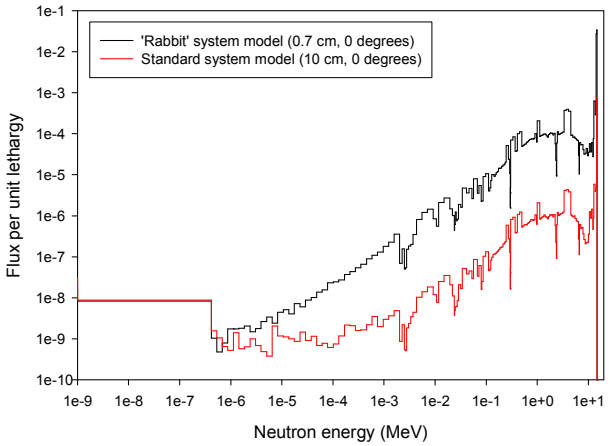

Fig. 2. Neutron spectra derived at two irradiation positions, calculated with an ASP facility model using MCNP5.

3. Current experimental activities

CCFE have recently conducted a number of irradiations for a range of elemental foils to test experimental procedures, to characterise the facility at the foil irradiation position, to improve knowledge of measurement feasibility, and to allow optimisation of the measurement technique. The initial work was carried out over a four day period using the re-commissioned 'rabbit' system described earlier. It focused on measuring short-lived reaction products for irradiated elemental foils.

Measurements of 54 activation experiments with 17 types of elemental foils were carried out at ASP using an 80% relative efficiency HPGe detector. Gamma spectra were acquired using two MCAs; a low- and high-gain amplification in 32 k channels allowing measurement of gamma energies of up to approximately 2 and 5 MeV, respectively. Spectra were sub-divided into time bins (5 or 20 second bins, for example) to allow identification of and/or separation of interfering gamma lines on the basis of half-life.

Table 1 shows a list of reaction products that were measured and some of the associated decay data that is relevant to the measurements. Measurement times were typically quite short: ~15 minutes in this campaign. A number of medium- and long-lived reaction products have been excluded from the current analysis, but could be conducted at a later date using low background environments and longer acquisition times. Integral cross-section values using the measurements taken during this testing and characterisation phase have not been published here, since further work is still required to fully characterise the neutron spectrum and fluence at the new irradiation positions. However, the measurement of integral cross-section data and their use in validation of the EAF nuclear libraries is one of the main aims of this programme and is expected to be included as part of future work.

Table 1. Foils and details of reaction products and associated gamma lines measured.

Principal reaction pathway	Principal gamma energy (eV)	γ intensity	Half-life (s)
$^{27}Al(n,\alpha)^{24}Na$	1.37E+06	0.9999	5.38E+04
$^{27}Al(n,p)^{27}Mg$	8.44E+05	0.718	5.67E+02
$^{46}Ti(n,p)^{46m}Sc$	1.43E+05	0.58	1.87E+01
$^{47}Ti(n,p)^{47}Sc$	1.59E+05	0.68	2.90E+05
$^{48}Ti(n,p)^{48}Sc$	9.84E+05	1	1.57E+05
$^{50}Ti(n,p)^{50}Sc$	1.55E+06	1	1.03E+02
$^{51}V(n,p)^{51}Ti$	3.20E+05	0.942	3.48E+02
$^{52}Cr(n,p)^{52}V$	1.43E+06	1	2.25E+02
$^{53}Cr(n,p)^{53}V$	1.01E+06	0.896	9.72E+01
$^{54}Cr(n,p)^{54}V$	8.35E+05	0.971	4.98E+01
$^{50}Cr(n,2n)^{49}Cr$	1.53E+05	0.309	2.51E+03
$^{52}Cr(n,2n)^{51}Cr$	3.20E+05	0.0987	2.39E+06
$^{56}Fe(n,p)^{56}Mn$	8.47E+05	0.988	9.30E+03
$^{62}Ni(n,p)^{62m}Co$	1.17E+06	0.979	8.35E+02
$^{65}Cu(n,2n)^{64}Cu$	1.35E+05	0.0046	4.57E+04
$^{64}Zn(n,2n)^{63}Zn$	6.70E+05	0.0848	2.30E+03
$^{64}Zn(n,p)^{64}Cu$	1.35E+05	0.0046	4.57E+04
$^{89}Y(n,\alpha)^{86m}Rb$	5.56E+05	0.982	6.10E+01
$^{89}Y(n,2n)^{88}Y$	1.84E+06	0.993	9.21E+06
$^{89}Y(n,n')^{89m}Y$	9.09E+05	0.992	1.57E+01
$^{90}Zr(n,\alpha)^{87m}Sr$	3.89E+05	0.819	1.01E+04
$^{94}Zr(n,\alpha)^{91}Sr$	1.02E+06	0.335	3.47E+04
$^{90}Zr(n,p)^{90m}Y$	2.03E+05	0.973	1.15E+04
$^{92}Zr(n,p)^{92}Y$	9.35E+05	0.139	1.27E+04
$^{94}Zr(n,p)^{94}Y$	9.19E+05	0.560	1.12E+03
$^{90}Zr(n,2n)^{89m}Zr$	5.88E+05	0.891	2.51E+02
$^{96}Zr(n,2n)^{95}Zr$	7.57E+05	0.544	5.53E+06
$^{90}Zr(n,x)^{89m}Y$	9.09E+05	0.992	1.57E+01
$^{93}Nb(n,\alpha)^{90m}Y$	2.03E+05	0.973	1.15E+04
$^{93}Nb(n,2n)^{92m}Nb$	9.34E+05	0.990	8.77E+05
$^{92}Mo(n,\alpha)^{89m}Zr$	5.88E+05	0.891	2.51E+02
$^{92}Mo(n,p)^{92m}Nb$	9.34E+05	0.990	8.77E+05
$^{97}Mo(n,p)^{97}Nb$	6.58E+05	0.982	4.33E+03
$^{92}Mo(n,2n)^{91m}Mo$	6.53E+05	0.482	6.46E+01
$^{186}W(n,2n)^{185m}W$	6.59E+04	0.054	1.00E+02
$^{187}Re(n,2n)^{186}Re$	1.37E+05	0.094	3.26E+05
$^{185}Re(n,p)^{185}W$	1.25E+05	0.0002	6.49E+06
$^{191}Ir(n,2n)^{190}Ir$	1.87E+05	0.489	1.04E+06
$^{191}Ir(n,2n)^{192n}Ir$	6.30E+04	0.349	1.11E+04
$^{193}Ir(n,2n)^{192}Ir$	3.17E+05	0.828	6.38E+06
$^{197}Au(n,2n)^{196}Au$	3.56E+05	0.870	5.34E+05
$^{197}Au(n,2n)^{196n}Au$	1.48E+05	0.425	3.46E+04
$^{197}Au(n,n')^{197m}Au$	2.79E+05	0.708	7.74E+00
$^{204}Pb(n,2n)^{203}Pb$	2.79E+05	0.808	1.87E+05
$^{204}Pb(n,2n)^{203m}Pb$	8.25E+05	0.714	6.29E+00
$^{208}Pb(n,p)^{208}Tl$	5.83E+05	0.851	1.83E+02

Approximately 400 post-processed data sets were derived from the experiments. While it is not possible to present all results in this paper, two examples are given here for selected gamma lines resulting from Zr and Au foil irradiation experiments.

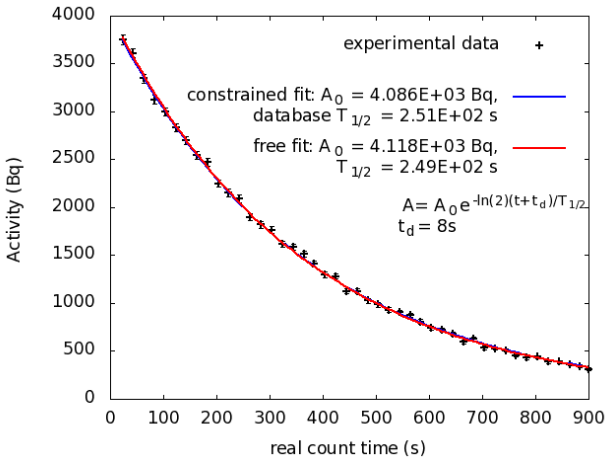

Fig. 3. Activity as a function of time for Zr-89m gamma line measurement at 587.8 keV for an irradiated Zr foil. Here and in later figures the constrained fit refers to a fit in which the half-life was fixed to the database value, while in the free fit both the half-life and A_0 were allowed to vary. t_d is the time delay associated with the time between the end of the irradiation and the start of the measurement.

3.1 Zr irradiation analysis

Data from the Zr foil irradiation (Zr001) is shown in Figure 3. The plot shows ^{89m}Zr activity as a function of time derived from the 587.8 keV gamma emission, produced via the $^{90}Zr(n,2n)^{89m}Zr$ reaction. The calculated half-life value from fitting parameters to the data of 248.7 ± 2.5 s and is consistent with the value of 250.8 s from the EAF-2010 decay data library.

Figure 4 shows data extracted from a different part of the gamma spectrum measurement of the same Zr foil. The count rate data has been extracted from the 909 keV line and has been background corrected. The short-lived contribution to this reaction is due to the direct reaction $^{90}Zr(n,x)^{89m}Y$, which is associated with deuteron or consecutive neutron and proton emission, see [11] It should be noted that the result in [11] is the only published measurement of this reaction that could be found in the literature. The contribution to the long-lived component shown in the figure is due to ^{89}Zr decay to ^{89m}Y. The $^{90}Zr(n,2n)^{89}Zr$ (ground state) reaction has some weak gamma lines which were not detected directly during this experiment, but the reaction can be inferred by the positron decay from ^{89}Zr to ^{89m}Y (branching ratio 99.87). The 909 keV line due to ^{89m}Y decay is in secular equilibrium with the ^{89}Zr decay. In the figure, the 16 s decay from ^{89m}Y and the longer lived decay via the ^{89}Zr parent have been separated on the basis on half-life using a double exponential fit. The fitting parameters are shown.

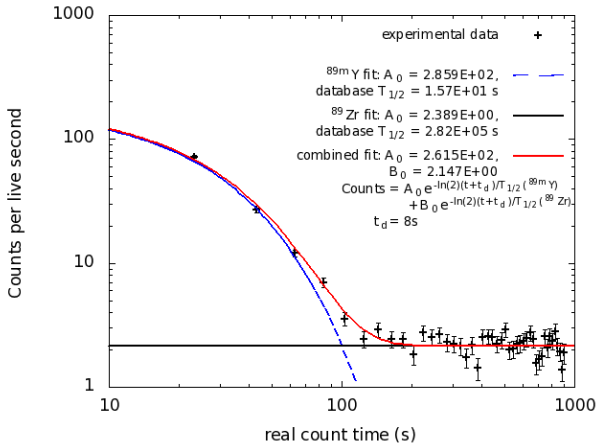

Fig. 4. Measured background corrected count rate as a function of time for the ^{89m}Y gamma line measurement at approximately 909 keV for an irradiated Zr foil.

To illustrate the importance of measurements such as those described here, the integral data C/E plot for ^{90}Zr(n,2n)^{89m}Zr measurements at other facilities is shown in Figure 5. C/E plots are used in conjunction with differential cross-section data as part of the evaluation and validation processes used to produce the EAF data libraries. The plots are generated using the SAFEPAQ-II tool [12]. The activity of a measured nuclide (E) is compared with a calculated value (C) using the library data. In SAFEPAQ-II the reaction producing the nuclide is identified and its average cross-section in the neutron spectrum is used as E. Similarly the library data are averaged in the neutron spectrum to form C. The experimental uncertainty of the measurement is shown by the error bar and the EAF-2010 library uncertainty by the error band. In this case, the two measurements were carried out at the Frascati Neutron Generator facility and the Fusion Neutron Source facility in Japan, respectively. However, only one of the measurement point's error bar overlaps with the EAF-2010 C/E uncertainty band and hence this reaction would benefit from additional integral cross-section measurements.

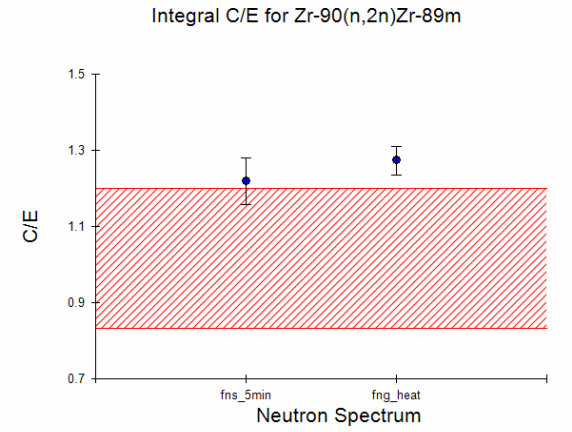

Fig. 5. C/E data for ^{90}Zr(n,2n)^{89m}Zr measured in the FNS and FNG neutron spectra. The band indicates the uncertainty in the library.

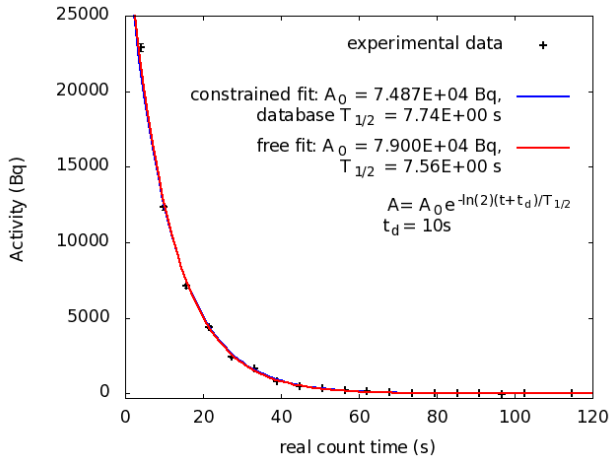

Fig. 6. Activity as a function of time for ^{197m}Au gamma line measurement at 278.99 keV for an irradiated Au foil.

3.2 Au irradiation analysis

Figure 6 shows activity data taken from a Au foil measurements (Au003). The gamma spectra data was stored in 5 second intervals and, as can be seen in the figure, it is possible to track the derived activity over time from the 278.99 keV gamma emission due to ^{197m}Au isomeric transition to the ground state. The measured half-life given by the free fit shown in the plot is 7.56 ± 0.25 s, which compares well to the EAF-2010 value of 7.74 s.

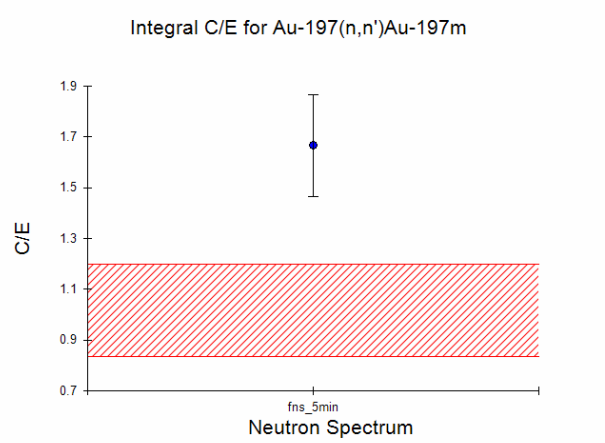

Fig. 7. C/E data for ^{197}Au(n,n')^{197m}Au measured in the FNS neutron spectra. The band indicates the uncertainty in the library.

Figure 7 shows the integral data C/E plot for the ^{197}Au(n,n')^{197m}Au reaction. One data point is shown and this was measured at the FNS facility. The experimental error bar lies outside the EAF-2010 C/E uncertainty band. Therefore this reaction would also benefit from further integral data measurements.

4. Future experimental work

The next stage of experimental work will aim to measure integral data for some of the reactions identified in this work. Characterisation of the neutron spectrum and fluence at the chosen irradiation positions using a

'sandwich' arrangement of foils are expected to be included. The sandwich will consist of the foil, chosen for the reaction measurement of interest, combined with a set of standard reference foils, which will typically include one or more of the following: Fe, Al, Nb, Zr or Si. Neutron spectrum characterisation is expected to be carried out using the Zr/Nb method detailed in [13] and with unfolding techniques using the MAXED and GRAVEL codes [14].

Following the preliminary experimental analysis in this work, a subset of reactions listed in Table 1 have been identified either as requiring additional integral cross-section measurements to support evaluations, or of sufficient interest in the preliminary experiments to merit future detailed experimental activities. These reactions are shown in Table 2.

Some additional reactions for consideration in future measurements can be found in [15, 16]. These references outline the needs for nuclear cross-section measurements from a validation perspective. However, the measurement feasibility of these additional reactions at the ASP facility still needs to be assessed.

Irradiations and gamma counting activities at ASP will be supported in the future with a recently developed in-house capability at CCFE, consisting of two HPGe detectors. It is expected to gain access to reaction channels leading to longer lived reaction products via long, low-background acquisitions using this capability.

Table 2: Reactions identified for future measurements at ASP

Reaction
$^{54}Cr(n,\alpha)^{51}Ti$
$^{59}Co(n,2n)^{58}Co$
$^{89}Y(n,\alpha)^{86m}Rb$
$^{92}Mo(n,2n)^{91m}Mo$
$^{197}Au(n,n')^{197m}Au$
$^{208}Pb(n,p)^{208}Tl$
$^{204}Pb(n,2n)^{203m}Pb$
$^{90}Zr(n,x)^{89m}Y$
$^{185}Re(n,p)^{185}W$
$^{52}Cr(n,2n)^{51}Cr$
$^{62}Ni(n,p)^{62m}Co$
$^{191}Ir(n,2n)^{192n}Ir$

5. Summary

In support of the technological requirements for fusion, the UK fusion technology programme is conducting several experiments using the ASP DT neutron irradiation facility at Aldermaston. The present experimental programme includes the aim to improve the quality of nuclear cross-section data required for fusion-related materials.

A number of irradiations of high purity elemental foils have been conducted to test experimental procedures, to characterise the facility at irradiation positions, to improve knowledge of measurement feasibility, and to allow optimisation of the measurement technique.

The paper described details of the range of reaction products that have been measured in these experiments and identifies some reactions which can serve as a focus for future experimental work at ASP.

Acknowledgments

The authors would like to thank Jason Hughes, Bernard Hynes and Gareth Davies from the ASP facility for their support with the experimental campaign; and Peter Kolkowski and Neil Roberts from the National Physical Laboratory for their helpful discussions in relation to radiation metrology.

This work was supported by United Kingdom Engineering and Sciences Research Council and the European Communities under the contract of Association between EURATOM and CCFE.

References

[1] D. Maisonnier, I. Cook, P. Sardain, et al., 'Final Report of the European Power Plant Conceptual Study' EFDA-RP-RE-50 (2005).

[2] J Molla et al., 'Overview of the main challenges for the engineering design of the test facilities system of IFMIF', Fus. Eng. Des. **84** (2009) 247–251.CTF

[3] G. M. Voss et al., 'Conceptual design of a component test facility based on the spherical tokamak', Fus. Eng. Des., **83** (2008) 1648.

[4] J-Ch Sublet, L W Packer, J Kopecky and R A Forrest 'The European Activation File: EAF-2010 neutron-induced cross-section library', CCFE-R (10) 05, 2010.

[5] L. W. Packer and J.-Ch. Sublet, 'The European Activation File: EAF-2010 decay data library', CCFE-R (10)02, 2010.

[6] L. W. Packer et al., 'Recent Progress in Neutron-, Proton- and Deuteron-induced Reaction Nuclear Data for EAF-2010 and the European Activation System' J. Kor. Phys. Soc., 59, July 2011.

[7] A. J. Koning, S. Hilaire, M.C. Duijvestijn, TALYS: comprehensive nuclear reaction modeling, in: Proceedings of ND2004, Santa Fe, USA, September 26–October 1, 2004, 2005, p. 1154.

[8] N. Bainbridge, 'ASP particle accelerator', Discovery Journal, Issue 9, August 2004.

[9] ASP facility MCNP model, Personal communication with J Pottage, 2010.

[10] X-5 Monte Carlo Team, "MCNP — A general Monte Carlo N-particle transport code, version 5", LANL report, LA-CP-03-0245, April 2003 (rev. March 2005).

[11] V. Semkova et al, Neutron activation cross sections for zirconium isotopes, Nucl. Phys A 832 (2010) 149-169.

[12] R. A. Forrest and L W Packer, *'SAFEPAQ-II User manual'*, **CCFE-RE (10) 05**, Issue 8, 2010.

[13] H. M. Agrawal, R. Pepelnik, Determination of the mean neutron energy using the Zr/Nb and the Ni method, Nucl. Instr. Meth. A 366 (1995) 349-353.

[14] M. Reginatto et al., MAXED/GRAVEL U_M_G version 3.3, PTB, March 2004.

[15] R. A. Forrest, Data requirements for neutron activation Part I: Cross sections, Fus. Eng. Des. 81 (2006) 2143-2156.

[16] R. A. Forrest et. al., Validation of EASY-2007 using integral measurements, UKAEA FUS 547 (2008).