THE ERANOS SYSTEM APPLIED TO SHIELDING CALCULATIONS WITH VALIDATION ON JANUS EXPERIMENTS

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ABSTRACT

The ERANOS code and data system has been specified to calculate all neutronic parameters required for the design of a fast reactor. With an appropriate choice of algorithmic options, the ERANOS system is used for shielding applications. The cell code ECCO prepares cross sections in a VITAMIN J group scheme (175 groups) while the BISTRO code treats the SN equation. Particular attention has been given to the accuracy of the deterministic method used (slowing down, spatial self shielding for window effects, angular scattering and flux, mesh).

The JANUS experimental program is analysed with the JEF2 evaluated nuclear data base and gives a validation for this fast reactor shielding procedure. Particular attention has been given at that stage to the modelling of the experiments. Results are very satisfactory, bringing evidence that the JEF2 evaluated data introduce no discrepancy in the calculation when algorithms are accurate enough. However, evaluations of response functions describing the detectors bring a large source of uncertainty in the experiment-calculation comparison and need to be improved.

INTRODUCTION

In order to design reactors more precisely but also to permit a better prediction of unconventional features such as one can found in plutonium burner cores, neutronic calculations need to be improved. The new ERANOS code and data system is creating a landmark on the route towards more precise results with both the sub group method[1] and the slowing down calculation in many groups.
Shielding applications however has particular features which, with the help of a new approach of the sub group method based on the exponential attenuation of the sources has enabled the improvement of calculations without increasing too much the running time or making it difficult to use.

The calculational route in ERANOS[2] uses the ECCO[3] module for cross section preparation and the transport SN BISTRO module for spatial neutron propagation. Careful check of the overall scheme has been performed on a benchmark case using non standard features of the code which can play a reference role. The benchmark has allowed the testing

and the optimisation of the calculational procedure which has been finally applied to the analysis of the ASPIS iron experiment and the JANUS experiments[4]. This is of particular importance for the applications envisaged, the JANUS European programme was formulated to provide a consistent set of experimental validation data for the assessment of calculational methods for fast reactor shielding.

CALCULATIONAL ROUTE

A. Overall scheme

Basic nuclear data come from JEF2 evaluated data files[5]. They have been processed in an ECCO format[6] with the help of NJOY[7] and CALENDF[8]. The ECCO libraries contain infinite dilution cross sections, matrices for different Legendre descriptions (P0 to P5) and probability tables for self shielding calculation.

Two different ECCO libraries are used with two different group schemes, one in 1968 groups for the most important isotopes encountered in fast reactor cores and shields, and another one in a 175 group scheme (VITAMIN J) for less abundant isotopes or detectors.

The overall scheme starts with a cell calculation (ECCO) for preparation of the effective cross sections and matrices for use in a SN transport code (BISTRO). The flux obtained with this transport code is then used to calculate the traverses of reaction rates through the shield.

ECCO calculations are performed over wide regions, which is sufficient for cross section preparation. It is however not accurate enough to represent the flux slope and a fine mesh SN transport calculation is then used.

B. Cross section preparation with the cell code ECCO

The cell code ECCO uses the subgroup method for calculating effective cross sections. This is performed either in broad groups (VITAMIN J scheme) or in 1968 fine groups.

The self shielding formula for standard effective cross section σ_x where x can be the total (Legendre order 0), capture, fission, elastic or inelastic is the following for each group g :

$$\tilde{\sigma}^g_{xi} = \frac{\sum_j S^g_j \sum_k \alpha^g_k \, \sigma^g_{x_k} \, p_{ij}\left(\Sigma^g_{t_k}\right)}{\sum_j S^g_j \sum_k \alpha^g_k \, p_{ij}\left(\Sigma^g_{t_k}\right)}$$

where S^g_j is the source in the current group and in region j.

α^g_k is the probability in group g to find the partial cross section $\sigma^g_{x_k}$ to which corresponds the total cross section $\sigma^g_{t_x}$ (used to calculate the macroscopic cross section $\Sigma^g_{t_k}$ in each region).

$p_{ij}\left(\Sigma^g_{t_k}\right)$ is the reduced collision probability for this subgroup k within the group g.

The self shielding of the total Legendre order one cross section (as well as order one of the elastic cross section) has a different formulation coming from the fact that this type of cross section has a current weighting.

$$\tilde{\sigma}_{tr_i} = \frac{\sum_j S_j \sum_k \alpha_k \, \sigma_{tr_k} \sum_l p_{il}\left(\Sigma_{t_k}\right) p_{lj}\left(\Sigma_{t_k}\right)}{\sum_j S_j \sum_k \alpha_k \sum_l p_{il}\left(\Sigma_{t_k}\right) p_{lj}\left(\Sigma_{t_k}\right)}$$

For core cells, a simplier formula is used $p^2_{ij}\left(\Sigma_{t_k}\right)$ instead of $\sum_l p_{il}\left(\Sigma_{t_k}\right) p_{lj}\left(\Sigma_{t_k}\right)$ and gives similar results. It has, however, less foundation and is insufficient for shielding applications.

Matrices are scaled on the vectors to preserve the balance assuming self shielding independent from the group transfer probabilities.

With these self shielded cross sections, flux and current are calculated with the P1 consistent method :

$$\phi^g_i = \sum_j \left(-B^g J^g_j + S^g_{fj} + \sum_{g'} \Sigma^{g' \to g}_{S_{0,j}} \phi^{g'}_j \right) p_{ji}\left(\Sigma^g_t\right)$$

$$J^g_i = \sum_j \left(B^g/3 \, \phi^g_j + \sum_{g'} \Sigma^{g' \to g}_{s_{1,j}} J^{g'}_j \right) p_{ji}\left(\Sigma^g_t\right)$$

where ϕ^g_i and J^g_i are the flux and the current in group g and region i.

Bg is the buckling and S^g_{fj} the fission source

Finally, cross sections and matrices are condensed, if necessary, to any broad group scheme (here VITAMIN J scheme) with the flux for partial cross sections and order 0 matrices, and with the current for total order 1 cross section and order 1 matrices.

This method works for any zone of application - core or shield -. It is a reference approach with both the sub group method[1] and the slowing down calculation in many groups. However, using it for shielding applications has the inconvenient of requiring many regions due to the flat hypothesis of the source. The running time increases as the square of the number of regions.

Shielding applications however has particular features which, with the help of a new approach of the sub group method based on the exponential attenuation of the sources has enabled the improvement of calculations without increasing too much the running time or making it difficult to use.

$$\phi_1^g(x,\Sigma_t) = \int_0^x S_{s0}^g e^{-B^g x_0} \frac{E_1(\Sigma_t(x-x_0))}{\Sigma_t}$$

where $E_n = \int_1^\infty \frac{e^{-xt}}{t^n} dt$

and where B^g is the source buckling and S_{s0}^g the scattering source.

This approach enable the use of a limited number of regions for cross section preparation and as a consequence a reduced running time.

Legendre order calculations for ECCO are performed for order larger than one matrices by using related equations for the self shielding by the subgroup method, the flux solutions and the condensation. However, another simplification is given to the calculational procedure by the direct use of a broad group library (in the VITAMIN J scheme) condensed on the collision density of various fine group ECCO runs. Each run concern a pure material (Iron,Na) which is then used to condense the corresponding material. The method creates the probability tables by using the CALENDF method - the condensation is performed on the moments of the cross sections - and preserves the transfer probabilities of the matrices. Comparison with the reference route has been analysed with the perturbation theory and has proved to be in excellent agreement.

C. Flux calculation with the SN transport code BISTRO

The SN calculation in Pn performed with BISTRO is requiring only one total cross section while ECCO with its algorithms give one total cross section per Legendre order expansion.

The calculation in BISTRO is performed using the Legendre order one total cross section $\Sigma_{t_1}^g$ for each region, the within group term being corrected for the use of that single total cross section :

$$\Sigma_0^{*g\to g} = \Sigma_0^{g\to g} - \Sigma_{t_0}^g + \Sigma_{t_1}^g$$

Similar formulations exist for higher order terms.

S_8 has been used for the angular distribution of the flux in this 2D geometry while a P3 pôlynomial expansion has been used for the anisotropy of the scattering. These choices have been validated by comparing the results with the ones obtained with higher order expansion.

ASPIS AND JANUS EXPERIMENTS

The ASPIS and JANUS experimental programmes have been set up near the NESTOR reactor for the validation of calculational schemes. The ASPIS experiments has been set up for the validation of the calculations in single materials. The JANUS European programme was formulated to provide a consistent set of experimental validation data for the assessment of calculational methods for fast reactor shielding.

For the purpose of this work. the ASPIS iron configuration and the JANUS phase1 and 2 have been chosen:

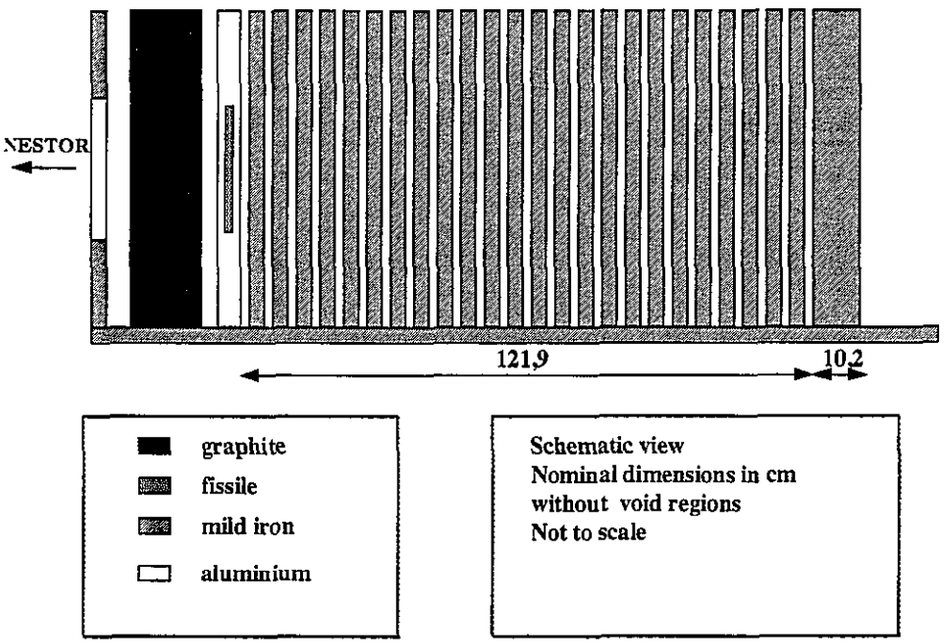


figure 1 Experimental configuration ASPIS iron.

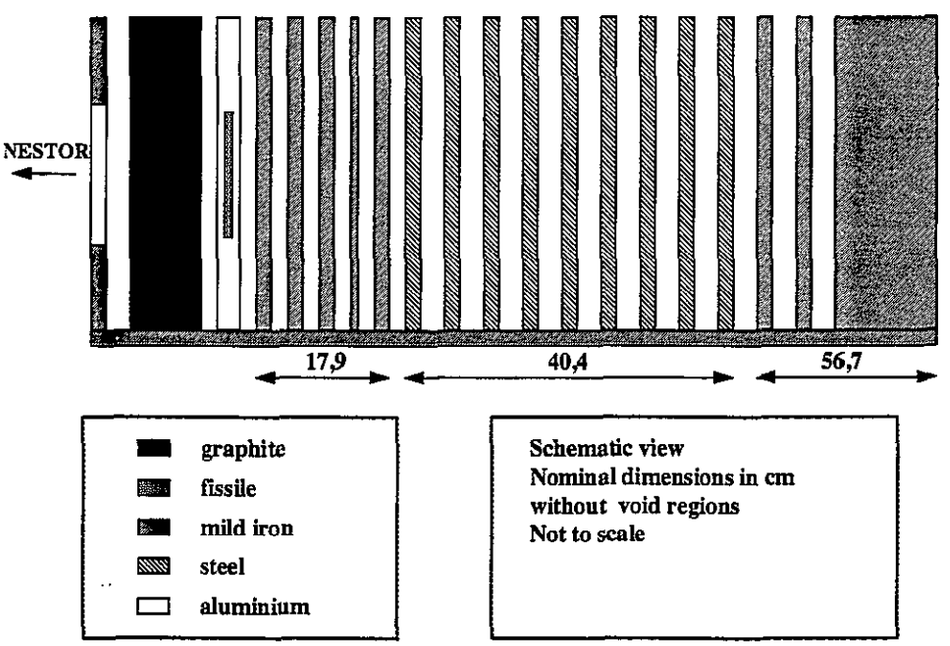


figure 2 Experimental configuration Janus phase 1

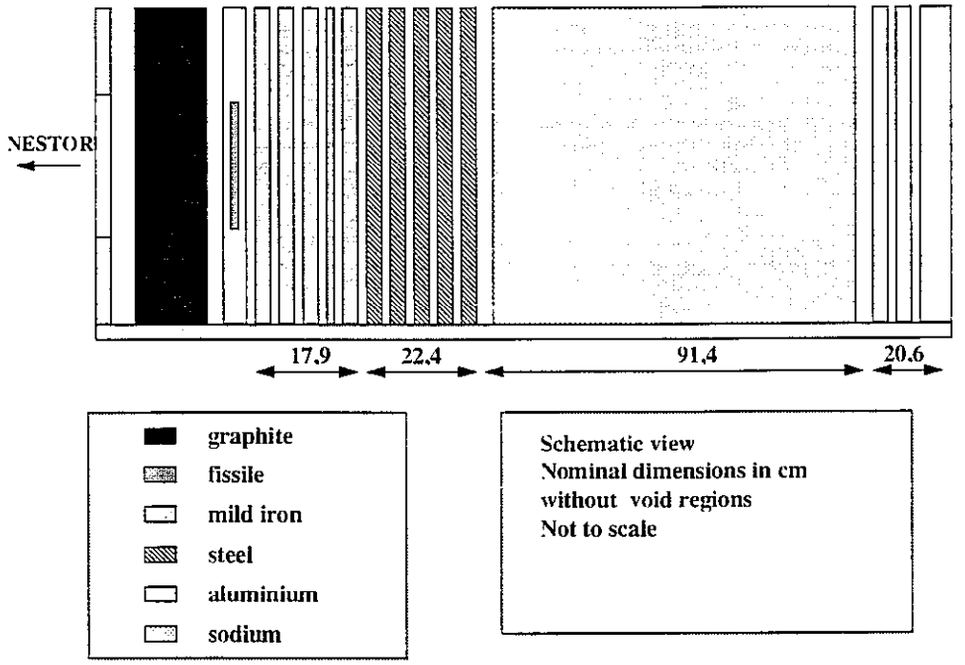


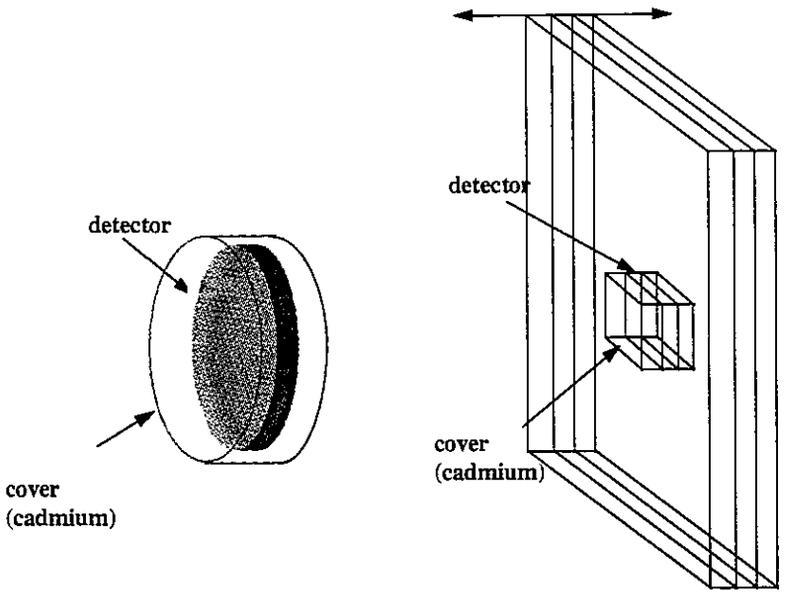
figure 3 Experimental configuration Janus phase2

Reactions of different isotopes have been measured in various positions of the shield in detectors surrounded by a box.

detector	response domain (MeV)	diameter (mm)	thickness (mm)	uncertainty on the calibration	uncertainty on the measurement
S32(n,p)P32	E > 1.6	38.1	2.41	5%	0.6-1.0%
S32(n,p)P32	E > 1.6	51.0	5.6	5%	0.7-16.0%
Rh103(n,n')Rh103m	E > 0.04	12.7	0.015	3%	1-2%
Mn55(n,g)Mn56/Cd (Mn 88%+ Ni 12%)	≈ total flux	38.0	1.63	1.5%	1%
Au197(n,g)Au198/Cd	≈thermal flux	12.7	0.05	0.9%	1%

DETECTOR MODELLING

The self shielding of the response functions is performed by ECCO macrocell calculations of the complete shield with a 3D representation of the detector.



Response functions are taken from the IRDF 90 file but some like Mn55(n,g)Mn56 are directly coming from the JEF 2 ECCO library.

- S32(n,p)P32	IRDF90,
- Rh103(n,n')Rh103m	IRDF90,
- In115(n,n')In115m	IRDF90,
- Mn55(n,g)Mn56	JEF2.2 general purpose file,
- Au197(n,g)Au198	JEF2.2 general purpose file.

Only Mn55 and Au197 detectors need a 3D representation for self shielding and flux corrections, the spatial calculation being performed without the local description of the detector.

It is therefore necessary not only to have activation files but a complete isotope evaluation to be able to do that correction.

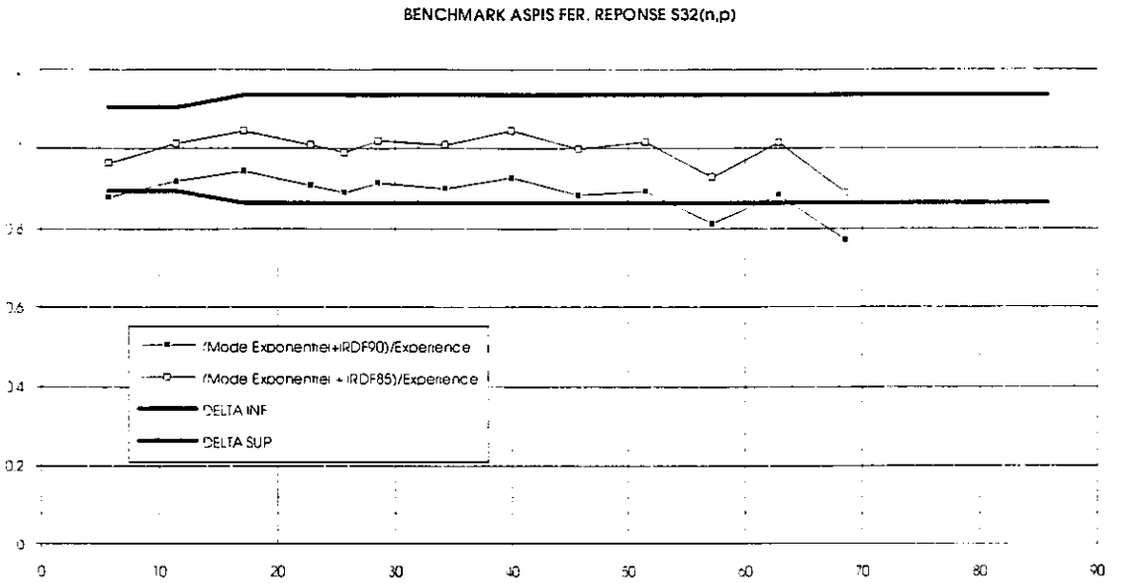


Figure 4 Comparison in the ASPIS iron configuration between S32(n,p) C/E results using IRDF90 and IRDF85 data.

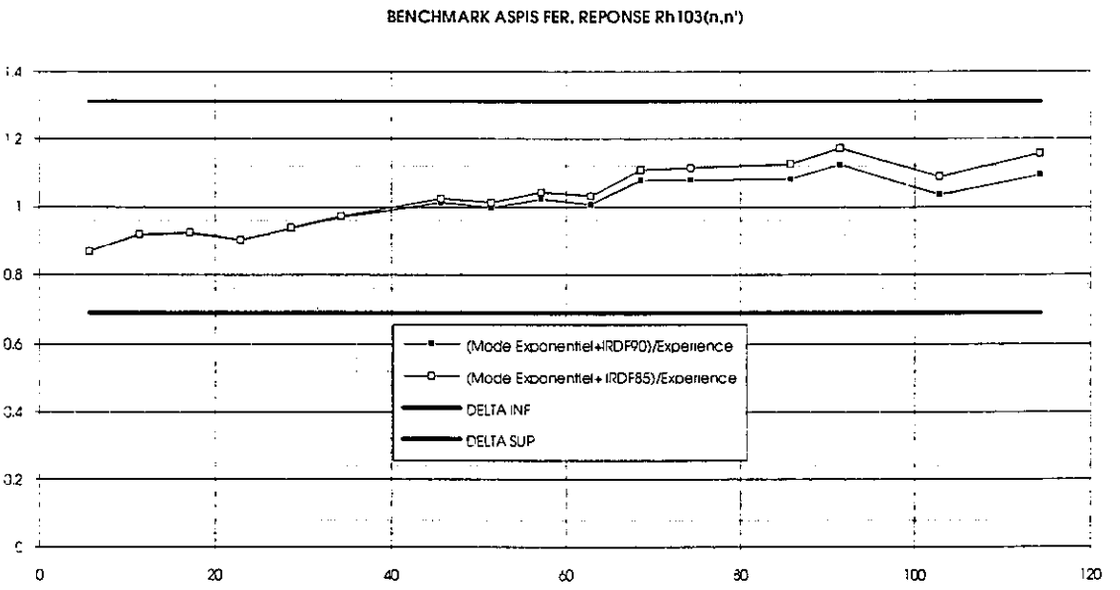


Figure 5 Comparison in the ASPIS iron configuration between Rh103(n,n')Rh103m C/E results using IRDF90 and IRDF85 data.

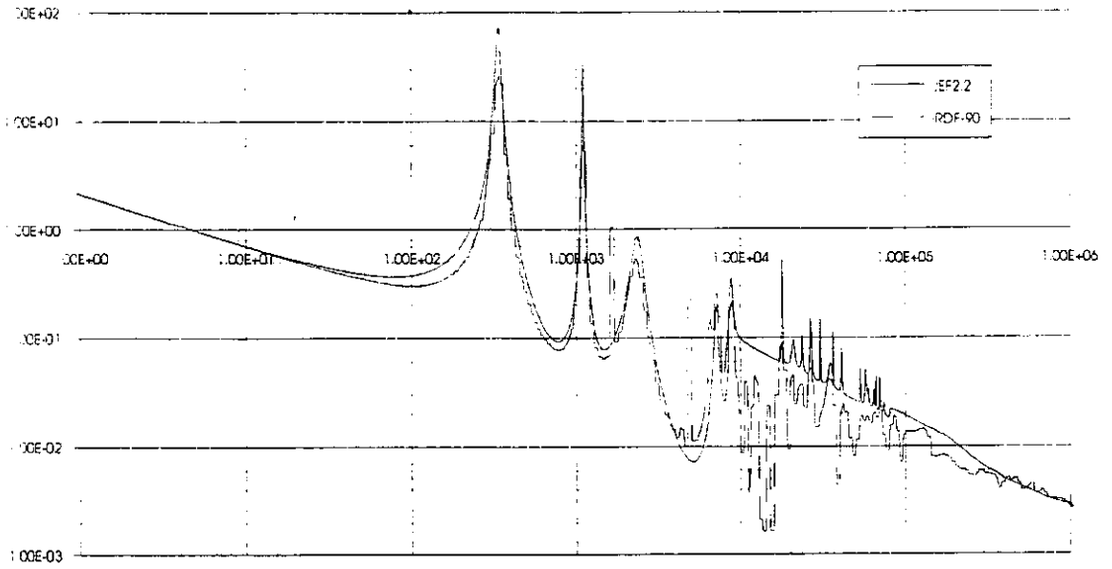


Figure 6 Comparison of Mn55(n,g)Mn56 activation cross sections of two different evaluations

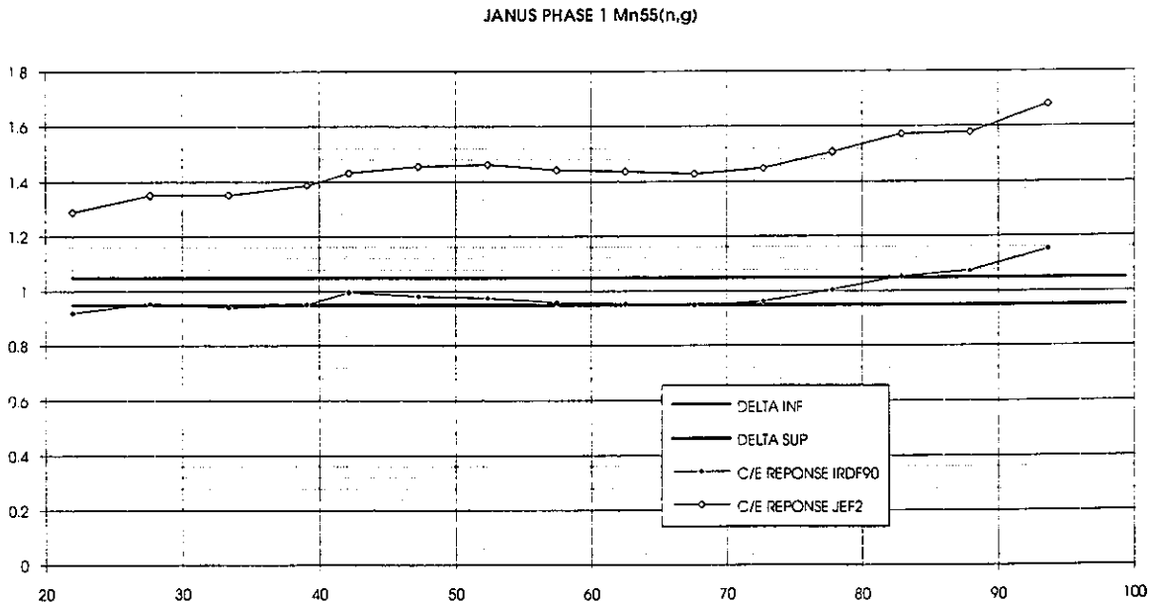


Figure 7 Comparison in the JANUS phase 1 configuration between Mn55(n,g)Mn56 C/E results using two different evaluations.

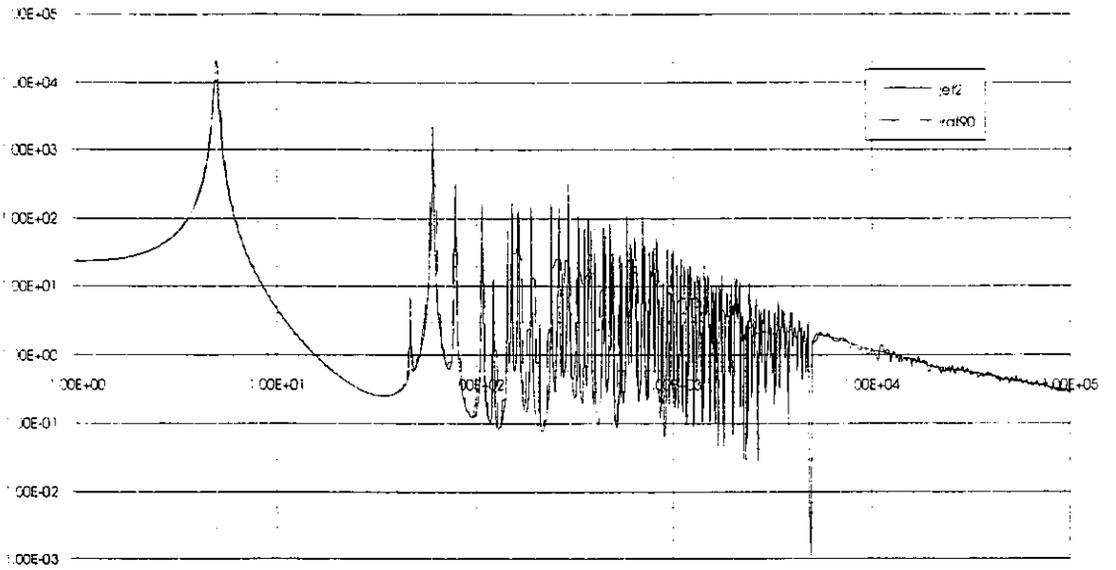


Figure 8 Comparison of Au197(n,g)Au198 activation cross sections of two diiferent evaluations

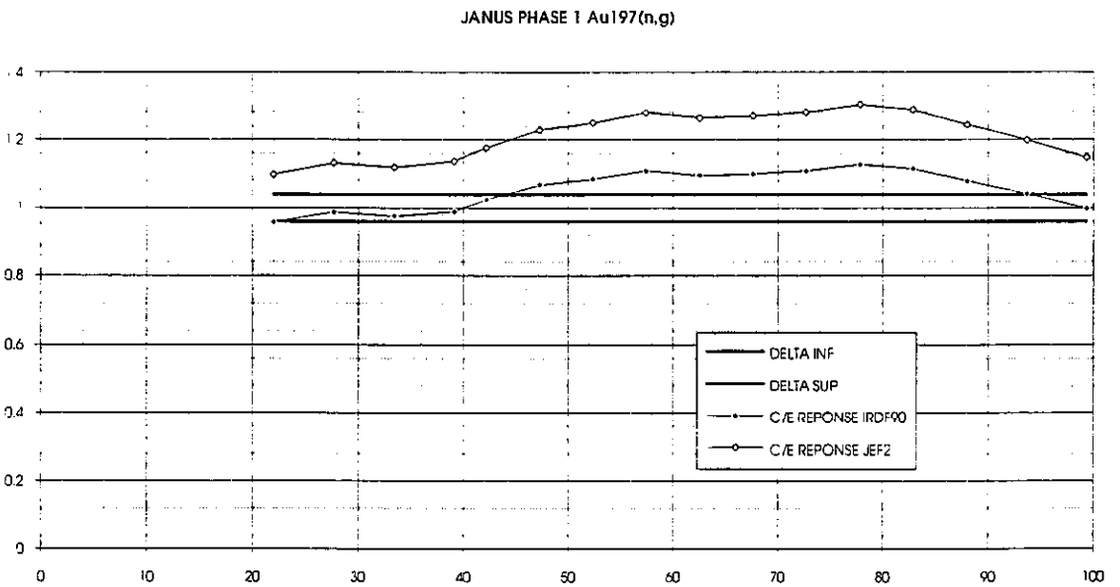


Figure 9 Comparison in the JANUS phase 1 configuration between Au197(n,g)Au198 C/E results using two different evaluations.

RESULTS of ANALYSIS

Results of the the analyses are given first for the ASPIS iron configuration.
S_{32} (n,p) P32 comparison with experiment is given in figure R-1 and is showing reasonable agreement.

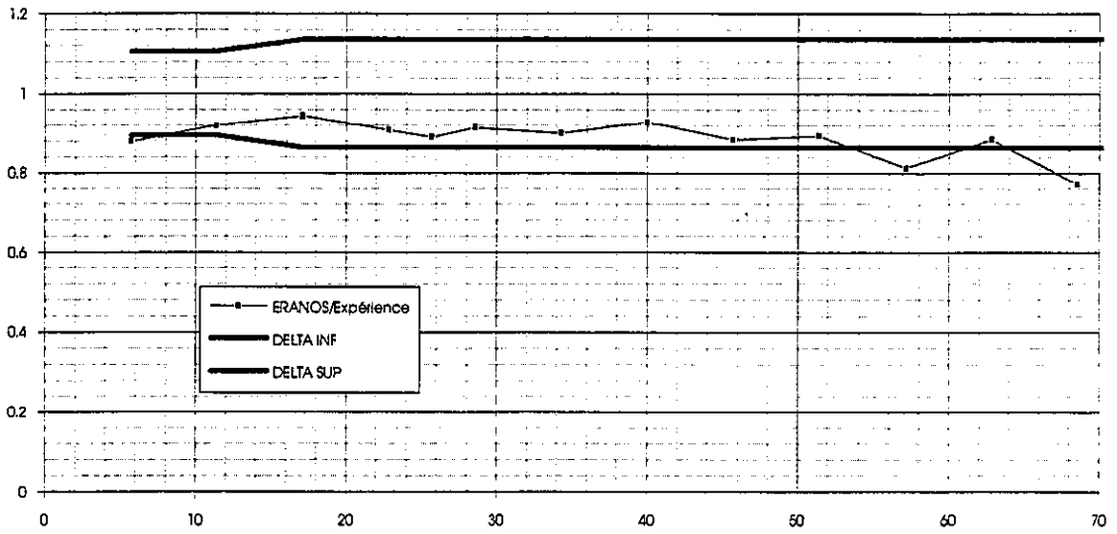


Figure R-1 - C/E ASPIS iron (S32 (n,p)P32) analysis with JEF2 and ERANOS

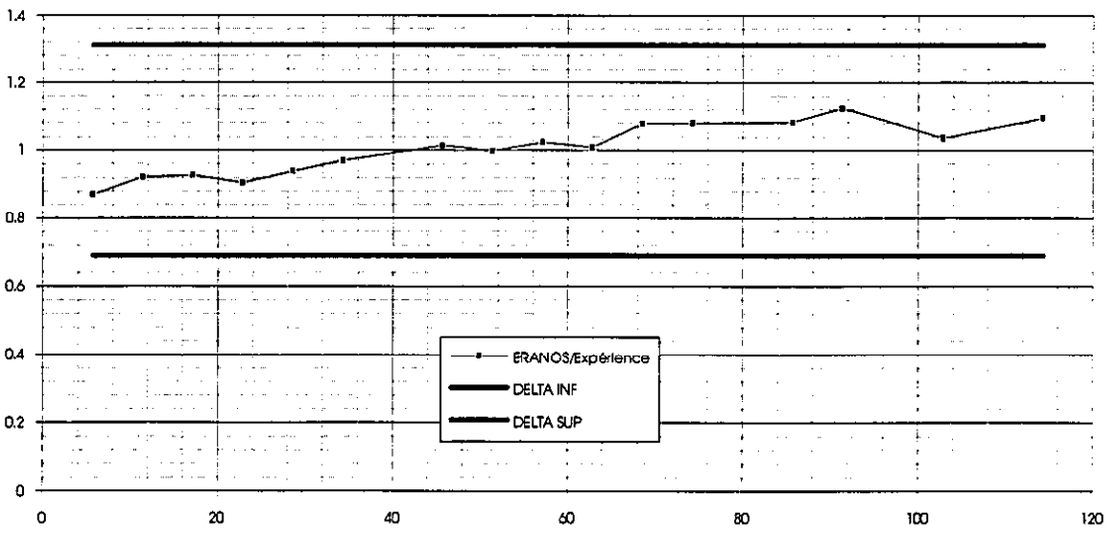


Figure R-2 - C/E ASPIS iron (Rh103(n,n')Rh103m) analysis with JEF2 and ERANOS

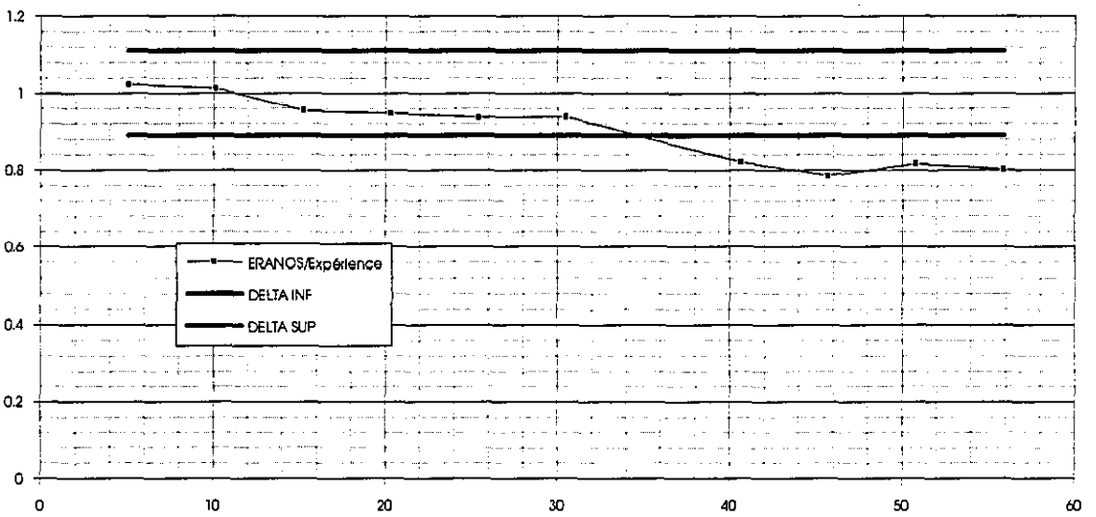


Figure R-3 - C/E ASPIS iron (In115(n,n')) analysis with JEF2 and ERANOS

Results of the the analyses arethen given for the JANUS Phase 1 configuration. Results are given with the ones of the former one which has been used for the SUPER PHENIX design. These two code and data system have nothing in common but BISTRO. Data are of ENDFB 4 origin for PROPANE and JEF2.2 for ERANOS.

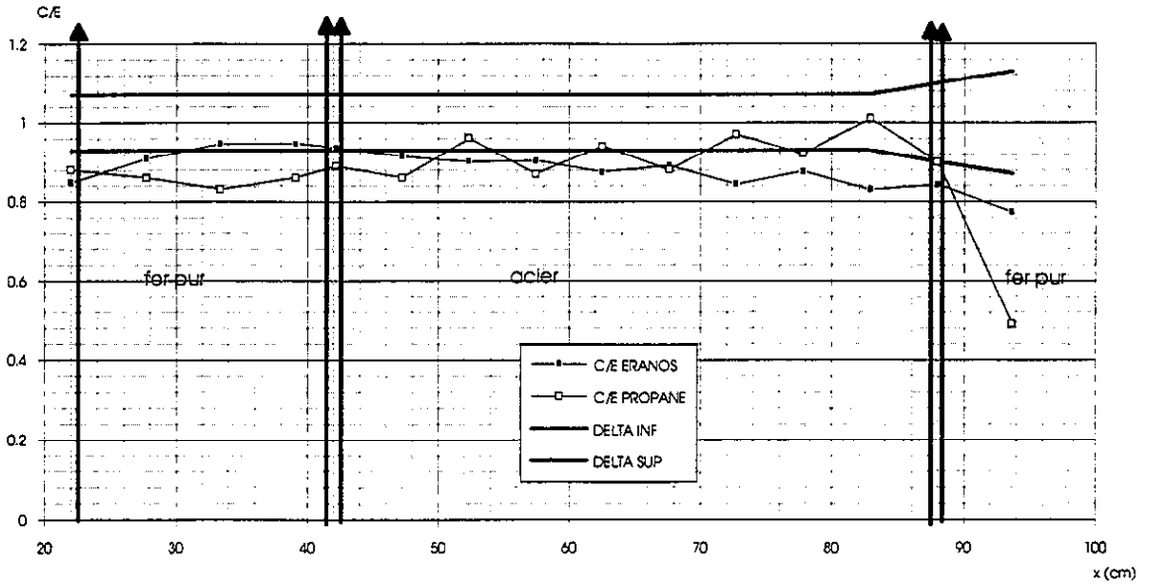


Figure R-4 - C/E JANUS Phase 1 (S32(n,p)) analysis

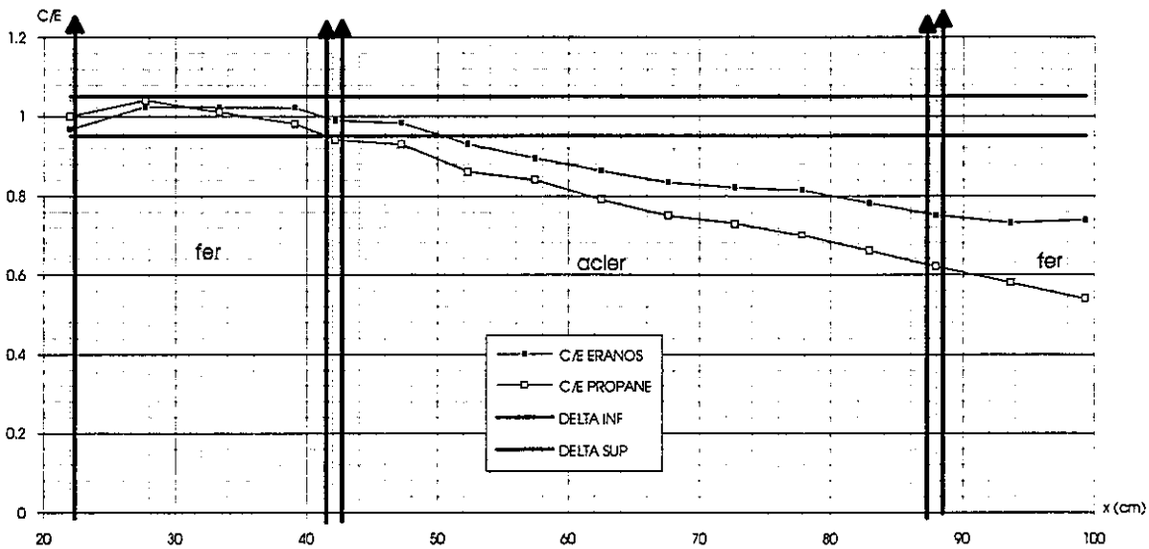


Figure R-5 - C/E JANUS Phase 1 (Rh103(n,n')) analysis

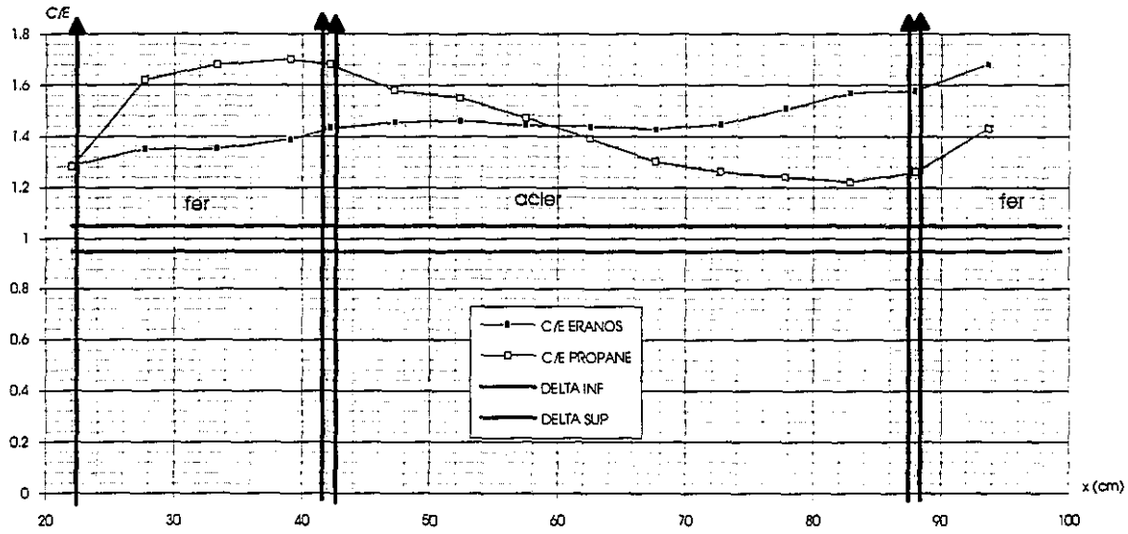


Figure R-6 - C/E JANUS Phase 1 (Mn55(n,g)) analysis

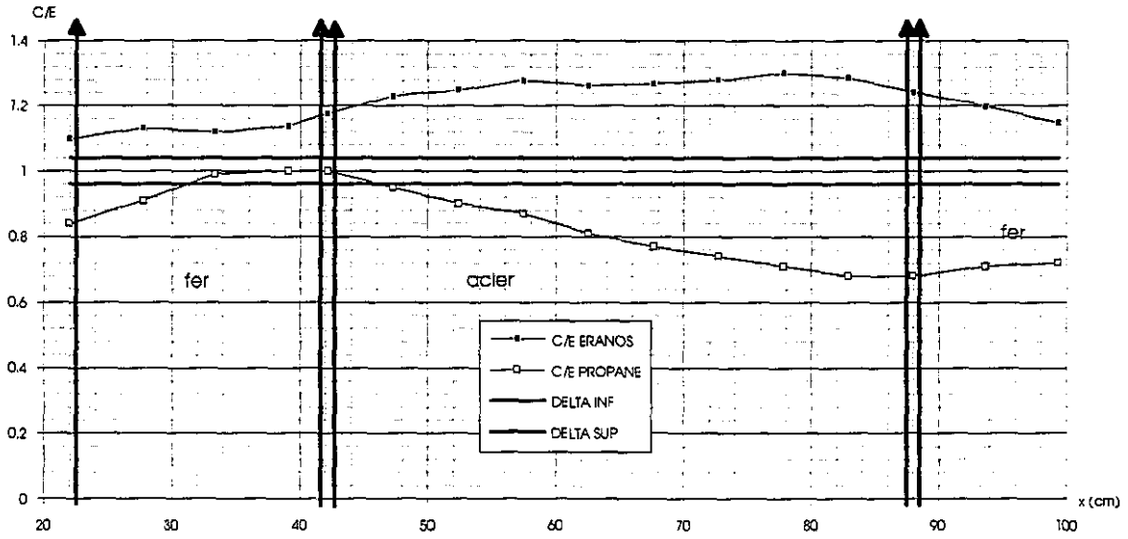


Figure R-7 - C/E JANUS Phase 1 (Au197(n,g)) analysis

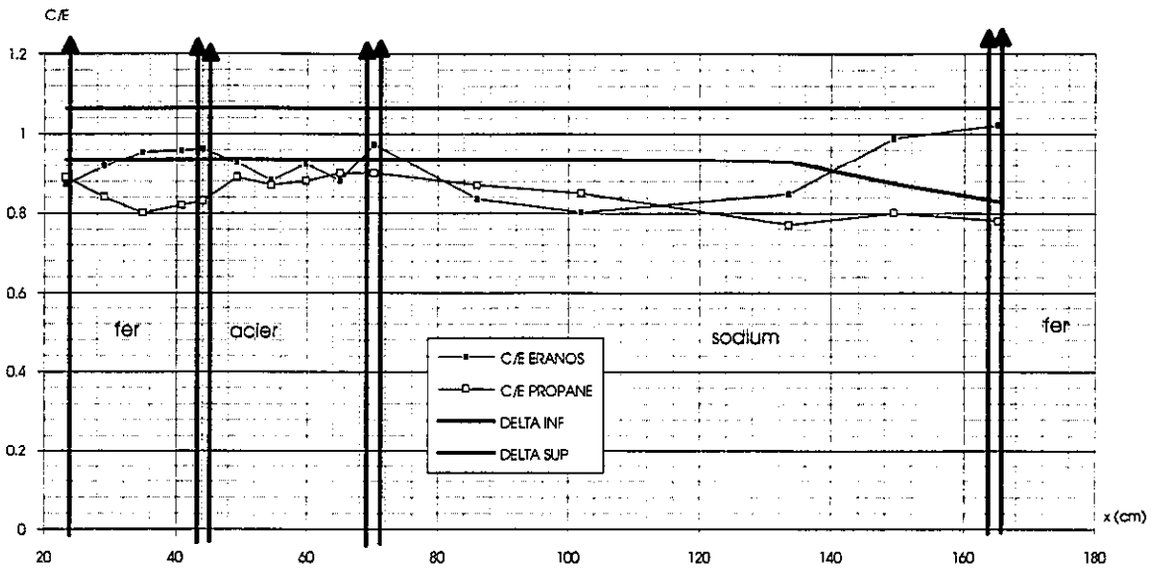


Figure R-8 - C/E JANUS Phase 2 (S32(n,p)) analysis

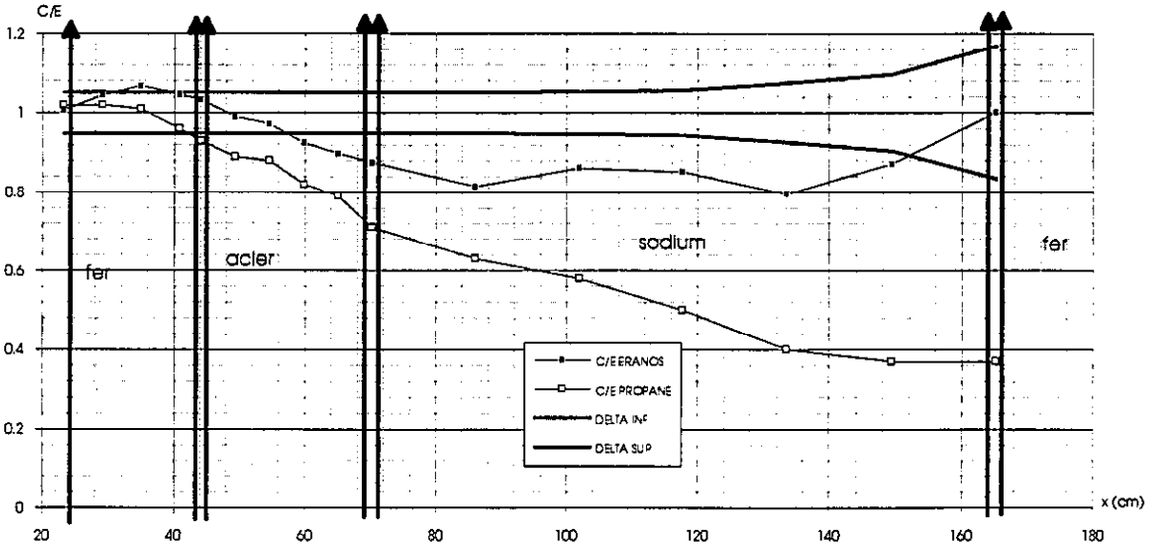


Figure R-9 - C/E JANUS Phase 2 (Rh103(n,n')) analysis

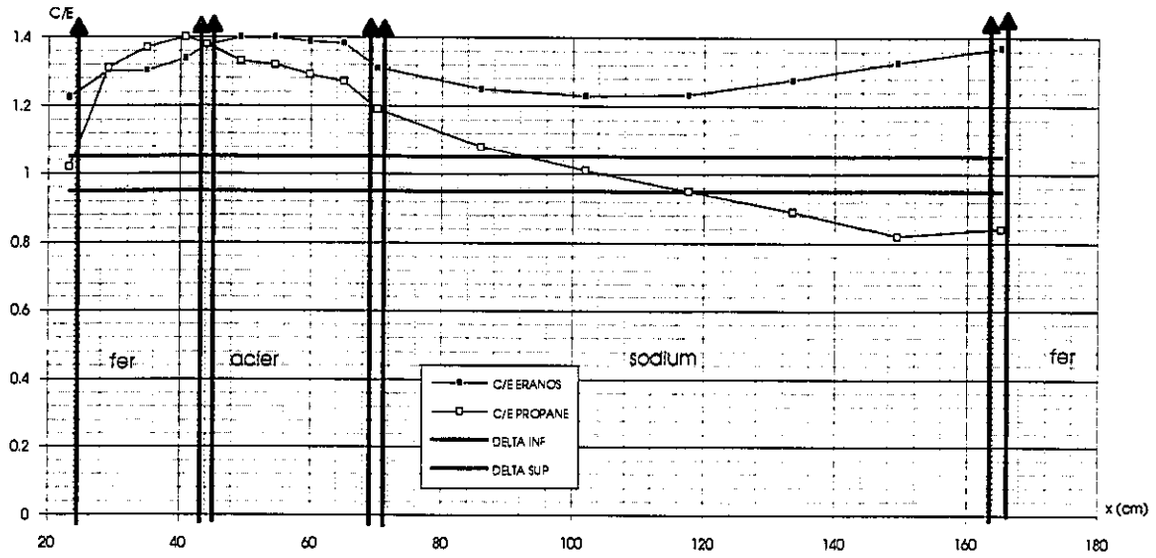


Figure R-10 - C/E JANUS Phase 2 (Mn55(n,g)) analysis

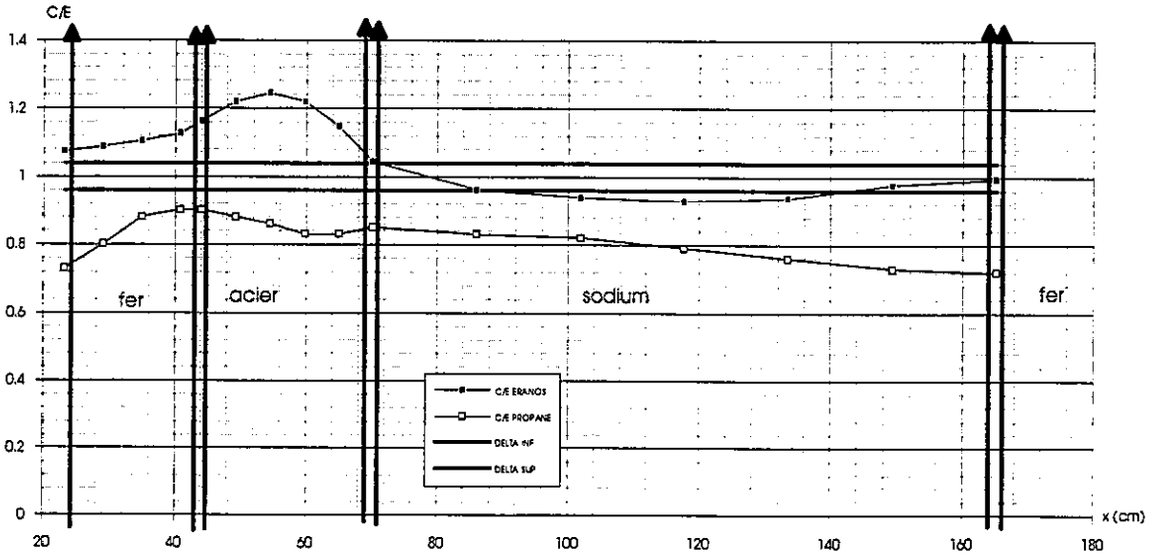


Figure R-11 - C/E JANUS Phase 2 (Au197(n,g)) analysis

CONCLUSIONS

The present calculational scheme is rather quick and has enable us to perform an accurate analysis of the ASPIS iron and JANUS phase 1 and phase 2 experiments.
The JEF2 evaluation is suitable for these calculations as no major discrepancy can be observed in the results. However, some results in steel look unreasonable - Chromium is suspected - .

Only Mn55 and Au197 detectors need a 3D representation for self shielding and flux corrections, the spatial calculation being performed without the local description of the detector.

It is therefore necessary not only to have activation files but a complete isotope evaluation to be able to do that correction.

The evaluation of response functions adds another source of uncertainties to the one of the other cross sections coming into the calculation of the flux. A complete reevaluation of isotopes coming into the definition of detectors is being required. These evaluations need to be in the general purpose file rather than in a separate dosimetry file, calculations being necessary to define the detector coorections.

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