JAERI-M

4660

Shielding Factors of Capture Cross-Sections with Temperature Dependence for Cr, Fe and Ni

December 1971

Yukio Ishiguro

日本原子力研究所
Japan Atomic Energy Research Institute

Shielding Factors of Capture Cross-Sections with Temperature Dependence for Cr, Fe and Ni

Yukio ISHIGURO
Div. of Reactor Engineering, Tokai, JAERI

(Received December 1971)

The Doppler effect due to the structural materials of reactor seems to be recently noticed in fast reactor systems. For the purpose of the analysis of the Doppler effect, the self-shielding factors of capture cross-sections with temperature dependence will be calculated for the natural Cr, Fe and Ni in the form of the ABBN and JAERI Fast group constant sets. Using these shielding factors, the Doppler experiments for stainless steel and natural iron performed in the FCA core are analysed by a simple perturbation method.

Cr，FeおよびNiの吸収断面積に対する温度依存のある自己遮へい因子

日本原子力研究所東海研究所原子炉工学部

石　黒　幸　雄

（1971年12月受理）

高速炉の安全性に重要な役割を果す可能性を持つ構造材のドップラー効果の解析のために，Cr，FeおよびNiの吸収断面積に対する自己遮へい因子をABBNの25群とJAERI－Fastセットの70群構造でテーブル化した。まず，構造材のドップラー領域と核データに関する簡単なサーヴェを行い，実効吸収断面積に対する計算法を示し温度依存性を考慮した自己遮へい因子を計算する。

これらの遮へい因子を用いてFCAで行なわれた構造材に対するドップラー実験を解析し，計算結果は実験値と良い一致をすることを示す。このことから，現在の構造材に対する核データの知識で充分ドップラー解析が可能なことが結論される。

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

The Doppler effect in neuclear reactors has been extensively studied on both experimental and theoretical sides. The reliability for the Doppler coefficient of reactivity obtained from a theoretical estimation has become fairly satisfactory, even in fast reactor systems. However, the objective materials of the study were limited to heavy isotopes such as ^{238}U, that is, only the Doppler effect contributed from the sharp resonances of fertiles or fissiles was studied.

Recently, the Doppler effect due to the structural materials of reactor seems to be noticed in fast reactor systems.[1,2] The recent Doppler experiment in FCA[1] shows that the stainless steel Doppler effect is considerably large (12 % of ^{238}U in $\Delta k/k/Kg$) and the Doppler effect of thin sample can is not less than that of the 90 % enriched UO_2 contained in the can. Since the volume ratis of the structural materials is quite large in fast reactor core, the Doppler effect will therefere play an imporrant role in fast reactor safty, probably being superior to the secondary contribution from ^{235}U or ^{239}Pu. Especialy in the experiments of uniform rising of core temperature or in the calculation of hypothetical accident of melt-down core, the Doppler effect of the structural materials can be supposed to be very important from the experimental results. Moreover, the Doppler effect might also serve to reduce the reactivity inserted accidently in fast reactor systems, with smaller time delay due to heat transmission from fuel pins to structural materials.

The characteristics of the Doppler effect can be considered as follows :

1. Only the sharp p-wave resonances of medium weight nuclei constituting

structural materials can contribute to the Doppler effect through their absorption.

2. The Doppler energy region spreads over the wider energy range from 1 to several hundred KeV, where the weighting function ($\phi \phi^*$) can be changed by a factc about 10^2.

3. Since the temperature of structural materials are lower compared to that of fuel pin, the steep parts of temperature gradient of the cross section are important for the Doppler effect.

4. Since the sharp p-wave resonances of medium nuclei exist in wider level spacing, the effective capture cross-sections can be calculated under the simple assumption of isolated resonance approximation.

The resonance parameters (Er and $\sigma_0 \Gamma_\gamma$) for the sharp p-wave neutron resonance were obtained for Na, Al, Fe, and Ni from 1 to 200 KeV[3]. The cross section data files such as ENDF/B-II and UK Data File adopt the nuclear data based on these resonance parameters, under proper spin-assignment. In the ENDF/B-II, we can also know the resonance parameters for Cr obtained from the resent measurement in PRI. According to the evaluation by Moxon[4] for the capture cross-section of the most important-structural material, iron, the cross-section fit to the observed data between 30 KeV and 100 KeV is reasonably satisfactory in the region of the strong resonances ; between resonances the fit is poor, but this is probably due mainly to small p-and d-wave resonances being missed in the experiments. The energy region above 100 KeV is considered to be unresolved resonance region for the sharp resonances of $\ell > 0$ and the uncertainty in the parameters enters directly into the cross section.

For the purpose of the analysis of the Doppler effect, a simple calculational method of effective capture cross-sections will be proposed and the shielding factors based on the conventional concept of group-constant set[5] will be prepared for natural Cr, Fe and Ni. Using these shielding factors, the Doppler experiments for stainless stell and natural iron performed in FCA will be analysed by a simple perturbation method.

2. CALCULATION OF EFFECTIVE CAPTURE CROSS-SECTIONS

When the resonance absorption by heavy nuclei such as ^{238}U was calculated in a fast reactor, a sufficient accuracy could be expected for the results obtained under the narrow resonance assumption.[6] It will be more sufficient for medium nuclei to use the narrow resonance approximation, since the maximum energy loss in elastic collisions with medium nuclei is larger than that with heavy one. The calculation of effective cross-sections here will be restricted to homogeneous cases, and it will be assumed that the heterogeneities in a fast reactor can be treated adequately by the usual equivalence relation between homogeneous and heterogeneous systems, as in the case of resonance absorption by heavy nuclei. This means that the flux distribution over an energy interval for the calculation of effective cross section will be simply

$$\phi(E) \cong \frac{1}{E(\sigma_t(E)+\sigma_0)} \tag{1}$$

where $\sigma_t(E)$ is the total cross-section of the element under consideration and σ_0 is that of other elements per the former element. Here, we used an approximation that the interference effect between isotopes in an element was taken into account but the interference between different elements was merely considered by σ_0. This approximation will be reasonable for our present interest, because the important resonances for the Doppler effects are located nearly at 1 KeV (Er = 1.15 KeV for iron and Er = 1.63 KeV for chromium) where the interference effects are quite umimportant, while other sharp resonances are not so much shielded. To make matters better, the total cross-section is little shielded in the energy range of interest,[5,7] so that the infinite dilution cross-section may be used in the estimation of σ_o in Eq. (1) without any significant errors.

The total cross-section σ_t in Eq. (1) can be given by

$$\sigma_t(E) = \sigma_{t0}(E) + \sigma_{t1}(E), \tag{2}$$

$$\sigma_{t0}(E) = \sigma_{tsm}(E) + \sum_i A_i \left\{ \frac{4\pi}{k^2} \sum_l \left[(2l+1)\sin^2\varphi_l + \sum_J g_J \sum_\lambda \frac{\Gamma_{n\lambda}}{\Gamma_\lambda} \frac{\cos(2\varphi_l) + 2\chi'_\lambda \sin(2\varphi_l)}{(\chi'_\lambda)^2 + 1} \right] \right\}_i$$

$$(\Gamma_\lambda(E_\lambda) \gg \Delta(E_\lambda)) \tag{3}$$

and

$$\sigma_{t1}(E) = \sum_i A_i \left\{ \sum_{\lambda'} \sigma_{\lambda'} \psi(\chi_{\lambda'}, \theta_{\lambda'}) \right\}_i \quad (\Gamma_{\lambda'} \approx \Delta(E_{\lambda'})) \tag{4}$$

with

$$\chi'_\lambda(E) = \frac{2}{\Gamma_\lambda(E)} (E - E'_\lambda(E)) \tag{5}$$

and

$$E'_\lambda(E) = E_\lambda + \frac{S_l(E_\lambda) - S_l(E)}{2P_l(E_\lambda)} \Gamma_{n\lambda}(E_\lambda) \tag{6}$$

where $\sigma_{tsm}(E)$, $\Delta(E)$ and Ai are the smooth part of total cross-section, the Doppler width and the abundance of the i th isotope, respectively ; the summation over λ in Eq. (3) runs only over the broad resonances unaffected by the Doppler effect, while the summation over λ' in Eq. (4) does over only the sharp resonances, and other notations have the customary meanings. In the above equations, the phase shift φ_ℓ (E), the total width $\Gamma_{i\lambda}$ (E), the shift factor S_ℓ (E) and the penetration factor P_ℓ (E) are calculated following the formulae of ENDF/B-II,[8] but these quantities are calculated at resonance energy, E_λ, in Eq. (4).

Similarly, the capture cross-section can be expressed as

$$\sigma_c(E) = \sigma_{c0}(E) + \sigma_{c1}(E), \tag{7}$$

$$\sigma_{c0}(E) = \sigma_{csm}(E) + \sum_i A_i \left\{ \frac{4\pi}{k^2} \sum_\lambda \frac{\Gamma_{n\lambda}\Gamma_{\gamma\lambda}}{\Gamma_\lambda^2} \frac{1}{(x_\lambda')^2 + 1} \right\}_i \tag{8}$$

and

$$\sigma_{c1}(E) = \sum_i A_i \left\{ \sum_{\lambda'} \sigma_{\lambda'} \frac{\Gamma_{\gamma\lambda'}}{\Gamma_{\lambda'}} \psi(x_{\lambda'}, \theta_{\lambda'}) \right\}_i \tag{9}$$

The effective capture cross-section over an energy interval ΔE can be calculated as follows :

$$\langle \sigma_c \rangle = \frac{\displaystyle\int_{\Delta E} \frac{\sigma_c(E)\,dE}{(\sigma_t(E)+\sigma_0)E}}{\displaystyle\int_{\Delta E} \frac{dE}{(\sigma_t(E)+\sigma_0)E}} = (W_0 + W_1)/Z \tag{10}$$

where

$$Z = \int_{\Delta E} \frac{dE}{(\sigma_t(E)+\sigma_0)E} \cong \int_{\Delta E} \frac{dE}{(\sigma_{t0}(E)+\sigma_0)E} \tag{11}$$

$$W_0 = \int_{\Delta E} \frac{\sigma_{c0}(E)\,dE}{(\sigma_t(E)+\sigma_0)E} \cong \int_{\Delta E} \frac{\sigma_{c0}(E)\,dE}{(\sigma_{t0}(E)+\sigma_c)E} \tag{12}$$

and

$$W_1 = \int_{\Delta E} \frac{\sigma_{c,}(E)\,dE}{(\sigma_t(E)+\sigma_0)E} \cong \sum_i \left[\sum_{\lambda'} \frac{\Gamma_{\gamma\lambda'}}{E_{\lambda'}} J(\theta_{\lambda'}, \beta_{i\lambda'}) \right]_i \quad (13)$$

with

$$\beta_{i\lambda} = (\sigma_{t0}(E_\lambda) + \sigma_0) / (A_i \sigma_{\lambda'}) \text{ and } J(\theta,\beta) = \int_0^\infty \frac{\psi\, dx}{\psi + \beta} \quad (14)$$

In deriving Eqs. (11) and (12) the small contribution of the sharp resonances to the total cross-section was neglected, and the equation (13) was derived under the assumprion of well seperation of the sharp resonances. The equations (11) and (12) can readily be calculated by a numerical integration, while the equation (13) can be evaluated using a subprogram for the usual J-function.

On the other hand, the infinitely dilute cross-section can be calculated by

$$\langle \sigma_c \rangle_{inf} = \int_{\Delta E} \sigma_c(E) \frac{dE}{E} \Big/ \Delta U$$

$$\cong \left[\int_{\Delta E} \sigma_{c0}(E) \frac{dE}{E} + \frac{\pi}{2} \sum_i A_i \left(\sum_{\lambda'} \sigma_{\lambda'} \frac{\Gamma_{\gamma\lambda'}}{E_{\lambda'}} \right)_i \right] \Big/ \Delta U \quad (15)$$

Hence, by preparing the self-shielding factor

$$f_c(T, \sigma_0) = \langle \sigma_c \rangle / \langle \sigma_c \rangle_{inf} \quad (16)$$

in the form of the ABBN group constants set, the effective capture cross-sections with temperature dependence can numerically be calculated by an interpolation method.

Using the expressions derived in the previous section, the effective capture cross-sections and the shielding factors were calculated for Cr, Fe, and Ni, which are the most important elements for structural materials in nuclear reactors. In the present calculations, the nuclear data in ENDF/B-II were used. The sharp p-wave resonance parameters for Fe and Ni in this file were determined from the experimental values for Er and $\sigma_o \Gamma_\gamma$ obtained by Hockenbury et al.,[3] while those for Cr adopted the recent measurements in PRI.

Here, one point should be mentioned in connection with determing the resonance parameters from the capture area ($\sigma_o \Gamma_\gamma$). In this case, ambiguity always exists in the spin and parity (J^π) for the levels made by the neutrons with $\ell > 0$. However, the resonance parameters for some levels may not always depend on (J^π), as about half of the sharp p-wave resonances of ^{56}Fe are so. The resonance absorptions for some levels may not be much shielded so that the effective resonance absorptions do not depend significantly on the assigument of the spin and parity. Fortunately, the above statements on the spin assignment will hold better except for the most important level of ^{56}Fe at Er = 1.15 KeV of which the spin was definitely assigned.[9] Therefore, in spite of the ambiguities in the spin assignment we can calculate the Doppler effect of structural materials without any primary errors. Lastly, the following point should be added : The spin of the level of ^{56}Fe at Er = 34.1 KeV was assigned to be J = 1/2 in the ENDF/D-II ($\Gamma \cong 34$ eV), but the experimental results for capture yield are fairly sharp,[3] compared to other near resonances. Hence, the assignment of J = 3/2 seems to be preferable for this level ($\Gamma \cong 1.18$ eV) as made in the UK data, and the data based on this assignment was used in the present calculation. Figure 1 shows the microscopic capture cross-section of natural iron in the UK file.

Figures from 2 to 4 show the infinitely dilution capture cross-sections of natural Cr, Fe and Ni, respectively, in the group structures of the ABBN and JAERI-Fast sets. It should be noticed that the capture cross-sections in the new version of ENDF/B is considerably larger than those in the old one, except for Fe.

Tables from I to III show the calculated results for the self-shielding factors in the 25-groups structure of the ABBN set. The shielding factors of these isotopes were prepared also for the 70-groups structure of the JAERI-Fast set, which are shown in Appendix.

3. AN ANALYSIS OF DOPPLER EFFECT OF STRUCTURAL MATERIALS

Using the shielding factors and the infinitely dilute capture cross sections obtained in the previous section, the Doppler experiments for stainless steel and natural iron performed in FCA V-1 and V-2 cores[1] were analysed by a simple perturbation method. In this case, the heterogeneity of the Doppler sample of 2.6 cm in diameter and 15.8 cm in length was treated by $\sigma_o = 1/(N\ell)$ with $\ell = 2.6$ cm under the assumption of infinitely long cylinder. Here, it should be noted that the final results did not depend severely on the value assumed for ℓ, about $\ell \cong 3$ cm. The criticality calculations were carried out by one-dimensional diffusion theory using the JAERI-Fast Set.[7]

Figure 5 shows the experimental values (errors $\lesssim \pm 20\,\%$) and the calculated results for stainless steel. For the Doppler effect of natural iron by temperature rising from 25°C to 800°C, we obtained $1.2 \times 10^{-6} \Delta k/k/Kg$ by the 70-groups and 25-groups calculations respectively, while the experimental value is $1.4 \pm 0.2 \times 10^{-6} \Delta k/k/Kg$. The agreement between the experimental and calculated values are fairly good, but the values obtained from the 70-groups calculation seen to be a little lower. The following should be noted : The most important resonance of ^{56}Fe exists in the lowest energy group of the 70-groups structure, hence the 25-groups calculation smoothing out the capture in three groups of the 70-groups structure into that in one group with equal weight will overestimate the Doppler effect of the materials including the iron. This will be seen from Figs. 6 and 7. These figures also show that 25 ～ 40 % of the total Doppler effect come from the energy region above 10 KeV where the calculated results do not depend so much on the group numbers used. The fact that the lower values were obtained for the Doppler effects of structural materials from the 70-groups calculation might be attributed to the level-missing in the energy region above 30 KeV, expected from the capture data evaluation,[4] or to the neglect of the contribution from unresolved resonances above 100 KeV. In this energy region, anyhow, the precise measurements would be needed for the capture cross-sections of structural materials in future experiment.

4. CONCLUSIONS

The Doppler effects of structural materials are supposed to be considerably important for the safty of fast reactors, probably being superior to the contributions from heavy higher isotopes such as ^{235}U and ^{239}Pu. For this analysis, a simple calculational method of effective capture cross-sections was proposed and the shielding factors based on the conventional concept of group-constant set were prepared. Using these shielding factors, the Doppler experiments for stainless steel and natural iron were analysed by a simple perturbation method. The calculated results were in fairly good agreement with the experiments, but they were a little lower in value. The lower values obtained from the calculation might be attributed to the level missing of the sharp p-and d-wave resonances above 30 KeV or to the neglect of the contributions from the unresolved resonances. By the present knowledge for the resonance parameters of structural materials, at any rate, the Doppler effect would be estimated fairly accurately.

Considering from the larger volume-ratio of the structural materials, the Doppler effect is supposed to contribute to keep reactor power from bursting when reactor cores are melt down or when moderator current stops flowing accidentally in some wrapper tubes. Anyhow a safty analysis of fast reactor should be made by taking accoun of the Doppler effect of structural materials in near future.

ACKNOWLEDGMENTS

The author would like to express his sincere thanks to Dr. T. Iijima and Mr. T. Mukaiyama for the discussions with them on the experimental results. He also wishes to acknowledge the suggestive discussions with Dr. S. Katsuragi and the assistance of Mrs. H. Ugajin.

REFFERENCES

1. T. Iijima et al., "Doppler Experiment in FCA", paper submitted to the 14 EACRP Meeting, Stockholm, June (1971) and T. Iijima and T. Mukaiyama, private communication (1971).
2. C. G. Campell and J. L. Rowlands, "The Status of UK Calculations of Doppler Coefficient in Sodium Cooled Fast Reactors", paper submitted to the 14 EACRP Meeting, Stockholm, June (1971).
3. R. W. Hockenbury et al., Phys. Rev., 178 , 1746 (1969).
4. M. C. Moxon, "Capture Cross Sections of Structural Materials", Conf. Proc. Nuclear Data for Reactors, Helsinki, June 1970, IAEA-CN-26/32, International Atomic Energy Agency, Vienna (1970).
5. L. P. Abagjan et al., "Group Constant for Nuclear Reactor Calculations", Consultant Bureau, New York (1964).
6. For example, L. W. Nordheim, "The Technology of Nuclear Reactor Safty", Vol. 1, Chap. 4, The M. I. T. Press, Cambridge (1964) and H. Takano et al., J. Nucl. Eng. Technol. (Tokyo), 7, 500 (1970).
7. S. Katsuragi et al., "JAERI Fast Reactor Group Constants Systems : Part I", JAERI-Report 1177 (1970) and "JAERI Fast Reactor Group Constants Systems : Part II", JAERI-Report 1195 (1970).
8. M. K. Drake, "Data Formats and Procedures for The ENDF Neutron Cross Section Library", BNL-Report 50274 (T-601) (1970).
9. R. E. Chrieu, M. R. Bhat, and O. A. Wasson, Phys. Rev. C., 1, 973 (1970).

TABLE I Capture Cross Section (σc) and Shielding Factor (fc) of Chromium

ABBN Group No.	Energy Range (KeV)	$\langle \sigma_c \rangle_{inf}$ (barns)	T (°K)	fc at σo equal to 0	1	10	10^2	10^3
9	46.5 - 100.	0.01317	300	0.7436	0.7742	0.8738	0.9701	0.9963
			600	0.7546	0.7851	0.8807	0.9713	0.9965
			900	0.7607	0.7910	0.8841	0.9719	0.9965
			2100	0.7720	0.8019	0.8899	0.9728	0.9966
10	21.5 - 46.5	0.03188	300	0.7493	0.7831	0.8849	0.9765	0.9970
			600	0.7647	0.7991	0.8995	0.9811	0.9977
			900	0.7741	0.8088	0.9078	0.9834	0.9981
			2100	0.7940	0.8289	0.9237	0.9874	0.9986
11	10. - 21.5	0.02837	300	0.9695	0.9741	0.9886	0.9981	0.9997
			600	0.9711	0.9754	0.9892	0.9982	0.9997
			900	0.9719	0.9761	0.9895	0.9983	0.9997
			2100	0.9732	0.9772	0.9899	0.9984	0.9998
12	4.65- 10.	0.07789	300	0.8742	0.8801	0.9137	0.9739	0.9959
			600	0.8742	0.8801	0.9137	0.9739	0.9959
			900	0.8742	0.8802	0.9137	0.9739	0.9959
			2100	0.8742	0.8802	0.9137	0.9739	0.9959
13	2.15 - 4.65	0.03887	300	0.8166	0.8263	0.8806	0.9701	0.9968
			600	0.8166	0.8263	0.8806	0.9701	0.9968
			900	0.8166	0.8263	0.8806	0.9701	0.9968
			2100	0.8166	0.8263	0.8806	0.9701	0.9968
14	1. - 2.15	0.15454	300	0.3332	0.3522	0.4780	0.8118	0.9735
			600	0.3625	0.3843	0.5236	0.8469	0.9795
			900	0.3841	0.4077	0.5541	0.8661	0.9825
			2100	0.4401	0.4670	0.6240	0.9016	0.9876

TABLE II Capture Cross Section (σc) and Shielding Factor (fc) of Iron

ABBN Group No.	Energy Range (KeV)	$\langle \sigma c \rangle_{inf}$ (barns)	T (°K)	fc at σ_0 equal to				
				0	1	10	10^2	10^3
9	46.5 - 100	0.02035	300	0.8530	0.8762	0.9341	0.9860	0.9983
			600	0.8583	0.8821	0.9391	0.9873	0.9985
			900	0.8613	0.8855	0.9417	0.9879	0.9985
			2100	0.8674	0.8922	0.9465	0.9889	0.9987
10	21.5 - 45.5	0.02713	300	0.7200	0.7813	0.8721	0.9533	0.9929
			600	0.7364	0.8002	0.8817	0.9548	0.9931
			900	0.7467	0.8110	0.8864	0.9556	0.9931
			2100	0.7692	0.8323	0.8943	0.9567	0.9933
11	10. - 21.5	0.01872	300	0.9078	0.9270	0.9728	0.9960	0.9994
			600	0.9135	0.9325	0.9758	0.9965	0.9995
			900	0.9166	0.9354	0.9773	0.9968	0.9996
			2100	0.9226	0.9407	0.9800	0.9973	0.9996
12	4.65 - 10.	0.05033	300	0.8255	0.8401	0.9053	0.9793	0.9968
			600	0.8272	0.8418	0.9065	0.9796	0.9969
			900	0.8237	0.8428	0.9072	0.9797	0.9969
			2100	0.8308	0.8452	0.9087	0.9800	0.9970
13	2.15 - 4.65	0.01214	300	0.9678	0.9709	0.9847	0.9975	1.0001
			600	0.9699	0.9728	0.9857	0.9978	1.0001
			900	0.9710	0.9738	0.9862	0.9979	1.0001
			2100	0.9728	0.9754	0.9870	0.9980	1.0001
14	1. - 2.15	0.15332	300	0.3370	0.3559	0.4825	0.8167	0.9744
			600	0.3720	0.3930	0.5294	0.8493	0.9799
			900	0.3973	0.4193	0.5605	0.8674	0.9826
			2100	0.4602	0.4845	0.6305	0.9012	0.9875

TABLE III Capture Cross Section (σc) and Shielding Factor (fc) Nickel

ABBN Group No.	Energy Range (KeV)	$\langle \sigma c \rangle_{inf}$ (barns)	T (°K)	fc at σo equal to 0	1	10	10^2	10^3
9	46.5 -100.	0.02037	300	0.8299	0.8458	0.9056	0.9775	0.9973
			600	0.8393	0.8550	0.9137	0.9805	0.9977
			900	0.8451	0.8607	0.9186	0.9821	0.9977
			2100	0.8575	0.8731	0.9288	0.9850	0.9982
10	21.5 - 46.5	0.03667	300	0.7395	0.7534	0.8300	0.9556	0.9943
			600	0.7625	0.7764	0.8506	0.9633	0.9955
			900	0.7763	0.7900	0.8624	0.9673	0.9961
			2100	0.8046	0.8179	0.8850	0.9743	0.9969
11	10. - 21.5	0.15551	300	0.8877	0.8897	0.9066	0.9647	0.9949
			600	0.8923	0.8943	0.9111	0.9673	0.9953
			900	0.8950	0.8970	0.9137	0.9687	0.9956
			2100	0.9005	0.9025	0.9190	0.9713	0.9960
12	4.65- 10.	0.04138	300	1.0765	1.0709	1.0428	1.0082	1.0000
			600	1.0787	1.0730	1.0443	1.0086	1.0002
			900	1.0800	1.0742	1.0451	1.0088	1.0002
			2100	1.0826	1.0767	1.0467	1.0092	1.0003
13	2.15- 4.65	0.04421	300	0.9345	0.9378	0.9570	0.9899	0.9987
			600	0.9562	0.9587	0.9727	0.9943	0.9995
			900	0.9681	0.9701	0.9810	0.9965	0.9998
			2100	0.9901	0.9910	0.9957	1.0002	1.0004
14	1. - 2.15	0.02254	300	0.9976	0.9976	0.9981	0.9990	0.9992
			600	0.9976	0.9977	0.9982	0.9990	0.9992
			900	0.9977	0.9977	0.9982	0.9990	0.9992
			2100	0.9978	0.9978	0.9983	0.9990	0.9992

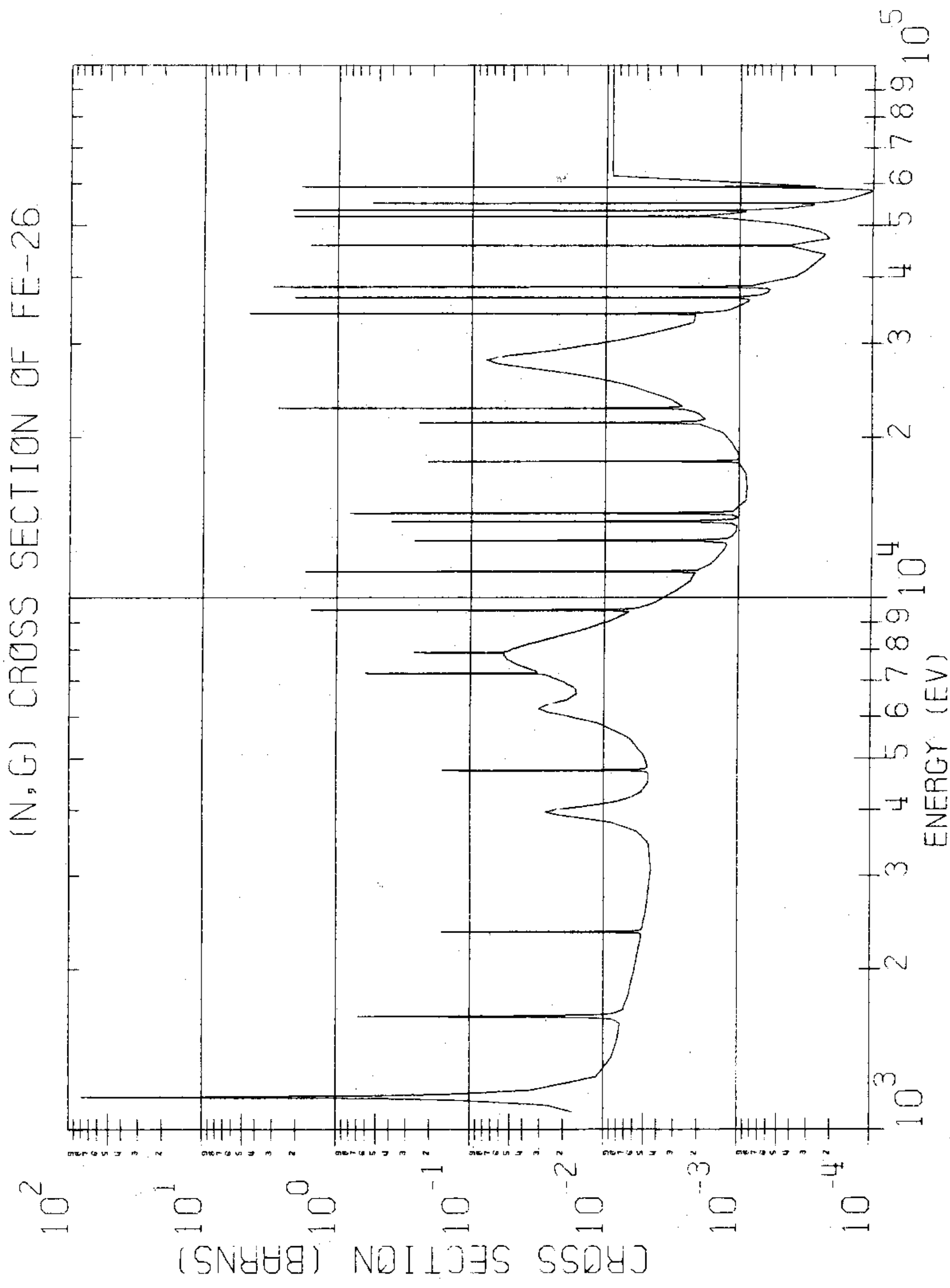


Fig. 1

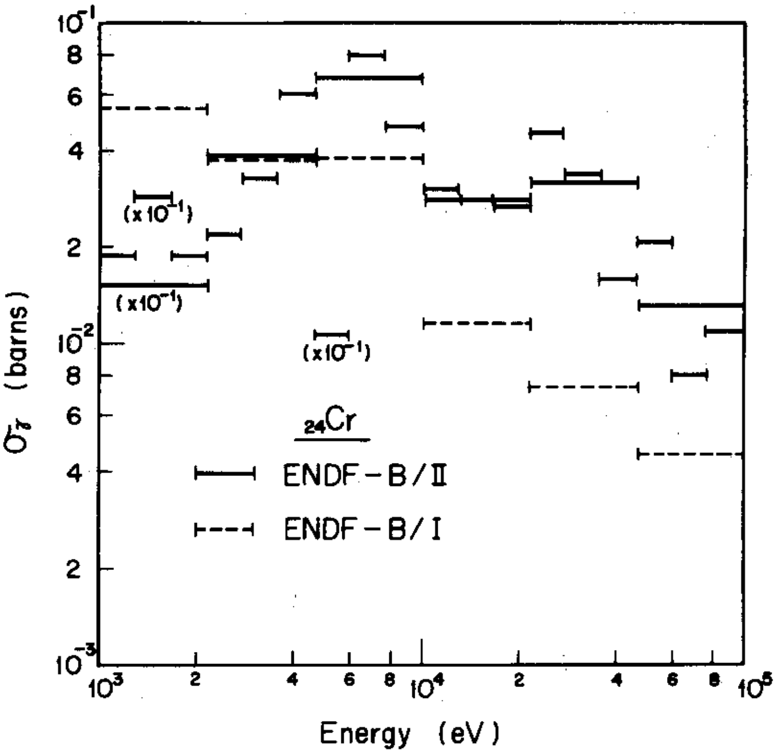

$_{24}$Cr
ENDF-B/II
ENDF-B/I
(x10^{-1})
(x10^{-1})
(x10^{-1})
σ_γ (barns)
Energy (eV)

Fig. 2

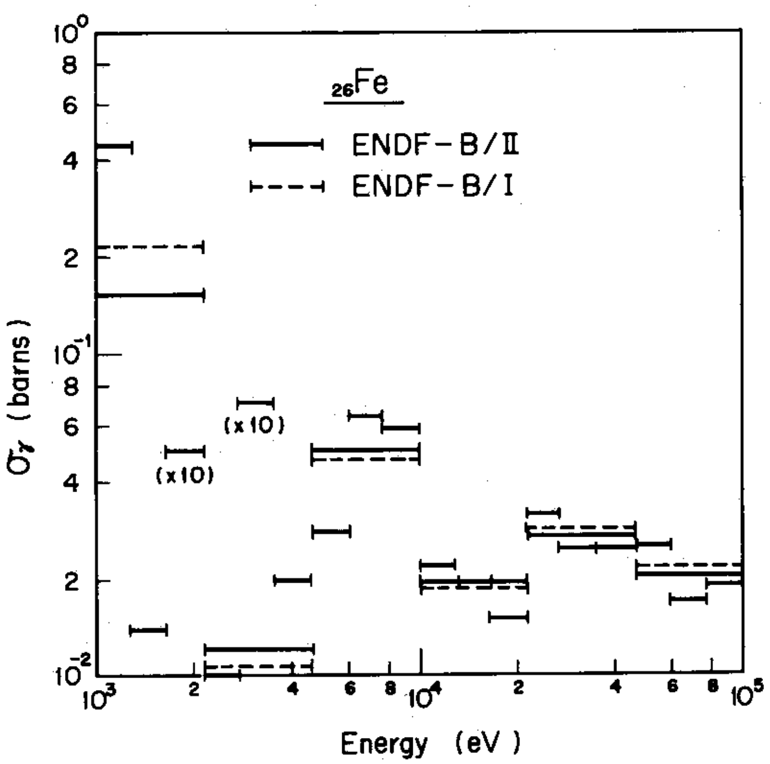
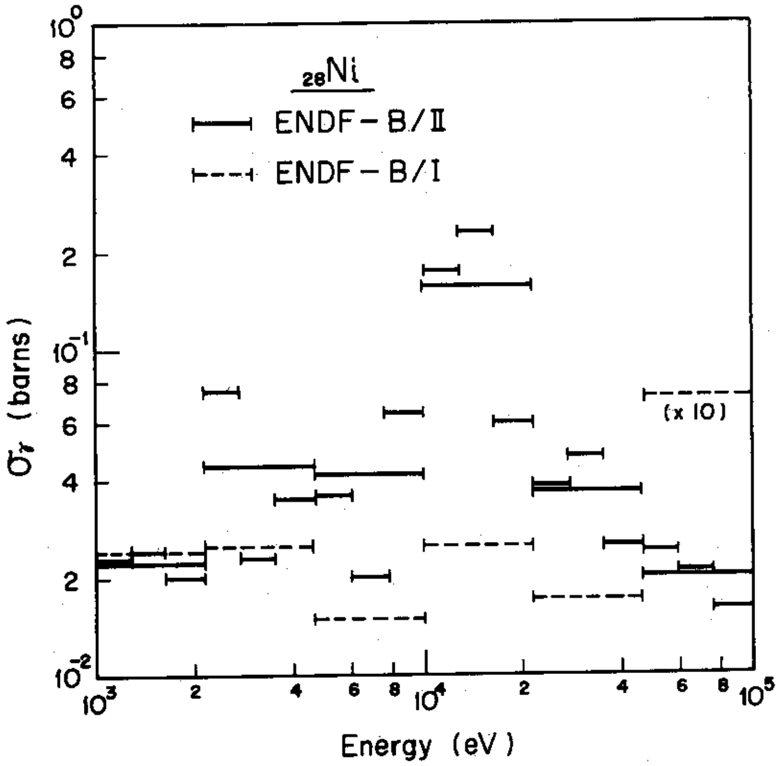
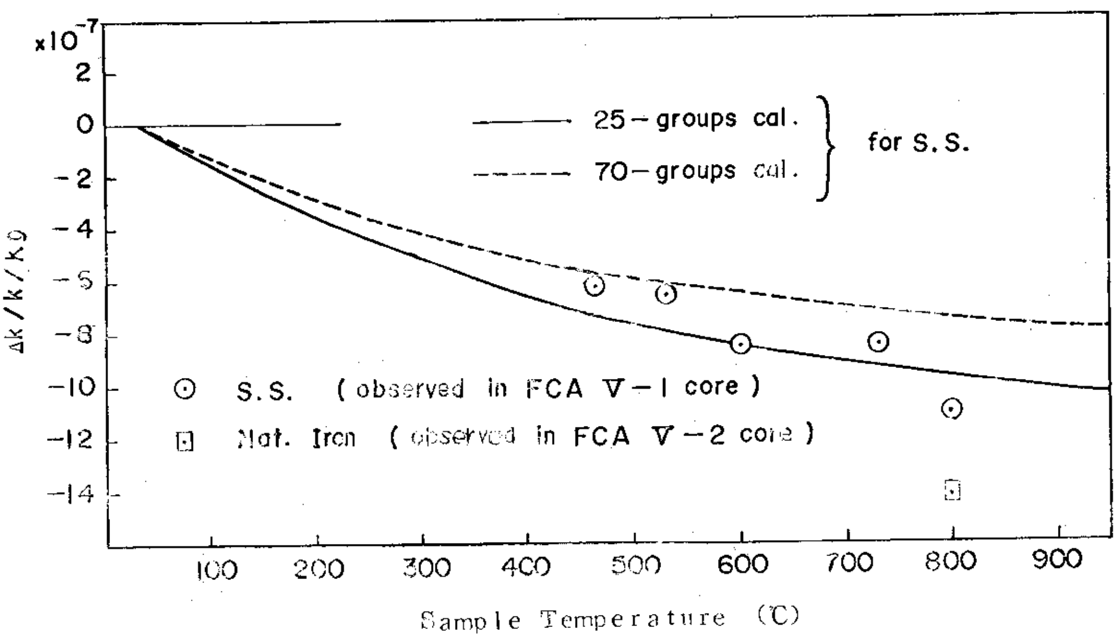

$_{26}$Fe
ENDF-B/II
ENDF-B/I
(x10)
(x10)
σ_γ (barns)
Energy (eV)

Fig. 3



$_{28}$Ni
ENDF-B/II
ENDF-B/I
(x 10)
σ_γ (barns)
Energy (eV)

Fig. 4



x10^{-7}
25-groups cal.
70-groups cal.
for S.S.
S.S. (observed in FCA V-1 core)
Nat. Iron (observed in FCA V-2 core)
Δk/k/k0
Sample Temperature (℃)

Fig. 5

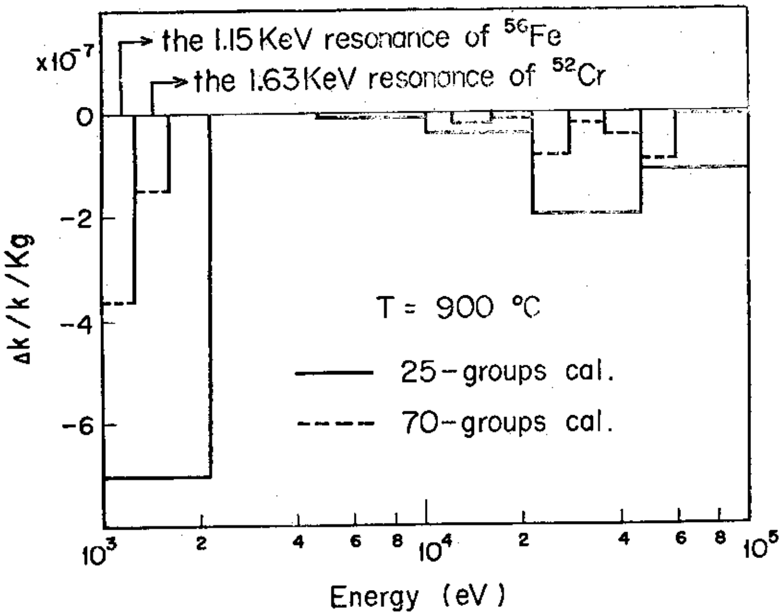

the 1.15 KeV resonance of 56Fe
the 1.63 KeV resonance of 52Cr
x10-7
0
-2
-4
-6
Δk/k/Kg
T = 900 °C
25-groups cal.
70-groups cal.
10^3
2
4
6
8
10^4
2
4
6
8
10^5
Energy (eV)

Fig. 6

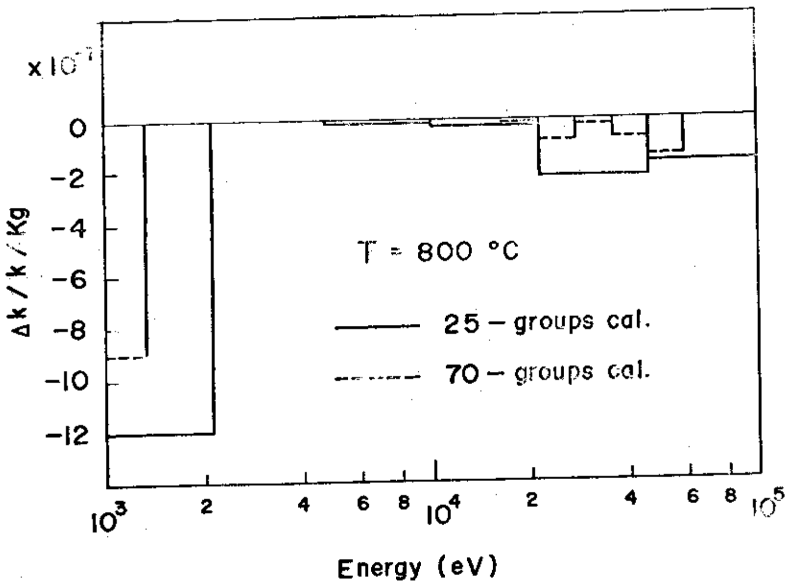

x10-7
0
-2
-4
-6
-8
-10
-12
Δk/k/Kg
T = 800 °C
25 – groups cal.
70 – groups cal.
10^3
2
4
6
8
10^4
2
4
6
8
10^5
Energy (eV)

Fig. 7

Appendix

TABLES OF SHIELDING FACTORS IN 70-GROUPS STRUCTURE

***** TABLE A1 *****

INFINITELY DILUTE CAPTURE CROSS-SECTIONS(SIGMA-C) AND SHIELDING FACTOR(FC) OF CHROMIUM

JAERI-GROUP NO.	ENERGY RANGE (KEV)	SIGMA-C (BARNS)	TEMPERATURE (K. DEG.)	FC AT SIGO EQUAL TO				
				0.0	1.0	10.0	100.0	100.0
20	77.30 -100.00	0.0108	300.0	0.7512	0.7790	0.8741	0.9731	0.9970
			600.0	0.7545	0.7817	0.8749	0.9732	0.9970
			900.0	0.7562	0.7830	0.8754	0.9733	0.9970
			2100.0	0.7591	0.7852	0.8760	0.9733	0.9970
21	59.80 - 77.30	0.0076	300.0	0.9777	0.9819	0.9929	0.9985	0.9993
			600.0	0.9777	0.9819	0.9929	0.9985	0.9993
			900.0	0.9777	0.9819	0.9929	0.9985	0.9993
			2100.0	0.9777	0.9819	0.9929	0.9985	0.9993
22	46.50 - 59.80	0.0212	300.0	0.7864	0.8206	0.9104	0.9780	0.9966
			600.0	0.8137	0.8471	0.9253	0.9803	0.9969
			900.0	0.8290	0.8615	0.9327	0.9814	0.9970
			2100.0	0.8579	0.8882	0.9452	0.9832	0.9972
23	36.00 - 46.50	0.0161	300.0	0.8641	0.8965	0.9660	0.9961	1.0002
			600.0	0.8657	0.8978	0.9666	0.9961	1.0002
			900.0	0.8666	0.8986	0.9669	0.9962	1.0002
			2100.0	0.8685	0.9001	0.9675	0.9963	1.0002
24	27.80 - 36.00	0.0339	300.0	0.8596	0.8735	0.9224	0.9804	0.9977
			600.0	0.8804	0.8926	0.9358	0.9852	0.9983
			900.0	0.8926	0.9036	0.9435	0.9877	0.9986
			2100.0	0.9172	0.9260	0.9587	0.9920	0.9991
25	21.50 - 27.80	0.0457	300.0	0.7037	0.7311	0.8472	0.9707	0.9972
			600.0	0.7234	0.7524	0.8682	0.9768	0.9982
			900.0	0.7359	0.7656	0.8800	0.9799	0.9987
			2100.0	0.7630	0.7936	0.9025	0.9851	0.9994

***** TABLE A 1(CONTINUED) *****

26	16.60 - 21.50	0.0269	300.0	0.9732	0.9764	0.9886	0.9988	1.0008
			600.0	0.9749	0.9777	0.9891	0.9989	1.0008
			900.0	0.9757	0.9784	0.9893	0.9989	1.0008
			2100.0	0.9771	0.9795	0.9897	0.9990	1.0008
27	12.90 - 16.60	0.0277	300.0	0.9875	0.9897	0.9964	1.0002	1.0008
			600.0	0.9887	0.9908	0.9969	1.0003	1.0008
			900.0	0.9893	0.9913	0.9971	1.0003	1.0008
			2100.0	0.9903	0.9921	0.9974	1.0004	1.0008
28	10.00 - 12.90	0.0306	300.0	0.9926	0.9938	0.9978	1.0005	1.0010
			600.0	0.9947	0.9956	0.9987	1.0007	1.0010
			900.0	0.9957	0.9965	0.9991	1.0008	1.0010
			2100.0	0.9975	0.9980	0.9998	1.0009	1.0011
29	7.73 - 10.00	0.0483	300.0	0.9030	0.9079	0.9363	0.9852	1.0000
			600.0	0.9030	0.9079	0.9363	0.9852	1.0000
			900.0	0.9030	0.9079	0.9363	0.9852	1.0000
			2100.0	0.9030	0.9079	0.9363	0.9852	1.0000
30	5.98 - 7.73	0.0802	300.0	0.9916	0.9920	0.9946	0.9996	1.0012
			600.0	0.9916	0.9920	0.9946	0.9996	1.0012
			900.0	0.9916	0.9920	0.9946	0.9996	1.0012
			2100.0	0.9916	0.9920	0.9946	0.9996	1.0012
31	4.65 - 5.98	0.1060	300.0	0.9151	0.9170	0.9310	0.9726	0.9933
			600.0	0.9151	0.9170	0.9310	0.9726	0.9933
			900.0	0.9151	0.9170	0.9310	0.9726	0.9933
			2100.0	0.9151	0.9170	0.9310	0.9726	0.9933

***** TABLE A 1(CONTINUED) *****

32	3.60 - 4.65	0.0609	300.0	0.9860	0.9866	0.9903	0.9981	1.0008
			600.0	0.9860	0.9866	0.9903	0.9981	1.0008
			900.0	0.9860	0.9866	0.9903	0.9981	1.0008
			2100.0	0.9860	0.9866	0.9903	0.9981	1.0008
33	2.78 - 3.60	0.0333	300.0	0.9687	0.9705	0.9807	0.9951	0.9987
			600.0	0.9687	0.9705	0.9807	0.9951	0.9987
			900.0	0.9687	0.9705	0.9807	0.9951	0.9987
			2100.0	0.9687	0.9705	0.9807	0.9951	0.9987
34	2.15 - 2.78	0.0225	300.0	0.9909	0.9915	0.9942	0.9966	0.9971
			600.0	0.9909	0.9915	0.9942	0.9966	0.9971
			900.0	0.9909	0.9915	0.9942	0.9966	0.9971
			2100.0	0.9909	0.9915	0.9942	0.9966	0.9971
35	1.66 - 2.15	0.0192	300.0	1.0027	1.0028	1.0033	1.0036	1.0037
			600.0	1.0027	1.0028	1.0033	1.0036	1.0037
			900.0	1.0027	1.0028	1.0033	1.0036	1.0037
			2100.0	1.0027	1.0028	1.0033	1.0036	1.0037
36	1.29 - 1.66	0.4297	300.0	0.2699	0.2907	0.4288	0.7957	0.9734
			600.0	0.3014	0.3252	0.4782	0.8340	0.9799
			900.0	0.3247	0.3504	0.5113	0.8550	0.9832
			2100.0	0.3850	0.4144	0.5872	0.8938	0.9888
37	1.00 - 1.29	0.0191	300.0	0.9993	0.9993	0.9992	0.9991	0.9991
			600.0	0.9993	0.9993	0.9992	0.9991	0.9991
			900.0	0.9993	0.9993	0.9992	0.9991	0.9991
			2100.0	0.9993	0.9993	0.9992	0.9991	0.9991

***** TABLE A2 *****

INFINITELY DILUTE CAPTURE CROSS-SECTIONS(SIGMA-C) AND SHIELDING FACTOR(FC) OF IRON

JAERI-GROUP NO.	ENERGY RANGE (KEV)	SIGMA-C (BARNS)	TEMPERATURE (K. DEG.)	FC AT SIGO EQUAL TO				
				0.0	1.0	10.0	100.0	100.0
20	77.30 -100.00	0.0188	300.0	0.8972	0.9248	0.9652	0.9920	0.9991
			600.0	0.8972	0.9248	0.9652	0.9920	0.9991
			900.0	0.8972	0.9248	0.9652	0.9920	0.9991
			2100.0	0.8972	0.9248	0.9652	0.9920	0.9991
21	59.80 - 77.30	0.0172	300.0	0.8987	0.9036	0.9317	0.9808	0.9971
			600.0	0.8987	0.9036	0.9317	0.9808	0.9971
			900.0	0.8987	0.9036	0.9317	0.9808	0.9971
			2100.0	0.8987	0.9036	0.9317	0.9808	0.9971
22	46.50 - 59.80	0.0251	300.0	0.8420	0.8574	0.9216	0.9846	0.9974
			600.0	0.8603	0.8751	0.9342	0.9877	0.9979
			900.0	0.8709	0.8852	0.9410	0.9892	0.9981
			2100.0	0.8919	0.9049	0.9532	0.9917	0.9985
23	36.00 - 46.50	0.0247	300.0	0.8750	0.8873	0.9398	0.9898	0.9995
			600.0	0.8962	0.9072	0.9522	0.9923	0.9998
			900.0	0.9074	0.9175	0.9583	0.9935	1.0000
			2100.0	0.9271	0.9355	0.9685	0.9954	1.0002
24	27.80 - 36.00	0.0249	300.0	0.8159	0.8221	0.8573	0.9421	0.9912
			600.0	0.8276	0.8330	0.8638	0.9432	0.9913
			900.0	0.8338	0.8386	0.8670	0.9438	0.9914
			2100.0	0.8446	0.8485	0.8724	0.9446	0.9915
25	21.50 - 27.80	0.0317	300.0	0.6029	0.6635	0.7947	0.9284	0.9903
			600.0	0.6168	0.6810	0.8032	0.9295	0.9905
			900.0	0.6259	0.6915	0.8075	0.9300	0.9905
			2100.0	0.6466	0.7128	0.8147	0.9309	0.9906

***** TABLE A 2(CONTINUED) *****

26	16.60 - 21.50	0.0149	300.0	0.9898	0.9927	0.9985	1.0006	1.0010
			600.0	0.9909	0.9936	0.9989	1.0007	1.0010
			900.0	0.9915	0.9941	0.9990	1.0007	1.0010
			2100.0	0.9926	0.9950	0.9993	1.0008	1.0010
27	12.90 - 16.60	0.0192	300.0	0.9385	0.9489	0.9797	0.9976	1.0003
			600.0	0.9459	0.9555	0.9829	0.9982	1.0005
			900.0	0.9501	0.9592	0.9847	0.9985	1.0005
			2100.0	0.9585	0.9665	0.9880	0.9991	1.0007
28	10.00 - 12.90	0.0221	300.0	0.9476	0.9556	0.9816	0.9981	1.0008
			600.0	0.9599	0.9664	0.9868	0.9989	1.0009
			900.0	0.9662	0.9719	0.9893	0.9993	1.0009
			2100.0	0.9771	0.9813	0.9934	1.0000	1.0010
29	7.73 - 10.00	0.0582	300.0	0.7672	0.7850	0.8695	0.9733	0.9984
			600.0	0.7720	0.7896	0.8727	0.9740	0.9986
			900.0	0.7753	0.7928	0.8747	0.9744	0.9987
			2100.0	0.7830	0.7999	0.8789	0.9752	0.9989
30	5.98 - 7.73	0.0643	300.0	0.9554	0.9591	0.9764	0.9962	1.0008
			600.0	0.9558	0.9595	0.9765	0.9963	1.0008
			900.0	0.9560	0.9596	0.9766	0.9963	1.0008
			2100.0	0.9563	0.9599	0.9768	0.9963	1.0008
31	4.65 - 5.98	0.0279	300.0	0.9784	0.9810	0.9897	0.9955	0.9965
			600.0	0.9786	0.9812	0.9898	0.9956	0.9965
			900.0	0.9787	0.9812	0.9898	0.9956	0.9965
			2100.0	0.9789	0.9814	0.9899	0.9956	0.9965

***** TABLE A 2(CONTINUED) *****

32	3.60 - 4.65	0.0194	300.0	0.9528	0.9582	0.9797	0.9976	1.0008
			600.0	0.9528	0.9582	0.9797	0.9976	1.0008
			900.0	0.9528	0.9582	0.9797	0.9976	1.0008
			2100.0	0.9528	0.9582	0.9797	0.9976	1.0008
33	2.78 - 3.60	0.0070	300.0	1.0156	1.0133	1.0055	1.0001	0.9993
			600.0	1.0156	1.0133	1.0055	1.0001	0.9993
			900.0	1.0156	1.0133	1.0055	1.0001	0.9993
			2100.0	1.0156	1.0133	1.0055	1.0001	0.9993
34	2.15 - 2.78	0.0096	300.0	0.9513	0.9566	0.9773	0.9935	0.9968
			600.0	0.9600	0.9644	0.9813	0.9944	0.9969
			900.0	0.9643	0.9682	0.9833	0.9948	0.9970
			2100.0	0.9717	0.9748	0.9865	0.9955	0.9971
35	1.66 - 2.15	0.0050	300.0	1.0022	1.0023	1.0030	1.0036	1.0037
			600.0	1.0022	1.0023	1.0030	1.0036	1.0037
			900.0	1.0022	1.0023	1.0030	1.0036	1.0037
			2100.0	1.0022	1.0023	1.0030	1.0036	1.0037
36	1.29 - 1.66	0.0136	300.0	0.9815	0.9836	0.9922	0.9993	1.0014
			600.0	0.9896	0.9909	0.9961	1.0003	1.0015
			900.0	0.9938	0.9946	0.9981	1.0008	1.0016
			2100.0	1.0011	1.0012	1.0014	1.0016	1.0017
37	1.00 - 1.29	0.4445	300.0	0.3320	0.3504	0.4758	0.8133	0.9738
			600.0	0.3710	0.3914	0.5261	0.8475	0.9795
			900.0	0.3991	0.4207	0.5594	0.8664	0.9824
			2100.0	0.4693	0.4927	0.6347	0.9018	0.9874

***** TABLE A3 *****

INFINITELY DILUTE CAPTURE CROSS-SECTIONS(SIGMA-C) AND SHIELDING FACTOR(FC) OF NICKEL

JAERI-GROUP NO.	ENERGY RANGE (KEV)	SIGMA-C (BARNS)	TEMPERATURE (K. DEG.)	FC AT SIGO EQUAL TO				
				0.0	1.0	10.0	100.0	100.0
20	77.30 -100.00	0.0160	300.0	0.9625	0.9665	0.9824	0.9969	0.9998
			600.0	0.9625	0.9665	0.9824	0.9969	0.9998
			900.0	0.9625	0.9665	0.9824	0.9969	0.9998
			2100.0	0.9625	0.9665	0.9824	0.9969	0.9998
21	59.80 - 77.30	0.0210	300.0	0.8928	0.9041	0.9414	0.9849	0.9976
			600.0	0.8929	0.9042	0.9414	0.9849	0.9976
			900.0	0.8930	0.9043	0.9415	0.9849	0.9976
			2100.0	0.8931	0.9043	0.9415	0.9849	0.9976
22	46.50 - 59.80	0.0242	300.0	0.7068	0.7298	0.8254	0.9560	0.9941
			600.0	0.7229	0.7464	0.8427	0.9633	0.9951
			900.0	0.7328	0.7567	0.8532	0.9673	0.9951
			2100.0	0.7542	0.7791	0.8749	0.9745	0.9963
23	36.00 - 46.50	0.0248	300.0	0.7723	0.7841	0.8524	0.9643	0.9960
			600.0	0.7884	0.8004	0.8675	0.9697	0.9969
			900.0	0.7980	0.8100	0.8760	0.9724	0.9973
			2100.0	0.8176	0.8294	0.8918	0.9769	0.9980
24	27.80 - 36.00	0.0469	300.0	0.7383	0.7492	0.8156	0.9468	0.9933
			600.0	0.7661	0.7769	0.8405	0.9569	0.9948
			900.0	0.7835	0.7940	0.8552	0.9623	0.9955
			2100.0	0.8207	0.8304	0.8850	0.9720	0.9965
25	21.50 - 27.80	0.0382	300.0	0.8501	0.8583	0.9045	0.9777	0.9980
			600.0	0.8785	0.8860	0.9263	0.9842	0.9990
			900.0	0.8949	0.9018	0.9380	0.9874	0.9995
			2100.0	0.9266	0.9321	0.9595	0.9928	1.0002

***** TABLE A 3 (CONTINUED) *****

26	16.60 - 21.50	0.0588	300.0	0.8823	0.8851	0.9042	0.9621	0.9952
			600.0	0.8924	0.8950	0.9136	0.9675	0.9962
			900.0	0.8995	0.9021	0.9202	0.9711	0.9968
			2100.0	0.9178	0.9202	0.9368	0.9792	0.9981
27	12.90 - 16.60	0.2363	300.0	1.0371	1.0371	1.0363	1.0237	1.0052
			600.0	1.0490	1.0488	1.0466	1.0280	1.0057
			900.0	1.0552	1.0549	1.0518	1.0301	1.0060
			2100.0	1.0663	1.0657	1.0610	1.0337	1.0066
28	10.00 - 12.90	0.1742	300.0	0.9518	0.9536	0.9648	0.9896	0.9996
			600.0	0.9518	0.9536	0.9648	0.9896	0.9996
			900.0	0.9518	0.9536	0.9648	0.9896	0.9996
			2100.0	0.9518	0.9536	0.9648	0.9896	0.9996
29	7.73 - 10.00	0.0673	300.0	0.9796	0.9813	0.9898	0.9996	1.0014
			600.0	0.9808	0.9825	0.9906	0.9998	1.0016
			900.0	0.9816	0.9833	0.9911	0.9999	1.0017
			2100.0	0.9837	0.9852	0.9924	1.0002	1.0018
30	5.98 - 7.73	0.0202	300.0	0.9830	0.9846	0.9921	0.9995	1.0012
			600.0	0.9877	0.9890	0.9949	1.0002	1.0013
			900.0	0.9900	0.9911	0.9962	1.0005	1.0013
			2100.0	0.9938	0.9947	0.9984	1.0010	1.0014
31	4.65 - 5.98	0.0358	300.0	0.9710	0.9723	0.9802	0.9925	0.9961
			600.0	0.9743	0.9755	0.9824	0.9932	0.9962
			900.0	0.9759	0.9770	0.9835	0.9936	0.9963
			2100.0	0.9785	0.9795	0.9853	0.9941	0.9963

***** TABLE A 3(CONTINUED) *****

32	3.60 - 4.65	0.0351	300.0	0.9797	0.9805	0.9855	0.9965	1.0006
			600.0	0.9797	0.9805	0.9855	0.9965	1.0006
			900.0	0.9797	0.9805	0.9855	0.9965	1.0006
			2100.0	0.9797	0.9805	0.9855	0.9965	1.0006
33	2.78 - 3.60	0.0228	300.0	0.9942	0.9944	0.9959	0.9983	0.9991
			600.0	0.9942	0.9944	0.9959	0.9983	0.9991
			900.0	0.9942	0.9944	0.9959	0.9983	0.9991
			2100.0	0.9942	0.9944	0.9959	0.9983	0.9991
34	2.15 - 2.78	0.0750	300.0	0.8316	0.8387	0.8820	0.9663	0.9927
			600.0	0.8639	0.8699	0.9064	0.9737	0.9941
			900.0	0.8815	0.8868	0.9193	0.9774	0.9947
			2100.0	0.9140	0.9181	0.9424	0.9837	0.9956
35	1.66 - 2.15	0.0200	300.0	1.0037	1.0037	1.0037	1.0037	1.0037
			600.0	1.0037	1.0037	1.0037	1.0037	1.0037
			900.0	1.0037	1.0037	1.0037	1.0037	1.0037
			2100.0	1.0037	1.0037	1.0037	1.0037	1.0037
36	1.29 - 1.66	0.0241	300.0	0.9994	0.9995	1.0000	1.0013	1.0016
			600.0	0.9995	0.9996	1.0003	1.0013	1.0016
			900.0	0.9997	0.9998	1.0004	1.0014	1.0016
			2100.0	1.0000	1.0001	1.0006	1.0014	1.0016
37	1.00 - 1.29	0.0235	300.0	0.9990	0.9990	0.9990	0.9991	0.9991
			600.0	0.9990	0.9990	0.9990	0.9991	0.9991
			900.0	0.9990	0.9990	0.9990	0.9991	0.9991
			2100.0	0.9990	0.9990	0.9990	0.9991	0.9991