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Cross-Section Uncertainty Study of the NET Shielding Blanket

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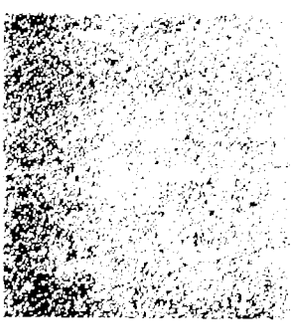

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Abstract

The Next European Torus (NET) is foreseen as the next step in the European development towards the controlled use of thermonuclear fusion. Detail design of the shielding blanket protecting the peripherals, more especially the super-conducting coils, is well advanced. A cross-section uncertainty study, i.e. a study of the expected inaccuracy due to the nuclear cross-section data, has been done for the neutron-gamma reactions in the insulation of the coils for such a design.

As an extension of previous work on the NET shielding blanket (e.g. MCNP calculations), it was deemed necessary to estimate the accuracy attainable with transport codes in view of the uncertainties in microscopic cross-sections. The code used, SENSIBL, is based on perturbation theory and uses covariance files, COVFILS-2, for the cross-section data. This necessitates forward and adjoint flux calculations with a transport code (e.g. ONEDANT, TRISM) and folding the information contained in these coupled fluxes with the accuracy estimates of the evaluators of the ENDF/B-V files. Transport, P_5S_{12}, calculations were done with the ONEDANT code, for a shielding blanket design with **714 MW** plasma fusion power. Several runs were done to obtain well converged forward and adjoint fluxes (ca. 1%). The forward and adjoint integral responses agree to 2%, which is consistent with the above accuracy. The n-γ response was chosen as it is typical of the general accuracy and is available for all materials considered. The present version of SENSIBL allows direct use of the geometric files of ONEDANT (or TRISM) which simplifies the input. Covariance data is not available at present in COVFILS-2 for all of the materials considered. Only H, C, N, O, Al, Si, Cr, Fe, Ni, and Pb could be considered, the big absentee being copper.

The resulting uncertainty for the neutron-gamma reactions in the insulation of the coil was found to be **17%**. Simulating copper by aluminium produces a negligible increase in the uncertainty, mainly because the copper is not in a region of large fast flux.

Résumé

Le Next European Torus (NET) est prévu comme prochaine étape dans le développement européen de l'utilisation controllée de la fusion thermonucléaire. Des projets détaillés de couvertures de protection des périphériques, et plus spécialement des bobines super-conductrices, sont déjà avancés. Une étude de l'incertitude due aux sections efficaces, c. à d. une étude de l'inexactitude attendue due aux sections efficaces nucléaires, a été faite pour les réactions neutrons-gammas dans l'isolation des bobines d'un tel projet.

En complément de travaux passés faits au sujet de la couverture de protection du NET (p. ex. calculs MCNP), il est devenu nécessaire d'estimer l'exactitude que l'on peut obtenir avec des logiciels de calcul de transport au vu des incertitudes des sections efficaces microscopiques. Le logiciel employé, SENSIBL, est basé sur la théorie des pérturbations et utilise les fichiers de covariance pour les sections efficaces, COVFILS-2. Celà nécessite des calculs de flux directs et adjoints avec des logiciels de calculs de transport (p. ex. ONEDANT, TRISM) et un 'folding' de l'information contenue dans ces flux couplés avec les estimations d'exactitude fournies par les évaluateurs de données du ENDF/B-V. Des calculs de transport en P_5S_{12} ont été faits avec le logiciel ONEDANT, pour un projet de couverture de protection d'un plasma d'une puissance de fusion de **714 MW**. Plusieurs calculs ont servi à obtenir des flux directes et adjoints bien

convergés ($\approx$1%). Les réponses intégrées directes et adjointes se recoupent à 2% près, ce qui est en accords avec l'exactitude ci-dessus. La fonction de réponse n-γ a été choisie parce que typique de l'exactitude générale et connue pour tous les matériaux considérés. La présente version de SENSIBL permet l'emploi direct des fichiers géométriques de ONEDANT (ou de TRISM), ce qui simplifie les données. Les covariances ne sont pas connues pour tous les matériaux utilisés. Seul les H, C, N, O, Al, Si, Cr, Fe, Ni et Pb peuvent-être pris en considération, le grand absent étant le cuivre.

L'incertitude résultante pour les réactions neutrons-gammas dans l'isolation des bobines est de **17%**. Si l'on simule le cuivre par de l'aluminium, l'augmentation d'incertitude est négligeable, principalement parce que le cuivre est dans une région de faible flux rapide.

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1 INTRODUCTION

In the European programme towards the controlled use of thermonuclear fusion, the Joint European Torus, JET, at Culham, is at present the largest machine investigating plasma physics. Its aim is to reach considerable α-heating from the D-T fusion reaction, but not ignition. The Next European Torus (NET) is foreseen as the next step. It has essentially two goals: the study of plasma physics with a long burning, ignited D-T plasma and the technological development of blankets, materials, tritium breeding, etc.. Initially, the machine will be run with an extended plasma, with a slightly larger plasma cross-section, and a blanket designed for shielding only, with no tritium breeding.

As 3-D Monte Carlo results from MCNP calculations on the shielding performance of this blanket became available[1,2], it became apparent that it would be difficult to get enough shielding of the super-conducting coils. In particular, the heat released in the coils and insulation determines the size of the liquid helium cooling requirements. It was also noted that on the inboard side, at least, much information might be obtained from 1-D and 2-D deterministic calculations, in particular the expected error due to cross-section uncertainty could be obtained from a sensitivity/uncertainty study.

Ideally this should have been done on the kerma cross-sections (heat released) for the insulation. Instead, the neutron-gamma, n-γ, reaction was chosen as it is available from the Joint European Files, JEF, for all the elements required - thus allowing a European assessment - whereas kerma data are sparse in this library and no kerma data are available in COVFILS-2, the most up-to-date uncertainty file[3].

The expected error on (n,γ), as it turns out, is almost entirely due to the global calculation and not the errors on the (n,γ) cross-section, $\sigma_{n,\gamma}$, in the insulation. However, as was said above, not much is known on the accuracy of the kermas themselves.

2 COMPUTATIONAL MODEL

2.1 Method and Codes

The method used has been described[4,5] and used several times before[6],

- condensation of the source library to produce the basic materials, e.g. stainless steel, with TRAMIX,[7]
- mixing to obtain the actual materials, with MIXIT,
- direct and adjoint flux calculations with a deterministic S_N-transport code,
- uncertainty analysis with SENSIBL[8].

This route was originally chosen to be used with TRISM[9], a 2-D code, in a quasi one-dimensional calculation. The use of ONEDANT[10], a 1-D code, instead, involved modifications to SENSIBL[11] to accept flux and geometry files from ONEDANT. SENSIBL is an

improved and accelerated version of SENSIT-2D[12], itself an extension of the 1-D sensitivity and uncertainty code SENSIT[13], and uses the cross-section data file COVFILS-2[3].

Two transport codes were used: TRISM in a 1-D way, as later 2-D calculations were envisaged and ONEDANT. With TRISM even 1-D calculations proved extremely expensive as this is a deep penetration problem necessitating P_5S_{12} calculations. With 175 meshes, a reasonable number considering the cost of TRISM, the fast flux in the vacuum is 10% lower than with ONEDANT, with the same meshes. In the steel the situation is only slightly better. Generally, the convergence of TRISM is no better than for ONEDANT. 1-D optimization calculations with ONEDANT showed the meshes initially chosen for TRISM to be too coarse, which puts the cost of using TRISM out of range. As a result an acceleration of TRISM is being developed[14,15].

2.2 Geometry

A vertical infinite cylinder is used to represent the tokamak. On the inboard side, this is quite a good representation, at least at the mid-plane. The geometry is taken the same as for the MCNP calculations[2] and supplemented by Ref. 16 on the inboard. On the outboard only the blanket and the first 4 cm of shield are modelled. At this distance, the neutron fluxes are only a few percents of their value in the plasma. As the code cannot have a vacuum boundary on the inside surface, 20 cm of stainless steel are used instead, with vacuum in the center.

2.3 Composition

As for the geometry, the compositions used for the transport calculations are those of the MCNP calculations [2] except for the super-conducting coils and their insulation which were not modelled then. These are taken from Ref. 16. The former compositions are based on standard 316LN stainless steel with impurity concentrations, Mn, Si, P, S, at their upper limit and on the actual volume of water. As the JEF (Joint European File) library is used, Sn and Ta are missing and neglected. As these are present only in the super-conducting coil which is beyond the insulation, this should not have a large effect on the results. The source library MAT187, a 187 neutron groups library, is condensed to the 74 groups structure of COVFILS-2.

For the SENSIBL calculations the COVFILS-2 files are used. These only have 14 elements, so that P, S, Mn, Mo, Ca, Mg, ^{10}B, ^{11}B, Nb, Sn, Ta, He, Co, and Cu have to be neglected in the coils and in the insulator. Of these the big absentee is copper representing an atomic fraction of 43% in the coil. However, simulating it as aluminium has only a very small effect. In the S.S., only Mn (2%) and Mo (1.4%) occur in any sizeable concentration so the error introduced should not be large. A further source of errors is the fact that there are no covariance files for the (n,γ) reaction for oxygen and silicon. This again is not serious as the uncertainty of the (n,γ) reaction only accounts for a small fraction of the total.

2.4 Mesh-Size

Based on previous experience, it is found that a convergence study is necessary. A convergence of 1-3%, 10-20%, 1-2% is required for the fast flux, the thermal flux and the total flux, respectively, as this is still accurate enough for engineering purposes. Alternatively, a convergence of

Table 1: Materials and Thicknesses

	Parallel Segments		
	Material	Δr (cm)	R_o (cm)
	(void)		168.0
	(M2)	20.0	188.0
Coils:		58.8	246.8
Insulator:		1.2	248.0
	void	7.0	
Vessel:			255.0
	M10	12.0	267.0
	M8	5.0	272.0
	M9	20.0	292.0
	M8	4.5	296.5
	M7	11.0	307.5
	M6	1.5	309.0
	M5	7.0	316.0
	M4	4.0	320.0
	void	3.0	323.0
Blanket:	void	5.0	328.0
	M2	20.0	348.0
	M1	2.0	350.0
Vacuum			373.0
plasma			395.22
			416.88
			437.97
			458.48
			478.42
			497.79
			516.59
			534.82
			552.47
			586.07
			602.02
			617.39
			632.19
			646.42
			660.08
			673.17
			685.68
			697.63
			709.0
Vacuum			726.0
Blanket:	M1	2.0	728.0
	M2	3.0	731.0
	void	7.7	738.7
	M2	19.6	758.3
	void	15.2	773.5
	M4	4.0	777.5

Table 2: Mesh Sizes Used

Material	Mesh size
graphite	0.5 cm
S.S.	1.0 cm
– near water	0.33 - 0.5 cm
water	0.075 cm
borated water	0.45 cm
insulation	0.6 cm
coil	1.0 cm
gap	4 cm
central gap	20 cm

< 1% on the total (n,γ) is deemed satisfactory. This leads to a model with 319 meshes, Table 2.

3 PLASMA SOURCE SIMULATION

The D-shaped plasma contours are described by the following set of parametric equations, which represent fairly realistically the results of the plasma physics:

$$R(\alpha,a) = R_p + a\cos(\alpha + \frac{a}{a_p}c_p \sin\alpha) + \epsilon_p a_p(1 - \frac{a^2}{a_p^2})$$

$$\begin{aligned} Z(\alpha,a) &= \frac{a}{a_p}b_p \sin\alpha \\ S(a) &= S_0(1 - \frac{a^2}{a_p^2})^{e_{pk}} \\ 0 \leq \alpha &< 2\pi \end{aligned}$$

They define the contour surfaces, $(R(\alpha,a), Z(\alpha,a))$, of equal source density, $S(a)$, for given values of the horizontal minor radius a. This gives a slightly broader distribution than in Ref. 1, where S is taken as the source strength (i.e. for the whole annulus), but this gives almost identical results in the first wall in a cylindrical case. For the NET Extended Plasma:

R_p,	plasma major radius	= 541 cm
a_p,	horizontal plasma minor radius	= 168 cm
b_p,	vertical plasma minor radius	= 366 cm
ϵ_p,	radial plasma shift	= 0.17
c_p,	triangularity	= 0.62
e_{pk},	peaking exponent	= 4

To obtain the source a circular horizontal cylinder, centered on $R = R_p + \epsilon_p a_p$ = 569.6 cm, length $2\pi R$, is considered to have a total source of $2.533 \cdot 10^{20}$ n/s as for the MCNP calculations[1]. This corresponds to 714 MW plasma power. The source is scaled down by the ellipticity and scaled

up for toroidal curvature to correct for a higher neutron current at the in-board graphite surface. The net 14 MeV neutron current is obtained at the surface of the graphite tiles ($3.84 \cdot 10^{13}$ n/cm^{2}s = 0.865 MW/m^2).

The source in the vertical model is then adjusted to this same 14 MeV neutron current. Current matching matches the two models best. The fluxes in the carbon tiles match less closely than for a flux match, but the doses in the insulation match better, (25% difference between the two models). This gives a "1-D" model with not as high a wall loading as on the mid-plane of a 3-D case[1,2], Table 3.

Table 3: Power on the First Wall

1-D virgin neutron current	0.865 MW/m^2
3-D virgin neutrons:	
– mid-plane	1.02 MW/m^2
– mean mid-inboard	0.63 MW/m^2

4 ADJOINT CALCULATIONS

The adjoint calculation is done with the (n,γ) cross-section as adjoint source in the insulator. The same mesh size is used as in the forward calculations. To check the consistency of both regular and adjoint calculations, a comparison of the (n,γ) reaction rate calculated using the regular flux in the insulation and the neutron source folded with the adjoint flux in the plasma is made. Perturbation theory predicts that the relationship:

$$< S, \phi^* > = < R, \phi >$$

should hold. The total (n,γ) reaction rates agree to 2.2%, which is consistent with the accuracy aimed for in choosing the mesh size:

- Forward activity = $5.12262 \cdot 10^9$ per sec/cm
- Adjoint activity = $5.23680 \cdot 10^9$ per sec/cm
- SENSIBL = $5.12501 \cdot 10^9$ per sec/cm.

As a check the reaction rate obtained by the code SENSIBL is also shown. It too agrees. However, not all (n,γ) cross-section are covered by the COVFILS-2 files, so that only 70% of the activity is actually covered in uncertainty calculations.

5 RESULTS OF 1-D CALCULATIONS

The neutron currents escaping the vacuum vessel and reaching the insulation are compared in Table 4 for the 1-D and the 3-D cases. It is clear that 1-D deterministic calculations underestimate the penetrating power of the neutrons compared to a 3-D Monte Carlo calculation for such a deep penetration problem. The fast, >0.1 MeV, and total neutron fluxes are shown in Fig.1.

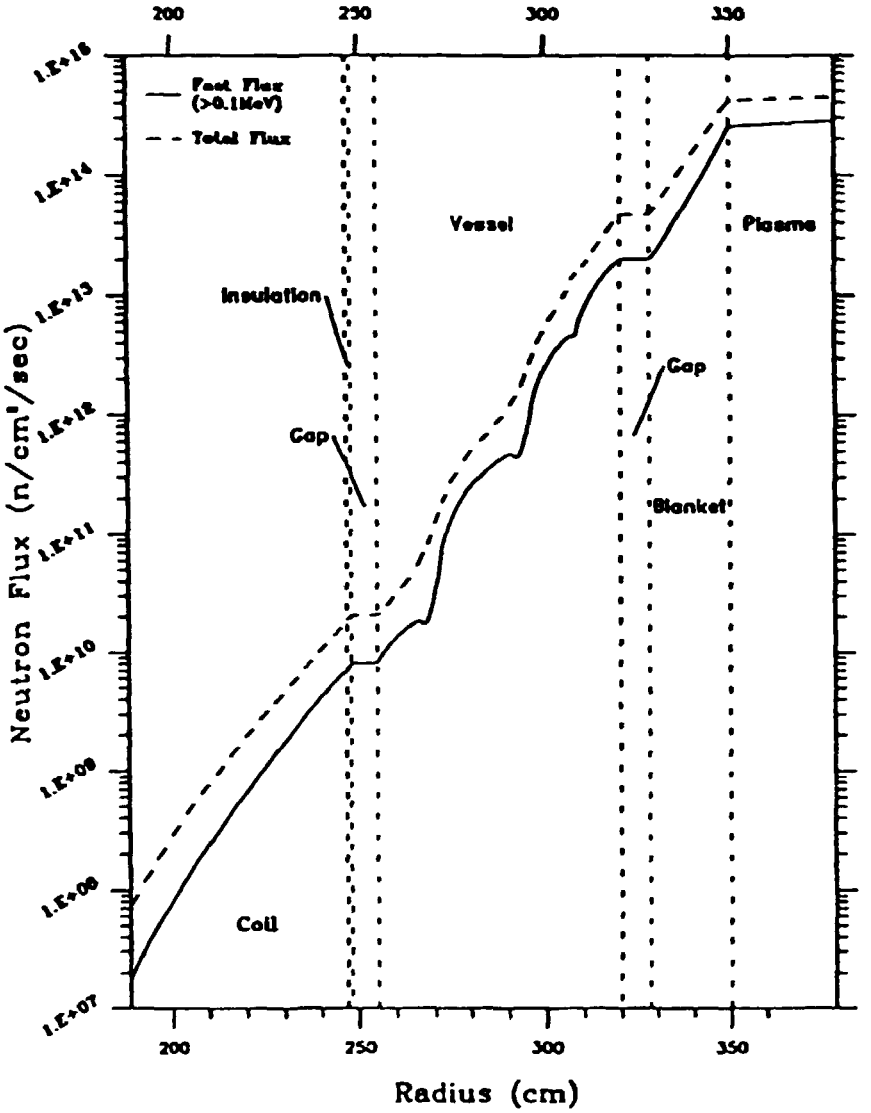

Figure 1: Fast and Total Neutron Fluxes

Table 4: Neutron Currents into the Insulation

E_u (MeV)	1-D Onedant	3-D MCNP
14.9	$5.07 \cdot 10^{8}$	$6.15 \cdot 10^{8}$
1.0	$1.12 \cdot 10^{9}$	$3.27 \cdot 10^{9}$
0.11	$2.50 \cdot 10^{8}$	$1.22 \cdot 10^{9}$
$9.12 \cdot 10^{-3}$	$1.04 \cdot 10^{8}$	$5.62 \cdot 10^{8}$
$1.01 \cdot 10^{-4}$	$4.17 \cdot 10^{6}$	$4.01 \cdot 10^{8}$
$4.14 \cdot 10^{-7}$	$-1 \cdot 10^{7}$	$\approx 1 \cdot 10^{7}$
Total	$1.94 \cdot 10^{9}$	$6.08 \cdot 10^{9}$

Table 5: Uncertainties due to Cross-Sections

Isotope	Mat	%
Fe	1326	14.8
Cr	1324	6.7
Ni	1328	4.9
^{12}C	1306	1.7
^{16}O	1276	1.6
^{1}H	1301	1.2
^{27}Al	1313	0.68
Si_{nat}	1314	0.49
^{14}N	1275	0.16
Pb	1382	0.003
Total		17.2

6 RESULTS OF UNCERTAINTIES

The detailed uncertainties are given in Table 5. The main contributors are Fe, Cr, Ni. Of the total standard deviation of 17.2%, 14.8% are caused by iron. As stainless steel (316LN) is, with water, the main constituent of the shield, this is to be expected. It must be remembered that, as the uncertainties are assumed to be uncorrelated, the squares of the uncertainties are summed, not the uncertainties themselves.

If the uncertainty due to the (n,γ) cross-sections under consideration in the insulation is neglected, the change is only 0.01% - mainly due to Al, showing that the uncertainty in this case is essentially due to the overall calculation of a relatively thick shield. As no information is available on the kermas in COVFILS-2, it is not possible to estimate the total uncertainty on the heat deposited.

The uncertainty of copper is not available in COVFILS-2. Simulating the copper in coil and insulation as aluminium, instead of neglecting it, increases the uncertainty by 0.04%. This is because the insulation is in a region of low flux, especially of low fast flux (where the cross-sections are usually less well known). As copper is not a reactor material (high absorption

cross-sections), it will be less well known than aluminium, but, nevertheless, the effect should still be small.

Because "non-reactor" materials are used for the insulation, only 71% of the total (n,γ) cross-sections are covered by the uncertainty table, the rest not having uncertainty estimates. Even Si and O, which are in COVFILS-2, do not have (n,γ) uncertainties.

7 DISCUSSION

It is clear that 1-D deterministic transport calculations with JEF group-wise cross-sections underestimates the penetration power of the neutrons. This could be due to:

- method:- deterministic v. Monte-Carlo
- 1-D v. 3-D
- JEF v. ENDF/B-IV
- group v. point cross-sections.

3-D calculations are clearly needed for good results. However, the error caused by the cross-sections in a 1-D case should still be relevant, as the evaluators took great care in using the best data for both libraries. Furthermore, doing an uncertainty evaluation on a 3-D basis is still a formidable task at present.

Not all the materials are available in the libraries. For the transport calculations only Sn and Ta are missing. As they are present only in the coils and in quantities relatively small compared to iron and copper, this should not influence the accuracy of the transport calculations. Much more relevent is the mesh size. There, a hand optimization was done to get mesh sizes giving a convergence of about 1%. This is considered as sufficient for engineering purpose. The agreement (2%) between both integral products shows this to have been obtained.

More important is the lack of many elements in the covariance files. However, most of the uncertainty comes from the overall computation, where the covariances are known, only 0.01% out of 17% from the (n,γ) response in the insulation itself. There, replacement of copper, which is unknown, by aluminium only adds another 0.04%. Even if only 71% of the (n,γ) cross-section are covered, the rest being "non-reactor" materials, this only affects uncertainties of the order of a few 0.01%. One can, thus, expect the overall influence not to be too large. Of course, if the kermas used in MCNP for example, are very inaccurately known, this will introduce more uncertainty.

8 CONCLUSIONS

Although not all the factors influencing uncertainty due to cross-sections have been covered, the results obtained should, nevertheless, indicate in a broad fashion the expected uncertainty. This resulting uncertainty for the neutron-gamma reactions in the insulation of the coil is found to be 17%. This does not cover, it must be stressed, uncertainties due to other factors such as lack

of accuracy in the density or the dimensions, (e.g. tolerances and corrosion). These could not be computed in the present state of the code.

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