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RESONANCE PARAMETER DATA UNCERTAINTY EFFECTS ON INTEGRAL CHARACTERISTICS OF FAST REACTORS

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RESUME :

Sensitivity studies are presented of integral parameters of interest for fast reactors to uncertainties of resonance parameters of U-238, Pu-239, Pu-240 and Pu-241. Consequences due to some uncertainty correlation hypothesis are also considered.

1 - INTRODUCTION

Resonance data for actinides play a major role in the calculations of fast neutron reactor neutronics characteristics. All major parameters, from critical mass to safety parameters, like the Doppler reactivity effect, are dependent on actinide nuclear data in the resonance region.

The reactor physicist is faced by a twofold problem, namely to correctly process the basic nuclear parameters in order to produce multigroup cross sections, and to assess the effects of the uncertainties that affect these basic data.

The first problem has been treated in detail in the years '70, and one should quote in particular the fundamental work in this field by R. HWANG at Argonne /1,2,3/ that lead to algorithms to process the resonance data. Even if it is not quite completely closed and uncertainties are still present in the basic data processing in the resonance regions, this problem will not be treated here.

In what follow we will try to indicate a methodology to assess the resulting uncertainties on integral parameters of interest for fast reactors and in particular the safety related parameters, due to uncertainties on the resonance parameters of U-238, Pu-239, Pu-240 and Pu-241.

First, sensitivity tables will be generated for separate variation of individual resonance parameters in selected energy regions. The sensitivity coefficients are relevant to the main integral and safety related parameters of a typical large power fast reactor, i.e. Keff, control rod worth, Doppler and sodium void reactivity coefficients, breeding gain, and are calculated according to the standard methods of generalized perturbation theory.

Both infinite dilution and self-shielding effects will be considered separately.

Finally, several hypothesis of correlation of data uncertainties will be used, to indicate, if possible, realistic estimates of integral parameters uncertainties. This is by far the most delicate point in the uncertainty analysis, and the present work is intended only to point out the main areas where more work is needed.

For what concerns the consistency between integral and differential data, the ideas of the consistent method of basic data adjustement are recalled, and an experimental program to be performed on the critical facility ERMINE indicated, which will be mainly devoted to the low energy data validation ($E \leqslant 50$ KeV).

In fact, resonance data can be considered to be mainly related to the energy range below 50 KeV and in this energy region the number of significant clean integral experiments, which have been widely used in the past in many leading programs of Fast Reactors to validate or to adjust basic data, have been fairly scarce.

2 - SENSITIVITY ANALYSIS

2.1 - Basic Hypothesis

The standard techniques of the generalized perturbation methods /4/ were used to calculate sensitivity coefficients defined, for each isotope, as :

$$S_{iKj} = \frac{\partial R_i}{R_i} \Big/ \frac{\partial p_{Kj}}{p_{Kj}} \qquad (1)$$

where R_i is the following set of integral parameters, calculated in diffusion theory in one-dimension, for a large 1200 MWe fast power reactor of the homogeneous type (see table I) :

- Keff
- control rod worth of a two absorber ring system of partially inserted rods, for a total antireactivity of :

  $$\rho = -1.31 \ \% \ \Delta K/K$$

- core Doppler reactivity coefficient ($\Delta T = 1500$ K)
- internal core sodium void scattering component
- total breeding ratio.

The reference values of the R_i parameters calculated with the CARNAVAL IV formulaire are shown in table II. The p_{Kj} represent parameters of type K in energy range ΔE_j and they are indicated in table III.

The hypothesis in the calculation of the sensitivity coefficients S_{iK} was that of complete independence of each type of resonance parameter for each isotope. The correlations that actually can occur among parameters will be introduced at the moment of the use of the sensitivity coefficients, and their folding with data uncertainties (see paragraph 4).

For what concerns energy correlations, the following hypothesis were used.

First, for sake of simplicity, and to reduce the amount of computational work, the energy range of interest (i.e. approximately from 100 keV to 100 eV) was subdivided according to a standard multigroup cross-section scheme, based on half - lethargy widths (see table IV). In each energy range (corresponding to a group, in a multigroup scheme), all the parameters of each resolved resonance (or energy point where average parameters are defined, in the unresolved resonance region) which falls in that energy range, were varied simultaneously. In this way, each S_{iKj} actually represents the variation of the integral parameter R_i due to the variation of all the parameters of type K in the energy range j, all of the same percentage amount.

The different energy ranges were not correlated at this stage. Correlations in energy will be introduced successively.

The advantage of this type of definition of the sensitivity coefficients is that physical correlation of different type, related to different evaluation techniques or to different conservation hypothesis, can be introduced using always the same basic set of sensitivity coefficients S_{iKj}.

Finally, it should be noted that, in the case of partial width variation $\delta\Gamma_x$, the total resonance width was varied accordingly :

$$\frac{\delta\Gamma}{\Gamma} = \frac{\delta\Gamma_x}{\Gamma_x} \frac{\Gamma_x}{\Gamma} \tag{2}$$

2.2 - Self-shielding effects

The expression of S_{iKj} can be given more explicitely if one adopts the Bondarenko formalism of self-shielding factors :

$$S_{iKj} = \frac{\partial R_i}{\partial \sigma_j} \frac{d\sigma_j}{dp_{Kj}} \frac{pKj}{R_i} = \tag{3}$$

$$\left(\frac{\partial R_i}{\partial \sigma_{\infty j}} \frac{d\sigma\infty j}{dp_{Kj}} fj + \frac{\partial R_i}{\partial fj} \frac{dfj}{dp_{Kj}} \sigma\infty j \right) \frac{pKj}{R_i} = S^{\infty}_{iKj} + S^{f}_{iKj}$$

The two terms in equation (3) correspond to the effects of the variation of the resonance parameters p_{Kj} on the infinite dilution cross section $\sigma_{\infty j}$ and on the self-shielding factor f_j, according to the prescription that :

$$\sigma_j = \sigma_{\infty j} f_j \tag{4}$$

Even if in general the self-shielding effects are thought to be smaller than the infinite dilution cross-section effects in particular for the Pu isotopes, for which the f values are usually close to one, the self-shielding effects can play a significant role in the resolved resonance region for U-238, for which the f values can be fairly far from the asymptotic values in the standard fast reactor fuel composition (see table V).

In summary the following procedure was adopted :

1 - Calculate by means of standard GPT methods in one dimension (code system HOPES developed at CADARACHE /6/), the sensitivity of the integral parameters R_i to multigroup data σ_j.

2 - Calculate by means of standard cross section processing codes, compatible with the Bondarenko format, the sensitivity of the multigroup $\sigma_{\infty j}$ and f_j values to the variation of the resonance parameters p_{Kj}. The base data file used for the calculation of this step was ENDF/B-IV and the resonance parameter variation for the different energy intervals, according to what was said in paragraph 2.1, was chosen to be ± 20%. Linearity tests were carried out to verify the validity of this procedure.

3 - Folding of the sensitivity coefficients generated in step 1 and 2 to produce the sensitivity coefficients of tables VI - XI.

It should be again stressed that, in view of the hypothesis of the Γ variation due to Γ_x variation (see equation 2), in the case of Pu-239 and Pu-241 σ_f and σ_c variations were both involved as a consequence of Γ_γ (or Γ_f) variations.

This is obviously the case of <D> variations.

Conservation and correlation laws will be introduced in a later stage, as already mentioned.

2.3 - Comparison with previous sensitivity calculations

Previous sensitivity studies on resonance parameters effects can be found in References 7, 8, 9, 10, 11.

In particular, the relevance of the self-shielding factors was indicated in Ref. 8 with simplified calculation for isolated resonances. In Ref. 7 an example was worked out to show the relevance of p-wave parameter effects on U-238 cross sections. By the way, it is interesting to note that in that work the conservation laws were directly taken into account in the definition of the sensitivity coefficients.

The present work however gives data in a format directly exploitable to assess the consequences of parameters uncertainties on integral reactor parameters, together with the impact of different uncertainty correlation rules.

3 - NUMERICAL RESULTS

3.1 - Infinite dilution cross section variation effects

In table VI - XI the calculated sensitivity coefficients are shown for the effects due to σ_∞ (S^∞_{iKj} coefficients of expression 3).

The most important effects are obviously found for Pu-239 and U-238 data. Minor effects, shown only for Keff and control rod antireactivity, are found in the case of Pu-240 and Pu-241 (Tables X-XI) For what concerns the different integral parameters, the sensitivity coefficients are shown group-wise (energy group structure in Table IV), for the energy groups which cover the energy range 40 KeV - 200 eV.

K_{eff} effects are clearly shown both in the case of U-238 and of Pu-239 resonance parameters. In this last case, the hypothesis of combined variation of Γ_γ (or Γ_f) and Γ, leads to sensitivities to Γ_γ on Γ_f variations which are comparable in the energy region < 1 KeV, where Γ_n becomes negligible , due to the compensating effects on $\nu\sigma_f$ and σ_a. The $g\Gamma_n$ and $<D>$ effects are shown separately, even if the most reasonable way to look to these effects should be in the light of a constant (and fairly well known) strenght function value S_o.

Relatively small effects are found on the Doppler reactivity coefficient. It is to be noted that, in the case of the U-238 resonance parameters, the sensitivity coefficients shown in the table take into account both the effect on the cross section variation due to the temperature and the flux variation effects. In fact, if we define the Doppler coefficient in a simplified way as :

$$\rho_D = \int \sum_j \left(\sigma^{T_1}_{U-8} - \sigma^{T_2}_{U-8}\right)_j \phi_j \, \phi_j^+ \, dV \qquad (5)$$

$$= \int \sum_j \Delta\sigma_j^T \, \phi_j \, \phi_j^+ \, dV$$

one can write formally :

$$d\varrho_D = \int \left(\sum_j d\,(\Delta\sigma^T)_j\ \phi_j\ \phi_j^+ \ +\ \sum_j \Delta\sigma_j^T\ (d\phi_j + d\phi_j^+) \right) dV \qquad (6)$$

where $d(\Delta\sigma^T)$, $d\phi$ and $d\phi^+$ are the variation induced by the resonance parameter variations.

In the case of Pu-239, only $(d\phi + d\phi^+)$ effects are present.

In the case of the sodium void scattering component, the integral parameter taken into account is, in a simplified form :

$$\varrho_{Na} = \int_{\text{core 1}} \Sigma_{jK}\ N_{Na}\ \sigma_{j\rightarrow K}^{Na}\ \phi_j\ (\phi_K^+ - \phi_j^+)\ dV \qquad (7)$$

For this parameter only $d\phi$ and $d\phi^+$ effects are present, and, due to the peculiar form of the adjoint function ϕ^+ at low energies, these effects are fairly large both in the case of U-238 and of Pu-239.

Small effects, but not negligeable in view of the high precision requirements, are found in the case of the control rod system antireactivity. For this parameter the accuracy requirements of few percent, are such that even 1÷2% uncertainty due to low energy data, can be significant.

For all the integral parameters studied, it is valid the commentary previously made on Γ_f and Γ_γ variation effects in the case of Pu-239.

Moreover, it should be noted the compensating effects of the variation of $<D>$ and Γ_γ in the case of the unresolved resonance region for U-238, due to the large values of $g\Gamma_n$ in that energy range ($g\Gamma_n \approx 10$ times Γ_γ).

3.2 - Self - shielding variation effects

As it was previously described (see paragraph 2.2), self-shielding factor variation effects have been considered in the case of the variation of U-238 resonance parameters in the resolved resonance region. The main results are shown in table XII. The effects are smaller than the effects on the infinite dilution cross-section and non negligible only in few cases.

For what concerns the unresolved resonance region in principle one can say that apparently self-shielding effect can play a minor role. Howeve two recent results indicate that much care should be exerced in dealing with these effects.

First, a recent self-shielding measurement in the USSR (Ref. 12) have indicated that the experimental self-shielding factor for U-238 capture, can be different from the calculated value by approximately 5 ÷ 10% in the energy region between 100 KeV and 20 KeV for a potential σ_p cross section corresponding approximately to the range 1 - 10 barns.

Second,calculations performed at ORNL /Ref. 7/ have shown that a large self-shielding variation effect can be obtained at approximately 20 KeV if the average p-wave neutron width is changed, with a corresponding change in the average s-wave neutron width, to keep constant the infinite dilution cross section.

Actually, this is directly consequence of the fact that at these energies the self-shielding is mainly due to the narrow p-wave resonances, which contribute for approximately 30% ($< \sigma_R >_{l=0} \ / < \sigma_R >_{l=1} \approx 2.8$) to the resonant cross-section if one takes as p-wave and s-wave strenght function the following values :

$$S_o \approx 1.17 \times 10^{-4}$$

$$S_1 \approx 1.93 \times 10^{-4}$$

Calculations similar to those of ref. 7 have been performed for U-238.$< \Gamma_n >_{l=1}$ has been changed by + 5 %, and $< \Gamma_n >_{l=0}$ has been changed to keep constant the infinite dilution cross-section. The following results have been obtained at 300°K :

σ_p (barn) / Energy Group	1	10	50	100
10	.02	- 0.01	- 0.06	- 0.08
11	0.32	- 0.11	- 0.27	- 0.38
12	0.95	0.29	- 0.11	- 0.27
13	1.61	0.90	0.19	0.0
14	2.09	1.41	0.76	0.45
15	1.61	1.08	0.64	0.42

(Percentage values of self-shielding factor variation).

Of course, a similar calculation can be performed with a different combination of S and p wave $< \Gamma_n >$ values. As an example, the variation of $< \Gamma_n >_{l=1}$ of + 20 %, (with the corresponding $< \Gamma_n >_{l=0}$ variation to keep σ_∞ constant), gives a variation of 4,14 % in the self-shielding factor of the 15 th group (energy range 5.53-3.36 KeV) at σ_p = 10 b.

Finally the same calculations for T = 1800°K, show the following effects on the Doppler related self-shielding variation for U-238 :

$$\left[\left(f'(1800K) - f'(300K)\right) - \left(f(1800K) - f(300K)\right)\right] / \left(f(1800K) - f(300K)\right)$$

where f' represent the self-shielding factors obtained with a variation of $\langle \Gamma_n \rangle_{l=1}$ of + 5 %, as explained above :

σ_p (barn) / Energy Group	1	10	50	100
10	- 1.3	- 5.71	- 8.17	- 9.24
11	- 6.64	- 2.84	- 10.26	- 10.54
12	- 11.36	- 9.08	- 10.0	- 12.87
19	- 7.54	- 9.38	- 8.2	- 10.27
14	- 3.07	- 4.10	- 7.07	- 6.43
15	- 0.49	- 1.17	- 2.4	- 2.67

(percentage values of the Doppler related self-shielding variation)

If these hypothesis are made (i.e. p wave and s wave parameter changes without affecting σ_∞), $\delta\sigma/\sigma$ is equal to $\delta f/f$ and a new type of TABLE XII, related to high energies, where p-wave effects are important, can be written :

Energy Group	Na void	Doppler	Keff	Control Rod Antireactivity
10	.0	- 0.14	.0	.0
11	.0	- 0.36	.01	.0
12	- .01	- 0.70	.0	.0
13	+ .06	- 0.75	- .01	- .02
14	+ .07	- 0.26	- .02	- .03
15	- .10	- 0.16	- 0.1	- .02

(percentage values, relative to $\langle \Gamma_n \rangle_{l=1}$ variation of + 5 %)

Except for Doppler, these values are fairly small, but, as wehave seen, they are dependent on the hypothesis made an parameter variation.

Finally, the entire validity of the EDNF/B technique to represent resonance effects in this energy region, should be tested against more extended resolved resonance type representation.

3.3 - Effects on breeding

In table XIII the effects of the resonance parameter variations are shown in the case of the total breeding ratio.

The general trends already observed are again found here, and in general significant effects are found, mainly related to direct changes in the capture cross-section of U-238 and absorption cross-section of Pu-239. The data shown are relevant to the infinite dilution cross-section variations.

4 - CORRELATION HYPOTHESIS

The indicative results of the previous paragraphs are strongly dependent on the correlations that are assumed on the uncertainties on the separate resonance parameters. We recall that no explicit correlation was taken into account, nor among different resonance parameter neither in energy.

However, correlations play a central role in assessing realistic estimates of integral parameters, but are a difficult task to be properly established.

In fact they depend on the evaluation techniques used to establish the basic data files, on the experimental data type used, and on the model chosen to represent the different corss-sections.

Since the data of the previous paragraph were based on the simplest hypothesis, mainly the zero-correlation hypothesis (which is by no means the most realistic), we will try in what follows to examine the consequences of other correlation hypothesis.

Case A - For each resonance parameter type p_K a complete energy correlation hypothesis is introduced, which covers both the resolved and the unresolved resonance ranges.

Case B - In the unresolved resonance region the $< D >$ and $< \Gamma^{\circ}_{n} >$ values are completely correlated in order to keep constant, within an uncertainty limit, the S_o strength function.

Case C - A correlation was introduced among the Γ_γ and Γ_f values of Pu-239 in order to avoid extreme changes in the σ_c / σ_f ratio. Since the variation of both parameters produces a nearly constant $\delta\nu\sigma_f$ - $\delta\sigma_a$ value (and of opposite sign), a correlation hypothesis was used, with the introduction of fictitious correlation coefficients (1, 0.8, 0.5 and 0.3).

Case D - A total width conservation law is considered by means of the correlation between Γ_n and Γ_γ (or Γ_f).

This last type of correlation was introduced both in the case of U-238 and of Pu-239. Several fictitious correlation coefficients (1, 0.8, 0.5 and 0.3) were introduced to simulate different ratios between the two parameters.

Obviously, more hypothesis should be compared on the basis of the particular stategy followed in each evaluation. The data presented here, can however indicate major trends.

The numerical results are shown in table XIV and XV. The uncertainty on Keff and on the sodium void coefficient are the most significant and are strongly dependent on the correlation hypothesis adopted.

Several correlation hypothesis lead to uncertainties on Keff from ± 0.2% to ± 0.5% ΔK/K and to uncertainties on the sodium void scattering component up to 10%. Effects on the Doppler coefficient are, on the contrary, fairly small, due to compensating effects in the $\Delta\sigma_T^{U-238}$. It should be mentioned that other effects related to resonance parameters uncertainties could be introduced at very high temperatures /13/ or in the unresolved resonance region, according to what was previously discussed. Finally, it should be recalled that no multilevel effects were treated in the present work, and that the conclusion of previous work in this field /14,15/, indicated small effects due to the multilevel formalism.

For what concerns the control rod system worth, the small effects obtained can became not negligible, in view of the high accuracy required for this integral parameter.

5 - INTEGRAL EXPERIMENTS AND DATA ADJUSTEMENTS

The results presented in the previous sections are related to a large fast power reactor. The sensitivity, when they are significant, are related to the low energy range (generally < 10 KeV).

The data used in many leading fast reactor programs for neutronics calculations, have been adjusted using the so-called clean integral experiments /16-17-18/.

However, many of these experiments have shown a limited sensitivity to the low energy data. This means that low energy data (i.e. mainly in the resonance region) have been seldom adjusted, and that some integral parameter in fast power reactors can be affected directly by resonance parameter uncertainties in a significant way.

Moreover, future design of large fast power reactors can put even stronger emphasis on the low energy spectrum.

The situation is represented in fig.1, where the product $\phi_j \phi_j^+$ is plotted as a function of the energy group :

a) in the case of the power reactor considered as a reference in this work,

b) in the case of the large core used as Benchmark for comparison and proposed by NEACRP /19/ and

c) in the case of a typical fast reactor critical assembly.

With the aim to gain informations on this energy region data, ad-hoc tailored spectra will be obtained in an experimental program on the critical facility ERMINE at CADARACHE, to enhance the low energy neutron contribution. This will be mainly obtained with the introduction of graphite in $K_\infty \approx 1$ media with PuO_2/UO_2 fuel.

A larger sensitivity will be obtained to Pu-239 and U-238 data at energies lower than 10 KeV.

The analysis of these experiments could be done using sensitivity and uncertainty analysis of the type outlined in the preceding paragraphs in such a way that adjustments could be envisaged on the most signifiant resonance parameters, according to the principle of the so-called consistent method of basic parameter adjustment /5/.

6 - CONCLUSIONS

In the present paper an attempt has been made to indicate the main consequences on integral, mainly safety related, parameters of fast reactors due to the uncertainties on the resonance parameters of the major actinides (U-238, Pu-239, Pu-240 and Pu-241).

As expected, these consequences are strongly dependent on the assumed uncertainty level on individual parameters and their correlations. The 20% uncertainty value, assumed in the present work, can be considered as an upper limit at the present state of the art in this field for most parameters. Moreover, the uncertainties of different parameters are certainly correlated and the good knowledge of total cross-sections (and of total resonance widths), must also be taken into account.

However, numerical results have indicated that, for many significant resonance parameters like U-238 $g\Gamma_n$ in the resonance region and Γ_γ and Γ_f of Pu-239 in the unresolved resonance region, uncertainties in the range ± 5 - 10% are necessary to mesure a good use of standard integral experiments to produce both adjusted data or bias factors for the design calculation of large power reactors.

In fact, higher uncertainties will produce in a reference design system uncertainties on Keff, Sodium void effects, control rod system worth etc... which could not be easily related to the standard integral experiment results due to the different sensitivities to low energy data in critical experiments and in large power reactor configurations.

In this context, uncertainties on Pu-240 and Pu-241 play a more limited role. A further source of uncertainty, which was only touched upon in this paper, could be a substantial uncertainty in the calculation of self-shielding factors in the unresolved resonance region (case of U-238 in particular) due to both not yet entirely explained p-wave data effects, and cross-section representation in this energy range. This type of uncertainty seems to be pointed out by recent experimental results obtained in the USSR.

Finally, some low energy data dependent integral parameter, not mentionned in the present report, like structural material activation, can also be strongly influenced by the quality of the major actinide data in energy region below 10 KeV and should enhance the need for higher accuracy data.

The first step towards meeting these requirements should be however an appropriate assessment of resonance parameter uncertanties and their correlation within the current evaluated data files, and with the performance of ad-hoc integral experiments, enhancing the low energy neutron importance, which should be coupled to sensitivity and consistency analysis based on a consistent method of resonance parameter ajustment.

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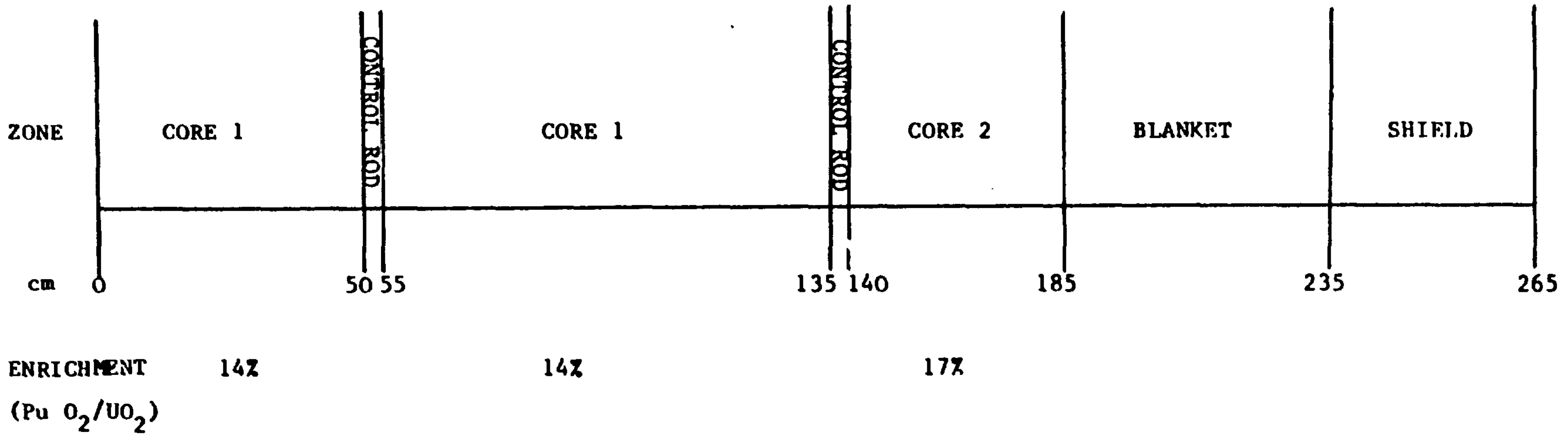


TABLE 1 - 1200 MWe FAST REACTOR GEOMETRY SPECIFICATIONS
(1D CYLINDRICAL GEOMETRY, $B^2_{AX} = 5.4 \times 10^{-4}$)

TABLE II - SENSITIVITY COEFFICIENTS WERE CALCULATED FOR THE FOLLOWING R INTEGRAL PARAMETERS

1 - Keff (= 1.0087)

2 - Core Doppler reactivity (ΔT = 1500 °K ρ = -1.92% $\Delta K/K$)

3 - Internal core sodium coefficient
(Scattering component ρ = 1.25% $\Delta K/K$)

4 - Control rod system worth (insertion equivalent to
ρ = -1.31% $\Delta K/K$)

5 - Total breeding ratio (=.96).

TABLE III

RESONANCE PARAMETERS CONSIDERED

U-238 : s-wave $g\Gamma_n$, Γ_γ both in the resolved (100 eV - 4 KeV) and unresolved resonance range (4-45 KeV) and $< D >$ in the unresolved range.

Pu-239 : s -wave, J=0 and J=1 $g\Gamma_n$, Γ_γ and Γ_f both in the resolved (100 - 300 eV) and in the unresolved range (300 eV - 25 KeV) and $< D >$ in the unresolved range.

Pu-240 : s-wave $g\Gamma_n$ and Γ_γ in the resolved (100 eV - 3.9 KeV) and unresolved range (3.9 KeV - 40 KeV), and $< D >$ in the unresolved range.

Pu-241 : s-wave $g\Gamma_n$, Γ_γ, Γ_γ and $< D >$ in the unresolved resonance region (100 eV - 52.4 KeV).

TABLE IV

ENERGY STRUCTURE

Group	Upper Energy
10	67.4.KeV
11	40.9
12	24.8
13	15.0
14	9.12
15	5.53
16	3.36
17	2.04
18	1.23
19	.748
20	.454
21	.275 (to .101 KeV)

TABLE V

U-238 CAPTURE SELF-SHIELDING FACTORS FOR POTENTIAL SCATTERING $\sigma_p = 50b$

Group	f
16	.719
17	.570
18	.465
19	.367
20	.322
21	.120

Energy group	Na void			Doppler		
	$g\Gamma_n$	Γ_γ	$< D >$	$g\Gamma_n$	Γ_γ	$< D >$
10	-.02	.0	.01	.01	-.02	.01
11	-.02	- .01	.03	.0	-.15	.13
12	.04	.57	- .53	.0	-.36	.31
13	.17	1.17	-1.17	-.05	-.51	.53
14	.15	.70	- .74	-.10	-.60	.61
15	-.34	-1.58	1.04	-.16	-.79	.53
16	.09	.25	-	-.12	-.35	-
17	1.45	4.05	-	-.47	-.13	-
18	1.76	3.88	-	-.64	-1.40	-
19	1.65	2.09	-	-.54	-.87	-
20	.77	.83	-	.34	-.37	-
21	.50	1.12	-	-.29	-.55	-

TABLE VI

U-238 Sensitivity Coefficients of Integral parameter R to variation of 20% of Resonance parameter p (percentage values). Effects due to σ_∞ variation.

Energy group	K_{eff}			Control Rod antireactivity		
	$g\Gamma_n$	Γ_γ	$< D >$	Γ_γ	$g\Gamma_n$	$< D >$
10	.0	-.02	.02	-.01	.0	.01
11	-.01	-.10	.10	-.10	-.01	.09
12	-.01	-.17	.17	-.22	-.01	.21
13	-.03	-.18	.19	-.31	-.04	.31
14	-.03	-.15	.17	-.30	-.07	.32
15	-.03	-.16	.11	-.29	-.09	.20
16	-.02	-.06	-	-.11	-.04	-
17	-.06	-.15	-	-.58	-.16	-
18	-.06	-.13	-	-.63	-.27	-
19	-.04	-.06	-	- .43	-.25	-
20	-.02	-.02	-	-.20	-.19	-
21	-.01	-.02	-	-.33	-.14	-

TABLE VII

U-238 Sensitivity coefficient of integral parameter R to variation of 20% of resonance parameter p (percentage values). Effects due to σ_∞ variation.

Energy group	Na void				Doppler			
	$g\Gamma_n$	Γ_f	Γ_γ	< D >	$g\Gamma_n$	Γ_f	Γ_γ	< D >
12	.32	.02	.18	-.46	-.52	-.17	-.05	.65
13	-.35	-.38	.48	.20	-.51	-.10	-.11	.64
14	.12	-.10	.23	- .23	-.45	-.06	-.13	.56
15	2.12	.10	-.83	-1.98	-.46	-.02	-.18	.58
16	.0	-.09	.14	-.05	-.25	.0	-.13	.36
17	-5.27	-2.90	2.92	4.44	-.49	.28	-.57	.69
18	-6.03	-3.48	3.32	5.26	.16	.63	-.82	.04
19	-4.78	-2.58	2.57	4.04	.50	.66	-.83	-.26
20	-2.29	-1.75	1.79	1.25	.34	.56	-.63	-.12
21	-1.83	-1.66	1.62	-	.42	.66	-.68	-

TABLE VIII

Pu-239 Sensitivity Coefficients of Integral Parameter R to variation of 20% of resonance parameter p (percentage values). Effects due to σ_∞ variation.

Energy group	K_{eff}				Control Rod Antireactivity			
	$g\Gamma_n$	Γ_f	Γ_γ	< D >	$g\Gamma_n$	Γ_f	Γ_γ	< D >
12	.25	.16	-.11	-.26	-.16	-.02	-.07	.22
13	.23	.13	-.10	-.22	-.11	.02	-.10	.17
14	.17	.09	-.08	-.15	-.06	.04	-.10	.11
15	.14	.08	-.07	-.12	-.04	.05	-.10	.08
16	.07	.04	-.04	-.06	-.01	.03	-.06	.03
17	.23	.12	-.12	-.19	.22	.26	-.34	-.11
18	.20	.11	-.11	-.18	.49	.43	-.47	-.38
19	.14	.07	-.07	-.12	.50	.41	-.47	-.36
20	.06	.05	-.05	-.03	.29	.36	-.39	-.13
21	.04	.04	-.04	-	.35	.44	-.45	-

TABLE IX

Pu-239 Sensitivity Coefficients of Integral Parameter R to variation of 20% of resonance parameter p (percentage values). Effects due to σ_∞ variation.

Energy Group	Na void		Doppler		K_{eff}	Control Rod worth
	$g\Gamma_n$	Γ_γ	$g\Gamma_n$	Γ_γ	Γ_γ	Γ_γ
12	.01	.04	.0	-.02	-.01	-.02
13	.02	.07	-.01	-.03	-.01	-.02
14	.01	.04	-.01	-.03	-.01	-.02
15	-.02	-.08	-.01	-.04	-.01	-.02
16	.01	.02	-.01	-.02	.0	-.01
17	.16	.44	-.06	-.14	-.02	-.06
18	.24	.60	-.10	-.21	-.02	-.10
19	.25	.22	-.11	-.09	-.01	-.05
20	.24	.28	-.11	-.13	-.01	-.07
21	.35	.27	-.18	-.13	-.01	-.08

TABLE X

Pu-240 Sensitivity Coefficients of Integral parameter R to variation of 20% of Resonance parameter p (percentage values). Effects due to σ_∞ variation.

Energy Group	Na void				K_{eff}	
	$g\Gamma_n$	Γ_f	Γ_γ	< D >	$g\Gamma_n$	< D >
10	.02	.01	.0	-.02	.01	-.01
11	.05	.02	-.01	-.06	.02	-.02
12	.01	.0	.01	-.02	.02	-.02
13	-.05	-.03	.02	.05	.02	-.02
14	.0	-.01	.01	.0	.02	-.02
15	.20	.08	-.05	-.20	.01	-.01
16	-.01	-.01	.01	.01	.01	-.01
17	-.52	-.19	.15	.49	.02	-.02
18	-.48	-.17	.15	.44	.02	-.01
19	-.35	-.13	.11	.31	.01	-.01
20	-.24	-.09	.08	.22	.01	-.01
21	-.18	-.06	.06	.16	.0	.0

TABLE XI

Pu-241 Sensitivity Coefficients of Integral Parameter R to variation of 20% of Resonance parameter p (percentage values). Effects due to σ_∞ variation

Energy Group	Na void		Doppler		K_{eff}		Control Rod antireactivity	
	$g\Gamma_n$	Γ_γ	$g\Gamma_n$	Γ_γ	$g\Gamma_n$	Γ_γ	$g\Gamma_n$	Γ_γ
16	-.03	-.04	.03	.06	.01	.01	.01	.02
17	-.33	-.91	.11	.03	.01	.03	.04	.13
18	-.47	-.88	.17	.32	.02	.03	.07	.14
19	-.80	-.37	.26	.15	.02	.01	.12	.08
20	-.35	-.17	-.15	.08	.01	.0	.09	.04
21	-.27	-.07	.15	.03	.01	.0	.07	.02

TABLE XII

U-238 Sensitivity Coefficients of Integral Parameter R to variation of 20% of Resonance Parameter p (percentage values). Effects due to self-shielding factor variation.

Energy group	U-238			Pu-239			
	$g\Gamma_n$	Γ_γ	< D >	$g\Gamma_n$	Γ_f	Γ_γ	< D >
10	.01	.08	-.08	.0	.0	.0	.0
11	.07	.45	-.45	-.01	.0	.0	.01
12	.13	.75	-.76	-.54	-.12	-.16	.72
13	.16	.76	-.80	-.54	-.09	-.14	.67
14	.15	.64	-.69	-.44	-.06	-.11	.54
15	.16	.65	-.44	-.41	-.05	-.10	.49
16	.08	.22	-	-.22	-.03	-.06	.26
17	.22	.59	-	-.70	-.05	-.12	.76
18	.21	.45	-	-.63	-.05	-.08	.66
19	.13	.21	-	-.46	-.03	-.06	.48
20	.07	.08	-	-.25	-.01	-.02	.17
21	.05	.10	-	-.20	-.01	-.02	-

TABLE XIII

U-238 and Pu-239 Sensitivity Coefficients of Total Breeding Ratio to variation of 20% of Resonance Parameter p (percentage values).

Table XIV

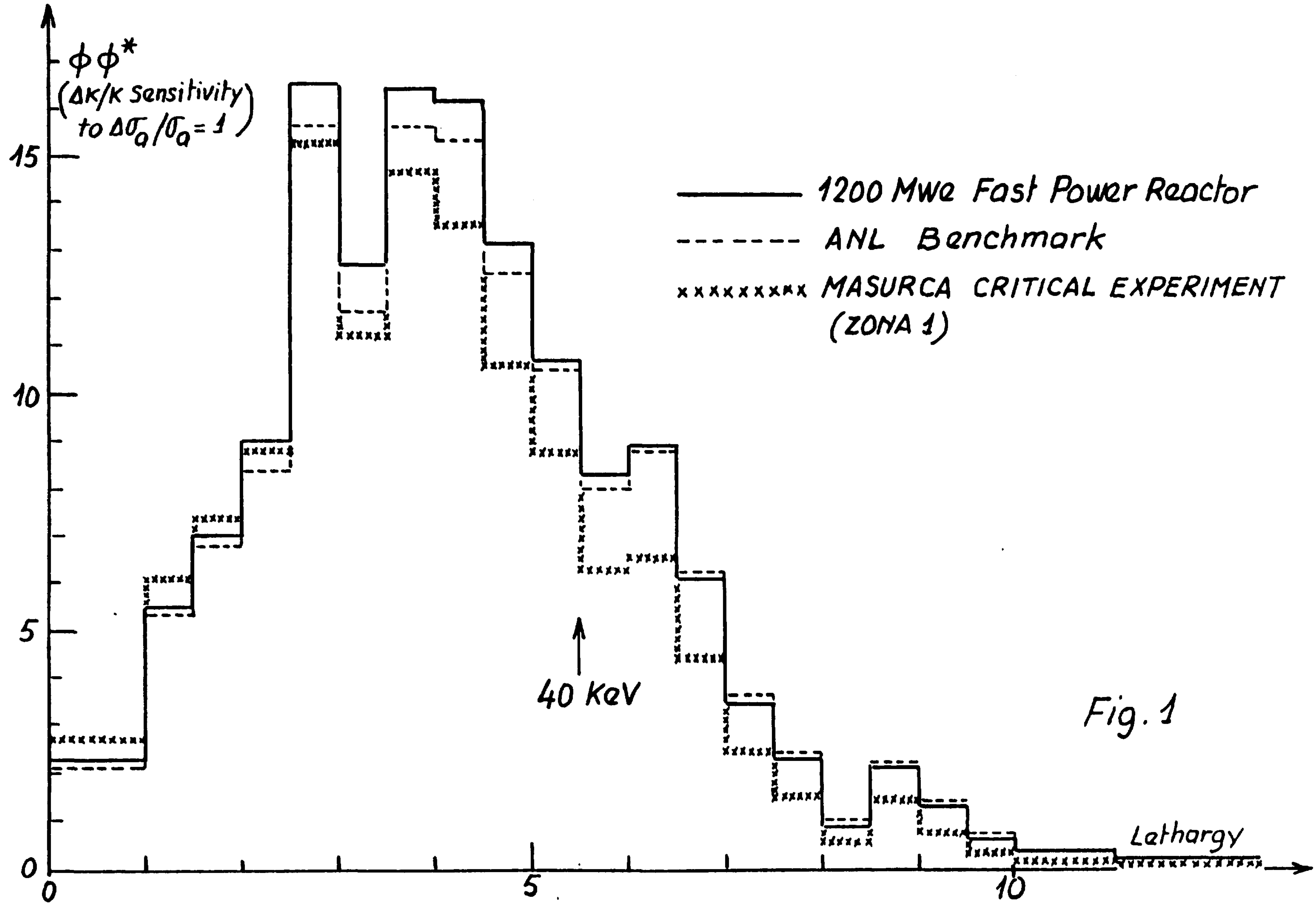
U-238 Resonance Parameter Uncertainty.
Effects (Standard Deviations in % due to ± 10% uncertainty in each parameter).

Correlation Hypothesis		K_{eff}	Na void	Doppler	Control Rod worth
No energy correlation :	$g\Gamma_n$	± 0.05	± 1.50	± 0.54	± 0.60
	Γ_γ	.21	3.26	1.09	.24
	$< D >$	.17	.90	.51	.27
Complete energy correlation	$g\Gamma_n$	± 0.16	± 3.10	± 1.01	± 1.75
	Γ_γ	.61	6.53	3.08	.63
	$< D >$	.38	6.8	1.06	.54
Correlation between $g\Gamma_n$ and $< D >$		± 0.14	± 2.56	± 0.16	± 1.30
Correlation between Γ_n and Γ_γ with correlation coefficient W =	1.	± 0.45	± 3.43	± 2.06	± 1.14
	0.8	.33	2.13	2.45	1.25
	0.5	.24	.17	.54	1.44
	0.3	.02	1.14	.08	1.56

Table XV

Pu-239 Resonance Parameter Uncertainty.
Effects (Standard deviations in % due to ± 10% uncertainty in each parameter).

Correlation Hypothesis		K_{eff}	Na void	Doppler	Control Rod worth
No energy correlation :	$g\Gamma_n$	± 0.27	± 5.00	± 0.68	± 0.44
	Γ_f	.15	2.88	.65	.43
	Γ_γ	.14	2.78	.81	.48
	$< D >$	.25	4.17	.73	.32
Complete energy correlation	$g\Gamma_n$	± 0.77	± 9.00	± 0.64	± 0.74
	Γ_f	.44	6.41	1.22	1.01
	Γ_γ	.39	6.20	2.06	1.27
	$< D >$	.66	6.22	1.55	.19
Correlation between $g\Gamma_n$ and $< D >$		± 0.23	± 4.00	± 0.61	± 0.59
Correlation between Γ_n and Γ_f with correlation coefficient W = (complete correlation in energy)	1.	± 0.32	± 2.59	± 1.90	± 0.27
	0.8	.41	3.87	1.62	.07
	0.5	.54	5.79	1.25	.23
	0.3	.63	7.07	1.01	.43
Correlation between Γ_n and Γ_f with correlation coefficient W = (complete correlation in energy)	1.	± [illegible]	± .20	± 0.85	± 0.28
	0.8	.13	1.44	.43	.0
	0.5	.25	3.30	.19	.37
	0.3	.33	4.55	.60	.63



$\phi\phi^*$
($\Delta K/K$ sensitivity to $\Delta\sigma_a/\sigma_a = 1$)
15
10
5
0
0
5
10
Lethargy
40 KeV
1200 Mwe Fast Power Reactor
ANL Benchmark
MASURCA CRITICAL EXPERIMENT (ZONA 1)

Fig. 1