REVIEW OF COMMERCIAL NUCLEAR FUEL REPROCESSING

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Arjun Makhijani, Ph.D.
President, Institute for Energy and Environmental Research,

www.ieer.org
arjun@ieer.org

REPROCESSING BASICS

Underlying the resource thinking about commercial reprocessing

- In the 1950s, uranium was thought to be a scarce resource.
- Uranium is the only natural material that contains a fissile isotope (U-235) – i.e., that can sustain a chain reaction and can be used as a fuel for reactors and bombs. (Thorium-232 is plentiful but not fissile – see note).
- Only about 0.7% of natural uranium is U-235. Essentially all the rest is uranium-238.
- But U-238 + neutron → U-239 → neptunium-239 + beta particle → plutonium-239 + beta particle gives a new, man-made fissile material. The Nagasaki bomb Pu was made at Hanford in this way.
- But neutrons are also needed to sustain the chain reaction and split U-235 to yield energy.
- To use the uranium resource more fully, there must be enough neutrons for the chain reaction plus neutrons to convert U-238 to Pu-239 in amounts greater than the amount of U-235 consumed. Breeding ratio (amount of Pu-239 produced to U-235 used up) needs to be greater than one. That way the fissile materials stock can be built up even as the uranium (235) resource is being consumed for power production (or bombs).
- Sodium-cooled reactors (aka “fast reactors” or “fast neutron reactors”) were the technology of choice because of a good breeding radio – up to 1.4. Light water reactors have a breeding ratio of about 0.4. (Ratio >1 means more fuel produced than was used.)
- Rough rule of thumb: About one ton of fissile material (U-235 or Pu-239) per year is consumed and turned to fission products in a 1,000 MW-electrical nuclear reactor.

BUT….

- On the order of $100 billion (circa 2020 dollars) cumulative have been spent worldwide to commercialize sodium-cooled reactors and associated reprocessing. The effort has not been successful to date.
- A lot of the problem has been with the liquid sodium – it burns on contact with air and explodes on contact with water. Sodium leaks have been a major issue.
- Some sodium-cooled reactors have operated reasonably well; others have not.
- The latest sodium-cooled reactors in the OECD countries were failures. France’s Superphénix operated at an average capacity factor of about 7% over 14 years before being shut in 1998. Monju, in Japan was closed in 1995 soon after opening due to a sodium-leak fire. It opened briefly after 15 years, but it had many more problems and has been shut permanently.
- Uranium turned out to be quite plentiful. Far fewer reactors than projected in the early years of nuclear power were built. The 1970 estimate for the year 2000 for the U.S. was 1,000 reactors; only 120 were built and commissioned.

Uranium basics

Natural uranium composition

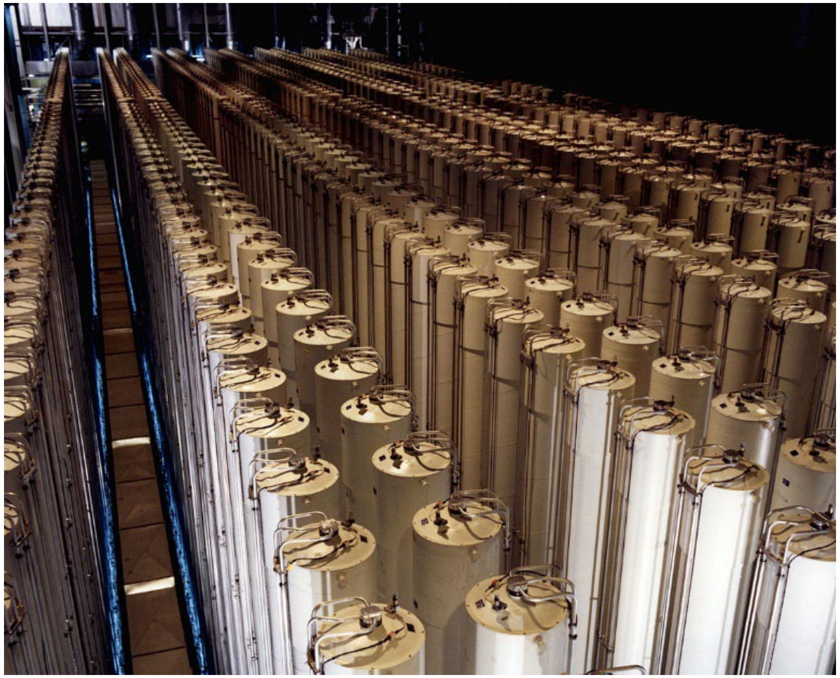
- U-238: 99.284%
- U-235: 0.711%
- U-234: 0.0054% (it is a decay product of U-238). Almost half the radioactivity of nat.-U is in U-234.
- Plutonium-239 is about 100,000 times more radioactive (per unit mass of material) than natural uranium.

Notes re: uranium as fuel

- Natural uranium can be used as fuel directly – as in heavy-water-moderated CANDU reactors and some graphite moderated reactors (both are low-neutron absorption moderators).
- In light water reactors, the fissile component, U-235, needs to be "enriched." Typical enrichment is from 0.711 percent in natural-U to 4% in the fuel. (U-234 also selectively goes with the U-235 since it is the lightest isotope of natural U.)

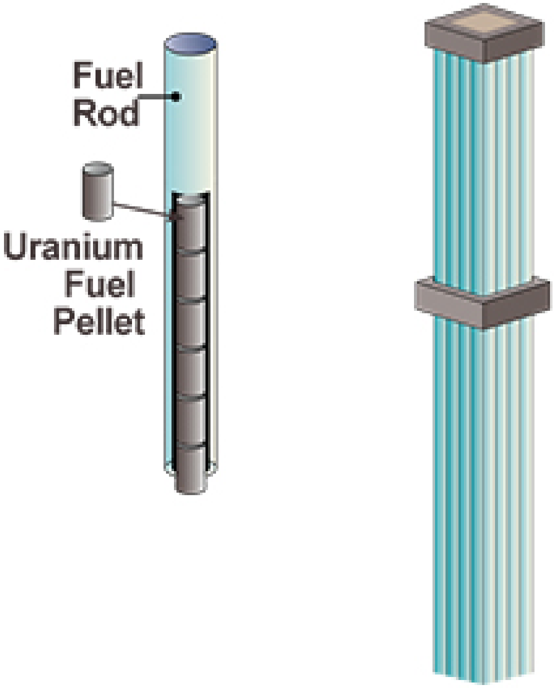
Uranium enrichment: 7.4 kg natural uranium, 1 kg enriched uranium fuel(4% uranium-235), 6.4 kg depleted uranium

Uranium enrichment - centrifuges



Depleted uranium waste cylinders (historical, US)

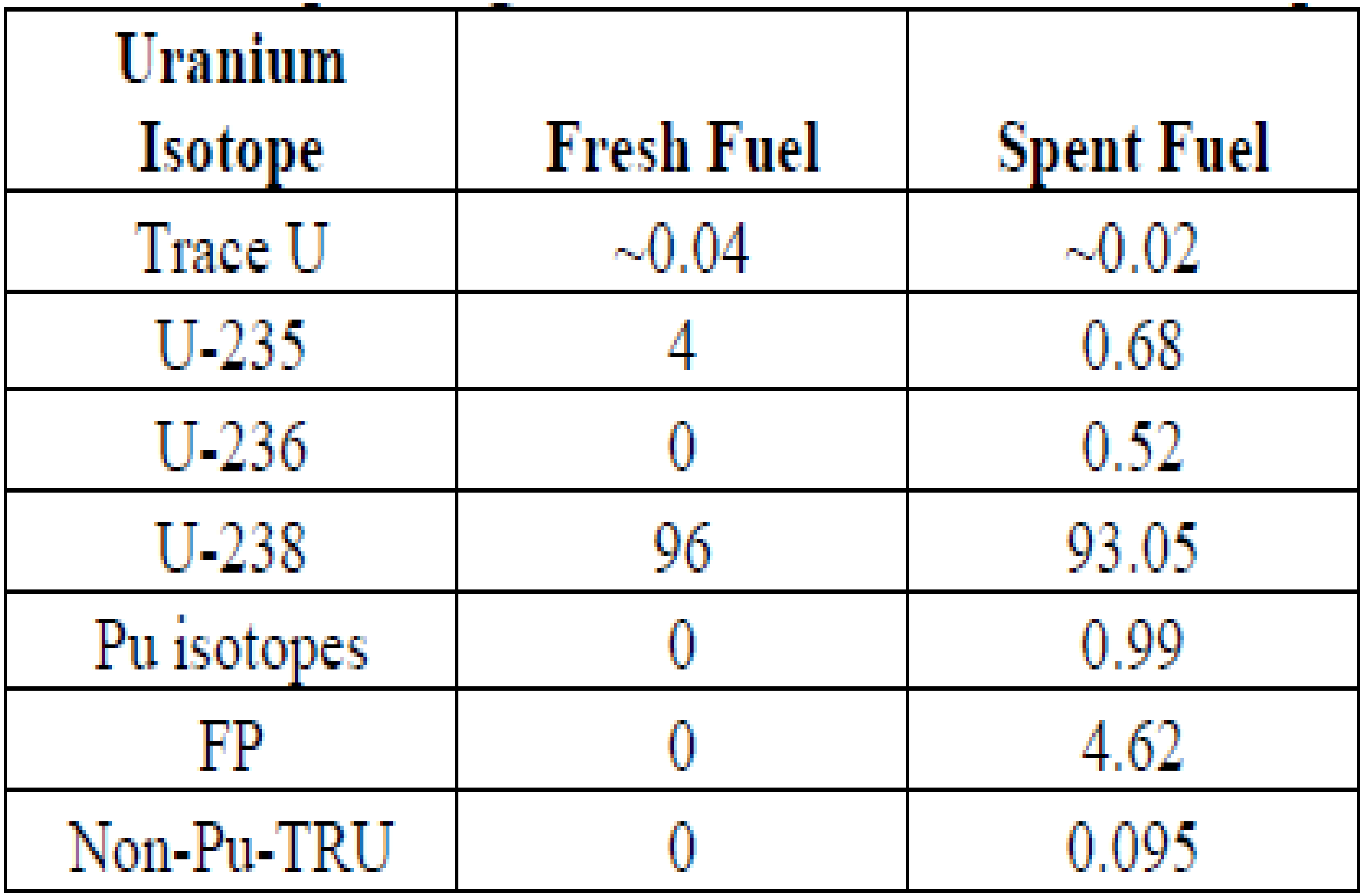
Fuel assemblies:157 in a 1,000 MW pressurized water reactor. ~150 million fuel pellets.



Fuel assembly

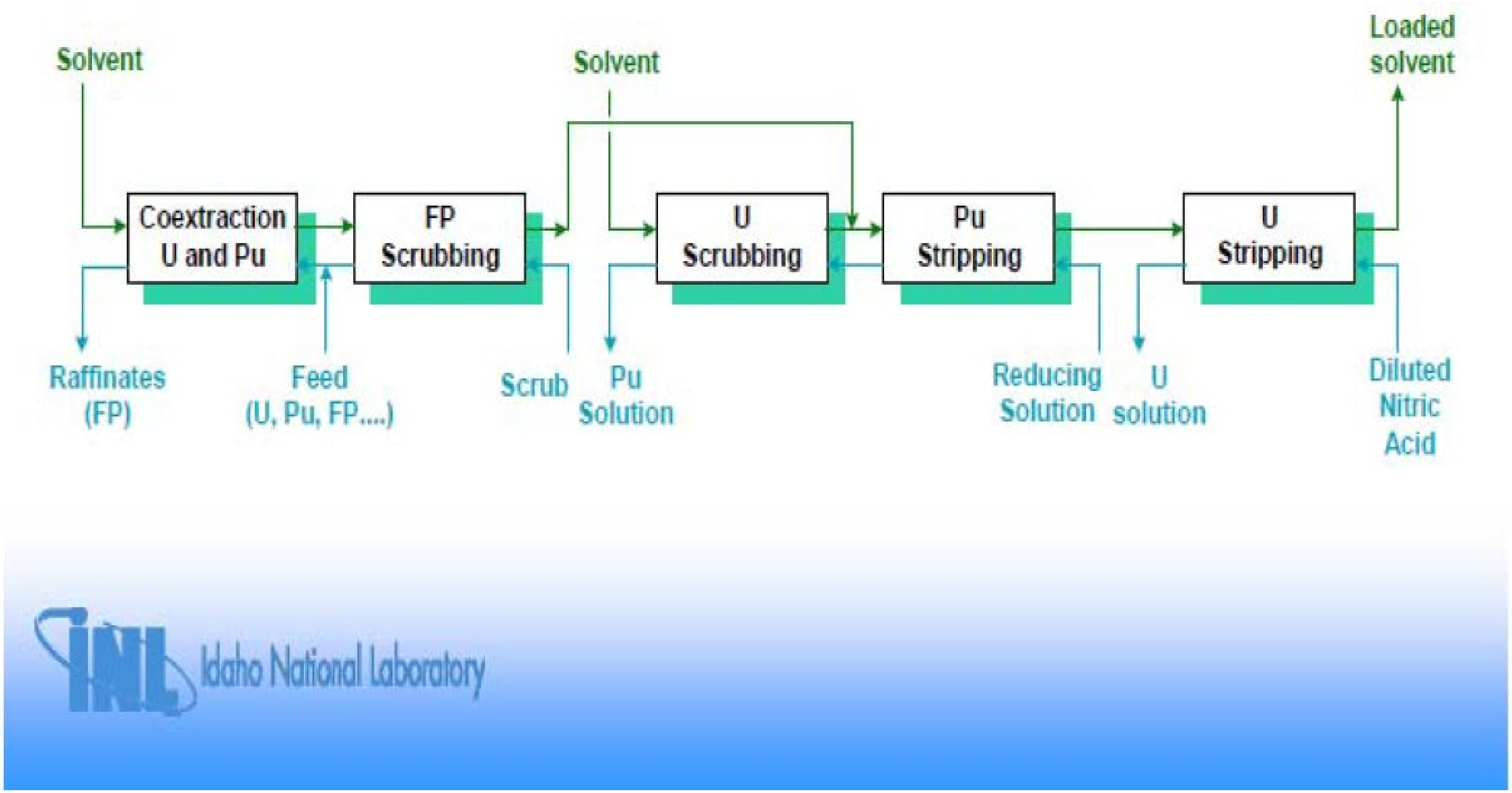
Spent fuel assemblies are typically 14 feet (4.3 meters) long and contain nearly 200 fuel rods for PWRs and 80–100 fuel rods for BWRs.

Fresh reactor fuel and spent fuel composition in percent. Typical values for 4% U-235 fuel for a PWR (FP = Fission Products; TRU = transuranic elements; Pu = plutonium). See Note for details.



Uranium Isotope	Fresh Fuel	Spent Fuel
Trace U	~0.04	~0.02
U-235	4	0.68
U-236	0	0.52
U-238	96	93.05
Pu isotopes	0	0.99
FP	0	4.62
Non-Pu-TRU	0	0.095

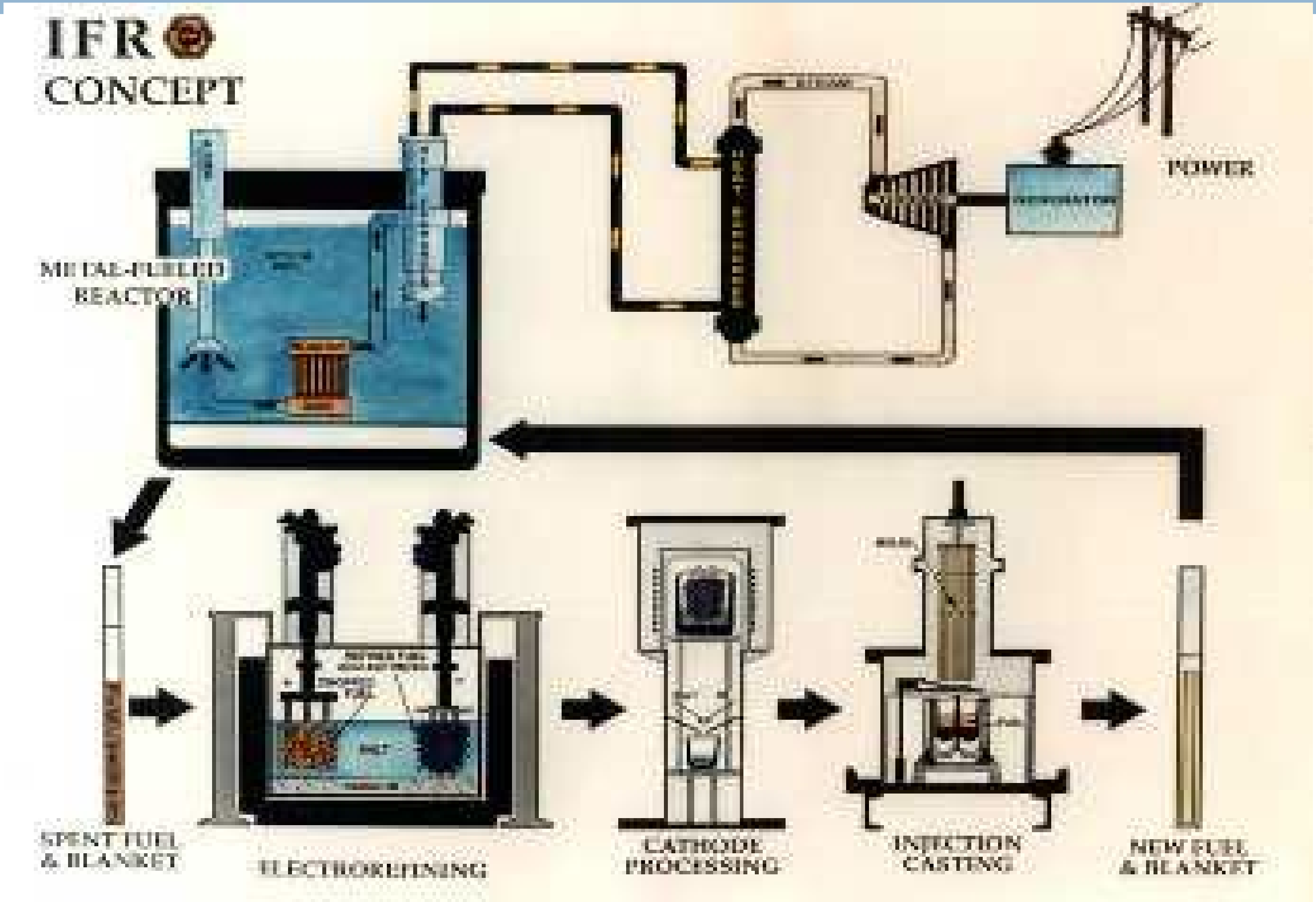
PUREX reprocessing schematic (most common for light water reactor spent fuel – used at La Hague for instance). FP = fission products.



Electrometallurgical reprocessing

- Developed at Idaho National Laboratory starting in the 1980s.
- Electrometallurgical reprocessing (aka “electrorefining” or “pyroprocessing”) has been proposed for sodium-cooled reactor fuel as well as for molten salt reactors.
- Often proposed as “inline” processing, where each reactor has a reprocessing plant on site.
- However, a standalone plant can also be built.
- Oklo is planning to build an electrometallurgical reprocessing plant in Tennessee. (It is also planning to build sodium-cooled small modular reactors).

Onsite ("inline") reprocessing + reactor. The "Integral Fast Reactor" (IFR) concept



SOME WASTE, PROLIFERATION, COST, SAFETY ISSUES

DOE comparison of radioactive waste volumes in a 200 light-water-reactor system: direct spent fuel disposal compared to reprocessing. Reprocessing does NOT obviate the need for a waste repository. It increases repository waste volume (see data for France in Slide 14.) This slide assumes that GTCC waste will be disposed of in a deep geologic repository (see Note).

System	Spent fuel or High-level waste	GTCC waste	Total repository waste	Low-level waste	Annual radiological transports (rail + truck)
LWR once-through	70,990	2,500	73,490	150,000 to 585,000	165,000
LWR with reprocessing	52,000	407,000	459,000	1,740,000 to 2,175,000	1,224,000
Ratio with/without reprocessing	0.73	163	6.2	3.7 to 11.6	7.4

Radioactive waste in France (see note)

- French policy is to reprocess light water reactor spent fuel when the fresh fuel was enriched uranium.
- France needs a high-level waste repository. Besides high-level waste, medium-activity long-lived waste also will be disposed of there. As of 2022 the volumes for a repository were
  - High-level waste: 4,420 cubic meters
  - Medium activity waste: 39,600 cubic meters
- Repository disposal may include some long-lived low-activity waste (mainly radioactive graphite from retired reactors): 104,000 metric tons.
- Other items (as of 2022), not yet designated as a waste but may be in the future, in all or in part:
  - Surplus separated plutonium: 70 metric tons.
  - MOX spent fuel: 2,460 metric tons (may or may not be reprocessed)
  - Reprocessed uranium: 34,600 metric tons
  - Depleted uranium: 331,000 metric tons (no realistic path to usage)
- All waste categories are growing due to continued use of nuclear power. Large uncertainties about additional waste volumes.
- Potential repository being investigated in the Meuse-Haute Marne region.

Grades of Pu – isotopic composition in percent. Pu-240 has higher spontaneous fission probability (hence limited by design in weapon-grade Pu to limit pre-detonation risk).

	Pu-238	**Pu-239 (main fissile isotope)**	**Pu-240 (problematic for fuel)**	**Pu-241 (decays into Am-241 with 14.4 year half-life)**	**Pu-242**
Weapon-grade	~0	93+	~6	Low (~0.1 to 0.5)	~0
Reactor-grade (40 MWdth per MTHM)	3	55	22	14	6

Proliferation concerns

- Reactor-grade plutonium can be used to make nuclear weapons.
- Uranium enrichment and reprocessing technologies represent the most difficult part of the weapon-making problem: the capacity to make weapon-usable materials.
- Global weapons-usable commercial plutonium stocks are now over 300 metric tons (~40,000 Nagasaki-bomb equivalent); over 2x global weapons stock.
- Japan, a non-nuclear weapon state, has large stocks of separated commercial plutonium.
- India used Atoms for Peace facilities to build the “peaceful nuclear explosive” detonated underground in 1974. This contributed to the U.S. reassessment of commercial reprocessing.
- Inline reprocessing, for instance as proposed for the Integral Fast Reactor, would mean each reactor would have weapons-usable separated material, complicating safeguards and inspections.
- US spent fuel stock of 90,000 metric tons has ~800 to 900 metric tons reactor-grade Pu, which would be equivalent to ~100,000 Nagasaki-bomb equivalent, if separated.

Some safety issues

- The PUREX process generates highly acidic liquid waste containing almost all the highly radioactive fission products.
- These liquid wastes are stored in stainless steel tanks. They generate an immense amount of heat and need to be cooled.
- A prolonged failure of electricity (a few days) and the cooling system would dry out the waste, which could lead to an explosion.
- A complete loss of power (including a failure of emergency backup) occurred at the La Hague reprocessing plant in France in April 1980. Only a spare generator from a military arsenal nearby saved the day.
- A high-level waste tank explosion would contaminate vast areas for hundreds of years.
- A high-level waste tank explosion due to loss of cooling occurred in 1957 at the Mayak nuclear weapons plant in the Soviet Union. About 6,000 square miles (about 15,000 square kilometers) were contaminated and dozens of towns and villages had to be evacuated.

NOTES ON NUCLEAR FUEL RESOURCES

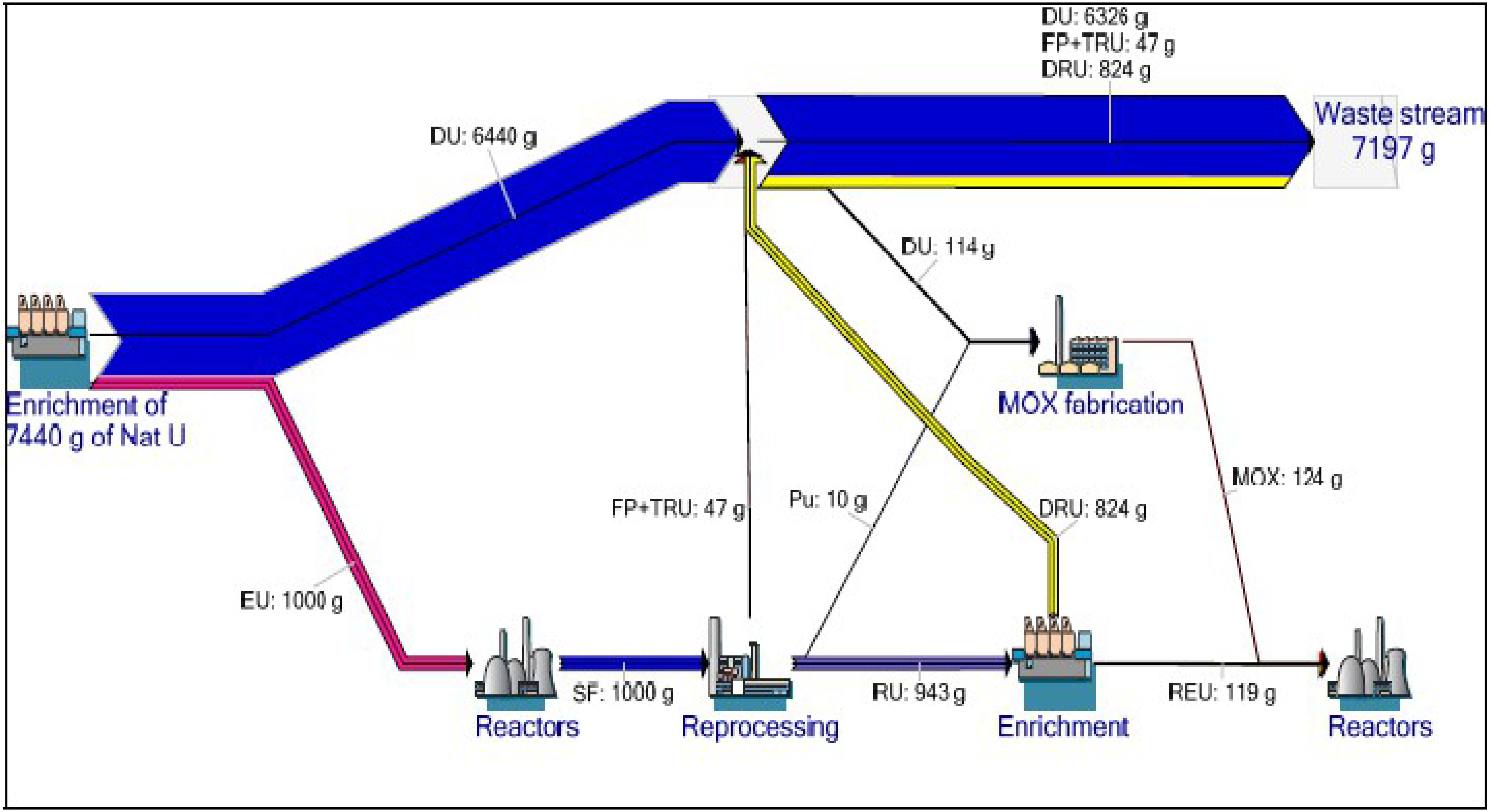
Uranium reserves

- Current world requirement for power reactors: almost 70,000 metric tons of natural uranium per year.
- Global uranium reserves are ~10 million tons (various estimates depending on price). This does not include uranium in seawater, which contains billions of tons of uranium.
- Price in the 1950s was $20/kg U (AEC procurement price), which is about $180/kg U in 2024 dollars (using the producer price index). The average price paid by US purchasers in 2024 was $137/kg U. (See Notes 1and 2.)
- A sustained significant price increase could spur sustained exploration, potentially greatly increasing reserves – as happened with oil after the large crude oil price increases of the 1970s.

Perspective on reprocessed uranium

- Light water reactor spent fuel has about the same U-235 concentration as natural uranium (Slide 8 above). Uranium recovered in reprocessing can be re-enriched to make LWR fuel. This is complex due to trace contamination with plutonium and other radionuclides. The depleted uranium that results from re-enriching reprocessed uranium is also similarly contaminated.
- Uncontaminated depleted uranium (DU) can be obtained at lower cost and from enrichment plants, such as the one in New Mexico, if it is needed for breeder reactors.
- France sent its reprocessed uranium to the Soviet Union/Russia for re-enrichment, transferring pollution externalities there. They have not yet committed resources to build dedicated domestic facilities to re-enrich reprocessed uranium. Stocks of reprocessed uranium stocks were at 34,600 metric tons by 2022 (Slide 14 above) and are set to grow further.

Resource material balance for a light-water reactor system with reprocessing. Even repeated reprocessing would not use more than about 1 percent of the natural uranium resource. See note.



Perspective on plutonium from spent fuel for use in light water reactors

- Reprocessing and plutonium fuel fabrication as a mixed oxide (MOX) fuel increases cost.
- IEER calculated that, circa 2000, France spent an added 2.3 cents/kWh for electricity from MOX fuel more than natural uranium fuel. The annual added cost was $1.4 billion.
- In France, MOX fuel only displaces about 10% of natural uranium requirements at huge economic and environmental cost. It creates new waste management and disposal problems (relative to natural uranium spent fuel). See Slides 13 and 14.
- At about 130 metric tons, Britain has the world's largest stock of separated commercial plutonium. It is not being used as a fuel. Britain's MOX fuel plant was closed in 2011. Reprocessing has also been ended.
- Conclusions: Separating plutonium from spent fuel increases cost, safety risks, and proliferation risks relative to using natural uranium fuel.

Some resources

- **Reprocessing**: Arjun Makhijani (201). *The Mythology and Messy Reality of Nuclear Fuel Reprocessing*, IEER. http://www.ieer.org/reports/reprocessing2010.pdf

- **Reprocessing proliferation risk**: R.Bari et al. (2009). *Proliferation Risk Reduction Study of Alternative Spent Fuel Processing*, Brookhaven National Laboratory, July. http://www.bnl.gov/isd/documents/70289.pdf

- **Transmutation**: H. Zerriffi and Annie Makhijani (2000). *The Nuclear Alchemy Gamble*, IEER. http://www.ieer.org/reports/transm/report.pdf