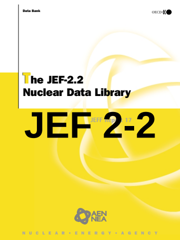

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EXPERIMENTAL VALIDATION OF NUCLEAR DATA AND METHODS FOR STEEL REFLECTED PLUTONIUM BURNING FAST REACTORS

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ABSTRACT

There is currently considerable interest in the possibilities for fast reactors to burn plutonium. The CAPRA project has been established with the aim of determining the characteristics of plutonium and minor actinide burning cores. One major core design feature used to achieve net plutonium burning is the removal of breeder blankets and their replacement by steel reflectors. This modification creates specific problems in predicting core characteristics due to nuclear data and computational methods. This paper presents the progress made in the solution of such problems. The CIRANO experimental programme at the MASURCA facility has been proposed and is being realised in support of plutonium burning cores. The experiments performed in this programme (critical masses, spectral indices, material buckling and fission chamber rate traverses) have been analysed with the aim of clarifying these problems by a stepwise parametric approach. The correct prediction of the critical mass for the CIRANO cores can be achieved by using the JEF2/ECCO/ERANOS data and code system with a specific fine group slowing treatment of the reflectors. Sensitivity analyses have shown that the remaining discrepancies concerning fission rate traverses can be resolved in the future by adjustment of nuclear data.

INTRODUCTION

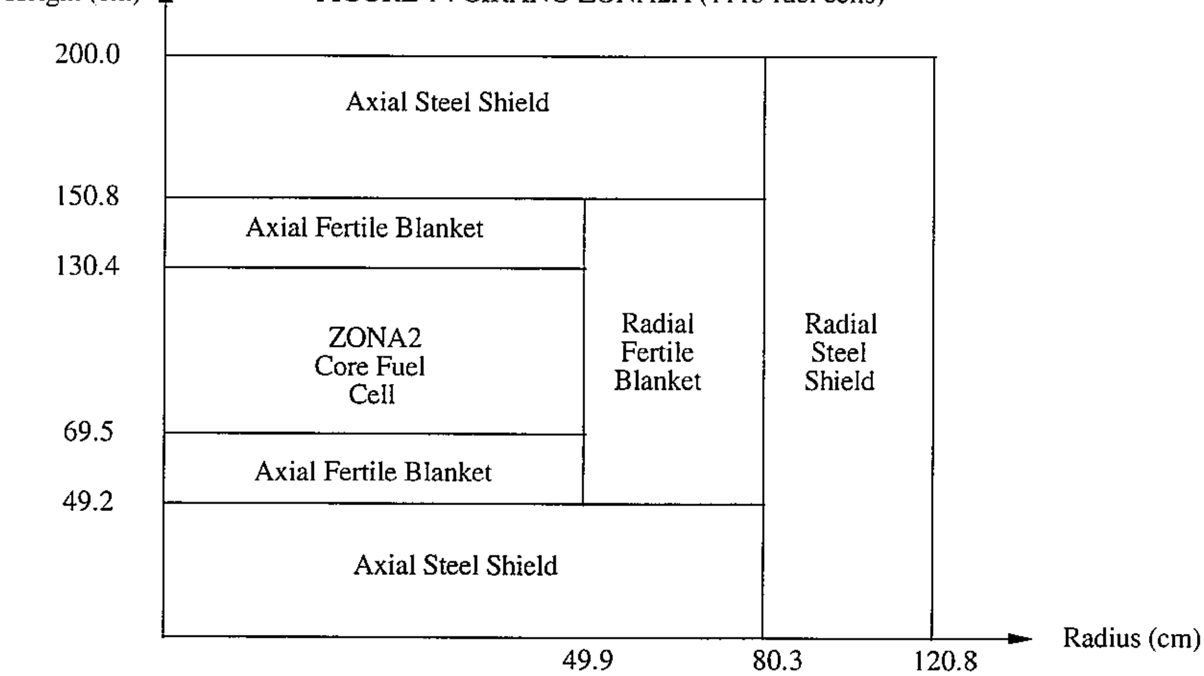
Several countries world-wide have decided to take effective steps for the management of the long term growth of their plutonium stockpiles, thus making the maximum use of the energy source present in plutonium while reducing the associated long term toxicity and proliferation risks. The first step in this approach consists of recycling LWR-produced plutonium in LWRs using MOX fuel : this step has been effectively demonstrated for limiting the growth of stockpiles. Nevertheless, core design and safety considerations currently limit the amount of plutonium available in a core as well as the number of possible LWR recycles. Various studies[1] have demonstrated that fast reactor cores can be used to burn the degraded plutonium resulting from LWR recycling. However, the required modifications alter the overall physics and safety behaviour of these cores, and it is thus necessary to validate the basic nuclear data and computational methods used for their design.

One major feature used to achieve net plutonium burning is the removal of breeder blankets and their replacement by steel reflectors. This replacement significantly modifies the neutronics at the core outer boundary, and past experiments at ZPPR, FCA and MASURCA have demonstrated that the accuracy of available nuclear data and codes needs to be improved in order to effectively address this problem. Thus CEA and its partners PSI/EPFL and AEA have launched an extensive development and validation program. The objective of this program is to validate the European calculational scheme JEF2[2]/ECCO[3]/ERANOS[4] for these specific features and it comprises four phases : acquisition of experimental data, nuclear data sensitivity studies, numerical code validation and an overall validation of the calculational scheme. The important steps and first results are given below.

EXPERIMENTS

A major experimental program (CIRANO[5]) has been undertaken at the MASURCA facility at CEA Cadarache to provide the basis for the validation of the nuclear data and methods used to model the innovative features of plutonium burning fast reactor cores : higher enrichment, degraded plutonium isotopics, removal of blankets and their replacement by steel reflectors, heterogeneous subassembly designs and heterogeneous core designs. Three configurations have been specifically devoted to the replacement of blankets by steel reflectors:
- ZONA2A configuration has both axial and radial fertile blankets (Figure 1) ,
- ZONA2A3 configuration has the radial fertile blanket replaced by steel reflectors (Figure 2),
- ZONA2B configuration has both axial and radial steel reflectors (Figure 3).

FIGURE 1 : CIRANO ZONA2A (1115 fuel cells)



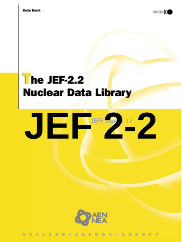


FIGURE 2 : CIRANO ZONA2A3 (992 fuel cells)

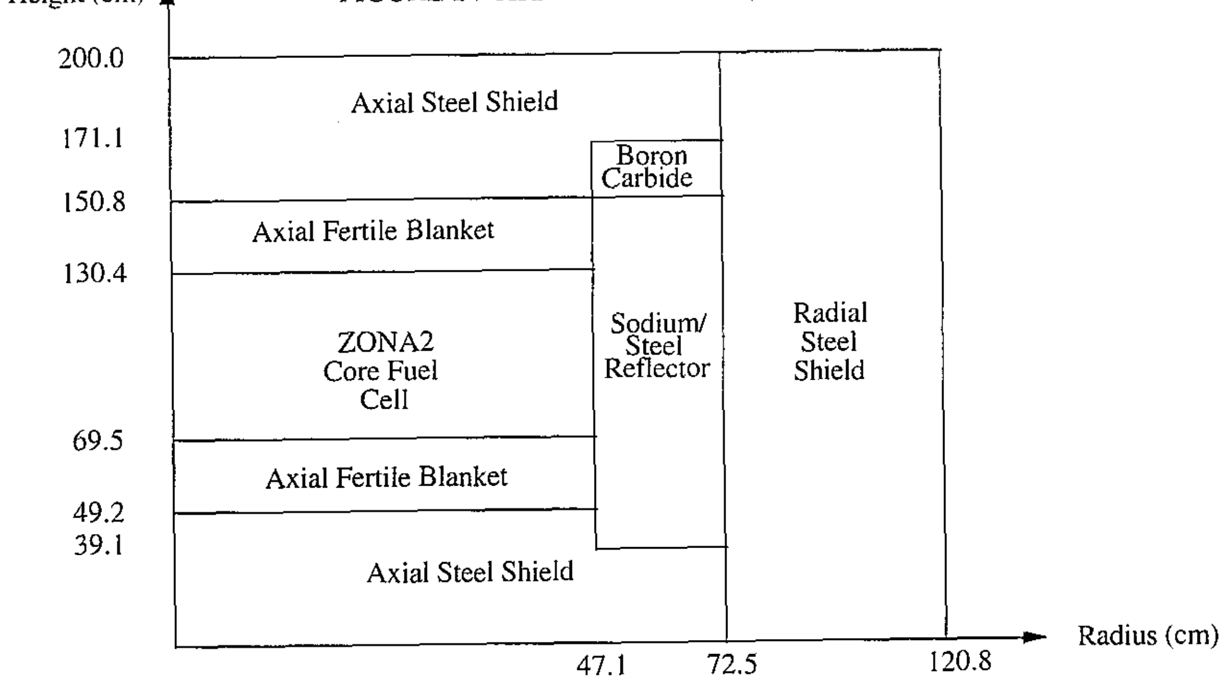
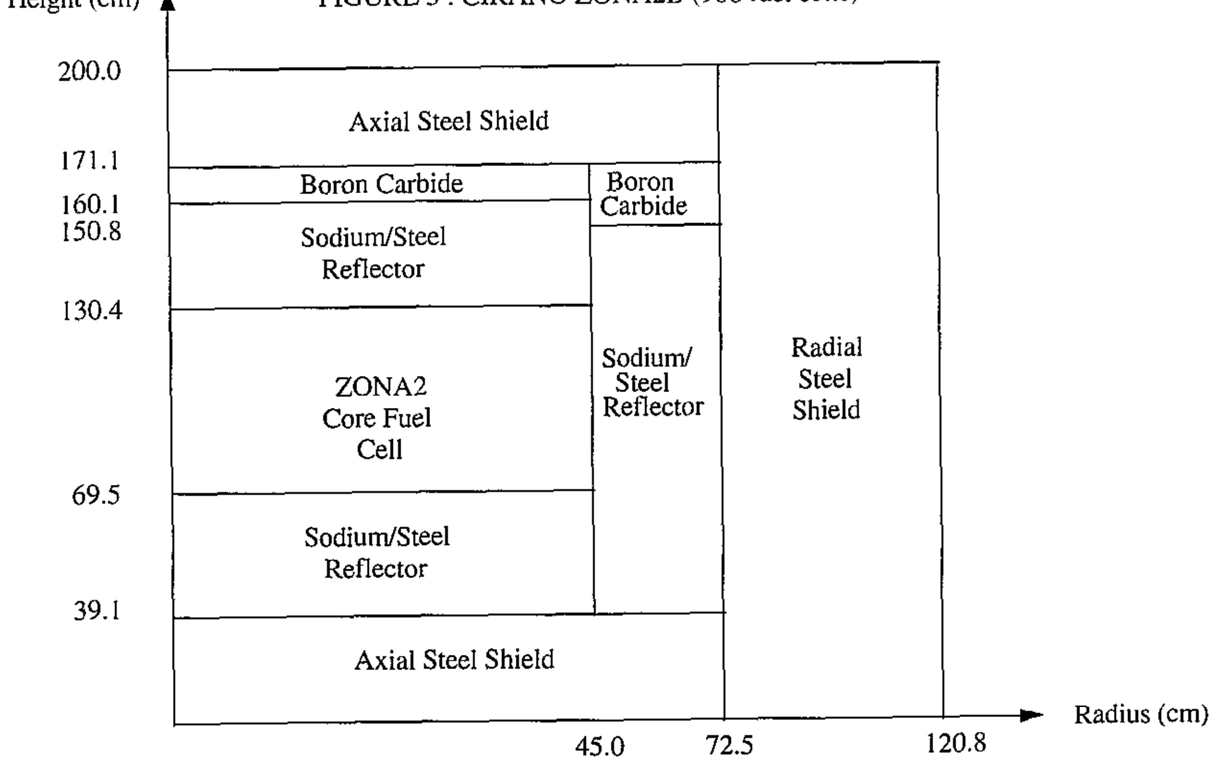


FIGURE 3 : CIRANO ZONA2B (906 fuel cells)



All three configurations are fuelled with the ZONA2 core fuel cell containing ~25% enriched plutonium oxide fuel. In the ZONA2A3 and ZONA2B configurations the fertile blanket is replaced by sodium/steel reflectors containing 25% sodium/ 75% stainless steel. This stepwise or parametric approach has been adopted in order to obtain a complete characterisation of reflector saving effects. The reflector saving can be defined as the size saving of the core caused by its surrounding environment. It increases with the use of sodium/steel reflectors due to the lower neutron absorption rate when compared with the fertile blankets. This is confirmed by the reduction in the size of the core given by the transition from ZONA2A (core with blankets) to ZONA2B (core with steel reflectors). The reflector saving is deduced from the determination of the critical mass and the material buckling (obtained from experimental fission chamber traverses).

The measurements performed during the first phase of the CIRANO experiments, and which are covered by the scope of this paper, are as follows :

- critical mass (the reactor is made critical by a shim rod calibrated by inverse kinetics) ,
- spectral indices measured in a central ZONA2 fuel cell (together with a material buckling deduced from measured fission traverses),
- fission rate traverses performed for the fissile isotopes U235, Pu239, U238 and Np237 using fission chambers or activation detectors positioned along axial and radial channels.

The material buckling is an important parameter as it describes the fundamental mode characteristics of the core fuel cell. Fundamental mode theory supposes the existence of a single spatial flux profile ($e^{i\vec{B}.\vec{r}}$). In fast reactors $\vec{B}$ is defined as a vector dependent on energy (or lethargy u) as the fission rate traverses for U235, Pu238, U238 and Np237 do not have the same shape. A single value for $\vec{B}$ can be deduced from these traverses which corresponds to the material buckling. In the experiment the material buckling is equal to the geometrical buckling when the reactor is critical. For the calculated value of the buckling however this is not true because of nuclear data deficiencies and method approximations.

The calculated material buckling can be obtained either by a cell calculation or by a spatial calculation. For the spatial calculation the material buckling is determined from the profile representing the neutrons leaving the core (i.e. the leakage, described by the function $D\Phi^*$). To obtain consistent values from both cell and spatial calculations similar conditions should be imposed (to obtain the same k-effective for the same approximations). A given approximation (diffusion, transport P0, transport P1) gives a specific value for k-effective for the critical experimental core configuration. The buckling deduced from the $D\Phi^*$ traverse corresponds to the value obtained from the equivalent cell approximation (P1 inconsistent, B1 inconsistent and B1 consistent) providing that a buckling search is performed for the same k-effective value as the corresponding spatial one. As the traverse $D\Phi^*$ is a purely theoretical function, the experimental value is deduced by an interpolation of the buckling values obtained from the experimental and calculated fission rate traverses. Various calculational schemes have been used for this process, all of which give the same value for the experimental material buckling of the CIRANO ZONA2 fuel cell :

$$B^2_{exp} = 2.156\ 10^{-3} \pm 0.020\ 10^{-3}\ cm^{-2}$$

CALCULATIONAL SCHEME

The newly developed European scheme consists of the JEF2 data library[6] combined with the ECCO cell code[3] to produce homogenised cross sections in 33 energy groups. These cross sections are then used in spatial calculations with the ERANOS code scheme[4]. This route provides an accurate transport approximation using the P1 consistent method and a precise coupling of core and subcritical media with a fine group treatment (1968 groups). The effect of this, particularly on the reflector saving will be discussed in this paper.

Standard ECCO cell calculations for cross section preparation model the influence of the neutrons from the core by making use of a simplified source for the slowing down treatment, and a simplified self shielding treatment where the usual dilution of the elements with resonances is modified by an empirical B^2 value.

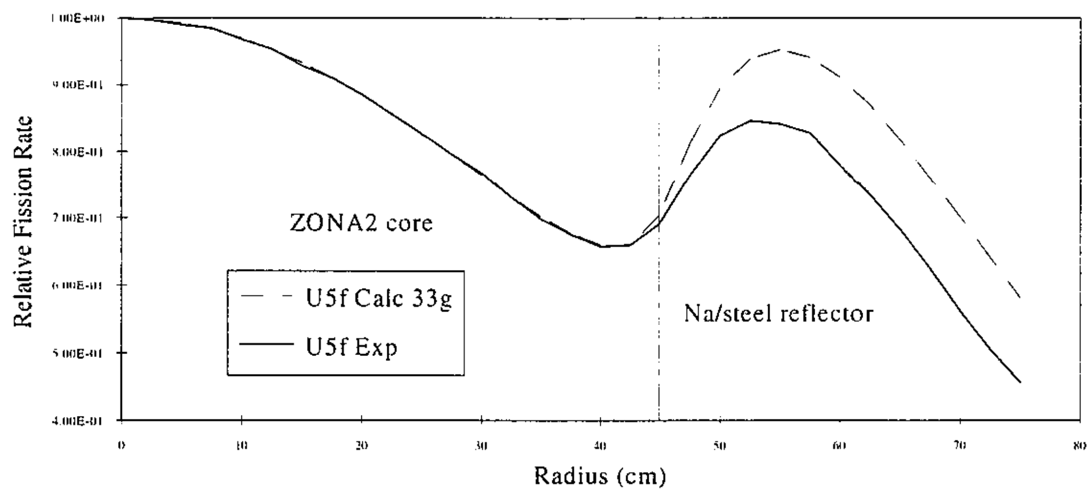
RESULTS AND DISCUSSION

To determine the critical mass, standard keff calculations were performed in RZ geometry using a transport Sn code.The following modelling corrections were subsequently applied :
- cylindrisation (quantifies the difference between the RZ model and the exact XYZ representation),
- Pu241 decay (measured to be -0.2 pcm per day),
- grids (small steel/void regions to allow cooling of the core fuel),
- end caps (the fuel pins are sealed at each end by end caps).

In addition the following method corrections were investigated :
- heterogeneity (quantifies the difference between the homogeneous, 1D cylindrical and 2D rectangular lattice representations of the ZONA2 core fuel cell),
- Sn approximation (S4 and S8 approximations were used in order to determine the S_∞ result),
- Pn approximation (P0 and P1 approximations were used to investigate neutron anisotropic scattering effects).

The resulting values of k-effective were found to be 0.99916, 1.00138 and 1.00508 for the CIRANO ZONA2A, ZONA2A3 and ZONA2B configurations respectively. When compared with the experimental values, these results show a significant discrepancy for the reflector configurations. This is confirmed by the analyses of the fission rate traverses which show an increasing discrepancy in the reflector regions, particularly for the fissile isotopes more sensitive to the lower part of the energy spectrum (Figure 4).

FIGURE 4 : CIRANO ZONA2B - U235 Fission Radial Traverse



These results suggest that the calculated reflector saving (i.e. the number of neutrons reflected back into the core, particularly at lower energies) is too large. This might imply an incorrect neutron slowing down treatment in the reflector regions surrounding the core. Further investigations have been performed to determine if this problem arises from inaccuracies in the calculational methods, the cross section data, or both. Uncertainties on the experimental values realised with very small chambers are thought to be equal to 3%.

An analysis of the spectral indices measured at the core centre was performed in order to obtain detailed information on the flux characteristics of the ZONA2 fuel cell, as well as a validation of the cross section data for the higher isotopes of plutonium and the higher actinides. Significant attention was given to the precise calibration of the fission chambers thus giving very good confidence in the experimental values. The JEF2 results, given in Table I, are within the margins given by the experimental uncertainties.

TABLE I : (E-C)/C Discrepancies for Fission Chamber Indices in the
ZONA2 Cell of the CIRANO Programme

$\sigma_{c_{U238}} / \sigma_{f_{U235}}$	+1.7 % $\pm$ 3.0 %
$\sigma_{f_{U238}} / \sigma_{f_{U235}}$	0.0 % $\pm$ 2.7 %
$\sigma_{f_{Pu238}} / \sigma_{f_{U235}}$	-3.3 % $\pm$ 4.9 %
$\sigma_{f_{Pu239}} / \sigma_{f_{U235}}$	-1.7 % $\pm$ 1.8 %
$\sigma_{f_{Pu240}} / \sigma_{f_{U235}}$	-4.3 % $\pm$ 4.5 %
$\sigma_{f_{Pu241}} / \sigma_{f_{U235}}$	-1.7 % $\pm$ 3.9 %
$\sigma_{f_{Pu242}} / \sigma_{f_{U235}}$	-4.4 % $\pm$ 4.6 %
$\sigma_{f_{Np237}} / \sigma_{f_{U235}}$	+0.4 % $\pm$ 2.9 %
$\sigma_{f_{Am241}} / \sigma_{f_{U235}}$	-5.1 % $\pm$ 4.5 %
$\sigma_{f_{Am243}} / \sigma_{f_{U235}}$	-5.4 % $\pm$ 4.6 %

There is no evidence from these results of any significant discrepancy concerning nuclear data for the ZONA2 core fuel cell.

Another property of the core fuel is the material buckling . The calculation of the buckling was performed using the most accurate method available in the ECCO cell code (B1 consistent option) which corresponds to a transport Sn P1 spatial ERANOS calculation. A buckling search was performed with the condition k-effective = 1 to give a calculated value for the buckling of 2.184 $10^{-3} \pm 0.020\ 10^{-3}$, with a corresponding (E-C)/C value of -1.3 % ± 1.0 %. This discrepancy is then converted into a variation of reactivity which gives a value of -590 pcm ± 450 pcm. This value indicates that the reactivity of the ZONA2 cell is almost correct but the discrepancy is in the direction opposite to the critical mass of the three CIRANO configurations studied here.

To obtain a better understanding of the neutron slowing-down treatment in the reflectors, a study of the different methods used for cross section preparation has been undertaken. The 33 group JEF2 library used in the standard calculation was obtained via a condensation based on a typical fast reactor cell (i.e. containing oxygen). However, in the reflectors the neutron slowing down caused by elastic and inelastic collisions with elements such as iron, nickel and chromium significantly modifies the spectrum. Hence the preparation of the cross sections for the reflectors was performed by a neutron slowing down calculation using the 1968 group JEF2 library. This refined method for cross section preparation is expected to be better adapted to the treatment of reflector materials. Spatial calculations with a larger number of groups (~300) have been performed which confirm these trends, and a similar study performed for the EBR-II reactor has shown that a correct core/reflector interface treatment requires a refined energy group structure[7]. For a correct treatment of the core/reflector interface this method should be verified by a macrocell calculation where the cross section preparation for subcritical media takes into account the environment in which these materials are found. Preliminary macrocell calculations have been performed, giving encouraging results. The use of this refined method results in k-effective values of 0.99949, 0.99861 and 0.99905 for the CIRANO ZONA2A, ZONA2A3 and ZONA2B configurations respectively. The previously observed C/E discrepancies in the critical masses of the reflector configurations are considerably reduced, although the fission rate traverses in the reflector regions remain relatively unchanged, a result that has been confirmed via a comparison with Monte Carlo methods using the JEF2 data evaluation[8].

SENSITIVITY TO NUCLEAR DATA

Sensitivity calculations have shown that for the configuration with blankets (ZONA2A) the reflector saving is mostly sensitive to the elastic cross section of U238 and Na. For the configurations without blankets, however, the reflector saving is mostly influenced by the elastic cross section of Fe and Na. These results seem to provide further confirmation that the observed discrepancies are caused by an overestimation of the neutron slowing down effect. To try and understand the nature of the discrepancies concerning the critical mass and the fission rate traverses in the reflectors, two types of sensitivity calculations were performed for the reflector isotopes :

- sensitivity of the critical mass,
- sensitivity of the ratio of the peak of the U235 fission rate in the reflector to the U235 fission rate at the core centre.

The results for the CIRANO ZONA2B configuration are shown in the following table:

TABLE II CIRANO ZONA2B
Absolute Sensitivity of Nuclear Data for the Steel Reflector Zone
(in brackets, relative percentage)

	Critical Mass	U235 Fission Rate Ratio
Fe56	0.02601 (54.16)	0.27452 (48.04)
Ni58	0.00470 (9.78)	0.14165 (24.79)
Cr52	0.01234 (25.68)	0.03835 (6.71)
Na	0.00489 (10.19)	0.11096 (19.42)
C	0.00008 (0.16)	0.00509 (0.89)

These results seem to indicate that Fe56 has a dominant influence on both the critical mass and the fission rate traverses. Considering the importance of Fe56 the sensitivity to iron cross sections has been further investigated by using the MICROX/TWODANT[9] code package with various cross section evaluations. The results obtained with this scheme have been shown to be very consistent with those given by the JEF2/ECCO/ERANOS European scheme. Iron were generated from the JEF2.2, ENDF/B-VI, JENDL3.2, BROND2.1 and JEFF3.0 cross section evaluations. Collapsed cross sections are then used in TWODANT Sn core calculations. The impact on the critical mass of using different Fe56 evaluations in selected regions of ZONA2A3 and ZONA2B is shown in Tables III and IV.

TABLE III Changes* (%) in K-effective for CIRANO ZONA2A3 as a Function of Fe56 Data

Cross Section Evaluation	Radial Reflector	Axial Blanket	Core	Total
JENDL3.2	-0.22	-0.03	-0.11	-0.39
ENDF/B-VI	-0.20	-0.01	+0.02	-0.23
BROND2.1	-0.41	+0.07	-0.07	-0.59
JEFF3.0	-0.11	-0.00	+0.07	-0.06

TABLE IV Changes* (%) in K-effective for CIRANO ZONA2B as a Function of Fe56 Data

Cross Section Evaluation	Reflector	Core	Total
JENDL3.2	-0.42	-0.10	-0.56
ENDF/B-VI	-0.26	+0.01	-0.27
BROND2.1	-0.79	-0.07	-0.91
JEFF3.0	-0.21	+0.03	-0.18

The JEF2.2 value is taken as the reference.

A similar analysis has been performed concerning the peak in the U235 fission rate profile in the radial reflector, the results of which are shown in Table V below.

TABLE V Changes* (%) in the Peak in the U235 Fission Rate Radial Profile as a Function of Fe56 Data

Cross Section Evaluation	Radial Reflector Peak
JENDL3.2	-1.9
ENDF/B-VI	-1.1
BROND2.1	+2.5
JEFF3.0	-1.9

* The JEF2.2 value is taken as the reference.

The recent JEFF3.0 evaluation, as well as the JENDL3.2 evaluation, reduce the observed discrepancies, but the improvement is of small magnitude.

Nuclear data sensitivies indicate that several other isotopes may have an influence on the discrepancies observed. As shown in Table II, the influence of Cr52 would appear to be significant for the critical mass whereas Ni58 would appear to be of greater importance for the fission rate traverses and hence the neutron slowing down in the reflectors. These results indicate a more complex source of discrepancy than that originally suggested concerning the overestimation of the slowing down of neutrons in the reflector. The adjustment of the JEF2 data library will help to determine the source of these uncertainties[10].

CONCLUSIONS

Studies performed within the framework of the collaboration between CEA, PSI/EPFL and AEA, with an experimental basis provided by the CIRANO program currently being carried out at the MASURCA facility, have allowed the establishment and development of reference calculational schemes based on the JEF2/ECCO/ERANOS European scheme for plutonium burning fast reactors. In particular, methods have been developed for the accurate prediction of configurations with sodium/steel reflectors.

It has been shown that a standard broad group treatment for reflector materials leads to significant C/E discrepancies for the critical mass and fission rate traverses in the reflector regions. A considerable reduction in these discrepancies can be achieved by using a refined 1968 group treatment for the reflector cell calculation coupled with a macro cell calculation to represent correctly the neutron slowing down at the core/reflector interface. A further validation of these methods will be carried out via a series of benchmark studies comparing the deterministic methods presented in this paper with Monte Carlo calculations.

Nuclear data sensitivity studies have highlighted several isotopes and reactions for which data accuracy needs to be improved, in particular concerning Fe and Na elastic scattering cross sections for reflector materials. These improvements are being obtained in the framework of an overall data adjustment procedure taking into account these and other trends[10].

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