This is the Accepted version of the article; the final Published version of the paper can be accessed in the journal:

Fusion Science and Technology, 60:2, 538-543. Print ISSN: 1536-1055 Online ISSN: 1943-7641

https://doi.org/10.13182/FST11-A12438

EVALUATION OF THE ELECTROFORMING TECHNIQUE FOR IFMIF-EVEDA BEAM DUMP MANUFACTURING

F. Arranz[1], B. Brañas[1], M. Busch[2], M. González[1], A. Muñoz[1], B. Szcepaniak[2], L. Castro[1], P. Galán[1], D. Iglesias[1], J. Lapeña[1], D. López[3,4], I. Rucandio[1], D. Plaza[1], M. García[3,4], B. Gómez.[1]

[1]*CIEMAT, Avda. Complutense,22, 28040 Madrid, Spain, fernando.arranz@ciemat.es*
[2]*Galvano-T. Raiffeisenstrasse,8. 51570 Windeck-Rosbach. Germany.*
[3]*Dpto. de Ingeniería Energética, ETSII-UNED, C/ Juan del Rosal 12, 28040 Madrid, Spain*
[4]*Instituto de Fusión Nuclear, UPM, C/ José Gutiérrez Abascal 2, 28006 Madrid, Spain*

Abstract

The IFMIF-EVEDA beam dump must be able to stop deuteron continuous and pulsed beams with energies up to 9 MeV. The maximum beam power is 1.12 MW corresponding to a beam current of 125 mA. The design is based on a copper cone 2500 mm long, 300 mm aperture diameter, 5-6.5 mm thickness, whose inner surface faces the beam. The cooling is provided by water flowing at high velocity along its outer surface.

Electroforming of copper on an aluminum mandrel has been considered the most suitable manufacturing technology. Nevertheless some issues must be addressed before the final decision is taken. The joint of the flange at the aperture and the possibility of manufacturing different parts subsequently joining them by electroforming is analyzed by carrying out tensile tests with specimens with and without joints.

Mechanical properties and chemical composition are studied. The radiological impact of the measured impurities due to their activation under the deuteron flux is also assessed.

The comparison of the properties obtained with the different manufacturing possibilities will allow choosing the most adequate one.

Keywords:

Electroforming, copper, manufacturing

1. INTRODUCTION

The IFMIF-EVEDA accelerator[1] will be a 9 MeV, 125 mA cw deuteron accelerator, identical to the low energy section of one of the IFMIF accelerators, thus including the ion source, the RFQ and the first module of a superconducting (sc) linac. As no target is foreseen for the accelerated beam, a beam dump is required to stop the beam exiting the accelerator during commissioning and accelerator tests. The maximum beam power will be 1.12 MW.

Design of the beam dump[2] has been done taking into account thermomechanical loads and radioprotection issues. Both factors considered simultaneously resulted in pure copper as the best performing material. The beam profile is best managed using an axisymmetrical geometry. Taking into account the available space a

conical surface 300 mm diameter in the aperture and 2500 mm long was chosen. Heat removal is performed with water flowing between inner cone and shroud (figure 1). Detailed FEM analyses have been performed[3] for singularities in the cooling channel (cone tip, water return and thermocouples).

Radioprotection studies[4] were performed to design a local shield based on water an iron such that the resulting dose values comply with the legal dose limits.

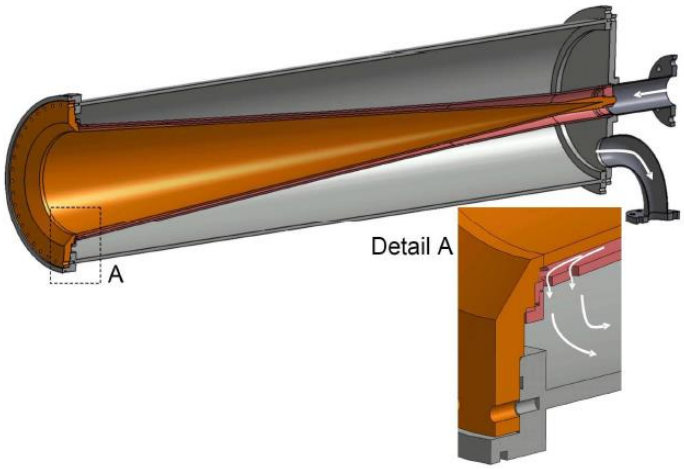

Fig. 1 Beam dump cartridge cross section.

As the inner cone is subjected to high heat fluxes (up to 250 W/cm^2) it is desirable to avoid joints. For this reason, and taking into account the geometrical characteristics of the piece, the electrodeposition technique has been chosen for its manufacturing. It is known that electroformed copper exhibits better yield strength, ultimate tensile strength and fatigue behaviour than pure annealed copper[5].

Although the flow shroud will probably be manufactured also by electrodeposition, currently efforts are concentrated in the manufacturing of the inner cone, as it is the most difficult to obtain due to the required geometrical tolerances. In order to define the most adequate manufacturing procedure, chemical composition of electrodeposited copper (bulk and surface) and mechanical behavior of electrodeposited joints have been studied.

2. FORESEEN MANUFACTURING PROCEDURE

Basically the production of the raw copper cone will be performed by electroforming a Cu layer about 8 mm thick in an electrolytic bath that will be identified for the purpose of this paper as “Normal bath”. The electrolyte in Normal bath is based on a solution of copper sulfate (30- 50 g/l) in sulfuric acid (20 %) containing a small part of organic ingredients to assure a small grain size of the Cu. This electroforming will be done on an aluminum core.

As sulfuric acid corrodes the aluminum, a protective layer must be applied on the aluminum core before introducing it in the Normal bath. Two options have been evaluated:

a) A layer of silver paint

b) A layer of 15-30 microns of Cu deposited in an electrolytic bath that will be identified for the purpose of this paper as “pH 8 bath”.

The electrolyte in the pH 8 bath is based on a phosphoric copper salt non corrosive for the Al core.

The foreseen manufacturing procedure consists of the following steps.

1) Producing an aluminum truncated cone that will be used as the mandrel or core.

2) Fitting a flange machined from laminated copper and a cylindrical piece with the conical tip volume empty, obtained previously by electrodeposition (Figure 2) on the aluminium truncated cone.

3) Coating the aluminum truncated cone either with silver paint or with a layer of 15-30 microns copper from pH 8 bath.

4) Electroforming the copper cone in the Normal bath on the aluminum core, obtaining at the same time the bonding of the aperture flange and the tip.

5) Machining of the outer surface of the cone in a lathe obtaining the desired thickness.

6) Removal or etching of the aluminum core subsequently cleaning and vacuum baking the resultant Cu cone.

With regard to the choice for step 3:

a) Use of a layer of silver paint has the advantage of allowing the removal of the Al core without damage, so that it can be used again. As a drawback some silver paint may remain attached to the copper surface. EDX-SEM analysis was performed on a test copper cone manufactured in this way. Silver was found on the surface in a percentage ranging from 0.4 % up to 3.12 %. Also SIMS analysis was performed showing a dramatic decay in silver content in the first 2.5 microns. Figure 3 shows the decay of ion counts. It has been checked that the silver remains do not contribute significantly to the dose rates during maintenance. In fact as Fig. 4 shows, doses from the activated pure silver would be more than two orders of magnitude lower than those coming from activated pure copper. The tools used and the details of the activation analysis performed are described in section 4. Although the interaction of the deuterons with Ag produces the long-lived Ag108m radionuclide, given the low silver content expected no problem is foreseen from the waste management point of view.

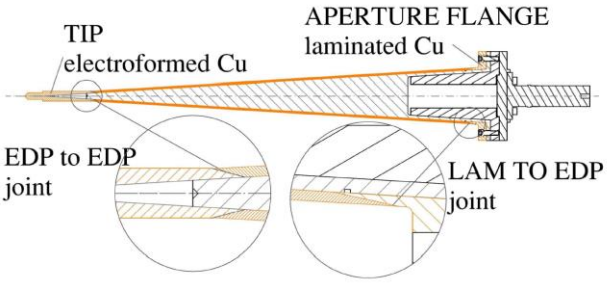

Fig. 2 Lay out for manufacturing a 1500mm

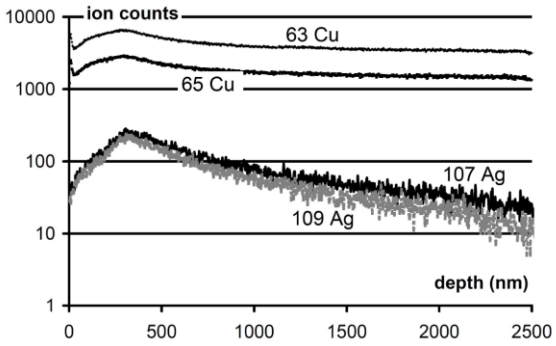

Fig. 3 SIMS data of silver and copper conten t.

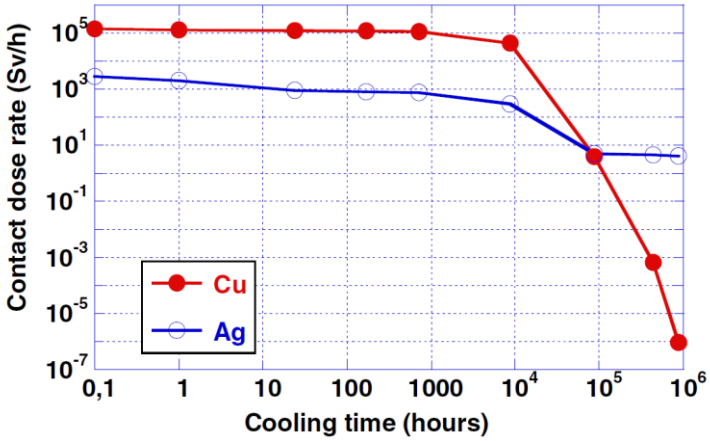

Fig. 4 Contact dose rates comparison between Cu and Ag for a semi-infinite slab as function of cooling time.

b) Use of a layer of pH 8 electrolyte (15-30 microns) has the advantage that no silver remains on the inner surface of the copper cone. Furthermore EDX-SEM analysis performed on a test copper cone manufactured in this way revealed the absence of aluminium remains and a slightly smoother surface (figure 5). As a drawback the aluminium mandrel must be etched using hydrochloric acid and therefore the mandrel is lost. A hollow aluminum mandrel should be used in order to reduce etching time to a reasonable value.

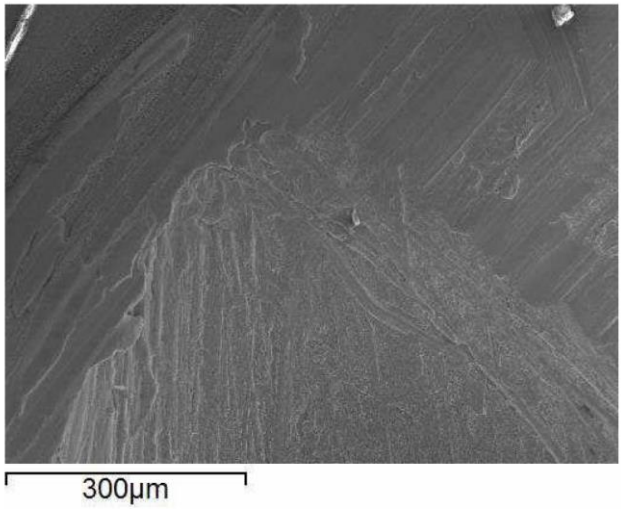

Fig. 5 SEM image of the inner cone tip obtained

3. TENSILE TESTS

Tensile tests were carried out to check the different types of joints obtained depending on the manufacturing procedure (step 3). If silver paint is used the joint at the aperture flange (figure 2) will be Laminated to Electrodeposited copper in Normal bath (LEN) and at the tip it will be Electrodeposited to Electrodeposited copper in Normal bath (EEN). If a layer of electrodeposited copper in pH8 bath is used, the joint at the aperture flange will be Laminated to Electrodeposited copper with pH 8 interlayer (LE8) and at the tip it will be Electrodeposited to Electrodeposited copper with pH 8 interlayer (EE8). Figure 6a shows a micrograph of an LE8 joint.

Tensile tests results of specimens with joints were compared with those of specimens Electrodeposited with No Joint (ENJ), which are representative of most of the cone wall obtained by electroforming on the aluminium mandrel.

In order to reproduce the procedure planned for the real beam dump as far as possible, the tensile test specimens were electroformed on aluminum tubes with an outer diameter of 6.35 mm. The tubes were electroformed in a horizontal position turning them 90 º once a day. After reaching the necessary wall thickness the aluminium was etched with hydrochloric acid and the outer surface got machined to the final geometry.

The geometry of the test specimens was the same for all types of joints with a contact surface machined to 15 º (see figure 6b). Test specimens with no joint have the same geometry but they were electrodeposited in one go. As a maximum temperature of 150 ºC is foreseen to be reached in some beam dump locations in case of misaligned beam, tests were carried out at this temperature as well as at room temperature.

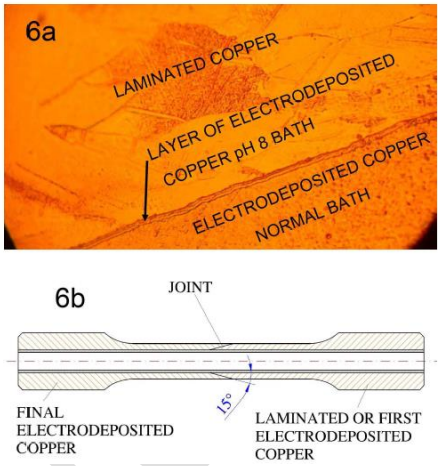

Fig. 6(a) Laminated to electrodeposited copper with an interlayer of pH8 copper joint. (b) Geometry of the test specimens.

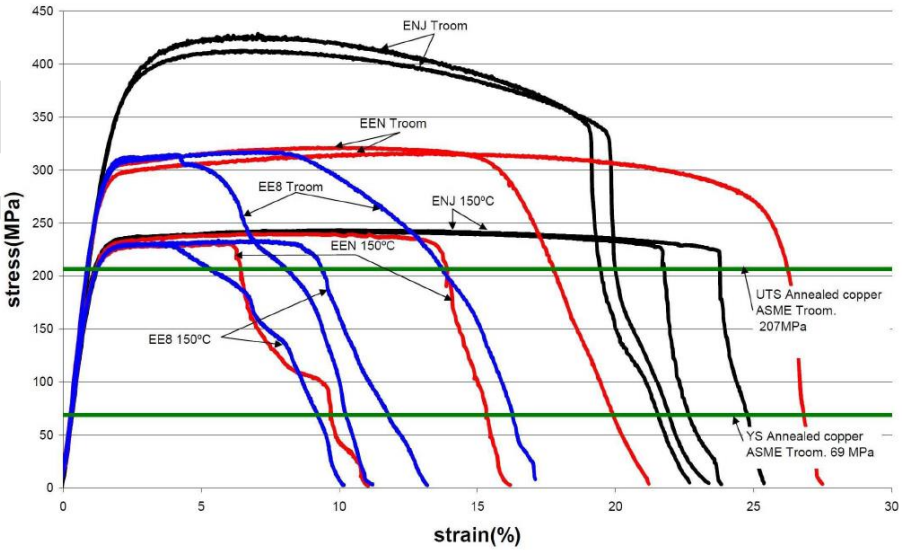

Fig. 7 Tensile tests results for ENJ, EEN and EE8 specimens.

Temperature was monitored with a thermocouple and speed during tests was 0.640 mm/min. Figure 7 shows the stress-strain curves for ENJ, EEN and EE8 specimens at room temperature as well as at 150 ºC. Results of the tests are summarized in Table I from which some observations can be obtained:

At room temperature the Yield strength (YS) and Ultimate tensile strength (UTS) are larger for Electrodeposited with no joint (ENJ) specimens than for the rest of the specimens with joint. No significant differences were observed between specimens with joint with or without pH8 layer.

At 150 ºC the values YS and UTS are quite similar for ENJ and the rest of specimens with joint. No significant differences were observed between specimens with joint.

Elastic behavior shows good reproducibility in all cases. Plastic behavior shows good reproducibility for ENJ specimens and quite a big dispersion in other specimens with joint.

Table 1 Tensile test results.

	T[ºC]	YS [MPa]	% from ref.[(a)]	UTS [MPa]	UTS [MPa] % from ref.[(a)]
ENJ	Room	309	0%	422	0%
LEN	Room	278	-10%	298	-29%
LE8	Room	278	-10%	320	-24%
EEN	Room	259	-16%	318	-25%
EE8	Room	262	-15%	316	-25%
ENJ	150	201	0%	242	0%
LEN	150	204	+1%	222	-8%
LE8	150	210	+5%	244	+1%
EEN	150	197	-2%	235	-3%
EE8	150	198	-1%	232	-4%

(a) Reference values are those of the Electrodeposited No Joint specimens (ENJ).

All tested specimens with joint except one broke at the joint zone. Figure 8 shows a typical fracture surface. It was sometimes possible to distinguish the inner circular edge of the joint.

Due to a defective machining of the inner surface, one specimen broke out of the joint zone (figure 9), this allows observation of tensile test effect on the joint. A zone in which fluence has taken place develops around the crevice originated at the joint.

Fig. 8 Typical fracture surface in the joint.

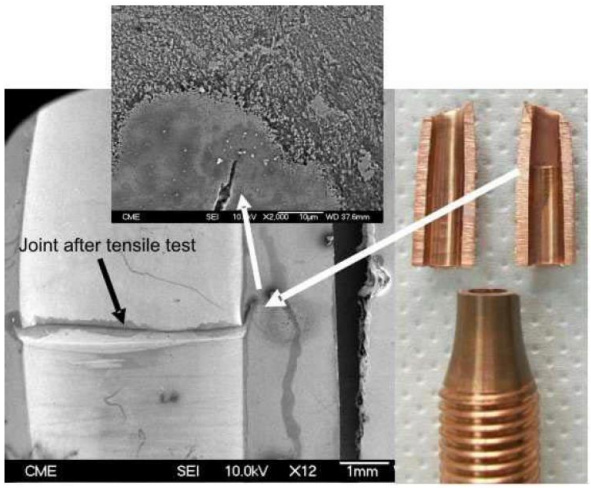

Fig. 9 Joint state after tensile test for the only specimen that broke out of the joint.

4. CHEMICAL ANALYSIS

From the point of view of radioprotection related issues, chemical composition of the beam dump material is essential, therefore impurities were looked for using different techniques. Elemental composition (Ag, Al, As, B, Ba, Be, Bi, C, Ca, Cd, Cl, Co, Cr, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sb, Se, Si, Sr, Ta, Te, Ti, V, Zn and Zr as impurities and Cu as major element) was determined by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) with Varian 735-ES and Jobin Yvon JY38+ spectrometers, and K and Na by Flame Emission Photometry in a Perkin Elmer 2280 spectrometer. Samples were treated for these analyses by obtaining carefully shavings. They were totally dissolved with concentrated nitric and hydrochloric acids and then diluted to the mark.

A LECO CS 244 elemental analyzer was used for C and S determinations in the shaving samples, by combustion in an induction furnace in the presence of oxygen gas and infrared detection of CO2 and SO2. X-ray fluorescence analysis in a PANalytical Axios spectrometer was used to confirm the results with samples prepared as solid discs polished with Al2O3 or SiC papers. Results of the measured impurities are summarized in table II.

Table 2Chemical impurities (ppm)

	EDP Normal bath[(a)]	EDP pH8[(b)]	Cu OFE[(c)]	Cu ETP[(d)]
Al	< 6	80	< 6	< 6
Ca	< 6	40	22	< 6
Cr	< 6	280	< 6	< 6
Fe	< 6	680	< 6	< 6
Mn	< 6	14	< 6	< 6
Ni	< 6	168	< 6	< 6
Pb	< 6	8.0	< 6	< 6
Cl	240	-	610	360

(a) EDP normal bath is the copper electrodeposited in the sulfuric acid bath. (b) EDP pH8 is the copper electrodeposited in pH 8 bath. (c) Cu OFE is copper Oxygen free electronic. (d) Cu ETP is copper Electrolytic-Tough-Pitch.

In all the cases Cu is very pure, higher than 99.8 %. Limits of quantification were 100 ppm for C and Na, 50 ppm for S and K and 6 ppm for the rest of the elements. EDP pH8 was electrodeposited in a bath with phosphoric salt, nevertheless no phosphorus was found above the quantification limit. However, this is the sample with the highest content of impurities. EDP normal bath was electrodeposited in sulfuric acid solution with organic ingredients to control the grain size nevertheless no sulphur or carbon was found above the quantification limit. Results for Fe show a low reproducibility, perhaps due to heterogeneity in the impurity distribution.

The analysis by different techniques is necessary for impurities determination. Massive analysis (disc or shaving) allow quantitative analysis in the global sample although certain elements could remain insoluble when digestion is required. In contrast, analysis by SEM is superficial and impurities coming from environment could be found.

A study has been made of the radiological behaviour of the beam dump real material including impurities. Given the high purity of the copper the neutron and gamma fluxes will not be affected by the impurities.

However it is important to check their contribution to radioprotection related issues. The radioactive inventory and derived response functions are calculated using the ACAB activation code6 using EAF-2007 nuclear data libraries[7]. Six months of continuous operation time at full current has been assumed. The deuteron flux considered ($1.7 \cdot 10^{15}$ deuterons/cm^2 per s) corresponds to the location of maximum power deposition into the cone. The results show that the majority of the activation is due to deuteron induced reactions while the activation caused by secondary neutrons is negligible.

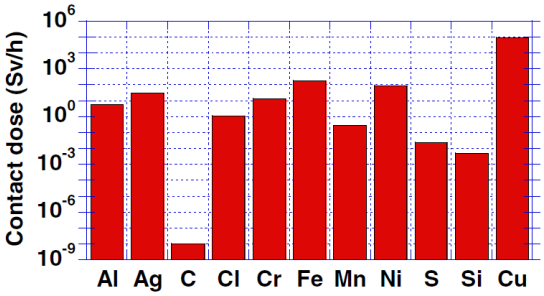

Fig. 10 Contribution to semi-infinite contact dose rates from pure Cu matrix and from impurities placed in a non-active Cu matrix (1 day cooling time)

To assess the effect of the impurities under the deuteron flux environment expected in the beam stop, firstly the contact dose rate from a semi-infinite slab made of pure copper has been calculated, and then, it has been compared with the dose rates associated to the activation in a non-active matrix of copper with its content taken from Table II, column 2. Figure 10 shows the results, stressing that impurities do not contribute significantly to contact dose rates. This figure shows also the small impact of silver using a conservative assumption of ~3% content in volume, equal to the maximum surface concentration measured in the tests (section 3). It has also been checked that impurities are not troublesome for waste management purposes. Although some of them like Si, Cl, Al and Ni produce long-lived radionuclides, given their small concentration and the fact that only a small layer of around 10 microns is activated by the deuteron beam, they do not represent a problem.

5. CONCLUSIONS

Manufacturing by electroforming is considered the best fitted technology to produce a slender piece as the beam dump internal cone, as it produces a continuous surface without induced thermal stresses.

The radiological impact of impurities has been assessed raising no concern regarding contact dose rates and waste management.

The good mechanical properties of the electroformed copper have been confirmed with the tensile tests.

Tensile tests have been performed to check the adequacy of the joints obtained by electroforming. Satisfactory results have been obtained with very good reproducibility in elastic behavior.

Some issues must be addressed and investigation is still ongoing particularly about the obtained geometry at the joint location and the manufacturing of the tip.

ACKNOWLEDGMENTS

This work has been partially supported by the Spanish ministry of Science and Innovation under project ENE2009-11230 and project ENE2008-06403-C06-02.

REFERENCES

1. B. BRAÑAS et al. "IFMIF-EVEDA accelerator: Beam Dump Design". Proceedings of the European Particle Accelerators Conference. Genoa. Italy. 2008. pp. 259-261.

2. B. BRAÑAS et al. "Design of a Beam Dump for the IFMIF EVEDA accelerator". Fusion Engineering and Design. 84 (2009). 509-513

3. M. PARRO et al. "Design and analysis of the IFMIFEVEDA Beam Dump cooling system". Preprint submitted to Elsevier. September 8, 2010

4. J. SANZ et al. "First IFMIF EVEDA radioprotection studies for the preliminary design of the accelerator

beam dump". Fusion Science and Technology (56), July 2009. pp. 273-280.

5. P. AGOSTINETTI et al. "Investigation of the Thermomechanical properties of electrodeposited copper for ITER". Preprint submitted to Journal of Nuclear Materials. August,2010.

6. J. SANZ et al. 'ACAB-2008: Activation Code V2008'. Nuclear Energy Agency, NEA Data Bank. NEA-1839, (2008).

7. R.A. FORREST et al. 'The European Activation File: EAF-2007 deuteron and proton-induced cross section libraries", UKAEA FUS 53(2007); 'The European Activation File: EAF-2007 neutron-induced cross section libraries', UKAEA FUS 535(2007); R.A. Forrest, "EAF-2007 decay data library" UKAEA FUS 537 (2007)