Economic & Environmental [and Proliferation] Costs & Benefits of Reprocessing

(Repeating mistakes of 75 years ago for no good reason.)

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Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors, 7 June 2021, 1:35 PM

Outline (1945-2021)

- Reprocessing as a route to nuclear weapons
- The uranium scarcity problem, plutonium breeder reactors and reprocessing
- Atoms for Peace and nuclear proliferation (1953-74)
- No uranium scarcity and breeder failure but reprocessing continues in some countries
- Reprocessing and radioactive waste disposal
- The economic failure of conventional nuclear power reactors
- DOE now supporting RD&D on small modular reactors and reprocessing
- What could go wrong?

Reprocessing as a route to nuclear weapons

Reprocessing, like uranium enrichment, was originally developed to produce nuclear weapons

- Uranium enrichment (Hiroshima, 6 August 1945)
- Reprocessing (Nagasaki, 9 August 1945)

The Acheson-Lilienthal (Oppenheimer) *Report on the International Control of Atomic Energy* (16 March 1946) therefore labeled uranium and enrichment and reprocessing as "***dangerous*** activities" and proposed they be put under international control.

We got the Cold War nuclear arms race instead.

The uranium scarcity problem & plutonium breeder reactors

At the beginning of the nuclear era, ***uranium was thought to be scarce***. Leo Szilard estimated US would be able to import only enough to support 2 GWe of U-235 burner reactors.

He therefore invented (March 1945) the liquid-sodium-cooled plutonium "breeder" reactor that would convert U-238 (99.3% of natural uranium) into its own chain-reacting plutonium-239 fuel.

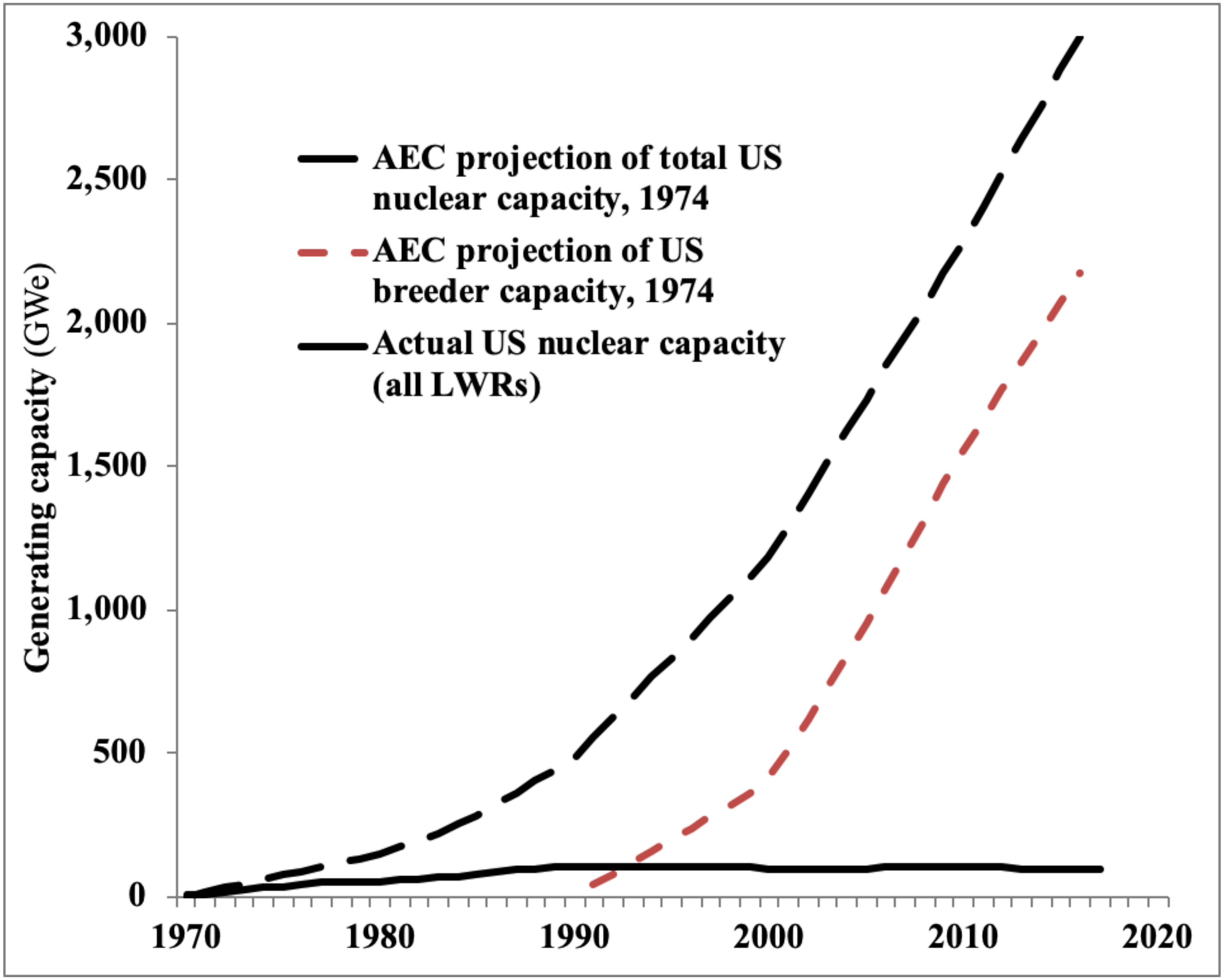
A breeder reactor could, in theory, release from the 3 grams of uranium in average crustal rock energy equivalent to that obtained from the combustion of up to 10 tons of coal ("***burning the rocks***").

Sodium-cooled reactors became focus of US civilian nuclear energy R&D and the ***US Atomic Energy Commission promoted them abroad as part of the Atoms for Peace program*** (1953-)

Light water reactors were developed for submarine propulsion.

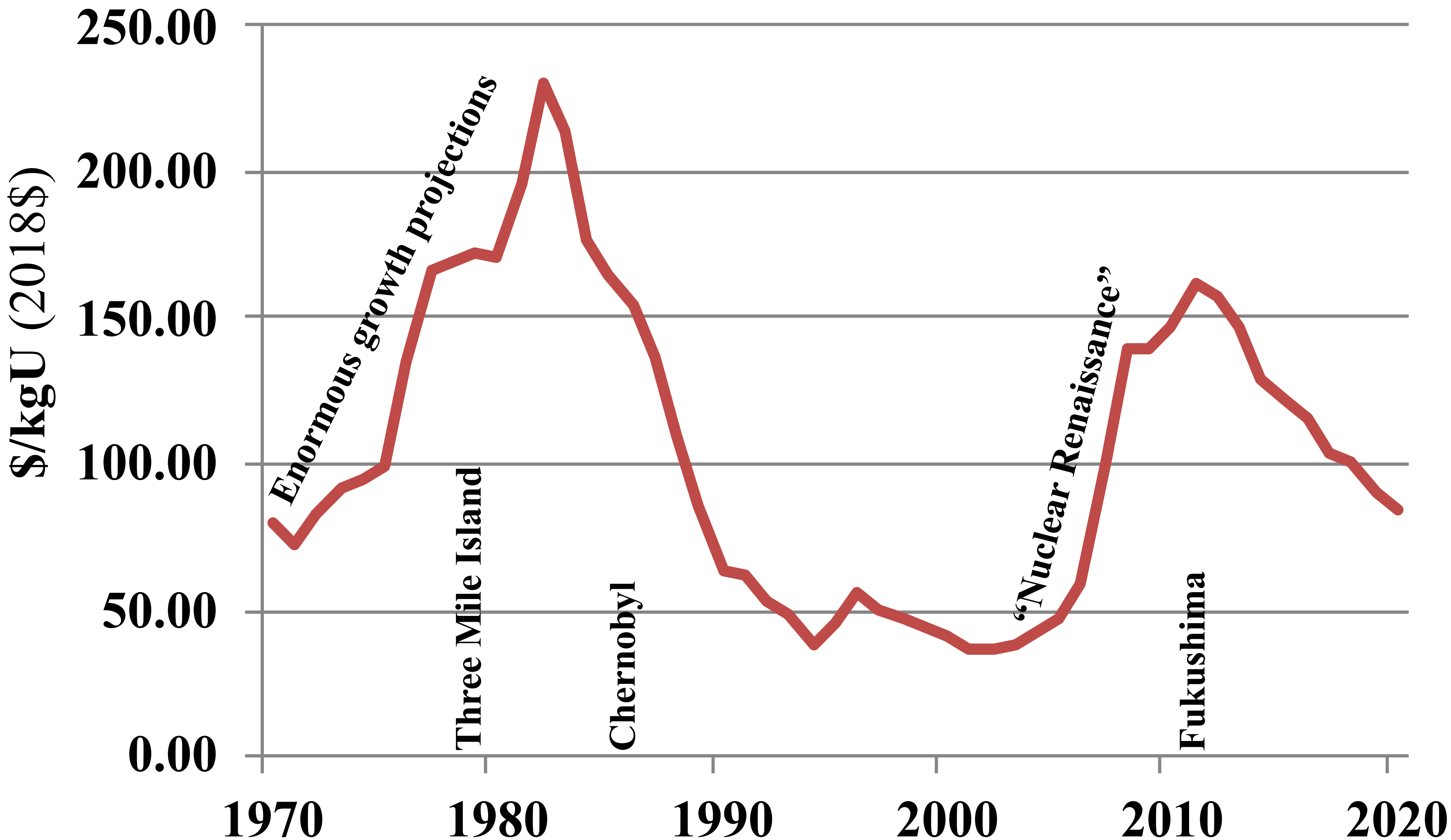
But nuclear power did not grow as fast as expected

(US Atomic Energy Commission, *Proposed Final Environmental Impact Statement: Liquid Metal Fast Breeder Reactor Program*, 1974, Fig. 11.2-27 + actual)



Uranium cost did not increase; uranium costs a declining share (now 3-4%) **of cost of nuclear power**

($100 kg/U → 0.25 cent/kWh vs. 7 cents/kWh for new plant [EIA])



Nuclear proliferation via reprocessing

- **1974.** India's "Smiling Bhudda" nuclear test
- Plutonium produced with 40 MWt heavy-water-moderated, natural-uranium-fueled research reactor provided by Canada and the US AEC and separated with ***reprocessing technology provided by US AEC***.
- US discovered other countries were going down the same track: ***Argentina, Brazil*** (Germany), ***Pakistan*** (France), **South Korea** (France) and ***Taiwan*** (Germany)
- Ford Administration organized the **Nuclear Suppliers Group** (1975) to shut down export of reprocessing and enrichment technology
- Carter Administration review concluded **breeder reactors and reprocessing neither necessary or economic**.
- It was right.

After 8 years of debate over proliferation, US, under the Reagan Administration, abandoned reprocessing and breeder reactors because of cost

1982. US nuclear utilities got Nuclear Waste Policy Act under which DOE will build a repository and take their spent fuel for 0.1 cent/kWh

1983. After 5-fold increase in projected cost of Clinch River Demonstration Breeder Reactor, Congress terminated the project.

1994. Experimental Breeder Reactor II at Idaho National Lab was shut down but bizarrely became the lost Holy Grail* of a significant fraction of US nuclear engineering community – starting with INL.

* "a cup, dish or stone with miraculous powers that provide happiness, eternal youth or sustenance in infinite abundance," https://en.wikipedia.org/wiki/Holy_Grail

Economic failure of grid-connected sodium-cooled reactors worldwide

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Grid-connected fast-neutron reactors	**Power** (MWe)	**Operating**	**Lifetime Capacity Factor**
Demonstration Fast Reactor (U.K.)	11	1962-77	35%
Fermi-1 (U.S.)	61	1966-72	1%
BN-350 (USSR, Kazakhstan, desalinizati	150->50	1973-99	18% (last 8 years)
Phénix (France)	130	1973-2010	40%
Prototype Fast Reactor (U.K.)	234	1976-94	18%
BN-600 (Russia)	560	1980-	76%
Superphénix (France)	1200	1986-98	3%
SNR-300 (Germany)	300	safety concerns	0%
Monju	246	1995-2017	0%
China Experimental Fast Reactor	20	2011-	4% (through 2016)
BN-800 (Russia)	789	2015-	68%
Median (average) **performance**			**18** (**24**)%
Light water reactors	***890***		***80%***
Clinch River Breeder Reactor (U,S.)	350	too costly	***not completed*** (1983)
Prototype Fast Breeder Reactor (India)	470	under construction	**dual purpose?**
China Fast Reactor-1	600	under construction	***dual purpose?***
China Fast Reactor-2	600	under construction	***dual purpose?***

IAEA, Power Reactor Information System

~ $100 B, 30 sodium fires in Russia. Admiral Rickover after pulling a sodium-cooled reactor out in his 2nd nuclear submarine (~1957): they are "***expensive to build, complex to operate, susceptible to prolonged shutdown as a result of even minor malfunctions, and difficult and time-consuming to repair***."

Civilian reprocessing continues elsewhere

(Holy Grail effect?)

- **United Kingdom,** with no new reprocessing contracts, foreign or domestic, will end in 2022 with 140 tons of separated plutonium (including 22 tons of marooned Japanese Pu). ***(~20,000 Nagasakis***)
- **Russia** has accumulated 100 tons, including 40 tons of excess weapon plutonium. ***Reprocessing began in 1977; first plutonium use*** **(*BN-800*)** ***in 2015.***

  Rosatom has deferred construction of BN-1200 until it can be convinced it can compete with its VVER-1200.
- **France and Japan** suspended their fast-reactor programs but ***require all LEU spent fuel to be reprocessed***. Fast-reactor programs suspended. Plutonium recycled in LWRs. Mixed oxide (MOX) fuel costs ~10x LEU fuel cost (including reprocessing).
- **India, China** are building prototype breeders. ***Suspected of being dual-purpose: electric power plus production of plutonium for weapons in blanket***.
- **South Korea.** Nuclear-energy R&D establishment wants same right to reprocess as Japan. ***Public wants a nuclear deterrent against DPRK.***

The Spent Fuel Repository Problem

1987. Amendments to Nuclear Waste Policy Act (NWPA) designated ***Yucca Mountain*** as site of the first US radioactive waste repository.

Nevada pushed back and project stalled.

Obligated by NWPA to start taking spent fuel by 31 January 1998, ***DOE began paying for on-site dry cask storage after spent fuel pools filled up***.

2001. V.P. Cheney's 2001 National Energy Policy Development Group promoted **pyroprocessing as "proliferation resistant" way to drastically reduce the amount of radioactive waste.** (6-lab study in 2009: pyroprocessing not significantly more proliferation resistant than PUREX.*)

2006. G.W. Bush Administration proposed ***Global Nuclear Energy Partnership*** (GNEP) as a way to "solve" the spent fuel problem by reprocessing without causing proliferation. Nuclear weapon states and Japan would reprocess their own and other countries' spent fuel and "burn" the plutonium and minor transuranics in fast-neutron reactors.

Bush Administration told Congress reprocessing would cost less than dry cask storage (~$100/kgU, 0.025 cents/kWh).

* R. Bari et al, "Proliferation Risk Reduction Study of Alternative Spent Fuel Processing," Brookhaven National Laboratory, 2009, https://www.bnl.gov/isd/documents/70289.pdf.

DOE has commissioned previous Academy reviews on potential spent fuel management benefits of separation and transmutation

- ***1996. Nuclear Wastes: Technologies for Separations and Transmutation***

  "The once-through LWR fuel cycle should not be abandoned…***Taken alone, none of the dose reductions seem large enough to warrant the expense and the additional operational risk of transmutation.***"

  2008. Review of DOE's Nuclear Energy Research & Development Program

  "all committee members agree that the GNEP program should not go forward and that it should be replaced by a less aggressive research program."

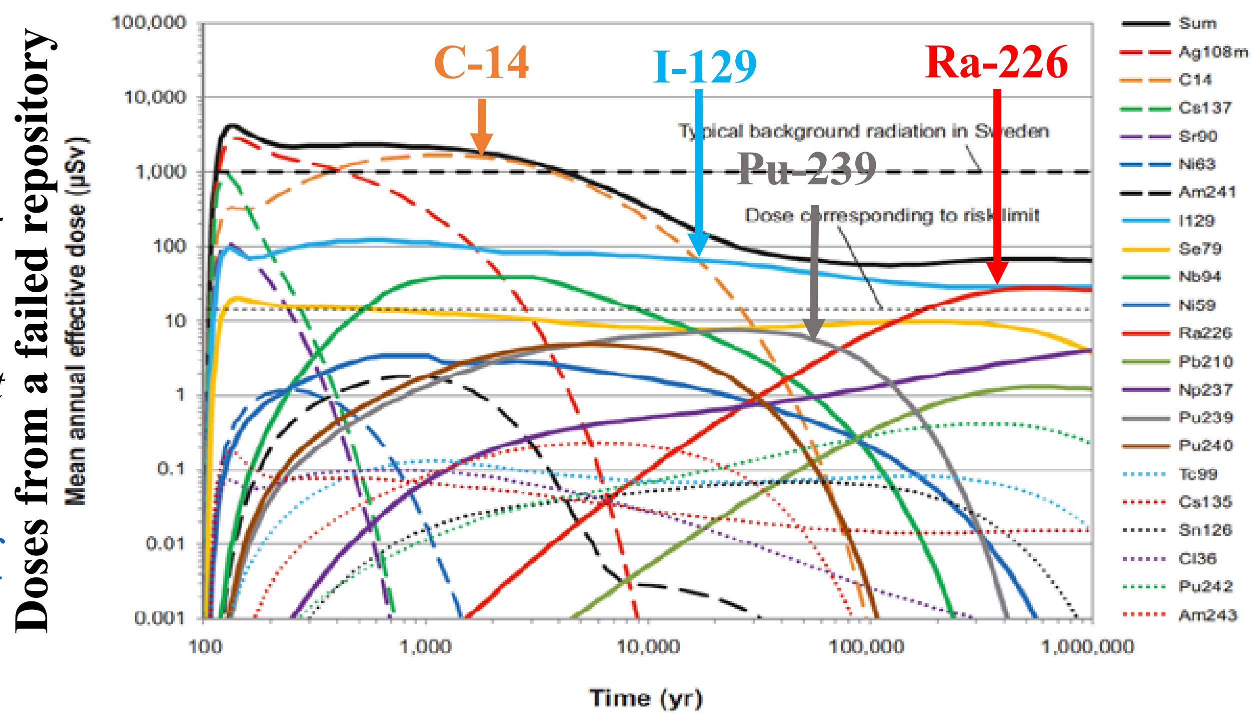
  (GNEP [Global Nuclear Energy Partnership] was the Bush Administration's proposal to share the benefits of reprocessing globally with the weapon states and Japan doing the reprocessing and keeping the plutonium and transuranics for fuel and "possibly ultimate disposition."*)

* https://www.energy.gov/sites/default/files/edg/media/GNEPfactsheet.pdf.

Reprocessing and Radioactive Waste Disposal

- ***Objectively***, deeply disposed spent fuel is not a serious hazard compared to nuclear-weapon proliferation, spent-fuel pool fires or reactor meltdowns.
- ***Politically****,* siting is difficult. Finland, France and Sweden have succeeded. (France reprocesses. Finland and Sweden do not but have sited their repositories next to nuclear power plants.)
- ***Separation and fissioning transuranics.*** Costs a lot, creates proliferation danger, but does not achieve much dose reduction from a failed repository.

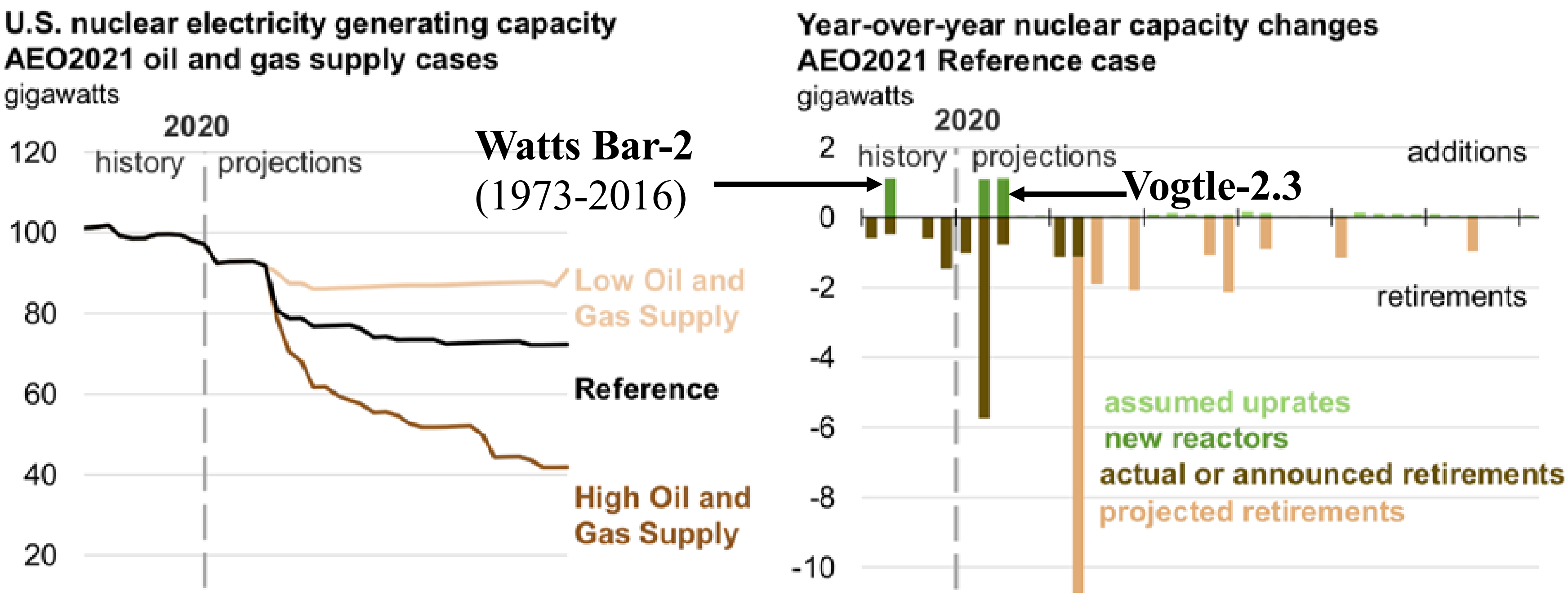
Subsistence farmer over a repository with failed casks and bentonite clay barrier (SKB, *Long-Term Safety for the Final Repository for Spent Nuclear Fuel at Forsmark [Sweden]: Main Report of the SR-Site Project,* TR-11-01, Vol. 3, 2011, Fig. 13-63, [http://skb.se/upload/publications/pdf/TR-11-01_vol3.pdf)](http://skb.se/upload/publications/pdf/TR-11-01_vol3.pdf)



Economic failure of conventional LWRs (~1 Gwe)

2013. VC Summer 2,3 and Vogtle 3,4, first construction starts in US since 1970s. Huge cost overruns. VC Summer 2,3 cancelled, Westinghouse bankrupted, Vogtle 3,4 to be completed at an estimated cost of $25-30 billion with DOE loan guarantees of $12 billion.

2021. DOE's Energy Info Admin: *no* new nuclear capacity before 2050.



DOE promoting *both* small modular reactors & reprocessing

2012. Originally small LWRs based on naval reactors. DOE chose Babcock & Wilcox, 180 MWe for 50-50 cost share. ***B&W dropped out in 2017***.

NuScale (45 → 77 MWe LWRs) up to $1.4 billion DOE funding for 12→4-6)

Now, DOE funding old reactor concepts as "advanced":

- ***X-energy, HTGR; Terrapower, molten salt***
- INL is focused on sodium-cooled reactors:
- ***Pu-fueled Versatile Test Reactor for INL, 300-MWe EBR II***, $3-6 billion
- ***Natrium*** (Terrapower), ***345-MWe EBR II***, ***HALEU*** $80 million + cost-share
- ***ARC-100*** (Canada), ***100-MWe scale up of EBR II; Oklo, 1.5 MWe***

Moltex (Canada), ***300-500-MWe molten salt reactor plus small reprocessing plants*** to extract plutonium from CANDU reactor spent fuel, $50.5 million from Canadian government. ***Promises to make Canada an industrial hub for exporting these reactors and reprocessing plants – under IAEA safeguards.***

5/19/2021. ***ARPA-E put out a request for proposals for reprocessing R&D***

What could go wrong?