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Nuclear Fuel Cycle

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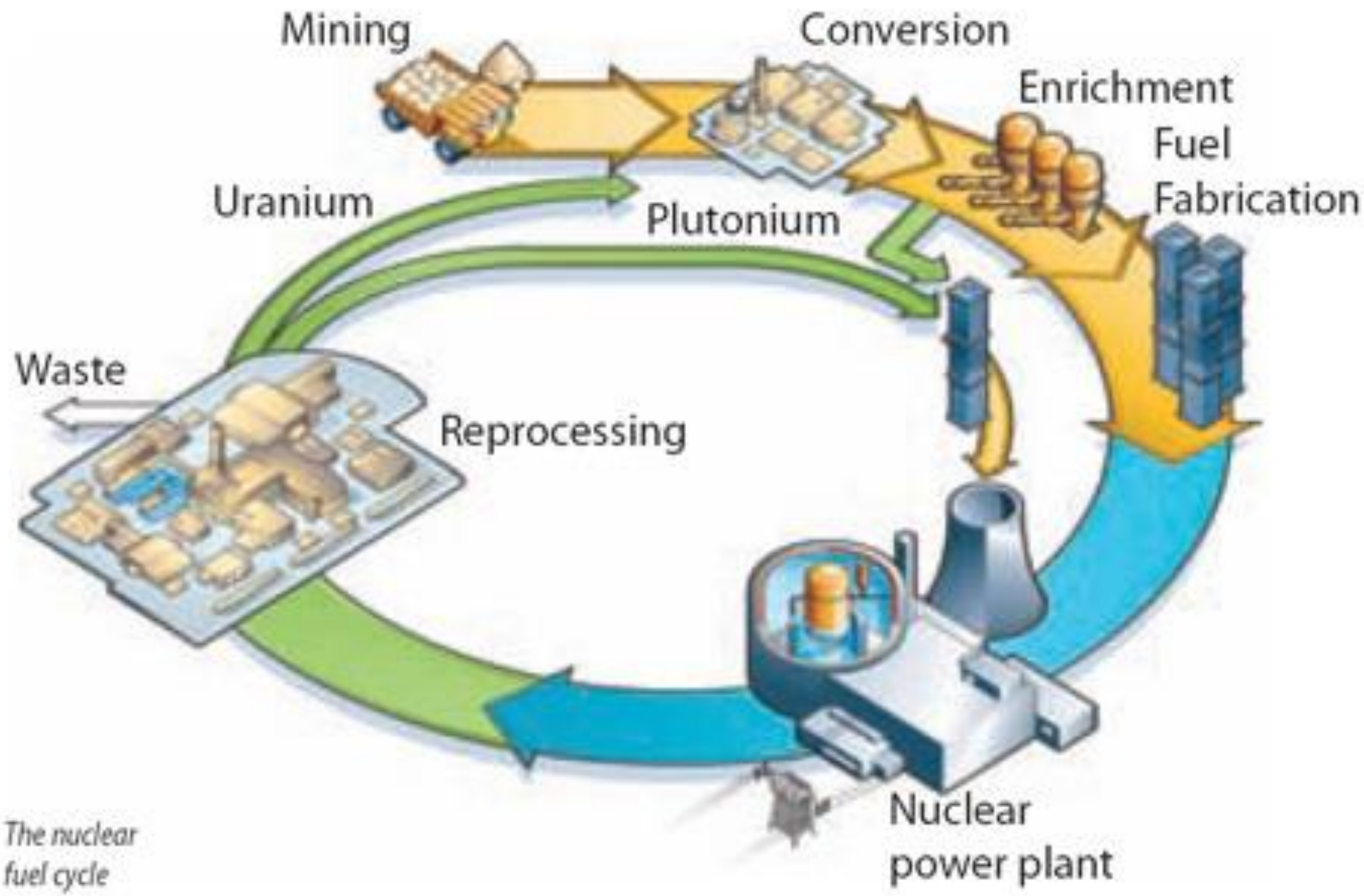
Nuclear Fuel Cycle



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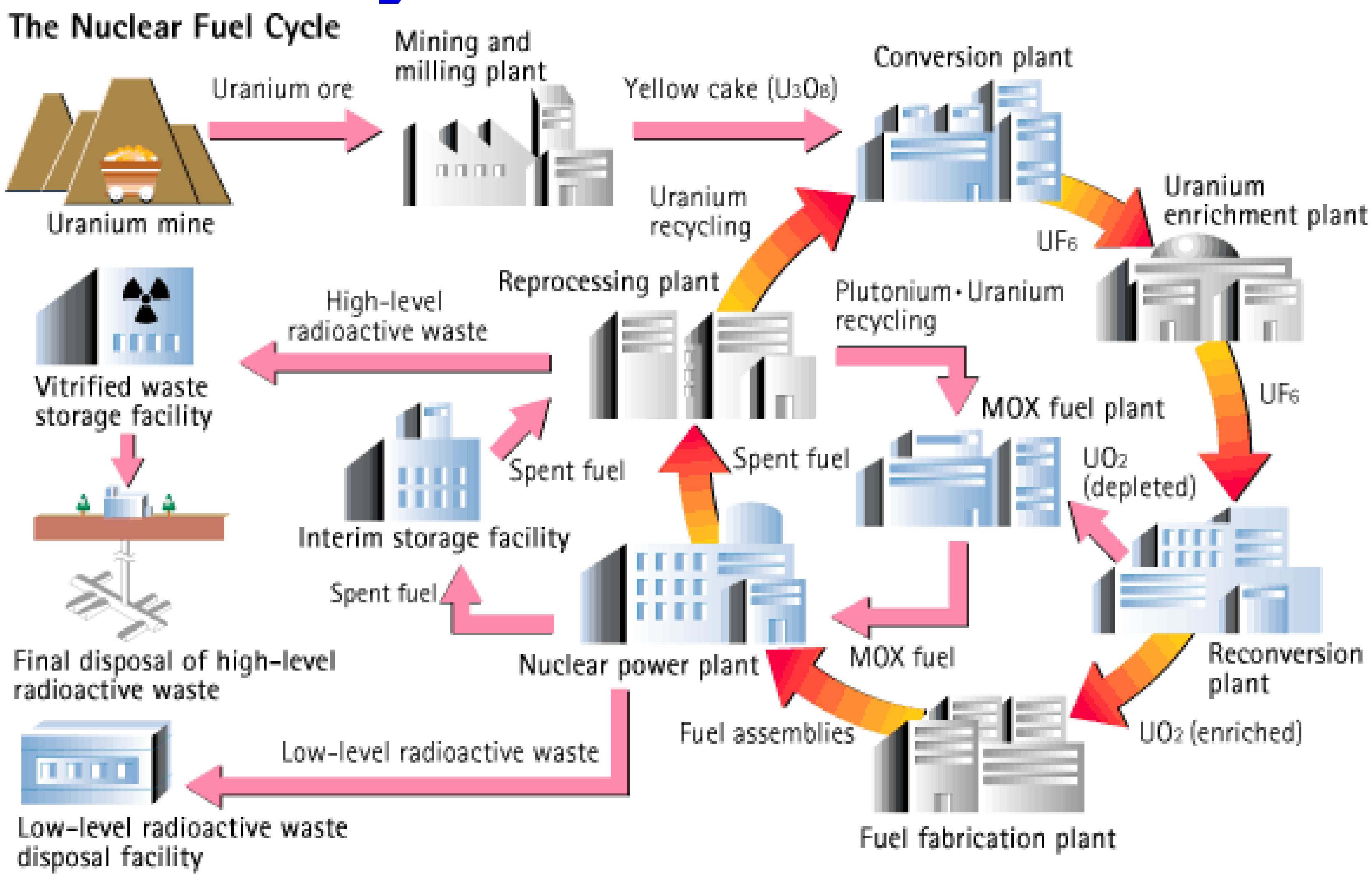
Nuclear Fuel Cycle



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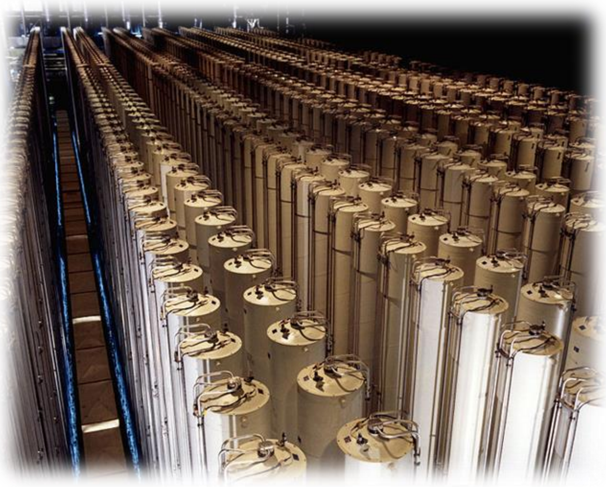
Nuclear Fuel Cycle



Uranium

Front end fuel cycle costs of 1 kg of uranium as UO_2 fuel (2017 costs, source: WNA)

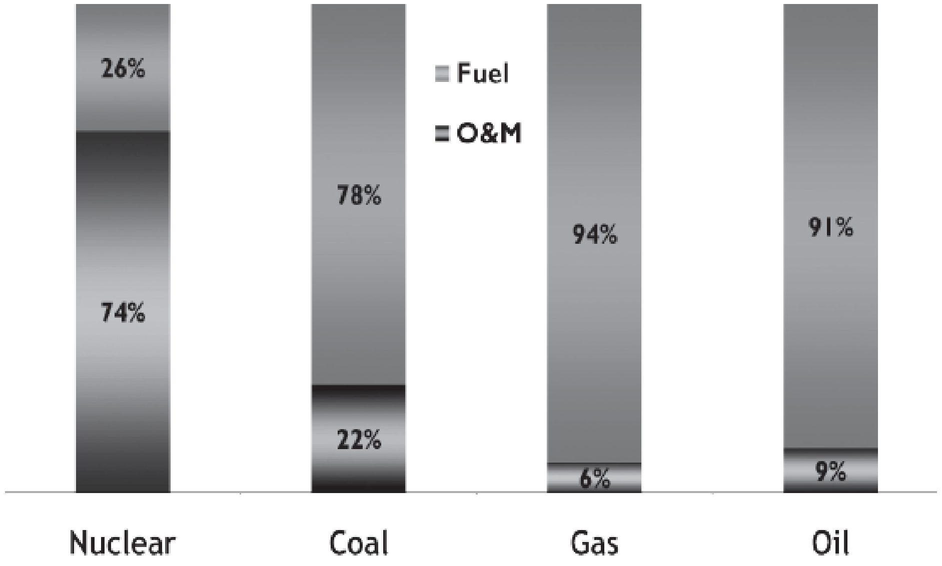
Uranium	8.9 kg U_3O_8	$ 68 per kg	**$ 605**	**43%**
Conversion	7.5 kg U	$ 14 per kg	**$ 105**	**8%**
Enrichment	7.3 SWU	$ 52 per SWU	**$ 380**	**27%**
Fabrication	1 kg	$ 300 per kg	**$ 300**	**22%**
Total			**$ 1390**	**100%**

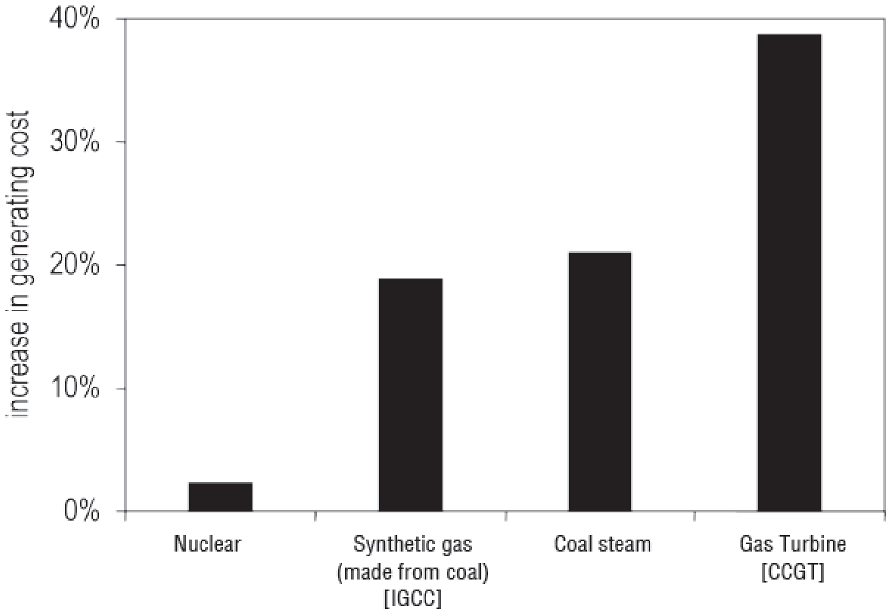
About 20 tonnes of enriched uranium for an average large reactor refuel is needed, the cost is thus about **$ 50 million.**

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

Source: Steve Kidd, World Nuclear Association

Uranium





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.

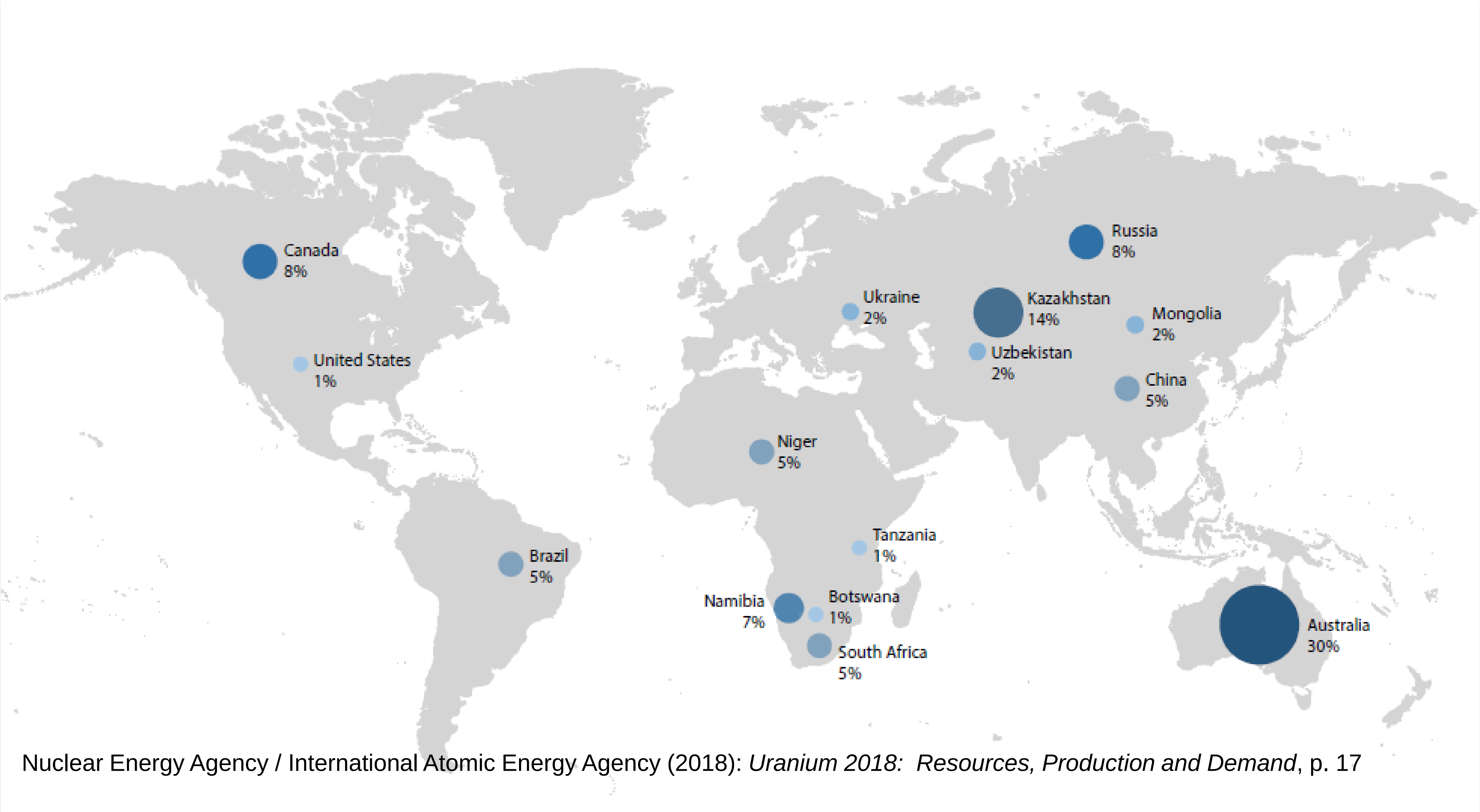
Impact of 50 % increase in fuel costs on generating costs

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

Uranium

- Natural uranium is relatively abundant and evenly spread in the earth's crust. The occurrence is about 500 times higher than with gold.
- Granite (around 75% of the earth's crust) is less concentrated with uranium = 4 ppm (0,0001 %).
- Coal is more abundant with uranium, 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

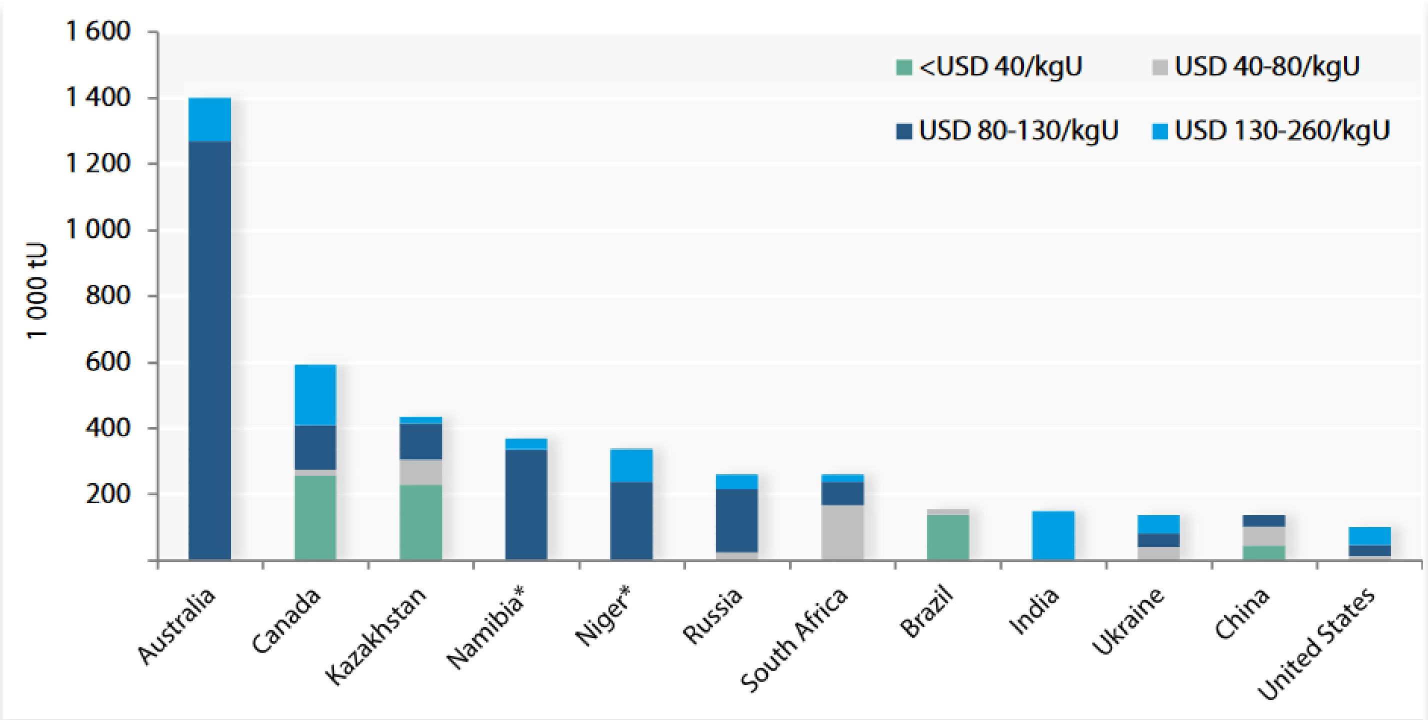
Figure 1.1. **Global distribution of identified resources**
(<USD 130/kgU as of 1 January 2017)



9 Nuclear Energy Agency / International Atomic Energy Agency (2018): *Uranium 2018: Resources, Production and Demand*, p. 17

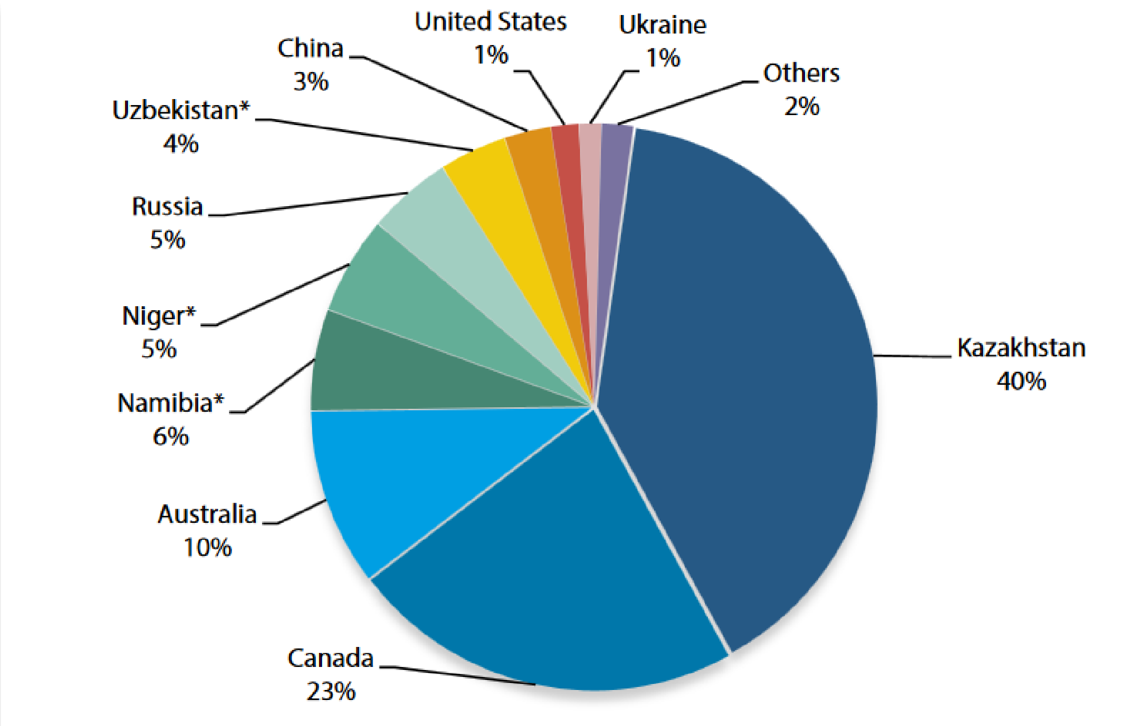
Uranium

Figure 1.2. **Distribution of reasonably assured resources among countries with a significant share of resources**



* Secretariat estimate.

Figure 1.5. Uranium production in 2016: 62 071 tU



* NEA/IAEA estimate.

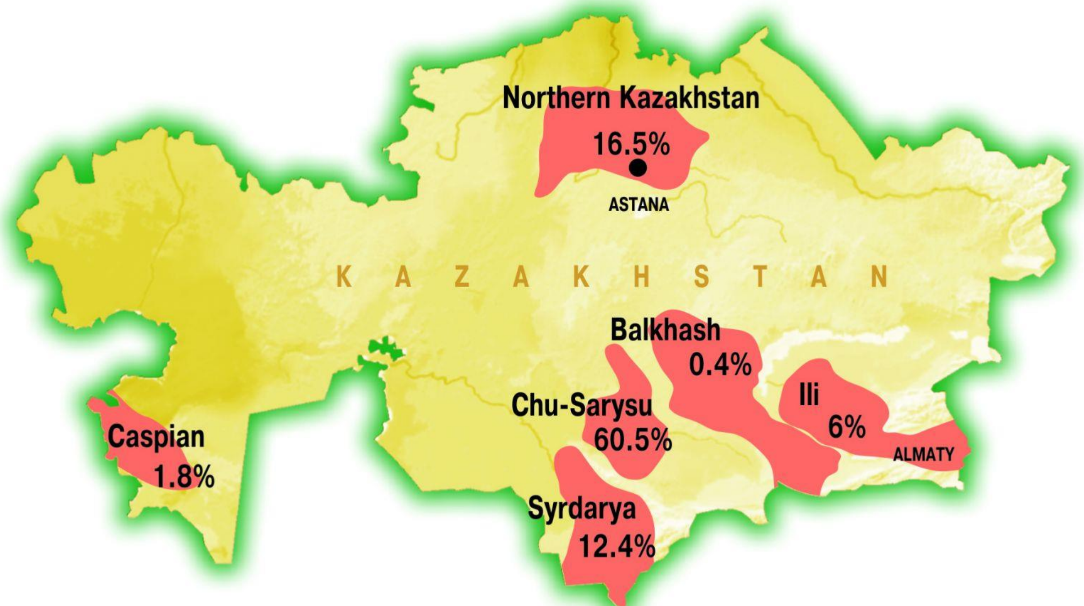
Nuclear Energy Agency / International Atomic Energy Agency (2018): *Uranium 2018: Resources, Production and Demand*, p. 26, 56

Table 1: The largest-producing uranium mines in 2018

Mine	Country	Main owner	Type	Production (tonnes U)	% of world
Cigar Lake	Canada	Cameco/Orano	underground	6924	13
Olympic Dam	Australia	BHP Billiton	by-product/ underground	3159	6
Husab	Namibia	Swakop Uranium (CGN)	open pit	3028	6
Inkai, sites 1-3	Kazakhstan	Kazaktomprom/Cameco	ISL	2643	5
Rössing	Namibia	Rio Tinto	open pit	2102	4
Budenovskoye 2	Kazakhstan	Uranium One/Kazatomprom	ISL	2081	4
Tortkuduk	Kazakhstan	Orano/Kazatomprom	ISL	1900	4
SOMAIR	Niger	Orano	open pit	1783	3
Ranger	Australia	Rio Tinto/ERA	open pit	1695	3
Kharasan 2	Kazakhstan	Kazatomprom	ISL	1631	3
Top 10 total				**26,946**	**51%**

Uranium mines operate in some 20 countries, though in 2018 some 51% of world production came from just ten mines in four countries (see Table 1).

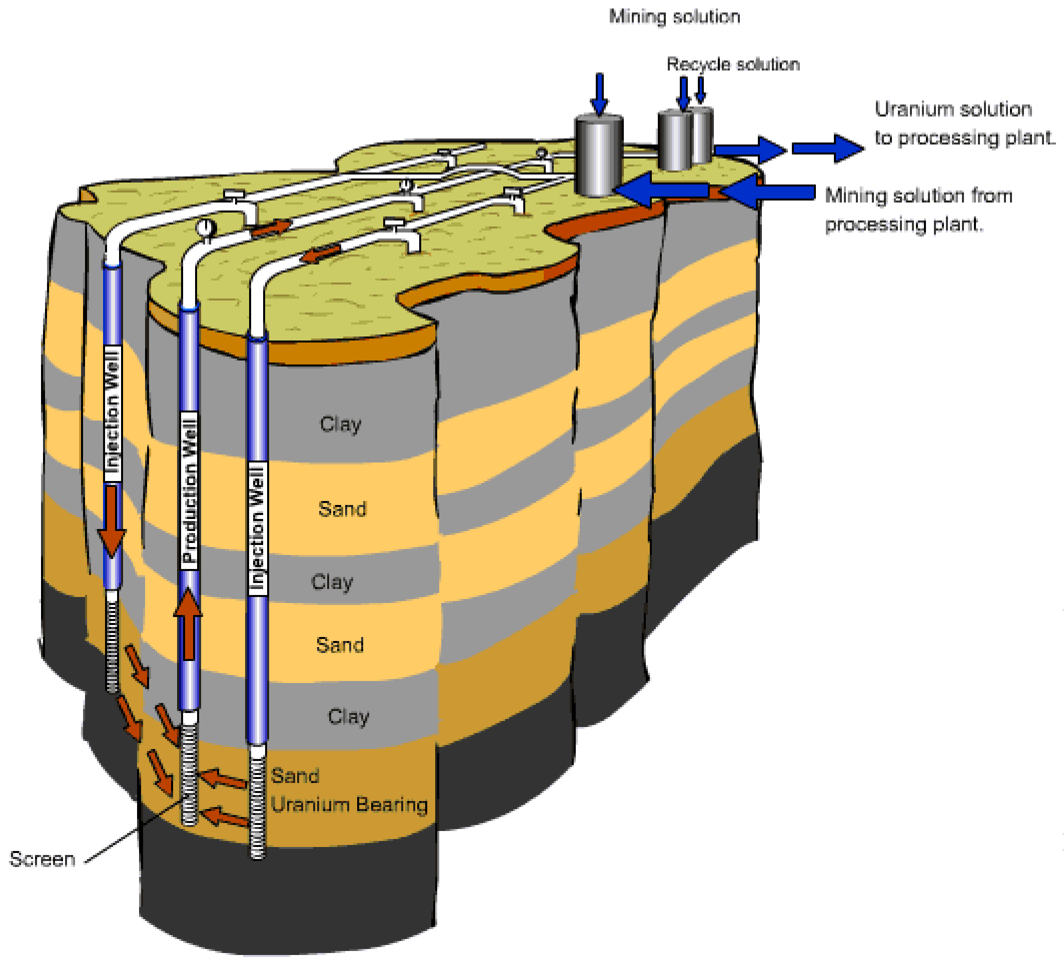
Source: WNA


Northern Kazakhstan
16.5%
ASTANA
K A Z A K H S T A N
Balkhash
0.4%
Ili
6%
ALMATY
Chu-Sarysu
60.5%
Caspian
1.8%
Syrdarya
12.4%


1400


KONTROLOVANÉ PÁSMO
SE ZDROJI IONIZUJÍCÍHO ZÁŘENÍ
VSTUP NEPOVOLANÝM OSOBÁM ZAKÁZÁN

Uranium



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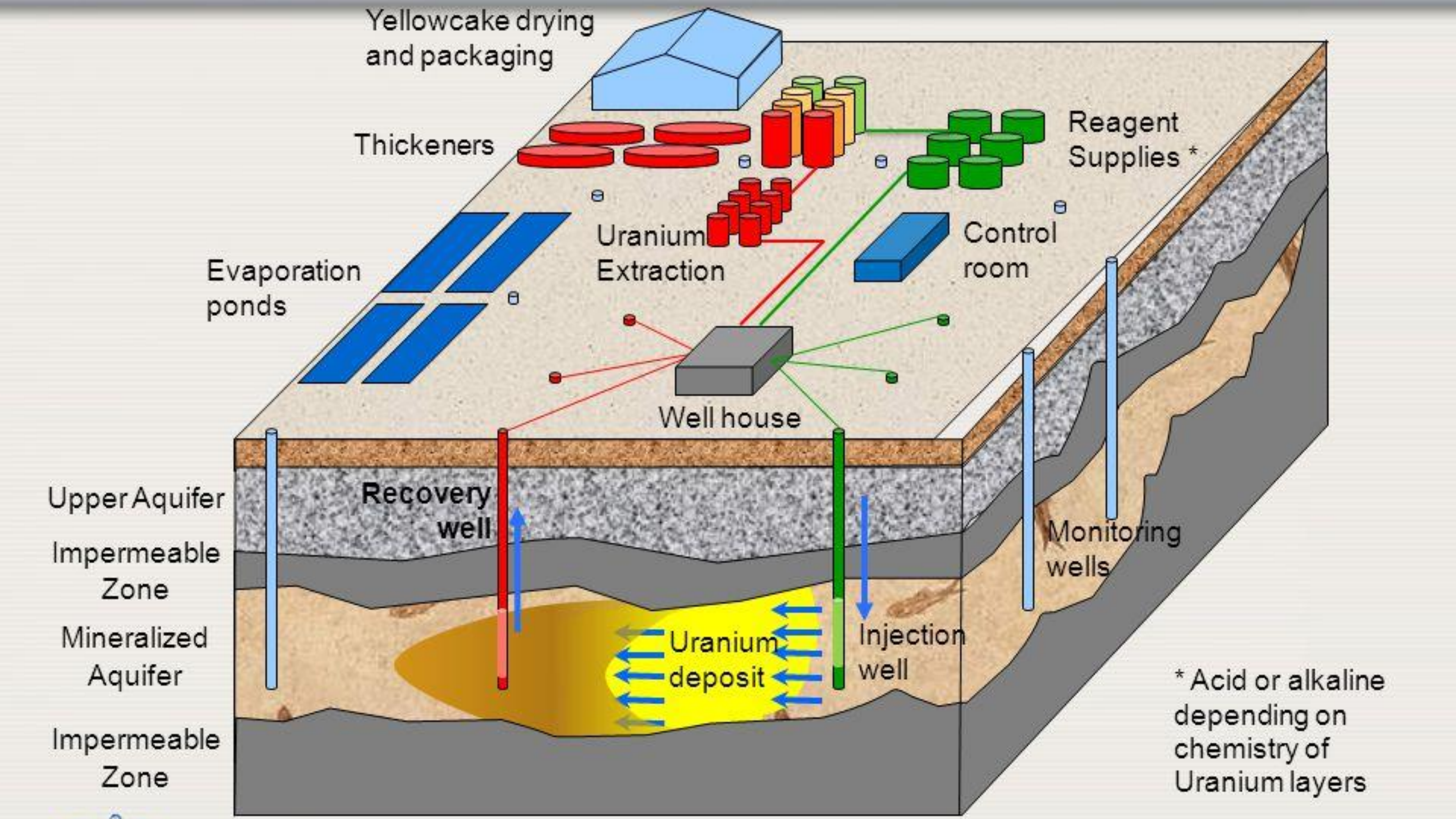
ODSTAVNÉ
MÍSTO
JEŘÁBU


Yellowcake drying and packaging
Thickeners
Reagent Supplies *
Uranium Extraction
Control room
Evaporation ponds
Well house
Upper Aquifer
Impermeable Zone
Mineralized Aquifer
Impermeable Zone
Recovery well
Injection well
Uranium deposit
Monitoring wells
* Acid or alkaline depending on chemistry of Uranium layers

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 7.989 Mt of Identified resources of U, not counting resources with current production price above 260 USD/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% of uranium, sometimes even less.
- In this form it is unusable and any transport would be simply too expensive.
- Processing plants therefore usually surround the mine.
- First, uranium ore 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 resultiis 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). These tailings are then placed back into the mine or tailing ponds, where they are artificially isolated from the environment.


2

Conversion

- Uranium enrichment can currently only happen in gaseous form
- Triuranium octoxide (U_3O_8) can be directly converted to uranium trioxide (UO_3) 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 U_3O_8 is converted into uranium hexafluoride (UF_6), 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 (and Reconversion)

Table 3. Commercial UF_6 conversion facilities

Company	Nameplate capacity in 2018 (tU as UF_6)	Share of global capacity (%)
Atomenergoprom* (Russia)	18 000	31.3
Comurhex** II (France)	15 000	26.0
Cameco (Canada)	12 500	21.7
ConverDyn*** (United States)	7 000	12.2
CNNC (China)	5 000	8.7
IPEN (Brazil)	100	0.1
Total nameplate capacity	57 600	100

Source: Euratom Supply Agency

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

Plan to develop Ulba plant in Kazakhstan in 2020 (6,000 tU)

Enrichment

Source: Euratom Supply Agency; WNA

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

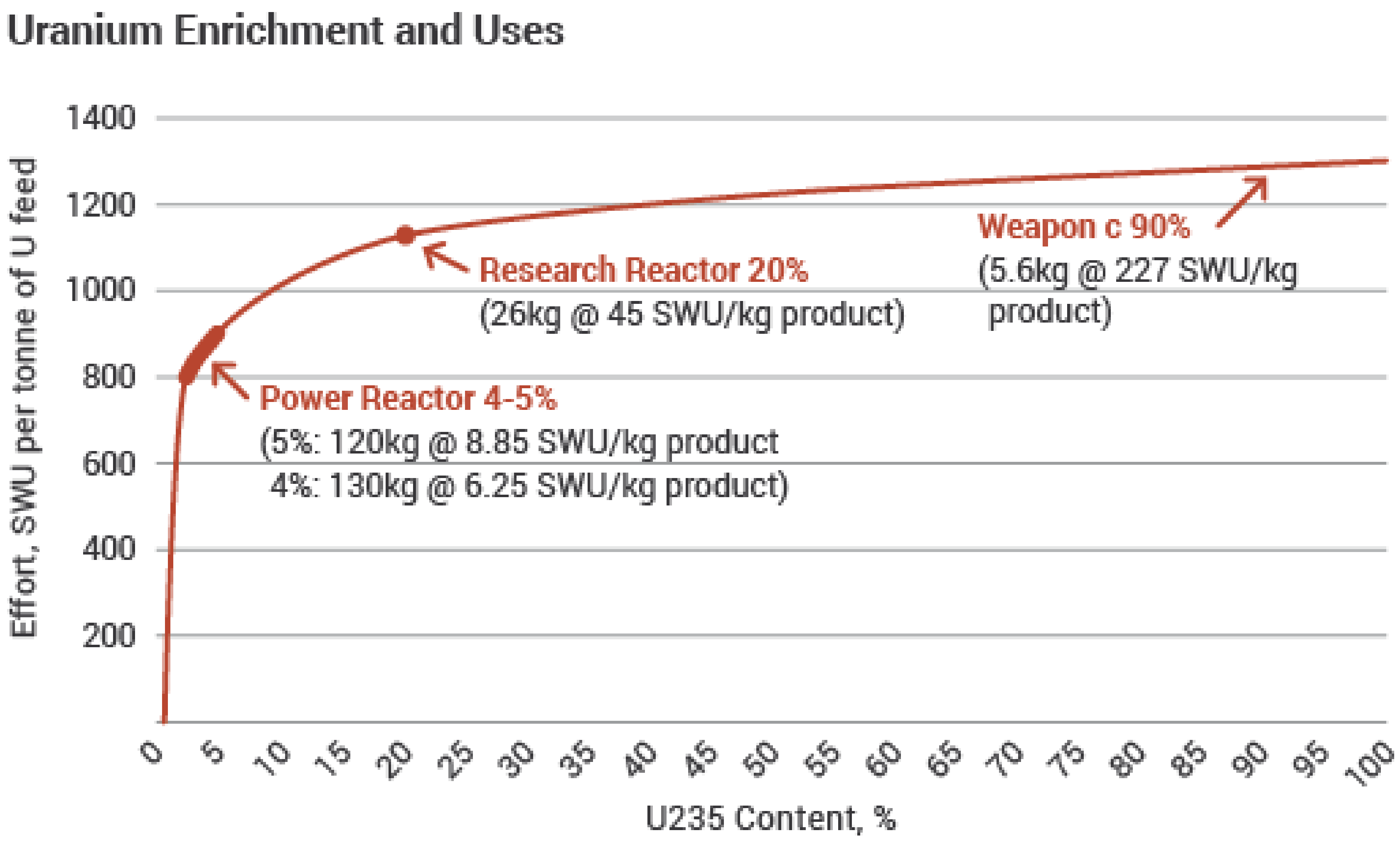
World enrichment capacity – operational and planned (thousand SWU/yr)

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	5760	10,700+
Other	Various: Argentina, Brazil, India, Pakistan, Iran	75	100	170
	Total SWU/yr approx	**51,550**	**58,600**	**66,700**
	Requirements (*WNA reference scenario*)	49,154	47,285	57,456

Table 4. Operating commercial uranium enrichment facilities, with approximate 2018 capacity

Company	Nameplate capacity (tSW)	Share of global capacity (%)
TVEL (Russia)	28 416	45.0
Urenco (UK/Germany/Netherlands/United States)	18 758	32.3
Orano (France)	7 500	12.7
CNNC (China)	5 210	9.8
Others* (CNEA, INB, JNFL)	188	0.3
World total	60 072	100

Enrichment



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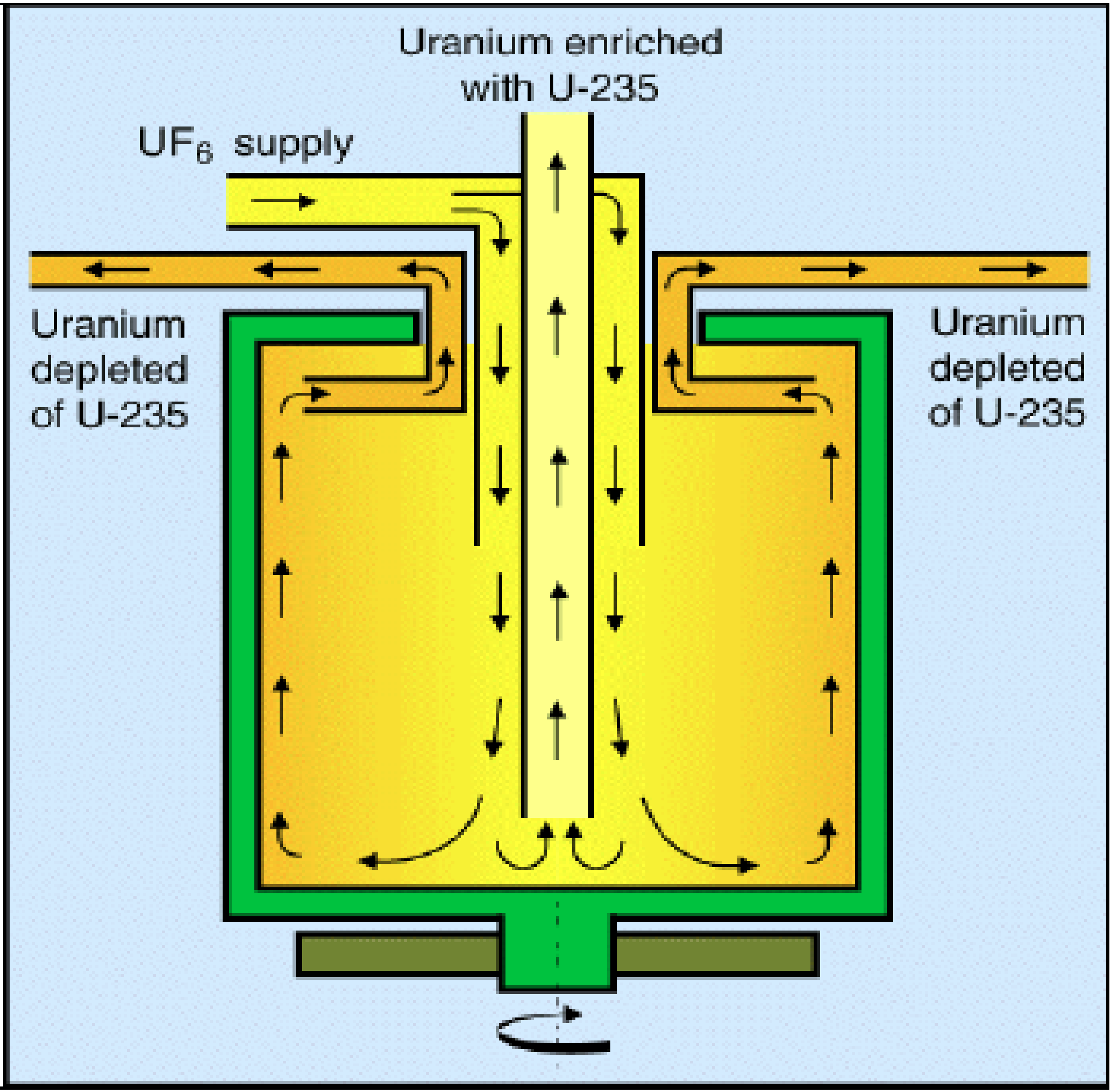
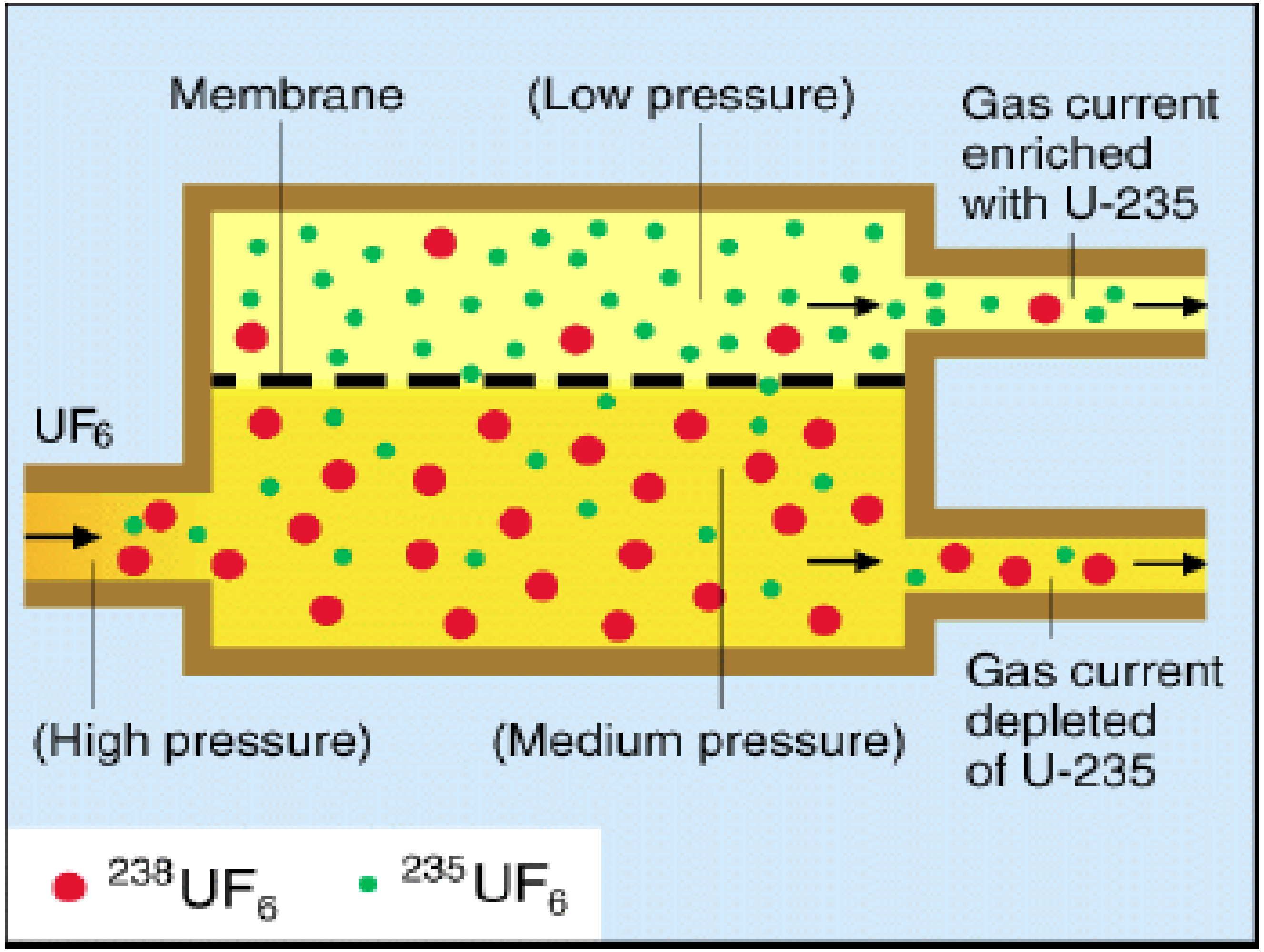
Enrichment

Supply source:	2000	2010	2015	projected 2020
Diffusion	50%	25%	0	0
Centrifuge	40%	65%	100%	93%
Laser	0	0	0	3%
HEU ex weapons	10%	10%	0	4%





Enrichment

SWU calculator:

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

Nuclear Fuel Cost Calculator:

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

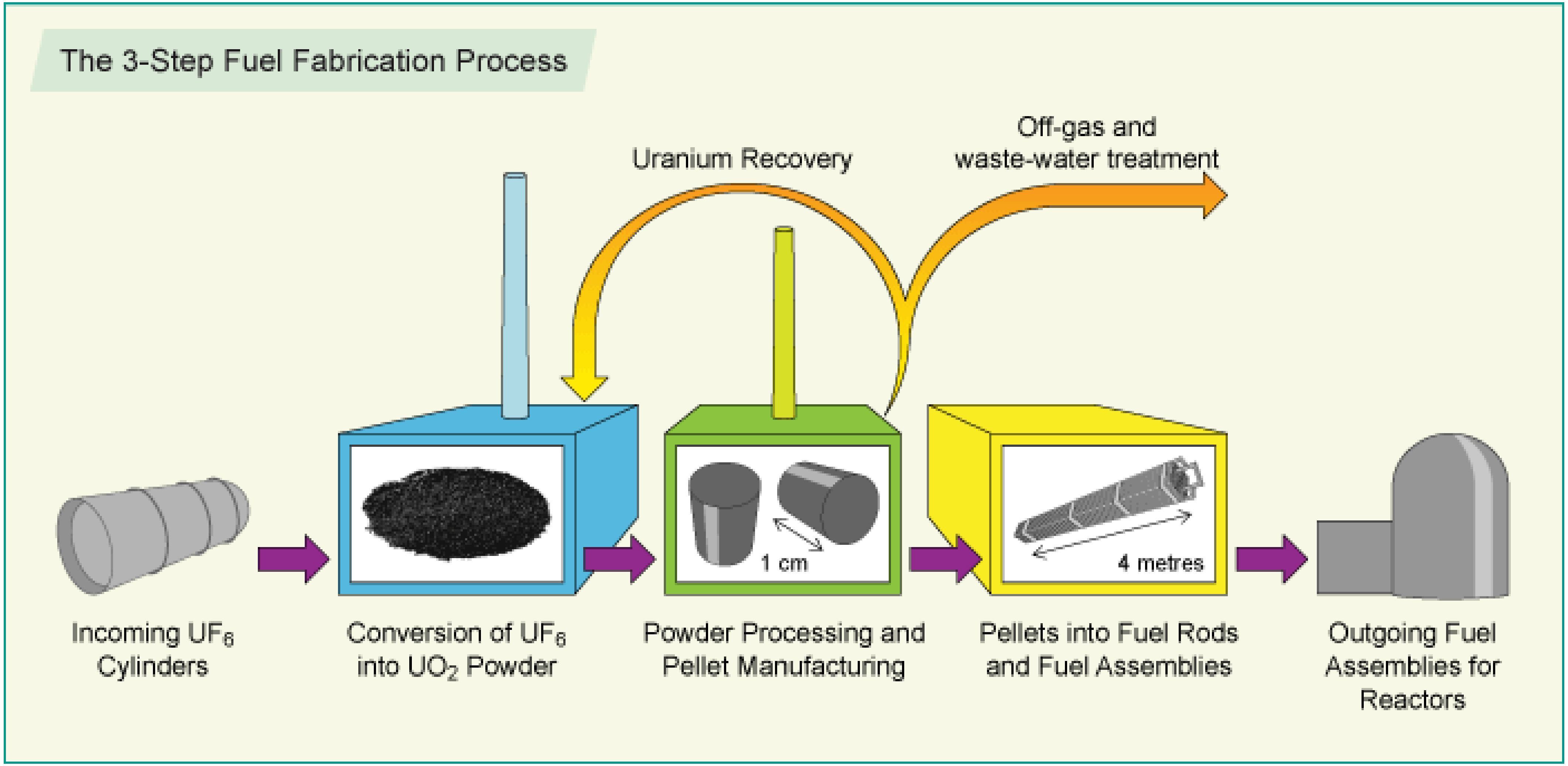

17
16

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

Fabrication



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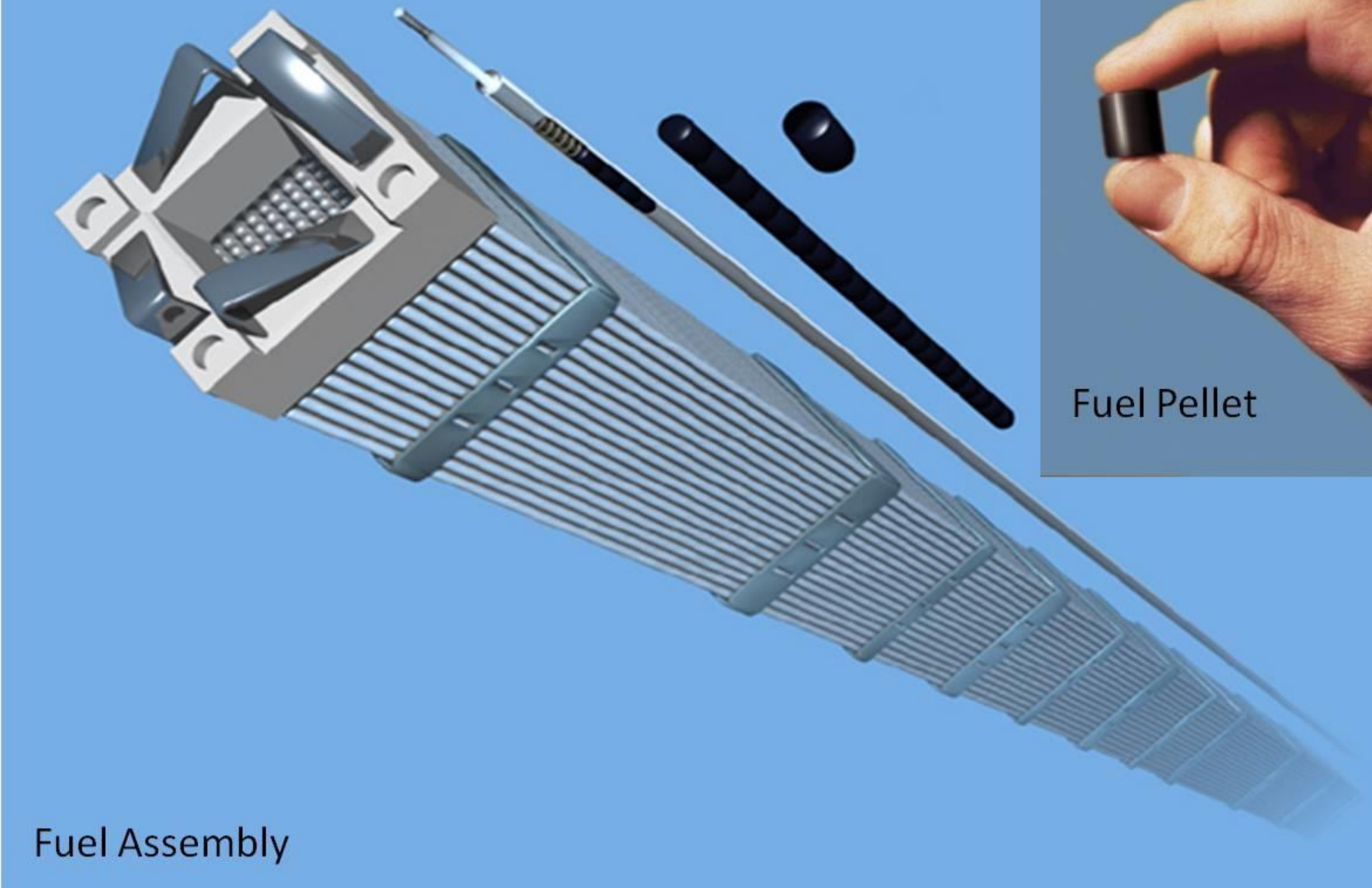

Fuel Assembly


Fuel Pellet

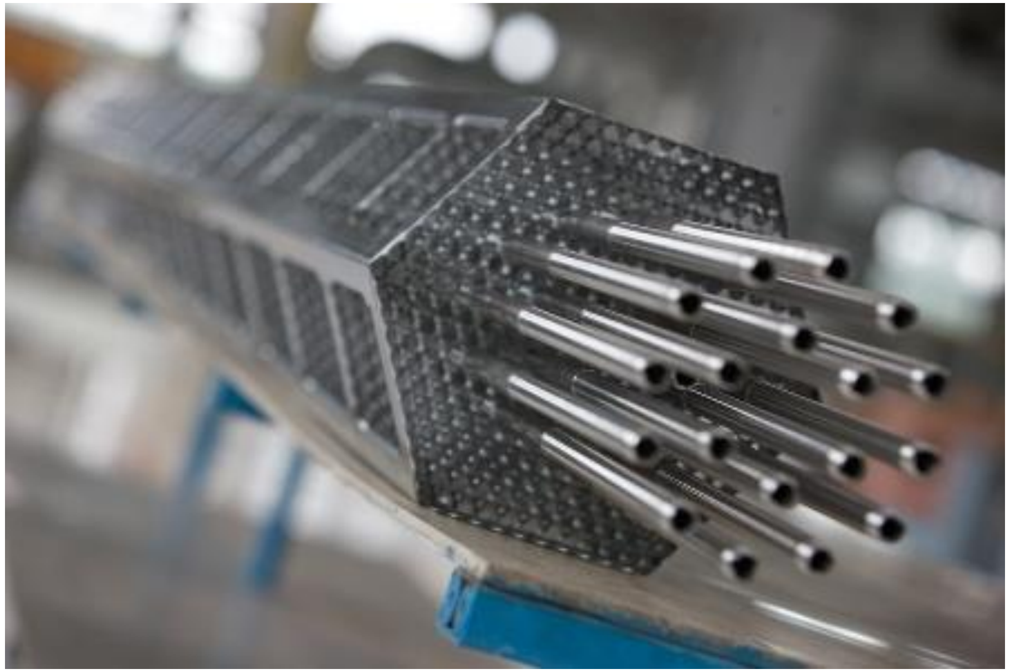

1
1

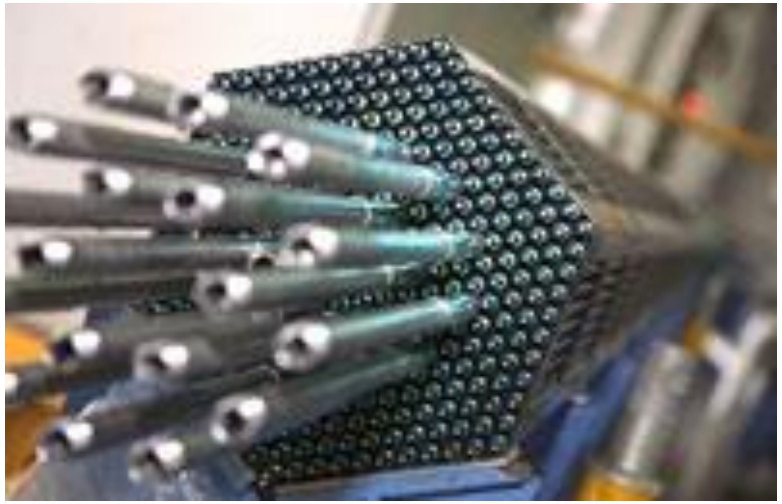

№ 1-103
48


39

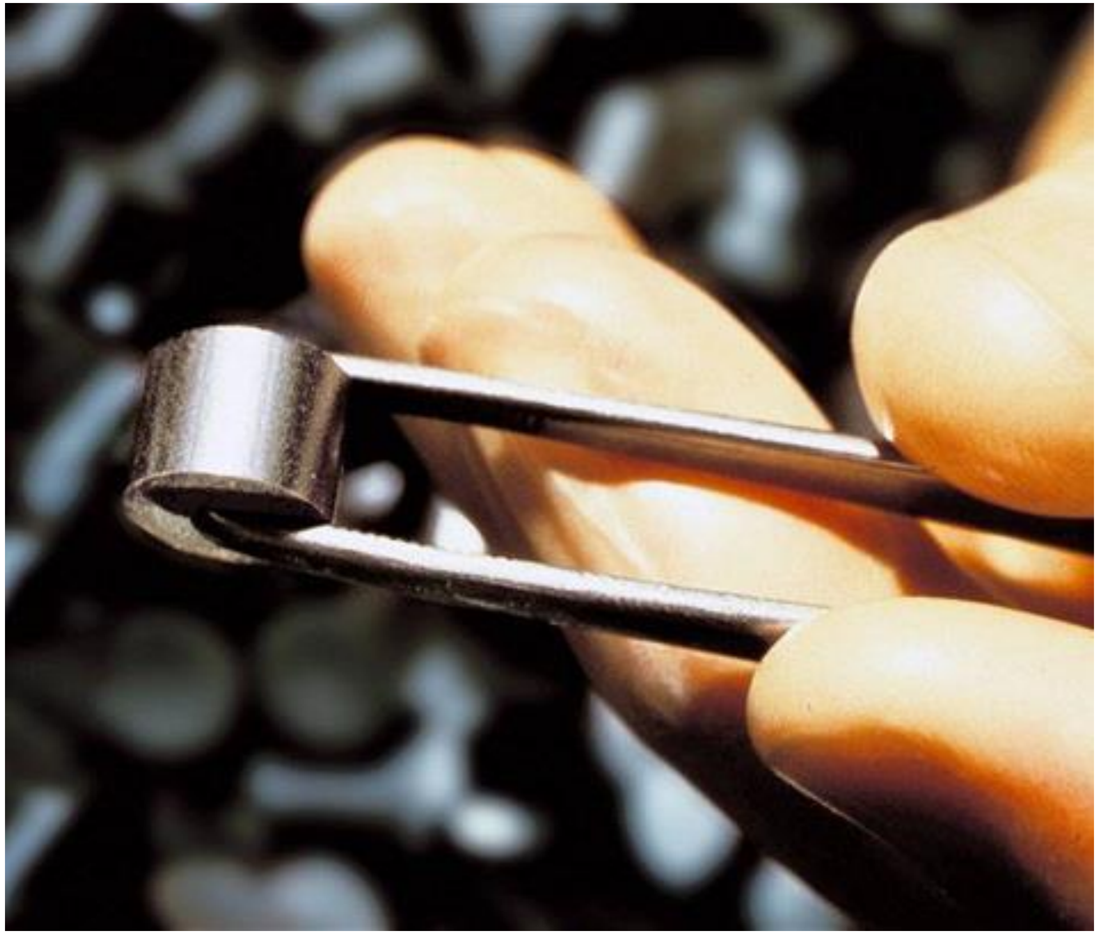

max
min
СТЕНД №2
3502-057.000.00

Fabrication

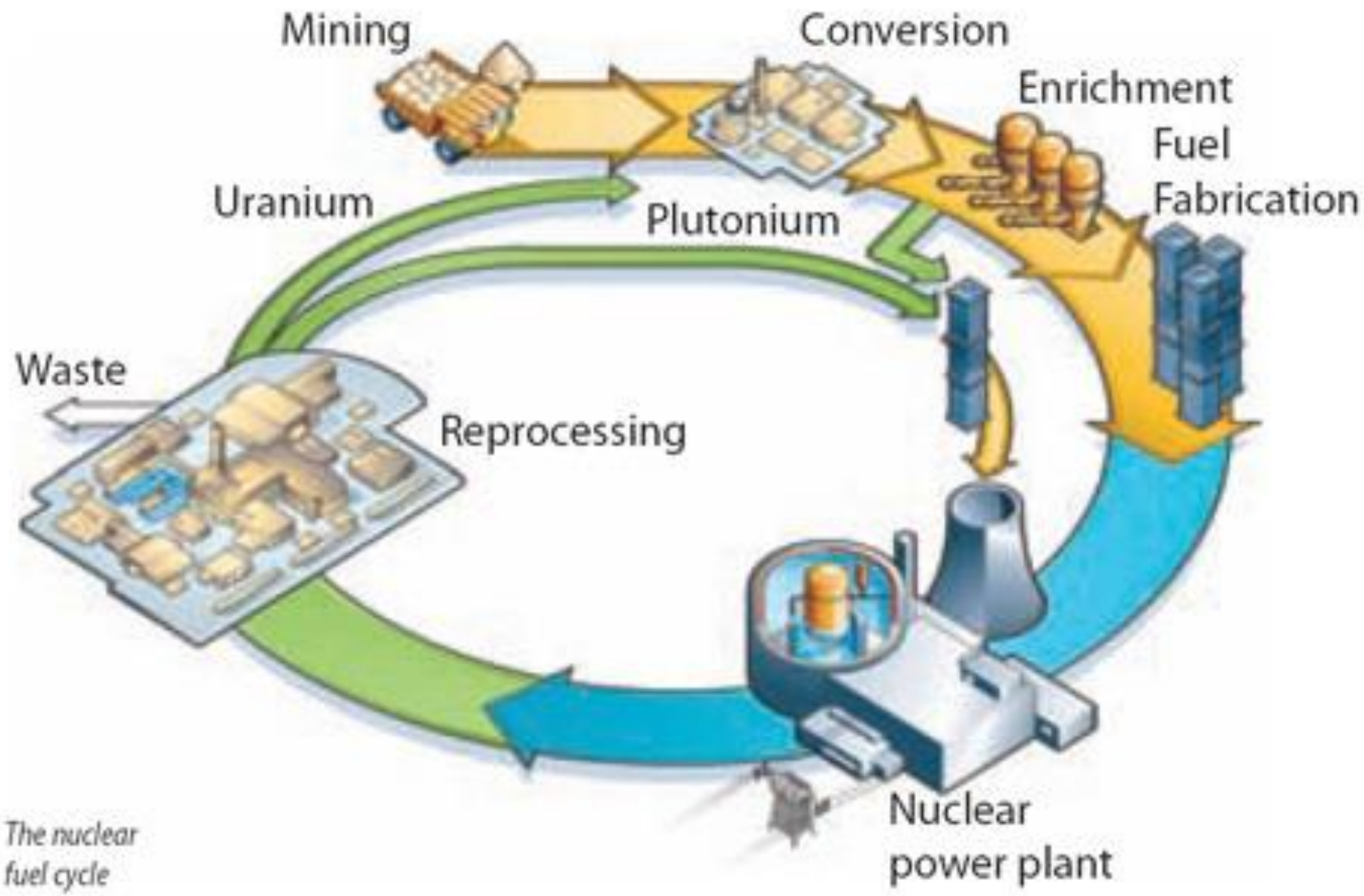




Fabrication



Nuclear Fuel Cycle



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History

When and where took the first chain reactions in nuclear reactor place?

When and where was the first nuclear reactor connected to the electricity grid?

When and where was the world's first privately owned commercial power plant opened?

History

When and where took the first chain reactions in nuclear reactor place?

- **December 20, 1951; Experimental Breeder Reactor EBR-I, Arco, Idaho, USA (0.2 Mwe, 14% efficiency)**

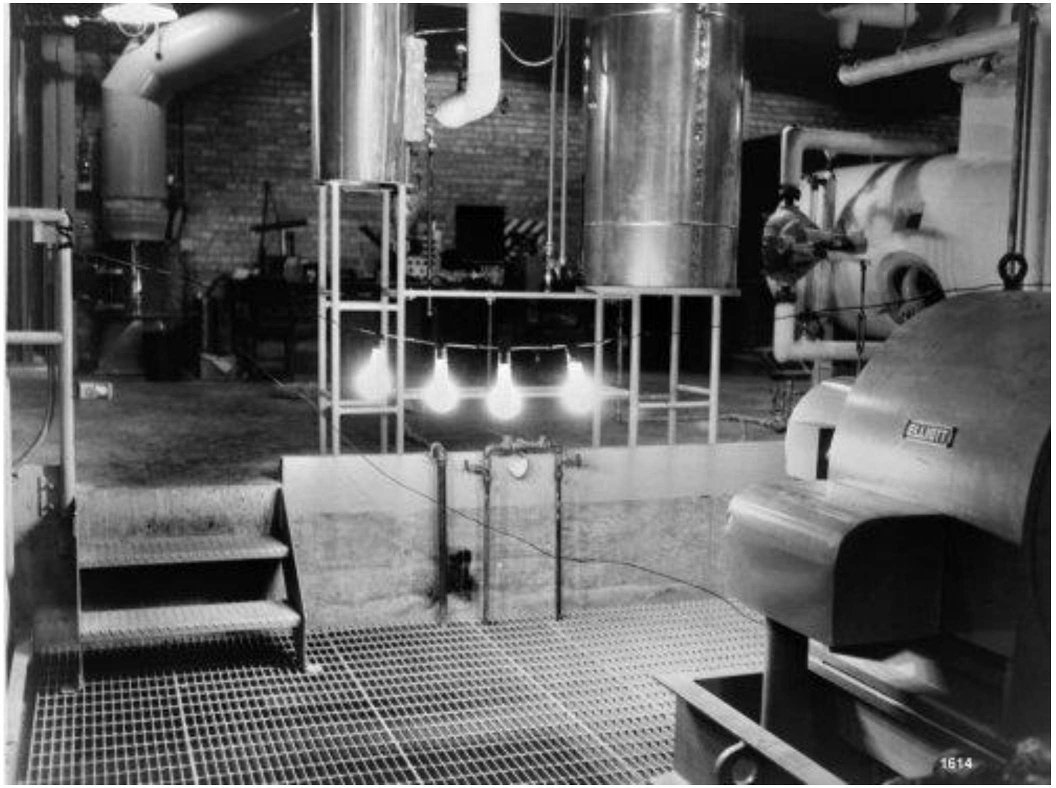
When and where was the first nuclear reactor connected to the electricity grid?

- **June 26, 1954; Obninsk, USSR, APS-1 (5 MWe, 17% efficiency)**

When and where was the world's first privately owned commercial power plant opened?

- **October 17, 1956; Calder Hall, Sellafield, UK (46 MWe, 23% efficiency)**

History



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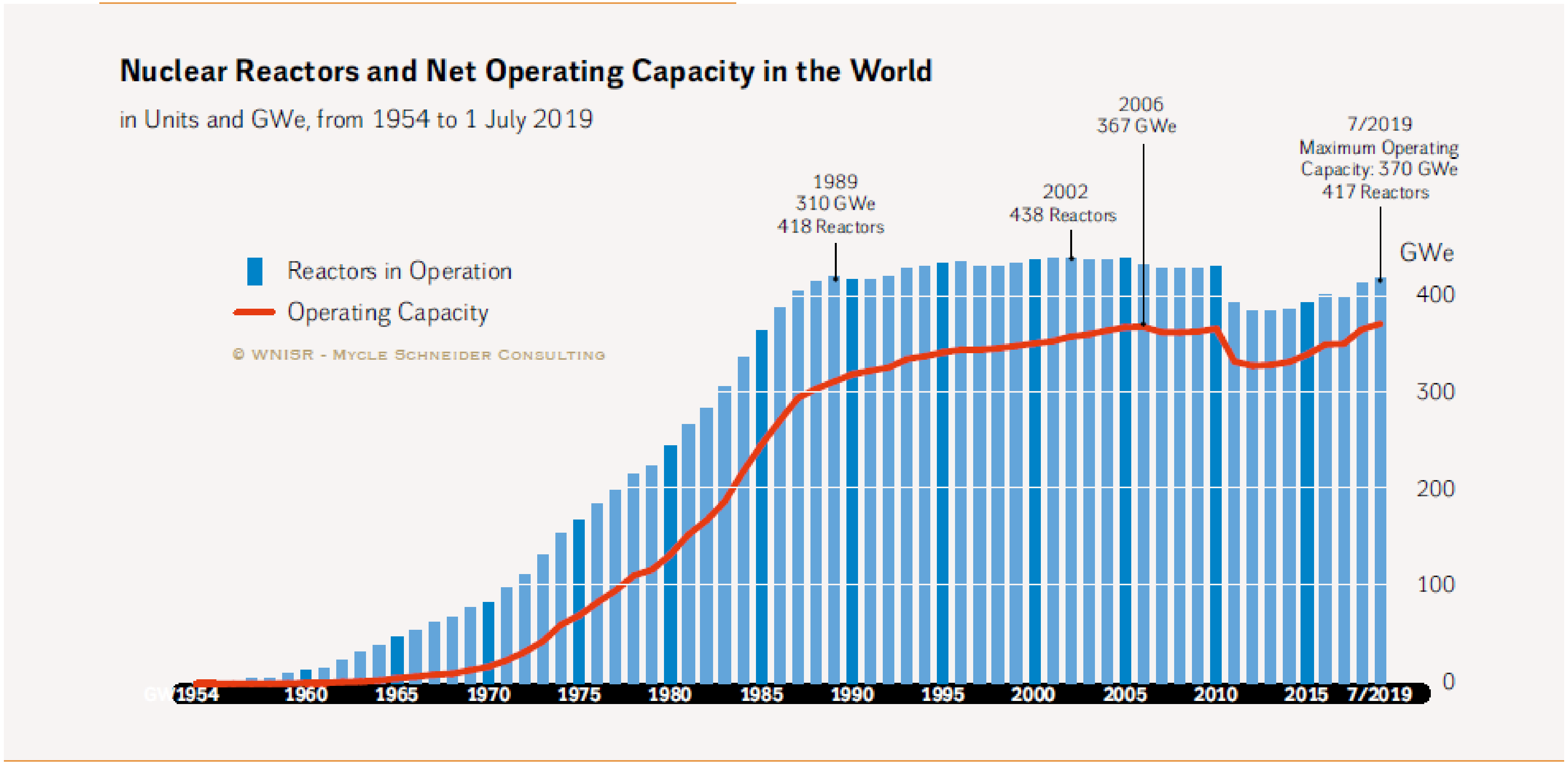
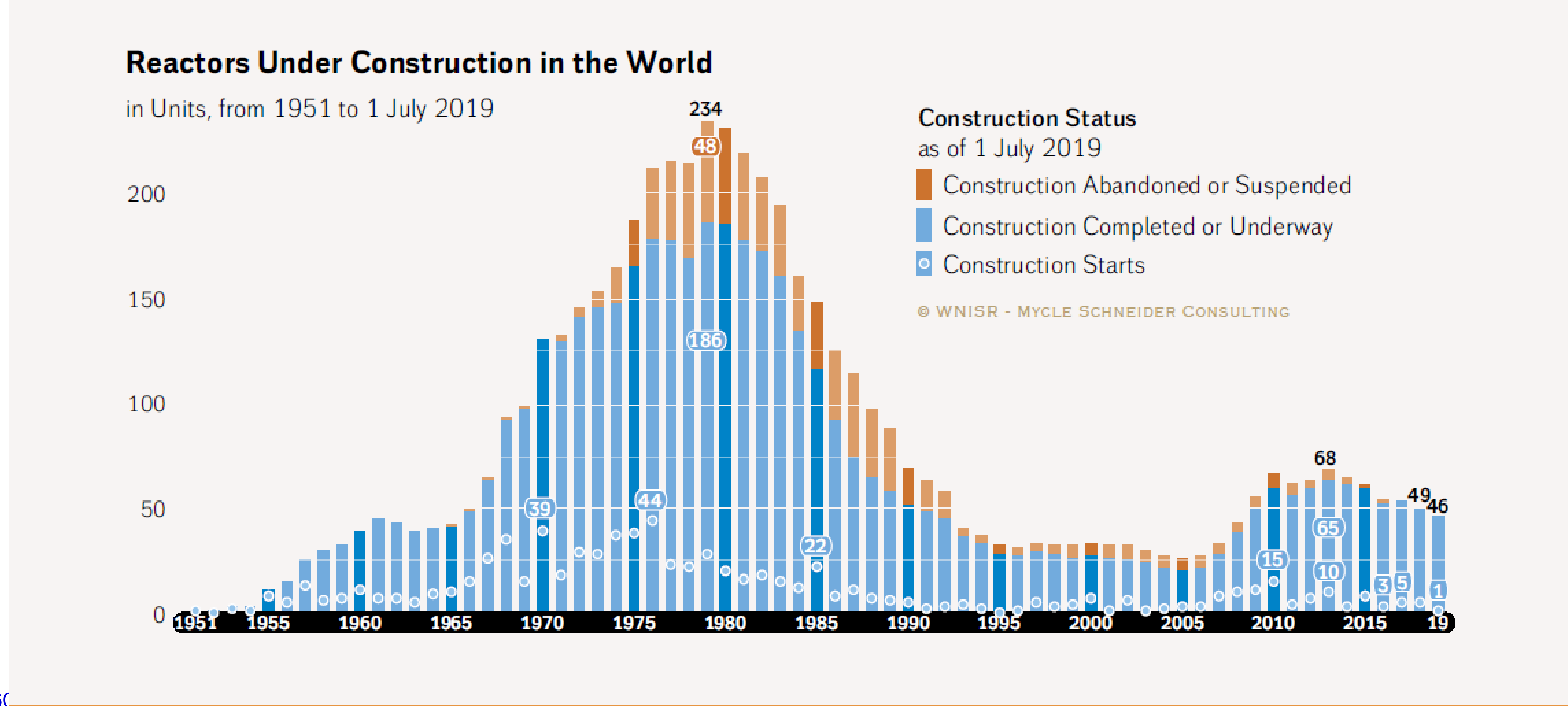
World Reactor Fleet



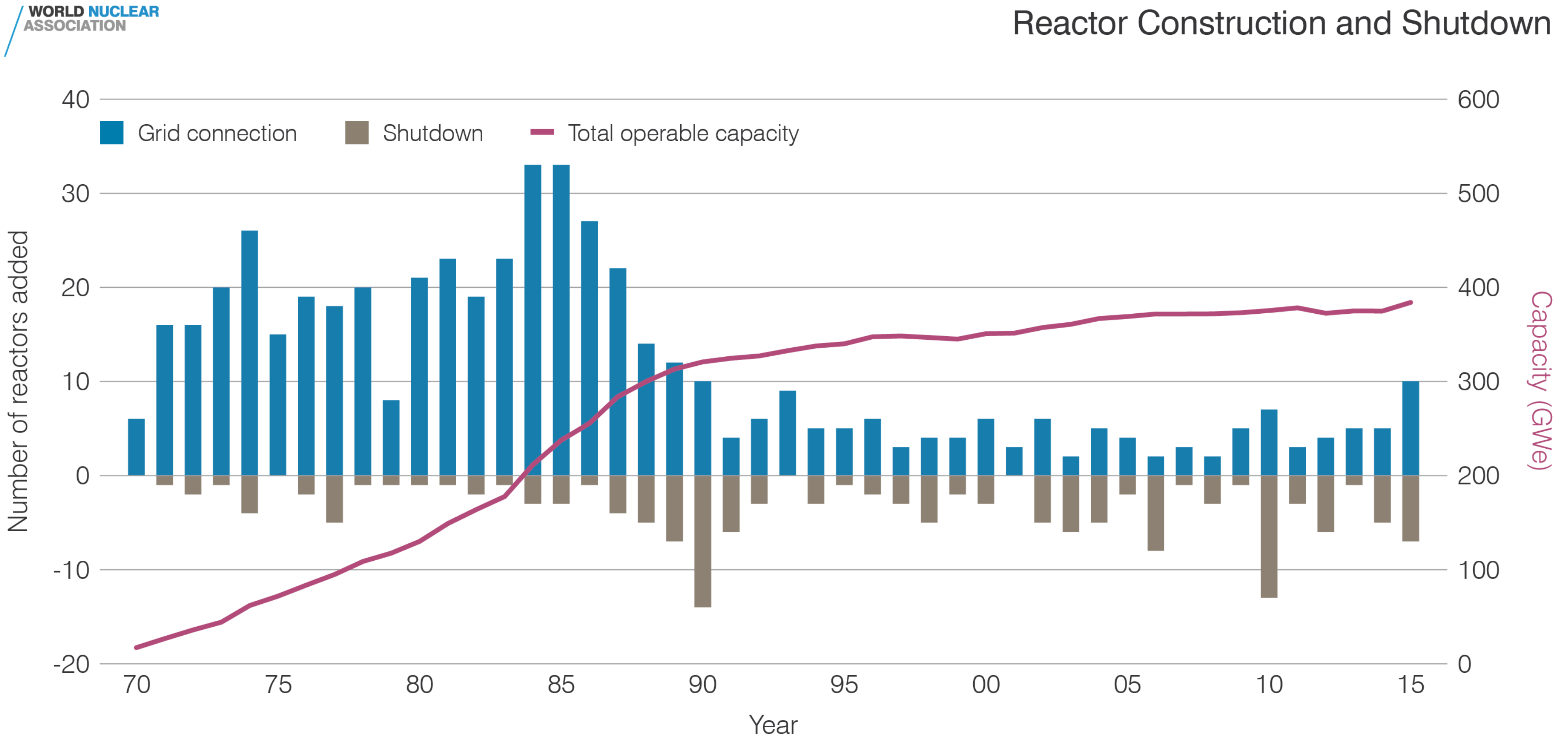
Sources: WNISR, with IAEA-PRIS, 2019

World Reactor Fleet



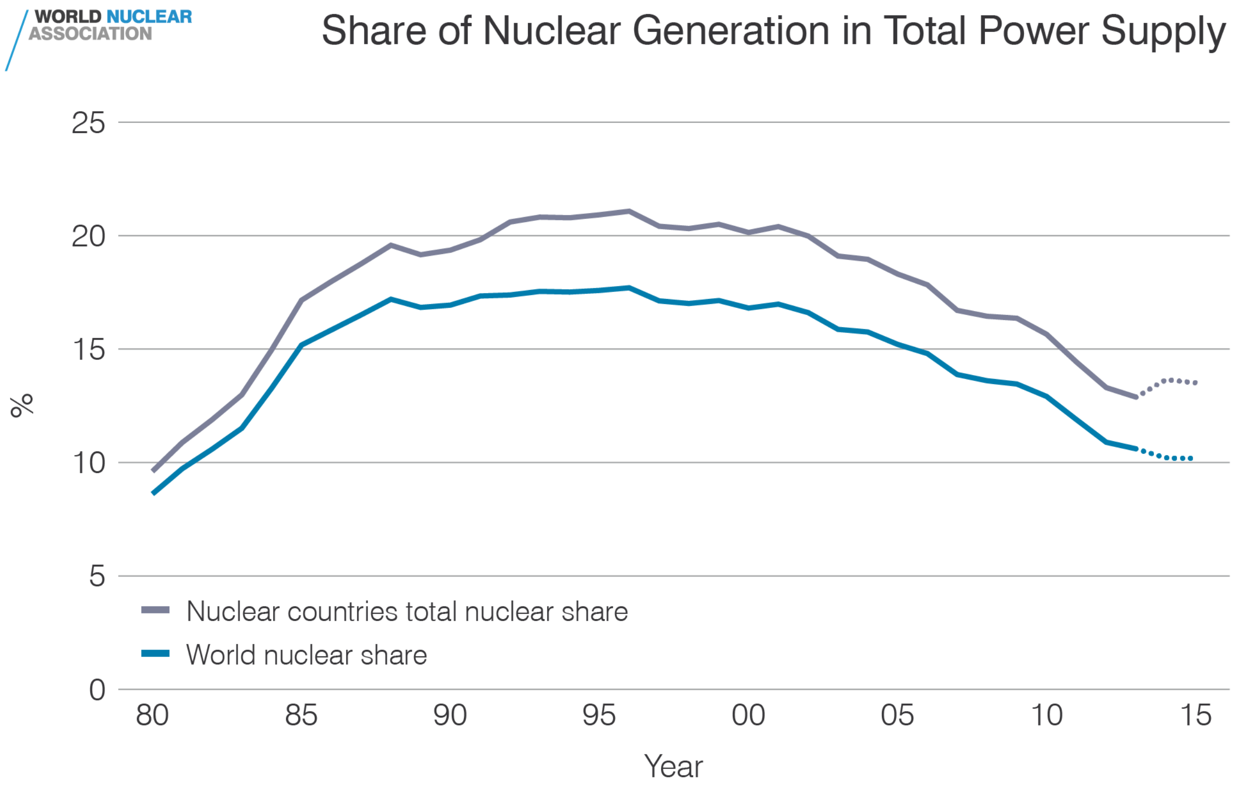
Sources: WNISR, with IAEA-PRIS, 2019

World Reactor Fleet

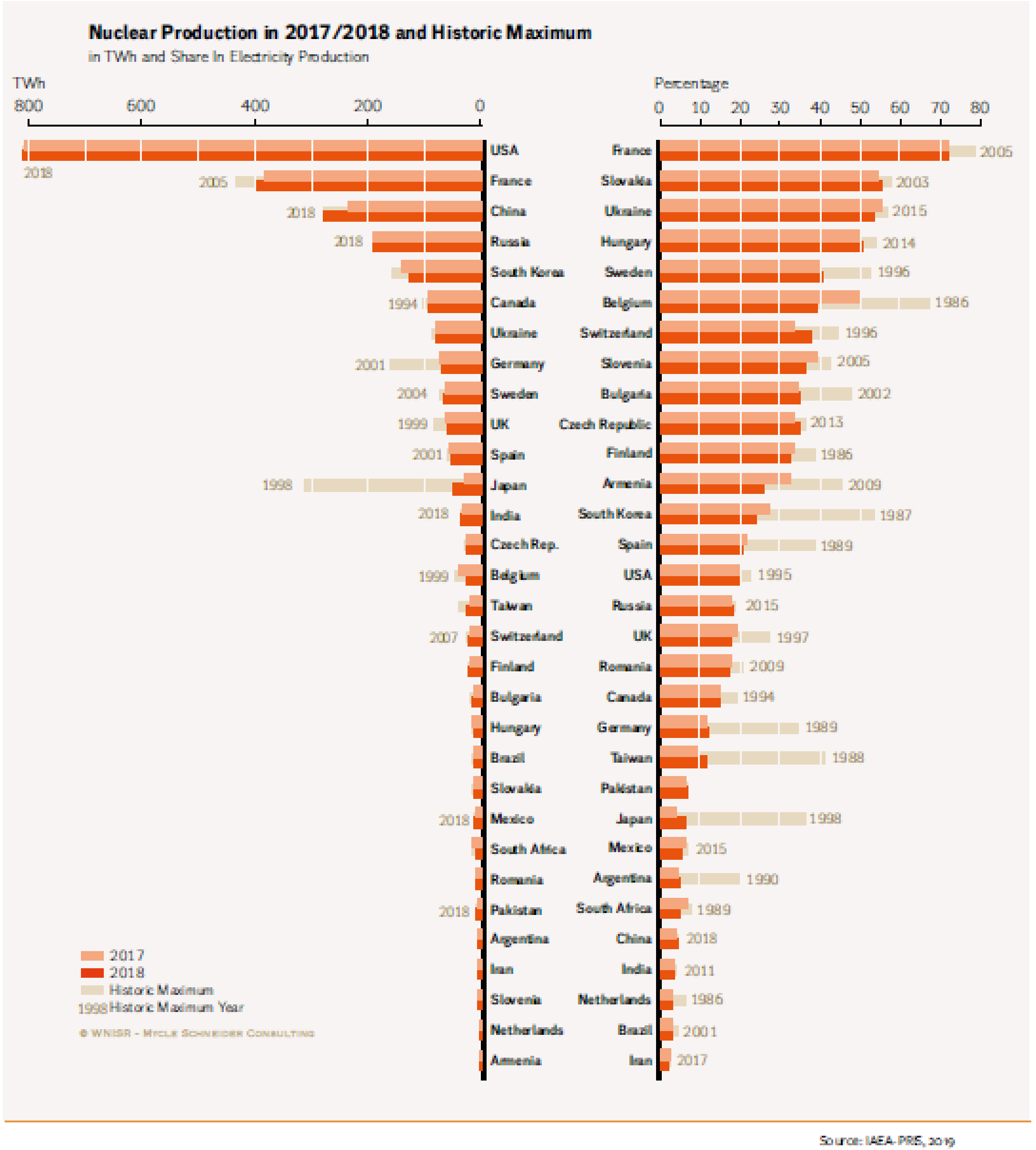


Source: IAEA PRIS

World Reactor Fleet



Source: IEA, World Energy Outlook 2014; IAEA PRIS; World Nuclear Association (for 2014-15 data)



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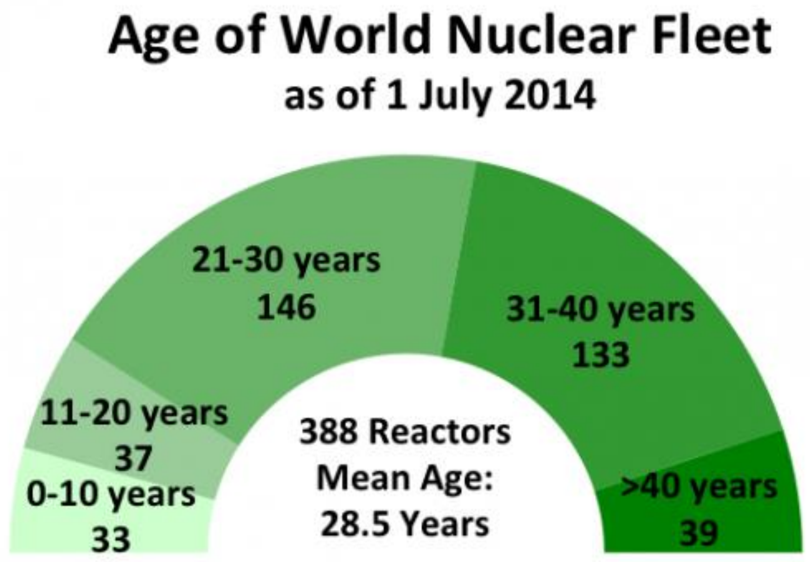
World Reactor Fl



Nuclear Reactors "Under Construction" as of July 2019

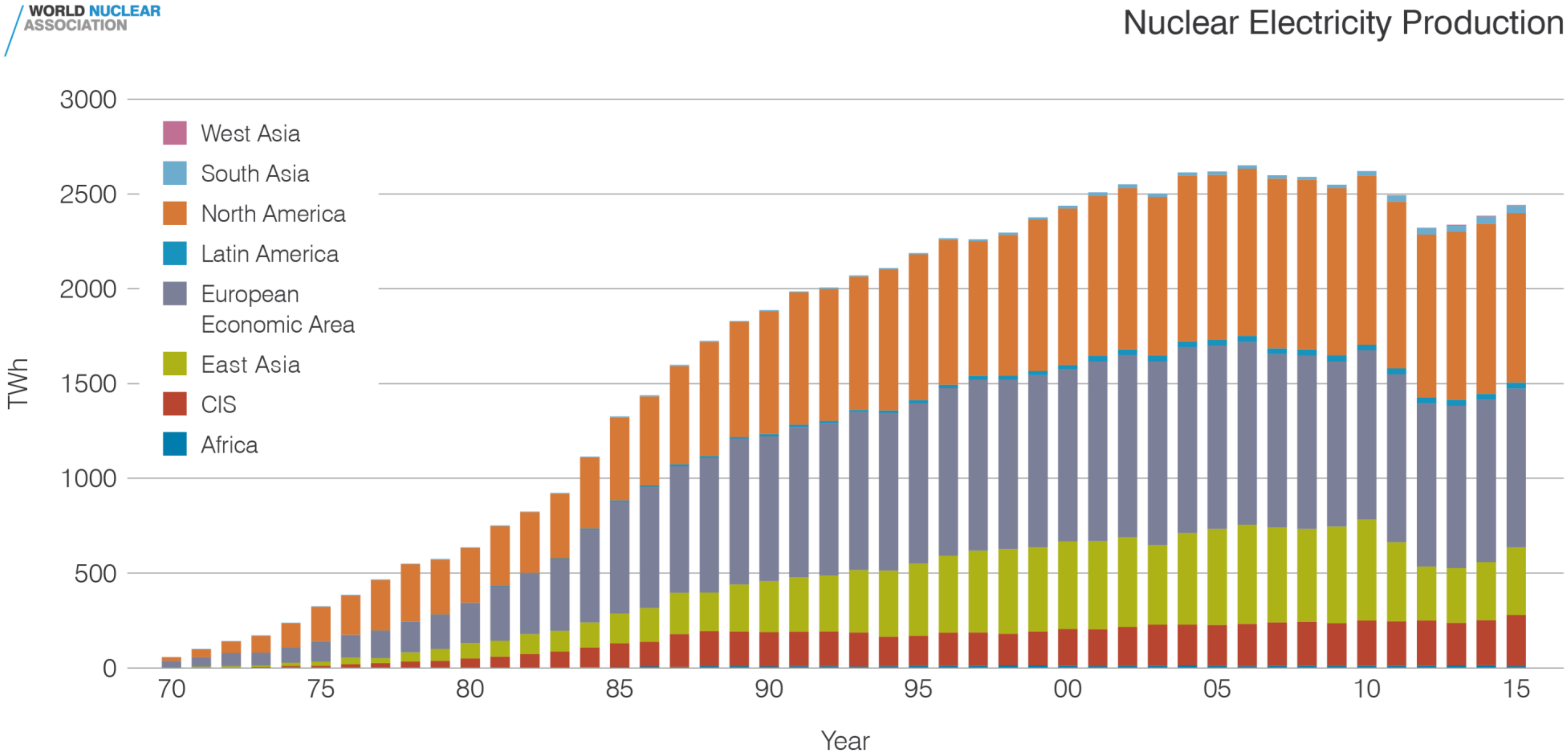
Country	Units	Capacity (MW net)	Construction Starts	Grid Connection	Units Behind Schedule
China	10	8 800	2012 - 2017	2020 - 2023	2-3
India	7	4 824	2004 - 2017	2019 - 2023	5
Russia	5	3 379	2007 - 2019	2019 - 2023	3
UAE	4	5 380	2012 - 2015	2020 - 2023	4
South Korea	4	5 360	2012 - 2018	2019 - 2024	4
Belarus	2	2 218	2013 - 2014	2019 - 2020	1-2
Bangladesh	2	2 160	2017 - 2018	2023 - 2024	0
Slovakia	2	880	1985	2020 - 2021	2
USA	2	2 234	2013	2021 - 2022	2
Pakistan	2	2 028	2015 - 2016	2020 - 2021	0
Japan	1	1 325	2007	?	1
Argentina	1	25	2014	2021	1
UK	1	1 630	2018	2025	0
Finland	1	1 600	2005	2020	1
France	1	1 600	2007	2022	1
Turkey	1	1 114	2018	2024	0
Total	46	44 557	1985 - 2019	2019 - 2025	27-29

Sources: Compiled by WNISR. 2019

Note

This table does not contain suspended or abandoned constructions.

World Reactor Fleet



Source: IAEA PRIS

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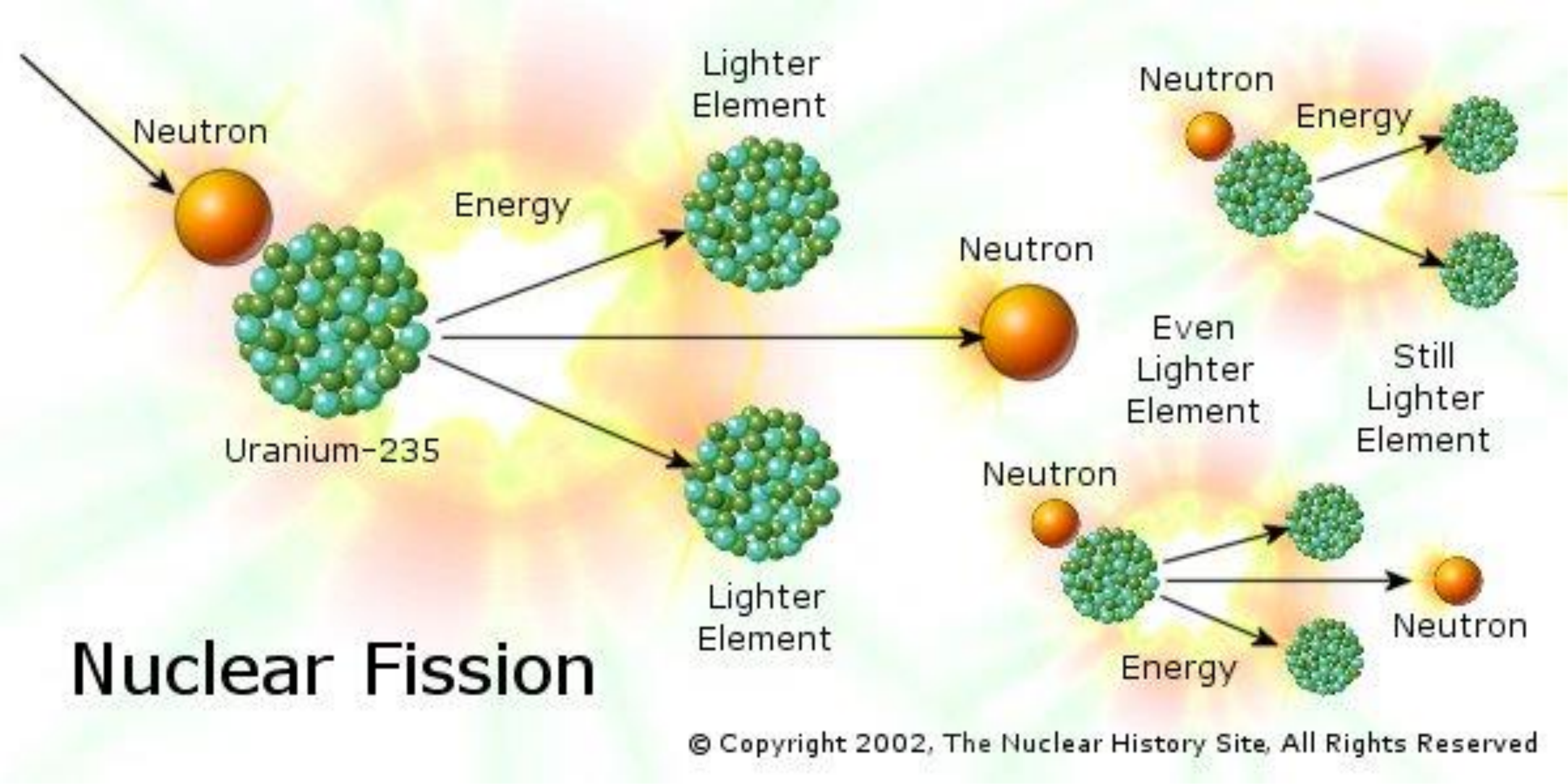
Service part

Nuclear power plants in commercial operation or operable

Reactor type	Main countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised water reactor (PWR)	US, France, Japan, Russia, China	292	275	enriched UO_2	water	water
Boiling water reactor (BWR)	US, Japan, Sweden	75	73	enriched UO_2	water	water
Pressurised heavy water reactor (PHWR)	Canada, India	49	25	natural UO_2	heavy water	heavy water
Gas-cooled reactor (AGR & Magnox)	UK	14	8	natural U (metal), enriched UO_2	CO_2	graphite
Light water graphite reactor (RBMK & EGP)	Russia	11 + 4	10	enriched UO_2	water	graphite
Fast neutron reactor (FBR)	Russia	3	1.4	PuO_2 and UO_2	liquid sodium	none
	TOTAL	448	392			

Source: IAEA

PWR Reactors



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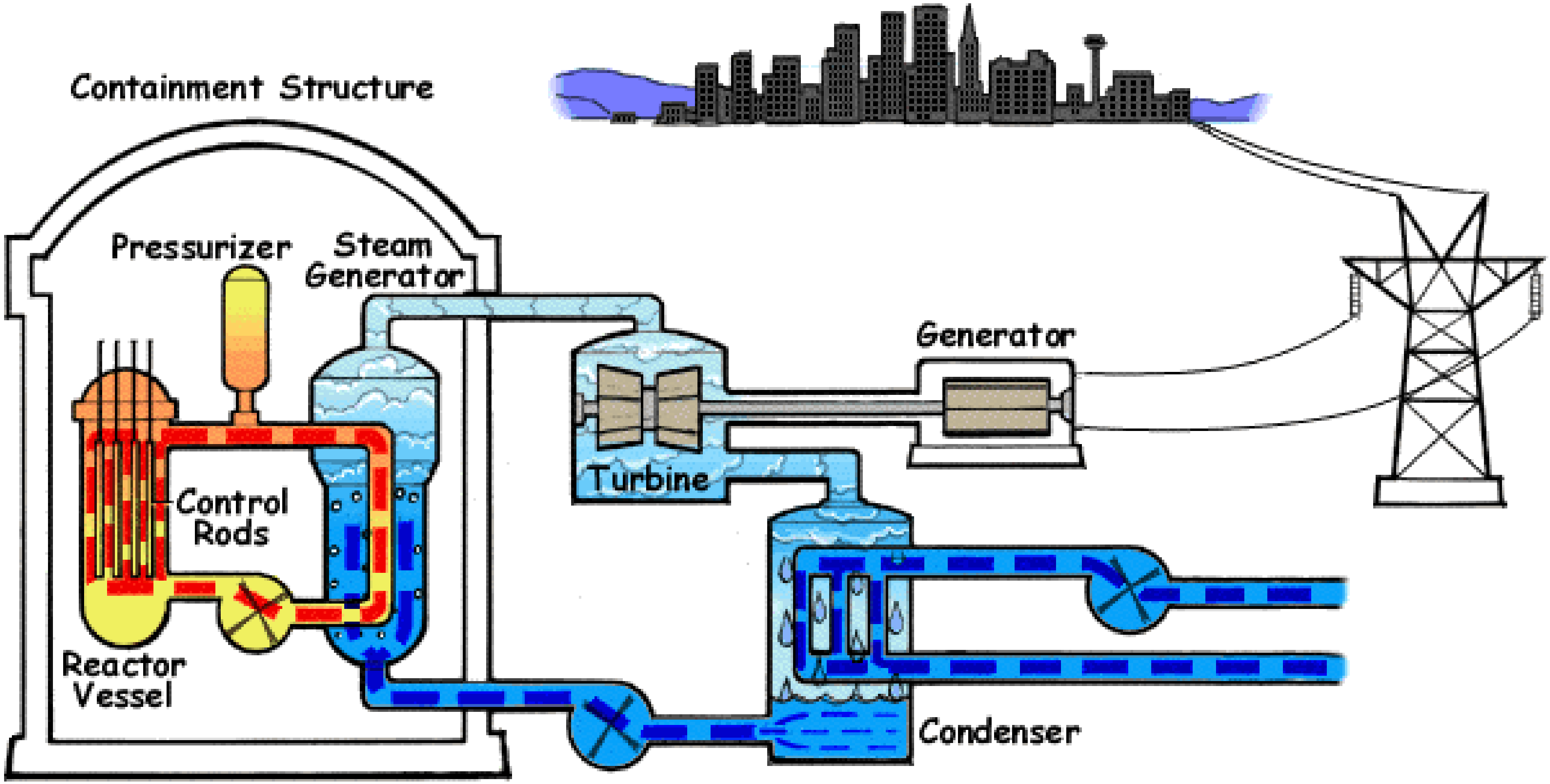
PWR Reactors



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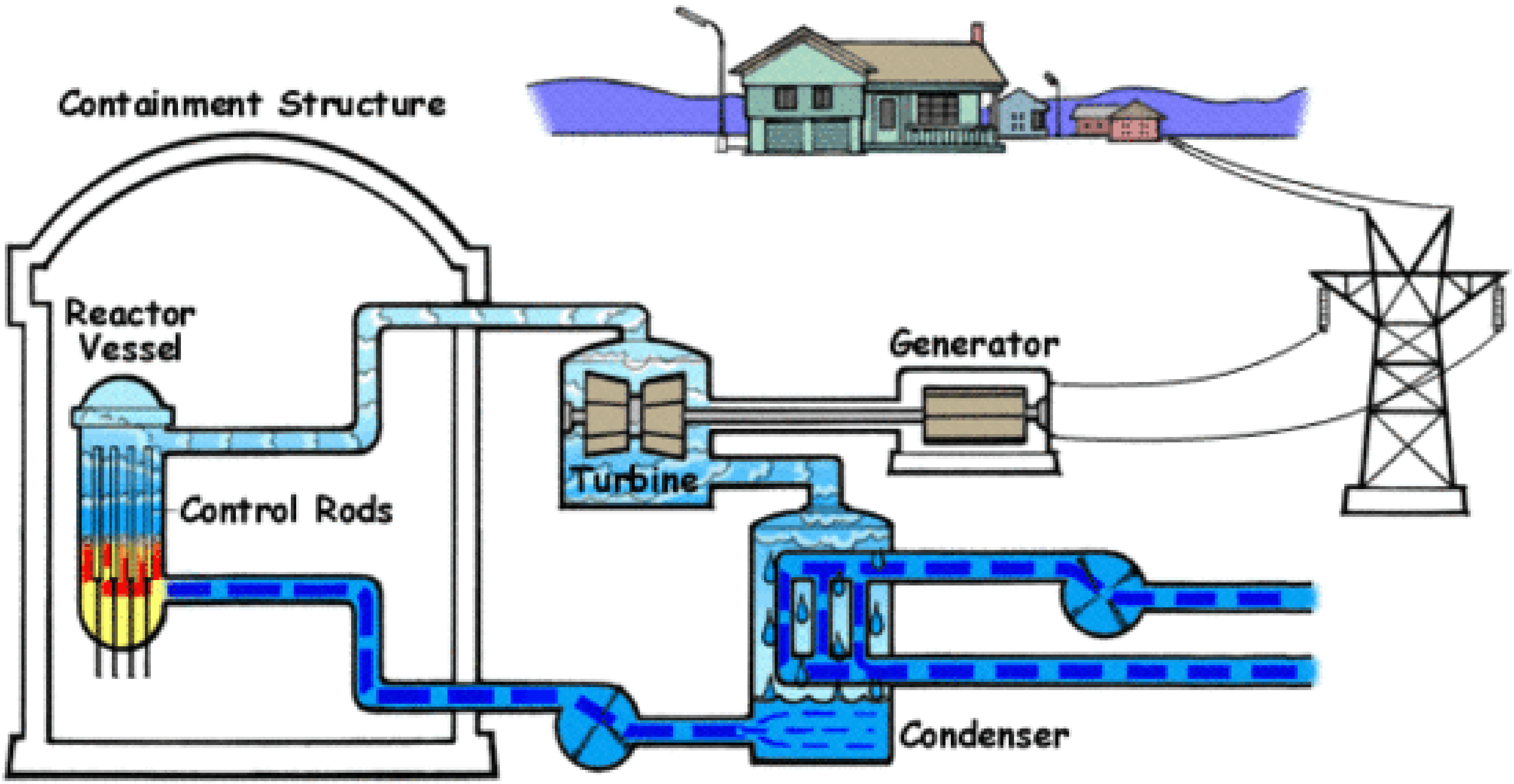
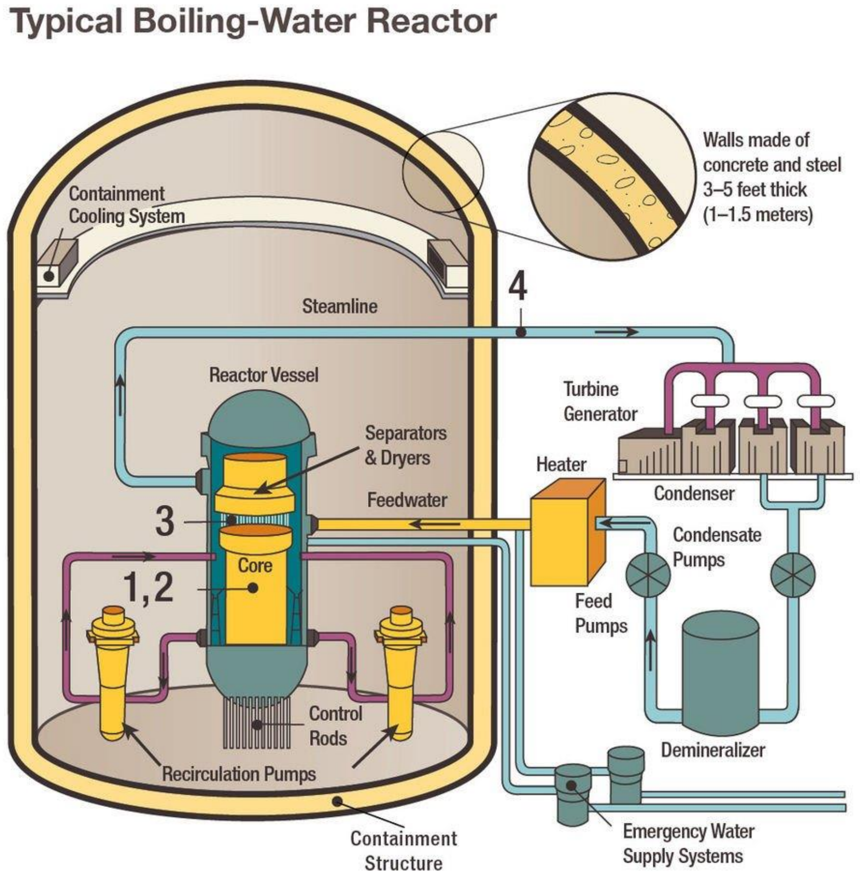
БАЛТКРАН
180(220)/32+220+6,3т
БАЛТКРАН
15т

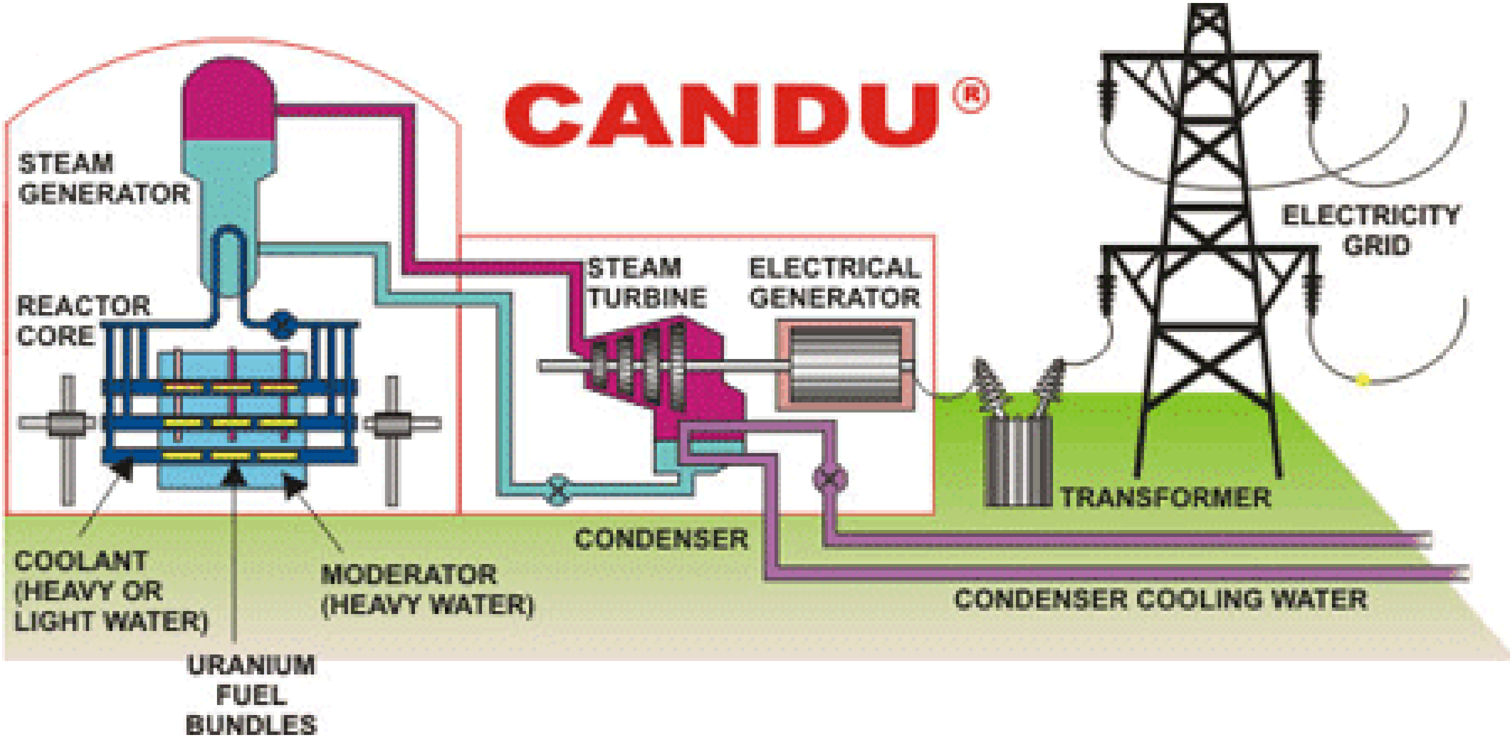
BWR Reactors





PHW Reactor

- Generally the same structure as PWR
- Heavy water (not radioactive, but posionous) absorbs less neutrons, thus is able both to moderate nuclear reaction and secure criticality = non-enriched fuel can be used



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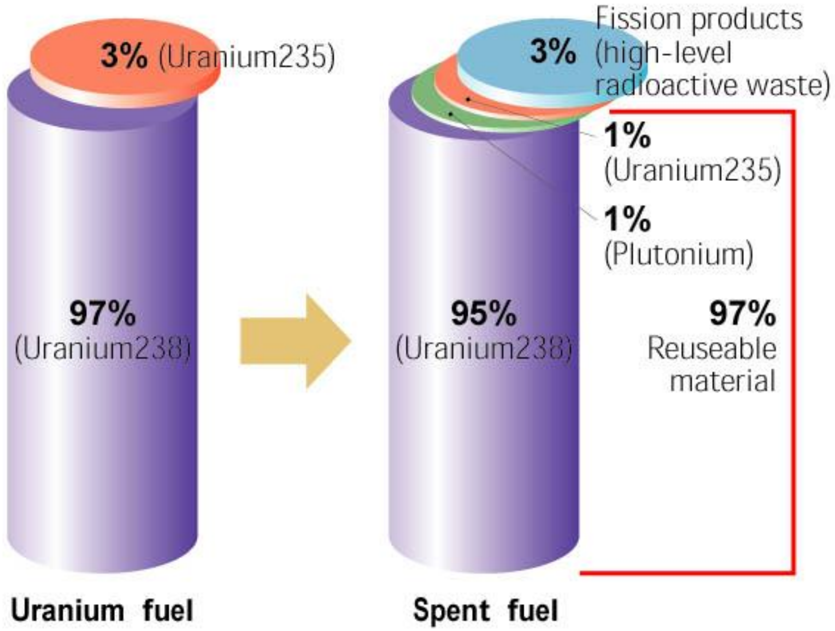
Back End

- Fission chain reaction consumes only uranium isotope 235U.
- Used fuel contains approximately a quarter of the original value of this isotope, thus still remains enriched to about 1% 235U.
- The fuel consists of more than 96% uranium dioxide (UO2) and newly developed plutonium dioxide (PuO2) in an amount of about 1%, and other compounds (3%), while most of the fission products are radioactive isotopes.



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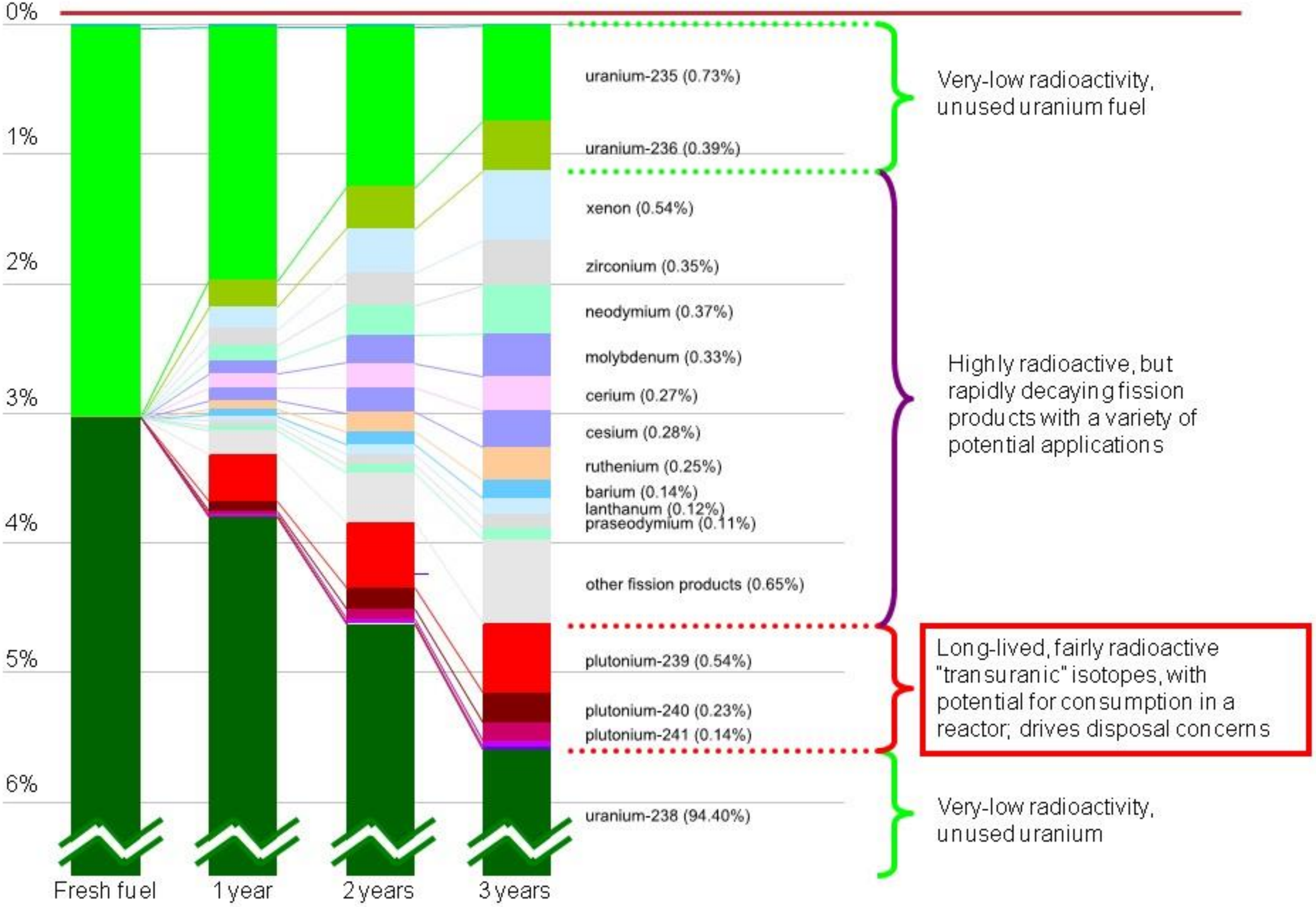
Composition of Conventional Nuclear Fuel

(17x17 Westinghouse, 3% enr., 1100 day irrad, 33000 MWD/MTU, discharge composition, Origen Arp analysis)



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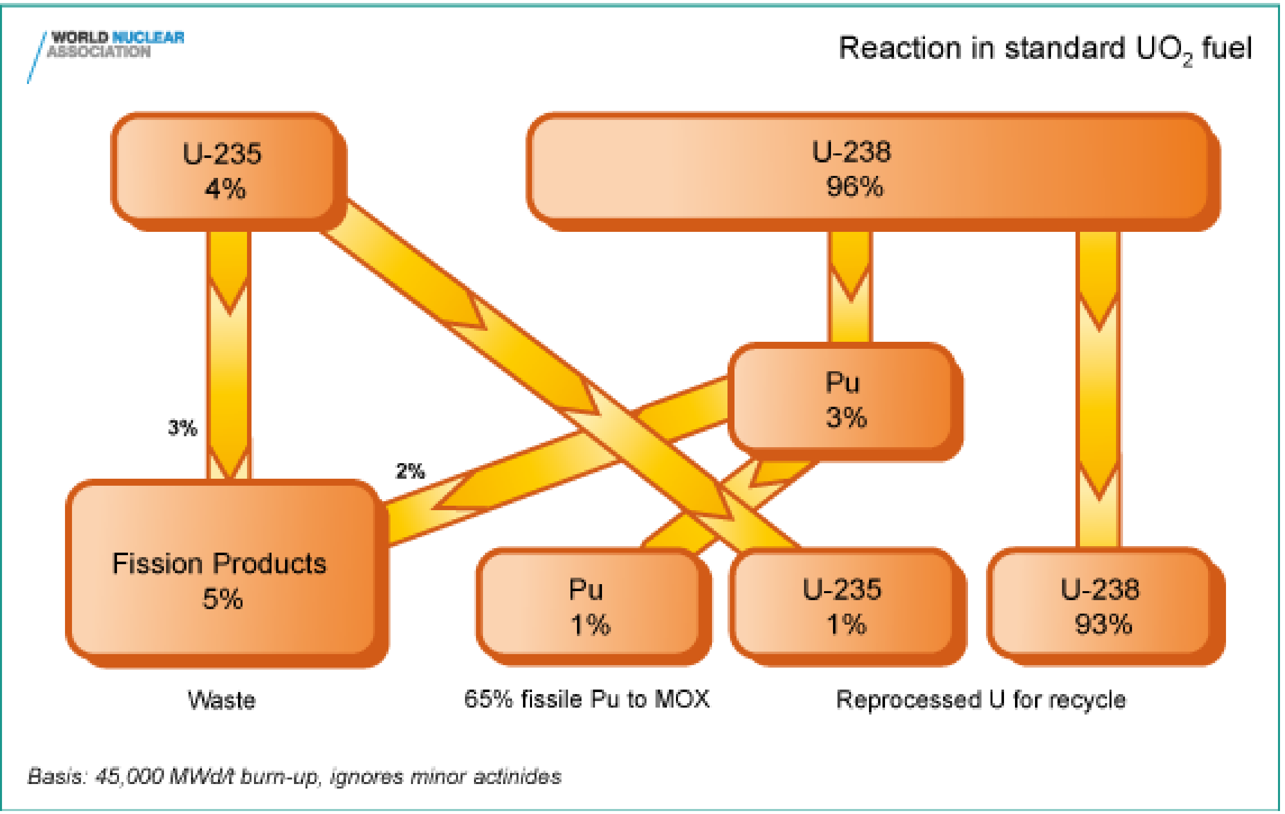
MOX Fuel

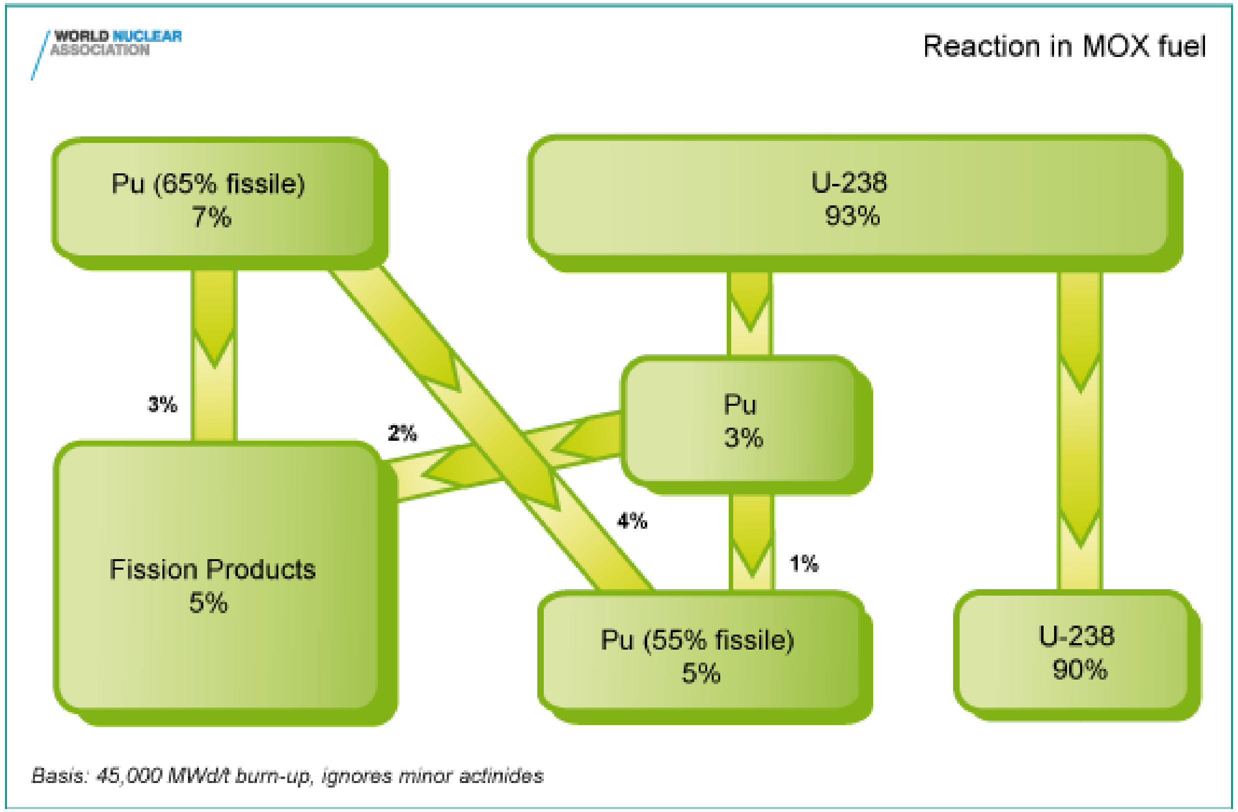
- Mixed oxide (MOX) fuel provides almost 5% of the new nuclear fuel used today.
- MOX fuel is manufactured from plutonium recovered from used reactor fuel, mixed with depleted uranium.
- MOX fuel also provides a means of burning weapons-grade plutonium (from military sources) to produce electricity.
- Mixed uranium oxide + plutonium oxide (MOX) fuel has been used in about 30 light-water power reactors in Europe and about ten in Japan.

World mixed oxide fuel fabrication capacities (t/yr)

	2017
France, Marcoule	195
Japan, Tokai-Mura	5
Japan, Rokkasho-Mura (from 2022)	130
Russia, Zheleznogorsk	60
India, Tarapur	50
Total for LWR	**440**

MOX Fuel

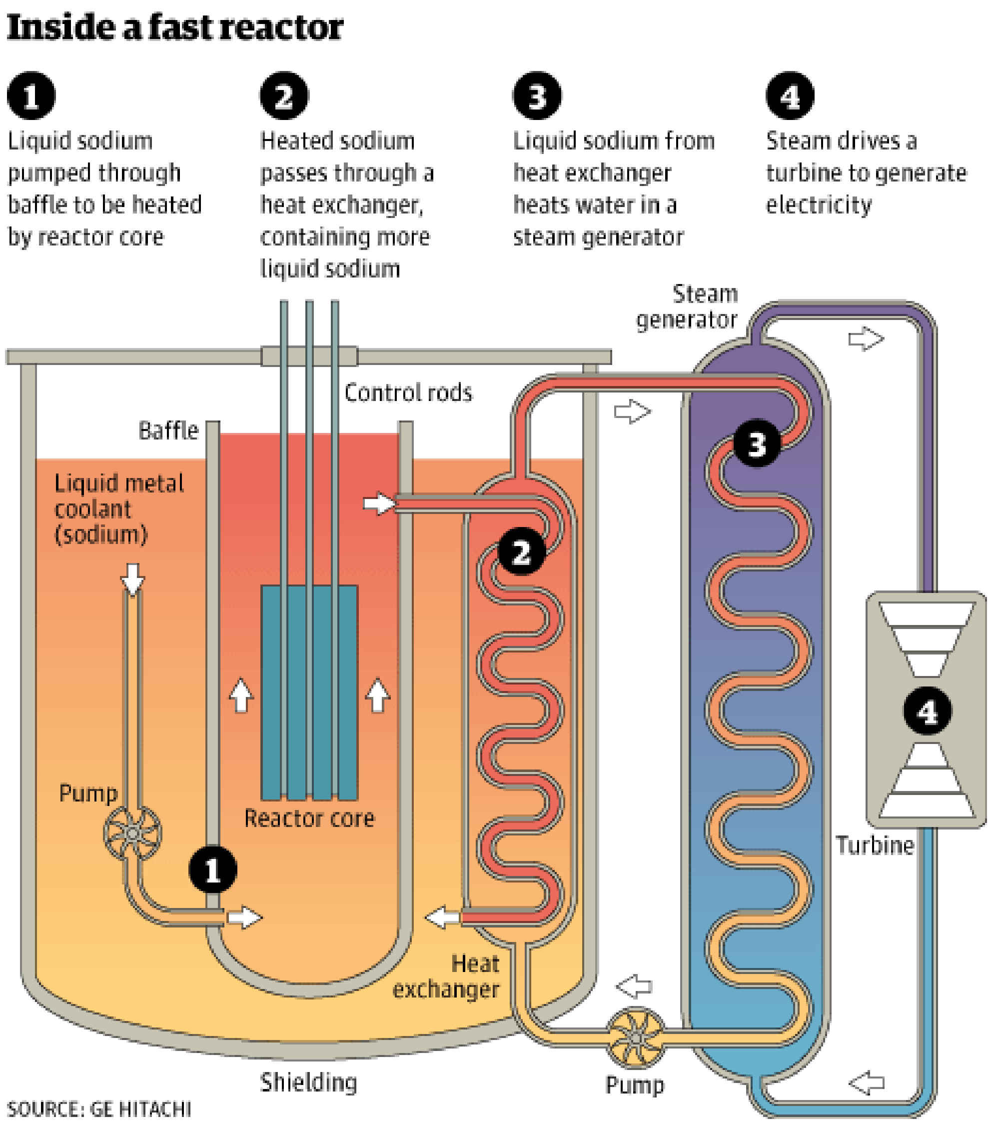




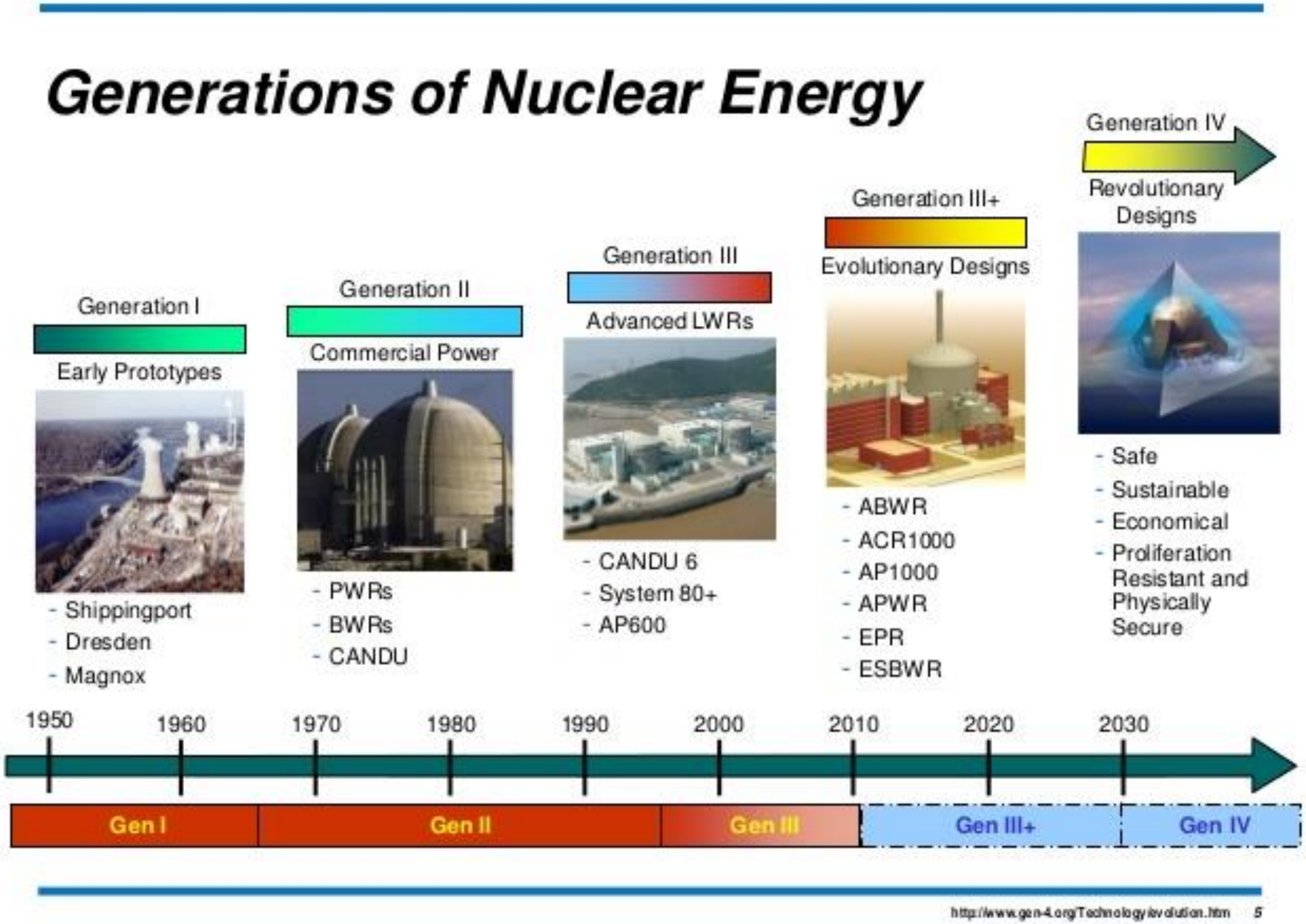
MUNI FSS

Fast Neutron Reactors

- About 400 reactor-years of operating experience have been accumulated to the end of 2010.
- A fast neutron reactor or simply a fast reactor is a category of nuclear reactor in which the fission chain reaction is sustained by fast neutrons.
- Such a reactor needs no neutron moderator, but must use fuel that is relatively rich in fissile material when compared to that required for a thermal reactor.
- Fuel consists of U-235, Pu-239 (products of fission with higher radiation) that produce more fast neutrons = waste from Gen II and III reactors is used



MUNI FSS


Generations of Nuclear Energy
Generation I
Early Prototypes
- Shippingport
- Dresden
- Magnox
Generation II
Commercial Power
- PWRs
- BWRs
- CANDU
Generation III
Advanced LWRs
- CANDU 6
- System 80+
- AP600
Generation III+
Evolutionary Designs
- ABWR
- ACR1000
- AP1000
- APWR
- EPR
- ESBWR
Generation IV
Revolutionary Designs
- Safe
- Sustainable
- Economical
- Proliferation Resistant and Physically Secure
1950
1960
1970
1980
1990
2000
2010
2020
2030
Gen I
Gen II
Gen III
Gen III+
Gen IV
http://www.gen-4.org/Technology/evolution.htm
5

MUNI
FSS

Back End

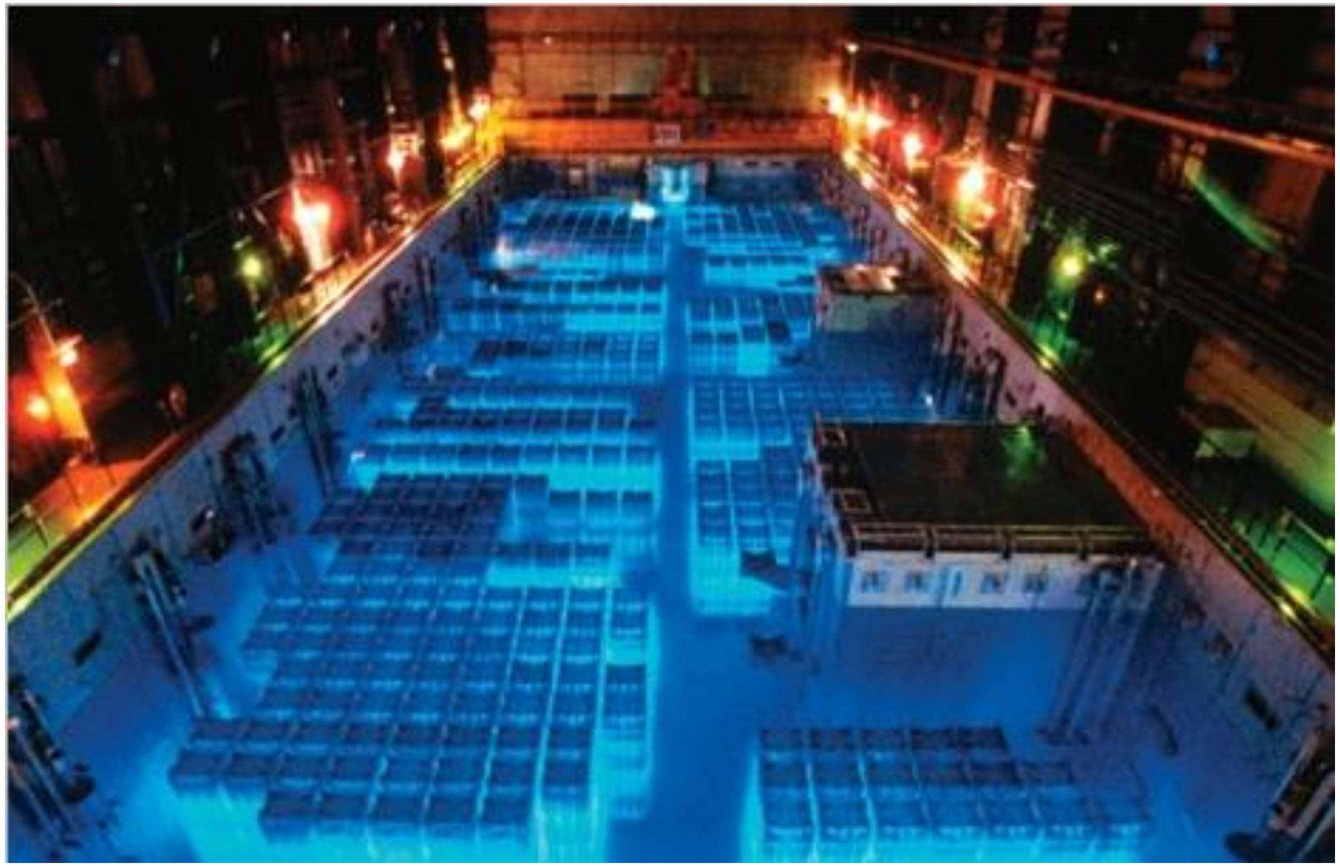
- In the **first phase**, the fuel is actively cooled in a pool next to the reactor. After five-ten years they are put into dry containers and passively cooled in interim storages.
- The dry interim storage facility is constructed to store fuel for about 80 years.

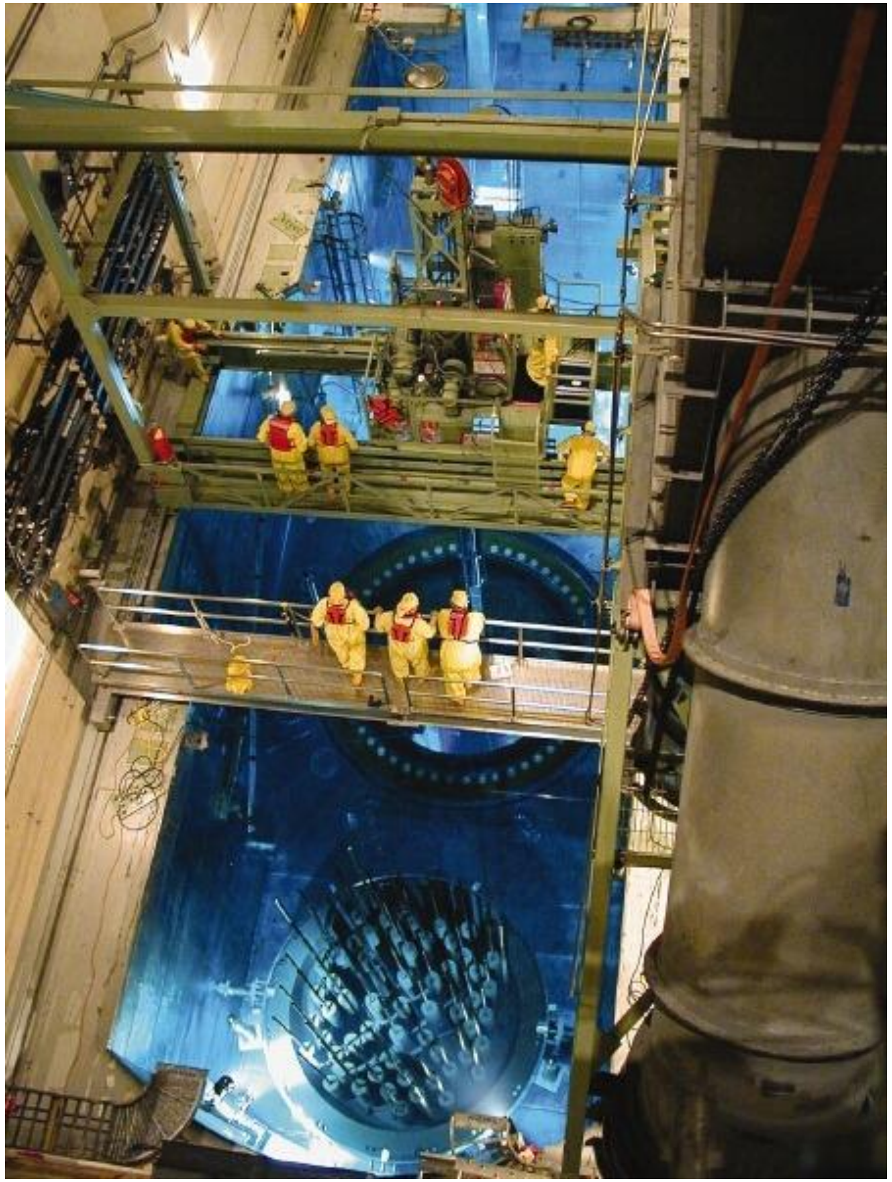
- The **second phase**, i.e. transport phase, is/will be provided by rail.

- The **third phase** is the underground geological repository

MUNI FSS

Back End





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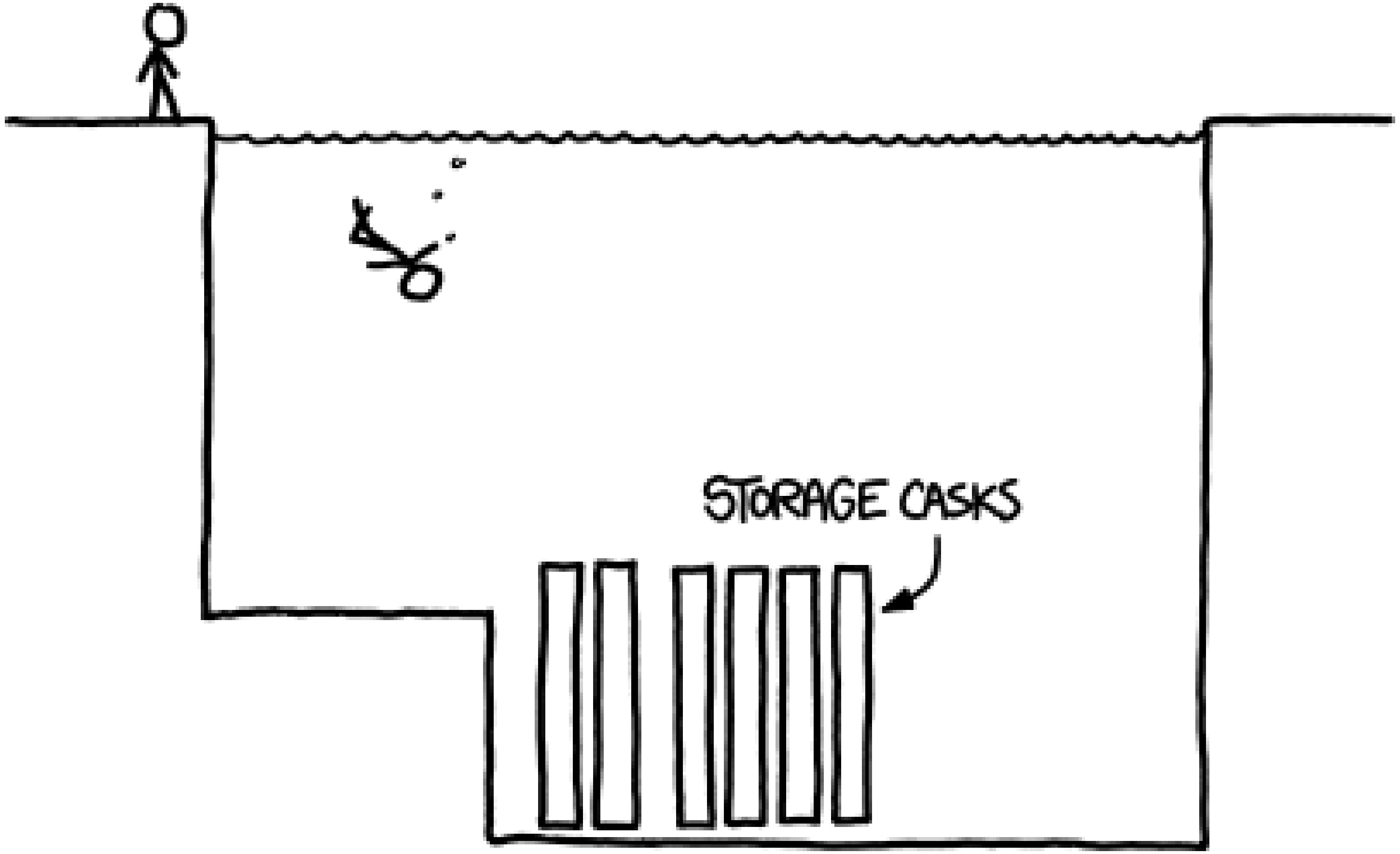
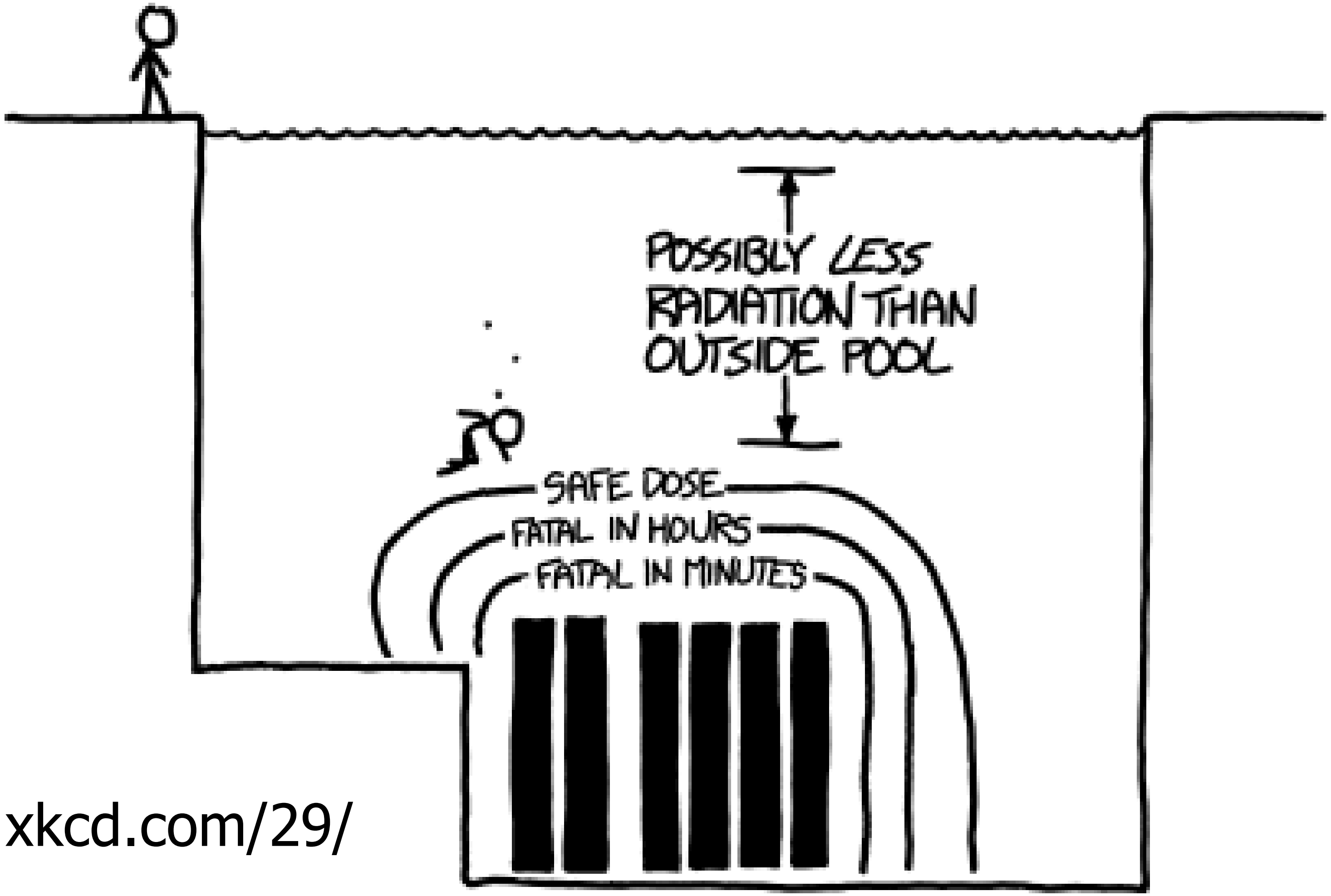
FSS

Is it safe to swim in the spent fuel?



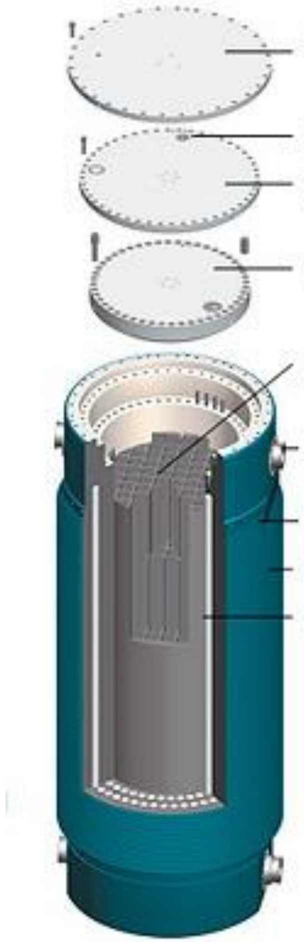
Is it safe to swim in the spent fuel?

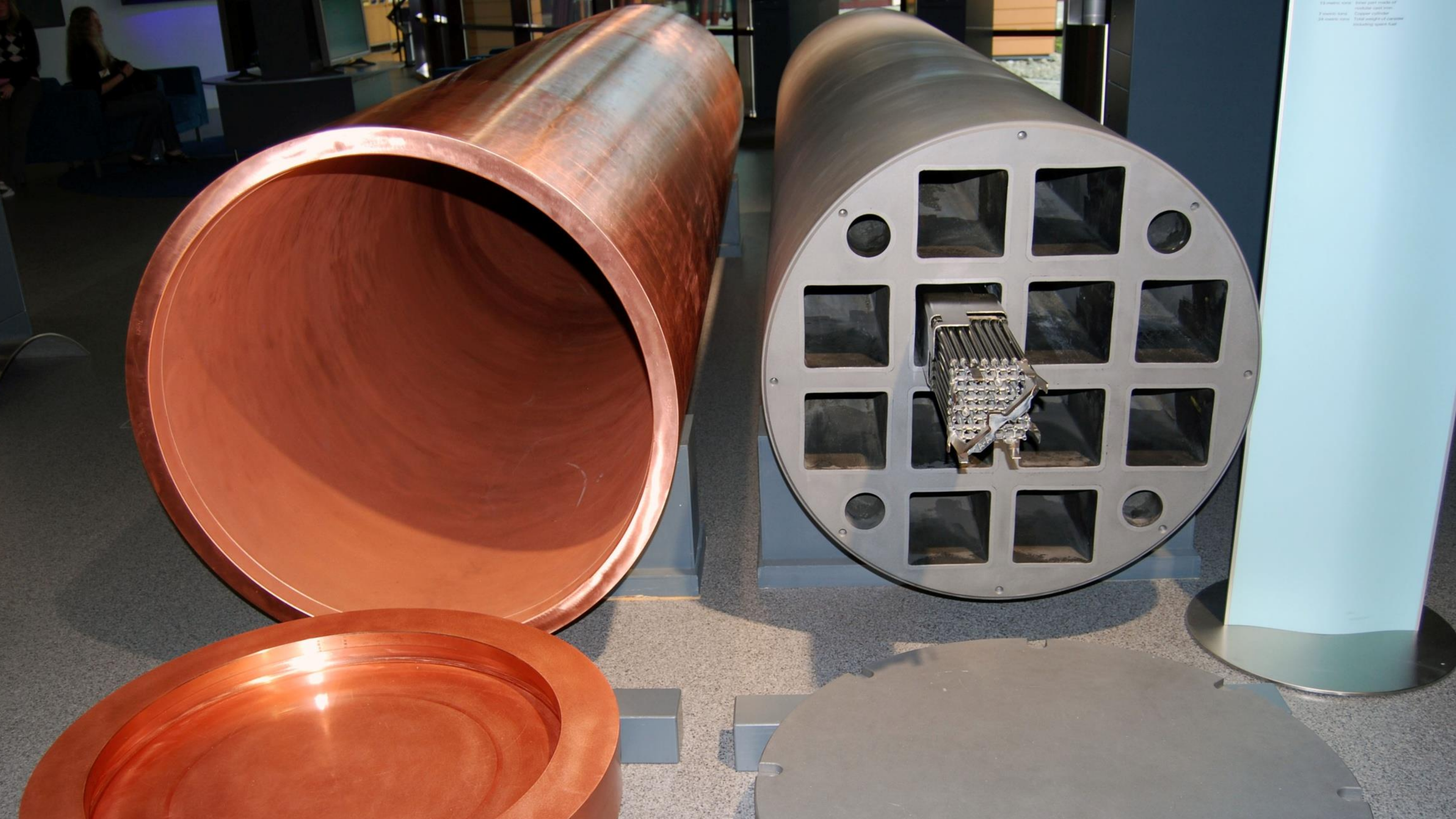


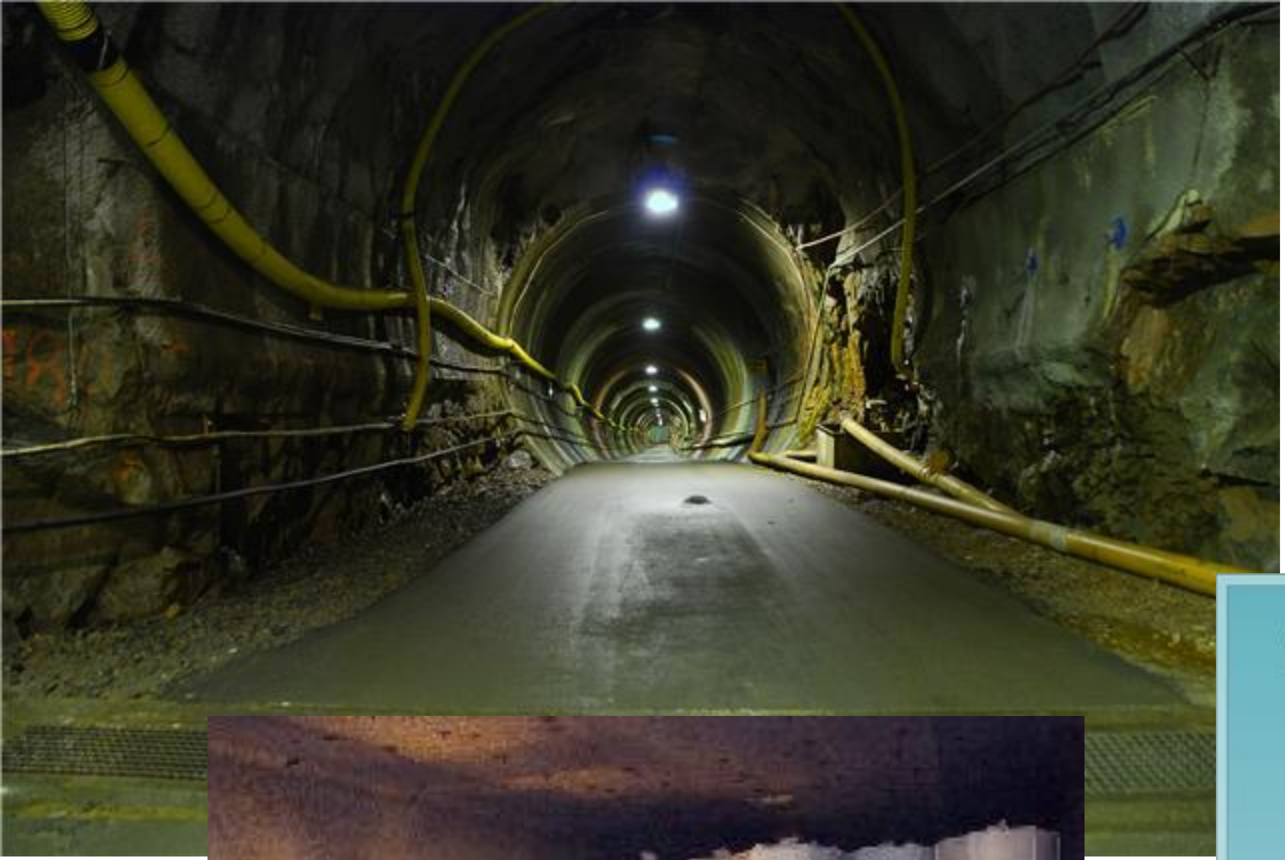
https://what-if.xkcd.com/29/

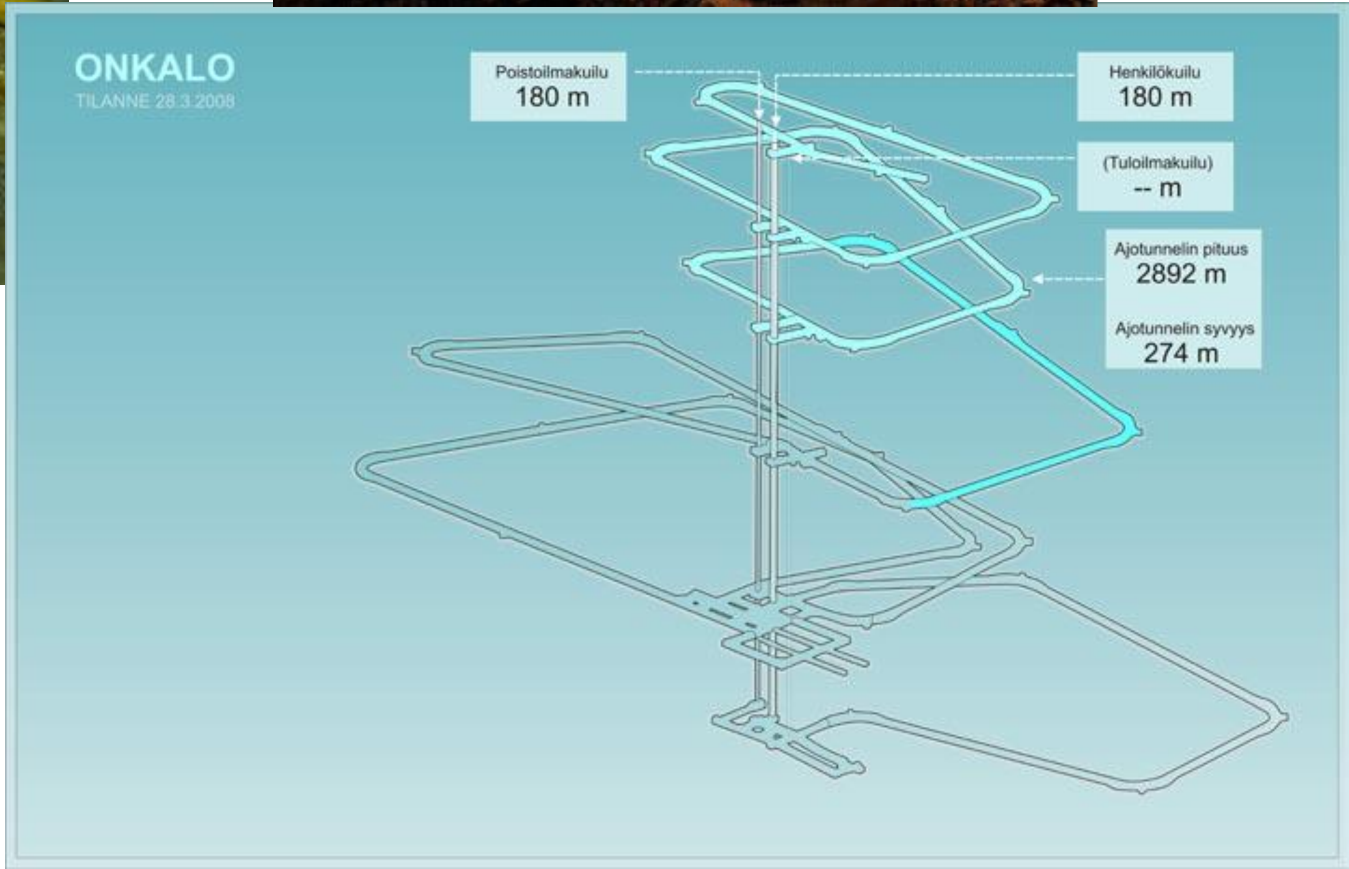
MUNI FSS

Back End


Top cover
Pressure monitor
Secondary lid
Primary lid
Fuel bin
Radial pin
Container casing
Radial ribbing
Deceleration rods






ONKALO
TILANNE 28.3.2008
Poistoilmakuilu
180 m
Henkilökuilu
180 m
(Tuloilmakuilu)
-- m
Ajotunnelin pituus
2892 m
Ajotunnelin syvyys
274 m

Back End

- Surface storage is needed for at least 40-50 years, after which the temperature and the radioactivity drops to a level that is acceptable for underground geological repository with limited or no access of cooling.
- Geological surveys and technical plans are fairly advanced in Sweden and Finland, which have a defined location. U.S. repository should be built at Yucca Mountain in Nevada, but the decision was postponed.
- **Variants of Storage**

  - Underground
  - Space
  - Long-term surface storage

Thank you for your attention.