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Neutron Activation Studies on JET

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ABSTRACT

Extensive neutron transport calculations have been performed to determine the neutron spectrum at a number of points throughout the JET torus hall. The model has been bench-marked against a set of foil activation measurements which were activated during an experimental campaign with deuterium/tritium plasmas. The model can predict the neutron activation of the foils on the torus hall walls to within a factor of three for reactions with little sensitivity to thermal neutrons. The use of scandium foils with and without a cadmium thermal neutron absorber was a useful monitor of the thermal neutron flux. Conclusions regarding the usefulness of other foils for benchmarking the calculations are also given.

1. INTRODUCTION

Over the past several years a computer model of the JET tokamak has been developed for use in neutron transport calculations. The model includes the machine itself, the torus hall in which it is housed and the associated diagnostic and auxiliary heating equipment. Neutron transport calculations are required for estimates of the induced activation of the machine structure, the torus hall and the biological shielding around it. These are used for projections relating to operations, determination of dose rates, and decommissioning.

The calculations are complicated by a number of factors. Firstly, the neutron transport must be followed down to thermal energies from the initial birth energy of 14MeV, some nine orders of magnitude. Secondly, the JET machine and the torus hall are large with little repeated structures or symmetry. The vacuum vessel has large ports (eight horizontal and sixteen vertical) through which neutrons may easily escape. However, most ports are exploited in several ways for neutral beam injection, pumping and diagnostic views, so blocking the ports to a degree that is difficult to predict. The rest of the vessel is surrounded by heavy shielding made up by concrete, steel, and freon-cooled copper toroidal field coils. A significant number of neutrons may pass through this shielding so part of the transport calculation is a deep penetration problem. Thirdly, the device is extremely complex. It would not be cost effective to model it in perfect detail and some degree of approximation is necessary.

During 1997 a series of experiments were carried out at JET using deuterium/tritium fuelled plasmas, the so-called “DTE1”. This provided an excellent opportunity to study neutron activation throughout the torus. A number of sets of foils were placed at various locations throughout the torus hall and were left there for the duration of the experiment. The foils were selected to provide a range of threshold activation reactions which could be used to provide benchmarks for the neutron transport calculations.

This paper describes the foil packs and the JET model and compares the calculations and measurements.

2. ACTIVATION FOIL PACKS

Fifty Activation Foil Packs (AFP) containing either seven or nine foils were placed at 32 locations. Eighteen of the packs had cadmium liners to absorb thermal neutrons and each was positioned with an unlined pack. The foils and the activation reactions of interest are listed in Table 1.

TABLE 1

Foils used in AFP and the activation reactions of interest

Foil	Reaction	Measured Product	Usage
Nickel	$^{58}Ni(n,p)$	^{58}Co	All packs
Aluminium (99%), Cobalt (1%)	$^{59}Co(n,\gamma)$	^{60}Co	All packs
Thorium (99.98%), Iron (0.01%), Calcium (0.01%)	$^{232}Th(n,\gamma)^{233}Th \rightarrow ^{233}Pa$ (β–decay)	^{233}Pa	All packs
Silver	$^{109}Ag(n,\gamma)$	^{110m}Ag	All packs
Tantalum	$^{181}Ta(n,\gamma)$	^{182}Ta	All packs
Scandium (99.98%), Gallium (0.02%)	$^{45}Sc(n,\gamma)$	^{46}Sc	All packs
Uranium	$^{235}U(n,f)$ $^{235}U(n,f)$	^{141}Ce ^{103}Ru	All packs
Iron	$^{58}Fe(n,\gamma)$ $^{54}Fe(n,p)$	^{59}Fe ^{54}Mn	Packs 45 to 50
Manganese (80%), Copper (20%)	$^{55}Mn(n,2n)$	^{54}Mn	Packs 45 to 50

The packs were fixed on the torus hall walls, on the vertical sections of the transformer limbs, approximately 8m from the machine centre axis, on the upper horizontal section of the transformer, or on the ceiling at approximately 4m from the machine axis.

3. NEUTRON TRANSPORT CALCULATIONS AND FISPACT

The activity in each foil in each pack is calculated using the MCNP[1] and FISPACT[2] codes. MCNP is the neutron and charged particle transport maintained by the Los Alamos, National Laboratory, USA. It was used to calculate the neutron spectra using the 175 group “Vitamin-J” energy group structure at the 32 foil pack locations. FISPACT is a neutron activation inventory code developed and maintained by the UKAEA. It is used to determine the activation of the foils using the neutron spectra calculated by MCNP and the known irradiation history resulting from JET shots.

3.1 The JET machine

The JET tokamak[3] consists of a double walled inconel vacuum vessel. Interior components include a divertor and its four coils, carbon limiters and RF antennas. The vacuum vessel is surrounded by 32 freon-cooled copper toroidal fields coils. This is encased in the mechanical structure which consists primarily of steel and concrete. Outside this shell are a set of poloidal field coils, a stack which occupies most of the central column and five others around the outside of the machine. There are eight horizontal ports and sixteen vertical ports which penetrate between the TF coils and through the mechanical structure. Beyond the poloidal field coils are the eight huge iron limbs of the transformer core. In addition to the machine itself there are the auxiliary heating and diagnostic systems which are of equal significance for neutron transport calculations throughout the torus hall.

3.2 The model of JET

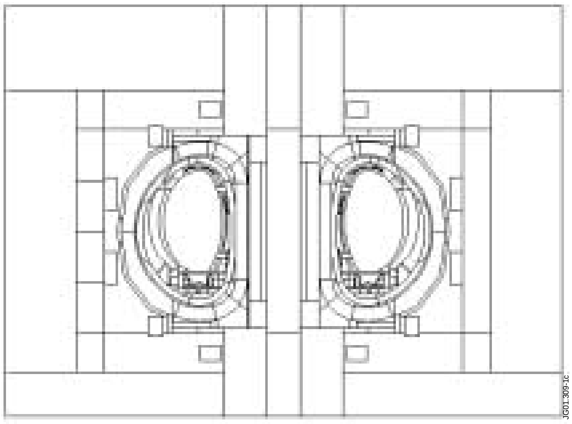

Figure 1: Vertical cross-section through the model of JET showing the cells describing the tokamak and the transformer limbs.

The model of JET consists of approximately 1300 cells defined using 760 surfaces. Over 300 material descriptions are given. The vacuum vessel and most of its internal components have been modelled in some detail. The TF coils are not modelled explicitly. The central section consists of one cell filled with a material that represents the coils, the epoxy/glass-fibre insulation and the freon cooling fluid in a homogeneous mix. The same principal has been employed to describe the outer sections of the mechanical structure and the coils. They are filled with the same mix of cooper steel, concrete, etc. as in reality and the density of this material has been adjusted to maintain the total mass of the sections. The poloidal field coils and the transformer limbs have been modelled in detail since the geometry is simple but the rest of the equipment in the torus hall was not. Instead the torus hall was divided into 64 sectors by vertical planes 5.625∞ apart; these sectors were further divided by horizontal planes and cylinders centred on the machine centre-line (See Figure 1). The cells were filled with homogeneous material mixtures which represented the material content of those regions.

The neutron source was modelled by a specially written subroutine which generates particles with the correct mean energy for a DT plasma (i.e. ~14MeV) and the appropriate energy spread for a plasma with an ion temperature of 20keV which is a reasonable approximation for the neutron spectrum generated in neutral-beam heated plasmas. These are the plasmas which produced the most neutrons during the DTE1 campaign. The spatial distribution is also correctly modelled, being toroidally symmetrical and peaked on an axis which is 10 cm above the vessel midplane.

The Monte-Carlo code was used to determine the neutron spectrum at the 32 foil pack locations by calculating the cell averaged flux in 50x50x50 cm void cells. Each of these cells is centred on the real foil pack location.

For the purposes of neutron transport calculations the impurities present in construction materials have not been included. By “impurities” it is meant elements which make up less than 0.1% of the total weight. This would not be adequate for determining the induced activity for decommissioning purposes which is calculated separately using the inventory code FISPACT, which is supplied with the neutron spectrum and the full list of elements present along with other necessary data. However, the foils in the activation packs were selected to be of high purity and specific gamma lines were measured so there was no chance of interference from competing reactions. FISPACT was used to calculate the induced activity in the foils. A crucial element for the FISPACT calculations is using the correct times for irradiation and decay. Details of the DT pulses are available and from these a scenario has been constructed which mimics the actual DTE1 operation. The individual shots of the last few days operation are included. For earlier times it is acceptable to replace the pulses by averaged continuous irradiation. As mentioned above, the neutron spectra were calculated in void cells. In reality the foil packs themselves have an effect on the neutron spectrum. This needs to be taken into account only for the tantalum and silver foils and is accomplished by applying flux suppression factors according to the scheme shown in Table 2. The effect of thermal neutron absorption by the cadmium is taken into account by setting the neutron flux below 0.5 eV to zero.

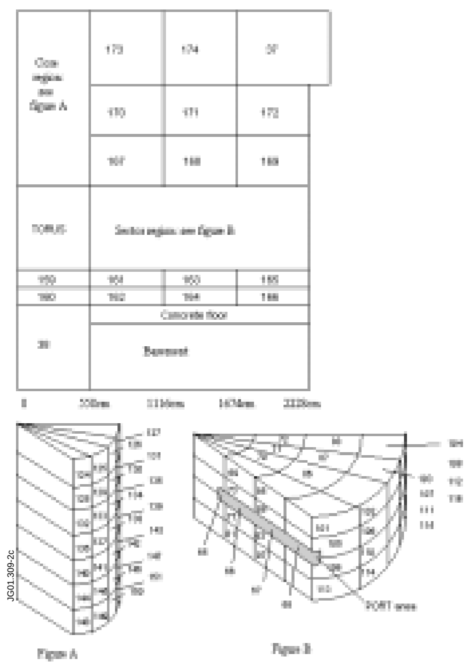

Figure 2: The layout of the SAFER zoning schemes and the system used to divide the Torus hall in the MCNPmodel.

4. MEASUREMENTS

In total, 362 foils were analysed. Attempts to measure the presence of two reaction products in uranium and iron foils were made. This amounts to 418 data points. No ^{141}Ce was detected in any of the foils in spite of the fact that the uranium foils were dissolved and the solution placed in an optimised geometry around the detector in order to maximise detection efficiency and prevent self attenuation in the foils. ^{103}Ru was detected in 23 of the 50 foils with accuracies between 8% and 25%. In eleven other cases no activity was measurable.

TABLE 2

Flux suppression factors for silver and tantalum foils

Energy Range (eV)	Silver Factor	Tantalum Factor
3.93 – 10.68	0.23	0.30
10.68 – 13.71	0.423	0.383
13.71 – 47.85	0.81	0.55
47.85 – 167.0	0.74	0.86

The activities ranged from 14 kBq in the case of a tantalum foil down to the minimum detectable levels of approximately 1 Bq/g. Tantalum foils showed the most and uranium the least. The ratio of silver and tantalum activities was constant to within 10% for packs without cadmium lining. The Cd-lined foil packs also showed a constant ratio but at a 17% higher value. This is due to the increased sensitivity of silver to thermal neutron activation. The ratio of tantalum activities in Cd-lined and unlined packs was 1.08, for silver the ratio was 1.27. The largest ratio was observed for the scandium foils for which the ratio was 3.6.

5. RESULTS

The quality of the MCNP model is determined by the ratio of the calculated to the experimental activities (C/E). The activities in the Cd-lined and unlined packs are calculated using the same neutron spectrum (except for the lowest energy bins) so the C/E values for pairs of packs at the same location will be highly correlated. Therefore, for the purposes of examining the quality of the model, the C/E values from the unlined packs only will be discussed. The calculated activity in pairs of foils from lined and unlined packs, will be compared the experimental values. The measurements indicated that the ratio was independent of location. The C/E values for unlined packs are shown in Figure 3. For the sake of clarity the tantalum results have not been included since they closely following the silver results. The iron and manganese results are not shown since there are so few of them; they are adequately summarised in Table 3. Table 3 lists the average C/E values for each reaction averaged over all packs. From figure 3 it can be seen that the C/E values for foils 1 to 7 have a tendency to be low. These packs were located close to and above the machine. The other foil packs were positioned further away on the torus hall walls. Foils closer to the machine are more sensitive to the details of the location of materials. Work is in progress to add greater detail to the model in these regions.

As Table 3 indicates, the average ratios are close to 1.0. The spread is approximately ×/÷ 3. There are two foils for which modelling is poor, scandium and uranium. An examination of the scandium results showed that the ratio of activities in unlined and lined packs was 3.6 but the calculations indicated a ratio of only 1.5. This indicates that the calculated thermal flux is too low. The instances when no activity was measured can still be used. The MCNP/FISPACT calculations must predict levels of activity less than the minimum detectable activities determined for the detectors used. For 90% of the uranium foils this was the case.

TABLE 3

Mean C/E values for each reaction. (N is the number of measurements obtained.)

Reaction	Mean C/E	N
$^{58}Ni(n,p)^{58}Co$	1.09	50
$^{59}Co(n,\gamma)\ ^{60}Co$	0.97	50
$^{232}Th(n,\gamma)\ ^{233}Pa$	1.49	50
$^{109}Ag(n,\gamma)\ ^{110m}Ag$	0.89	50
$^{181}Ta(n,\gamma)\ ^{182}Ta$	1.03	50
$^{45}Sc(n,\gamma)\ ^{46}Sc$	0.50	50
$^{235}U(n,f)\ ^{103}Ru$	0.69	23
$^{58}Fe(n,\gamma)\ ^{59}Fe$	0.81	2
$^{54}Fe(n,p)\ ^{54}Mn$	0.74	4
$^{55}Mn(n,2n)\ ^{54}Mn$	1.69	1

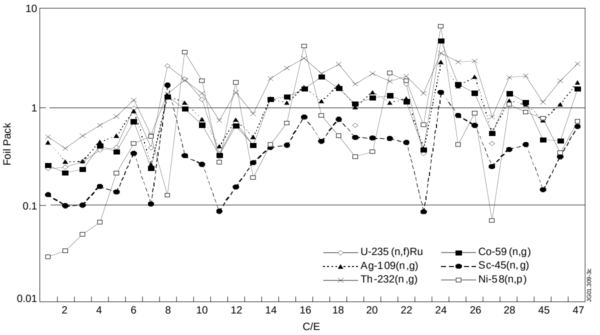

Figure 3: C/E values for foil packs wihtout cadmium lining

6. CONCLUSION AND SUMMARY

An MCNP model has been used to calculate the neutron spectrum through the JET torus hall. The model has been bench-marked against a set of foil activation measurements. The model can predict the neutron activation of the foils on the torus hall walls to within a factor of three for reactions with less sensitivity to thermal neutrons. Of the set of foils used in the packs, the uranium foils were too insensitive, as predicted by the MCNP calculations. The tantalum and silver results were so well correlated that there is little purpose in using both foils. The scandium activities were most sensitive to thermal neutrons and so were of great value in helping to refine the calculations. ^{57}Co, produced in the $^{58}Ni(n,d)$ reaction, was detected in all the nickel foils. This is a high threshold reaction and could be used to examine the transport of high energy neutrons. However, the precision of both the measurements and the calculations of the flux at high energies is currently low and further work is needed to assess the results.

ACKNOWLEDGEMENTS

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