Safety Aspects of Thorium Fuel in Sodium-Cooled Fast Reactors

C. Fiorina(1), *F. Franceschini*(2,*), M. Memmott(2)

(1) Polytechnic of Milan, Italy
(2)Westinghouse Electric Company LLC
* *Presenting author*

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Thorium and Fast Reactors

- Th is not the traditional choice for fast reactor fuel (or fuel in general):
  - *Significantly lower breeding potential than U*
  - Difficulties in reprocessing
  - Remote fuel refabrication
  - No current industrial infrastructure
- However Th could be of interest when emphasis is on TRU burning
  - Substantial developments required regardless of adopting U or Th
  - **High TRU burning rate (burner cores)**
  - **Coolant voiding coefficients (burner and especially breakeven cores)**
- **Focus of this study is reactivity feedback of Na FRs with U vs. Th fuel**
  - Fuel cycle and transmutation performance presented elsewhere, e.g. Franceschini et al. "Promises and Challenges of Thorium for Transuranic Transmutation", Waste Management Symposia 2013, Feb. 24 – 28, 2013, Phoenix, AZ, USA

ARR Conceptual Core Design Analyzed (GNEP)

- Sodium-cooled, 1 GWt, pool-type

Thermal power	1,000 MWt
Coolant	Na
Coolant inlet/outlet T	395/550 °C
Clad/duct material	HT-9
Assembly type	Hexagonal with duct
Pin lattice/pitch	Triangular, 7.41 mm
Pins per assembly	271
Core Barrel Diameter	3.5 m
Driver fuel height	0.6 m
Pellet OD; clad ID/OD	4.71; 5.44/6.50 mm
Fuel/coolant/structure	41/33/26 vol %
Driver inner/outer FAs	192/132
Fuel Management	1 Year cycle with 3 batch reloading strategy

Methodology & Outline

- U and Th fuel core designs developed for the ARR
  - Breakeven
  - Burner
- Reactor physics evaluation with ECCO/ERANOS/EQL3D Jeff 3.1
- Equilibrium cycle results presented
  - Fuel Inventory
  - **Reactivity coefficients**
  - **Reactivity Decomposition**
  - Impact on safety (quasi-static approach)

Breakeven Configurations – Fuels

- Ternary metal fuel for U with 10% Zr
- Nitride (95% N-15 enriched) for Th

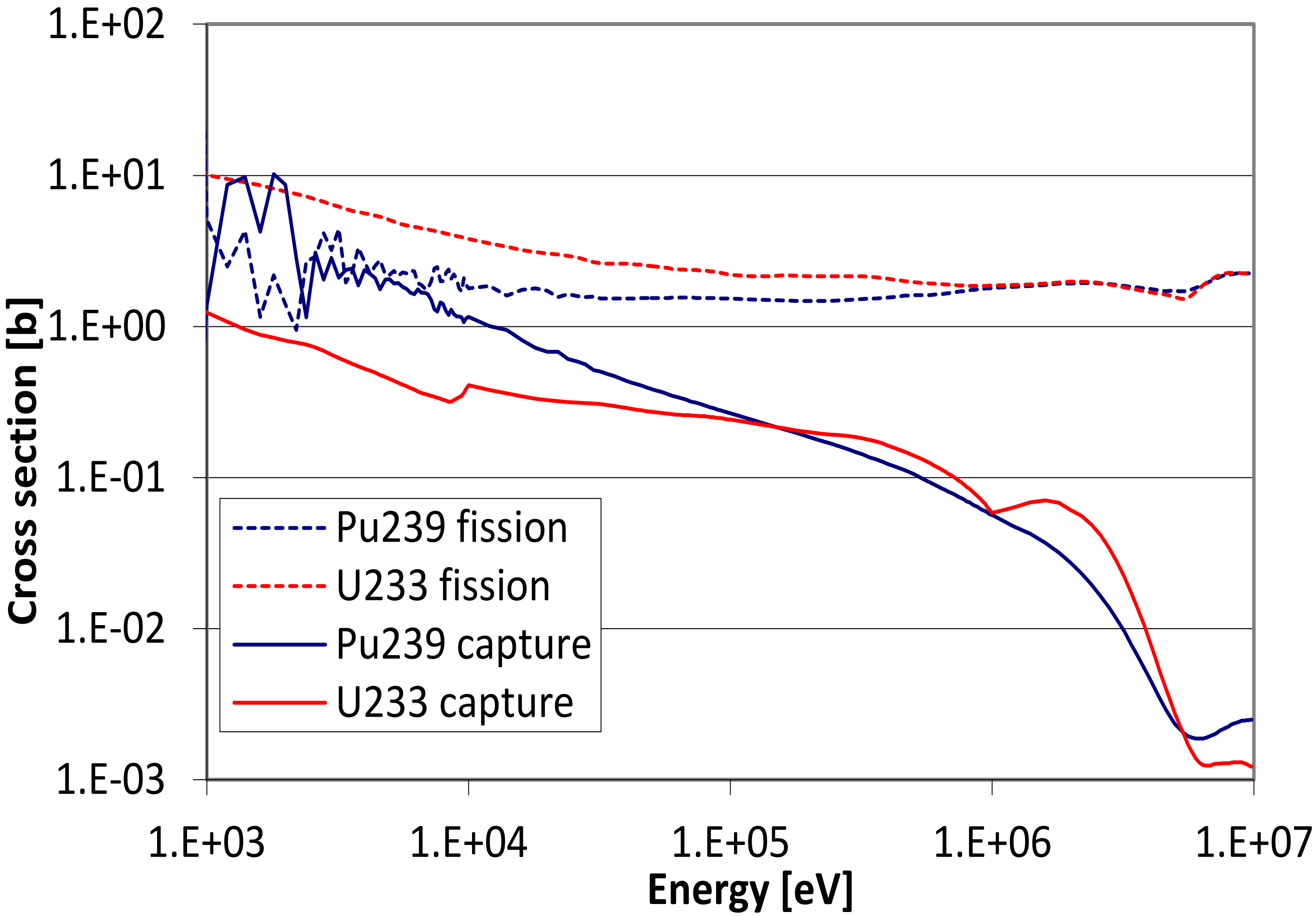
	U- Fuel	**Th- Fuel**
Fuel form	**Metallic 10% Zr**	**Nitride 95% N-15**
Feed	Natural U	**Natural Th**
Actinides Recycled	All	All
Smeared density	75%	85%
Core HM inventory [t]	13.2	12.1
Axial blankets (total, cm)	20 cm	**65 cm**
Radial blankets (# of FAs)	97	97
Driver Fuel Assemblies	322	322

Smaller blanket in U core (better internal breeding)

Fuel Inventories and Reactivity Coefficients - Equilibrium

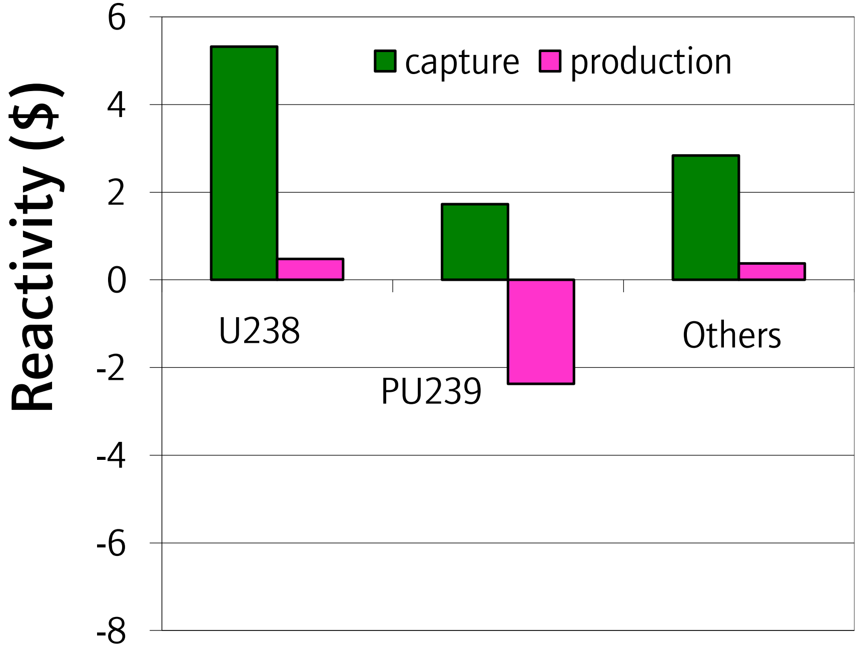
	U-TRU-Zr Metal	**Th-U3 Nitride**	**Th vs. U (Delta)**
Inventories [w/o]:			
Natural U or Th	80.6 (U8)	77.5 (Th)	-3.1
Pu or U from Th	18.8 (Pu)	22.0 (U3)	3.2
Other	0.6 (MAs)	0.2 (TRU/Pa)	-0.4
Reactivity Coefficients:			
Doppler coeff. [m$/K]	-1.03	-1.94	-0.91
Active core voiding [$]	4.91	-1.01	**-5.92**
Coolant exp. coeff. [m$/K]	1.28	-0.26	-1.54
Fuel exp. coeff. [m$/K]	-0.51	-0.17	0.34
Radial exp. coeff. [m$/K]	-2.81	-2.25	0.56
βeff [pcm]	361	342	-19
Reactivity swing [%]	2.9	4.9	2.0

Fissile Cross-Section Reactivity Impact

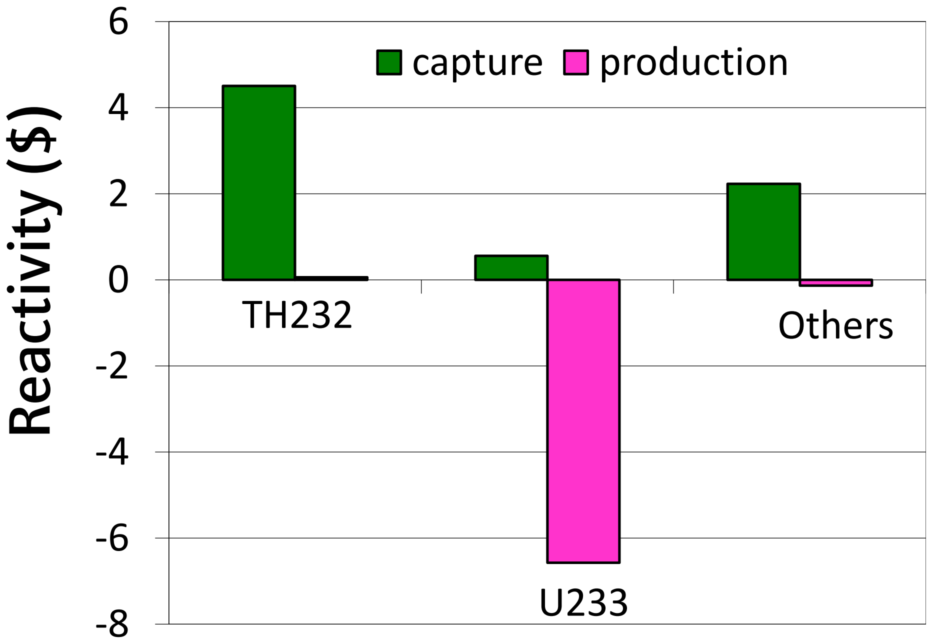


Reactivity Decomposition – Void Coefficient

U-breakeven (+5$ voiding)



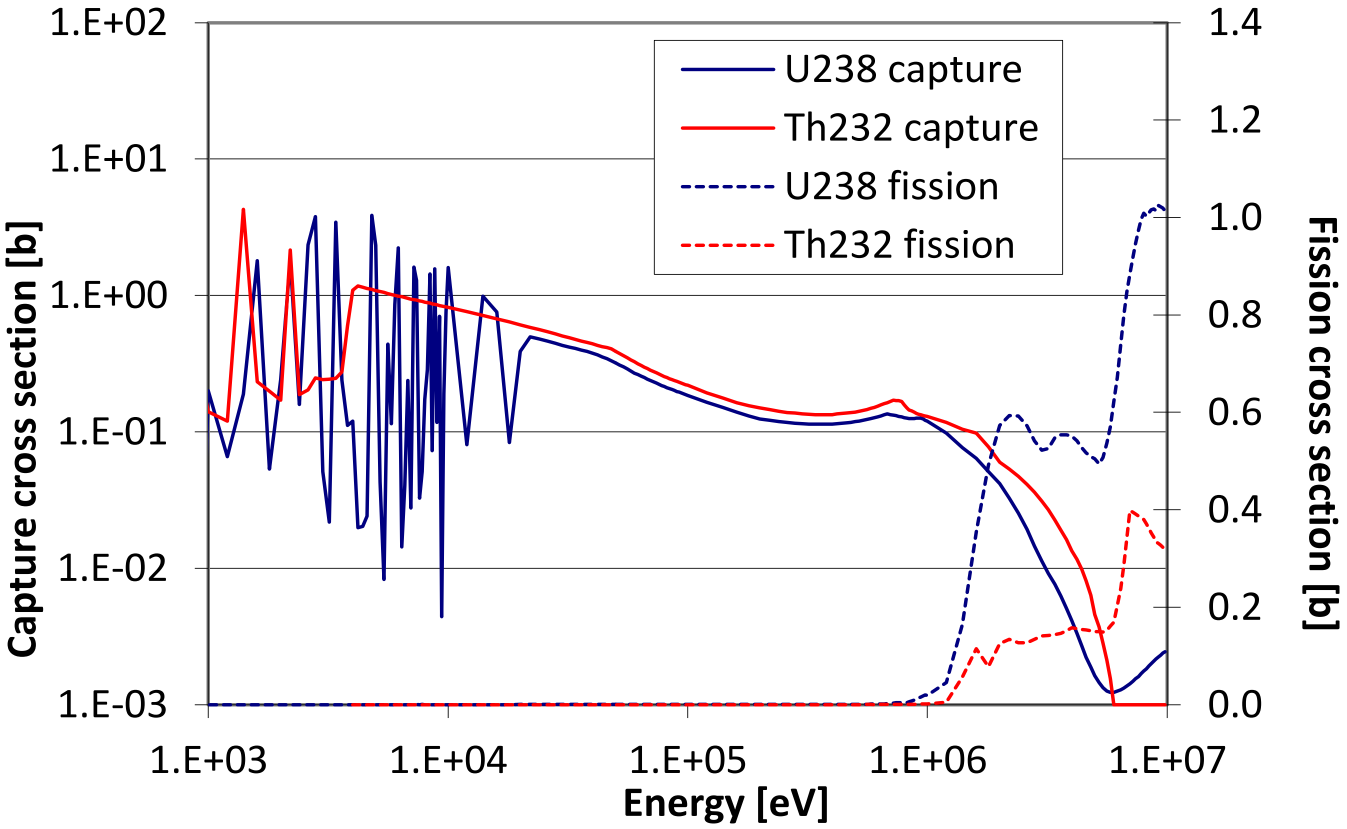
Th-breakeven (-1$)



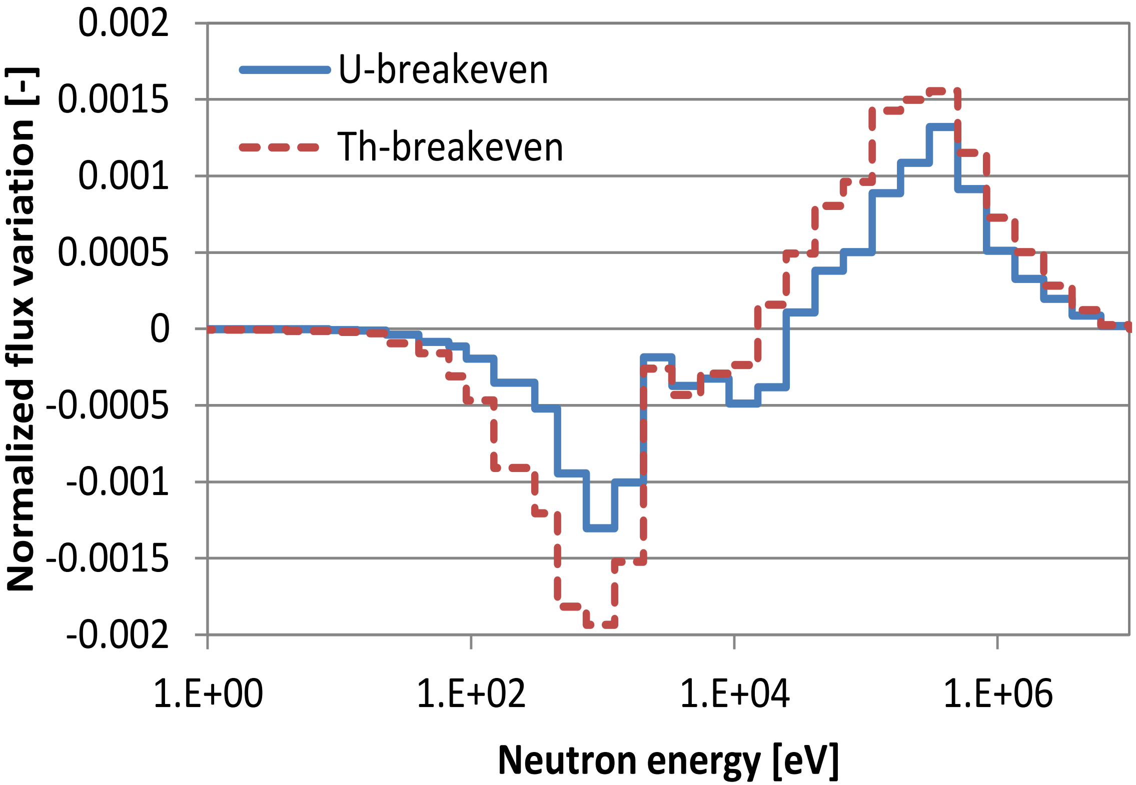
<u>Lower voids in Th-breakeven mostly from U-233</u>

- ➢ steeper decrease w/ energy of U-233 vs. Pu-239 fission XS and flatter capture XS
- ➢ synergistic contribution from Th-232 vs. U-238 (higher fission threshold and lower relative fertile content than in the U core)

Fertile Cross-Section Reactivity Impact



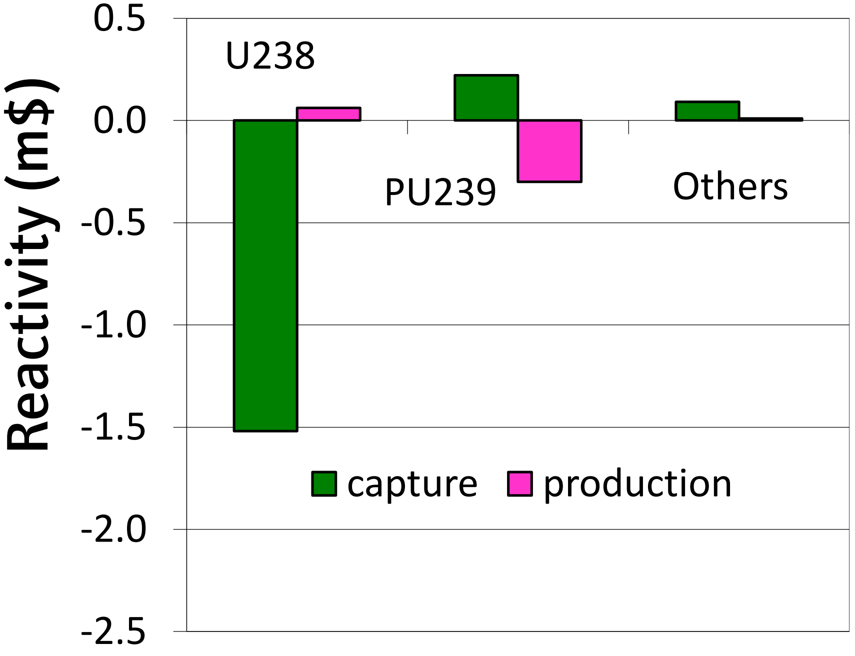
Doppler – Impact of fuel T increase on Flux



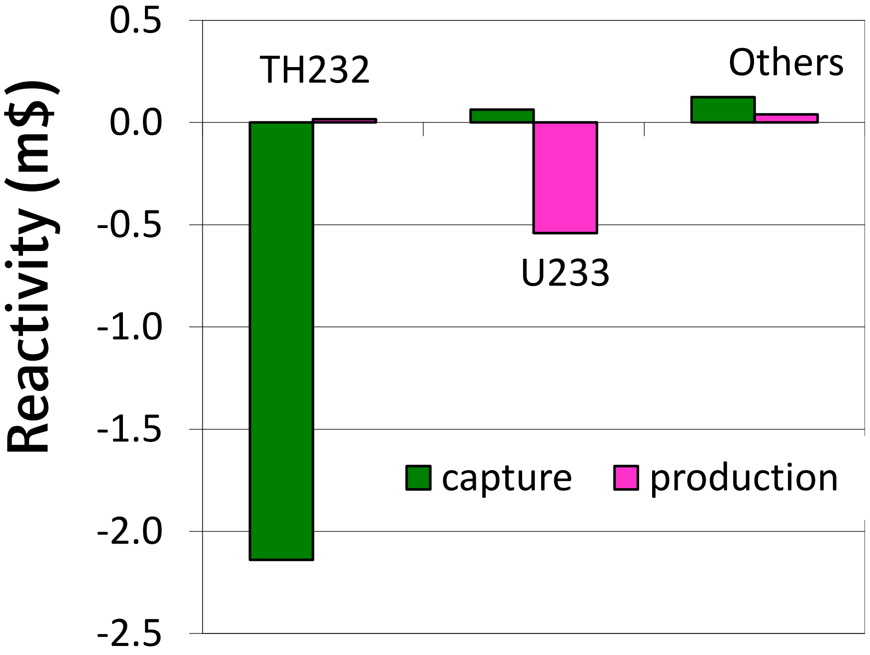
Larger resonance captures from Doppler broadening -> more marked flux hardening ensuing fuel temperature increase-> larger Doppler effect in Th

Reactivity Decomposition – Doppler Coefficient

U-breakeven (-1m$/K)



Th-breakeven (-2m$/K)



Larger resonance captures in Th. Vs. U from Doppler broadening

- As a result of Doppler broadening, more marked flux hardening and more markedly negative contribution from U-233 vs. Pu-239

Burner Configurations – Fuels

- Oxide Fuel for both U and Th ARR burner designs
- Homogeneous recycle and no blankets

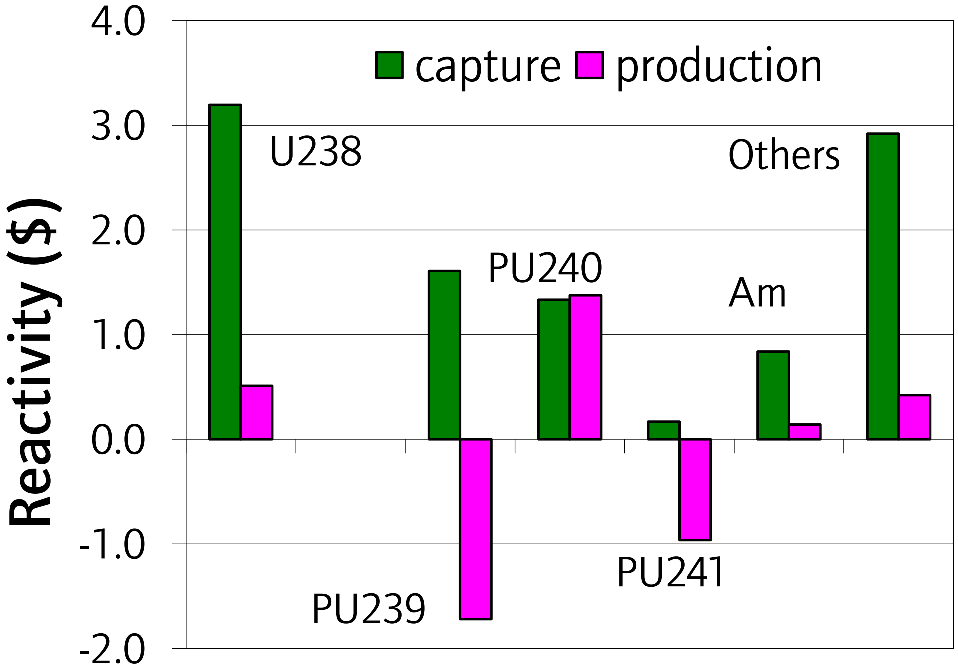
	U- Fuel	Th- Fuel
Fuel form	Oxide	Oxide
Fertile Feed	Natural U	Natural Th
Fissile Feed	TRU LWR	TRU LWR
Actinides Recycled	All	All
Smeared density	85%	85%
Core HM inventory [MT]	10.2	9.6
Driver Fuel Assemblies	322	322

Fuel Inventories and Reactivity Coefficients – Equilibrium

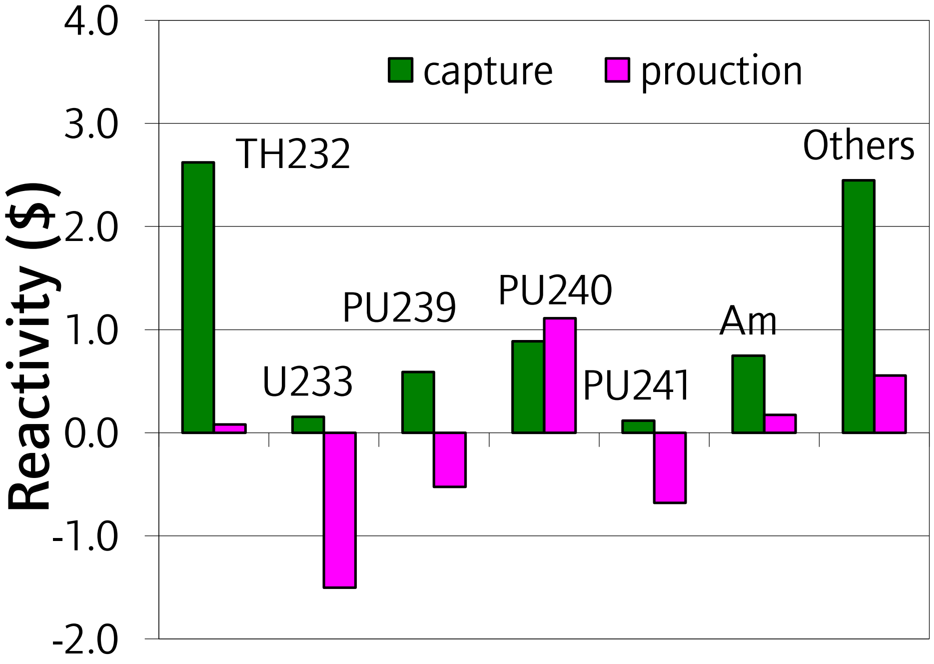
Core	U-TRU Ox	Th-U3-TRU Ox	Th vs. U (Delta)
Conversion Ratio	0.47	0.36	-0.11
TRU burning [kg/Gw_e-yr]	494	593	+99
Natural U or Th [w/o]	63.8 (U8)	58.3 (Th)	-4.8
U from Th [w/o]	-	9.9 (U3)	+9.3
Pu [w/o]	31.4 (Pu)	25.9 (Pu)	-5.5
Other elements [w/o]	4.8 (MAs)	5.9 (MAs)	+1.1
Doppler coeff. [m$/K]	-0.88	-0.88	0
Active core voiding [$]	4.20	2.66	-1.54
Coolant exp. coeff. [m$/K]	1.09	0.69	-0.4
Fuel exp. coeff. [m$/K]	-0.38	-0.30	+0.08
Radial exp. coeff. [m$/K]	-3.00	-3.24	-0.24
βeff [pcm]	315	285	-30
Reactivity swing [%]	5.1	5.6	+0.5

Void Coefficient Reactivity Decomposition – Burner Cores

U-burner



Th-burner



Lower but significant improvement from Th than in the breakeven cores

- lower U-233 content and higher proportion of TRU in the burner core
- Most of the improvement from Th-232 vs. U-238 and U-233 vs. Pu-239 contents in the respective burner cores inventories

Comparison of Inherent Safety Characteristics (All Cases)

Core Type	**Burners**		**Breakevens**	
Fuel Type	**U-TRU Ox**	**Th-U3-TRU Ox**	**U-TRU-Zr Metal**	**Th-U3 Nitride**
Doppler coeff. [m$/K]	-0.88	-0.88	-1.03	-1.94
Active core voiding [$]	4.20	2.66	4.91	-1.01
Coolant exp. coeff. [m$/K]	1.09	0.69	1.28	-0.26
Fuel exp. coeff. [m$/K]	-0.38	-0.30	-0.51	-0.17
Radial exp. coeff. [m$/K]	-3.00	-3.24	-2.81	-2.25
Reactivity swing [%]	5.1	5.6	2.9	4.9
β_{eff} [pcm]	315	285	361	342
A/B <1 (ULOF)	0.63	0.53	0.45	0.62
1<CΔTc/B<2 (ULOHS – chilled inlet)	1.27	1.31	1.26	1.29
CRs for inherent safety (UTOP)	14	14	10	11

Comparable performances of Th vs U in terms of asymptotic behavior in double-fault accidents

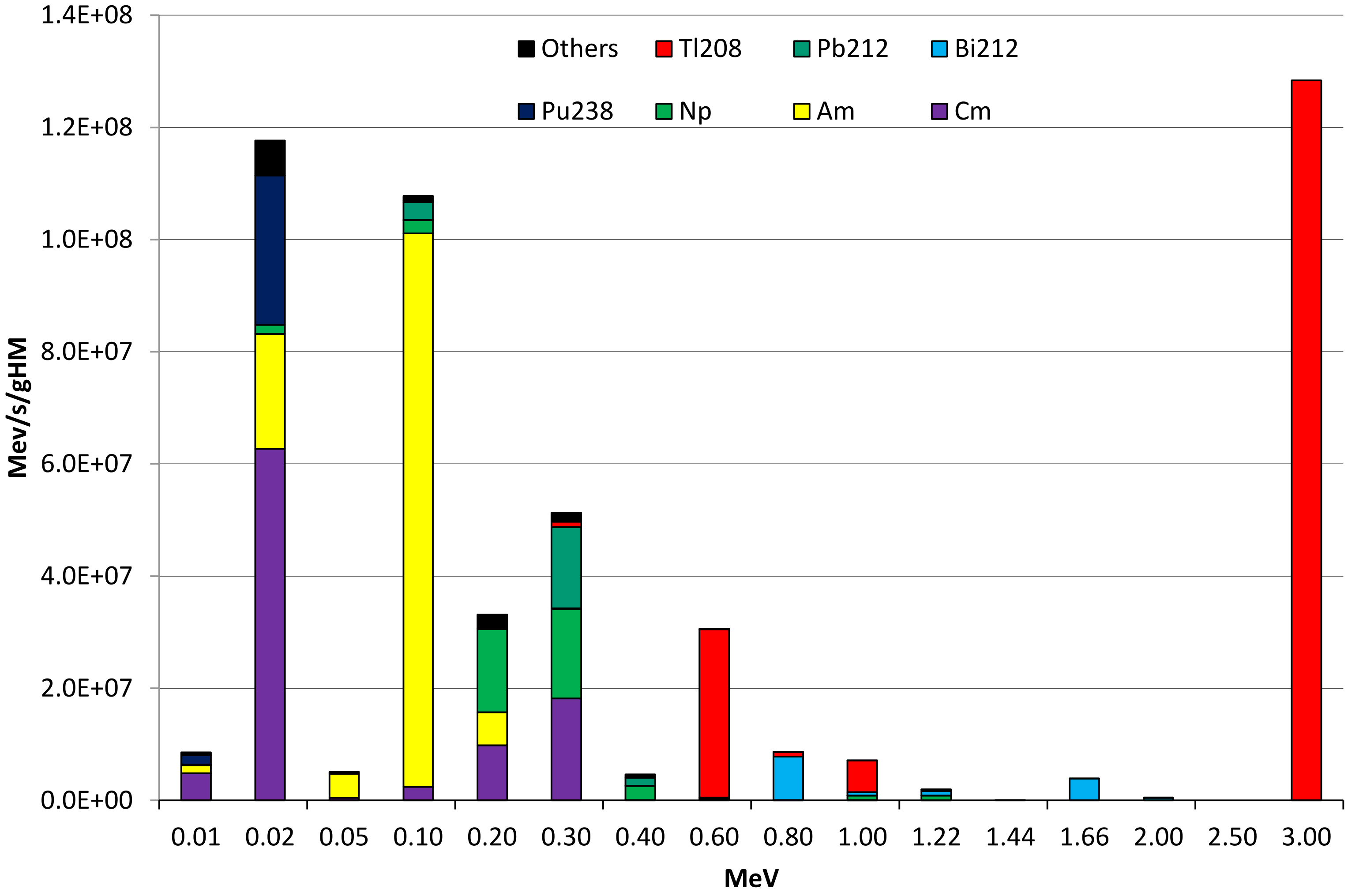
Neutron Source

(5-years cooling and various cumulative irradiation-years)

Designation	U-based FRBurner	Th-based FRBurner
Fuel Requirements:		
MT/GWe-yr System	3.6	3.1
Assembly/GWe-yr System	139	127
n/s/gHM		
0 EFPY*	1.6E+04	1.9E+04
21 EFPY	6.8E+04	7.6E+04
42 EFPY	1.1E+05	1.1E+05
110 EFPY	1.6E+05	1.7E+05
n/s/assembly		
0 EFPY	4.24E+08	4.65E+08
21 EFPY	1.77E+09	1.85E+09
42 EFPY	2.75E+09	2.77E+09
110 EFPY	4.20E+09	4.11E+09
% Contribution of Cm, (Cf)		
0 EFPY	98% (0%)	98% (0%)
21 EFPY	96% (3%)	97% (2%)
42 EFPY	78% (21%)	85% (14%)
110 EFPY	58% (41%)	65% (34%)

* EFPY = Effective Full Power Years

Gamma Source
(5-year cooling and 1-year after reprocessing)



Conclusions

- Thorium fuel significantly reduces void positive reactivity insertion
  - ~2$ reduction for the ARR burner design (oxide fuel)
  - ~6$ reduction for the ARR breakeven design (nitride Th vs. U metal)
- ~ 1m$/K more negative Doppler for the Th breakeven design
- *Effects on transients need to be assessed (underway)*
- Larger blankets, higher fuel manufacturing/reprocessing and larger reactivity swing in Th-breakeven
- Comparable long-term capability to withstand double-fault accidents
- ➢ *Thorium can be appealing for TRU burning and/or decreasing void reactivity keeping a simple design (e.g. axially homogeneous)*
- **Very high sources requiring remote fuel manufacturing for all cases (U and Th)**
- **Long term options with substantial developments/additional costs when full actinide recycle is pursued in U and for all cases in Th**

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