CLM-R295

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J-Ch. Sublet
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CULHAM
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Culham Laboratory, AEA Technology, Abingdon, Oxon OX14 3DB U.K.

*Westinghouse Hanford Company, Richland, WA 99352 USA

**Joint Research Centre Ispra, 21020 Ispra, Varese, Italy

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ABSTRACT

D-T plasmas are strong sources of 14 MeV neutrons, which are transmitted through the different components of the fusion reactor. During this process they induce activity by transmutation reactions in the structural materials.
Three different computer code systems for predicting induced activation and transmutation reactions have been implemented with the same input data appropriate to JET conditions in order to compare their predictions. The computer codes and their associated data libraries are:

FISPACT/UKACT1, ANITA/GREAC-ECN-3, REAC/REAC2

The Joint European Torus is the largest fusion experiment in Europe and one of its goals is to study pulse reactions of D-T plasma during its final phase.The neutron generation will be significant during this period and the radioactivity induced in all the structural materials of the machine is of concern for maintenance (short-lived radioactivity) and finally the decommissioning of the device (long-lived radioactivity).
The results of this benchmark comparison show, in general, fairly close agreement. However, differences of up to a factor 84 could appear between the predictions of the induced activity of the different codes for specific radionuclides.
In the case of some shorter-lived radionuclides the lack of agreement could be due to differences in the decay data, whilst for the better-known and less numerous long lived isotopes the differences are associated with variations in the cross section data for those isotopes.

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1. INTRODUCTION

For activation codes to produce accurate results activation cross sections for all possible components of fusion reactors (pratically all elements) must be known. For this reason much effort has been expended in the past few years in the production of activation data libraries for fusion. Because of the high energy of the neutrons many threshold reactions can occur and this further increases the data needed, in fact up to 12 reactions could be possible with a single nucleus for this range of neutron energy. For light nuclides some break-up reactions may even occur. In 1985 the REAC data library [1] became available. This file contains pointwise data for more than 6000 reactions and 338 isotopes and is based upon modern data sources such as ENDF/B-V, ACTL-84 and the THRESH code when systematics have been necessary, which was generally the case. It was the starting point of all three libraries included in this benchmark comparison.

Renormalisation of many reactions to the best known systematics at 14.5 MeV has been performed for UKACT1 [2] and GREAC-ECN-3 [3], including those for the isomer production cross-sections. These developments involved considerable cooperation between HARWELL and PETTEN and consequently the libraries though not identical-show a close resemblance. This has led to an increase in the number of reactions to nearly 9000, with more than 600 target nuclides. Decay library information for all relevant isotopes is also required with data on secondary gamma and beta emission; here sources such as the GE Chart of the Nuclides, ICRP38 and JEF1 have been used.

The calculation of multi-group constants from the pointwise library is made using the versatile VITAMIN-E micro flux weighting spectrum while the collapsing of the one-group-averaged cross-section is made using the GAM-II (100 groups) structure for FISPACT and ANITA [4] and the REAC (63 groups) structure for the latter. It is important to note at this point that for this benchmark study we have to make the assumption that the method of solution for the differential equations and the necessary simplifications assumed in order to follow the decay and transmutation pathways will not significantly influence the result. It should be a fair assumption in this particular case as these codes have been developed especially for fusion applications.

There have been cases in the literature of disparities between predictions of the various codes. It was decided that a code comparison was justified and that it should take the form of a benchmark study.
JET was chosen as an example because of the fact that a thorough neutronics study has been done for all its mains conponents and thus emphasis the completeness of the irradiation conditions of this study.

Seven spectra were derived from Monte-carlo calculations for the five most important component regions of the JET machine. These were: the first wall, the toroidal field coil, the mechanical structure, the poloidal coils and the transformer core. One spectrum per region exists except for the mechanical structure, where three spectra have been employed. In this region the flux attenuation is strong, such that the flux profile is modified along the thickness of the structure which acts as a strong shield. Morever, the structural materials composition is not uniform. Calculations were performed for the main materials present within each region, using the three different codes FISPACT, ANITA, REAC linked to their appropriate collapsed library. The results compared in this benchmark exercise are the specific activity and the contact dose rates at different cooling times, up to 5000 years.

2. IRRADIATION CONDITIONS AND STRUCTURAL MATERIALS

During D-T operation the maximum credible output is 10^{24} neutrons emitted from the plasma at an energy of 14 MeV during a total of 10,000 shots over a 2 years interval. This corresponds to a source strength of 10^{20} neutrons per 10 second pulse. This irradiation condition is not steady state but is characterised by a duty cycle which varies over the entire period. However, as we are only interested in long lived radioactivity, it is assumed that the irradiation period is 2 years over which a properly averaged neutron flux is applied.

Seven different spectra from the innermost to the outermost region have been taken in a 100 group GAM-II format. The GAM-II energy group structure is defined by lethargy intervals of 0.1 for the groups 1-49 and 0.25 for the groups 50-99. The unique thermal group lower energy is 1.10^{-5} eV and the upper energy of the first group is $1.4918\ 10^{7}$ eV.

The profile of the spectrum in the first wall region represented in Fig.1 shows a very strong 14 MeV peak and a broad peak around 1 MeV. This profile changes from one region to another because of neutron scatter within the materials; the 14 MeV component is gradually attenuated and the 1 MeV broad peak moves to lower energy as illustrated Fig.2. The seven locations chosen along the "thickness" of the JET machine appear in order of increasing distance from the plasma region and are constituted of different materials.

The various regions considered and their main materials are: the first wall region with Inconel 600, the toroidal coil region with a mixture of copper and epoxy resin, the mechanical structure 1 with a special cast iron (GGG Ni-Mn), the mechanical structure 2 with a special concrete (Colemanite), the mechanical structure 3 with another cast iron (GS45-3), the poloidal coil with another copper-epoxy resin mixture and finally the transformer core region with a low carbon steel (Nomatil). The chemical compositions of these materials are given in Table 1, and correspond to averaged values from analyses of actual JET materials made during the commissioning period.

	Inconel 600	**TF coil**	**GGG Ni-Mn**	**Con-crete**	**GS 45-3**	**PF coil**	**Nomatil**
Ni	75.11	-	13.9	-	0.12	-	300ppm
Cr	15.75	-	800ppm	-	900ppm	-	150ppm
Fe	7.9	-	74.63	1.76	98.14	-	99.17
Na	-	300ppm	-	600ppm	-	470ppm	-
Al	0.16	0.29	-	0.72	210ppm	0.47	-
Ca	-	0.44	-	7.11	-	0.7	-
C	60ppm	1.59	2.64	700ppm	0.2	2.52	27ppm
Ba	-	-	-	38.07	-	-	-
Cu	600ppm	93.9	300ppm	-	0.2	90.41	470ppm
O	-	2.35	-	36.36	-	3.73	-
Mn	0.41	-	6.01	-	0.67	-	0.56
Mo	100ppm	-	-	-	0.1	-	-
Si	0.35	0.97	2.55	3.81	0.45	1.53	170ppm
Ti	0.2	-	300ppm	100ppm	-	-	-
Co	500ppm	-	-	-	-	-	-
Nb	300ppm	-	-	-	-	-	-
S	20ppm	-	50ppm	9.14	40ppm	-	190ppm
P	70ppm	-	500ppm	-	50ppm	-	0.17
Mg	300ppm	-	700ppm	0.17	-	-	-
Pb	10ppm	-	-	-	-	-	-
Sn	100ppm	-	50ppm	-	-	-	-
Sr	-	-	-	0.93	-	-	-
B	20ppm	0.15	-	0.84	-	0.23	-
K	-	-	-	0.1	-	-	-
N	50ppm	130ppm	-	-	-	210ppm	190ppm
H	-	0.15	-	0.85	-	0.23	-
Ag	-	900ppm	-	-	-	890ppm	-

Table 1. **Chemical analyses of JET main materials:** In % weight or ppm (parts per million)

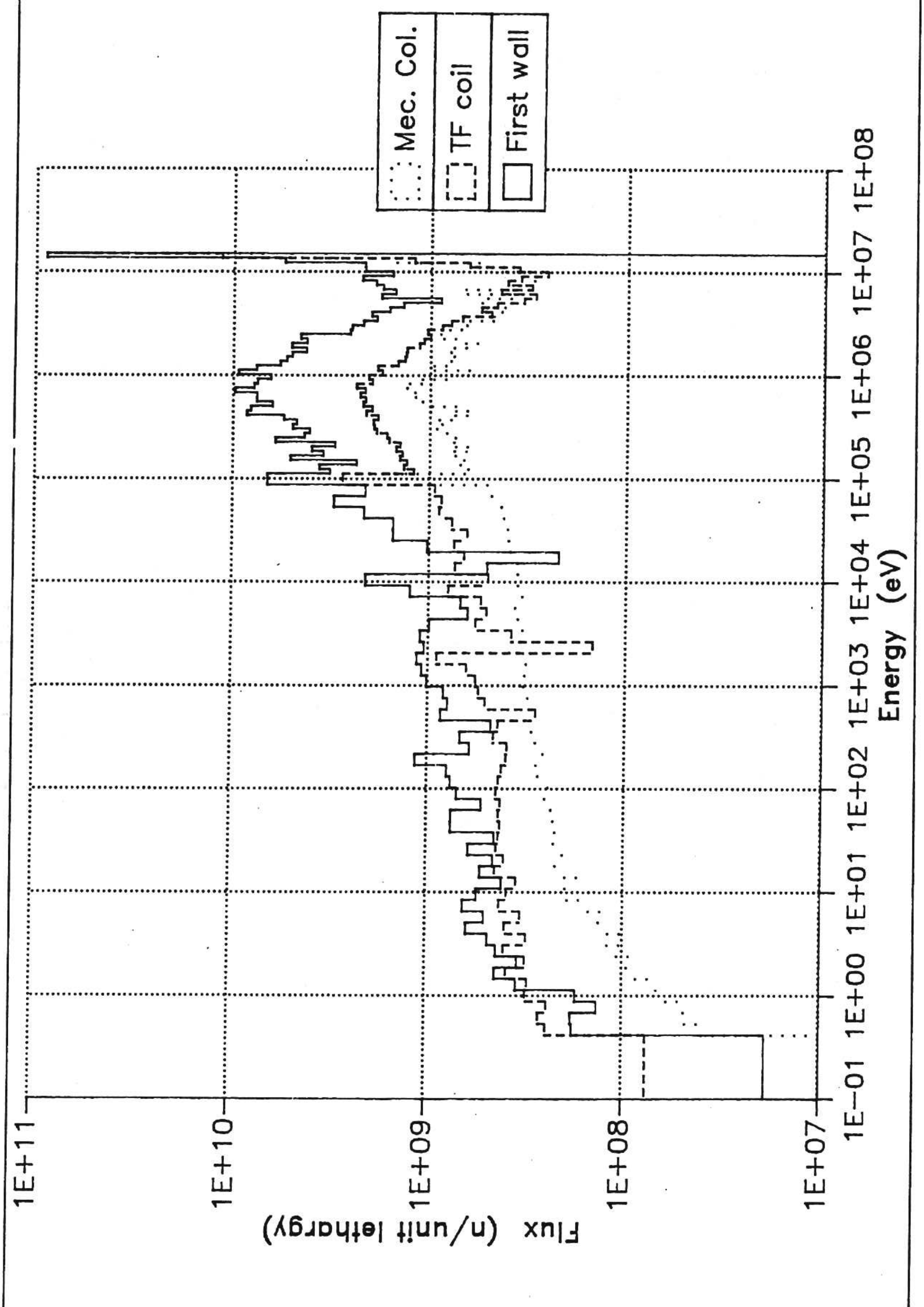

Figure 1. Neutron fluxes: Histogram of the flux in different regions

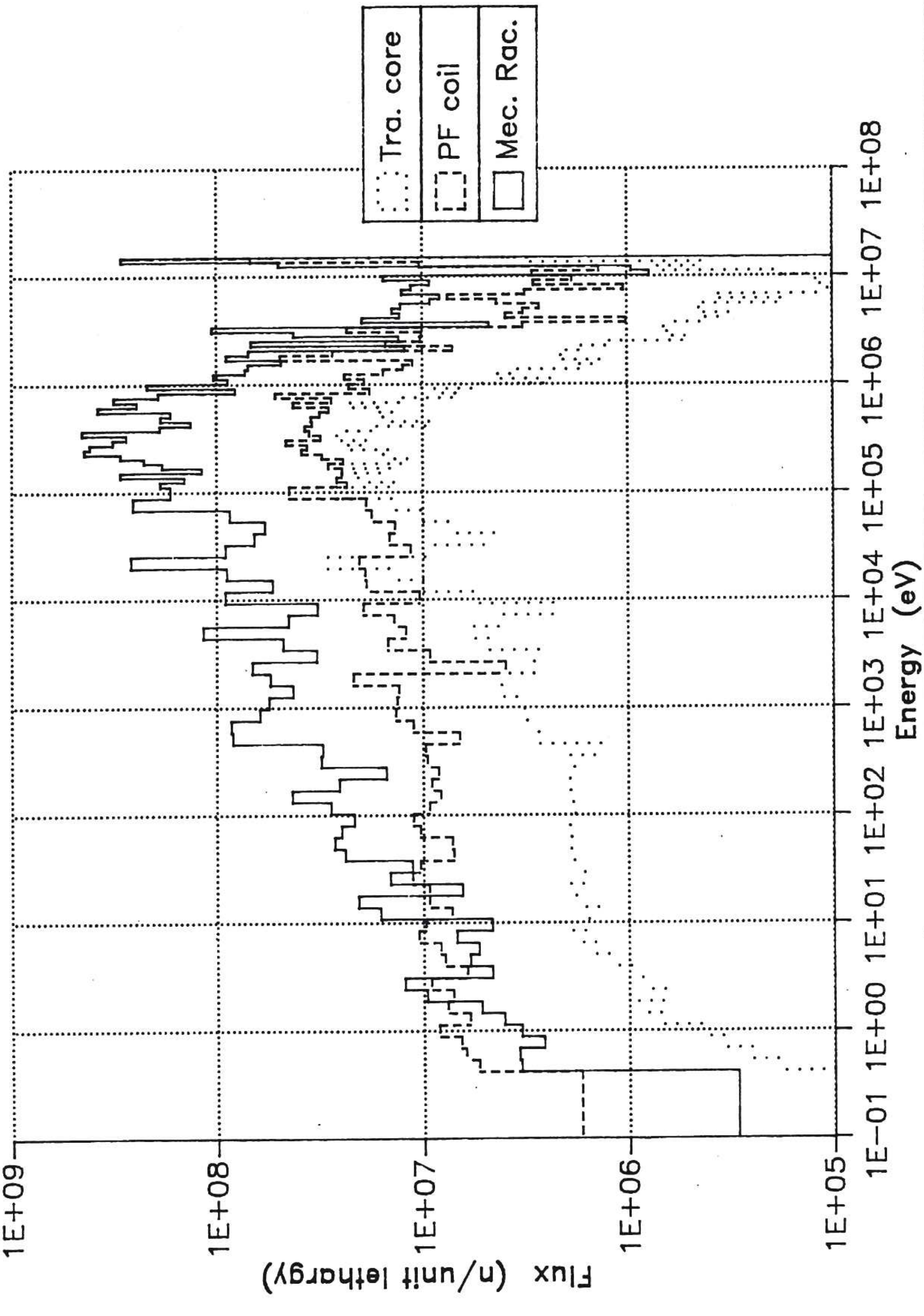

Figure 2. **Neutron fluxes:** Histogram of the flux in different regions

3. CODE SPECIFICITIES

To be able to compare results one has to be aware of the methods used in the different codes since they could lead to slight discrepancies. Apart from the fact that the codes employ different units for the activity no special preparation has been necessary to compare these data. However, while FISPACT and ANITA give the dose rate as calculated for an infinite, thick slab of material, REAC gives it at a distance of one metre in air from an isotropic point source. Appendix 1 explains the normalisation applied to REAC data to include them in the benchmark. The necessary simplification could lead to a slight error depending on the material in which the gammas are emitted particularly when the range of gamma-energies is very wide. This is likely to be more important for short cooling times .

Another difference is that while FISPACT sums the dose over a 24-group gamma scheme ANITA employs a different method. It uses the mean energy of the gamma spectra of a given isotope. This does not seem to greatly influence the overall dose. However, this could lead to discrepancies when applied to a particular gamma-emitter for which very low energy gamma-rays are important. Meanwhile it is clear that these dose rate values should only be considered as estimates. Proper gamma transport calculations will be needed to refine those data with complete geometrical specification to allow their use in radiological assays.

All the three codes used decay libraries which have been separately formed and upgraded. Differences in their libraries could, therefore, be an important source of disagreement between the code predictions. Variations in the half-life could be important, particularly for isomer states, however, such differences do not apply for the main isotopes included in this benchmark. Differences in the gamma ray data could lead to disparity in dose rates even where there is no difference in the predicted activity of a specific isotope.

4. THE BENCHMARK STUDY

In this section the results of the seven different calculations made with the three codes are examined in detail. To restrict the amount of data involved to a manageable level the total activity and gamma dose rates are presented in graphical and tabular form for all the defined time steps : from shutdown to 5000 years , with a more detailed comparison at shutdown of the main isotopes which allows those responsible for any discrepancies to be identified.
It is important to keep in mind that the graphs are logarithmic on both axes, this implies that differences of a few percent are not perceptible.

4.1 THE FIRST WALL REGION

The main elements present in Inconel at the beginning of the ɪradiation are Ni 75%, Cr 16%, Fe 8% and 500 ppm of Co. An extremely good agreement can be seen in Fig 3. between the specific activities predictions of FISPACT and ANITA, however REAC does not give the same answer at short cooling times. This can be explained by a greater production of short lived isotopes like Co58, Co57, Al28, V49 and V52, which represent the major activity shortly after shutdown, and by a predicted inventory of Co60 which is twice that of FISPACT and ANITA.
This difference is shown on Fig.7 where we have compared the specific activity of these important isotopes at shutdown, and have calculated their ratio. This difference of up to 70% at short cooling time disappears after 100 years when most of those isotopes have decayed to an unimportant level. After that, only two isotopes are of significance, namely Ni63 and Ni59, for which the production rates are in very good agreement for all the three codes.

It may be noted that if agreement exists on the specific activity this does not imply the same for the dose rate as this quantity may not involve the same set of isotopes. However, Fig.4 again shows a good agreement between FISPACT and ANITA while REAC gives an higher response at all cooling times. At times up to 100 years this differences arises as a result of variations in the predicted inventories of the gamma emitters Co58, Co57 and Co60. The discrepancy at longer times arises because REAC predicts a Nb94 inventory approximatly three times that of FISPACT or ANITA. The maximum standard deviation, of about a factor of 5, appears after 100 years cooling time.
In this case the disagreement in dose rates is traceable to the difference in activity of the isotopes involved, however this may not always be the case if the gamma data are not the same.
One should note that even between FISPACT and ANITA slight discrepancies occur for the production of Co60 and Co60m and this is certainly related to a different branching ratio used for the production of the isomer. The same behaviour seems to occur for REAC and also involves the second Co metastable isomer Co58m.

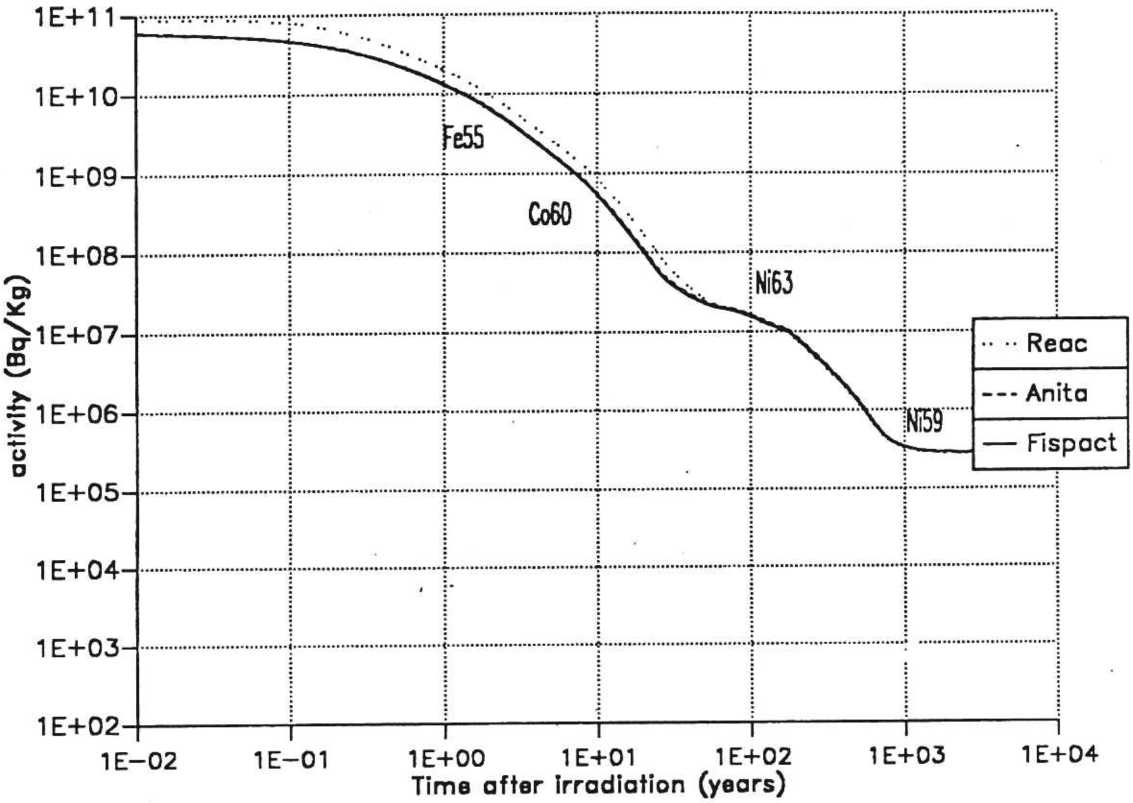

Figure 3. Inconel 600: First wall specific activity versus cooling time.

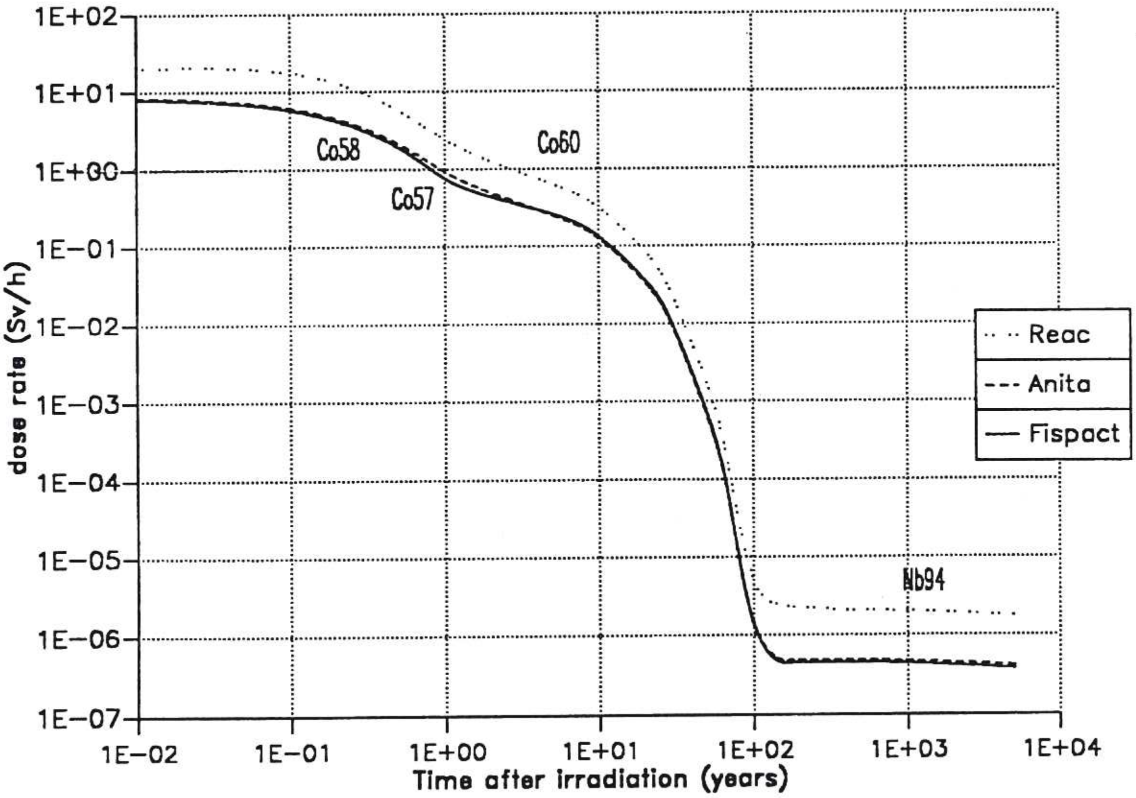

Figure 4. Inconel 600: First wall gamma dose rate versus cooling time.

	Fispact	Anita	A/F	Reac	R/F
shutdown	8.29E+10	8.30E+10	1.00E+00	1.02E+11	1.23E+00
1 day	6.34E+10	6.42E+10	1.01E+00	8.55E+10	1.35E+00
1 month	4.90E+10	4.96E+10	1.01E+00	8.27E+10	1.69E+00
6 months	2.30E+10	2.32E+10	1.01E+00	3.63E+10	1.57E+00
1 year	1.31E+10	1.34E+10	1.02E+00	2.03E+10	1.55E+00
2 years	6.42E+09	6.53E+09	1.02E+00	9.77E+09	1.52E+00
5 years	1.75E+09	1.77E+09	1.02E+00	2.67E+09	1.53E+00
10 years	5.37E+08	5.51E+08	1.03E+00	8.62E+08	1.61E+00
20 years	1.02E+08	1.07E+08	1.05E+00	1.75E+08	1.72E+00
30 years	4.07E+07	4.28E+07	1.05E+00	6.27E+07	1.54E+00
50 years	2.30E+07	2.39E+07	1.04E+00	2.60E+07	1.13E+00
70 years	1.93E+07	2.00E+07	1.04E+00	1.96E+07	1.02E+00
100 years	1.57E+07	1.62E+07	1.04E+00	1.53E+07	9.77E-01
150 years	1.12E+07	1.16E+07	1.04E+00	1.08E+07	9.67E-01
200 years	7.98E+06	8.26E+06	1.03E+00	7.71E+06	9.66E-01
500 years	1.27E+06	1.30E+06	1.03E+00	1.23E+06	9.67E-01
1000 years	3.38E+05	3.38E+05	1.00E+00	3.28E+05	9.70E-01
5000 years	2.96E+05	2.95E+05	9.99E-01	2.87E+05	9.70E-01

Figure 5. **Inconel 600:** First wall specific activity in Bq/Kg at given cooling time

	Fispact	Anita	A/F	Reac	R/F
shutdown	1.00E+01	1.02E+01	1.01E+00	2.11E+01	2.10E+00
1 day	8.38E+00	8.72E+00	1.04E+00	1.90E+01	2.26E+00
1 month	6.21E+00	6.54E+00	1.05E+00	1.86E+01	2.99E+00
6 months	1.90E+00	2.13E+00	1.12E+00	5.80E+00	3.06E+00
1 year	7.54E-01	9.22E-01	1.22E+00	2.44E+00	3.24E+00
2 years	4.35E-01	4.91E-01	1.13E+00	1.26E+00	2.90E+00
5 years	2.61E-01	2.53E-01	9.67E-01	6.40E-01	2.45E+00
10 years	1.34E-01	1.27E-01	9.50E-01	3.21E-01	2.41E+00
20 years	3.58E-02	3.40E-02	9.50E-01	8.63E-02	2.41E+00
30 years	9.60E-03	9.12E-03	9.50E-01	2.32E-02	2.41E+00
50 years	6.91E-04	6.57E-04	9.50E-01	1.68E-03	2.42E+00
70 years	5.03E-05	4.77E-05	9.48E-01	1.24E-04	2.46E+00
100 years	1.41E-06	1.41E-06	9.97E-01	5.11E-06	3.62E+00
150 years	4.60E-07	4.94E-07	1.07E+00	2.45E-06	5.33E+00
200 years	4.58E-07	4.92E-07	1.07E+00	2.28E-06	4.98E+00
500 years	4.53E-07	4.86E-07	1.07E+00	2.08E-06	4.60E+00
1000 years	4.45E-07	4.78E-07	1.08E+00	2.04E-06	4.59E+00
5000 years	3.83E-07	4.18E-07	1.09E+00	1.77E-06	4.63E+00

Figure 6. **Inconel 600:** First wall gamma dose rate in Sv/h at given cooling time

	Fispact	Anita	A/F	Reac	R/F
Al 28	1.74E+08	1.74E+08	1.00E+00	2.27E+08	1.30E+00
V 49	1.66E+08	1.66E+08	1.00E+00	1.86E+08	1.12E+00
V 52	1.27E+09	1.27E+09	9.99E−01	1.45E+09	1.14E+00
Cr 51	4.58E+09	4.58E+09	9.99E−01	4.66E+09	1.02E+00
Mn 54	4.38E+08	4.37E+08	9.99E−01	4.15E+08	9.49E−01
Mn 56	1.27E+09	1.26E+09	9.93E−01	1.25E+09	9.88E−01
Fe 55	4.14E+09	4.11E+09	9.92E−01	5.53E+09	1.33E+00
Co 57	2.08E+10	2.07E+10	9.94E−01	3.04E+10	1.46E+00
Co 58	2.96E+10	2.94E+10	9.92E−01	4.05E+10	1.37E+00
Co 58m	1.56E+10	1.55E+10	9.92E−01	1.21E+10	7.73E−01
Co 60	6.98E+08	7.57E+08	1.08E+00	1.39E+09	2.00E+00
Co 60m	2.34E+09	1.58E+09	6.77E−01	1.52E+09	6.50E−01
Ni 57	1.01E+09	1.00E+09	9.92E−01	1.07E+09	1.06E+00
Ni 59	3.07E+05	3.07E+05	9.99E−01	2.96E+05	9.61E−01
Ni 63	3.07E+07	3.18E+07	1.04E+00	2.96E+07	9.65E−01
Nb 94	1.15E+03	1.24E+03	1.08E+00	3.36E+03	2.91E+00
total	8.22E+10	8.09E+10	9.85E−01	1.01E+11	1.23E+00
real	8.29E+10	8.30E+10	1.00E+00	1.02E+11	1.23E+00

Figure 7. Inconel 600: Main first wall isotopes inventory in Bq/Kg at shutdown

4.2 THE TOROIDAL COIL REGION

The coils are made of hollow section copper conductors isolated by resin impregnated glass cloth that gives an inventory at the beginning of Cu 94%, O 3%, C 2% and Si 1% with a very important impurity of silver at 900ppm. Here again quite a good agreement between specific activities predicted by FISPACT and ANITA exists, as it can be see on Fig.8 REAC gives a specific activity value higher than FISPACT and ANITA at times up to approximatly 20 years and lower thereafter. It is very difficult to pinpoint the important isotopes at very short cooling times, as their number are over 200, and our knowledge on their characterics is based on systematics. This generally explains why such disparities occur.

At short cooling times the disparity arises from the high production of Co60 and Co60m predicted by REAC, as can be seen in Fig.12, while after 10 years the difference arises because the Ni63 production prediction of REAC is 0.2 times that of FISPACT or ANITA. The difference between FISPACT and ANITA at around 5000 years is due to differences in C14 production.
It should be noted here that the bump in the REAC curve at around 0.1y cooling time is due to H3 production for which FISPACT has not be implemented to take accounts of the emitted particles yet, such as H3, H2 or He and for which ANITA gives a negligeable amount.

The disparity in the estimated gamma dose rates for short cooling times, shown in Fig.9, can also be explained by the higher production of Co60 give by REAC, while after 100 years the difference arise because there is no data in the REAC gamma library for the Ag108m. All the three codes reach a plateau due to the dose rate of Al26, the level being governed by the activity of this particular isotope. This means that, because of the disparity in the activity predictions, there is a proportional disparity in the dose rate estimation.

For this region FISPACT and ANITA agree within 10% for both activity and gamma dose values but still give a different prediction for the Co60 and Co60m, while the REAC specific activity prediction could be higher by a factor of as much as 8 or lower by a factor of 0.2 . Because of the missing data on Ag108m the standard deviation for the gamma dose rate could be wide.

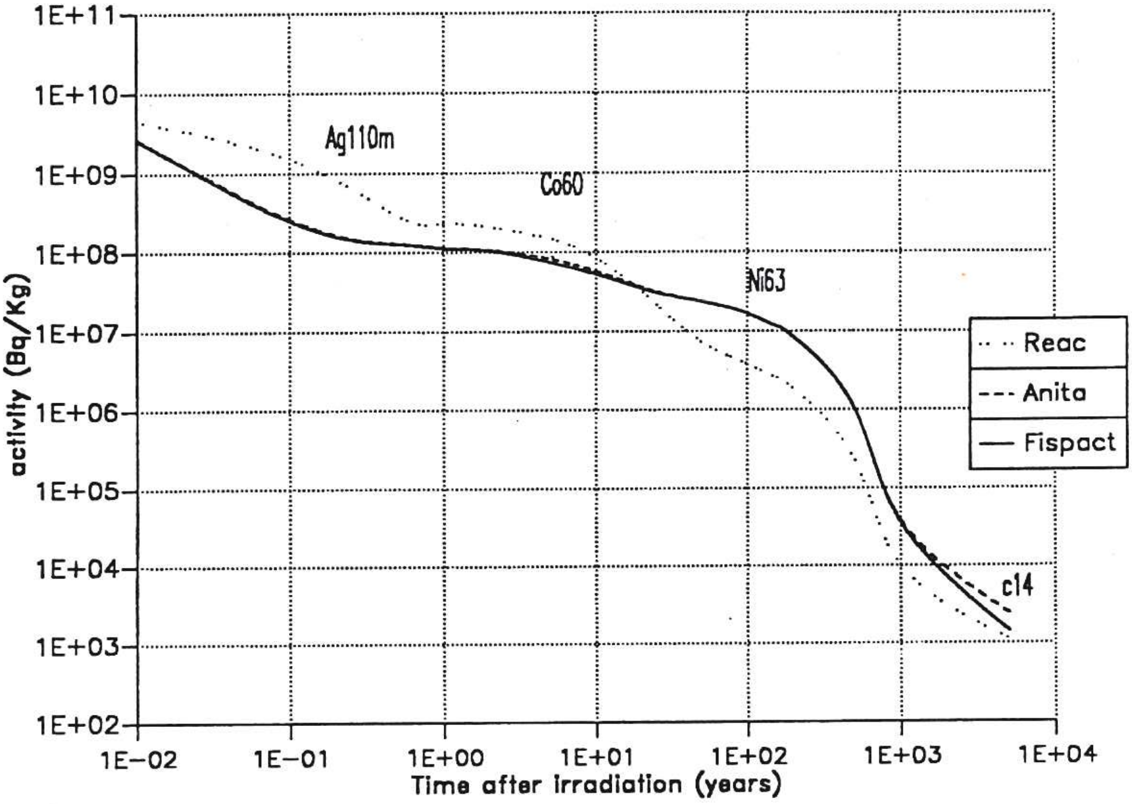

Figure 8. Copper: Toroidal coil specific activity versus cooling time.

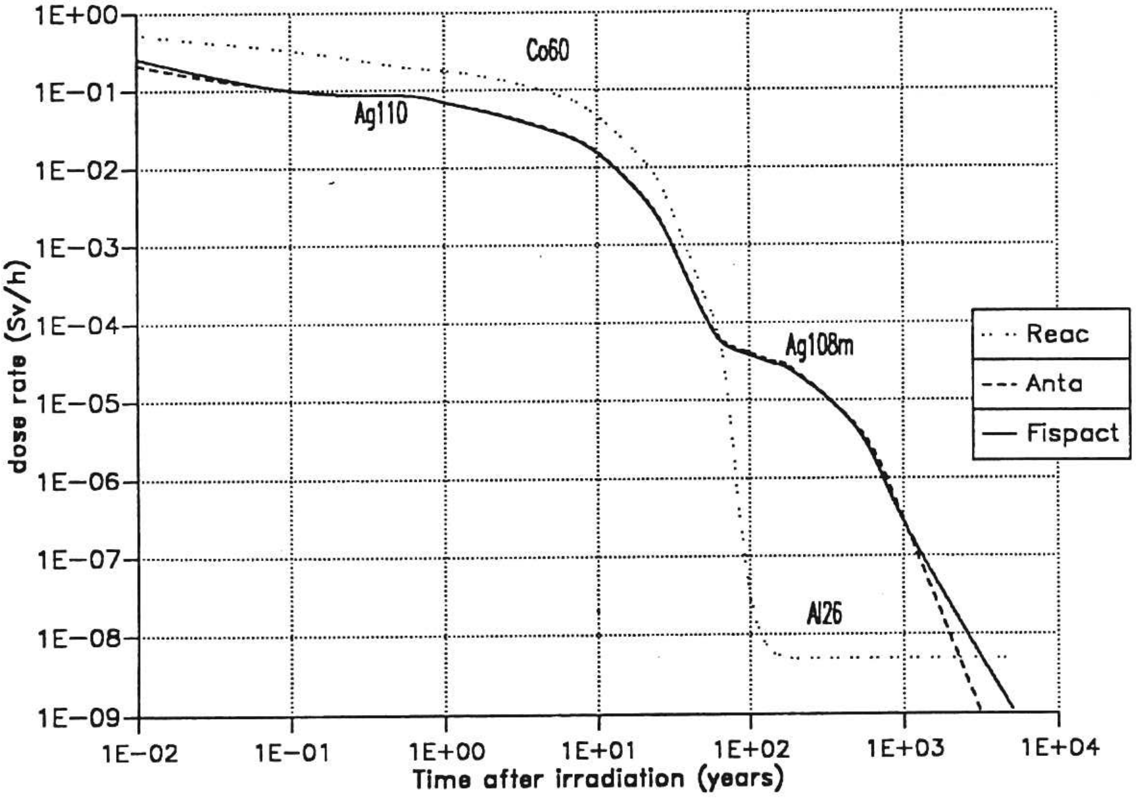

Figure 9. Copper: Toroidal coil gamma dose rate versus cooling time.

	Fispact	Anita	A/F	Reac	R/F
shutdown	4.49E+10	4.49E+10	9.99E−01	3.51E+10	7.80E−01
1 day	9.02E+09	8.99E+09	9.97E−01	7.18E+09	7.97E−01
1 month	1.99E+08	2.13E+08	1.07E+00	1.75E+09	8.78E+00
6 months	1.57E+08	1.70E+08	1.08E+00	2.94E+08	1.87E+00
1 year	1.32E+08	1.45E+08	1.10E+00	2.62E+08	1.98E+00
2 years	1.05E+08	1.17E+08	1.12E+00	2.19E+08	2.09E+00
5 years	7.41E+07	8.26E+07	1.11E+00	1.49E+08	2.01E+00
10 years	5.26E+07	5.72E+07	1.09E+00	8.54E+07	1.63E+00
20 years	3.48E+07	3.63E+07	1.04E+00	3.27E+07	9.41E−01
30 years	2.86E+07	2.92E+07	1.02E+00	1.60E+07	5.60E−01
50 years	2.37E+07	2.38E+07	1.01E+00	7.37E+06	3.11E−01
70 years	2.05E+07	2.06E+07	1.00E+00	5.18E+06	2.52E−01
100 years	1.67E+07	1.67E+07	1.00E+00	3.83E+06	2.29E−01
150 years	1.18E+07	1.18E+07	1.00E+00	2.64E+06	2.24E−01
200 years	8.36E+06	8.35E+06	9.99E−01	1.87E+06	2.24E−01
500 years	1.05E+06	1.05E+06	1.00E+00	2.41E+05	2.29E−01
1000 years	3.62E+04	3.79E+04	1.05E+00	1.02E+04	2.81E−01
5000 years	1.44E+03	2.45E+03	1.70E+00	1.13E+03	7.83E−01

Figure 10. **Copper:** Toroidal coil specific activity in Bq/Kg at given cooling time

	Fispact	Anita	A/F	Reac	R/F
shutdown	2.65E+00	2.41E+00	9.09E−01	3.69E+00	1.39E+00
1 day	4.93E−01	3.77E−01	7.64E−01	7.52E−01	1.53E+00
1 month	1.07E−01	1.06E−01	9.93E−01	3.41E−01	3.19E+00
6 months	8.67E−02	8.65E−02	9.97E−01	2.05E−01	2.36E+00
1 year	6.99E−02	7.05E−02	1.01E+00	1.79E−01	2.56E+00
2 years	5.11E−02	5.21E−02	1.02E+00	1.45E−01	2.84E+00
5 years	2.99E−02	3.08E−02	1.03E+00	9.23E−02	3.09E+00
10 years	1.53E−02	1.58E−02	1.03E+00	4.69E−02	3.06E+00
20 years	4.15E−03	4.29E−03	1.03E+00	1.28E−02	3.08E+00
30 years	1.15E−03	1.19E−03	1.03E+00	3.43E−03	2.98E+00
50 years	1.29E−04	1.35E−04	1.05E+00	2.48E−04	1.92E+00
70 years	5.05E−05	5.38E−05	1.07E+00	1.79E−05	3.54E−01
100 years	3.81E−05	4.08E−05	1.07E+00	3.51E−07	9.21E−03
150 years	2.90E−05	3.10E−05	1.07E+00	5.65E−09	1.95E−04
200 years	2.20E−05	2.36E−05	1.07E+00	4.99E−09	2.27E−04
500 years	4.29E−06	4.58E−06	1.07E+00	4.99E−09	1.16E−03
1000 years	2.81E−07	2.98E−07	1.06E+00	4.99E−09	1.78E−02
5000 years	1.13E−09	1.03E−10	9.04E−02	4.97E−09	4.38E+00

Figure 11. **Copper:** Toroidal coil gamma dose rate in Sv/h at given cooling time

	Fispact	Anita	A/F	Reac	R/F
Co 60	8.00E+07	9.40E+07	1.18E+00	2.26E+08	2.82E+00
Co 60m	2.21E+08	2.44E+08	1.10E+00	3.26E+08	1.48E+00
Co 62	5.91E+07	5.87E+07	9.93E-01	4.00E+07	6.76E-01
Ni 63	3.31E+07	3.31E+07	9.99E-01	7.23E+06	2.18E-01
Ni 65	8.18E+07	8.20E+07	1.00E+00	6.99E+07	8.54E-01
Cu 62	4.02E+09	4.02E+09	9.99E-01	2.98E+09	7.42E-01
Cu 64	3.25E+10	3.25E+10	9.99E-01	2.53E+10	7.78E-01
Cu 66	5.66E+09	5.67E+09	1.00E+00	4.45E+09	7.86E-01
Ag 108m	1.79E+05	1.94E+05	1.08E+00	1.44E+05	8.05E-01
Ag 108	1.71E+08	1.82E+08	1.06E+00	1.33E+08	7.74E-01
Ag 110m	7.73E+07	7.73E+07	1.00E+00	6.38E+07	8.24E-01
Ag 110	1.43E+09	1.43E+09	9.99E-01	1.18E+09	8.24E-01
Al 26	1.52E+00	1.52E-01	9.90E-02	5.89E+00	3.86E+00
total	4.44E+10	4.44E+10	1.00E+00	3.48E+10	7.84E-01
real	4.49E+10	4.49E+10	9.99E-01	3.51E+10	7.80E-01

Figure 12. Copper: Toroidal coil isotopes inventory in Bq/Kg at shutdown

4.3 THE MECHANICAL STRUCTURE REGION

For this region calculations were performed for three materials with three different irradiation conditions involving both the fluence and the flux profile.

4.3.1 Inner mechanical structure with GGG Ni-Mn (cast iron)

The GGG Ni-Mn is a cast austenitic iron mainly composed of Fe 74%, Ni 14% and Mn 6%. In this case there is good agreement, as shown in Fig.13, between the specific activities predicted by ANITA and REAC at all times, while FISPACT gives a lower answer for short cooling times. This is due to a lower prediction for nearly all the important isotopes such as Mn54, Fe55, Cr51, Co58 and Co57 at short cooling times, while after that all the codes agree very well on the production of Ni63 and Ni59.
In Fig.17 the very different predictions given by the three codes for the inventories of Co60 and Co60m may be noted. This particular isotope could only arise from other elements since no Co had been included at the beginning of the irradiation.

Fig.14 shows the estimated gamma dose rates for this material. Before 100 years of cooling time the three codes follow the same previous pattern for the same reasons but here REAC gives slightly higher results as it estimates the highest amount of Co60. The disparity after this period is due to disparities in the prediction for Sn121m where differences exist between the three codes; firstly on the predicted amount and secondly on the gamma dose attributed to this particular isotope.

In this case an agreement within 10% exists between REAC and ANITA but FISPACT diverges for short cooling times in prediction of the specific activity. The gamma dose rate behaviour follows the activity behaviour for the set of isotopes involved exepting that for Sn121m.

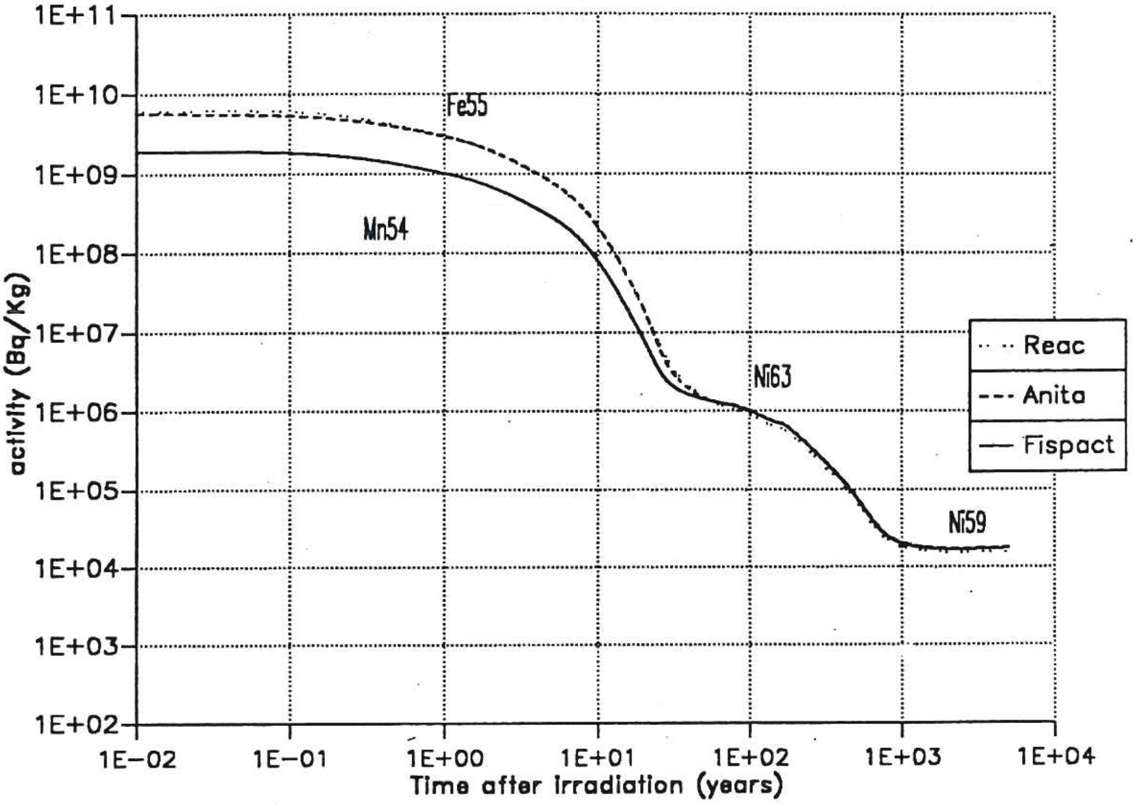

Figure 13. GGG Ni-Mn: Mechanical structure specific activity versus cooling time.

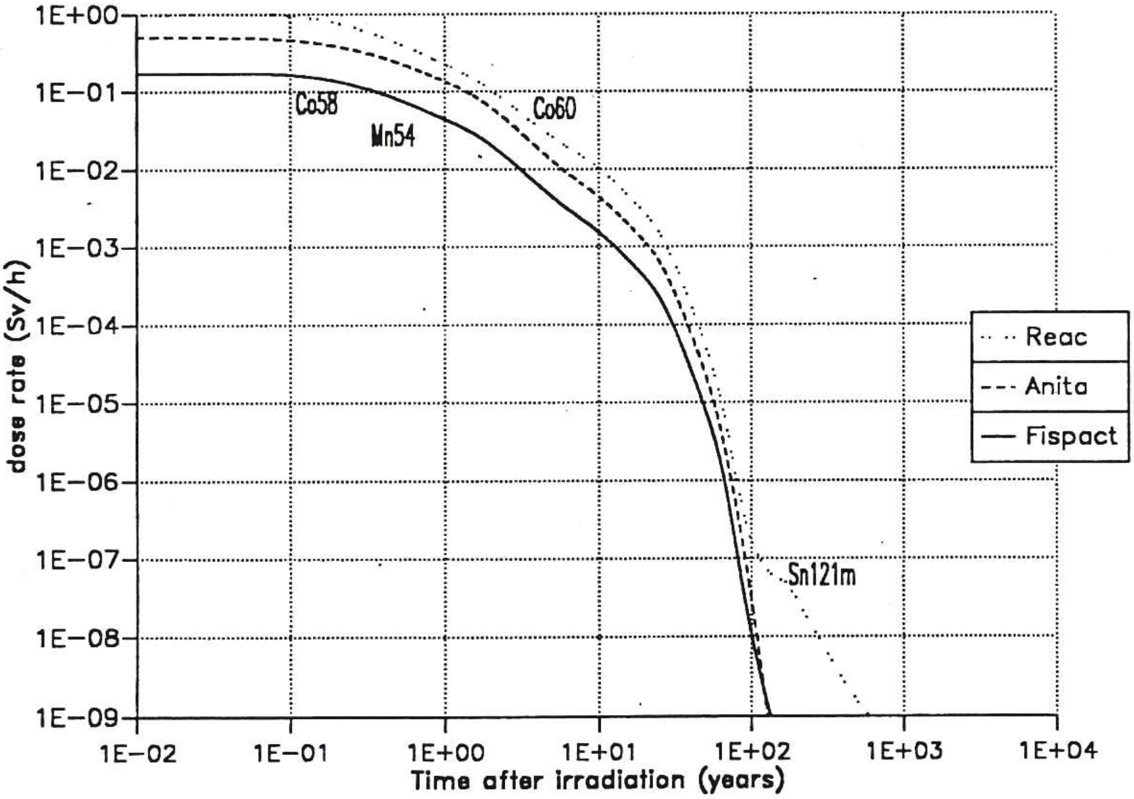

Figure 14. GGG Ni-Mn: Mechanical structure gamma dose rate versus cooling time.

	Fispact	Anita	A/F	Reac	R/F
shutdown	5.52E+09	1.10E+10	1.99E+00	1.07E+10	1.93E+00
1 day	2.12E+09	6.14E+09	2.90E+00	6.24E+09	2.94E+00
1 month	1.87E+09	5.42E+09	2.90E+00	6.13E+09	3.28E+00
6 months	1.32E+09	3.84E+09	2.91E+00	4.01E+09	3.04E+00
1 year	1.01E+09	2.94E+09	2.90E+00	2.97E+09	2.94E+00
2 years	6.89E+08	1.96E+09	2.84E+00	1.94E+09	2.82E+00
5 years	2.80E+08	7.72E+08	2.76E+00	7.59E+08	2.71E+00
10 years	7.77E+07	2.11E+08	2.72E+00	2.09E+08	2.69E+00
20 years	7.93E+06	1.91E+07	2.40E+00	2.02E+07	2.55E+00
30 years	2.19E+06	3.32E+06	1.52E+00	3.93E+06	1.79E+00
50 years	1.41E+06	1.47E+06	1.04E+00	1.48E+06	1.04E+00
70 years	1.22E+06	1.25E+06	1.02E+00	1.13E+06	9.26E-01
100 years	9.95E+05	1.02E+06	1.02E+00	8.82E+05	8.86E-01
150 years	7.09E+05	7.25E+05	1.02E+00	6.21E+05	8.76E-01
200 years	5.07E+05	5.18E+05	1.02E+00	4.44E+05	8.75E-01
500 years	7.93E+04	8.11E+04	1.02E+00	6.98E+04	8.81E-01
1000 years	2.00E+04	2.05E+04	1.03E+00	1.81E+04	9.04E-01
5000 years	1.74E+04	1.79E+04	1.03E+00	1.58E+04	9.08E-01

Figure 15. **GGG Ni-Mn:** Mechanical structure activity in Bq/Kg at given cooling time

	Fispact	Anita	A/F	Reac	R/F
shutdown	1.71E+00	2.31E+00	1.35E+00	3.21E+00	1.87E+00
1 day	2.10E-01	5.81E-01	2.77E+00	1.00E+00	4.77E+00
1 month	1.69E-01	4.75E-01	2.81E+00	9.84E-01	5.81E+00
6 months	7.91E-02	2.34E-01	2.96E+00	4.22E-01	5.34E+00
1 year	4.38E-02	1.35E-01	3.09E+00	2.26E-01	5.17E+00
2 years	2.03E-02	6.23E-02	3.08E+00	1.05E-01	5.18E+00
5 years	4.33E-03	1.26E-02	2.91E+00	2.60E-02	6.01E+00
10 years	1.53E-03	4.38E-03	2.87E+00	1.03E-02	6.73E+00
20 years	3.99E-04	1.16E-03	2.90E+00	2.74E-03	6.86E+00
30 years	1.07E-04	3.10E-04	2.91E+00	7.36E-04	6.90E+00
50 years	7.67E-06	2.23E-05	2.91E+00	5.33E-05	6.94E+00
70 years	5.60E-07	1.60E-06	2.86E+00	3.98E-06	7.10E+00
100 years	1.11E-08	3.10E-08	2.80E+00	1.76E-07	1.59E+01
150 years	4.62E-10	9.71E-11	2.10E-01	5.47E-08	1.18E+02
200 years	4.43E-10	3.46E-11	7.81E-02	2.95E-08	6.65E+01
500 years	4.18E-10	1.28E-11	3.06E-02	1.55E-09	3.71E+00
1000 years	3.77E-10	1.23E-11	3.25E-02	8.96E-10	2.38E+00
5000 years	4.99E-11	1.21E-11	2.43E-01	8.70E-10	1.74E+01

Figure 16. **GGG Ni-Mn:** Mechanical structure dose rate in Sv/h at given cooling time

	Fispact	Anita	A/F	Reac	R/F
Cr 51	2.92E+07	8.82E+07	3.02E+00	6.72E+07	2.30E+00
Cr 55	2.95E+07	9.07E+07	3.07E+00	5.70E+07	1.93E+00
Mn 54	3.63E+08	1.11E+09	3.07E+00	9.78E+08	2.70E+00
Mn 56	2.99E+09	3.77E+09	1.26E+00	3.47E+09	1.16E+00
Fe 55	9.59E+08	2.63E+09	2.75E+00	2.51E+09	2.62E+00
Co 57	2.22E+08	7.49E+08	3.37E+00	1.02E+09	4.59E+00
Co 58	4.77E+08	1.19E+09	2.49E+00	1.52E+09	3.18E+00
Co 58m	2.64E+08	6.38E+08	2.42E+00	4.63E+08	1.75E+00
Co 60	7.84E+06	2.57E+07	3.28E+00	4.43E+07	5.65E+00
Co 60m	2.89E+07	5.31E+07	1.84E+00	4.90E+07	1.70E+00
Ni 59	1.82E+04	1.85E+04	1.02E+00	1.63E+04	8.97E-01
Ni 63	1.95E+06	2.00E+06	1.02E+00	1.71E+06	8.73E-01
Sn 121m	9.87E-02	2.22E+02	2.25E+03	3.94E+03	3.99E+04
total	5.37E+09	1.05E+10	1.96E+00	1.02E+10	1.89E+00
real	5.52E+09	1.10E+10	1.99E+00	1.07E+10	1.93E+00

Figure 17. GGG Ni-Mn: Main mech. structure isotopes inventory in Bq/Kg at shutdown

4.3.2 Mechanical structure with concrete (Colemanite)

The type of concrete known as Colemanite because of its high content of this sort of stone (which includes a substantial amout of boron) is mainly composed of Ba 38%, O 37%, S 9% ,Ca 7%, Si 4% with other minor constituents.

The specific activities predicted by REAC and ANITA are higher than these for FISPACT at short cooling times, as shown on Fig.18. This is due to differences in the estimated quantities of Ba135m and P32 produced. At longer times there is closer agreement but ANITA and REAC still give slightly larger predictions due to differences in the predicted inventories of Fe55 and Ba133. For cooling times greater than 100 years, where Ar39 is dominant, there is better agreement between FISPACT and REAC while ANITA still gives higher values.

Fig.19 shows the predicted gamma dose rates from Colemanite. The general trends are similar to those for the specific activity, but in this case at short cooling times it is the Ba131 which is responsible for the higher ANITA response. However, as Fig.22 shows, the difference arises from the gamma library because the activity predicted by FISPACT is actually higher. For longer cooling times the disparity between the predicted quantities of Ba133 produces the disparity in the dose rates between FISPACT and ANITA while REAC has no gamma library for this particular isotope.
For long cooling times the dose rate difference is explained by the different activity predictions for isotopes such as K40 and Al26.

In this case a disparity by up to a factor of 3 appears in the specific activity and much higher disparities are apparent for the dose rates, there are the result of missing data or differences in the gamma data library.

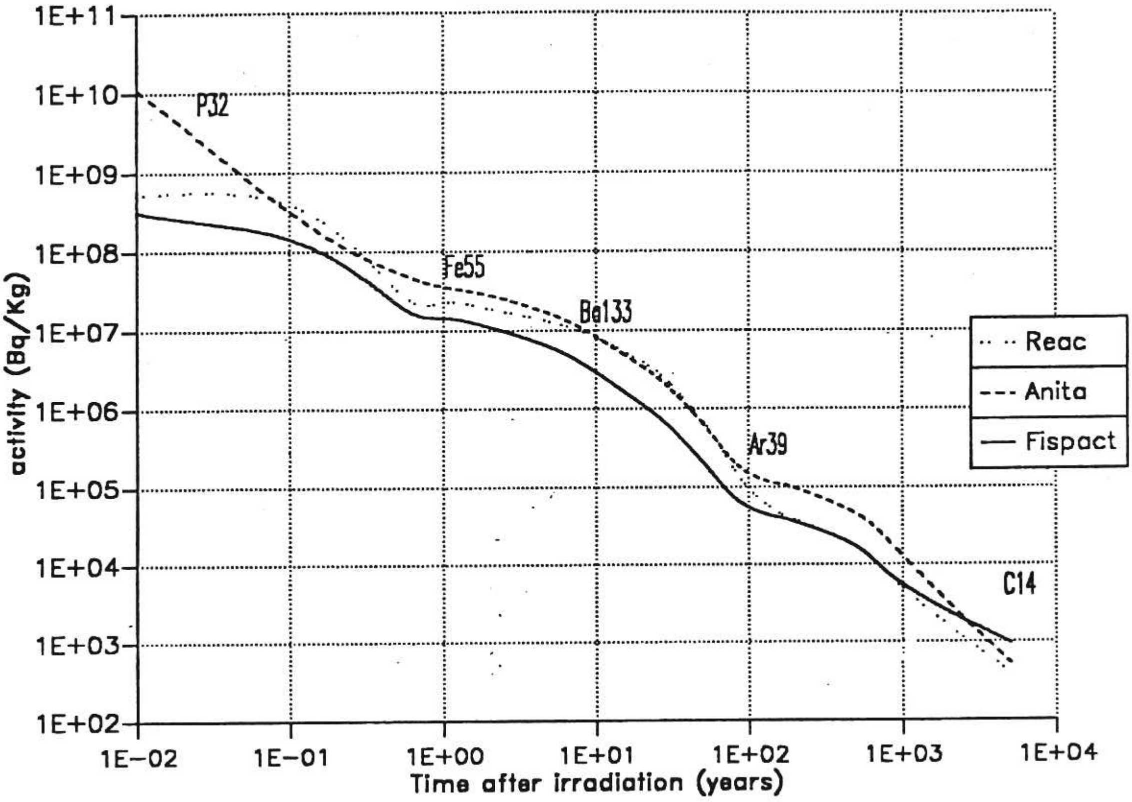

Figure 18. Colemanite: Mechanical structure specific activity versus cooling time.

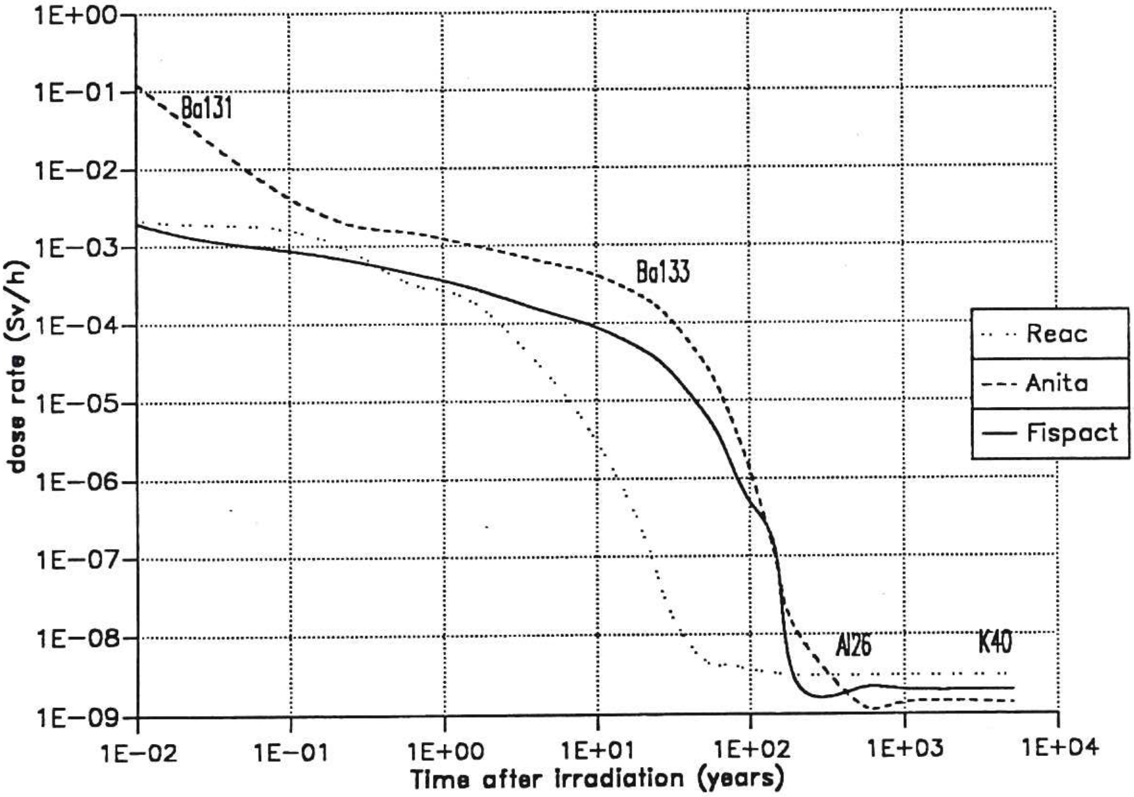

Figure 19. Colemanite: Mechanical structure gamma dose rate versus cooling time.

	Fispact	Anita	A/F	Reac	R/F
shutdown	1.17E+11	2.44E+11	2.08E+00	3.73E+09	3.19E−02
1 day	6.65E+08	5.57E+10	8.38E+01	5.36E+08	8.06E−01
1 month	1.63E+08	4.33E+08	2.66E+00	4.51E+08	2.77E+00
6 months	2.19E+07	5.50E+07	2.51E+00	3.29E+07	1.50E+00
1 year	1.45E+07	3.60E+07	2.48E+00	2.29E+07	1.58E+00
2 years	1.10E+07	2.80E+07	2.54E+00	1.89E+07	1.72E+00
5 years	6.11E+06	1.62E+07	2.65E+00	1.29E+07	2.11E+00
10 years	2.91E+06	8.21E+06	2.82E+00	8.07E+06	2.77E+00
20 years	1.14E+06	3.47E+06	3.04E+00	4.02E+06	3.52E+00
30 years	5.97E+05	1.86E+06	3.11E+00	2.19E+06	3.67E+00
50 years	2.06E+05	6.38E+05	3.10E+00	7.08E+05	3.44E+00
70 years	9.55E+04	2.81E+05	2.94E+00	2.65E+05	2.77E+00
100 years	5.45E+04	1.48E+05	2.72E+00	9.54E+04	1.75E+00
150 years	4.12E+04	1.11E+05	2.69E+00	4.91E+04	1.19E+00
200 years	3.53E+04	9.63E+04	2.73E+00	3.83E+04	1.09E+00
500 years	1.68E+04	4.47E+04	2.65E+00	1.69E+04	1.00E+00
1000 years	5.47E+03	1.27E+04	2.33E+00	4.99E+03	9.13E−01
5000 years	9.70E+02	5.32E+02	5.48E−01	4.00E+02	4.12E−01

Figure 20. Colemanite: Mechanical structure activity in Bq/Kg at given cooling time

	Fispact	Anita	A/F	Reac	R/F
shutdown	1.62E+01	2.31E+01	1.43E+00	2.02E+00	1.25E−01
1 day	7.13E−03	8.34E−01	1.17E+02	4.38E−03	6.14E−01
1 month	9.16E−04	2.34E−03	2.55E+00	1.70E−03	1.85E+00
6 months	4.89E−04	1.55E−03	3.17E+00	3.99E−04	8.17E−01
1 year	3.59E−04	1.23E−03	3.43E+00	2.72E−04	7.56E−01
2 years	2.43E−04	9.09E−04	3.74E+00	1.31E−04	5.37E−01
5 years	1.35E−04	5.89E−04	4.37E+00	2.01E−05	1.49E−01
10 years	8.75E−05	4.11E−04	4.70E+00	3.01E−06	3.44E−02
20 years	4.50E−05	2.16E−04	4.79E+00	2.05E−07	4.55E−03
30 years	2.39E−05	1.13E−04	4.72E+00	1.94E−08	8.10E−04
50 years	7.02E−06	3.12E−05	4.44E+00	4.75E−09	6.77E−04
70 years	2.21E−06	8.67E−06	3.92E+00	4.14E−09	1.87E−03
100 years	4.97E−07	1.31E−06	2.63E+00	3.65E−09	7.34E−03
150 years	9.00E−08	7.47E−08	8.30E−01	3.28E−09	3.65E−02
200 years	2.44E−09	1.11E−08	4.55E+00	3.09E−09	1.26E+00
500 years	2.05E−09	1.38E−09	6.72E−01	3.09E−09	1.51E+00
1000 years	2.04E−09	1.37E−09	6.73E−01	3.08E−09	1.51E+00
5000 years	2.04E−09	1.37E−09	6.75E−01	3.07E−09	1.51E+00

Figure 21. Colemanite: Mechanical structure dose rate in Sv/h at given cooling time

	Fispact	Anita	A/F	Reac	R/F
N 16	2.00E+08	5.68E+08	2.84E+00	1.96E+08	9.81E−01
Na 24	1.05E+07	2.81E+07	2.67E+00	1.03E+07	9.73E−01
K 40	3.12E+01	3.26E+01	1.04E+00	.	.
Al 26	8.38E−01	2.30E−01	2.75E−01	3.84E+00	4.58E+00
P 32	2.49E+08	6.99E+08	2.80E+00	2.54E+08	1.02E+00
Ar 37	1.32E+08	3.10E+08	2.35E+00	8.90E+07	6.72E−01
Ar 39	5.62E+04	1.60E+05	2.84E+00	5.91E+04	1.05E+00
Fe 55	1.21E+07	2.87E+07	2.37E+00	1.02E+07	8.40E−01
Sr 87m	1.56E+07	3.96E+07	2.55E+00	2.04E+07	1.31E+00
Ba 131	8.52E+06	4.46E+06	5.24E−01	3.27E+06	3.84E−01
Ba 133	3.59E+06	7.77E+06	2.17E+00	8.58E+06	2.39E+00
Ba 133m	1.34E+07	2.87E+07	2.14E+00	2.34E+07	1.74E+00
Ba 135m	4.22E+08	9.75E+10	2.31E+02	2.07E+08	4.90E−01
Ba 136m	2.05E+09	2.77E+09	1.36E+00	1.24E+09	6.03E−01
Ba 137m	1.14E+11	1.40E+11	1.23E+00	9.53E+08	8.39E−03
Ba 139	4.87E+07	1.42E+09	2.92E+01	5.07E+08	1.04E+01
total	1.17E+11	2.43E+11	2.08E+00	3.52E+09	3.01E−02
real	1.17E+11	2.44E+11	2.08E+00	3.73E+09	3.19E−02

Figure 22. Colemanite: Main mech. structure isotopes inventory in Bq/Kg at shutdown

4.3.3 Top mechanical structure with GS 45-3 (cast iron)

The GS 45-3 is a cast ferritic iron mainly composed of Fe 98%, Mn 0.7% and Si 0.4%.
Fig.23 shows a very good agreement on the specific activities for the three codes for short cooling times where Fe55 and Mn54 are dominant. But at around 70 years differences start to appear. This is initially due to the Ni63 estimate, which is 10 times lower for ANITA compared with FISPACT and REAC, as can be seen in Fig.27.
At later times, the difference between the predictions of REAC and FISPACT involves Nb91 production while differences from ANITA involves Nb93m and Mo93 production.
Note that we are dealing here with very low activity levels which are not really significant for industrial purposes, but which are still valid within this benchmark.

Fig.24 shows the predicted gamma dose rates from GS 45-3, the curves generally reflect those for the activity. REAC gives a higher answer at short cooling times because it predicts Co60 production 3 times higher that ANITA or FISPACT. This is significant for the dose rate but not for the activity because of its low level. At long cooling time REAC estimates a Mo93 production 3 times higher than FISPACT and 30 times higher than ANITA.
FISPACT and ANITA disagree for cooling times greater than 100 years because of their estimation of Nb94 which, as it is shown in Fig.27, is 10 times higher for FISPACT.

In this case a disparity by up to a factor 10 appears in the specific activity but most of the time the agreement is closer. Much higher disparities are apparent in the dose rate and are the result of dissension in activity prediction.

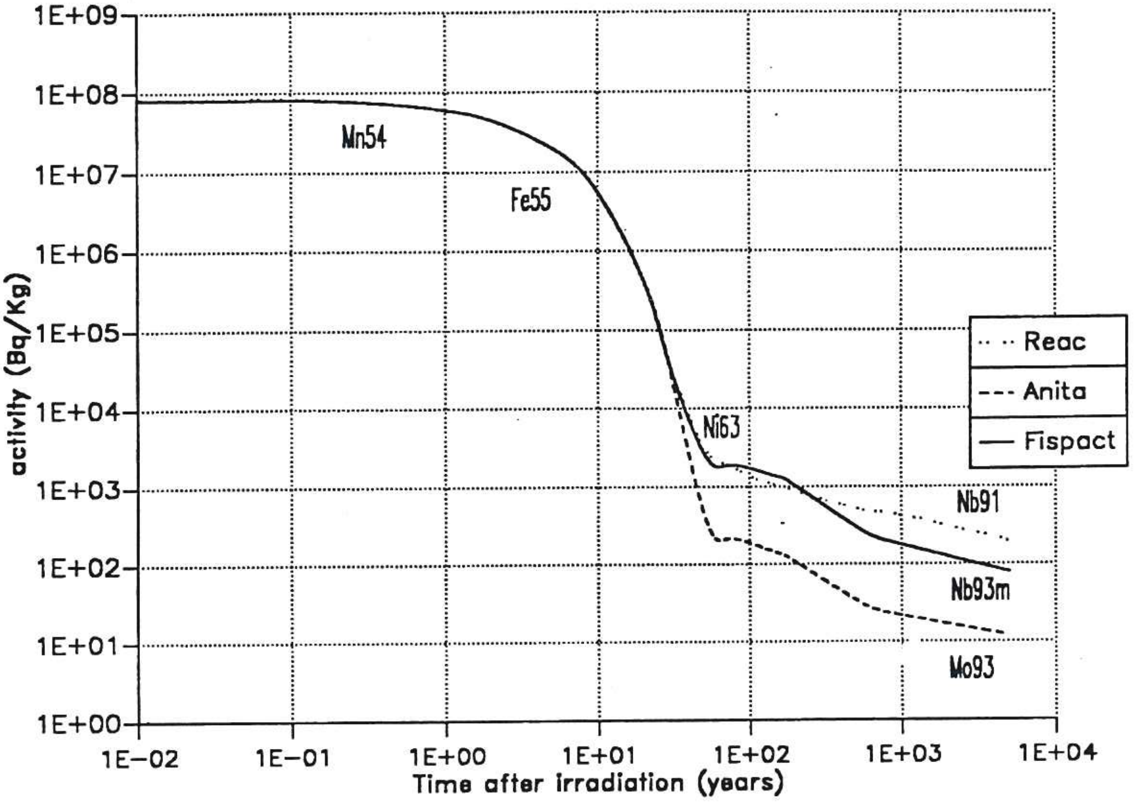

Figure 23. GS 45-3: Mechanical structure specific activity versus cooling time.

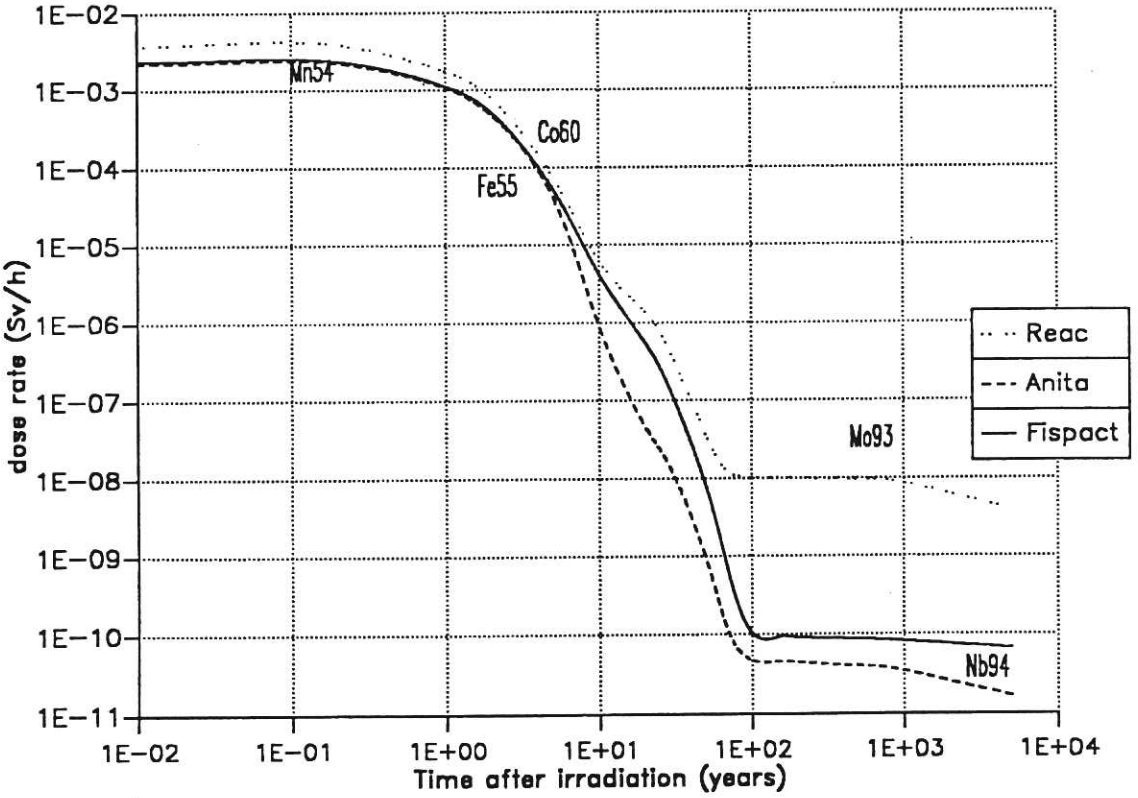

Figure 24. GS 45-3: Mechanical structure gamma dose rate versus cooling time.

	Fispact	Anita	A/F	Reac	R/F
shutdown	1.59E+08	1.58E+08	9.92E−01	1.58E+08	9.91E−01
1 day	8.76E+07	8.70E+07	9.93E−01	8.59E+07	9.81E−01
1 month	8.21E+07	8.17E+07	9.96E−01	8.46E+07	1.03E+00
6 months	7.04E+07	7.02E+07	9.98E−01	7.06E+07	1.00E+00
1 year	6.00E+07	6.01E+07	1.00E+00	6.02E+07	1.00E+00
2 years	4.47E+07	4.48E+07	1.00E+00	4.46E+07	9.98E−01
5 years	1.99E+07	1.99E+07	1.00E+00	1.96E+07	9.89E−01
10 years	5.45E+06	5.45E+06	9.99E−01	5.35E+06	9.81E−01
20 years	4.21E+05	4.17E+05	9.91E−01	4.13E+05	9.79E−01
30 years	3.50E+04	3.23E+04	9.22E−01	3.72E+04	1.06E+00
50 years	2.67E+03	4.52E+02	1.69E−01	3.35E+03	1.25E+00
70 years	2.18E+03	2.29E+02	1.05E−01	1.94E+03	8.90E−01
100 years	1.81E+03	1.89E+02	1.04E−01	1.35E+03	7.43E−01
150 years	1.35E+03	1.41E+02	1.04E−01	1.04E+03	7.71E−01
200 years	1.01E+03	1.07E+02	1.05E−01	8.74E+02	8.62E−01
500 years	3.00E+02	3.44E+01	1.15E−01	5.17E+02	1.72E+00
1000 years	1.77E+02	2.19E+01	1.24E−01	4.23E+02	2.40E+00
5000 years	7.88E+01	1.21E+01	1.53E−01	1.97E+02	2.50E+00

Figure 25. GS 45-3: Mechanical structure activity in Bq/Kg at given cooling time

	Fispact	Anita	A/F	Reac	R/F
shutdown	3.55E−02	3.10E−02	8.71E−01	4.30E−02	1.21E+00
1 day	2.99E−03	2.77E−03	9.26E−01	4.43E−03	1.48E+00
1 month	2.58E−03	2.41E−03	9.35E−01	4.25E−03	1.65E+00
6 months	1.70E−03	1.61E−03	9.50E−01	2.67E−03	1.57E+00
1 year	1.11E−03	1.07E−03	9.56E−01	1.75E−03	1.57E+00
2 years	5.03E−04	4.73E−04	9.40E−01	7.83E−04	1.56E+00
5 years	5.23E−05	4.18E−05	7.99E−01	7.72E−05	1.48E+00
10 years	4.15E−06	8.90E−07	2.15E−01	6.29E−06	1.52E+00
20 years	5.50E−07	4.64E−08	8.44E−02	1.38E−06	2.52E+00
30 years	1.20E−07	1.24E−08	1.04E−01	3.79E−07	3.17E+00
50 years	7.96E−09	9.37E−10	1.18E−01	3.68E−08	4.63E+00
70 years	6.56E−10	1.11E−10	1.69E−01	1.21E−08	1.85E+01
100 years	1.05E−10	4.77E−11	4.53E−01	1.02E−08	9.71E+01
150 years	9.35E−11	4.56E−11	4.88E−01	1.01E−08	1.08E+02
200 years	9.26E−11	4.47E−11	4.83E−01	9.99E−09	1.08E+02
500 years	8.81E−11	4.03E−11	4.58E−01	9.43E−09	1.07E+02
1000 years	8.27E−11	3.47E−11	4.19E−01	8.56E−09	1.03E+02
5000 years	6.76E−11	1.68E−11	2.48E−01	3.98E−09	5.88E+01

Figure 26. GS 45-3: Mechanical structure dose rate in Sv/h at given cooling time

	Fispact	Anita	A/F	Reac	R/F
Cr 51	1.12E+06	1.79E+06	1.60E+00	1.74E+06	1.56E+00
Mn 54	1.14E+07	1.15E+07	1.01E+00	1.15E+07	1.01E+00
Mn 56	6.57E+07	6.56E+07	9.99E−01	6.51E+07	9.91E−01
Fe 55	7.09E+07	7.10E+07	1.00E+00	6.93E+07	9.77E−01
Fe 59	1.03E+06	7.74E+05	7.52E−01	1.01E+06	9.84E−01
Co 60	7.97E+03	1.03E+03	1.29E−01	2.22E+04	2.79E+00
Co 60m	2.54E+04	.	.	2.96E+04	1.17E+00
Cu 64	3.83E+06	3.82E+06	9.99E−01	3.75E+06	9.80E−01
Ni 63	3.17E+03	3.22E+02	1.02E−01	1.47E+03	4.64E−01
Nb94	1.84E−01	1.88E−02	1.02E−01	4.01E−01	2.18E+00
Nb 91	5.23E+01	5.12E+00	9.79E−02	3.84E+01	7.34E−01
Nb 93m	2.84E+01	1.18E+00	4.16E−02	3.98E+01	1.40E+00
Mo 93	8.59E+01	8.46E+00	9.84E−02	2.38E+02	2.77E+00
total	1.54E+08	1.55E+08	1.00E+00	1.52E+08	9.90E−01
real	1.59E+08	1.58E+08	9.92E−01	1.58E+08	9.91E−01

Figure 27. GS 45-3: Main mech. structure isotopes inventory in Bq/Kg at shutdown

4.4 THE POLOIDAL COIL REGION

The coils are made of hollow section copper conductors insulated by resin impregnated glass cloth which give an inventory at the beginning of Cu 90%, O 4%, C 2% and Si 1% with a very important impurity, silver at 890ppm.

Although the composition of the poloidal coils is very similar to that for the toroidal coils the conclusions drawns may not be the same, however, because the flux profile, and therefore the one-group average cross sections, will be different. In fact the agreement between FISPACT and ANITA is not good particularly for the production of the Ag108m. ANITA gives a slightly higher specific activity at all time.

The profile of the spectra differs in that the 14 Mev component is more attenuated for the PF coil region and the broad peak at 1 MeV is shifted to lower energy. That means that threshold reactions such as (n,2n) and (n,p) are less important relative to the (n,γ) reaction.
Obviously this readjustment is leading ANITA to give a higher response for most of the important isotopes for the specific activity and a lower response in the particular case of the Ag108m.
This lead us to conclude that there is disparity within the cross section itself concerning the (n,γ) reaction in particular for the elements Cu and Ag..

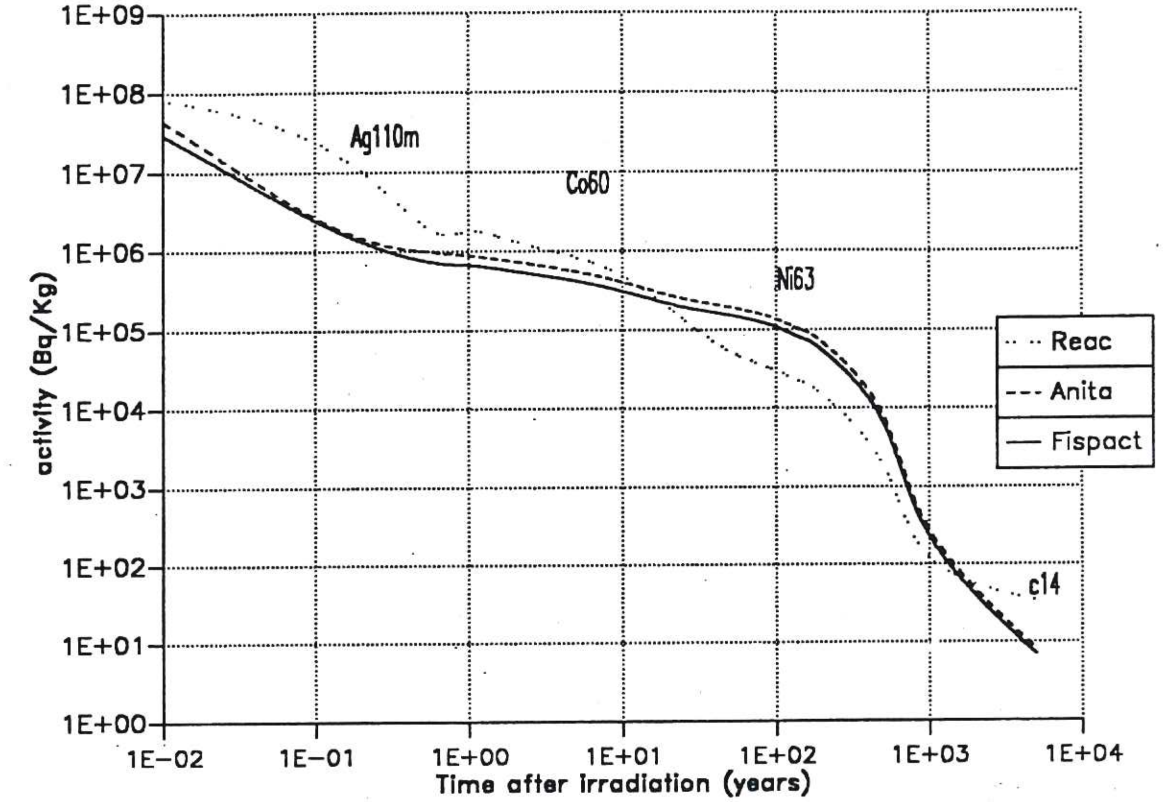

Figure 28. **Copper:** Poloidal coil specific activity versus cooling time.

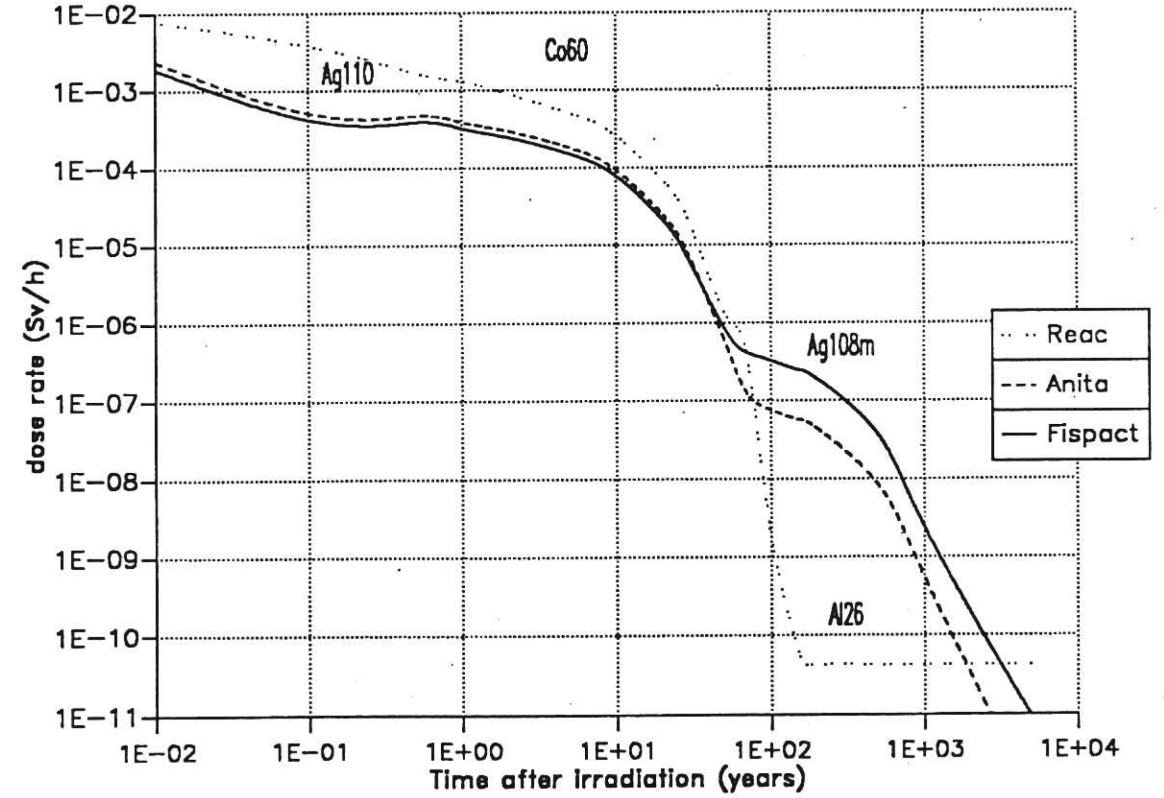

Figure 29. **Copper:** Poloidal coil gamma dose rate versus cooling time.

	Fispact	Anita	A/F	Reac	R/F
shutdown	4.38E+08	8.25E+08	1.88E+00	6.03E+08	1.38E+00
1 day	9.80E+07	1.78E+08	1.82E+00	1.29E+08	1.32E+00
1 month	1.05E+06	1.30E+06	1.24E+00	2.88E+07	2.75E+01
6 months	7.70E+05	1.01E+06	1.31E+00	2.23E+06	2.90E+00
1 year	6.68E+05	8.84E+05	1.32E+00	1.81E+06	2.71E+00
2 years	5.58E+05	7.40E+05	1.33E+00	1.34E+06	2.40E+00
5 years	4.17E+05	5.51E+05	1.32E+00	8.32E+05	1.99E+00
10 years	3.08E+05	4.01E+05	1.31E+00	4.80E+05	1.56E+00
20 years	2.15E+05	2.75E+05	1.28E+00	1.93E+05	8.97E-01
30 years	1.81E+05	2.30E+05	1.27E+00	1.02E+05	5.61E-01
50 years	1.52E+05	1.92E+05	1.26E+00	5.25E+04	3.46E-01
70 years	1.32E+05	1.66E+05	1.26E+00	3.90E+04	2.97E-01
100 years	1.07E+05	1.35E+05	1.26E+00	2.97E+04	2.78E-01
150 years	7.56E+04	9.55E+04	1.26E+00	2.13E+04	2.81E-01
200 years	5.35E+04	6.75E+04	1.26E+00	1.47E+04	2.75E-01
500 years	6.76E+03	8.46E+03	1.25E+00	1.97E+03	2.92E-01
1000 years	2.32E+02	2.79E+02	1.20E+00	1.24E+02	5.35E-01
5000 years	7.10E+00	8.30E+00	1.17E+00	3.44E+01	4.85E+00

Figure 30. Copper: Poloidal coil activity in Bq/Kg at given cooling time

	Fispact	Anita	A/F	Reac	R/F
shutdown	2.19E-02	3.03E-02	1.39E+00	4.78E-02	2.19E+00
1 day	4.64E-03	5.92E-03	1.28E+00	1.16E-02	2.51E+00
1 month	4.65E-04	5.66E-04	1.22E+00	4.09E-03	8.80E+00
6 months	3.88E-04	4.68E-04	1.20E+00	1.68E-03	4.32E+00
1 year	3.23E-04	3.90E-04	1.21E+00	1.31E-03	4.06E+00
2 years	2.47E-04	2.98E-04	1.21E+00	9.11E-04	3.69E+00
5 years	1.50E-04	1.81E-04	1.20E+00	5.08E-04	3.38E+00
10 years	7.74E-05	9.29E-05	1.20E+00	2.59E-04	3.35E+00
20 years	2.11E-05	2.50E-05	1.18E+00	6.96E-05	3.29E+00
30 years	6.01E-06	6.79E-06	1.13E+00	1.87E-05	3.11E+00
50 years	8.26E-07	5.79E-07	7.01E-01	1.35E-06	1.63E+00
70 years	4.12E-07	1.23E-07	2.99E-01	9.73E-08	2.36E-01
100 years	3.26E-07	7.59E-08	2.33E-01	1.93E-09	5.91E-03
150 years	2.48E-07	5.72E-08	2.31E-01	4.53E-11	1.83E-04
200 years	1.89E-07	4.35E-08	2.31E-01	4.27E-11	2.26E-04
500 years	3.67E-08	8.45E-09	2.30E-01	4.27E-11	1.16E-03
1000 years	2.40E-09	5.51E-10	2.29E-01	4.27E-11	1.77E-02
5000 years	9.34E-12	9.36E-13	1.00E-01	4.25E-11	4.55E+00

Figure 31. Copper: Poloidal coil dose rate in Sv/h at given cooling time

	Fispact	Anita	A/F	Reac	R/F
Co 60	4.04E+05	5.54E+05	1.37E+00	1.23E+06	3.04E+00
Co 60m	1.12E+06	1.44E+06	1.29E+00	1.78E+06	1.59E+00
Co 62	3.03E+05	3.41E+05	1.12E+00	2.11E+05	6.97E-01
Ni 63	2.12E+05	2.69E+05	1.27E+00	5.50E+04	2.60E-01
Ni 65	4.23E+05	4.92E+05	1.16E+00	3.85E+05	9.09E-01
Cu 62	2.10E+07	2.35E+07	1.12E+00	1.56E+07	7.42E-01
Cu 64	3.58E+08	6.58E+08	1.84E+00	4.67E+08	1.30E+00
Cu 66	4.40E+07	1.21E+08	2.76E+00	8.77E+07	1.99E+00
Ag 108m	1.54E+03	3.57E+02	2.32E-01	2.50E+03	1.62E+00
Ag 108	1.43E+06	3.54E+06	2.48E+00	2.42E+06	1.69E+00
Ag 110	5.16E+06	3.10E+07	6.02E+00	2.34E+07	4.54E+00
Ag 110m	2.77E+05	3.54E+05	1.28E+00	1.26E+06	4.55E+00
Al 26	1.26E-02	1.42E-03	1.13E-01	5.03E-02	4.00E+00
total	4.32E+08	8.41E+08	1.94E+00	6.01E+08	1.39E+00
real	4.38E+08	8.43E+08	1.92E+00	6.03E+08	1.38E+00

Figure 32. Copper: Main poloidal coil isotopes inventory in Bq/Kg at shutdown

4.5 THE TRANSFORMER CORE REGION

The main type of iron used within the transformer is a low carbon iron with Fe 99%, Mn 0.6% and P 0.2%.

Fig.33 shows good agreement between ANITA and REAC for the specific activities at short cooling times, and the lower result of FISPACT is mainly due to a lower prediction on Mn54 , Fe55 and Co60. It may be noted that the GS 45-3 of the mechanical structure region is mainly composed of Fe and that the agreement in that case was very close for short cooling times.
Here, the profile of the spectra differs in that the 14 Mev component is more attenuated. That means that the (n,γ) reaction becomes more important and leads to FISPACT giving a lower results.
For longer cooling periods REAC and FISPACT tend to agree more on the production of Ni63 and C14 while ANITA gives a lower answer.

In Fig.34, which shows the gamma dose rates, the disparities between the three codes predictions arise principally from discrepancies within the gamma library for Mn54 and Fe55. For the latter, which is responsible for the bump in the FISPACT curve after 10 years, the dose estimated using a theoretically derived gamma spectra. No gamma data are include in ANITA library and extremely low gamma dose are estimated by REAC.

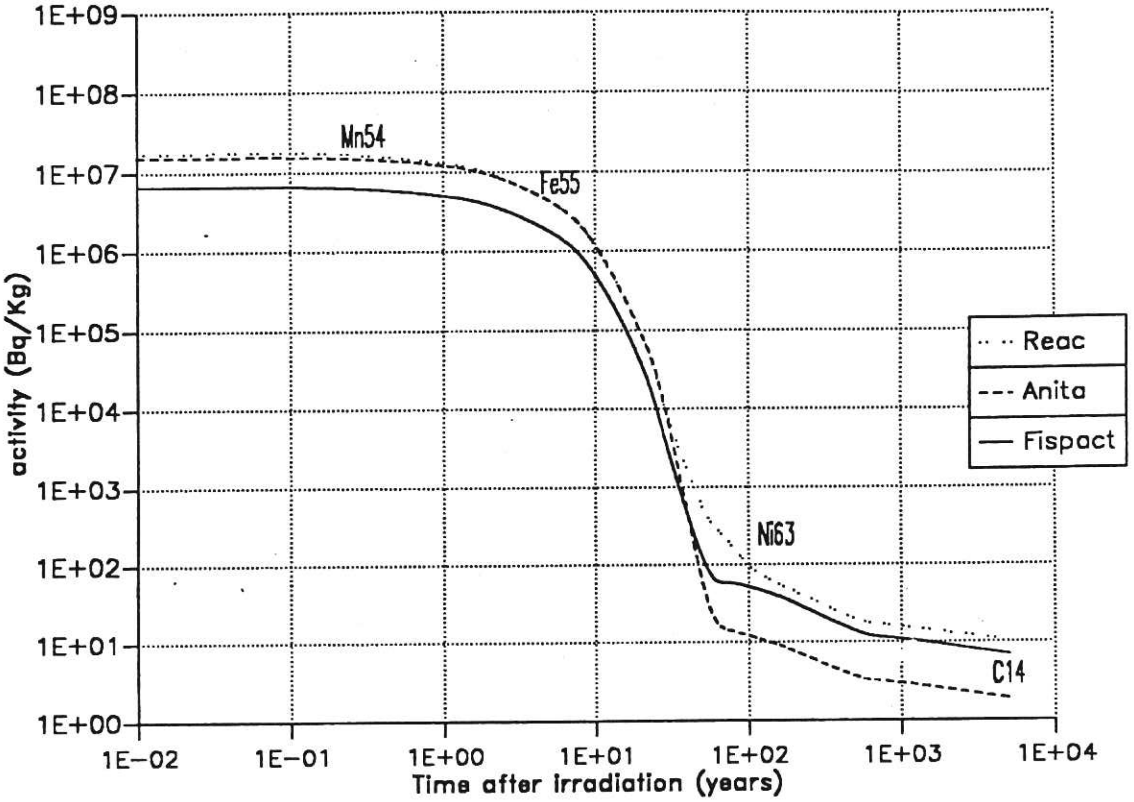

Figure 33. **Nomatil:** Tramsformer core specific activity versus cooling time.

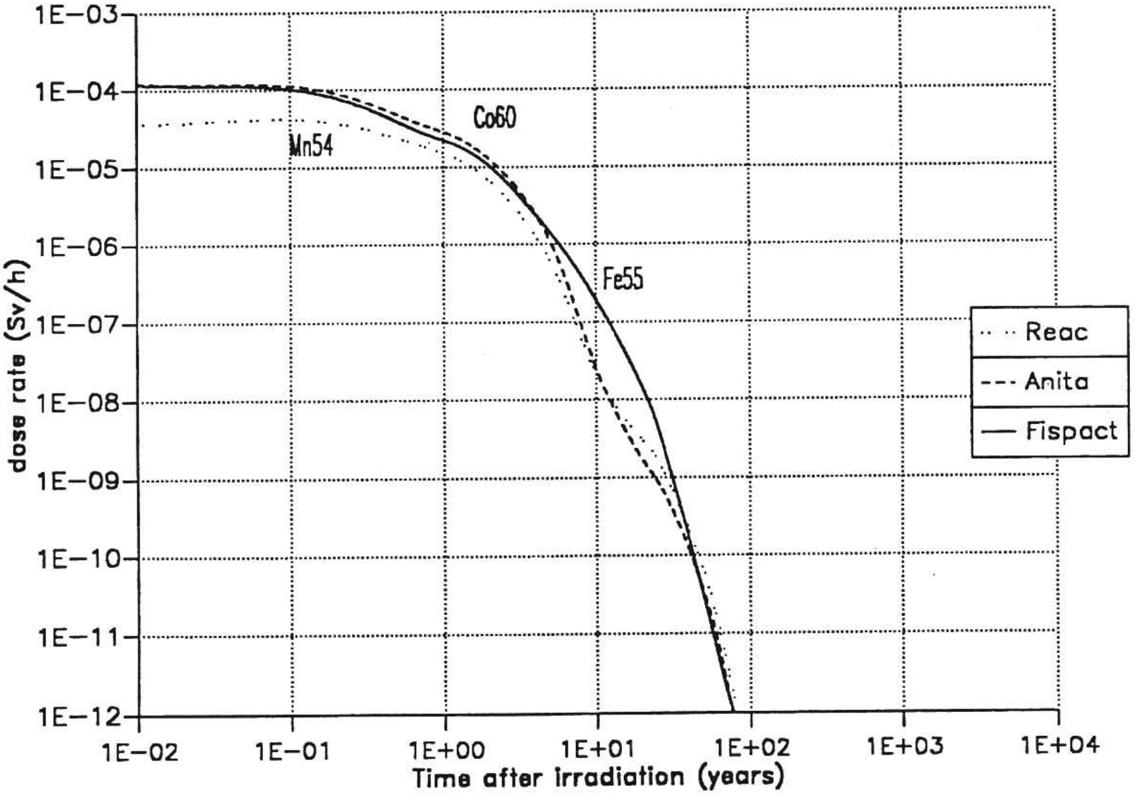

Figure 34. **Nomatil:** Transformer core gamma dose rate versus cooling time.

	Fispact	Anita	A/F	Reac	R/F
shutdown	1.35E+07	2.98E+07	2.20E+00	3.15E+07	2.33E+00
1 day	7.11E+06	1.65E+07	2.31E+00	1.79E+07	2.52E+00
1 month	6.66E+06	1.57E+07	2.35E+00	1.78E+07	2.67E+00
6 months	5.78E+06	1.38E+07	2.38E+00	1.50E+07	2.60E+00
1 year	5.03E+06	1.20E+07	2.39E+00	1.30E+07	2.57E+00
2 years	3.86E+06	9.27E+06	2.40E+00	9.75E+06	2.52E+00
5 years	1.77E+06	4.27E+06	2.41E+00	4.36E+06	2.46E+00
10 years	4.90E+05	1.18E+06	2.41E+00	1.19E+06	2.43E+00
20 years	3.77E+04	9.04E+04	2.40E+00	9.18E+04	2.44E+00
30 years	2.96E+03	6.95E+03	2.34E+00	8.14E+03	2.75E+00
50 years	8.61E+01	5.86E+01	6.81E−01	5.53E+02	6.42E+00
70 years	6.17E+01	1.51E+01	2.44E−01	2.22E+02	3.59E+00
100 years	5.23E+01	1.22E+01	2.34E−01	9.84E+01	1.88E+00
150 years	4.05E+01	9.52E+00	2.35E−01	5.85E+01	1.45E+00
200 years	3.21E+01	7.67E+00	2.39E−01	4.54E+01	1.42E+00
500 years	1.41E+01	3.70E+00	2.63E−01	2.02E+01	1.44E+00
1000 years	1.10E+01	2.99E+00	2.72E−01	1.60E+01	1.45E+00
5000 years	6.98E+00	1.89E+00	2.71E−01	1.04E+01	1.49E+00

Figure 35. Nomatil: Transformer core activity in Bq/Kg at given cooling time

	Fispact	Anita	A/F	Reac	R/F
shutdown	3.16E−03	5.70E−03	1.81E+00	5.13E−04	1.62E−01
1 day	1.60E−04	1.73E−04	1.08E+00	4.33E−05	2.71E−01
1 month	1.07E−04	1.17E−04	1.09E+00	4.21E−05	3.93E−01
6 months	3.85E−05	4.75E−05	1.23E+00	2.36E−05	6.14E−01
1 year	2.21E−05	2.84E−05	1.28E+00	1.52E−05	6.86E−01
2 years	1.03E−05	1.25E−05	1.22E+00	6.74E−06	6.57E−01
5 years	1.41E−06	1.11E−06	7.85E−01	6.11E−07	4.33E−01
10 years	1.89E−07	2.52E−08	1.34E−01	2.16E−08	1.14E−01
20 years	1.42E−08	1.68E−09	1.18E−01	3.06E−09	2.15E−01
30 years	1.30E−09	4.49E−10	3.45E−01	8.22E−10	6.31E−01
50 years	2.76E−11	3.23E−11	1.17E+00	5.93E−11	2.15E+00
70 years	1.93E−12	2.32E−12	1.20E+00	4.28E−12	2.21E+00
100 years	3.64E−13	4.48E−14	1.23E−01	3.76E−18	1.03E−05
150 years	3.64E−13	.	.	3.76E−18	1.03E−05
200 years	3.64E−13	.	.	3.76E−18	1.03E−05
500 years	3.63E−13	.	.	3.75E−18	1.03E−05
1000 years	3.62E−13	.	.	3.73E−18	1.03E−05
5000 years	3.49E−13	.	.	3.60E−18	1.03E−05

Figure 36. Nomatil: Transformer core dose rate in Sv/h at given cooling time

	Fispact	Anita	A/F	Reac	R/F
P 32	7.25E+04	8.12E+04	1.12E+00	8.22E+04	1.13E+00
Cr 51	2.52E+04	2.54E+05	1.01E+01	2.46E+05	9.75E+00
Mn 54	2.10E+05	3.02E+05	1.44E+00	1.61E+06	7.69E+00
Mn 56	6.17E+06	1.31E+07	2.13E+00	1.31E+07	2.12E+00
Mn 57	5.33E+03	.	.	7.69E+04	1.44E+01
Fe 55	6.38E+06	1.54E+07	2.41E+00	1.55E+07	2.42E+00
Fe 59	2.99E+05	2.99E+05	1.00E+00	3.94E+05	1.32E+00
Cu 64	1.74E+05	1.64E+05	9.45E−01	1.64E+05	9.44E−01
Co 60	2.18E+01	3.73E+01	1.71E+00	7.92E+02	3.63E+01
Ni 63	8.04E+01	1.76E+01	2.19E−01	1.12E+02	1.39E+00
C 14	1.15E+01	3.17E+00	2.77E−01	1.59E+01	1.39E+00
total	1.33E+07	2.96E+07	2.22E+00	3.11E+07	2.33E+00
real	1.35E+07	2.98E+07	2.20E+00	3.15E+07	2.33E+00

Figure 37. Nomatil: Main transformer core isotopes inventory in Bq/Kg at shutdown

5. CONCLUSIONS

For this benchmark comparison we have performed calculations using an assumed neutron flux in JET, for the First Wall, Toroidal Coil, Mechanical Structure, Poloidal Coil and Transformer Core, for a selection of materials.
We have concentrated on comparing the most important isotopes from the point of view of specific activity or gamma dose rates for a given materials. This does not mean that the codes agree for other isotopes which contribute to the activation behaviour of these materials. However, those isotopes are less likely to change the overall picture.
Nevertheless they may become important if new types of materials are encountered or if new irradiation conditions are predicted.
For each material we have identified the main isotopes responsible for the specific activity and gamma dose and attempted to explain the discrepancies in the predictions of each code by investigating the disparity in activity of these isotopes.

The specific activity results are most of the time quite similar but in some cases they differed by up to a factor of 84 . It may be noted that the largest differences appear at short cooling times (< 1month) or long cooling time (> 100years) while between, the results do not differ by more than a factor of 3. Results from FISPACT and ANITA in most cases show close agreement; within the 10 percent.
All codes identified the same radionuclides as being significant though they sometimes disagreed on the amount produced, this could be explained by two factors: disagreement on the cross section value and/or missing reactions. The former is influenced by the value of the point-wise data and the group scheme used to collapse them, the latter by gaps in the data base which leads to missing channels of depletion or transmutation. Generally REAC tended to give higher predictions than FISPACT and ANITA.

For the gamma dose rates the results could differ by up to a factor of 10,000 but this was due to missing data within the gamma library. In fact our general comments should be the same as for the specific activity with a warning firstly on the exactitude (Mo93, Ba131) and completeness (Ag108m, Ba133) of those gamma libraries and to the assumption made to assess the dose rates.
Knowing these differences and the isotopes responsible, and from which elements they are likely to be produced it would be possible with the complete one-group averaged cross-section and a pathway analyses to discern more clearly the reaction involved. This would allow the cross sections responsible to be identified and checked on their source.

From this benchmark we can pinpoint a set of important isotopes for which disparities occur: Co60, Co60m, Fe55, Mn54, Ag110m and Ba133, for the activity and Nb94, Sn121m, Mo93 and Ba131 for the gamma dose rates.
It would be possible to clarify which first elements are involved in this process by comparing the different answers given for different irradiated elements.
It is likely that the (n,γ),(n,2n) and (n,p) cross sections for elements such as Ni, Fe, Cu, Co, Ba and Ag will be the important factors.

Finally one should note that after 100 years cooling time some small amount of an impurity could have been transmuted into a long lived isotope such as Nb94, Nb91, Mo93, Al26 and that they may be dominant and still will be for a very long time. For these isotopes disparities in cross sections could be very wide and thus induce large difference in the codes predictions.

6. REFERENCES

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APPENDIX A. DOSE RATE CALCULATION

FISPACT uses equation (1) taken from Jaeger [5] to calculate the gamma dose which holds at the surface of an infinitly thick slab of material.

$$D = 5.76\ 10^{-10}\ \mu_a\ S\ \frac{B}{2\mu_m} \quad [\mathrm{Sv/h}] \qquad (1)$$

where

μ_a = μ_{en}/ρ mass energy-absorption coefficient of air [$cm^2\ g^{-1}$]
μ_m = μ/ρ mass energy-attenuation coefficient of the material [$cm^2 g^{-1}$]
B = build up factor (=2)
S = rate of gamma emission [MeV $kg^{-1}s^{-1}$]

The value of μ_m for the material is calculated from the elemental values μ_{mj} using equation (2)

$$\mu_m = \sum_j F_j \mu_{mj}. \qquad (2)$$

where F_j = (mass of element j)/total mass

Hubbell [6] gives values for μ_a, μ_m for 40 elements at a series of energy points. FISPACT uses linear interpolation to obtain both values at the group energies and at these energies for other elements.

The quantities S, μ_a, μ_m are expressed in a 24 group structure above 100 keV so that equation (1) must be summed over these groups to obtain the final answer.

ANITA uses equation (3) taken from Ponti [7] to calculate the same gamma dose.

$$D = 2.5\ 10^{-5}\ S_m \quad [\mathrm{Rem/h}] \qquad (3)$$

Where

S_m = Rate of gamma emission [MeV $g^{-1}s^{-1}$]

The quantities S_m are expressed for gamma energy above 10 keV.

REAC uses equation (4) taken from Glasstone [8] to express the gamma doses from a small volume ($1 cm^3$) at a distance of R (1m) in air.

$$D = 5.76\ 10^{-8}\ \frac{3.7\ 10^{10}\ C}{4\pi R^2}\ E_\gamma\ \mu_a\ e^{-\mu R}\quad [Rem/h] \qquad (4)$$

Where

$e^{-\mu R} \approx 1$ For $E_\gamma >> 10$ keV
$\mu_a = \mu_{en}/\rho$ mass energy-absorption coefficient of air [$cm^2\ g^{-1}$]
E_γ = gamma energy [MeV]
C = Source terms [$Curies/cm^3$]
R = 1 metre

the quantities $3.7\ 10^{10} C.E_\gamma$ which represent the source term in [$MeV\ cm^{-3} s^{-1}$] are expressed for gamma energy above 10 keV.

This implies that a correction factor F has to be applied to the REAC dose to convert it into the dose for an infinite thick slab of material which is:

$$F = 1\ 10^{-2}\ 4\pi\ \frac{1000}{\rho}\ \frac{1}{\mu_m}$$

Where

ρ =density of the material [$g\ cm^{-3}$]
$\mu_m = \mu/\rho$ mass energy-attenuation coefficient of the material for the mean gamma energy of the main gamma emitter [$cm^2\ g^{-1}$]

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