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# REVIEW OF THE NUCLEAR DATA STATUS AND REQUIREMENT FOR FISSION REACTORS

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**Abstract**: The nuclear data involved in high conversion light water reactors with tighter pitch lattice are reviewed from the viewpoint of calculating the conversion ratio, burnup and coolant void reactivity coefficient, which are of primary important for the core characteristics evaluation. With the intermediate spectrum, various problems in the nuclear data used for fission reactor analysis appear. The resulting understanding will be also useful to enhance accuracy of the data/methods for thermal and/or fast reactors.

**(intermediate spectrum, resonance parameters, FPs and higher actinides)**

## Introduction

Recently much ***R & D*** work has been done for high conversion light water reactors (HCLWRs) with tighter pitch lattice. The design efforts have aimed at achieving both high conversion and high burnup. Details of HCLWRs are readily available in the literature[(1)-(18)]. The HCLWR design concepts proposed so far can be classified into two groups: The first group is the tight HCLWR ($V_M/V_F$ = 0.5 - 0.75; KWU, KFK)[(8)-(11)], while the second is the semitight one with a spectral shift mechanism ($V_M/V_F$ = 1.1 - 1.4 ; Framatome, CEA)[(13)-(17)].

An HCLWR with tighter pitch lattice has the following two design features, compared with the conventional LWR: (i) reduced volume ratio of water to fuel ($V_M/V_F$) and (ii) higher plutonium fissile enrichment. From the viewpoint of reactor physics, the first feature results in an intermediate neutron spectrum in the core, while the second one likely brings a positive void reactivity, mainly provided by $^{240}$Pu and $^{239}$Pu. These reactor characteristics are peculiar in the sense that the intermediate energy region is quite important, but little understood.

It is necessary to take a general look at the reactor physics aspects of HCLWR, before considering any details. Figure 1 compares an HCLWR spectrum with typical PWR and FBR spectra. Figures 2 - 4 show the neutron spectra and the energy distributions of capture and fission rates, respectively, for a hexagonal lattice with homogeneously mixed material of two fuel materials of PROTEUS-LWHCR Cores[(6),(12)] at EIR. These figures were obtained by using the SRAC system[(18)]. More than 40% of the fission reactions and 70% of the capture reactions take place at the resonance energy (E ≦ 10 KeV). At particular, most of the capture reactions are due to the typical resolved resonances of major actinide isotopes.

One of the most critical problems in designing of HCLWR concerns the trade-off relation between enhancement of the conversion ratio and the safety margin related to coolant void coefficient[(19)-(22)]. Hence, reliable data and methods for the reactor physics calculations are essential to assess and confirm the HCLWR concept.

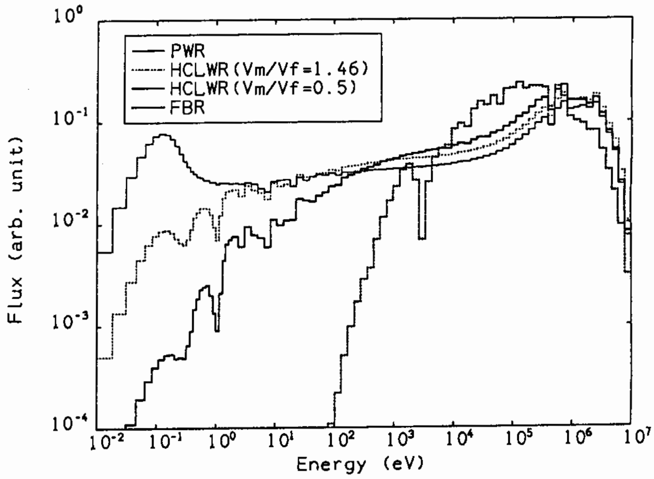


Fig. 1 Comparision of Neutron Spectrum

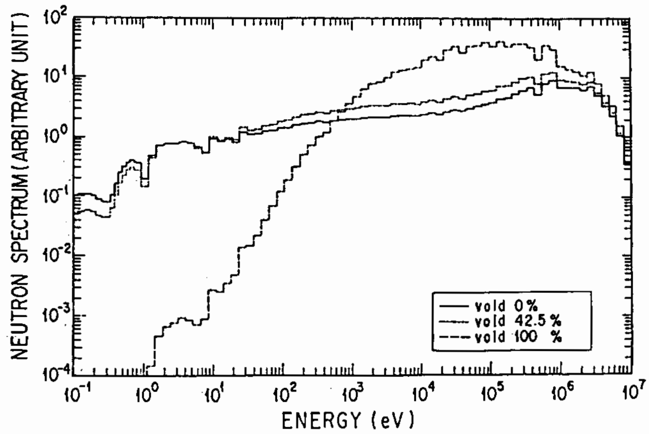


Fig.2 Neutron Spectra in Test Region of PROTEUS Cores

The conceptual designs so far proposed however seem to have insufficient accuracy for the data/methods in reactor physics. Taking this situation into consideration, a benchmark problem of a tight lattice cell burnup calculation[(23)] was proposed at the 29th Meeting of the Nuclear Energy Agency Committee on Reactor Physics (NEACRP), in September 1986. This benchmark problem aims to extract the problems included in the

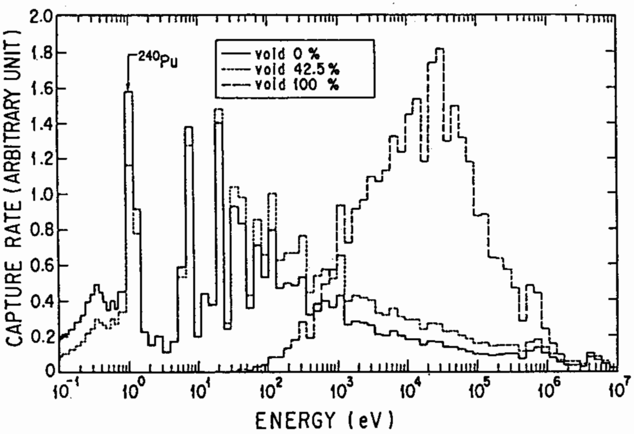


Fig.3 Macroscopic Capture Rate Distribution in Test Region of PROTEUS Cores

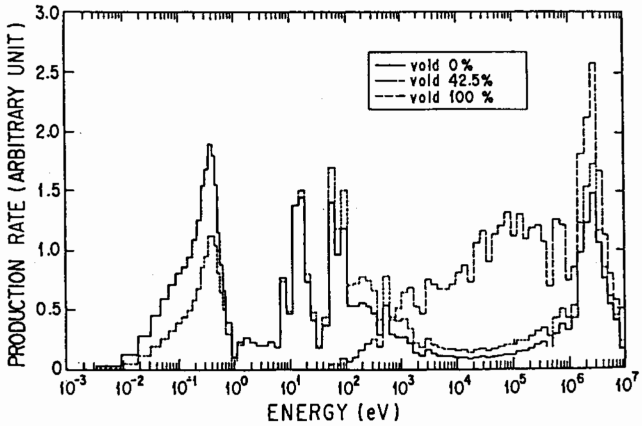


Fig.4 Macroscopic Fission Rate Distribution in Test Region of PROTEUS Cores

activities for the data/methods. The preliminary report[24] for the benchmark calculations however shows that a large discrepancy is found in the $k_\infty$, conversion ratio and void reactivity coefficients obtained. This discrepancy seems to be much larger than generally encountered on an existing LWR cell.

Following the recommendation of the 30th NEACRP Meeting, in September 1987, a specialists meeting concerning the results of the NEACRP HCLWR cell burnup benchmark problem was convened in April 1988 at the NEA Data Bank. In spite of the extensive development work done for the HCLWR data/methods, there are still unacceptable differences among the revised results, especially in the calculation of void coefficients and conversion ratios. Also the burnup reactivity changes have considerable disagreement. Presently the range of deviations for $k_\infty$ is about 3%, for conversion ratios up to about 10% and for void coefficient about 0.03($\Delta k/k$) (See Figs.5 – 7).

In this review, data requirements for fission reactors are described, focusing attention on the HCLWR, since this core has intermediate nuclear characteristics between the FBR and LWR and thus the data requirements are assumed to be common for both these reactors types. Some typical problems recognized while undertaking the nuclear data evaluation of the JENDL-3 are also presented.

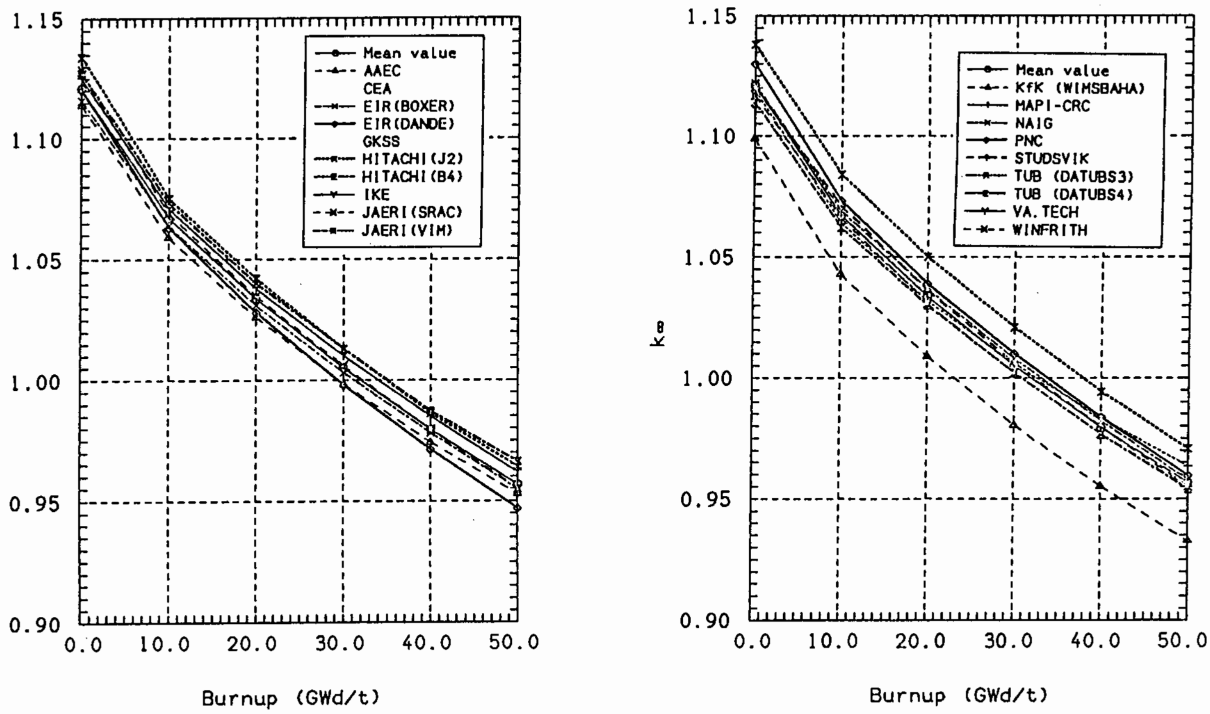


Fig.5 Burnup dependence of $k_\infty$ : Vm/Vf=1.1, enrich.=7%

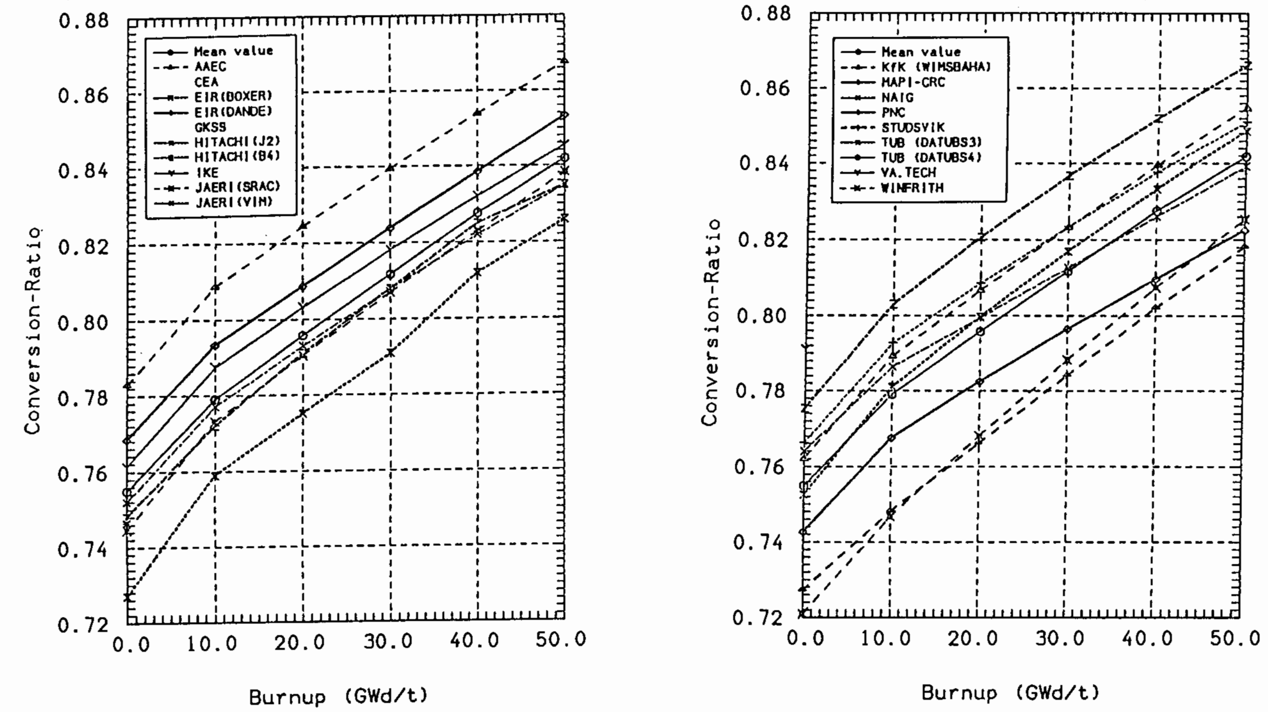


Fig.6 Burnup dependence of conversion ratio : Vm/Vf=1.1, enrich.=7%

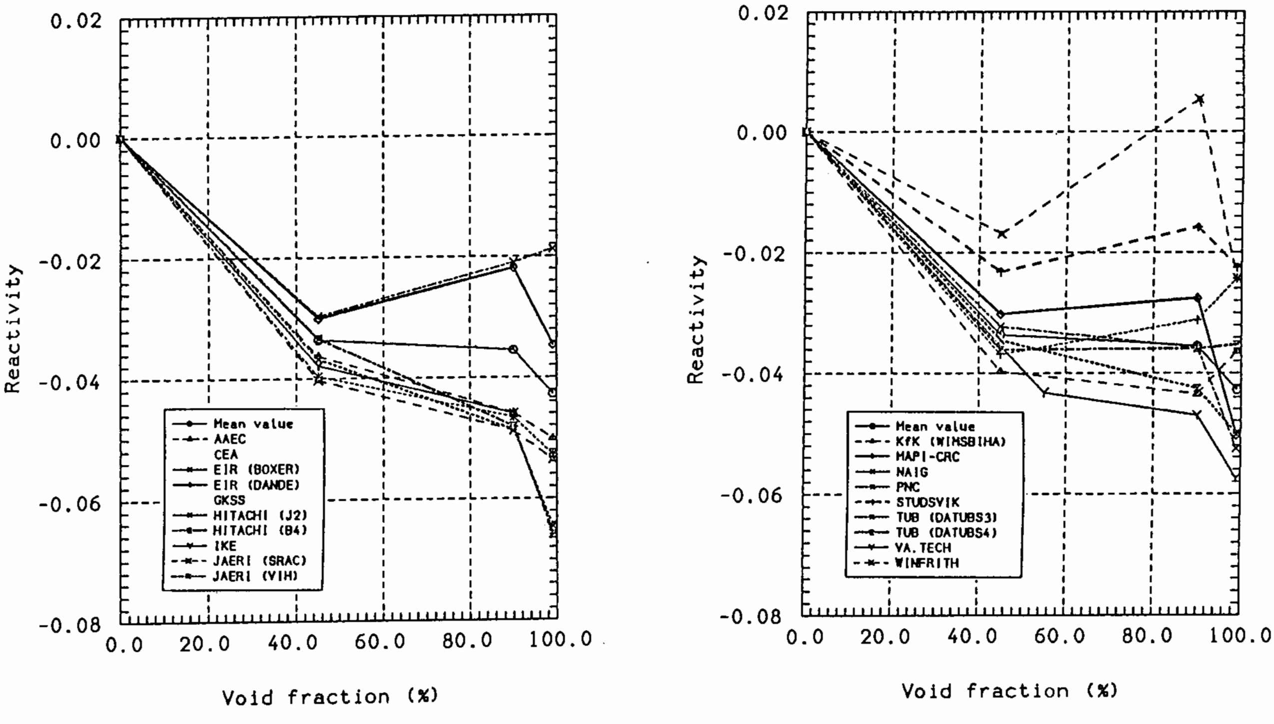


Fig.7 Void reactivity : Vm/Vf=1.1, 0GWd/t

## Major Heavy Isotopes

One of the fundamental concerns in analysis of nuclear physics characteristics is to estimate accurately the neutron spectrum in the lattice cell. In particular, the HCPWR core has a spectrum differing from both the LWR's and FBR's, which has not been fully studied. The accuracy of the calculated lattice spectrum is determined by the nuclear data used, and the way the effective multigroup cross sections are calculated. Overall sensitivity analyses[25] made for a typical HCLWR lattice show that $^{238}$U capture, $^{239}$Pu fission and capture, and $^{240}$Pu capture cross sections have very considerable sensitivities to the basic physical quantities, while $^{241}$Pu fission cross section also has a reasonably large sensitivity.

## Resonance Parameters

Figure 8 shows the deviations of the infinite dilution and effective cross sections of $^{238}U$ based on the ENDF/B-IV[26] from those on JENDL-2, where the effective cross sections are calculated again for the lattice of PROTEUS-LWHCR Core 1. These evaluations were made to estimate the cross section uncertainty for use in a sensitivity analysis for the lattice system[27]. It is significant that deviations of the effective cross sections are much larger than those of the infinite cross section in the energy range from 4 KeV to 100 eV, which is the resolved resonance region of $^{238}U$. Moreover, the two deviations are opposite in sign each other below 1 KeV. This can be attributed to the difference of the resonance shielding effects calculated by the different sets of resonance parameters, while the difference by the different calculational methods is highlighted in the lower energy region.

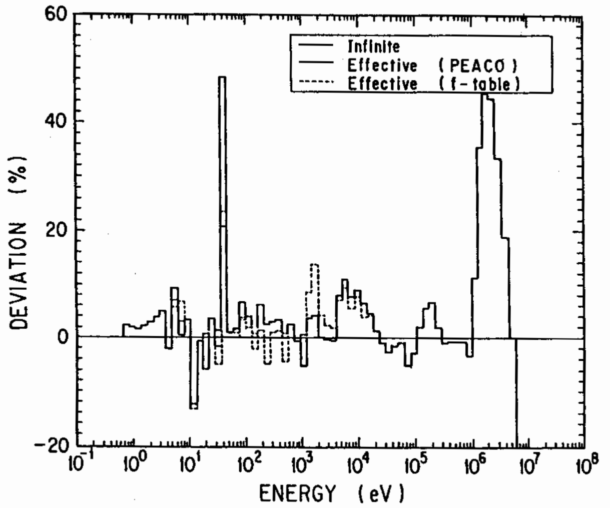


Fig. 8 Deviation of U-238 capture cross section of ENDF/B-IV from JENDL-2

As seen from Fig.9, each resonance shielding factor obtained from a sequence of independently evaluated resonance parameters has a different value in the energy region from 2.03 to 1.58 KeV, though they give almost the same values for the infinitely dilute cross section. In fact, a large difference can be seen between the resonance parameters of ENDB/B-IV and JENDL-2 in this energy region. In any case, a reevaluation work will be essential for the resonance parameters of $^{238}U$ and $^{239}Pu$ in the resolved resonance regions.

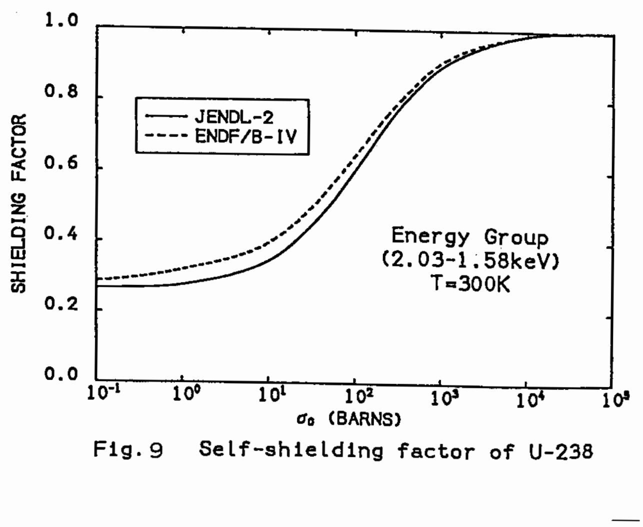


Fig.9 Self-shielding factor of U-238

## Adaptability of Adjustment Method

The above facts show that it will be quite difficult to define the cross section uncertainties of typical resonance nuclides in the resonance energy range to be used in a conventional sensitivity analysis. So, a cross section adjustment method based on a multigroup scheme should be considered when applied to a strong resonance nuclide such as $^{238}U$ in the intermediate spectrum system under study. Here, it should be noted that the error originated from the calculational methods themselves is generally not so large in the higher energy region. Nevertheless, the sensitivity method can provide useful information. That is to say, the sensitivity analysis is a valuable tool to identify the nuclear data requirement and to assess the accuracy of calculated integral quantities in fission reactors. As just mentioned, it is generally difficult to assign the cross section uncertainty in a multi-group scheme, which depends on neutron energy and reaction. Hence, the resulting conclusions should be considered cautiously. The discussions made here should also be applicable to fast reactor analysis.

## Inelastic Scattering Cross Section of $^{238}U$

The inelastic scattering partial cross sections of $^{238}U$ are still scattered to a large extent. Moreover, only few measured points are available for the total inelastic scattering cross section of $^{238}U$ in the energy region above 1 MeV, as seen from Fig. 10. More experimental data for the total inelastic scattering cross section will be required in this energy region for accurate estimate of scattering matrices in the spectrum codes.

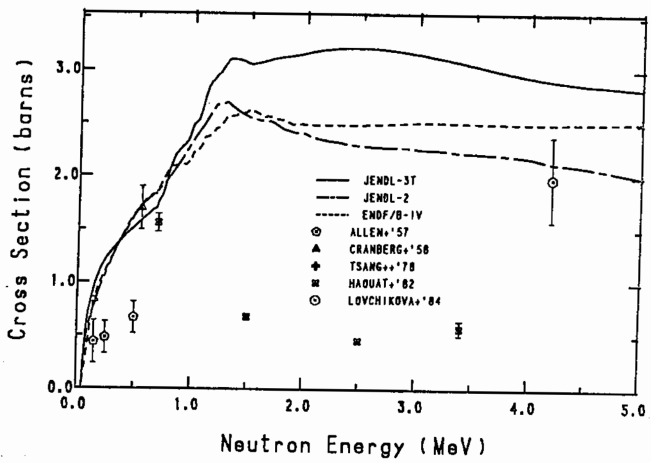


Fig. 10 Total inelastic cross section of $^{238}U$

## Fission Cross Section of $^{239}Pu$

In figure 11, the fission cross sections of $^{239}Pu$ are compared among the various evaluated nuclear data files in the energy range 10 KeV – 1 MeV, where the sensitivity coefficients for $k_\infty$ and the void reactivity coefficient show higher values predominantly at higher void fraction. Unfortunately, the so-called "file discrepancy" of about 10 % can be observed in this energy region.

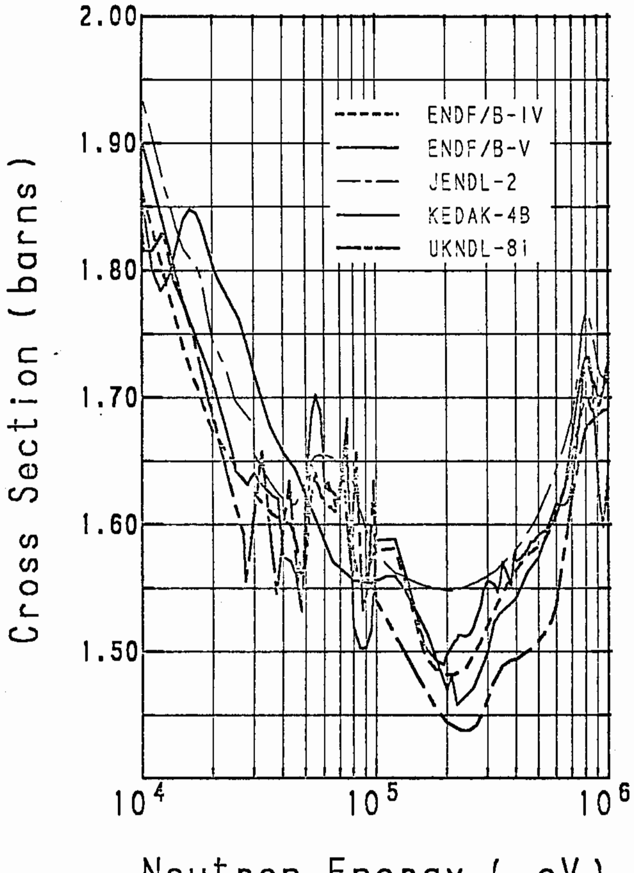

Fig. 11 $^{239}$Pu fission cross sections

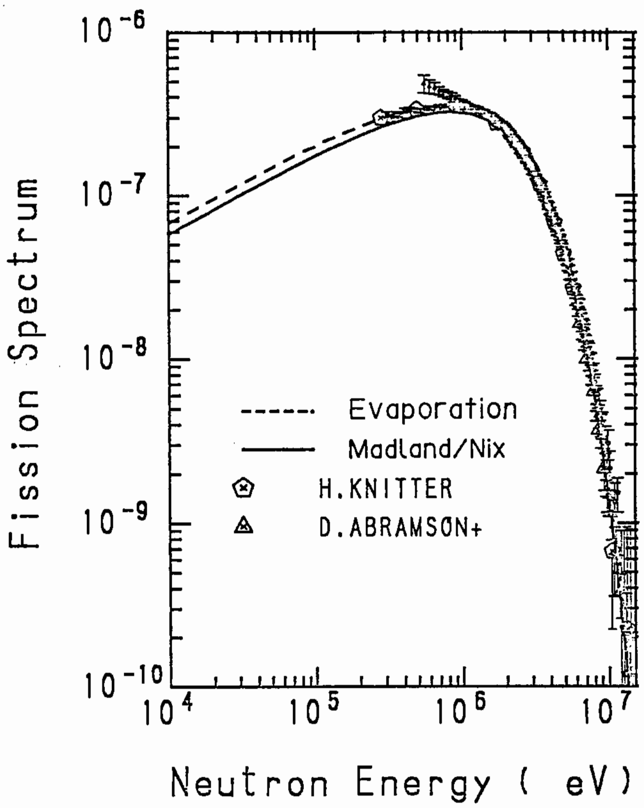

Fig. 12 $^{239}$Pu Fission Spectrum

**Fission Spectrum of $^{239}$Pu**

The fission spectrum evaluated by the Madland-Nix formula(28) will be compiled in JENDL-3. Figure 12 plots the evaluated and experimental spectra of $^{239}$Pu. The spectrum increases around the peak but contrarily decreases at the both sides, compared with that of JENDL-2. According to a fast reactor benchmark test, the present spectrum makes the neutron spectra hard and overestimates the fission rate of $^{238}$U to $^{235}$U by about 5%. As for the $^{239}$Pu spectrum, agreement with the experimental data is not always good at the off-peak region. An optimization of the parameters used for the Madland-Nix formula as well as an investigation on the applicability to the other fissiles excluding $^{235}$U are required.

**The First Resonance of $^{240}$Pu**

As shown in Table 1, the resonance integral RI($\gamma$) have become larger as time has passed with one exception. The most recent experimental work by Spencer et al.(29) shows the largest RI-value and smaller 2200m/s total cross section. The older data files ENDF/B-IV and JENDL-2 support the higher value of RI($\gamma$), but the new version ENDF/B-V and JENDL-3 adopt the smaller ones and have almost the same value for the total cross section $\sigma_t$(2200m/s). The effect of the change in the $^{240}$Pu 1 eV resonance parameters from JENDL-2 to ENDF/B-V is reported to be about 0.2% $\Delta$k/k for a typical HCLWR lattice.(30)

Table 1 Comparison of $^{240}$Pu Resonance Parameters and 2200m/s Total Cross Sections[a]

| Experiment | Date | RI($\gamma$) (b) | $\sigma_T$(2200m/s) (b) |
|---|---|---|---|
| Fluharty et al. | 1957 | 6800 | |
| Egelstaff et al. | 1958 | 6900 | |
| Cate et al. | 1959 | 7900 | |
| Pattenden and Rainy | 1970 | 7600 | |
| Ramakrish and Navalken | 1970 | 7366 | |
| Abov[6] | 1971 | 10000 | |
| Harvey et al. | 1982 | 8112 | |
| Lio and Chrien | 1985 | 8020 | |
| Spencer et al. | 1987 | 8384 | 284 |
| **Evaluation** | | | |
| Weigmann et al. | 1970 | 8081 | |
| ENDF/B-IV | 1974 | 8357 | |
| JENDL-2[b] | 1982 | 8453 | 290.1 |
| ENDF/B-V | 1980 | 8034 | 291.5 |
| JENDL-3[b] | 1988 | 8105 | 291.5 |

a) R.R.Spencer et al. Nucl. Sci. Eng. 96, 318-329 (1987)
b) Private Communication from T.Nakagawa

**Burnup Calculation, Related Cross Sections**

A better conversion ratio is obtainable in tighter pitch lattices, but lower plutonium enrichment is allowed to avoid the positive void coefficient. This means that higher burnup is not achievable. Thus, there is a trade-off relation between effective fuel utilization and safety requirements. The void reactivity coefficient become lesser negative with increasing burnup due to accumulation of fission products and higher actinides. Hence, it is very important to forecast accurately the burnup behaviour of HCLWR and to evaluate the void characteristics in case of coolant loss.

Table 2 shows the contribution of different families of isotopes to the reactivity loss of an equilibrium cycle of a PWR and a plutonium fueled semitight HCLWR(13). Fission products are the most important part, contributing about 55% of the total, while minor actinides affect the isotopic evolution.

Table 2 Contribution of the main isotopes families to reactivity change / cycle.

| | PWR | PU-HCLWR |
|---|---|---|
| Reactivity Change/Cycle | -14% | - 6% |
| Breakdown: | | |
| Uranium Isotopes | -87 | - 1 |
| Plutonium Isotopes | +21 | -26 |
| Am, Cm Isotopes | - 2 | -16 |
| Fission Products | -32 | -57 |
| (norm.) | 100 | 100 |

Changing the volume ratio $V_M/V_F$ of the HCLWR cell, investigations were made on the burnup dependence of the sensitivity coefficients in order to identify the effect of the cross section uncertainty of minor actinides and fission products(25). As burnup proceeds, the sensitivities of $k_\infty$ to $^{238}$U, $^{239}$Pu and $^{240}$Pu decrease, while those to the typical fission products increase. The fission products also have a large effect on the change of coolant void worth with burnup.

The capture cross sections of minor actinides have larger sensitivity than the fission cross sections. In particular, $^{243}$Am and $^{241}$Am have large sensitivities for $k_\infty$. As shown later, if these nuclides are neglected in the burnup calculation of HCLWR, the $k_\infty$ after 50 GWd/t burnup is overestimated by more than 1.5%. This means that accurate nuclear data of the minor actinides are required for evaluation of the burnup characteristics in the HCLWR.

Fission Products

Takano et al(31) made a detailed investigation on the effects of fission products on the burnup characteristics. For this investigation, a typical hexagonal lattice of the HCLWR was selected: 1.0-cm-diameter fuel pin, 0.04-cm-thick stainless steel cladding, $V_M/V_F$ = 0.74 and 8% enrichment of fissile plutonium. In addition to this lattice, another lattice of $V_M/V_F$ = 1.4 with 0.064-cm-thick Zircalloy cladding was also considered.

Since a number of fission product nuclides have very large resonance capture cross sections, the resonance shielding effect on the reactivity change with burnup is very important. It was observed that the resonance shielding effects of $^{131}$X and $^{133}$Cs are remarkable in comparison with other nuclides. The reactivity loss by burnup is considerably reduced when taking into account the self-shielding effects of fission products.

Discrepancies among nuclear data of fission products are more remarkable than those of fuel materials. Table 3 makes comparison of primary data; the cross sections at 2200m/s, and resonance integrals for typical fission product nuclides obtained from the evaluated nuclear data files JENDL-1, JENDL-2, ENDF/B-V, and JEF-1(32). Large discrepancies are observed for these primary nuclear data, especially for the resonance cross section data, the uncertainty is significant. As the typical examples, the resonance cross sections for $^{155}$Eu and $^{103}$Ru are compared for the three evaluated files in Figs.13 and 14, respectively. From these figures, it can be observed that the discrepancies among the evaluated capture data for $^{155}$Eu and $^{103}$Ru are incredibly large. The same discrepancies can be found in those nuclides which have a large discrepancy in the resonance integral (See Table 3).

In order to examine the effects of the nuclear data uncertainty of the fission products on burnup reactivity change, the cell burnup calculations were performed using the above four data files for the lattice of $V_M/V_F$ = 0.75. Here, the effective cross sections for the 65 explicit fission products were calculated by taking account of the self-shielding factors. Figure 15 compares the contributions of fractional absorption rates

Table 3 **Comparison of Thermal Cross Sections and Resonance Integrals (b)**

| Nuclide | | JENDL-2 | JENDL-1 | ENDF/B-V | JEF-1 |
|---|---|---|---|---|---|
| $^{99}$Tc | 2200 m/s | 19.8 | 17.7 | 19.5 | 19.0 |
| | RI 1) | 319.2 | 207.0 | 351.0 | 359.0 |
| $^{103}$Ru | 2200 m/s | 5.0 | | 7.7 | 66.8 |
| | RI | 92.0 | | 70.0 | 595.0 |
| $^{107}$Pd | 2200 m/s | 1.9 | 10.0 | 10.0 | 1.9 |
| | RI | 101.0 | 120.0 | 76.4 | 103.7 |
| $^{108}$Pd | 2200 m/s | 8.5 | | 12.2 | 7.4 |
| | RI | 252.4 | | 226.0 | 188.0 |
| $^{131}$Xe | 2200 m/s | 85.0 | 88.0 | 90.1 | 85.5 |
| | RI | 900.0 | 904.0 | 891.0 | 1015.0 |
| $^{133}$Cs | 2200 m/s | 29.0 | 29.0 | 29.6 | 29.0 |
| | RI | 437.2 | 398.0 | 405.0 | 383.0 |
| $^{145}$Nd | 2200 m/s | 43.8 | 41.9 | 42.0 | 42.0 |
| | RI | 204.0 | 266.0 | 233.0 | 233.0 |
| $^{152}$Sm | 2200 m/s | 206.0 | | 207.0 | 206.0 |
| | RI | 2766.0 | | 3001.0 | 2982.0 |
| $^{155}$Eu | 2200 m/s | 4046.0 | 4040.0 | 4040.0 | 3647.0 |
| | RI | 18840.0 | 3218.0 | 1857.0 | 2178.0 |
| $^{155}$Gd | 2200 m/s | 60890.0 | 61130.0 | 60930.0 | 61130.0 |
| | RI | 1548.0 | 2589.0 | 1555.0 | 2589.0 |

1) Resonance integral in the 0.5-eV to 10-MeV energy range.

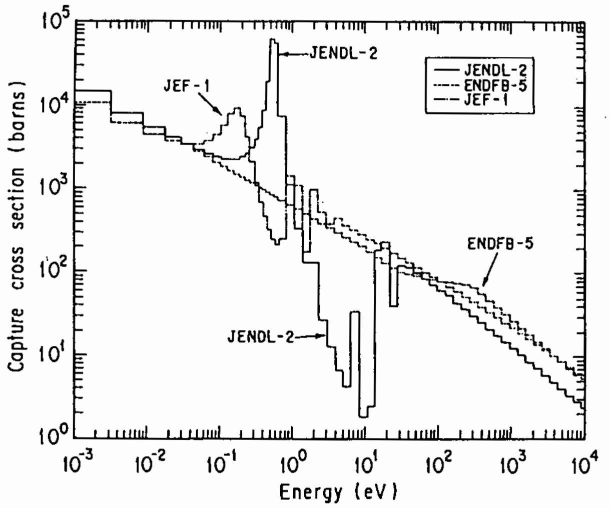


Fig.13 Comparison of capture cross sections of Eu-155 among the three nuclear data files. The cross sections of ENDF/B-4 are the same as those of ENDF/B-5

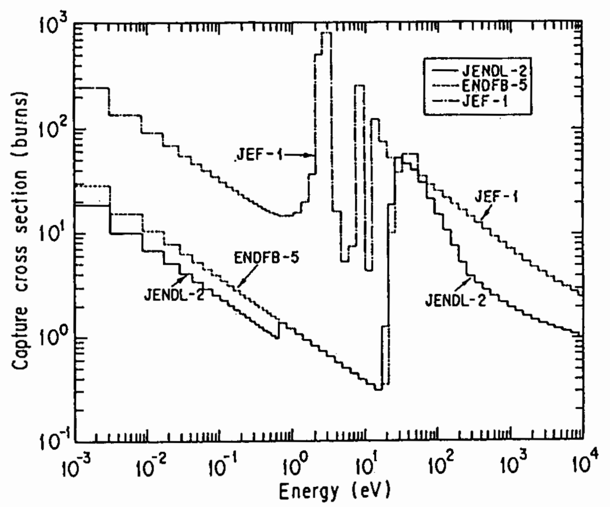


Fig.14 Comparison of capture cross seetions of Ru-103 among the three nuclear data files. The cross sections of ENDF/B-4 are the same as those of ENDF/B-5

of the individual fission products nuclides calculated from JENDL-2, ENDF/B-V, and JEF-1. Remarkable differences between the absorption fractions are observed for several nuclides, $^{99}$Tc, $^{108}$Pd, $^{135}$Cs, $^{103}$Ru, and $^{155}$Eu. The burnup reactivity changes are shown as relative values to JENDL-2 in Fig.16. A considerable difference is observed between JENDL-2 and ENDF/B-V, while the difference between JENDL-2 and JEF-1 is very small. This situation is merely due to an accidental cancellation as seen from Fig.16.

It was shown that the fractional absorption rates for individual fission product nuclides are considerably scattered in existing nuclear data files. The buildup of fission products was also shown to affect the void reactivity characteristics. A consistent reevaluation of the nuclear data of the fission product is needed for a better estimate of HCLWR and/or LWR burnup characteristics.

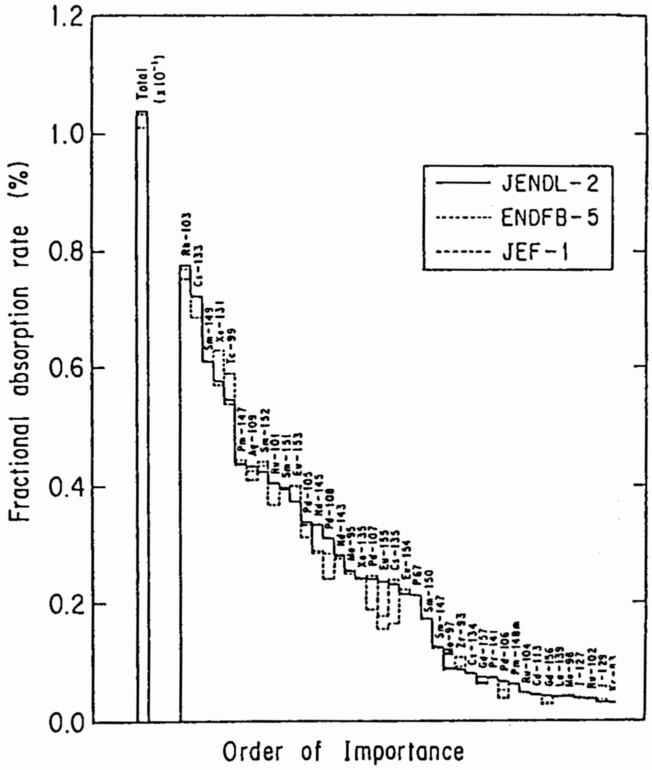


Fig. 15 Contribution of individual nuclide to total absorption at the burnup stage of 50 GWD/t

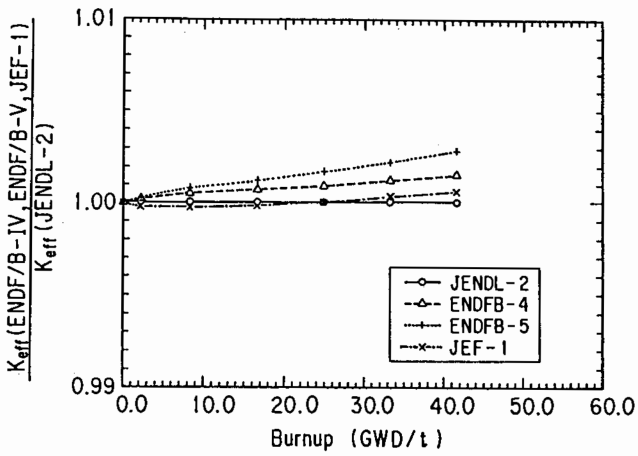


Fig.16 Burnup dependence of the ratios of the multiplication factors calculated with the other files to those obtained with JENDL-2

**Minor Actinides**

As pointed out in the previous subsections, fission products and actinide nuclides play an important role in predicting burnup characteristics and burnup-dependent void reactivity coefficient. The prediction accuracy primarily depends on the quality of the nuclear data for these nuclides, the calculational methods of group cross sections and burnup chain model. An investigation was also made on the effect of minor actinides on the burnup changes in HCLWRs(33).

Figure 17 shows the burnup reactivity changes for the lattice of $V_M/V_F = 0.74$. The contributions of $^{241}$Am and $^{243}$Am to the burnup reactivity loss are very large to be about 1.0% and 1.6% $\Delta$k/k, respectively, at the burnup 60 GWd/t. This effect of $^{241}$Am and $^{243}$Am is almost equal to reducing the burnup by about 10 GWd/t.

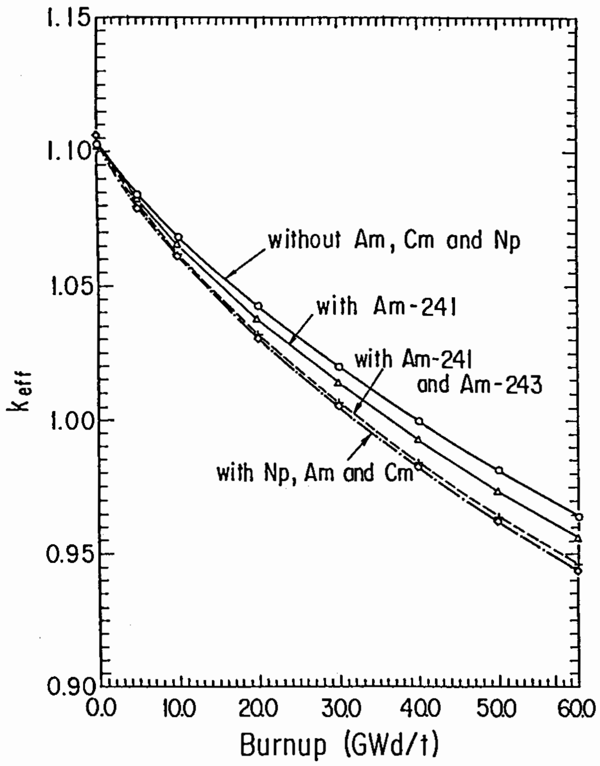


Fig. 17 Comparison of burnup reactivity changes

Nuclear data uncertainties for minor actinides are usually larger than those of major ones such as $^{238}U$ and $^{239}Pu$. The capture and fission cross sections of $^{243}Am$ are compared in Figs.18 and 19, respectively. Considerable discrepancies are found among the existing four nuclear data files, JENDL-2, JEF-1, ENDF/B-IV, and V. Figure 20 compares the fractional absorptions of minor actinides calculated by using four different cross section data, where the total absorption in the lattice is normalized to 100%. The results obtained with ENDF/B-IV, which has older data, deviate more from the others which are in good agreement with each other.

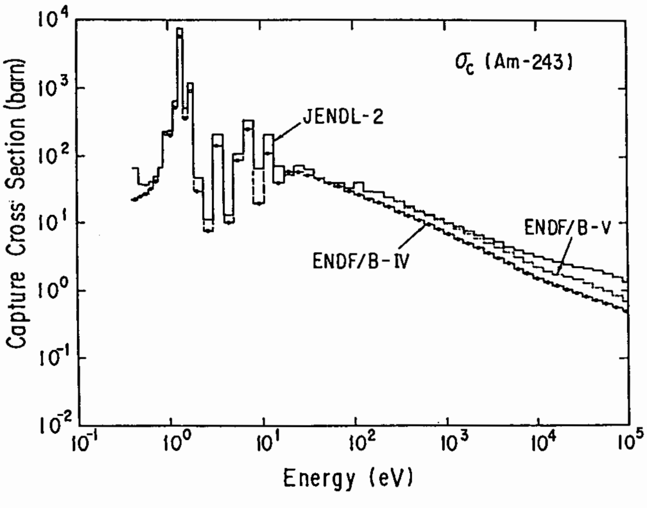


Fig. 18 Comparison of capture cross sections of Am-243

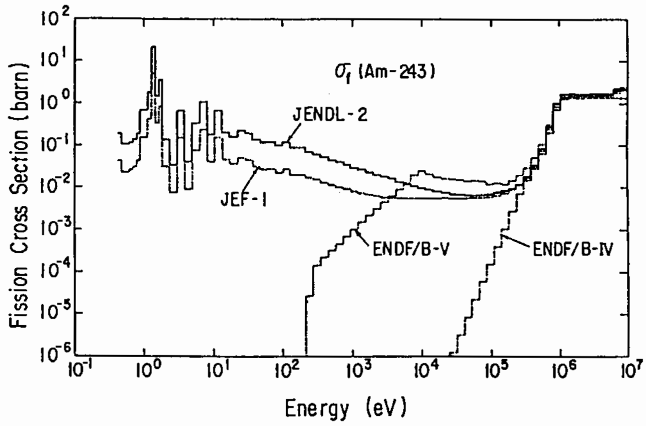


Fig. 19 Comparison of fission cross sections of Am-243

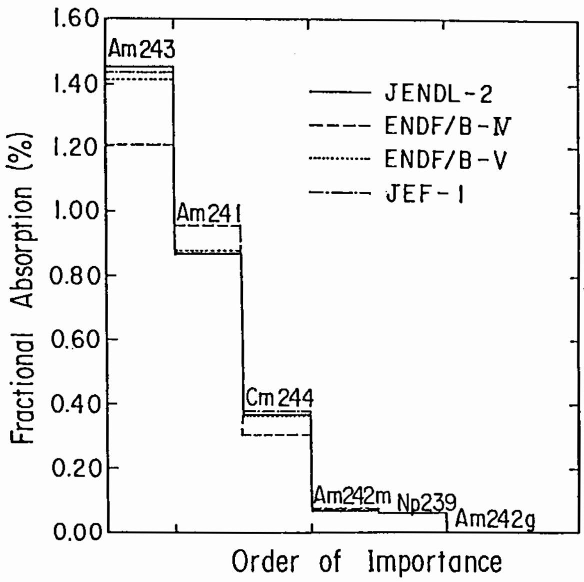


Fig. 20 Comparison of fractional absorptions for minor actinides at the burnup stage of 50 GWd/t. The total absorption in cell is normalized to 100 %.

The 2.67eV resonance of $^{242}Pu$ plays an important role in void reactivity change as well as the 1.06eV resonance of $^{240}Pu$. The neutron absorption by this resonance is often calculated with an infinitely dilute cross section, because of its lower atomic number density compared with other Pu isotopes. The resonance absorption cross section is however very large, hence the self-shielding effect is also significant. This effect on the HCLWR neutronic characteristics was examined by cell calculations(34). If the shielding effect is taken into account, $k_\infty$ becomes larger by more than 1% for a typical HCLWR lattice. The self-shielding effect on $k_\infty$ decreases with increasing void fraction due to spectrum hardening, which results in the increase of negative void coefficient. As for the 2.67eV resonance of $^{242}Pu$, existing nuclear data files adopt the almost same resonance parameters except for ENDF/B-V, which gives a higher resonance integral by about 20 %.

Concerning the minor actinides, the nuclear data seem to be fairly satisfactory for the analysis of the HCLWR core characteristics. It should however be noted that a large "file discrepancy" is observed in the entire energy region of interest.

## Conclusions

Much effort has been devoted to conceptual design of HCLWRs. In spite of the extensive developments, there are still unacceptable differences in the calculation of the main physics quantities. The reasons for the deviations are related primarily to the insufficient quality of the evaluated nuclear data.

Since a considerable amount of the nuclear reactions in the HCLWRs occur in the resonance energy region, reevaluation work will be essential for the resonance data, particular of $^{238}U$ and $^{239}Pu$ both in the resolved and unresolved resonance energy regions. Integral experiments in the intermediate spectra will offer useful information to evaluate the nuclear data.

As for $^{240}Pu$ which is the major positive contributor to the void coefficient, the resonance parameters of the 1.06 eV level may influence the calculated results significantly and uncertainty analysis of the nuclear data is left for the future.

The accumulation of fission product nuclides greatly affects the burnup and void reactivity characteristics of HCLWRs. A large difference was found in the absorption cross sections of several nuclides, $^{99}Tc$, $^{108}Pd$, $^{135}Cs$, $^{103}Ru$, and $^{155}Eu$ among existing nuclear data files.

Minor actinides are also important for the HCLWR burnup characteristics; the nuclear data seem to be comparatively satisfactory for their effect on reactor parameters in spite of the large file discrepancy.

## Acknowledgement

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