

# Why recycle actinides ? Closed fuel cycles and reactor concepts

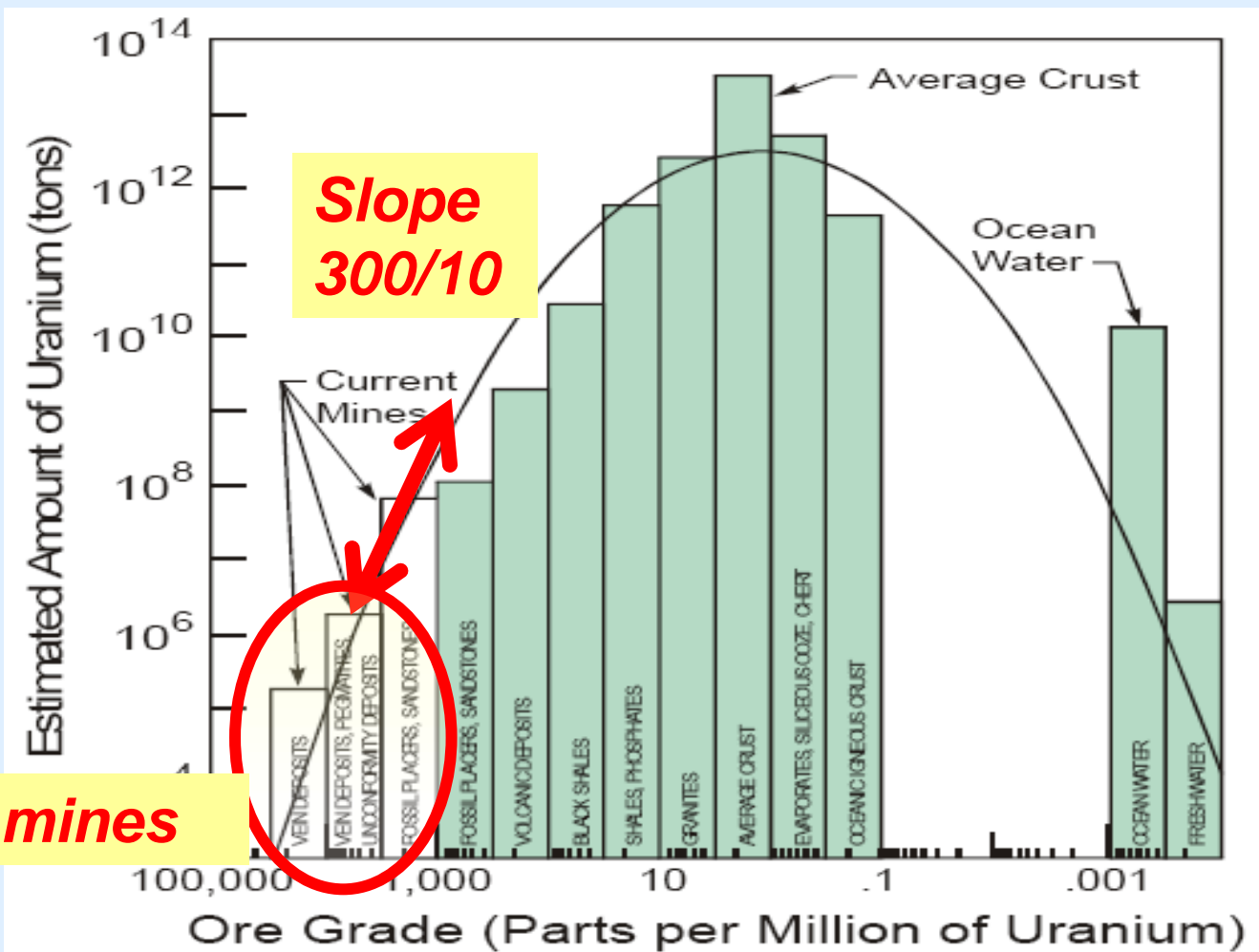
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Nuclear Energy and Safety - Paul Scherrer Institut , Switzerland

Workshop « Reactors for Actinide Management »

Interlaken, September 17th 2007

# There is enough Uranium distributed in Earth's crust



**Current mines**

## There is no medium-term shortage of Uranium

- Only the richest deposits are currently being mined
- The slope at our present location on the concentration versus resource curve is 2.5 to 1. Thus, one would expect a 300-fold increase in the available resource for every tenfold decrease in the ore grade.
- No reactor built in the next couple of decades and operating on the once-through cycle would ever be shut down due to uranium scarcity, regardless of its conversion ratio.
- Conventional reserves = 11.5 million tonnes U. If used in once through cycles... **will last for multiple decades but not for a century**

*H.M. Prasser, this conference*  
“Soft Results” on Uranium sources

- Natural uranium can be the primary energy source for a fleet of LWRs in the long term – *provided prospection is intensified*
- This would lead to a slow but continuous growth of necessary mining activities – *provided acceptance is given*
- New reactor generation are desirable to limit mining and the connected environmental impact – *provided the new technology becomes economic*

Nuclear energy has more than one option for a long term fuel supply:

*Natural Uranium*

*Plutonium 239 from Uranium 238*

*Uranium 233 from Thorium*

*Nuclear Fusion*

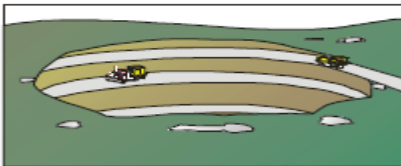
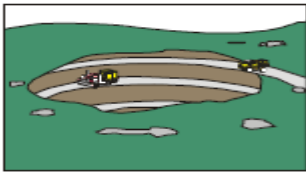
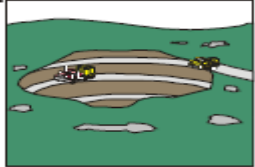
## So, why should we recycle actinides ? What are *your* reasons to recycle them ?

- Better use of easily accessible (i.e. cost-effective) resources
- Less waste, with shorter lifetimes
- Less repository sites, more densely packed
- Less heat in waste
- Better national independence
- Lesser risk of proliferation

# Reversing waste build-up in a growing nuclear economy is possible

ORNL DWG 2001-125

**Resource Base  
(Thorium and Uranium)**



**Waste Arisings**



## A guided tour of 4 studies and references

- **FCCG study** : Generation IV Roadmap Fuel Cycle Assessment Report, Fuel Cycle Crosscut Group, GIF-014-00, December 2002 and references therein
- **NEA study** : Advanced Nuclear Fuel Cycles and Radioactive Waste Management, NEA 5990, Nuclear Energy Agency, 2006 and references therein
- **Red-Impact study** : Final Report of EU-FP6 Red-Impact Project, 2007, to be published
- **NEA Conference** : Actinide and Fission Product Partitioning and Transmutation, NEA, 9IEMPT-Nîmes Sept.2006, published November 2007

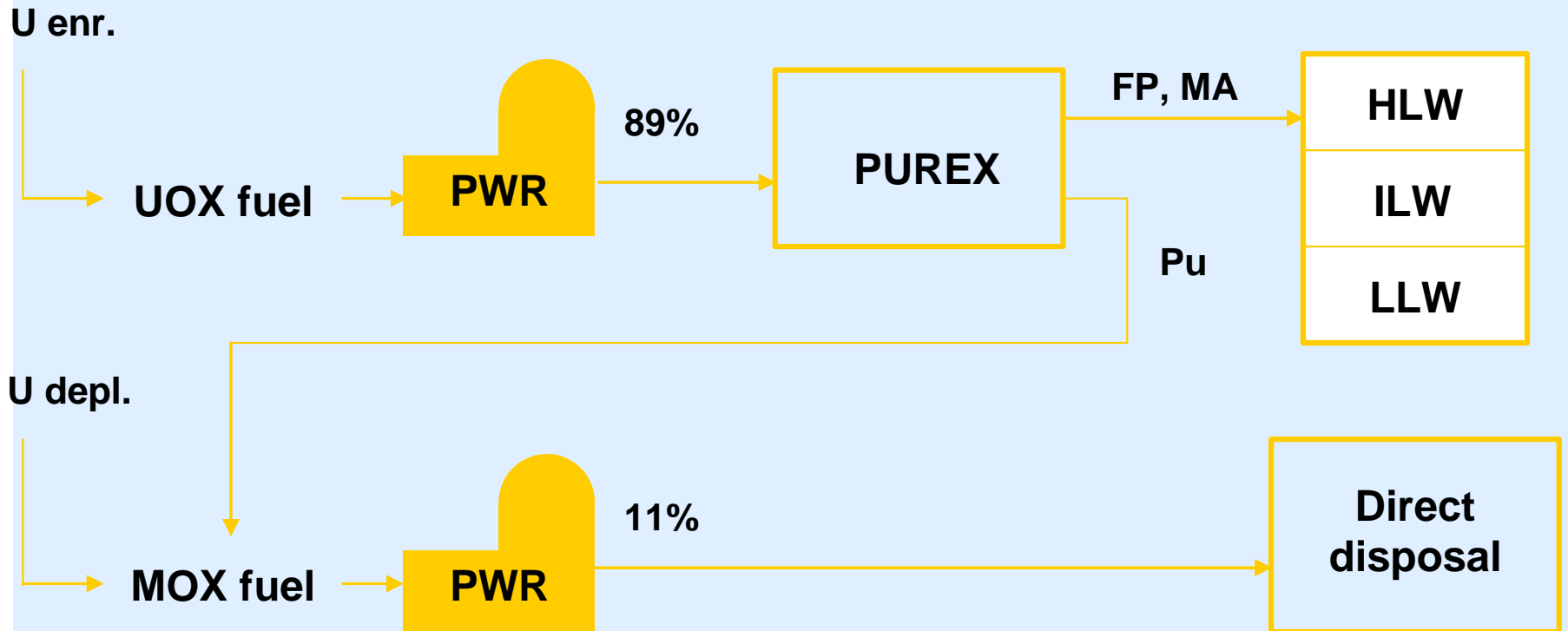
## There are many transition paths to sustainability

- Example of NEA study : 13 fuel cycle schemes
  - Present industrial practice and evolutions : 1a...1d
  - Partially closed cycles (Pu + ...) : 2a...2cV
  - Fully closed cycles for all An : 3a...3cV2
- 6 fuel reprocessing plants, with different feeds and products
- 4 underground repository concepts : clay, granite, salt and tuff

## Present industrial practice

### Scheme 1b PUREX reprocessing fuel cycle

Plutonium is recycled once in the form of MOX.

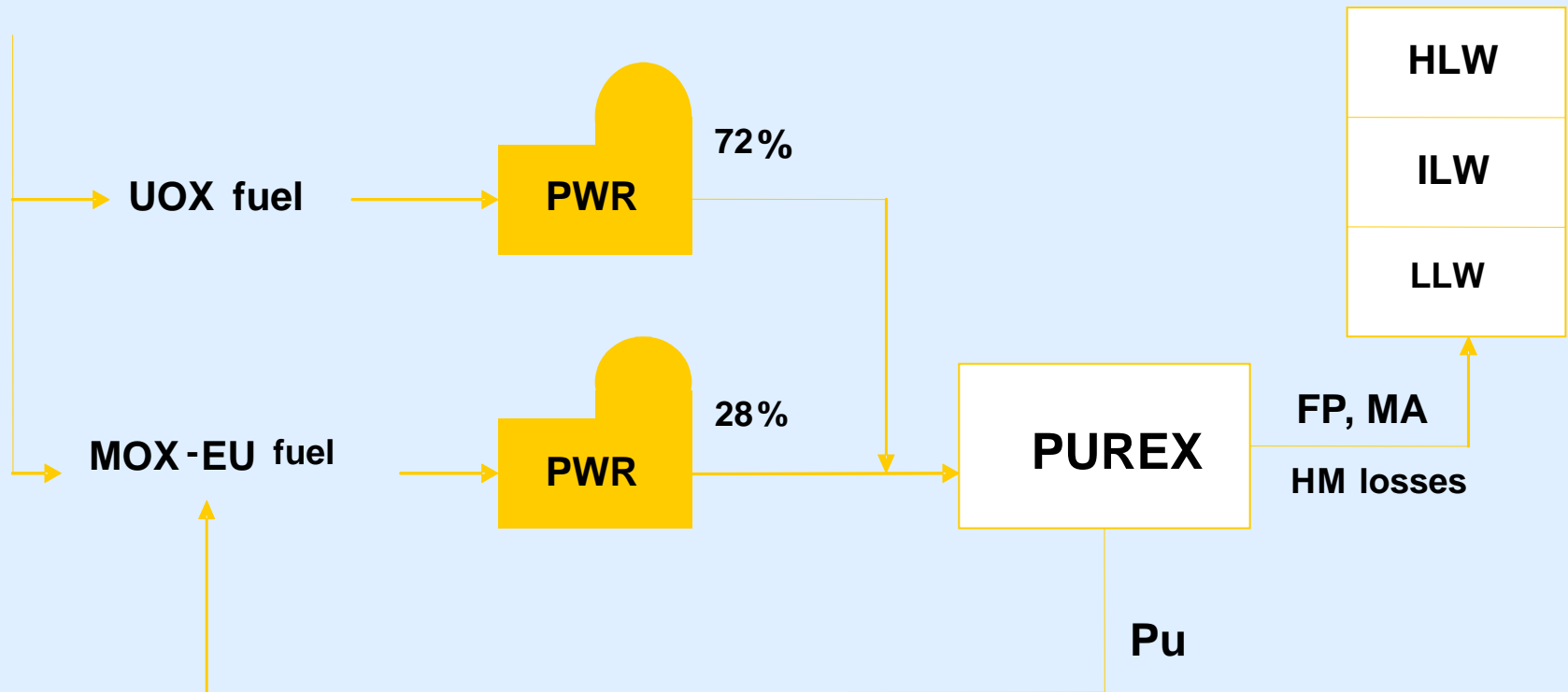


## Partially closed cycle

### Scheme 2a : Plutonium burning in LWR

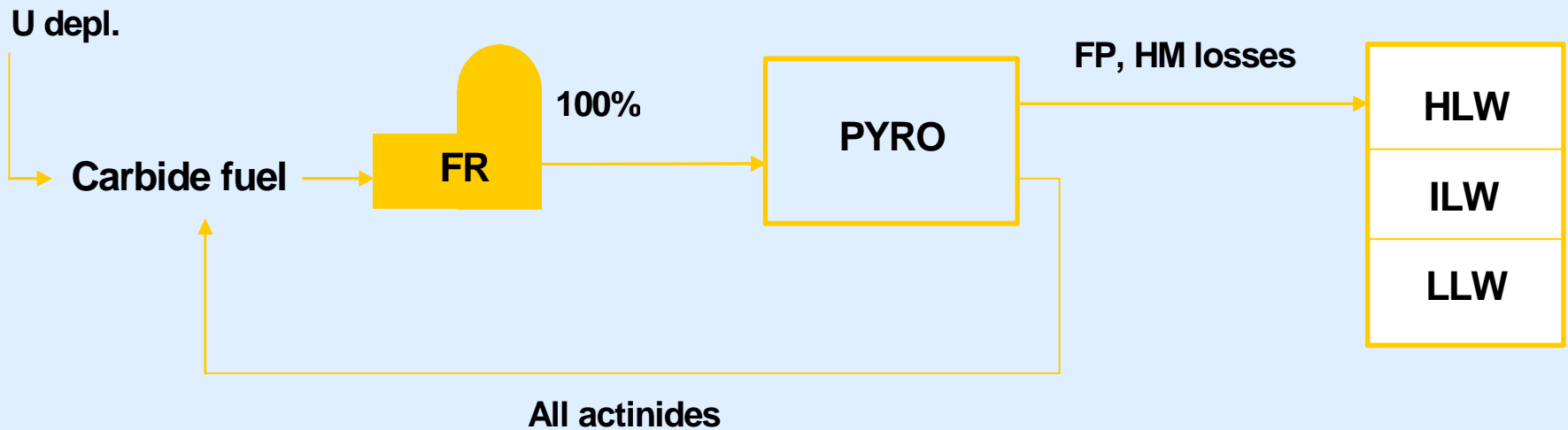
Uses LWRs only. Requires MOX fuel with enriched uranium (MOX-EU).

**U enr.**

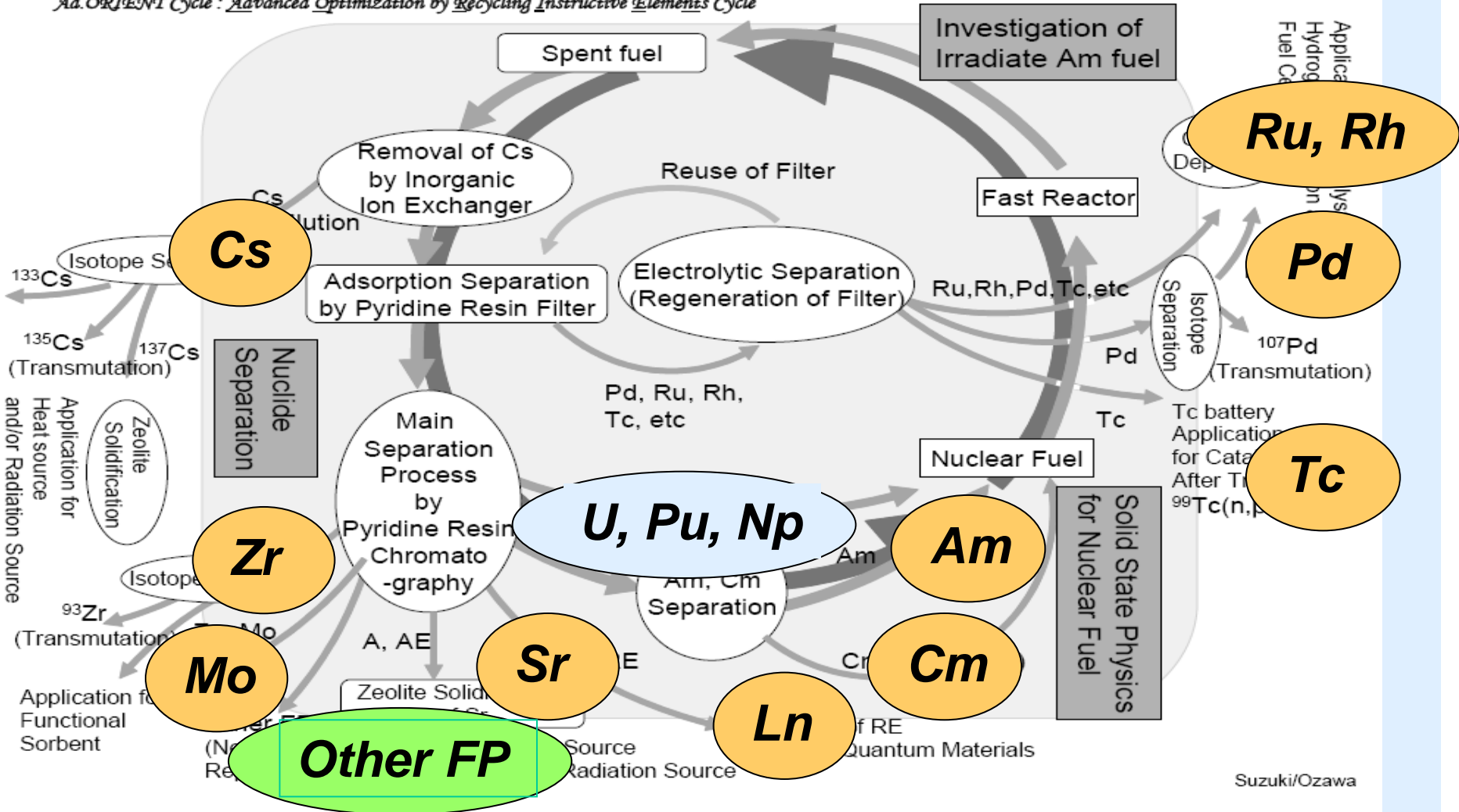


## Fully closed cycle, all Actinides

Scheme 3cV1 All-FR strategy *Based on Gen-IV gas-cooled fast reactor*



*Ad. ORIENT Cycle : Advanced Optimization by Recycling Instructive Elements Cycle*



**All separations are possible, e.g. ORIENT cycle**

## A sustainable use of resources is possible over millennia

- For recycle-based fuel cycles, if exploited fully, at least a millennium of energy supply
- A tenfold increase of the nuclear park *and* a tenfold increase of resource duration are possible, and more !
- The energy potential of thorium is greater still

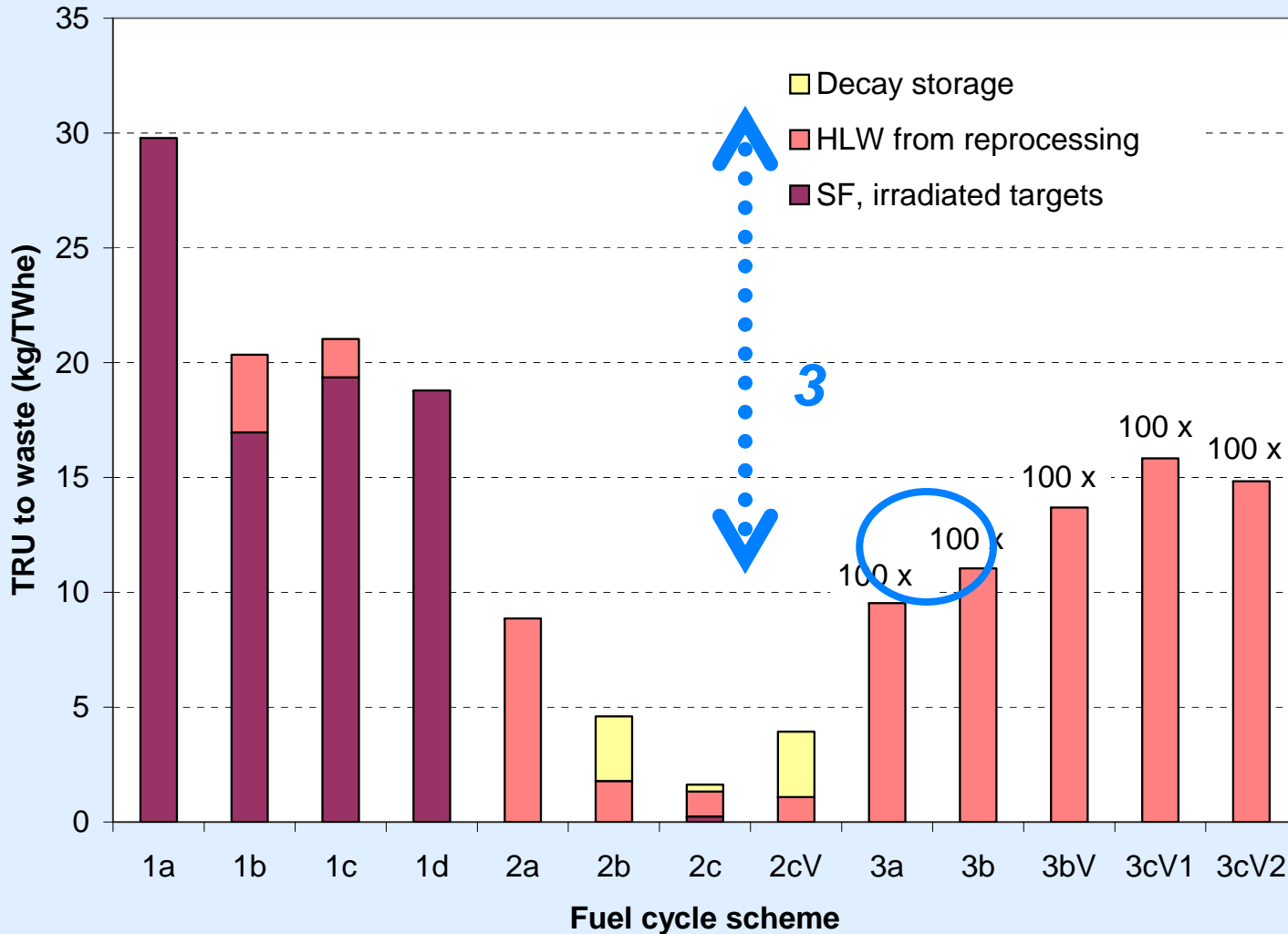
## Natural uranium consumption may be reduced by 1/250 relative to once-through fuel cycle (1a)

1b	1c	1d	2a	2b	2c(V)	3a	3b	3bV	3cV1	3cV2
0.89	0.90	0.59	0.87	0.99	0.44	0.63	0.65	0.76	0.004	0.036

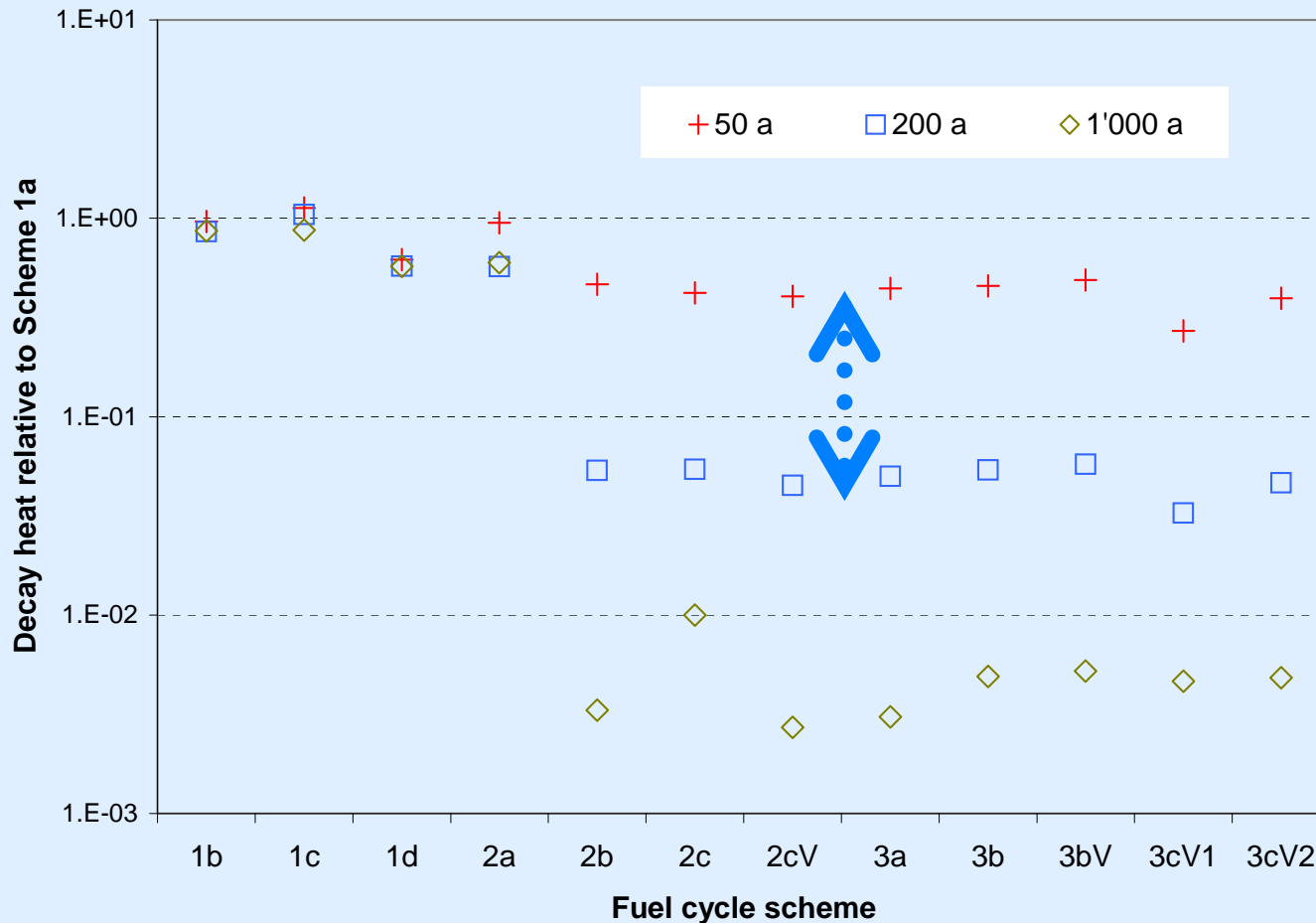
Note: Schemes 3cV1 and 3cV2 operate with depleted uranium.

- U lasts 100 years in once-through use of conventional reserves
- It lasts 250 times more in all-FR mode
  - 10 times more NPPs for 2500 years
  - 25 times more NPPs for 1000 years
- Transition Mix LWR + FR = U consumption of LWRs dominate

# TRU losses to waste may be reduced by 1/300



# Decay storage for 200 years may reduce heat load by 1/30



## Gallery length in clay may be reduced by 1/10

Fuel cycle scheme	1a	1b	2a	3cV1	3cV1 (separation of Cs, Sr)
Thermal output HLW after 50 years (W/TWhe)	2 110	2 031	1 997	571	12.5
Thermal output Cs-waste after 100 years (W/TWhe)	n.a.	n.a.	n.a.	n.a.	120.9
Length of disposal galleries (m/TWhe)	7.033	6.77	6.657	2.016	0.755
Length of disposal galleries relative to 1a	1	0.963	0.947	0.287	0.107

## Gallery length and area in tuff may be reduced by 1/16

Scheme	1a	1b	2a	3cV1
Linear (TWhe/m)	0.52	0.60	0.85	8.27
Areal (TWhe/m <sup>2</sup> )	6.42E-03	7.35E-03	1.05E-02	1.02E-01
Linear relative to Scheme 1a	1.00	1.14	1.63	15.90

## Disposing of “cold” waste may reduce heat load by 1/30

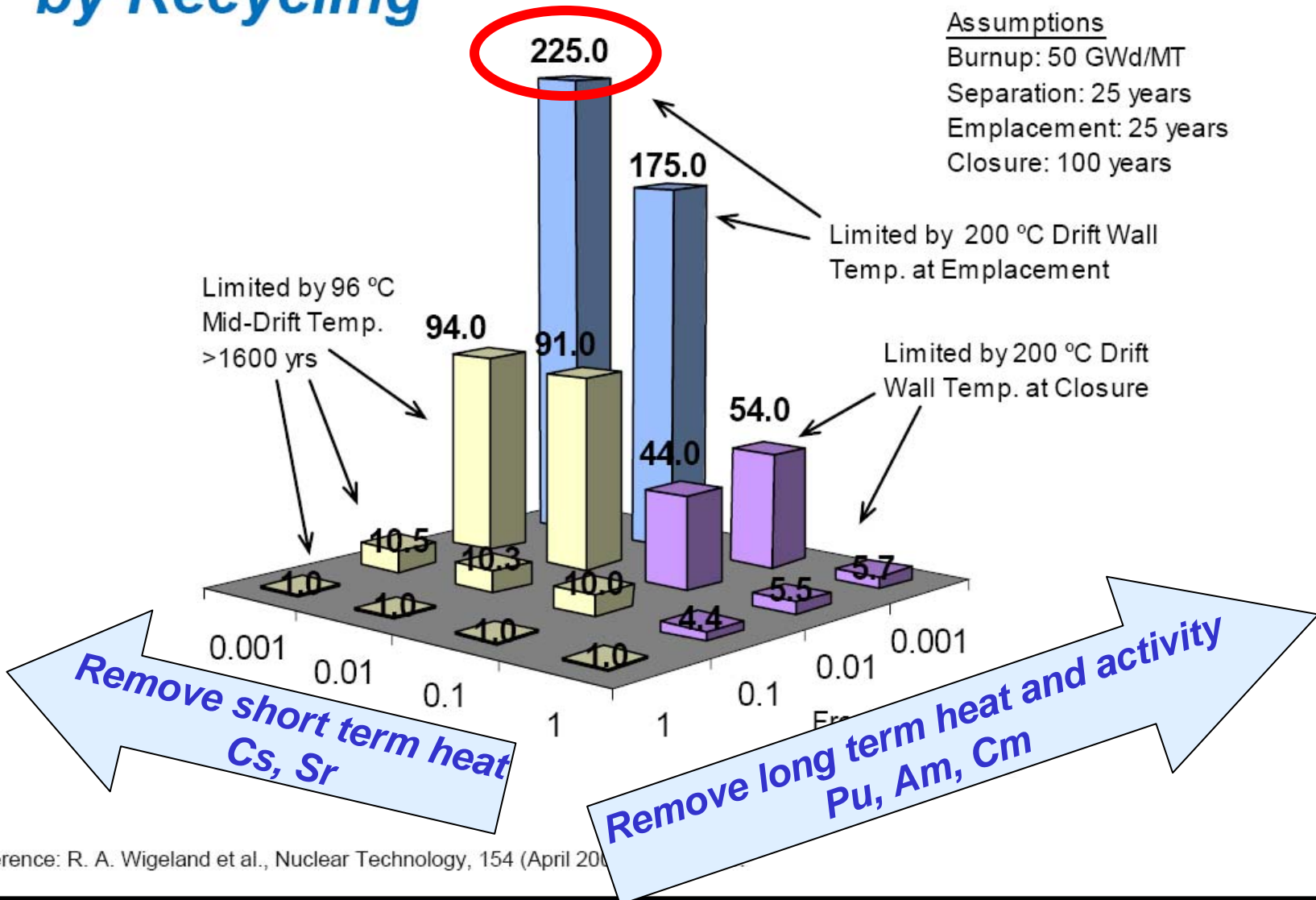
Decay storage period extended from 50 to 200 years

	Unit	Fuel cycle scenario			
		1a	1b	2a	3cV1
A. Thermal output HLW (50 y)	W/TWhe	2 110	2 031	2 000	571
B. Thermal output HLW (200 y)	W/TWhe	591	506	337	19.3
A/B		3.57	4.01	5.93	29.59
A for given Scheme/A for Scheme 1a		1	0.963	0.948	0.271
B for given Scheme/A for Scheme 1a		0.280	0.240	0.160	0.009

# Relative Increase in Repository Capacity by Recycling

## Assumptions

Burnup: 50 GWd/MT  
 Separation: 25 years  
 Emplacement: 25 years  
 Closure: 100 years

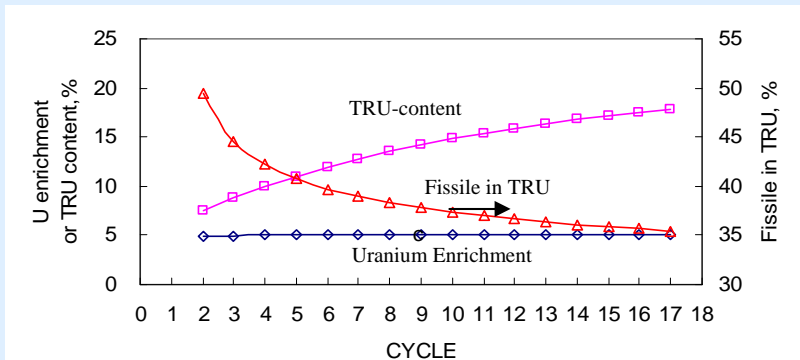
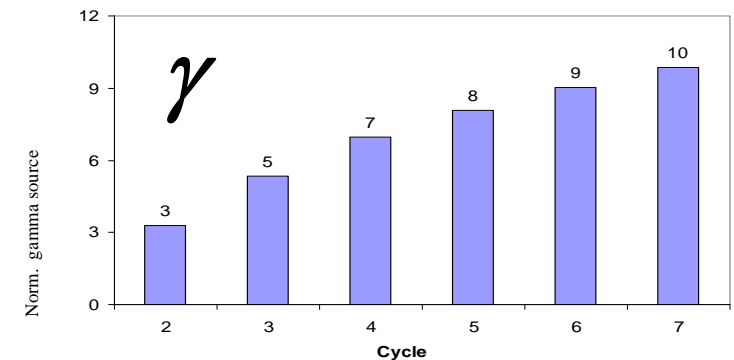
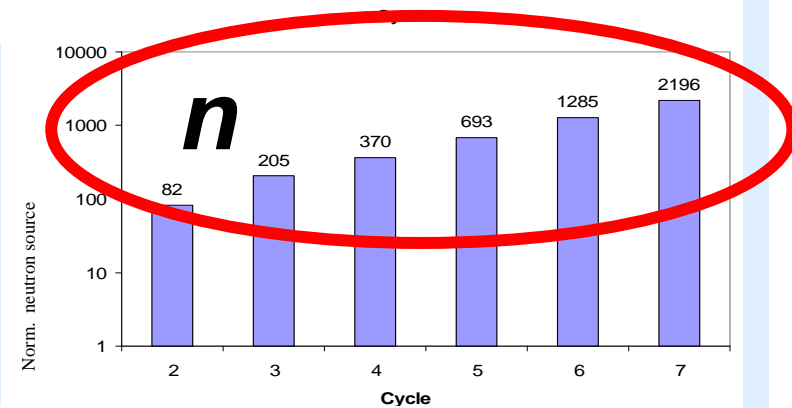
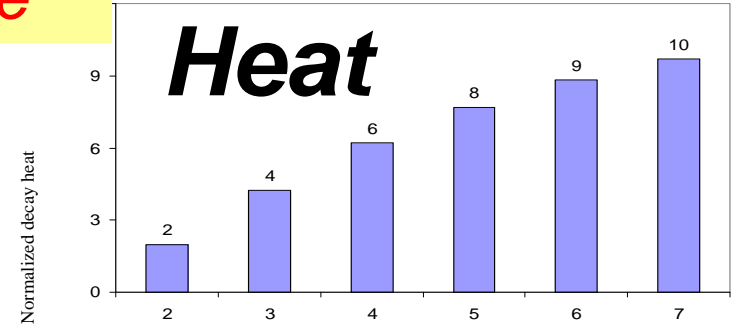


Reference: R. A. Wigeland et al., Nuclear Technology, 154 (April 2001)

# T.Taiwo, this conference

## TRU Multi-recycling Results and Fuel Handling Parameters

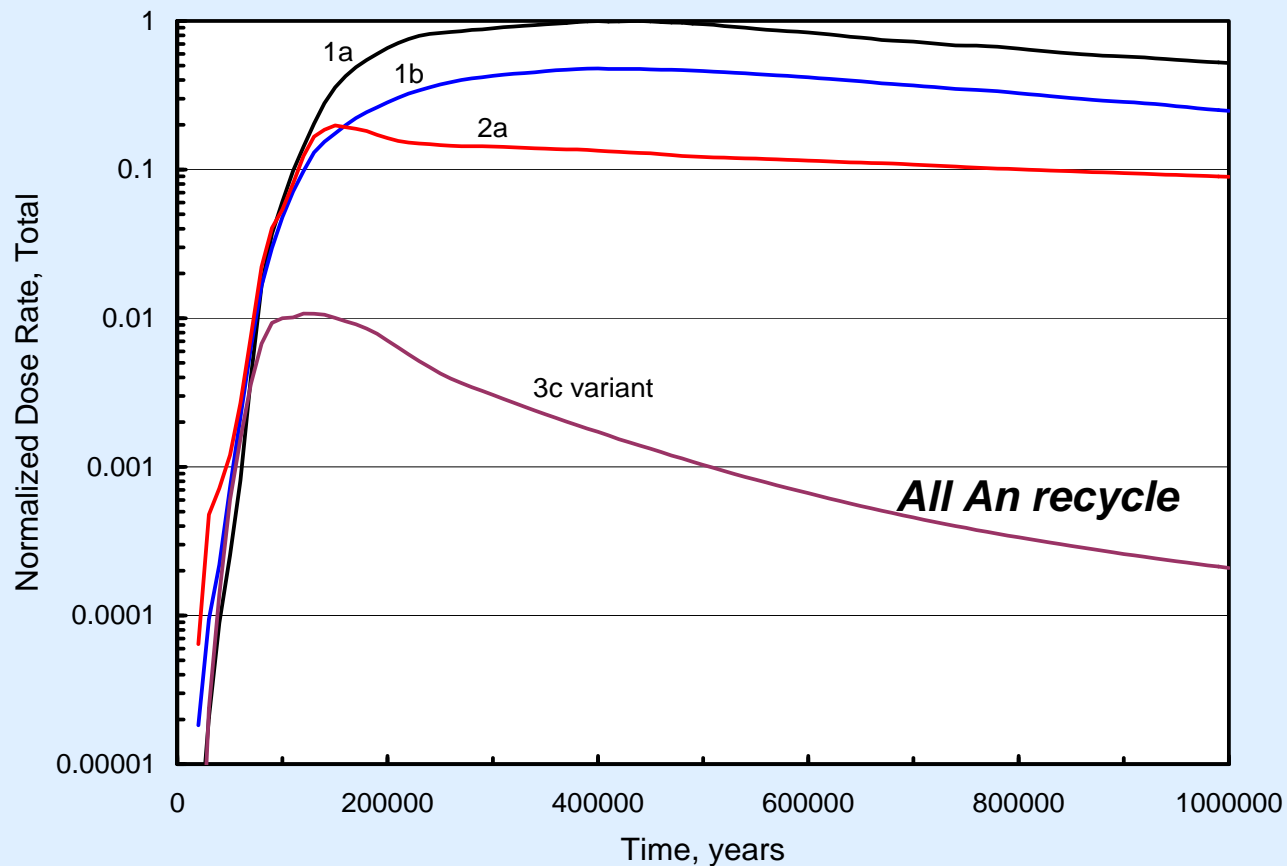
- From physics perspective, repeated recycle can be achieved
  - Enriched uranium support needed
- TRU content gradually increases with recycle stage
- Power peaking may be a problem at high TRU enrichment
- High MA content complicates fuel handling and usage, thus, number of recycles may be limited in practice
- Other designs have been investigated



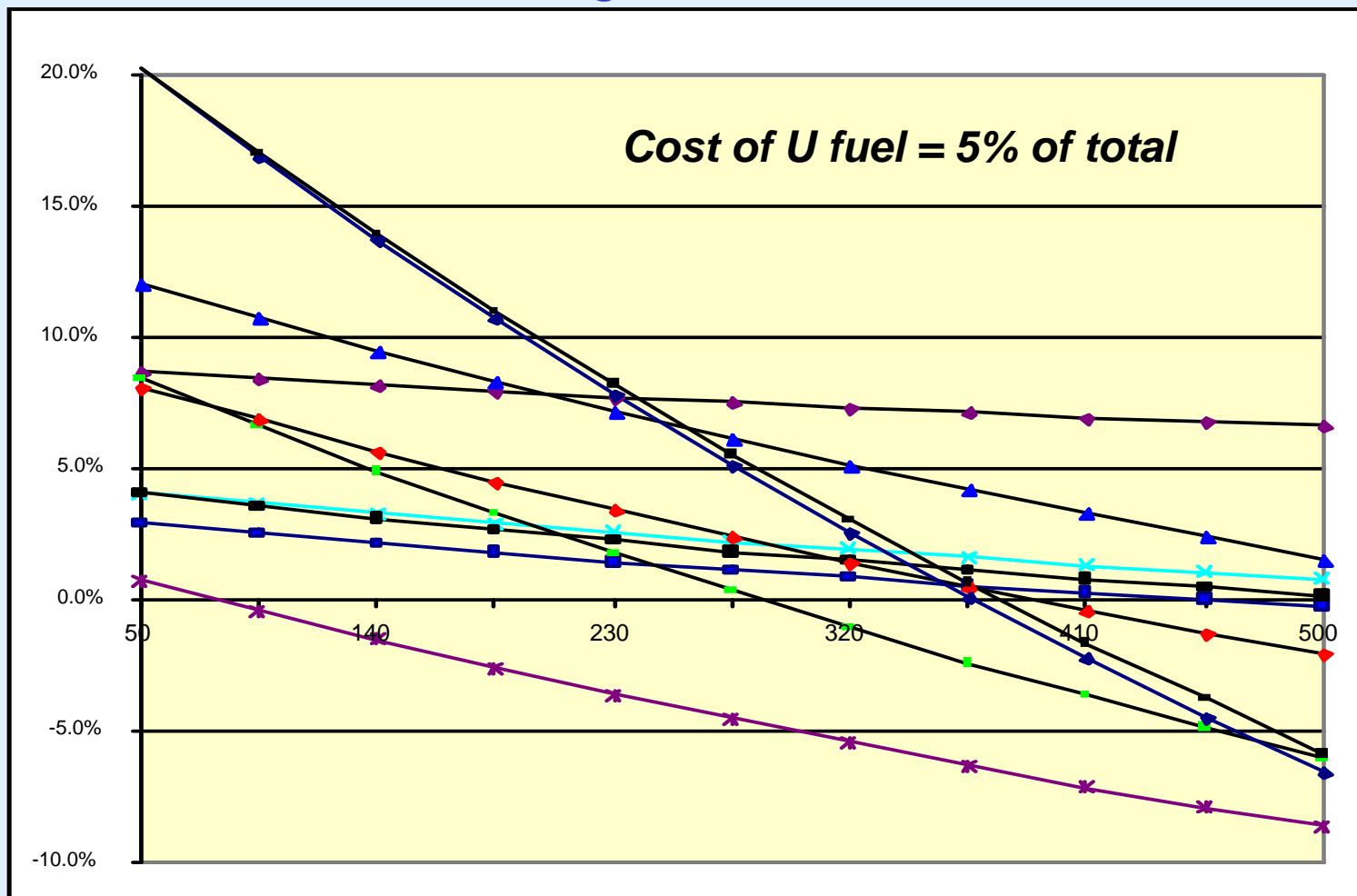
Mass Evolution with TRU Recycling

Fuel Handling Indices at Fabrication Stage Compared to CORAIL-Pu Cycle 7

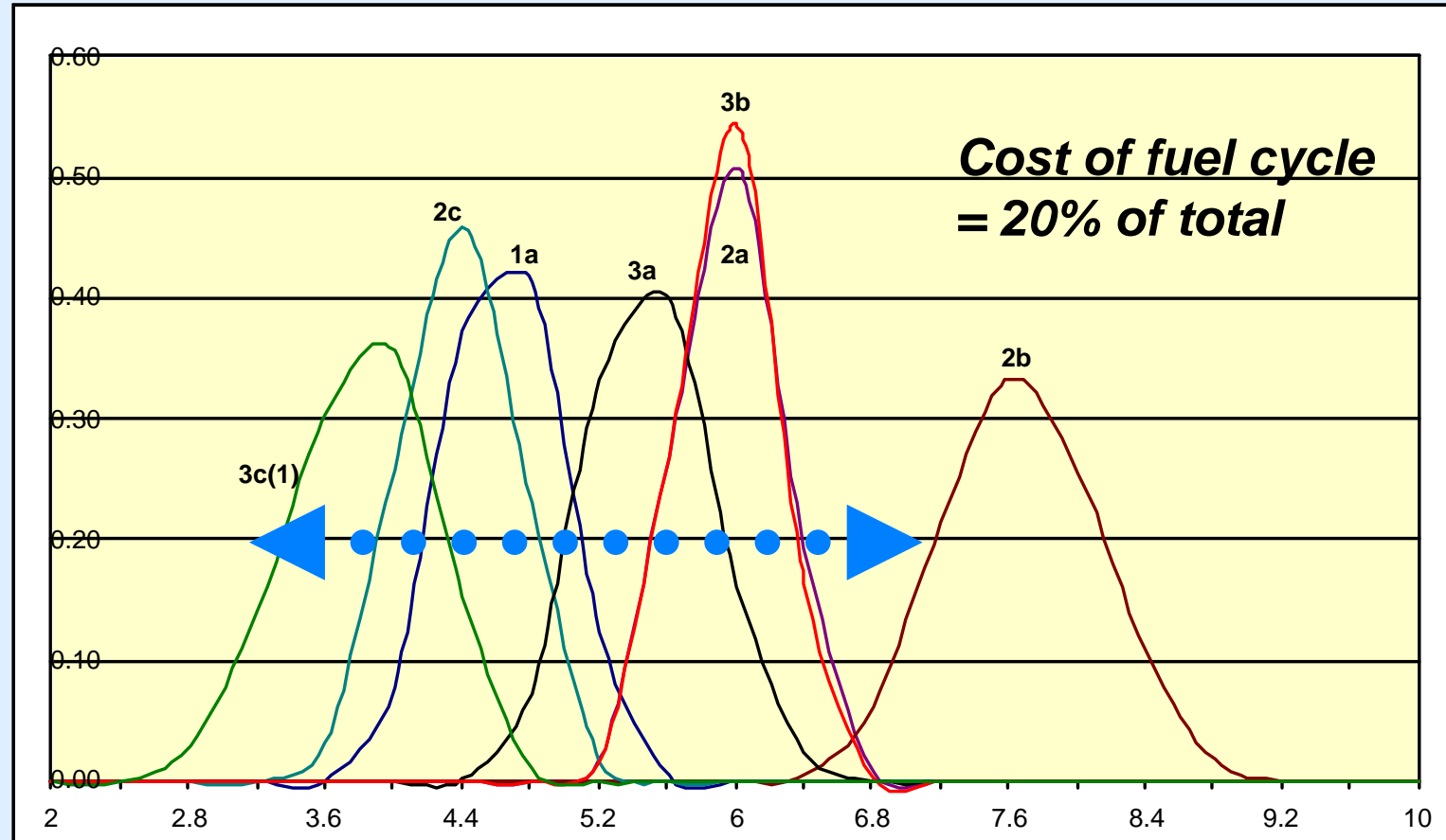
All doses remain below regulatory limits  
for all schemes, safety factors increased up to x100



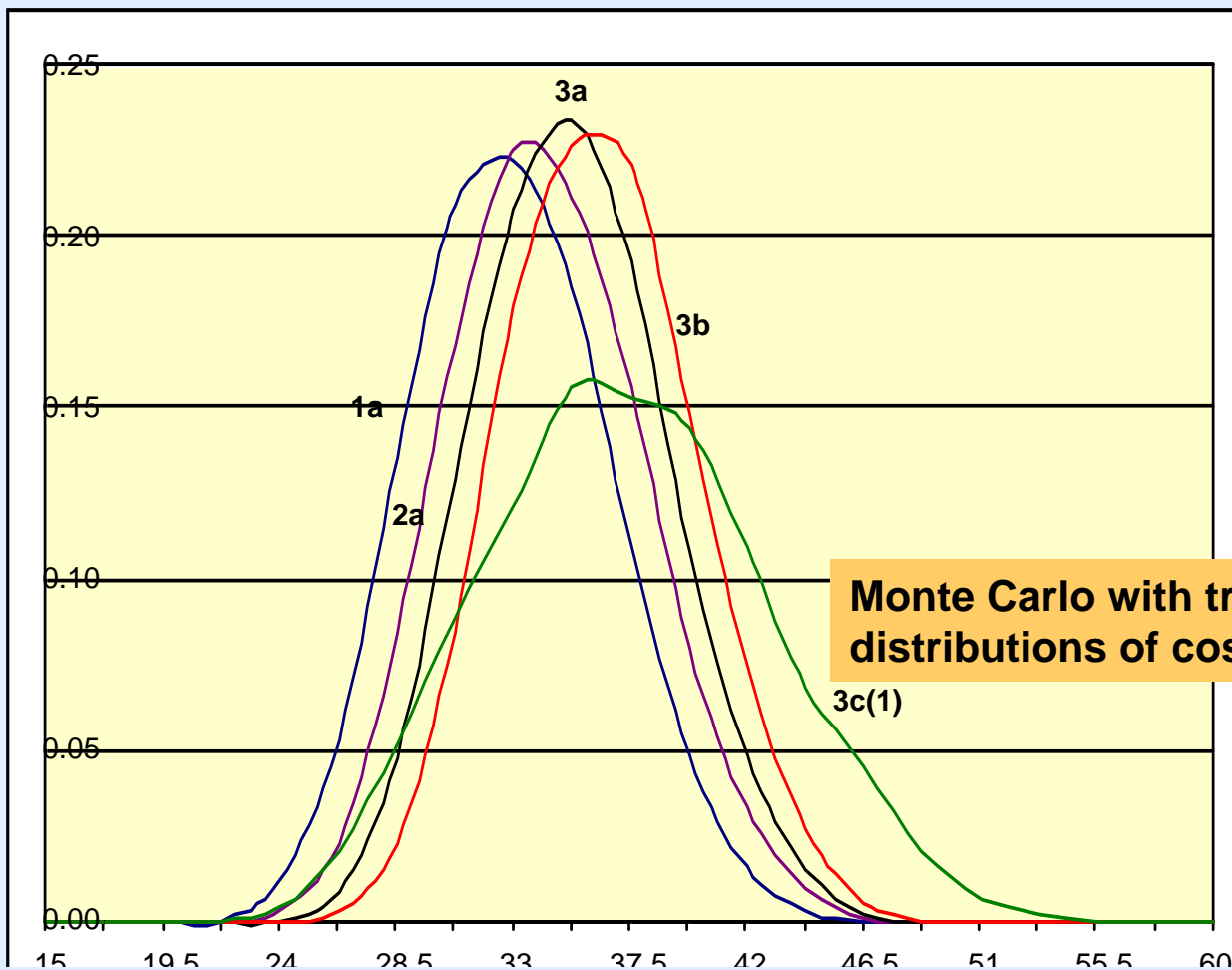
# Uranium price does not change the ranking of schemes unless it reaches 200 \$ /kg



# Fuel cycle cost has some sensitivity to the schemes (3 to 7 \$/MWh)

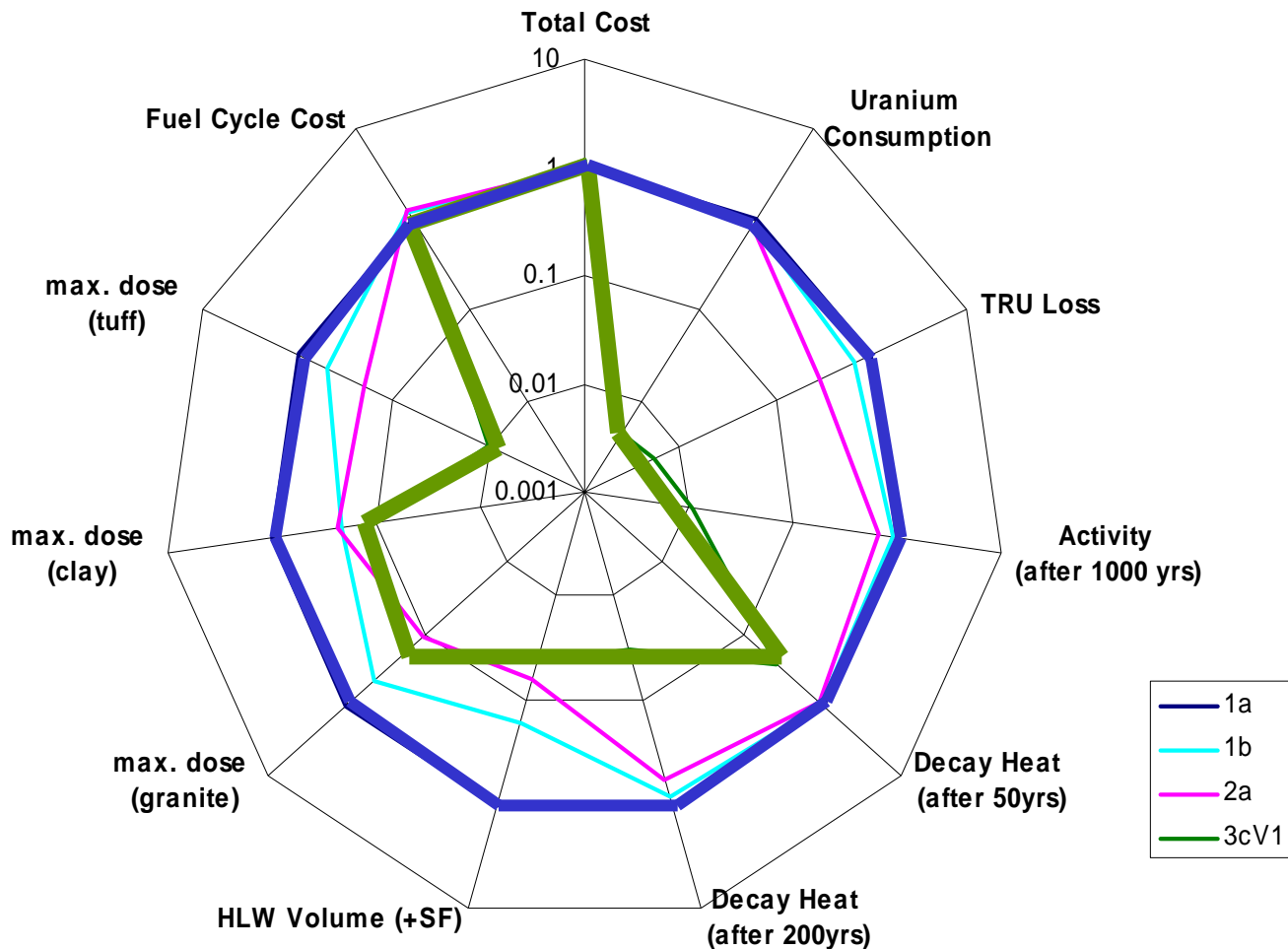


# There are many economically sound paths to sustainability



**Monte Carlo with triangular distributions of costs**

# Main results of NEA study (2006)



**1a** Once-through cycle as reference.

**1b:** full LWR park, Pu re-used once

**2a:** full LWR park, multiple re-use of Pu

**3cV1:** full fast reactor park and fully closed fuel cycle.

## Findings of Red-Impact study (2007)

- “An-free” HLW reduce gallery length use by 1.5 to 6 in granite and clay
- Sr removal and Cs decay storage for 100 y reduce further by x4 (total reduction by x13)
- Dose comes from FP in normal scenarios: no gain
- Dose comes from An in intrusion scenarios : gain 1/100
- Yucca Mountain tuff repository = 50 years with open cycle, 250 years to 1000 with fully closed cycle.
- **Intermediate Level Waste ILW give a lower limit to HLW minimization when dose (HLW) = dose (ILW)**

## Main results of all studies

- Resource use is controlled by U + Pu recycling
- Repository space use is controlled by
  - An recycling
  - Cs + Sr decay storage
- Intermediate steps towards full fast reactor parks already improve some aspects of sustainability
- Fast spectra with fully closed cycles are much more sustainable :
  - *Ecology*: full use of resources : a few millennia of Uranium
  - *Society*: much less waste x1/100, much better use of repository sites
  - *Economy*: almost unchanged : ~ 20%

# Nuclear Energy is sustainable

*Neither fossil nor renewable, Nuclear Energy with fast neutrons is sustainable for thousands of years*

- *Economically :*
  - *At the same affordable price as today ! All externalities included*
  - *Expansion of nuclear park not limited by resources or waste cost*
- *Socially :*
  - *Few radwaste repositories, very high safety*
- *Ecologically :*
  - *No greenhouse gases, resources for millennia*

*One may already profit from progresses in sustainability along the way , with Gen III + reprocessing + Pu sparing for Gen IV*