

The 2<sup>th</sup> International Summer School  
**Physics and Design of Small and Medium Reactors (SMRs)**  
June 16 - 19, 2010, in Berkeley, CA

# Understanding the reactivity response of your system: theory and examples

Dr. Francesco Ganda

16<sup>th</sup> June 2010



The evaluation of the reactivity coefficients is essential for:

- a) Safety;
- b) Dynamic response;
- c) System and fuel comparison;
- d) Understanding of the physics of your system.

# Definition of reactivity coefficients

Example with Temperature (T)

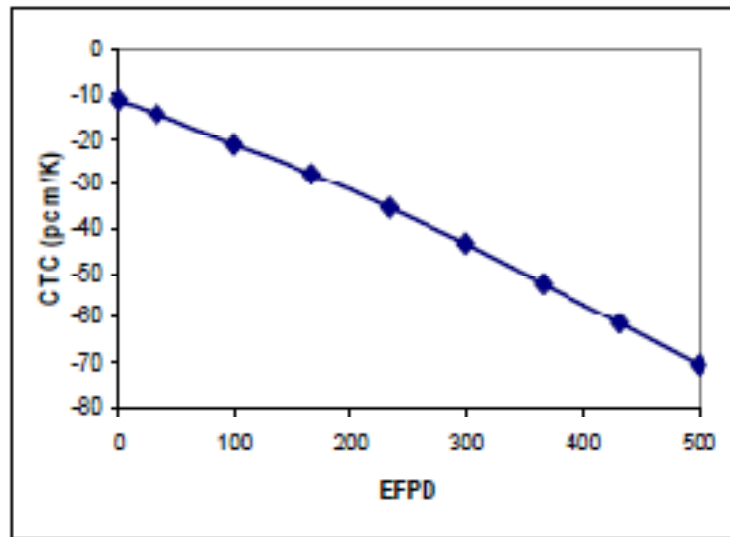
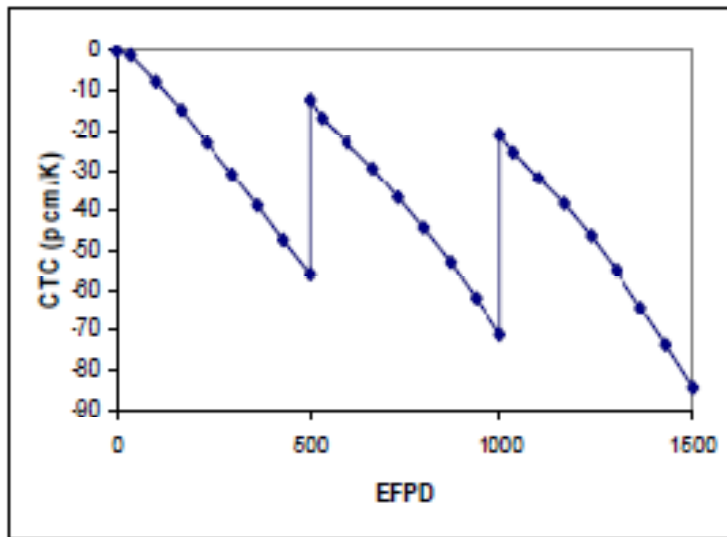
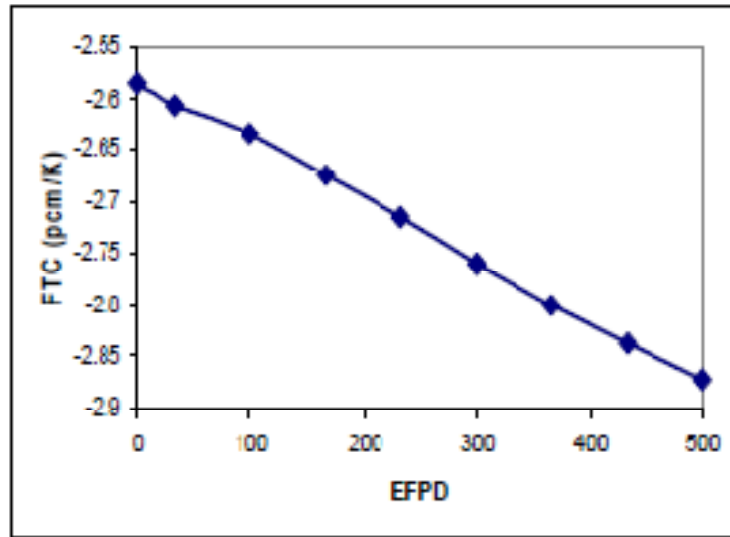
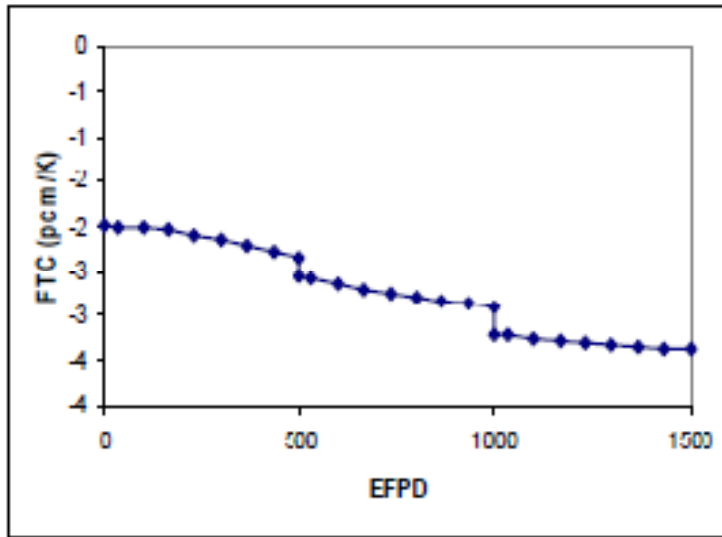
$$\begin{aligned} RC_T &= \frac{\partial \rho}{\partial T} \cong \frac{\Delta \rho}{\Delta T} = \frac{(\rho_p - \rho_n)}{\Delta T} \\ &= \frac{1}{\Delta T} \left( \frac{k_\infty^p - 1}{k_\infty^p} - \frac{k_\infty^n - 1}{k_\infty^n} \right) \\ &= \frac{k_\infty^p - k_\infty^n}{k_\infty^p \cdot k_\infty^n} \frac{1}{\Delta T} \end{aligned}$$

It could be void of the moderator, coolant flow rate, etc...

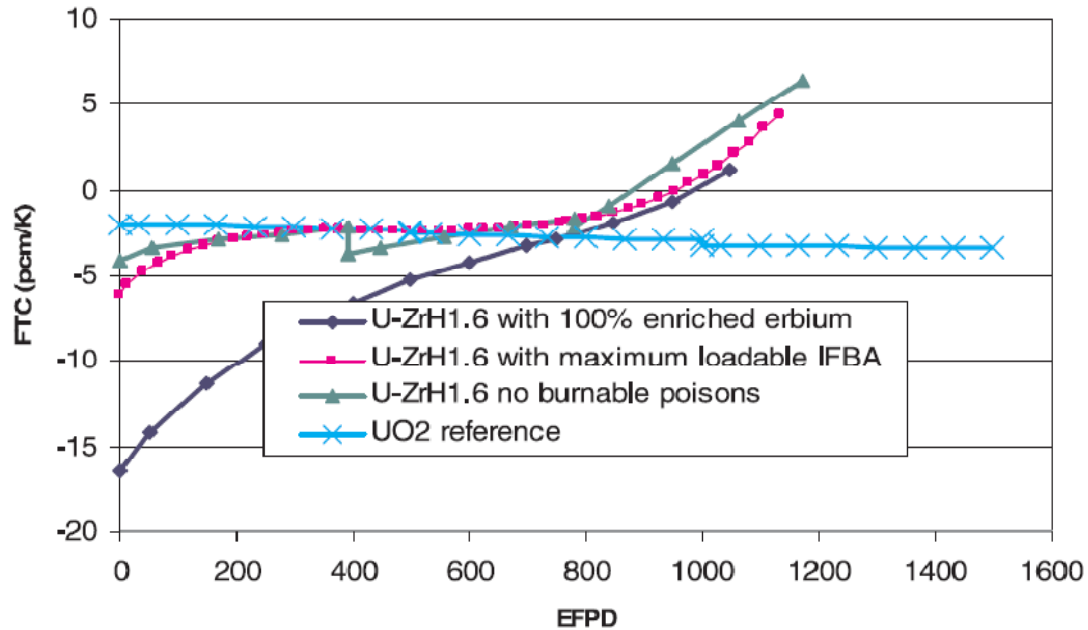
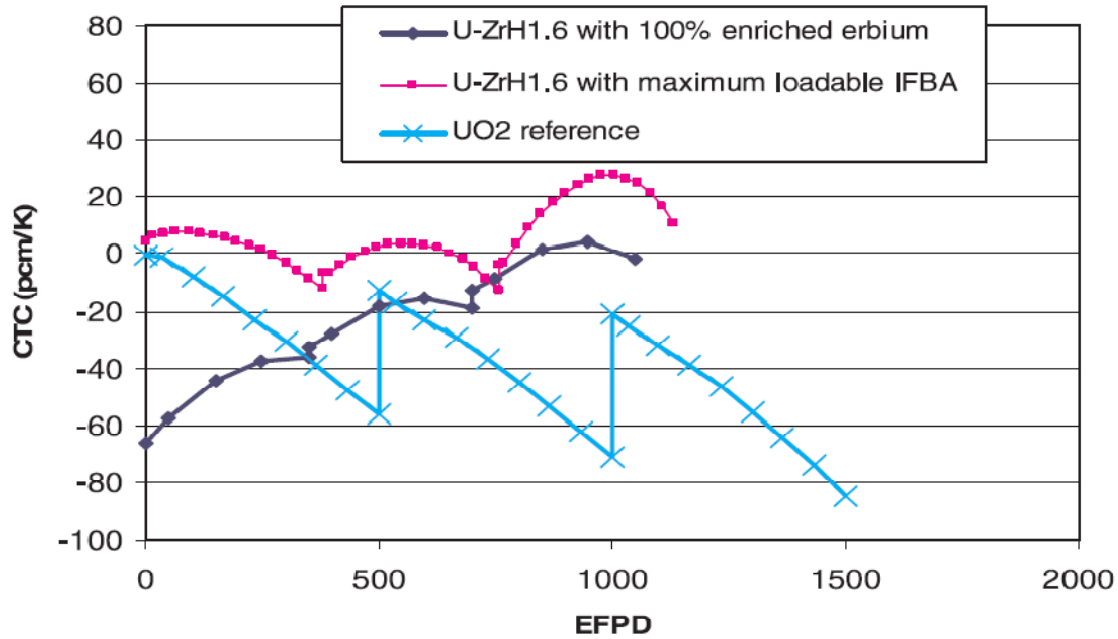
Are reactivity coefficients constant with burnup for each fuel type?

Are they the same for the same fuel type?

Not in general, even for the standard  $\text{UO}_2$  fuel of PWR.



# It can get worse: RC of hydrides without burnable poisons



Why you may want to understand the reason for the behavior of your system:

For example:

In our case (studying the feasibility of using hydride U-ZrH<sub>1.6</sub> for PWR), the sign of the reactivity coefficients (RC) turned out to be a major limiting factor.

Additionally, in general you may want to:

- 1) Assess the accuracy and reliability of the calculations;
- 2) Identify ways to overcome the limits imposed by the RC.

Today we'll learn about a new methodology\* that, allows you to improve your understanding of the reactivity response of your system by:

1. Ranking the contribution to a reactivity coefficient of each of the system's constituents;
2. Investigating, the spectral reasons for their specific response to the perturbation.

We will first introduce the methodology, and then apply it to specific examples.

(Note: although this methodology has been published only 6 months ago, papers have been submitted that adopt this methodology for different systems)

\* F. GANDA and E. GREENSPAN, "Analysis of Reactivity Coefficients of Hydride-Fueled PWR Cores," NUCLEAR SCIENCE AND ENGINEERING: **164**, 1–32, (2010)

# Methodology

To investigate the contribution of each isotope to reactivity coefficients,  
We normalize the emitted fission neutron per neutron absorbed in the system

The system  $k_\infty$  is broken down as follows:

$$k_\infty = \eta \cdot f = \frac{\sum_i \nu_i \Sigma_{fi} \Phi_i}{\sum_i \Sigma_{ai} \Phi_i} = \frac{\nu_1 \Sigma_{f1} \Phi_1}{\sum_i \Sigma_{ai} \Phi_i} + \frac{\nu_2 \Sigma_{f2} \Phi_2}{\sum_i \Sigma_{ai} \Phi_i} + \dots = \frac{\nu_1 \Sigma_{f1} \Phi_1}{\Sigma_{a1} \Phi_1} \cdot \frac{\Sigma_{a1} \Phi_1}{\sum_i \Sigma_{ai} \Phi_i} + \frac{\nu_2 \Sigma_{f2} \Phi_2}{\Sigma_{a2} \Phi_2} \cdot \frac{\Sigma_{a2} \Phi_2}{\sum_i \Sigma_{ai} \Phi_i} + \dots$$

$i$  represents a system constituent.

Defining:  $\eta_j \equiv \frac{\nu_j \Sigma_{fj} \Phi_j}{\Sigma_{aj} \Phi_j}$ ;  $\tilde{f}_j \equiv \frac{\Sigma_{aj} \Phi_j}{\sum_i \Sigma_{ai} \Phi_i}$   $k_\infty$  can be written as:  $k_\infty = \eta_1 \tilde{f}_1 + \eta_2 \tilde{f}_2 + \dots$

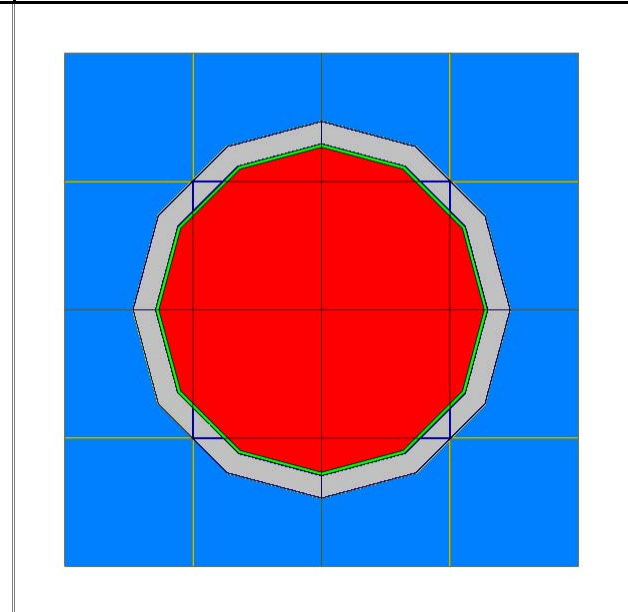
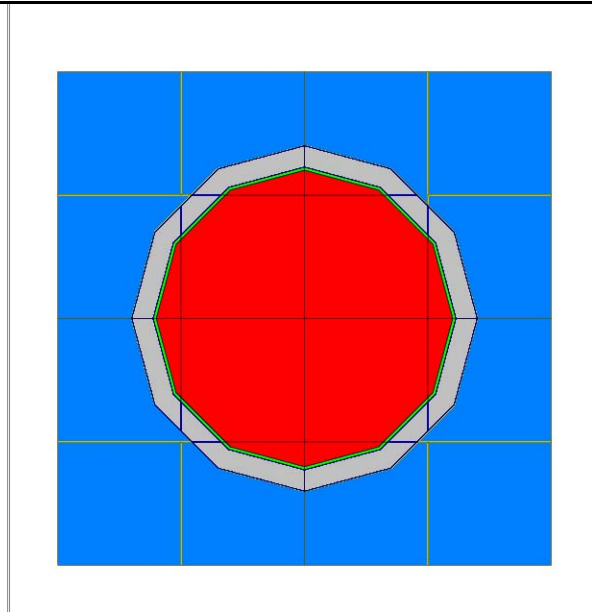
And finally for the reactivity coefficients:

(“n” and “p” stands for nominal and perturbed conditions)

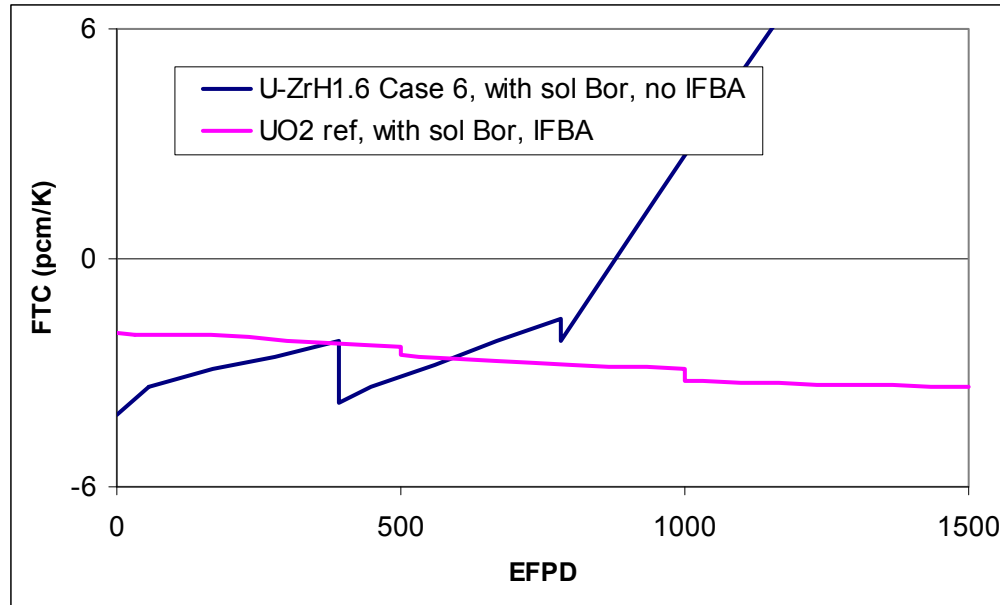
$$RC_T = \frac{k^p_{\text{inf}} - k^n_{\text{inf}}}{k^p_{\text{inf}} \cdot k^n_{\text{inf}}} \frac{1}{\Delta T} = \frac{1}{\Delta T} \frac{(\eta_1 \tilde{f}_1|_p - \eta_1 \tilde{f}_1|_n) + (\eta_2 \tilde{f}_2|_p - \eta_2 \tilde{f}_2|_n) + \dots}{k^p_{\text{inf}} \cdot k^n_{\text{inf}}}$$

# Description of the geometries of interest for this lecture

	U-ZrH <sub>1.6</sub> (Most economical geometries)	UO <sub>2</sub> (Westinghouse reference geometry)
Fuel diameter	0.747 cm	0.8192 cm
Clad inside diameter	0.762 cm	0.8357 cm
Clad outside diameter, D	0.871 cm	0.95 cm
Lattice Pitch, P	1.211 cm	1.26 cm
P/D	1.39	1.393
HM density (g/cm <sup>3</sup> )	3.71	9.19
Specific power	108.4 W/giHM	36.3 W/giHM
Achievable burnup	127.1 (GWD/MTiHM)	55.3 (GWD/MTiHM)
Uranium enrichment	12.5%	5%



# Case 1: FTC evolution for $\text{UO}_2$ and $\text{U-ZrH}_{1.6}$



Observation 1: at BOL  $\text{FTC}_{\text{hydrides}} \ll \text{FTC}_{\text{oxides}}$ : why?

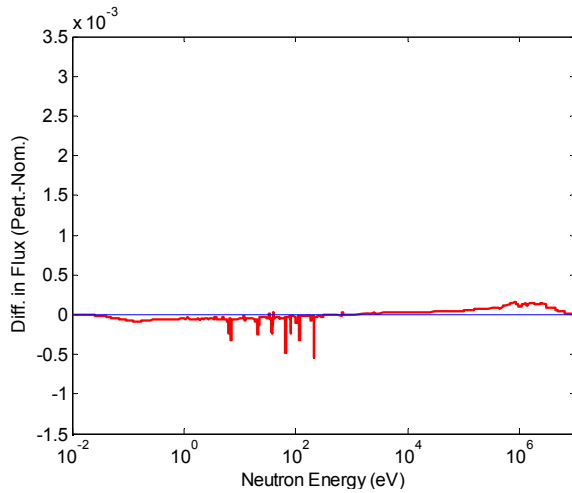
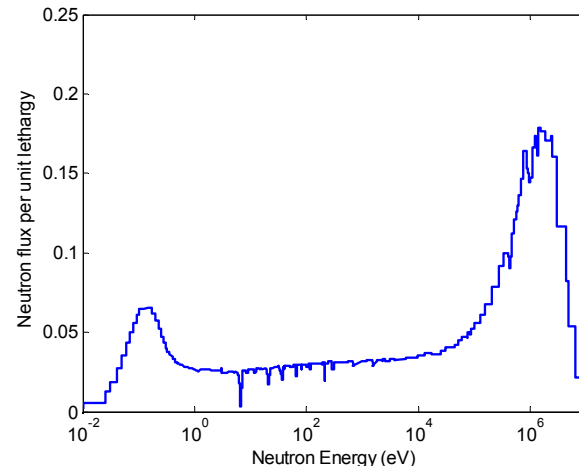
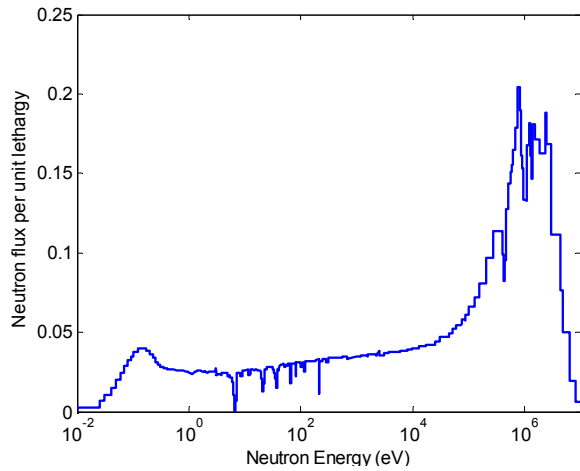
Fuel Isotopes  
Contribution to the BOL  
FTC for  $\text{UO}_2$  Fueled  
Unit Cell

Isotopes	$\eta$ nominal	f nominal	$\eta$ perturbed	f perturbed	RC (in pcm)
$^{234}\text{U}$	0.0700	2.09E-04	0.0702	2.08E-04	-0.0002
$^{238}\text{U}$	0.308	0.272	0.306	0.274	-0.0373
$^{235}\text{U}$	1.953	0.540	1.953	0.539	-199.657

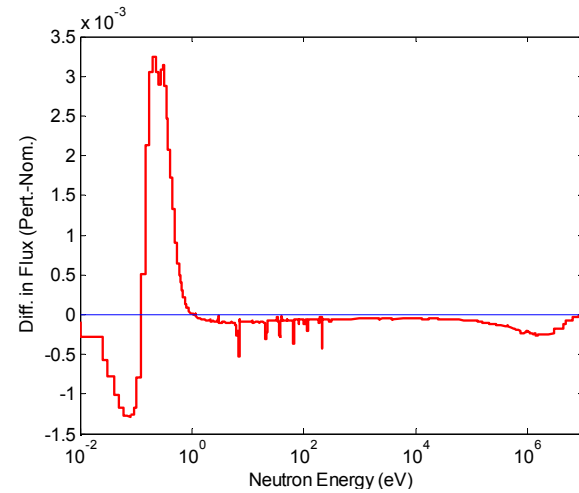
Fuel Isotopes  
Contribution to the  
BOL FTC for  $\text{U-ZrH}_{1.6}$   
Fueled Unit Cell

Isotopes	$\eta$ nominal	f nominal	$\eta$ perturbed	f perturbed	RC (in pcm)
$^{234}\text{U}$	0.0593	1.85E-04	0.0595	1.84E-04	-0.0003
$^{238}\text{U}$	0.181	0.129	0.179	0.131	-9.20E-03
$^{235}\text{U}$	1.985	0.599	1.984	0.596	-409.372

# BOL Spectrum and spectral shift (with critical soluble boron)



$\text{UO}_2$

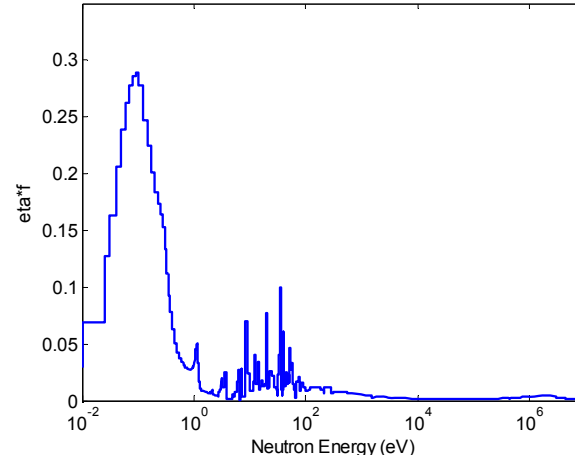
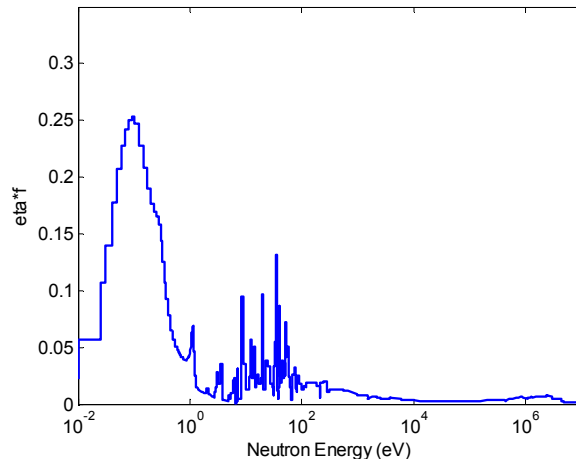


$\text{U-ZrH}_{1.6}$

Mostly  
doppler

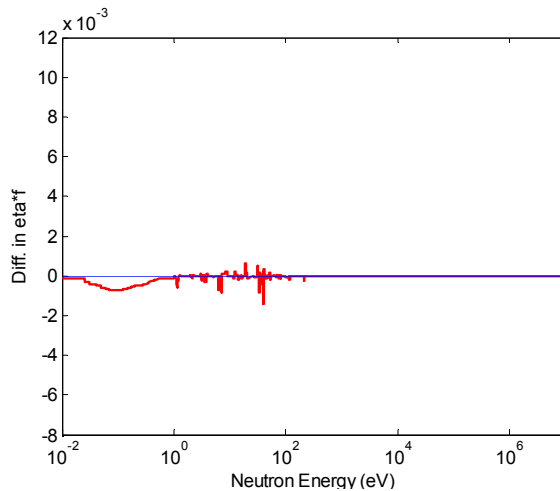
Mostly  
spectral  
shift

# BOL $^{235}\text{U}$ $\eta f$ spectrum and difference in the $^{235}\text{U}$ $\eta f$ spectrum (# of $^{235}\text{U}$ fission neutrons emitted per neutron absorbed by all core constituents)

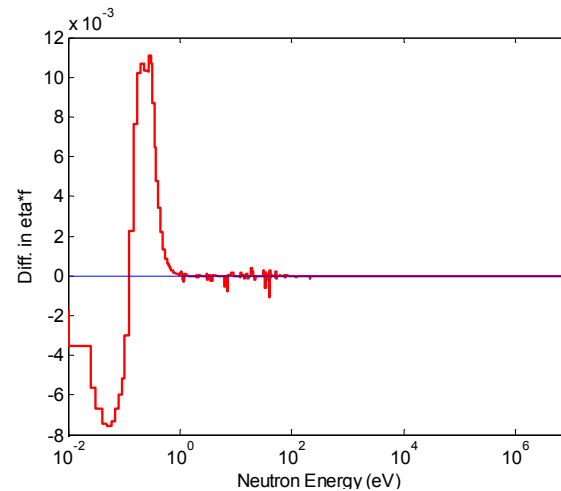


Integral over the spectrum difference below is the contribution from  $^{235}\text{U}$  to the FTC

Because of increased resonance absorption, The thermal flux drops



$\text{UO}_2$



$\text{U-ZrH}_{1.6}$

Mostly spectral shift, negative part larger by 400 pcm than positive part

# Case 1: FTC evolution for UO<sub>2</sub> and U-ZrH<sub>1.6</sub>

Observation 2: at EOL FTC<sub>hydrides</sub> (even positive!) >> than FTC<sub>oxides</sub>: why?

Isotopes	η nominal	f nominal	η perturbed	f perturbed	RC (in pcm)
<sup>236</sup> U	0.1265	0.0118	0.1259	0.0118	0.2422
<sup>238</sup> U	0.3014	0.2742	0.2995	0.2759	0.0183
		...			
<sup>245</sup> Cm	3.1552	0.0003	3.1552	0.0003	-0.3488
<sup>242m</sup> Am	2.7198	0.0003	2.7198	0.0003	-0.3674
<sup>241</sup> Pu	2.1613	0.0666	2.1612	0.0664	-54.4041
<sup>235</sup> U	1.9611	0.1230	1.9611	0.1226	-94.6414
<sup>239</sup> Pu	1.8464	0.2529	1.8463	0.2520	-187.853

Fuel Isotopes  
Contribution to the EOL  
FTC for UO<sub>2</sub> Fueled  
Unit Cell

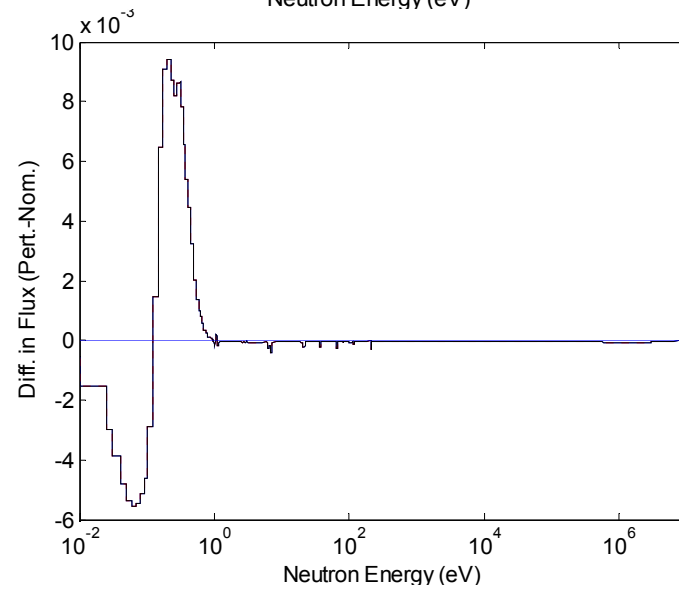
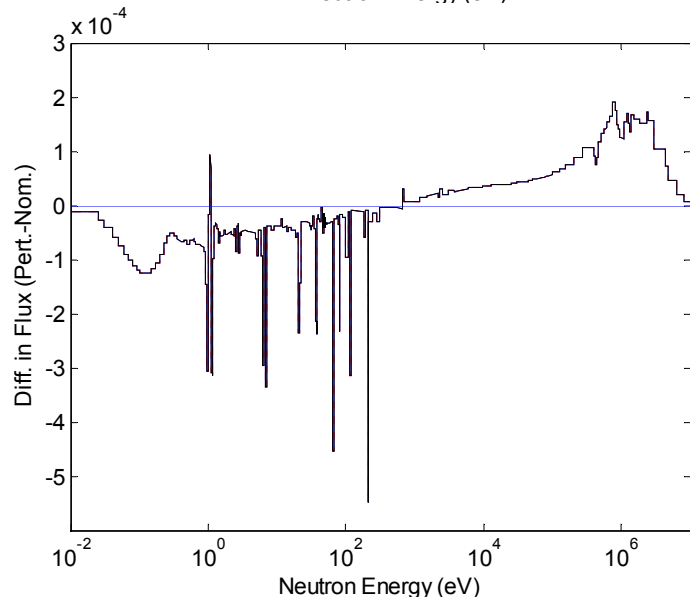
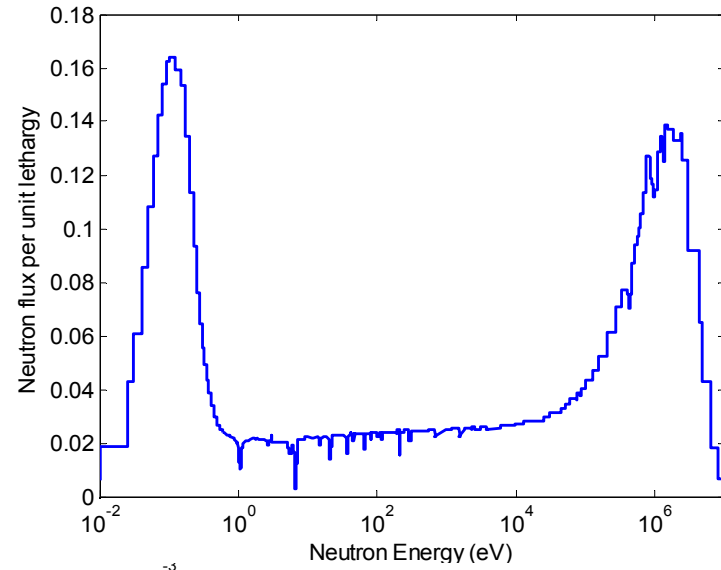
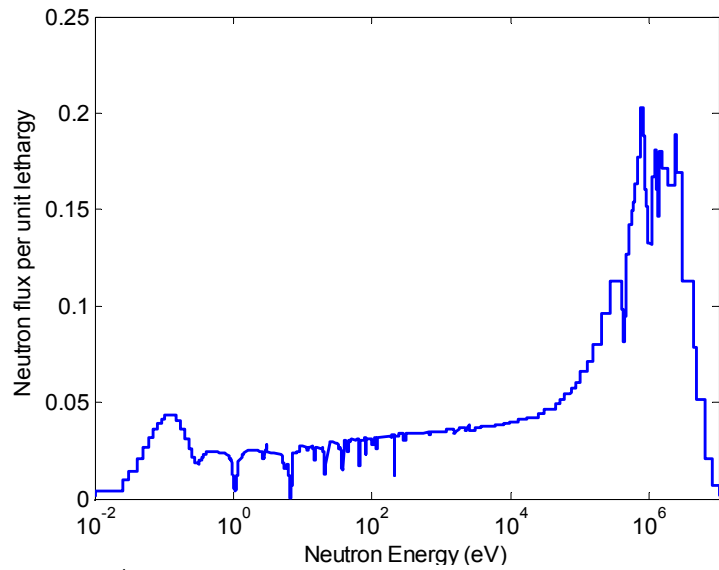
Contribution of <sup>235</sup>U is ½ that at BOL (because of lower fission neutrons emitted by <sup>235</sup>U)

Isotopes	η nominal	f nominal	η perturbed	f perturbed	RC (in pcm)
<sup>239</sup> Pu	1.8700	0.1980	1.8500	0.2040	1510.456
<sup>241</sup> Pu	2.1600	0.0716	2.1600	0.0720	75.0874
<sup>236</sup> U	0.0989	0.0127	0.0987	0.0128	0.2503
		...			
<sup>242m</sup> Am	2.7100	0.0001	2.7100	0.0001	-0.4599
<sup>238</sup> Pu	0.1230	0.0065	0.1240	0.0063	-2.8921
<sup>245</sup> Cm	3.1400	0.0003	3.1400	0.0003	-4.4828
<sup>235</sup> U	2.0400	0.1320	2.0400	0.1290	-942.863

Fuel Isotopes  
Contribution to the  
EOL FTC for U-ZrH<sub>1.6</sub>  
Fueled Unit Cell

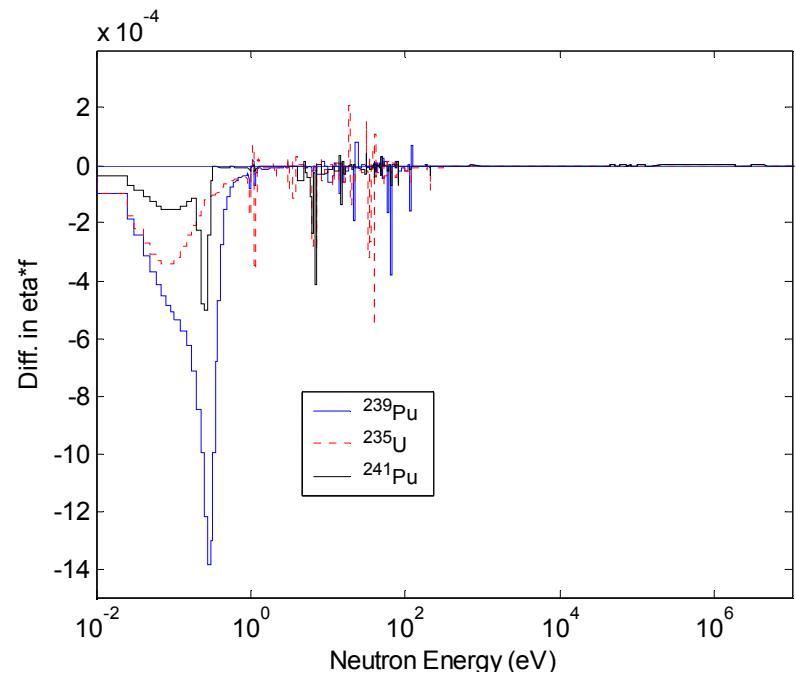
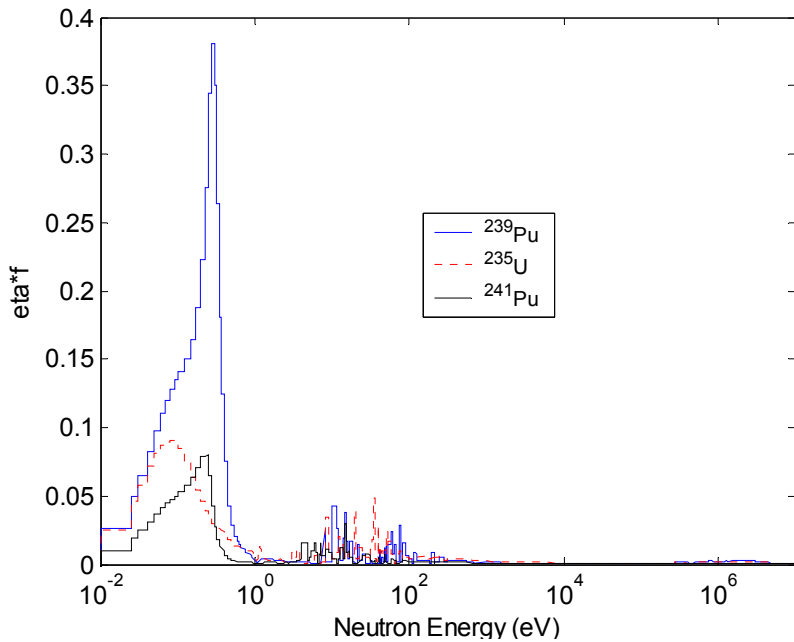
Contribution of <sup>235</sup>U is double that of BOL; <sup>239</sup>Pu and <sup>241</sup>Pu give positive contributions.

# EOL neutron spectrum $\text{UO}_2$ (left) and $\text{U-ZrH}_{1.6}$ (right)



UO<sub>2</sub> EOL  $\eta f$  spectrum (left) and difference in the  $\eta f$  spectrum (right) of <sup>235</sup>U, <sup>239</sup>Pu and <sup>241</sup>Pu,

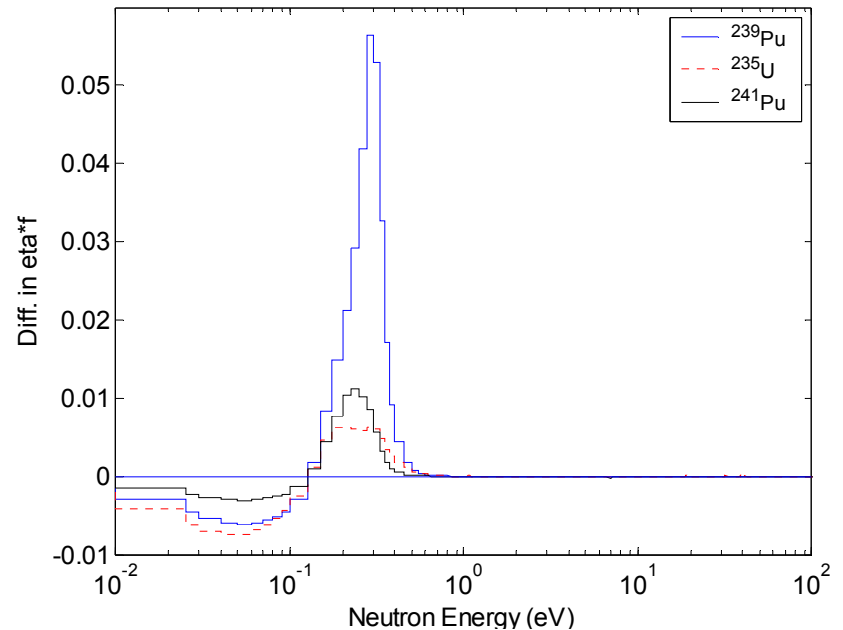
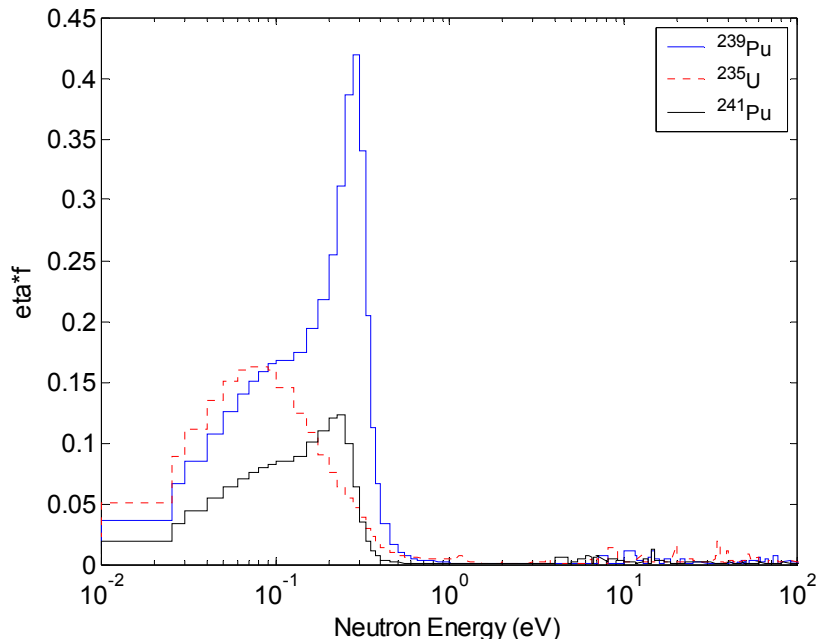
The negative contributions to the FTC comes mainly from the thermal component of the flux (reduced because of increased capture during slowing down, because of Doppler).



U-ZrH<sub>1.6</sub> EOL  $\eta f$  spectrum (left) and difference in the  $\eta f$  spectrum (right) of <sup>235</sup>U, <sup>239</sup>Pu and <sup>241</sup>Pu,

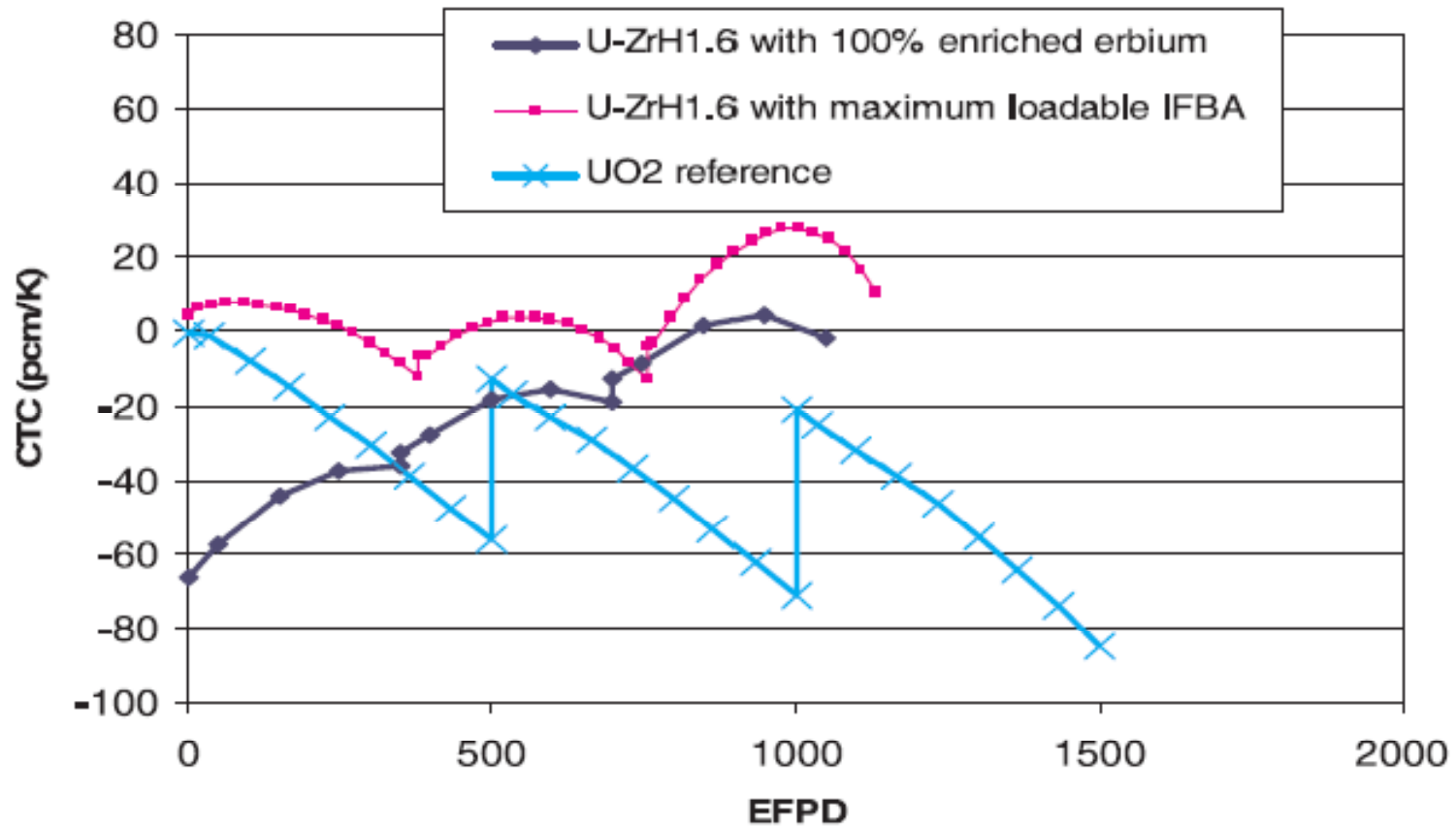
Main effect, as at BOL, thermal spectral shift:  
 $\eta f$  of <sup>239</sup>Pu and <sup>241</sup>Pu better overlaps  $\eta f$  of <sup>235</sup>U, so the positive component of the difference in  $\eta f$  of <sup>239</sup>Pu and <sup>241</sup>Pu is larger than the negative component, as compared to the case of <sup>235</sup>U

This is why the FTC contribution of <sup>235</sup>U is negative and that of <sup>239</sup>Pu and of <sup>241</sup>Pu is negative



What about the Coolant Temperature Coefficient of Reactivity (CTC)?

CTC of U-ZrH<sub>1.6</sub> with Erbium is negative at BOL, but with IFBA it is positive, even for a similar initial amount of soluble boron.



Why is that?

To understand it is useful to look at absorption per fission neutrons, instead of fission neutrons per emitted per absorbed neutrons.

First,  $k_\infty$  is expressed as follows: 
$$k_\infty = \eta \cdot f = \frac{\nu \Sigma^{fuel}_f \Phi}{\Sigma^{fuel}_a \Phi} \frac{\Sigma^{fuel}_a \Phi}{\Sigma^{total}_a \Phi} = \frac{\nu \Sigma^{fuel}_f \Phi}{\Sigma^{total}_a \Phi}$$

Therefore: 
$$\frac{1}{k_\infty} = \frac{\Sigma_{a1} \Phi}{\nu \Sigma^{fuel}_f \Phi} + \frac{\Sigma_{a2} \Phi}{\nu \Sigma^{fuel}_f \Phi} + \dots$$

Denoting the number of absorption of isotope  $n$  per fission neutron by: 
$$\bar{\Sigma}_{an} \equiv \frac{\Sigma_{an} \Phi}{\nu \Sigma^{fuel}_f \Phi}$$

$k_\infty$  is expressed as follows: 
$$\frac{1}{k_\infty} = \bar{\Sigma}_{a1} + \bar{\Sigma}_{a2} + \dots$$

In terms of which the reactivity coefficients can be expressed as:

$$RC_T = \frac{\partial \rho}{\partial T} \cong \frac{\Delta \rho}{\Delta T} = \frac{(\rho_p - \rho_n)}{\Delta T} = \frac{1}{\Delta T} \left( \frac{k^p_\infty - 1}{k^p_\infty} - \frac{k^n_\infty - 1}{k^n_\infty} \right) = \frac{k^p_\infty - k^n_\infty}{k^p_\infty \cdot k^n_\infty} \frac{1}{\Delta T}$$

$$RC_T = \frac{k^p_\infty - k^n_\infty}{k^p_\infty \cdot k^n_\infty} \frac{1}{\Delta T} = \left( \frac{1}{k^n_\infty} - \frac{1}{k^p_\infty} \right) \frac{1}{\Delta T} = \frac{1}{\Delta T} \left( (\bar{\Sigma}^n_{a1} - \bar{\Sigma}^p_{a1}) + (\bar{\Sigma}^n_{a2} - \bar{\Sigma}^p_{a2}) + \dots \right)$$

# CTC of IFBA versus Erbium

The most critical point without BP is BOL; with BP is usually during first cycle.

To show that boron alone does not explain the difference, analysis done for comparable soluble boron amounts: (270 ppm) at 150 EFPD (erbium) and 40 (IFBA):  
 CTC is +7.2 pcm/K for IFBA and -44.7 pcm/K in case of the erbium.

Fuel Isotopes  
 Contribution to the  
 FTC at 40 EFPD  
 for U-ZrH<sub>1.6</sub>  
 Fueled Unit Cell  
 With the Maximum  
 Loadable **IFBA**

Isotopes	RC (in pcm)
<sup>10</sup> B in IFBA	159.998
<sup>1</sup> H in H <sub>2</sub> O	124.8716
<sup>10</sup> B in H <sub>2</sub> O	67.3295
<sup>135</sup> Xe	22.4411
<sup>16</sup> O in H <sub>2</sub> O	4.4997
<sup>149</sup> Sm	4.386
...	...
<sup>236</sup> U	-1.977
Zr in Clad	-7.4205
<sup>239</sup> Pu	-10.5714
Zr in ZrH <sub>1.6</sub>	-18.5803
<sup>235</sup> U	-26.3325
<sup>238</sup> U	-243.583

Isotopes	RC (in pcm)
<sup>1</sup> H in H <sub>2</sub> O	127.4983
<sup>10</sup> B in H <sub>2</sub> O	65.6526
<sup>135</sup> Xe	21.4236
<sup>149</sup> Sm	4.19
...	...
<sup>131</sup> Xe	-2.5306
<sup>147</sup> Pm	-2.8647
<sup>235</sup> U	-5.7255
<sup>236</sup> U	-6.198
Zr in Clad	-7.964
<sup>240</sup> Pu	-12.6061
Zr in ZrH <sub>1.6</sub>	-19.4394
<sup>239</sup> Pu	-32.6588
<sup>238</sup> U	-267.004
<sup>167</sup> Er	-304.612

Fuel Isotopes  
 Contribution to the  
 FTC at 150 EFPD for  
 U-ZrH<sub>1.6</sub> Fueled Unit  
 Cell with the Maximum  
 Loadable **Erbium**

Positive contributions from <sup>1</sup>H and <sup>10</sup>B in H<sub>2</sub>O, and <sup>135</sup>Xe are similar in both cases.

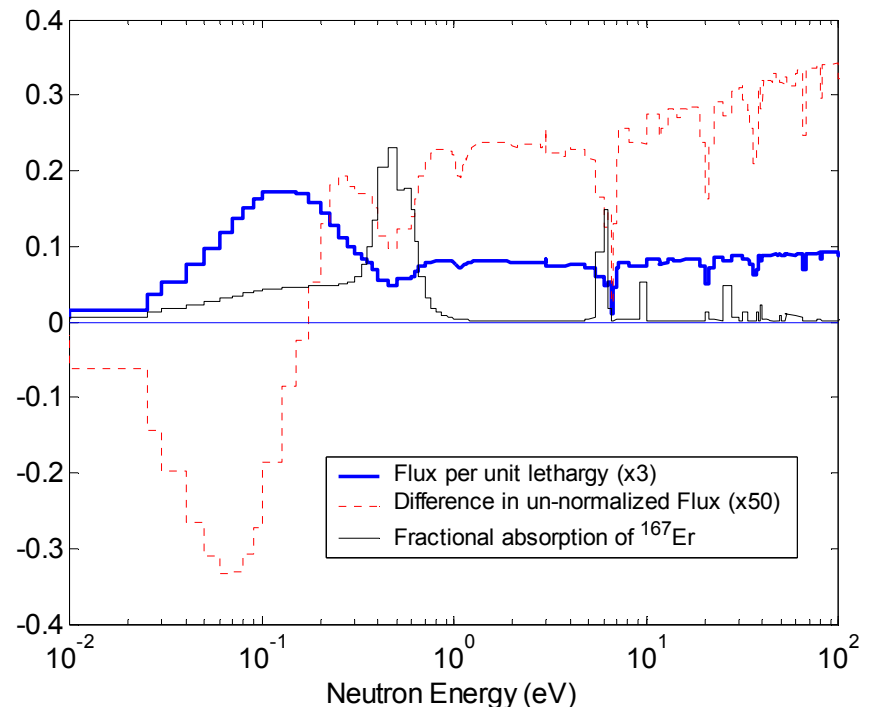
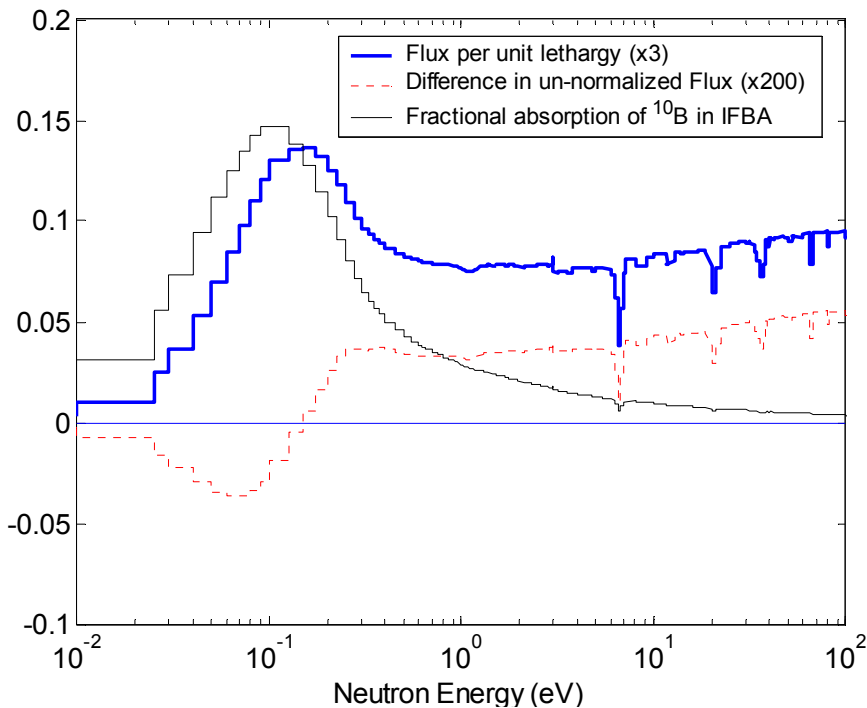
Contribution <sup>10</sup>B in IFBA >0;  
 Contribution of <sup>167</sup>Er < 0, (twice  
 than the contribution from the  
<sup>10</sup>B in IFBA)

# Why the opposite behavior?

Drop in thermal flux (normalized per absorbed neutron) is because of reduced moderation, at  $E > 0.15$  eV it increases to compensate for reduction in fission XS.

$^{10}\text{B}$  fractional absorption peaks where the Flux drops, so introducing a positive CTC contribution due to reduced absorption; the opposite for  $^{167}\text{Er}$ .

**Flux, difference in Flux and  $^{10}\text{B}$  absorption (left) and  $^{167}\text{Er}$  absorption (right)**



**Now FTC at BOL:** with erbium is -16 pcm/K, with IFBA is -6 pcm/K and with no burnable poisons is -4 pcm/K (already analyzed).

Let's analyze the reason for the difference (IFBA vs erbium), ranking the most important contributions to the FTC by abs per fission neutron.

In both cases  $^{238}\text{U}$ ,  $^{235}\text{U}$  and  $^1\text{H}$  in  $\text{H}_2\text{O}$  give contributions of the same order of magnitude.  
The difference is entirely attributed to the  $^{10}\text{B}$  in the IFBA (-244 pcm) and to  $^{167}\text{Er}$  (-1161 pcm)

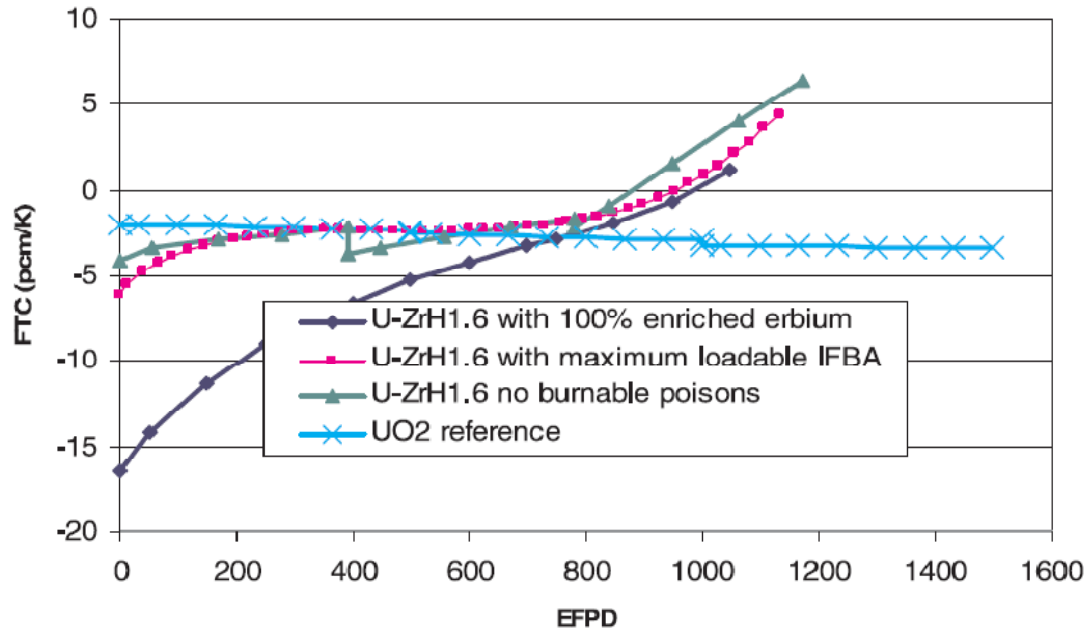
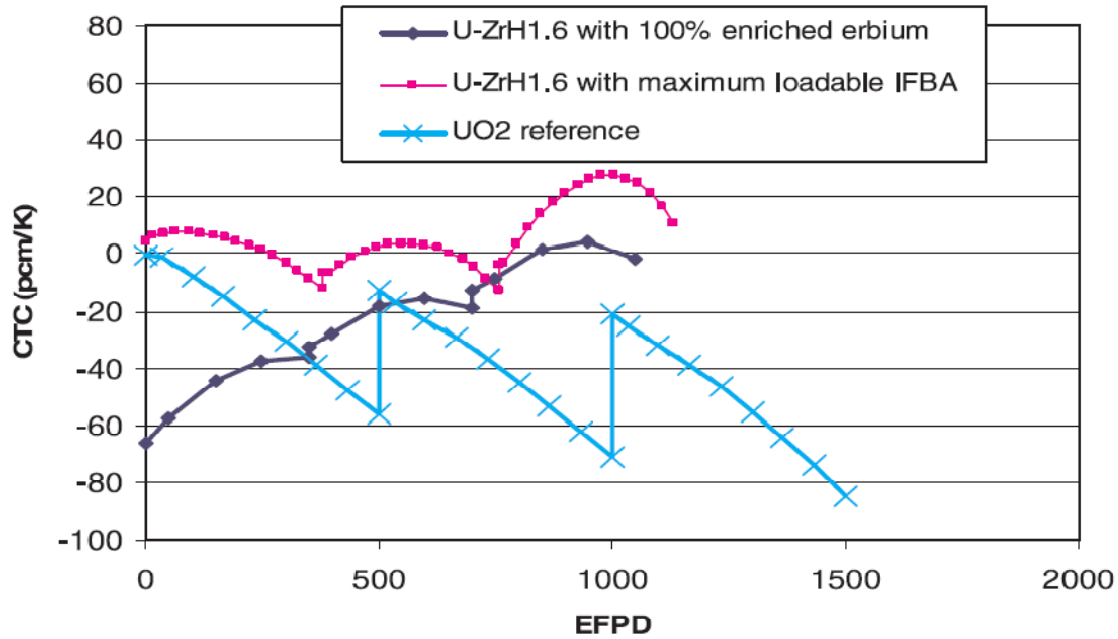
Fuel Isotopes  
Contribution to the  
BOL FTC for U-ZrH<sub>1.6</sub>  
Fueled Unit Cell With  
the Maximum  
Loadable **IFBA**

Isotopes	RC (in pcm)
$^{11}\text{B}$ in IFBA	-0.0014
$^{234}\text{U}$	-0.0304
$^1\text{H}$ in ZrH <sub>1.6</sub>	-0.2065
$^{16}\text{O}$ in H <sub>2</sub> O	-1.2314
Zr in Clad	-2.6329
$^{10}\text{B}$ in H <sub>2</sub> O	-6.1338
Zr in ZrH <sub>1.6</sub>	-8.2448
$^1\text{H}$ in H <sub>2</sub> O	-18.503
$^{235}\text{U}$	-24.0563
$^{10}\text{B}$ in IFBA	-244.837
$^{238}\text{U}$	-310.301

Fuel Isotopes  
Contribution to  
the BOL FTC for  
U-ZrH<sub>1.6</sub> Fueled  
Unit Cell With the  
Maximum  
Loadable **Erbium**

Isotopes	RC (in pcm)
$^1\text{H}$ in ZrH <sub>1.6</sub>	0.5083
$^{166}\text{Er}$	-0.0005
$^{234}\text{U}$	-0.1398
$^{16}\text{O}$ in H <sub>2</sub> O	-3.2532
$^{10}\text{B}$ in H <sub>2</sub> O	-4.7833
Zr in Clad	-5.6258
Zr in ZrH <sub>1.6</sub>	-14.5088
$^1\text{H}$ in H <sub>2</sub> O	-18.6887
$^{235}\text{U}$	-37.3319
$^{238}\text{U}$	-390.739
$^{167}\text{Er}$	-1161.61

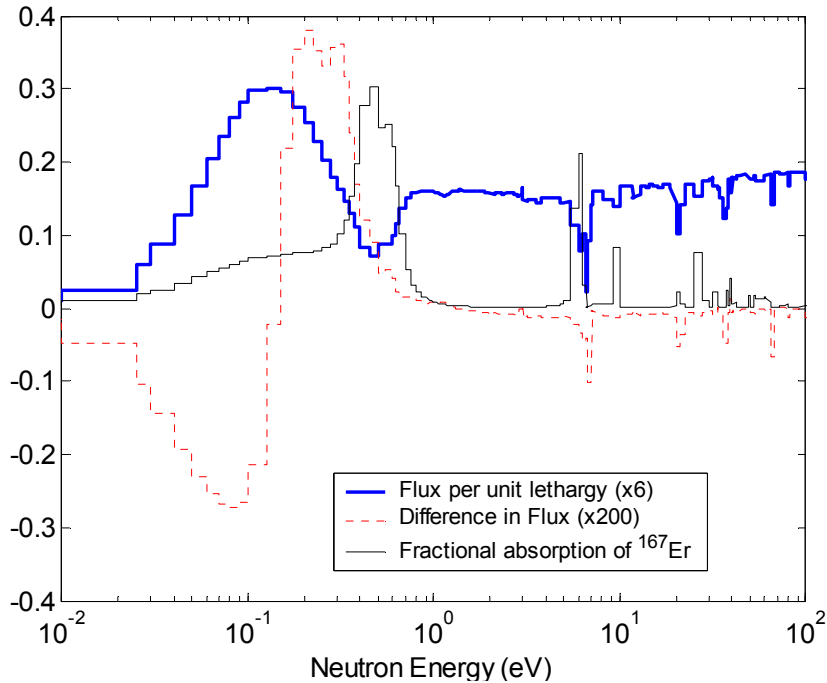
# It can get worse: RC of hydrides without burnable poisons



# What creates the difference?

$^{167}\text{Er}$  has a 0.45 eV resonance (similar to  $^{239}\text{Pu}$ )  
 $^{10}\text{B}$  of IFBA is a  $1/v$  absorber

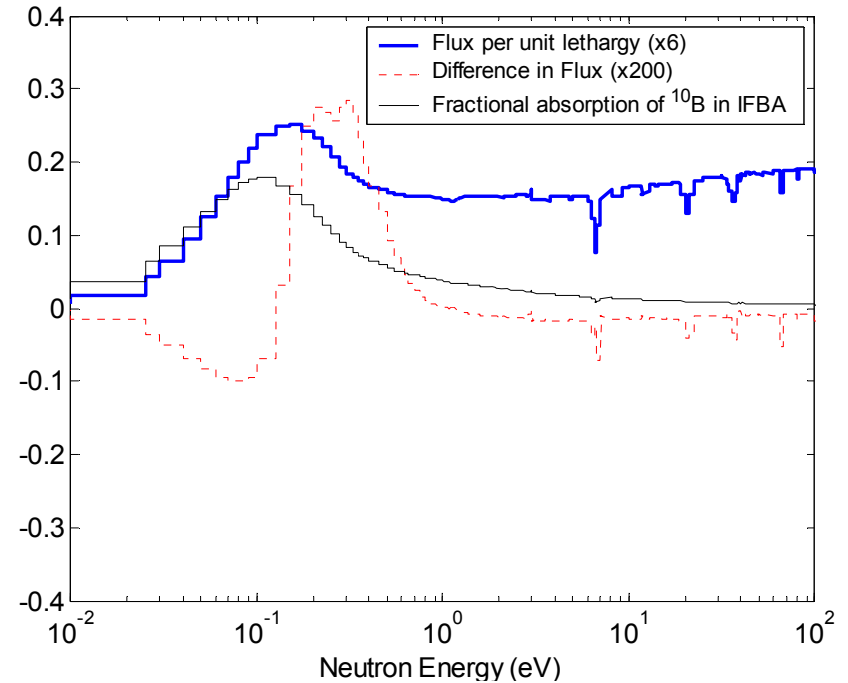
## Spectral shift $\rightarrow$ over $^{167}\text{Er}$ resonance



U-ZrH<sub>1.6</sub> spectrum, spectral shift, absorption of  $^{167}\text{Er}$

## Spectral shift $\rightarrow$ out of $^{10}\text{B}$ absorption region:

- Abs  $\downarrow$  below 0.125 eV (dominant);
- Abs  $\uparrow$  above 0.125 eV.



U-ZrH<sub>1.6</sub> spectrum, spectral shift, absorption of  $^{10}\text{B}$

# Conclusions

A two-step technique was developed to analyze the physics behind the different trends observed in the burnup dependence of the reactivity coefficients of  $\text{UO}_2$  and  $\text{U-ZrH}_{1.6}$  fuels:

- (1) ranking the contribution to the reactivity coefficients of interest by each of the isotopes;
- (2) investigating, for each of the more important isotopes, the spectral reasons for its specific response to the perturbation.

This technique has been applied to understand:

- 1) The difference in FTC behavior at BOL and EOL of hydrides as compared to oxides;
- 2) The different properties of burnable poisons (IFBA and erbium) for both the FTC and CTC.

# Additional Cases

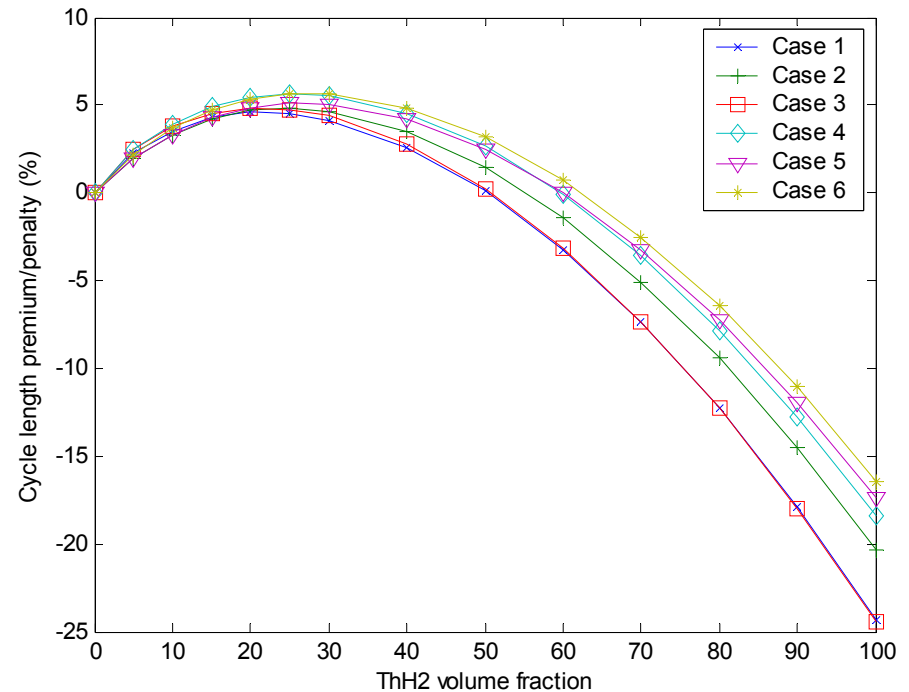
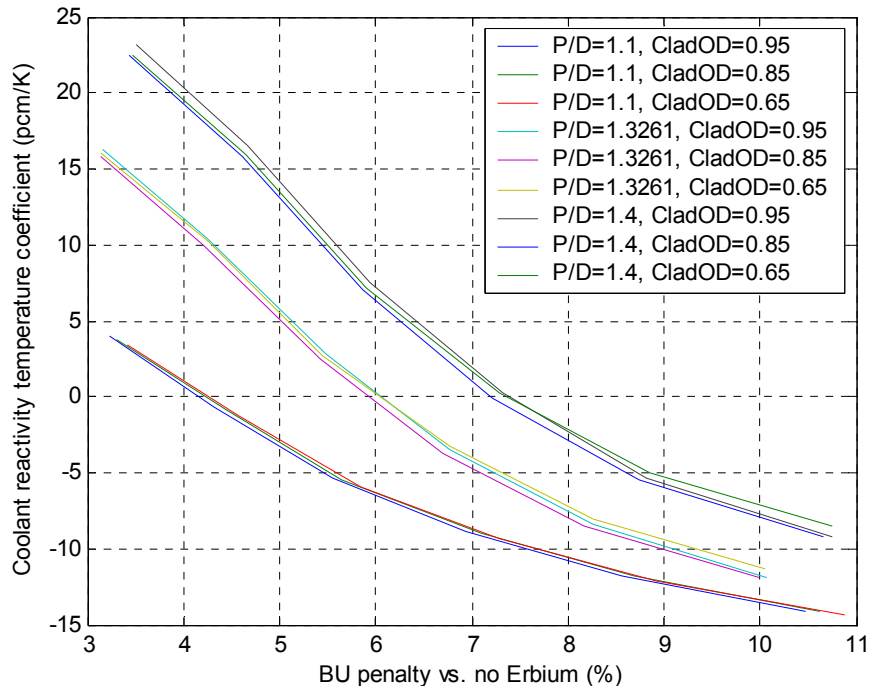
# What we learned

$^{167}\text{Er}$  as burnable poison is effective in reducing both the FTC and the CTC.

## Drawback

Large burnup penalty that more than erases the economic advantage.

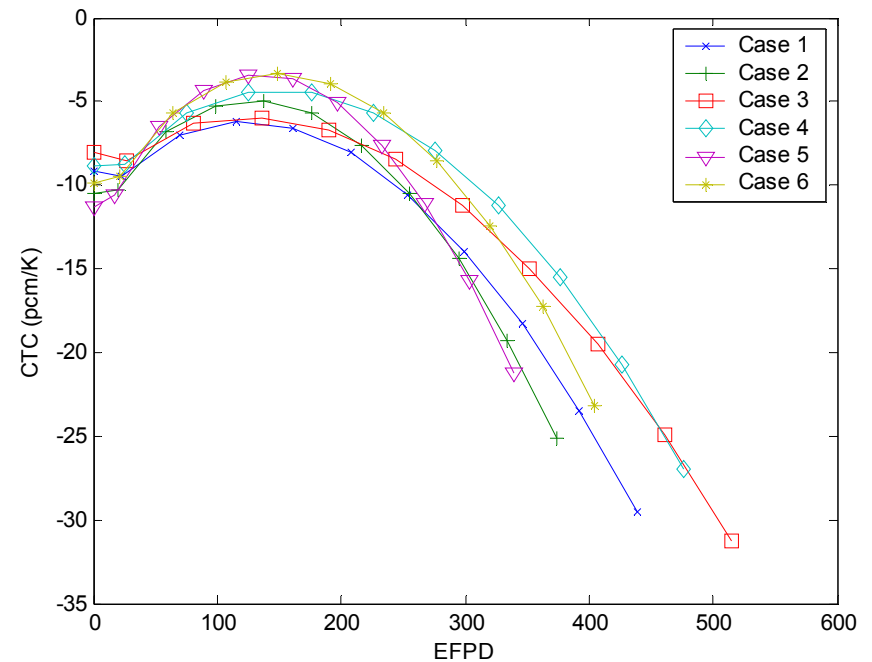
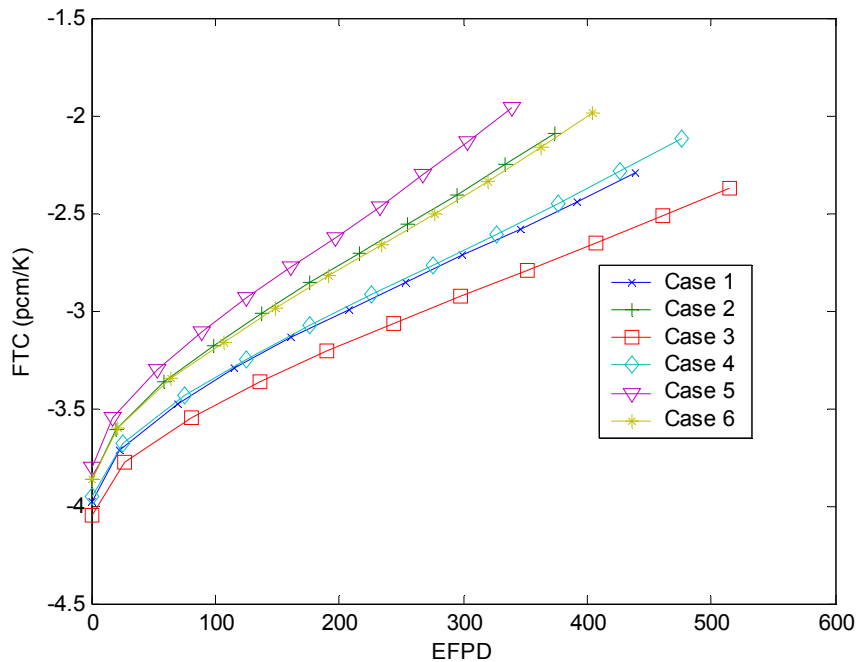
## Alternative solution: ThH<sub>2</sub>



# Thorium (ThH<sub>2</sub>)

25 % achieves the maximum burnup premium, but CTC still is positive;  
100 % achieves negative CTC, but burnup penalty is high(15% to 25%).

Best solution: 25 % ThH<sub>2</sub> and enough IFBA CTC to ~-3 pcm/K.  
Still higher burnup than without thorium, (+1.78% with 0.94 mg<sup>10</sup>B/cm).



# Physics of the FTC at EOL of U-ThH<sub>2</sub>-ZrH<sub>1.6</sub> 25 % with IFBA

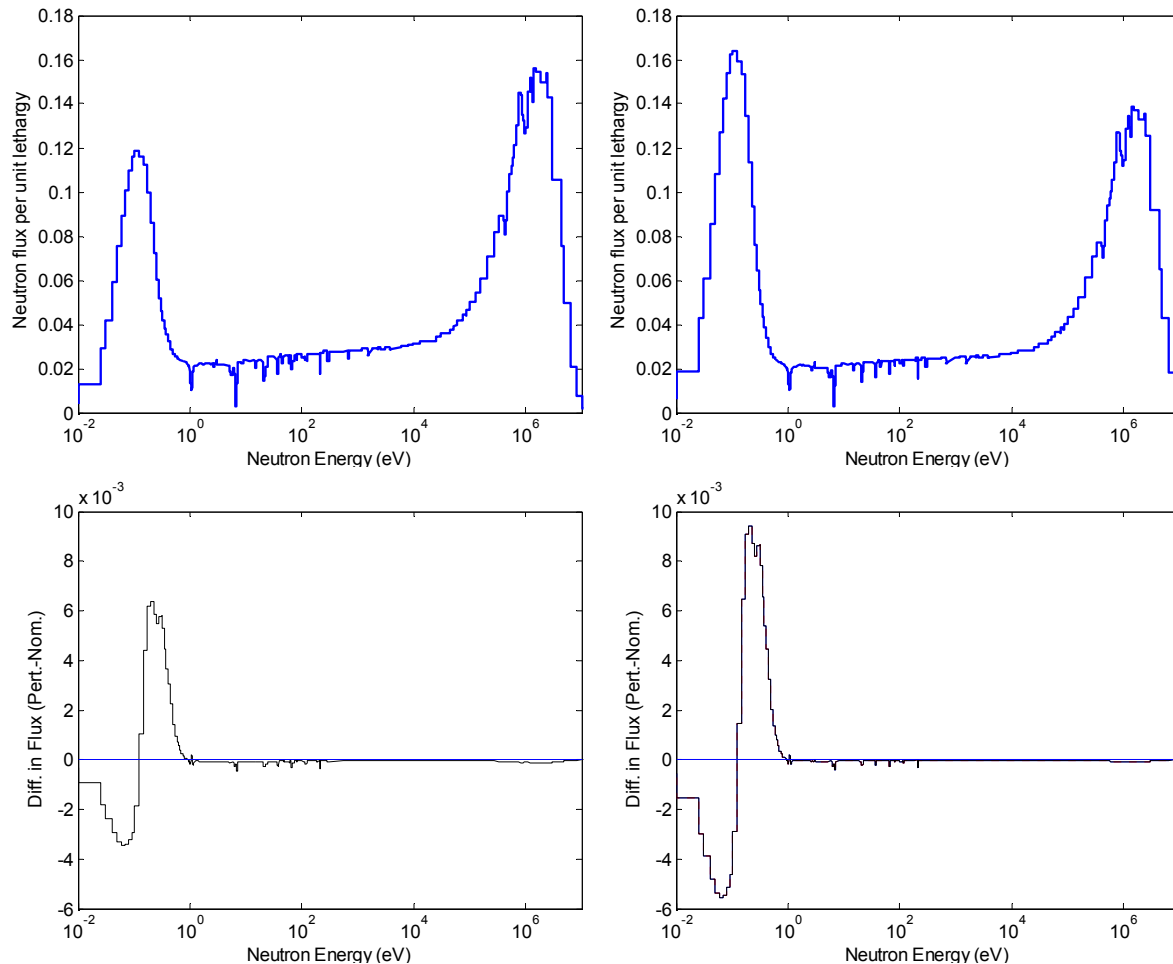
FTC remains negative throughout the fuel life (which is longer than in the case without thorium).

Negative contributions of <sup>233</sup>U and <sup>235</sup>U (was -942 pcm for no Th) together are larger than the positive ones of <sup>239</sup>Pu and <sup>241</sup>Pu (was 1510 and 95 pcm)

Fuel Isotopes  
Contribution to the  
EOL FTC for the  
U-ZrH<sub>1.6</sub>-ThH<sub>2</sub> (25  
% ThH<sub>2</sub>)

Isotopes	η nominal	f <sub>nominal</sub>	η perturbed	f <sub>perturbed</sub>	RC (in pcm)
<sup>239</sup> Pu	1.8556	0.1438	1.8462	0.1484	889.5717
<sup>241</sup> Pu	2.1579	0.04923	2.1547	0.04958	73.1822
<sup>236</sup> U	0.1086	0.01117	0.1082	0.01122	0.2026
<sup>241</sup> Am	0.027	0.000787	0.0268	0.000811	0.0551
<sup>240</sup> Pu	0.0104	0.04852	0.0104	0.04876	0.009
<sup>231</sup> Pa	0.013	0.000273	0.0127	0.000281	0.0002
			...		
<sup>243</sup> Cm	3.1278	1.18E-05	3.1276	1.17E-05	-0.0516
<sup>234</sup> U	0.0516	0.004624	0.052	0.004571	-0.0644
<sup>232</sup> U	1.7933	0.000121	1.7961	0.000119	-0.3439
<sup>242m</sup> Am	2.7116	0.000129	2.7116	0.000128	-0.4354
<sup>238</sup> Pu	0.1435	0.00365	0.1452	0.003546	-1.1083
<sup>245</sup> Cm	3.1461	0.000126	3.1473	0.000123	-1.3659
<sup>233</sup> U	2.2437	0.0923	2.2429	0.09106	-356.151
<sup>235</sup> U	2.0249	0.1415	2.023	0.139	-643.862

# Fuel-average neutron spectrum at EOL and fuel-average flux variation in U-ZrH<sub>1.6</sub>-ThH<sub>2</sub> (25 % ThH<sub>2</sub>) (on the left) and U-ZrH<sub>1.6</sub> (on the right)

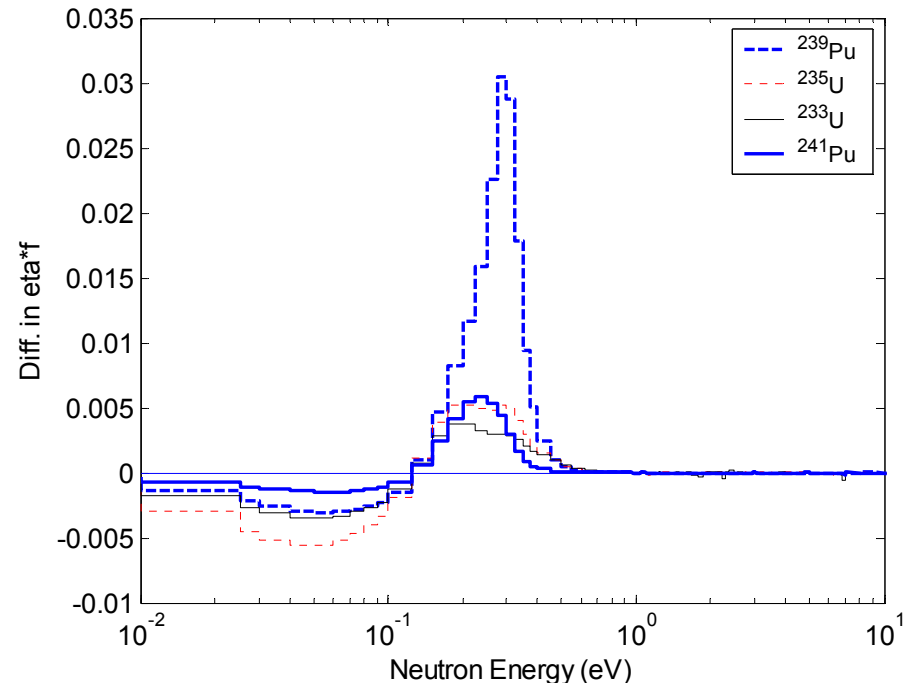
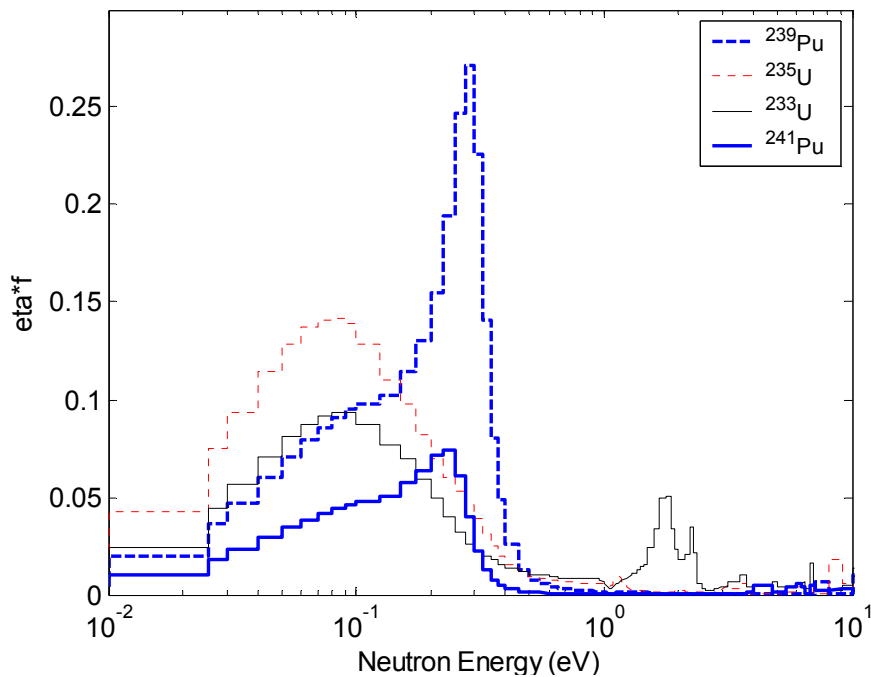


- 1) Smaller spectral shift reduces the positive contribution of <sup>239</sup>Pu;
- 2) Negative contribution of <sup>233</sup>U.

Both  $^{239}\text{Pu}$  and  $^{241}\text{Pu}$  have peak in  $\eta f$  for  $E > 0.15$  eV,  
(break-even point for spectral variation)  
so mostly positive contributions.

Both  $^{233}\text{U}$  and  $^{235}\text{U}$  have peak in  $\eta f$  for  $E < 0.15$  eV,  
so mostly negative contributions.

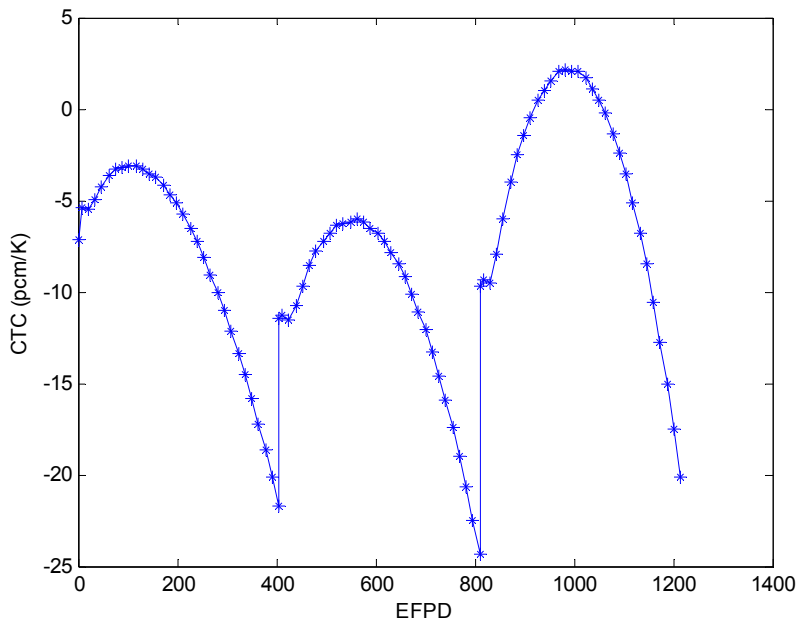
$\eta f$  (left) and difference in  $\eta f$  (right) of  $^{239}\text{Pu}$ ,  $^{241}\text{Pu}$ ,  $^{233}\text{U}$  and  $^{235}\text{U}$



# Physics of the CTC of U-ThH<sub>2</sub>-ZrH<sub>1.6</sub> 25 % with IFBA

CTC remains negative throughout the fuel life, analyzed during the second batch (549 EFPD), at its most negative peak (-6.8 pcm/K)

$\eta f_{\infty}$  of <sup>235</sup>U is the only negative, but large enough to compensate for all the other positive contributions.



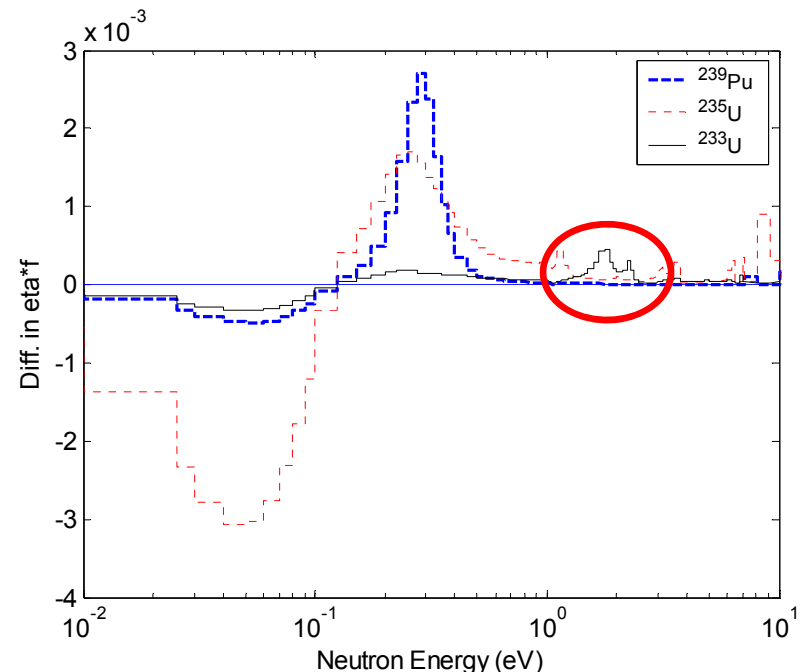
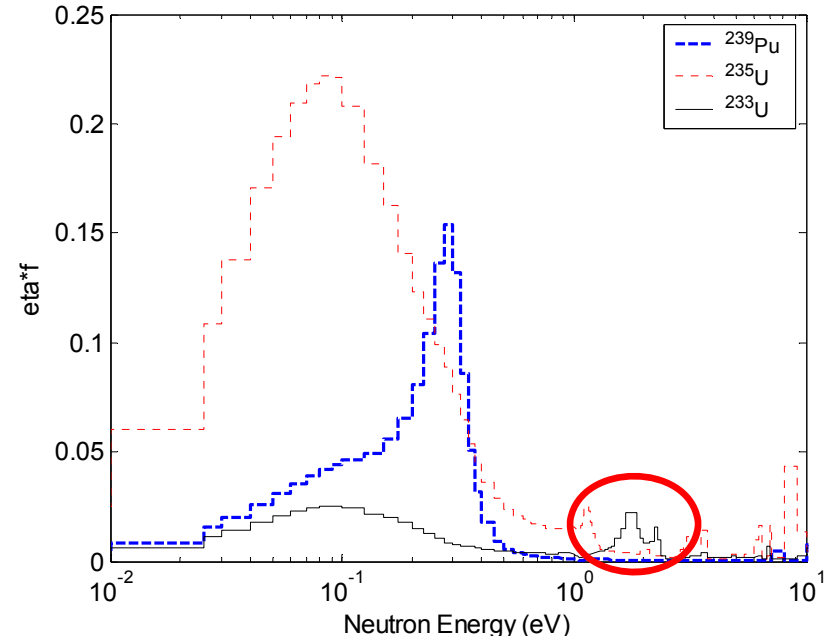
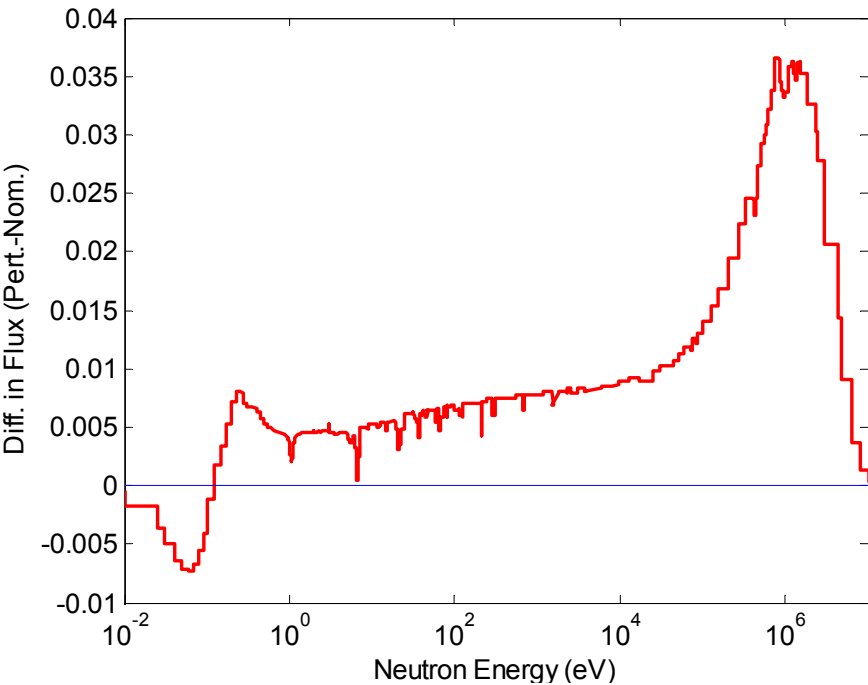
Neutron balance  
(as difference in  $\eta f_{\infty}$ )  
at 549 EFPD for CTC

Isotopes	RC (in pcm)
<sup>239</sup> Pu	75.8079
<sup>238</sup> U	36.3617
<sup>233</sup> U	9.0344
<sup>232</sup> Th	4.5614
<sup>241</sup> Pu	2.6408
<sup>236</sup> U	1.2512
<sup>240</sup> Pu	0.513
<sup>237</sup> Np	0.1258
<sup>245</sup> Cm	-0.0016
<sup>242m</sup> Am	-0.0241
<sup>235</sup> U	-198.869

$\eta f$  spectrum (above) and difference in  $\eta f$  spectrum (below) at 549 EFPD of  $^{239}\text{Pu}$ ,  $^{235}\text{U}$  and  $^{233}\text{U}$

$\eta f$  of  $^{235}\text{U}$  peaks where the spectral shift decreases;  $^{239}\text{Pu}$  has a resonance on the spectral increase,  $^{233}\text{U}$  has a 1.5 eV resonance.

Variation in flux normalized per absorbed neutron upon  $\text{H}_2\text{O}$  temperature increase



$\eta f$  spectrum (above) and difference in  $\eta f$  spectrum (below) at 549 EFPD of  $^{238}\text{U}$  and  $^{232}\text{Th}$

The positive contributions of  $^{238}\text{U}$  and  $^{232}\text{Th}$  are explained by the increase in fast fission probability, driven by the strong increase in the flux in the region above 1 MeV, where fast fissions in both isotopes is dominant .

