INSTITUTE FOR ENERGY AND ENVIRONMENTAL RESEARCH

NUCLEAR POWER

An overview slide presentation on the basics, climate, environmental justice, health, security, and outstanding issues.

Short presentation portion with supplementary slides
(U.S. data)
2024-12-13 (typos corrected and minor clarifications, 2024-12-17)

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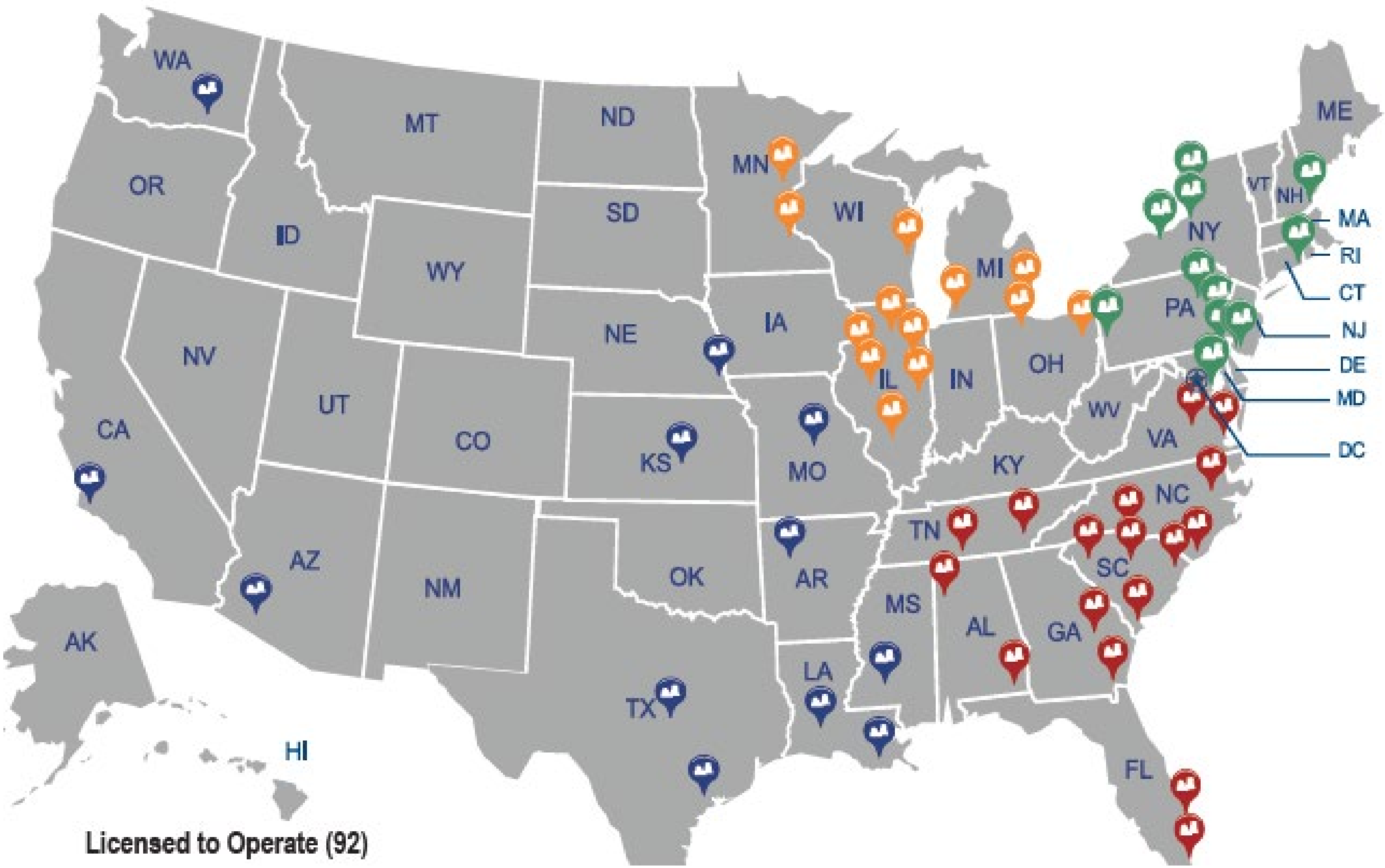
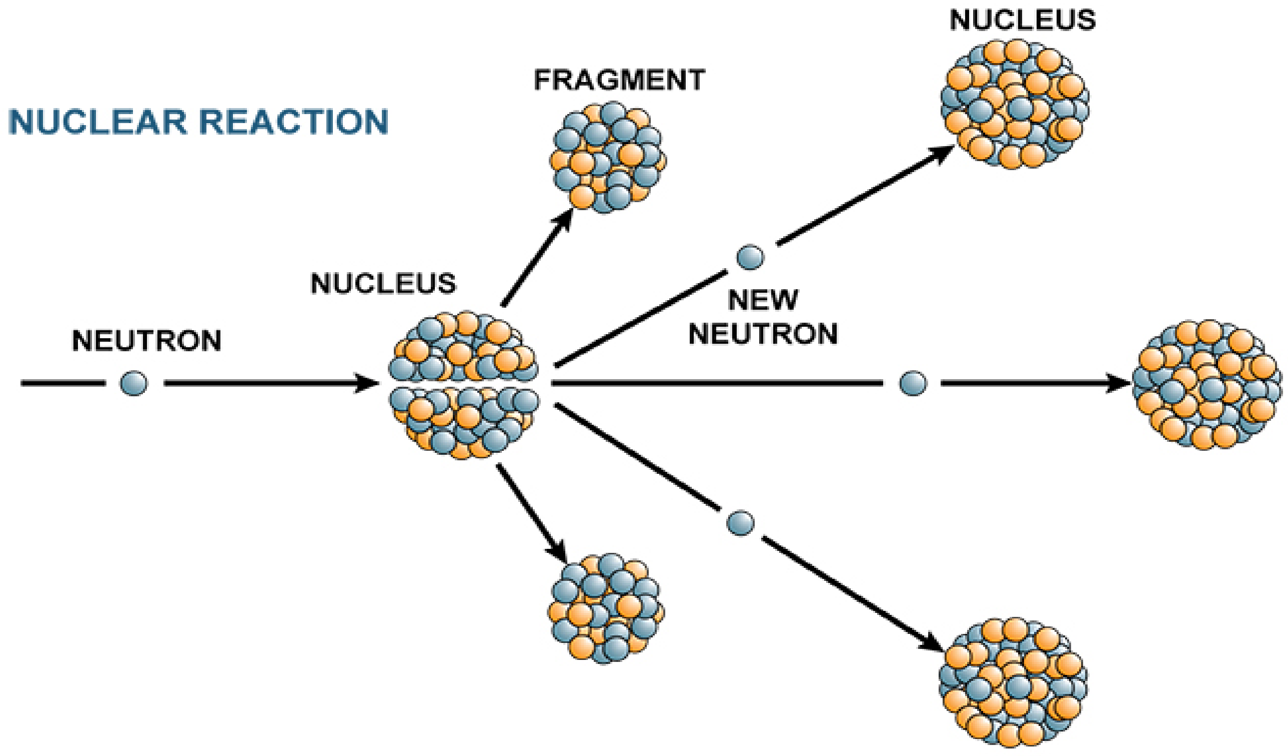
FUEL, REACTOR, AND POWER PRODUCTION BASICS

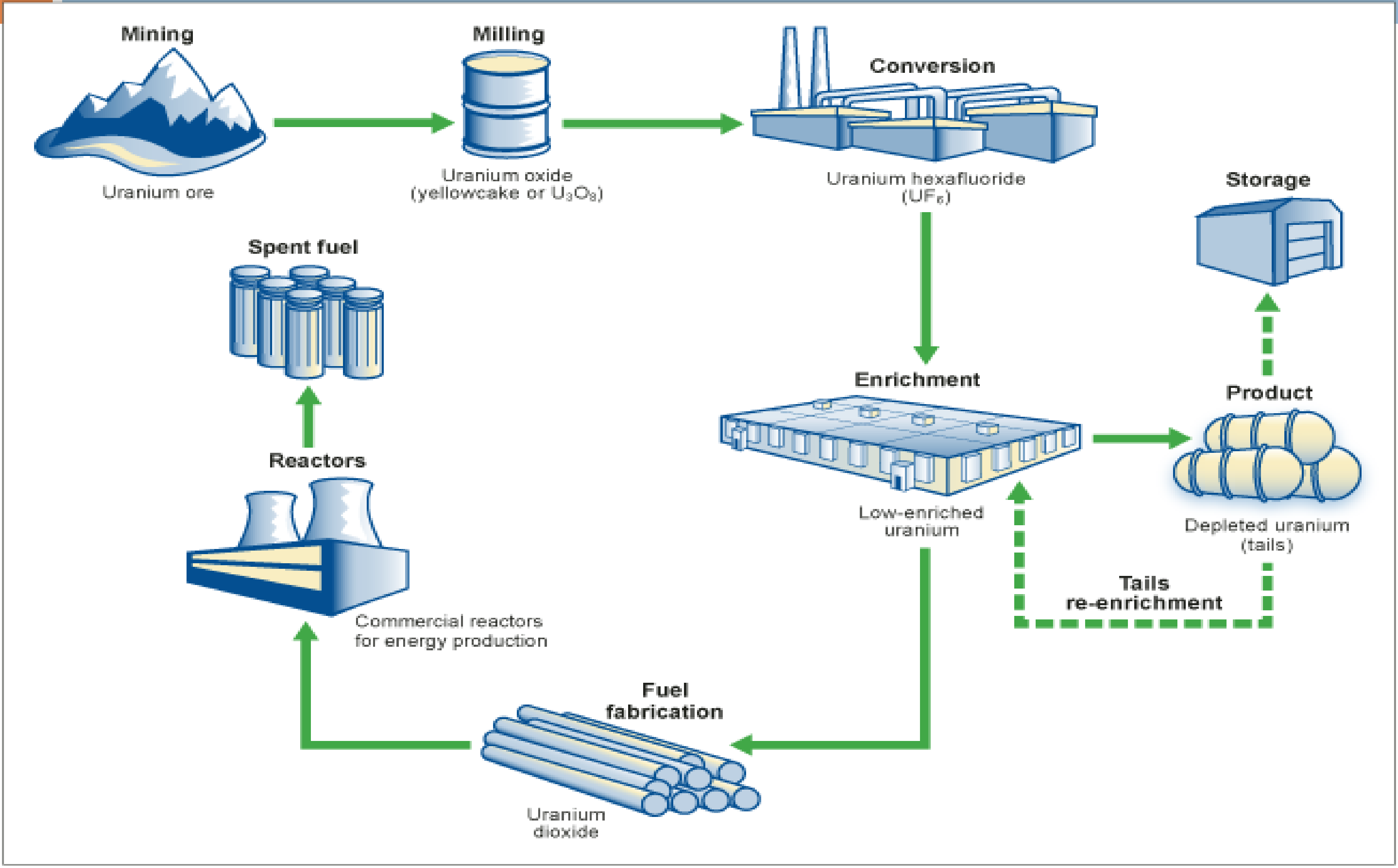
92 operating reactors (~20% of electricity supply) in 2022 + 2 new in Georgia = 94



Nuclear fission: ~0.09% of the mass of uranium-235 converted to energy ($E=mc^2$)



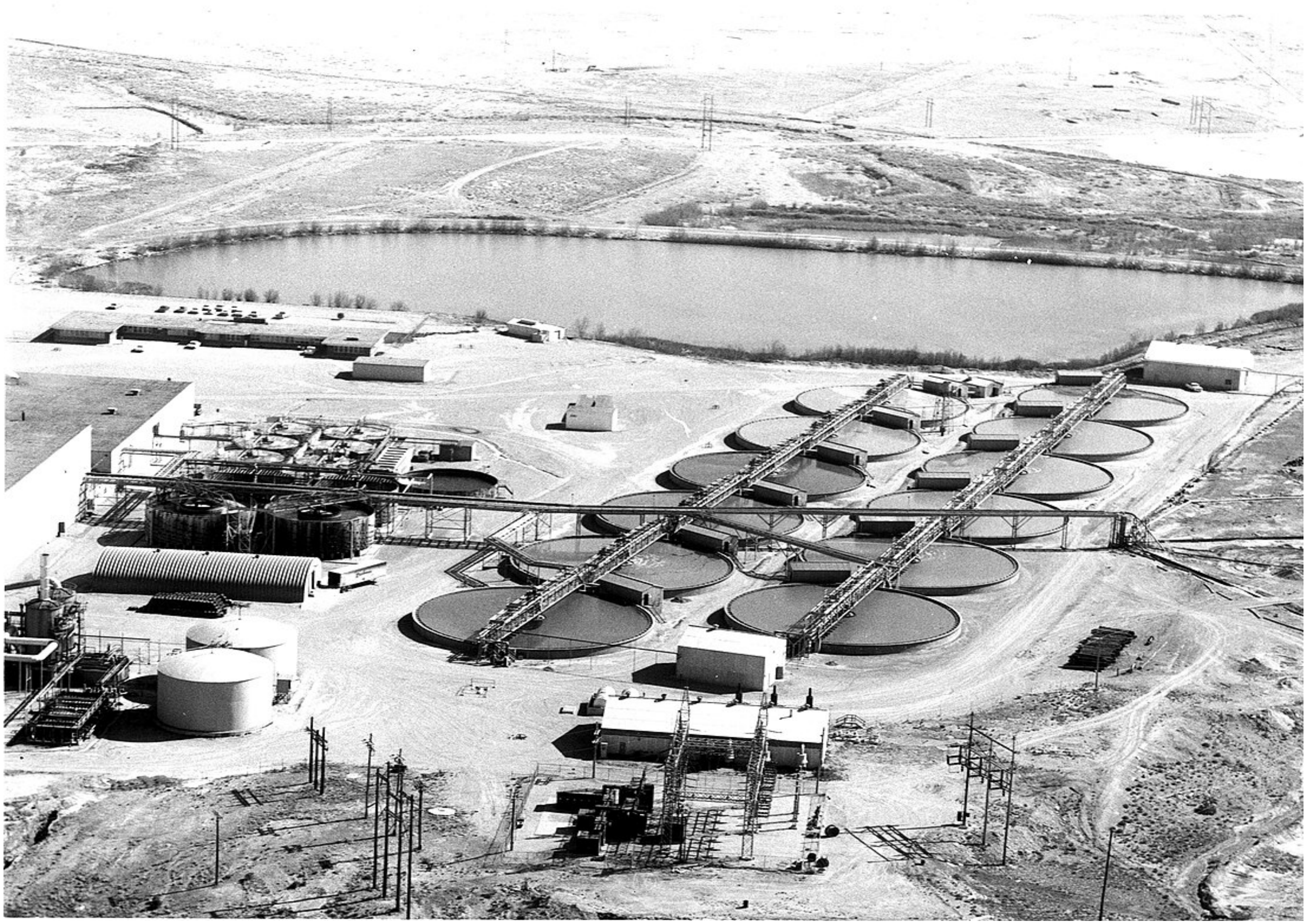
Uranium – mining, processing, use, waste



Sources: GAO analysis of International Atomic Energy Agency, Nuclear Regulatory Commission, Congressional Research Service, Department of Energy, and Tennessee Valley Authority documents.
GAO-17-472T

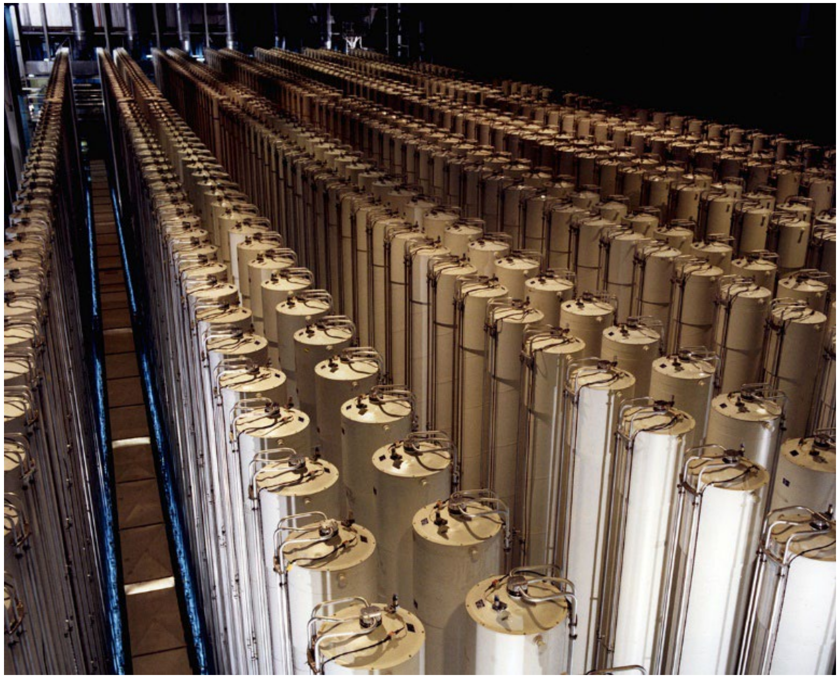
Uranium mine, Grants, New Mexico, ca. 1968. (Ores typically range from ~0.4% to ~10% uranium; Congo Shinkilobwe ores were much richer)

Uranium mill and tailings pond, New Mexico



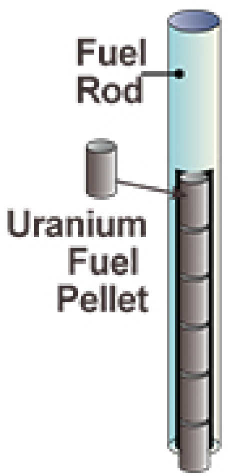
Uranium enrichment: 7.4 kg natural uranium, 1 kg enriched uranium fuel(4% uranium-235), 6.4 kg depleted uranium

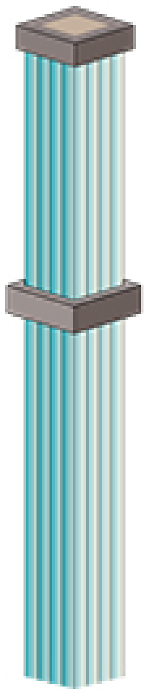
Uranium enrichment - centrifuges



Depleted uranium waste cylinders

Fuel assembly (~150 assemblies/large reactor). 15 million fuel pellets in a large reactor

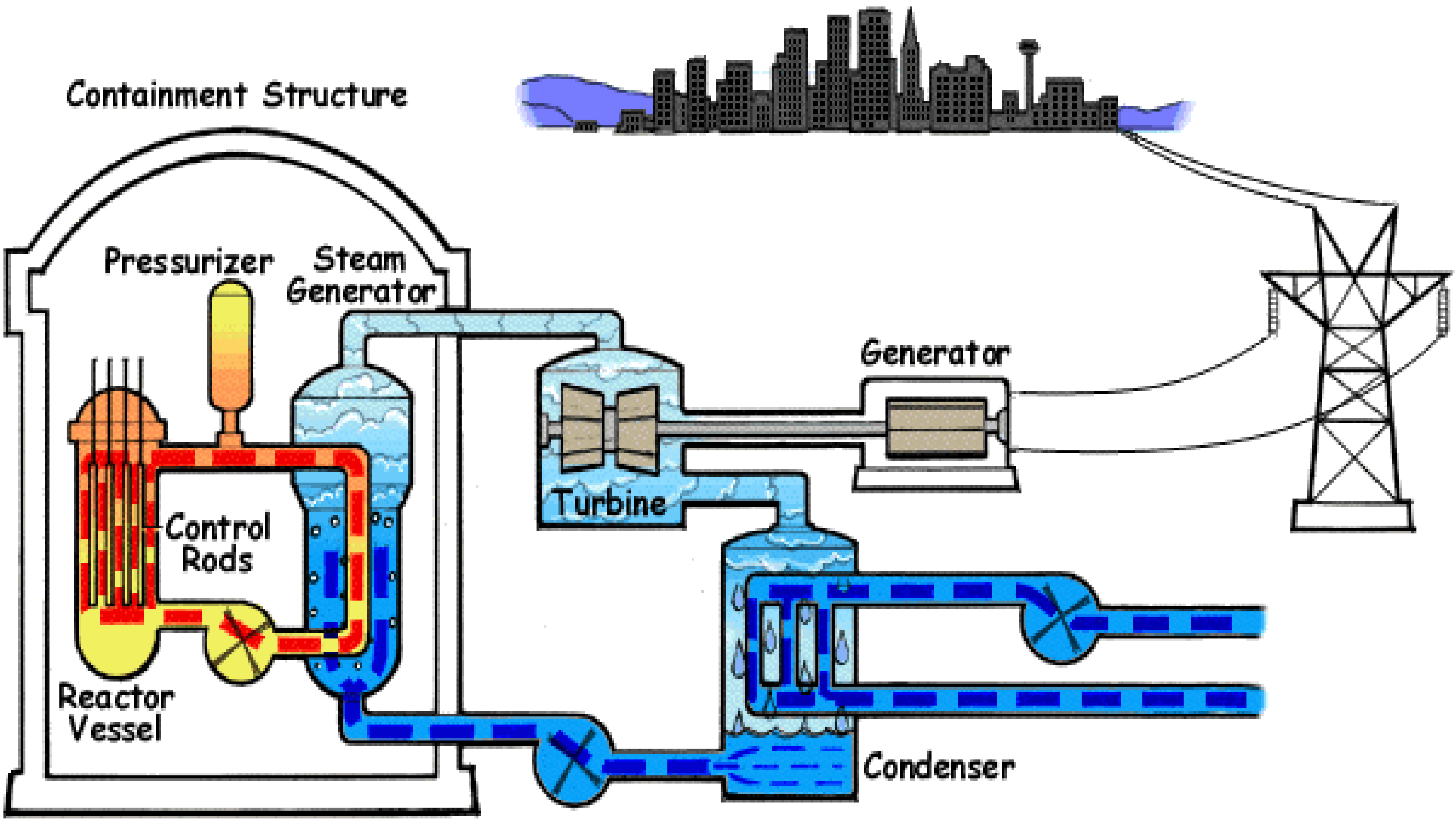




Fuel assembly

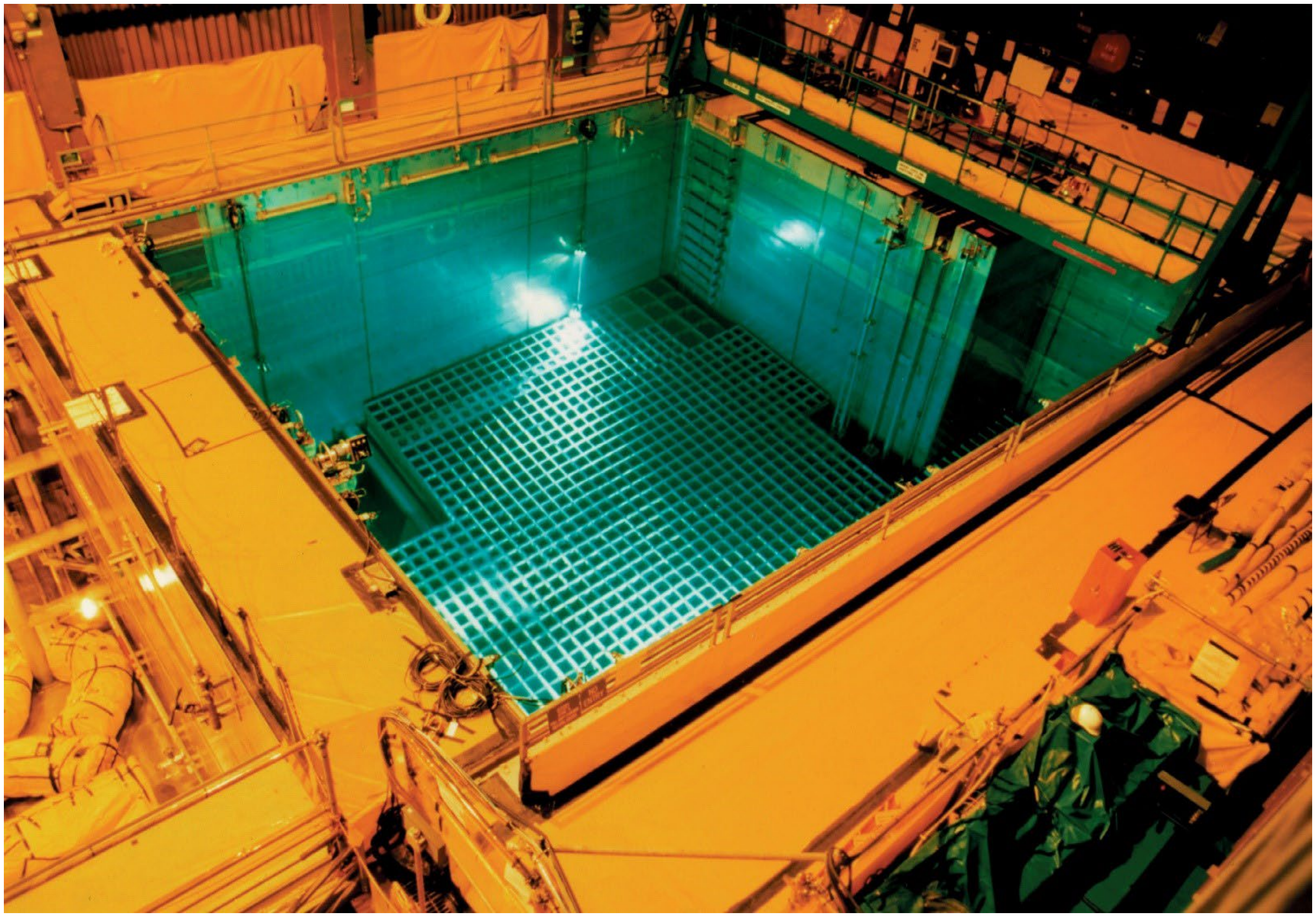
Spent fuel assemblies are typically 14 feet (4.3 meters) long and contain nearly 200 fuel rods for PWRs and 80–100 fuel rods for BWRs.

Pressurized Water Reactor (PWR) Schematic: 1/3rd of energy into electricity; rest in waste heat via condenser



Spent fuel pool: San Onofre, 2014

Fresh spent fuel: bare surface radiation dose rate – lethal in a couple of seconds. Stored with >20 feet deep in water to the top of the fuel to shield the radiation



Dry cask storage of spent fuel

NUCLEAR POWER PLUSES AND MINUSES

Why some people without a financial interest in nuclear advocate for it

- Low life-cycle carbon emissions – comparable to utility-scale wind and solar.
- 24/7 electricity when operating well. U.S. industry average capacity factor is over 90%. Down time is mainly refueling and maintenance.
- “Dispatchable”: that is supply is, in principle, controllable.
- 18 to 24 months fuel supply in the reactor (at refueling).
- Fuel, operating, and maintenance costs can be relatively low compared to natural gas, and in many multi-reactor sites, they have been. Main variable – the price of gas.
- Overall nuclear is about 20% of electricity supply. About the same as wind and solar (14% together), and hydro (6%).

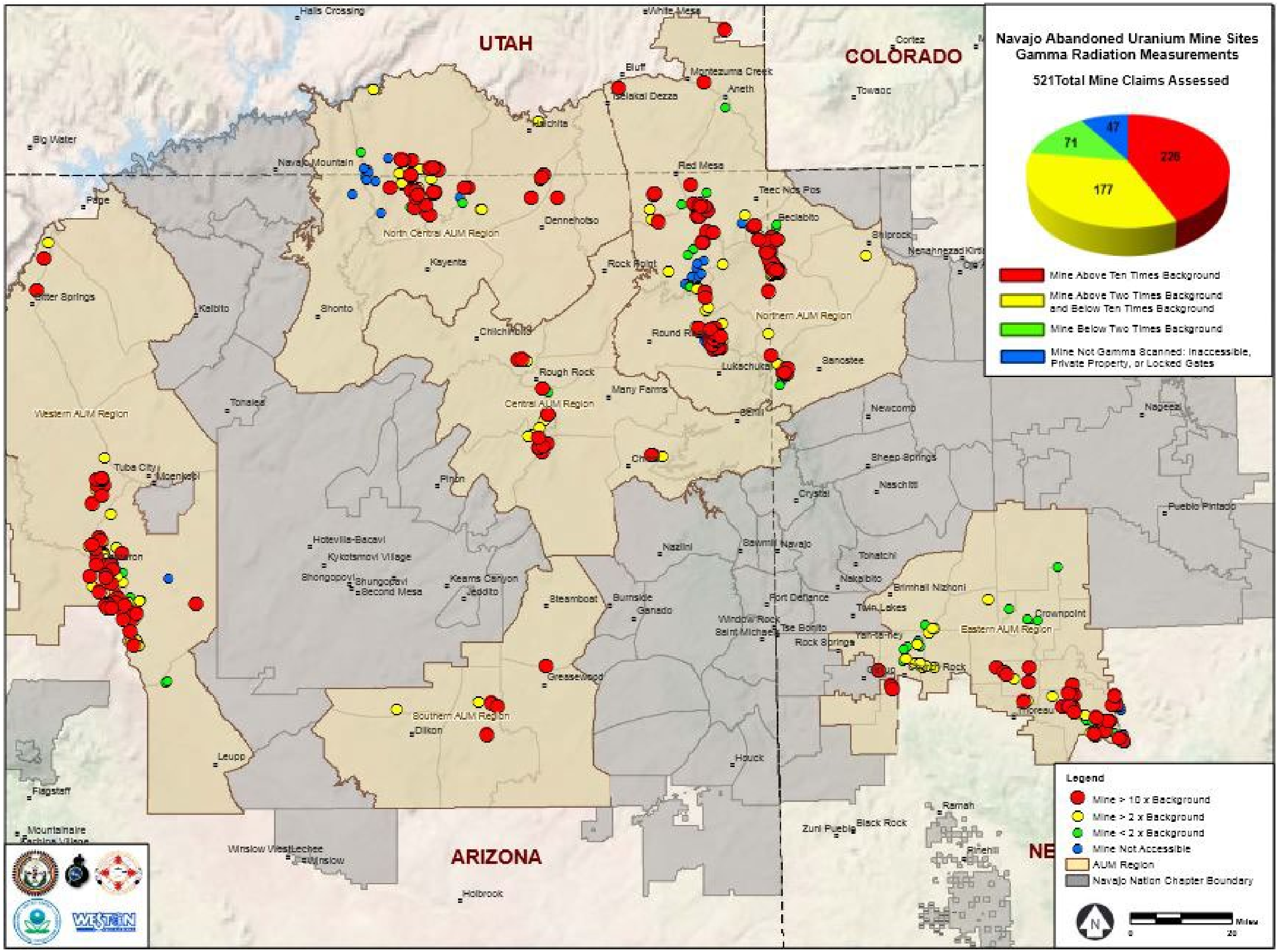
Climate downsides – Slide 1

- **Very high capital cost** per kilowatt makes total nuclear electricity cost high – much higher now than utility-scale solar plus storage or wind plus storage. Evidence and history indicate that SMRs will not solve this problem. (See link in the notes.) Indeed, new serious issues would arise from mass manufacturing, notably the possibility of common problems and recalls.)
- No learning curve as to cost: Estimated **nuclear cost up 49% since 2009**; **solar cost down by 83%; wind cost down by 65%.** (Lazard 2024)
- **High water use:** A serious vulnerability during heat waves and droughts. To supply one-month's generation for an efficient all-electric home with EVs:
  - Consumption (evaporation): 400 (once-through) to 9,000 gallons (cooling tower)
  - Water withdrawal: 50,000 (once-through) to 1,500 (cooling tower)
- **Ill-matched to respond to variations in wind and sun.** So solar and wind tend to be curtailed, as they are in Texas and California.
- **Must shut down preemptively in anticipation of extreme weather events,** notably hurricanes. Cannot be restarted unless the grid is supplying power to the plant –i.e., no "black-start" capability, unlike solar, wind, and hydro.

Climate downsides – Slide 2
Huge opportunity cost

- **Long-lead times to build.** CO2 emissions in the meantime. More than 30 reactors announced after the 2005 "nuclear renaissance" was proclaimed.
- **Only two completed:** Only two new reactors completed to end of 2024. Cumulative generation 2005-2024: almost 40 terawatt-hours.
- **Cumulative new wind and solar 2005-2024:** Over 120 times greater, totaling about 4,960 TWh.
- **Cumulative CO_2 penalty of nuclear relative to solar and wind growth 2005-2024:** On the order of 2 billion tons more displaced CO_2 by solar and wind compared to new nuclear -- effectively the penalty of delays and cancellations.

More than 500 abandoned mines in the Navajo Nation – a large number with high radiation levels (in red). Over 200 million tons of mine waste (uranium, thorium-230, radium, radon gas, heavy metals)



Mill tailings sites in the United States: Over 200 million metric tons of mill tailings (thorium-230 half life: 75,400 years, radium, radon gas, heavy metals – arsenic, vanadium, lead…)

Radium and acid leaking into San Miguel River Colorado, 1972

Moab mill tailings site on the Colorado River – 16 million tons of tailings. Groundwater contaminated. Tailings being moved 30 miles north to a disposal site at Crescent Junction

Other environmental justice issues

- >500,000 metric tons depleted uranium in dangerous chemical form in rusting cylinders – billions in cost just to convert to safer chemical form.
- 90,000 metric tons highly radioactive spent fuel with plutonium and other long-lived radionuclides in it.
- No good solution for any of this.
- At present almost all uranium is imported – so the United States is exporting environmental injustice.
- Indigenous people most affected by the U.S. nuclear system.

Nuclear insecurities

- About 100,000 Nagasaki bombs equivalent of plutonium in U.S. spent fuel alone.
- The largest nuclear power plant in Europe, Zaporizhzhia in Ukraine, 6 reactors, is in a war zone. (Fortunately, it is shut.)
- A nuclear weapon on a plant like Zaporizhzhia would render a country uninhabitable. More cesium-137 in the spent fuel there than was released in all atmospheric nuclear weapons testing.
- Using nuclear for climate is, in effect, creating long-term nuclear bomb risks to reduce CO_2 emissions.
- Short term nuclear bomb proliferation risks also exist. Globally there more than 300 metric tons of separated surplus (~40,000 Nagasaki bombs equivalent), weapons-usable plutonium in civilian sector– *more than double the global weapons stock*.

Children and females have the highest cancer risk per unit of exposure

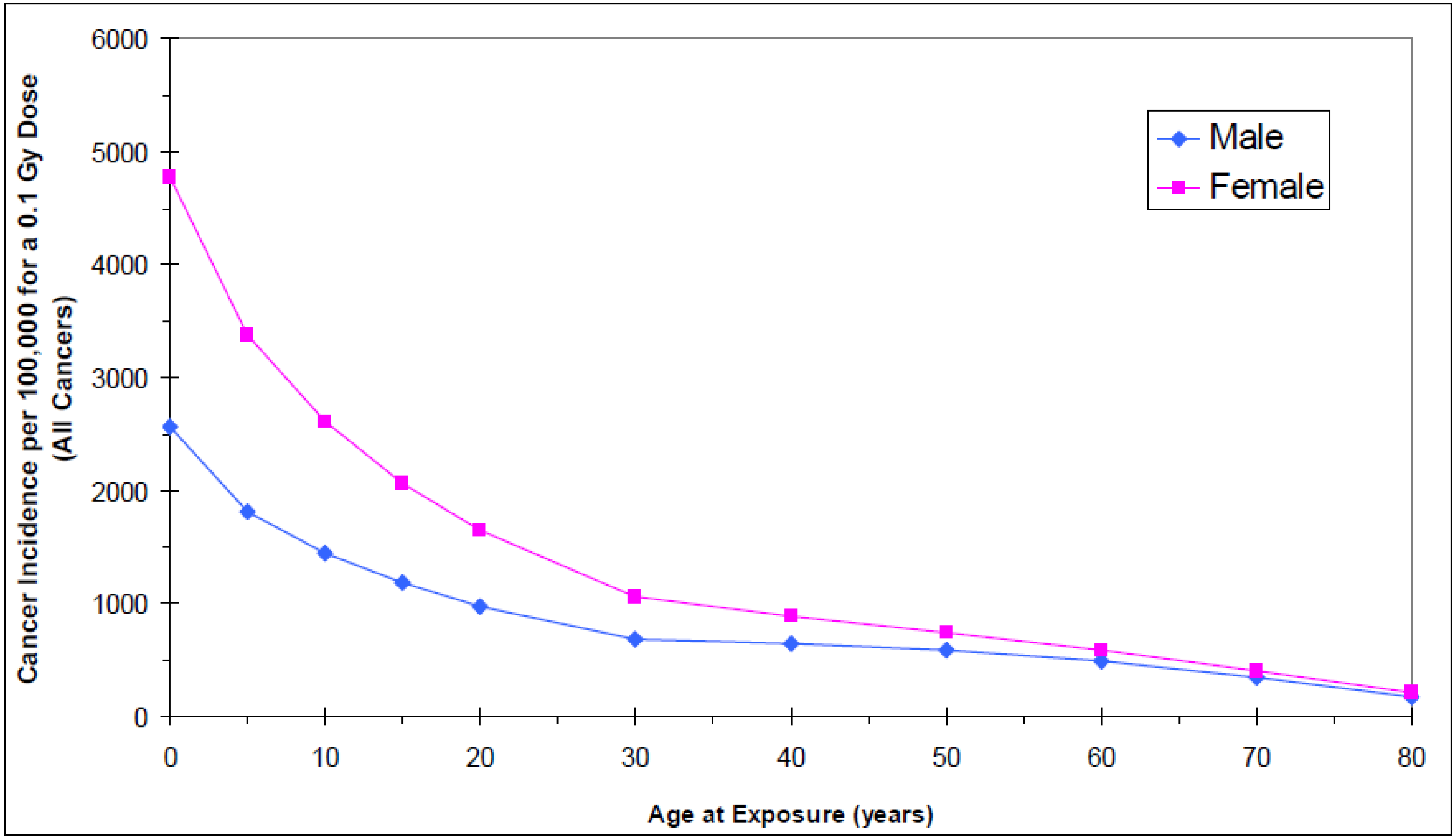
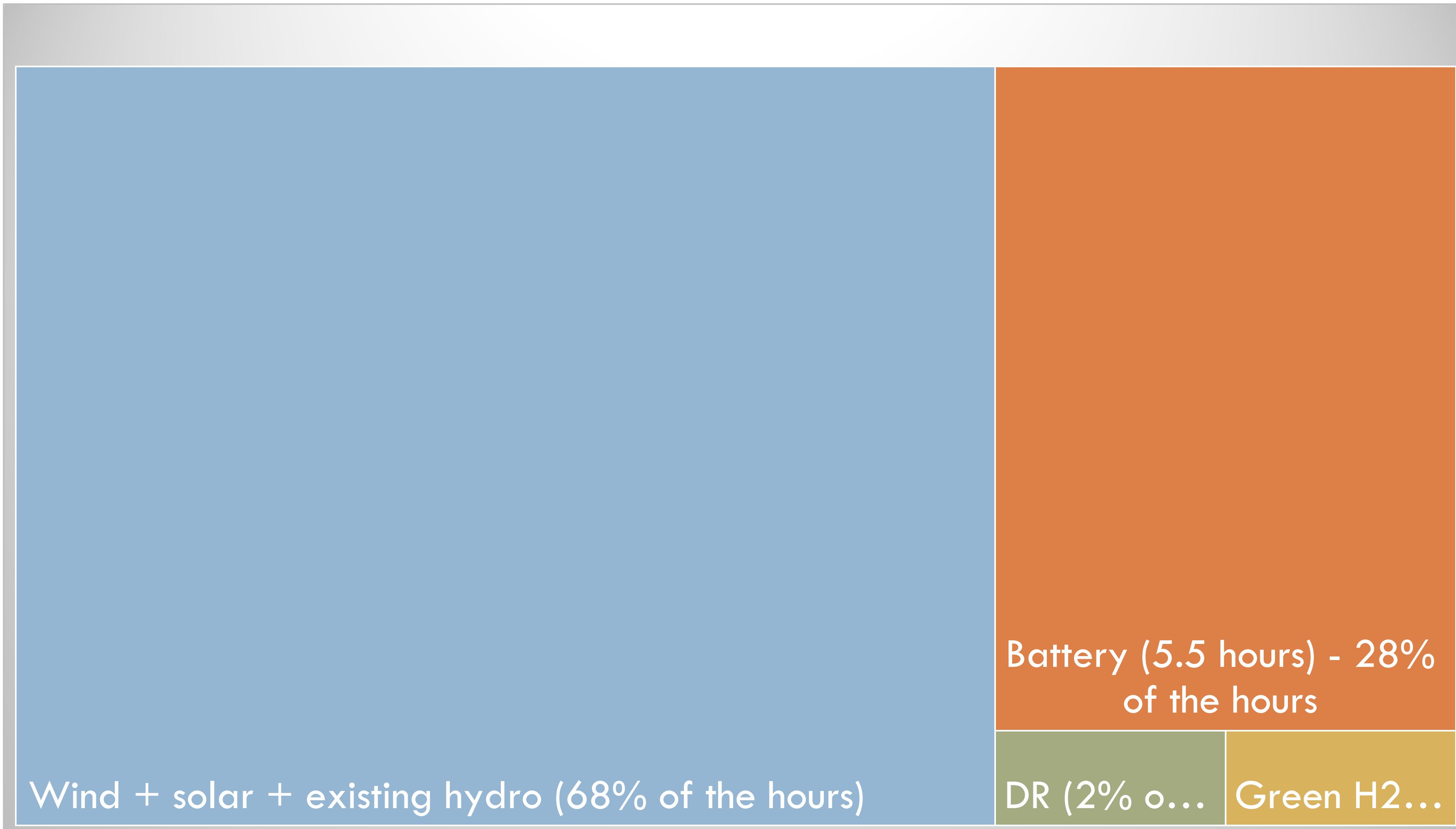


Figure 6: Graph of cancer incidence risk per unit of radiation exposure as a function of age from the BEIR VII Committee. The change in cancer risk for people under the age of 20 is steeper for females than males, resulting in an increase in the difference between their risks. The exposure occurs at the stated age; the risk is over the lifetime remaining after that age.

Crossing the placenta: pregnant members of the public are not protected by any regulation (ratios of concentrations in fetus to that in the mother)

Element	Intakes prior to Pregnancy	Intakes during Pregnancy
H in HTO	1.6	1.6
H in OBT	1.6	1.6
Organic carbon	1.5	1.5
Uranium	0.1	1
Plutonium (see Note)	0.03	0.1; 0.3; 1
Americium	0.01	0.1

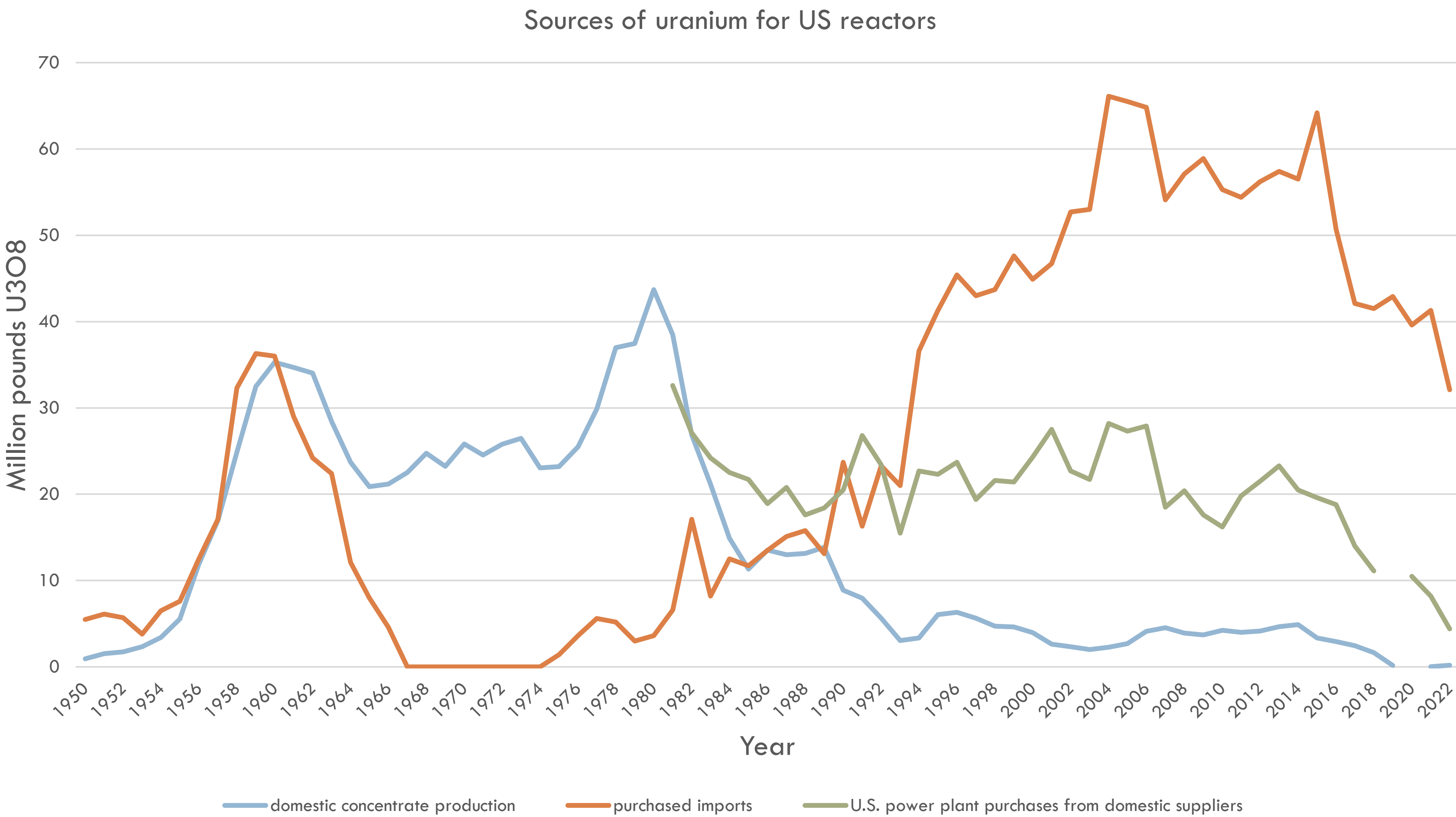
We can do better: Renewable Maryland modeling (four-year project to examine decarbonization with equity): percentage of hours with load fully met – renewable alone = 68%; add storage = 96%; add demand response = 98%; add fuel cell peaking with green hydrogen: 100%. Green hydrogen would be produced with renewable electricity that would otherwise be curtailed.



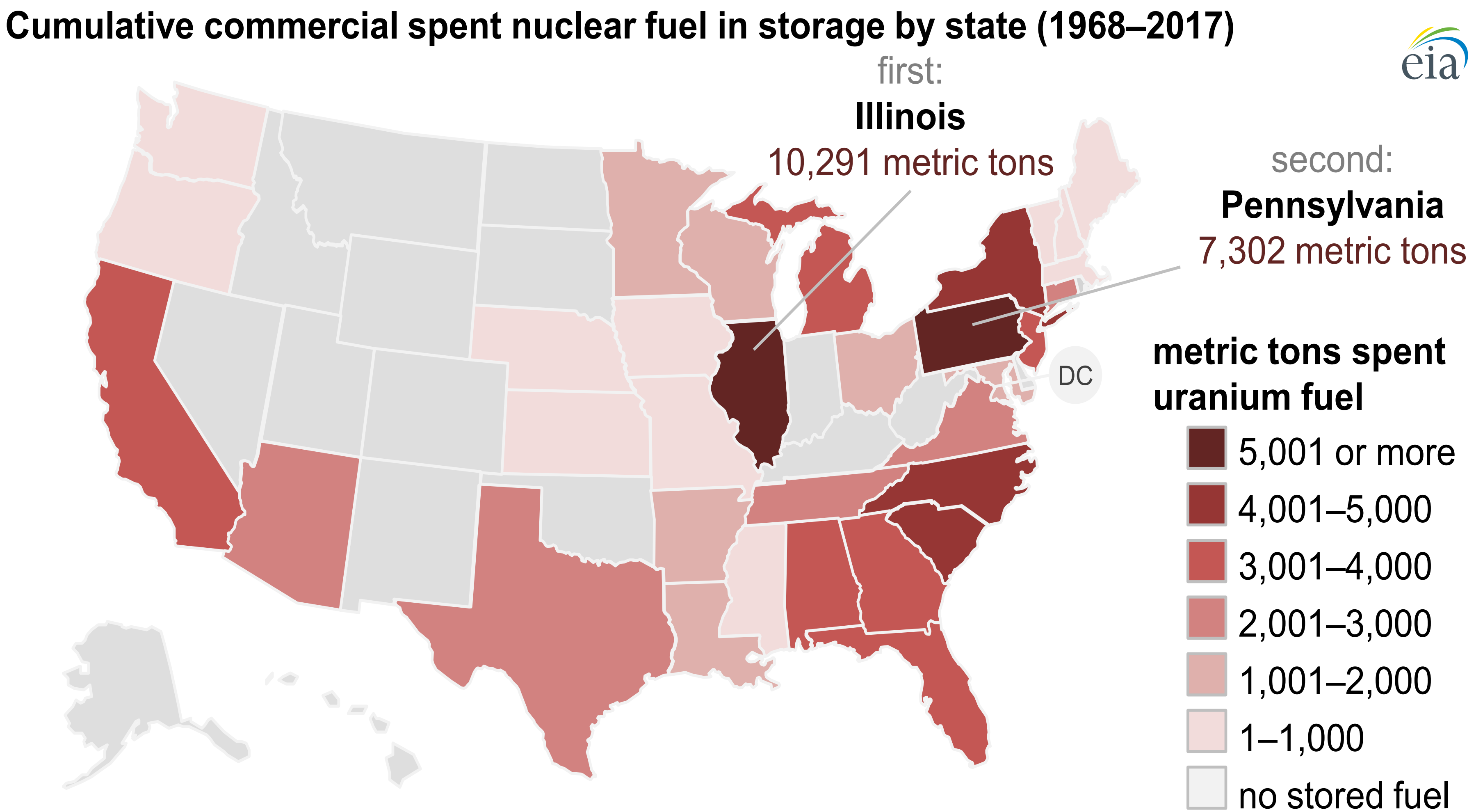
SUPPLEMENTARY SLIDES

Materials

Uranium requirement in 2022
Sources: Canada 27%; Kazakhstan 25%; Russia 12%; Uzbekistan 11%, Australia 9%; rest 16%



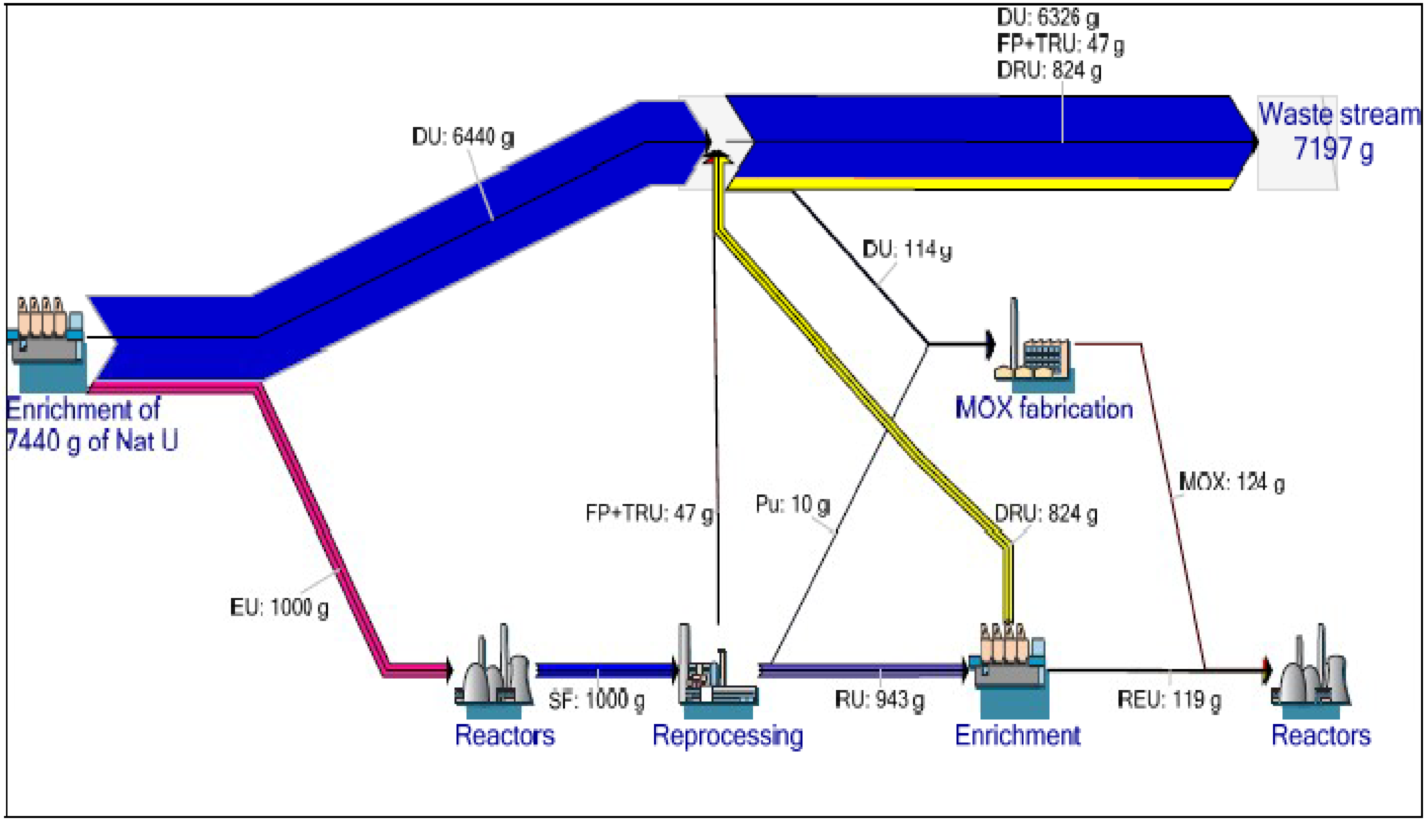
Spent fuel 2022 inventory ~90,000 metric tons, adding ~2,000 metric tons/year



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

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

Recovering plutonium ("reprocessing") and reuse in light water reactors. Maximum uranium resource use – necessarily less than ~1 percent even with repeated reprocessing



SUPPLEMENTARY SLIDES

Extreme events and long time-frames can create extreme outcomes

Fort Calhoun nuclear plant, Nebraska, June 2011 Missouri River flood. A complex series of events and investigations thereafter led to permanent shutdown in 2016

Fukushima Daiichi in 2007

Fukushima Daiichi, March 16, 2011

A failure to learn key lessons – An example

- Zircaloy fuel rods are at the technical center of the "meltdown" vulnerability:
  - loss of coolant → remaining water in the reactor boils
  - steam + zirconium → zirconium oxide + hydrogen gas
  - Explosion vulnerability. The Fukushima accident had severe hydrogen explosions.
- Zircaloy/loss-of-coolant vulnerability known since before the 1979 TMI accident).
- NRC failed to consider this generic issue in its 2011 post-Fukushima assessment.

Failure to account for more extreme weather events

- Initial nuclear plant licenses were issued for 40 years based on historical climate data.
- Licenses of most plants have been extended by 20 years; extensions by another 20 are now in active consideration. Two have been granted.
- Extensions beyond that, to 100-year totals, are under official discussion.
- Much more extreme climate events – in terms of duration and intensity – and not considered. As a result, license extensions are occurring based on climate data generally understood to not be representative of future extremes and stresses (flooding, hurricanes, extreme heat waves and droughts in relation to water supply…).

A strange NRC ruling on long-term spent nuclear fuel storage

- The NRC is confident there will be a deep geologic repository spent fuel disposal.
- In case there is no repository, it ruled that spent fuel could be stored onsite for the indefinite future, meaning that the NRC would be there essentially forever, with sufficient appropriations to ensure safety and security – guns and guards, and the safe repackaging of spent fuel, possibly every 100 years.
- This decision was issued despite these facts:
  - No human institution has endured for anything close to the 24,100-year *half-life* of plutonium-239, the principal nuclear bomb proliferation risk.
  - The U.S. federal government has shut down multiple times in the past few decades
  - There was a Civil War less than 0.1% of the half-life of plutonium ago, when the country had not one but two governments at war with each other.
  - After ~200 to 300 years, the external radiation barrier of spent fuel declines drastically making it more susceptible to diversion in case of loss of institutional control. *The means proliferation and bomb risks increase over time in case of accessibly stored spent fuel.*

SUPPLEMENTARY SLIDES

Radiation, environmental health, and ecosystem protection. Scientific and regulatory issues

Modeling the body as a bag of water and Relative Biological Effectiveness

- The basic scientific paradigm is that the body is a bag of water.
- The main adjustment is to add a "relative biological effectiveness" (RBE) factor for different types of radiation.
- For cancer risk, alpha particle internal radiation risk is set at 20 times external gamma radiation. This works reasonably well for regulating most radiogenic cancer risks for adults.
- The risks at times of rapid change in the body (embryo, fetus, infancy, and puberty) are not well-captured, including
  - Many non-cancer endpoints, including during first trimester of pregnancy.
  - Certain kinds of genetic damage where RBE is in the hundreds (or more).
  - Unrepaired mitochondrial DNA damage.
- Conclusion: radiation protection is seriously deficient so far as reproductive issues, non-cancer endpoints, and ecosystem protection are concerned.

Focus on tritium, radioactive hydrogen) the most ubiquitous radioactive pollutant (weapons and power). In some ways, the most underappreciated in terms of risks. Makes radioactive rain around power plants. One teaspoon of tritiated water (HTO) would contaminate100 billion gallons of water to drinking water standard

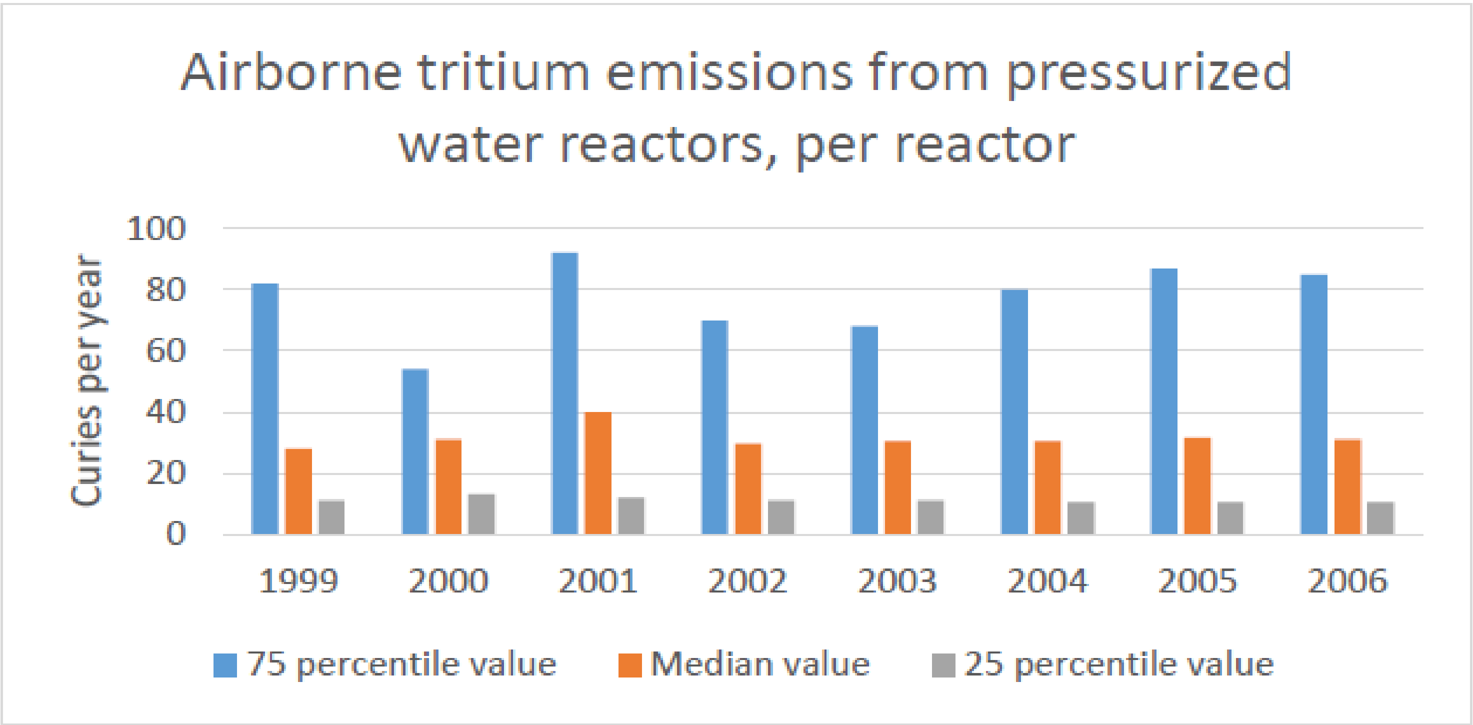
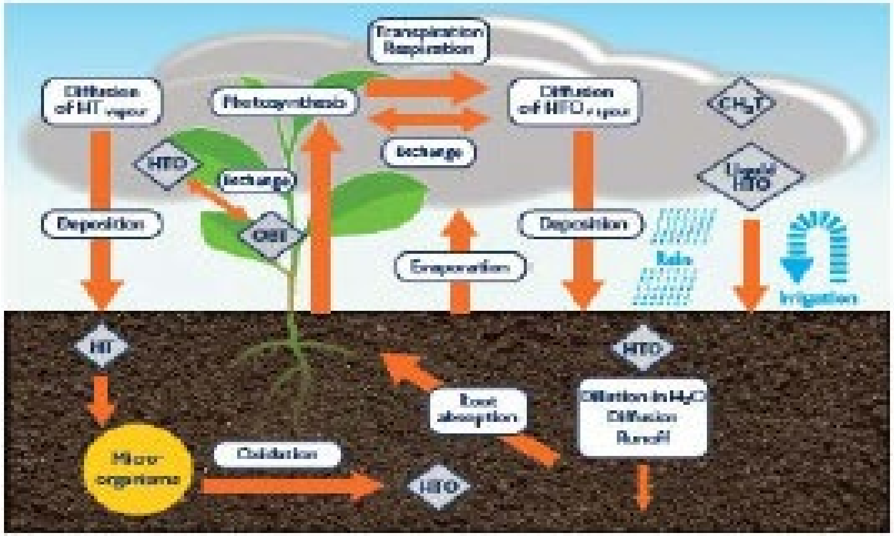
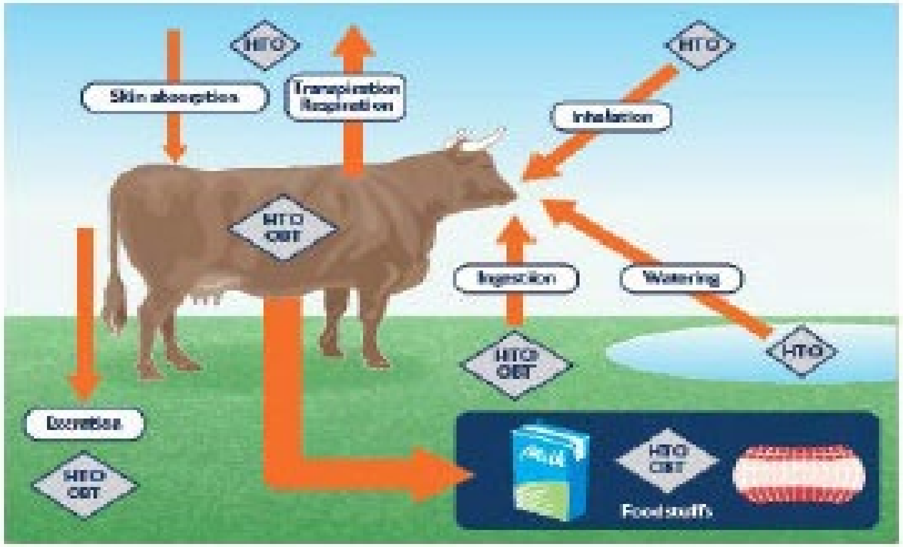


Figure II-3: Air borne tritium emissions from U.S. pressurized water reactors

Source: Jones circa 2007

Agricultural pathways for tritium





Mitochondrial damage

- Tritium in the form of HTO or T_2O (radioactive water) becomes part of the cell and ionizes the water in it, creating highly reactive hydroxyl radicals.
- The result: Excess reactive oxygen species and oxidative stress, mitochondrial DNA damage, with multiple risks.
- Disruption of the energy system of the body.
- Essentially all eukaryotes share the mitochondrial energy system, meaning risks are ecosystem wide.
- Potential additive or synergistic effects with other toxins, like heavy metals.

Reproductive and ecosystem risks

- Early failed pregnancies
- Malformations
- Severe neurological damage, including what the International Commission on Radiological Protection has called "severe mental retardation", defined as "an individual unable to form simple sentences, to solve simple problems in arithmetic, to care for himself or herself, or is (was) unmanageable or institutionalized." Based on Hiroshima/Nagasaki survivor data.
- Damage during oocyte formation creates multigenerational risks.
- There is evidence of reproductive risks in other creatures. Example: statistically significant damage to fish eggs (carp) was documented at water contamination about two-thirds of the U.S. drinking water standard.
- Yet, the bodies of animals, such as owls, are allowed to have hundreds of times the drinking water standard, according to DOE guidelines.

Health and ecosystem regulatory considerations

- Standards are oriented to cancer – an incomplete framework.
- U.S.: 500 millirem (5 millisievert) limit during pregnancy in regulated nuclear workplaces when pregnancy declared. Lax relative to other OECD countries, where the limit 100 mrem (1 mSv).
- Pregnant members of the public are not protected by any specific regulation.
- Ecosystem exposure guidelines are very weak.
- Revisiting Relative Biological Effectiveness (RBE), especially for non-cancer endpoints and for infants and children, is essential.

Environmental and ecosystem protection

- We do not have a scientifically sound framework for environmental and ecosystem health.
- Environmental health should consider multiple-pollutant exposure (chemical and radiation).
- From the point of view of *homeostasis* and recovery (or not) from biological damage, the body functions as an information system (rather than as a bag of water). That should be one starting point for a sound scientific paradigm for environmental health.
- Similar considerations are needed for ecosystem health protection.

QUESTIONS?

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