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Nuclear Fuel Cycle

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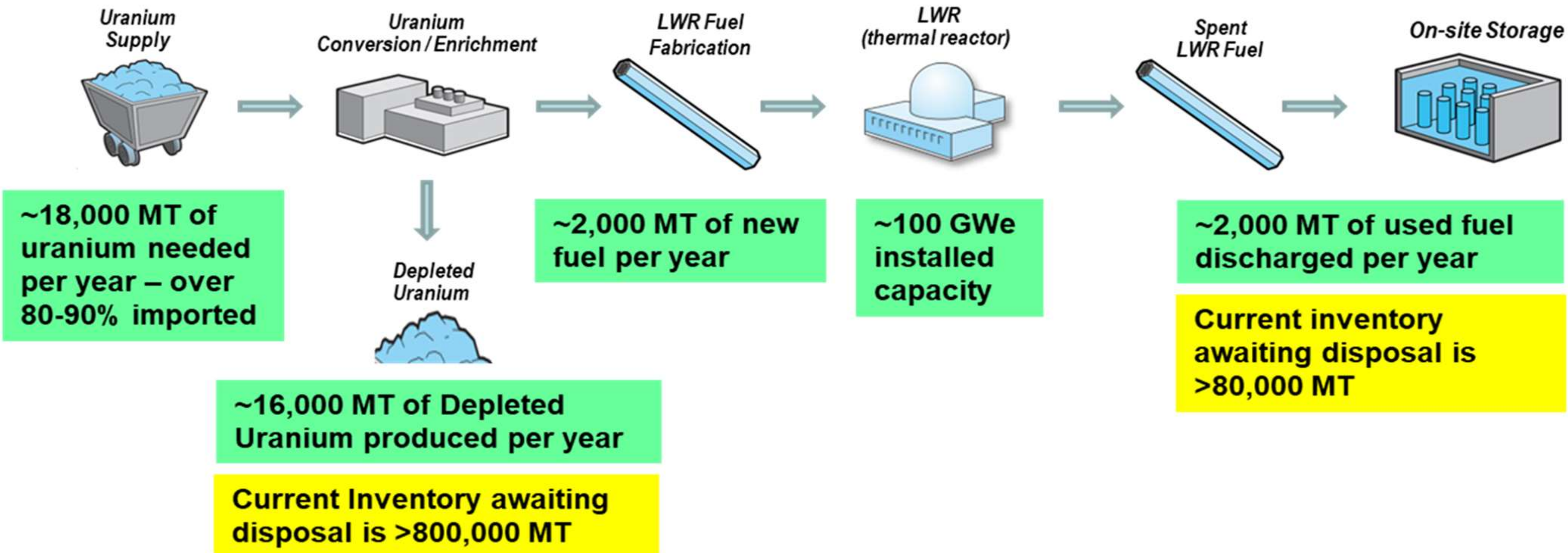
Current U.S. (Open) Fuel Cycle

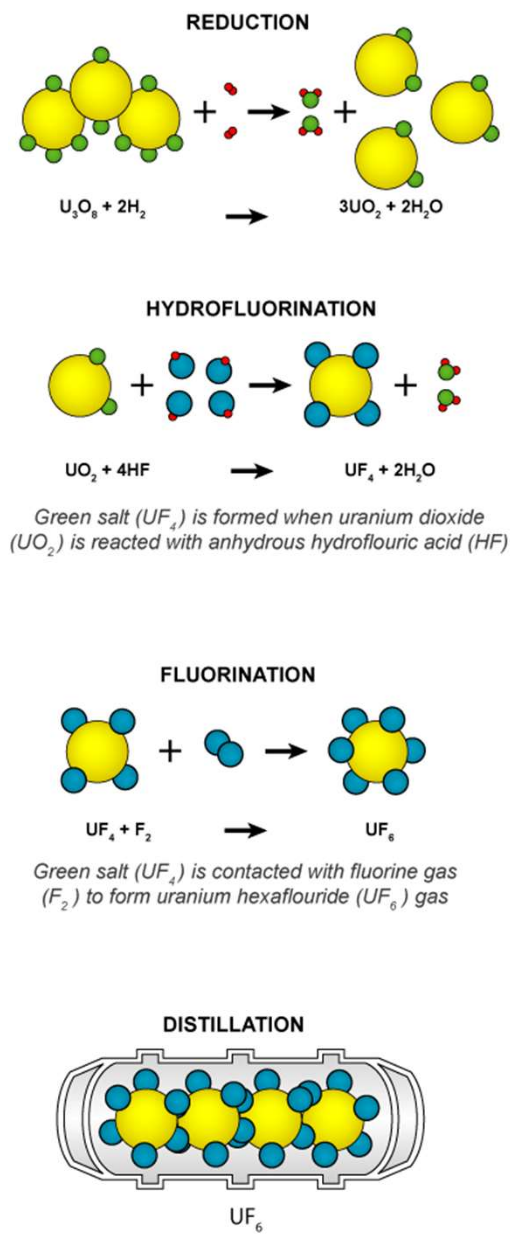


Mining and Milling

- A reliable source of enriched uranium is needed for reactor demonstrations and deployment
- Uranium is mined in three ways:
  - In situ leaching
  - Open pit mining
  - Underground mining
- Wyoming is the US's largest uranium producer, but most of our uranium is imported.
- Advanced reactors utilize low enriched uranium
  - Most use 19.75% U-235 enriched uranium (High-Assay Low Enrichment Uranium)
  - This is in comparison to LWRs which currently use < 5 %
- Supply chains for uranium and enrichment will be needed to support future reactor deployment.

Conversion

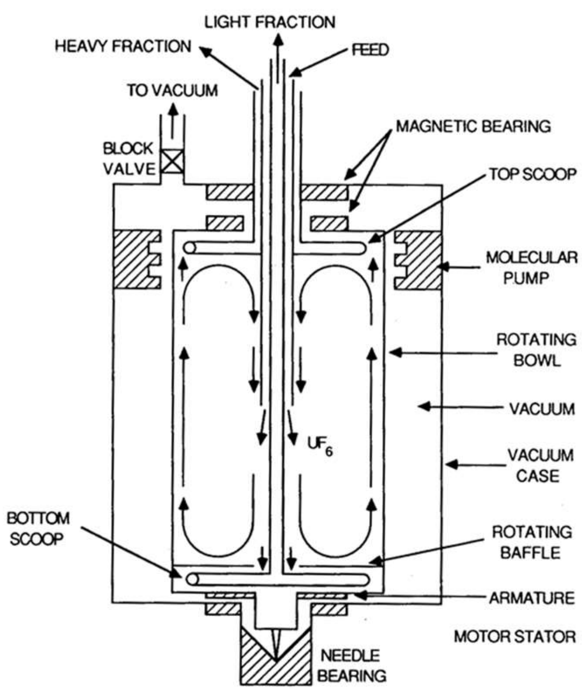
- Natural uranium (U) contains two isotopes
  - 0.7% is “fissile” ^{235}U which is easily split in a reactor
  - 99.3% is “fertile” ^{238}U which is not
- Natural uranium is in an oxide form (U_3O_8)
  - At the conversion plant U_3O_8 is converted to uranium hexafluoride (UF_6), which is a solid at room temperature but a gas at slightly higher temperatures
  - UF_6 is stored and shipped in large cylinders
- Fresh nuclear fuel in current reactors is ~4.5% fissile content, requiring enrichment:
  1. Convert the Uranium to a gas
  2. Spin the gas at high speeds in centrifuges
  3. The lighter ^{235}U partially separates from the heavier ^{238}U

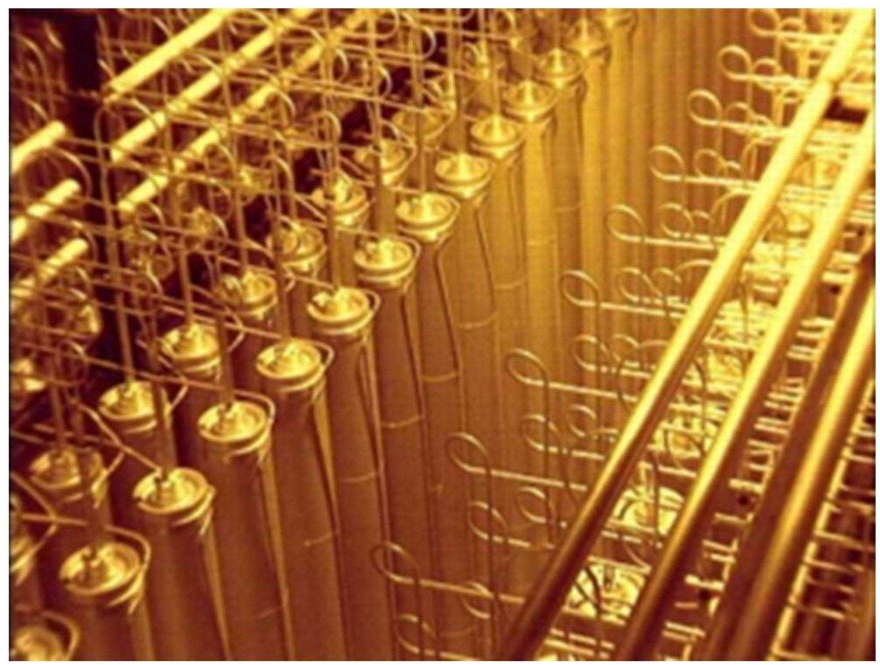


http://www.theupa.org/uranium_technology/conversion/

Enrichment

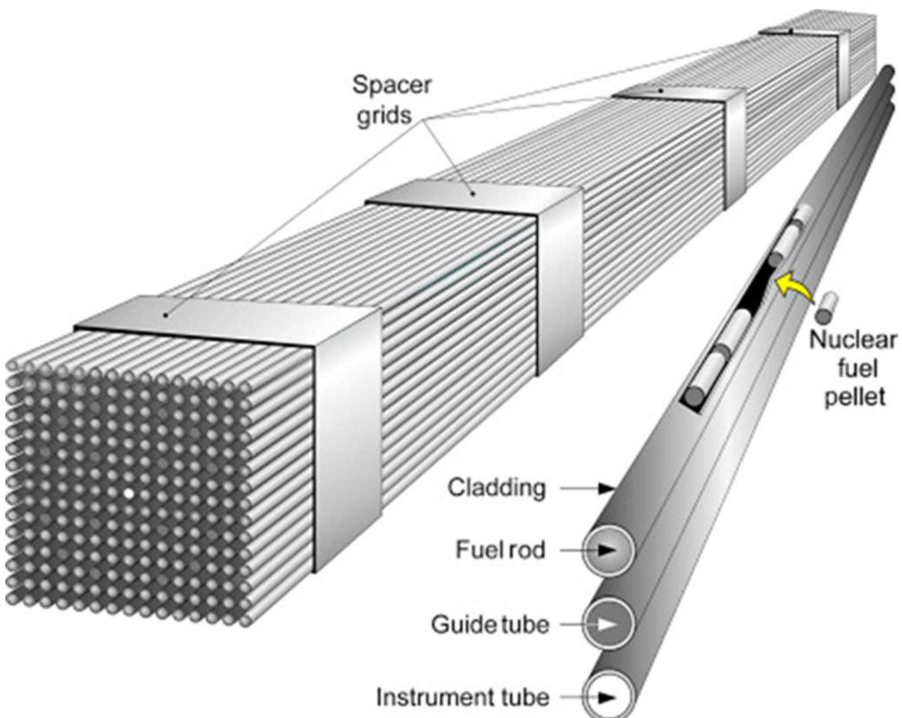
- Enrichment involves passing UF_6 through high-speed centrifuges
  - In each centrifuge the ratio of ${}_{235}U$ to ${}_{238}U$ is changed slightly into a “heavy fraction” scooped from the outside and a “light fraction” scooped from the inside
  - Hundreds of centrifuges are linked in “cascades” to produce enriched U while also generating larger amounts of depleted U that is discarded





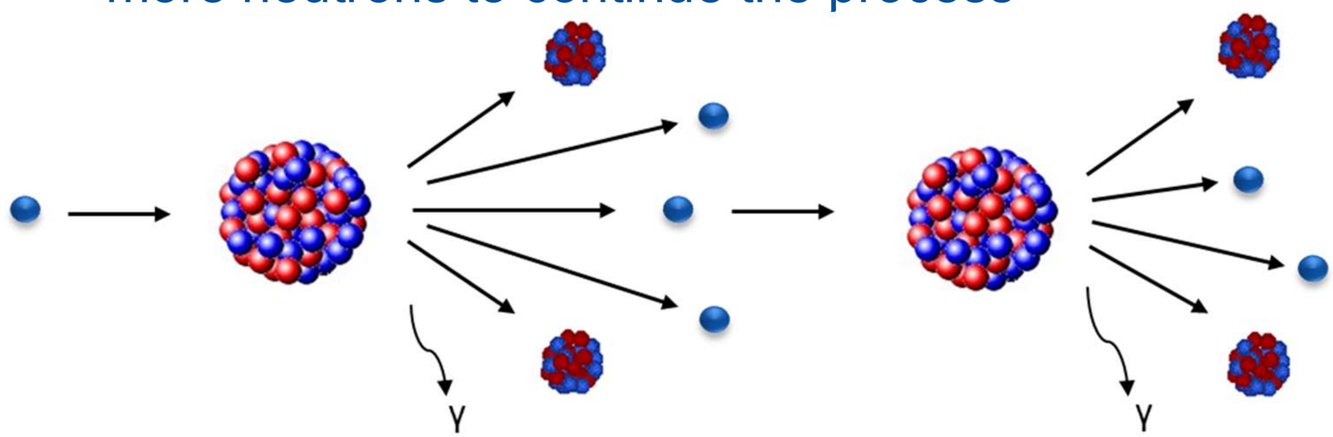
Fuel Fabrication

- Fuel fabrication is a multi-step process
  - UF_6 is received and converted to an oxide powder (UO_2)
  - The powder is pressed into pellets
  - The pellets are heated (sintered) to create a ceramic
  - The ceramic pellets are stacked inside cladding to make fuel rods, which are welded shut
  - The fuel rods are loaded into assemblies which are typically 16 to 17 inches square and ~16 feel long
  - The very slightly radioactive assemblies are inspected, then shipped to reactors
  - 150 to 250 assemblies are loaded into a core, depending on the reactor size.



Irradiation

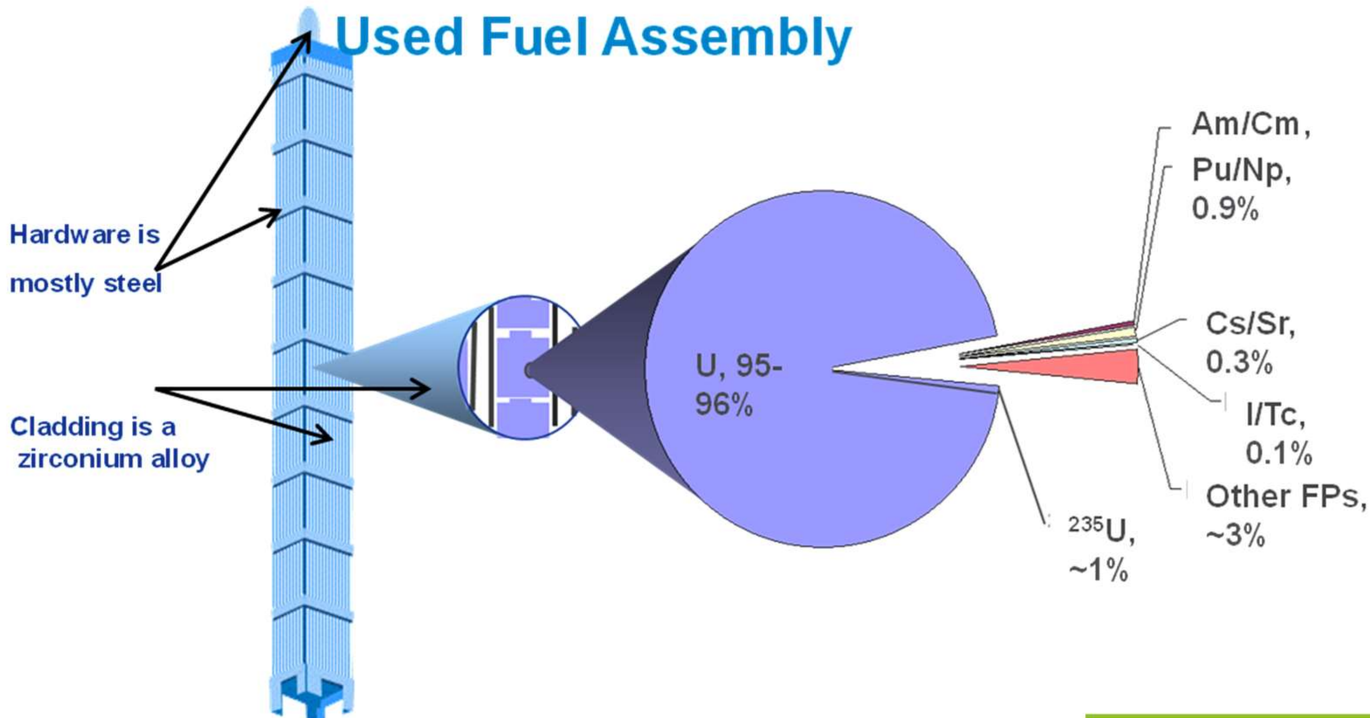
- In the reactor, nuclear fuel is irradiated for ~4.5 years
  - During this time, ^{235}U is fissioned (split) by neutrons to produce electricity
  - Fissioning results in heat, fission products (smaller atoms) and more neutrons to continue the process



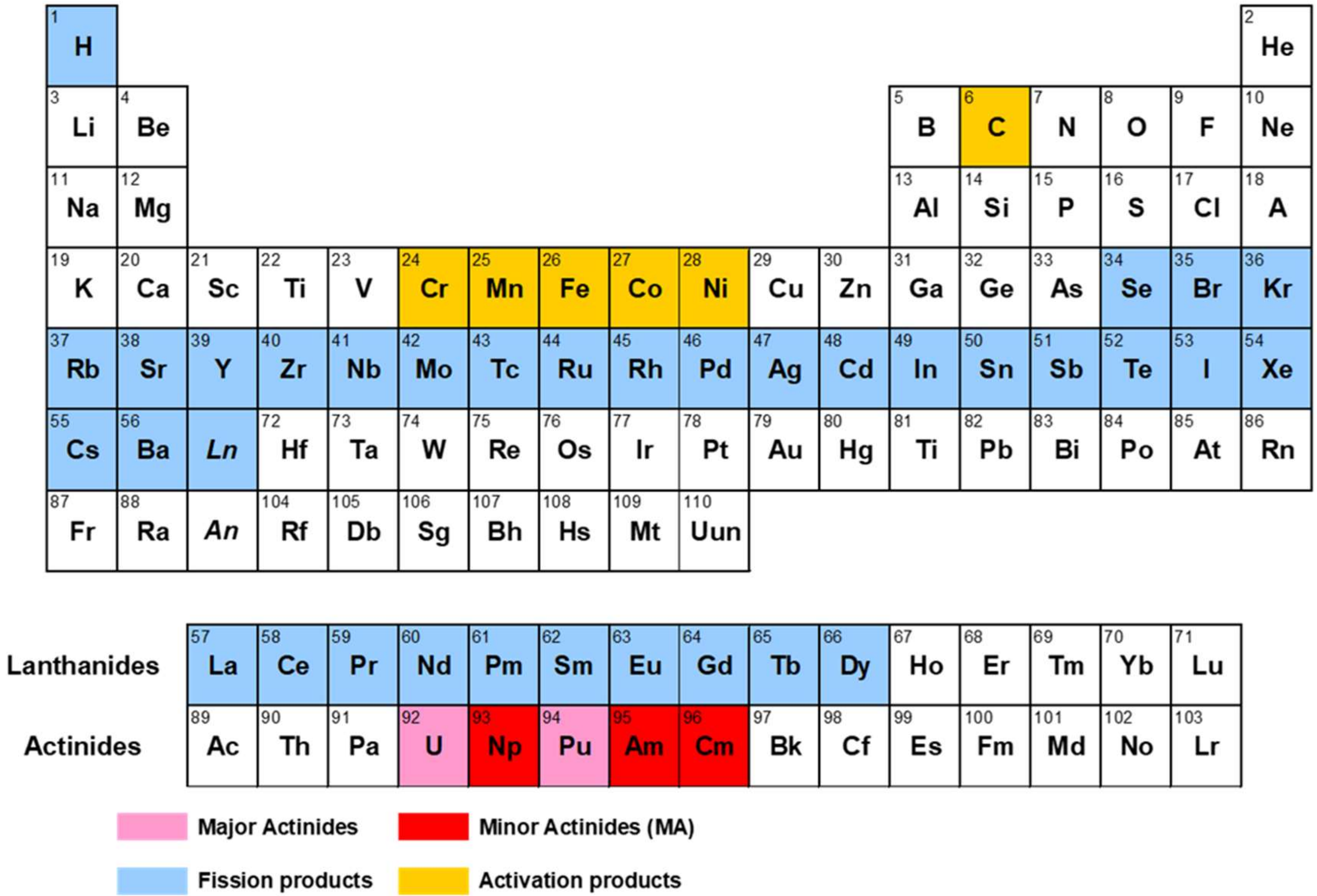
- After the fissile material is depleted and fuel is “spent” and replaced during refueling
  - The highly radioactive used fuel is initially stored in water to “cool”, then may be transferred to dry storage

Used fuel characteristics (1/3)

- Used fuel is composed mostly of ^{238}U, along with:
  - ~4% fission products
  - ~1% residual ^{235}U
  - ~1% heavier “transuranic” isotopes from neutron capture of ^{238}U (breeding)



Used fuel characteristics (2/3)



Used fuel characteristics (3/3)

- Used fuel is initially highly radioactive due to short-lived fission products
- Radioactivity is a property of unstable isotopes which decay by giving off particles and rays (radiation) to become different (lighter) isotopes.
  - If the new isotope is also unstable, it will also decay
  - If the new isotope is stable, the process stops
- Every radioactive isotope has a "half life" which is the time until half of the atoms of the isotope decay
  - In 10 half lives, one thousandth (0.1%) of the isotope remains
  - In 20 half lives, one millionth remains
  - (Example: Carbon-14 dating measures the amount of ^{14}C left in plant and animal remains to determine when they died using a half live of 5,730 years)
- Most fission products have half lives of less than a second to a few days
  - Used fuel typically is "cooled" for at least 5 years to allow most of the fission products to decay away
  - The remaining fission products and transuranics have half lives that are measured in years to centuries or longer
  - The longer the half life, the longer the material remains radioactive, but at a lower level because less decay is occurring, and less radiation is produced

Used Fuel Disposition Options

- After cooling, used fuel is currently stored waiting for final disposition
  - While used fuel becomes less radioactive with time, it remains a health hazard for thousands of years
- The disposition options are:
  - Direct disposal in a geologic repository designed to contain residual hazards for 100,000 years or more (current U.S. approach)
  - Recycling (practiced in some countries in Europe and Asia)
- Recycling separates the fuel:
  - Uranium and plutonium are recovered for reuse
  - Fission products and hardware are disposed in a geologic repository
  - Other transuranics may be recovered for reuse or included in the waste

Recycling Options

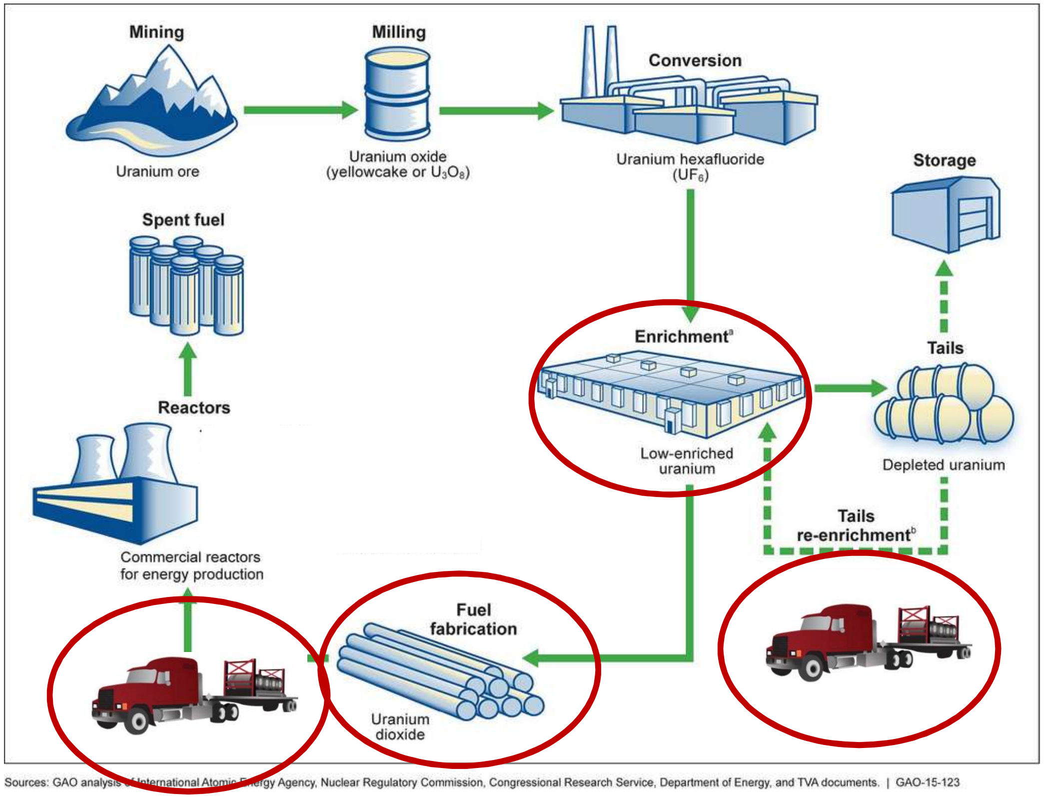
- With current reactors, only limited recycle is possible:
  - Recover the U for re-enrichment
  - Recover the Pu, which is mostly fissile
  - One recycle is feasible, after which too little fissile remains and the used fuel would be direct disposed
  - Results in ~30% more electricity from the original mined uranium and a small reduction in waste
  - Currently not cost effective
- With advanced reactors, continuous recycle may be cost effective:
  - Recover U, Pu, other transuranics (optional)
  - Irradiate in a fast spectrum reactor which supports enough breeding to produce fissile as fast as it is consumed
  - Recycle the resulting used fuel adding depleted uranium to make up for the fission products that are discarded
    - Existing inventories of depleted uranium would last for 3,000 years at the current level of nuclear generation without any new mining
  - Could result in over 100 times as much electricity from the original mined uranium and ~1/10th the waste to geologic disposal
  - Requires technology development

Commercial application of recycling abroad

- France
  - UP-1 plant in Marcoule began operation in 1958 (~400 MT/yr)
  - UP-2 plant in La Hague began operation in 1967 (~400 MT/yr)
  - LWR oxide plant (UP2-400) began in La Hague in 1976 (400 MT/yr)
  - LWR oxide plant (UP3) began in La Hague in 1990 (800 MT/yr)
  - LWR oxide plant (UP2-800) upgrade in La Hague in 1994
- United Kingdom
  - Windscale plant for Magnox fuel began in 1964 (1200-1500 MT/yr)
  - THORP LWR oxide plant began in 1994 (~1200 MT/yr)
- Japan
  - Tokai-Mura plant began in 1975 (~200 MT/yr)
  - Rokkasho plant currently undergoing hot commissioning (800 MT/yr)
- Russia
  - Plant RT-1
  - Began operation in 1976, (400 MT capacity)
- China
  - Reprocessing pilot plant (60 MT/yr capacity)
  - Hot commissioning in progress
  - Planning 800 MT/year plant to begin operation in 2030

Fuel Cycle Infrastructure Updates Needed to Support Advanced Reactors

- Enrichment
  - Variety of U-235 enrichments between 5 and 20 wt.%
- Fuel fabrication/de-conversion
  - Multiple fuel form options (metallic, oxide, liquid, etc.)
- Transportation
  - UF_6 to fuel fabrication facility
  - As fuel to reactor facility



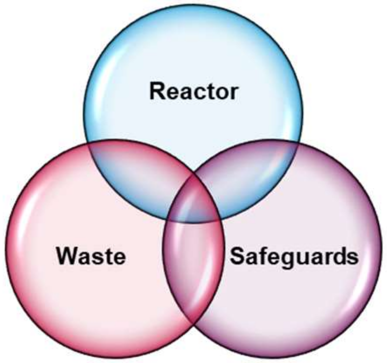
Sources: GAO analysis of International Atomic Energy Agency, Nuclear Regulatory Commission, Congressional Research Service, Department of Energy, and TVA documents. | GAO-15-123

Fuel Cycle of the Future

We don't know what it will look like, but we know what attributes are needed

Today's fuel cycle is bounded by LWRs

- Cost competitive
- Manage proliferation risk
- Manage of waste
- Address safety and security



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