ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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Uranium for a sustainable nuclear fuel cycle

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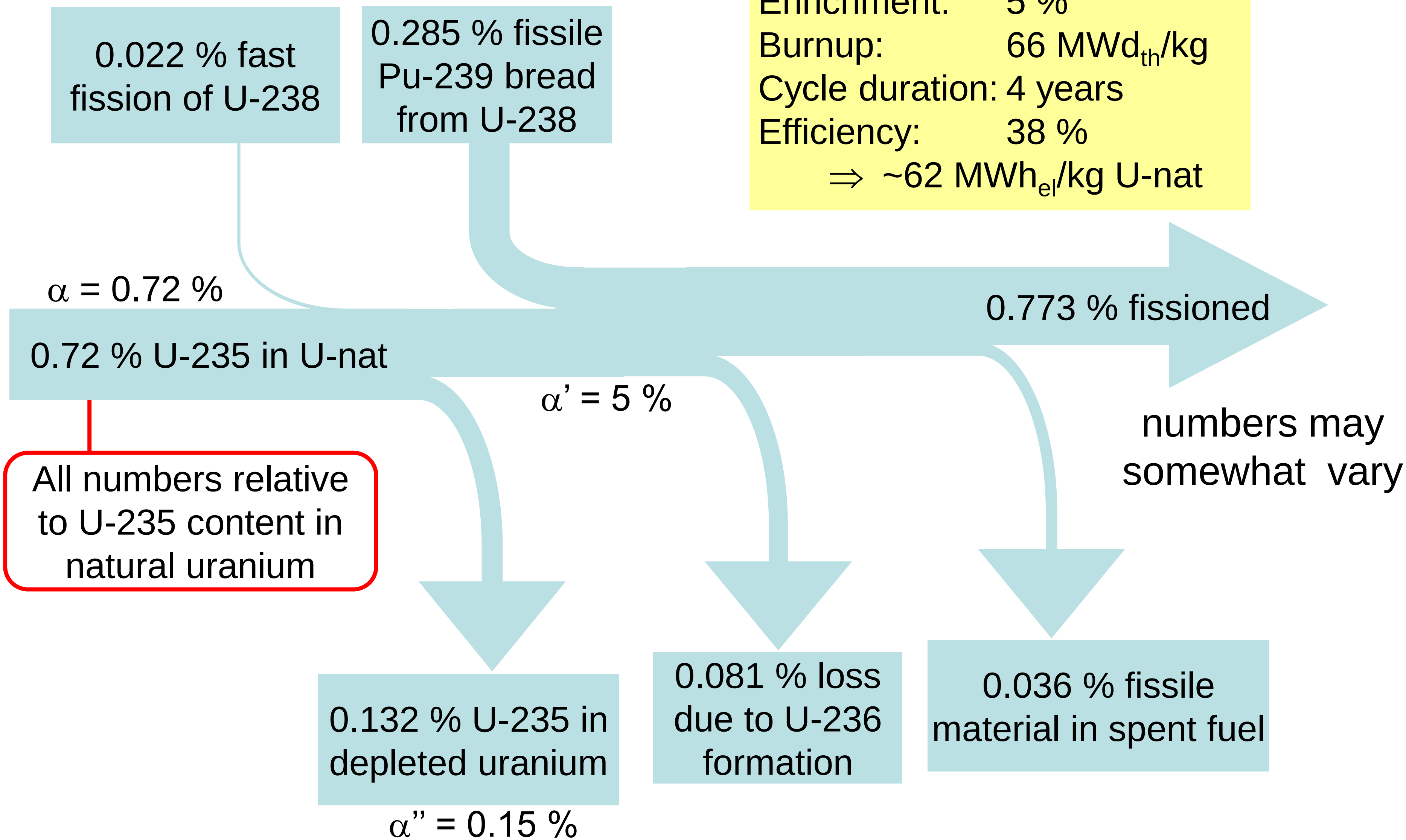
Content

- Electric energy equivalent of uranium in light water reactors (LWR)
- Cost contribution of natural uranium to the produced MWh
- Conventional uranium resources
- Energy and cost cliffs
- Unconventional uranium resources in the world and in Poland
- Summary

Balance of fissile material in a modern LWR

Enrichment: 5 %
Burnup: 66 MWd_{th}/kg
Cycle duration: 4 years
Efficiency: 38 %
$\Rightarrow$ ~62 MWh_{el}/kg U-nat



Cost contribution from the natural uranium price

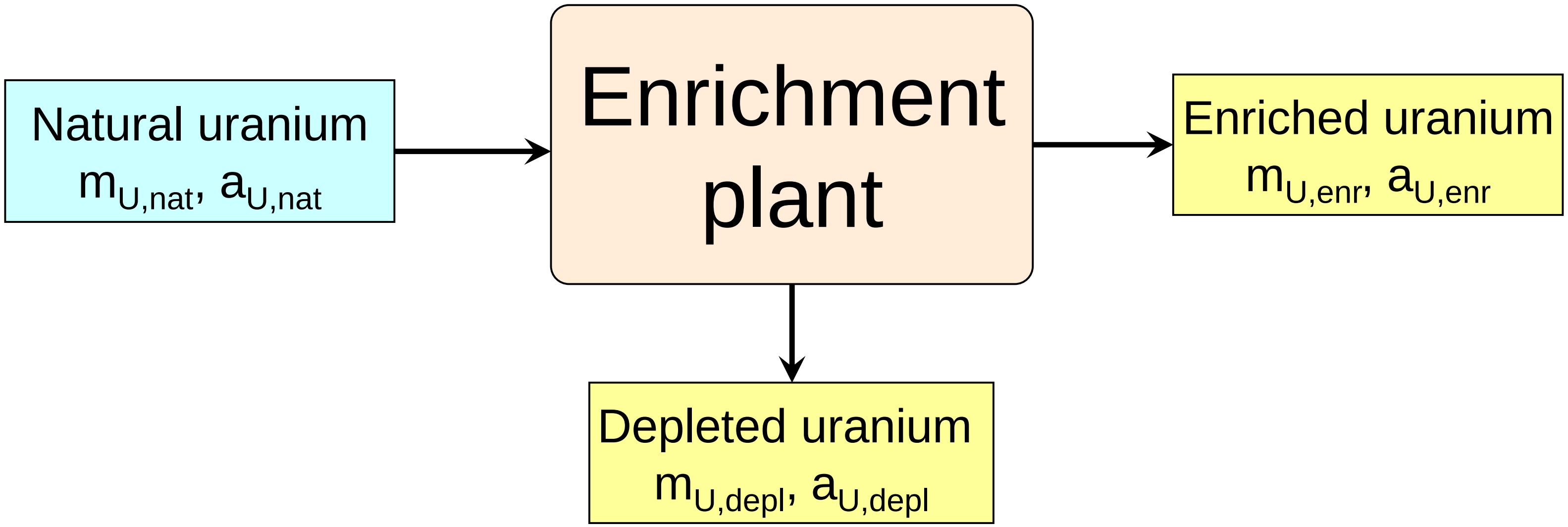
Quantities:	***Units:***	
Burnup	[Bu]	= $GWd_{th}/t_{U,enr}$
Uranium energy yield	[$E_{U,nat}$]	= $MWh_{el}/kg_{U,nat}$
Uranium price	[$P_{U\text{-}nat}$]	= $USD/kg_{U\text{-}nat}$
Cost contribution	[$c_{U,nat}$]	= USD/MWh

Electric energy per kg U-nat: $$E_{U,nat} = Bu \cdot \eta_{plant} \cdot \frac{m_{U,enr}}{m_{U,nat}}$$

Cost contribution of U-nat: $$c_{U,nat} = \frac{P_{U,nat}}{E_{U,nat}} = \frac{P_{U,nat}}{Bu \cdot \eta_{plant}} \cdot \frac{m_{U,nat}}{m_{U,enr}}$$

Unit conversion: $$c_{U,nat} = \frac{d}{24h} \cdot \frac{P_{U,nat}}{Bu \cdot \eta_{plant}} \cdot \frac{m_{U,nat}}{m_{U,enr}}$$

Mass balance of an enrichment plant



Mass balance total uranium: $m_{U,nat} = m_{U,enr} + m_{U,depl}$

Mass balance U-235: $a_{U,nat} \cdot m_{U,nat} =$

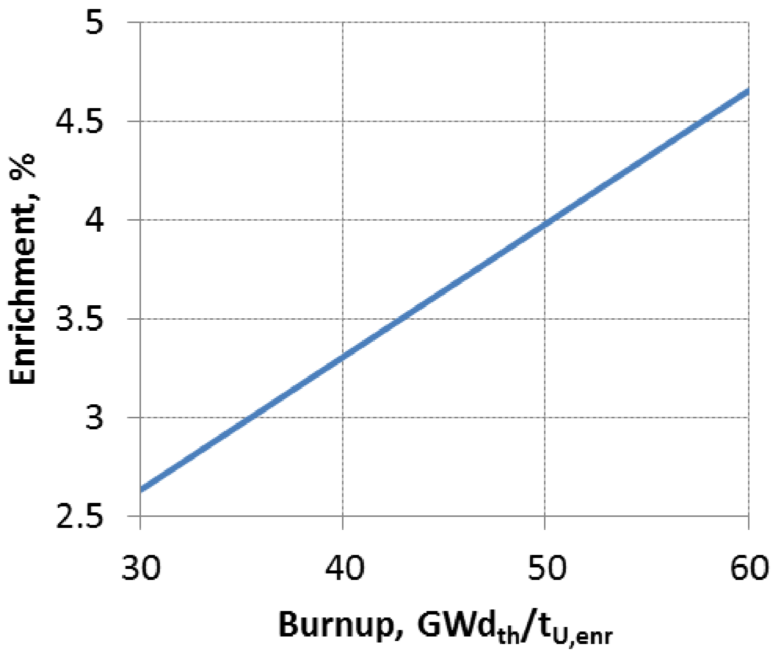
$$a_{U,enr} \cdot m_{U,enr} + a_{U,depl} \cdot m_{U,depl}$$

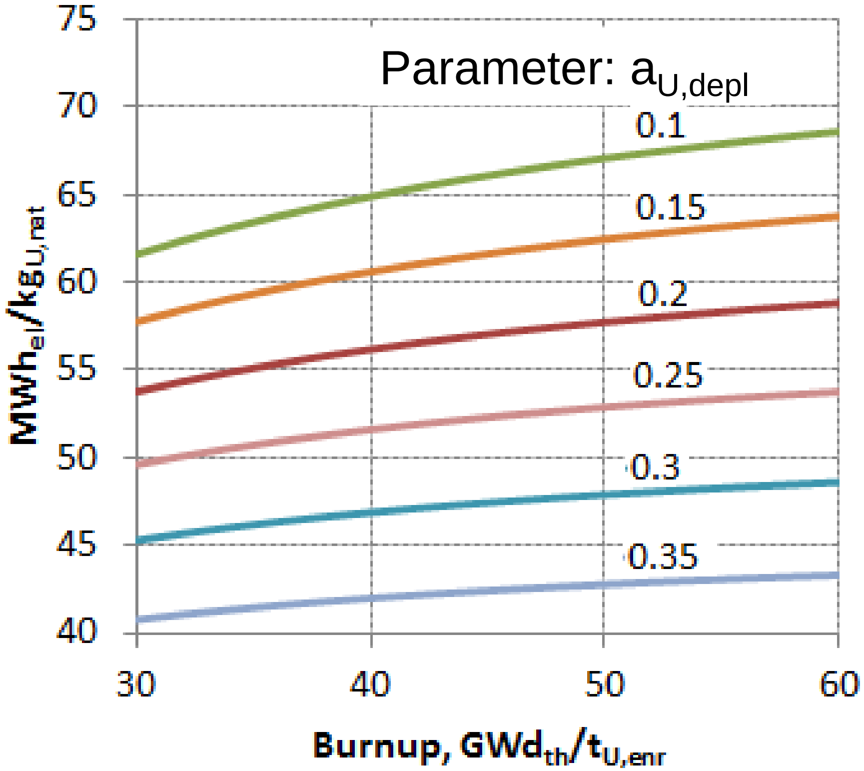
$$\Rightarrow \quad \frac{m_{U,nat}}{m_{U,enr}} = \frac{a_{U,enr} - a_{U,depl}}{a_{U,nat} - a_{U,depl}}$$

Energy yield of natural uranium

$$E_{U,nat} = Bu \cdot \eta_{plant} \cdot \frac{m_{U,enr}}{m_{U,nat}} = Bu \cdot \eta_{plant} \cdot \frac{a_{U,nat} - a_{U,depl}}{a_{U,enr} - a_{U,depl}}$$

Attention! Higher Burnup requires higher enrichment of fresh fuel





Main direction of improvement: better enrichment technology, diffusion cells ⇒ ultra-centrifuges allows lower uranium content in tail assays ⇒ higher energy yield

Cost contribution from the natural uranium price

$$c_{U,nat} = \frac{P_{U,nat}}{E_{U,nat}} = \frac{P_{U,nat}}{Bu \cdot \eta_{plant}} \cdot \frac{a_{U,enr} - a_{U,depl}}{a_{U,nat} - a_{U,depl}}$$

Example:

Current PWR + modern centrifuge enrichment

Burnup: 60 $GWd_{th}/t_{U,enr}$

Enrichment: 4.66 %

U-235 in tails: 0.15 %

Plant efficiency: 35 %

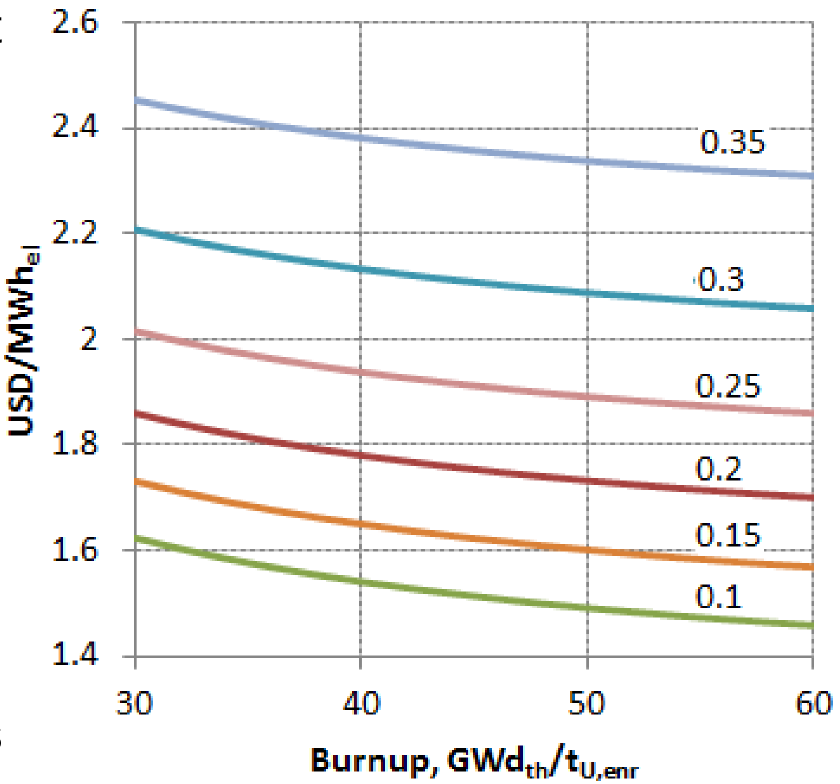
Electricity yield: 63.8 $MWh_{el}/kg_{U,nat}$

Uranium price: 130 $USD/kg_{U,nat}$

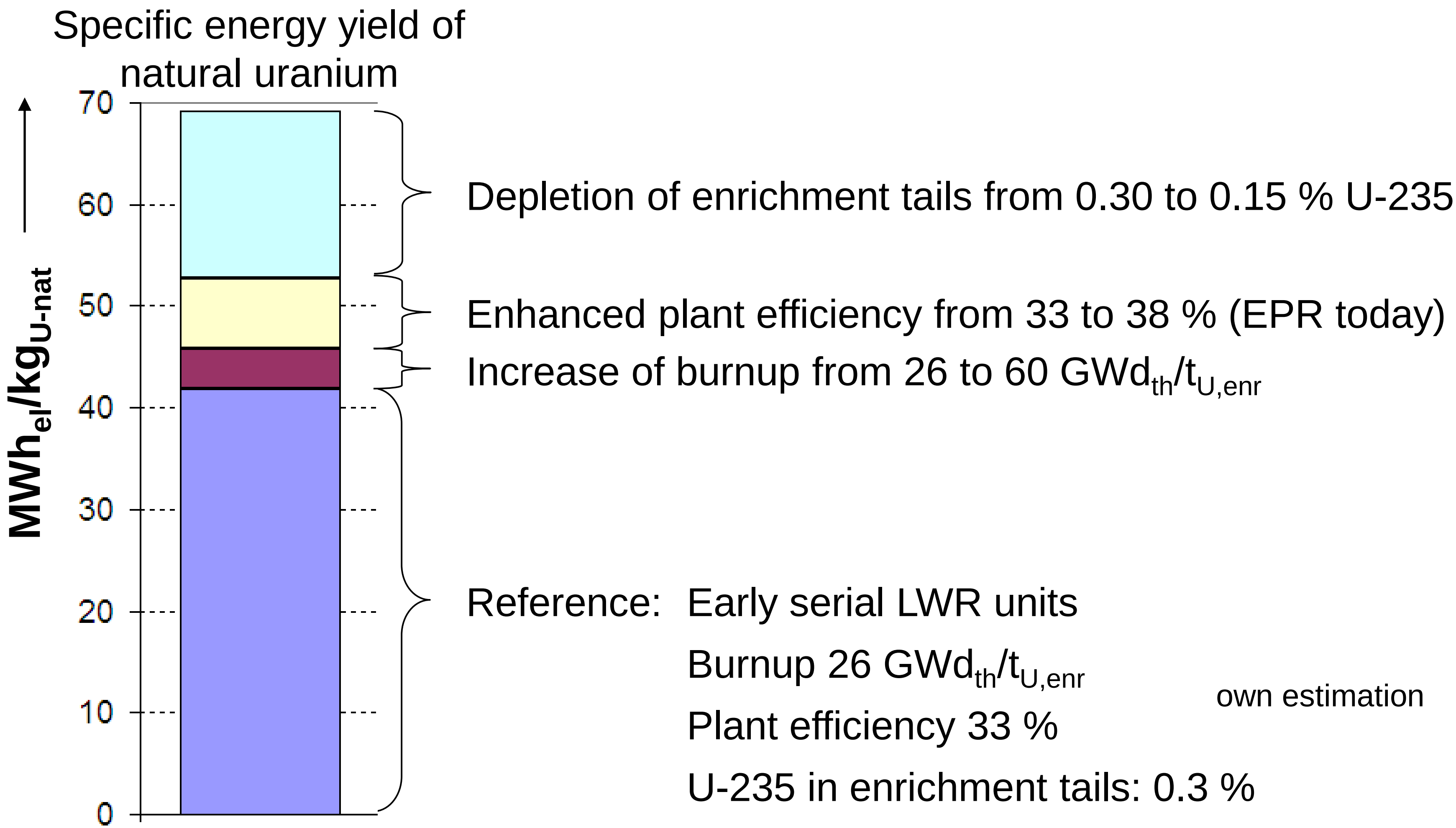
Cost contribution of natural uranium:

2 USD/MWh_{el}

which is **2 – 4 %** if the typical production costs of electricity: 50 – 70 USD/MWh_{el}

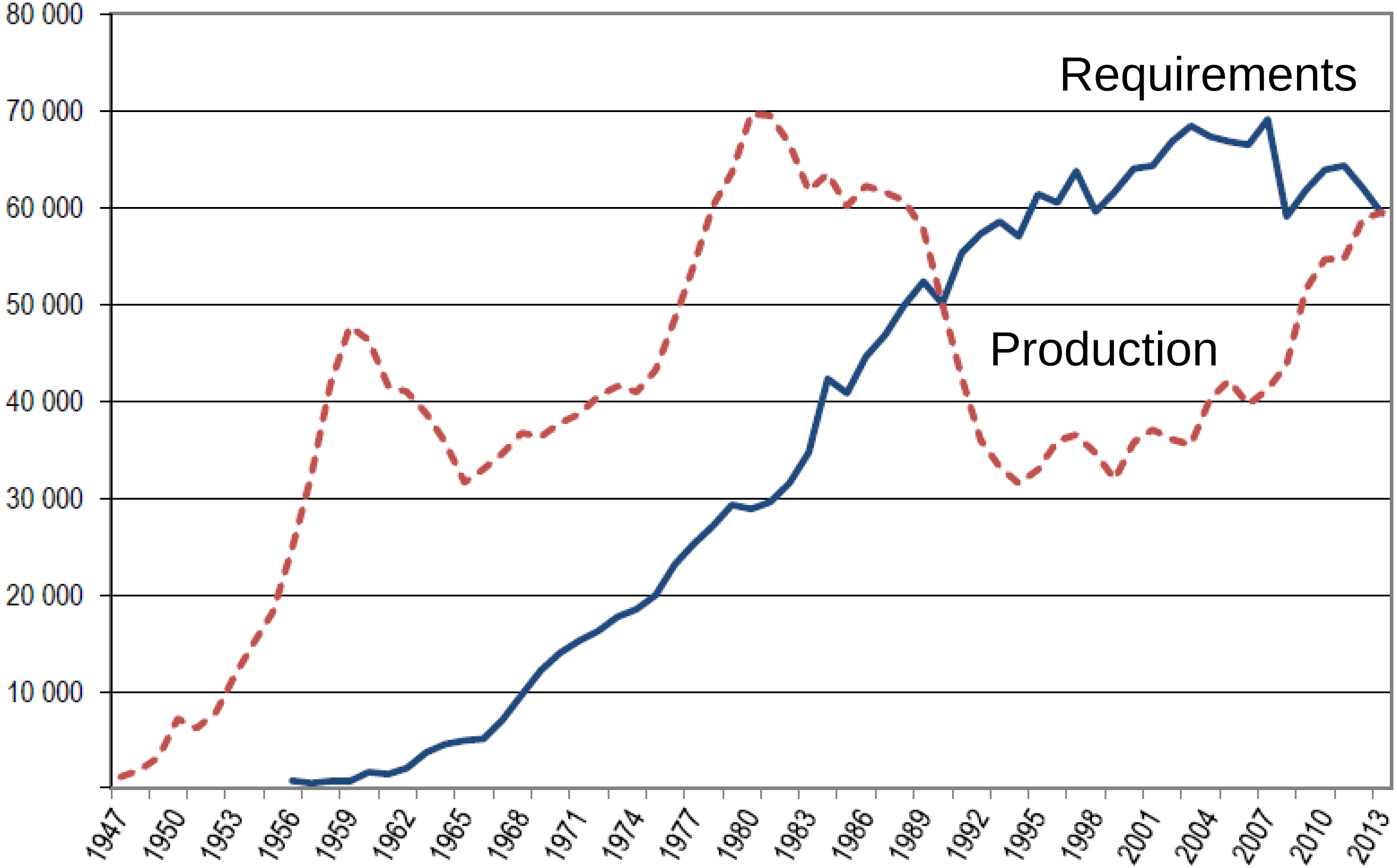


Elements of the improvement of energy yield from U-nat

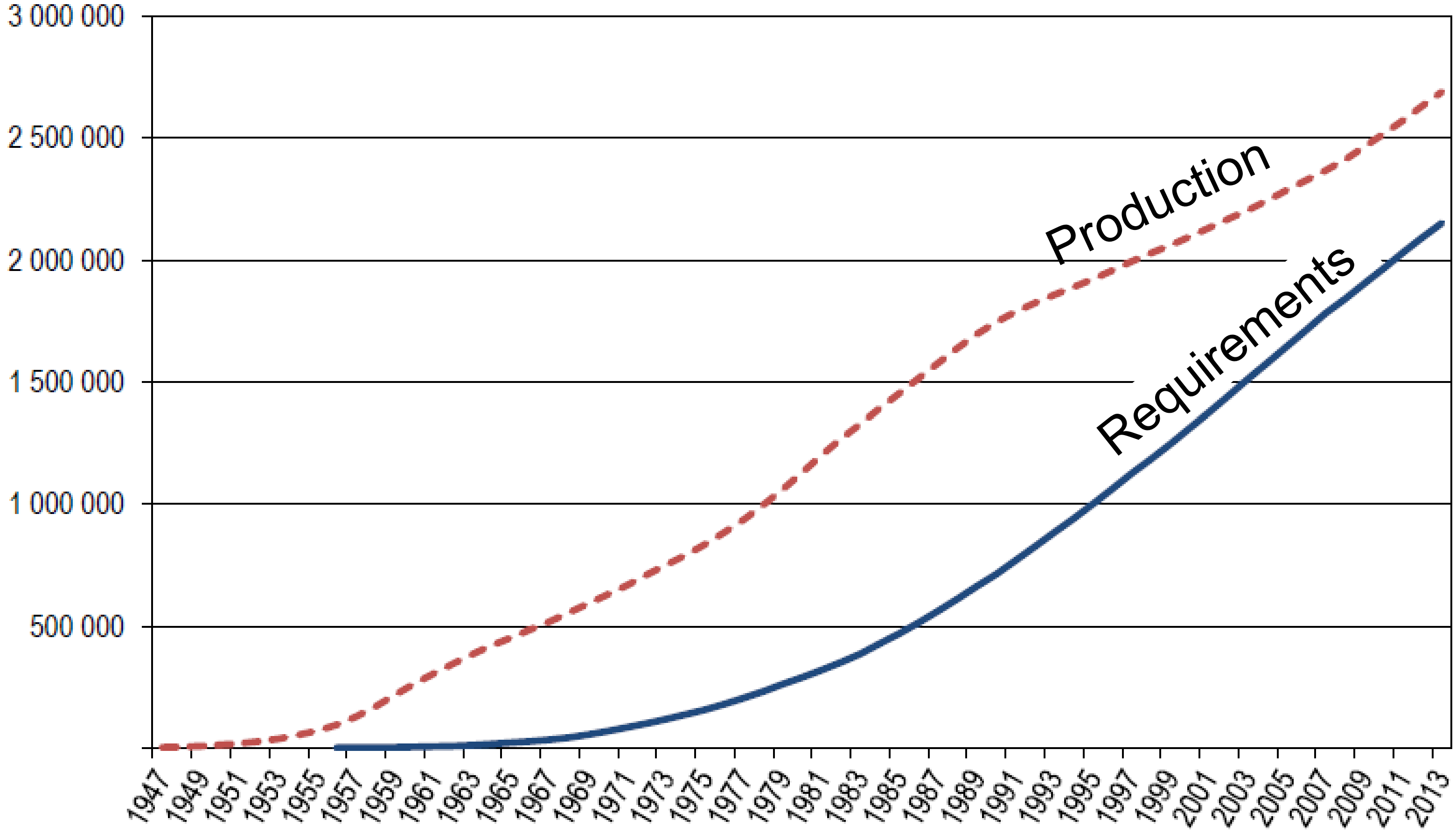


Additional yield possible by reprocessing and Pu recycling

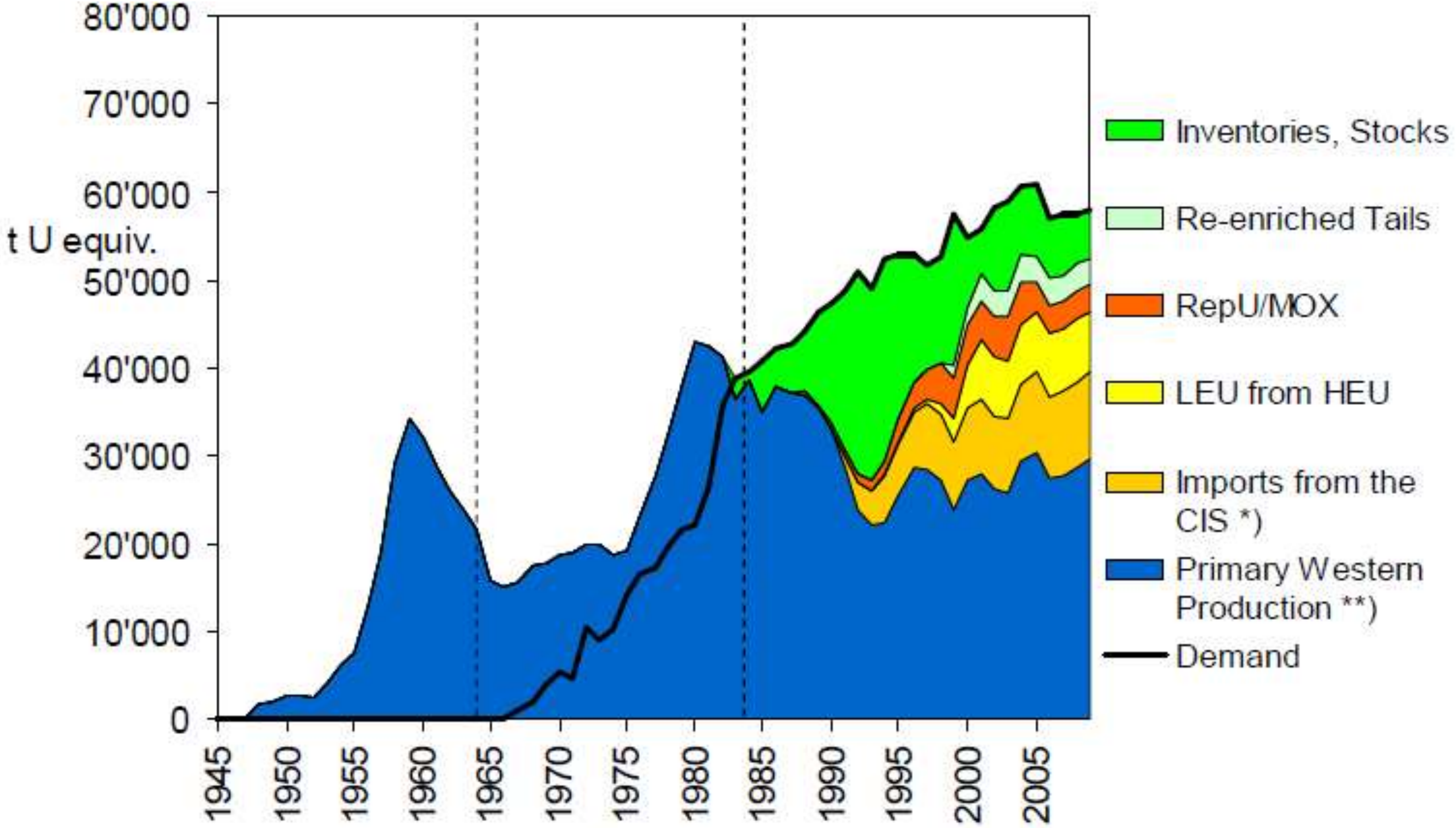
Annual uranium production and requirements



Cumulative uranium production and requirements



Big inflow from secondary sources in the past



Uranium resources - NEA/IAEA uranium group methodology

Identified resources		Undiscovered resources	
Reasonably assured	Inferred	Prognosticated	Speculative

Reasonably assured resources (RAR): known mineral deposits of delineated size, grade and configuration, quantities recoverable within given cost ranges with currently proven technology. Estimates based on specific sample data and measurements and on knowledge of deposit characteristics.

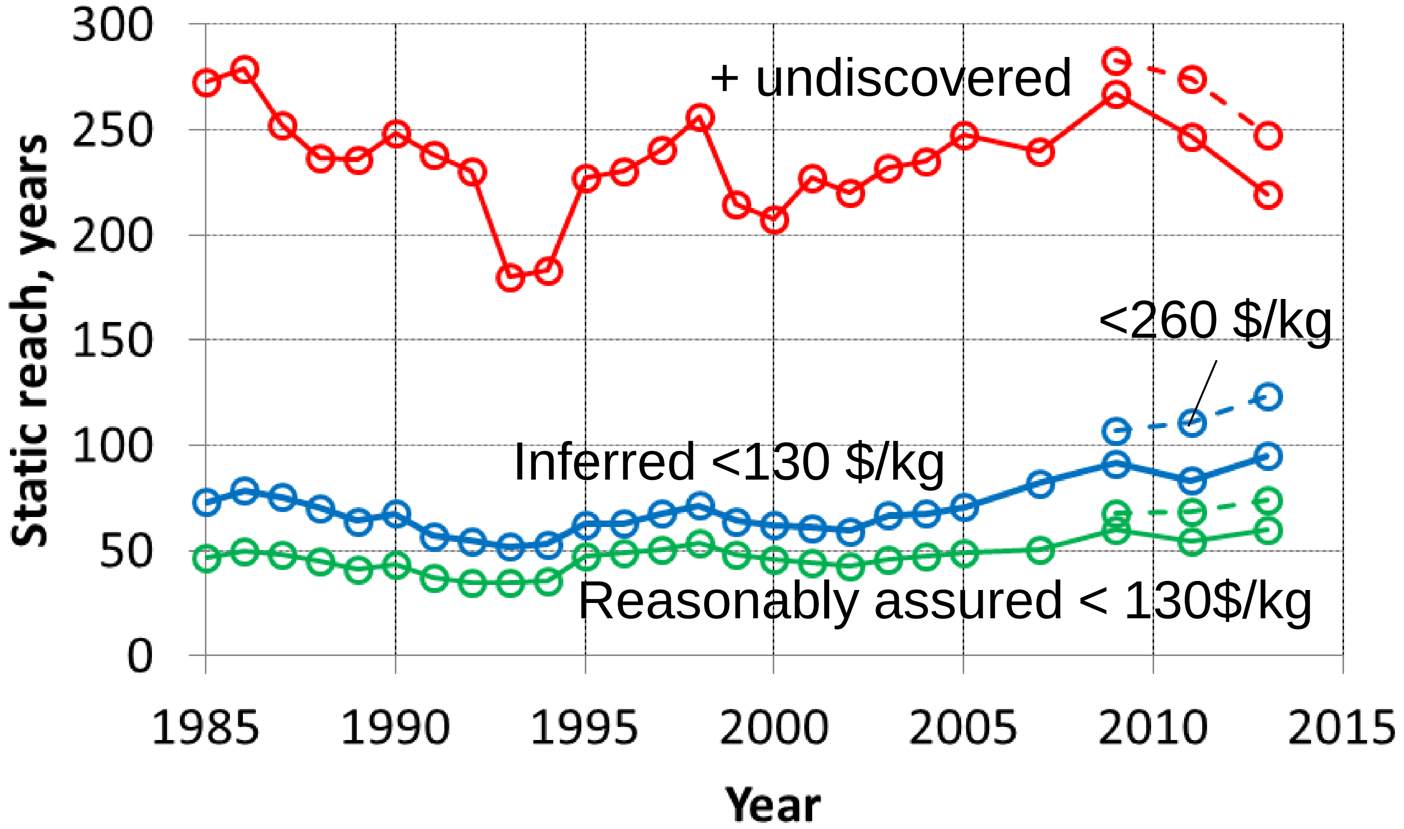
Inferred resources (IR): inferred to occur based on direct geological evidence, in extensions of well-explored deposits, or in deposits in which geological continuity has been established but where specific data are still inadequate.

Prognosticated resources (PR): expected to occur in deposits for which the evidence is mainly indirect and which are believed to exist in well-defined geological trends or areas of mineralisation with known deposits.

Speculative resources (SR): thought to exist, mostly on the basis of indirect evidence and geological extrapolations, in deposits discoverable with existing exploration techniques.

Static reach of known conventional uranium resources

$$\text{Static reach} = \frac{\text{Resources}}{\text{Annual consumption}}$$



Uranium 2014 and earlier “OECD/NEA RedBooks”

In-situ uranium resources in Poland

B-plan: Can Poland be independent, even with LWRs?

Region	In situ (t U-nat)	Ore grade, ppm	Lignite equivalent
Rajsk (Podlasie Depression)	5320	250	18
Perybaltic Syneclise	-		
Okzeszyn (Sudetes)	940	500 – 1100	35 - 77
Grzmiaca (Sudetes)	790	500	35
Wambierzyce (Sudetes)	220	236	16

Σ = 7270 t $\Rightarrow$ > 45 Years of 1000 MW LWR operation

OECD NEA Red Book, 2008

Prognosticated uranium resources in Poland

(<1000 m deep)

Region	Prognosticated (t U-nat)
Rajsk deposit (Podlasie Depression)	88’850
Perybaltic Syneclise	10’000
Wambierzyce (Sudetes)	2’000

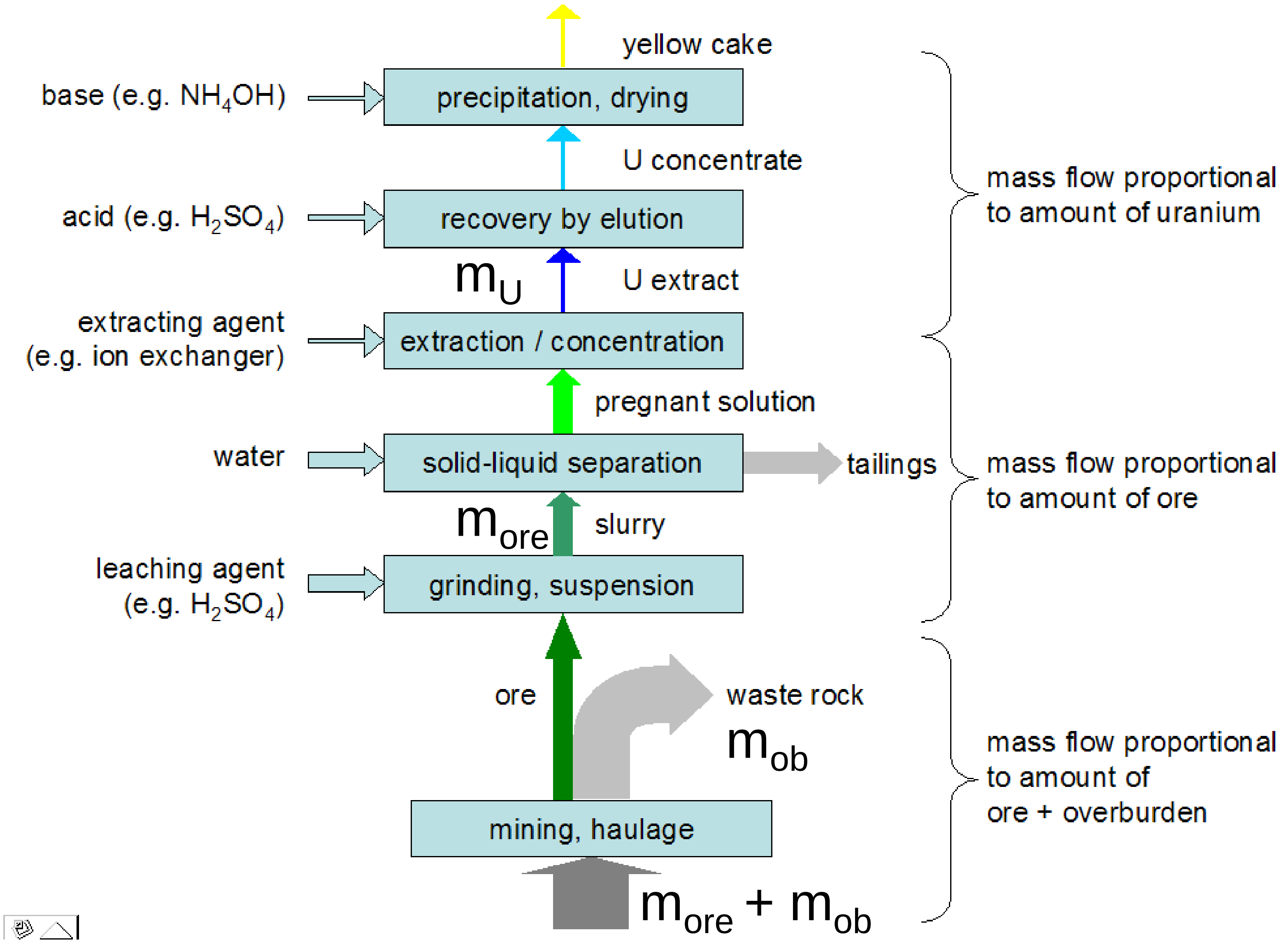
Σ ~ 100’000 t $\Rightarrow$ > 625 Years of 1000 MW LWR operation

OECD NEA Red Book, 2008

Are these energetic resources?

- From an **economic** point of view
- From an **energetic** point of view

Characteristic mass flows of uranium mining and milling



Model of Chapman (1975)

Accounts for Individual mass flows of ore, overburden and uranium

$$E_{mm} = E_{ore} + E_{ob} + E_{mill} + E_U$$

$$e_{mm} \cdot m_U = e_{ore} \cdot m_{ore} + e_{ob} \cdot m_{ob} + e_{mill} \cdot m_{ore} + e_U \cdot m_U$$

Ore and waste rock removal equally energy consuming:

$$e_{ore} \approx e_{ob} \Rightarrow e_{mine}$$

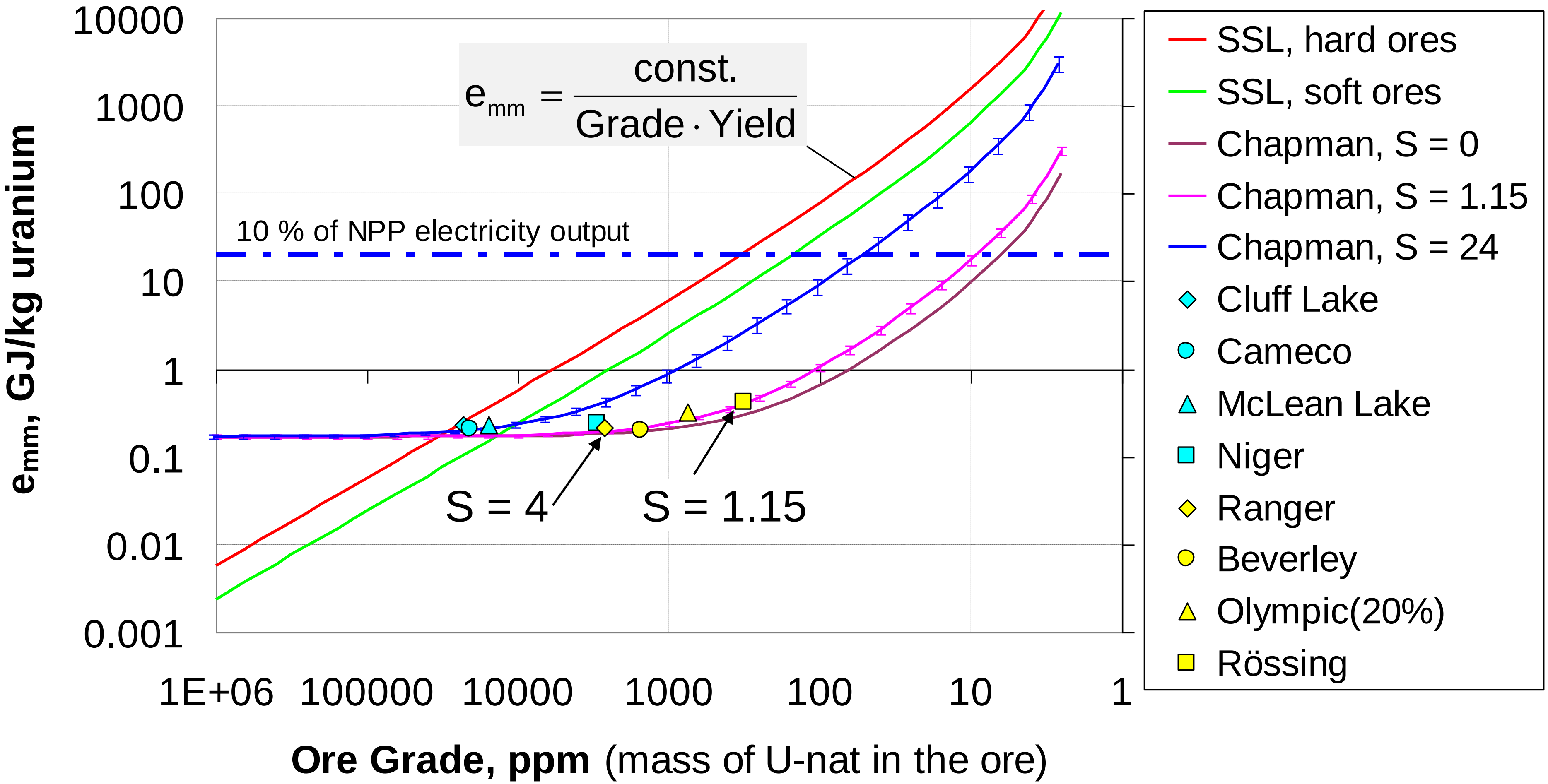
Stripping ratio

$$S = \frac{m_{ob}}{m_{ore}}$$

$$e_{mm} = \frac{1}{G \cdot Y}\left(e_{mine} \cdot (1 + S) + e_{mill}\right) + e_U$$

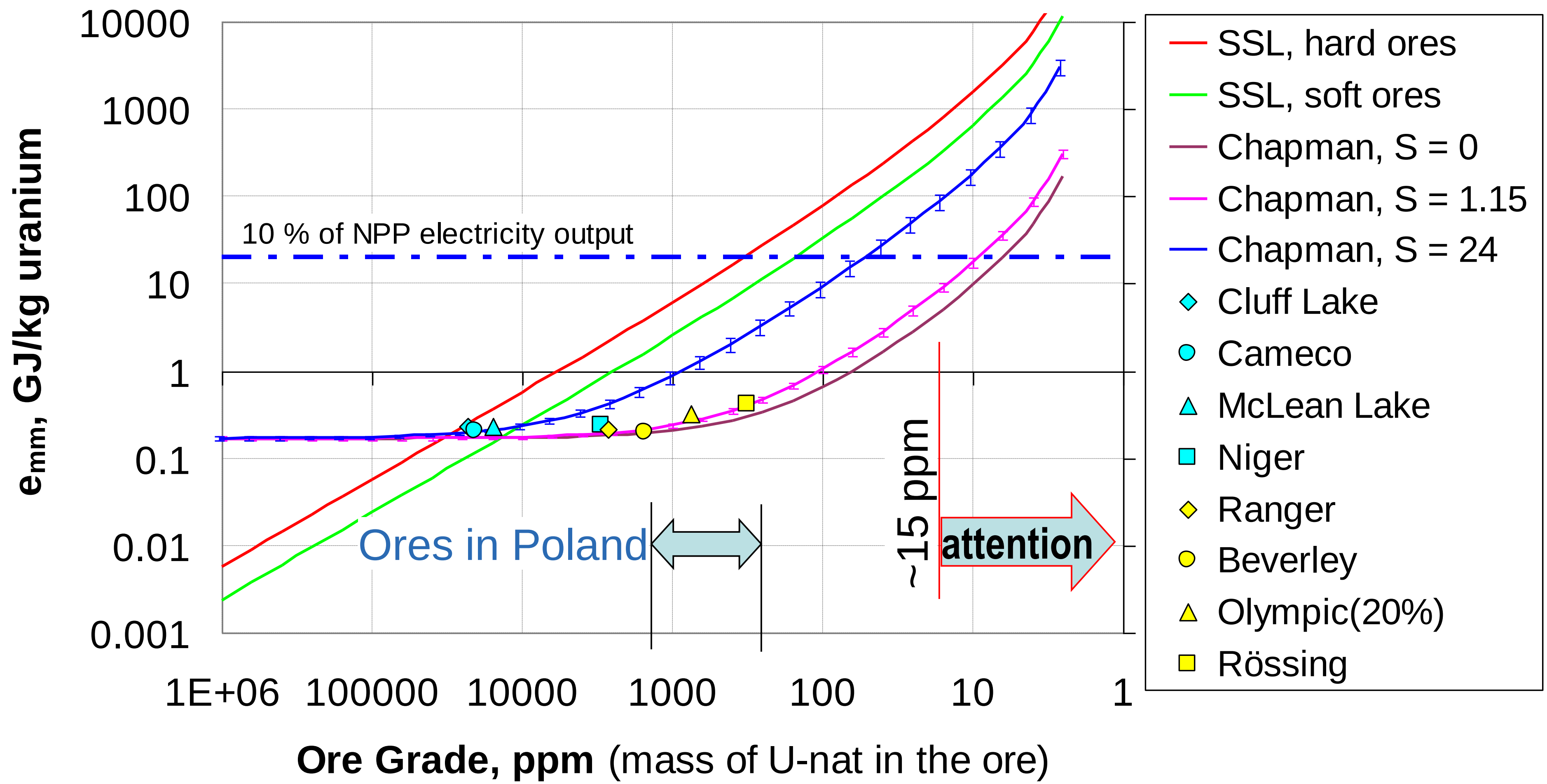
Where can we take the coefficients from?

Improvement of the extrapolation to low ore grades by using the model of Chapman (1975)

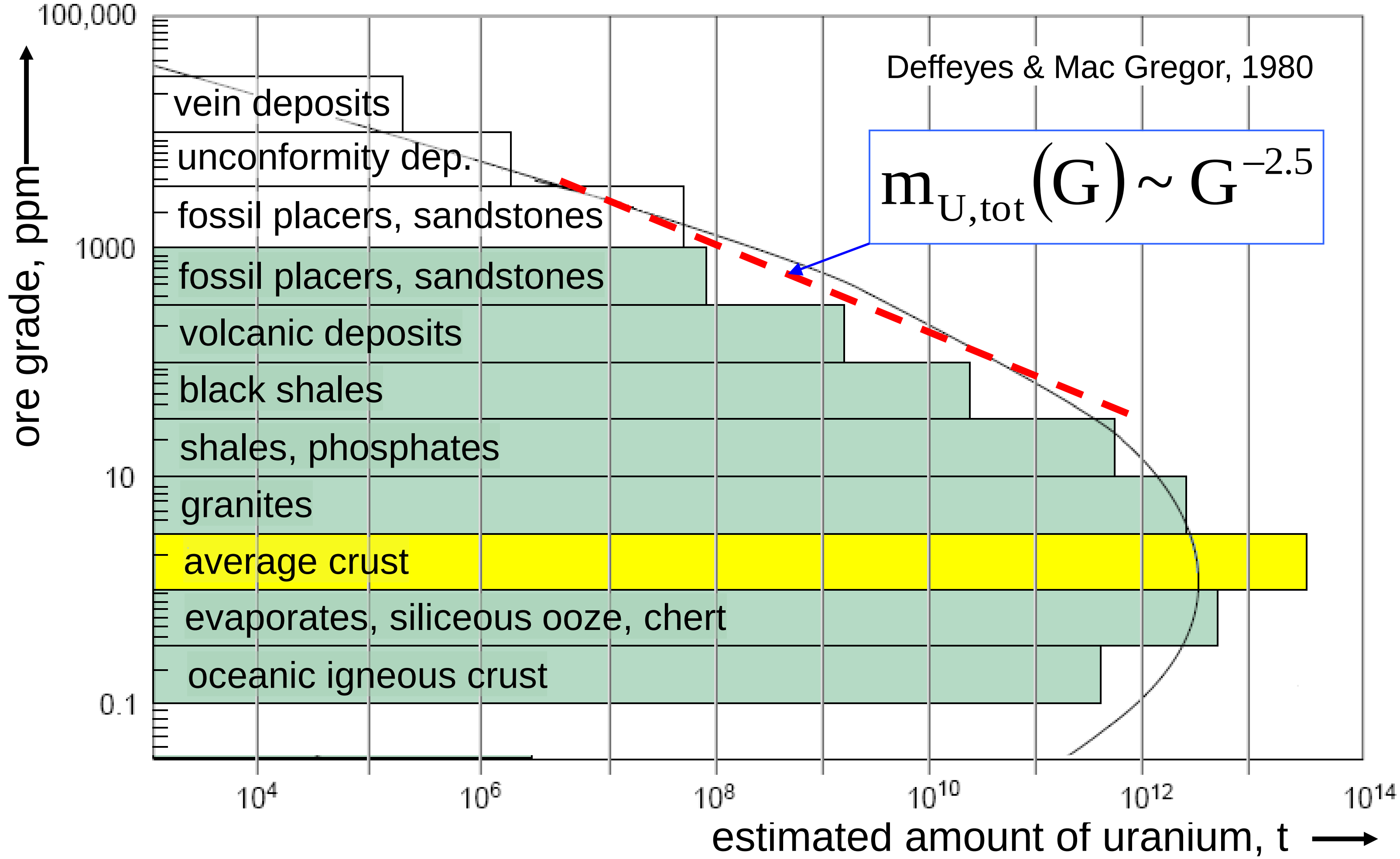


Indirect energy consumption is of the same order of magnitude

Position of the low grades ores in Poland

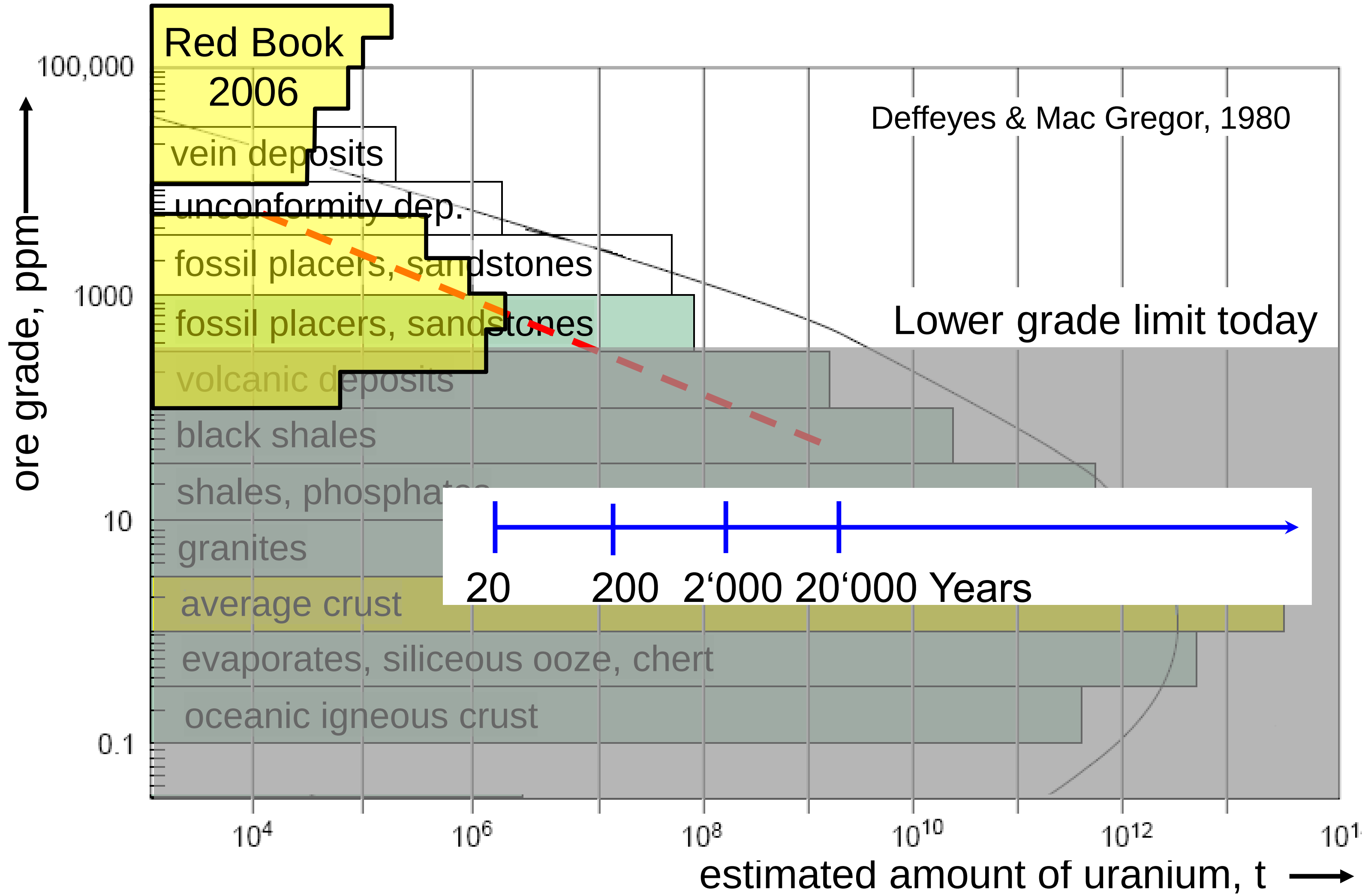


Situation worldwide

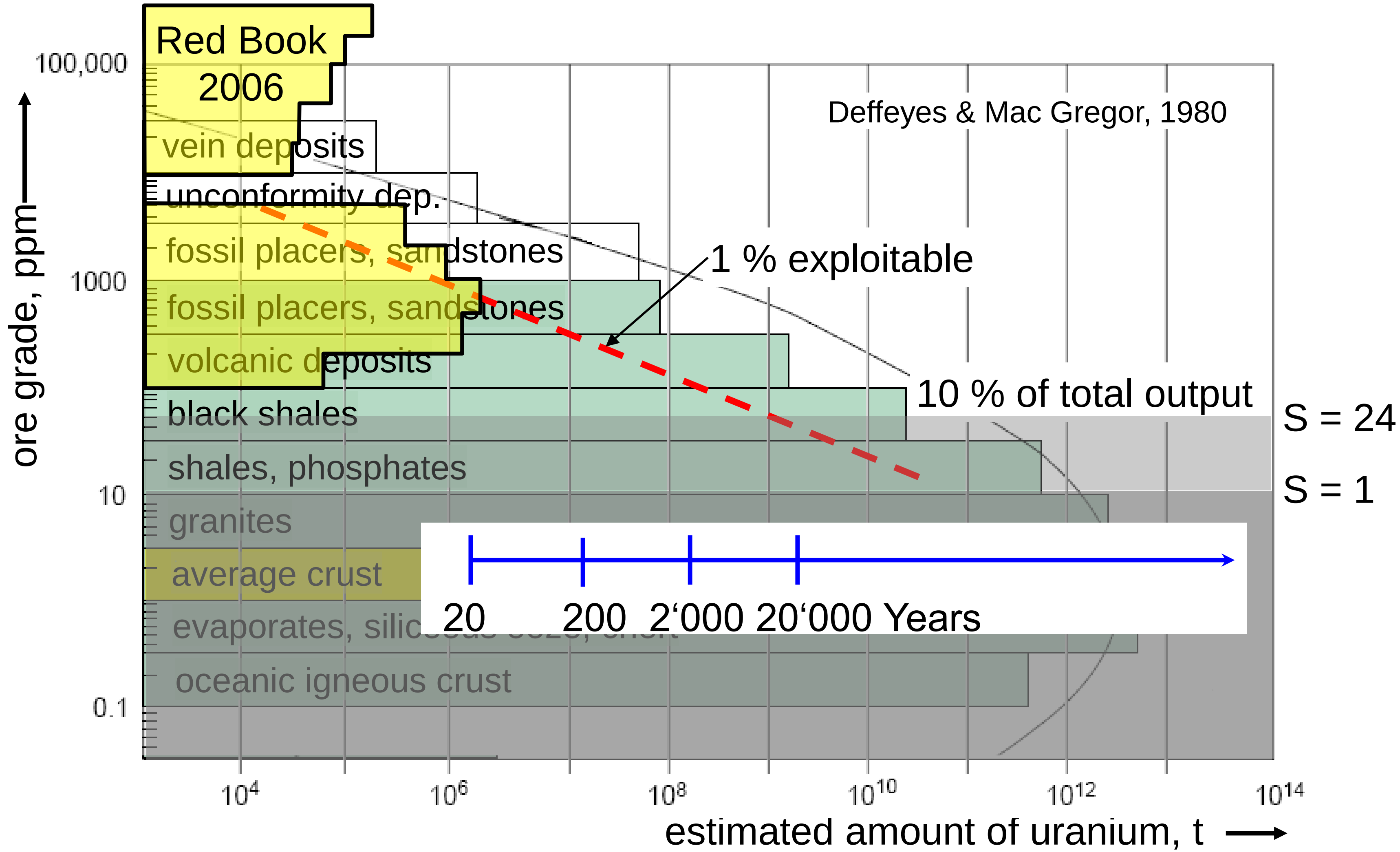


Abundance of uranium in earth crust

Uranium minable at today's mining limit



Uranium minable for ~10 % of gross NPP output



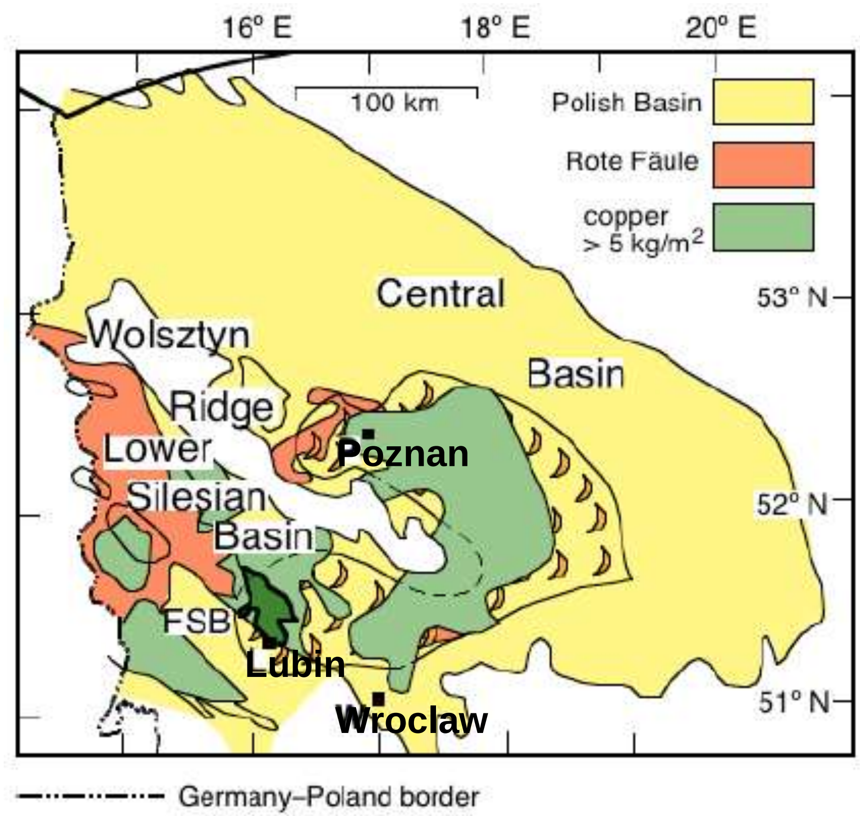
Alternatives: Uranium in copper ores

Kupferschiefer from the Lubin-Sieroszowice district

Mean uranium content:	~ 60 ppm
Copper content:	~ 2 %
Total reserves:	~ 2'400 Mt ore
Copper reserves:	~ 48 Mt
⇒ Uranium total:	~ 144 kt U-nat
⇒ Electric equivalent:	~ 900 GWa

- Extractable at <5 % of an LWR output
- Reduction of radioactive tailings

Annual production today:	~ 569 kt Cu
⇒ Uranium content:	~ 1'700 t/a
⇒ Electric equivalent:	~ 10 GW



Piestrzyfiski (1990), Oszczepalski & Blundell (2005)

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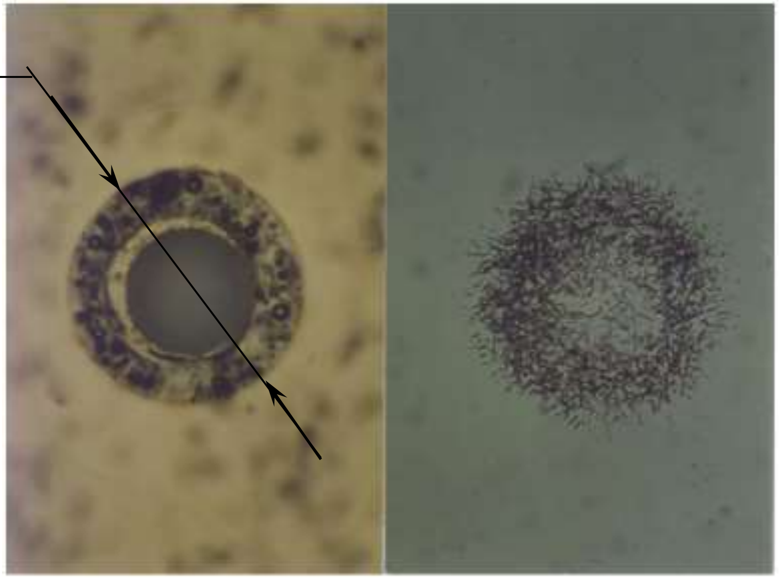
China: Xiaolongtang Guodian Power, Fly ash from 2 hard coal boilers

- Existing depository: ~5.5 Mio. t fly ash = 1.2 kt uranium
- Throughput: 600 kt/a fly ash = 125 t/a uranium
- Reach of local coal resources: 20 years

Similar uranium prospection programs in USA, Ungarn, Polen, Südafrika

∅ 100 µm



Uranium in „Ore“	
ppm	1 kg Ash =
220	4 kg hard coal

USGS Fact Sheet FS-163-97 October, 1997

Ash processing solves important environmental problems of coal power

- Uranium + other valuable metals (e.g. vanadium)

Alternatives: Uranium from polish hard coal

Mine / Plant	$A_{U\text{-}238}$, fly ash	$C_{U\text{-}238}$, fly ash
	Bq/kg	ppm
Polaniec	111.0	9.0
Dolna Odra	117.0	9.5
Wroclaw 1	110.0	8.9
Wroclaw 2	110.0	8.9
Lublin	126.0	10.2
Pomorzany	126.0	10.2
Kozienice	96.0	7.8
Skawina	160.0	12.9
Rybnik	183.0	14.8
Krakow Leg	143.0	11.6
Maximum	436.8	35.3

Novina-Konopka (1993)

Polish fly ash has around 10 ppm U-nat

- No anomalies in Poland
- Uranium in coal: ~ 2 ppm
- Ash accumulation: ~ 100 Mt/a
- Contained uranium: ~ 200 t/a

⇒ electric equiv. ~ 1.25 GW

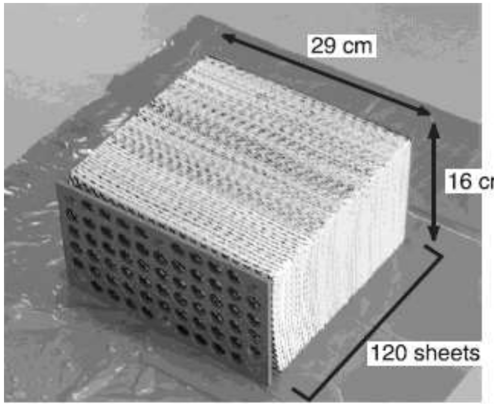
Alternatives: Extraction of Uranium from sea water

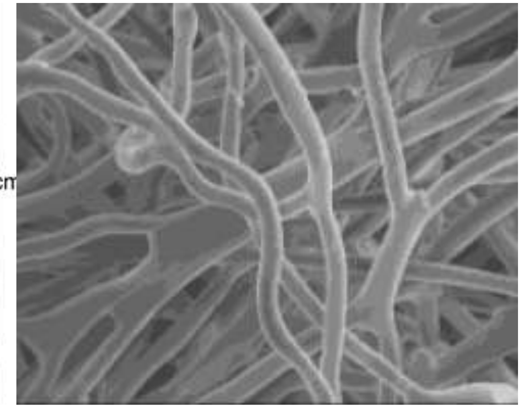
Seawater: 5 Billion ton of uranium

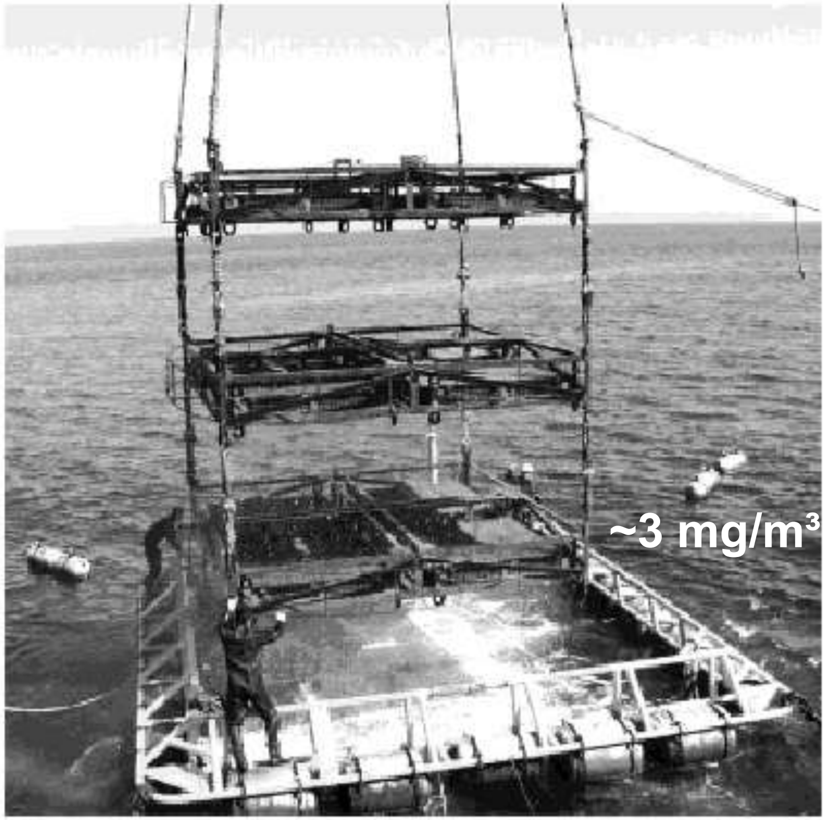
Concentration: 3 ppb (μg/kg)

Energy content at ~50 MWh/$kg_{U\text{-}nat}$: 540 J/kg

equiv. to hydropower from 1 kg water over 54 m







Field experiment: 450 days in the Pacific Ocean

Gain: ~2.9 kg/a U-nat on 50 m² rag size ⇒ ~0.058 kg/(a·m²) ⇒ ~ **2900 kWh/(a·m²)**

for comparison: photovoltaics 90 - 120 (...200) kWh/(a·m²)

N. Seko et al., NT Vol. 144 Nov. 2003

Summary

- Very low sensitivity of electricity cost from changing uranium prices
- Low sensitivity of energy consumption in mines from ore grade
- Low sensitivity of uranium price from ore grade
- High conventional resources (RAR ~50 a, speculative ~200 a)
- Huge unconventional resources
- Option of a closed fuel cycle with breeders (and transmuters)
- Poland has own strategic uranium reserves

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Thank you for your attention.