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# IMPACT OF DIFFERENT NUCLEAR DATA ON THE PERFORMANCE OF FAST SPECTRUM SYSTEMS BASED ON THE THORIUM-URANIUM FUEL CYCLE

S. PELLONI[1], G. YOUINOU[1,2] and P. WYDLER[1]

[1] PSI, Paul Scherrer Institut, CH-5232 Villigen PSI
[2] CEA, CE Cadarache, DER/SPRC/LEDC, F-13108 Saint-Paul-lez-Durance

## 1 Introduction

Thorium fuels have been used in thermal reactors as e.g. the high temperature gas-cooled reactor because, in a thermal neutron spectrum, the bred $^{233}$U provides a good neutron economy which improves the fuel utilisation. On the other hand, thorium-fuelled fast reactors and hence the integral validation of high energy nuclear data for the thorium-uranium fuel cycle have not been given much attention because, in the past, the long system doubling time of fast reactors with thorium in the core was perceived to be incompatible with the needs of a rapidly expanding nuclear energy system. Nowadays, the priorities are different, and possible safety advantages of thorium-fuelled fast systems such as the relatively small positive void reactivity effect and the small build-up of higher actinides in the fuel may become dominating issues.

## 2 Data for the Thorium Cycle in Fast Systems

In the Th cycle, the fertile and fissile nuclides are $^{232}$Th and $^{233}$U, respectively. $^{233}$Pa, the precursor of $^{233}$U, is also important: due to its relatively long half-life (27 d), it has an important equilibrium concentration in the fuel. For the reasons indicated above, the neutron cross sections for these nuclides have not been extensively validated in the fast energy range 0.01-10 MeV.

Figs 1A-1C display the important cross sections for these nuclides from three modern data libraries, JEF-2.2, JENDL-3.2 and ENDF/B-VI (Rev. 4). Whereas the different $^{233}$U fission cross sections are in good agreement, there are significant differences in the capture cross sections: for $^{232}$Th, the JEF-2.2 cross section is up to 15 % bigger than the JENDL-3.2 cross section, the ENDF/B-VI cross section lying inbetween; for $^{233}$Pa, the

JEF-2.2 cross section is up to three times lower than the JENDL-3.2 cross section, the ENDF/B-VI cross section being the same as the JEF-2.2 cross section. This indicates a need for integral checks on the reliability of these data.

# 3 Data Validation

Such a check has been performed using integral data from fast reactor benchmark experiments with thorium performed in the 1970's in the framework of the PROTEUS-GCFR programme [1]. In this series of experiments, the reference central test zone (Core 11) of the zero power reactor PROTEUS was a fast reactor lattice consisting of $PuO_2/UO_2$ pins, driven critical by surrounding driver zones. By introducing various detectors, a range of important integral parameters could be measured: for example, thorium foils, irradiated in the centre pin, yielded infinitely diluted thorium reaction rates. In the following core (Core 12) the original lattice was modified such that one mixed oxide fuel rod in three was replaced by a rod of $ThO_2$, allowing $^{232}$Th capture reactions to be measured in an environment with resonance self-shielding effects. Calculated-to-experimental reaction rate ratios are summarized in Table 1 (C and F mean capture and fission, respectively, and nuclides are denoted according to the (Z,A) convention).

| C/E | Core 11 | | | Core 12 | | |
|---|---|---|---|---|---|---|
| | JEF-2.2 | JENDL-3.2* | ENDF/B-VI* | JEF-2.2 | JENDL-3.2* | ENDF/B-VI* |
| C02/F49 | 1.00 | 0.91 | 0.95 | 1.02 | 0.94 | 0.98 |
| F02/F49 | 0.91 | 1.00 | 0.95 | 0.93 | 1.00 | 0.96 |
| F23/F49 | 1.00 | 0.98 | 0.99 | Experimental data not available | | |
| F28/F49 | 1.06 | | | 1.01 | | |
| C28/F49 | 0.98 | | | 0.96 | | |

Table 1: Ratios of Calculated-to-Experimental (C/E) Reaction Rate Ratios at the Centre of PROTEUS Fast Reactor Lattices

The reference calculation was based on a pure JEF-2.2 library. Alternatively, mixed libraries were used which combine either JENDL-3.2 or ENDF/B-VI (Rev. 4) data for $^{232}$Th and $^{233}$U, with JEF-2.2 data for the remaining nuclides (the mixed libraries are denoted JENDL-3.2* and ENDF/B-VI*). In the processing of these data sets, NJOY (Ed. 89.62) was used. The cell calculations (multicell calculation for Core 12) were based on the MICROX-2 spectrum code.

Interestingly, the JEF-2.2 cross sections, which are based on the older ENDF/B-IV evaluation, predict the measured C02/F49 ratio well, i.e. within the ($1\sigma$) experimental uncertainties of 1 to 2%. Because measurements are relative to $^{239}$Pu fission, this does not rule out a deficiency in the $^{232}$Th capture cross section. However, the fact that the measurements were carried out for two cores, with and without resonance self-shielding effects in $^{232}$Th, gives confidence in the JEF-2.2 data for this reaction. It then appears that, in the other, more recent and complete evaluations, the capture cross section of $^{232}$Th in the fast energy range is too small. Although less important from a neutron balance point of view, a significant improvement of the prediction of the measured $^{232}$Th fission rate is achieved when the JENDL-3.2* library is used. As regards $^{233}$U, the measured fission rate appears to be well predicted by all data libraries.

# 4 Application to a Thorium-Based Reactor System

A thorium-fuelled, accelerator-driven system (ADS) with a fast neutron spectrum, called Energy Amplifier (EA), has recently been proposed by a group from CERN [2]. In this system, the control rods have been eliminated and the power during the single batch reactor cycle is controlled solely by varying the proton current of the accelerator. Considering the cost of the accelerator and the overall electrical efficiency of an energy producing ADS, the $k_{eff}$ of the subcritical core should not drop below about 0.97. This implies that the maximum $k_{eff}$ variation over the reactor cycle due to burnup (BU effect) and the reactivity effect resulting from the decay of $^{233}$Pa when the accelerator is switched off (Pa effect) are subject to the constraint

$$k_{min} = 1 \text{ - BU effect - Pa effect - SM} \geq \sim 0.97,$$

where SM is the nominal shut-down reactivity margin[1]. The BU effect depends on the initial $k_{eff}$ ($k_{BOL}$) of the core and can therefore be minimised by adjusting the $^{233}$U enrichment. Assuming the Pa effect to be independent of the burnup, this can approximately be achieved by adjusting the initial $^{233}$U enrichment to satisfy the condition

$$k_{BOL} \text{ - Pa effect} = k_{EOL}.$$

For this enrichment, the effective shut-down margin can then be adjusted to the desired value SM by changing the core geometry (leakage).

The optimisation has been performed for an EA-type system[2] using the aforementioned JEF-2.2 and JENDL-3.2* data libraries in deterministic two-dimensional transport and burnup calculations below 20 MeV, the spallation neutron source being obtained from a HETC calculation [3]. Calculations were performed for three different $k_{BOL}$ values (0.982, 0.962, 0.941), and optimised values for the $^{233}$U enrichment, the BU effect and $k_{BOL}$ as described above were then determined with parabolic interpolations between the three calculations.

Fig. 2 shows the $k_{eff}$ evolution for $k_{BOL}$=0.982. The corresponding initial $^{233}$U enrichments calculated with JEF-2.2 and JENDL-3.2* are 10.28% and 9.88%, respectively. The lower enrichment correlates with the lower Th capture cross section (0.35 barns and 0.33 barns for JEF-2.2 and JENDL-3.2, respectively). Because different Th capture cross sections also signify different $^{233}$U breeding rates, the $k_{eff}$ deviation in Fig. 2 increases continuously with time, reaching about 0.8% at EOL, i.e. after 1800 EFPD or the target burnup of 100 GWd/tHM (in the two calculations, the fission products are the same and can therefore not explain the observed $k_{eff}$ deviation).

The parameters for the optimised core are compared in Table 2. It can be seen that the optimum initial $^{233}$U inventory is reduced by ~5% (about 140 kg) and the minimum BU effect is increased by almost 20%, if JENDL-3.2 data for $^{232}$Th and $^{233}$U are used. The $k_{min}$ values are close to the target value of 0.97, and the maximum proton currents, corresponding to a calculated target yield of $3.38 \cdot 10^{18}$ neutrons per second, lie distinctly below 20 mA. The feasibility of the concept is herewith confirmed. From the optimised

[1] A shut-down margin is necessary because the reactor has no control rods and possible scram devices must be reset before the reactor can be started up after a longer shut-down.

[2] The model is that used in the "ADS neutronic benchmark calculations" carried out in the framework of the IAEA Coordinated Research Programme on the Use of Thorium-Based Fuel Cycles in Accelerator-Driven-Systems to Incinerate Plutonium and to Reduce Long-Term Waste Toxicities.

$k_{BOL}$, the effective shut-down margins can be evaluated to be close to the desired value of 1% in the case of JEF-2.2, but about 1% too high in the case of JENDL-3.2*. In the latter case, a global reactivity adjustment of 1% by means of a change in the core geometry is therefore indicated.

Table 2 also contains void coefficients at BOL and after 2250 EFPD. It can be seen that the void coefficients based on JENDL-3.2* are always more positive, but remain within the nominal shut-down margin of 1%, meaning that the voided core would remain subcritical under all circumstances.

| Parameter | BOL | | EOL | |
|---|---|---|---|---|
| | JEF-2.2 | JENDL-3.2* | JEF-2.2 | JENDL-3.2* |
| Pa (pcm) | | | +1495 | +1677⁴ |
| $^{233}$U Enr. (%)¹ | 10.32 | 9.75 | | |
| BU (pcm)¹ | | | +640 | +741 |
| $k_{BOL}$¹ | 0.9842 | 0.9730 | | |
| $k_{min}$¹,² | 0.9686 | 0.9658 | | |
| $I_{pmax}$ (mA)¹,² | | | 16 | 18 |
| Void IC (pcm)³ | +770 | +940 | +820 | +920 |
| Void IC+OC (pcm)³ | -520 | -110 | +530 | +900 |

[1] For optimised core [2] For SM=1% [3] For $k_{BOL}$=0.982
[4] Includes effect of JENDL-3.2 data for $^{233}$Pa

Table 2: Influence of Nuclear Data on ADS Parameters

## 5 Conclusions

Calculations using two different data libraries were performed for an EA-type system with a fast neutron spectrum. The calculations

- predict a significant dependence of the optimised core parameters on the data set (~5% and ~20% deviations for the initial $^{233}$U inventory and the burnup effect, respectively),
- confirm the feasibility of the control-rod free core concept for both data sets, but
- indicate that the effects of the uncertainties in the data must also be evaluated.

The observed deviations can be attributed mainly to the difference in the $^{232}$Th capture cross section. Earlier benchmark experiments performed at the zero power reactor PROTEUS support the JEF-2.2 evaluation for this cross section. Nevertheless, additional benchmark experiments are desirable to independently check this observation and reduce data uncertainties to satisfy the needs of more refined core optimisation studies for fast, accelerator-driven systems based on the thorium fuel cycle.

## References

[1] U. Schmocker et al, Neutron Physics and Nuclear Data, OECD/NEA (1978) 999.

[2] C. Rubbia et al, CERN/AT/95-44(ET), (1995).

[3] F. Atchison, PSI-Proceedings 92-02, (1992) 440.

Fig.1A: Th-232 Capture X-Sec (Barns)

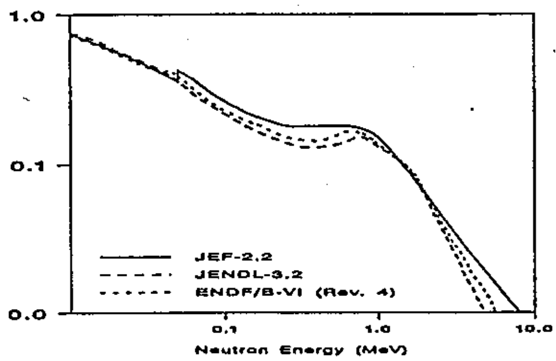



Fig.1B: Pa-233 Capture X-Sec (Barns)

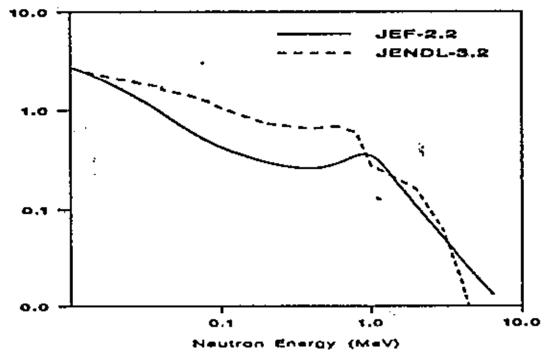



Fig.1C: U-233 Fission X-Sec (Barns)

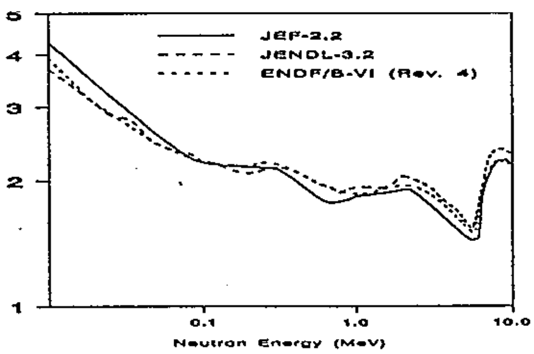
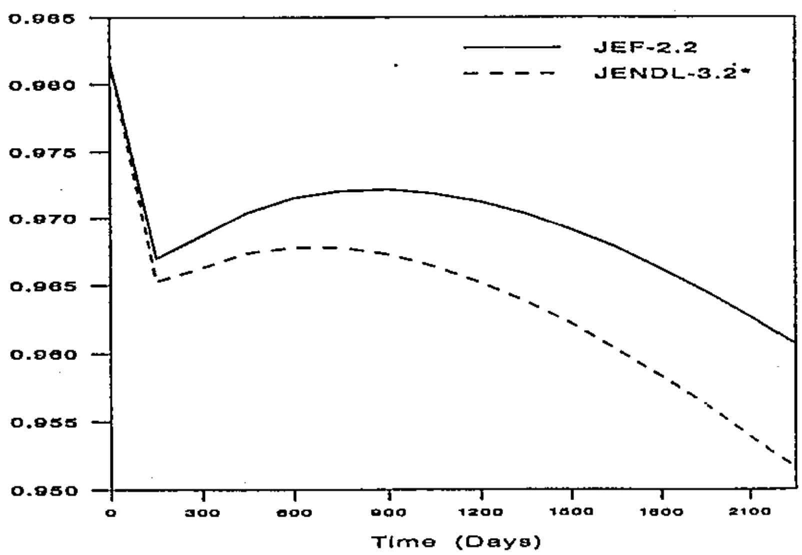



Fig.2: Time Evolution of k-eff for the EA

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