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ANITA-IEAF Intermediate Energy Neutron Activation Package: Updating and Validation of the Decay and Cross Section Data Libraries

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ANITA-IEAF INTERMEDIATE ENERGY NEUTRON ACTIVATION PACKAGE: UPDATING AND VALIDATION OF THE DECAY AND CROSS SECTION DATA LIBRARIES

Manuela Frisoni - ENEA

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ANITA-IEAF intermediate energy neutron activation package: updating and validation of the decay and cross section data libraries

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Sommario

ANITA-IEAF is an activation package (code and libraries) developed in the past in ENEA-Bologna in order to assess the activation of materials exposed to neutrons with energies greater than 20 MeV. It is suitable to be applied to the study of the irradiation effects on materials in facilities like the International Fusion Materials Irradiation Facility (IFMIF) and, more recently, the DEMO Oriented Neutron Source (DONES), in which a considerable amount of neutrons with energies above 20 MeV is produced. The original package contained: a) the activation code ANITA-IEAF, able to manage the large amount of reactions with threshold higher than 20 MeV and up to 150 MeV, b) the activation cross section library based on the Intermediate Energy Activation File IEAF-2001, c) the Decay, Hazard and Clearance data library (file fl1) containing the quantities describing the decay properties of unstable nuclides and d) the Gamma library (file fl2) containing the gamma ray spectra emitted by the radioactive nuclei. The ANITA-IEAF package has been recently updated. The data contained in the fl1 and fl2 files are actually based on the JEFF-3.1.1 Radioactive Decay Data Library. The updated code uses the EAF-2010 group-wise neutron activation cross section library "eaf_n_gxs_211_flt_20010" in the VITAMIN-J+ (211 energy groups structure) up to 55 MeV . In this report the validation effort related to the comparison between the code predictions and the activity measurements obtained from the Karlsruhe Isochronous Cyclotron is presented.

Note

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ANITA-IEAF intermediate energy neutron activation package: updating and validation of the decay and cross section data libraries

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June 2016

1 INTRODUCTION

The ANITA-IEAF activation code package (code and libraries) was developed in the past in ENEA-Bologna for the study of the activation characterization of materials exposed to neutrons with energies up to 150 MeV [1], [2]. It was an extension of the ANITA-2000 code, developed by ENEA and freely distributed at OECD-NEADB [3] and ORNL-RSICC [4], which is able to handle neutron energies up to 20 MeV. The ANITA-IEAF package is needed in order to perform neutron activation calculations for some plants as the International Fusion Materials Irradiation Facility (IFMIF) and, more recently, the DEMO Oriented Neutron Source (DONES), that have been proposed as neutron sources to test samples of candidate materials to be used in future fusion power plants. In both these facilities the neutron source is produced through the reaction of 40 MeV deuterons impinging on a liquid lithium target and a considerable amount of neutrons with energies above 20 MeV is produced. The availability of reliable nuclear data and activation codes in the neutron energy range extended over 20 MeV is required in order to perform activation calculations for these devices.

The original ANITA-IEAF package contained: a) the activation code ANITA-IEAF, able to manage the large amount of reactions with threshold higher than 20 MeV and up to 150 MeV, b) the activation cross section library based on the Intermediate Energy Activation File IEAF-2001 [5] c) the Decay, Hazard and Clearance data library (file fl1) containing the quantities describing the decay properties of unstable nuclides and d) the Gamma library (file fl2) containing the gamma ray spectra emitted by the radioactive nuclei. The data contained in the fl1 and fl2 files were based on the evaluated nuclear data library FENDL/D-2.0.

Recently, an updated version of the ANITA-IEAF activation code package, able to use the most recent nuclear evaluated libraries, has been developed. The data contained in the fl1 and fl2 files are based on the JEFF-3.1.1 Radioactive Decay Data Library [6].

The original ANITA-IEAF activation code used a 256 neutron energy group structure up to 150 MeV. The updated code uses the EAF-2010 [7] group-wise neutron activation cross section library "eaf_n_gxs_211_flt_20010" in the VITAMIN-J+ (211 energy groups structure) up to 55 MeV,contained in the EASY-2010 code package [8].

In this report the validation effort related to the comparison between the code predictions and the activity measurements obtained from the Karlsruhe Isochronous Cyclotron is presented.

2 ANITA-IEAF ACTIVATION CODE

The package ANITA-IEAF includes the activation code ANITA-IEAF that computes the radioactive inventory of a material exposed to neutron irradiation, continuous or stepwise. The ANITA-IEAF code provides activity, atomic density, decay heat, biological hazard, clearance index and decay gamma-ray source spectra at shutdown and at different cooling times. Results are given as for each nuclide as for the material. The code traces back to the ANITA code (Analysis of Neutron Induced Transmutation and Activation) [9]. It treats all the elements with the atomic number up to 94.

The ANITA-IEAF activation code requires the following data libraries:

- Decay, Hazard and Clearance data library (file “fl1”)
- Gamma library (file “fl2”)
- Neutron activation cross section data library (file “lib211”)

The schematic block diagram of the data/libraries required by the ANITA-IEAF code is shown in Figure 1.

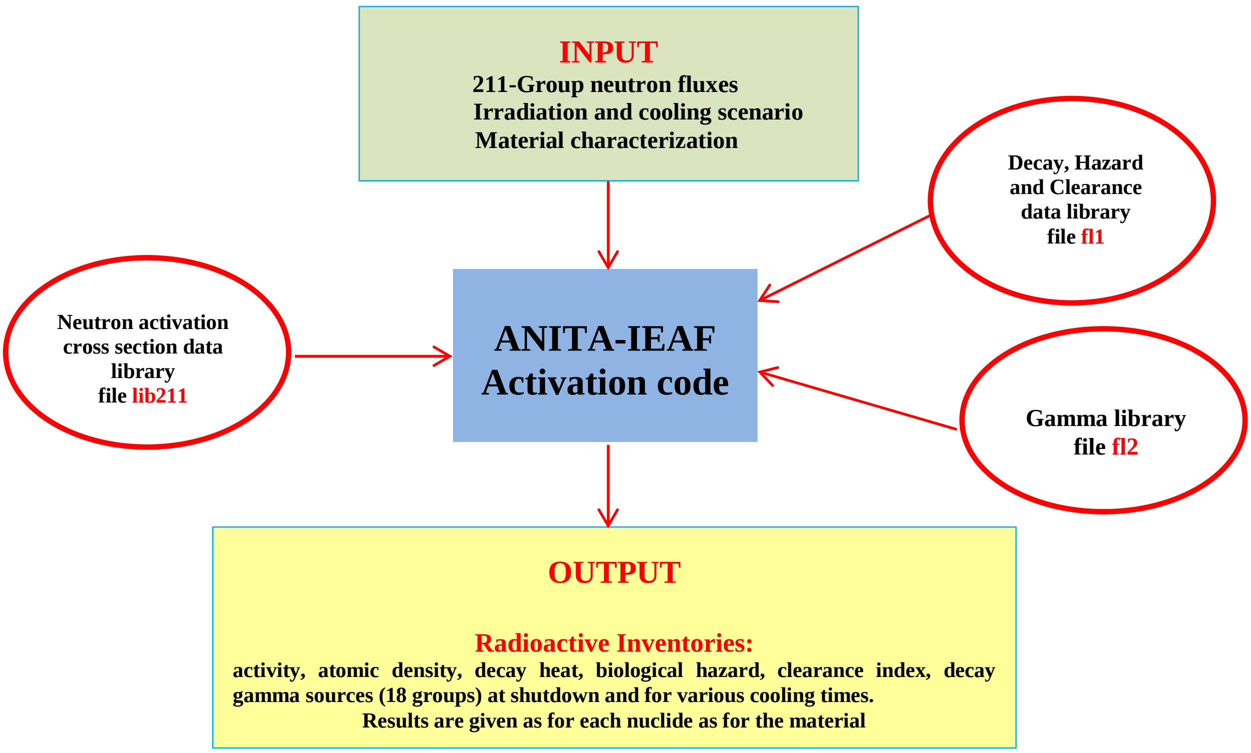

Figure 1 – ANITA-IEAF activation code block diagram

2.1 Decay, Hazard and Clearance Data library (file "fl1")

This library contains the information describing the decay properties of unstable nuclides useful for the calculations performed by ANITA-IEAF.

For each nuclide, the decay data, as the decay mode, the decay constant (s^{-1}), the total energy (MeV) released in the decay and the energy (MeV) released in the form of gamma or X-rays are provided. Different competitive decay modes are taken into account when contemporary.

The file contains also the hazard data (ALI) for each radionuclide describing its potential biological impact on human beings. The ALI quantities are defined as the Annual Limit of Intake (Bq) by ingestion or inhalation for the public or workers.

The library contains also the clearance level for each radionuclide.

The fl1 file contains data for 3433 nuclides. The description of the data contained in the file and their sources are described in the following.

2.1.1 Decay data

The decay data have been taken from the JEFF-3.1.1 Radioactive Decay Data library [6]. The standard library JEFF-3.1.1 is in ENDF-6 [10] format. The radioactive decay data are given in the section identified by MF=8, MT=457 (in ENDF-6 standard format notation). This section is restricted to single nuclides in their ground state or an isomeric state (a "long lived" excited state of the nucleus). The main purpose of MT=457 is to describe the energy spectra resulting from radioactive decay and give average parameters useful for applications such as decay heat and waste disposal studies, shielding, etc. For each isotope the following decay data are given: nuclide identification, half-life, number of decay modes, fractions of decay in each decay mode (branching ratio), energy released by the decay, gamma-ray intensity and energy spectrum in each decay mode. The standard library contains data for 3853 nuclei, ranging from the neutron (0-nn-1) to roentgenium 272 (111-Rg-272).

In the fl1 file used by ANITA-4M code the following basic decay data are included for each unstable nuclide:

- nuclide identification
- decay mode
- decay constant
- total energy released in the decay (MeV) used to calculate decay heat
- energy released in the form of gamma or X-rays (MeV)

For the stable nuclides the isotopic abundances from Ref. [11] are given.
The new fl1 file contains data for the nuclei ranging from 1-H-1 to 94-Pu-247.

2.1.2 Hazard data

The ALI quantities were obtained from the “eaf_haz_20100” file contained in the EASY-2010 code package [12]. In the fl1 file used by the ANITA- IEAF code, the ALI values by ingestion for the public are given. A conversion factor of 0.001 (Sv/y) has been adopted to convert the dose coefficients from [12] to the ALI quantities. The ALI quantity is provided only for the 2006 nuclides contained in the “eaf_haz_20100” file.

2.1.3 Clearance level data

The fl1 file provides also for each radionuclide the clearance level C_L (Bq/g). This value allows to establish if a radioactive material can be potentially moved out of the originating facility and recycled.

The safe handling of radioactive waste is recognized as crucial to ensure protection of human health and the environment. IAEA publish regulations on these issues and Ref. [13] gives information on suggested clearance level values for a set of important radionuclides.

The clearance level data contained in the new fl1 file have been produced by including the information contained in [13].The clearance levels for the 242 nuclides up to Pu-244 contained in Table 2 of Ref. [13] were included in the file fl1. The clearance level C_L=10 has been attributed to ^{40}K as suggested in Table 1 of Ref. [13].

Following the suggestion of Table 1 of Ref. [13], moreover, the clearance level C_L=1 has been attributed to radionuclides of natural origin. The list of the “Radioactive Nuclides in Nature” has been taken from Ref. [11].

For any other nuclide the clearance level was calculated by using the following Eq. (6) taken from Ref. [14]:

$$C_L = \min \{1/(E_\gamma + 0.1 \times E_\beta) \; ; \; ALI_{inhaled}/10^3 \; ; \; ALI_{ingested}/10^5\} \quad (6)$$

The values of E_γ and E_β in Eq. (6) have been taken from the JEFF-3.1.1 library [6].

The ALI quantities in Eq. (6) have been obtained from the “eaf_haz_20100” file of EASY-2010 [12]. The conversion factor of 0.020 (Sv/y) has been adopted to convert the dose coefficients from Ref. [12] to the ALI quantities.

2.1.4 Nuclide and Material Clearance Indexes

The Isotope Clearance Index (ICI) of a single nuclide is calculated in ANITA-IEAF as:

$$Isotope \quad Clearance \quad Index = \frac{C_i}{C_{Li}} \quad (7)$$

where C_i is the specific activity of the radionuclide "i" in the material and C_{Li} is the clearance level for that radionuclide.

In Eq. (7) activities and clearance levels have units of Bq g^{-1}.

When a material contains several nuclides, the equation given below, and suggested in [14], is used to evaluate in ANITA-IEAF the Material Clearance Index (MCI) :

$$Material \quad Clearance \quad Index = \sum_{i=1}^{n} \frac{C_i}{C_{Li}} \tag{8}$$

If MCI $\leq$ 1 then it is possible to clear the material.

2.2 Gamma Library (file "fl2")

This data base contains the gamma ray spectra emitted by the radioactive nuclei in the Vitamin-J 42-γ energy group structure given in Table 1.

Energy Group N.	Upper Boundary [eV]
1	5.00E+07
2	3.00E+07
3	2.00E+07
4	1.40E+07
5	1.20E+07
6	1.00E+07
7	8.00E+06
8	7.50E+06
9	7.00E+06
10	6.50E+06
11	6.00E+06
12	5.50E+06
13	5.00E+06
14	4.50E+06
15	4.00E+06
16	3.50E+06
17	3.00E+06
18	2.50E+06
19	2.00E+06
20	1.66E+06
21	1.50E+06
22	1.34E+06
23	1.33E+06
24	1.00E+06
25	8.00E+05
26	7.00E+05
27	6.00E+05
28	5.12E+05
29	5.10E+05
30	4.50E+05
31	4.00E+05
32	3.00E+05
33	2.00E+05
34	1.50E+05
35	1.00E+05
36	7.50E+04
37	7.00E+04
38	6.00E+04
39	4.50E+04
40	3.00E+04
41	2.00E+04
42	1.00E+04

Table 1 – Upper boundaries of the Vitamin-J 42-γ energy group structure

The data contained in the library are based on the JEFF-3.1.1 evaluated decay data file (gamma radiation spectra). In the gamma library of ANITA-IEAF in each group the contribution in MeV of the total γ energy emitted is given. The gamma spectra include both the γ-rays spectra and the x-rays and annihilation radiation spectra (photons not arising as transitions between nuclear states) (STYP=0 and STYP=9 in the ENDF-6 standard format). In the library, four cards are given for each nuclide: the first one contains the identification number IDNUC (Z*10000+A*10+M), the alphanumeric symbol and the total energy E_γ calculated as the sum over the 42-group values.

The data given in the gamma library are used in ANITA-IEAF to compute the intensity and the energy distribution of the gamma-rays emitted by the irradiated composition. This gamma-ray source (Photons/cm^3 s) in the VITAMIN-J 42-γ energy group structure (see Table 1) may be given as input to a radiation transport code to compute the space and energy distribution of the decay gamma-rays and the relative dose equivalent rate.

2.3 Neutron activation cross section data library (file “lib211”)

As shown in Figure 1 the updated version of ANITA-IEAF code requires a neutron activation cross section data library, defined as “lib1211” in binary format, in order to perform the activation calculations.

Actually, the ANITA-IEAF code performs activation calculations by using the 211-energy groups neutron-induced cross section library contained in the package EASY-2010, named “eaf_n_gxs_211_flt_20010”. This library is in card image format.

The VITAMIN-J+ (211 energy groups structure) of the EAF-2010 group-wise neutron activation up to 55 MeV is listed in Table 2.

In the updated ANITA-IEAF code new MT numbers have been introduced, from 151 to 200, the same as in FISPACT code [15], that allow describing reactions with up to 8 emitted particles corresponding to a set of unallocated numbers in the standard ENDF-6 format.

In Table 3 the 85 MT values used in the ANITA-IEAF code package are shown. In the Table, in column 3, for each MT, the corresponding reaction label that describes the neutron reaction is given. Each reaction corresponds to a well-defined ZA (ZA=Z*1000+A) difference with respect to the target nuclide and this ZA is used in the activation code to create and follow the decay chains.

The MODBIN module must be used for the conversion of the card image file to lib211 in binary format as required by ANITA-IEAF code.

Table 2 – Upper boundaries of the Vitamin-J +(211-neutron energy group structure)

Energy Group N.	Upper Boundary [eV]
1	5.5000E+07
2	5.4000E+07
3	5.3000E+07
4	5.2000E+07
5	5.1000E+07
6	5.0000E+07
7	4.9000E+07
8	4.8000E+07
9	4.7000E+07
10	4.6000E+07
11	4.5000E+07
12	4.4000E+07
13	4.3000E+07
14	4.2000E+07
15	4.1000E+07
16	4.0000E+07
17	3.9000E+07
18	3.8000E+07
19	3.7000E+07
20	3.6000E+07
21	3.5000E+07
22	3.4000E+07
23	3.3000E+07
24	3.2000E+07
25	3.1000E+07
26	3.0000E+07
27	2.9000E+07
28	2.8000E+07
29	2.7000E+07
30	2.6000E+07
31	2.5000E+07
32	2.4000E+07
33	2.3000E+07
34	2.2000E+07
35	2.1000E+07
36	2.0000E+07
37	1.9640E+07
38	1.7333E+07
39	1.6905E+07
40	1.6487E+07
41	1.5683E+07
42	1.4918E+07
43	1.4550E+07
44	1.4191E+07
45	1.3840E+07
46	1.3499E+07
47	1.2840E+07
48	1.2523E+07
49	1.2214E+07
50	1.1618E+07
51	1.1052E+07
52	1.0513E+07
53	1.0000E+07
54	9.5123E+06

Energy Group N.	Upper Boundary [eV]
55	9.0484E+06
56	8.6071E+06
57	8.1873E+06
58	7.7880E+06
59	7.4082E+06
60	7.0469E+06
61	6.7032E+06
62	6.5924E+06
63	6.3763E+06
64	6.0653E+06
65	5.7695E+06
66	5.4881E+06
67	5.2205E+06
68	4.9659E+06
69	4.7237E+06
70	4.4933E+06
71	4.0657E+06
72	3.6788E+06
73	3.3287E+06
74	3.1664E+06
75	3.0119E+06
76	2.8650E+06
77	2.7253E+06
78	2.5924E+06
79	2.4660E+06
80	2.3852E+06
81	2.3653E+06
82	2.3457E+06
83	2.3069E+06
84	2.2313E+06
85	2.1225E+06
86	2.0190E+06
87	1.9205E+06
88	1.8268E+06
89	1.7377E+06
90	1.6530E+06
91	1.5724E+06
92	1.4957E+06
93	1.4227E+06
94	1.3534E+06
95	1.2873E+06
96	1.2246E+06
97	1.1648E+06
98	1.1080E+06
99	1.0026E+06
100	9.6164E+05
101	9.0718E+05
102	8.6294E+05
103	8.2085E+05
104	7.8082E+05
105	7.4274E+05
106	7.0651E+05
107	6.7206E+05
108	6.3928E+05

Energy Group N.	Upper Boundary [eV]
109	6.0810E+05
110	5.7844E+05
111	5.5023E+05
112	5.2340E+05
113	4.9787E+05
114	4.5049E+05
115	4.0762E+05
116	3.8774E+05
117	3.6883E+05
118	3.3373E+05
119	3.0197E+05
120	2.9850E+05
121	2.9720E+05
122	2.9452E+05
123	2.8725E+05
124	2.7324E+05
125	2.4724E+05
126	2.3518E+05
127	2.2371E+05
128	2.1280E+05
129	2.0242E+05
130	1.9255E+05
131	1.8316E+05
132	1.7422E+05
133	1.6573E+05
134	1.5764E+05
135	1.4996E+05
136	1.4264E+05
137	1.3569E+05
138	1.2907E+05
139	1.2277E+05
140	1.1679E+05
141	1.1109E+05
142	9.8037E+04
143	8.6517E+04
144	8.2500E+04
145	7.9500E+04
146	7.2000E+04
147	6.7379E+04
148	5.6562E+04
149	5.2475E+04
150	4.6309E+04
151	4.0868E+04
152	3.4307E+04
153	3.1828E+04
154	2.8500E+04
155	2.7000E+04
156	2.6058E+04
157	2.4788E+04
158	2.4176E+04
159	2.3579E+04
160	2.1875E+04

Energy Group N.	Upper Boundary [eV]
161	1.9305E+04
162	1.5034E+04
163	1.1709E+04
164	1.0595E+04
165	9.1188E+03
166	7.1017E+03
167	5.5308E+03
168	4.3074E+03
169	3.7074E+03
170	3.3546E+03
171	3.0354E+03
172	2.7465E+03
173	2.6126E+03
174	2.4852E+03
175	2.2487E+03
176	2.0347E+03
177	1.5846E+03
178	1.2341E+03
179	9.6112E+02
180	7.4852E+02
181	5.8295E+02
182	4.5400E+02
183	3.5358E+02
184	2.7536E+02
185	2.1445E+02
186	1.6702E+02
187	1.3007E+02
188	1.0130E+02
189	7.8893E+01
190	6.1442E+01
191	4.7851E+01
192	3.7267E+01
193	2.9023E+01
194	2.2603E+01
195	1.7603E+01
196	1.3710E+01
197	1.0677E+01
198	8.3153E+00
199	6.4760E+00
200	5.0435E+00
201	3.9279E+00
202	3.0590E+00
203	2.3824E+00
204	1.8554E+00
205	1.4450E+00
206	1.1254E+00
207	8.7642E-01
208	6.8256E-01
209	5.3158E-01
210	4.1399E-01
211	1.0000E-01

Table 3 – List of MT numbers used in ANITA-IEAF package

Ordering Number	MT	Reaction label	Change in ZA of the target
1	4	(n, n’)	0
2	11	(n, 2nd)	-1003
3	16	(n, 2n)	-1
4	17	(n, 3n)	-2
5	22	(n, nα)	-2004
6	23	(n, n3α)	-6012
7	24	(n, 2nα)	-2005
8	25	(n, 3nα)	-2006
9	28	(n, np)	-1001
10	29	(n, n2α)	-4008
11	30	(n, 2n2α)	-4009
12	32	(n, nd)	-1002
13	33	(n, nt)	-1003
14	34	(n, nHe^3)	-2003
15	35	(n, nd2α)	-5010
16	36	(n, nt2α)	-5011
17	37	(n, 4n)	-3
18	41	(n, 2np)	-1002
19	42	(n, 3np)	-1003
20	44	(n, n2p)	-2002
21	45	(n, npα)	-3005
22	102	(n, γ)	+1
23	103	(n, p)	-1000
24	104	(n, d)	-1001
25	105	(n, t)	-1002
26	106	(n, He^3)	-2002
27	107	(n, α)	-2003
28	108	(n, 2α)	-4007
29	109	(n, 3α)	-6011
30	111	(n, 2p)	-2001
31	112	(n, pα)	-3004
32	113	(n, t2α)	-5010
33	114	(n, d2α)	-5009
34	115	(n, pd)	-2002
35	116	(n, pt)	-2003
36	117	(n, dα)	-3005
37	152	(n, 5n)	-4
38	153	(n, 6n)	-5
39	154	(n, 2nt)	-1004
40	155	(n, tα)	-3006
41	156	(n, 4np)	-1004
42	157	(n, 3nd)	-1004
43	158	(n, ndα)	-3006
44	159	(n, 2npα)	-3006
45	160	(n, 7n)	-6
46	161	(n, 8n)	-7

Ordering Number	MT	Reaction label	Change in ZA of the target
47	162	(n, 5np)	-1005
48	163	(n, 6np)	-1006
49	164	(n, 7np)	-1007
50	165	(n, 4nα)	-2007
51	166	(n, 5nα)	-2008
52	167	(n, 6nα)	-2009
53	168	(n, 7nα)	-2010
54	169	(n, 4nd)	-1005
55	170	(n, 5nd)	-1006
56	171	(n, 6nd)	-1007
57	172	(n, 3nt)	-1005
58	173	(n, 4nt)	-1006
59	174	(n, 5nt)	-1007
60	175	(n, 6nt)	-1008
61	176	(n, 2nHe^3)	-2004
62	177	(n, 3nHe^3)	-2005
63	178	(n, 4nHe^3)	-2006
64	179	(n, 3n2p)	-2004
65	180	(n, 3n2α)	-4010
66	181	(n, 3npα)	-3007
67	182	(n, dt)	-2004
68	183	(n, npd)	-2003
69	184	(n, npt)	-2004
70	185	(n, ndt)	-2005
71	186	(n, npHe^3)	-3004
72	187	(n, ndHe^3)	-3005
73	188	(n, ntHe^3)	-3006
74	189	(n, ntα)	-3007
75	190	(n, 2n2p)	-2003
76	191	(n, pHe^3)	-3003
77	192	(n, dHe^3)	-3004
78	193	(n, He$^3\alpha$)	-4006
79	194	(n, 4n2p)	-2005
80	195	(n, 4n2α)	-4011
81	196	(n, 4npα)	-3008
82	197	(n, 3p)	-3002
83	198	(n, n3p)	-3003
84	199	(n, 3n2pα)	-4008
85	200	(n, 5n2p)	-2006

3 ANITA-IEAF ACTIVITY CALCULATIONS

ANITA-IEAF predictions were compared with the activity measurements obtained from the Karlsruhe Isochronous Cyclotron [16] .

In this experiment a saturation thick target of natural lithium was irradiated with 40 MeV deuterons.

The resulting neutron spectrum and yield were measured by multi-foil activation.

Samples of two different steels, SS-316 and F82H, pure vanadium and a vanadium alloy were activated in the neutron field. These are structural materials of interest in fusion technology. For each sample, the specific activities of many radio nuclides (Bq/kg), were determined by gamma spectrometry.

The details of the experimental set-up (material composition, irradiation time, neutron flux, etc.) used as ANITA-IEAF input to model the experiment are given in the following.

3.1 Neutron Flux

The Centre position neutron flux of [16], in the 211 energy groups structure, was used in the ANITA-IEAF calculations (see Figure 2). It resembles very closely the IFMIF neutron spectrum.

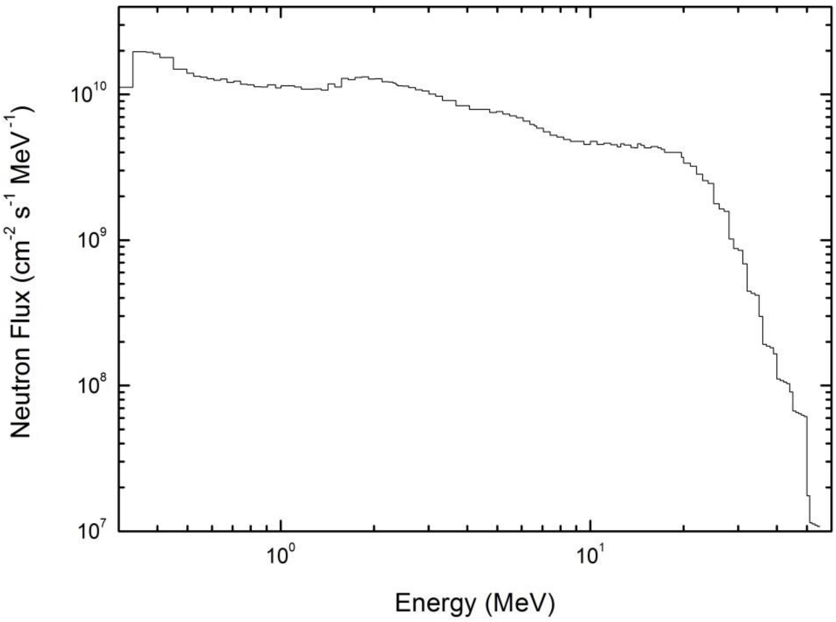

Figure 2 – Neutron flux

3.2 Samples and activation parameters

The activation parameters are given in Table 4.

Material	Neutron Flux density $\Phi(cm^{-2}\ s^{-1})$	Irradiation time (s)
SS-316	4.10 E11	7525
F82H	4.14 E11	7525
V- alloy	4.22 E11	7525
V- pure	4.27 E 11	7525

Table 4 – Activation parameters

3.3 Samples compositions

The sample compositions in weight% are given in the following Table 5.

Element	SS-316	F82H	V-alloy	V-pure
B	0.0002	0.0002	0.0005	0.0005
C		0.09	0.0045	0.0027
N		0.008	0.011	0.013
O			0.037	0.041
Mg			0.001	0.001
Al	0.05	0.003	0.020	0.025
Si	0.4	0.11	0.034	0.017
P		0.002	0.003	0.003
S		0.002	0.001	0.001
Ti	0.15	0.01	4.1	
V		0.16	91.8483	99.8658
Cr	17.5	7.70	3.9	
Mn	1.8	0.16		
Fe	65.1648	89.7467	0.021	0.016
Co	0.03	0.005		
Ni	12.3	0.02		
Cu	0.1	0.01	0.005	0.005
Nb	0.005	0.0001	0.0087	0.004
Mo	2.5	0.003	0.005	0.005
Ta		0.02		
W		1.95		

Table 5 – Composition of samples in weight%

3.4 Cooling times

The measurements on the activated samples were performed at different cooling times ranging from about 1 hour up to 150 days. They are given in the following Table 6.

SS316	F82H
5965 s ≈ 1.7 h	4173 s ≈ 1.2 h
18848 s ≈ 5.2 h	18011 s ≈ 5 h
93333 s ≈ 1.1 d	92043 s ≈ 1.1 d
178860 s ≈ 2.1 d	158665 s ≈ 1.8 d
432539 s ≈ 5 d	424416 s ≈ 4.9 d
2520240 s ≈ 29.2 d	2922060 s ≈ 33.8 d
12962640 s ≈150 d	13036200 s ≈ 150.9 d

V-alloy	V-pure
5477 s ≈ 1.5 h	4983 s ≈ 1.4 h
17189 s ≈ 4.8 h	16396 s ≈ 4.6 h
90710 s ≈ 1 d	90001 s ≈ 1 d
417962 s ≈ 4.8 d	412474 s ≈ 4.8 d
2254080 s ≈ 26.1 d	3100500 s ≈ 35.9 d
13341780 s ≈154.4 d	13146900 s ≈ 152.2 d

Table 6 – Cooling times

4 ANITA-IEAF CALCULATIONS AND EXPERIMENTAL RESULTS COMPARISON

The results of the comparison between the measured activities and the corresponding ANITA-IEAF predictions are given in Table 7 to Table 10 for SS-316 and F82H steels, V-alloy and V-pure respectively.

For each nuclide at the various cooling times these quantities are given :

- experimental activity
- experimental uncertainty
- ANITA-IEAF calculated activity
- percentage respect to the total activity (calculated by ANITA-IEAF)
- calculation-to-experiment C/E ratio

N.B In the tables the cooling times are in seconds for sake of comparison with the experimental values of FZKA 6764 Report.

The C/E ratios calculated as averages over more than one cooling time for each nuclide are shown in Figure 3 to Figure 9.

The error bars (1 σ) account for the experimental uncertainties only.

For SS-316, F82H steels and V-alloy samples the C/E ratios of the main contributors to the total activity are shown separately, while for V-pure the C/E values of all the nuclides are given together.

Table 7 – SS-316 specific activity- Experimental and calculated results

Isotope product	Cooling time	Experimental data		ANITA-IEAF calculation		C/E
		Specific activity	uncertainty	Specific activity	percentage of the total activity	
	s	Bq/kg	± %	Bq/kg	%	
Sc-46	178860	5.33E+04	54	1.25E+05	1.47E-02	2.34
	2520240	5.72E+04	13	9.95E+04	3.43E-02	1.74
	12962640	2.20E+04	18	3.66E+04	4.05E-02	1.66
Sc-48	93333	3.37E+06	13	3.90E+06	2.19E-01	1.16
	178860	1.57E+06	9	2.67E+06	3.16E-01	1.70
	432539	6.55E+05	14	8.74E+05	1.68E-01	1.33
V-48	93333	1.04E+06	14	1.43E+06	8.03E-02	1.38
	178860	1.08E+06	9	1.38E+06	1.63E-01	1.28
	432539	9.03E+05	9	1.22E+06	2.36E-01	1.36
	2520240	3.41E+05	6	4.29E+05	1.48E-01	1.26
Cr-48	178860	1.05E+05	25	1.59E+05	1.88E-02	1.51
Cr-49	5965	2.22E+08	35	1.77E+08	5.02E-01	0.80
Cr-51	18848	3.14E+08	27	3.01E+08	1.86E+00	0.96
	93333	2.91E+08	5	2.95E+08	1.65E+01	1.01
	178860	2.78E+08	5	2.87E+08	3.40E+01	1.03
	432539	2.58E+08	5	2.67E+08	5.14E+01	1.03
	2520240	1.38E+08	5	1.46E+08	5.03E+01	1.06
	12962640	6.83E+06	5	7.09E+06	7.84E+00	1.04
Mn-52	18848	1.14E+07	40	1.11E+07	6.83E-02	0.97
	93333	1.01E+07	6	1.03E+07	5.80E-01	1.02
	178860	7.72E+06	5	9.22E+06	1.09E+00	1.19
	432539	5.38E+06	5	6.42E+06	1.24E+00	1.19
	2520240	2.74E+05	6	3.21E+05	1.11E-01	1.17
Mn-54	18848	2.68E+07	33	2.03E+07	1.25E-01	0.76
	93333	1.82E+07	5	2.03E+07	1.14E+00	1.11
	178860	1.73E+07	5	2.02E+07	2.39E+00	1.17
	432539	1.71E+07	5	2.01E+07	3.87E+00	1.17
	2520240	1.59E+07	5	1.90E+07	6.56E+00	1.20
	12962640	1.22E+07	5	1.46E+07	1.61E+01	1.19
Mn-56	5965	2.61E+10	5	2.76E+10	7.84E+01	1.06
	18848	9.60E+09	5	1.06E+10	6.53E+01	1.10
	93333	3.83E+07	5	4.10E+07	2.30E+00	1.07
Fe-52	93333	3.41E+05	50	1.48E+06	8.29E-02	4.34
Fe-59	178860	3.50E+05	18	3.68E+05	4.35E-02	1.05
	2520240	2.33E+05	10	2.41E+05	8.31E-02	1.04
	12962640	3.21E+04	39	3.67E+04	4.06E-02	1.14
Co-55	93333	2.30E+06	16	1.70E+06	9.52E-02	0.74
	178860	5.81E+05	10	6.64E+05	7.85E-02	1.14
Co-56	93333	2.54E+06	21	2.89E+06	1.62E-01	1.14
	178860	2.82E+06	5	2.87E+06	3.39E-01	1.02
	432539	2.67E+06	7	2.80E+06	5.40E-01	1.05
	2520240	2.12E+06	5	2.27E+06	7.84E-01	1.07
	12962640	7.22E+05	5	7.70E+05	8.51E-01	1.07

Table 7 – SS-316 specific activity- Experimental and calculated results (continued)

Isotope product	Cooling time	Experimental data		ANITA-IEAF calculation		C/E
		Specific activity	uncertainty	Specific activity	percentage of the total activity	
	s	Bq/kg	± %	Bq/kg	%	
Co-57	18848	2.19E+07	39	2.16E+07	1.34E-01	0.99
	93333	2.08E+07	6	2.22E+07	1.24E+00	1.07
	178860	2.03E+07	5	2.25E+07	2.66E+00	1.11
	432539	2.01E+07	5	2.29E+07	4.41E+00	1.14
	2520240	1.91E+07	5	2.17E+07	7.49E+00	1.14
	12962640	1.41E+07	5	1.60E+07	1.77E+01	1.13
Co-58	18848	5.71E+07	16	6.03E+07	3.72E-01	1.06
	93333	7.18E+07	5	7.87E+07	4.41E+00	1.10
	178860	7.36E+07	5	8.19E+07	9.68E+00	1.11
	432539	7.13E+07	5	8.03E+07	1.55E+01	1.13
	2520240	5.53E+07	5	6.34E+07	2.19E+01	1.15
	12962640	1.70E+07	5	1.94E+07	2.15E+01	1.14
Co-60	178860	2.35E+05	15	2.25E+05	2.66E-02	0.96
	432539	2.88E+05	27	2.25E+05	4.33E-02	0.78
	2520240	2.60E+05	6	2.23E+05	7.68E-02	0.86
	12962640	2.23E+05	6	2.13E+05	2.36E-01	0.96
Co-61	5965	1.04E+08	34	2.48E+08	7.04E-01	2.39
Ni-56	93333	1.32E+06	17	4.04E+05	2.27E-02	0.31
	178860	1.21E+06	7	3.61E+05	4.27E-02	0.30
	432539	9.21E+05	11	2.58E+05	4.97E-02	0.28
Ni-57	5965	2.59E+08	27	3.40E+08	9.63E-01	1.31
	18848	2.49E+08	23	3.17E+08	1.96E+00	1.27
	93333	1.72E+08	21	2.13E+08	1.19E+01	1.24
	178860	9.44E+07	21	1.34E+08	1.59E+01	1.42
	432539	2.70E+07	21	3.45E+07	6.63E+00	1.28
Y-87m	178860	1.25E+05	28	6.14E+04	7.25E-03	0.49
Y-87	178860	1.80E+05	19	9.50E+04	1.12E-02	0.53
Y-88	12962640	1.05E+04	34	1.77E+04	1.96E-02	1.69
Zr-86	178860	1.16E+05	23	2.97E+03	3.51E-04	0.03
Zr-88	2520240	2.28E+04	60	3.88E+04	1.34E-02	1.70
Zr-89	93333	1.71E+06	18	2.22E+06	1.24E-01	1.30
	178860	1.29E+06	5	1.80E+06	2.12E-01	1.39
	432539	7.68E+05	11	9.63E+05	1.85E-01	1.25
Zr-97	178860	5.44E+06	21	1.05E+05	1.25E-02	0.02
Nb-90	93333	7.55E+06	8	4.82E+06	2.70E-01	0.64
	178860	1.73E+06	6	1.63E+06	1.93E-01	0.94
Nb-92m	93333	1.39E+06	31	2.47E+06	1.39E-01	1.78
	178860	1.82E+06	11	2.31E+06	2.73E-01	1.27
	432539	1.79E+06	9	1.89E+06	3.64E-01	1.06
	2520240	2.89E+05	7	3.63E+05	1.25E-01	1.26

Table 7– SS-316 specific activity- Experimental and calculated results (continued)

Isotope product	Cooling time	Experimental data		ANITA-IEAF calculation		C/E
		Specific activity	uncertainty	Specific activity	percentage of the total activity	
	s	Bq/kg	± %	Bq/kg	%	
Nb-95	93333	5.90E+05	37	7.08E+05	3.97E-02	1.20
	178860	4.88E+05	8	7.08E+05	8.37E-02	1.45
	432539	5.36E+05	17	6.96E+05	1.34E-01	1.30
	2520240	3.29E+05	6	4.69E+05	1.62E-01	1.42
	12962640	4.09E+04	19	5.57E+04	6.16E-02	1.36
Nb-95m	178860	9.39E+05	13	6.30E+05	7.45E-02	0.67
Nb-96	93333	5.36E+06	9	7.26E+06	4.07E-01	1.35
	178860	2.28E+06	5	3.58E+06	4.24E-01	1.57
	432539	3.37E+05	25	4.42E+05	8.52E-02	1.31
Mo-90	178860	1.45E+04	55	2.21E+04	2.62E-03	1.53
Mo-93m	93333	1.85E+06	18	1.79E+06	1.00E-01	0.97
	178860	7.26E+04	35	1.62E+05	1.91E-02	2.23
Mo-99	93333	4.84E+07	7	5.12E+07	2.87E+00	1.06
	178860	3.21E+07	6	3.99E+07	4.71E+00	1.24
	432539	1.57E+07	7	1.90E+07	3.66E+00	1.21
Tc-99m	18848	5.69E+07	16	2.97E+07	1.83E-01	0.52
	93333	4.45E+07	5	4.67E+07	2.62E+00	1.05
	178860	3.08E+07	5	3.84E+07	4.55E+00	1.25
	432539	1.54E+07	5	1.84E+07	3.55E+00	1.20
	2520240	2.24E+04	47	4.15E+04	1.43E-02	1.85

Table 8 – F82H specific activity- Experimental and calculated results

Isotope product	Cooling time	Experimental data		ANITA-IEAF calculation		C/E
		Specific activity	uncertainty	Specific activity	percentage of the total activity	
	s	Bq/kg	± %	Bq/kg	%	
Sc-46	158665	4.13E+04	44	2.05E+04	8.54E-03	0.50
	2922060	3.56E+04	10	1.57E+04	1.16E-02	0.44
	13036200	1.44E+04	15	5.97E+03	9.40E-03	0.41
Sc-47	92043	7.17E+05	20	1.44E+06	4.59E-01	2.01
	158665	6.78E+05	12	1.23E+06	5.13E-01	1.82
	424416	3.59E+05	20	6.53E+05	2.98E-01	1.82
Sc-48	92043	2.06E+06	11	1.68E+06	5.35E-01	0.82
	158665	1.35E+06	5	1.26E+06	5.23E-01	0.93
	424416	5.00E+05	10	3.89E+05	1.78E-01	0.78
V-48	92043	3.53E+05	32	6.59E+05	2.09E-01	1.87
	158665	5.57E+05	16	6.41E+05	2.67E-01	1.15
	424416	3.55E+05	13	5.65E+05	2.58E-01	1.59
	2922060	1.25E+05	6	1.61E+05	1.19E-01	1.29
Cr-48	158665	7.81E+04	30	8.66E+04	3.61E-02	1.11
Cr-49	4173	3.14E+08	28	1.35E+08	3.04E-01	0.43
Cr-51	92043	1.42E+08	5	1.46E+08	4.63E+01	1.03
	158665	1.37E+08	5	1.43E+08	5.96E+01	1.04
	424416	1.27E+08	5	1.32E+08	6.05E+01	1.04
	2922060	6.00E+07	4	6.42E+07	4.72E+01	1.07
	13036200	3.31E+06	5	3.43E+06	5.40E+00	1.04
Mn-52	92043	1.13E+07	6	1.42E+07	4.51E+00	1.26
	158665	1.02E+07	5	1.30E+07	5.42E+00	1.27
	424416	7.13E+06	5	8.90E+06	4.06E+00	1.25
	2922060	1.73E+05	6	2.48E+05	1.82E-01	1.43
Mn-54	92043	1.80E+07	5	2.10E+07	6.67E+00	1.17
	158665	1.76E+07	5	2.10E+07	8.74E+00	1.19
	424416	1.78E+07	5	2.08E+07	9.52E+00	1.17
	2922060	1.65E+07	4	1.95E+07	1.44E+01	1.18
	13036200	1.27E+07	4	1.51E+07	2.37E+01	1.19
Mn-56	4173	4.08E+10	5	4.39E+10	9.85E+01	1.08
	18011	1.45E+10	5	1.56E+10	9.81E+01	1.08
	92043	5.71E+07	6	6.26E+07	1.99E+01	1.10
	158665	2.70E+05	11	4.36E+05	1.82E-01	1.61
Fe-52	92043	5.39E+05	22	2.11E+06	6.71E-01	3.92
	158665	1.09E+05	18	4.49E+05	1.87E-01	4.12
Co-55	92043	1.01E+06	22	2.83E+03	8.99E-04	2.80E-03
	158665	6.65E+05	9	1.36E+03	5.67E-04	2.05E-03
Co-56	158665	7.52E+05	8	4.75E+03	1.98E-03	0.01
	424416	7.20E+05	13	4.64E+03	2.12E-03	0.01
	2922060	5.74E+05	5	3.61E+03	2.65E-03	0.01
	13036200	2.04E+05	7	1.26E+03	1.99E-03	0.01
Co-57	2922060	3.91E+04	13	3.63E+04	2.67E-02	0.93
	13036200	3.69E+04	16	2.69E+04	4.24E-02	0.73

Table 8 – F82H specific activity- Experimental and calculated results (continued)

Isotope product	Cooling time	Experimental data		ANITA-IEAF calculation		C/E
		Specific activity	uncertainty	Specific activity	percentage of the total activity	
	s	Bq/kg	± %	Bq/kg	%	
Co-58	158665	1.74E+05	17	1.81E+05	7.56E-02	1.04
	424416	1.68E+05	28	1.79E+05	8.17E-02	1.06
	2922060	1.12E+05	7	1.35E+05	9.90E-02	1.20
	13036200	3.76E+04	18	4.29E+04	6.75E-02	1.14
Co-60	2922060	1.40E+04	16	5.03E+02	3.70E-04	0.04
	13036200	7.05E+03	30	4.83E+02	7.59E-04	0.07
Ni-57	158665	2.51E+05	24	2.46E+05	1.02E-01	0.98
Tc-99m	158665	4.57E+04	40	4.92E+04	2.05E-02	1.08
Ta-182	424416	1.31E+05	13	3.51E+04	1.60E-02	0.27
Ta-183	92043	1.05E+06	20	8.54E+05	2.71E-01	0.81
	158665	1.02E+06	18	7.69E+05	3.20E-01	0.75
	424416	7.88E+05	29	5.05E+05	2.31E-01	0.64
Ta-184	92043	7.10E+05	44	9.25E+05	2.94E-01	1.30
	158665	9.81E+04	52	2.12E+05	8.83E-02	2.16
W-187	92043	4.60E+06	17	1.87E+06	5.93E-01	0.41
	158665	2.83E+06	7	1.09E+06	4.55E-01	0.39

Table 9 – V-alloy specific activity- Experimental and calculated results

Isotope product	Cooling time	Experimental data		ANITA-IEAF calculation		C/E
		Specific activity	uncertainty	Specific activity	percentage of the total activity	
	s	Bq/kg	± %	Bq/kg	%	
Ca-47	417962	1.09E+06	18	7.32E+05	1.38E-01	0.67
	2254080	5.06E+04	15	2.85E+04	4.65E-02	0.56
Sc-43	5477	3.85E+07	26	1.33E+06	5.34E-02	0.03
Sc-44	5477	1.92E+07	21	2.82E+07	1.13E+00	1.47
	17189	1.62E+07	18	1.66E+07	8.44E-01	1.03
Sc-44m	417962	4.43E+05	28	3.94E+05	7.45E-02	0.89
Sc-46	5477	4.00E+06	72	4.55E+06	1.83E-01	1.14
	17189	6.05E+06	47	4.54E+06	2.31E-01	0.75
	90710	4.09E+06	27	4.51E+06	3.24E-01	1.10
	417962	4.97E+06	6	4.37E+06	8.26E-01	0.88
	2254080	4.40E+06	4	3.67E+06	5.98E+00	0.83
	13341780	1.47E+06	4	1.27E+06	7.69E+00	0.86
Sc-47	5477	4.87E+08	5	7.58E+08	3.05E+01	1.56
	17189	5.36E+08	5	7.37E+08	3.74E+01	1.38
	90710	4.46E+08	5	6.18E+08	4.44E+01	1.39
	417962	2.05E+08	5	2.83E+08	5.35E+01	1.38
	2254080	1.92E+06	7	3.56E+06	5.81E+00	1.86
Sc-48	5477	9.72E+08	5	9.79E+08	3.94E+01	1.01
	17189	1.04E+09	5	9.30E+08	4.72E+01	0.89
	90710	7.30E+08	5	6.72E+08	4.83E+01	0.92
	417962	1.70E+08	5	1.59E+08	3.00E+01	0.93
	2254080	3.08E+04	11	4.84E+04	7.90E-02	1.57
V-48	2254080	2.12E+06	4	1.47E+06	2.40E+00	0.69
	13341780	1.94E+04	24	5.62E+03	3.40E-02	0.29
Cr-49	5477	5.89E+07	15	4.54E+07	1.83E+00	0.77
Cr-51	5477	8.00E+07	37	6.56E+07	2.64E+00	0.82
	17189	6.98E+07	27	6.54E+07	3.32E+00	0.94
	90710	8.74E+07	16	6.40E+07	4.59E+00	0.73
	417962	6.16E+07	5	5.82E+07	1.10E+01	0.94
	2254080	3.55E+07	4	3.42E+07	5.58E+01	0.96
	13341780	1.38E+06	5	1.38E+06	8.36E+00	1.00
Mn-52	2254080	9.50E+03	25	1.54E+02	2.51E-04	0.02
Nb-92m	2254080	3.85E+04	10	3.56E+04	5.81E-02	0.93

Table 10 – V-pure specific activity- Experimental and calculated results

Isotope product	Cooling time	Experimental data		ANITA-IEAF calculation		C/E
		Specific activity	uncertainty	Specific activity	percentage of the total activity	
	s	Bq/kg	± %	Bq/kg	%	
Ca-47	412474	1.11E+06	18	4.49E+05	1.04E-01	0.40
	3100500	4.53E+03	36	3.88E+03	1.79E-02	0.86
Sc-46	412474	3.01E+06	8	1.78E+06	4.13E-01	0.59
	3100500	2.31E+06	4	1.38E+06	6.36E+00	0.60
	13146900	8.47E+05	4	5.26E+05	3.44E+00	0.62
Sc-47	4983	4.99E+08	5	6.54E+08	3.56E+01	1.31
	16396	4.80E+08	5	6.36E+08	3.97E+01	1.33
	90001	3.98E+08	5	5.34E+08	4.38E+01	1.34
	412474	1.84E+08	5	2.47E+08	5.73E+01	1.34
	3100500	2.08E+05	7	4.08E+05	1.89E+00	1.96
Sc-48	4983	9.38E+08	5	9.51E+08	5.17E+01	1.01
	16396	9.01E+08	5	9.04E+08	5.65E+01	1.00
	90001	6.56E+08	5	6.54E+08	5.36E+01	1.00
	412474	1.52E+08	4	1.58E+08	3.66E+01	1.04
V-48	412474	6.10E+06	4	3.77E+06	8.75E-01	0.62
	3100500	1.33E+06	24	9.78E+05	4.52E+00	0.74
	13146900	9.14E+03	33	6.30E+03	4.12E-02	0.69
Cr-51	412474	1.05E+07	10	3.67E+03	8.51E-04	3.49E-04
	3100500	4.33E+06	4	1.68E+03	7.78E-03	3.89E-04
	13146900	2.33E+05	11	9.18E+01	6.00E-04	3.94E-04
Nb-92m	3100500	6.53E+03	27	8.74E+03	4.04E-02	1.34

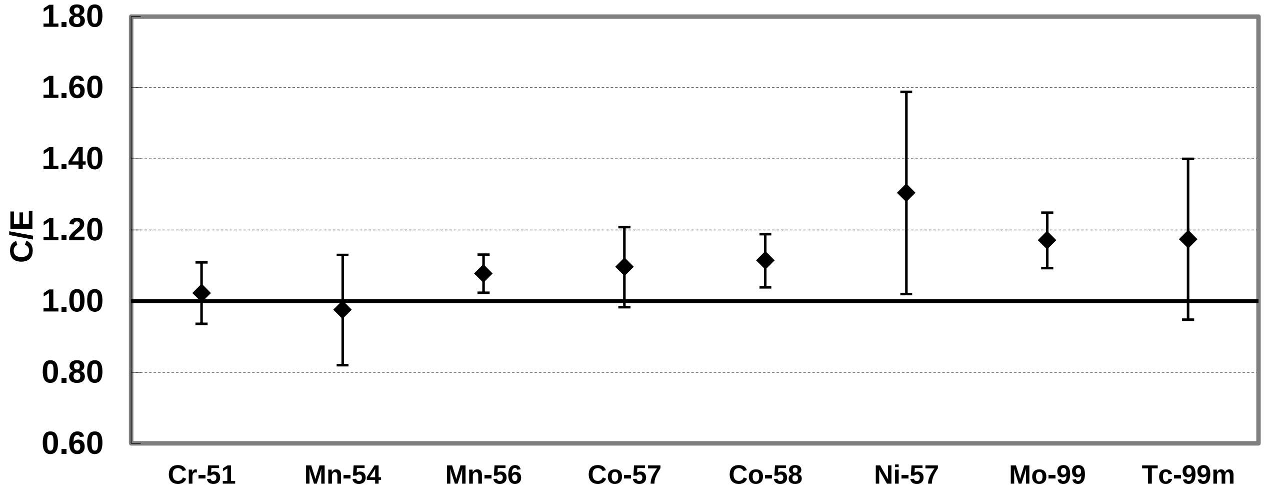

Figure 3 – SS-316 specific activity: calculation to experiment ratios (C/E). Main isotope contributors.

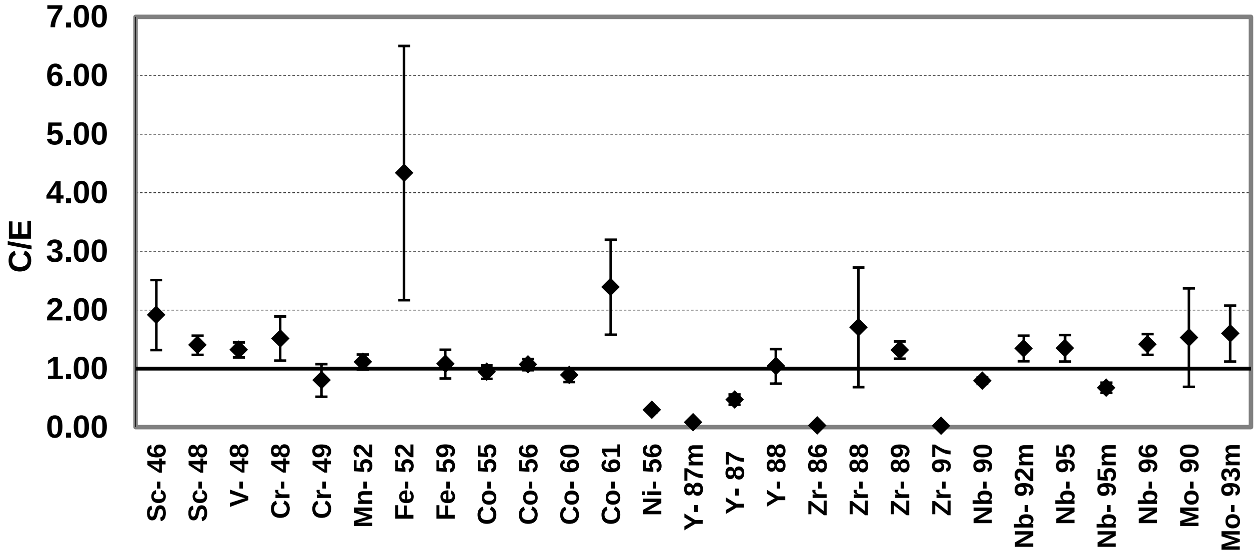

Figure 4 – SS-316 specific activity: calculation to experiment ratios (C/E). Other isotopes.

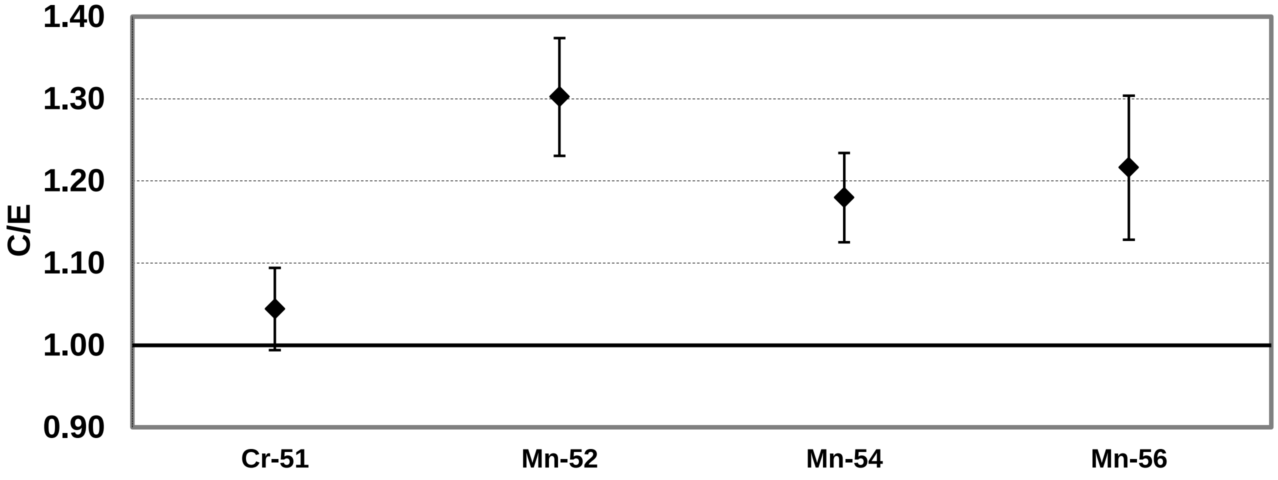

Figure 5 – F82H specific activity: calculation to experiment ratios (C/E). Main isotope contributors.

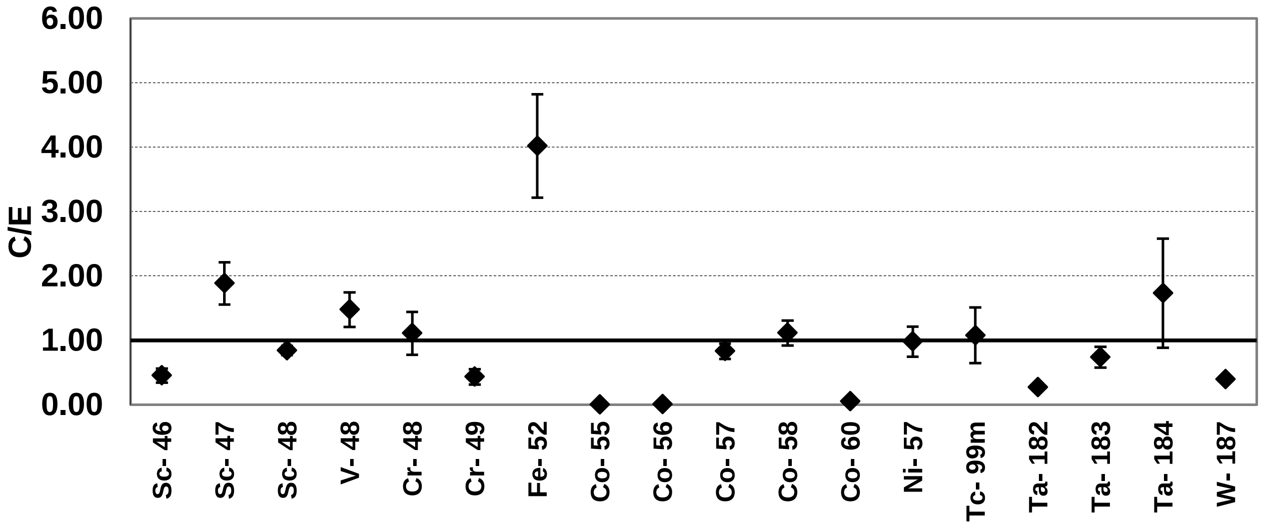

Figure 6 – F82H specific activity: calculation to experiment ratios (C/E). Other isotopes.

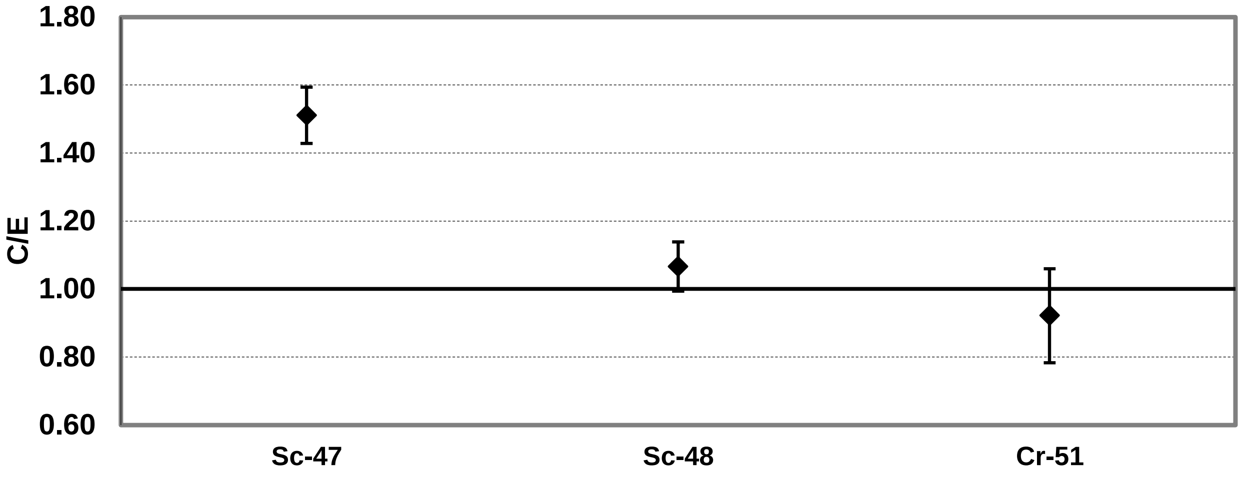

Figure 7 – V-alloy specific activity: calculation to experiment ratios (C/E). Main isotope contributors.

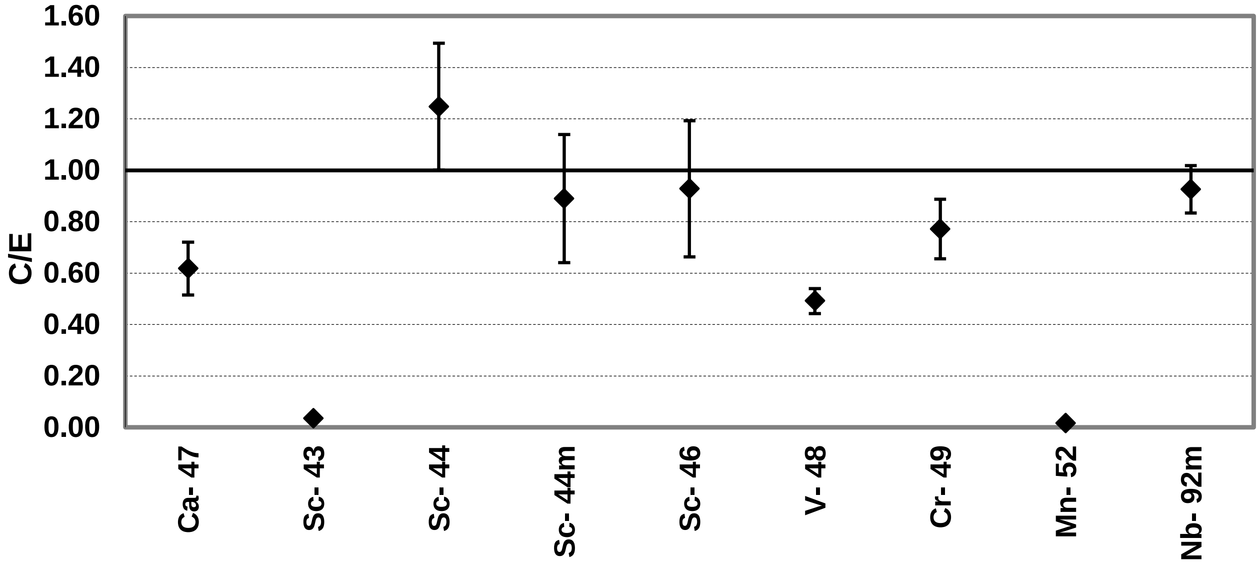

Figure 8 – V-alloy specific activity: calculation to experiment ratios (C/E). Other isotopes.

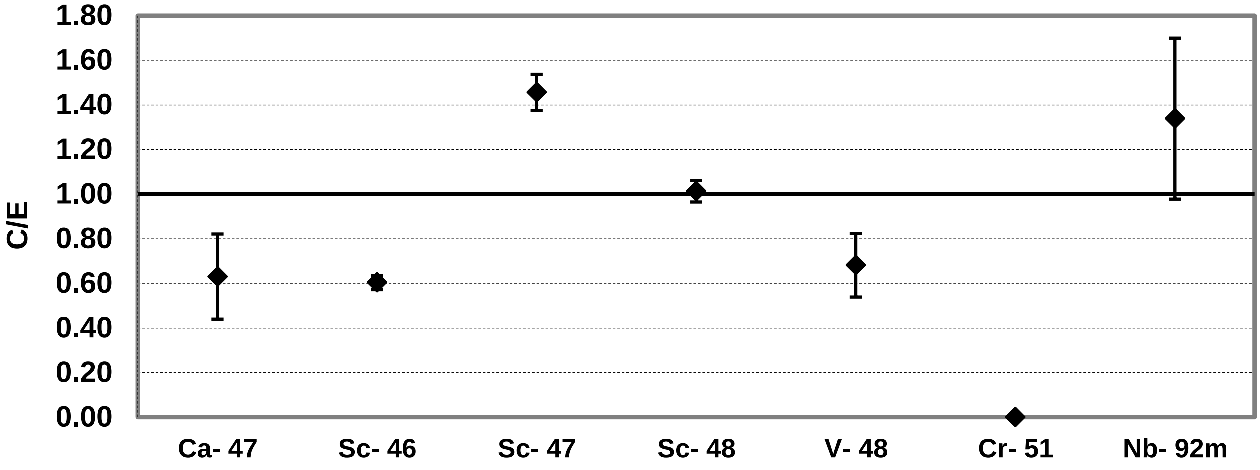

Figure 9 – V-pure specific activity: calculation to experiment ratios (C/E). All isotopes.

5 ANITA-IEAF RESULTS ANALYSIS

In this section the results analysis related to the comparison between the updated ANITA-IEAF predictions and the activity measurements obtained from the Karlsruhe Isochronous Cyclotron is presented. The comparison is performed for samples of two different steels, SS-316 and F82H, pure vanadium and a vanadium alloy.

From such a validation work the following detailed information can be drawn.

SS-316

- among the measured nuclides the main contributors to the total activity are: Mn-56, Cr-51, Ni-57, Mn-54, Co-57, Co-58, Mo-99 and Tc-99m.
- Mn-56: is the most important contributor to the total activity, from 78% to 65%, up to 6 hours cooling time. The measured values and the ANITA-IEAF predictions, in term of C/E, show a very good agreement. For all the cooling times the discrepancies are lower than 10%.
- Cr-51: is an important contributor, up to 50%, for all the cooling times considered. The discrepancies between experimental and calculated activities are within 6%, showing a very good agreement.
- Ni-57: is an important product in the first 5 days (half-life=36h); its contribution increases from 1% at the first cooling time up to about 15% at 2.1 days. The discrepancies range from 24% to 42%.
- Mn-54: its contribute is not relevant, 0.1%,in the first two hours cooling time where the discrepancy is large (24%). The importance of Mn-54 increases up to 16.1% at the last cooling time considered. The corresponding C/E values show discrepancies up to 20%.
- Co-57: is an important activation contributor, up to 17.7%, at 150 days. The measured values and the ANITA-IEAF predictions, in term of C/E, show a good agreement. For all the cooling times the discrepancies are lower than 15%.
- Co-58 : this nuclide becomes significant after 1 day cooling time; its contribution grows up to 22% at 150 days. The discrepancies are always within 15%.
- Mo-99: its contribution is about 4%, from 1 to 5 days cooling time. The C/E values show discrepancies up to 24%.
- Tc-99m: has a contribution of about 4%, between 1 and 5 days cooling time. For these times the C/E values show discrepancies within 25%. The largest discrepancies, about 50%, are found at the cooling time where its contribute is negligible (lower than 0.2%).
- the averaged C/E values of Cr-51, Mn-54, Co-57, Tc-99m show a good agreement within the error bars. The discrepancies are lower than 20% except for Ni-57.
- the other less important nuclides show larger discrepancies as, mainly, Fe-52, Y-87m, Zr-86 and Zr-97.

F82H

- the main isotope contributors to the total activity are Cr-51, Mn-52, Mn-54 and Mn-56.
- Cr-51: is an important contributor, up to 60%, for all the cooling times. The discrepancies between experimental and calculated activities are within 7%, showing a very good agreement.
- Mn-52 : its contribute is relevant up to 5 days cooling time; the discrepancies between experimental and calculated activities are large, up to 43%, showing an overestimation of the experimental results.
- Mn-54 : its contribute increases from about 7% at the first cooling time up to 23.7% at 150 days. The corresponding C/E values show discrepancies up to 19%.
- Mn-56: is the most important contributor to the total activity, 98%, up to 6 hours cooling time. For these times the C/E values show a good agreement, discrepancies within 10%, between experimental and calculated results. The largest discrepancy, about 60%, is found at the cooling time where its contribute is negligible (lower than 0.2%).
- the averaged C/E values of Cr-51 only show a good agreement within the error bars with a discrepancy lower than 10%. The biggest discrepancy is found for Mn-52.
- the other less important nuclides show larger discrepancies as, mainly, Fe-52,Co-55, Co-56 Co-60.

V-alloy

- the main isotope contributors to the total activity are Sc-48, Cr-51 and Sc-47.
- Sc-48: is the most important contributor to the total activity up to 5 days cooling time. At these times the C/E values show a good agreement, discrepancies within 11%, between experimental and calculated results. The largest discrepancy, greater than 50%, is found at 26 days cooling time where its contribute is negligible (lower than 0.1%).
- Cr-51: is an important contributor, up to 56%, for all the cooling times. The biggest discrepancy between experimental and calculated activities is found at 1 day cooling time where the discrepancy grows up to 27%. The calculated values are in general underestimate with respect to the experimental data.
- Sc-47: is an important contributor, up to about 54%, for all the cooling times considered. The discrepancies between experimental and calculated activities are up to 86%, showing an overestimation of the calculated results with respect to the experimental ones.
- the averaged C/E values of the previous nuclides show a good agreement within the error bars, except for Sc-47.The discrepancy for this nuclide rises up to 50%.
- for the other less important nuclides the major discrepancies are found for Sc-43 and Mn-52. All the experimental results are underestimated except for Sc-44.

V-pure

- Sc-48: is the most important contributor, up to 56%, to the total activity for all the cooling times considered. The C/E values show a very good agreement, discrepancies within 4%, between experimental and calculated results.
- Sc-47: is an important contributor, up to 57%, up to 5 days cooling times. The agreement between experimental and calculated activities is rather poor. The calculated results show a general overestimation of the experimental values.
- Sc-46: contributes up to 6% to the total activity. The calculated activities show an underestimation, up to 40%, of the experimental ones.
- For the other nuclides the agreement between experimental and calculated activities is rather poor. In particular for Cr-51 the calculated results show a huge underestimation of the experimental values.

6 COMPARISON BETWEEN THE ANITA-IEAF/EAF-2010 AND ANITA-IEAF/IEAF-2001 RESULTS

As previously stated, the updated ANITA-IEAF code package uses the 211 neutron energy groups cross section library of the European Activation File EAF-2010 provided in the package EASY-2010. The first ANITA-IEAF version used a neutron cross section library based on the IEAF-2001 library . The comparison between the calculated results obtained by the two ANITA-IEAF versions is shown in Figure 10 to Figure 16.

As already outlined, the two code packages use also different decay data libraries. Anyway, the specific activities are mainly sensitive to the activation cross sections. So a comparison between the two calculations enable to validate the evaluated activation cross sections.

(N.B For sake of simplicity the two ANITA-IEAF calculations performed by using IEAF-2001 +FENDL/D-2 and EAF-2010+JEFF-3.1.1 libraries, in the following are referred to as IEAF-2001 and EAF-2010, respectively)

The following conclusions can be drawn:

SS-316

- the IEAF-2001 and EAF-2010 calculations show a similar behaviour for the main contributors to the total activity. The major differences are found for Mn-54, Mo-99 and Tc-99m that show discrepancies between the two calculations up to 10%. For Mo-99 and Tc-99m the IEAF-2001 calculations present a lower discrepancy with respect to the experimental data. The opposite occurs for Mn-54.
- the differences between the two calculations are bigger in the case of the nuclides with lower contributions to the total activity. In general the EAF-2010 calculations show a better agreement with the experimental data

F82H

- for the main isotope contributors the IEAF-2001 calculations show a quite similar behaviour for Cr-51, Mn-54 and Mn-56. For Mn-52 the EAF-2010 calculations show an improvement with respect to the IEAF-2001 results.
- for the other isotopes the two calculations give different results, mainly for Sc-47, V-48, Cr-48, Fe-52, Ta-182 and Ta-184. For V-48 and Cr-48 the EAF-2010 calculations show a better agreement with the experimental data, whereas, for Fe-52, the IEAF-2001 calculations show a quite better agreement.

V-alloy

- for the main isotope contributors, the largest differences between IEAF-2001 and EAF-2010 calculations are found for Sc-47. In this case the EAF-2010 calculations overestimate the experimental data, whereas the IEAF-2001 calculations show an underestimation.
- for the other isotopes the biggest differences between the two calculations are found for Ca-47, Sc-44 and V-48. For Ca-47 and V-48 the IEAF-2001 calculations show a better agreement with the experimental data. On the contrary for Sc-44 the EAF-2010 calculations show a better agreement with the experimental data.

V-pure

- the largest differences between IEAF-2001 and EAF-2010 calculations are found for Sc-47 and V-48. In the case of Sc-47 the EAF-2010 calculations overestimate the experimental data, whereas the IEAF-2001 show a huge underestimation.

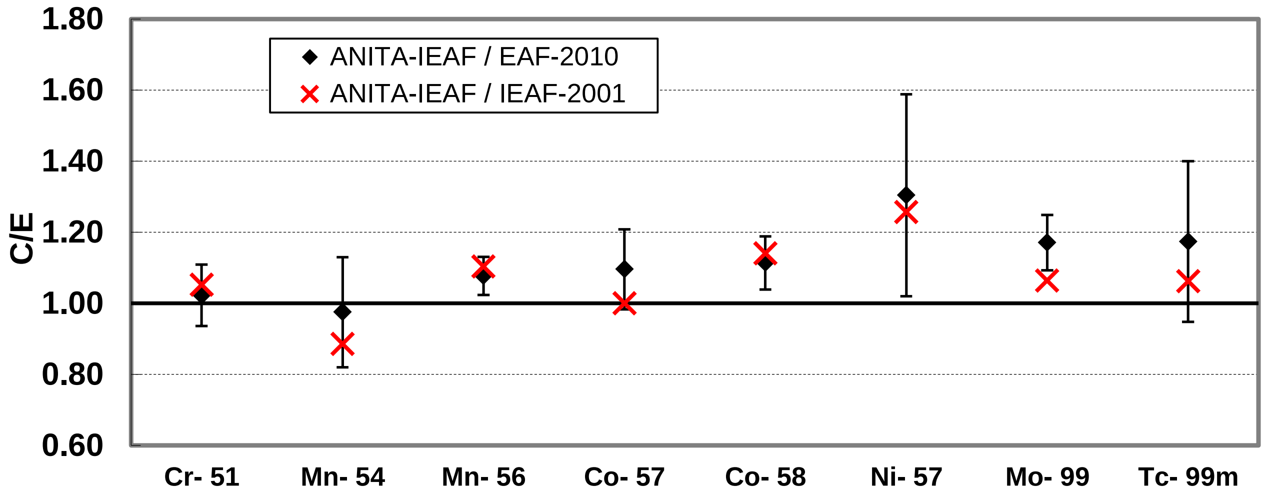

Figure 10 – SS-316 specific activity: calculation to experiment ratios (C/E). Comparison between ANITA-IEAF/EAF-2010 and ANITA-IEAF/IEAF-2001. Main isotope contributors.

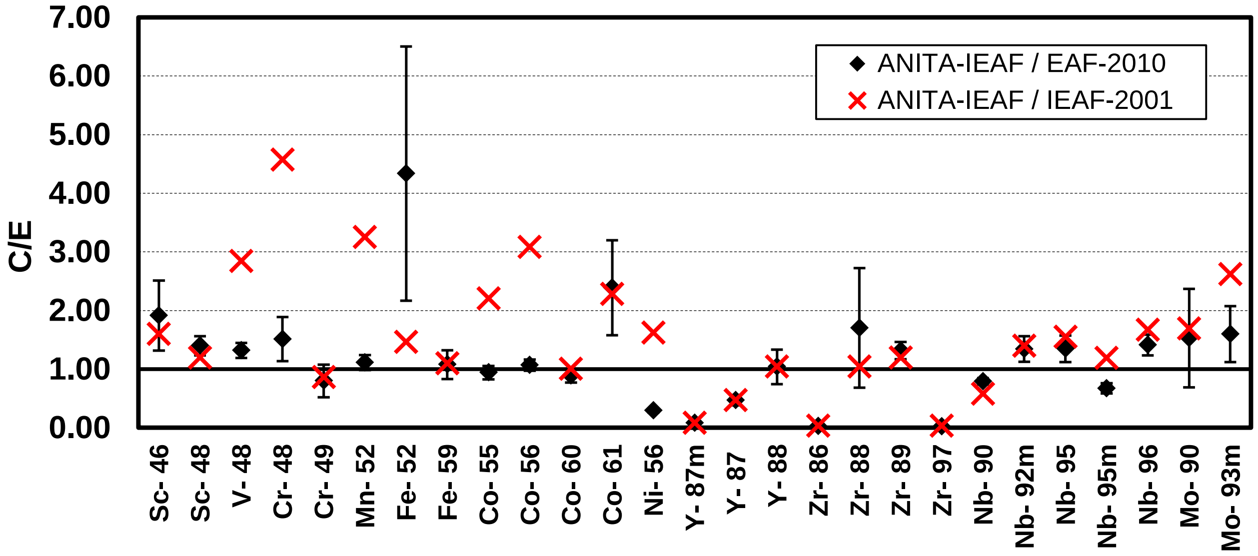

Figure 11 – SS-316 specific activity: calculation to experiment ratios (C/E). Comparison between ANITA-IEAF/EAF-2010 and ANITA-IEAF/IEAF-2001. Other isotopes.

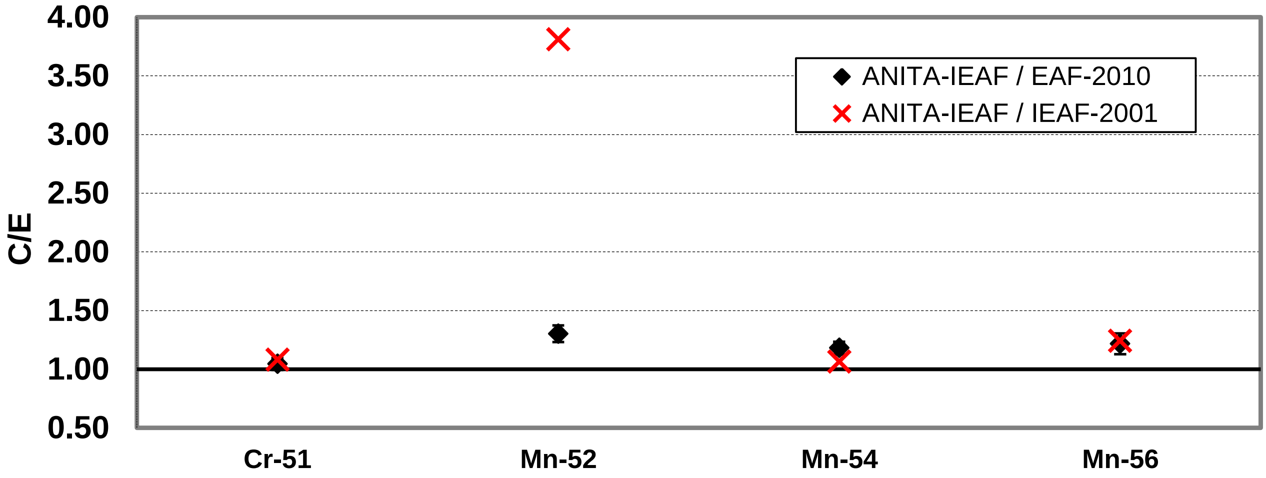

Figure 12 – F82H specific activity: calculation to experiment ratios (C/E). Comparison between ANITA-IEAF/EAF-2010 and ANITA-IEAF/IEAF-2001. Main isotope contributors.

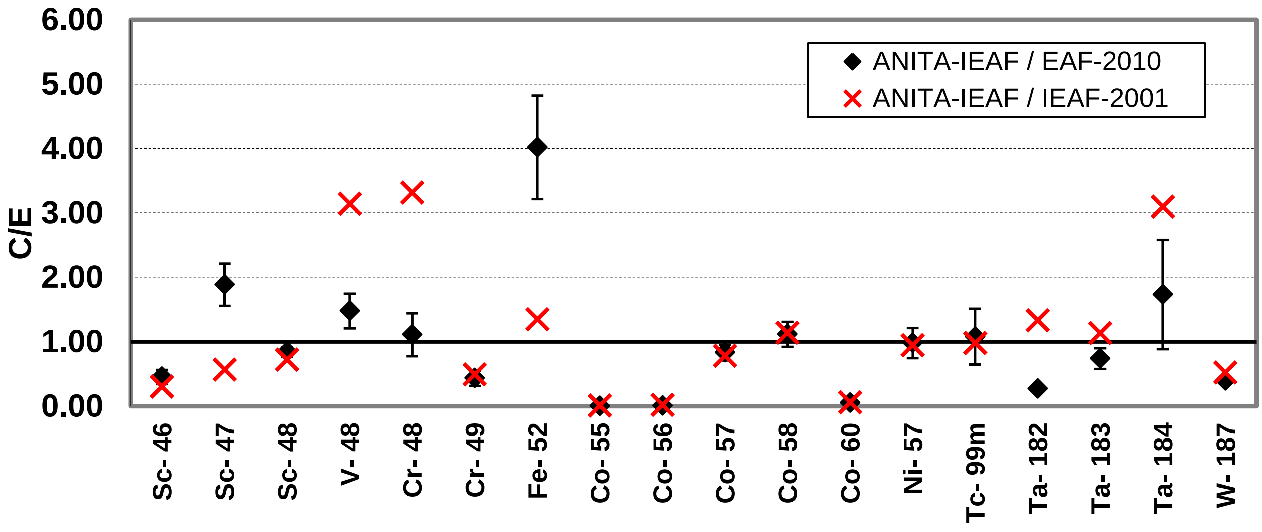

Figure 13 – F82H specific activity: calculation to experiment ratios (C/E). Comparison between ANITA-IEAF/EAF-2010 and ANITA-IEAF/IEAF-2001.Other isotopes.

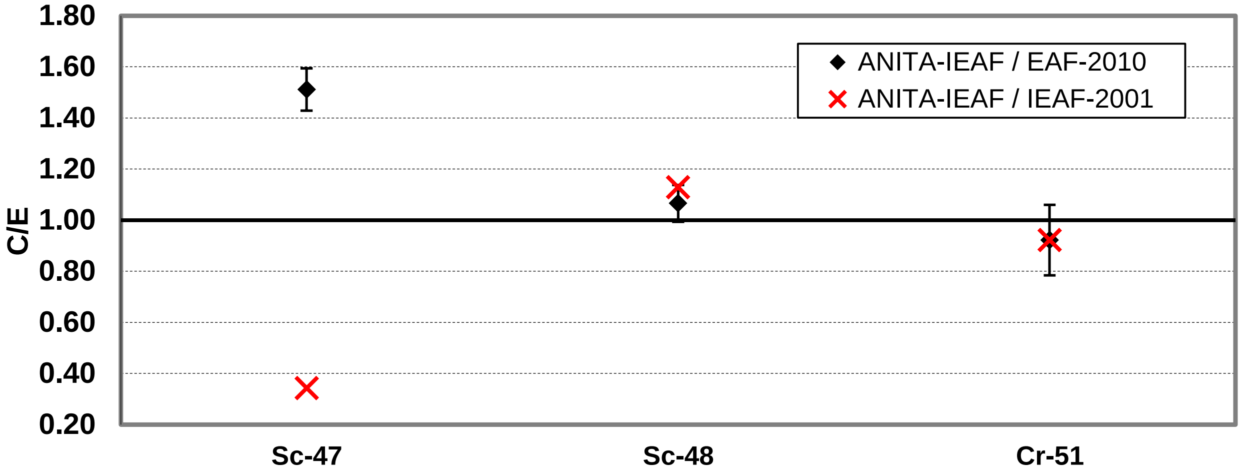

Figure 14 – V-alloy specific activity: calculation to experiment ratios (C/E). Comparison between ANITA-IEAF/EAF-2010 and ANITA-IEAF/IEAF-2001. Main isotope contributors.

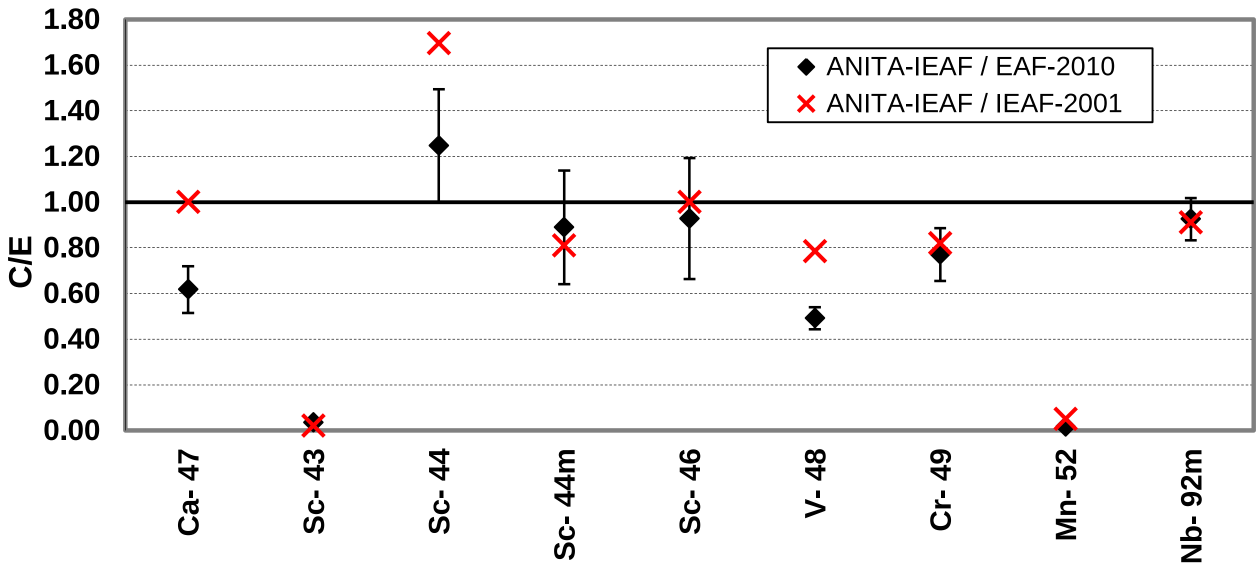

Figure 15 – V-alloy specific activity: calculation to experiment ratios (C/E). Comparison between ANITA-IEAF/EAF-2010 and ANITA-IEAF/IEAF-2001. Other isotopes.

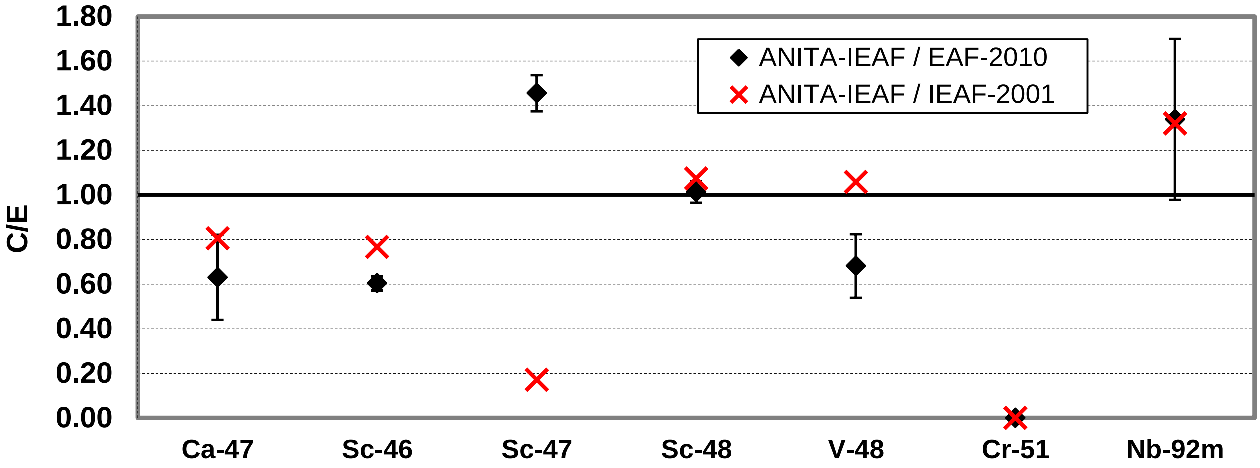

Figure 16 – V-pure specific activity: calculation to experiment ratios (C/E). Comparison between ANITA-IEAF/EAF-2010 and ANITA-IEAF/IEAF-2001. All isotopes.

7 CONCLUSION

ANITA-IEAF is a package (code and libraries) able to perform activation calculations for materials exposed to neutrons with energies greater than 20 MeV.

It is suitable to be applied to the study of the irradiation effects on materials in facilities like the International Fusion Materials Irradiation Facility (IFMIF) and the DEMO Oriented Neutron Source (DONES).

The ANITA-IEAF code package has been recently updated. The data contained in the decay data libraries are actually based on the JEFF-3.1.1 Radioactive Decay Data Library.

The updated code uses the EAF-2010 group-wise neutron activation cross sections library "eaf_n_gxs_211_flt_20010" in the VITAMIN-J+ (211 energy groups structure) up to 55 MeV .

In this report the validation effort related to the comparison between the ANITA-IEAF predictions and the activity measurements obtained from the Karlsruhe Isochronous Cyclotron has been presented.

In this experiment a thick target of natural lithium was irradiated with 40 MeV deuterons.

Samples of two different steels, SS-316 and F82H, pure vanadium and a vanadium alloy were irradiated in the resulting neutron spectrum, similar to the IFMIF neutron spectrum, and the specific activities of many radio nuclides were measured at various cooling times.

The calculation to experiment C/E ratios, obtained through the updated ANITA-IEAF code using the EAF-2010 neutron cross section activation library, have been presented.

The specific activities are mainly sensitive to the activation cross sections, so a comparison between the ANITA-IEAF/EAF-2010 and ANITA-IEAF/IEAF-2001 results has been also presented. This comparison is useful in order to validate the evaluated activation cross sections.

For some nuclides still remain discrepancies between the calculated and the experimental results suggesting the need to improve the nuclear cross section data contained in the actually available neutron activation cross section libraries.

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