

**The International Conference ICENES-2007,
ISTANBUL, Turkey, June 03 – 08, 2007.**

**“A study on the Physical Characteristics of a Super-Critical LWR
loaded with ($^{233}\text{U} - \text{Th} - ^{238}\text{U}$)-oxide Fuel”**

E. Kulikov, A. Shmelev, G. Kulikov¹, V. Apse

Moscow Engineering Physics Institute (State University), Moscow, Russia

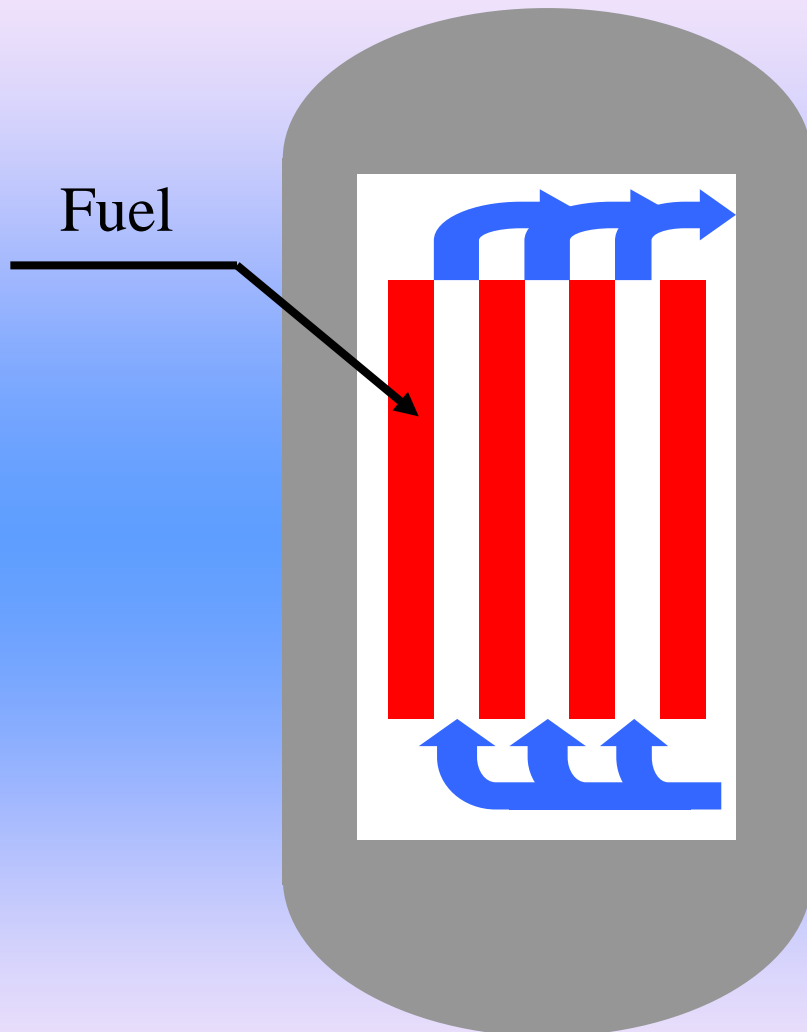
¹ International Science and Technology Center, Moscow, Russia



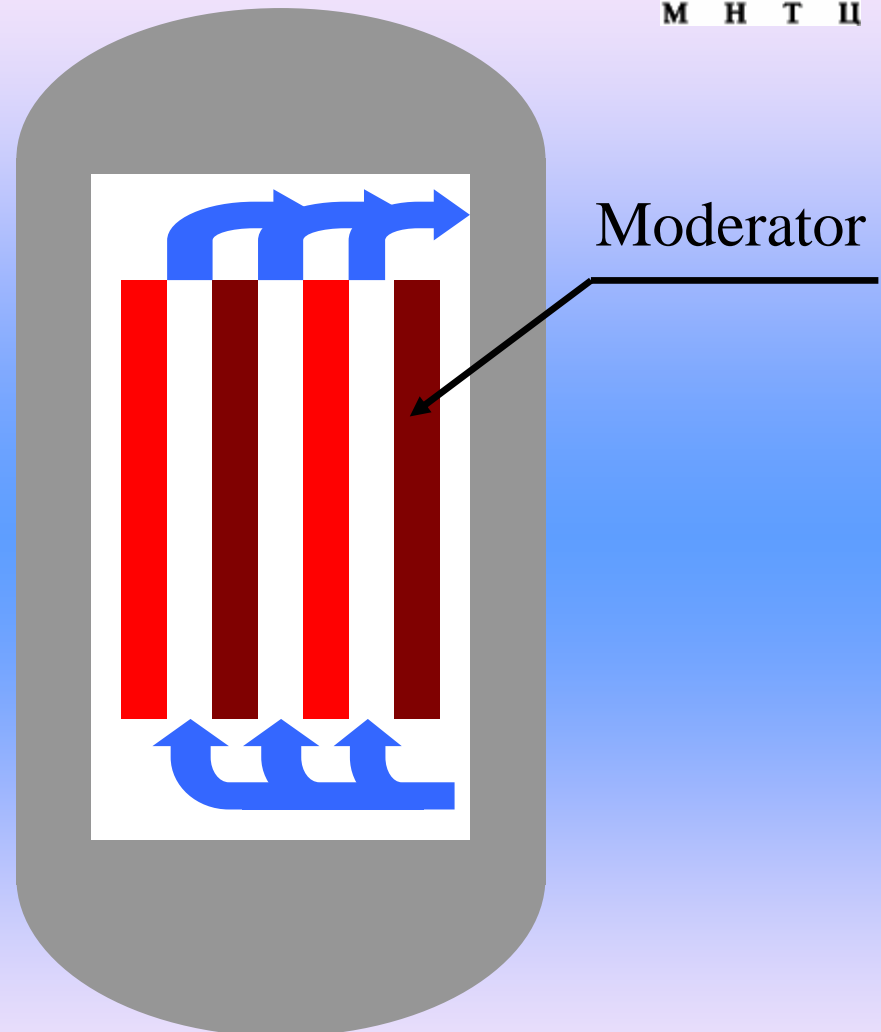
Points for Discussion:

1. Homogeneous mixture of ^{232}Th and ^{238}U :
neutron resonance structure;
2. On neutron multiplication properties
of ^{233}U and ^{239}Pu ;
3. Neutronics of fuel lattice in SCLWR;
4. Increase of ($^{233}\text{U} + ^{232}\text{Th} + ^{238}\text{U}$)-fuel burn-up;
5. On Proliferation Resistance of Closed Fuel Cycle

Super-Critical LWR concepts



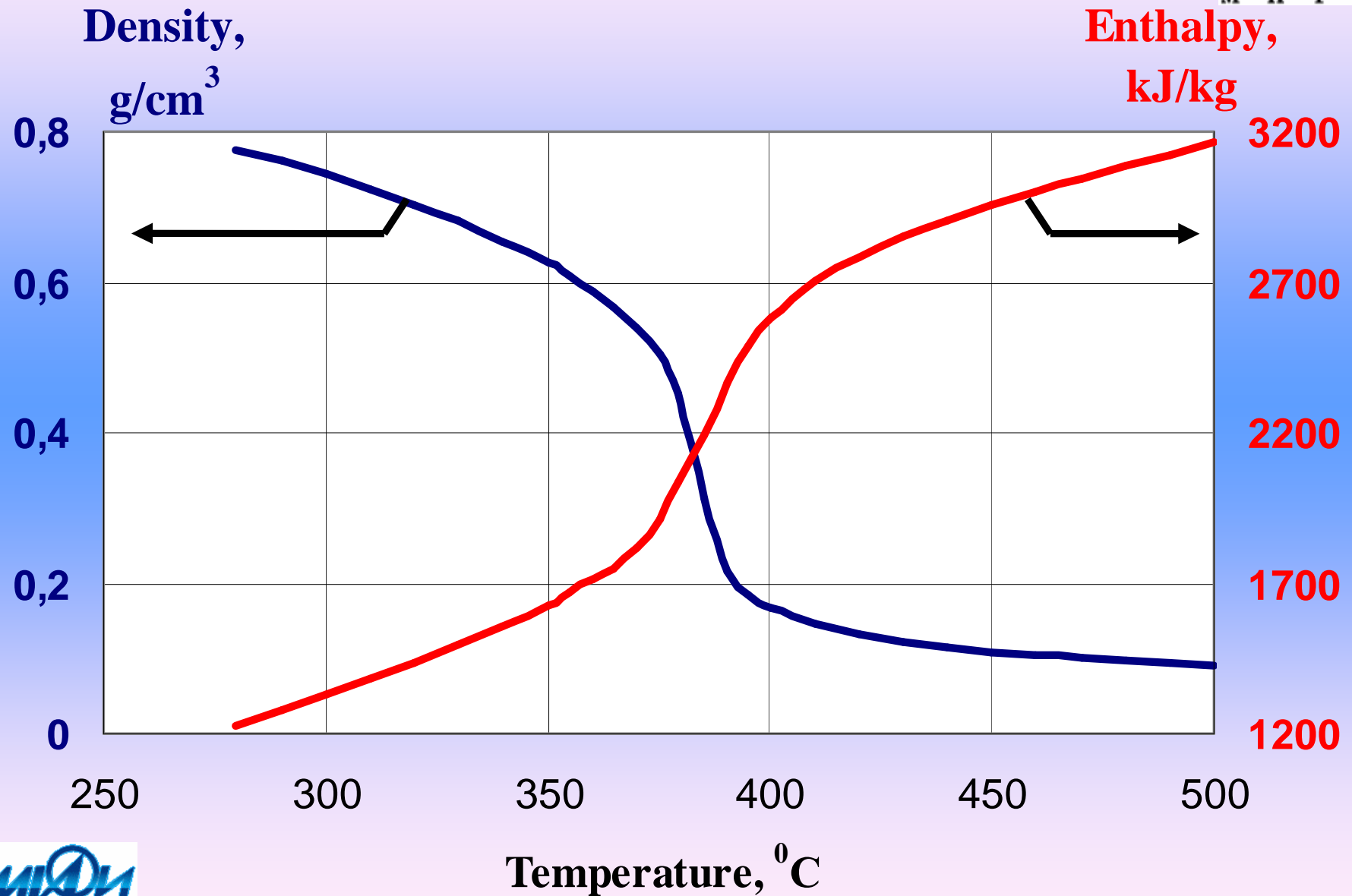
Option for analysis



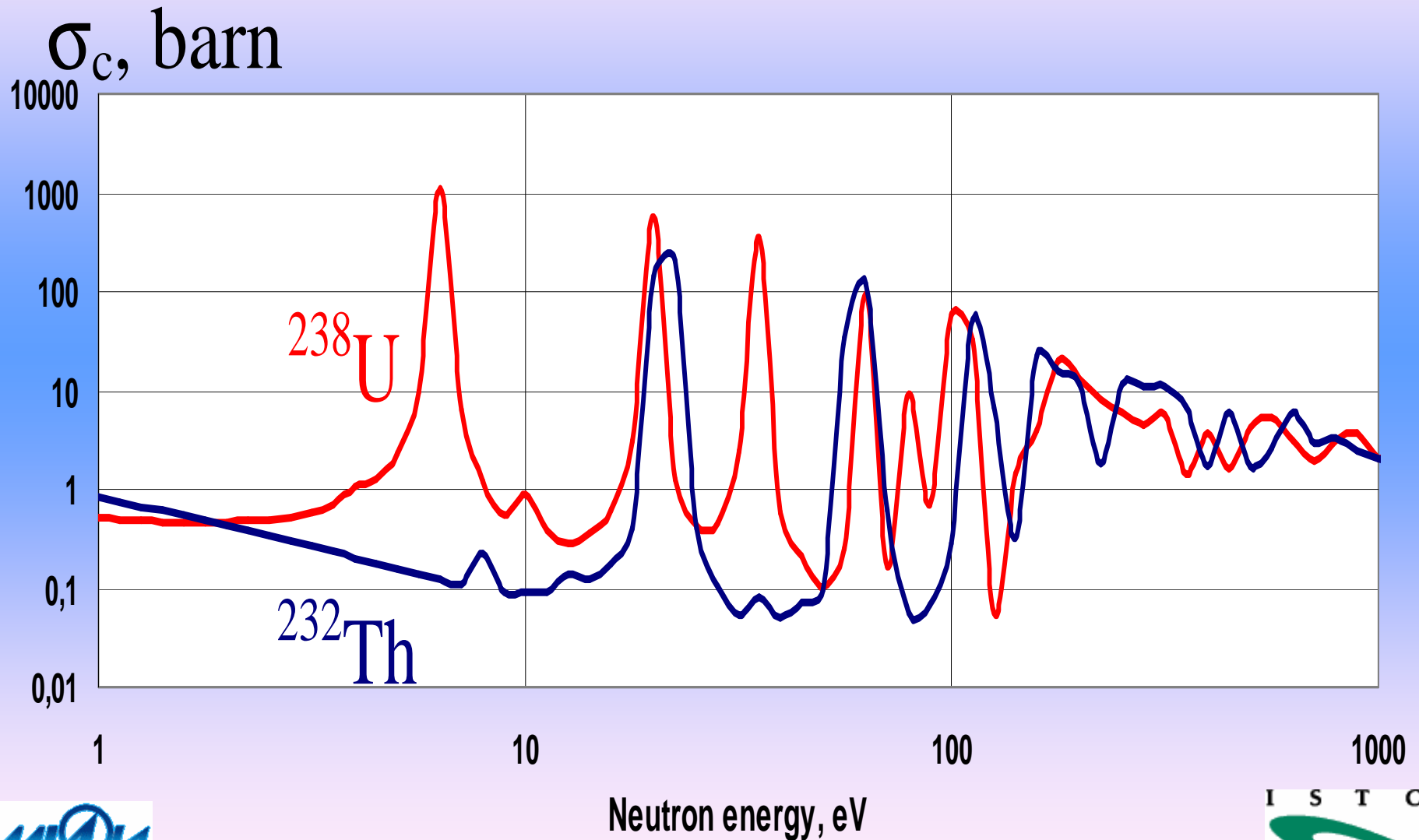
Some part of fuel elements in SA is replaced by moderator



Water properties under $p = 25 \text{ MPa}$



Neutron Capture of ^{238}U and ^{232}Th vs. neutron energy (1 ÷ 1000 eV)



$\alpha = \sigma_c / \sigma_f$ vs. neutron spectrum of SCLWR ($\gamma_{\text{H}_2\text{O}} = 0,72 \div 0,4 \text{ g/cm}^3$)

Fraction, %		$\gamma_{\text{H}_2\text{O}} = 0,72 \text{ g/cm}^3$		$\gamma_{\text{H}_2\text{O}} = 0,4 \text{ g/cm}^3$	
Th-232	U-238	U-233	Pu-239	U-233	Pu-239
96	0	$\frac{7}{59} = 0,12$	$\frac{70}{123} = 0,57$	$\frac{4,6}{35} = 0,13$	$\frac{43}{72} = 0,60$
48	48	$\frac{5,5}{44} = 0,13$	$\frac{47}{84} = 0,56$	$\frac{3,4}{24} = 0,14$	$\frac{23}{39} = 0,59$
0	96	$\frac{6}{48} = 0,13$	$\frac{48}{87} = 0,55$	$\frac{3,6}{25} = 0,14$	$\frac{21}{36} = 0,58$

$$v_f (^{233}\text{U}) = 2,50 \quad \rightarrow \quad v_{\text{eff}} (^{233}\text{U}) = 2,23$$

$$v_f (^{239}\text{Pu}) = 2,89 \quad \rightarrow \quad v_{\text{eff}} (^{239}\text{Pu}) = 1,83$$

Multiplication properties of ^{233}U are more preferable than that for ^{239}Pu



$\alpha = \sigma_c / \sigma_f$ vs. neutron spectrum of SCLWR ($\gamma_{\text{H}_2\text{O}} = 0,4 \div 0,1 \text{ g/cm}^3$)

Fraction, %		$\gamma_{\text{H}_2\text{O}} = 0,4 \text{ g/cm}^3$		$\gamma_{\text{H}_2\text{O}} = 0,1 \text{ g/cm}^3$	
Th-232	U-238	U-233	Pu-239	U-233	Pu-239
96	0	$\frac{4,6}{35} = 0,13$	$\frac{43}{72} = 0,60$	$\frac{1,5}{11} = 0,14$	$\frac{7,8}{12} = 0,65$
48	48	$\frac{3,4}{24} = 0,14$	$\frac{23}{39} = 0,59$	$\frac{0,86}{6,4} = 0,14$	$\frac{4,4}{7,1} = 0,62$
0	96	$\frac{3,6}{25} = 0,14$	$\frac{21}{36} = 0,58$	$\frac{1,3}{9,2} = 0,14$	$\frac{2,4}{4,2} = 0,57$

$$v_f(^{233}\text{U}) = 2,51 \quad \rightarrow \quad v_{\text{eff}}(^{233}\text{U}) = 2,24$$

$$v_f(^{239}\text{Pu}) = 2,91 \quad \rightarrow \quad v_{\text{eff}}(^{239}\text{Pu}) = 1,82$$

Multiplication properties of ^{233}U are more preferable than that for ^{239}Pu

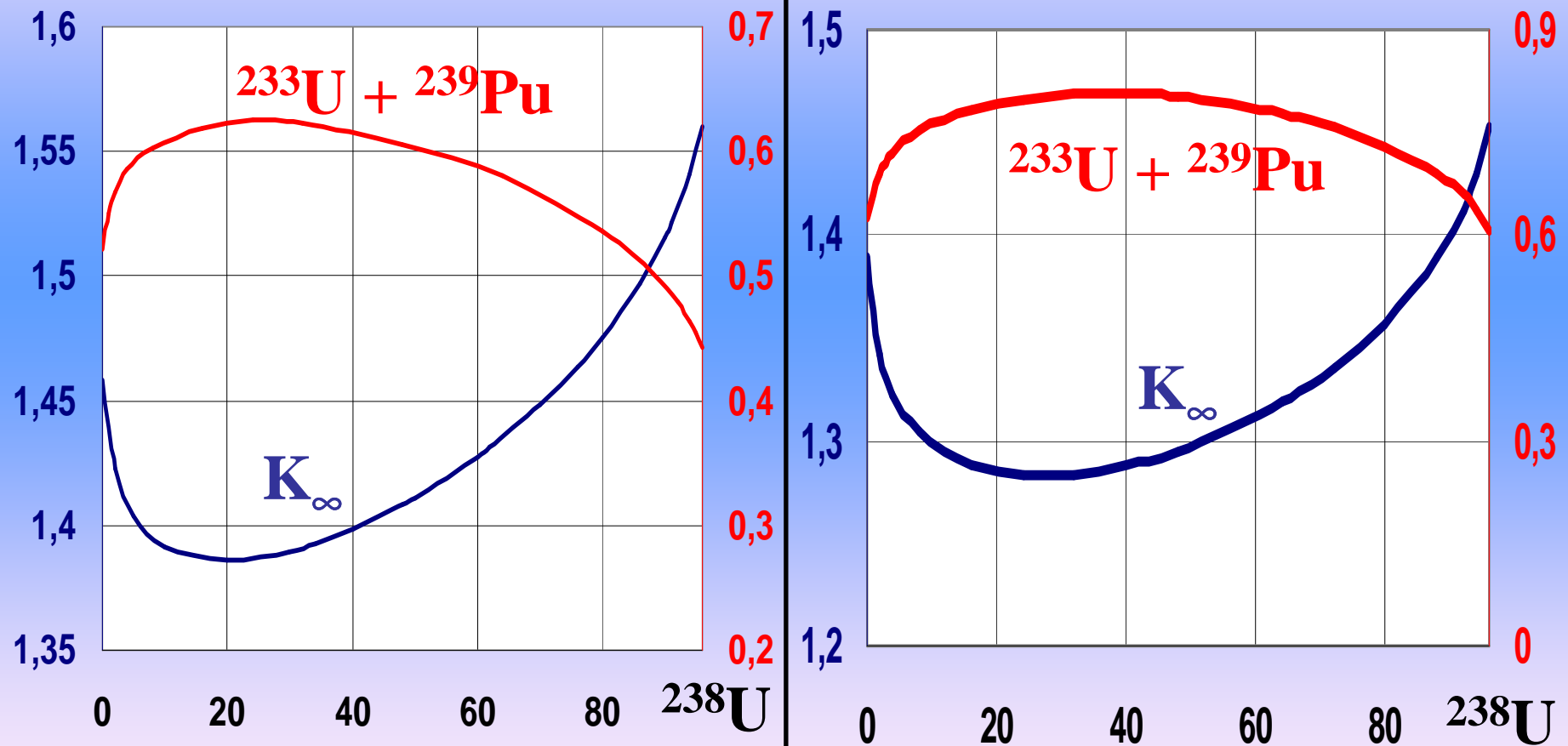


Multiplication factor K_∞ and Breeding Ratio ($^{233}\text{U} + ^{239}\text{Pu}$)

Fuel: (4% $^{233}\text{U} + 96\%$ [$^{232}\text{Th} + ^{238}\text{U}$]) O_2

$\gamma_{\text{H}_2\text{O}} = 0,72 \text{ g/cm}^3$

$\gamma_{\text{H}_2\text{O}} = 0,4 \text{ g/cm}^3$



^{238}U fraction in ($^{232}\text{Th} + ^{238}\text{U}$), %



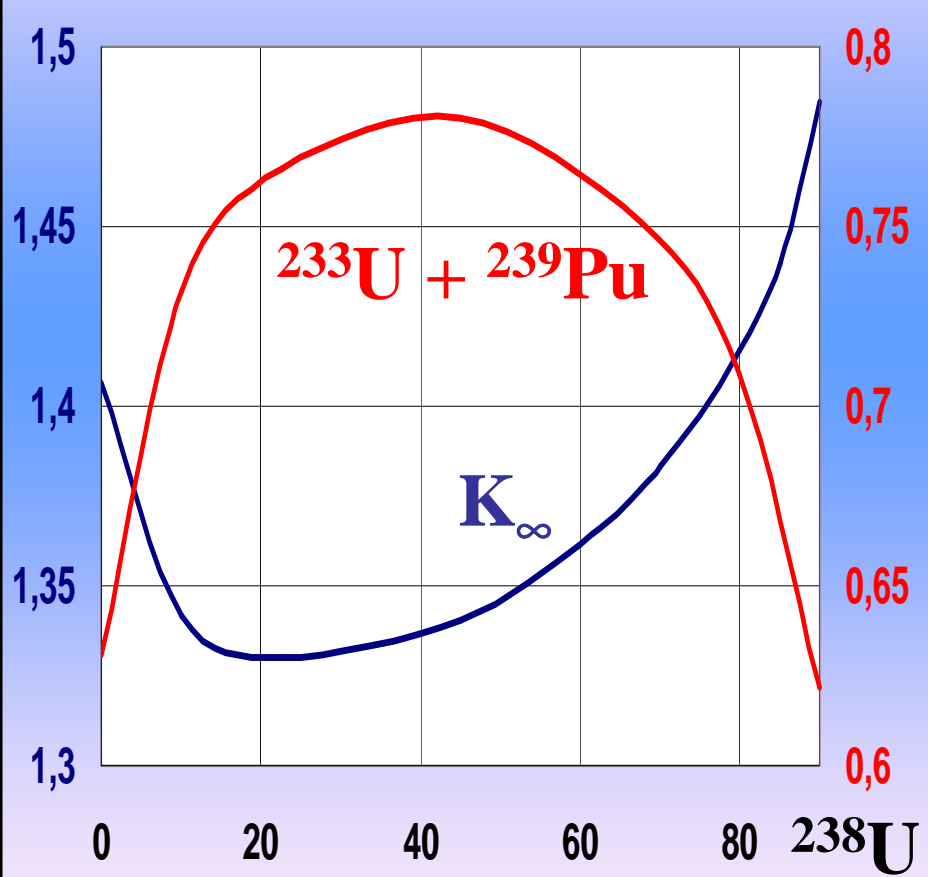
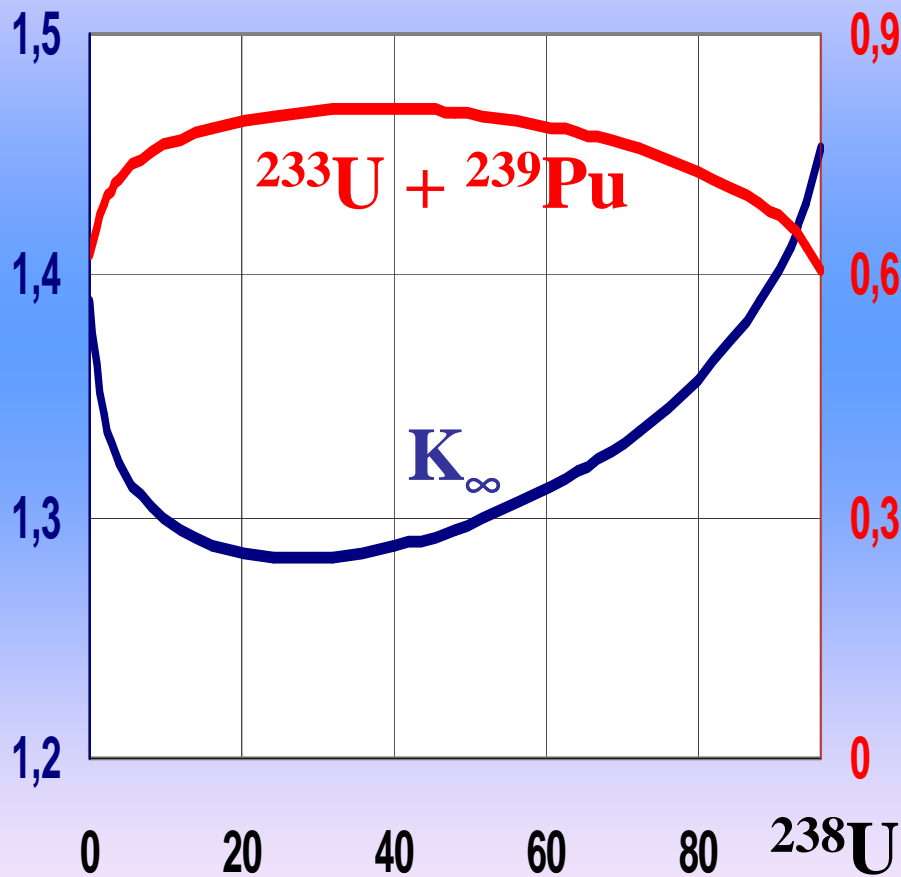
Multiplication factor K_∞ and Breeding Ratio ($^{233}\text{U} + ^{239}\text{Pu}$)

(4% $^{233}\text{U} + 96\%$ [$^{232}\text{Th} + ^{238}\text{U}$]) O_2

$\gamma_{\text{H}_2\text{O}} = 0,4 \text{ g/cm}^3$

(10% $^{233}\text{U} + 90\%$ [$^{232}\text{Th} + ^{238}\text{U}$]) O_2

$\gamma_{\text{H}_2\text{O}} = 0,1 \text{ g/cm}^3$



^{238}U fraction in ($^{232}\text{Th} + ^{238}\text{U}$), %



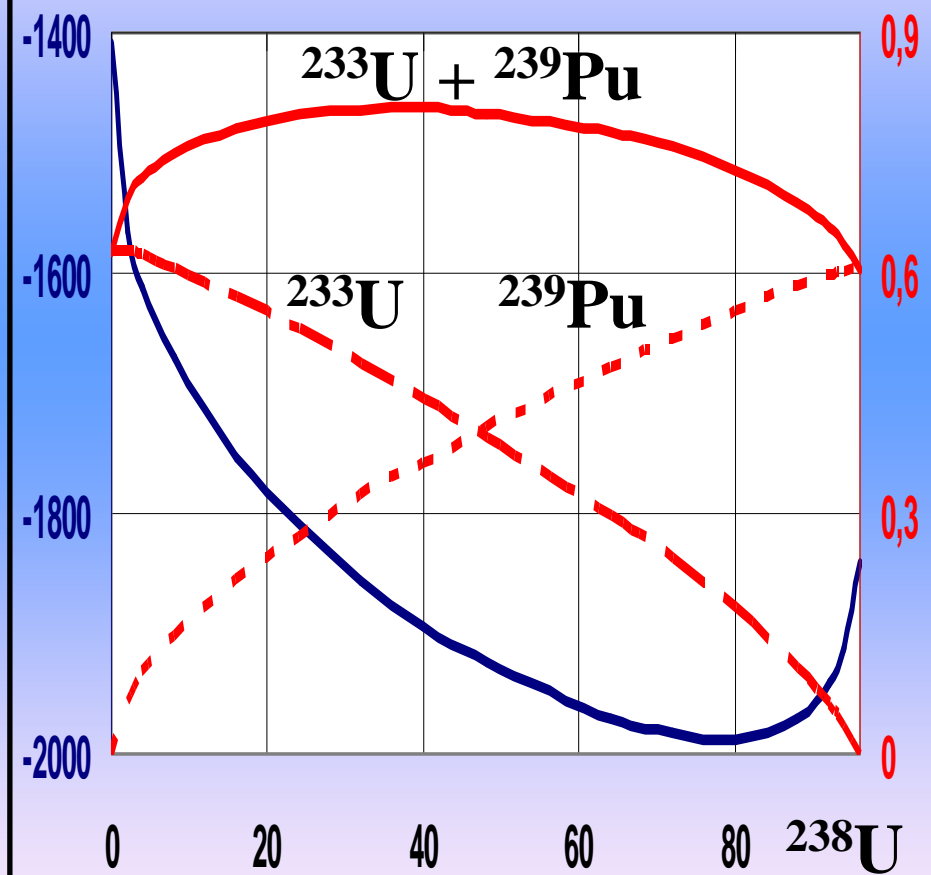
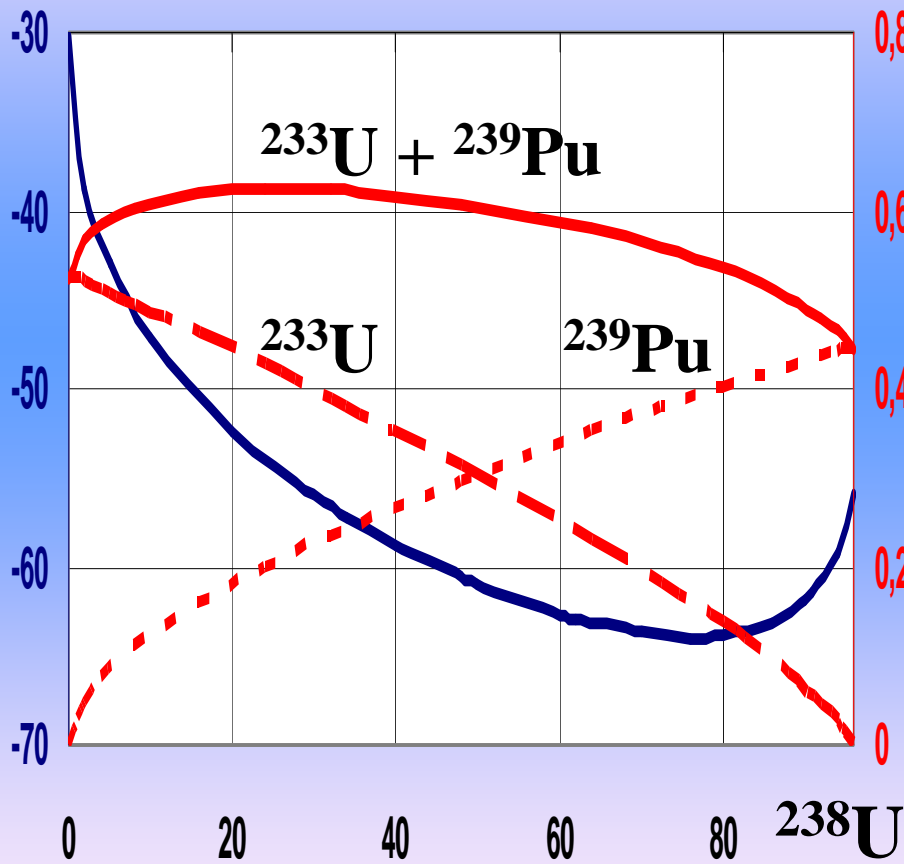
M H T U

Temperature Coefficient of Reactivity and ^{233}U & ^{239}Pu breeding (per one fission)

Fuel: (4% ^{233}U + 96% [^{232}Th + ^{238}U]) O_2

$\gamma_{\text{H}_2\text{O}} = 0,72 \text{ g/cm}^3$

$\gamma_{\text{H}_2\text{O}} = 0,4 \text{ g/cm}^3$



^{238}U fraction in (^{232}Th + ^{238}U), %



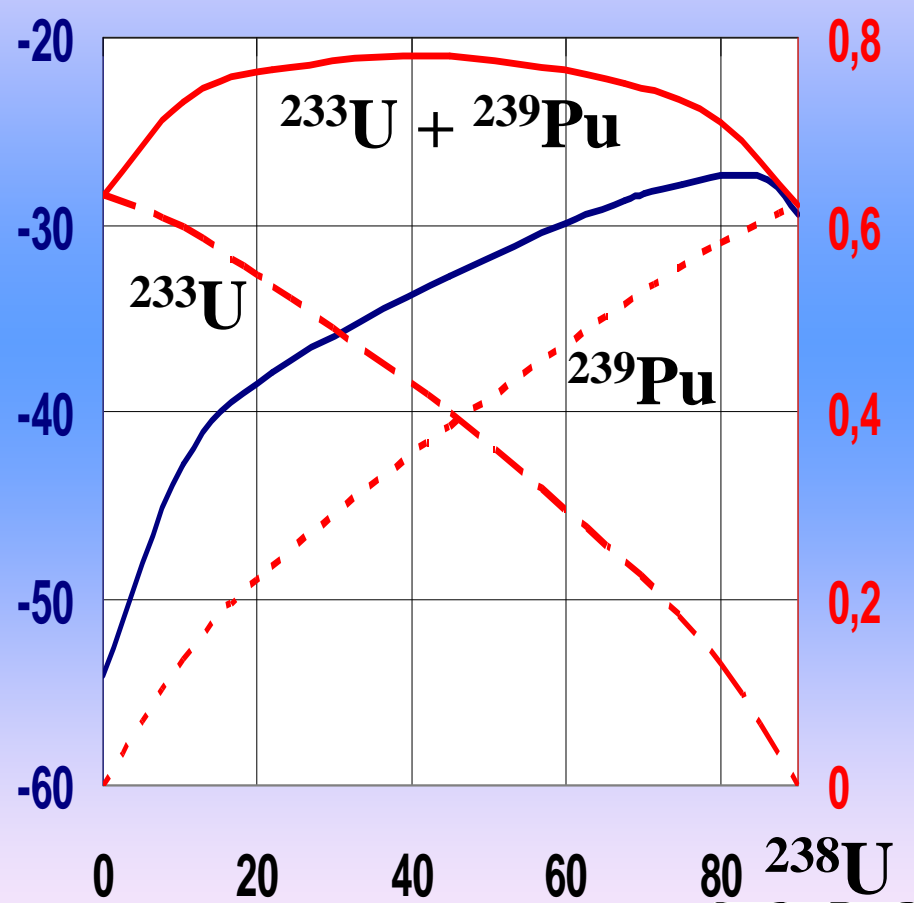
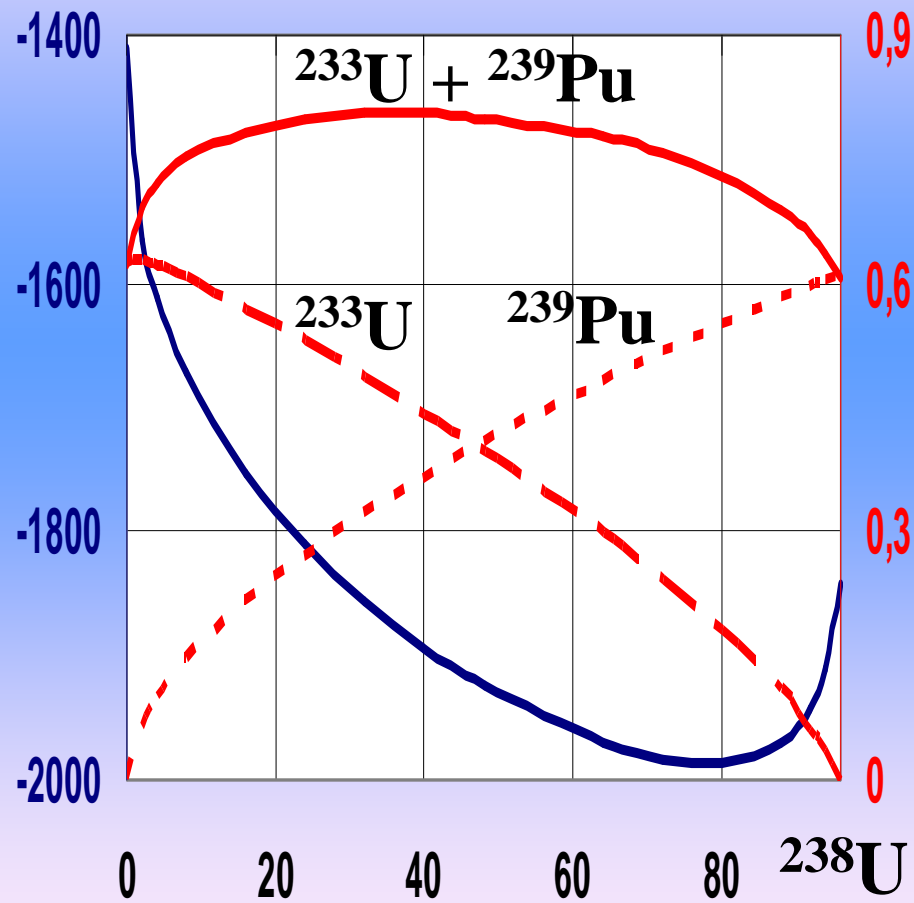
Temperature Coefficient of Reactivity and ^{233}U & ^{239}Pu breeding (per one fission)

(4% ^{233}U + 96% [^{232}Th + ^{238}U]) O_2

(10% ^{233}U + 90% [^{232}Th + ^{238}U]) O_2

$\gamma_{\text{H}_2\text{O}} = 0,4 \text{ g/cm}^3$

$\gamma_{\text{H}_2\text{O}} = 0,1 \text{ g/cm}^3$

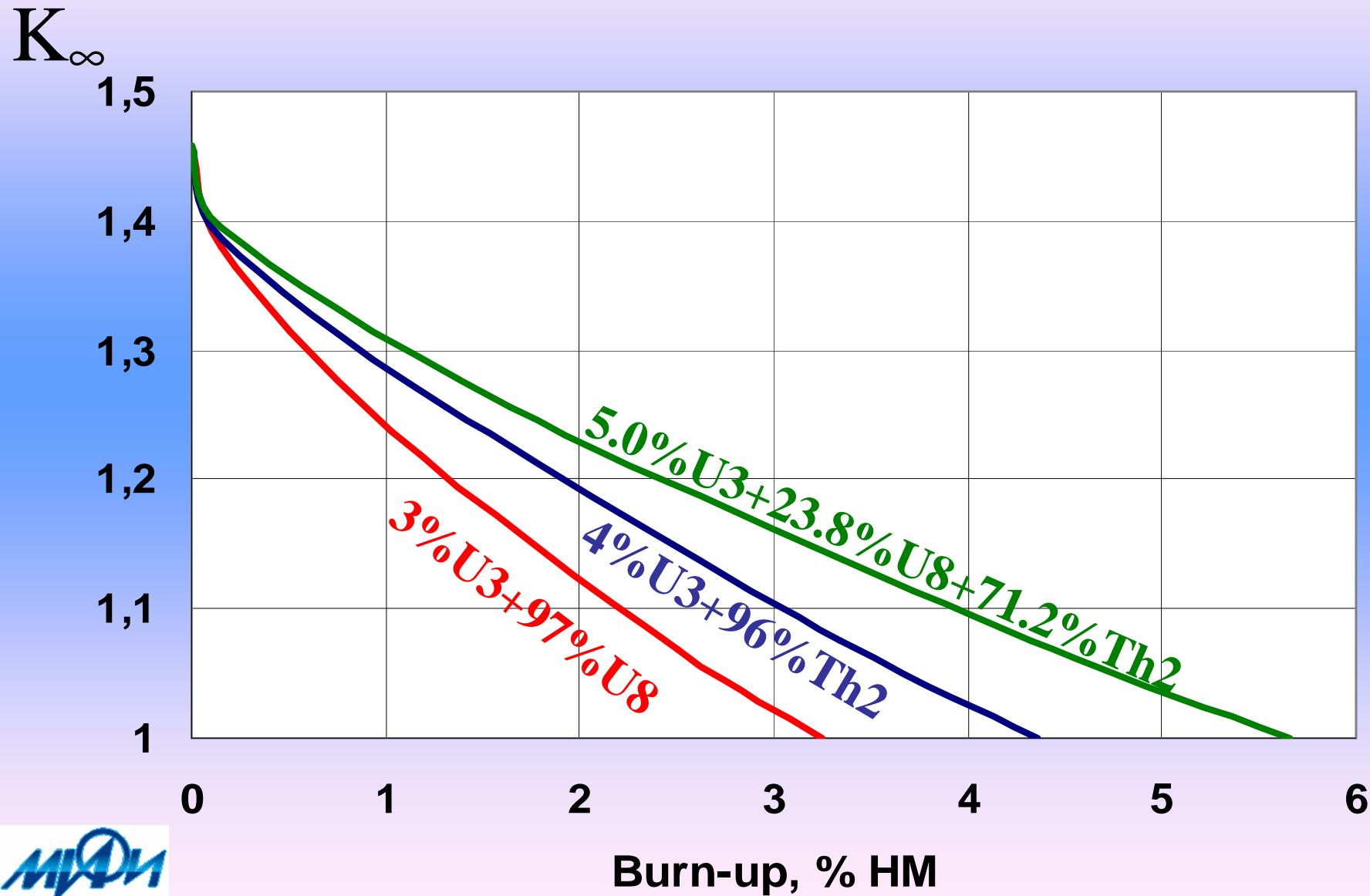


^{238}U fraction in $(^{232}\text{Th} + ^{238}\text{U})$, %



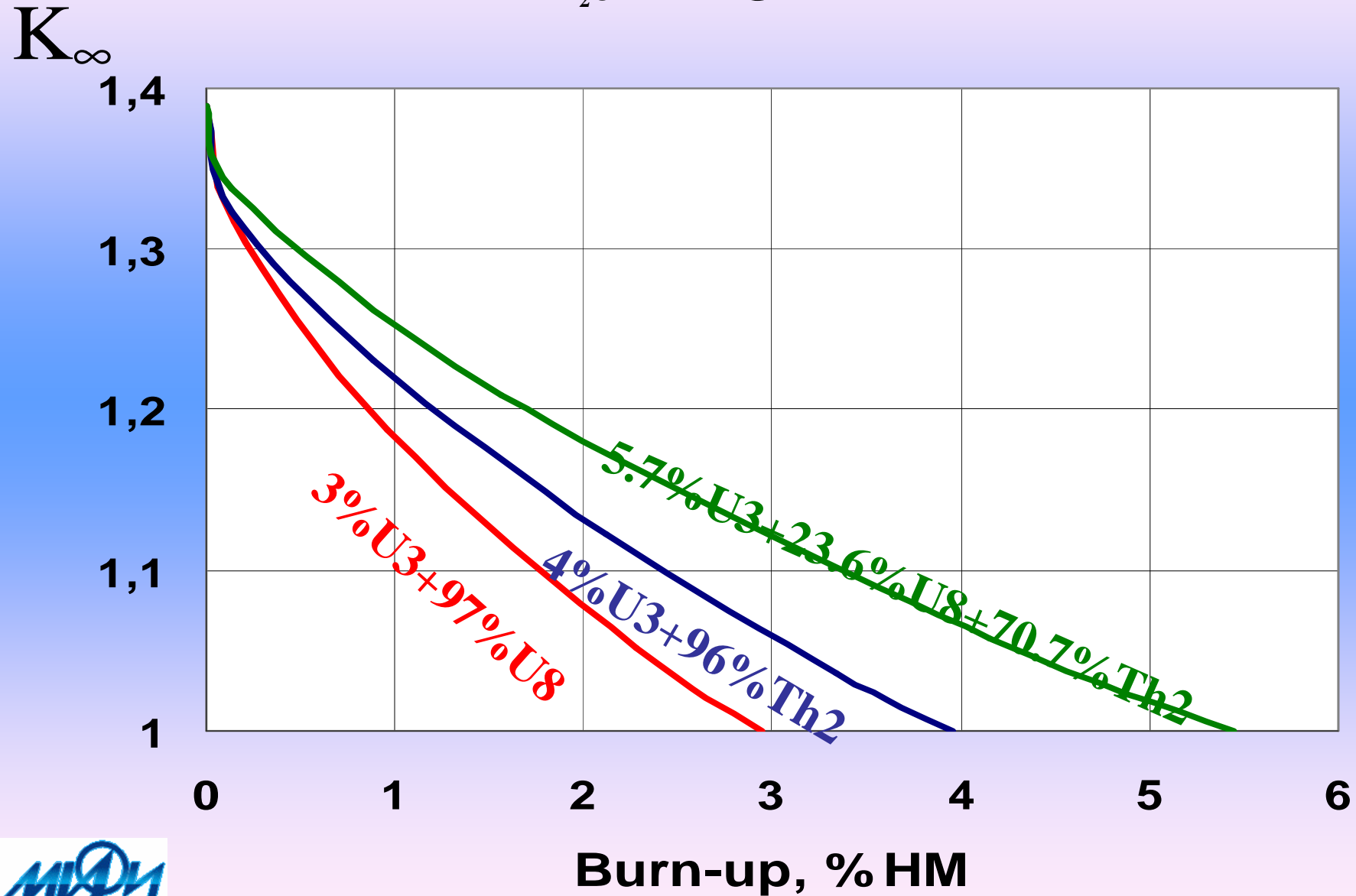
Dependence of K_{∞} on fuel burn-up

$$\gamma_{H_2O} = 0,72 \text{ g/cm}^3$$



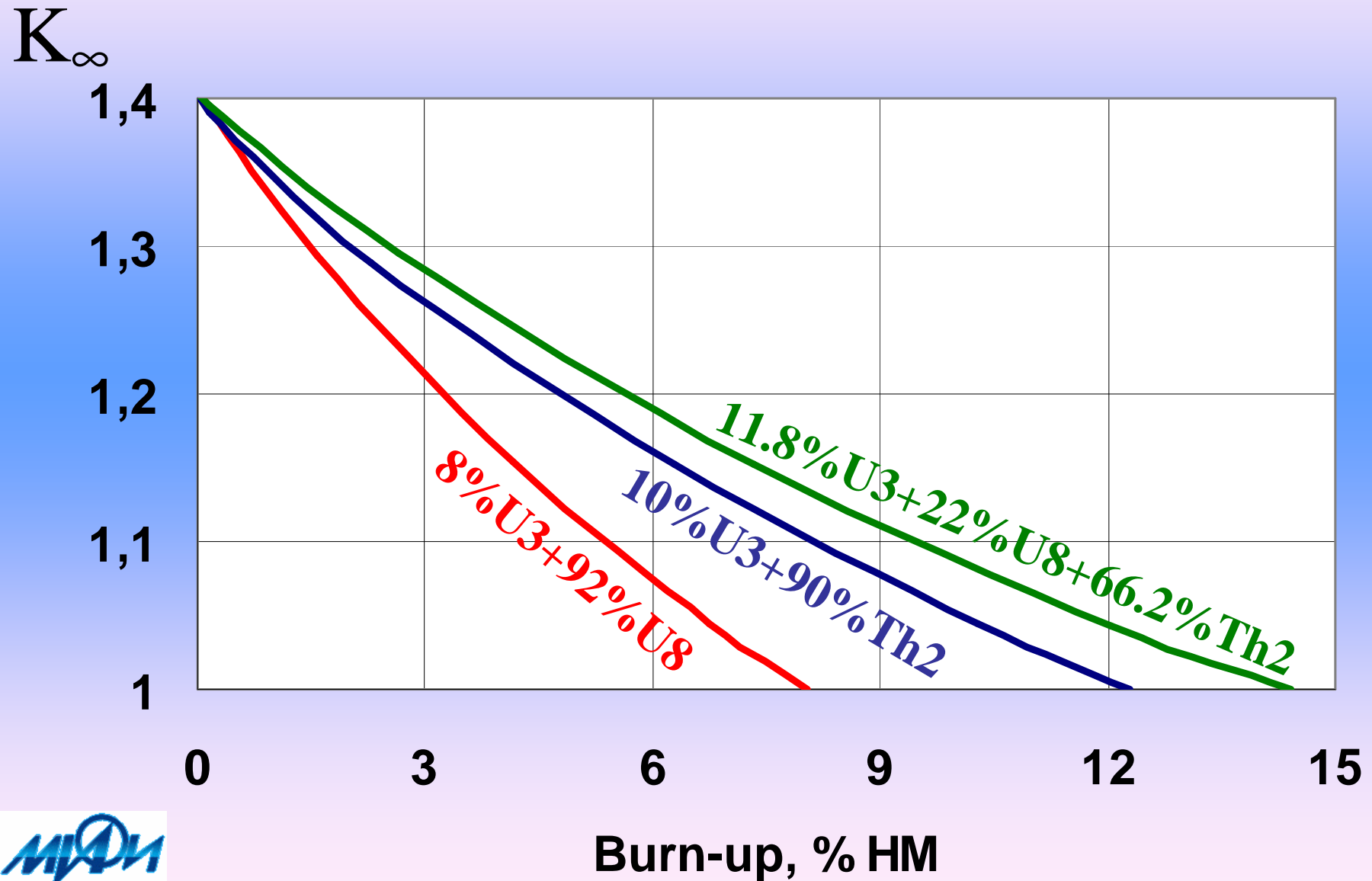
Dependence of K_{∞} on fuel burn-up

$$\gamma_{H_2O} = 0,4 \text{ g/cm}^3$$

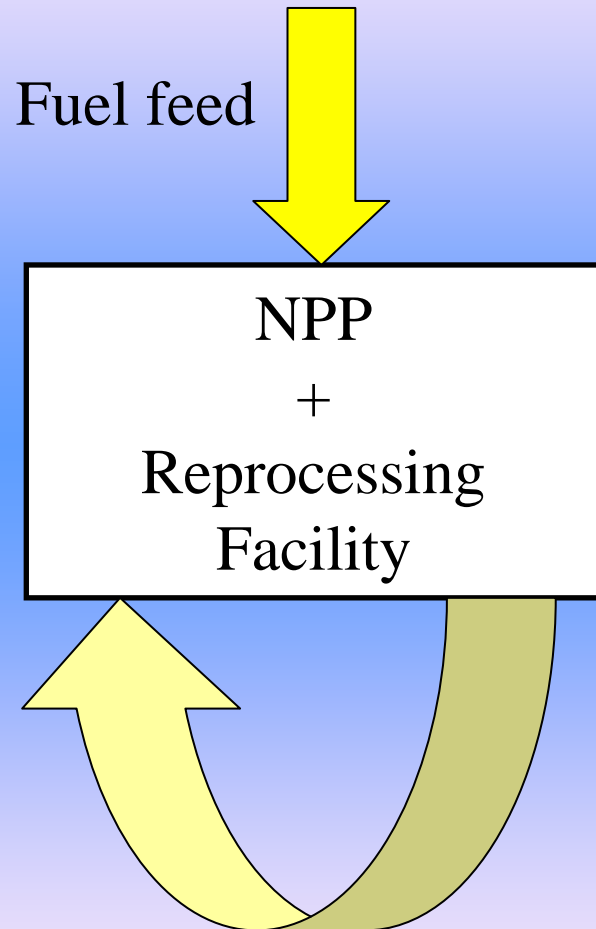


Dependence of K_∞ on fuel burn-up

$$\gamma_{H_2O} = 0,1 \text{ g/cm}^3$$



Closed Fuel Cycle with (U-Th)-fuel



Proliferation Protection Criteria of IAEA

$$\frac{{}^{235}\text{U}}{{}^{235}\text{U} + {}^{238}\text{U}} \leq 20\% \quad (G_{\text{krit}} = 809 \text{ kg})$$

Analogue for (${}^{233}\text{U} + {}^{238}\text{U}$)-mixture

$$\frac{{}^{233}\text{U}}{{}^{233}\text{U} + {}^{238}\text{U}} \leq 12\% \quad (G_{\text{krit}} = 809 \text{ kg})$$

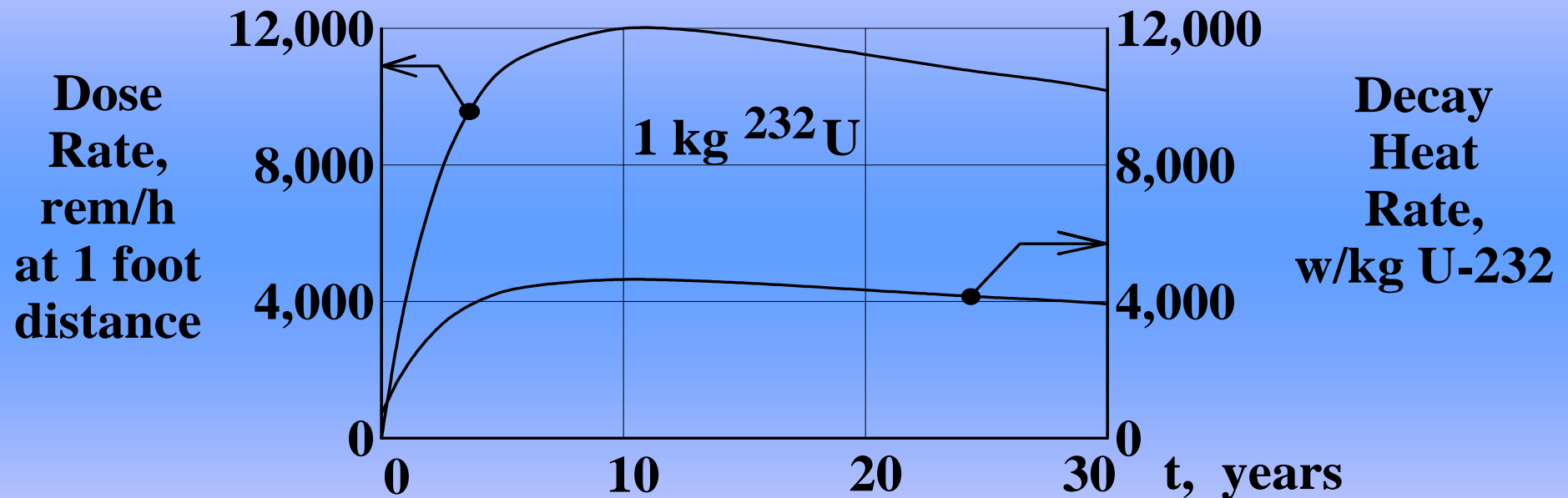
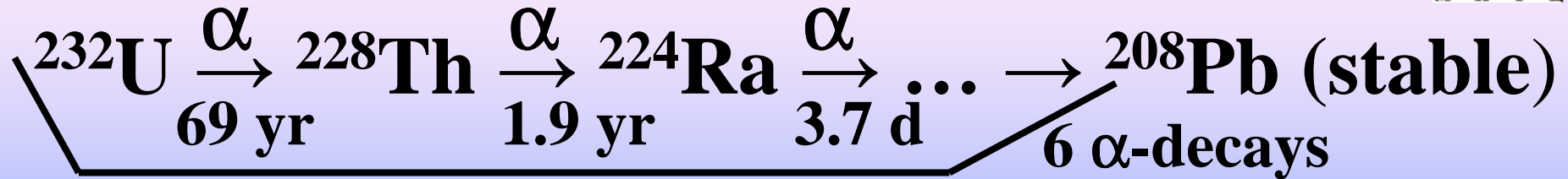
(20% ${}^{233}\text{U} + 80\% {}^{238}\text{U}$) can be denatured
by admixture of ${}^{232}\text{U}$

Fresh Fuel: (${}^{233}\text{U} + {}^{238}\text{U} + \text{Th}$)

Spent Fuel: (${}^{233}\text{U} + {}^{238}\text{U} + \text{Th} + \text{Pu} + \text{MA}$)



^{232}U as a doping isotope



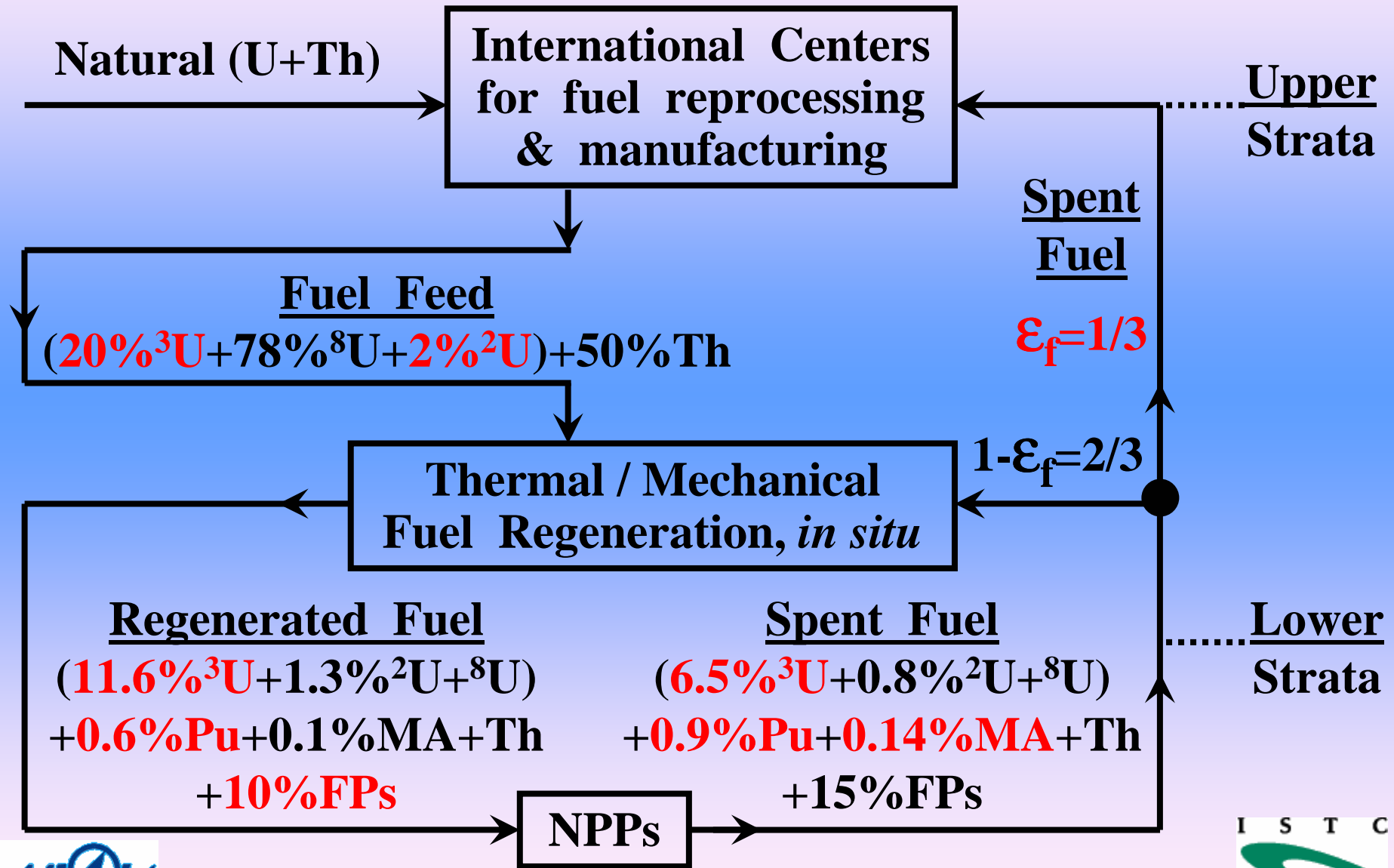
$$Q_{\text{SF}} \text{ (Spontaneous Fission Neutrons)} = 1.3 \cdot 10^{+3} \text{ n} / (\text{s} \cdot \text{kg} \text{ } ^{232}\text{U});$$

$$Q_{\alpha, \text{n}} \text{ (Uranium Dioxide)} = 15 \cdot 10^{+6} \text{ n} / (\text{s} \cdot \text{kg} \text{ } ^{232}\text{U}) \text{ (}\cdot 20 \text{ – equilibrium)};$$

^{232}U –leader among U isotopes as a spontaneous neutrons generator.



Example: (Th-U-Pu) Closed Fuel Cycle Protected



Conclusions

1. Within the SCLWR operation range of water density (from **0.78** g/cm³ to **0.1** g/cm³), **^{233}U remains remarkably more preferable than ^{239}Pu** on neutron multiplying properties: $\nu_{\text{eff}}(^{233}\text{U}) = 2.22$; $\nu_{\text{eff}}(^{239}\text{Pu}) = 1.82$.
2. **Homogeneous mixed ($^{233}\text{U} - ^{232}\text{Th} - ^{238}\text{U}$)-based fuel composition** provides higher values of achievable fuel burn-up than ^{232}Th -based and ^{238}U -based fuel compositions, respectively.
3. **A three-to-one ratio of ^{232}Th and ^{238}U contents** in mixed ($^{232}\text{Th} - ^{238}\text{U}$)-based fuel composition provides maximal values of fuel breeding ratio and achievable fuel burn-up.
4. **Uranium fraction of this fuel ($^{233}\text{U} + ^{238}\text{U}$) can be effectively doped by ^{232}U isotope admixture** to enhance proliferation protection.
5. **Plutonium breeding is suppressed** due to small fraction of ^{238}U in fuel.

