I- Radiation damage in nuclear materials: progress and challenges

II- Small Modular Reactors, the future of nuclear energy?

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Joint ICTP-IAEA-MAMBA School on Materials Irradiation: from Basics to Applications

February 11 2025

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Outline

- Climate Change
- Nuclear energy
- Storage and Decommissioning
- Safety and Cost
- Situation today and other technologies
- Are solar and wind the solution?
- Future of nuclear. Small Modular Reactors?
- Conclusions

Nuclear Energy and Energy Transition Today

There are ~8000 GW of installed capacity in the world

400 GW are nuclear

3870 GW are renewable

In 2023, solar increased by 473 GW

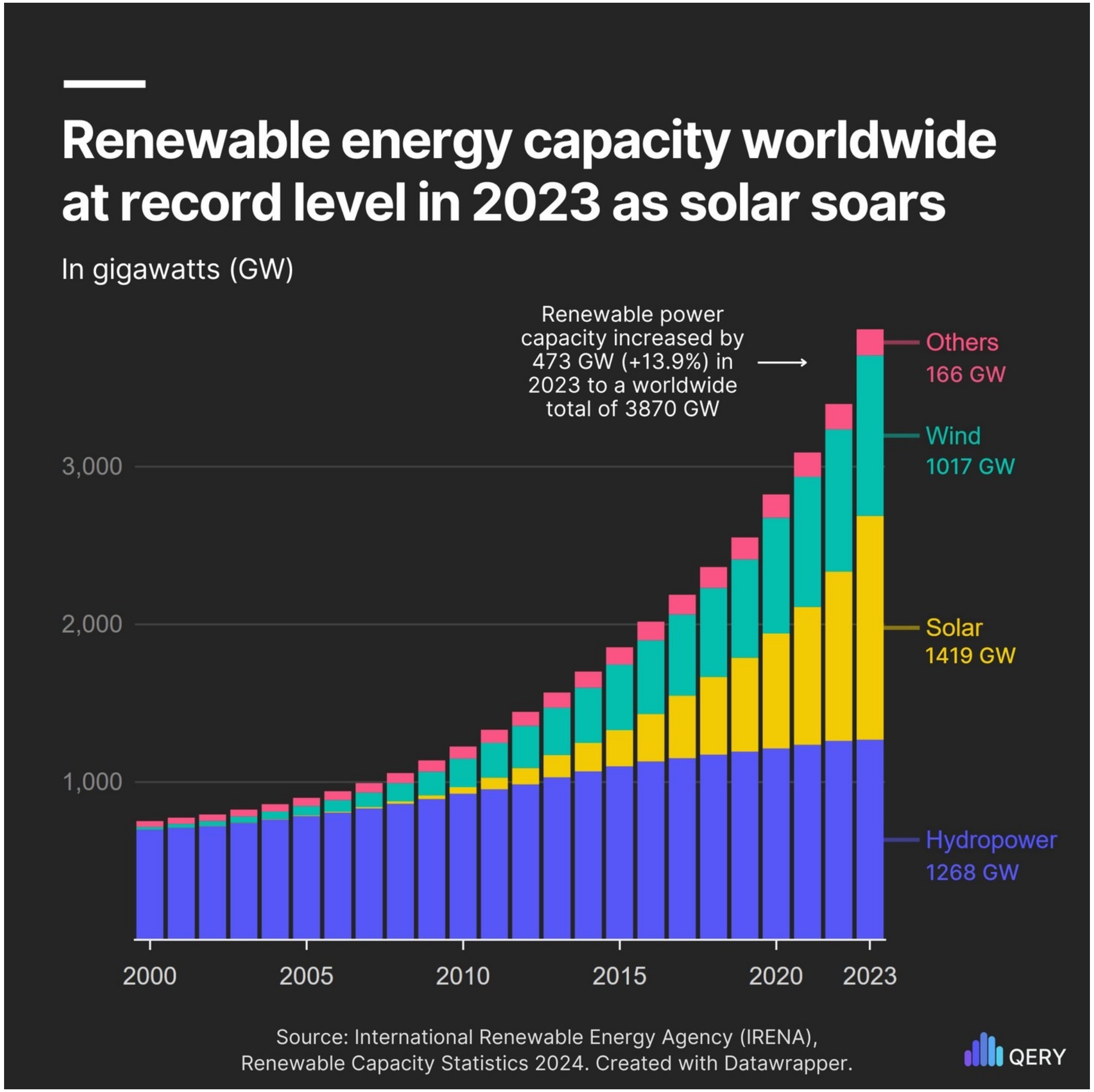
Reaching ~2000 GW in 2024

In 2023 nuclear connected 5 reactors and shut down 5

In 2024 +3 and -1

In 2023 Europe obtained 44% of its energy from renewable sources

In 2024, more than 50%!



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NEA at COP29: Focus on nuclear financing, new technologies and engagement with young generation

Published date: 25 November 2024 |

Climate change | COP | Financing | ...

Exaggerated optimism, expressed by groups of interest

During COP28 last year, more than 20 countries issued a Declaration to Triple Nuclear Energy by 2050, marking a historic moment for nuclear energy. At COP29, six more countries endorsed the declaration, bringing the total number of countries that formally support the tripling of nuclear capacity to 31.

The **World Nuclear Industry Status Report (WNISR)** is an independent, non-governmental publication

A Mycle Schneider Consulting Project
Paris, September 2024

The World Nuclear Industry
Status Report 2024

What does it say?

https://www.worldnuclearreport.org/IMG/pdf/wnisr2024-v2.pdf

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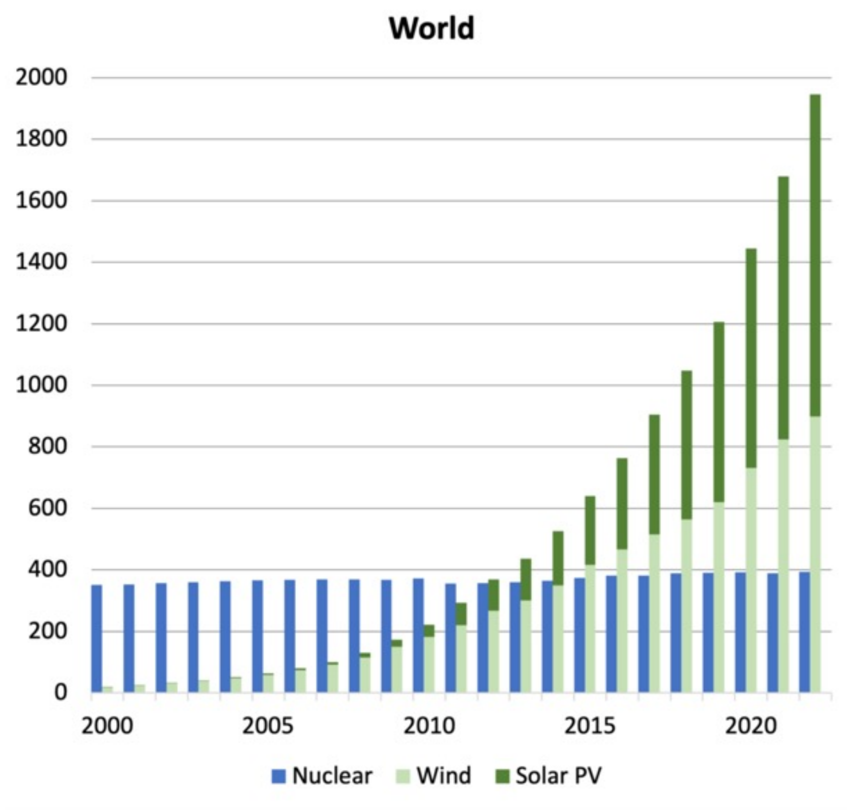
Main conclusions of that report

Overall Conclusion

Contrary to widespread perception, nuclear power remains irrelevant in the international market for electricity generating technologies. Solar plus storage might be the game changer for the adaptation of policy decisions to current industrial realities.



Tripling nuclear participation by 2050 (in 25 years) implies:

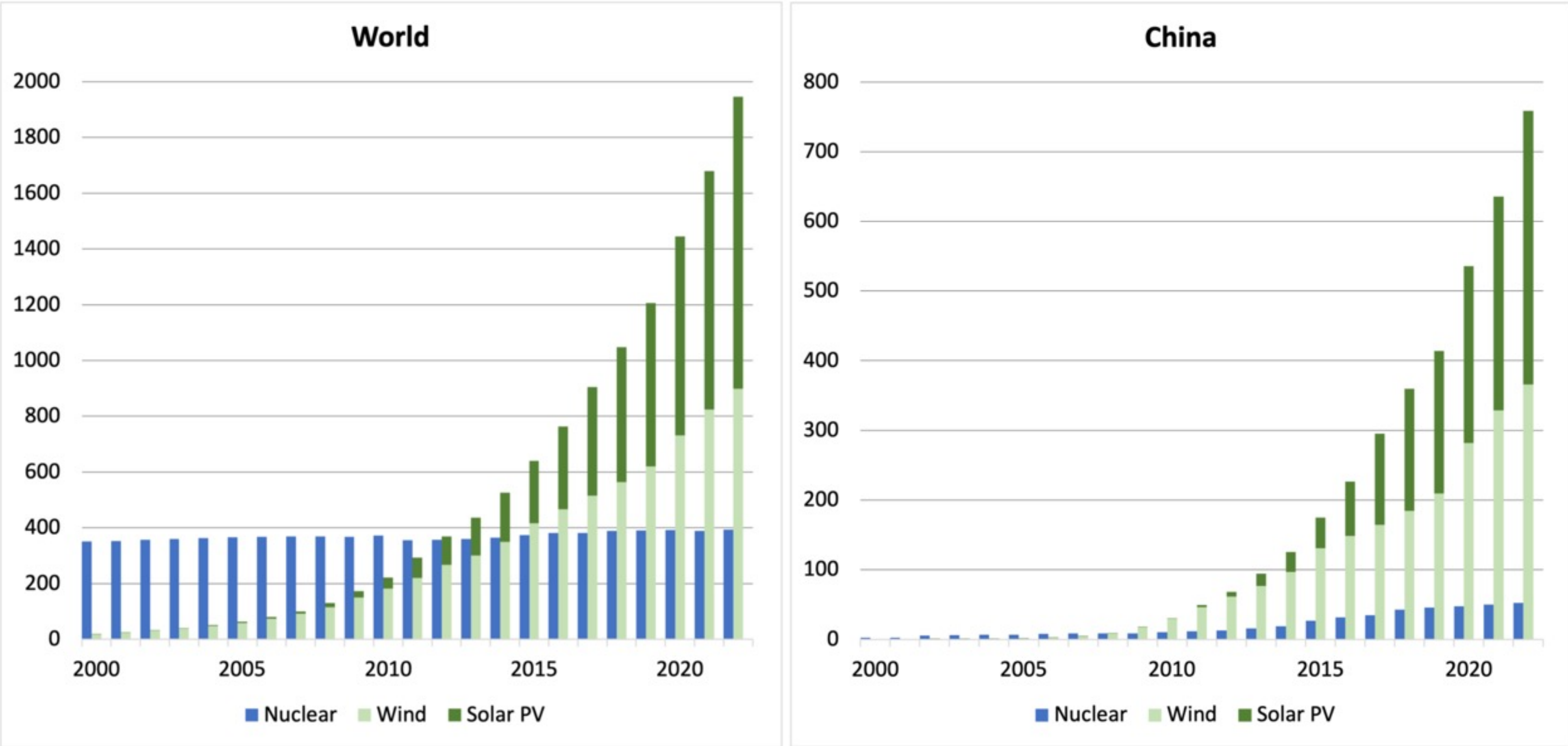
Construction of ~1100 new 1 GW reactors (or many more if they are SMRs)

This is ~ 1 new large reactor per week for 25 years. NO industry is capable of such production!

https://www.worldnuclearreport.org/IMG/pdf/wnisr2024-v2.pdf

Evolution of different technologies

Capacity in GW



Installed capacity (in gigawatt) of nuclear energy, wind, and solar PV in the World and China for the period 2000-2022. World nuclear installed capacity includes reactors in long-term outage. (Sources: Nuclear, WNISR2023 with IAEA-PRIS; wind and solar PV, IRENA. Compilation: WNISR2023. Visualization: François Diaz-

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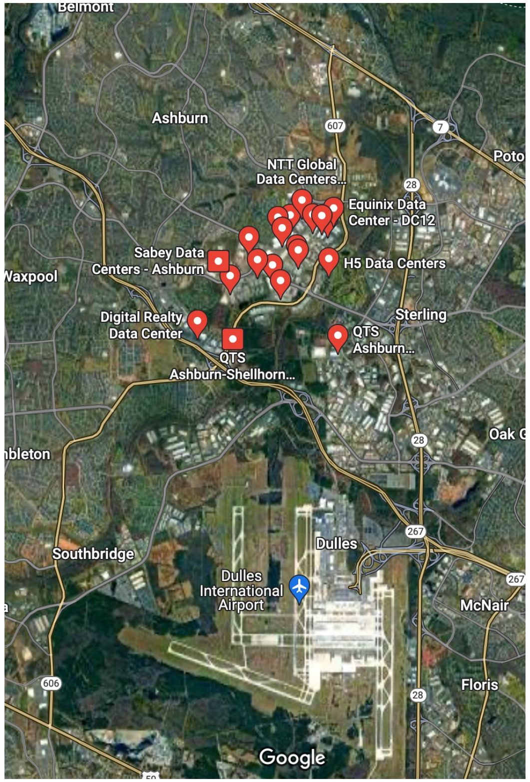
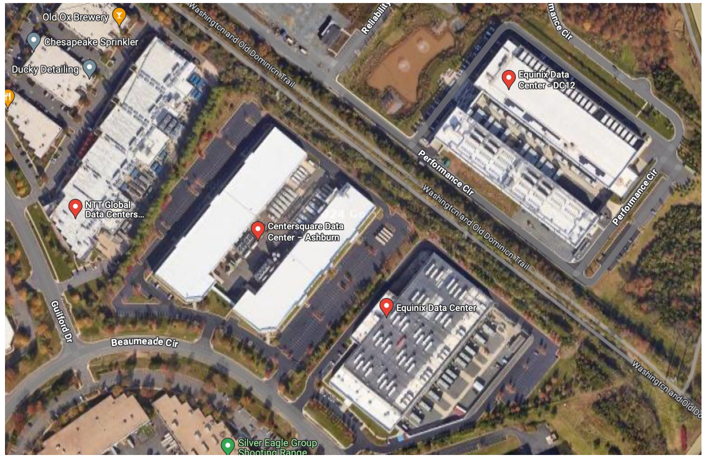
AI's insatiable energy demand may go nuclear

Ashburn, Virginia, the “Data Center Capital of the World,” with estimates suggesting that up to 70% of global internet traffic passes through data centers in this region.

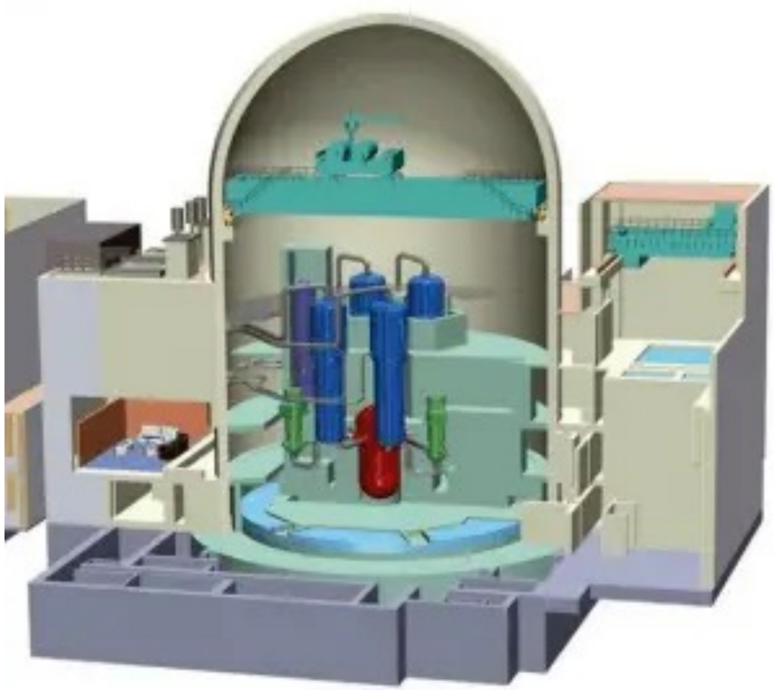


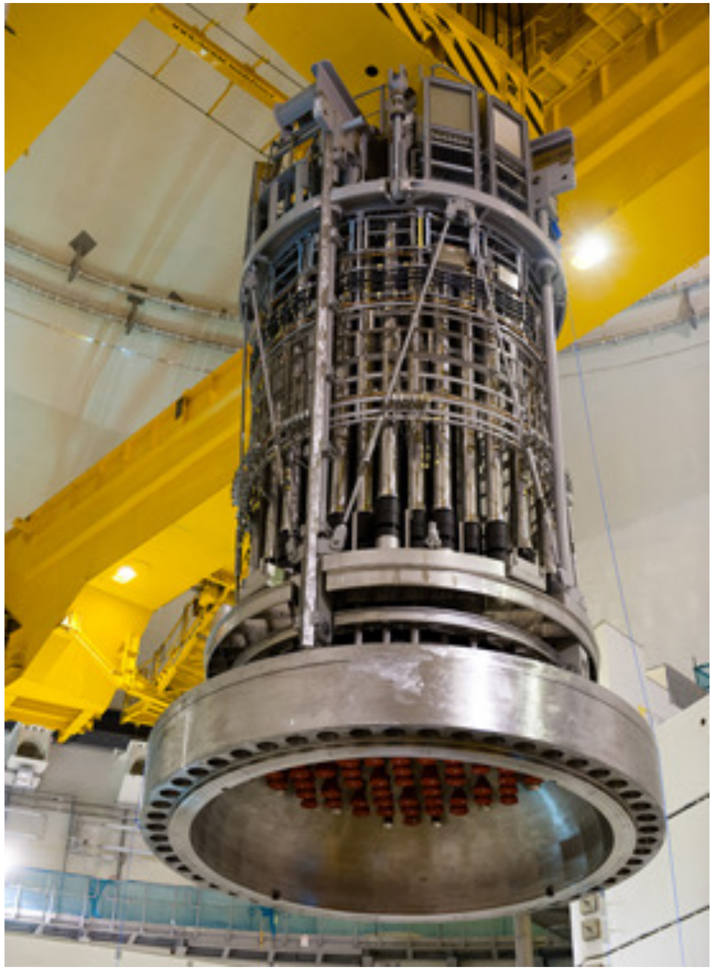


The Energy Information Administration said Aug. 19, 2024, that it expects power plant developers and owners will add 62.8 GW this year in the United States, mainly through solar energy and battery storage facilities.

Strategies to increase nuclear power

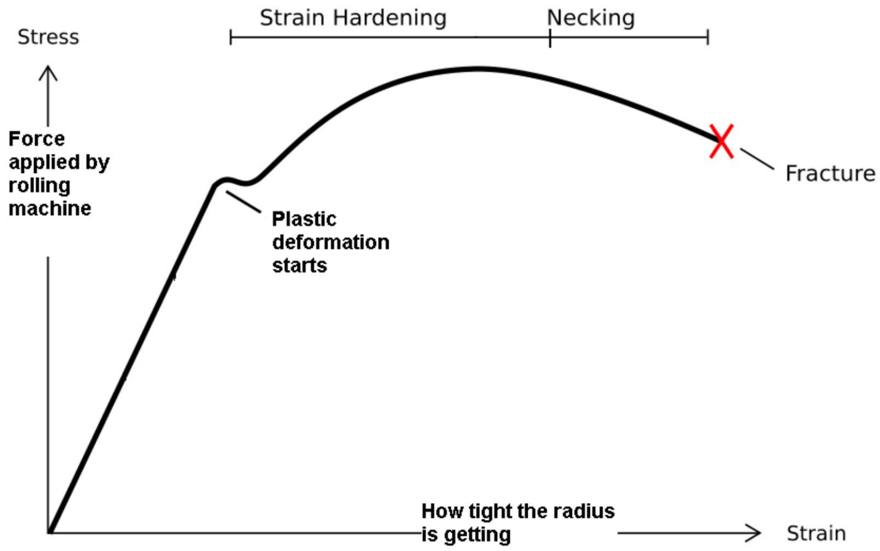
- Extend operational lifetime (from 40y to 80-100y)
  - Critical to this end are the integrity of the pressure vessel RPV, the steam generators (radiation damage, corrosion), and other components
- Re-start closed facilities (Palisades, Three Mille Island, USA)
- Finish those stopped (Rumania, USA, Brazil)
- Small Modular Reactors

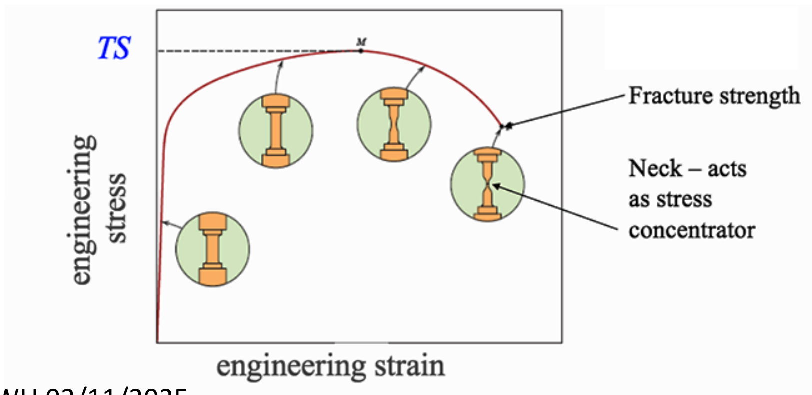


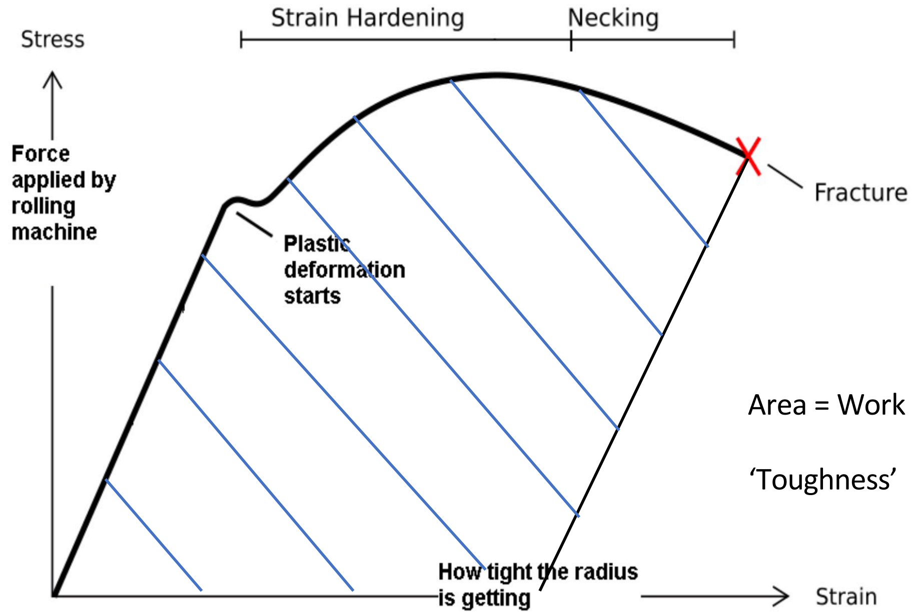


Basics of metallurgy

Metals deform plastically







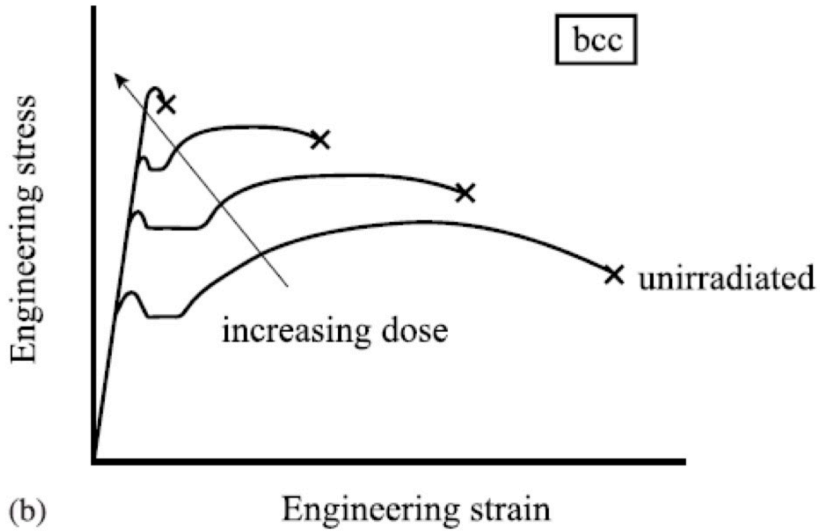
Area = Work

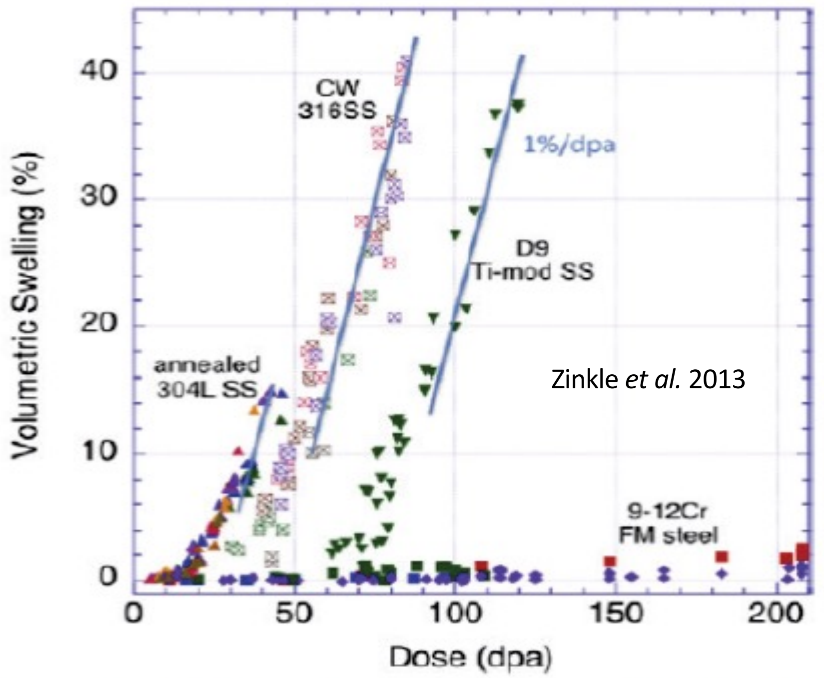
'Toughness'

A. Caro GWU 02/11/2025

Basics of radiation damage

irradiated metals are harder and more brittle

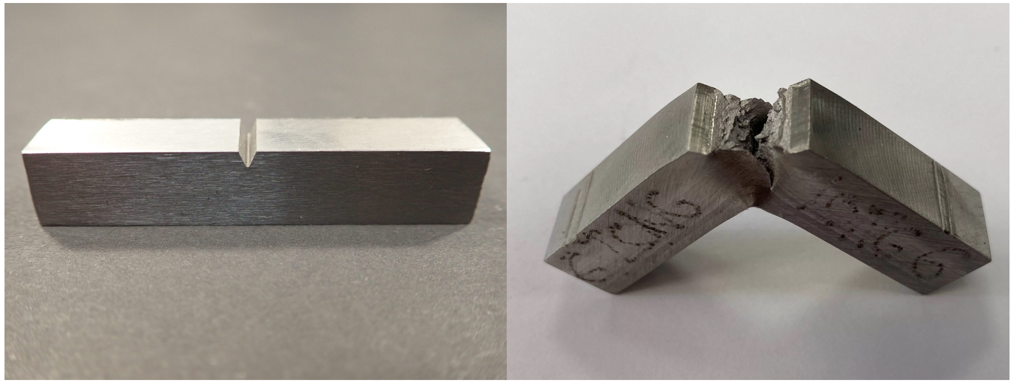


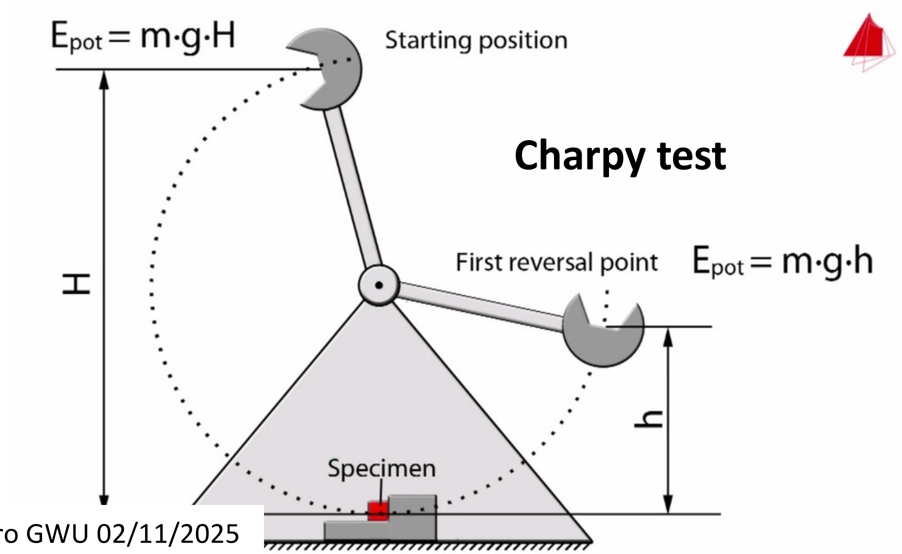


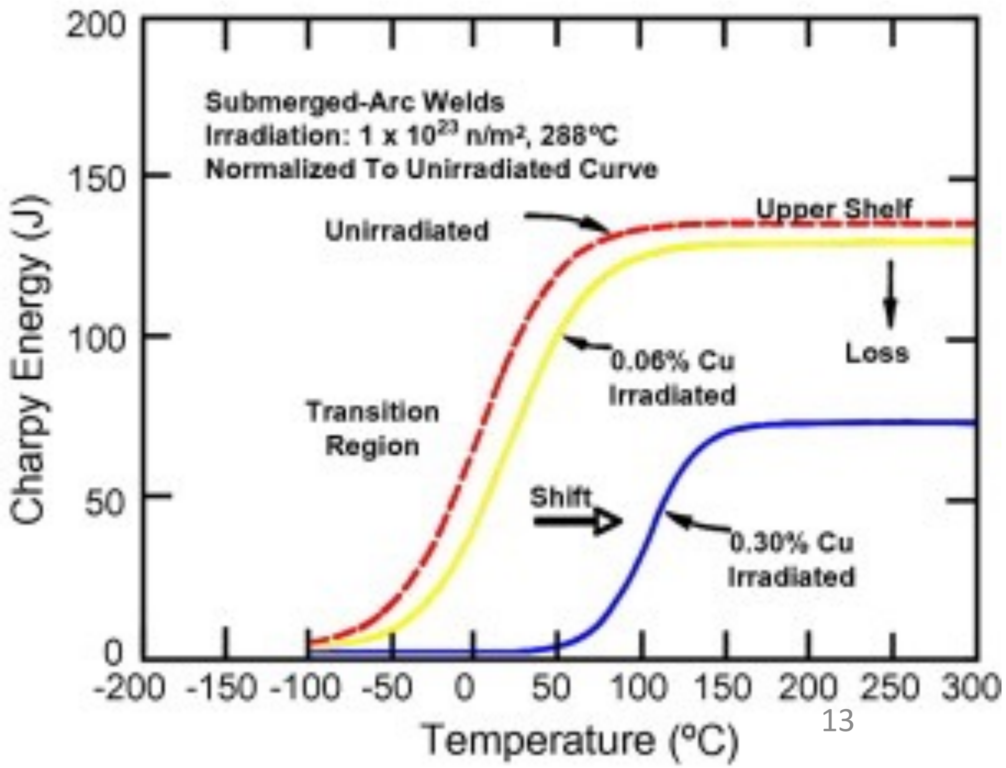
Many other effects appear:

Swelling, Growth, Radiation Induced Segregation RIS, Radiation Induced Precipitation RIP, Radiation Induced Stress Corrosion Cracking RISCC, …

Effects of irradiation on Ductile-to-Brittle Transition Temperature



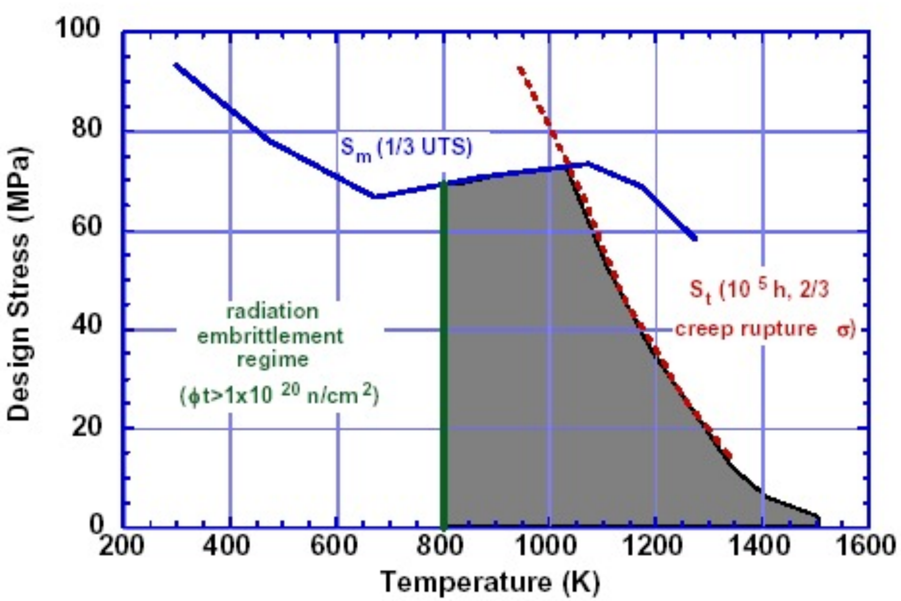


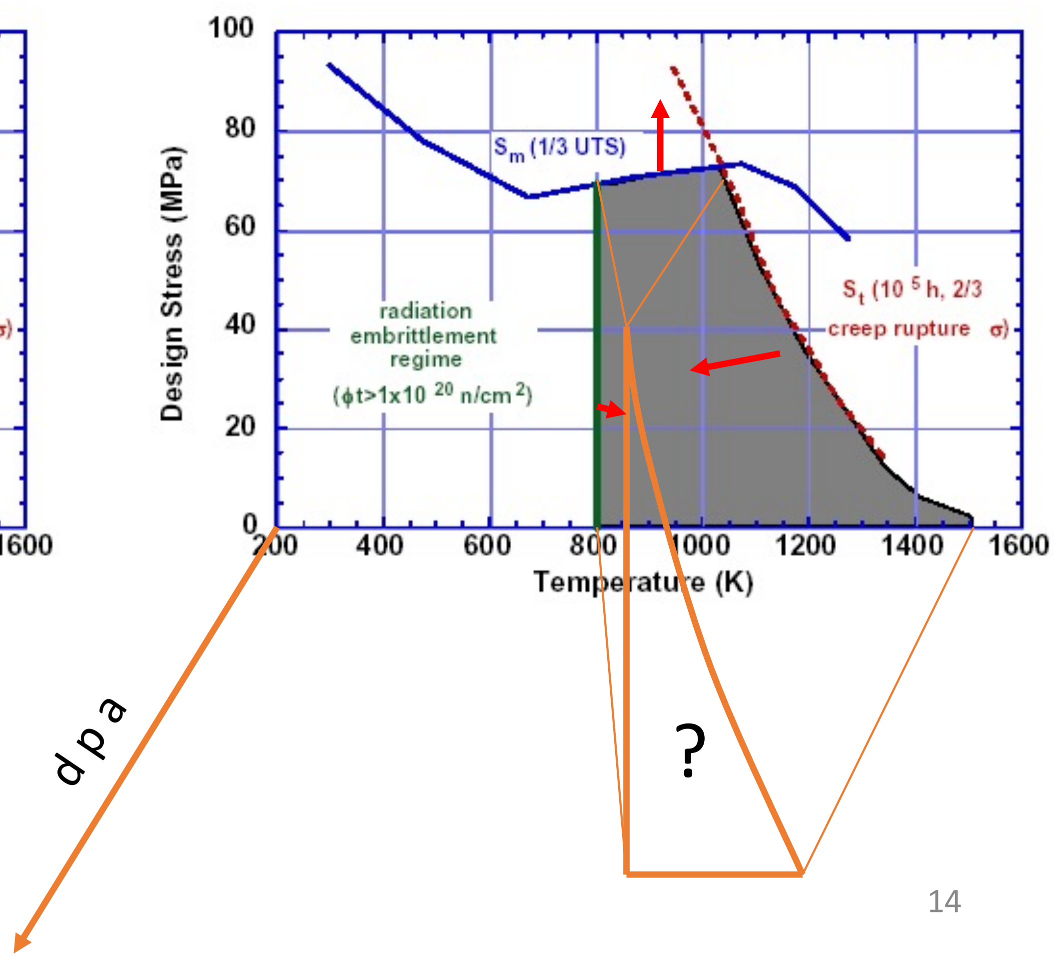


Material properties define a design window for applications

Example: Stress-temperature design window (From S. Zinkle)

- Radiation hardening increases the Ultimate Tensile Stress, UTS
- Radiation embrittlement increases the Ductile-to-Brittle transition Temperature, ΔDBTT
- Radiation damage decreases creep strength





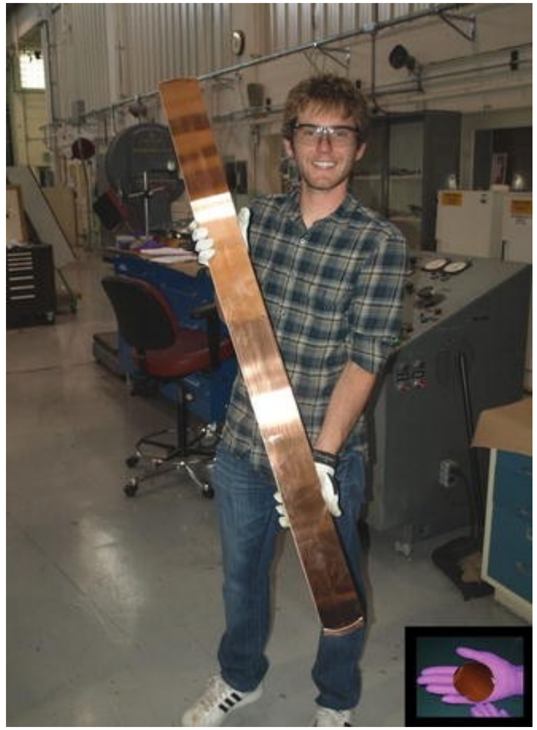
The design window evolves with dose

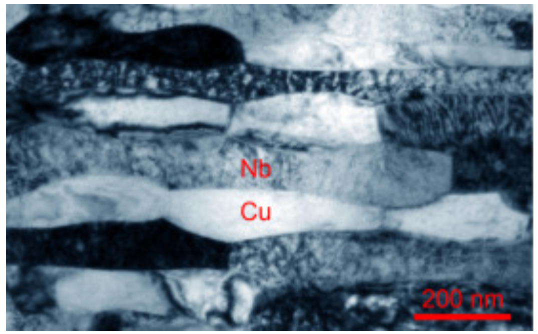
50 years of research in radiation damage

Ferritic steel (1960-1970)
EOL at ~ 0.01 dpa

4 orders of magnitude improvement!

Cu-Nb nanolaminate (2015)
EOL at ~ 200 dpa



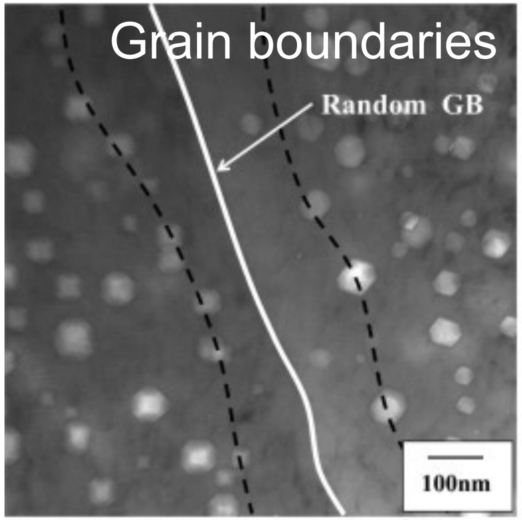


From LANL

Interfaces in materials can act as very efficient sinks for point defects

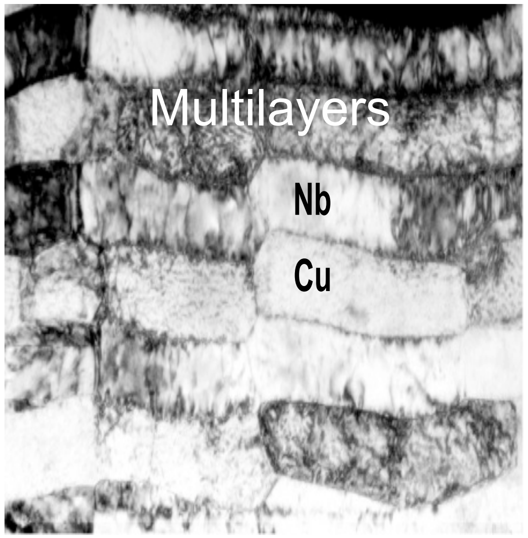
Internal interfaces are the secret to radiation resistance

They help I-V recombination

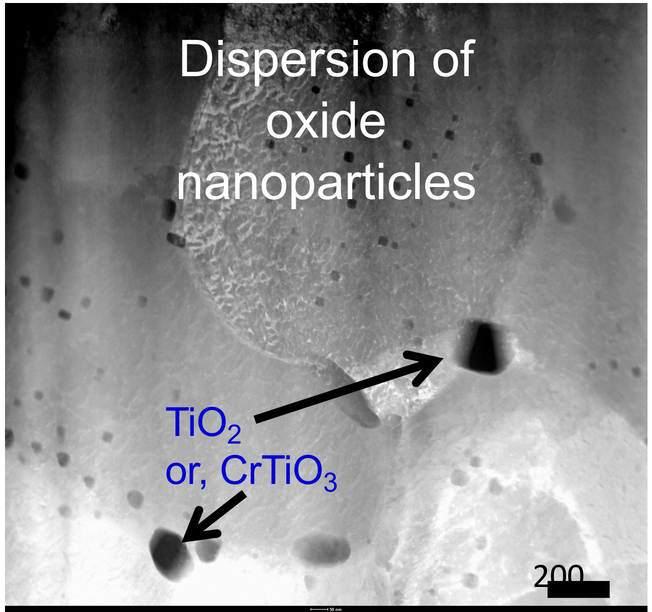


(a)

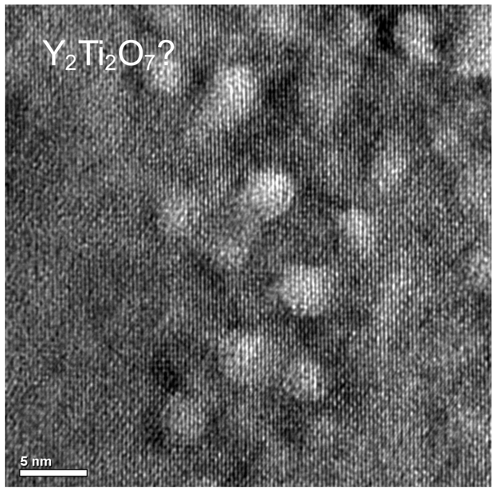
Void distributions near random GBs in the Fe–15Cr–15Ni steel neutron-irradiated at 749 K to 18 dpa



Sputter-deposited 75-nm Cu/75-nm Nb multilayer, vacuum annealed at 800°C for 1 hour.

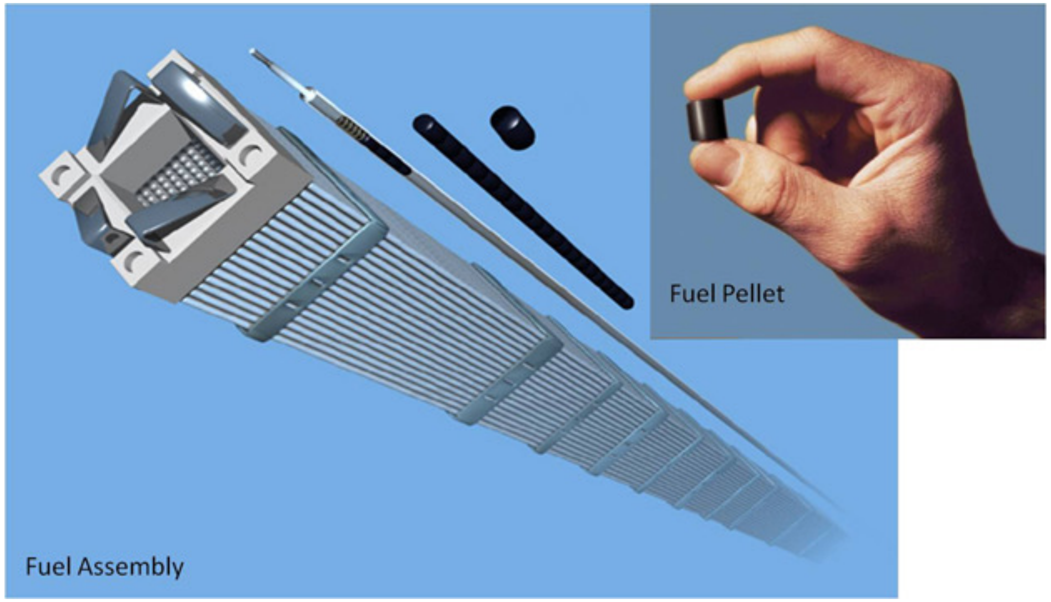


U14YWT
Ball milled and HIP-ed
Fe-14%Cr-3%W-0.4%Ti-0.3%Y_2O_3



D. Bhattacharyya, S.A. Maloy, M. Nastasi, G.R. Odette, A. Misra, et al., Phil. Mag., (2011)

Nuclear fuel



Different external shapes

Common internal structure: UO_2 ceramic pellets and metallic cladding

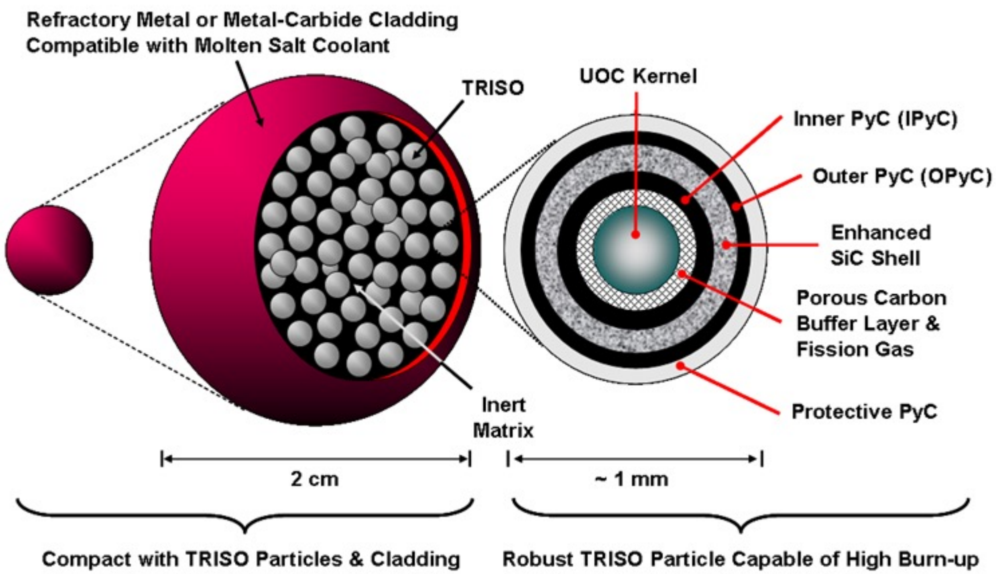
Life-time in the reactor: about 1-3 years

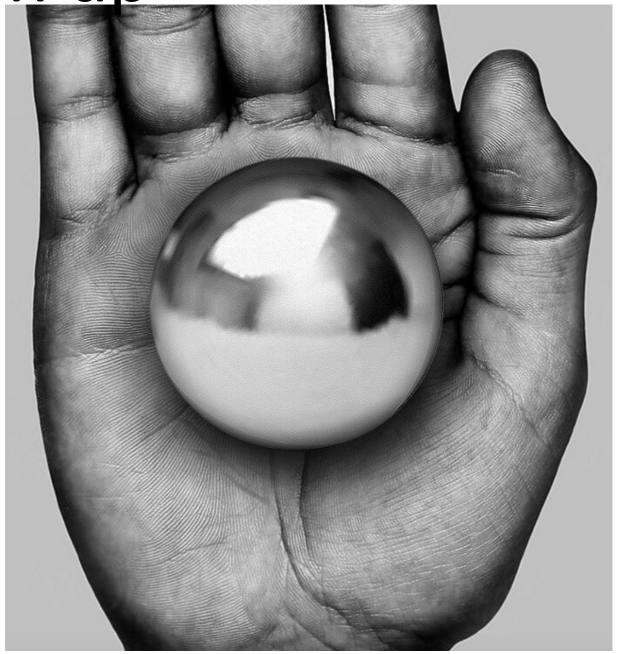

Westinghouse
SERVING OUR
CUSTOMER NEEDS

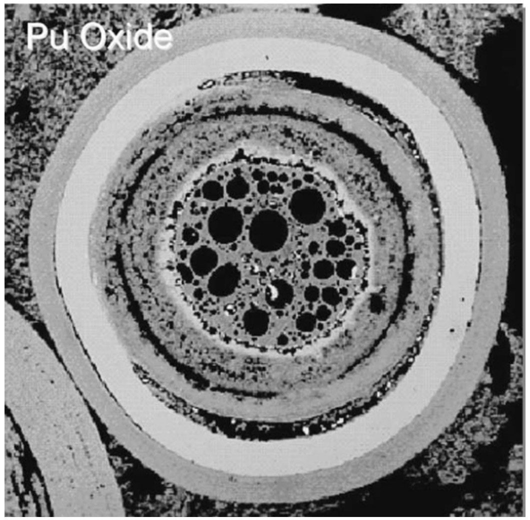

AREVA

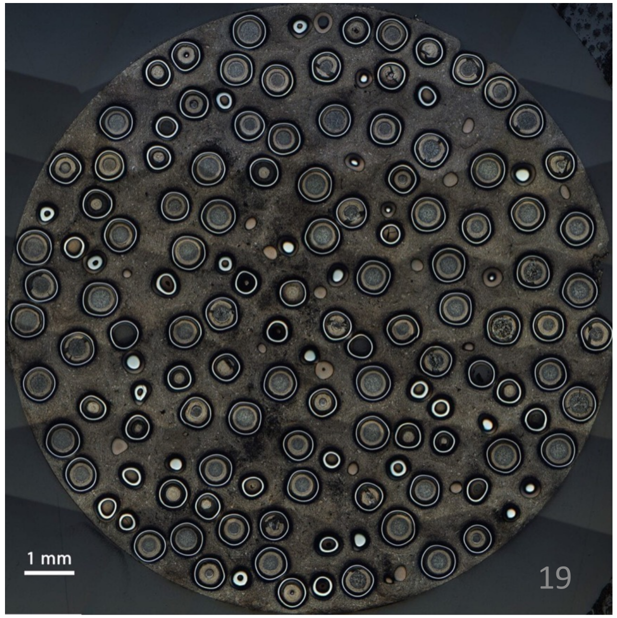
Other forms of nuclear fuel:

TRISO, high T, high burn up



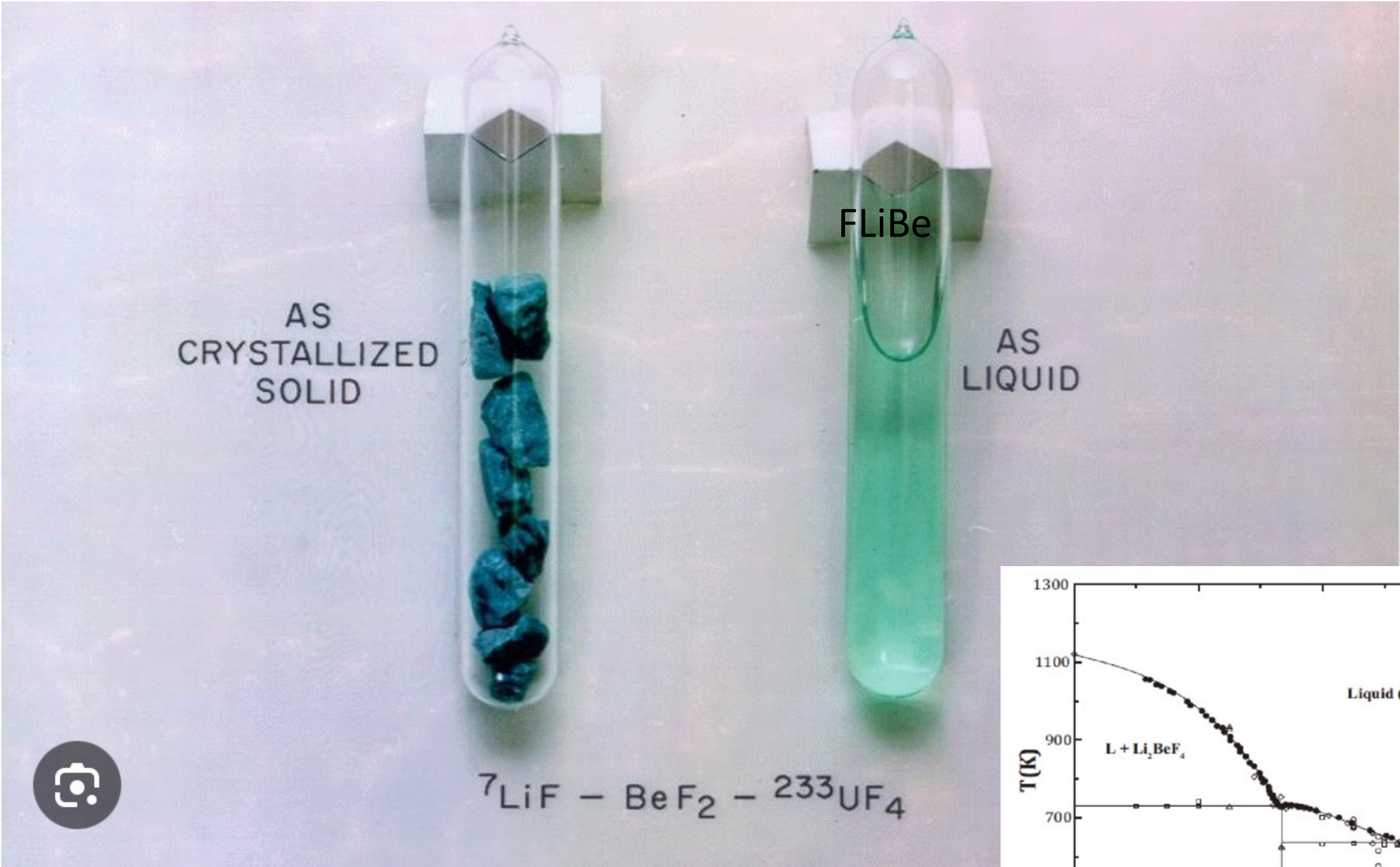


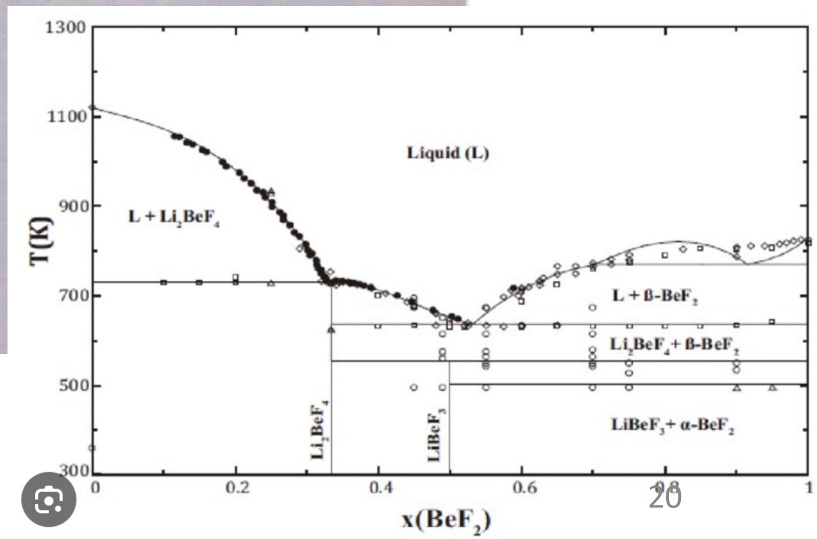




Molten Salt Fuel

Lithium Fluoride-Beryllium Fluoride



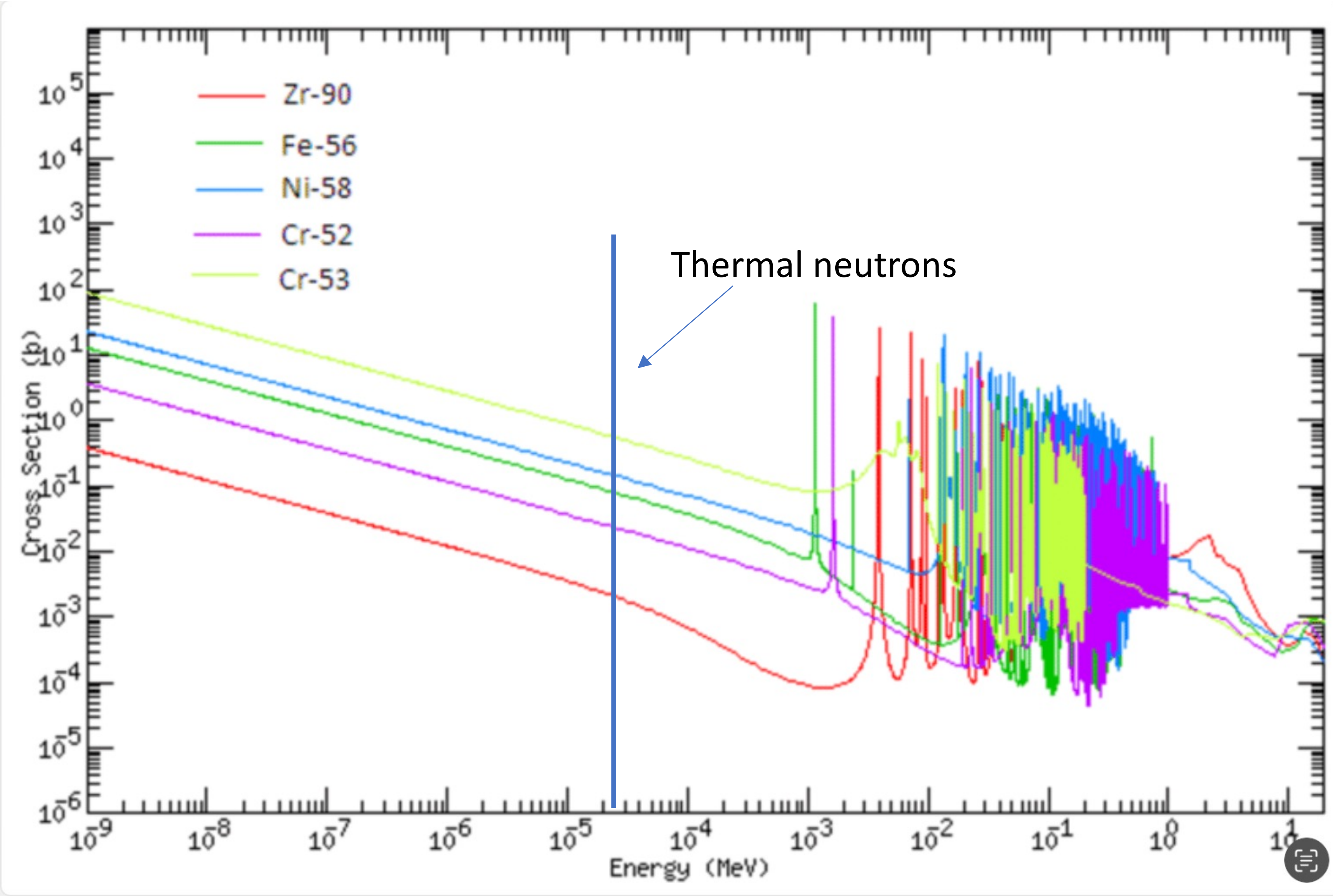


Accident Tolerant Fuel

Fukishima accident:
Loss of cooling led to the formation of ZrO_2 from the fuel cladding and steam, liberating highly explosive H_2 gas

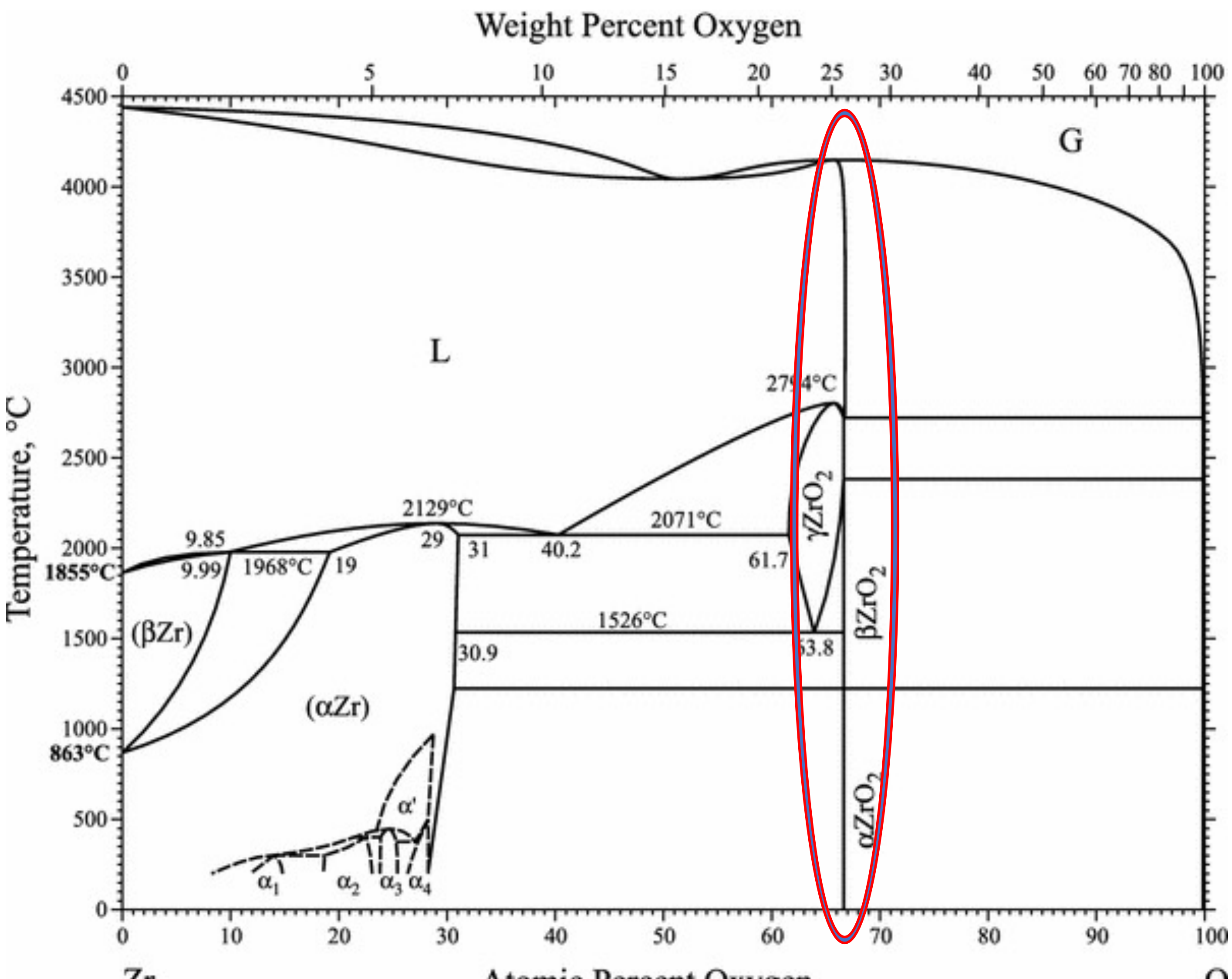
Cladding is generally made of Zirconium alloys

because of its low neutron capture cross sections



However, Zr is eager of O

$$Zr + 2\,H_2O \rightarrow ZrO_2 + 2\,H_2$$



Zirconia (ZrO_2) is very hard and is used for jewelry

What's the best ATF choice?

- Near-term ATF (now in Switzerland!): **Doped UO_2** (with small amounts of Cr_2O_3 or Al_2O_3) for higher thermal conductivity+ **Cr-coated Zr** for retarded oxidation

- Mid-term ATF (~2030s): U_3Si_2 + FeCrAl (better performance and accident tolerance)

- Long-term ATF (Gen IV & beyond): UN or UC + SiC/SiC (ultimate accident tolerance).

Framatome's PROtect Accident Tolerant Fuel reaches New Operational Milestone at Gösgen Nuclear Power Plant in Switzerland

November 14, 2024 | 1 min | Partager

Topic: Fuel

Framatome's PROtect Enhanced Accident Tolerant Fuel (E-ATF) technology has reached a significant operational milestone at the Gösgen Nuclear Power Plant in Switzerland. With this achievement, Framatome's E-ATF chromium-coated M5^{Framatome} cladding becomes the world's first ATF technology to operate with full length fuel rods above 60 GWd/tU, supporting licensing efforts and demonstrating its readiness for commercial use.

Strategies to increase nuclear power

- Extend operational lifetime (from 40y to 80-100y)
  - Critical to this end is the integrity of the pressure vessel RPV, and steam generators (radiation damage, corrosion)
- Re-start closed facilities (Palisades, Three Mille Island, USA)
- Finish those stopped (Rumania, USA, Brazil)
- Small Modular Reactors

Palisades (USA): from closure (2022) to restart …

Holtec specializes on decommissioning

HOLTEC INTERNATIONAL

Holtec Highlights

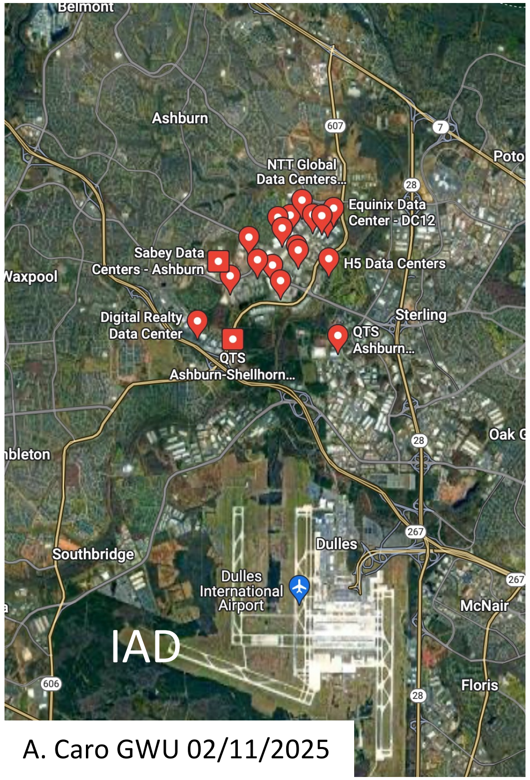
HH #39.17 | September 30, 2024 — Page 1 of 2

Holtec Closes $1.52B DOE Loan to Restart Palisades, Support Revitalization of Domestic Nuclear Industry

Three Mille Island-1 (USA): from closure (2019) to restart …

September 20, 2024

Microsoft will re-open Three Mille Island-1,
Site of the partial meltdown of TMI-2 in 1979



A. Caro GWU 02/11/2025

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Romania to finish Cernavoda 3 and 4

Sept 2023

Romania covers ~ $2b

Canada provides the nuclear island, $2b

USA provides the Balance Of Plant, $3b

Estimated $7b

U.S. bill to return to a leadership position in nuclear energy:

The International Nuclear Energy Act aims to develop a strategy to counteract the growing influence of Russia and China in the global nuclear export market

This bill would allow U.S. financial institutions to fund nuclear projects overseas

V. C. Summer NC USA

world nuclear news

Home · Energy & Environment · New Nuclear · Regulation & Safety · Nuclear Policies · Corporate · Uraniu

Thursday, 23 January 2025

Santee Cooper is seeking proposals to acquire and finish the VC Summer nuclear power plant in South Carolina in the USA, where construction of two AP1000 units was abandoned in 2017, but has no plans to operate the units itself.

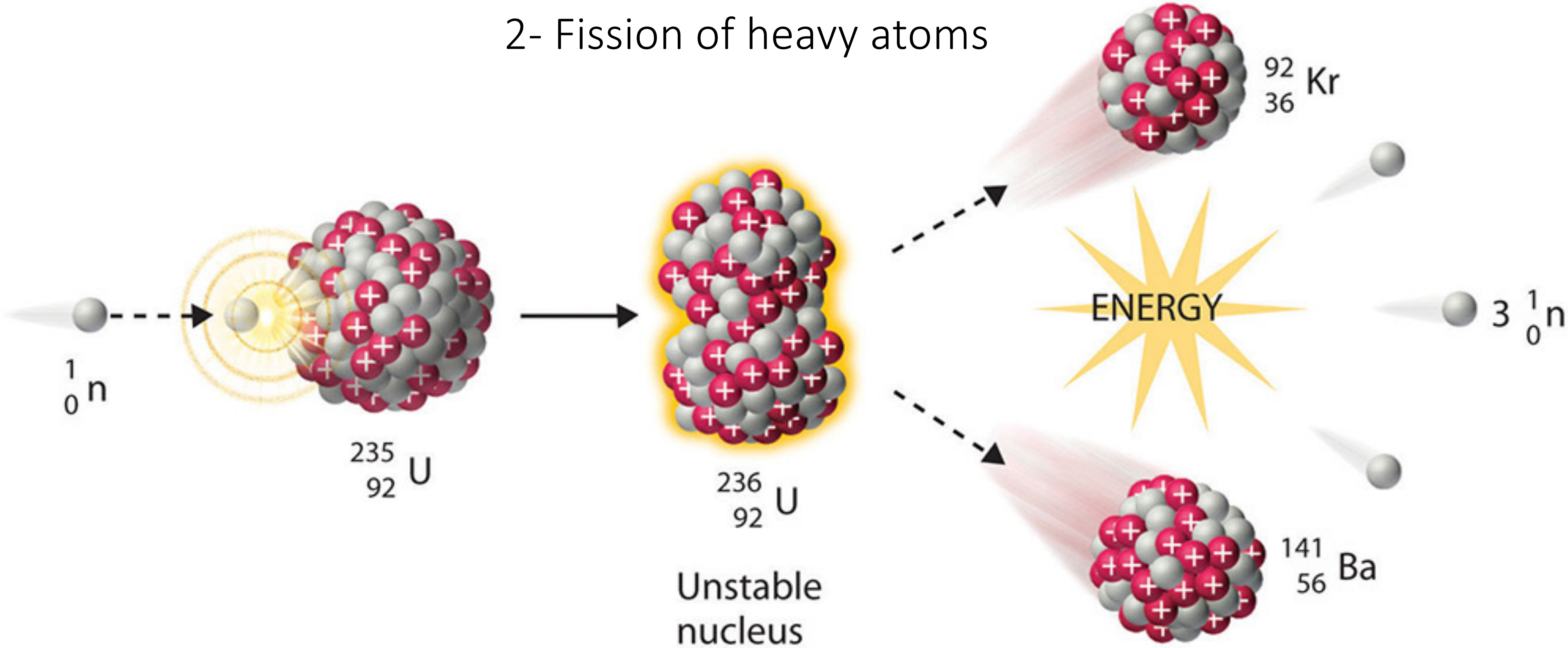
Summer unit 2's final containment ring was lifted into place in June 2017 (Image: SCE&G)

Social License

Nature gives us two pathways

to exploit the mass–energy equivalence

2- Fission of heavy atoms

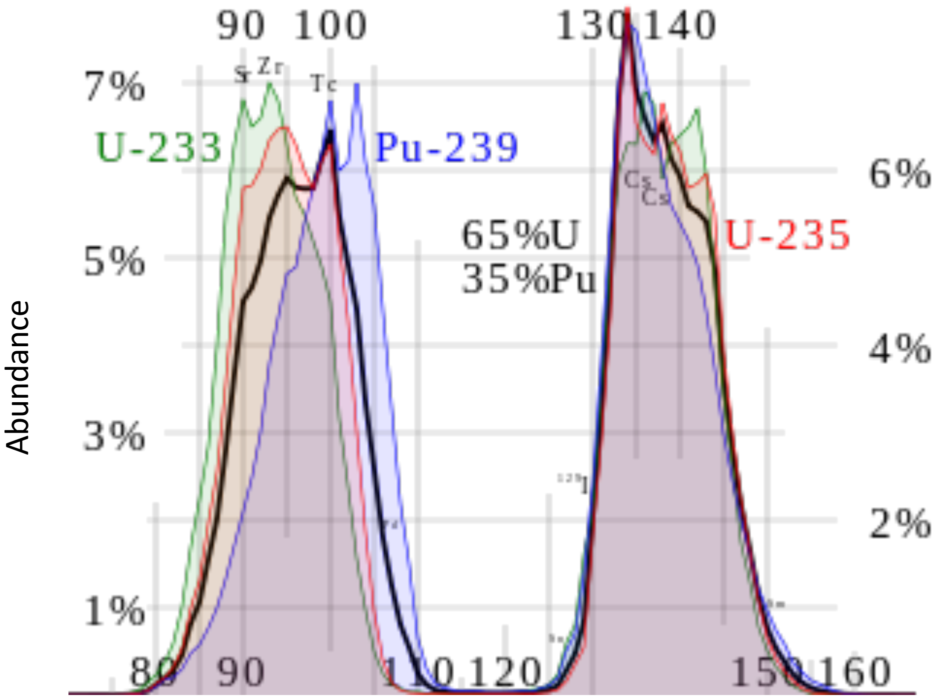


Initial mass greater than final

Fission, via nuclear reactors

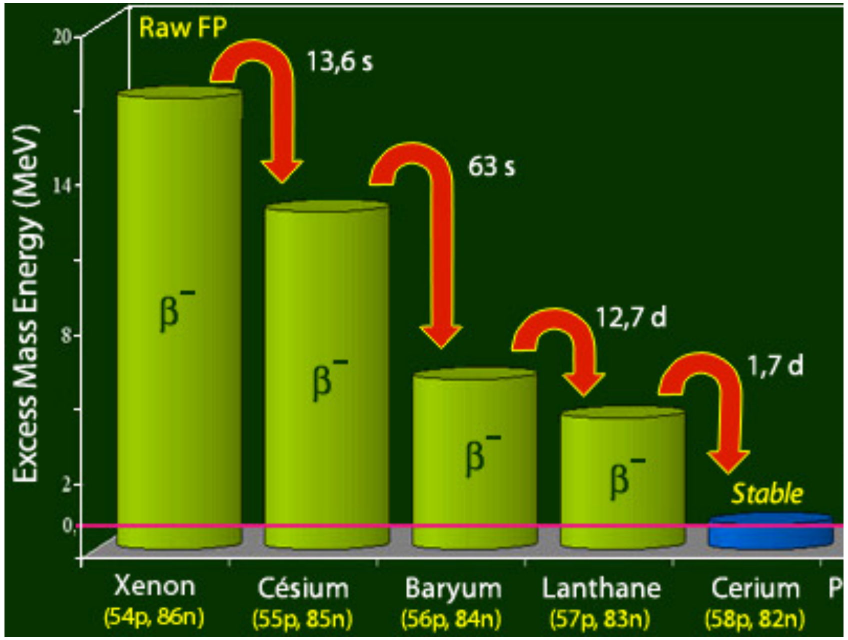
has some drawbacks

Many fission products are unstable → radioactive



Mass of fission products

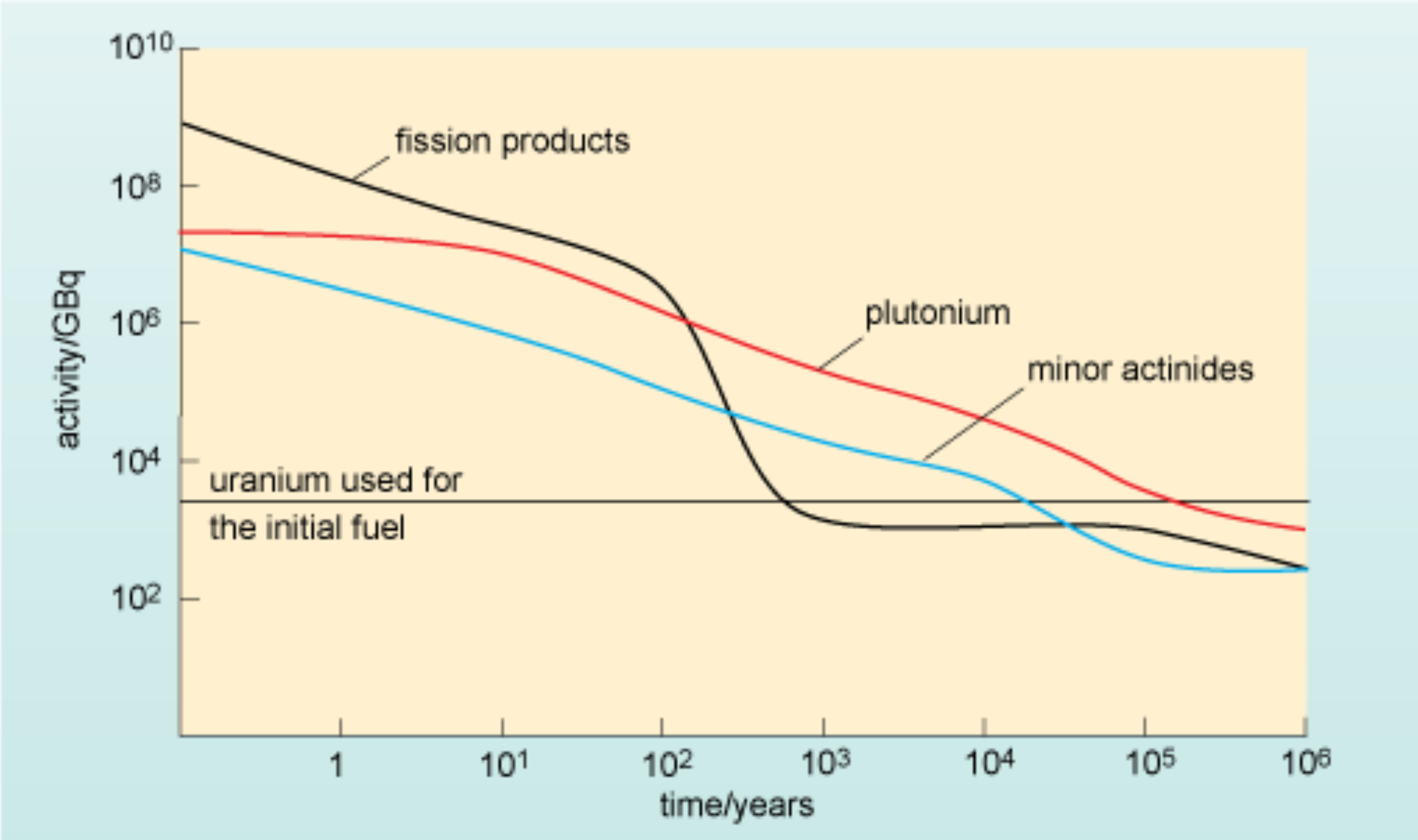
Example: Xenon



Xenon decays into Cerium in a cascade process

The mass dispersion of the fission products means that
many elements and isotopes are created with unstable combinations of protons and neutrons

Spent nuclear fuel (SNF) management



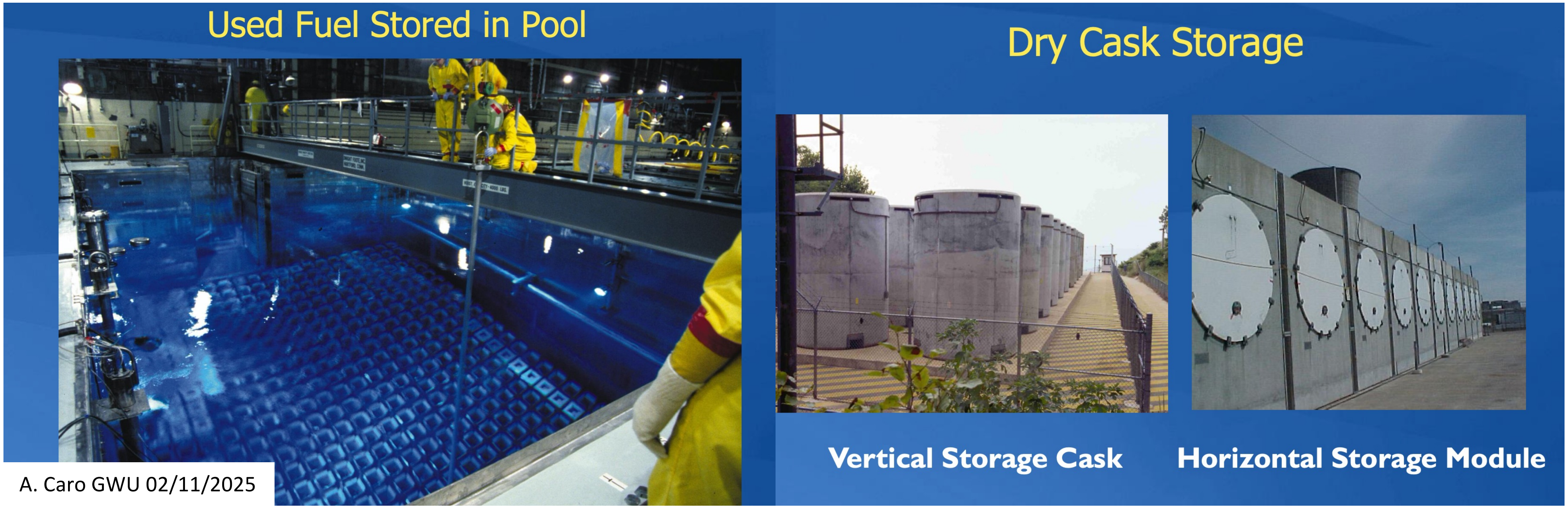
Worth mentioning: No country except Finland has permanent deep geological repository for SNF or high-level waste

The “once through” approach in USA

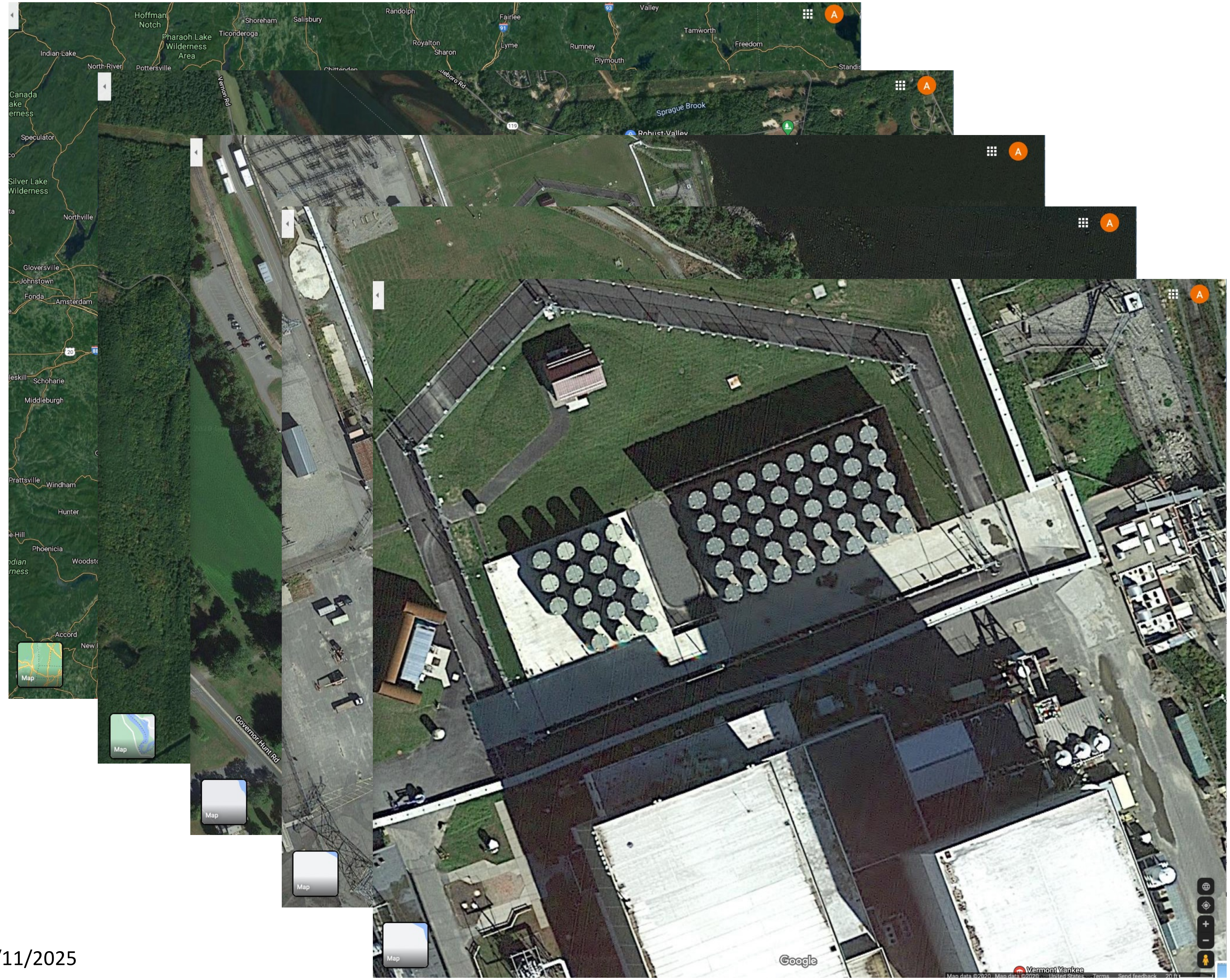
- In 1977 President Carter banned the reprocessing of SNF
  - (India demonstrated in 1974 nuclear weapons capabilities using reprocessing technology)
- This decision implies the need of a large permanent repository
- It also implies the loss of energetically valuable materials

Spent fuel storage

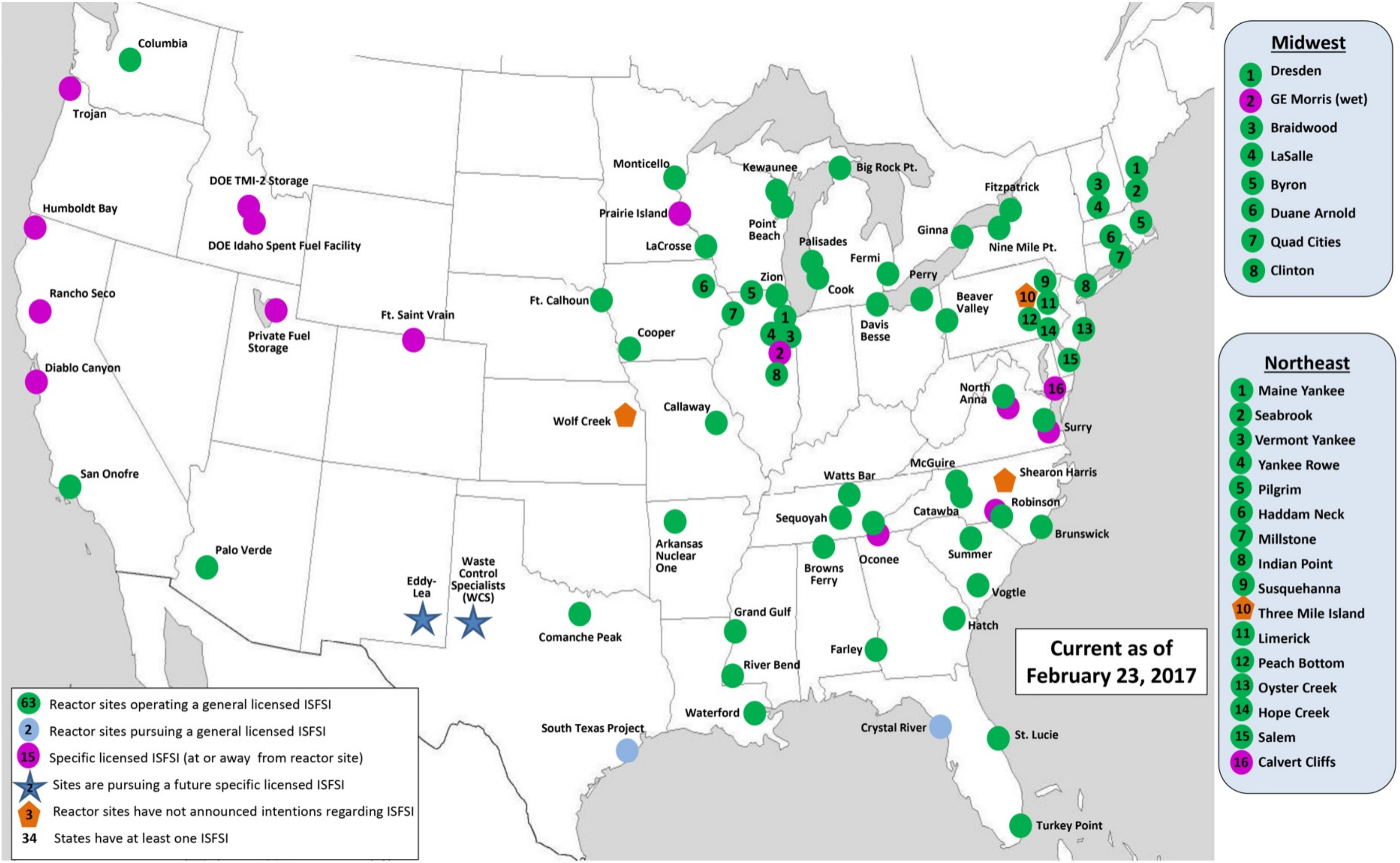
Wet (initial) and dry (temporary) storage



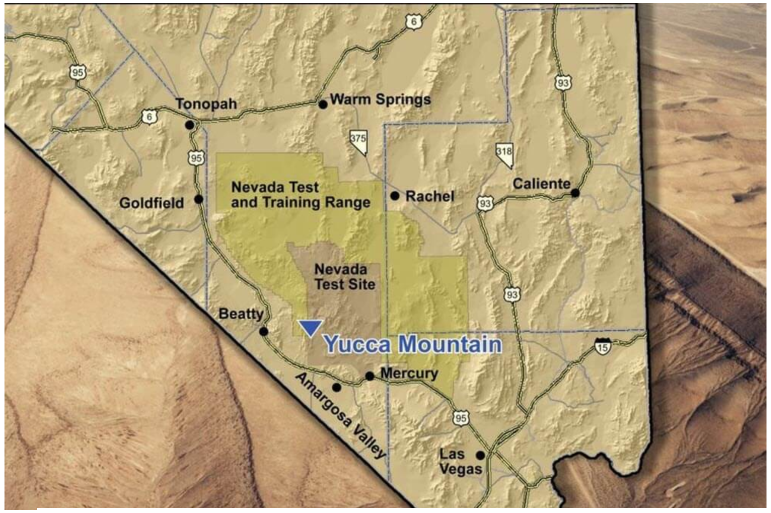
Google maps shows the storage facilities



Independent Spent Fuel Storage Installations (ISFSI)

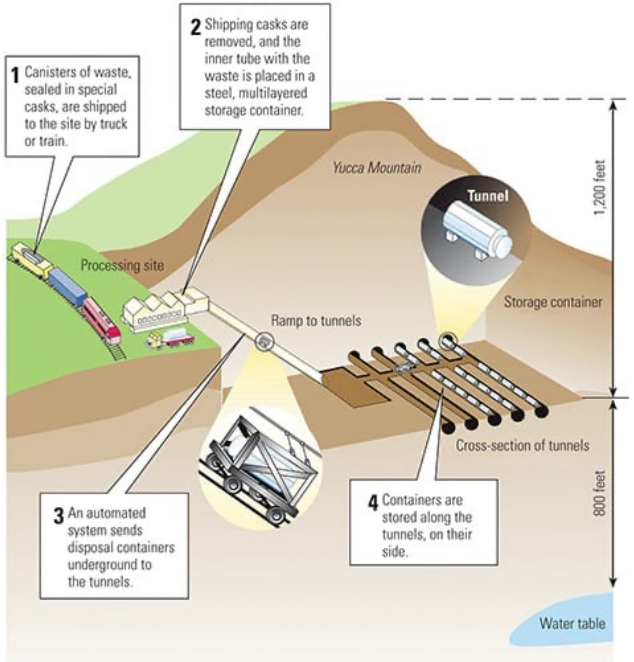


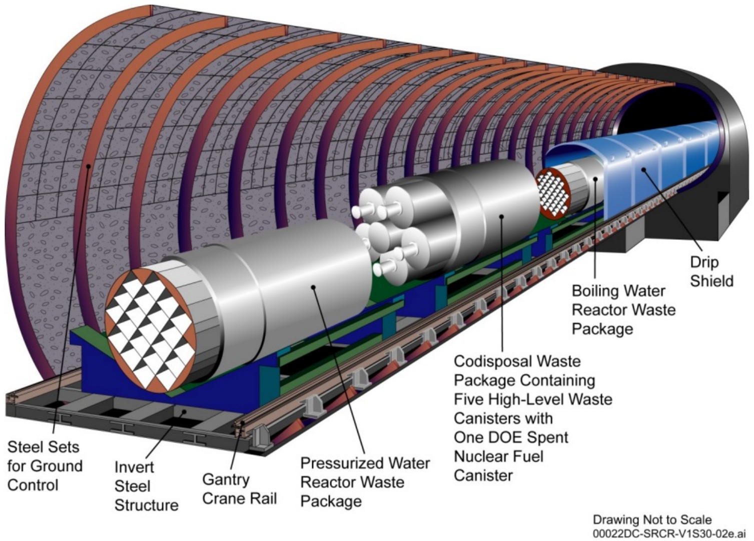
The USA Repository
Yucca Mountain (NV)



The project was contested by the public, Native Americans, politicians, State and regional organizations

Federal funding ended in 2011





First permanent repository

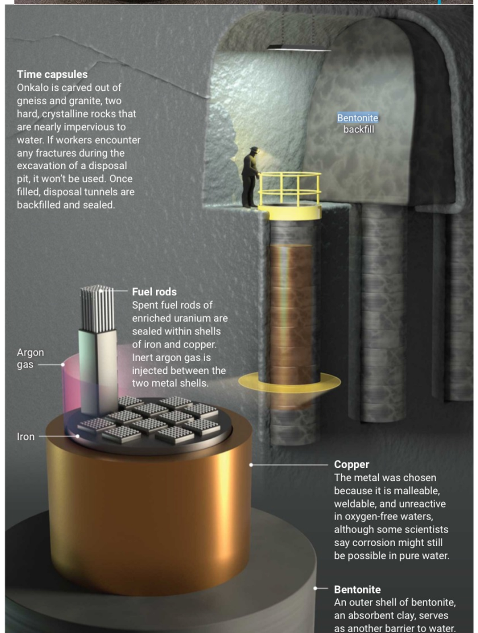
A 100,000-year Tomb for once-through Nuclear Waste

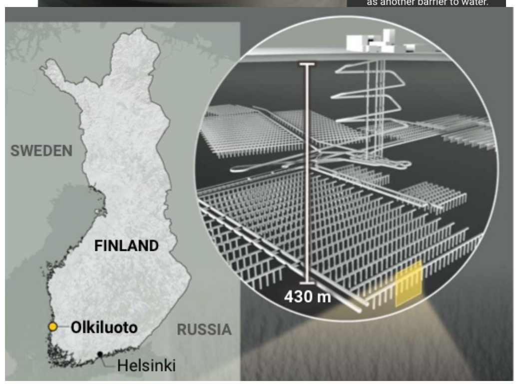
Trial run at Finnish repository starts
Waste & Recycling 30 August 2024

Finland in Front: The World's Likely First Spent Fuel Repository Moves Toward Licensing

Fri, Mar 1, 2024, 4:03PM | Radwaste Solutions | Edited by Tim Gregoire. Photos courtesy of Tapani Karjanlahti/Posiva.

The site of the Onkalo deep geological repository near Eurajoki in southwestern Finland with the Olkiluoto nuclear power plant in the background. In 2015, Posiva received a construction license from the Finnish government for the repository, which will be constructed to a depth of 1,300 to 1,500 feet.



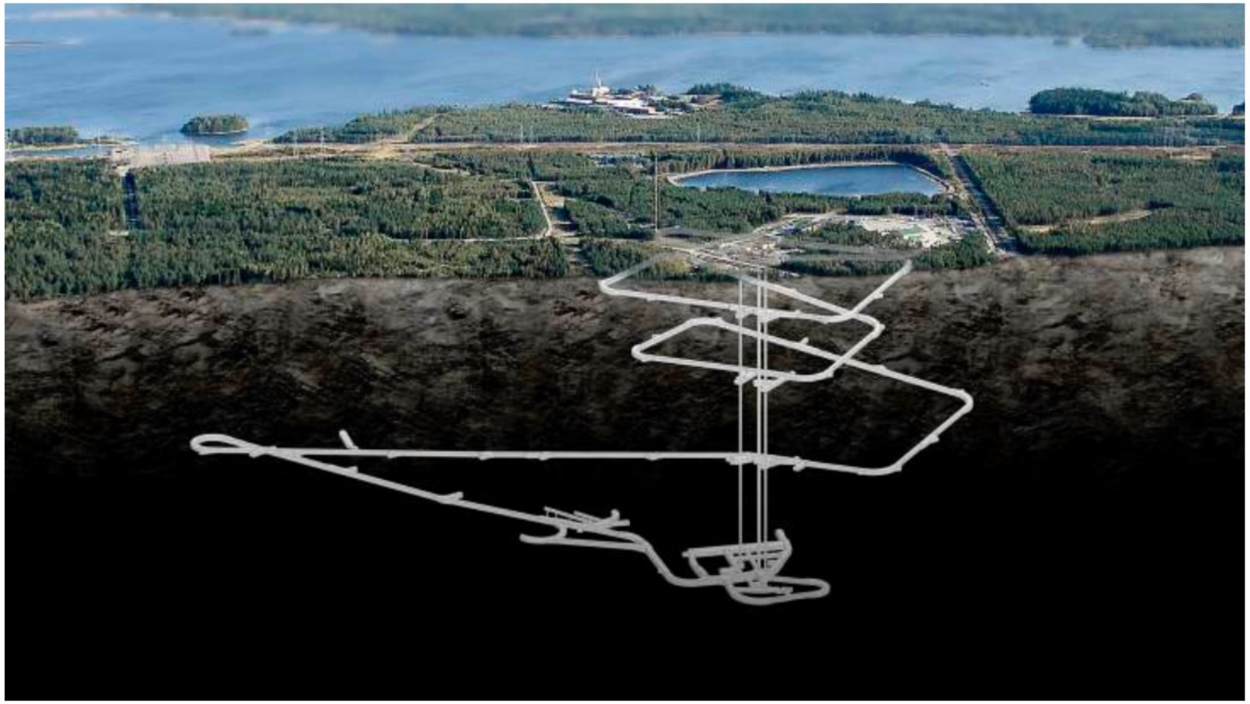


world nuclear news

Licensing of Finnish repository further delayed

Thursday, 5 December 2024

Finland's Radiation and Nuclear Safety Authority has been given another one-year extension to complete its review of Posiva Oy's operating licence application for the world's first used nuclear fuel repository.

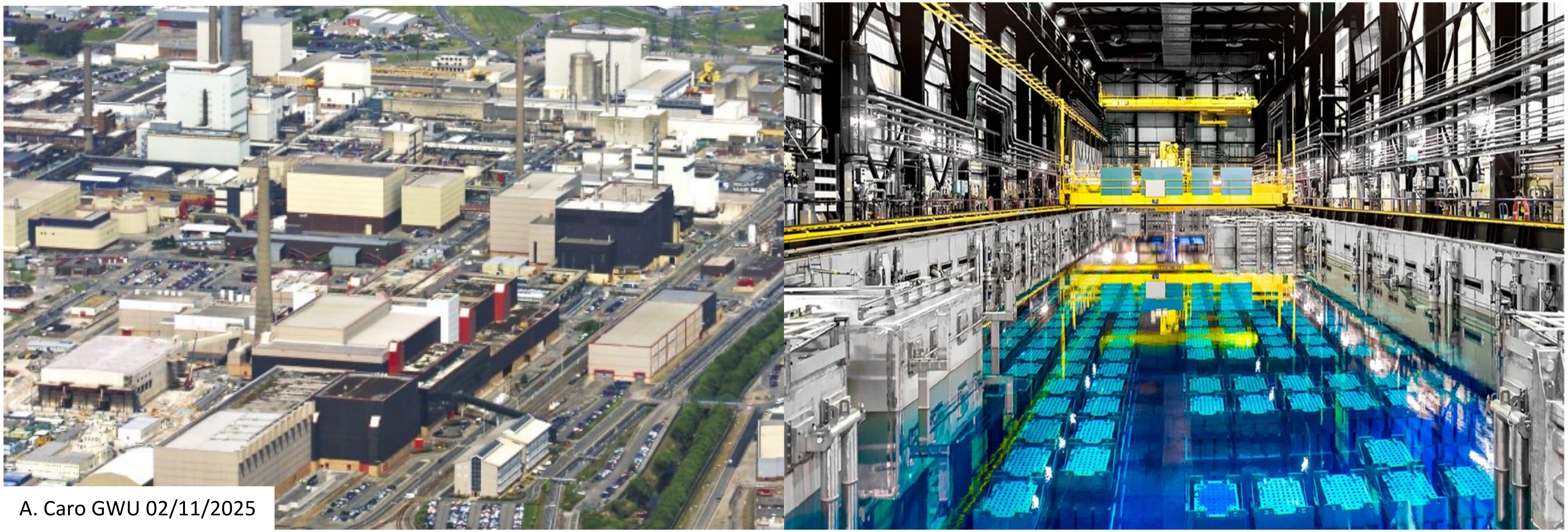


A rendering of the underground used fuel repository at Olkiluoto (Image: Posiva)

The “closed cycle” approach

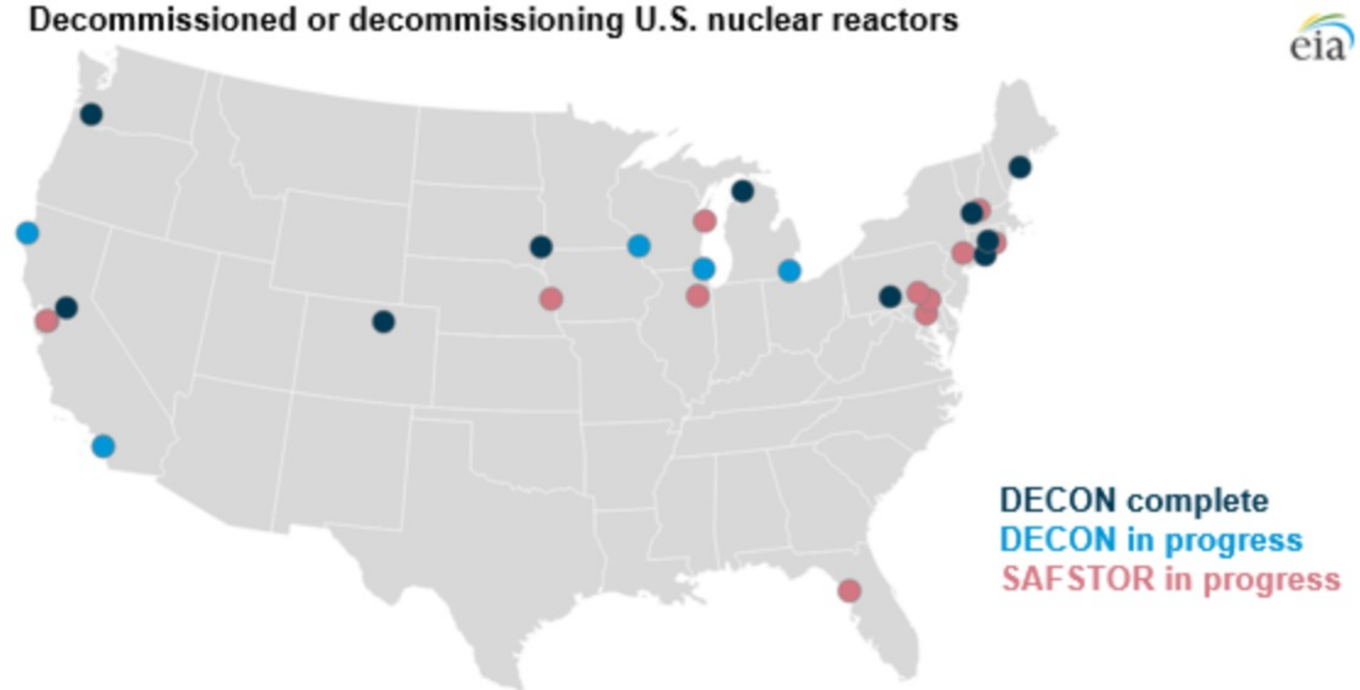
- France, Great Britain and Japan, among other nations, took a different route: SNF is a valuable asset, not a waste requiring disposal
- France offers reprocessing services to several countries: Japan, Germany, Belgium, Switzerland, Italy, Spain and the Netherlands
- The non-recyclable part of the radioactive waste is eventually sent back to the user nation

La Hague site (Fr)



At the end of life: decommissioning

a long-term and costly process

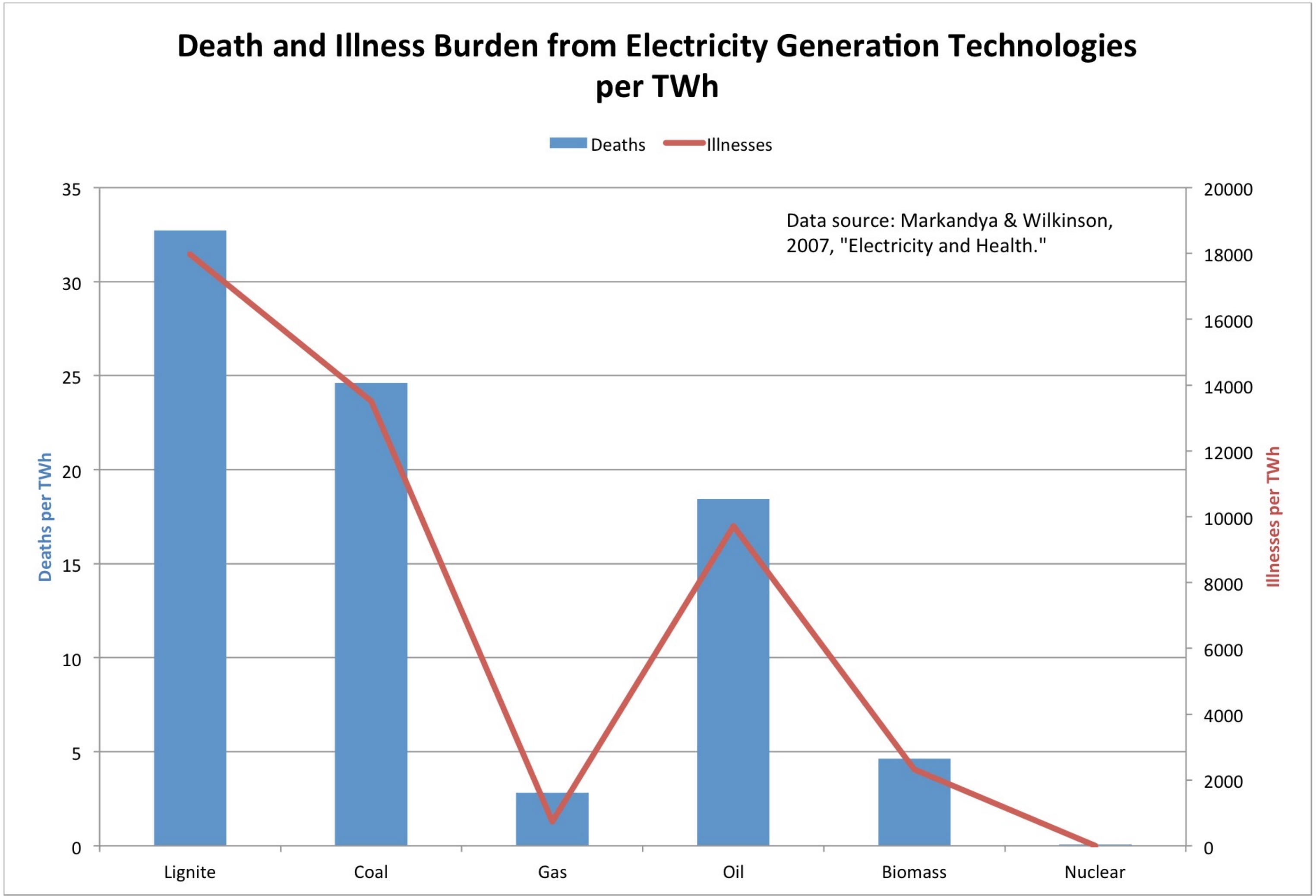


Source: U.S. Energy Information Administration, based on Nuclear Regulatory Commission and IAEA Power Reactor Information System

To fully decommission a power plant, the facility must be deconstructed and the site returned to greenfield status

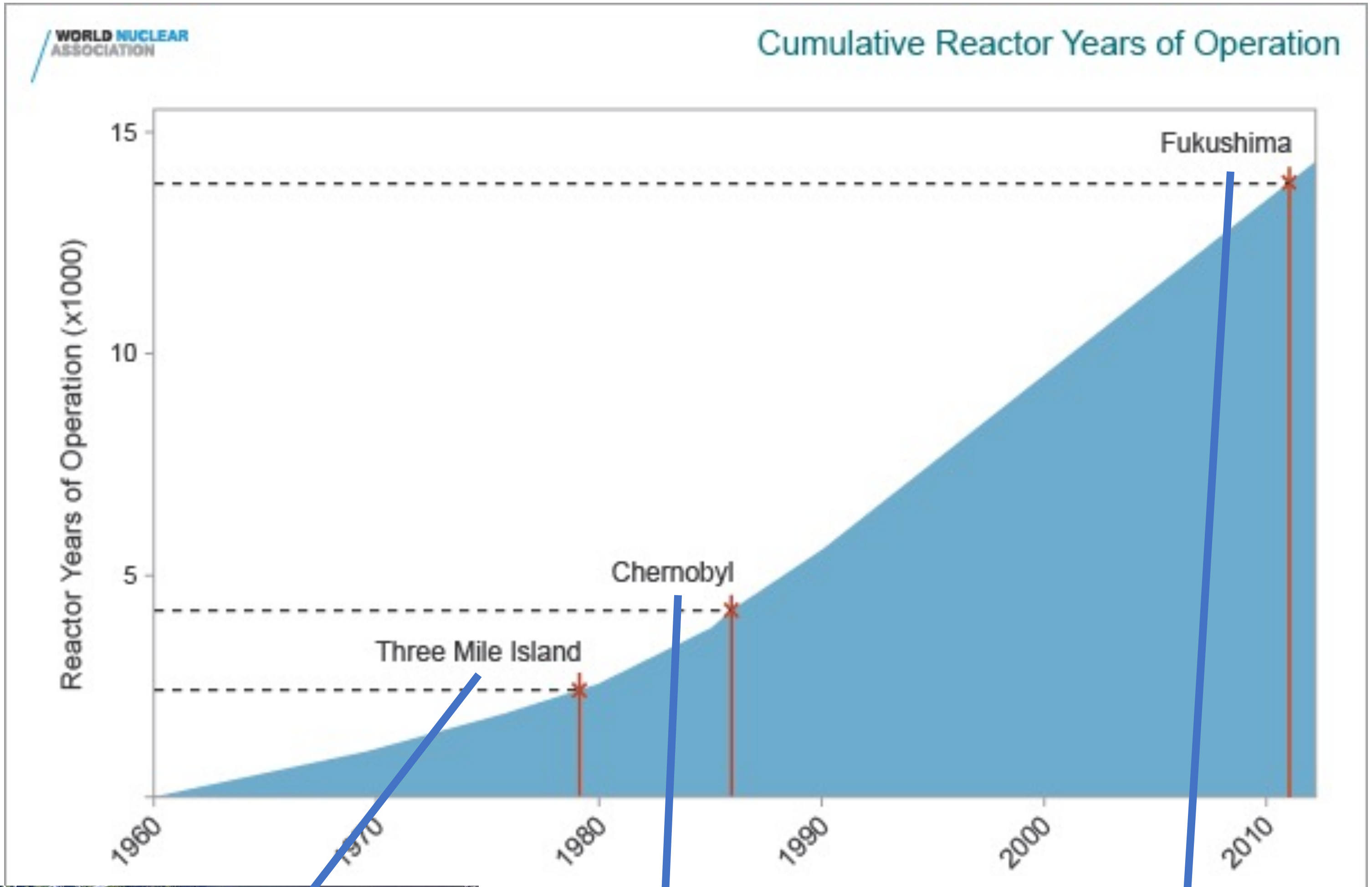
About 2/3 of the total estimated cost of decommissioning all US nuclear reactors has already been collected (World Nuclear Association)

Safety of nuclear reactors



From all technologies to produce electricity, nuclear is by far the safest

Cumulative experience (20000 reactor-years)



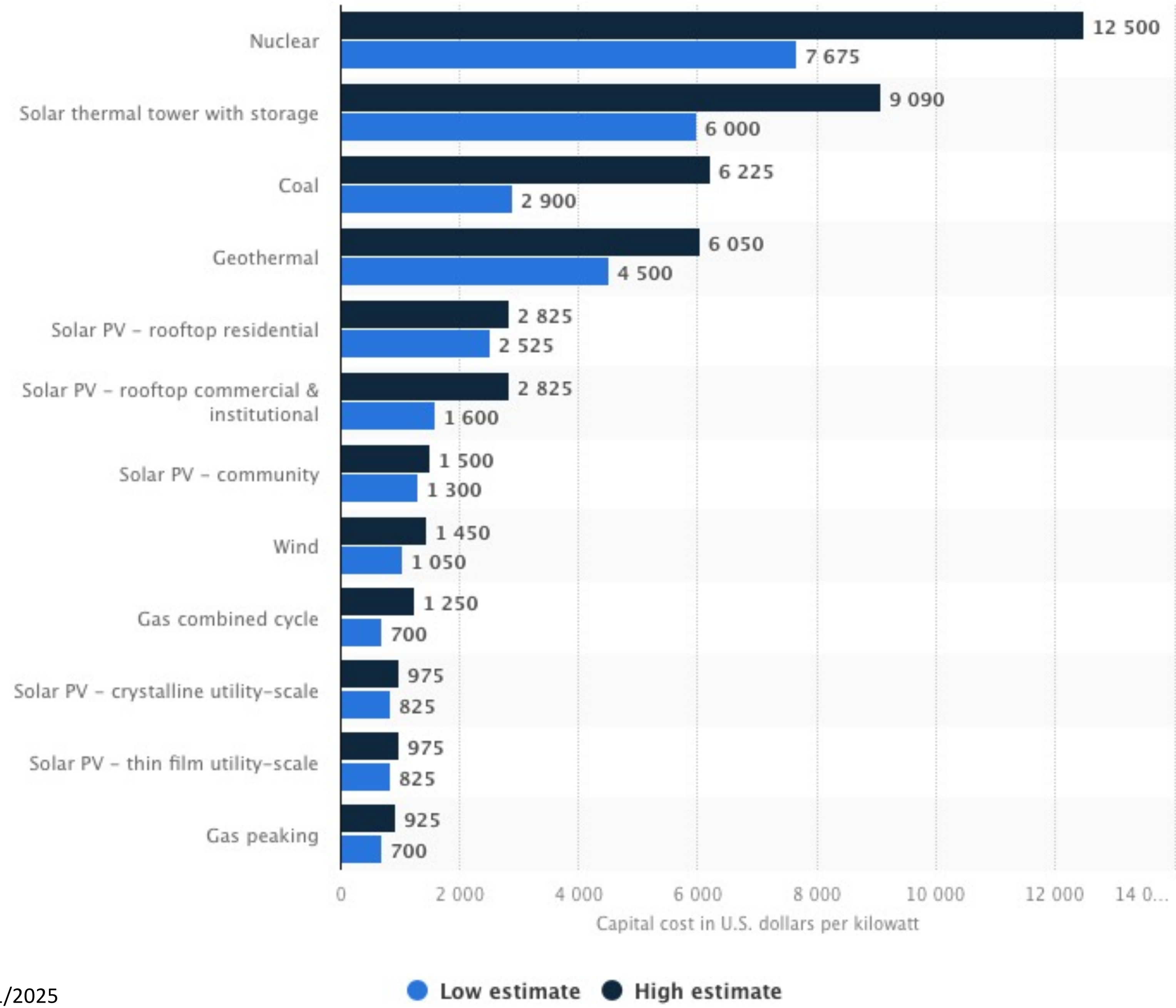
Energy & Environment › Energy

PREMIUM

Estimated capital costs of energy generation in the United States in 2020, by energy source

(in U.S. dollars per kilowatt)

https://www.statista.com/statistics/654401/estimated-capital-cost-of-energy-generation-in-the-us-by-technology/



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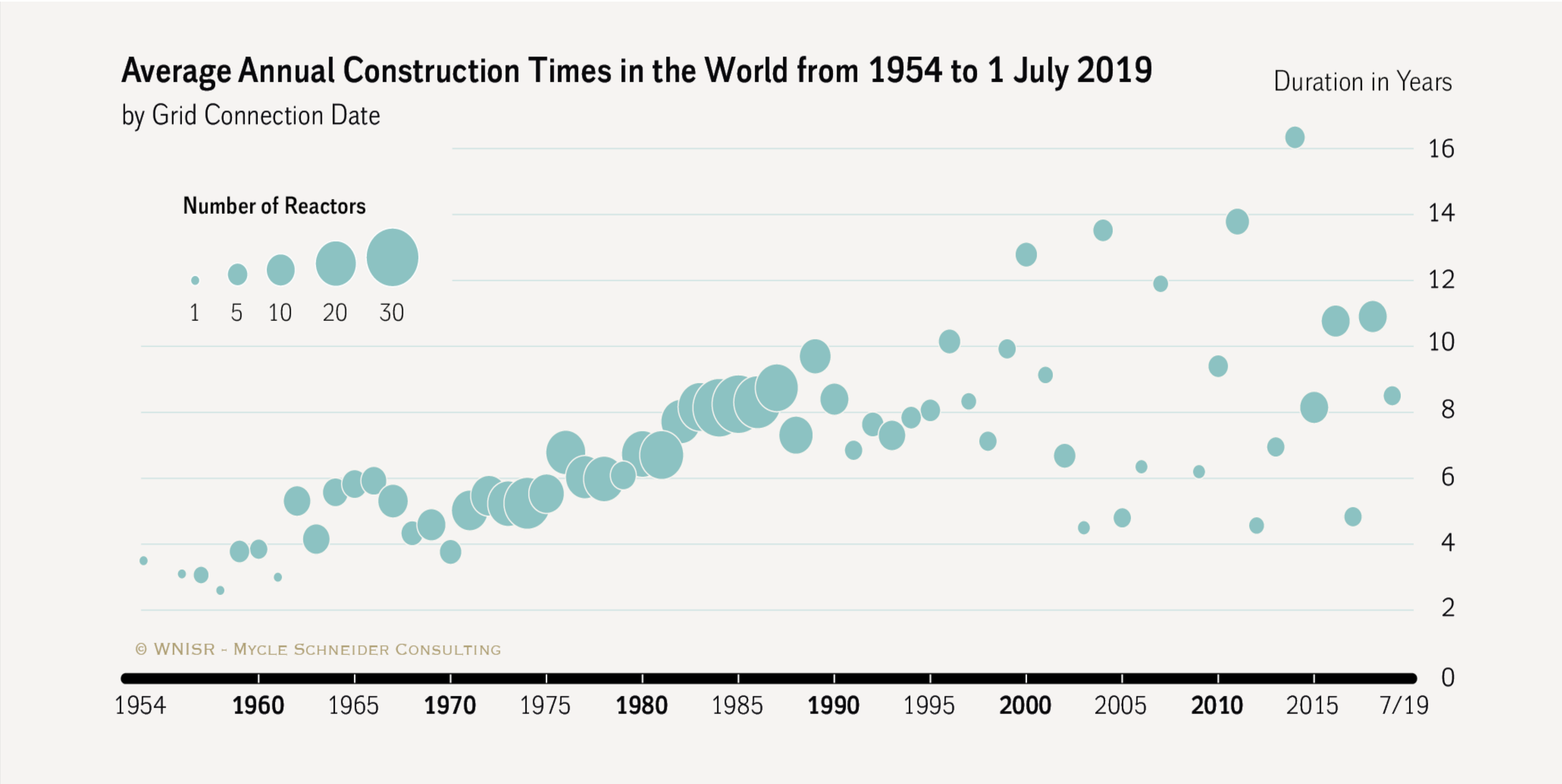
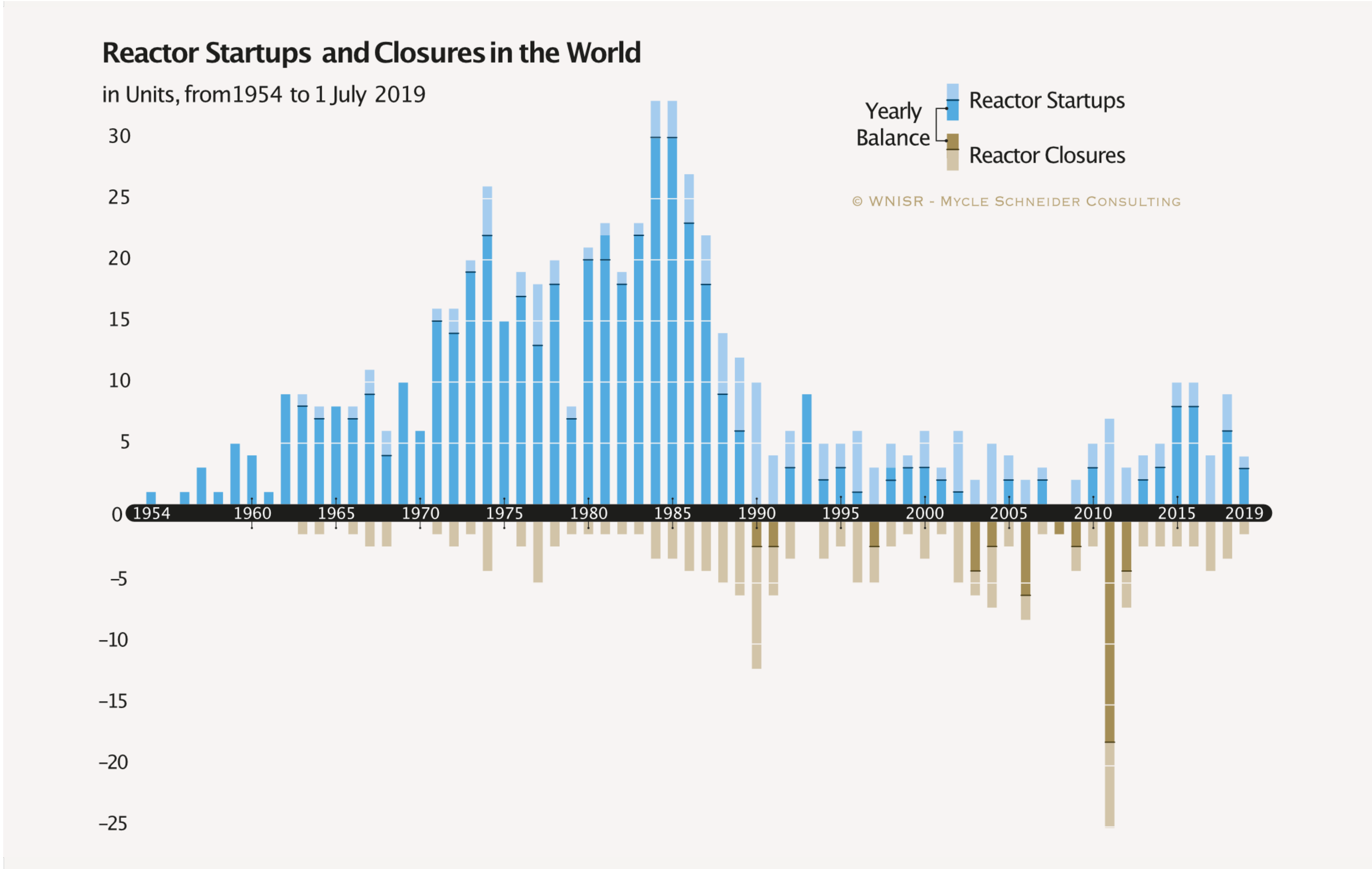
World average construction time

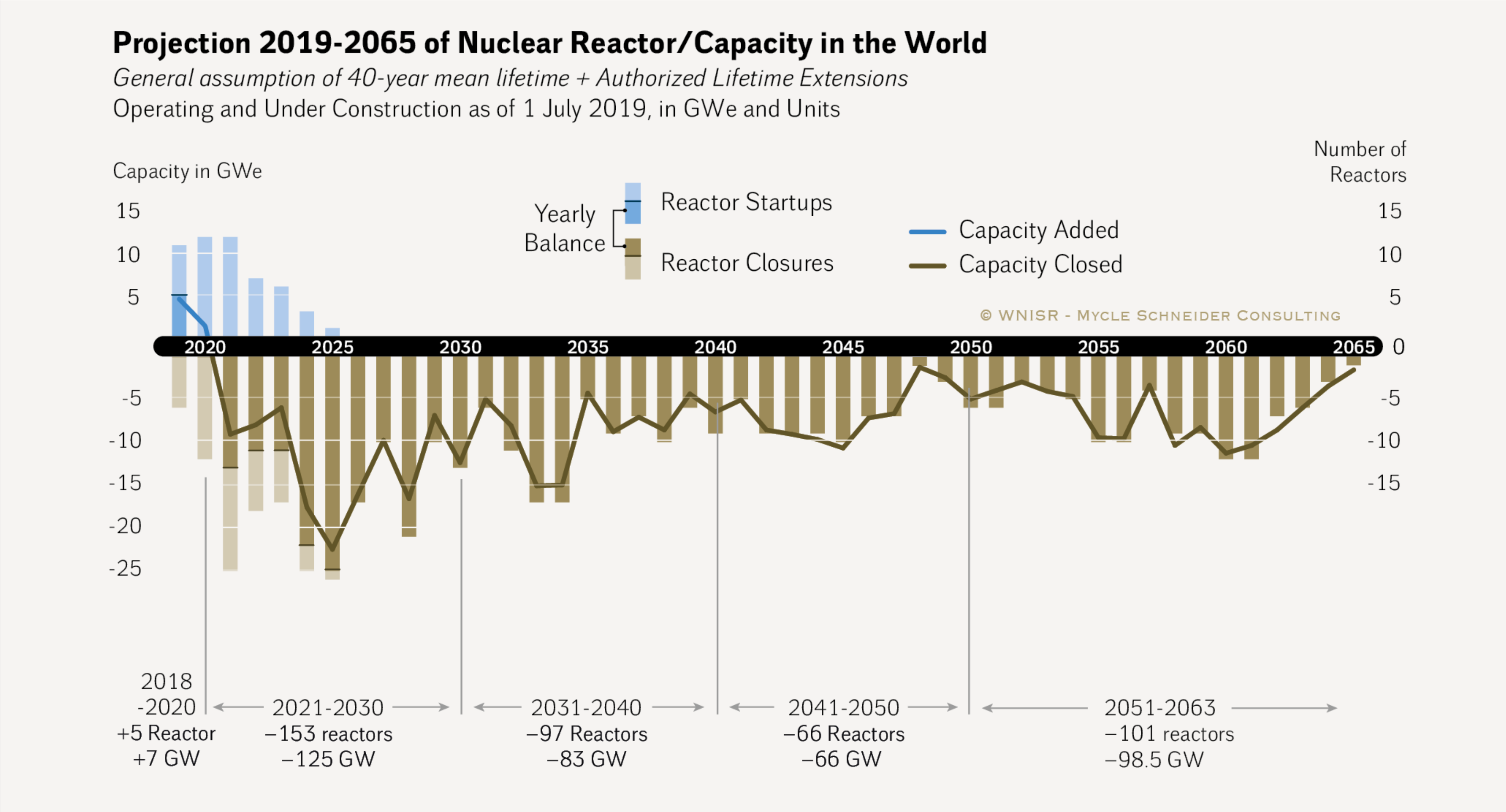


https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2019-HTML.html



https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2019-HTML.html

Does nuclear energy expand or contract?



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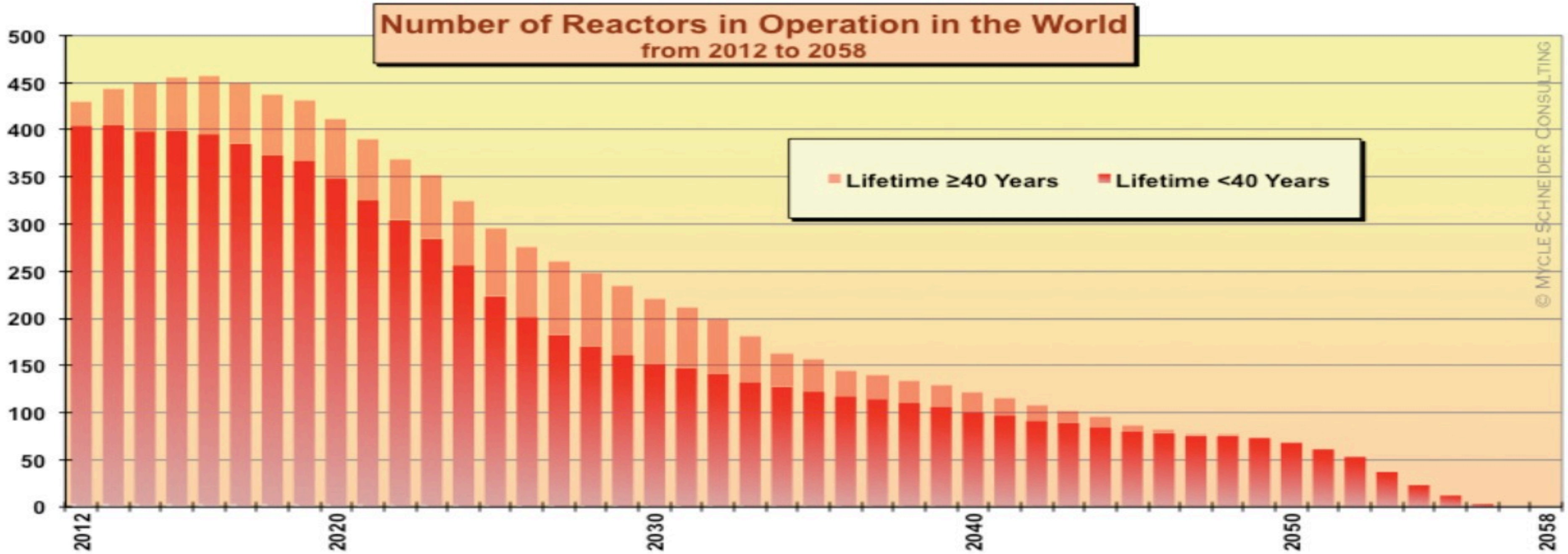
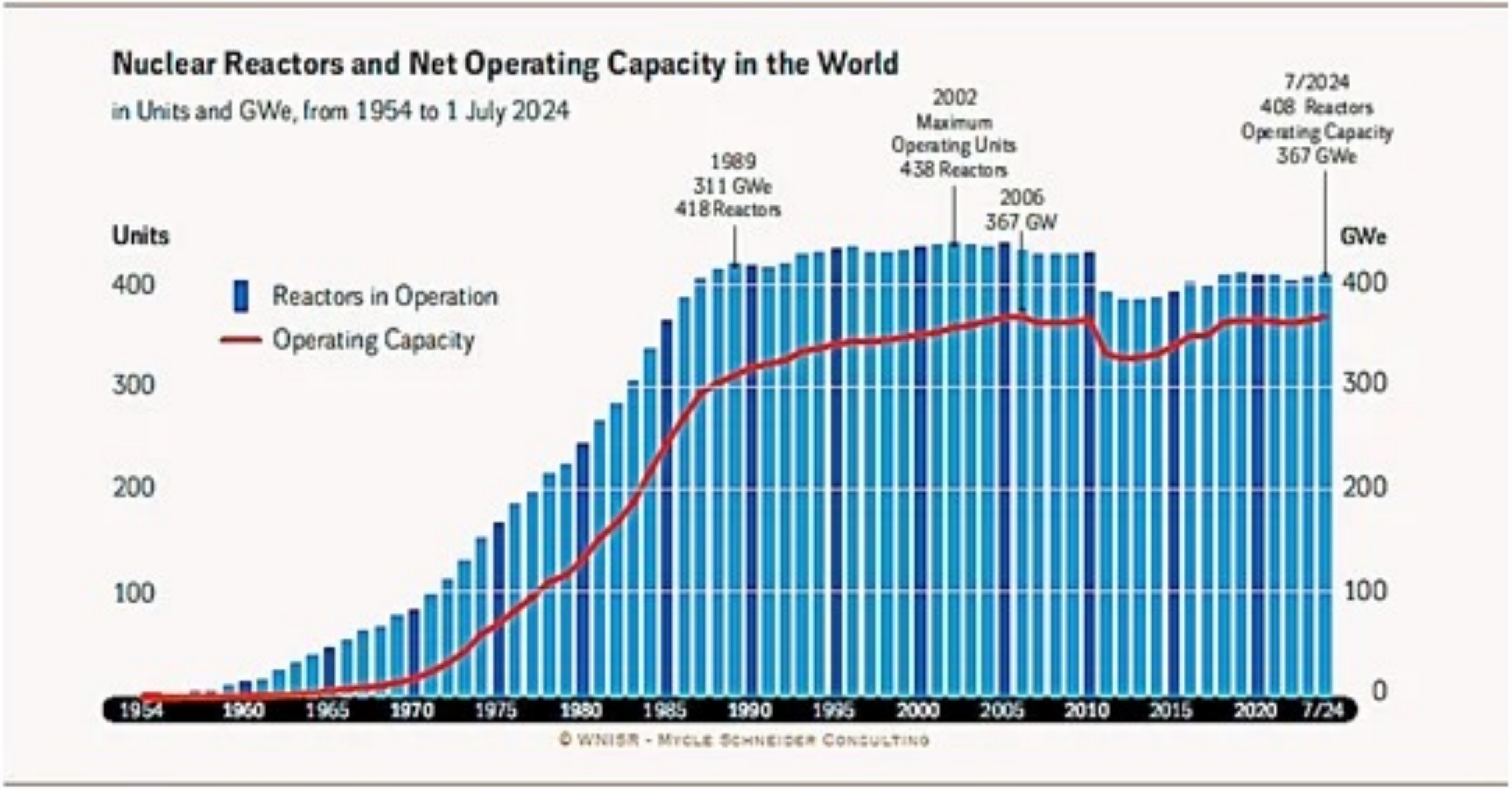
Projection 2060



The figure suggests a decline, unless 100+ reactors start to be built in this decade

- At present there are 27 reactors - including 20 in Japan - in Long-Term Outage (LTO)
- Globally, in the last 5 years, more Reactors have been shut-off (32) than plugged-in (27). However, the total capacity increased

https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2019-HTML.html



The average age of the world fleet is 32 years, with 20% over 40 years
In the USA, av. age is 42 years!

https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2024-HTML.html

Pause

Situation today

- There are a few reactor designs commercially available today:
  - **AP1000** from Westinghouse (US) ,
  - **EPR** from Areva (FR),
  - **APR1400** from Korea,
  - **Hualong-I** or HPR1000 from China,
  - **ABWR** from Japan,
  - **VVER1000**/1200/1400 from Russia.
- In reality, only China, Russia and Korea are selling reactors
- In US, Westinghouse filed for **bankruptcy** in 2017 while building 4 AP1000 reactors (2 in Vogtle, Georgia*, and 2 in V. C. Summer in South Carolina**)
- In France, Areva filed for **bankruptcy** in 2016 while building 4 EPR reactors (1 in Finlandia***, 1 in Francia, and 2 in UK in association with China)

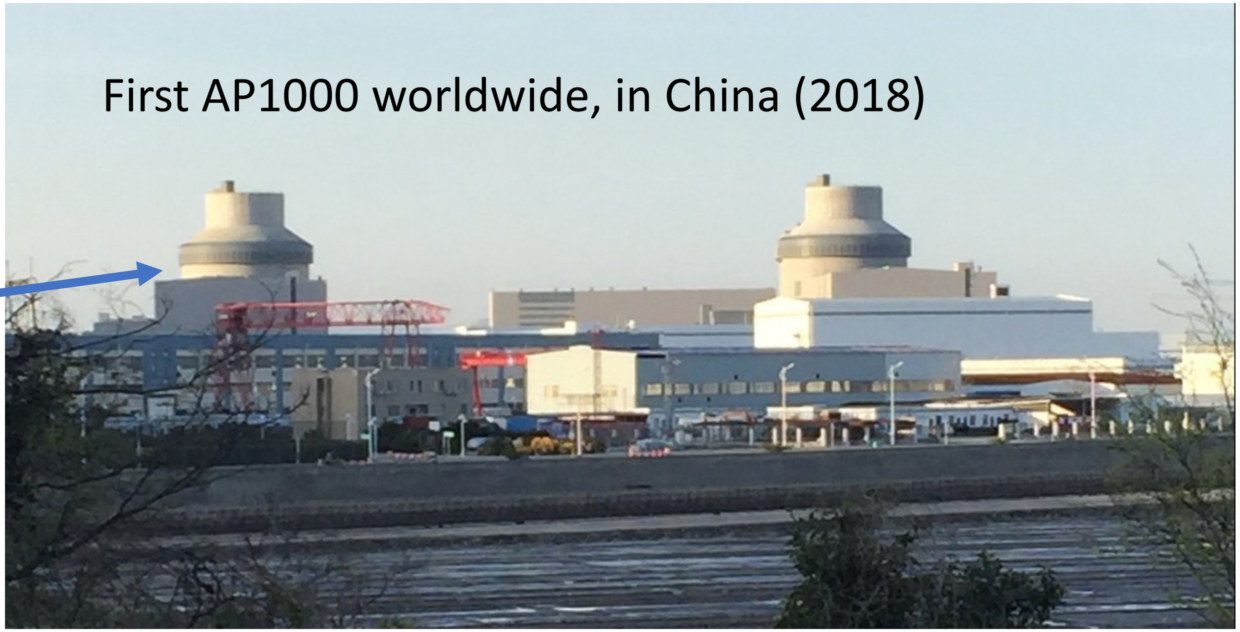
* Started 2013, estimated $25 billion for 2.5 GWe. Rescued by Bechtel

** Started 2013 Delayed and overbudget. Abandoned in 2017

*** 17 years construction and 3 times overbudget

First of the kind

- Commercial designs (Gen III+):
  - AP1000 Westinghouse (US)
  - EPR Areva (FR)
  - APR1400 Korea
  - Hualong-I (or HPR1000) China
  - ABWR Japan
  - VVER Russia.



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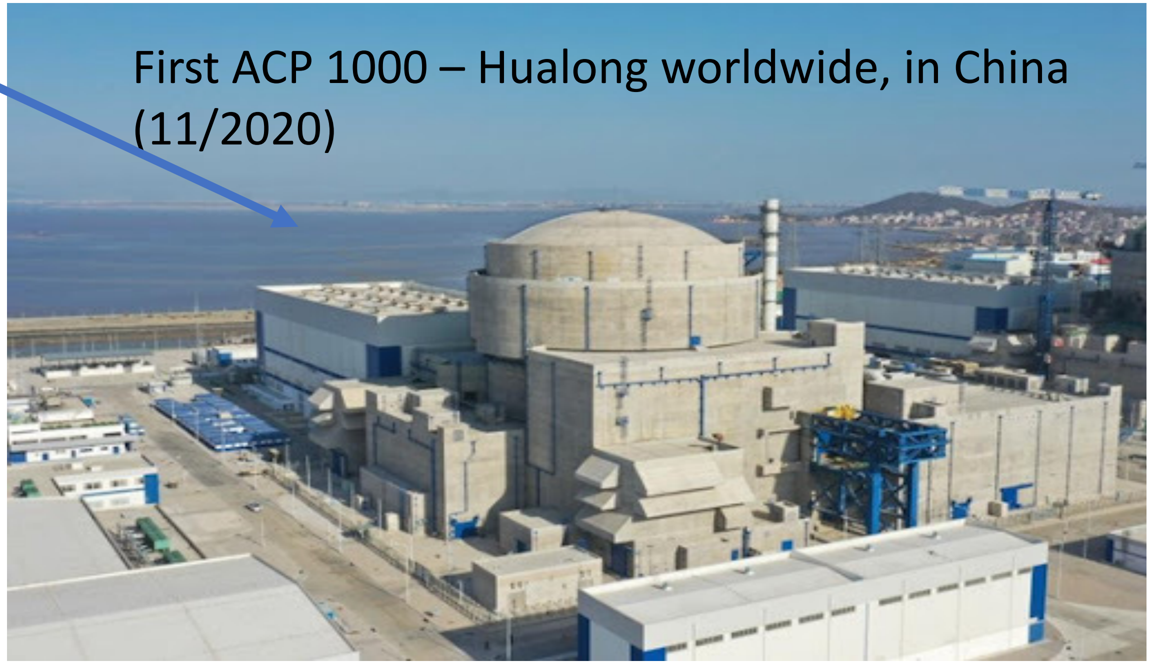


Large reactors under construction

64 reactors under construction in August 2024, 38 of them in China + Russia + India + Korea

Let's consider the 20 large reactors built in foreign countries

Countries without nuclear weapons				Countries with nuclear weapons		
País	#	Vendedor		País	#	Vendedor
Bangladesh	2	Russia		India	4	Russia
Iran	1	Russia		UK	2	France
Slovakia	1	Russia		China	4	Russia
Turkey	4	Russia				
Ukraine	2	Russia				

Few countries buy large reactors today

Russia leads sales; offers a 'build, own, operate' scheme
and also to take away the spent fuel

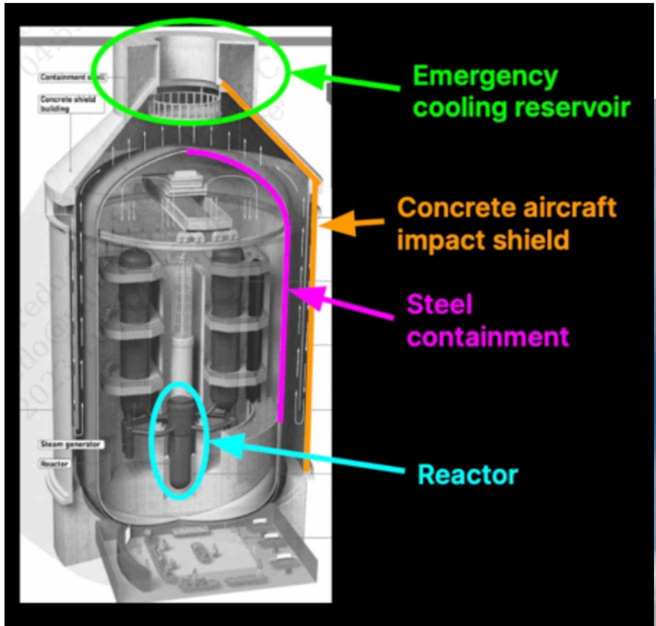
https://www.world-nuclear.org/information-library/current-and-future-generation/plans-for-new-reactors-worldwide.aspx

Large reactors recently finished

Olkiluoto 3 in Finland - EPR PWR 1.6 GW (Framatome, Fr)

Large reactors recently finished

Voghtle 3 & 4 USA - AP1000 PWR 1.4 GW (Westinghouse USA)



Large reactors recently finished

Barak 1-4 UAE PWR APR-1400 (KEPCO, Korea)

~8 años en construcción; operacional (2021, 2022, 2023, 2024)

25 mil millones USD o 4.4 MMUSD/GW

world nuclear news

Large reactors recently finished

Home · Energy & Environment · New Nuclear · Regulation & Safety · Nuclear Policies · Corporate · Uranium

EPR PWR 1.6 GW

France's Flamanville EPR starts supplying power

Saturday, 21 December 2024

The long-delayed Flamanville 3 EPR reactor in Normandy in northern France has begun delivering electricity to the grid, EDF announced.

The Flamanville EPR (Image: EDF)

The utility said the 1630 MWe (net) pressurised water reactor was connected to the grid for the first time at 11:48 (local time) on Saturday.

17 años en construcción

14 mil millones USD

8.75 MMUSD/GWe

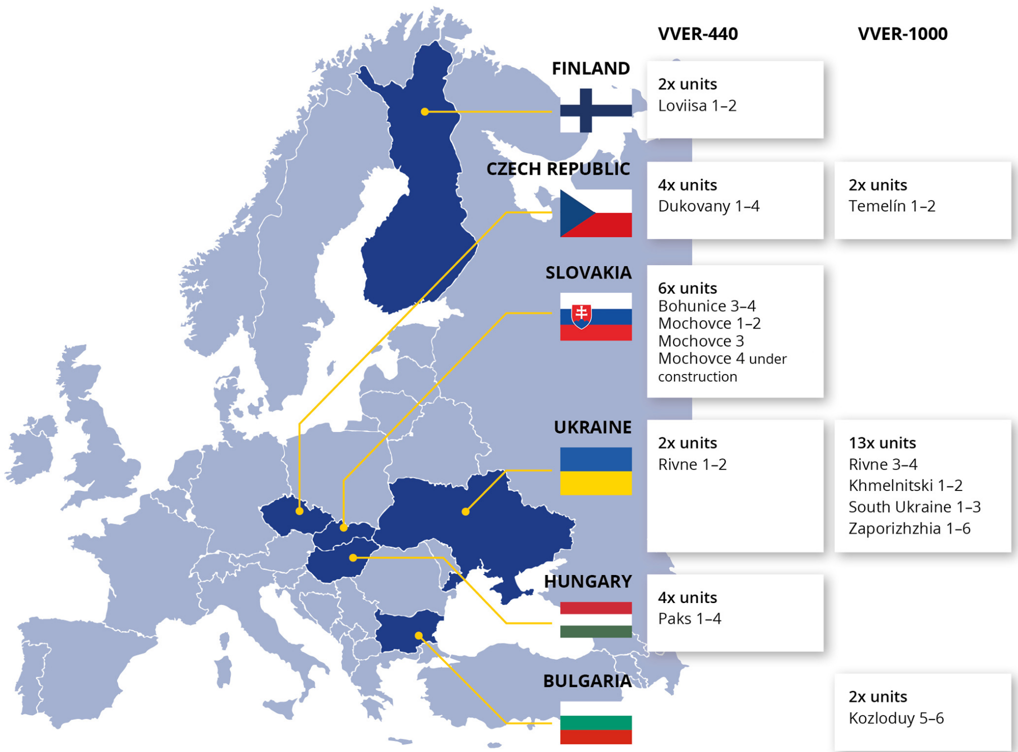
Large reactors recently finished

VVER PWR   0.4-1.5 GWe (Rosatom, Rusia)

In Bielorrusia

"Build, own, operate, and eventually, take home spent fuel"

~ 5500 MUSD/GW – LCOE ~80 USD/kWh



A. Caro GWU 02/11/2025

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Russia leads the sales; offers a 'build, own, operate' scheme
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https://www.world-nuclear.org/information-library/current-and-future-generation/plans-for-new-reactors-worldwide.aspx

Large reactors under construction

Hinkley Point C – England 2 EPRs 1630 MWe each

Unit 1 expected in June 2027. Began in December 2018.

Costs ~$40 billion, or ~$13 billion / GWe

The most expensive nuclear power station ever built, 4 x more than South Korea's!

In 2015, China took a 33.5% stake in the project

Under the deal, EDF and CGN also planned to build a replica EPR plant at Sizewell C

and a new plant in Essex, using China's HPR1000 (Hualong I) reactor technology.

Strategies to increase nuclear power

- Extend operational lifetime (from 40y to 80-100y)
  - Critical to this end is the integrity of the pressure vessel RPV, and steam generators (radiation damage, corrosion)
- Re-start closed facilities (Palisades, Three Mille Island, USA)
- Finish those stopped (Rumania, USA, Brazil)

- Small Modular Reactors

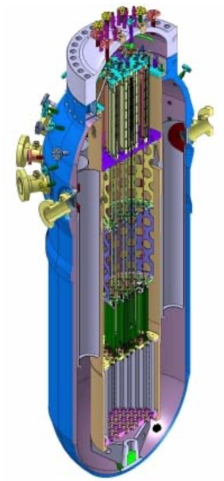
SMR - Small Modular Reactors

Built in factory, in series, and transported by boat, train… to site

Modular construction allows for rapid in-service times

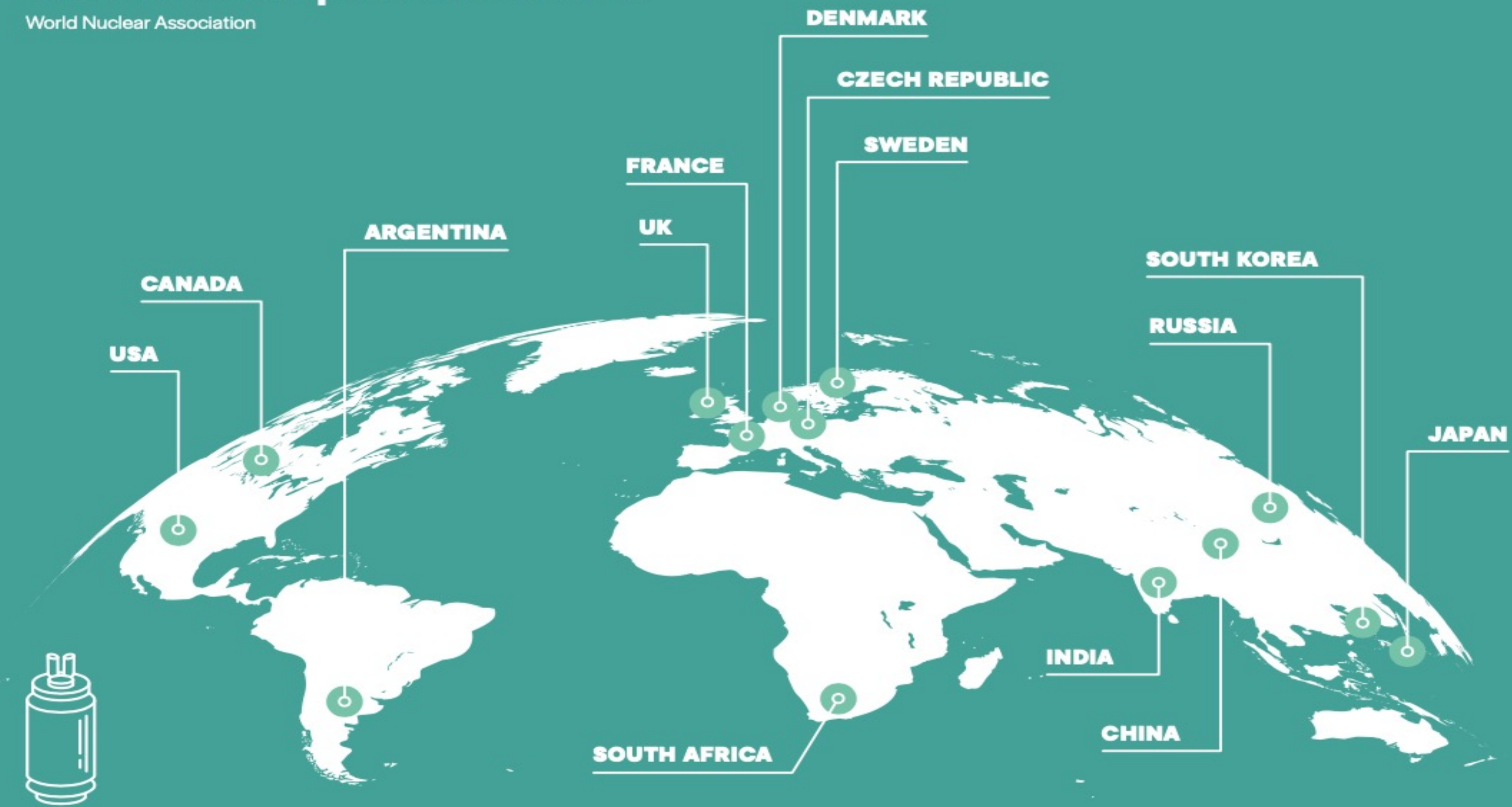
Enhanced safety

About 80 projects around the world



Global development of SMRs

World Nuclear Association



The benefits of SMRs

Lower cost

SMR construction time and capital costs are considerably less than large scale nuclear reactors or equivalent energy production methods.

Enhanced safety

Passive cooling systems, fewer mechanical parts requiring maintenance and auto fail safe makes SMRs among the safest forms of energy production.

Configurability

Factory-built and easily transportable, SMRs can be scaled to meet energy demand. Increasing capacity is as simple as adding another module.

Less waste

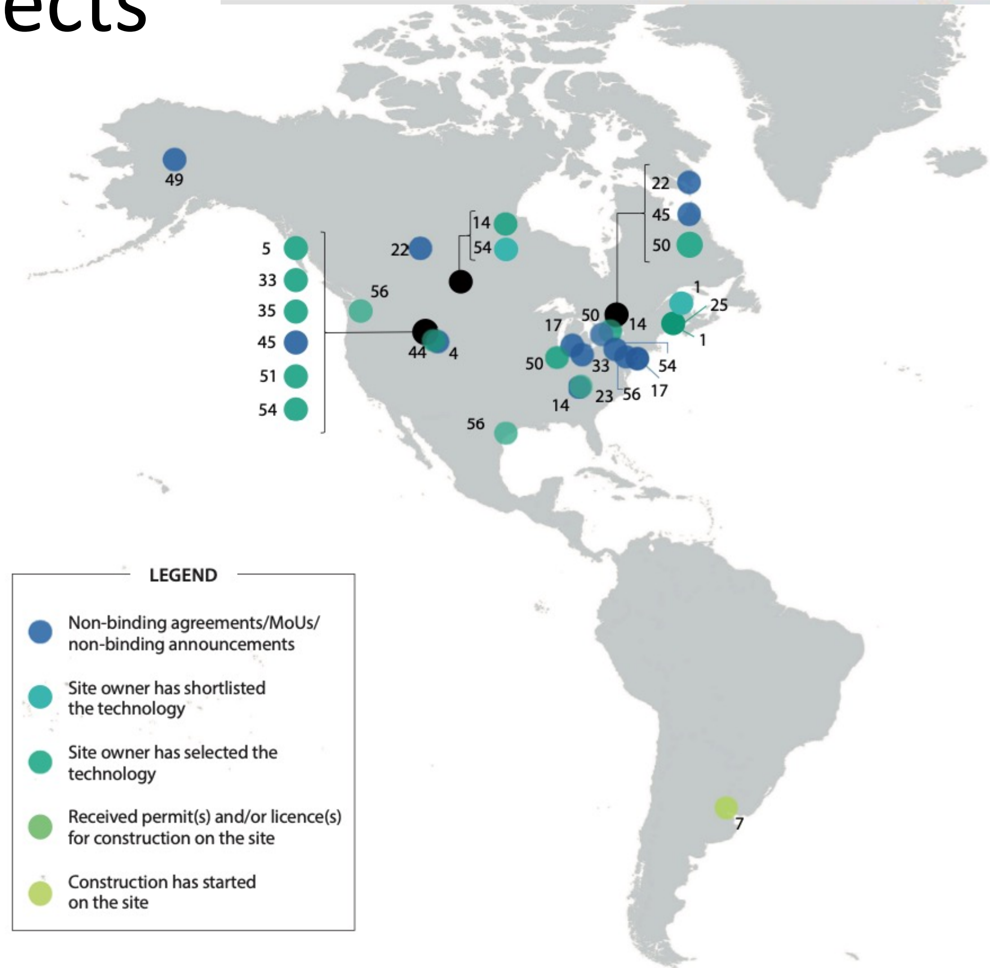
Some SMRs will use fuel more efficiently than current reactors, producing less waste. Advanced fuels will be easier to recycle for even greater energy production.

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

SMR projects

02/2024

NEA (2024b), The NEA Small Modular Reactor Dashboard: Second Edition, OECD Publishing, Paris, www.oecd-nea.org/smr-dashboard-2nd-edition



1	ARC-100	ARC Clean Technology	15	Calogena	Gorgé
2	Blue Capsule	Blue Capsule Technology	16	HEXANA	Hexana
3	SEALER-55	Blykalla	17	SMR-300	Holtec International
4	BANR	BWXT	18	HTR-PM	INET
5	Project Pele	BWXT	19	GTHTR300	JAEA
6	ACPR50S	CGN	20	HTTR	JAEA
7	CAREM	CNEA	21	Jimmy SMR	Jimmy
8	ACP100	CNNC	22	SMART	KAERI
9	Energy Well	CVŘ	23	Hermes	Kairos Power
10	DF300	Dual Fluid Energy	24	PWR-20	Last Energy
11	A-HTR-100	Eskom	25	SSR-W	Moltex Energy
12	LFTR	Flibe Energy	26	FLEX	MoltexFLEX
13	SC-HTGR	Framatome	27	XAMR	NAAREA
14	BWRX-300	GE Hitachi Nuclear Energy	28	HTGR-POLA	NCBJ

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SMR projects

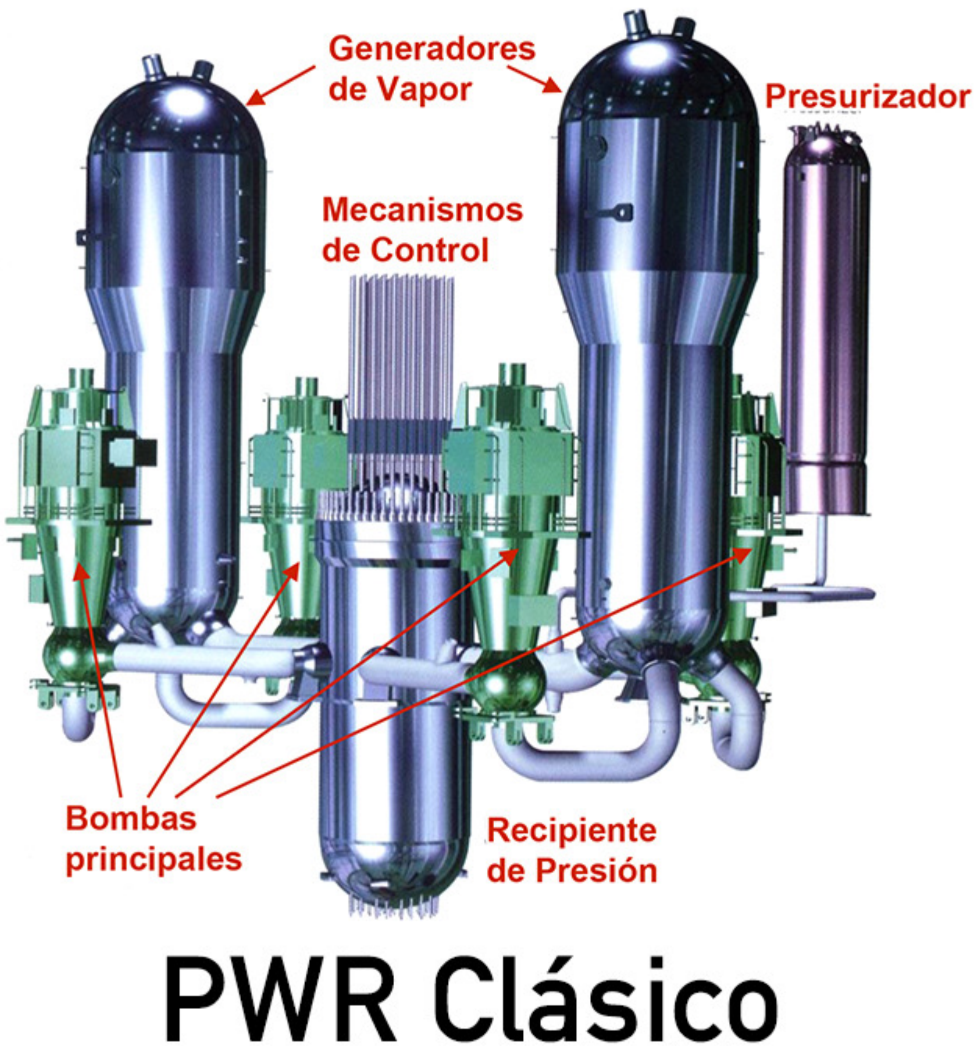
NEA (2024b), The NEA Small Modular Reactor Dashboard: Second Edition, OECD Publishing, Paris, www.oecd-nea.org/smr-dashboard-2nd-edition

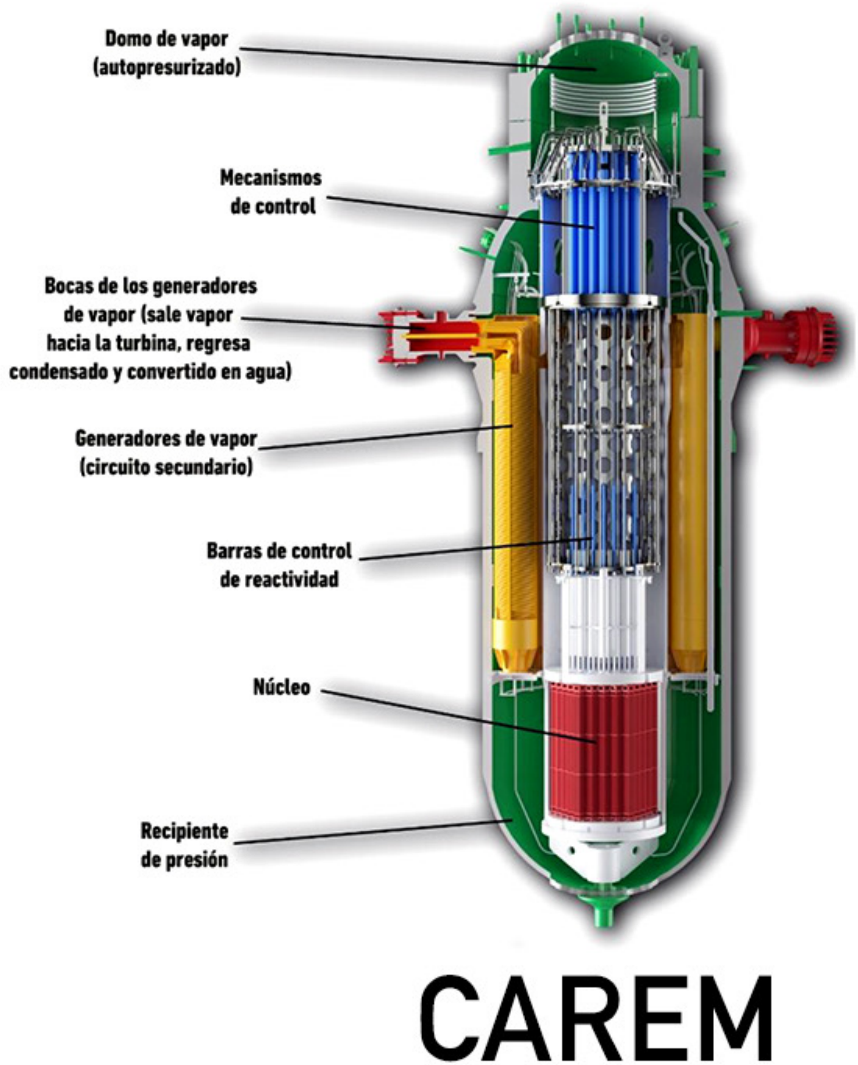
02/2024

29	LFR-AS-200	*newcleo*
30	BREST-OD-300	NIKIET
31	VOYGR	NuScale Power
32	NUWARD SMR	NUWARD
33	Aurora Powerhouse	Oklo
34	Otrera 300	Otrera Nuclear Energy
35	Kaleidos	Radiant Industries
36	RR SMR	Rolls-Royce SMR
37	KLT-40S	ROSATOM
38	RITM-200M	ROSATOM
39	RITM-200N	ROSATOM
40	RITM-200S	ROSATOM
41	CMSR	Seaborg Technologies
42	HAPPY200	SPIC

43	HTMR-100	Stratek Global
44	Natrium Reactor Plant	TerraPower
45	IMSR	Terrestrial Energy
46	ThorCon 500	ThorCon International
47	Thorizon One	Thorizon
48	MoveluX	Toshiba Energy Systems & Solutions Corporation
49	4S	Toshiba Energy Systems & Solutions Corporation
50	MMR	USNC
51	Pylon D1	USNC
52	TEPLATOR	UWB and CIIRC CTU
53	AP300™ SMR	Westinghouse Electric Company
54	eVinci microreactor	Westinghouse Electric Company
55	Westinghouse LFR	Westinghouse Electric Company
56	Xe-100	X-energy

Water-cooled **Integral** Reactors





Darío Delmastro / Engineering Manager / CAREM Project
https://nucleus-new.iaea.org/sites/htgr-kb/twg-smr/Documents/TWG-1_2018/12_ARGENTINA_Delmastro_TWG_SMR_240418.pdf

Operational SMRs

KLT-40S – Russia

Akademic Lomonosov: 2 x 35 MWe PWR derived from KLT-40 for naval propulsion

With enriched U at ~20%

Planned for 3.7 y of construction, took 12,7 y
Connected in 2019

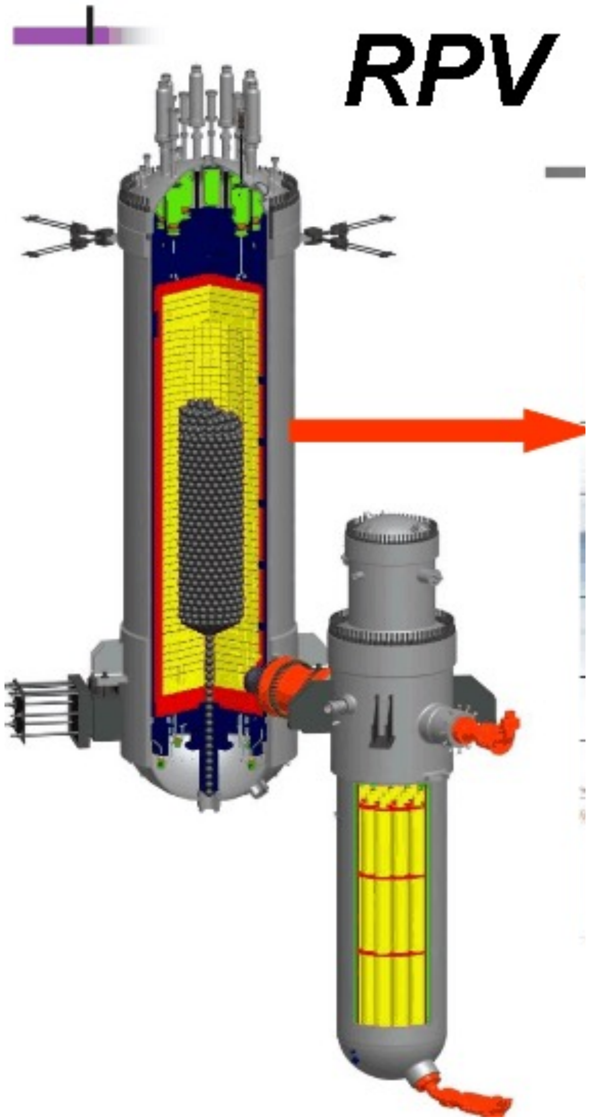
The Akademik Lomosov at Pevek (Image: Rosenergoatom)

The load factors reported by Russia in PRIS (IAEA), are "ridiculously" low (~0,35)

Operational SMR
HTR-PM China

High-Temperature Gas-cooled Reactor

Started operation in Dec 2023 (10 y construction time)

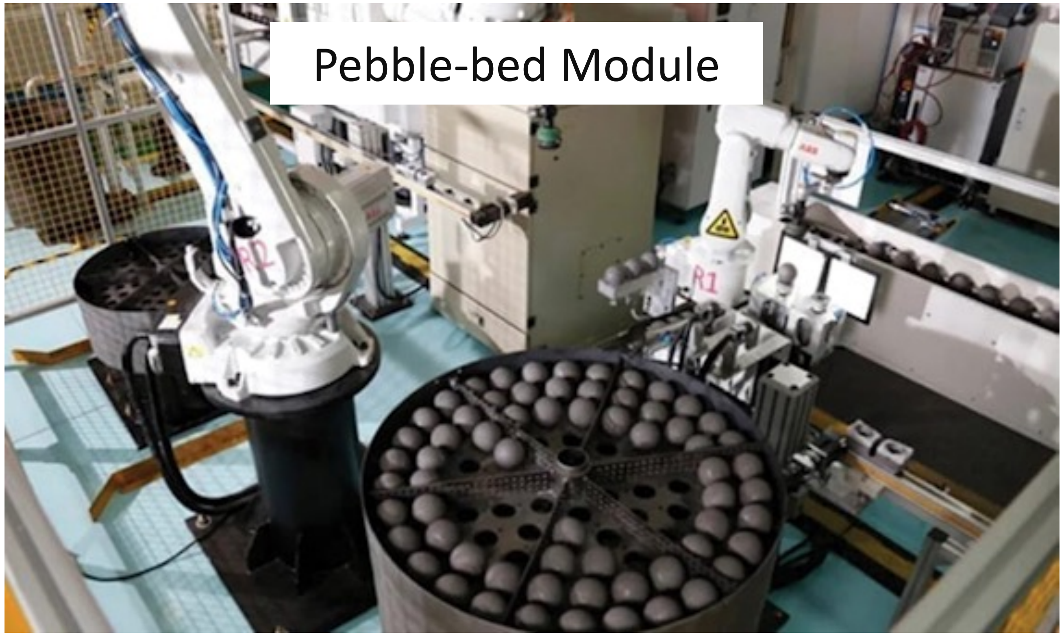


First HT high power reactor in the world, 105 MWe

Helium as coolant and graphite as moderator

12.000 TRISO pebbles with U at 8,5%

Pressure 70 at. Steam pressure 130 at, T 567 °C



No reports on operational performance

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BREST-OD-300 - Russia

Lead cooled fast reactor

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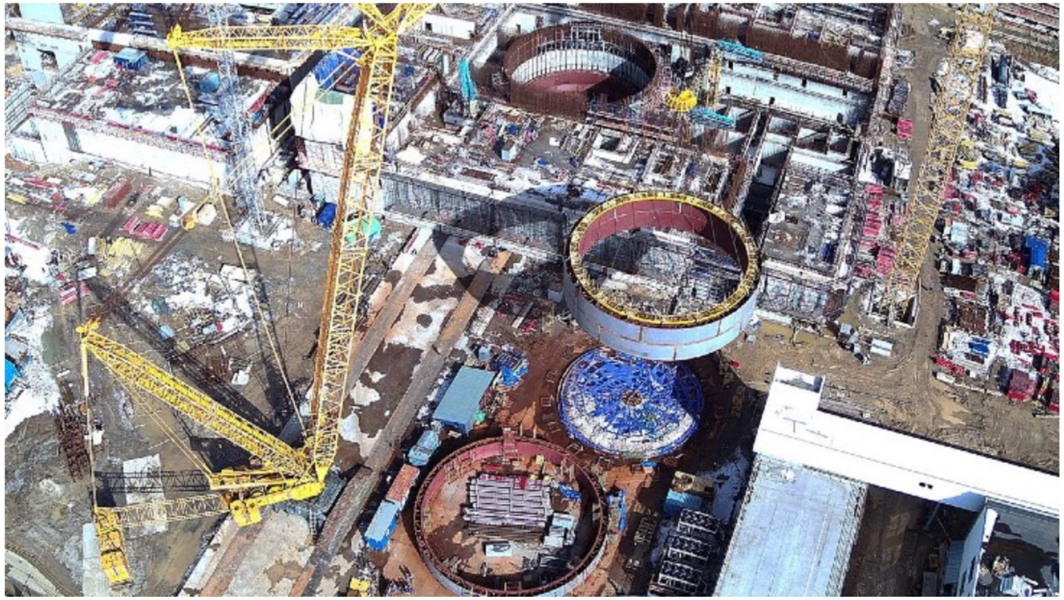
Second tier of containment installed for BREST-OD-300

Friday, 19 April 2024

The 184-tonnes section - the second of three - has been lifted into place for the lead-cooled fast neutron reactor under construction at the Siberian Chemical Combine site in Russia.



(Image: SCC)

The steel reactor base plate and lower tier of the containment were installed at the turn of the year, the third enlarged unit is planned to be installed in the reactor shaft in December ... structure will be 17 metres.

300 MWe Lead cooled fast reactor

Uranium/Plutonium Nitride:

- FOR: is said to be safer, stronger, denser, more thermally conductive and having a higher temperature tolerance
- AGAINST: complex conversion route from enriched UF_6, the need to prevent oxidation during manufacturing and the need to define and license a final disposal route. Also, the necessity to use expensive, highly isotopically enriched ^{15}N

Fuel production plant – BRESYT-OD-300 power unit – fuel reprocessing plant → 'practically autonomous'

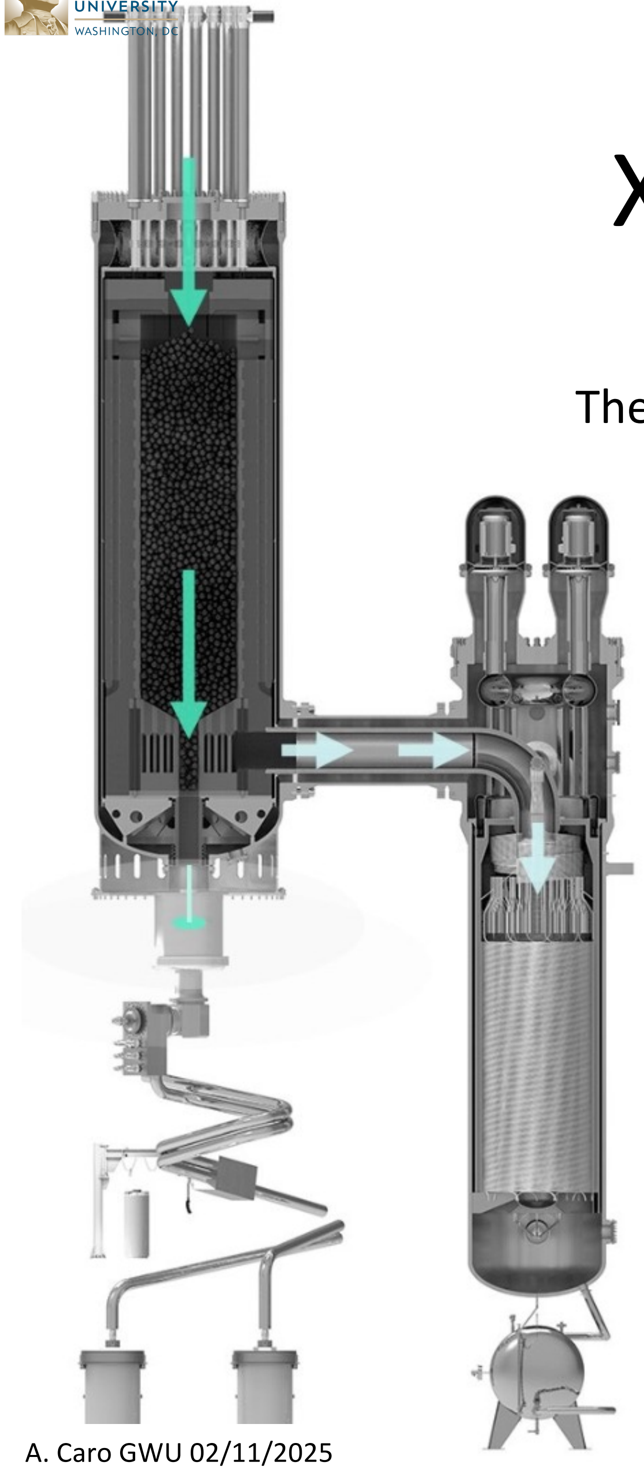
USA’s reaction

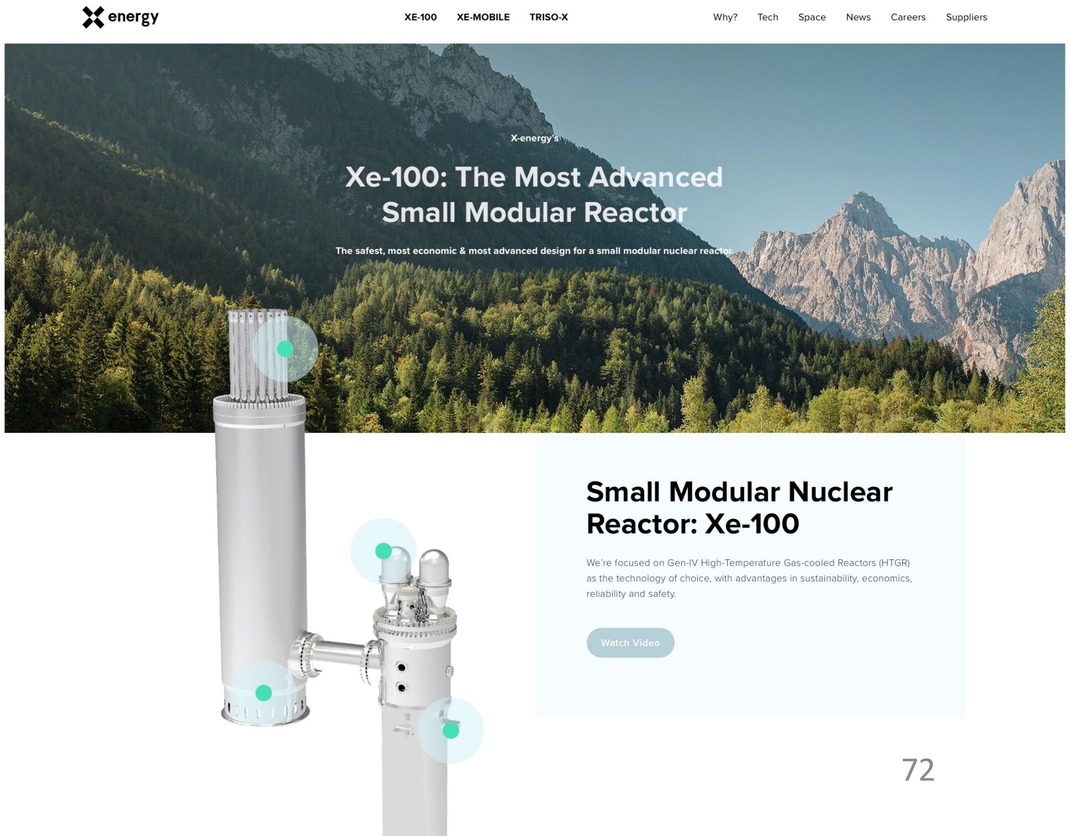
Xe-100 SMR from X-Energy HT-GCR 80 MWe

The TRISO fuel enters from the top and exits from the bottom; continuously

Still not under construction

750C! Uninterrupted operation for 60 years!





KP-FHR USA Kairos Power

Pebble-bed HT-MSR 140 MWe Triso

Pebble bed with static matrix

Fabrication of TRISO fuel with HALEU in USA is a growing field, with players such as BWXT and X-Energy leading the way, with DOE support

Oak ridge TN

Kairos Power fabricates and installs test unit reactor vessel

Friday, 31 January 2025

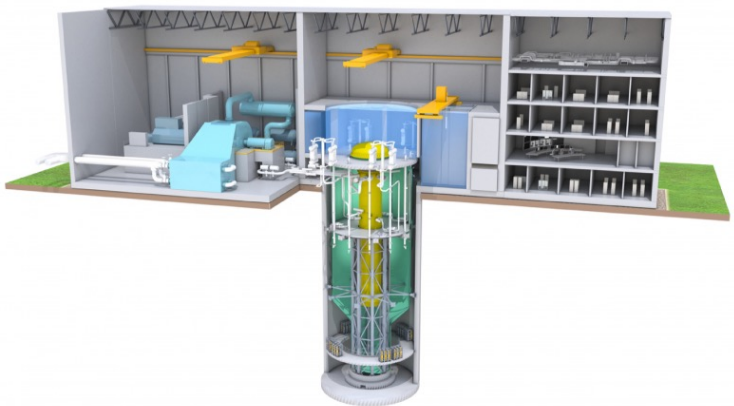
The central component for the second-iteration test unit for Kairos Power's Hermes reactor is the first reactor vessel to be fabricated in-house at Kairos Power's Manufacturing Development Campus in Albuquerque, New Mexico.

(Image: Kairos Power)

Kairos is following an iterative approach for the development of its Fluoride Salt-Cooled High-Temperature Reactor (KP-FHR) technology. The non-power Engineering Test Unit 2

BWRX-300 USA GE-Hitachi

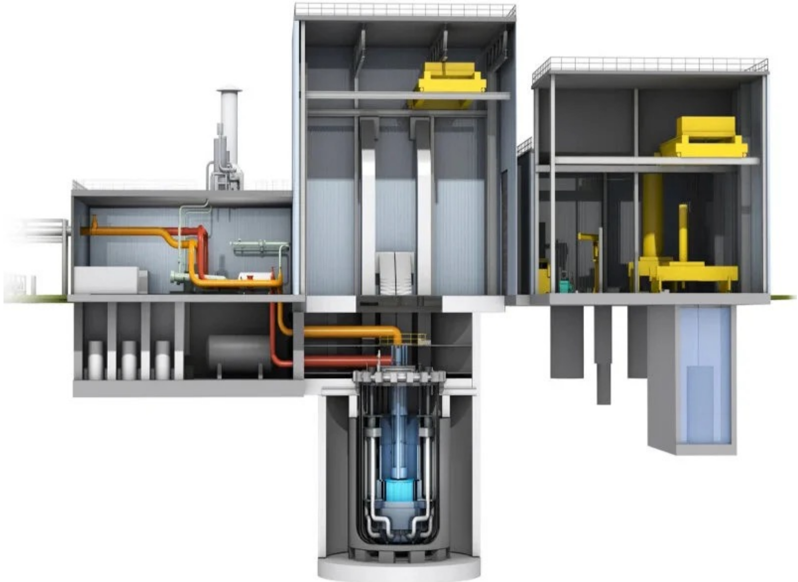
- Boiling water reactor
- ¡Natural Convection!
- 300 MWe

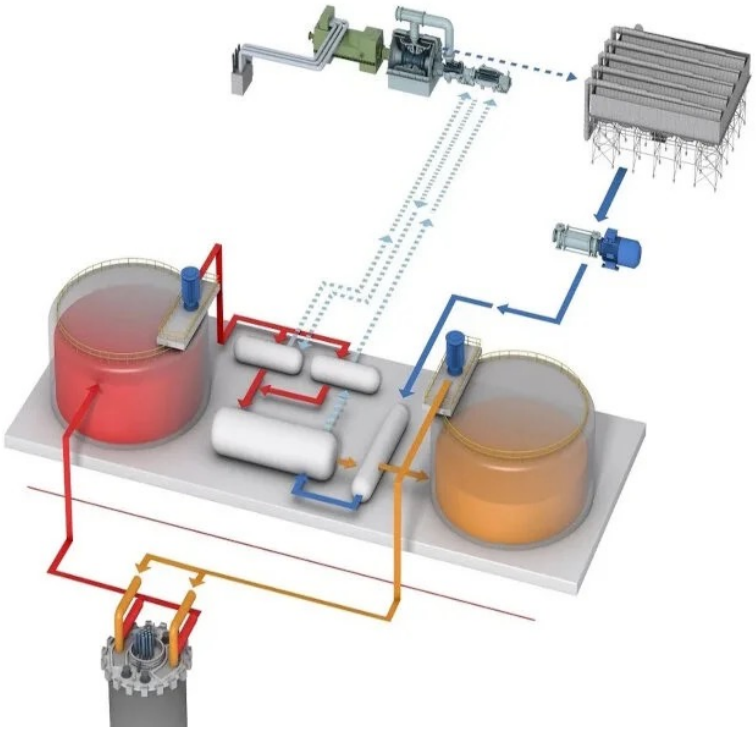


Official construction start in 2023 in Canadá

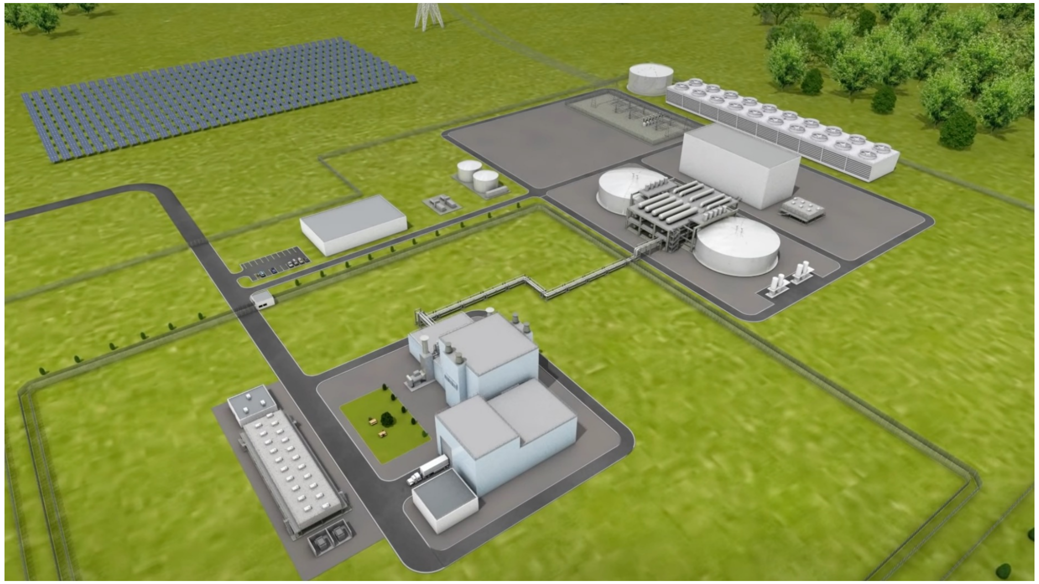
Natrium USA TerraPower & GE Hitachi
SC-FR 345 MWe

- Sodium-cooled fast reactor
- 340 MWe
- Molten salts thermal storage





The groundbreaking ceremony marks the start of non-nuclear construction work at the site (Image: TerraPower)



Natrium

Sodium cooled fast reactor

(Terra Power (Bill Gates) + GE Hitachi)

345 MWe sodium cooled fast reactor, combined with a molten salt energy storage system

Metal fuel, HALEU enriched (Haigh Assay means close to the upper 20% enrichment limit)

U.S. DOE Awards TerraPower $80 Million to Demonstrate Advanced Nuclear Technology (Advanced Reactor Demonstration Program (ARDP), October 13, 2020

The Natrium reactor employs metal fuel that offers improved reactor economics, greater fuel efficiency, enhanced safety, and lower volumes of waste. It uses HALEU, which is not produced in the U.S. today. In September 2021, TerraPower announced that it would initiate efforts with Centrus to build American, commercial-scale enrichment capacity to produce HALEU for the Natrium technology’s metal fuel

The Natrium technology also separates nuclear and non-nuclear facilities and systems within the plant footprint, simplifying the licensing process and lowering construction costs.

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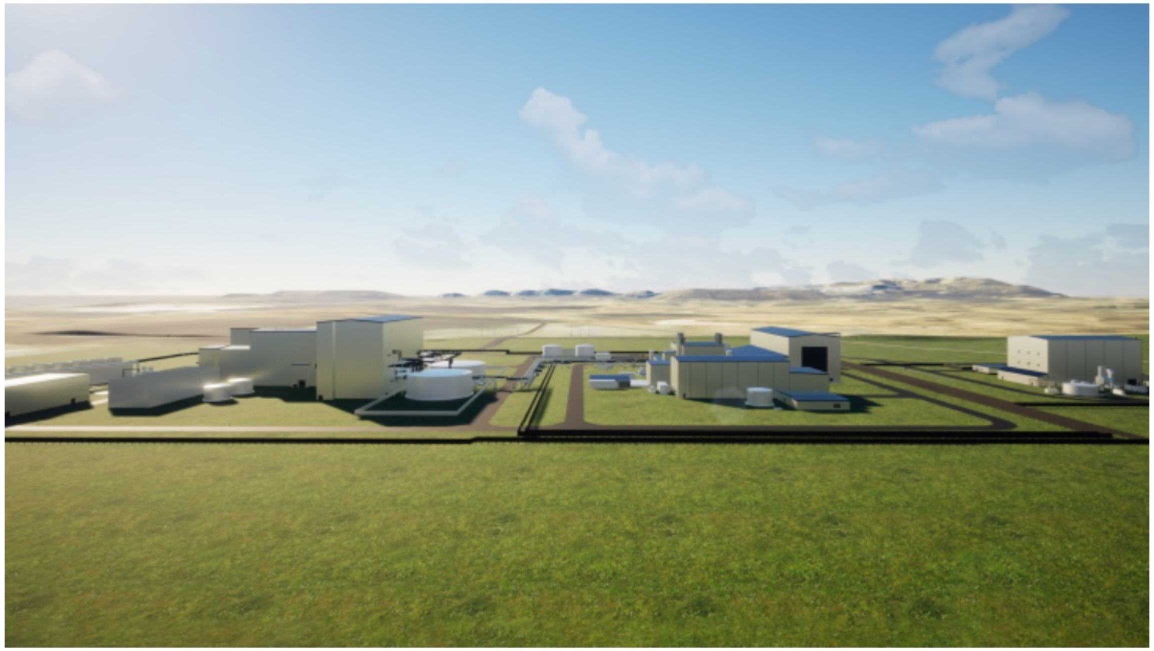
world nuclear news

Suppliers chosen for key components of Natrium demo plant

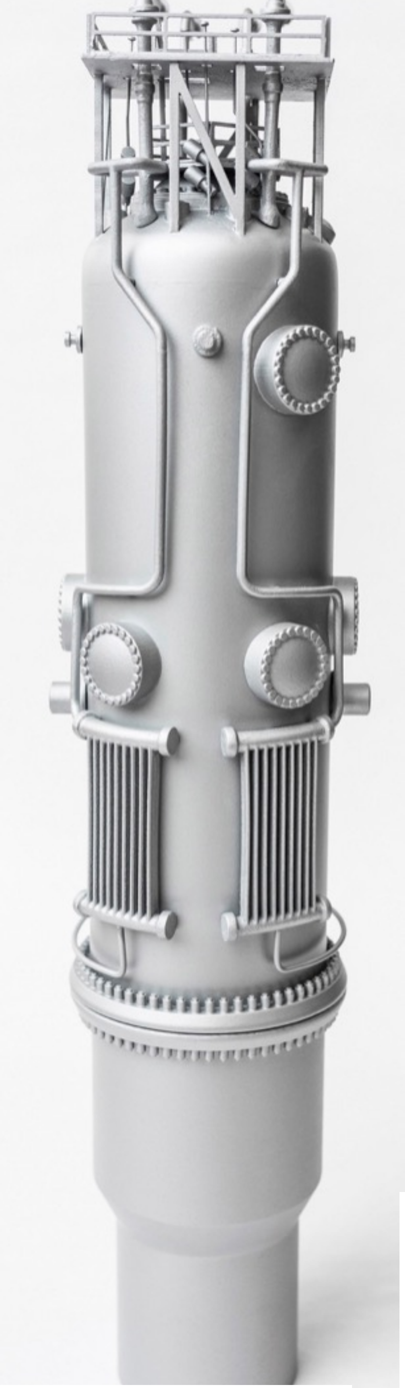
Thursday, 19 December 2024

TerraPower has awarded the major manufacturing contracts for the first Natrium sodium-cooled fast reactor enclosure system. The company says the contracts "represent a significant milestone in the deployment and commercialisation of America's first advanced reactor".



A rendering of a Natrium plant (Image: TerraPower)

Natrium technology features a 345 MWe sodium-cooled fast reactor using high-assay low-



NuScale USA

60 MWe PWR natural convection

NRC licensed in Sept 2020

Proposed 6 units, with the first ready in 2029, in Idaho

But….

The Cost Reimbursement Agreement, DCRA, of January 9, 2023
updated target price of $89 /MWh

The buyer withdrew the offer

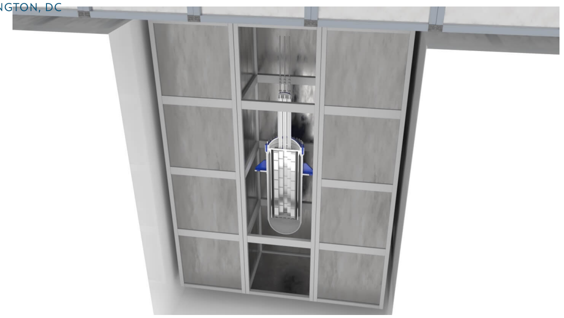
NuScale USA

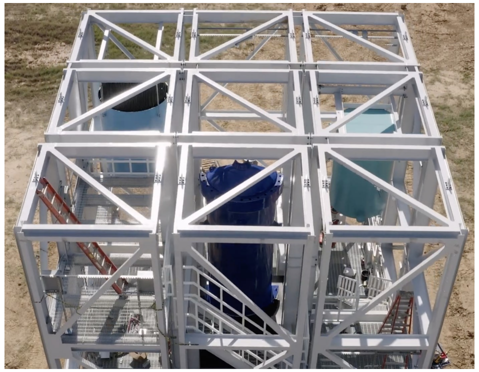
Idaho down - Rumania and Poland up

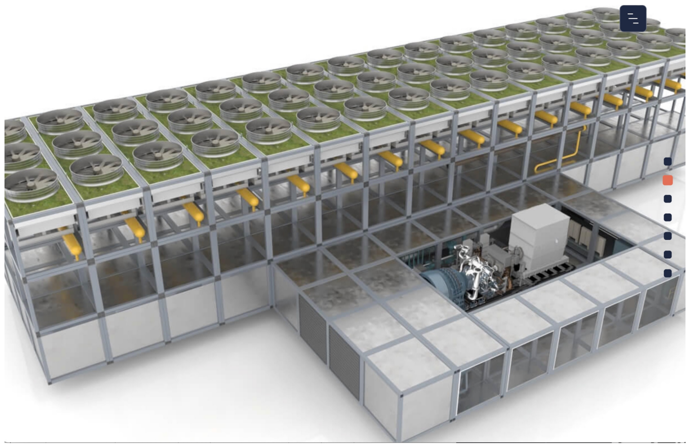
Evolution of Nuscale shares

Last Energy USA

PWR 20 MWe







The reactor is built from standardized modules!

Funding and commercial agreements grow for Last Energy

Thursday, 29 August 2024

US microreactor developer Last Energy announced it has raised USD40 million for its Series B round of funding, bringing total capital raised to USD64 million since the company's founding in 2019. It also said it has now reached commercial agreements for 80 of its microreactors.

European reaction

Alliance created by the European Commission in February 2024

Involves 27 countries

Promotes collaboration

Supports research and development

Regulatory harmonization

Market development

Sustainability and Climate Goals

Nuward - France

300-400 Mwe PWR

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world nuclear news

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French-developed SMR design unveiled

17 September 2019

Share

A new small modular reactor (SMR) design has been announced by the French Alternative Energies and Atomic Energy Commission (CEA), EDF, Naval Group and TechnicAtome. The Nuward - with a capacity of 300-400 MWe - has been jointly developed using France's experience in pressurised water reactors (PWRs).

A design concept for the Nuward SMR (Image: TechnicAtome)

In January 2025, Nuward relaunched its SMR development, unveiling a simplified design delivering 400 MW of power with an option for cogeneration of up to approximately 100 MWt.

Rolls-Royce SMR - UK

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UK SMR to start regulatory process this autumn

17 May 2021

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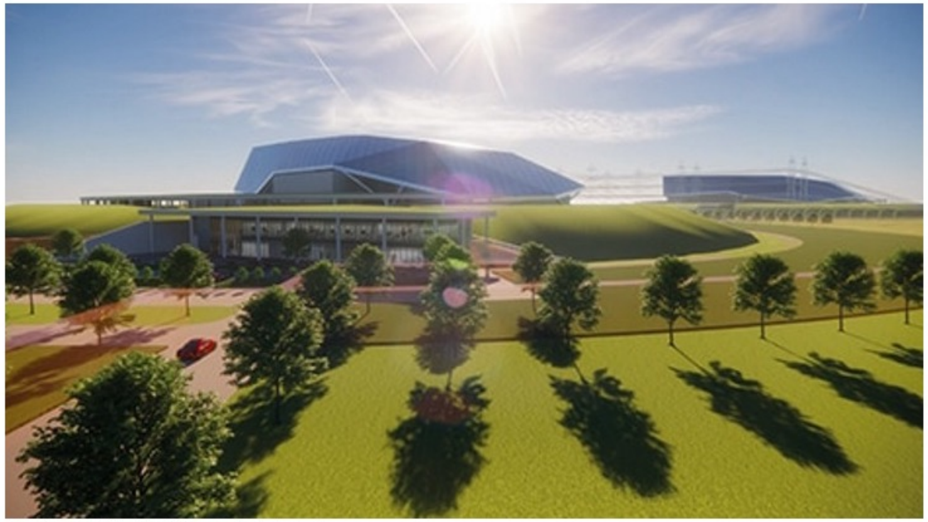
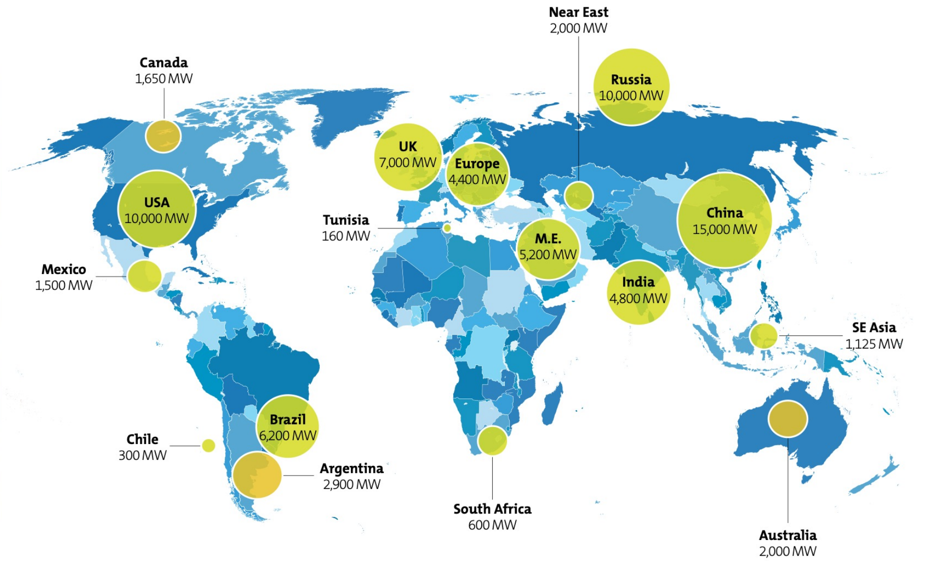
The UK SMR consortium, led by Rolls-Royce, has announced the latest design and an increase in power - from 440 MW to 470 MW - of its "compact" nuclear power station. The "refreshed design" features a faceted aesthetic roof; an earth embankment surrounding the power station to integrate with the surrounding landscape; and a more compact building footprint, the British engineering company said.



How the UK SMR will look (Image: Rolls-Royce)

Marketing

The size of the potential global SMR market, is approximately 65-85GW by 2035, valued at £250-£400bn.



ACP100 - China

small version of ACP1000 – Hualong

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China approves construction of demonstration SMR

07 June 2021

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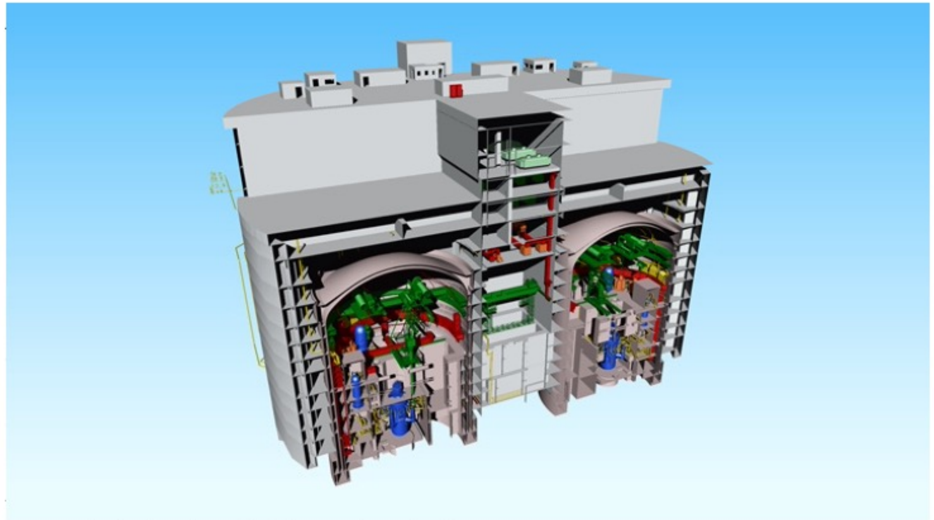
The construction of a demonstration ACP100 small modular reactor (SMR) at Changjiang in Hainan province has been approved by China's National Development and Reform Commission. The multi-purpose 125 MWe pressurised water reactor (PWR) - also referred to as the Linglong One - is designed for electricity production, heating, steam production or seawater desalination.



A cutaway of a plant featuring two ACP100 reactors (Image: CNNC)

125 MWe PWR integral

Uranium Oxide 4.2% enriched

Proyecto comenzado en 2010. concluido en 2014. No comenzo su construccion
En 2016 anunciaron la intencion de construir uno flotante

In negotiation on export: UK, Sweden, Slovenia, Russia, Egypt, Algeria, Sudan, Ghana, Nigeria, South Africa; Iran, Saudi Arabia, Jordan, Armenia, UAE; Pakistan, Malaysia, Kazakhstan, Indonesia; Argentina, Brazil, Mexico, Chile, Uruguay

The preliminary safety analysis report was approved by the National Nuclear Safety Administration in June 2020.

Construction of the 125 MWe reactor is expected to take 65 months, for startup in May 2025, subject to relevant government approvals

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

HPR-100 or Linglong-1

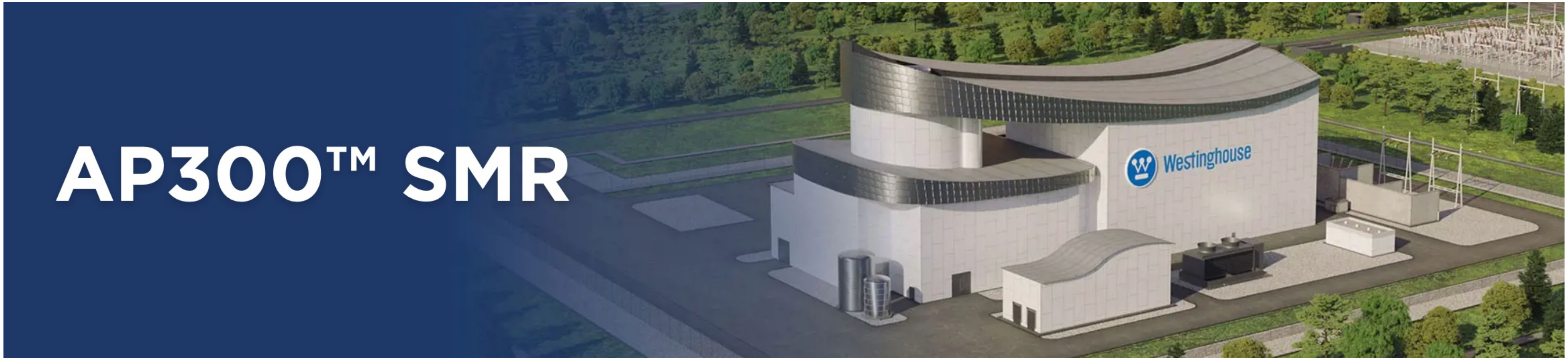
HPR 125 MWe

HPR-100 or Linglong-1, a SMR

Smaller version of the HPR-1000 Hualong 1

PWR, 'integrated' (steam generators inside the RPV)

USA's reaction



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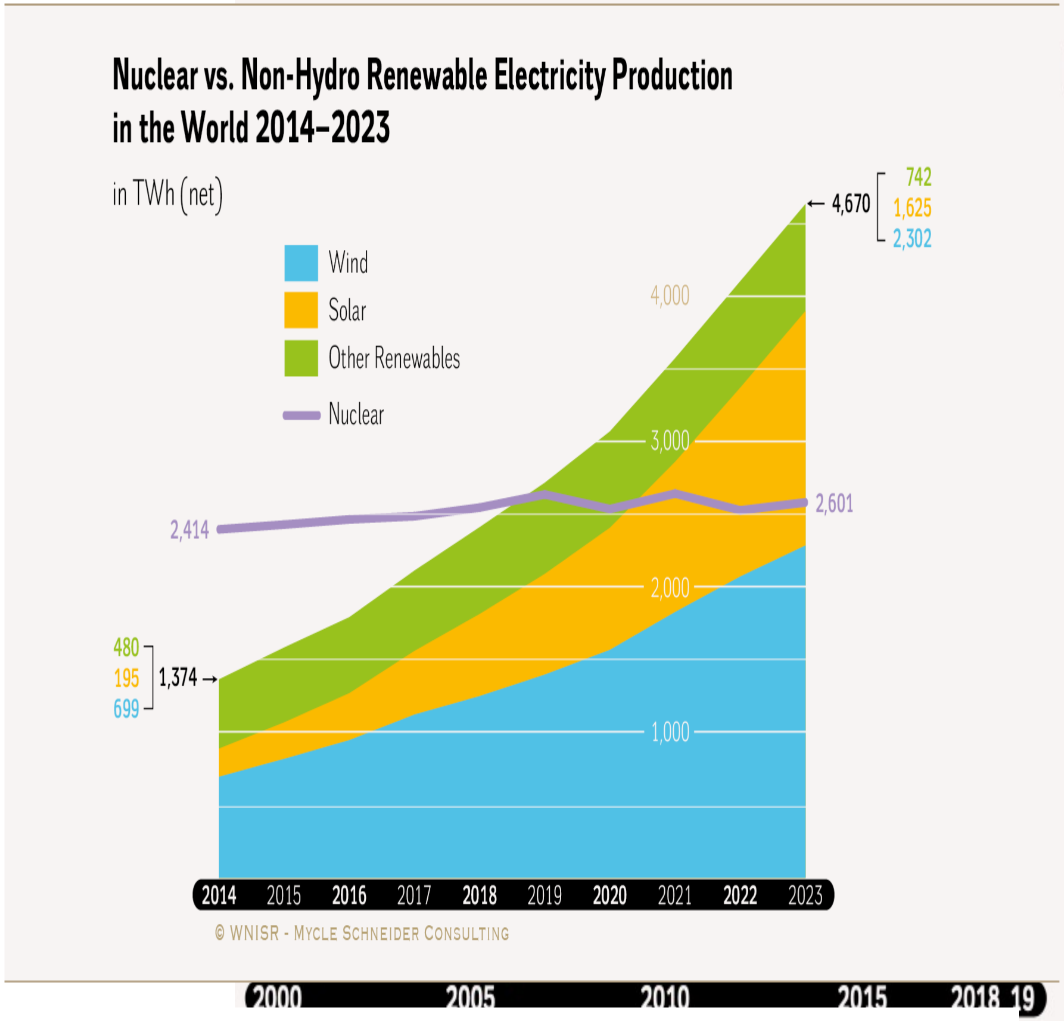
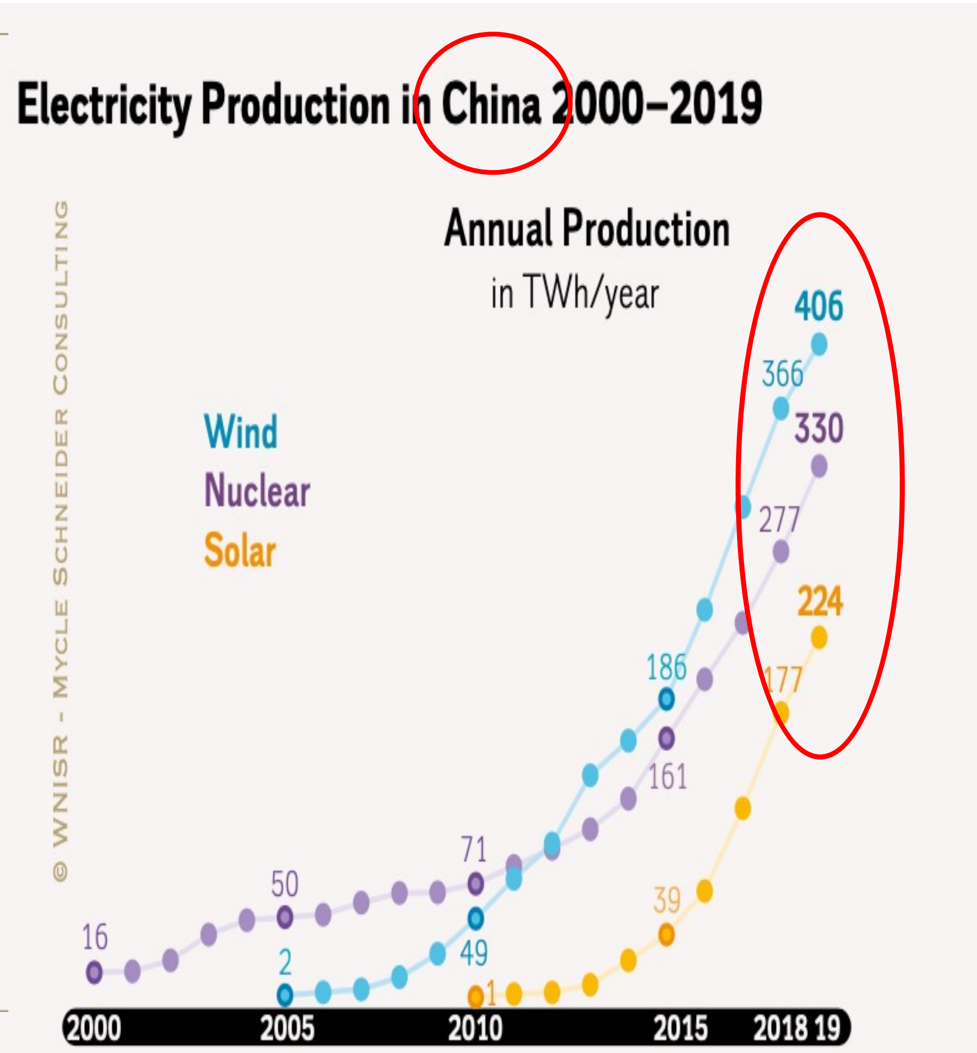
The AP300™ is the most advanced, proven and readily deployable SMR solution

Transformation of the energy matrix

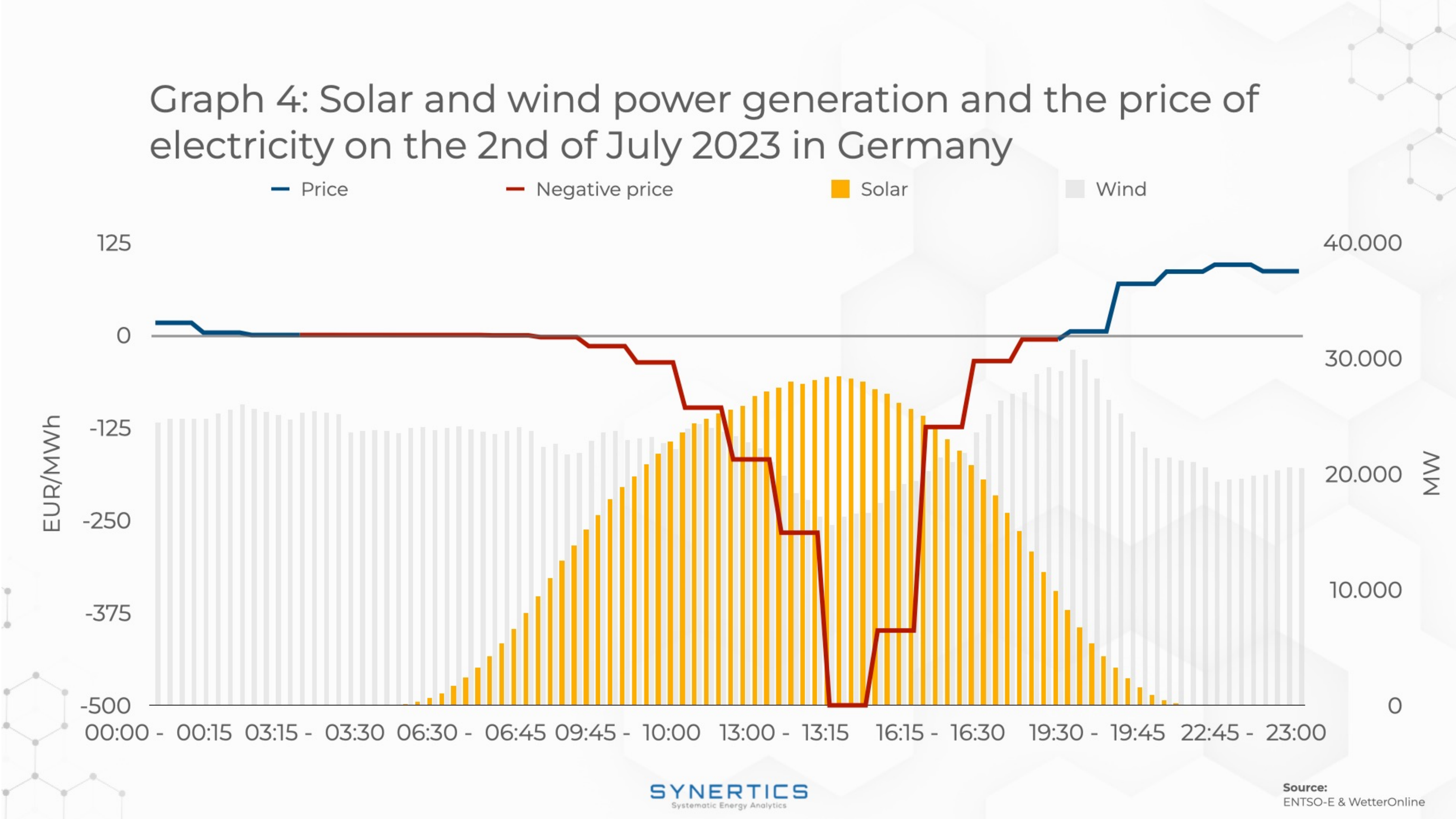
World, and China





In 2019, for the first time, renewables no-hydro generated more electricity than nuclear

Negative price of electric energy?



Conclusions

- Nuclear power has advantages and disadvantages, as any other technology

- Cost is probably the main reason why there is no new constructions of ~1GWe scale facilities

- Impact of accidents in public opinion is probably another reason

- Unresolved waste management is yet another reason

- Other technologies are rapidly coming to age

- The competition will be fierce

- Tax on carbon emissions may level the field


Thank you
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