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Scientific motivations for a reassessment of the neutron capture cross sections of erbium isotopes in the high-sensitivity thermal energy range for LWR systems

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Abstract: Research conducted in the last twenty years in the field of burnable absorbers showed that erbium isotopes can be considered as an excellent alternative absorber to gadolinium isotopes for their neutronic and nuclear safety improving features. The development of the Erbium Super High Burn up (Er-SHB) concept demonstrated that erbium could be directcly(?) mixed in all fuel pins of a fuel assembly (FA) at the Beginning of Life (BOL). This innovative design allows an improvement of nuclear safety, a better control of the operational and accidental transient phase and an extension of the fuel life with respect to the most used burnable absorber (i.e., gadolinium). Furthermore, the extensive use of an Er-SHB fuel design would allow the production of higher enriched nuclear fuel (i.e., > 5 wt%) within the existing manufacturing facilities without any modification of the facility itself and with a general improvement of the nuclear safety of the front-end phase of the nuclear fuel cycle. Nevertheless, reported erbium cross-sections are dated and poorly investigated in the high sensitivity thermal energy region for nuclear technology. In addition, some of them (i.e., Er-166) are reported with an uncertainty that is too high for their use in the future design of the erbia-doped LWR assembly by the industry. On the other hand, evaluated uncertainties by the ENDF/B-VIII.0 library in the thermal/epithermal region for the most sensitive isotopes (i.e., Er-167) seem to be too low with respect to both the experimental data and the analysis of the results provided by an erbia-doped critical system of the International Critical Safety Benchmark Evaluation Project (ICSBEP). Based on the reanalysis of the ICSBEP outcomes, and a sensitivity-uncertainty analysis (S&U) on an Er-SHB LWR assembly, this article shows that recent evaluations appear inadequate to provide accurate criticality calculations for a system all equipped with erbium fuel pins for neutronic design purpose. Moreover, the S&U results have shown the importance of erbium isotopes to evaluate correctly the uncertainty associated with a Light Water Reactor (LWR) critical system. They confirmed the need for a re-evaluation of their neutron capture cross section by means of a new experimental campaign. A proposal aiming at performing a new capture measurement of erbium isotope cross sections has already been submitted to GELINA facility at Geel (Belgium), which is particularly suitable for capture measurements in the thermal and epithermal energy regions. On August 2021, U.S. Nuclear Energy Agency (NEA) added the revaluation of Er-167(n, γ) in its High Priority Request List (HPRL) on the basis of the outcomes reported in this work.

1. Introduction

In the last decades, several studies were conducted to select isotopes that can act as Burnable Poisons (BPs) for their suitable neutronic and thermomechanical properties. BPs are currently used in many Light Water Reactors (LWRs) to hold-down the initial excess reactivity, to control power peaking and to extend the operational fuel cycle. In turn, extending the operation length of a LWR improves fuel utilization, increases total energy production per cycle, reduces the number of outages during a nuclear power plant life and the amount of spent fuel [1].

The most commonly investigated and currently used BP is gadolinia (Gd_2O_3) mixed directly within the UO_2 fuel matrix for which an accurate evaluation of neutron capture cross-section aiming at enhancing nuclear safety for LWRs has been extensively analyzed in a previous work of the same authors [2]. Over the past decades, the use of erbium homogenously dispersed in the fuel matrix as alternative poison to gadolinium was proposed for its potential benefits. In fact, erbium isotopes present a relatively low absorption cross section in the thermal range, a non-negligible resonance integral in the thermal range (i.e., ^{167}Er) that leads to a relatively slow consumption kinetic, and the ability to not down-grade power distribution [3]. Regarding

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currently operating PWRs, nuclear properties of erbium lead to the possibility of extending more than twice the fuel cycle reducing by half ^{239}Pu concentration at End of Life (EoL) and of decreasing the effective delayed neutron fraction ($\hat{\beta}_{eff}$) more slowly with burn-up [4].

Drawbacks in the use of erbia-doped fuel are directly linked to the increase in fuel temperature due to a reduction of the thermal conductivity and to a reduction of the control worth for Silver-Indium-Cadmium (SIC) rods caused by the hardening of the neutron spectrum. Anyway, all these limitations can be easily overcome by minor technical enhancements with respect to the standard design currently used in the commercial reactors [4,5].

Erbium is used as burnable poison in some RBMK-1000 reactors: as an example, a number of 1500 FAs equipped with U-Er FAs were operative in Leningrad, Kursk, and Smolensk NPPs in 2005 [6].

The use of uranium-erbium FAs in RBMK-1000 reactors allowed one to increase the fuel BU up to 40% and the fuel enrichment from 2.4 to 2.8 wt%. The economic assessment estimated that the transition from standard fuel (2.4% enrichment) to uranium-erbium fuel (2.8 wt% enrichment, with 0.6 wt% erbium content) makes it possible a total saving over 10 years of more than 3.5E+08 euros [7]. Nowadays, VVER-1000 reactors are equipped with a gadolinium absorber, but several experimental and computational studies were conducted or have been planned to create a set of data required for a new VVER technical design equipped with uranium-erbium fuel [8,9]. Moreover, computational studies for modern designs of VVER show that increasing enrichment above 5 wt% with the addition of erbium ($\leq$1 wt%) makes it possible for 18-month cycles to increase the average fuel burnup by 20%, reduce the number of makeup FA also by approximately 20%, and decrease the fuel component of the production cost of electricity roughly by 5% [10].

Erbium is also designed to be used as absorber in some PWRs; to give some examples U.S. Palo Verde NPP uses erbia as burnable absorber in their CE-16x16 Fuel Assembly [11]. Again, the Advanced Power Reactor (APR-1400) design based on the Korean Standard Nuclear Power (KSNP) foresees a core with erbium or gadolinium as burnable absorber [12].

In the last decades, several research activities were also performed to test the reliability and effectiveness of erbium as a burnable absorber. The Inert Matrix Fuel (IMF) Project developed over the last 15 years by several national and multinational research organizations has been devoted to the utilization of plutonium and the transmutation of minor actinides (MA: Np, Am, Cm) in thermal reactors by a selection of specific solid solution as fuel matrix [13]. After iterative study, at Paul Scherrer Institute (PSI) the selection has led to an yttria-stabilized zirconia plutonium-doped with an erbia fuel. With this IMF configuration it is possible to utilize plutonium in LWR and destroy plutonium more effectively than it is possible for uranium-plutonium mixed oxide fuel (MOX). It was found that, after utilization in LWR, the residual IMFs plutonium isotopic vector foreseen for direct disposal was reduced well beyond the standard MOX spent fuel composition [14]. In this context, erbium acts both as a burnable absorber and a spectrum hardener to effectively burn Pu and to extend the fuel irradiation time. Safety and proliferation issues would thus be reduced [15].

A more precise evaluation of the erbium cross sections enables both to better estimate the Pu values at the end of cycle and the s.c. “residual reactivity penalty” which is the value of antireactivity associated to the high-burnup, equilibrium concentration.

A feasibility study aiming at evaluating the possibility to fabricate Er-Zr clad materials for overrunning the traditional problems related to the presence of erbium in the fuel pellets (e.g., degradation of the thermal conductivity of the fuel pellet, decrease of the overall uranium quantity available for the fission reaction, generation of complex quaternary system (U, Pu, Gd/Er)Ox for MOX fuel, etc.) has been performed by French Alternative Energies and Atomic Energy Commission (CEA) during the last decades. This study established that it is possible fabricate fuel clads containing up to 10 wt% of erbium and that the optimal mechanical properties (i.e., strength, ductility, etc.) with respect to the reference Zr-Ng-O alloy is reached for an erbium content between 3-6 wt%.

Another test carried out in autoclave showed very poor corrosion which can be avoided if a 3-layers clad design in a sandwich configuration constitute by Zr-Nb(O)÷Zr-Er÷Zr-Nb(O) respectively, is adopted. [16]. A more accurate assessment of erbium isotopes cross sections would make it possible to better estimate the reactivity penalty at the end of cycle and the sub-criticality of the system at the BOL.

The Westinghouse Small Modular Reactor project, an evolution of the International Reactor Innovative and Secure (IRIS) project, foresees the use of burnable absorbers to minimize the reactivity swing over the expected lifetime, maximize the cycle length and minimize power peaking [17]. Erbia enables to reduce the power peak as well as to improve the moderator temperature coefficient (MTC), but it lead to an EoL residual reactivity penalty of about 6 MWd/kgU caused by the residual erbium isotopes (i.e., Er-166 and to lesser extent Er-168, Er-170). Whitin the IRIS project, an advanced fuel design (Er-ZrB_2) research has allowed to reduce the reactivity penalty without leading to an excessive power peak while maintaining an improving of the MTC [18]. Again, a more accurate assessment of erbium isotopes cross sections would allow to better define the criticality margin of the design configuration and to reduce the uncertainty in the residual reactivity penalty.

Studies on erbium as BA were also performed on CANDU reactors fueled by Recovered Uranium (RU) (i.e., 0.9 wt% enr.). The results showed an improvement of the safety parameters. Specifically, Fuel Temperature Coefficient (FTC) resulted 60% more negative, Void Reactivity Coefficient (VRC) turned out to be less positive of 30%, and Power Coefficient Reactivity (PCR) shifted from positive to negative values. From the point of view of fuel-cycle life, despite the discharge BU decrease of about 38%, it is still greater of 16% than the BU reached with standard Natural Uranium Fuel [19].

A more accurate assessment of erbium isotopes would permit to better evaluate the improvement of the safety parameters for this innovative design of CANDU reactor fuel and to also reduce the uncertainty in the value of the discharge BU.

2. Scientific motivation

This section presents a series of scientific motivations that support the proposal for a re-evaluation of the erbium isotopes capture cross section. More in detail, a Sensitivity and Uncertainty (S&U) analysis, whose results are reported in the next section, provides that Er-167 and, to a lesser extent, Er-166, are among the erbium isotopes that most impact the uncertainty associated to the effective criticality value of a LWR system due to the uncertainty in the cross sections data. This circumstance is essentially because Er-167 presents the higher neutron capture cross sections and is the only resonant isotope in the high thermal/epithermal range, and because Er-166 is the erbium isotopes with the largest neutron capture cross sections after Er-167 (Fig.1), not considering Er-162 and Er-164 due their low isotopic abundance in natural erbium (i.e., Er-162: 0.139 at%, Er-164: 1.601 at%). Focusing on Er-166 and Er-167, these two isotopes at the thermal point (i.e., 0.025 eV) and the latest version of ENDF/B-VIII.0 [referenza: https://doi.org/10.1016/j.nds.2018.02.001] presents uncertainty values of 9.47% and 1.23%, respectively (Fig. 2). These values can be considered not negligible for Er-166 and questionable for Er-167, as discussed in the following subsections.

2.1 EXFOR database

Data related to the Er-167 capture cross section at the thermal point provided by the EXFOR database are sparse and affected by a relative deviation with respect to the mean ranging from 0.3% to 16.7% (Table 1). Moreover, considering only the data with a relative percent deviation less than 10% from the mean value, the standard deviation was found to be equal to 8.4%. Again, the relative difference between the more accurate and more recent data (i.e., 1997, 1998) was found not negligible and equal to 11.9%.

Table 2 summarizes the scientific literature historical progression in the Er-167 neutron capture thermal cross sections evaluation that includes the data contained in the EXFOR database and other

more recent experimental evaluations [26-27]. Table 2 shows that the latest (1997–2010) Er-167 thermal capture cross sections evaluations have a significative (i.e., 0.8-12.5%) deviation with respect to ENDF/B-VIII.0 reference (2006) data. All these circumstances suggest that the Er-167 capture cross section experimental values at the thermal point are not consistent to each other, and the uncertainty (1.23%) associated with the reference ENDF/B-VIIII.0 data cannot be considered a safe estimate for nuclear technology to evaluate the actual range of values that could take the Er-167 neutronic capture thermal cross section.

2.2 ICSBEP experimental facilities

Additional needs for improvements of the erbium isotopes capture cross sections arise from the analysis of the experimental and calculated data obtained in a series of benchmarks performed on the critical facilities which contain erbium in solid state (i.e., LEU-MET-THERM-005, IEU-COMP-THERM-013, and CROCUS-LWR-REST-001) included in the International Criticality Safety Benchmark Evaluation Project database (ICSBEP-2020).

LEU-MET-THERM-005 experiment, performed in the KUCA facility in B-core configuration, is a multipurpose, reconfigurable array of several fuel elements that can be specifically tailored to match experimental goals. The experiments were conducted on this facility on five reactor configurations to support the Er-SHB fuel concept development program [28].

Table 3 reports the intercomparison between the calculated and the experimental values of the effective multiplication factor for each of the five reactor configurations. The calculated criticality values were obtained using MCNP5 code [29] and the ENDF/B-VII.0 evaluated library. It has been observed that the criticality difference between calculated and experimental values increases as erbia content increase (i.e., Δ(Δk), Table 3). Moreover, defining the difference between calculated and experimental k_{eff} value as:

$$\Delta k = k_{cal} - k_{ben} \quad (1)$$

where k_{cal} is the calculated criticality value and k_{ben} is the experimental criticality value considering the approximation of the model used to perform Monte Carlo analysis; and the uncertainty estimate associated with (1) given by:

$$\Delta k_{1\sigma} = \sqrt{\sigma_{cal}^2 + \sigma_{ben}^2} \quad (2)$$

The difference between calculated and experimental k_{eff} values (Δk) is not covered within the associated 1σ uncertainty ($\Delta k_{1\sigma}$) in each of the five-reactor configurations analyzed ($\Delta k_{1\sigma}/\Delta k$, Tab. 3). Again, even if the associated uncertainty is increased to 3σ, only one of the five reactor configurations has the associated criticality uncertainty covered by the experimental and calculated uncertainties values ($\Delta k_{3\sigma}/\Delta k$, Tab. 3). The aforesaid two issues (i.e., the criticality difference increase as the erbium content increases, and it is not covered by the associated uncertainty) suggest that erbium cross section values play a not negligible role in making inconsistent the experimental and calculated criticality values of the KUCA B-core criticality analysis performed within the LEU-MET-COMP-005 ICSBEP project. A further circumstance that suggests the high sensitivity of the erbium capture cross sections on the criticality coefficient of an erbia-doped facility is confirmed by the investigation of the trend of the calculated criticality value by means of MVP Monte Carlo code using several nuclear data libraries (i.e., JENDL-3.3, ENDF/B-VI-8, JEFF-3.0, ENDF/B-VII.0) on the KUCA 4 core configuration. The results were reported as C/E values of k_{eff} with an associated error bar based on 3σ statistical uncertainty. It was found that ENDF/B-VII.0 and ENDF/VI.8 tend to overestimate and underestimate, respectively [30]. The discrepancies are in the range of 220-300 pcm and are physically coherent with the different trend of the Er-167 (n, g) cross sections in the thermal resonance region evaluation used in the two libraries (Fig. 2).

IEU-COMP-THERM-013 is a 250 kW TRIGA Mark II tank-type research reactor located in the basement of the Hot Fuel Examination Facility (HEF) at the Idaho National Laboratory (INL). It is primarily used for neutron radiography analysis of both irradiated and not irradiated fuels materials. The fuel elements contain a uniform dispersion of 0.9 wt% natural Er that is used as burnable poison to offset initial reactivity of the fresh fuel and contribute to the prompt negative temperature coefficient. Two initial (i.e., Case 1, 56 fuel elements) and in operation (i.e., Case 2, 60 fuel elements)

configurations have been considered as reference benchmark experiments [31].

The benchmark calculations of Case 1 and 2 using the ENDF/B-VII.0, despite provided a relative difference of 1.29% between calculated and experimental value, show an absolute difference (i.e., C-E) equal to 1300 ± 150 pcm (Table 5). This difference has to be considered not negligible for safety purposes and at least partly due to low-fidelity erbia capture cross sections values.

CROCUS-LWR-RER-001 facility is a two-zone uranium-fueled, H_2O moderated critical research facility operated by the Swiss Federal Institute of Technology. The reactor is used to perform kinetic measurements by means of two absorber rods, one of which is a cylindrical aluminum tube filled with ZrO_2-Er_2O_3 pellets. Specifically, with the absorber rod inserted, the reactor was made critical by adjusting the water level. Afterwards, the absorber rod was withdrawn, the water level being kept constant. Three different water level configurations and two supercritical configurations after withdrawing the absorber rods were measured. The point kinetic model was used to determine the reactivity through measure of the inverse period (ω) with the "stable period method" (T=1/ω). Table 6 shows the benchmark results in which the largest discrepancy between calculated and mean values are in Case 6 (i.e., ~14 pcm, control rod erbia-doped) were erbium cross sections may play a role as well as the resonance shielding calculations for Er isotopes [32].

The reanalysis of the outcomes of the ICSBEP experimental facilities containing erbium in solid form suggested to submit a request to the U. S. Nuclear Energy Agency (NEA) databank to add the revaluation of the Er-167(n,γ) in the Nuclear Data High Priority Request List. On August 2021, NEA accepted the request and added the measurement in HPRL [33].

2.3 Indirect assessment of the nuclear data uncertainty

An indirect Er-167 (n,γ) uncertainty evaluation was performed using the sensitivity results provided by the LEU-MET-THERM-005. The aim has been to have an quantitative estimation of the goodness of the associated uncertainty of the Er-167(n,γ) reported in the ENDF/B-VIII.0. Substantially, assuming that the contribution to the criticality difference between each couple of reactor configurations is only due to erbium capture cross sections and moderation ratio – since the other neutronic related parameter are invariant between each couple of reactor configurations – it has been possible to estimate the uncertainty associated with the Er-167 capture cross sections by means on the inversion of the classical S&U equation.

$$\frac{\partial \sigma_i}{\sigma_i} = \frac{\partial k/k}{S_j} \qquad (3)$$

In relationship (3) it has been assumed that the contribution of the erbium capture cross sections to criticality uncertainty is due to Er-167(n, γ); this assumption is supported by the results of a S&U analysis reported in section five were Er-167(n, γ) contribute for 74% to the criticality uncertainty due to the erbium isotopes. The different moderation ratio value presents on some couples of reactor configuration (i.e., 2-3, 4-5) was considered assuming a linear dependence, according to the following analytic equation:

$$\Delta(\Delta k)_{j,i} = \left(\frac{S_j}{S_i}\right) \cdot \left(\Delta k_j - \Delta k_i\right) \qquad (4)$$

were $\Delta(\Delta k)_{j,i}$ is the variation of the calculated and experimental criticality difference between two different configurations, S_j is the integral sensitivity of Er-167(n,γ) to the criticality coefficient related to the *j-th* configuration and Δk_j is the calculated and experimental criticality difference of the *j-th* configuration. Table 4 reports the results obtained for each couple of reactor configurations. The results reveal that the Er-167(n,γ) uncertainty estimated with an indirect method seems to be generally higher than the evaluated values reported in ENDF-B-VIII.0 for the thermal/epithermal zone (i.e., 1.23÷2.35%).

3. Calculation tool

In this study, sensitivity and uncertainty analysis (S/U) was performed by TSUNAMI-2D code (Tools for Sensitivity and Uncertainty Analysis Methodology Implementation). TSUNAMI-2D is part of the TRITON (Transport Rigor Implemented with Time-Dependent Operation for Neutronic depletion) module of the

SCALE 6.2.3 suite which can be used for performing calculation of 2D forward and adjoint transport solutions, calculation of sensitivity coefficients, and calculation of the uncertainty in k_{eff} and other response due to cross section covariance data [24]. The detail of code's methods, steps, and sub-module to perform the S/U analysis can be found in a previous work of the same authors [2]. The use of the TSUNAMI 2-D module of the SCALE 6.2.3 suite allowed to take advantage of the new 252-groups energy discretization cross sections library based on ENDF/B-VII.1. Moreover, the uncertainty on the integral parameters of interest due to uncertainty in the basic nuclear data was evaluated using the updated cross-section covariance libraries based on ENDF/B-VII (release 1) with a 56-group energy structure (56groupcov7.1). The covariance data are available for 456 materials, including some duplication for materials with multiple thermal scattering kernels [34].

TSUNAMI-2D simulations have been executed using the v7-252 SCALE cross sections libraries based on the ENDF/B-VII (release 1) evaluated data library. The adjoint and forward transport calculations have been achieved with the following convergence numerical criteria: 10^{-5} for the critical eigenvalue and 10^{-4} for the inner and outer spatial convergence iterations. The quadrature and scattering orders (S_n and P_n) have been set to 16 and 1 (2 only for the moderator material), respectively. The iterative transport solutions have been accelerated using a coarse-mesh finite difference approach (CMFD).

4. Calculation models

To quantify the maximum impact of the erbium cross-sections uncertainty on the criticality of an LWR system, calculations were made on an Erbia-doped fuel assembly whose modelization was designed according to the Er-SHB concept [30]. Table 7 reports the detail of the physical parameters used to model the Er-SHB FA. Figure 4 shows a material and geometrical representation of the Er-SHB PWR assembly configurations as described above. Figure 5 shows the grid computational domain used by the code. Sensitivity and Uncertainty analyses have been performed to compute the contribution of the erbium isotopes cross sections to the overall uncertainty in criticality eigenvalue evaluation.

5. Results and discussion

A series of NEWT/TSUNAMI-2D calculations were executed on the reference Er-SHB FA configuration. Table 8 reports the sensitivity and uncertainty weights of the erbium isotopes on the neutron multiplication factor *k*. In detail, the S/U analysis provided the uncertainty contributions, in decreasing importance order, to *k* of any nuclear reaction involved. Specifically, Table 8 gives the first 26 most important contributors to the uncertainty of *k* for the reference Er-SHB configuration. The data analysis shows that the neutron capture reaction of the most impacting erbium isotopes (i.e., ^{167}Er and ^{166}Er) rank between 0.29 and 0.05 with respect to the most significant contributor which has rank set to one. Rank is here defined as the ratio between the contribution to uncertainty in *k* of a particular couple of nuclide-reaction and the value of the maximum contribution to the uncertainty in *k*.

Er-166 and Er-167 seem to play the most important role immediately after that of ^{235}U and ^{238}U, whose data are either not measurable at present at the or already measured or under experimental investigation.

Figure 6 presents the results of the S/U analysis of *k* with respect to ^{167}Er (n,γ) cross sections. From this figure, it can be seen that almost all the overall sensitivity of the FA to the erbium isotopes is due to the ^{167}Er contribute and that the energy range of highest sensitivity to the ^{167}Er(n,γ) reaction is between about 0.01 and 100 eV. It can be concluded that any amelioration of ^{167}Er(n,γ) cross sections in the 1/v range and especially if associated to low uncertainties values, can represent a real improvement in the overall assessment of the neutronic properties of the Er-SHB fuel assembly.

The overall impact on the *k* value due to erbium isotopes (n,γ) reactions uncertainty was evaluated to be 123 pcm for ^{167}Er(n,γ), 23 pcm for ^{166}Er (n,γ) 11 pcm for ^{168}Er(n,γ) and 9 pcm for ^{170}Er(n,γ).

However, any gain in the precision over the estimates of k_{eff} is more than welcome to the nuclear industry and nuclear safety authorities to better evaluate both the economic convenience and safety features of the Er-SHB concept. Any improvement in cross section knowledge is therefore considered necessary.

6. Conclusions

Erbia have been studied as alternative absorbers to gadolinia in the LWR system. Since the effectiveness of the erbium isotopes as burnable absorbers has been demonstrated by several publications, they are already employed in some LWR system. Nevertheless, neutron capture cross sections among those present in the EXFOR database show significative differences in the thermal range. An indirect analysis of the results of benchmarks for erbia-doped facilities included in the ICSBEP database revealed that the associated Er-167 evaluated uncertainty into the ENDF/B-VIII.0 library is questionable and probably too low. A S/U analysis on a Er-SHB Fuel assembly configuration showed that ^{166}Er and ^{167}Er capture cross sections are among the most significant contributors to uncertainty for the *k*-effective integral parameter after the uranium isotopes. For this reason and starting from the scientific motivations presented in this paper, a proposal for a re-evaluation with high accuracy, high resolution, and low uncertainty (i.e., <2%) of the erbium neutron cross sections isotopes in the high sensitivity thermal region for nuclear system was submitted to the scientific committee of GELINA experimental facility. GELINA has been chosen because it is particularly suitable for neutron capture and transmission measurements in thermal and epi-thermal energy zones.

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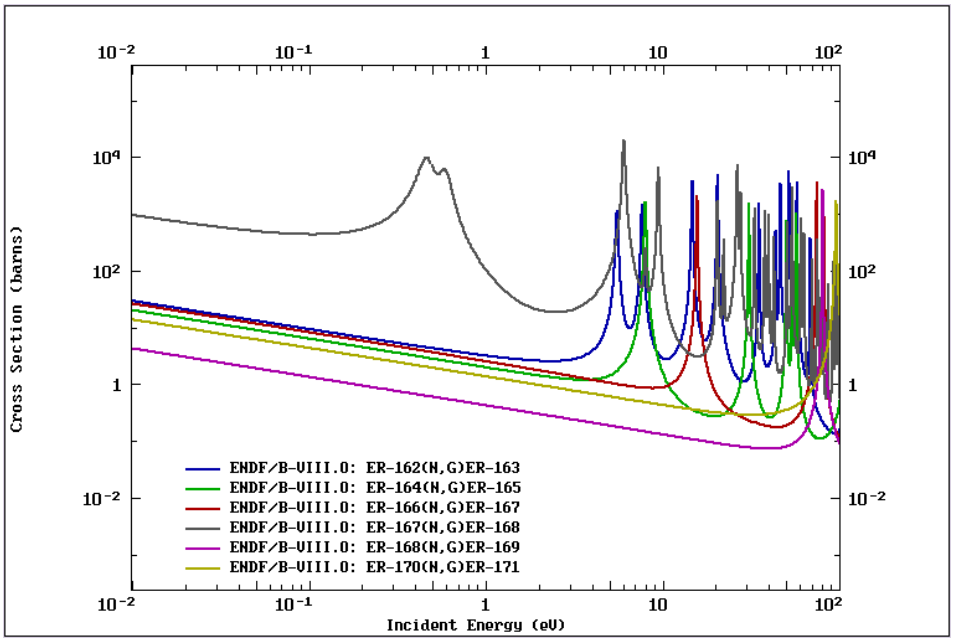

Figure 1111: Capture cross sections of erbium isotopes in the high sensitivity energy zone (0.01 – 100 eV) for a LWR.

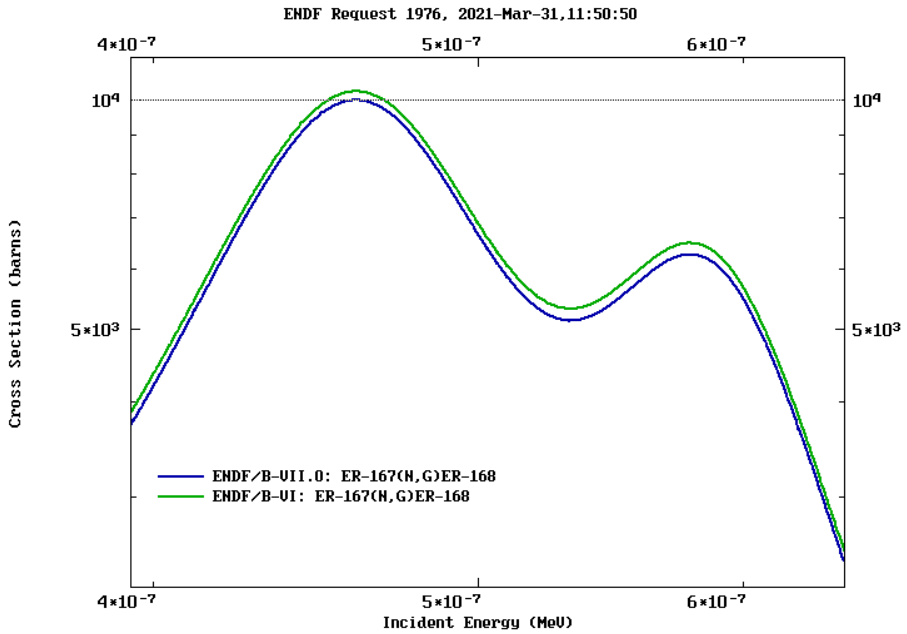

Figure 2222: Er-167 (n, γ) trend in the thermal region for ENDF/B-VII.0 and ENDF/B-VI evaluated library.

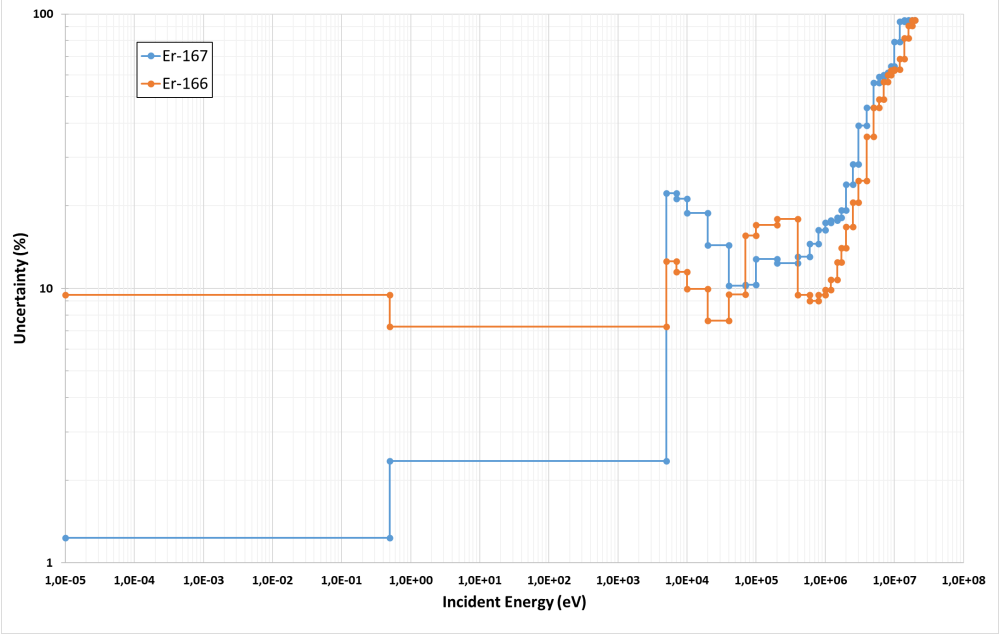

Figure 3333: Relative standard deviation of Er-166 and Er-167 capture cross sections – ENDF/B-VIII.0

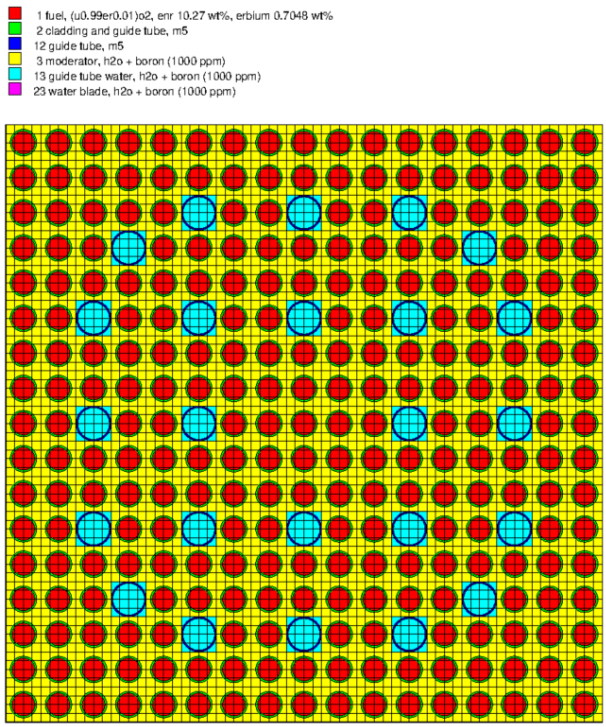

Figure 4444: Material composition of the Er-SHB FA, enr. 10.27 wt% @ 265 Er-doped fuel pins – SCALE 6.2.3

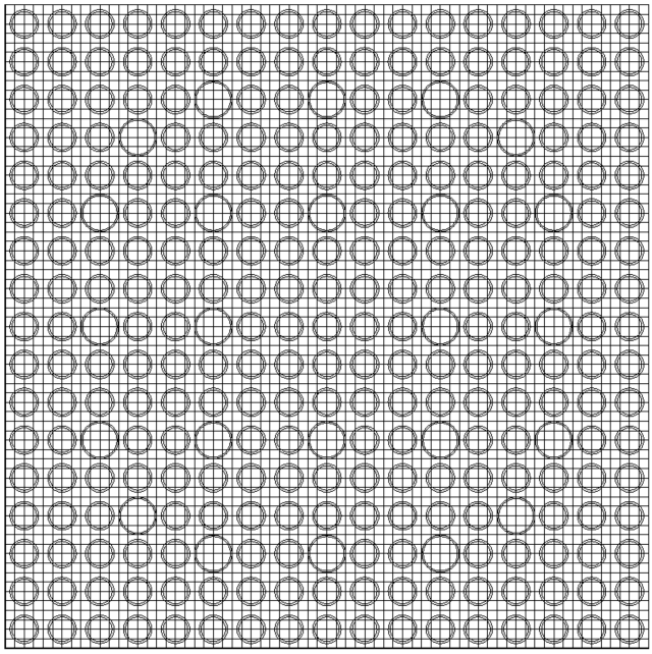

Figure 5555: Computational grid structure of the Er-SHB FA – SCALE 6.2.3

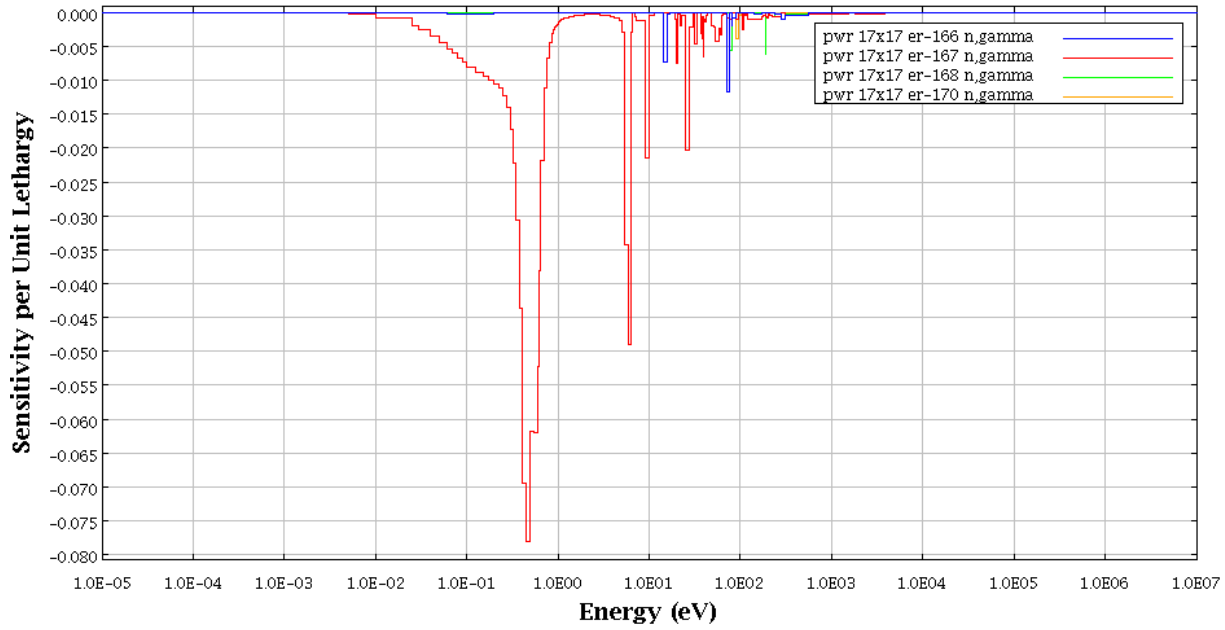

Figure 6666: Profiles of sensitivity per unit lethargy of the neutron capture cross sections of erbium isotopes.

Table 1111: List of experimental Er-167 capture cross sections at the thermal point as reported in EXFOR database.

Reference	Age (year)	Er-167 (enr wt%)	Thermal Xs (b)	Data error (%)	Deviation from average (%)
Hopkins [20]	1958	58.8	620	20.2	-6.0
C.S.Su [21]	1967	79.3	770	5.2	16.7
C.S.Su [21]	1967	100	699	2.9	5.9
V.P. Pasechnik [22]	1968	79.0	658	4.6	-0.3
K.Knopf [23]	1997	95.6	568	1.6	-13.9
Y. Danon [24]	1998	91.5	644	0.4	-2.3
	Average		660	-	-

Table 2222: List of Er-167 experimental capture cross sections as reported in EXFOR database and in the scientific literature

Reference	Age (year)	Thermal Xs (b)	Deviation from ENDF/B-VIII (%)
Hopkins [20]	1958	620	-3.7

C. S. Su [21]	1967	770	+18.6
C. S. Su [21]	1967	699	+7.7
V.P. Pasechnik [22]	1968	658	+1.4
K.Knopf [23]	1997	568	-12.5
Y. Danon [24]	1998	644	-0.8
Mughabghab [25] Evaluation (adopted in ENDF/B-VIII.0)	2006	649	-
T. Wang [26,27]	2010	708.4	+10

Table 3: Intercomparison between calculated and experimental criticality values of the LEU-MET-THERM-005

CASE	CORE	Enr.	Erbia	H/U^{238}	K_{ben}	K_{cal}	ΔK	Δ(Δk)	$\Delta K_{1\sigma}$	$\Delta K/\Delta K_{1\sigma}$	$\Delta K_{3\sigma}$	$\Delta K/\Delta K_{3\sigma}$
(-)	(-)	(wt%)	(wt%)	(-)	(-)	(-)	(pcm)	(pcm)	(pcm)	(-)	(pcm)	(-)
1	0	5.4	0	277	0.9988	1.0015	270	-	60	**4.5**	180	**1.5**
2	1	5.4	0.3	277	0.9988	1.0021	330	60	50	**6.6**	150	**2.2**
3	2	5.4	0.3	91	0.9988	1.0007	190	-	80	**2.4**	240	**0.8**
4	3	9.6	0.6	48	0.9989	1.002	310	120	90	**3.4**	270	**1.1**
5	4	9.6	1.12	148	0.9993	1.0047	540	230	60	**9.0**	180	**3.0**

Table 4: Indirect evaluation of the capture cross section uncertainty of Er-167(n, γ)

CASES	S_i	Δ(Δk)	dk/k	dσ/σ	dσ/σ
(-)	(-)	(pcm)	(-)	(-)	(%)
1-2	2.24E-02	**60**	5.99E-04	2.67E-02	**2.68**
2-3	2.00E-02	**46**	4.59E-04	2.29E-02	**2.29**
4-5	2.25E-02	**75**	7.42E-04	3.30E-02	**3.30**

Table 5: Comparison between calculated and benchmark eigenvalues – IEU-COMP-THERM-001

CASE	Enr.	Erbia	K_{ben}	Unc (1σ)	K_{cal}	Unc (1σ)	Δk	Unc (1σ)
(-)	(wt%)	(wt%)	(-)	(-)	(-)	(-)	(pcm)	(-)
1	19.75	0.9	1.0012	0.0015	1.01412	0.00007	1292	0.00152
2	19.75	0.9	1.0012	0.0015	1.01413	0.00007	1293	0.00152

Table 6: Calculated reactivity and discrepancy of each result against the mean values and uncertainty due to the Measured Inverse Period.

	Case 2	Case 3	Case 4	Case 5	Case 6
	H_2O	H_2O	H_2O	(Boron)	(Erbium)

Code	Cross Sections	Mean	88.4	109.6	130.5	83.8	169.6
HEXNOD	mainly based on ENDF/B		88.3 (-0.1)	109.3 (-0.3)	130.3 (-0.2)	--	--
MCU	ENDF/B-VI, JENDL-3.2, BROND		88.4 (+0.0)	109.5 (-0.1)	130.6 (0.1)	85.0 (+1.2)	179.5 (+9.9)
HELIOS	std. Library in 45 energy groups		89.2 (+0.8)	110.9 (+1.3)	132.3 (+1.8)	81.3 (-2.5)	163.8 (-5.8)
BOXER	JEF-1, BROND-2 (Er isotopes)		87.8 (-0.6)	108.6 (-1.0)	129.0 (-1.5)	85.1 (+1.3)	165.4 (-4.2)
$\Delta\rho_i$ (ω)			±0.40	±0.49	±0.58	±0.38	±0.76

Table 7: Technical specification of Er-SHB PWR fuel assembly

FA type	^{235}U enr (wt. %)	Er_2O_3 (wt. %)	Nr. of Er pins, Er_2O_3	Moderator density (g/cm^3)	Boron content in moderator (ppm)
Er-SHB	10.27	0.7	265 (All the FA fuel pins)	0.702	1000

Table 8: Contributions of the nuclear data to overall uncertainty in criticality eigenvalue for the Er-SHB FA.

Covariance matrix		Contribution to uncertainty in k_{eff} (% Δk/k)	Rank
Nuclide-reaction	Nuclide-reaction		
^{235}U nubar	^{235}U nubar	3.23E-01	1.00
^{235}U n,gamma	^{235}U n,gamma	2.32E-01	0.72
^{238}U n,gamma	^{238}U n,gamma	1.88E-01	0.58
^{235}U chi	^{235}U chi	1.65E-01	0.51
^{238}U n,n'	^{238}U n,n'	1.12E-01	0.35
^{235}U fission	^{235}U n,gamma	1.02E-01	0.32
^{167}Er n,gamma	^{167}Er n,gamma	9.25E-02	0.29
^{235}U fission	^{235}U fission	8.37E-02	0.26
^{238}U nubar	^{238}U nubar	6.42E-02	0.20
^{238}U elastic	^{238}U elastic	2.49E-02	0.08
^{238}U chi	^{238}U chi	2.41E-02	0.07
^{1}H n,gamma	^{1}H n,gamma	2.27E-02	0.07
^{91}Zr n,gamma	^{91}Zr n,gamma	1.94E-02	0.06
^{238}U elastic	^{238}U n,gamma	1.89E-02	0.06
^{166}Er n,gamma	^{166}Er n,gamma	1.72E-02	0.05
^{16}O elastic	^{16}O elastic	1.48E-02	0.05
^{238}U fission	^{238}U fission	1.44E-02	0.04
^{92}Zr n,gamma	^{92}Zr n,gamma	1.29E-02	0.04
^{235}U fission	^{238}U n,gamma	-1-24E-02	-0.04
^{235}U fission	^{238}U fission	1.24E-02	0.04
^{1}H elastic	^{1}H elastic	1.21E-02	0.04
^{238}U n,n'	^{238}U elastic	-1.18E-02	-0.04

^{90}Zr (n,gamma)	^{90}Zr (n,gamma)	9.73E-03	0.03
^{168}Er (n,gamma)	^{168}Er (n,gamma)	8.48E-03	0.03
^{16}O (n,alpha)	^{16}O(n,alpha)	8.44E-03	0.03
^{238}U(n,2n)	^{238}U(n,2n)	7.05E-03	0.02
^{170}Er(n,gamma)	^{170}Er(n,gamma)	7.01E-03	0.02
^{93}Nb (n,gamma)	^{93}Nb (n,gamma)	6.88E-03	0.02
^{235}U elastic	^{235}U (n,gamma)	-6.66E-03	-0.02