



# Uranium Enrichment

**Mikhail Platov, TENEX**  
(WNU Alumni 2008)

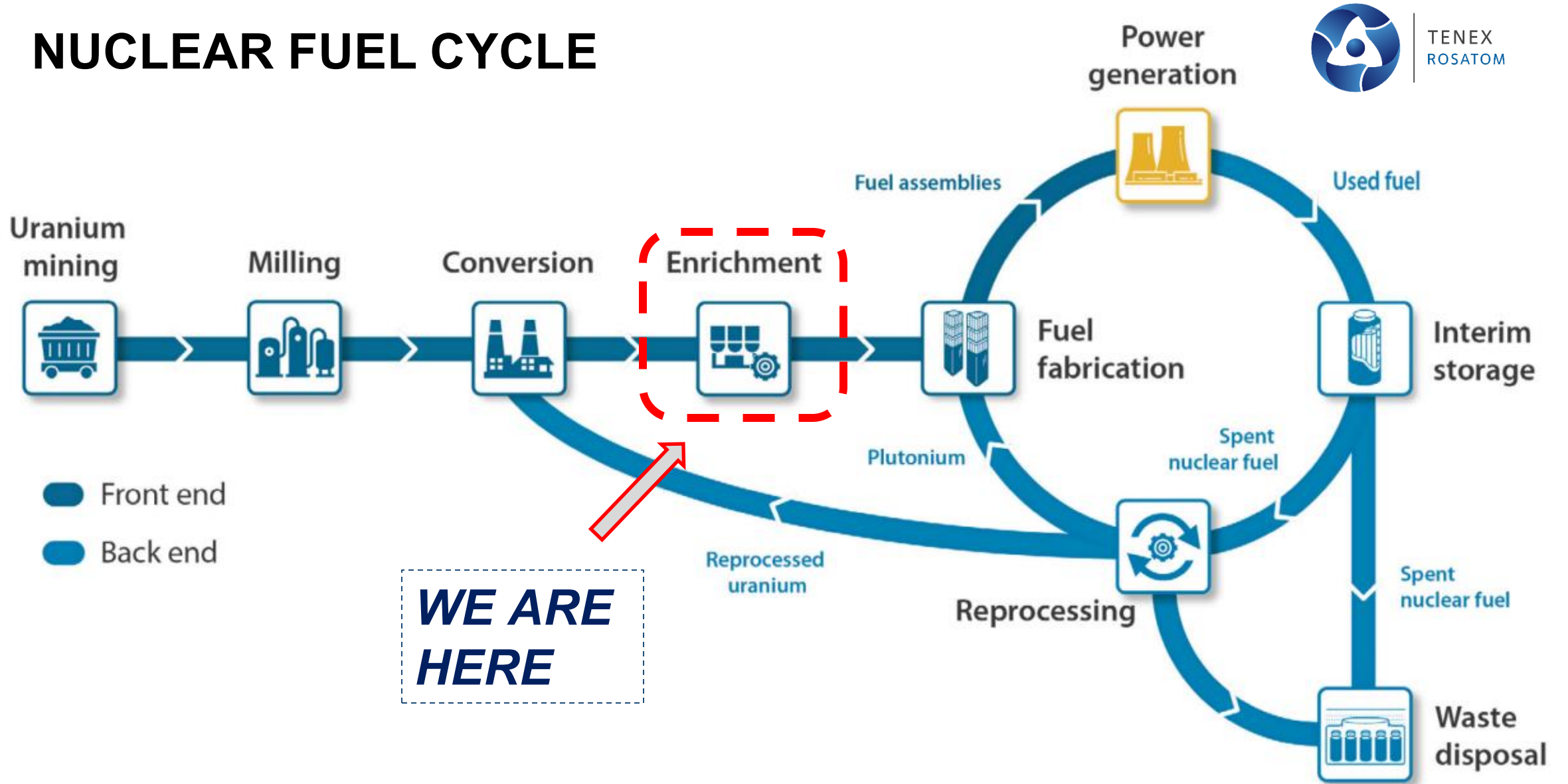
**WORLD NUCLEAR UNIVERSITY**  
**SUMMER INSTITUTE**  
June 2025, Shanghai, China

# OBJECTIVES



1. Explain what uranium enrichment and SWU is
2. Talk about basic methods of uranium enrichment
3. Describe major producers of enriched uranium
4. Give a short description for the Russian enrichment industry
5. Discuss recent trends (LEU+, HALEU) and market developments

# NUCLEAR FUEL CYCLE



# WHAT IS ENRICHMENT?

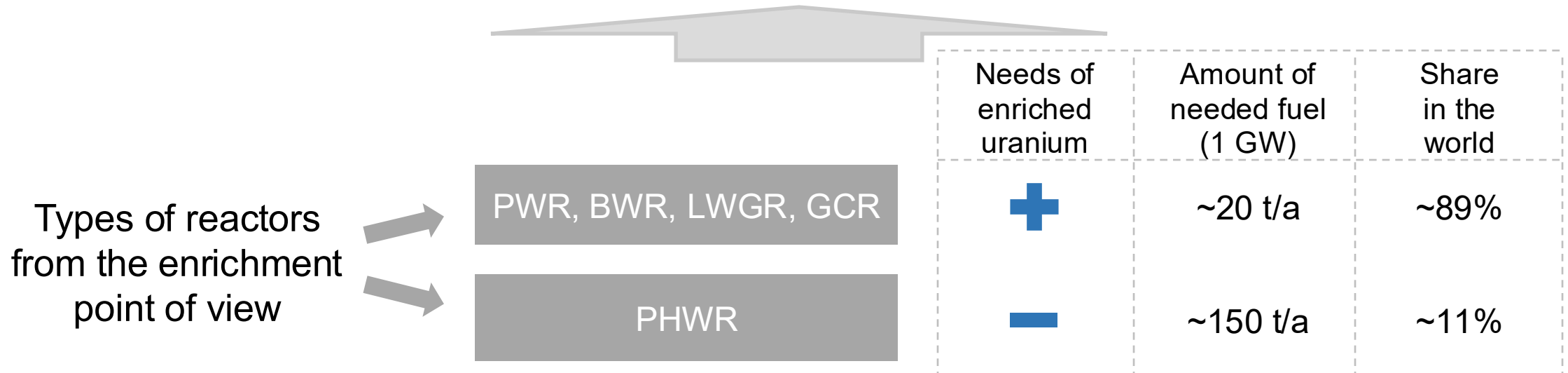


Natural uranium is a mixture of three **isotopes** with following percentages:

- U-234..... 0.0055 %
- **U-235.....0.711 %**
- U-238..... 99.2745 %

Only this isotope is capable of self-sustaining nuclear chain reaction

Concentration of U-235 isotope must be increased from 0.711% to 3-5%.  
This process is known as **Uranium Enrichment**



# METHODS OF URANIUM ENRICHMENT

1. Gas diffusion enrichment

2. Centrifuge enrichment

3. Laser enrichment

4. Aerodynamic processes

5. Electromagnetic isotope separation

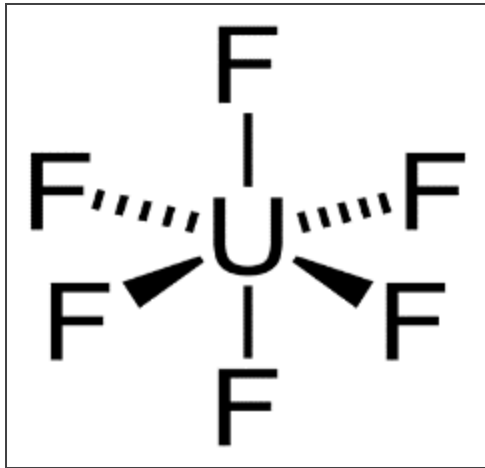
6. Plasma separation

7. Chemical separation



# WHY DO WE USE URANIUM HEXAFLORIDE?

**UF<sub>6</sub> (or Hex)** is a chemical compound consisting of one atom of uranium (U) combined with six atoms of fluorine (F).



Chemical  
Properties

Has only one stable  
isotope (F-19)\*

Solid at room  
temperature

Readily sublimates  
at sub-atmospheric  
pressure

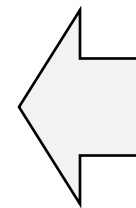
*\*If more than one isotope – enrichment is highly difficult by centrifuge or gas diffusion.*

# ONE MORE KEY CHEMICAL PROPERT



**Sublimation** is the conversion between the solid and the gaseous phases of matter, with no intermediate liquid phase

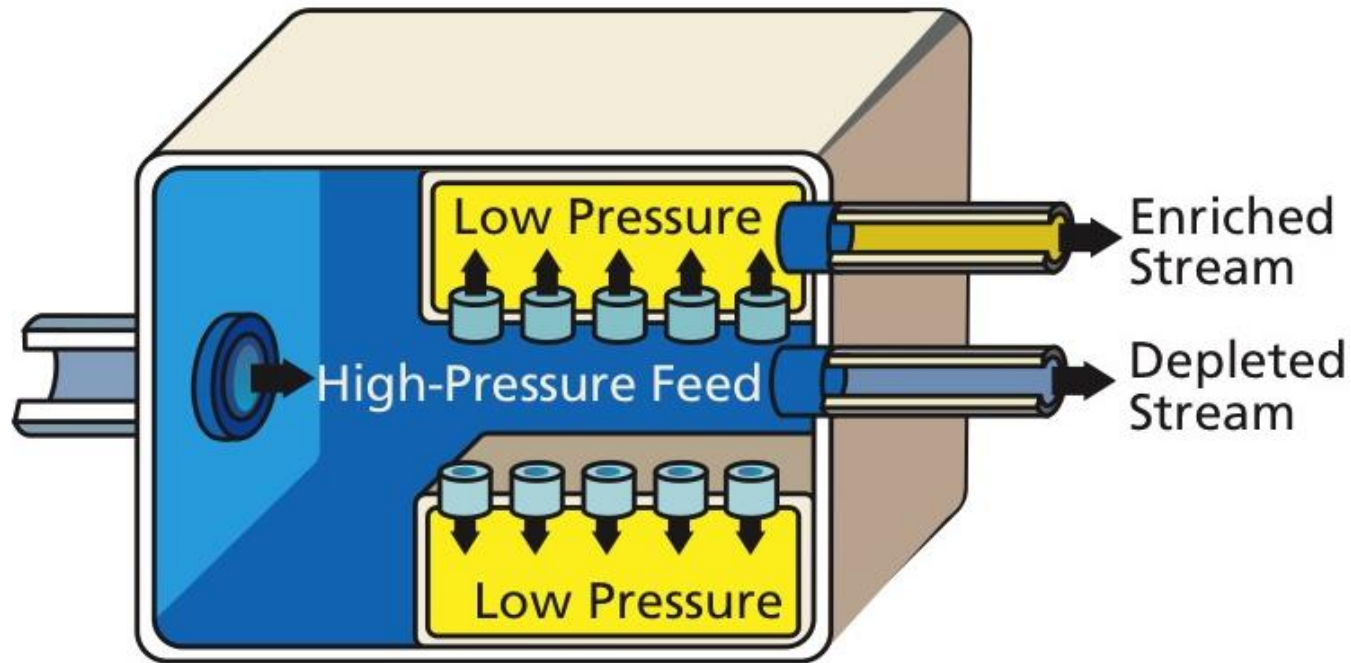
Make it very convenient to use UF<sub>6</sub> in centrifuges



**Example:**

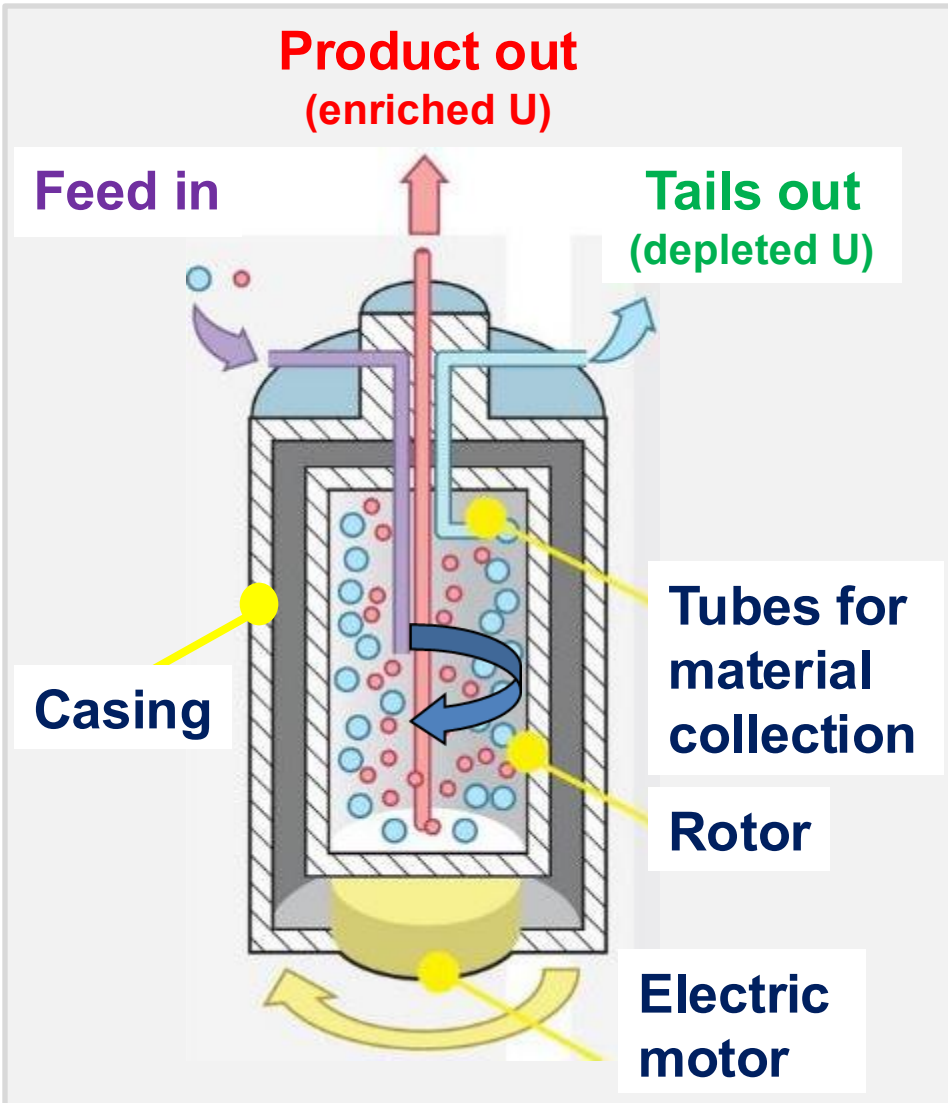
Sublimation of dry ice (CO<sub>2</sub>), water as catalyst

# GAS DIFFUSION ENRICHMENT



- First generation of industrial technologies
- Disadvantages – **high capital costs** and **extremely high power consumption** (up to 3,000 kWh/SWU)
- Last plant (Paducah in the USA) was shut down in 2013

# CENTRIFUGE ENRICHMENT



## Purposes

To receive gaseous UF<sub>6</sub> from feed system and to increase U-235 isotope concentration up to 5% (for “standard” LEU) or more

## When gaseous UF<sub>6</sub> is introduced into the centrifuge

Centrifugal forces push the heavier U-238 closer to the wall of the rotor than the lighter U-235



Gas closest to the wall becomes depleted in U-235



Gas that gathers at the center of the rotor (near the axis) becomes slightly enriched in U-235

# DO YOU KNOW?

Centrifuge  
rotation speed

**>1500**  
rotations per second

Height

**~1 to 12**  
meters

Lifetime

**30+**  
years



# DO YOU KNOW?

When the centrifuge plays



your favorite track

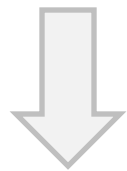
Performance  
can be  
checked  
by ear

# CASCADES



## Problem

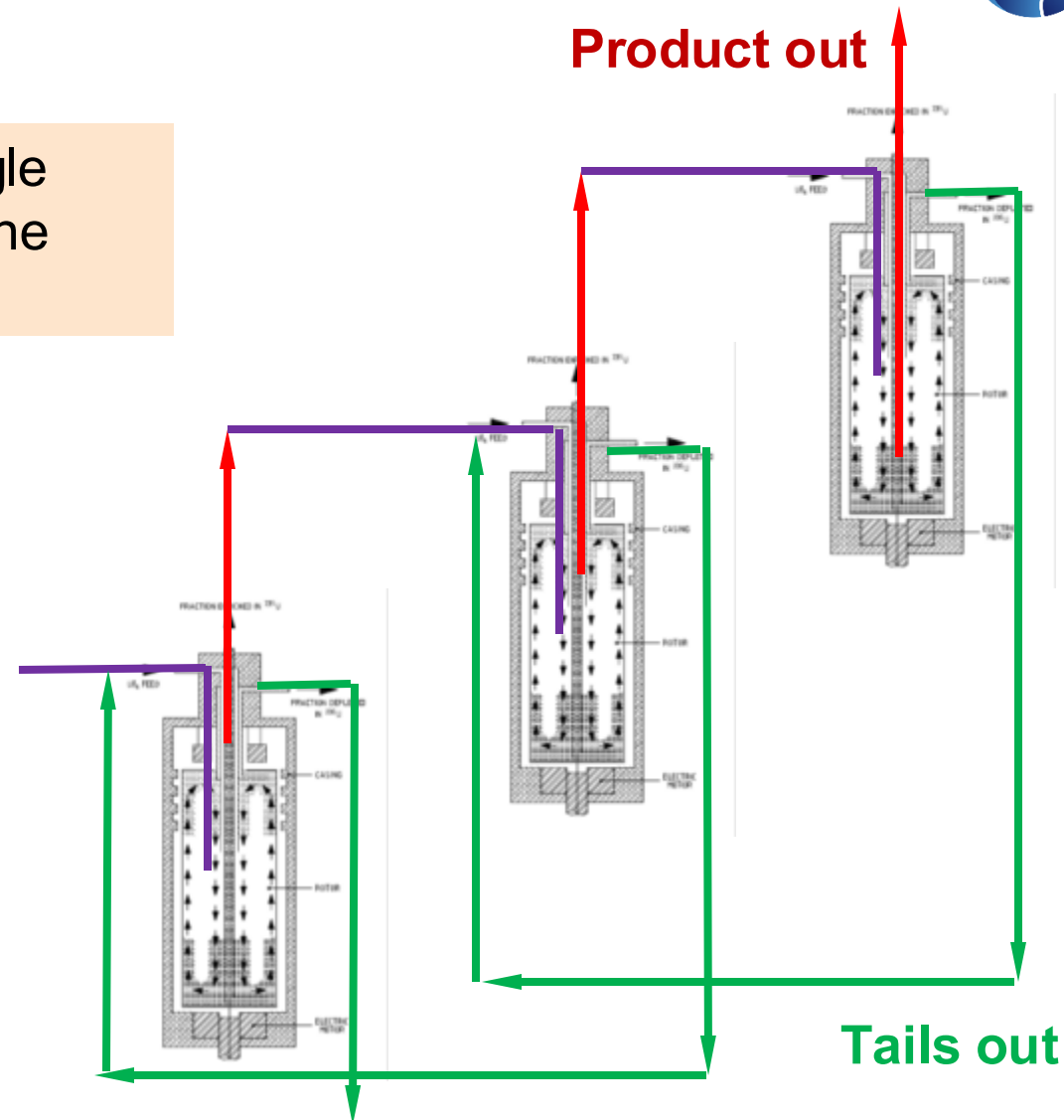
Enrichment level achieved by a single centrifuge is **insufficient** to obtain the desired concentration of  $U^{235}$



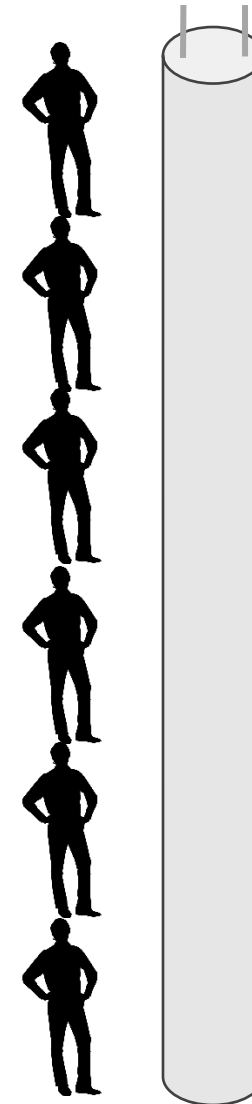
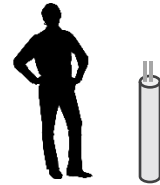
## Solution

To connect **numerous** centrifuges together in parallel & series

Arrangement of centrifuges called **“cascade”**



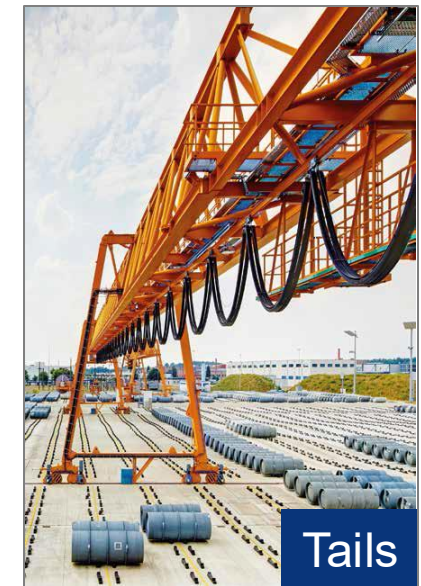
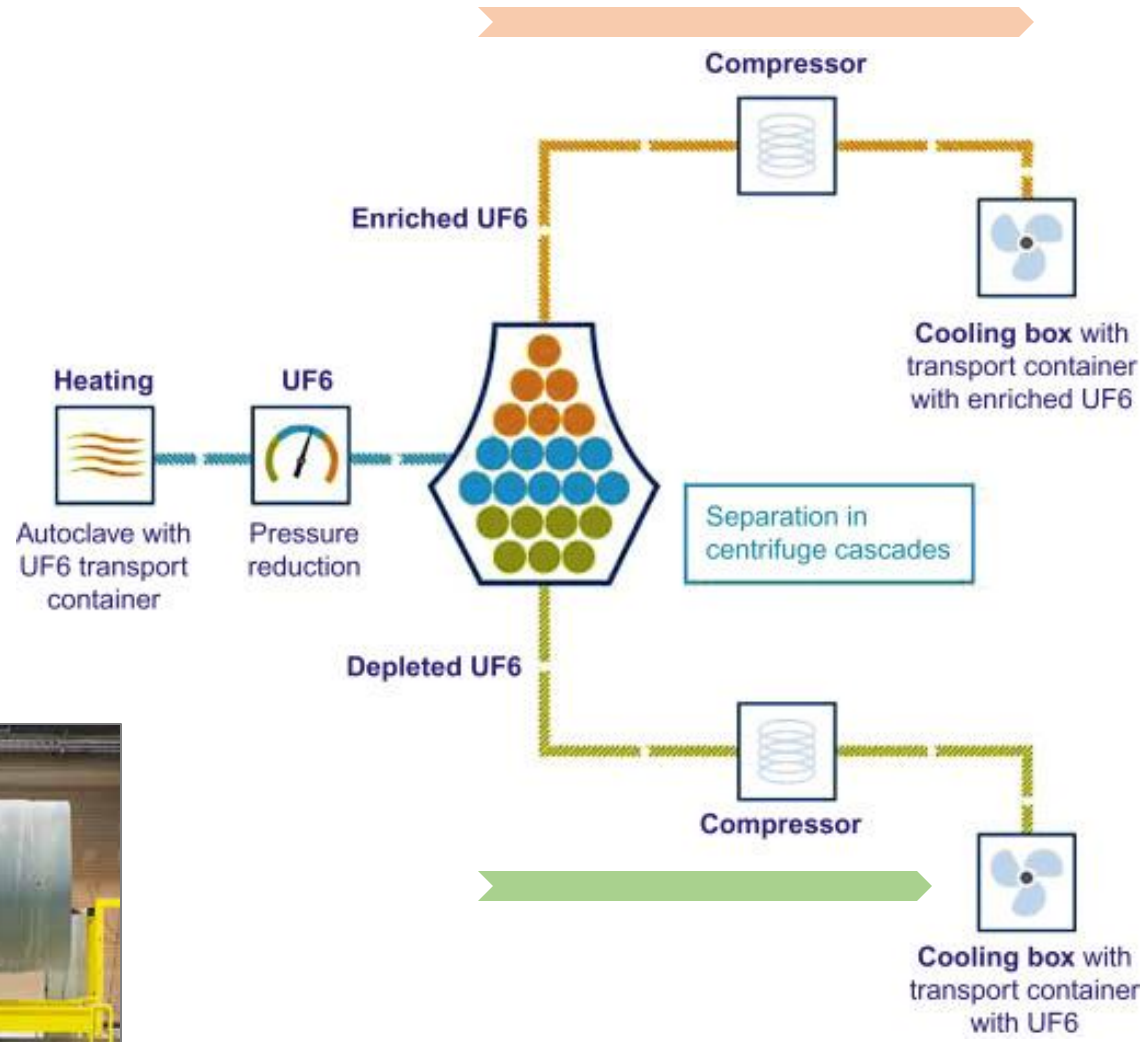
# CENTRIFUGES



American  
Centrifuge  
(Centrus)



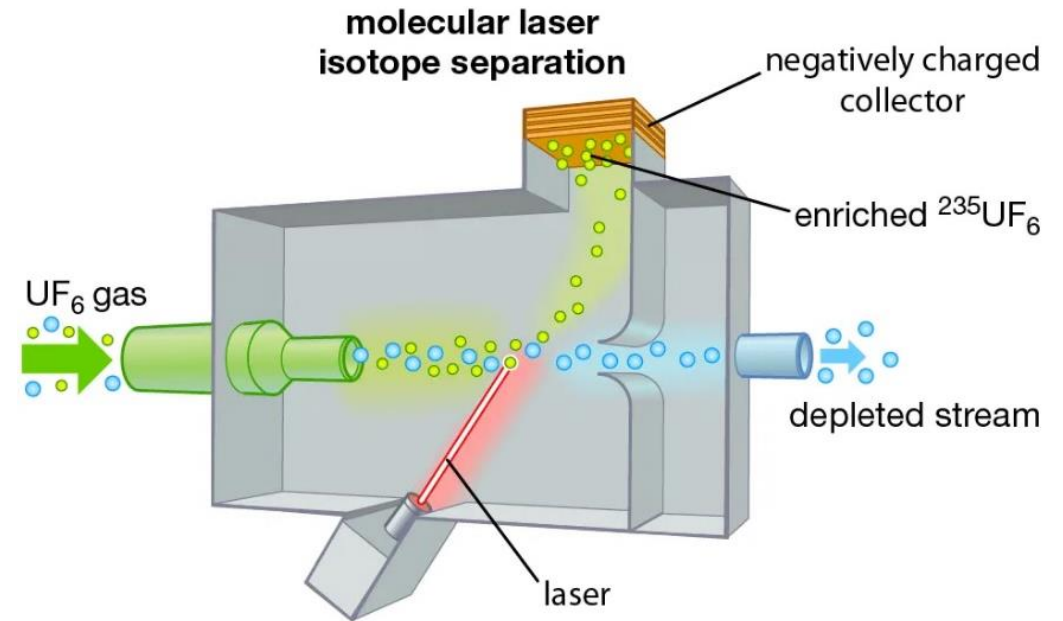
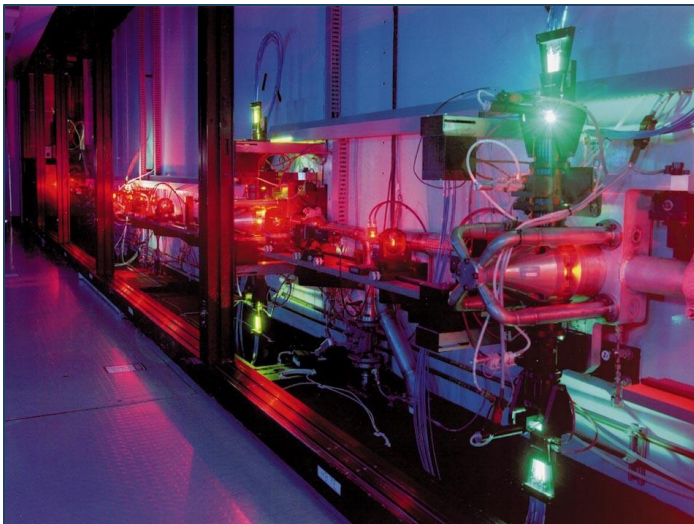
# ENRICHMENT PLANT SCHEME



# LASER ENRICHMENT

## AVLIS Technology

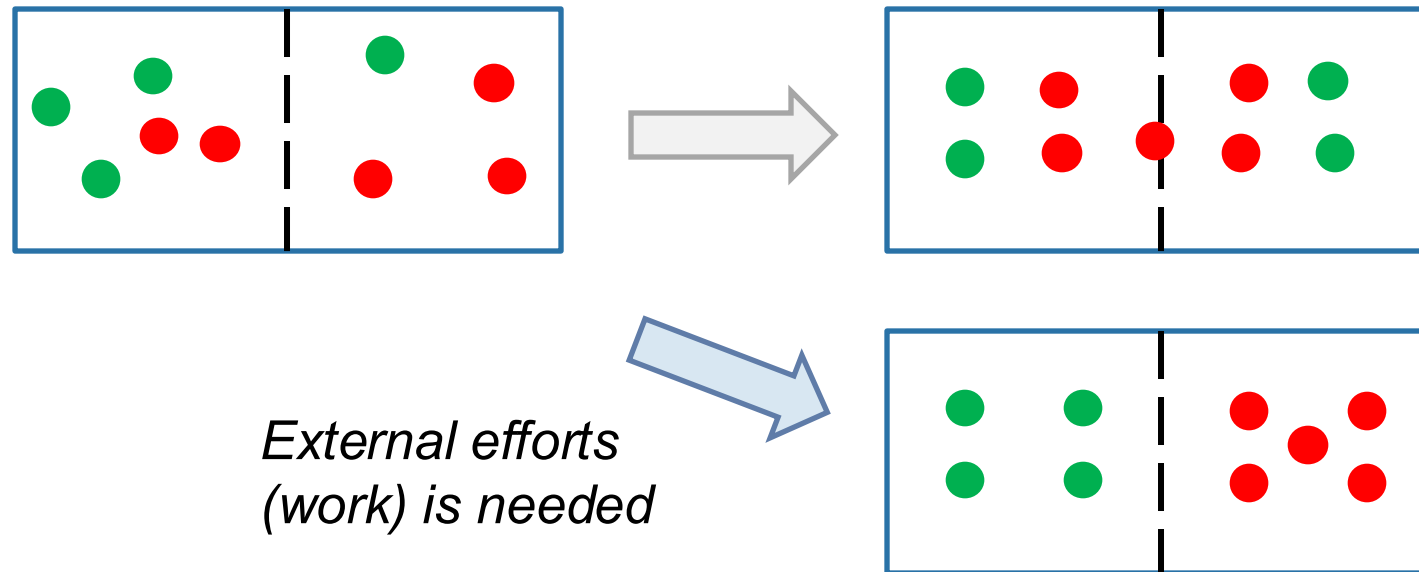
- AVLIS = Atomic Vapour Laser Isotope Separation
- Relies on the difference between absorption bands of  $U^{235}$  and  $U^{238}$
- U metal feed required
- High separation factor
- One stage separation
- Power consumption around 200 kWh/SWU



- Third generation of industrial technologies
- SILEX laser technology is in progress (and is anticipated to be ready for commercial production in 2030)
- Numerous other developers are arriving (General Matter, LIST, ASP Isotopes) – but technology details and economic competitiveness are still not clear

# WHAT IS SWU?

Second law of thermodynamics states that **the entropy of an isolated system never decreases**. Such systems spontaneously evolve towards thermodynamic equilibrium – a state with maximum entropy.



**Separative Work (SW)** is an effort necessary (in case of uranium) to separate U-235 and U-238 isotopes.

# SWU CALCULATIONS



The Separative Work (SW) could be calculated as follows, and is measured in kilograms of separative work (kg SW):

$$W_{SWU} = P \cdot V(x_p) + T \cdot V(x_t) - F \cdot V(x_f) , \quad V(x) = (1 - 2x) \ln\left(\frac{1 - x}{x}\right)$$

where:  $x_p$ ,  $x_t$ , and  $x_f$  are concentrations of U-235 in product, tails and feed,  
P, T, F – quantity of product, tails, feed

The following equations are also applicable:

$$F = P + T$$

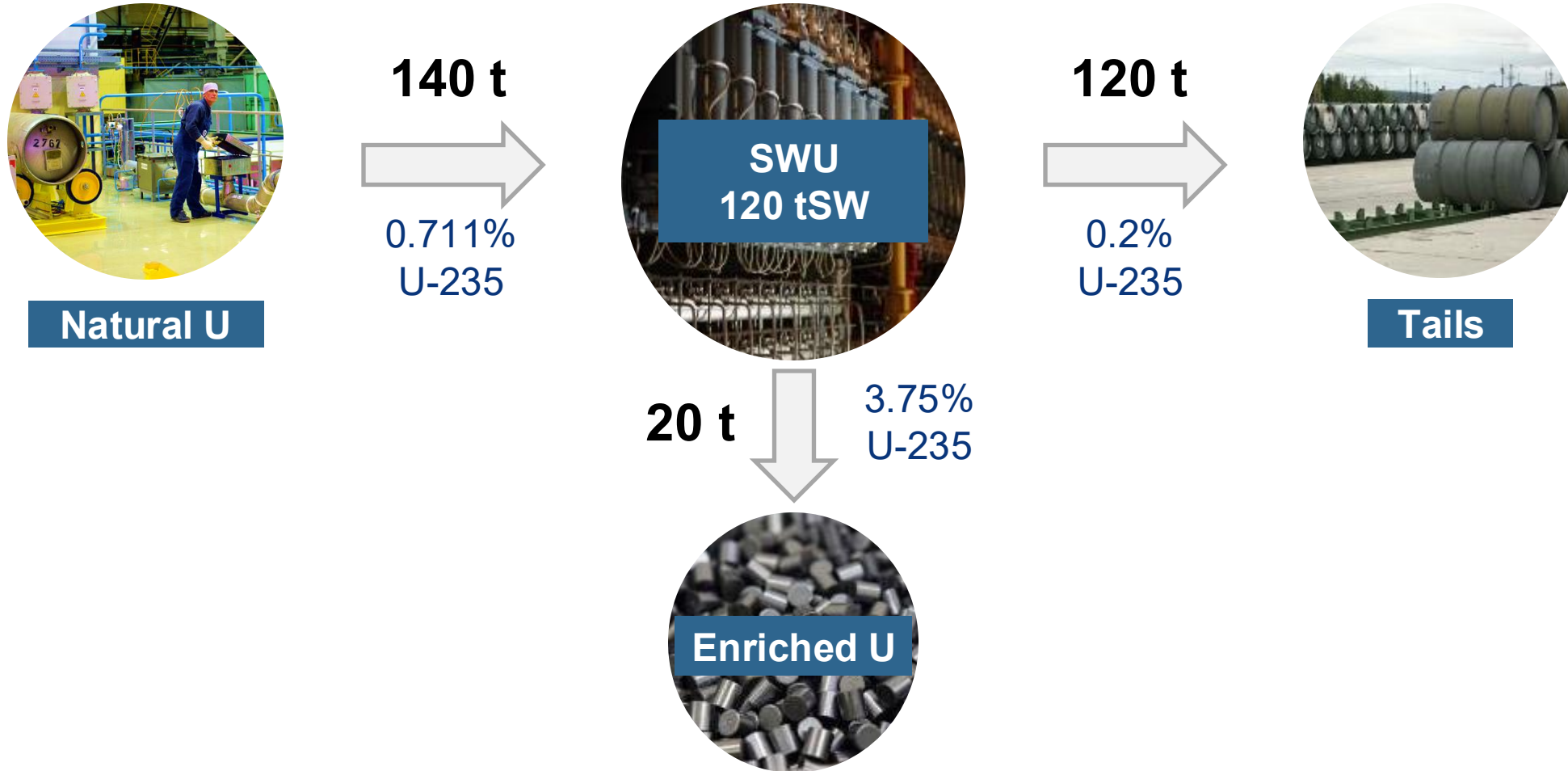
uranium material balance

$$F \cdot x_f = P \cdot x_p + T \cdot x_t$$

U-235 isotope balance

A term **Separative Work Unit (SWU)** is frequently used, where 1 SWU equals 1 kg SW. A larger unit, 1 metric tonne of separative work (1 t SW = 1,000 kg SW) is also used. Capacity of enrichment plants is measured in tonnes SW per year (t SW/a), or K/M SWU/a

# HOW MUCH SWU DO WE NEED FOR NPP (1GW)?



1,000 tSW/a is enough to enrich uranium for about 8 large nuclear power plants.

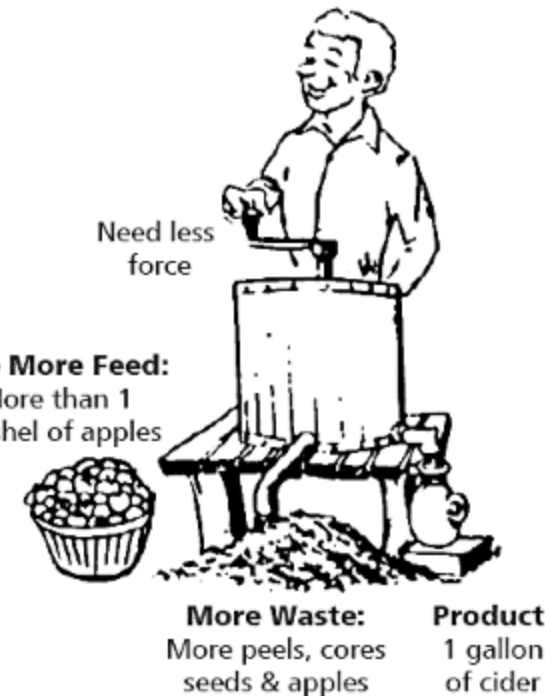
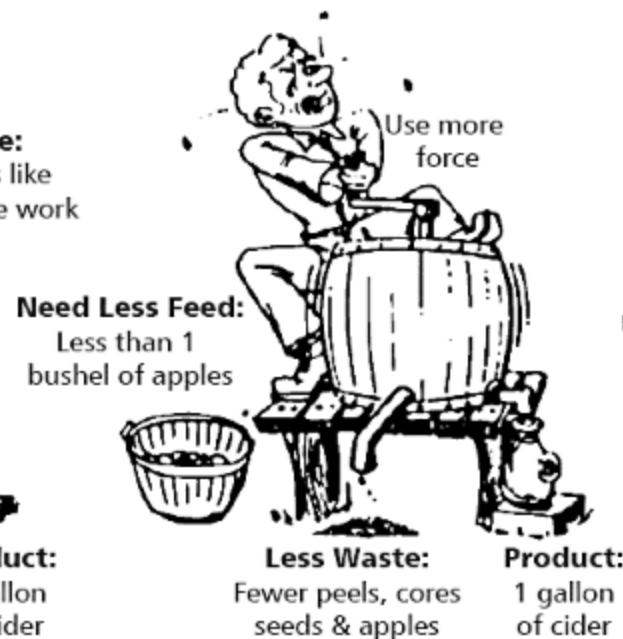
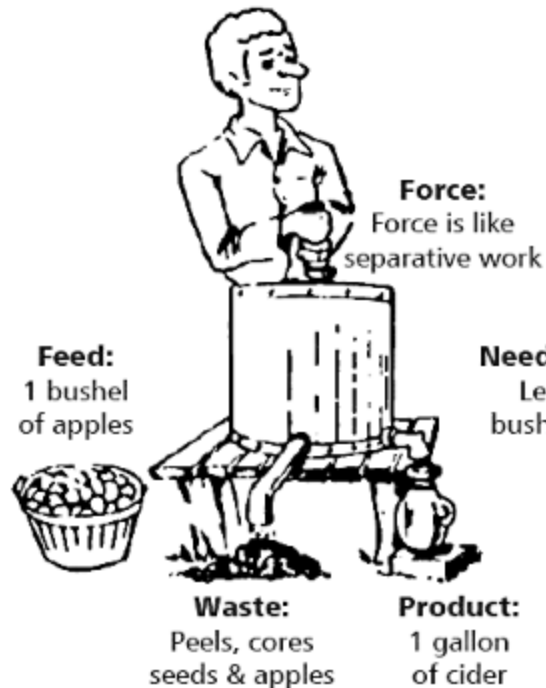
# ENRICHMENT AND MAKING CIDER

## Making 1 kg of EUP (4,0%)

**Usual Operation**

**More Force, But Less Feed**

**More Feed, But Less Force**



This simple and elegant case **is extremely important** when talking about the SWU market

0.25% tails:  
8.1 kg U + 5.8 SWU

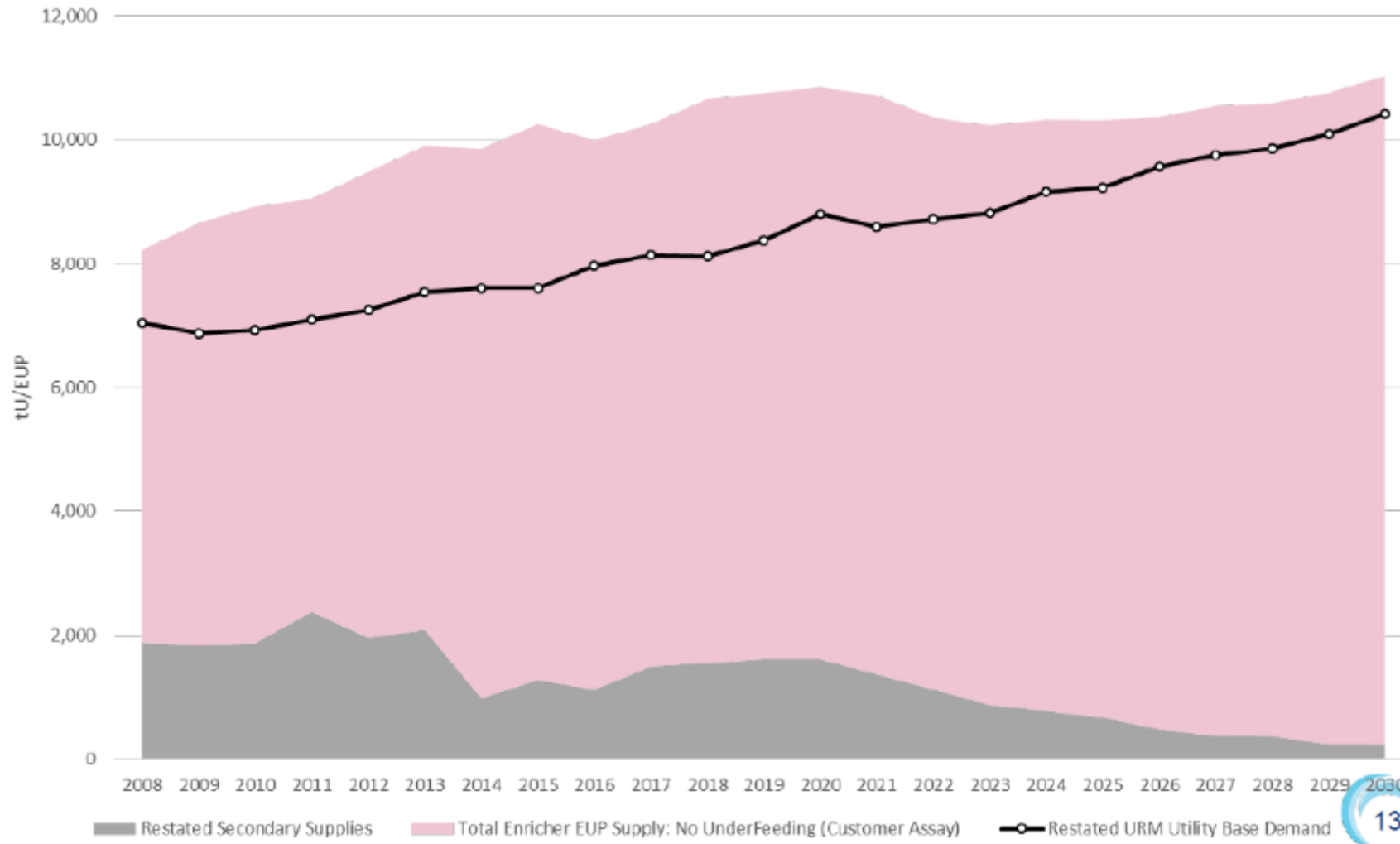
=

0.2% tails:  
7.4 kg U + 6.5 SWU

=

0.3% tails:  
9.0 kg U + 5.3 SWU

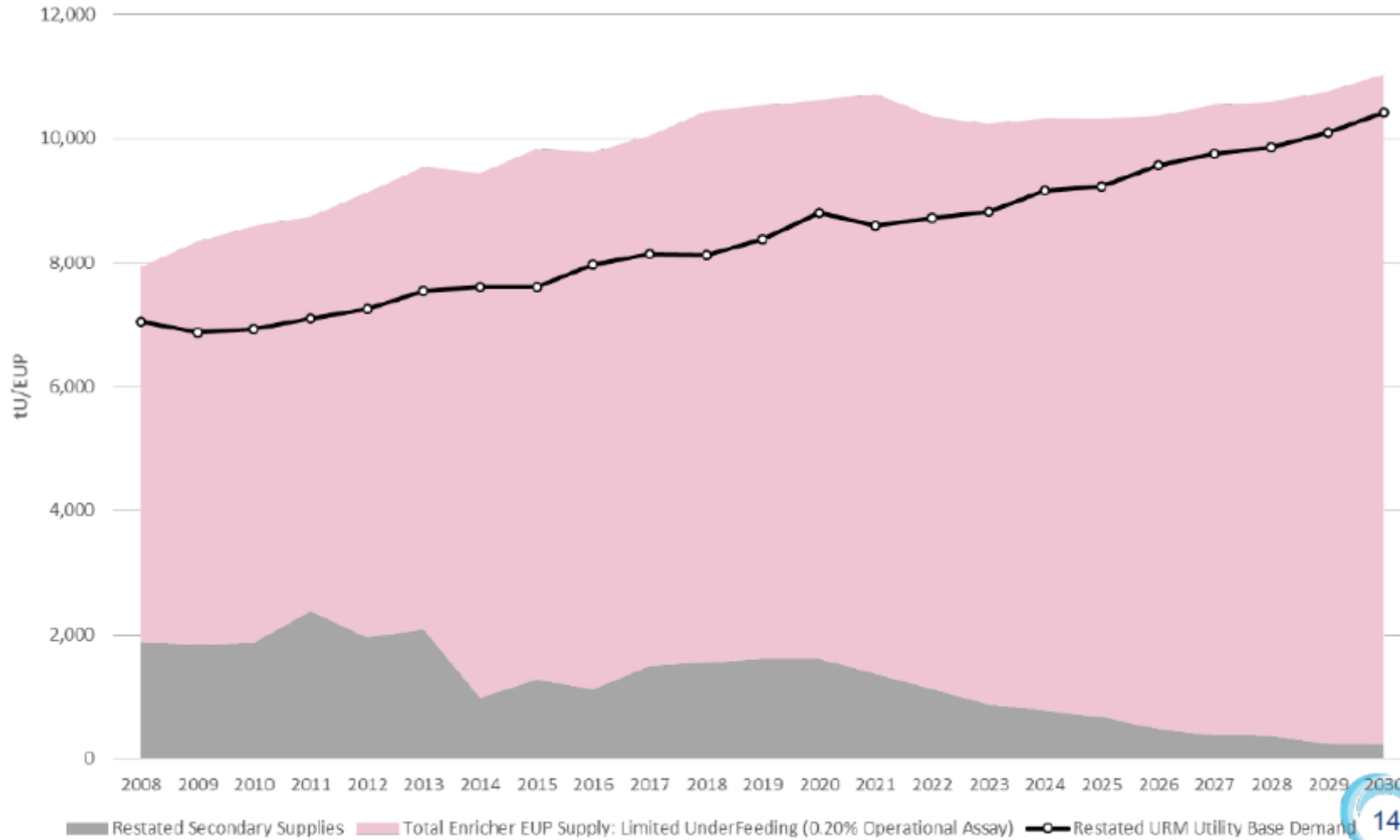
# AN ENRICHER VIEW OF SUPPLY AND DEMAND



**No Under-Feeding**

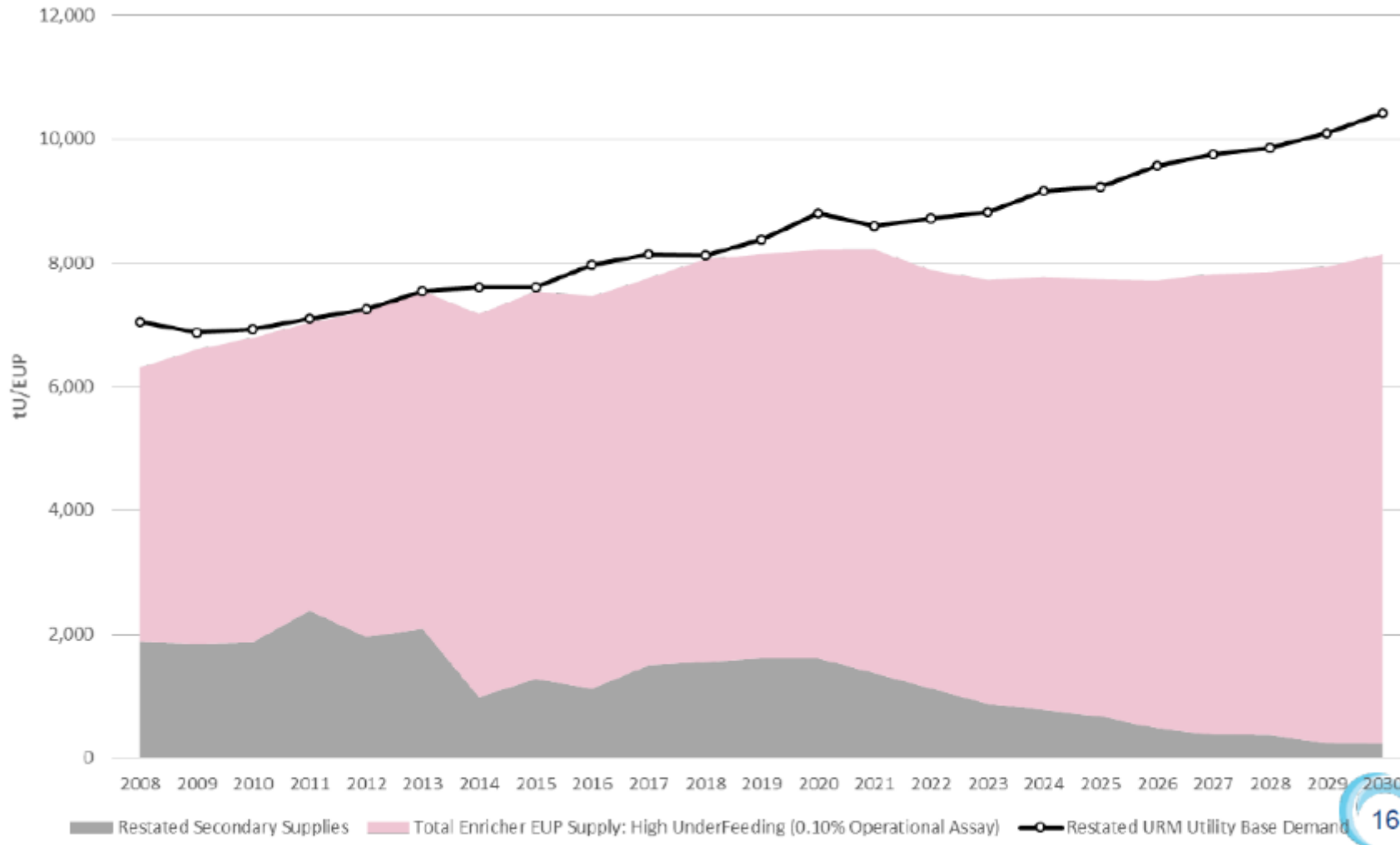
Source: URENCO, 2017

# AN ENRICHER VIEW OF SUPPLY AND DEMAND



**Limited Under-Feeding**

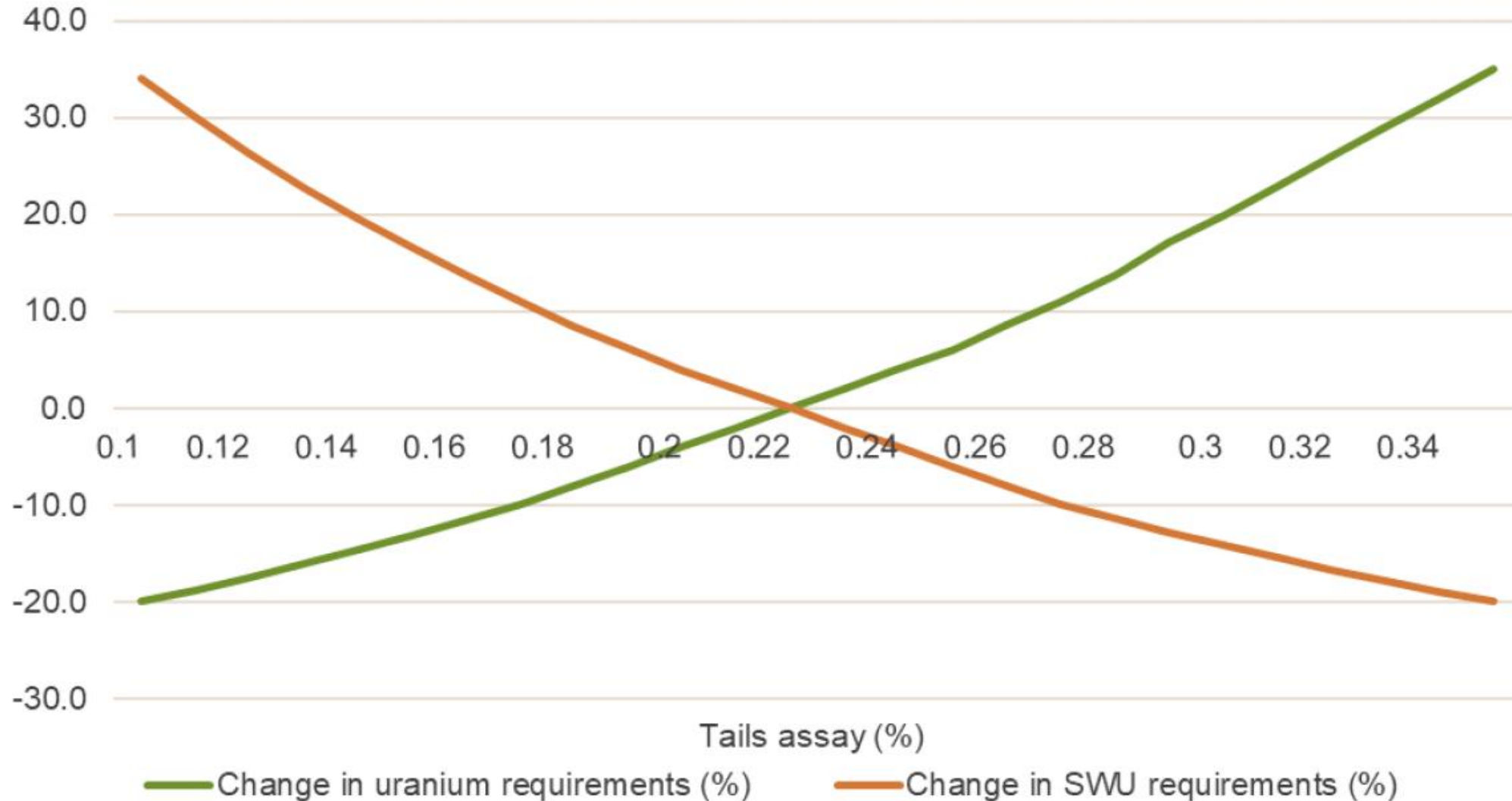
# AN ENRICHER VIEW OF SUPPLY AND DEMAND



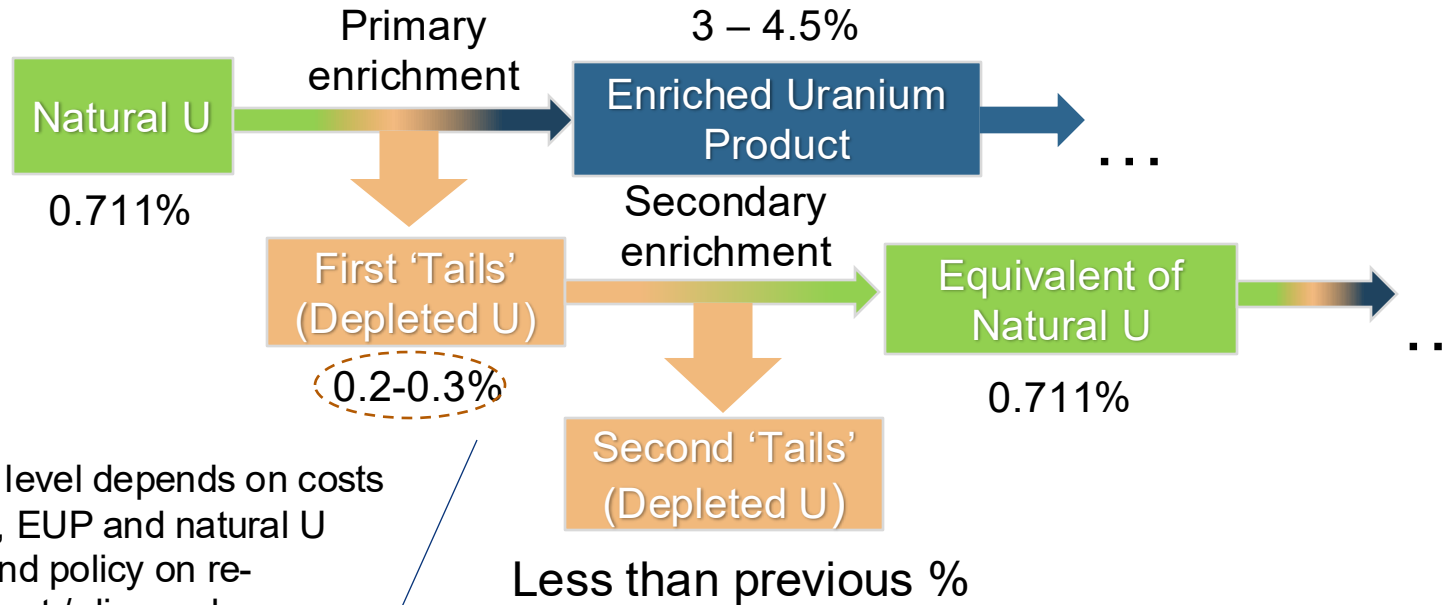
**High Under-Feeding**

Source: URENCO, 2017

# ECONOMIC OPTIMUM 'TAILS' ASSAY FROM BUYER'S POINT OF VIEW



# TAILS RE-ENRICHMENT



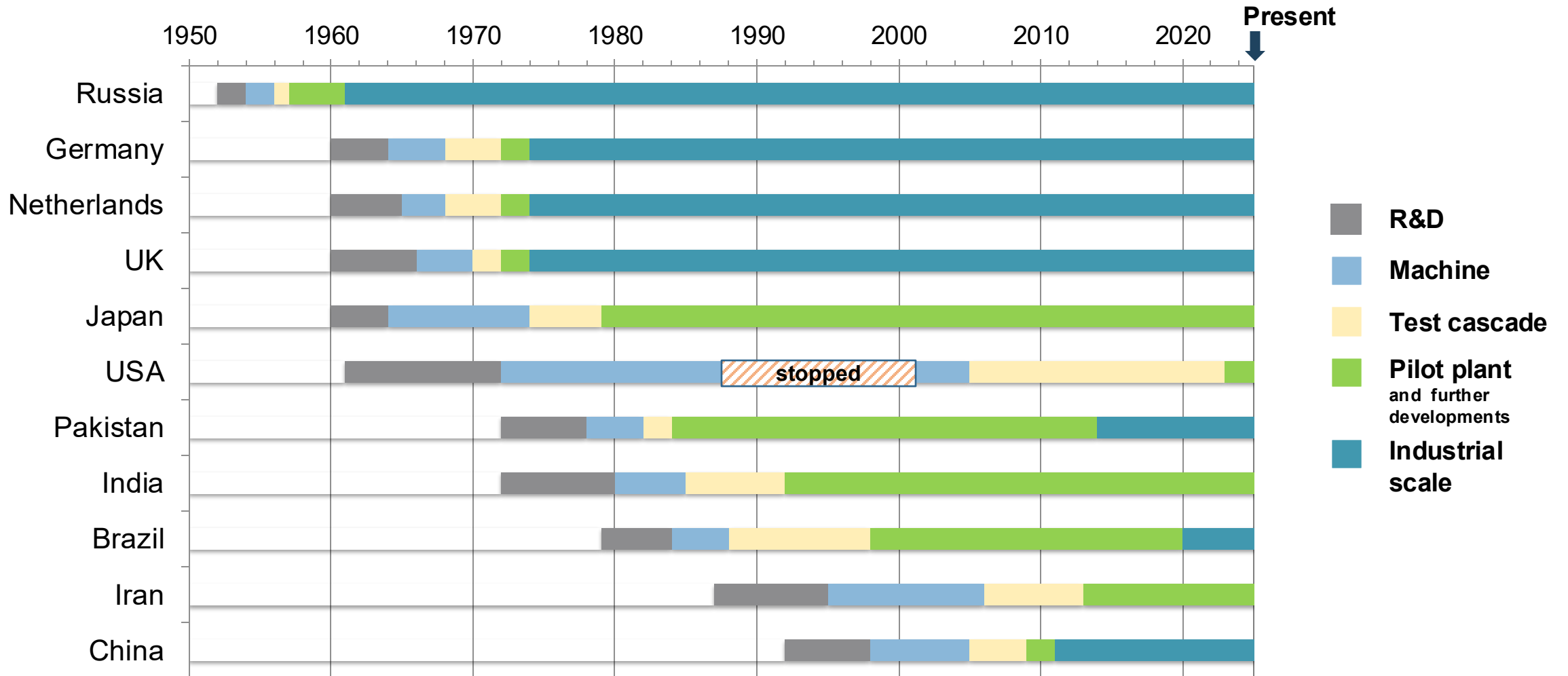
Optimal level depends on costs of SWU, EUP and natural U prices and policy on re-enrichment / disposal

Re-enrichment of tails is one of the most important “**secondary sources**” of uranium

In case of **high U prices** it's more efficient for enrichers to work with **lower 'tails' assay** maximizing revenues and returns

Dealing with 'tails'	
Re-enrichment to 0,711%	Ships constructing
Disposal after reconversion	

# TIMELINE OF WORLD CENTRIFUGE PROGRAMS



\*Based on SPLG 2010 and further developments (as of open sources of information).

# ENRICHMENT CAPACITY – NOW AND THEN



**>95%**  
of SWU is  
produced by  
**4 companies**

Country	Company and plants	2010	2015	2020	2025
Russia	Novouralsk, Zelenogorsk, Seversk, Angarsk	28 600	26 600	27 700	27 100
Germany Netherlands UK USA	Urenco: Gronau, Germany; Almelo, Netherlands; Capenhurst, UK; Eunice, USA	13 000	19 100	18 800	17 300
France	Orano: Georges Besse I & II	10 800	7 000	7 500	7 500
USA	USEC (Centrus)	10 300	0	0	0
China	CNNC: Hanzhun, Lanzhou & Emeishan	1 300	4 200	6 300	10 000
Other	Argentina, Brazil, Japan, India, Pakistan, Iran	100	200	300	400
	<b>Total, th SWU/a, approximately</b>	<b>64 100</b>	<b>57 100</b>	<b>60 600</b>	<b>63 300</b>
	Requirements (as of WNA Reference scenario)	<b>48 856</b>	<b>51 425</b>	<b>50 205</b>	<b>54 415</b>

# RUSSIAN ENRICHMENT FACILITIES

- 4 plants with millions of centrifuges
- ~40% of the world enrichment capacity
- 11 generations of centrifuges
- Ability to enrich RepU

**More than 70 years of reliable supply**

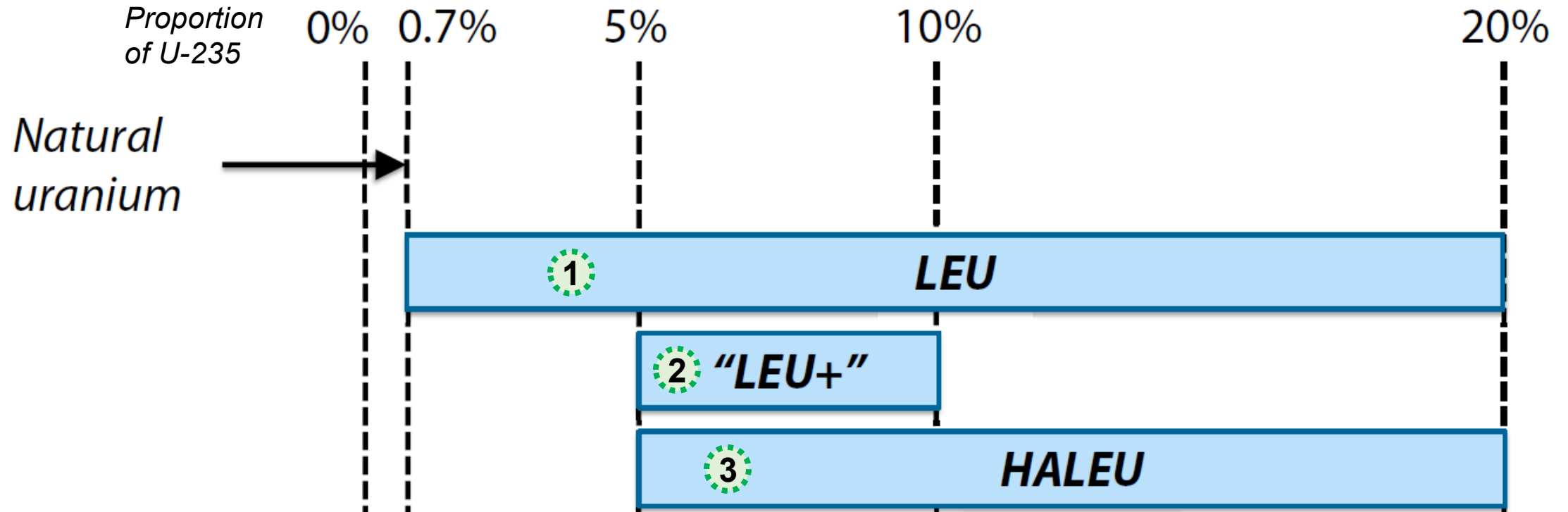
Sustainable solutions for 'tails' management



Centrifuge output is increased **25 times**, and lifetime is increased **10 times** – to **more than 30 years** compared to the 1<sup>st</sup> generation produced in 1953



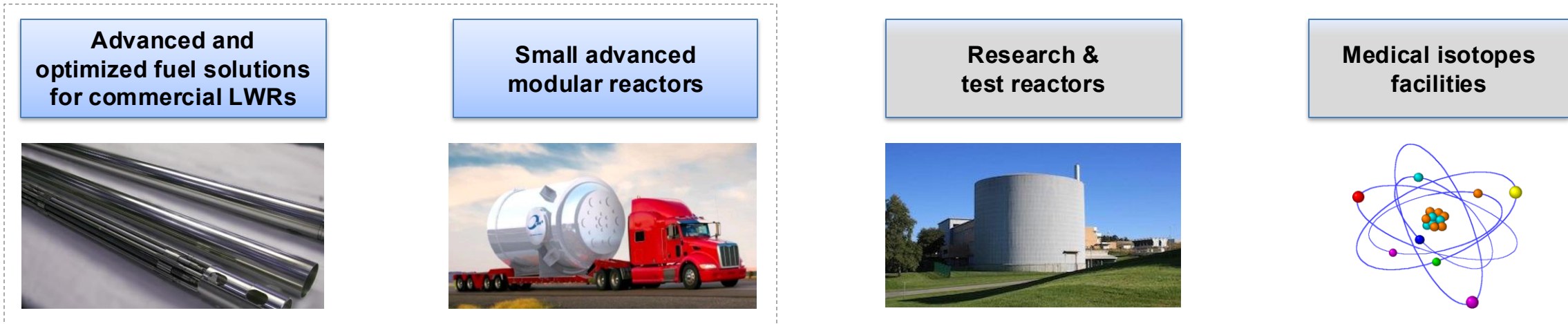
# LOW ENRICHED URANIUM AND MORE



1. Most reactors require “**standard**” **LEU** at 3-5% U-235
2. **LEU+** (5-10% U-235) is used for so-called accident tolerant fuel
3. High Assay Low Enriched Uranium (**HALEU**) is needed for research reactors, as well as for some innovative reactors (SMRs, etc.)

# WHAT IS HALEU?

**High Assay Low Enriched Uranium (HALEU)** is a product with U-235 assay **higher than 5% and below 20%**. HALEU is potentially required for such purposes as:



- ✓ **Market size:** US ~50 MTU/a by 2035 (**US DOE**), outside US  $\leq$  10MTU/a (**ESA**)
- ✓ **Common forms:**
  - metal
  - oxide ( $U_3O_8$ ,  $UO_2$ )
  - Hexafluoride ( $UF_6$ )
- ✓ **Technological processes for HALEU production:**
  - Natural  $UF_6$  enrichment
  - HEU downblending (*limited HEU availability*)

HALEU market is expected to be relatively small until the next decade but promising

# HALEU – AVAILABILITY AND ISSUES TO SOLVE

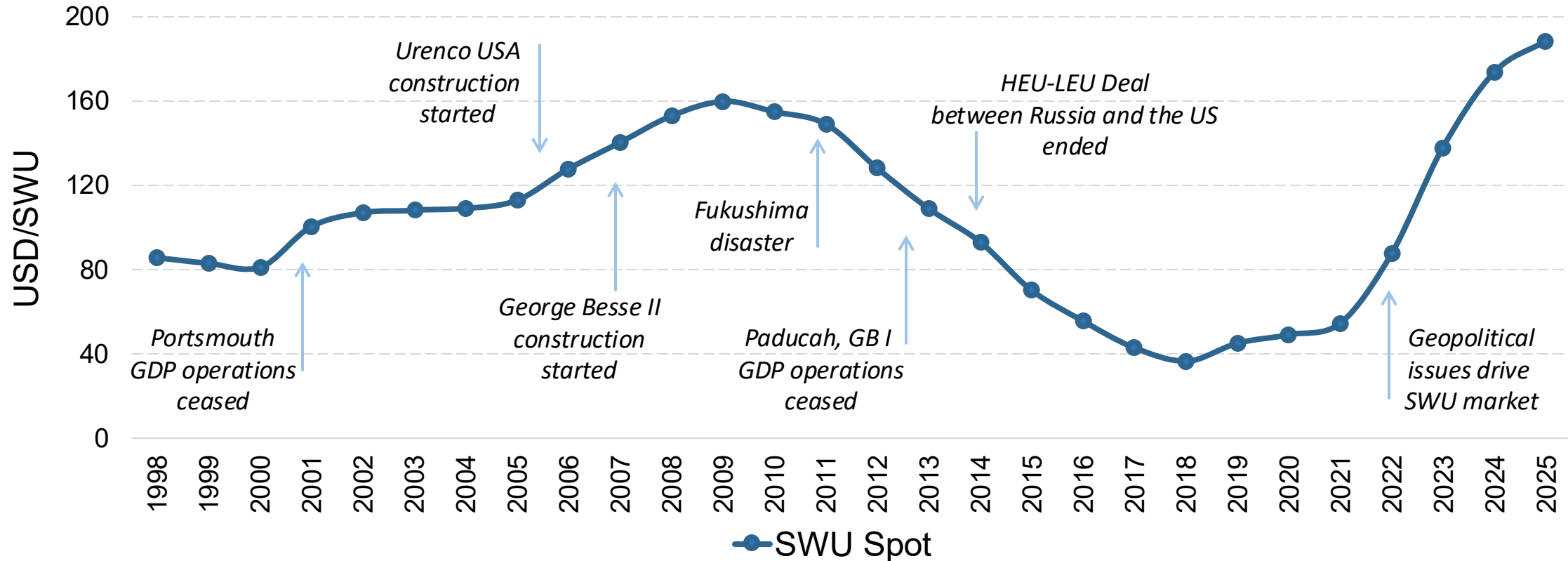
- As for now, Rosatom **is the only producer of HALEU in commercial quantities**
- Projects aimed at establishing new HALEU production lines are underway in the USA and the UK

## ISSUES TO SOLVE:

- “Chicken-and-egg problem” affecting HALEU demand
- Licensing (*lack of valid certificates for LEU+*)
- Construction of new facilities for HALEU 10%+ of U-235
- Limitations on U-235 quantity per cylinder (*but few packages allow commercial HALEU quantity*)
- Packaging & logistics (*lack / restricted quantity of reusable package, unique for each HALEU form*)



# SWU PRICE INDICATORS



SWU price indicators are based on actual full cost level, but usually follow **market perceptions** (rising or declining activity and/or demand, technology developments, etc.) and **new enrichment capacity requirements**

# KEY TAKE AWAY POINTS



1. Uranium enrichment is a process when a concentration of U-235 isotope in given material is increased. This is needed for most types of reactors.
2. Currently only gas centrifuge technology (where a gaseous compound,  $UF_6$ , comes inside a rapidly spinning rotor, and centrifugal forces push the heavier isotope, U-238, closer to the wall than the lighter U-235 isotope that gathers at the center of the rotor) is in operation.
3. One kilogram of enriched uranium can be produced from different amount of natural uranium and using different quantity of SWU. 'Tails' assay defines the mix that is being based on economic optimum – lowest EUP price.
4. There is a limited number of enrichers in the world. Russia is the world's leading provider of uranium enrichment services, incl. HALEU

# QUESTIONS?

## LINKS:

- <http://www.rosatom.ru/en/>
- <http://www.tenex.ru/en/>
- <http://www.orano.group/EN/about>
- <http://www.urencocom/about-us/about-urencocom/>
- <http://www.world-nuclear.org/information-library/nuclear-fuel-cycle>
- [https://www.uxc.com/p/products/uxc\\_Publications.aspx](https://www.uxc.com/p/products/uxc_Publications.aspx)
- <https://www.iaea.org/publications/reports>

**Thank you for your attention!**

**ONE MORE POINT...**

# INTERESTING STATISTICS - FIFA WORLD CUP WINNERS

(from the 2018 lecture at WNU)



Year	Winner	NPP	Enrichment
1982	Italy	✓	✓*
1986	Argentina	✓	✓
1990	Germany	✓	✓
1994	Brazil	✓	✓
1998	France	✓	✓
2002	Brazil	✓	✓
2006	Italy		✓*
2010	Spain	✓	✓*
2014	Germany	✓	✓
2018	France	✓	✓
2022	Brazil	✓	✓

\* as shareholder of Eurodif

# Nothing new



France – winner of FIFA World Cup 2018 in Russia...



... and Argentina – winner of FIFA World Cup 2022 in Qatar

# TRADE POLICY ISSUES



- Historically (starting from 1990s), trade restrictions were in place in the USA (*Agreement Suspending the Antidumping Investigation on Uranium from the Russian Federation – RSA*) and European Union (*Corfu Declaration of 1994*)
- Since 2022, **new restrictions** have been introduced or are under consideration, resulting in accelerating so-called ‘market regionalization’ into Western and Non-Western (BRICS+) countries. Examples:
  - Russian uranium ban in the USA (signed in 2024, import will be prohibited from 2028, but special waivers will be allowed from 2024 till 2027) and Russian countermeasures (export to the USA or under foreign trade contracts concluded with persons registered in the jurisdiction of the United States is restricted from 15 November 2024 and until the end of 2025)
  - Increased tariffs on Chinese EUP are introduced in 2025 (at 27.5% ad valorem)
  - EU considers a plan for a “gradual phasing out” of imports of Russian nuclear fuel