Nuclear Fuel Cycle I

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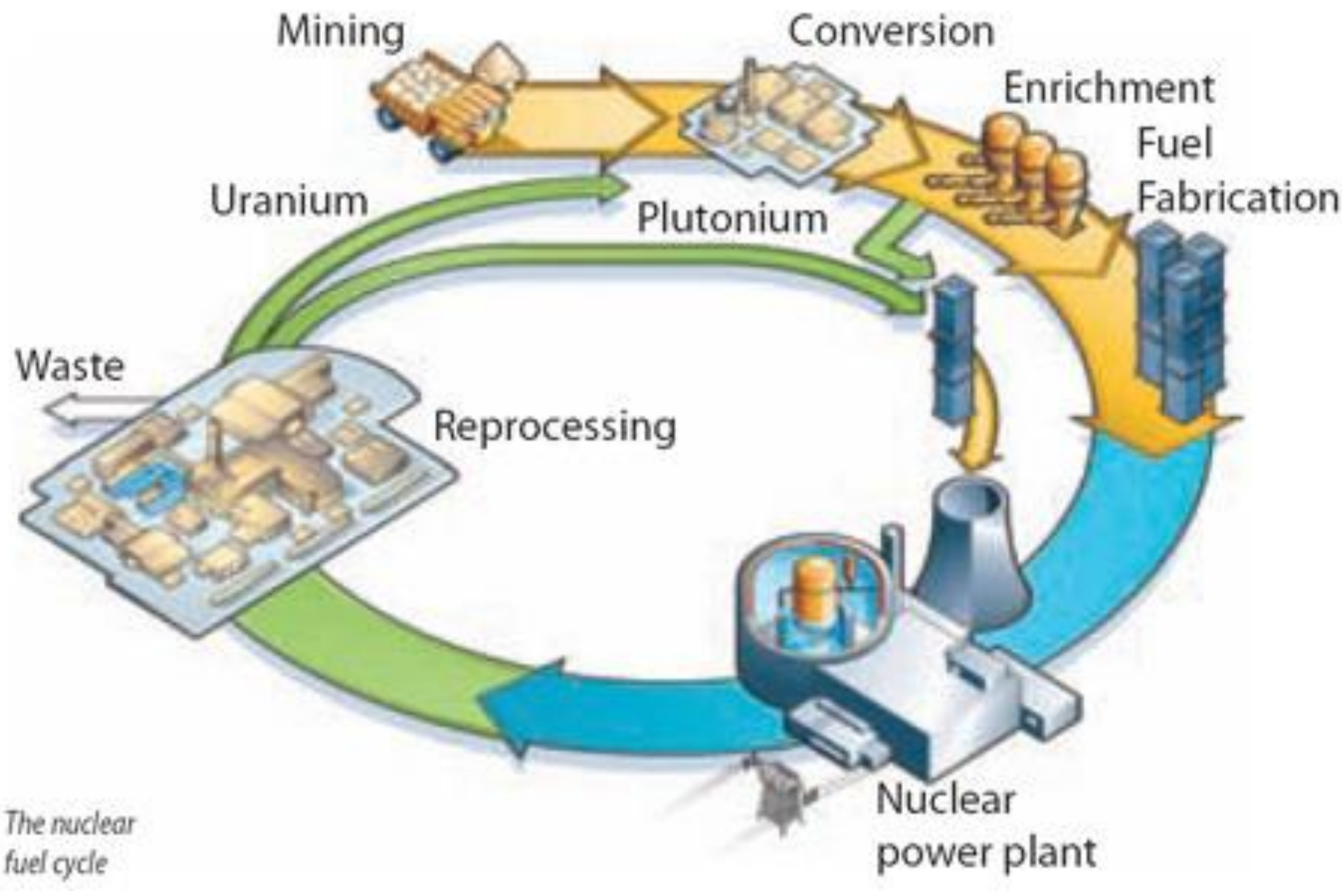
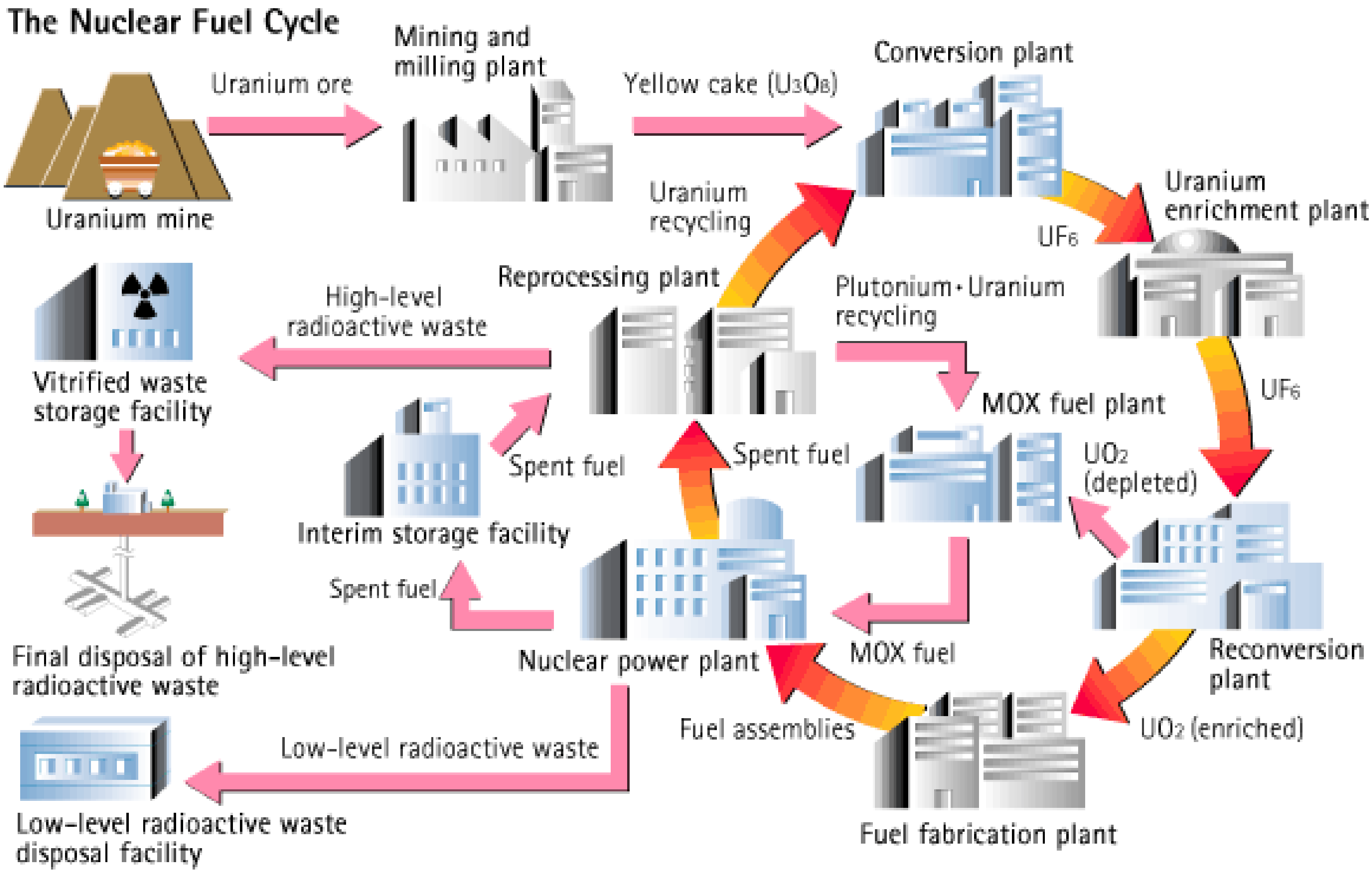
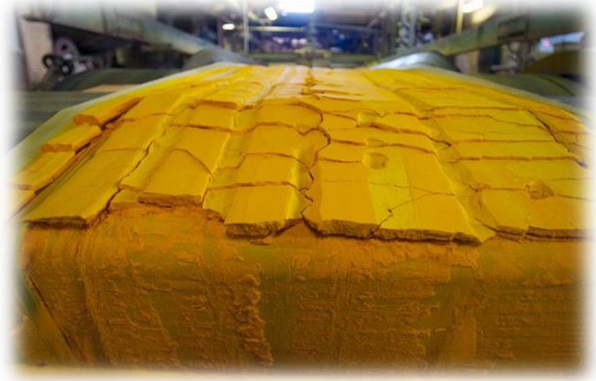
Nuclear Fuel Cycle

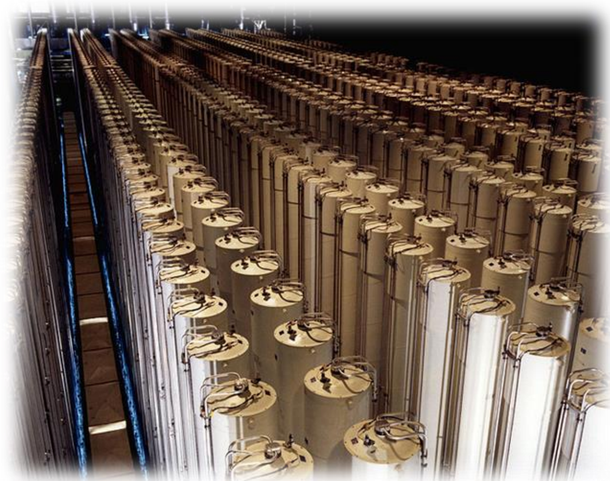


Nuclear Fuel Cycle






URANIUM HEXAFLUORIDE
GB/3572/H(U)-96
TYPE IP 2
Max. wt =15200 kg



Front End Price Break-down (2013)

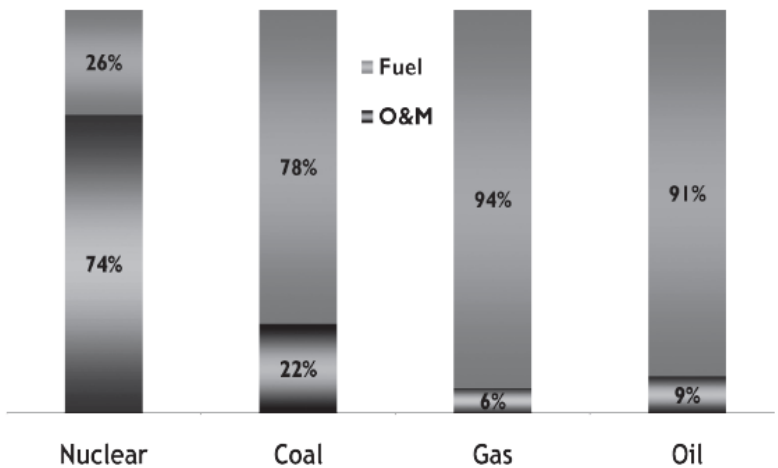
Uranium	9.0 kg U3O8	$ 50 per lb	**$ 990**	**41%**
Conversion	7.6 kg U	$ 13 per kg	**$ 99**	**4%**
Enrichment	7 SWU	$ 150 per SWU	**$ 1050**	**43%**
Fabrication	1 kg	$ 300 per kg	**$ 300**	**12%**
Total			**$ 2439**	**100%**

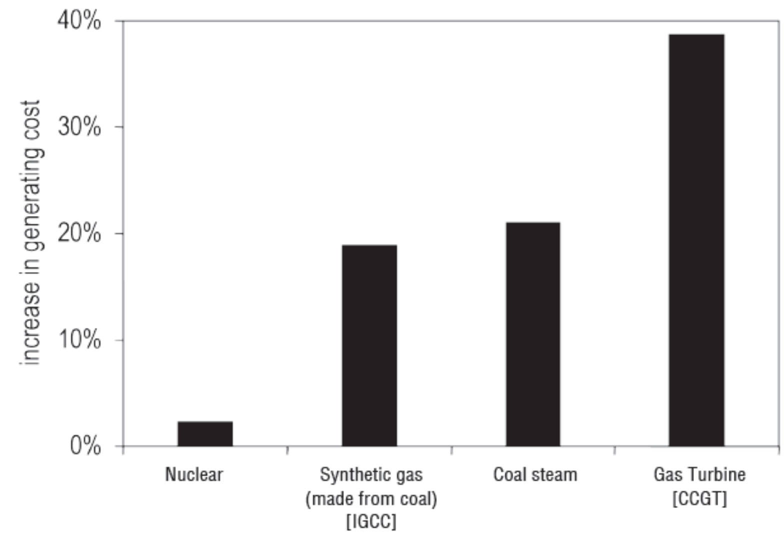
About 20 tonnes of enriched uranium for an average large reactor refuel is needed, the cost is thus about **$ 50 million**

Total front end world market is now worth about **$ 25 billion** annually

Source: Steve Kidd, World Nuclear Association

Nuclear Fuel Economy





The reactor fuel buyers fight hard to save every last cent because this is cost they feel they can influence. It has however minor role on the NPP operating costs.

Impact of 50 % increase in fuel costs on generating costs

Source: Global Energy Decisions, ERI, Inc.; IEA WEO 2006; in Steve Kidd, 2010, Nuclear Fuel: Myths and Realities

Mining

- Natural uranium is relatively abundant and evenly spread in the earth's crust. The occurence is about 500 times higher than with gold.
- Granite (% of the earth's crust) is less concentrated with uranium = 4 ppm (0,0001 %).
- Coal is more abundant with uraniu, the concentration is around 100 ppm (0,01 %), in some fertilizers up to 400 ppm (0,04 %).
- If the concentration is high (0,03 % and more), the matter is called uranium ore and could be mined with profit.

- Traditional mining (open mine pits, shaft mines)
- In-situ methods

Mining

Uranium Mine	Uranium Grade (%)	Annual Production (tU)	Country
Olympic Dam	0,05	4356	South Australia
Ranger	0,2	5544	Northern Australia
McArthur River mine	20,66	8491	USA
Dolní Rožínka	0,1-0,2	408	Czech Republic
Krasnokamensk	0,38	3431	Russian Federation
Cigar Lake	20,67	-	Canada
McClean Lake	2,4	2490	USA

Mining

Table 1. The largest-producing uranium mines in 2014

Mine	Country	Main owner	Type	Production (tU)	% of world
McArthur River	Canada	Cameco	underground	7356	13
Tortkuduk & Moinkum	Kazakhstan	Katco JV/Areva, Kazatomprom	ISL	4322	8
Olympic Dam	Australia	BHP Billiton	by-product/ underground	3351	6
SOMAIR	Niger	Areva	open pit	2331	5
Budenovskoye 2	Kazakhstan	Karatau JV/Kazatomprom, Uranium One	ISL	2084	4
South Inkai	Kazakhstan	Betpak Dala JV/Uranium One, Kazatomprom	ISL	2002	4
Priagunsky	Russia	ARMZ	underground	1970	4
Langer Heinrich	Namibia	Paladin	open pit	1947	4
Inkai	Kazakhstan	Inkai JV/Cameco, Kazatomprom	ISL	1922	3
Central Mynkuduk	Kazakhstan	JSC Ken Dala, Kazatomprom	ISL	1790	3
Top 10 total				**29,075**	**54%**


KONTROLOVANÉ PÁSMO
SE ZDROJI IONIZUJÍCÍHO ZÁŘENÍ
NEPOVOLANÝM OSOBÁM ZAKÁZÁN


ODSTAVNÉ
MÍSTO
JEŘÁBU

Production from mines (tonnes U)

Country	2007	2008	2009	2010	2011	2012	2013	2014	2015
Kazakhstan	6637	8521	14020	17803	19451	21317	22451	23127	23800
Canada	9476	9000	10173	9783	9145	8999	9331	9134	13325
Australia	8611	8430	7982	5900	5983	6991	6350	5001	5654
Niger	3153	3032	3243	4198	4351	4667	4518	4057	4116
Russia	3413	3521	3564	3562	2993	2872	3135	2990	3055
Namibia	2879	4366	4626	4496	3258	4495	4323	3255	2993
Uzbekistan (est)	2320	2338	2429	2400	2500	2400	2400	2400	2385
China (est)	712	769	750	827	885	1500	1500	1500	1616
USA	1654	1430	1453	1660	1537	1596	1792	1919	1256
Ukraine (est)	846	800	840	850	890	960	922	926	1200
South Africa	539	655	563	583	582	465	531	573	393
India (est)	270	271	290	400	400	385	385	385	385
Czech Republic	306	263	258	254	229	228	215	193	155
Romania (est)	77	77	75	77	77	90	77	77	77
Pakistan (est)	45	45	50	45	45	45	45	45	45
Brazil (est)	299	330	345	148	265	326	192	55	40
France	4	5	8	7	6	3	5	3	2
Germany	41	0	0	8	51	50	27	33	0
Malawi			104	670	846	1101	1132	369	0
Total world	**41 282**	**43 764**	**50 772**	**53 671**	**53 493**	**58 489**	**59,331**	**56,041**	**60,496**
tonnes U_3O_8	48 683	51 611	59 875	63 295	63 084	68 976	69,969	66,089	71,343
percentage of world demand*	64%	68%	78%	78%	85%	86%	92%	85%	90%

Uranium Production Perspective

- Rising NPP capacity factors (10 % in 1990s)
- Rising enrichment levels (up to 5 % U235)
- Uranium price levels limit usable deposits exploration and extraction (proven reserves vs. pure guesses) – U from oceans
- According to Red Book, there is 7,635 Mt of Identified resources of U, not counting resources with current production price above 260 USD/1 kg
- 400 junior uranium companies emerged recently (largely still in exploration stage)

- Stockpiles of natural and enriched uranium
- RepU (expensive U = pressure on reprocessing)
- P239 (Spent fuel, weapons)
- Down-blended weapons-grade uranium
- Re-enriched uranium tails assay (currently 0.25-0.3% U235)
- Higher enrichment (expensive U = pressure on higher enrichment/U235 extraction)
- Breeder reactors (U238 to P239)
- Fusion (?)

- Extreme short-term measures (lowering NPP production output means longer fuel campaigns)

Processing

- The ore usually contains about 0.1% uranium, sometimes even less.
- In this form it is unusable and any transport would be unnecessarily expensive.
- Processing plants therefore usually surround the mine.
- At first one, the uranium is freed from the so-called uranium tailings. The refined ore is then ground into mash. The mash is concentrated and then chemically leached by sulfuric acid. After drying the resulting product is the uranium concentrate U_3O_8 (yellow cake).
- After drying, and usually heating, the uranium is concentrated to about 80% and filled into 200 liter barrels in which it is transported for further processing.
- The rest of the rock contains residues after dissolution and most of the radioactivity (natural uranium radioactivity is consisted largely of radioactive elements emerging due to uranium´s natural decay, these remain in the uranium ore after precipitation of uranium). These tailings are then placed back into the mine or tailing ponds, where they are artificially isolated from the environment.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Conversion

- Given that uranium enrichment using existing technology can only happen in a gaseous form, is the conversion of yellowcake to gas a necessary step in the fuel supply chain.
- Pitchblende (U3O8) can be directly converted to uranium trioxide (UO3) which can be directly used in specific reactors that do not require enriched fuel.
- For most reactors the uranium concentration in directly produced uranium dioxide is not sufficiently high. Thus the pitchblende is converted into uranium hexafluoride (UF6), which is normally in a gaseous state.
- Uranium hexafluoride is then pumped into large metal cylinders, where it solidifies, and transported to the enrichment plants.

Conversion

Table 3: Commercial UF_6 conversion facilities (tonnes of uranium/year)

Company	Nameplate capacity in 2014 (tU as UF_6)	Share of global capacity (%)
Atomenergoprom (Rosatom) (Russia)	25 000 (*)	35
Cameco (Canada)	12 500	18
ConverDyn (United States)	15 000	21
Comurhex (AREVA) (France)	15 000	21
CNNC (China)	3 650	5
Ipen (Brazil)	40	0
Total nameplate capacity	71 190	100

Source: WNA, The global nuclear fuel market — Supply and demand 2013–30.
(*) Operating capacity estimated at 10 000 tU/y.

Source: Euratom Supply Agency

-China´s capacity is expected to grow considerably in 2025 and beyond

-Plan to develop Ulba plant in Kazakhstan (12 000 tU)

Enrichment

- The capacity of enrichment plants is determined in kg of SWU (Separative Work Unit).
- Example: Bigger nuclear power plant with an output of 1300 MWe (equivalent to 3 of 4 units of Dukovany) needs for annual operation about 25 tons of fuel enriched to 3.75%. For its production 210 tons of natural uranium and about 120,000 SWU is needed. Enrichment plant with a capacity of 1 million SWU / year - such as the Chinese plant in Lanzhou (900 kSWU / year) would be able to supply eight such plants.

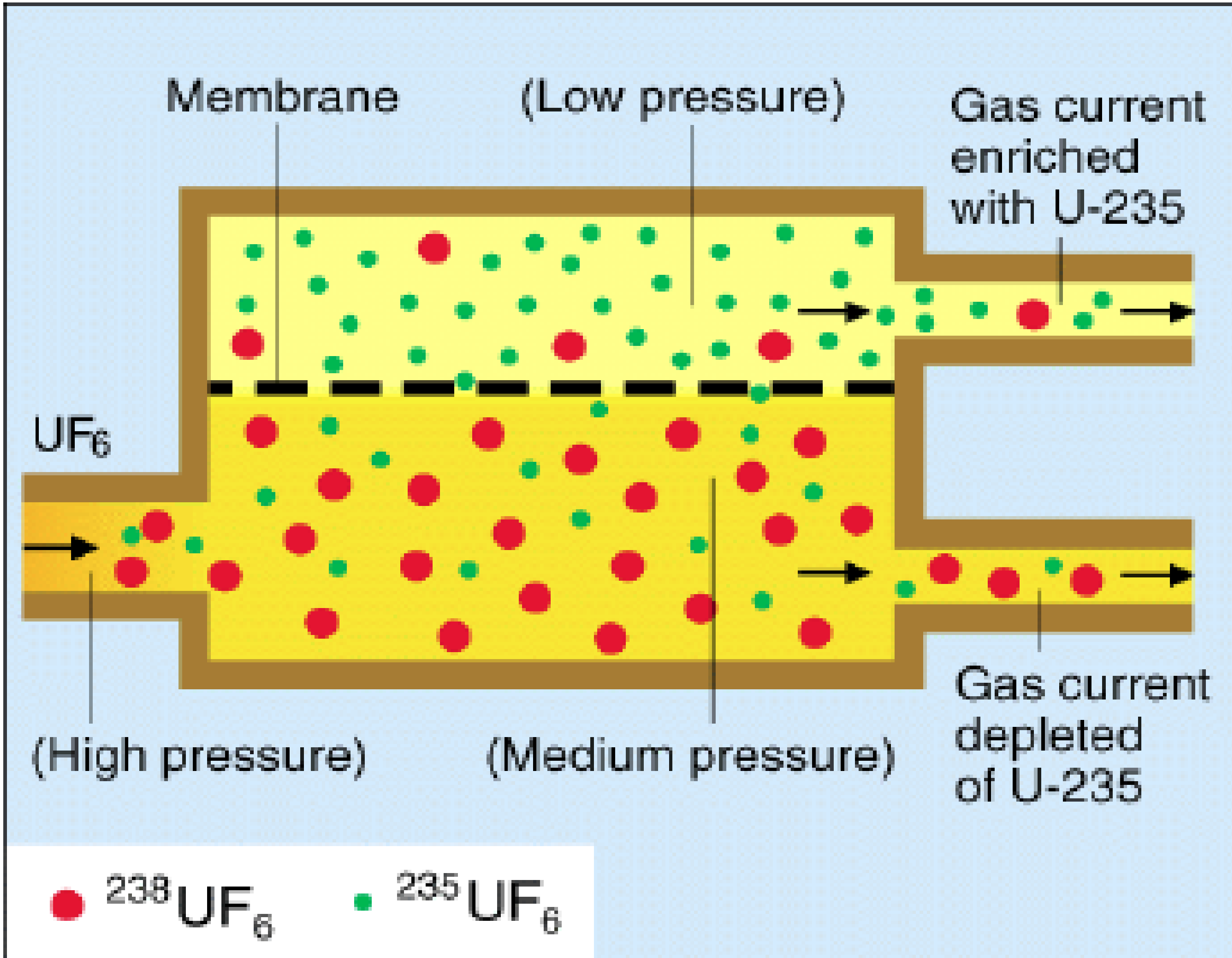
Enrichment

World enrichment capacity – operational and planned (thousand SWU/yr)

Country	Company and plant	2013	2015	2020
France	Areva, Georges Besse I & II	5500	7000	7500
Germany-Netherlands-UK	Urenco: Gronau, Germany; Almelo, Netherlands; Capenhurst, UK.	14,200	14,400	14,900
Japan	JNFL, Rokkaasho	75	75	75
USA	USEC, Piketon	0*	0	0
USA	Urenco, New Mexico	3500	4700	4700
USA	Areva, Idaho Falls	0	0	0
USA	Global Laser Enrichment, Paducah	0	0	0
Russia	Tenex: Angarsk, Novouralsk, Zelenogorsk, Seversk	26,000	26,578	28,663
China	CNNC, Hanzhun & Lanzhou	2200	4220	7520
Other	Various: Argentina, Brazil, India, Pakistan, Iran	75	100	170
	Total SWU/yr approx	**51,550**	**57,073**	**63,526**
	Requirements (*WNA reference scenario*)	49,154	47,285	57,456

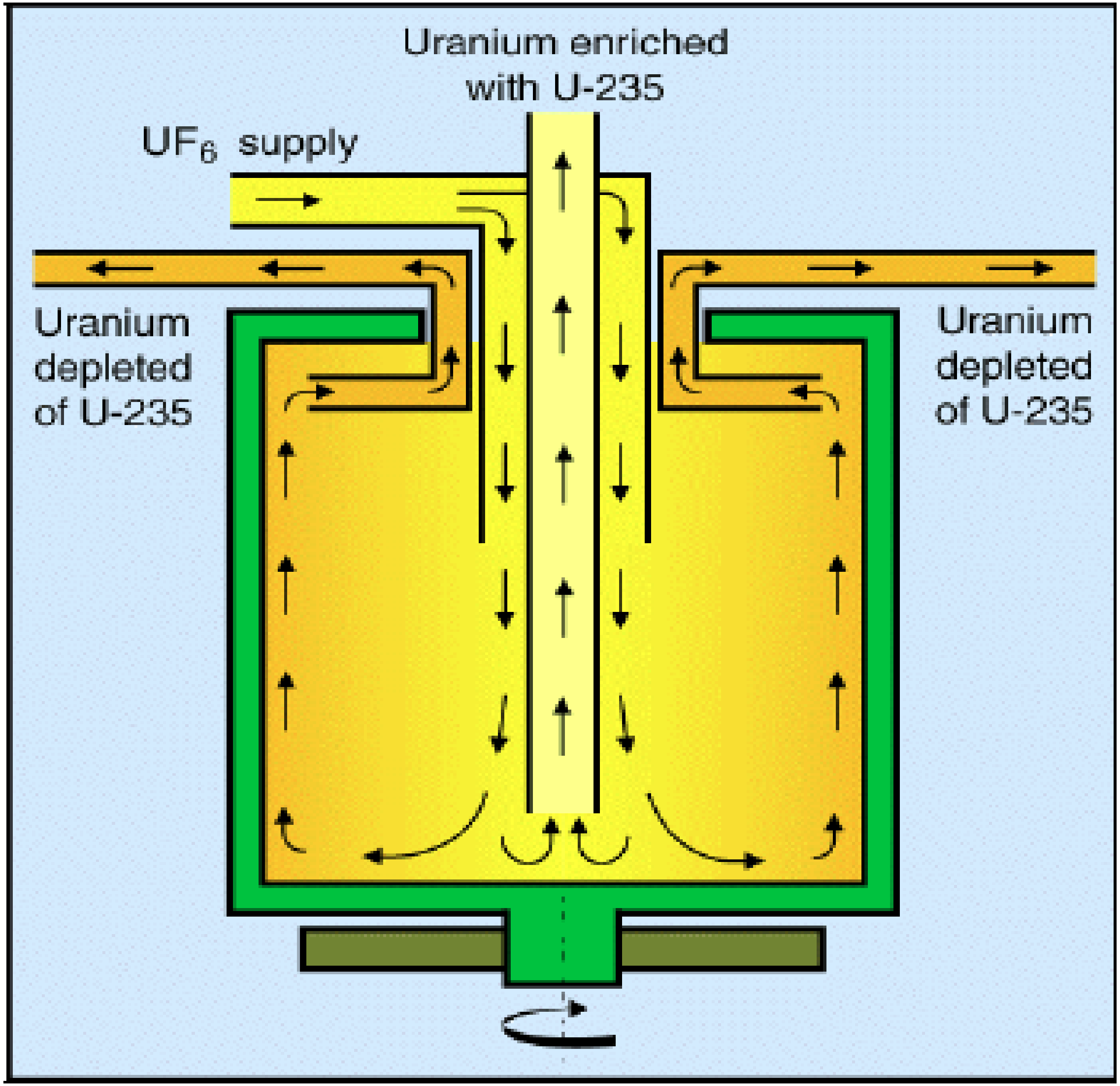
Source: World Nuclear Association Nuclear Fuel Report 2013 & 2105, Areva 2014 Reference Document for most 2013 figures.

SWU calculator: http://www.wise-uranium.org/nfcue.html



Membrane
(Low pressure)
Gas current enriched with U-235
UF6
(High pressure)
(Medium pressure)
Gas current depleted of U-235
238UF6
235UF6

Country	Company	Location	Capacity (1000 SWU/year)
Porous membrane enrichment			
Argentina	CNEA	Pilcaniyeu	20
Čína	CNNC	Lanzhou	900
Francie	EURODIF	Tricastin	10 800
USA	U. S. Enrichment Corp.	Paducah, Kentucky	11 300
Porous membrane enrichment total			23 020



Uranium enriched with U-235
UF6 supply
Uranium depleted of U-235
Uranium depleted of U-235

Centrifuge enrichment			
Brazil	INB	Resende	?
China	CNNC	Hanzhong	500
		Lanzhou	500
France	EURODIF	Gerges Besse II, Tricastin	Under Construction
India	DAE Nuclear Fuel Complex	Ratnahalli	4,5
Iran	AEOI	Nazanz	?
		Qom	?
Japan	JNC	Ningyo Toge	200
	Japan Nuclear Fuel Limited	Rokkasho-mura	1 050
North Korea		Yongbyon	8
Germany	Urenco Deutschland GmbH	Gronau	2 750
Netherlands	Urenco Nederland BV	Almelo	4 400
Pakistan	Pakistan Atomic Energy Commission	Kahuta	5
Russia	Rosatom	UEIE Yekaterinburg	7 000
		SKhK Seversk	4 000
		ECP Zelenogorsk	3 000
		AEKhK Angarsk	2 600
USA	Urenco USA	National Enrichment Facility, Lea County, NM	Under Construction
Great Britain	Urenco UK Ltd.	Capenhurst	5 050
Total centrifuge enrichment			31 067,5

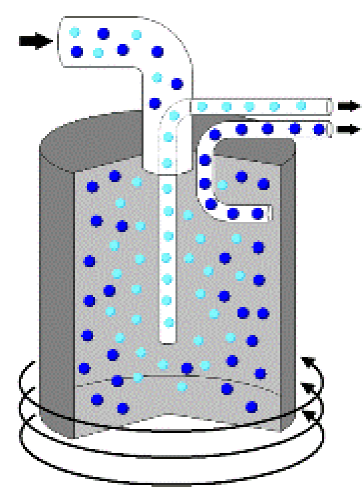
Enrichment Economy

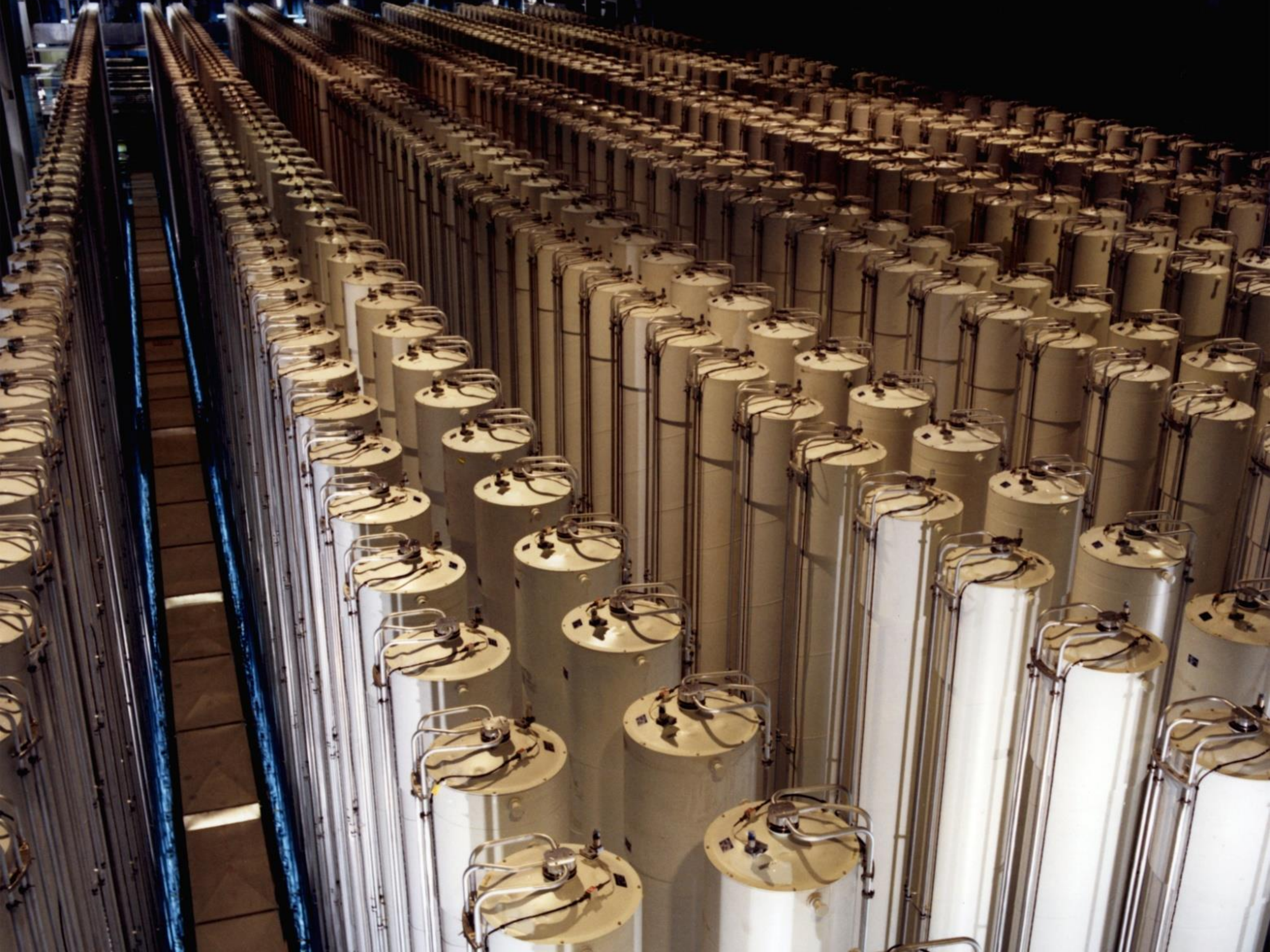
SWU calculator:

http://www.wise-uranium.org/nfcue.html

Nuclear Fuel Cost Calculator:

http://www.wise-uranium.org/nfcc.html



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Fabrication

Difference to every other step:

- 1) Fabrication is a highly specialised service rather than commodity (barrier for newcomers enetring the market)
- 2) TVEL offers full front end process as a product (i.e. fuel) vs. steps in the fuel cycle
- 3) Main technology (NPP) suppliers are also main fuel producers
- 4) Fuel is manufactured according to public tenders specifing the product in details
- 5) VVER technology was developed paralelly with western technology (legacy of cold war)
- 6) Markets were opened 25 years ago with no experience on both sides
- 7) The nuclear fuel quality is critical for NPP production. The financial implications of reduced plant performance would quickly outweigh any benefit from potentially lower fuel prices


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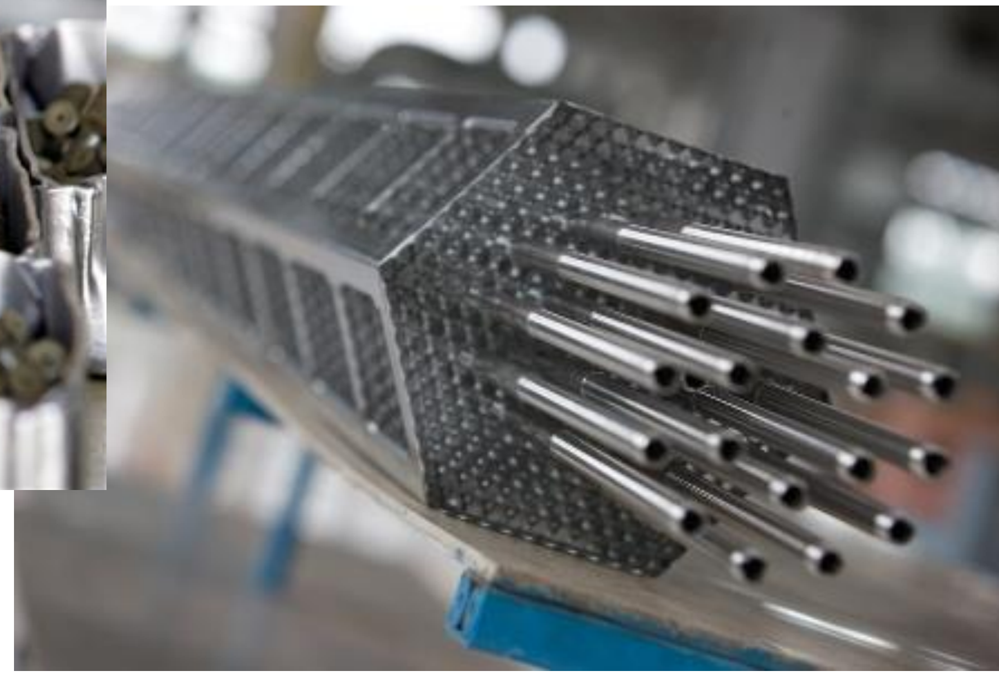


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