CENTER FOR USED FUEL RESEARCH

Management of Used Nuclear Fuel

What Happens After Power Generation?

July 16, 2026

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U.S. DEPARTMENT of ENERGY | Office of Nuclear Energy

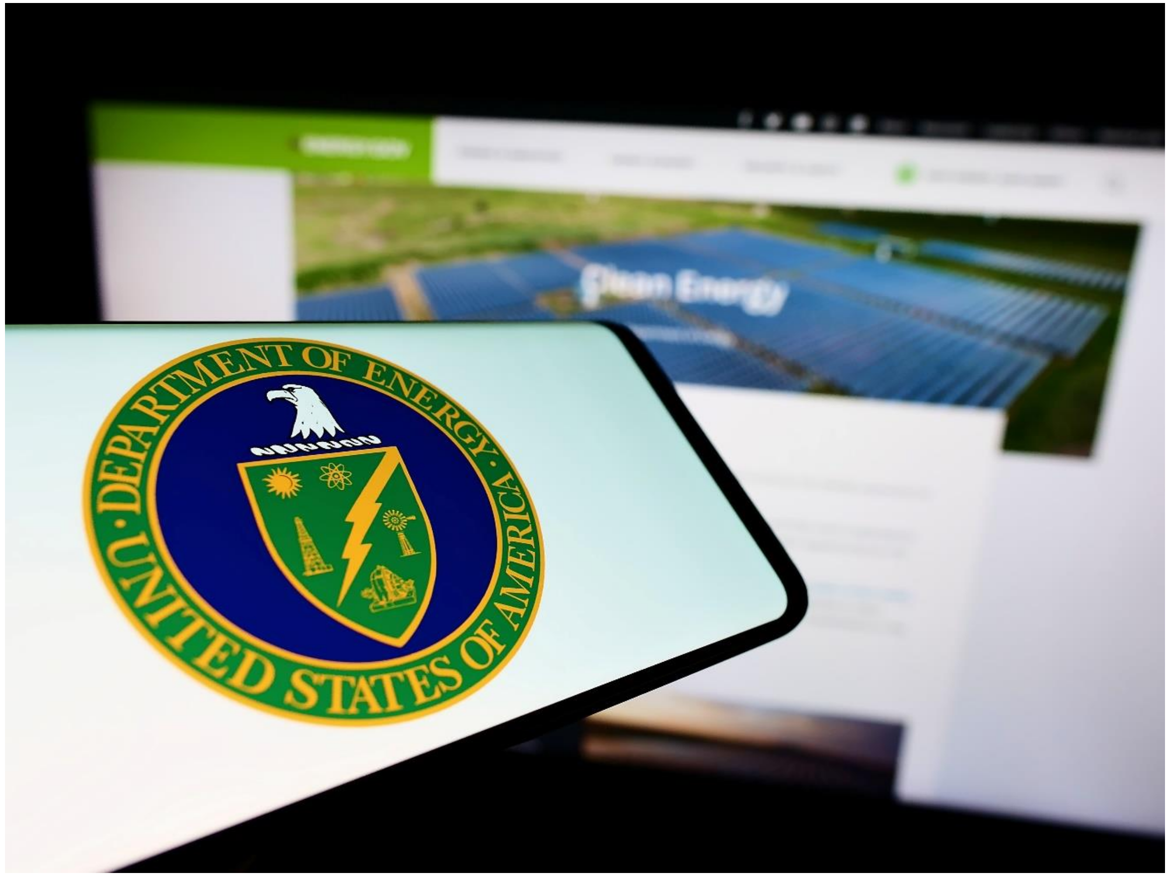
Center for Used Fuel Research

DISCLAIMER

This is a technical presentation that does not take into account contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961).

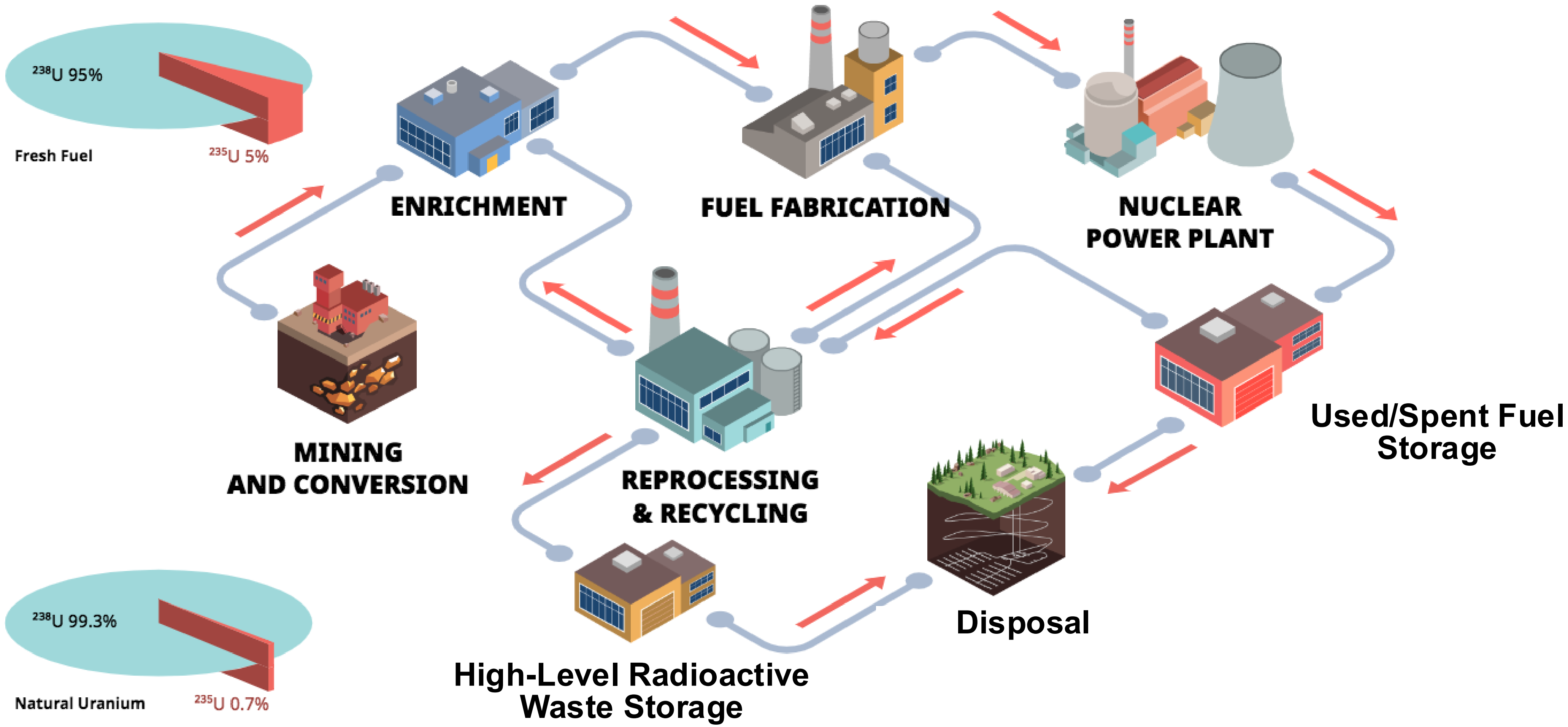
To the extent discussions or recommendations in this presentation conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this presentation in no manner supersedes, overrides, or amends the Standard Contract.

This presentation reflects technical work which could support future decision making by the U.S. Department of Energy (DOE or Department). No inferences should be drawn from this presentation regarding future actions by DOE, which are limited both by the terms of the Standard Contract and Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act including licensing and construction of a used nuclear fuel[1] repository.



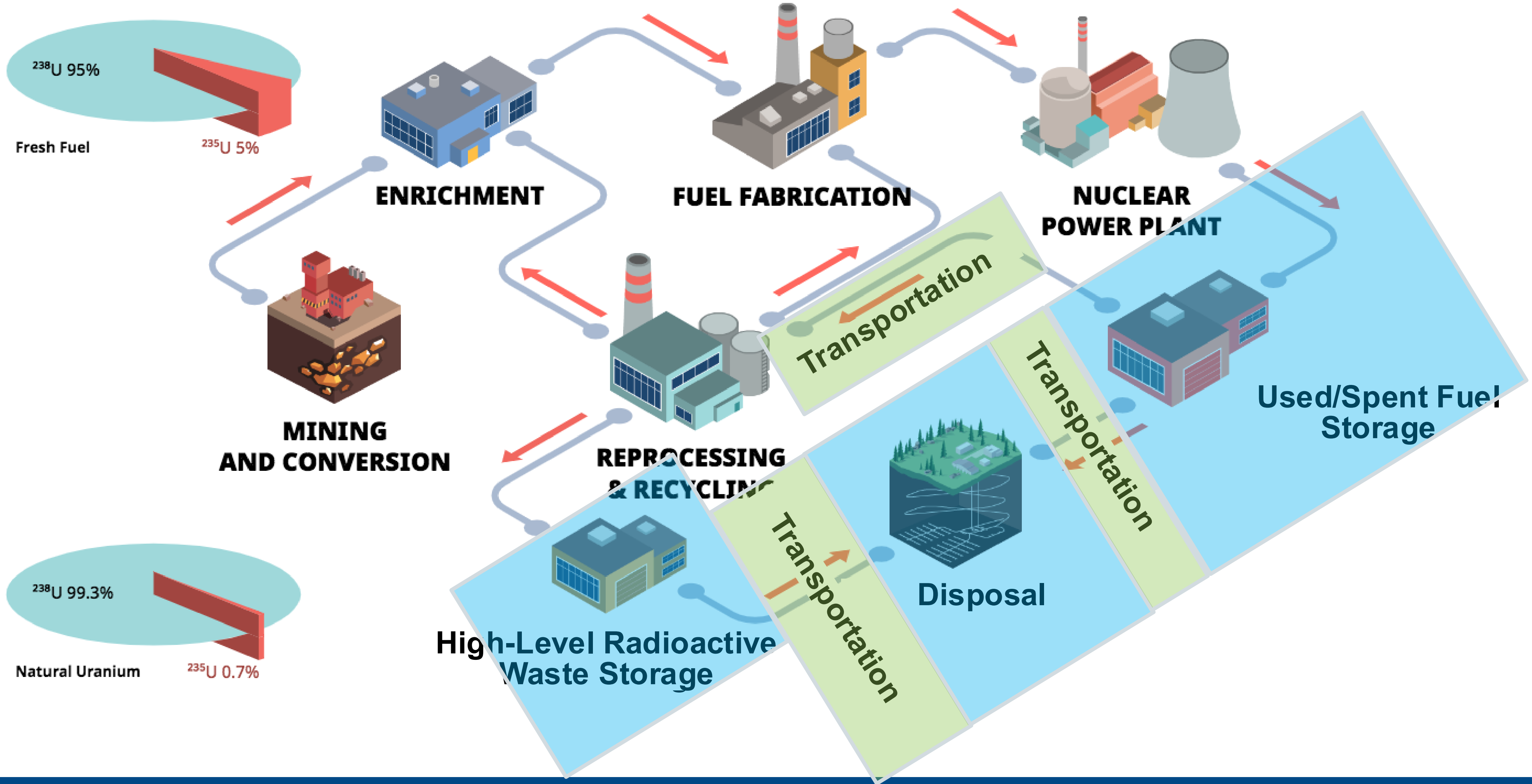
[1]The term "used nuclear fuel" is intended to be synonymous with the term "spent nuclear fuel" as used and defined in the Nuclear Waste Policy Act of 1982, as amended, and the Standard Contract for the Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (10 CFR Part 961).

Fuel Cycle Overview

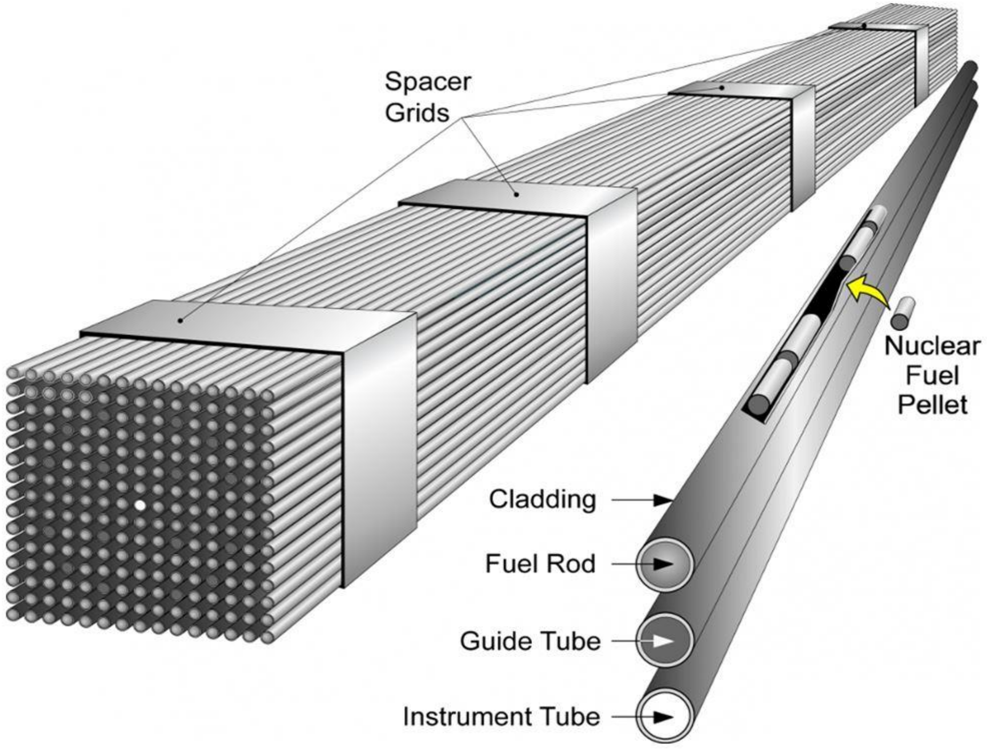


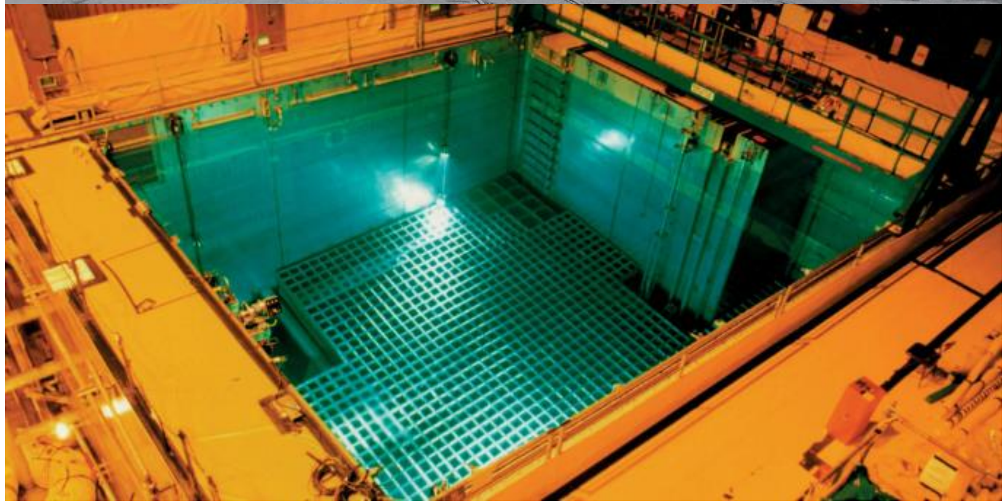
Source: International Atomic Energy Agency, Spent Fuel and Radioactive Waste Management, Decommissioning and Environmental Remediation e-learning curriculum, Module SFM1: Policy and Strategy for Spent Fuel Management (elearning.iaea.org – requires free IAEA Nucleus account)

Used Nuclear Fuel (UNF) and High-Level Radioactive Waste Management



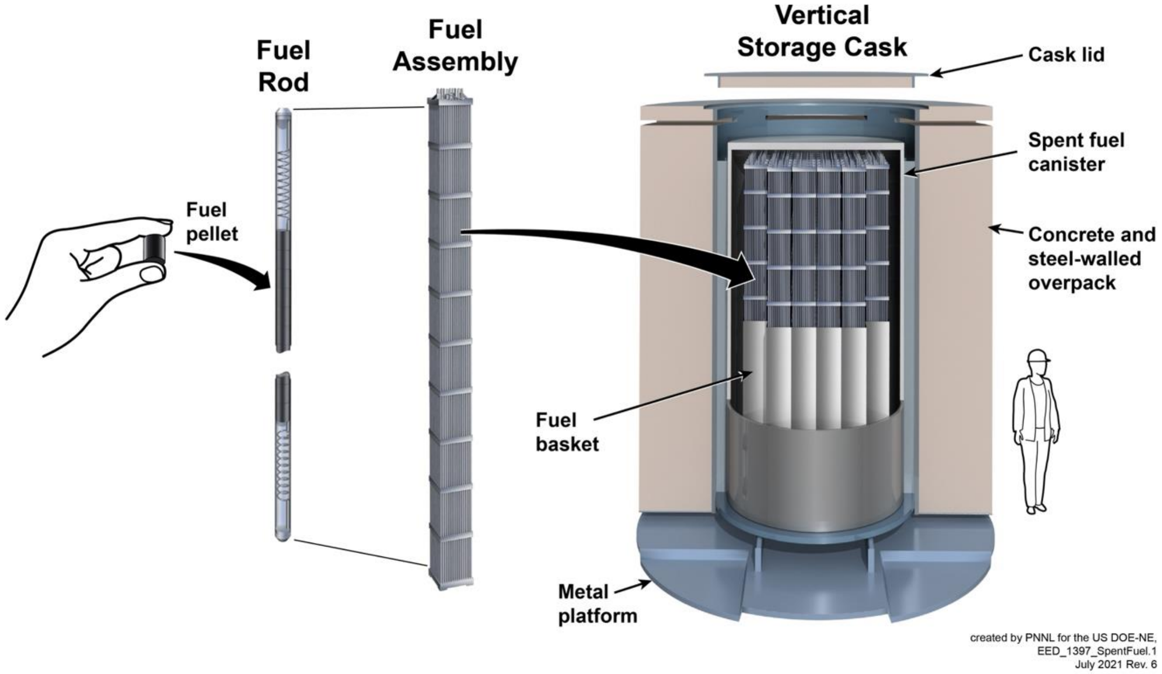
What is Used Nuclear Fuel?



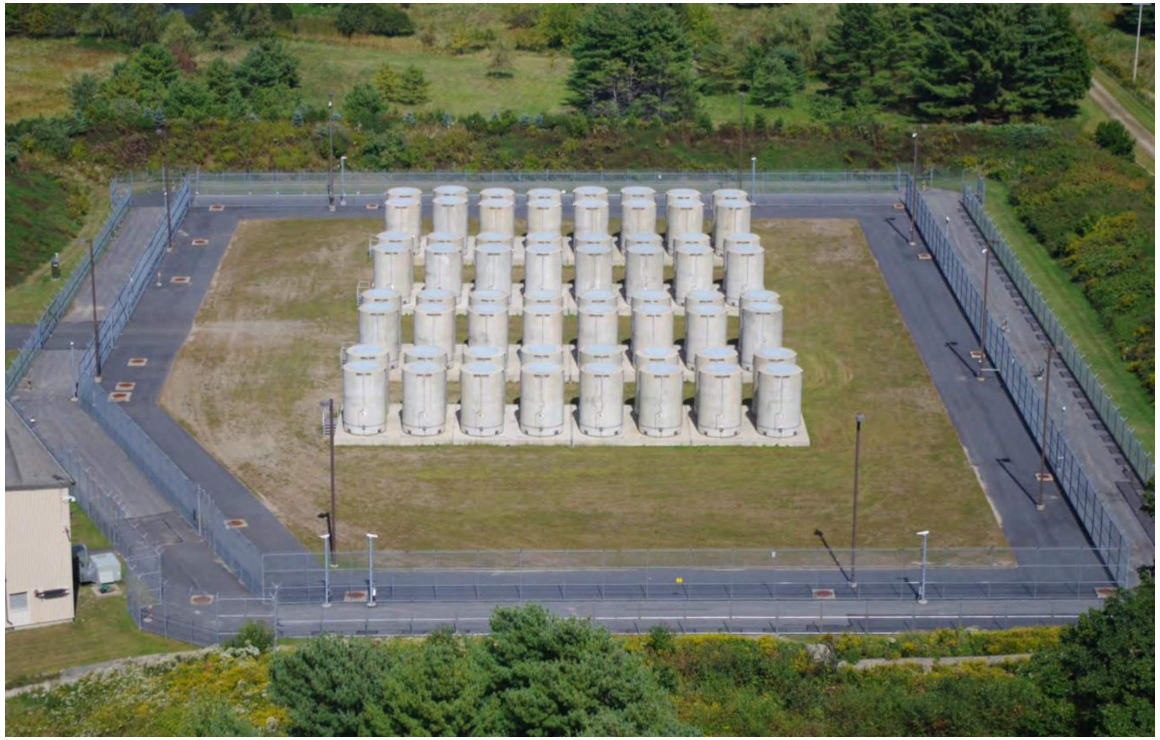


A cutaway figure of a nuclear fuel rod and rod assembly (left), a photo of a nuclear power plant Photo Credit: Three Mile Island (top right), and a photo of a pool for storage of UNF after removal from a nuclear power plant Photo Credit: San Onofre (bottom right).

Storing Used Nuclear Fuel



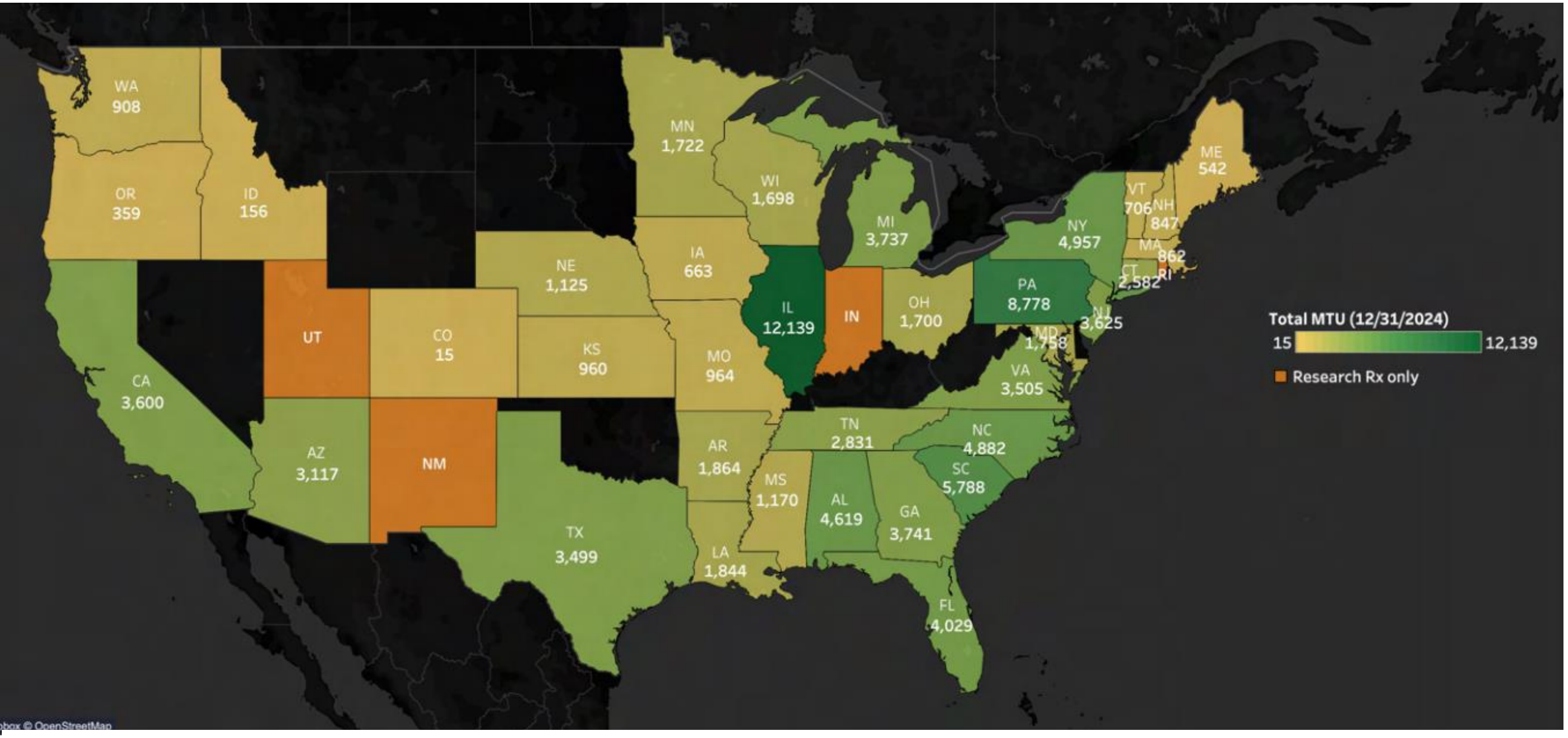
A diagram of nuclear fuel pellets stacked into a fuel rod and fuel assembly with a cutaway figure of a vertical UNF dry storage system (left) and a photo of vertical UNF dry storage systems (right). Photo Credit: Maine Yankee.



Independent Spent Fuel Storage Installation.
Photo Credit: Maine Yankee

39 States in the U.S. Store Used Nuclear Fuel

UNF by State in Metric Tons of Uranium (MTU) (Estimated 12/31/24)



Quantities of UNF from research and defense programs stored under U.S. Department of Energy (DOE) authority not included.

1958
United States began using commercial nuclear power

2026
94 operating commercial reactors at 52 nuclear power plants in 28 States

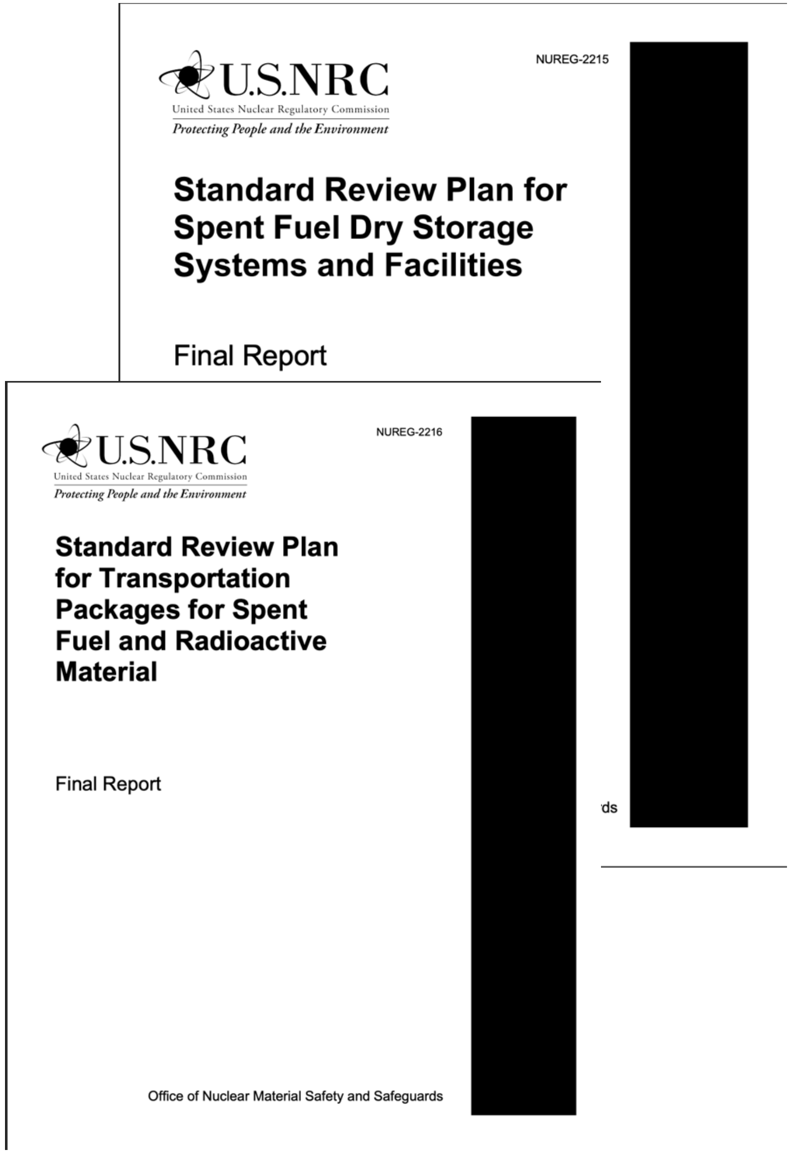
- 20 nuclear power plants have shut down
- ~97,000 metric tons of UNF
- Discharge ~2000 MTU)/yr

End of Current Fleet
United States estimated to have up to approximately 180,000 metric tons of commercial UNF.

Source: Banerjee, K. and Gadey, H. Spent Nuclear Fuel and Reprocessing Waste Inventory, INL/RPT-25-88353 Rev. 002. https://curie.pnnl.gov/document/spent-nuclear-fuel-and-reprocessing-waste-inventory-1

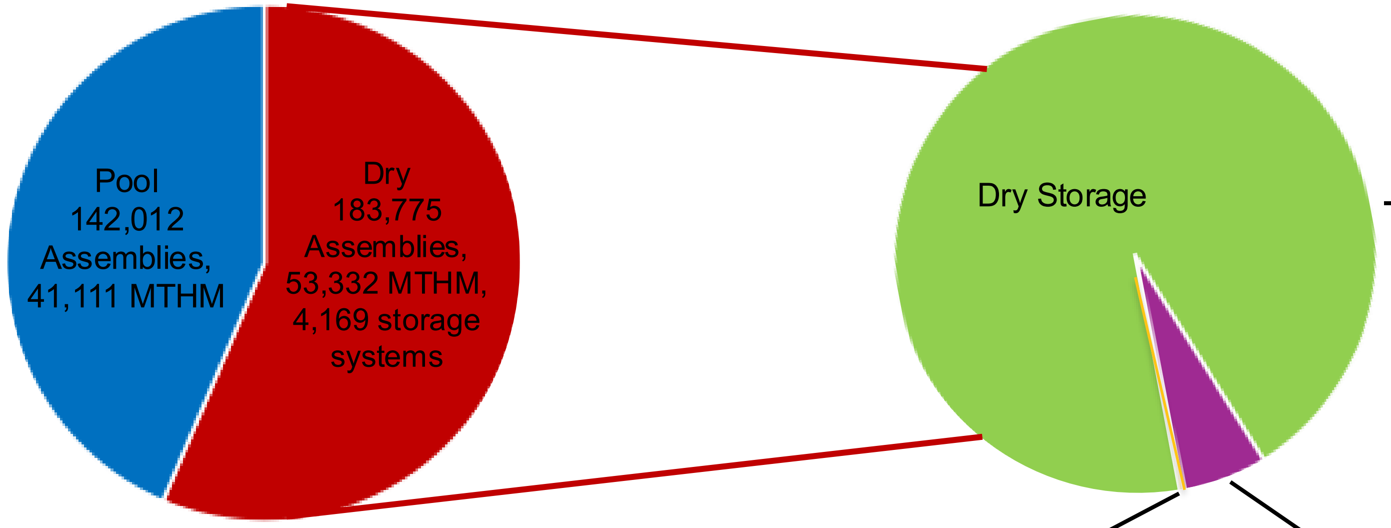
Regulatory Framework for Used Nuclear Fuel

- Dry Storage
  - 10 CFR Part 72 – *Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater than Class C Waste*
  - NUREG-2215 – *Standard Review Plan for Spent Fuel Dry Storage Systems and Facilities*
- Transportation
  - 10 CFR Part 71 – *Packaging And Transportation Of Radioactive Material*
  - NUREG-2216 – *Standard Review Plan for Transportation Packages for Spent Fuel and Radioactive Material*



Dry Storage Canisters Across the United States

Inventory as of December 31, 2024



3,922 welded metal canisters in vented concrete overpacks
171,967 assemblies
94% of dry storage

12 welded metal canisters in transport overpacks
866 Assemblies,
0.3% of dry storage

235 bare fuel casks
10,942 assemblies
5.6% of dry storage

- Majority are in large welded canisters
- Current dry storage inventory is diverse
- Trend toward higher capacities

Source: Banerjee, K. and Gadey, H. Spent Nuclear Fuel and Reprocessing Waste Inventory, INL/RPT-25-88353 Rev. 002. https://curie.pnnl.gov/document/spent-nuclear-fuel-and-reprocessing-waste-inventory-1

Transportation of Used Nuclear Fuel

- Global UNF Transport Scale & Experience
  - UNF has been transported safely for decades.
  - Tens of thousands of shipments worldwide since 1957.
- Safety Record & Incident Types
  - No injuries or fatalities have occurred from radiological causes in UNF or high-level radioactive waste transport.

The Atlas rail car loaded with a test weight resembling a cask

Source: Connolly, K. and Pope, R. A Historical Review of the Safe Transport of Spent Nuclear Fuel, ORNL/SPR-2021-2111. https://www.osti.gov/biblio/2205458

Center for Used Fuel Research (the Center) Established at Idaho National Laboratory – January 14, 2026

Department of Energy Establishes Center for Used Fuel Research at Idaho National Laboratory

U.S. Department of Energy designates Idaho National Laboratory as its leading institution for critical research, development, and demonstration efforts concerning used nuclear fuel management.

WASHINGTON — The U.S. Department of Energy (DOE) Office of Nuclear Energy today announced the establishment of the Center for Used Fuel Research (Center) at Idaho National Laboratory (INL), officially designating INL as its leading institution for critical research, development, and demonstration efforts concerning used nuclear fuel (UNF) management. This strategic move underscores the DOE's renewed commitment to solving one of the nation's most pressing energy and environmental challenges and delivers on a key element of the 1995 Idaho Settlement Agreement establishing INL as the DOE lead used nuclear fuel research laboratory.

https://www.energy.gov/ne/articles/department-energy-establishes-center-used-fuel-research-idaho-national-laboratory

Becoming the Premier Knowledge Hub For Used Nuclear Fuel Management

Mission: Develop innovative technologies and solutions, conduct applied research that helps support and maintain regulatory compliance, and enable public confidence in the storage and transportation of commercial and DOE-managed UNF.

- Reduce DOE's contractual (~$39 - $44 billion) and technical liabilities (TBD)
- Leverage U.S. and international research and operational experience
- Furnish data and methods to support extended storage and transportation

Used Nuclear Fuel transportation cask. Photo Credit: Orano.

Horizontal storage modules for used nuclear fuel. Photo Credit: Crystal River Site.

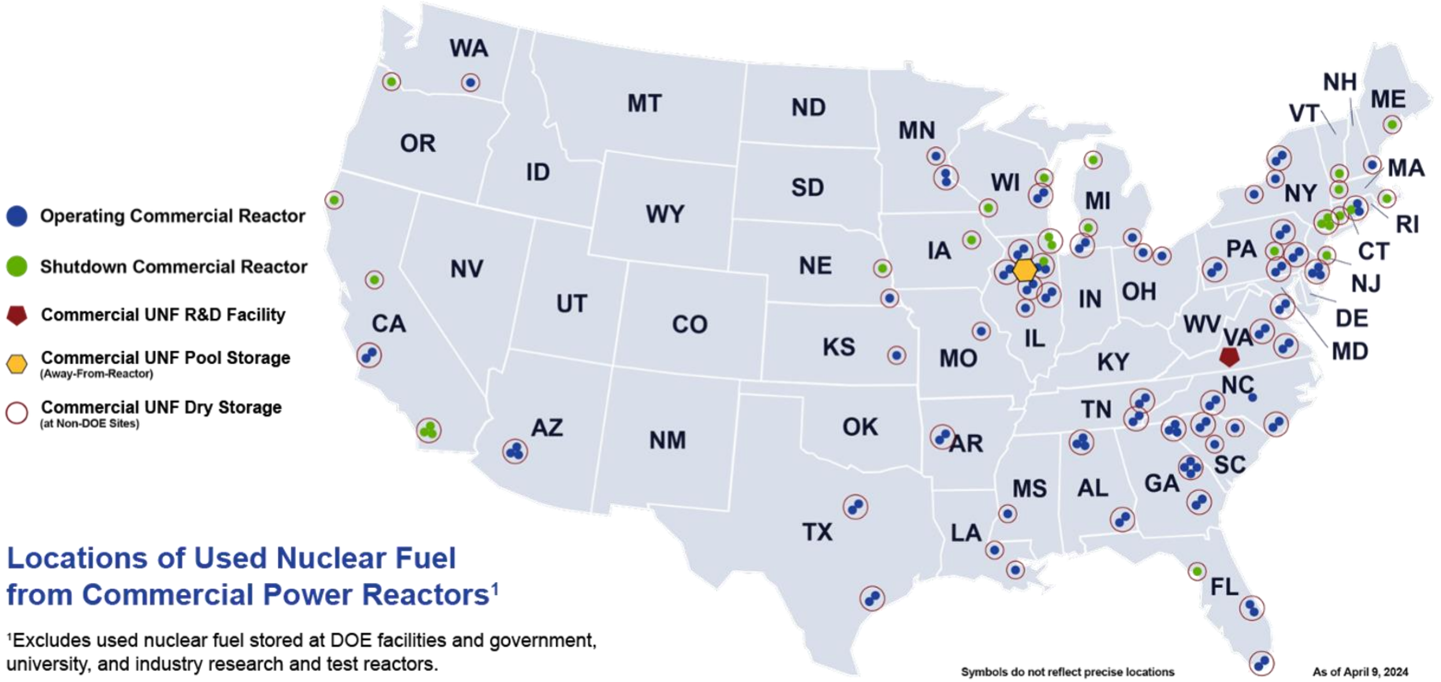
DOE's High Burnup Research Cask (HBURC) is Moving to INL in 2027

The HBURC shown as currently stored at the North Anna Power Station. The temperature measuring equipment that distinguishes it from the other casks will be removed prior to shipment to Idaho National Laboratory.

- Research project started in 2013 as a collaboration between DOE and the Electric Power Research Institute (EPRI)
- Monitoring characteristics of high burnup UNF in one dry cask at the North Anna Power Station near Mineral, Virginia
- Project will provide data to support safe storage of UNF for DOE's future Federal UNF staging facility(ies), and over 50 of currently operating U.S. nuclear power plants

Summary

- UNF has been stored safely and securely in the United States for decades.
- The HBURC is being transported cross-country via rail in 2027.
- Center for Used Fuel Research was established in January 2026 and is hosted at INL.



Locations of Used Nuclear Fuel from Commercial Power Reactors[1]

[1]Excludes used nuclear fuel stored at DOE facilities and government, university, and industry research and test reactors.

Photo credit: Crystal River Site

Photo credit: Crystal River Site

Photo credit: Maine Yankee

Discussion

[Center for Used Fuel Research](https://cufr.inl.gov/) - https://cufr.inl.gov/

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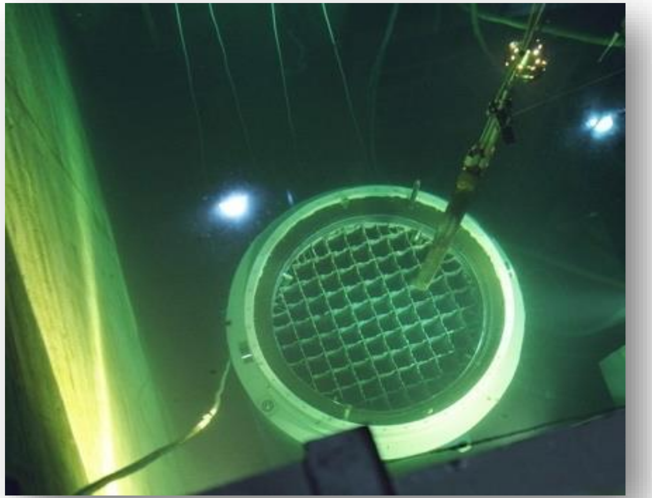
Center for Used Fuel Research

15

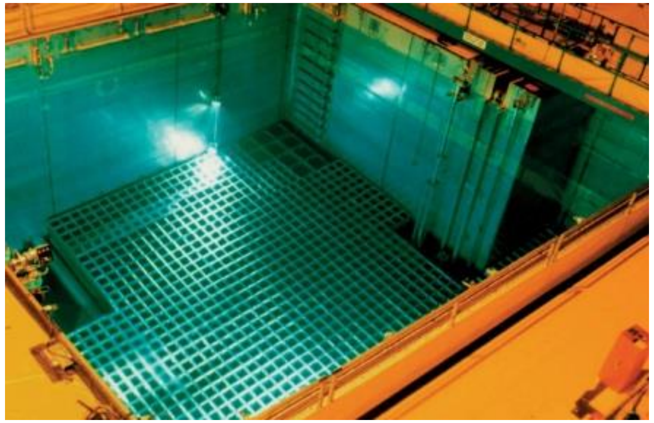
Backup Slides

Current At-Reactor Used Nuclear Fuel Management Practices

- All current commercial reactors are light water reactors (LWRs)
  - LWRs are fueled by low enriched uranium (UO_2) fuel (assemblies) with zirconium cladding
- After ~5 years in reactor, it is discharged and declared UNF
  - No longer useful in the current LWR
- The UNF is then moved into spent fuel pools ("wet storage")
  - Pool storage provides cooling and shielding of radiation
- To allow continued operations, utilities have implemented dry storage
  - Each site generally loads a few storage casks every other year



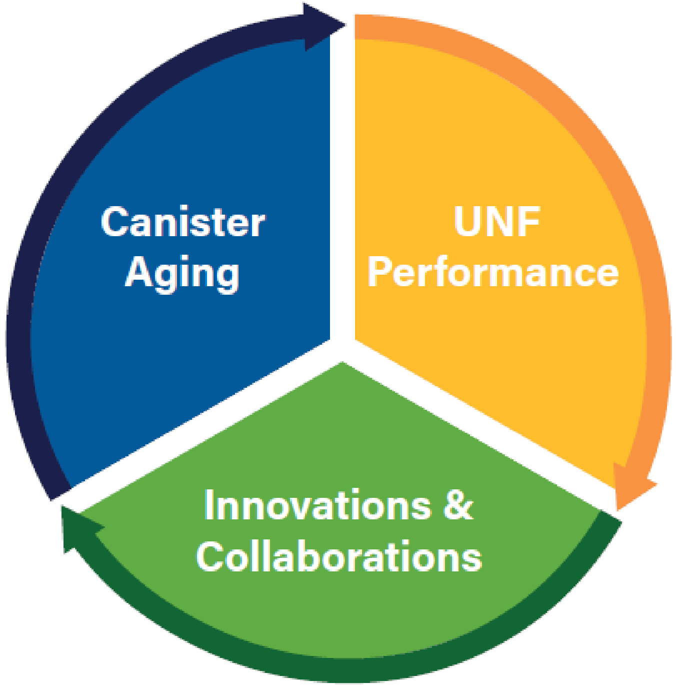
Loading a cask in a spent fuel pool.
Photo Credit: Holtec



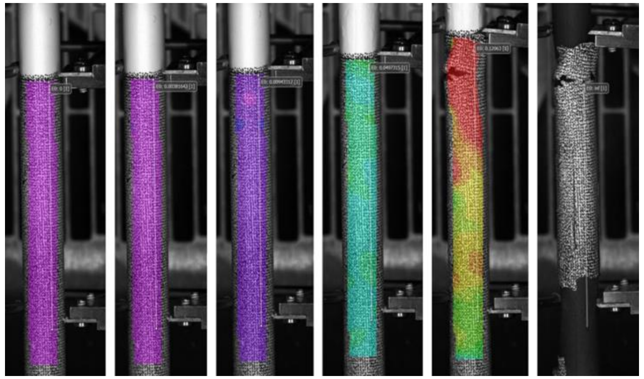
Independent spent fuel storage installation (left). Photo Credit: Portland General Electric Co.
Spent fuel pool for storage of UNF (right). Photo Credit: San Onofre.

Technical Focus Areas – Storage and Transportation

- Identify and disposition degradation mechanisms
- Evaluate advanced inspection technologies
- Develop mitigation strategies



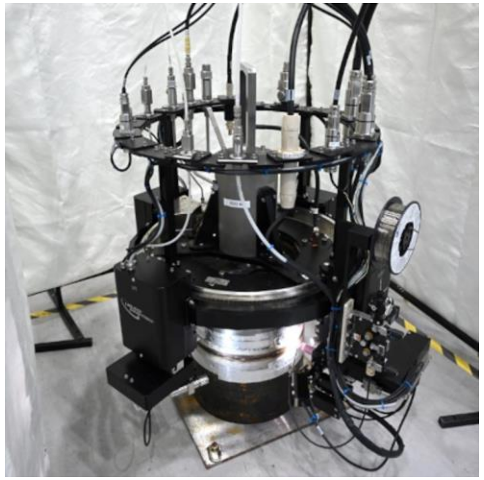
- Characterize high burnup UNF
- Predict fuel behavior for varying scenarios
- Provide empirical data supporting licensing



Strain map progression during axial tensile test

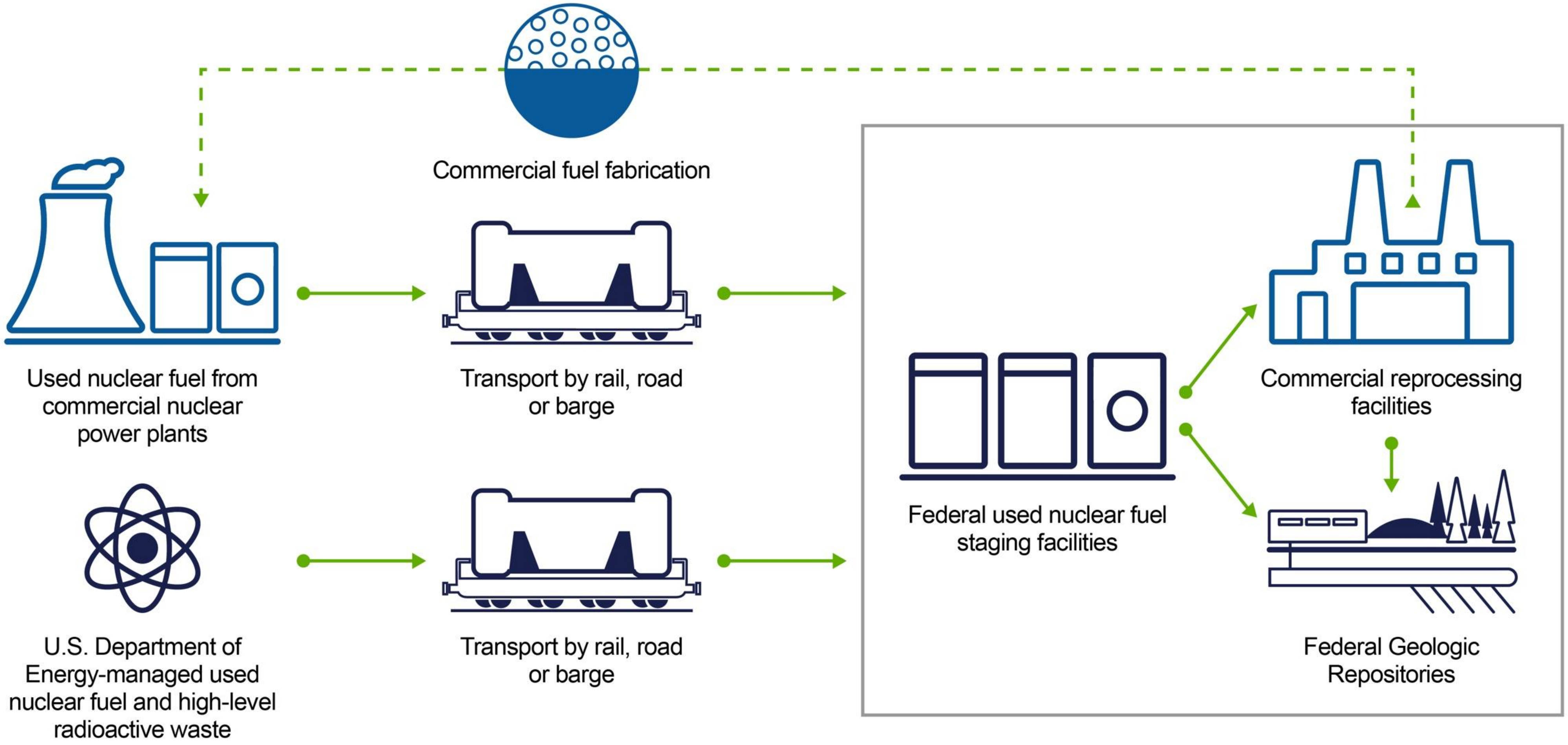
Chloride-induced stress corrosion cracking (CISCC) test systems

- Identify emerging technologies with high potential
- Mature technologies through prototyping, demonstration, and validation
- Facilitate knowledge transfer and adoption by end users



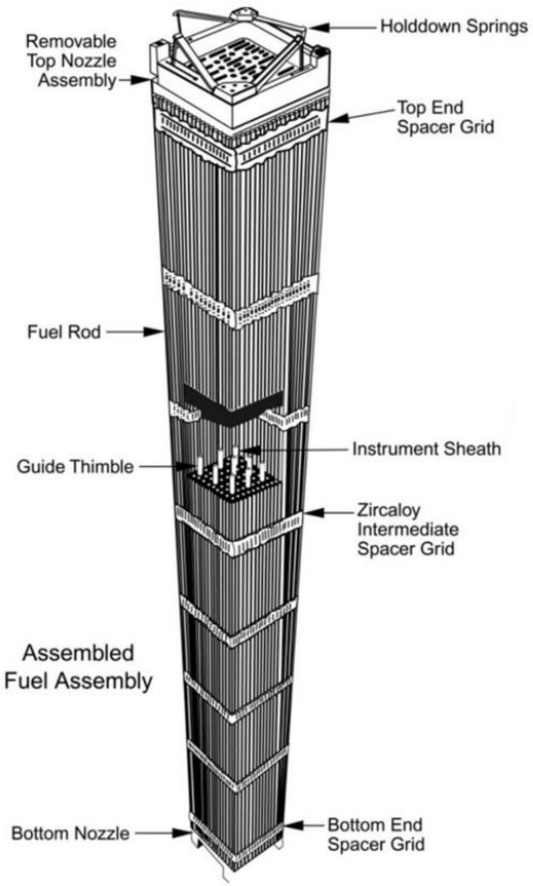
Circumferential weld platform on DOE Standard Canister weld coupon holder

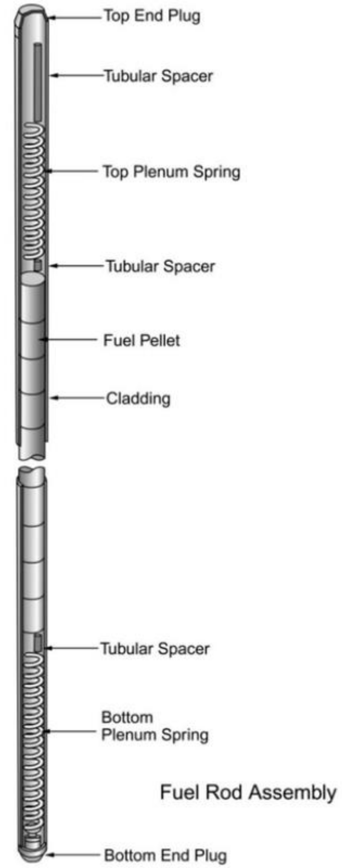
Integrated Waste Management System for Used Nuclear Fuel and High-Level Radioactive Waste

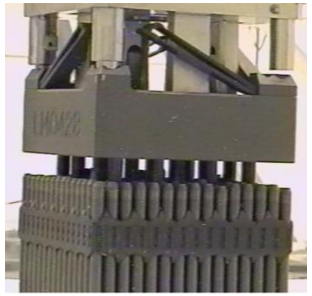


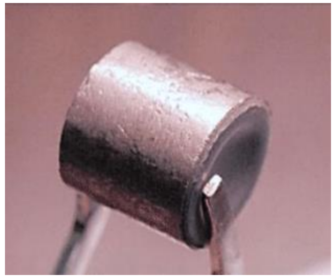
Commercial UNF

- Fuel from commercial power Light Water Reactors (LWRs)
  - Low enriched uranium dioxide (UO_2) fuel
    - Boiling Water Reactors (BWRs)
      - 6x6 to 11x11 arrays
    - Pressurized Water Reactors (PWRs)
      - 14x14 to 18x18 arrays
  - Cladding
    - Legacy (Stainless Steel, Zircalloy 2 and 4)
    - Current (M5, Zirlo)
    - New Accident Tolerant Fuel (coatings and new alloys)









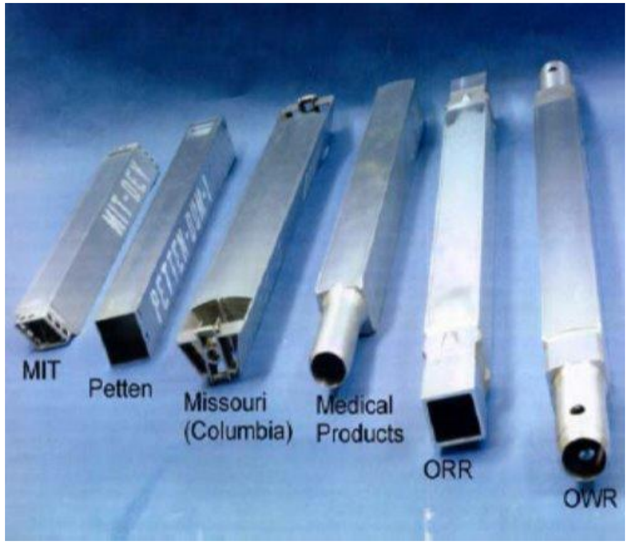
Typical fuel pellet loaded into a fuel rod (Tulenko).

Tulenko, J., & Subhash, G.. Development of an enhanced accident-tolerant composite UO_2 fuel pellet with a dopant of SiC whiskers 2013.
SCIP IV https://www.studsvik.com/key-offerings/fuel-and-materials-technology/international-programs/scip/technical-description-scip-iv/

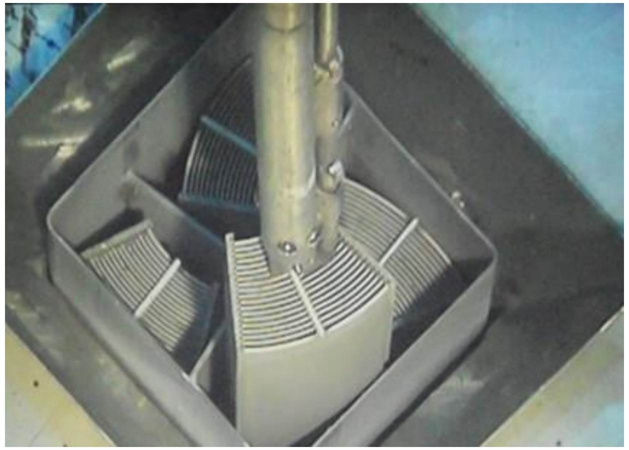
DOE-managed UNF

- DOE-managed Legacy UNF
  - 300+ types (wide range of enrichments, fuel matrices, claddings, and geometries)
  - 250+ types located at INL

CPP-603 IFSF (Irradiated Fuel Storage Facility)

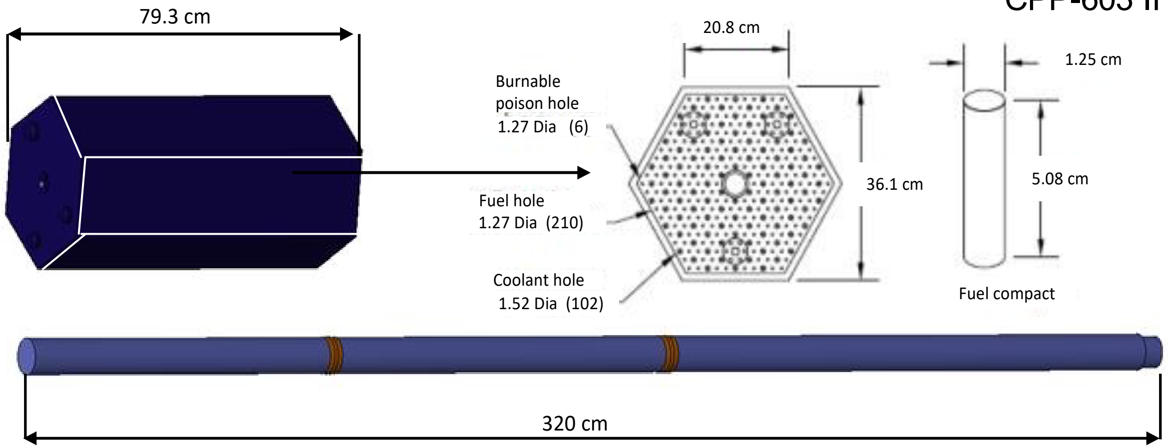


Aluminum Clad Fuel Elements

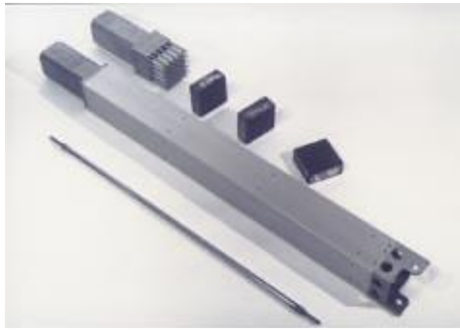


Advanced Test Reactor

Fort Saint Vrain



Peach Bottom Unit 1, Cycle 2

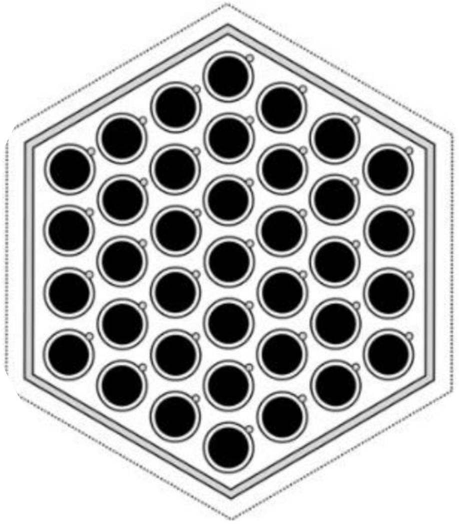


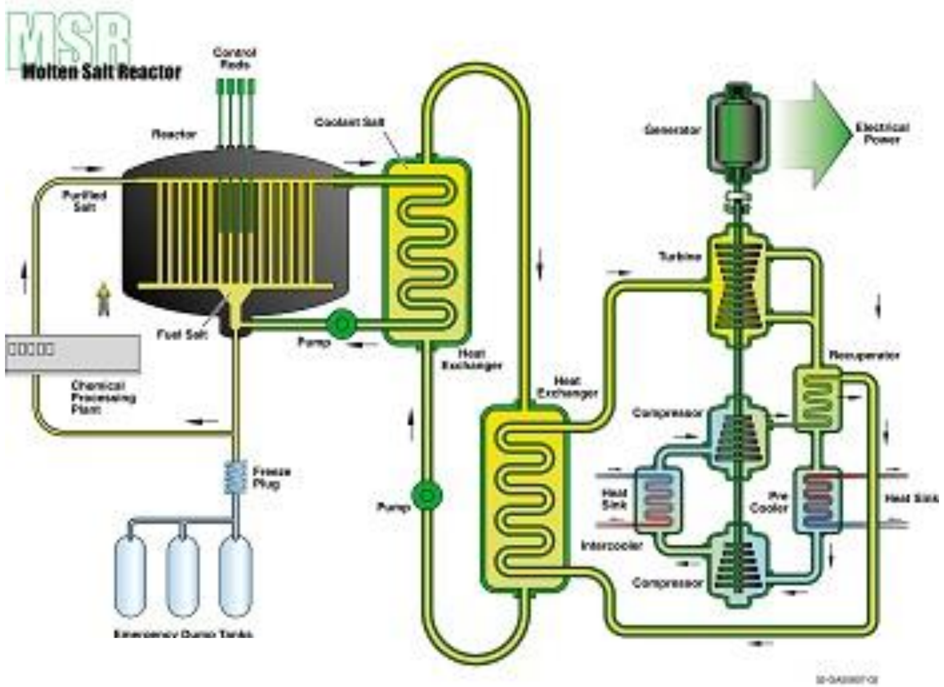
TRIGA

Several advanced reactor design concepts are in development in the United States and around the world.

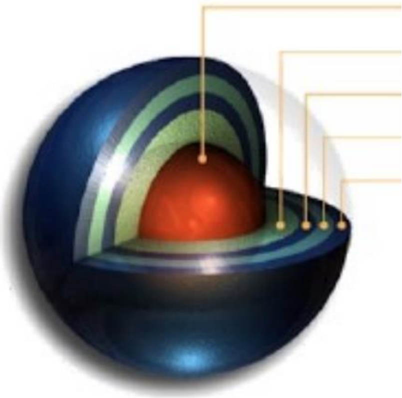
- Fast reactors
  - Sodium-cooled
  - Lead-cooled
  - Gas-cooled
  - Molten-salt cooled
- Molten-salt reactors (MSRs)
  - Fluoride or chloride salts as liquid fue
- High-temperature reactors
  - Graphite moderated thermal reactor
  - Tri-structural isotropic (TRISO) fuel

Cross-section of sodium fast reactor fuel assembly





Molten salt reactor concept (Credit Nuclear Energy Agency)

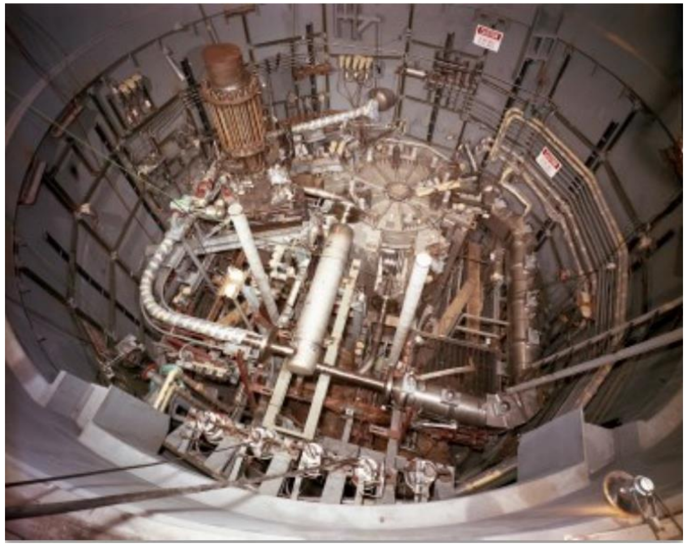


TRISO particle

Many advanced reactor fuel concepts are based on past designs or experiments.

- Fast Reactors
  - Experimental Breeder Reactor (EBR-II)
  - FERMI 1
  - Fast Flux Test Facility (FFTF)
- MSRs
  - Molten Salt Reactor Experiment (MSRE)
- High-Temperature Reactors
  - Peach Bottom Unit 1
  - Fort St. Vrain (FSV) – prismatic block

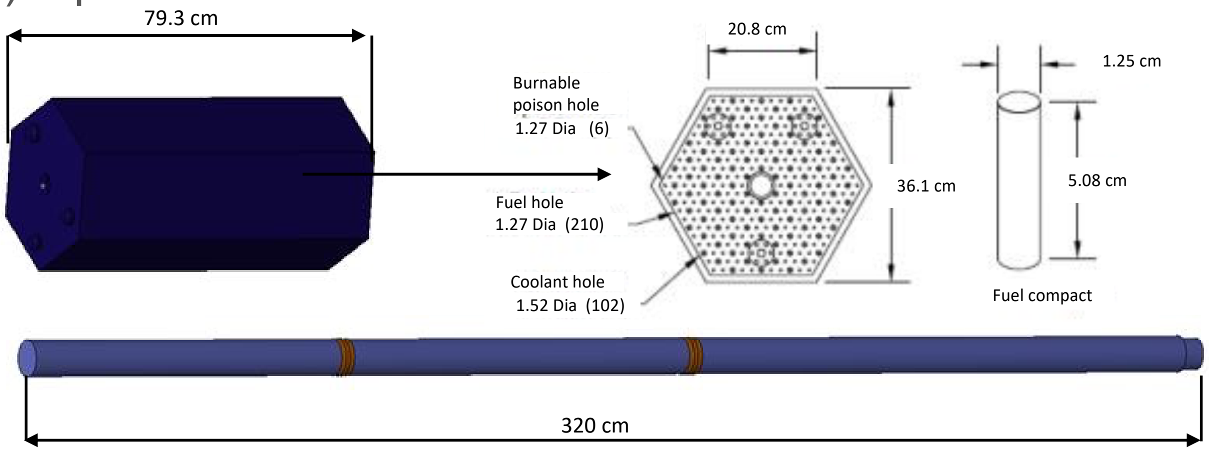
EBR-II fuel assembly



Top-down view of MSRE

FSV fuel element, cross section, and fuel compact

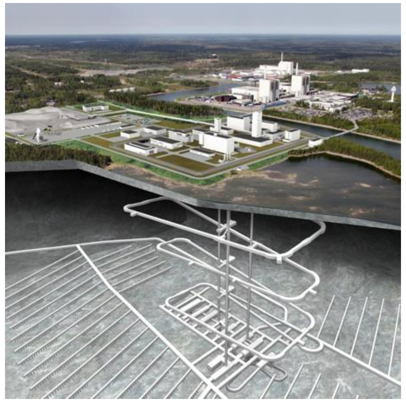
Peach Bottom Unit 1 Core 2 element with handling mechanism removed



Disposal Facilities for Used Nuclear Fuel

Finland

- Most advanced project for UNF in Europe
- Located near the Baltic coast in south-west Finland
- Formation of Finnish Waste Management Organization -Posiva
- Approval to start construction in 2015 and operational in the mid-2020s



Sweden

- UNF will be disposed in crystalline rock: Disposal facility for low-level waste (LLW) and intermediate-level waste (ILW) has been operational since 1988
- Site is close to the Forsmark Nuclear Power Plant near the Baltic Sea, 140 km north of Stockholm.
- License application for construction was submitted in 2011, granted in 2022, with construction possibly beginning in the mid-2020s.

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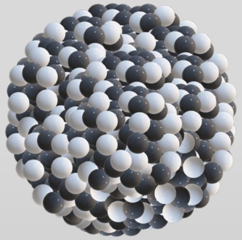
Nuclear Fuel Reprocessing and Recycling

Dr. Mario Gonzalez

Carbon County Events Center
July 16, 2026

What makes nuclear fuel "used"?

What makes nuclear fuel "used"?



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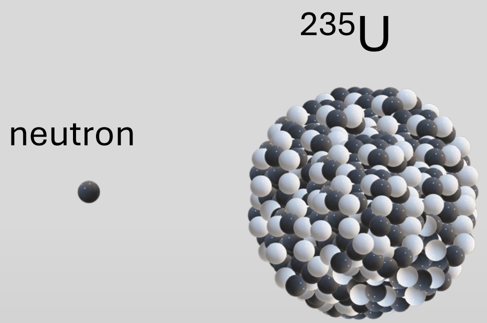

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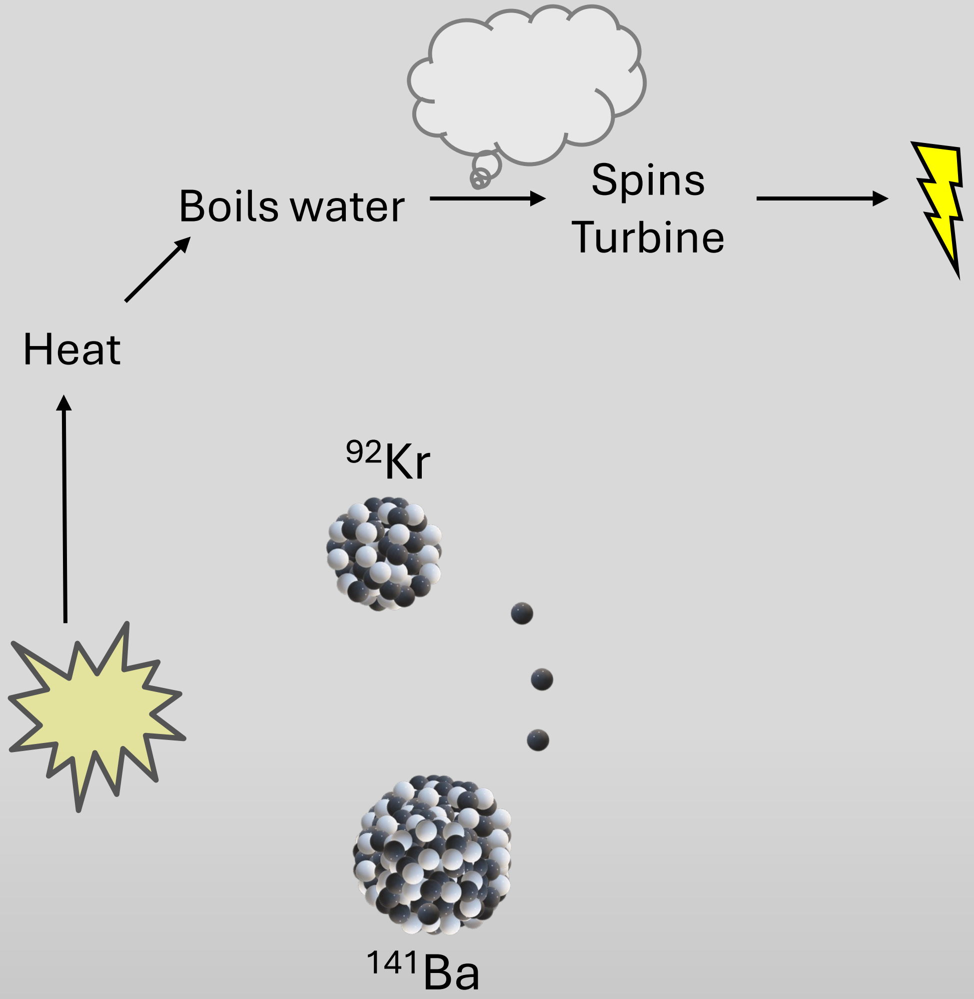

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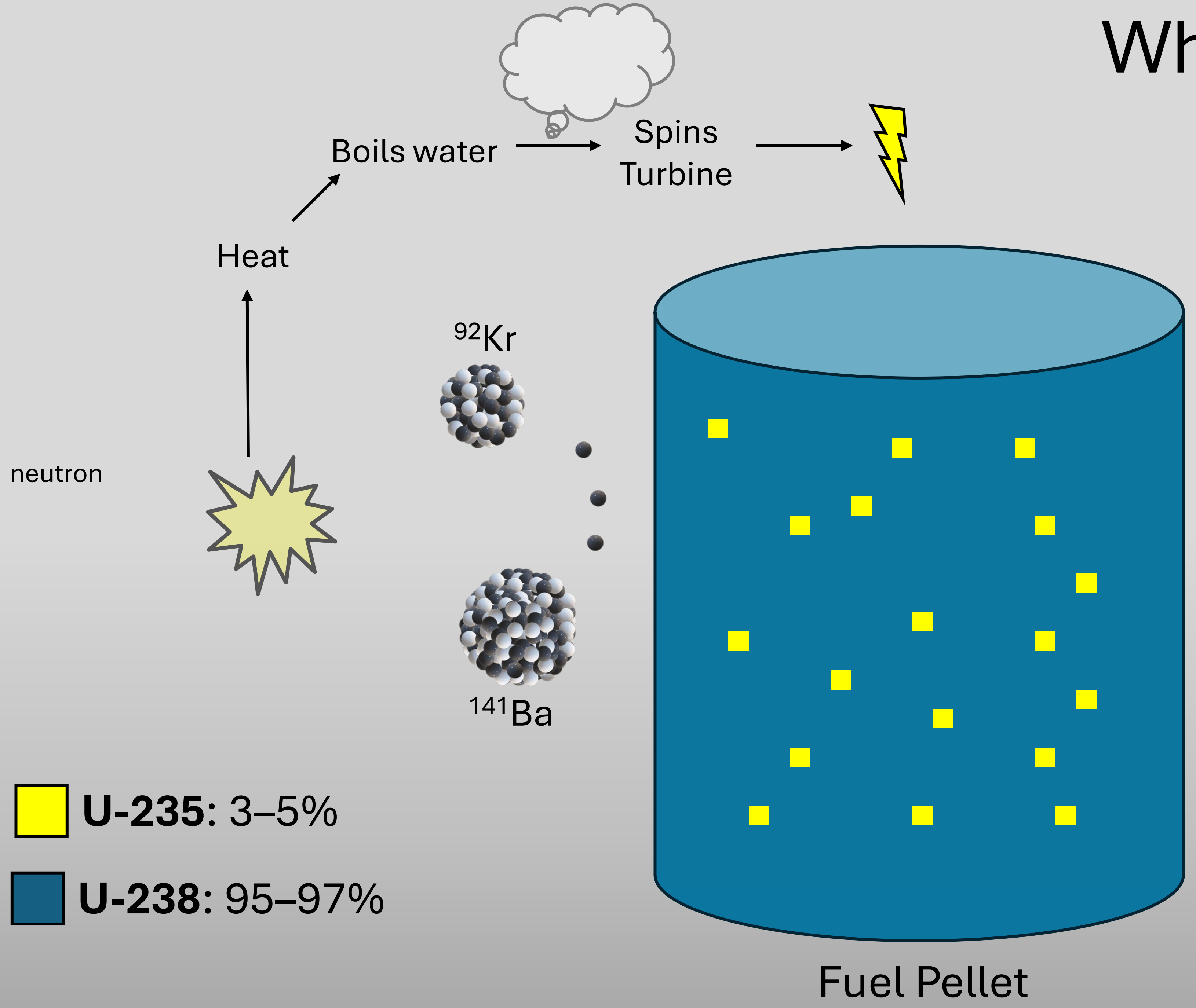

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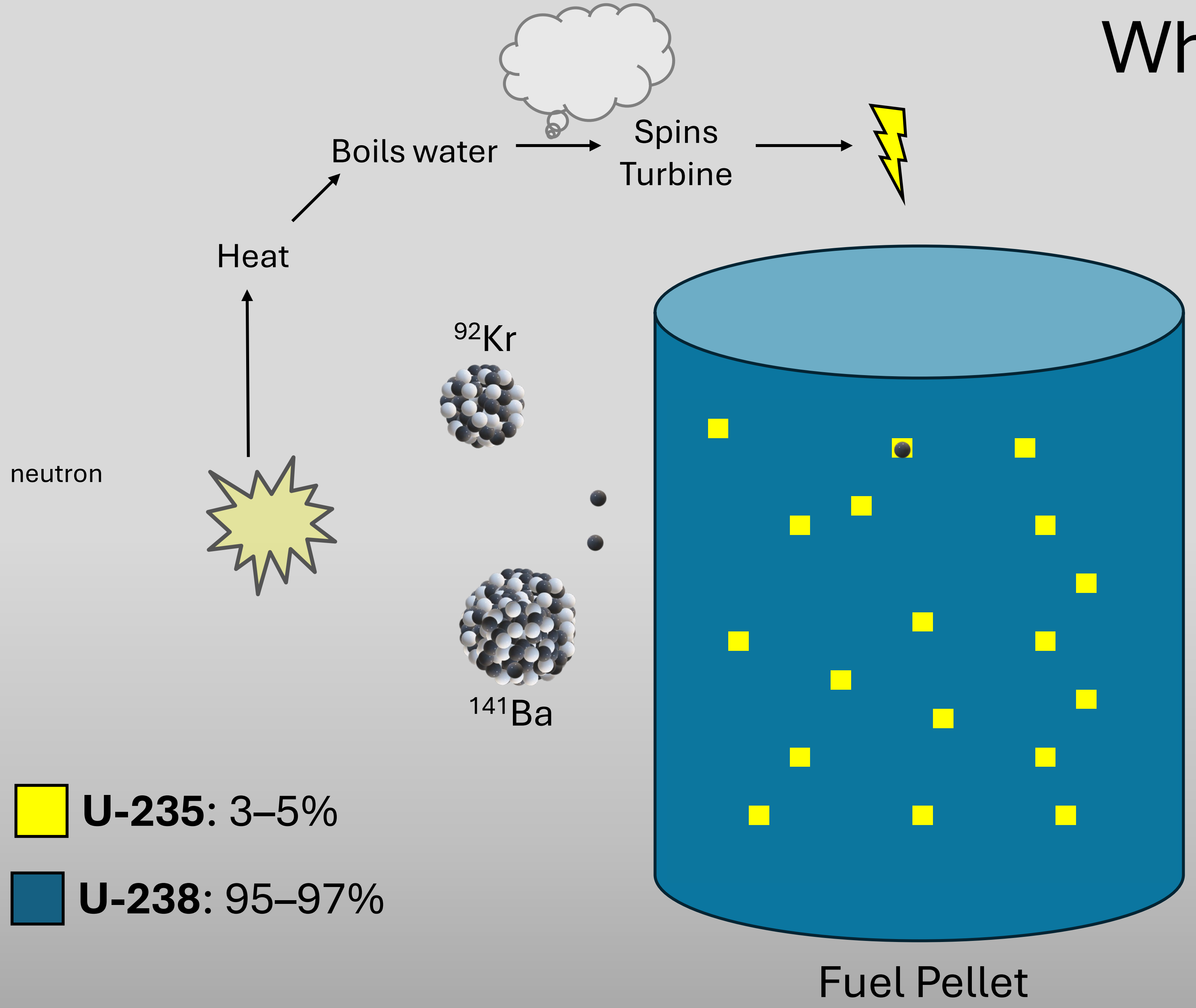
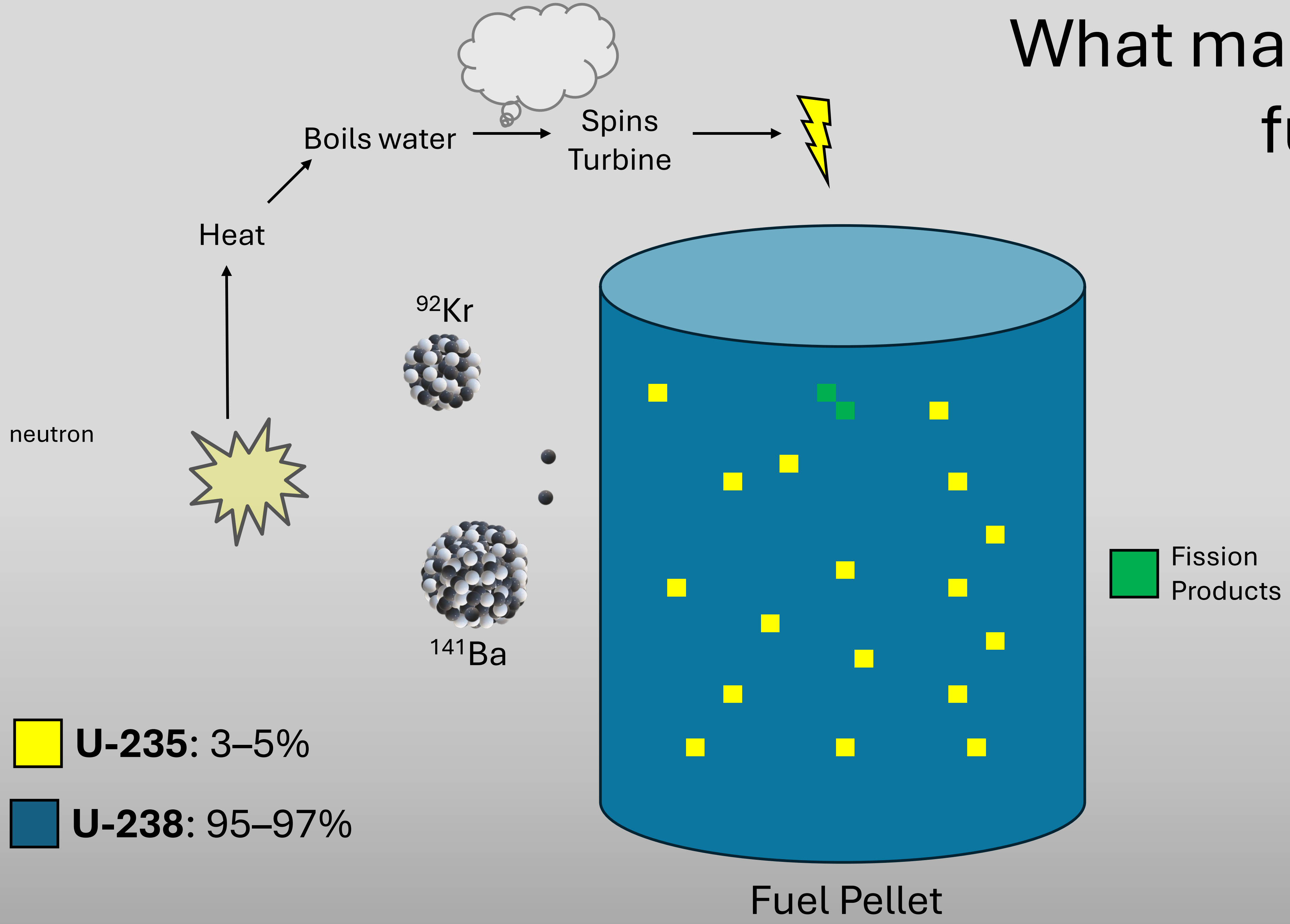


U-235: 3–5%

U-238: 95–97%

What makes nuclear fuel “used”?



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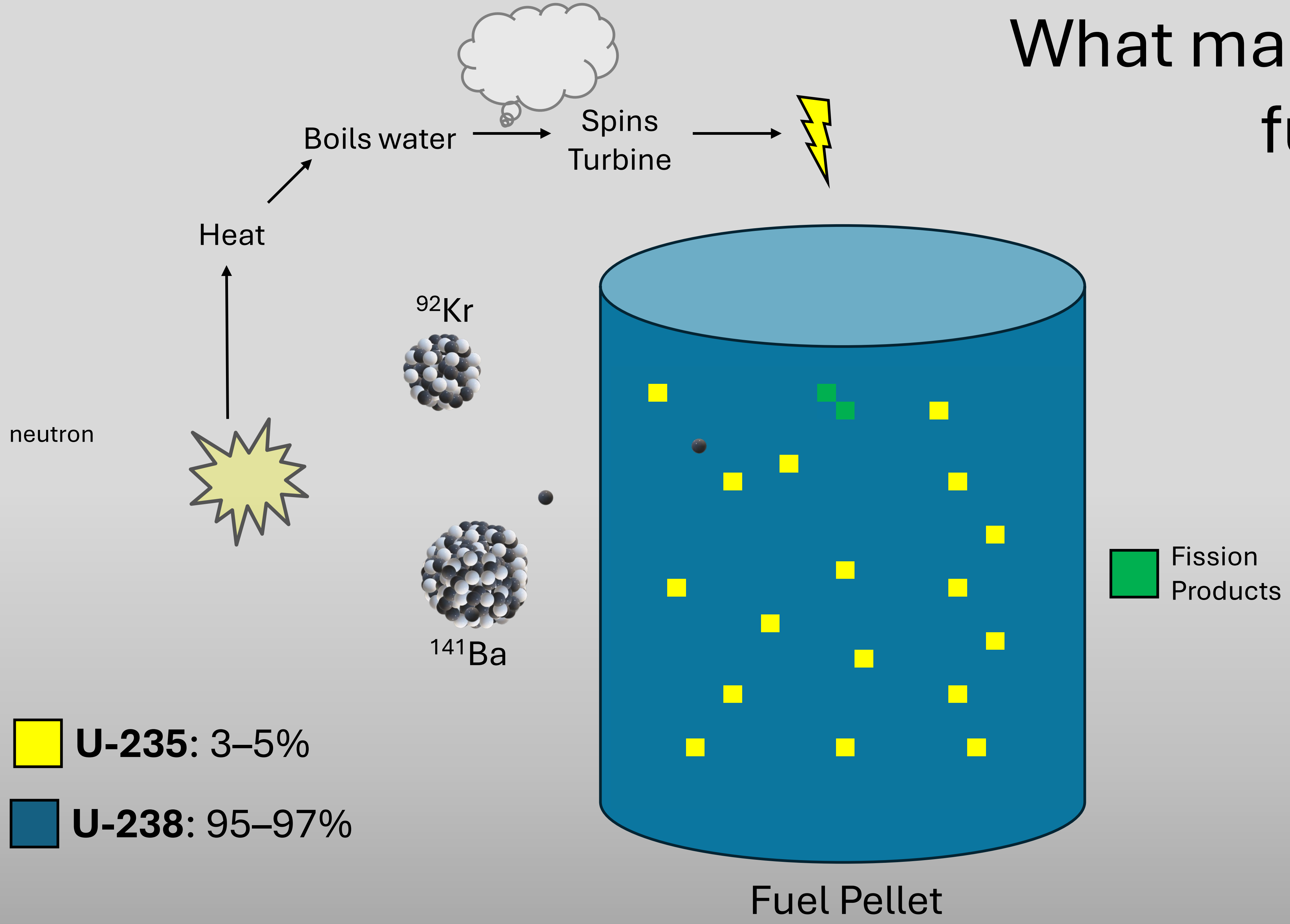

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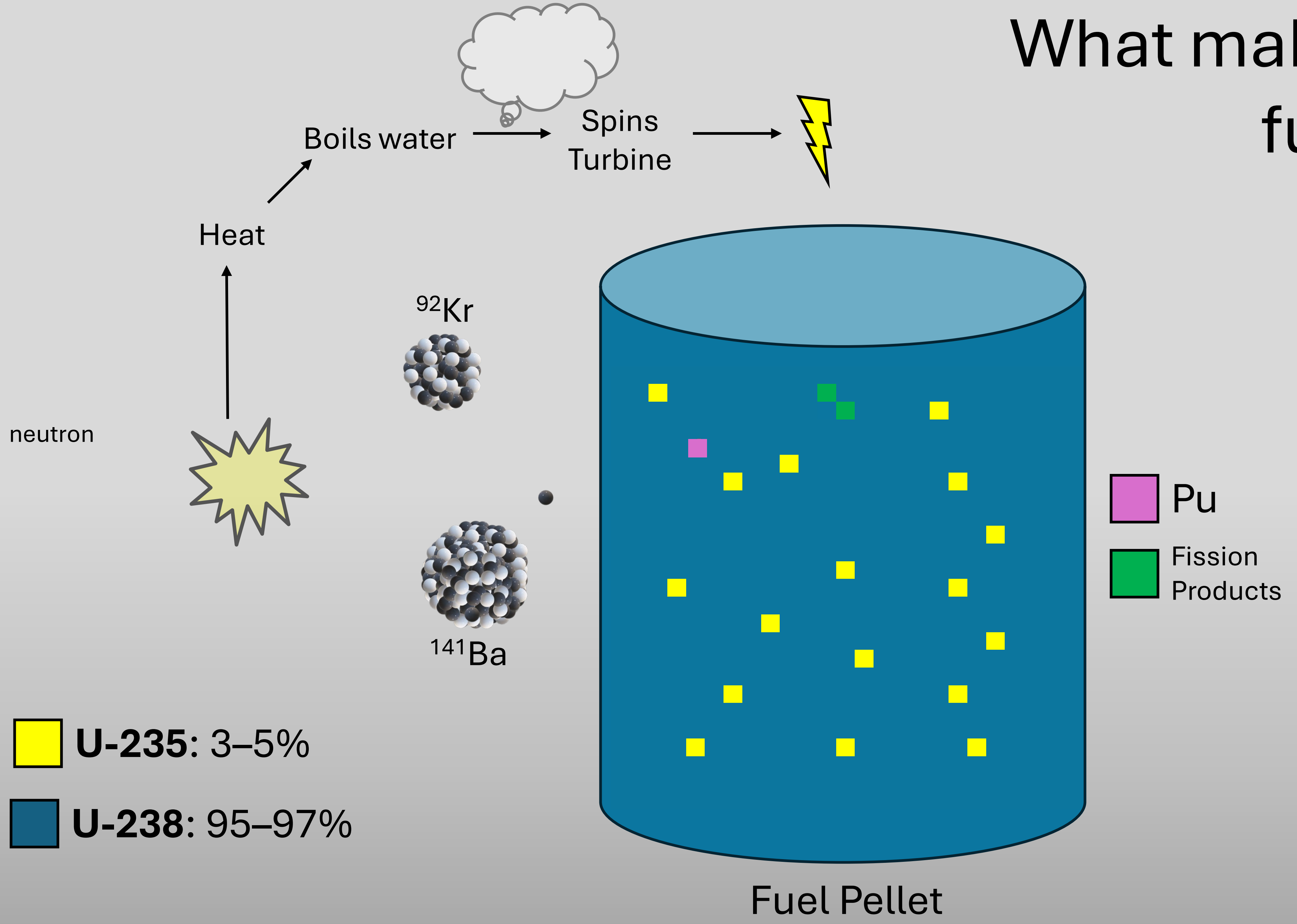

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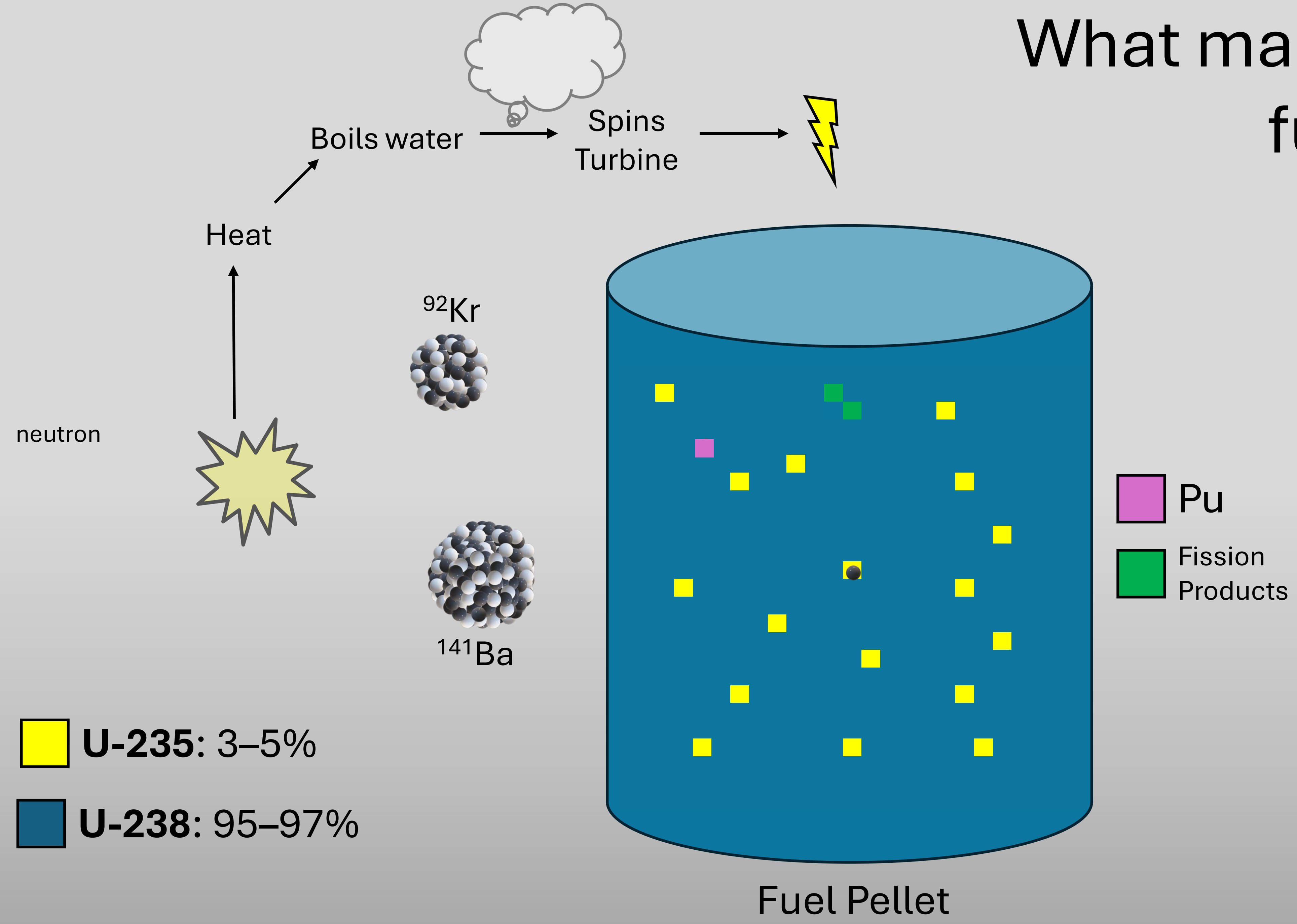

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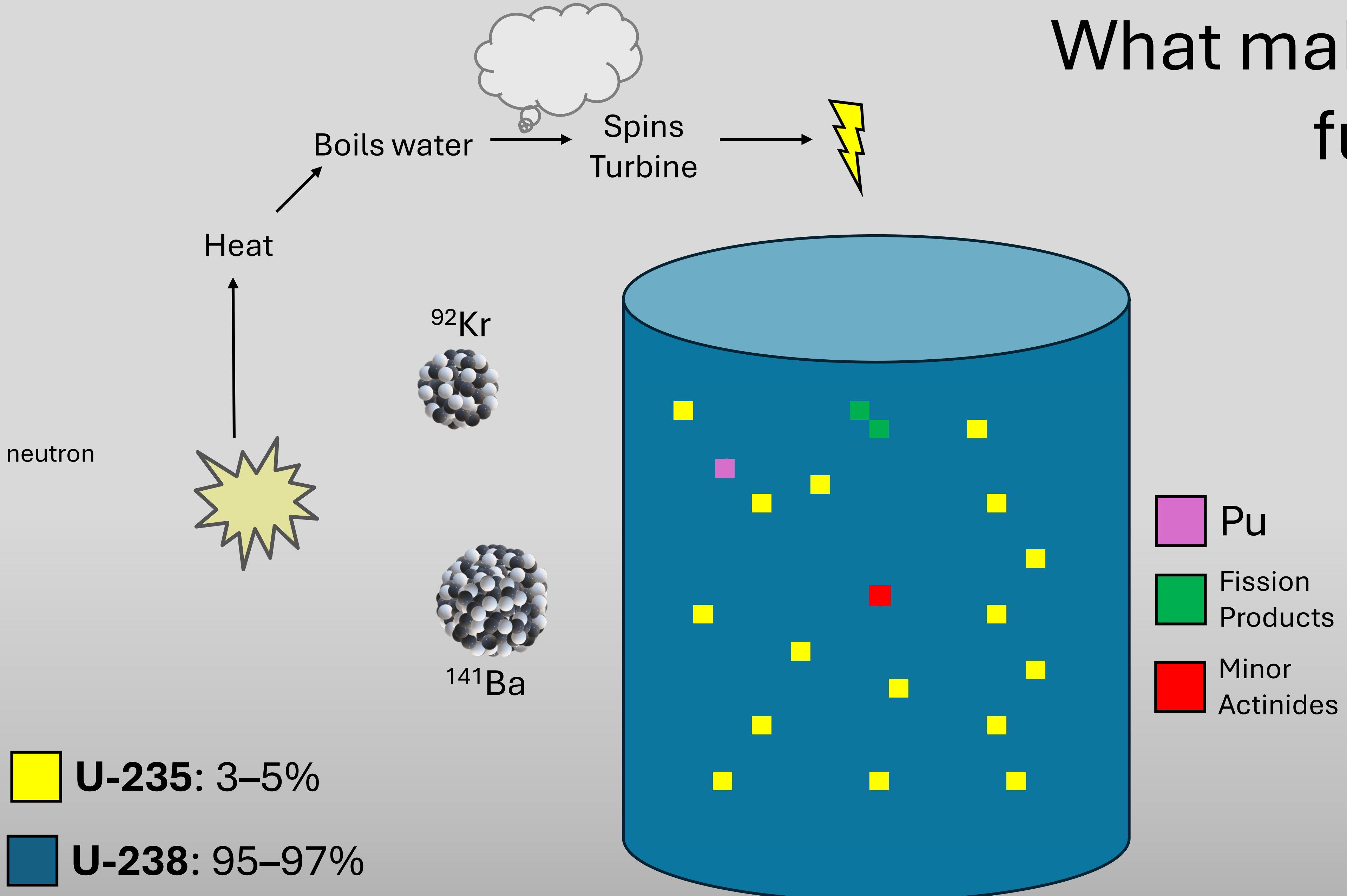
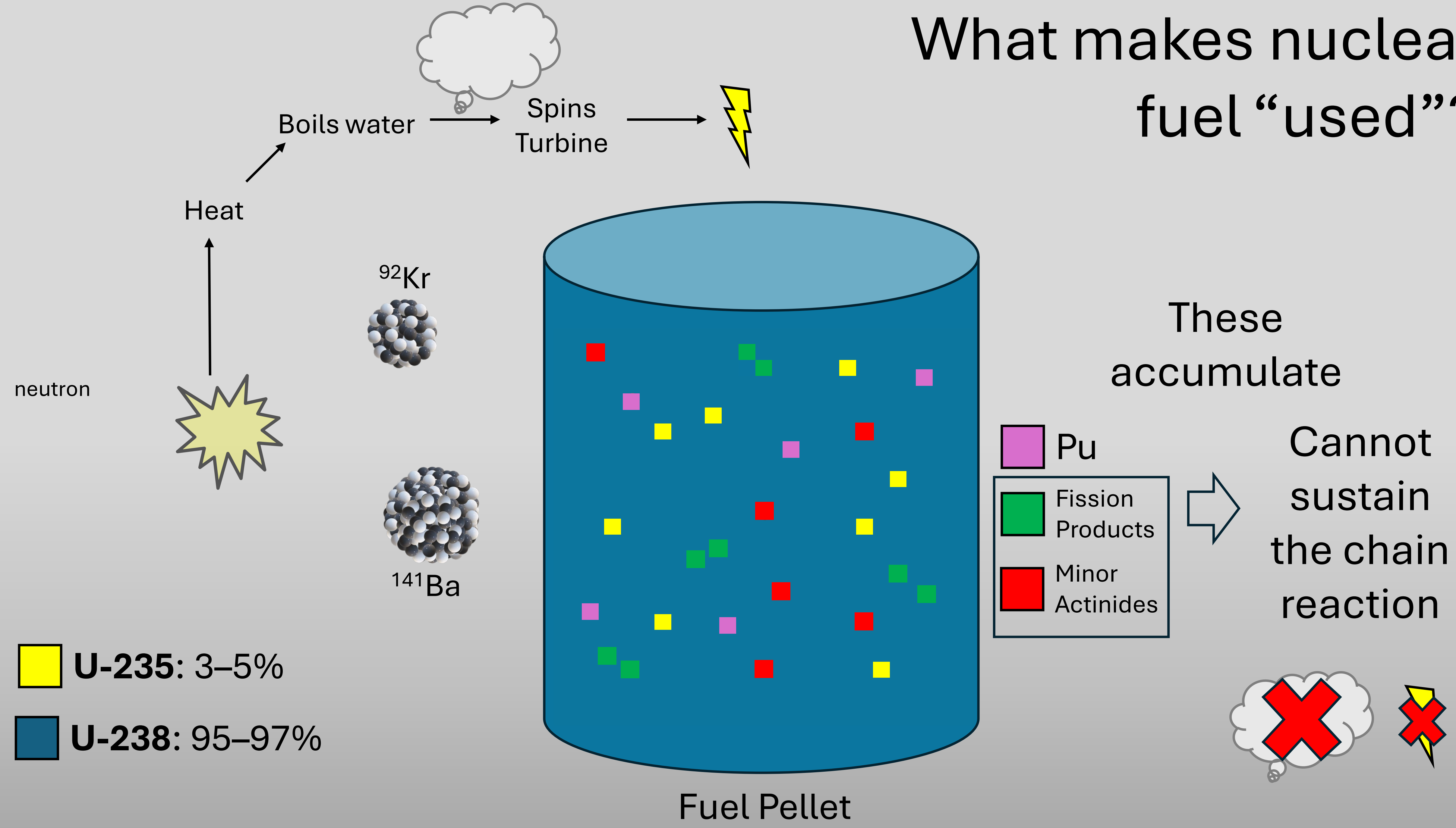
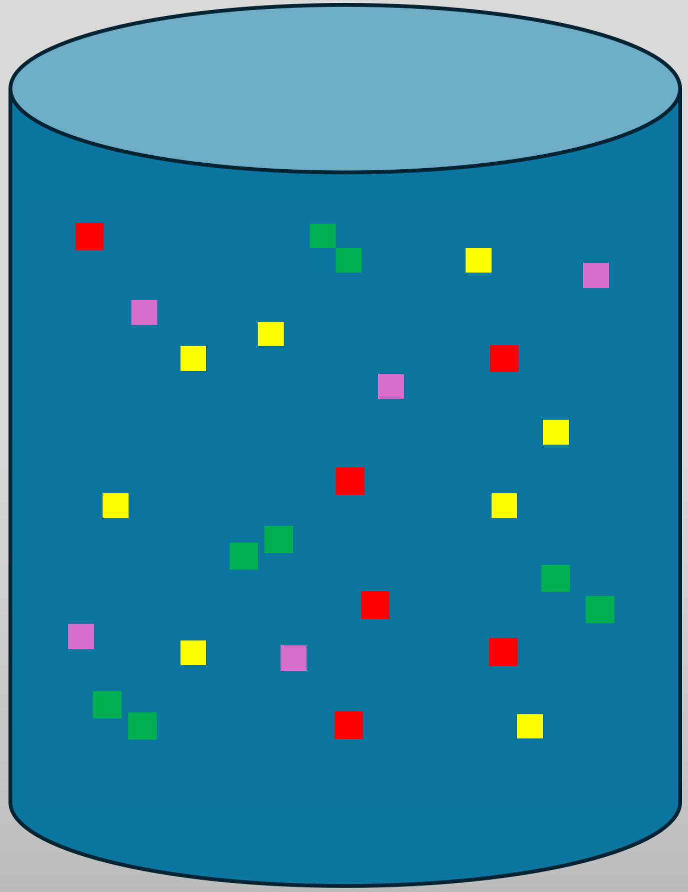


Fuel Pellet

What makes nuclear fuel "used"?



What is still useful?



U-235
U-238
Pu

~ 96%
of used fuel

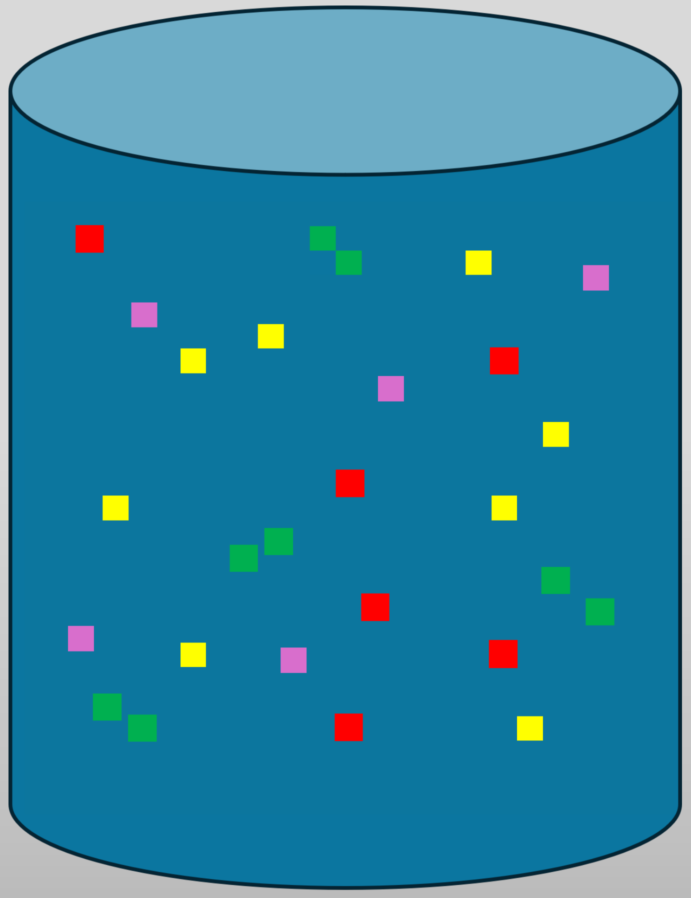
Fission Products ~**3.5%**

Minor Actinides

Newer reactors can also use this

Spent Fuel Pellet

What is still useful?



Spent Fuel Pellet

U-235

U-238

Pu

~ **96%**

of used fuel

Fission Products ~**3.5%**

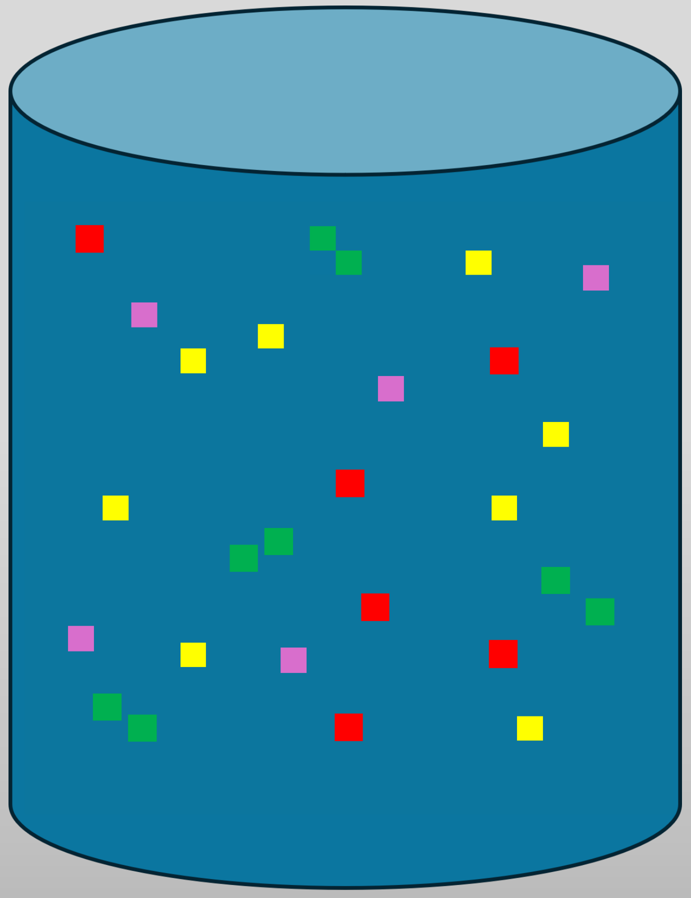
Minor Actinides

Newer reactors can also use this

We already have similar situations

Motor Oil

What is still useful?



Spent Fuel Pellet

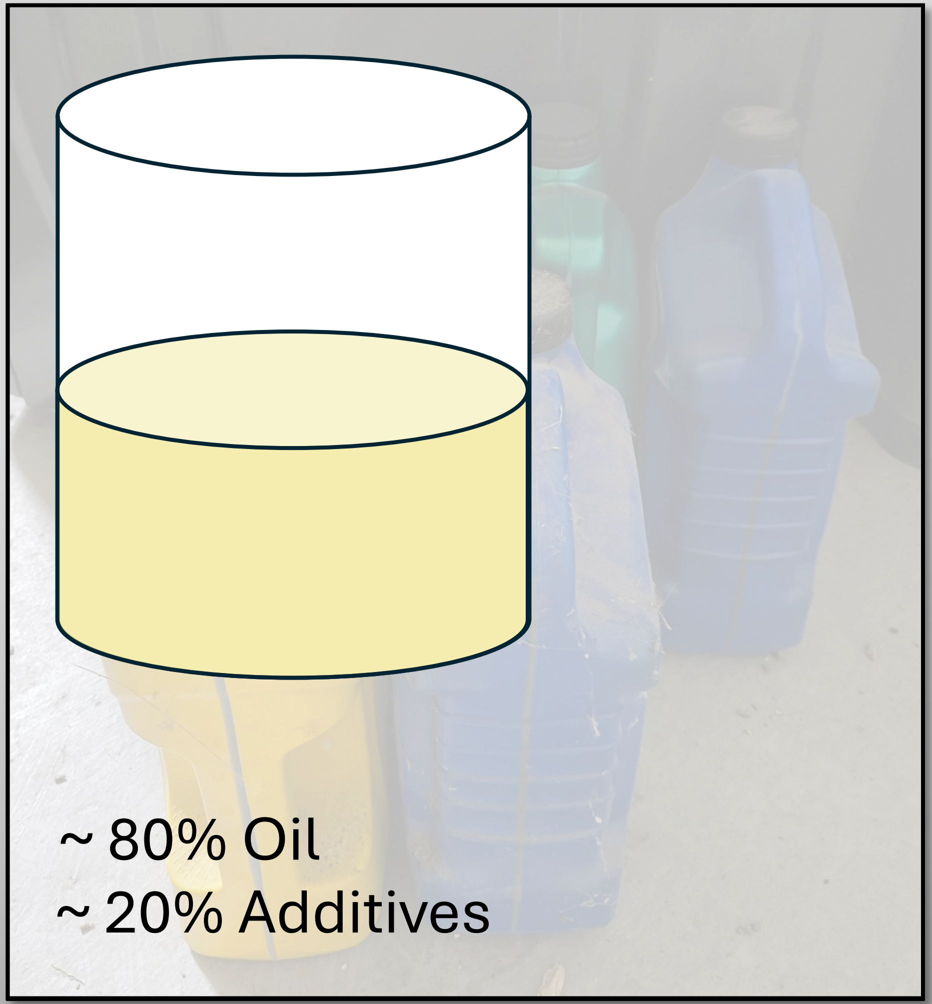
- U-235
- U-238
- Pu

~ 96% of used fuel

- Fission Products **~3.5%**
- Minor Actinides

Newer reactors can also use this

We already have similar situations



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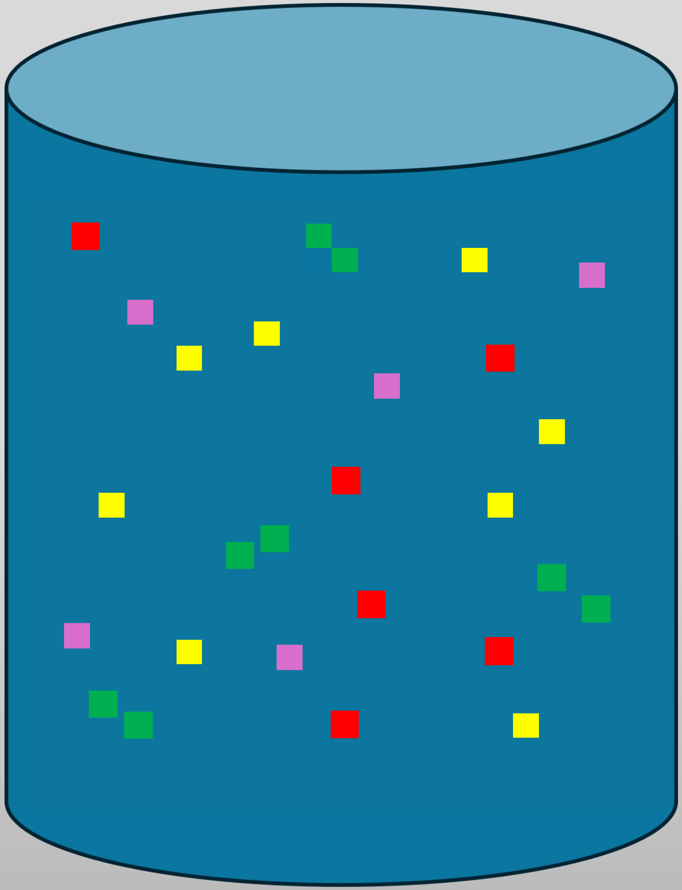

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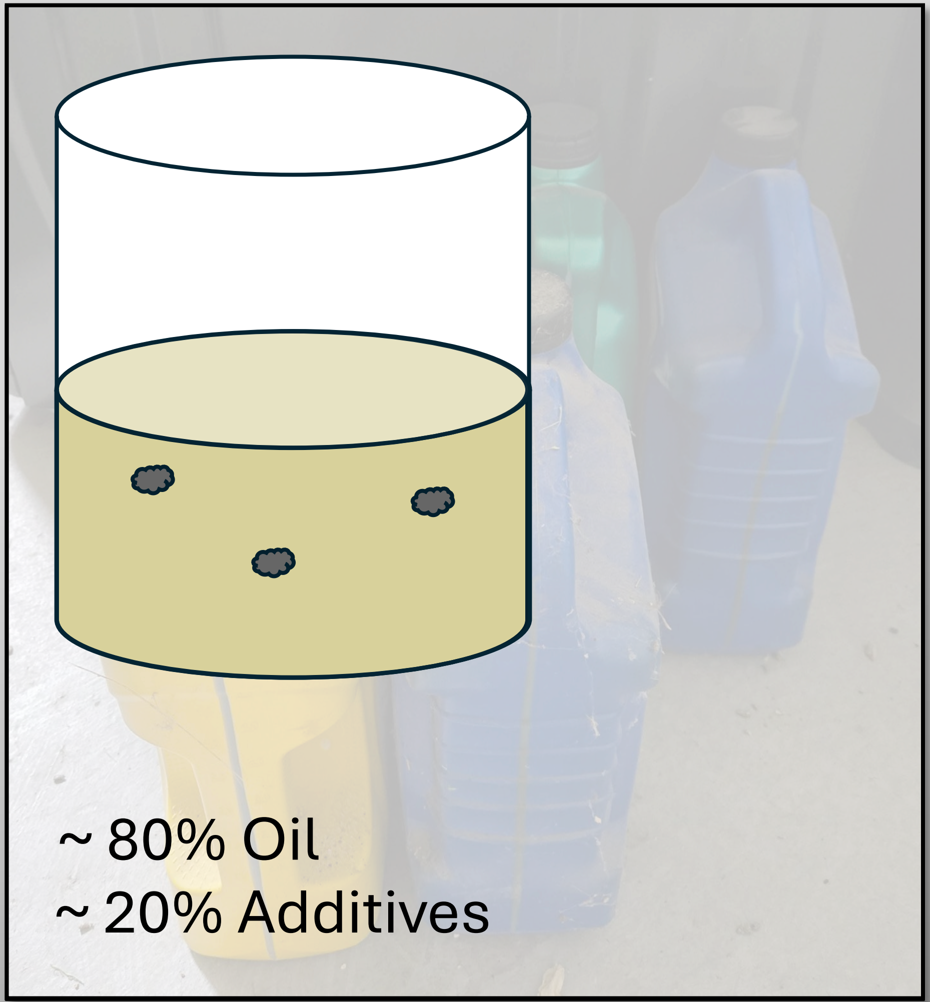

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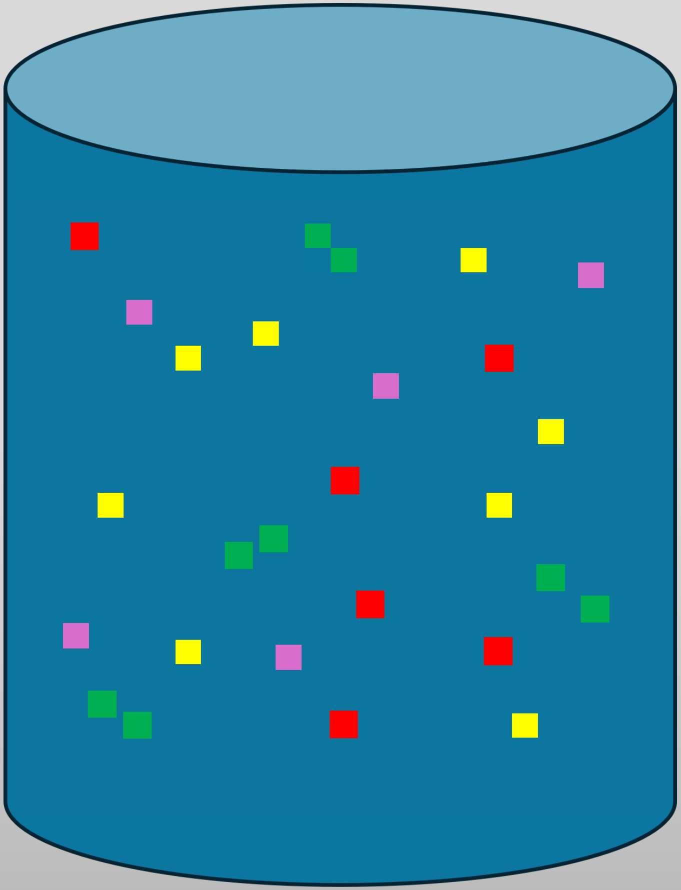

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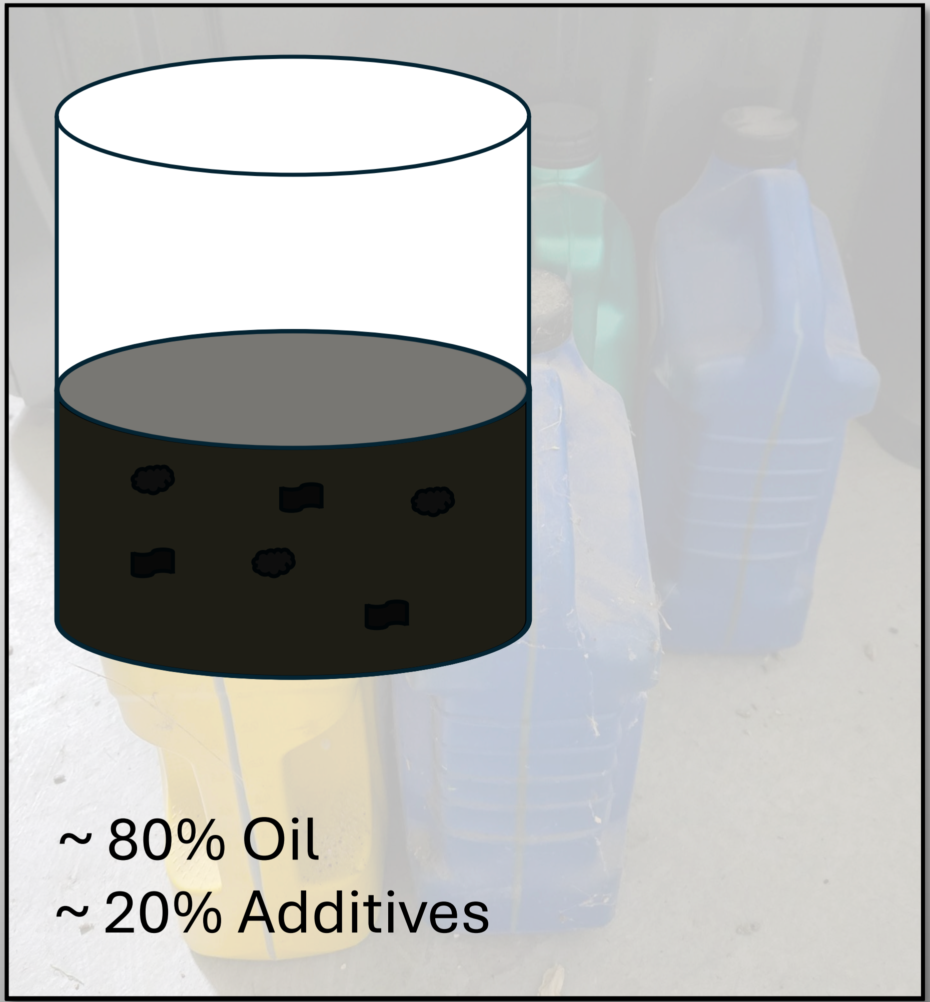

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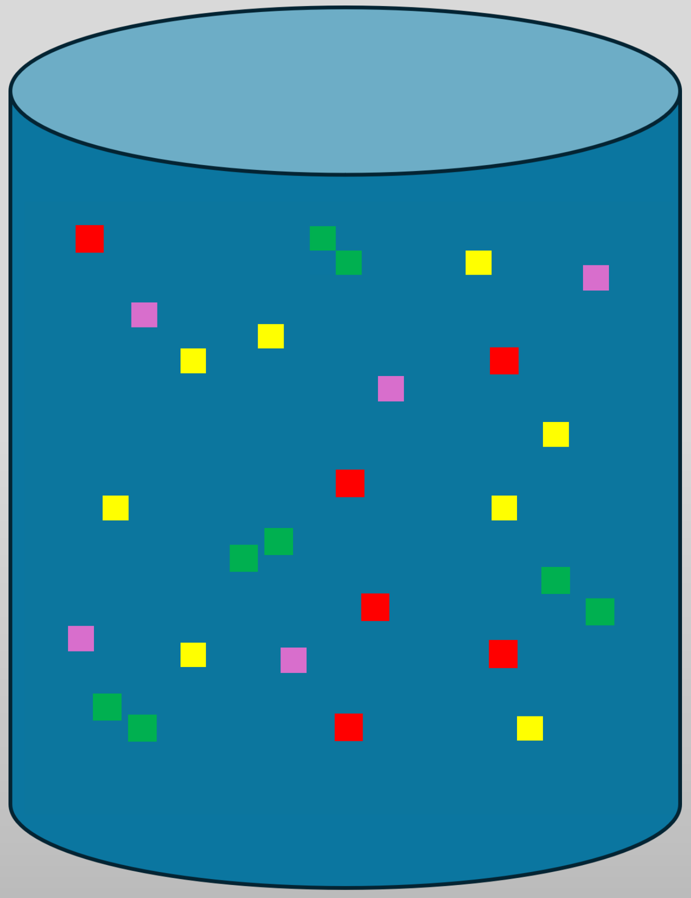

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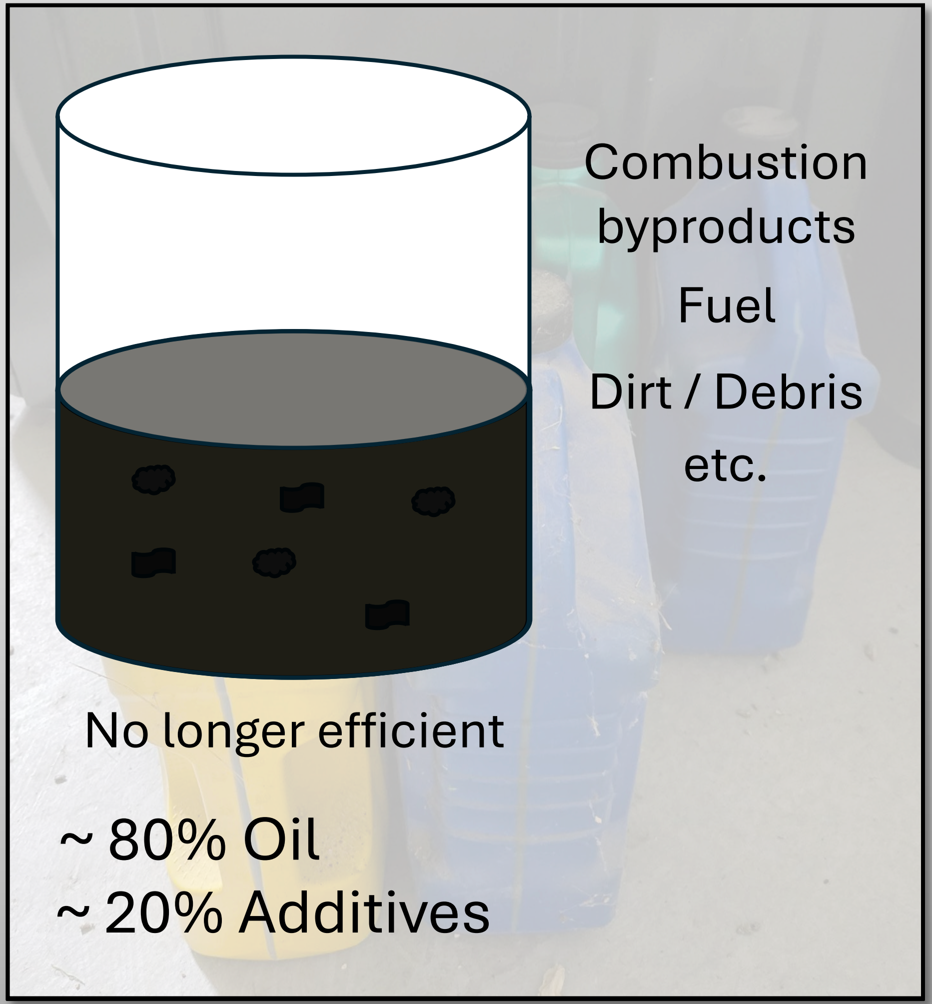

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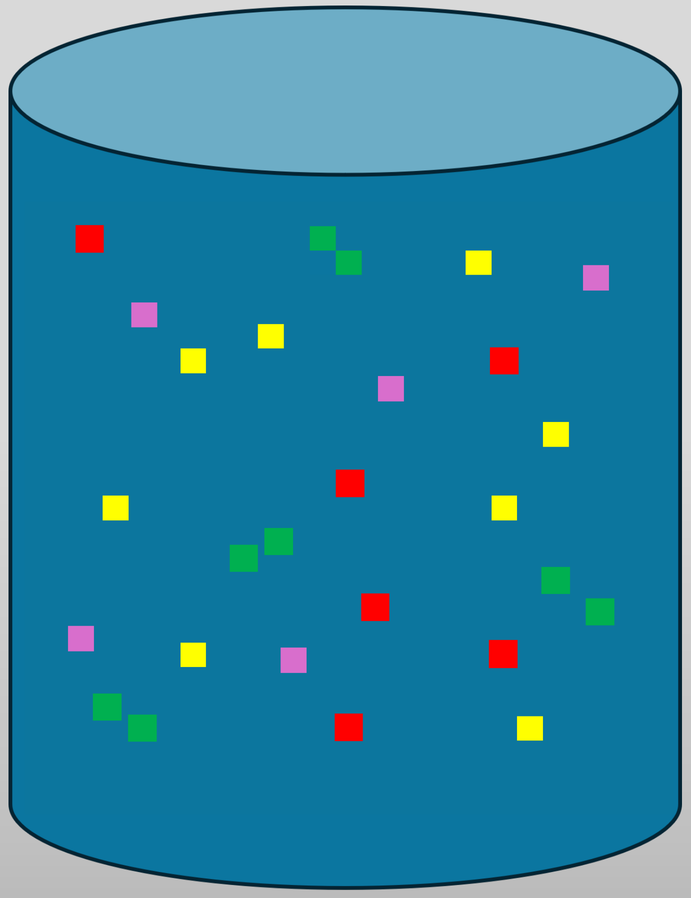

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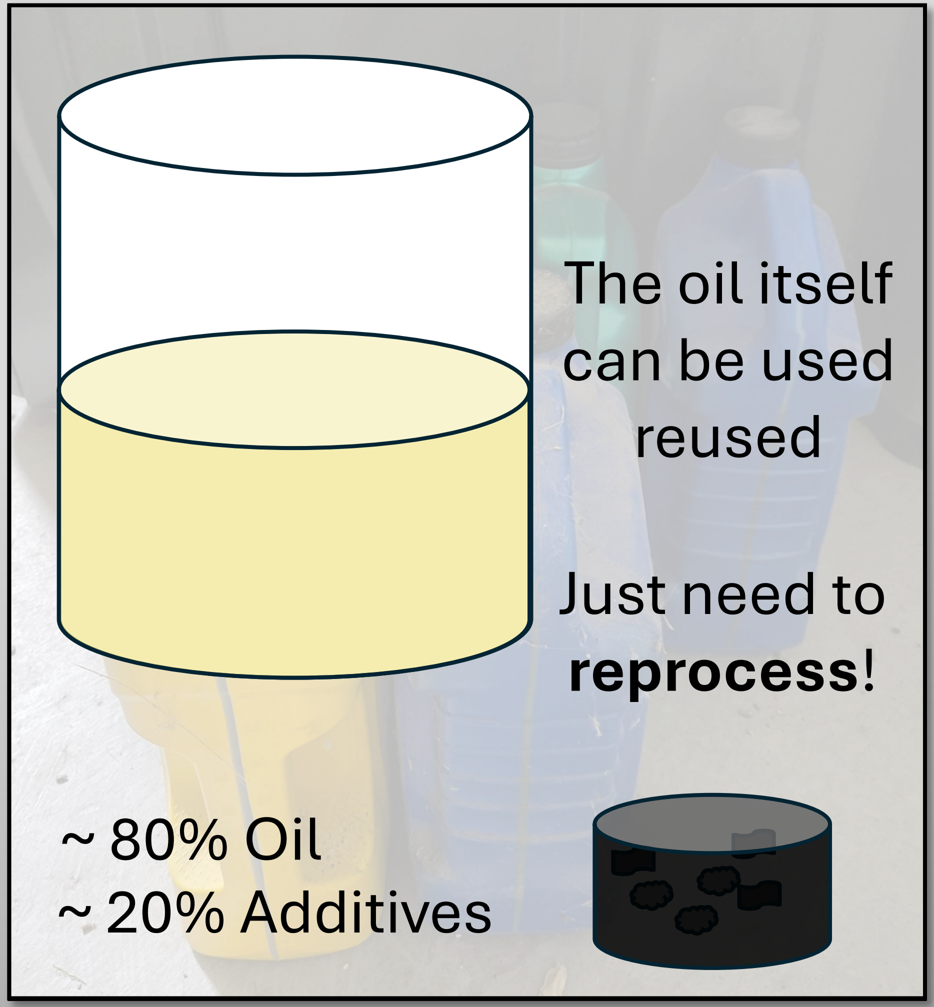

Motor Oil

What are the benefits beyond simply “extracting more energy” from the fuel?

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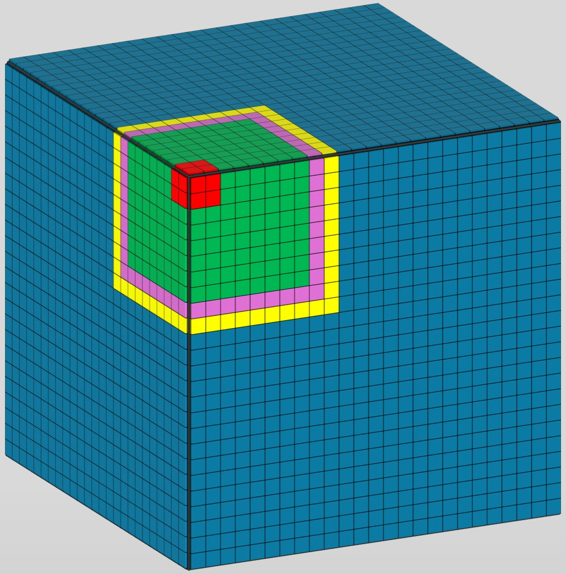
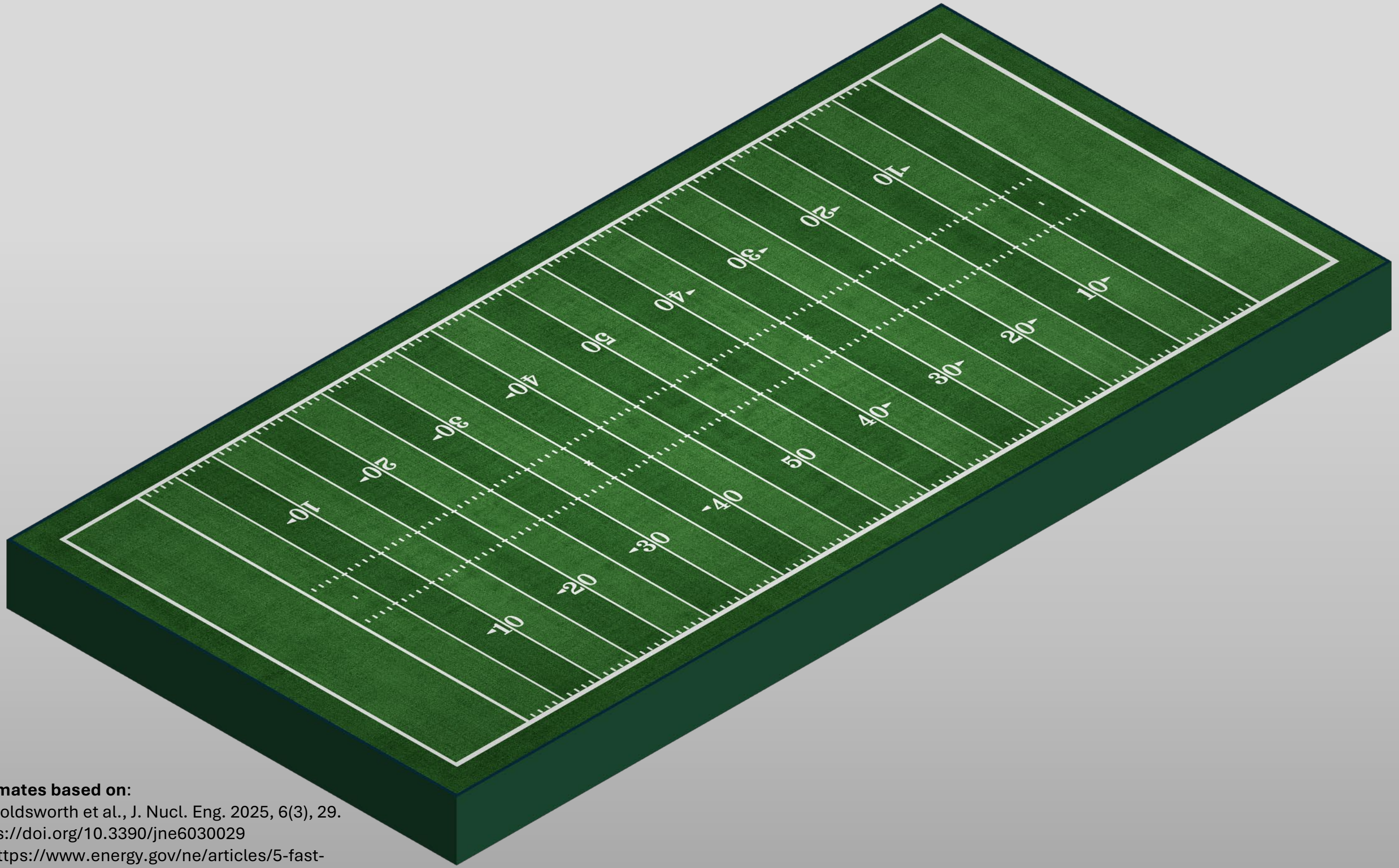
Current Stockpile: ~ **95,000** metric tons of spent fuel





Estimates based on:
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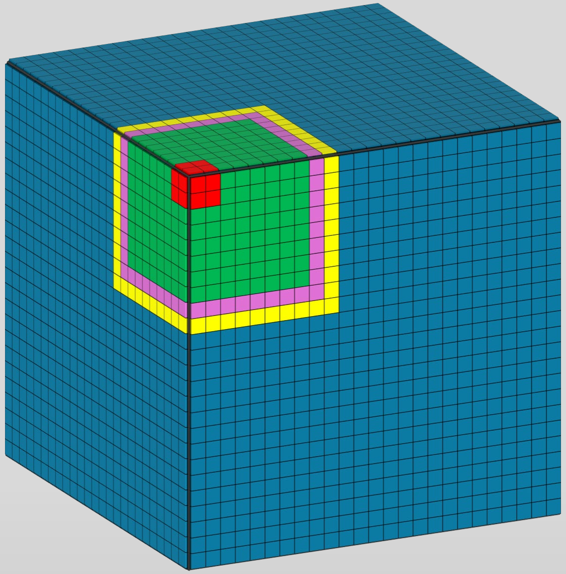

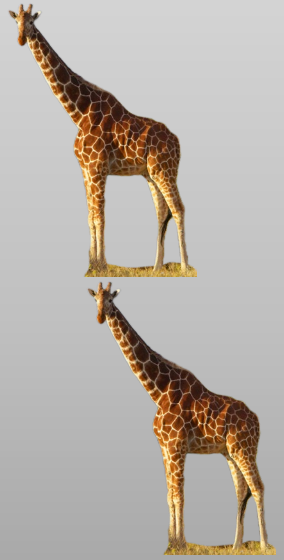

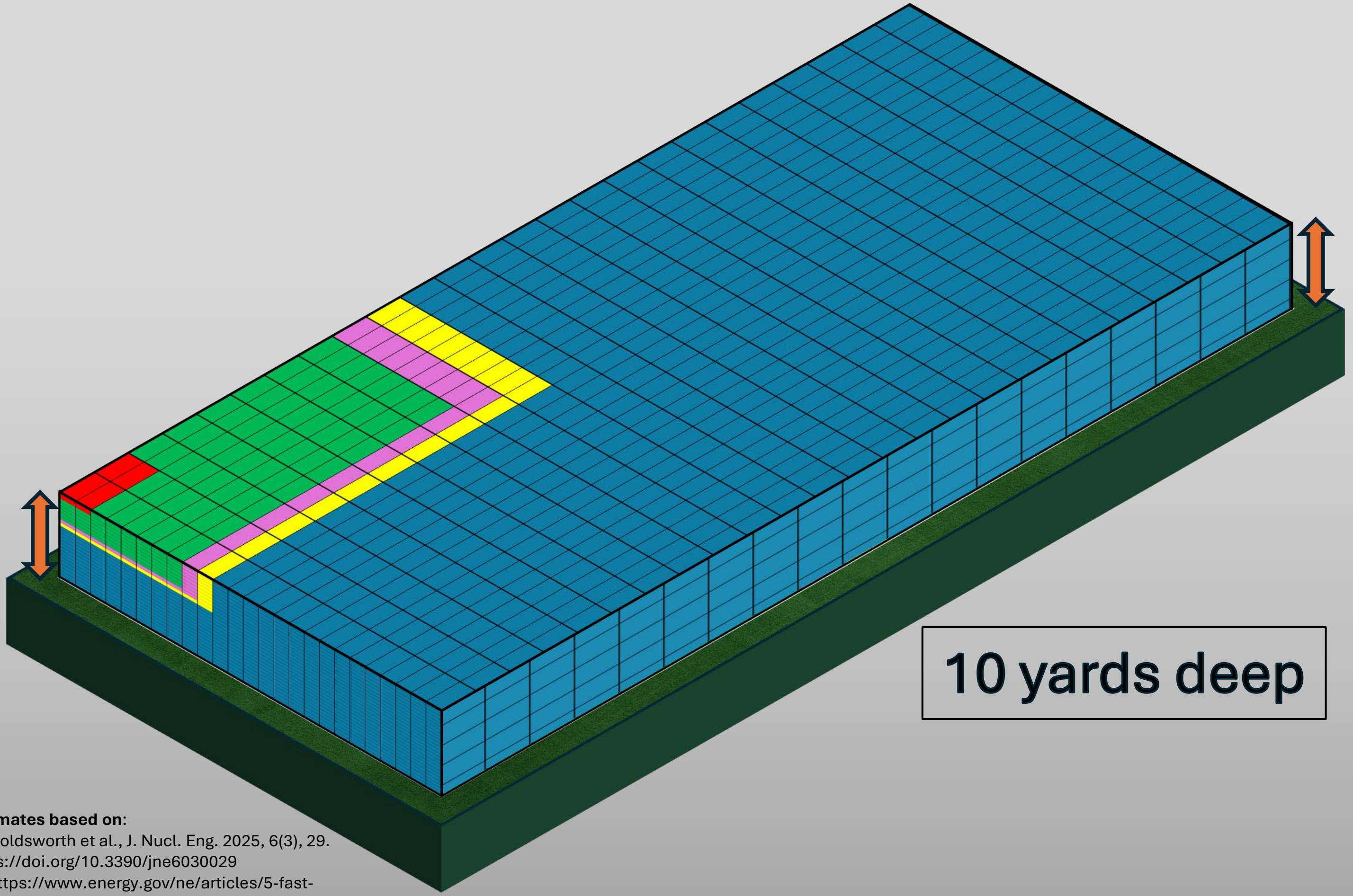

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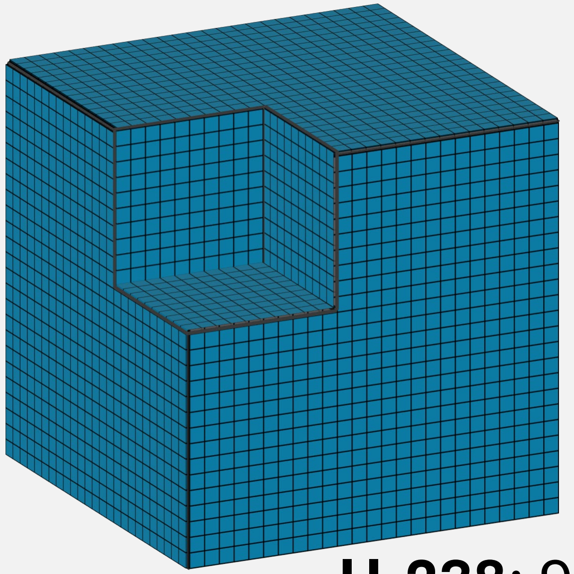
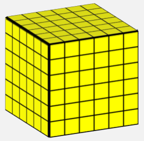
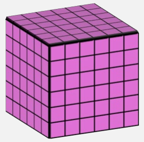
Recover



U-238: 94%



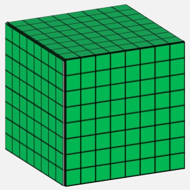
U-235: 1%



Pu: 1%

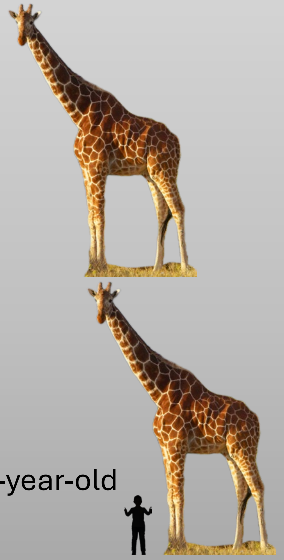
Minor Actinides: <0.1%

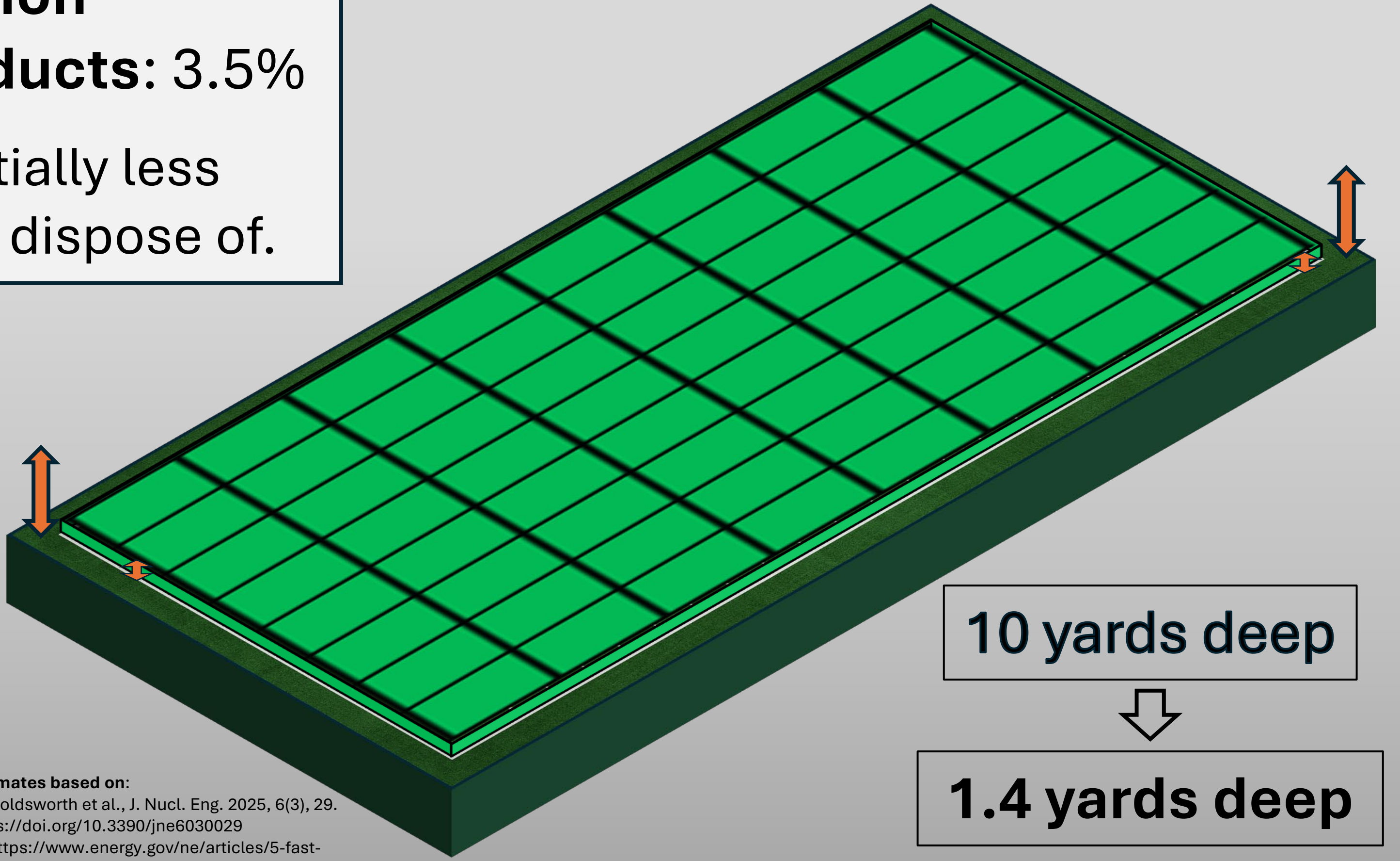
Current Stockpile: ~ **95,000** metric tons of spent fuel



Fission Products: 3.5%

Substantially less material to dispose of.





10 yards deep

1.4 yards deep

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And the radiotoxicity? Storage time?

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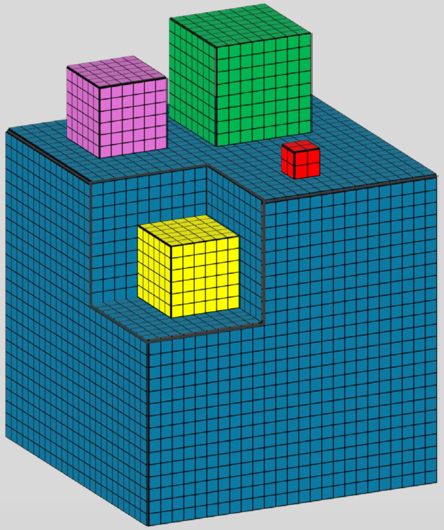

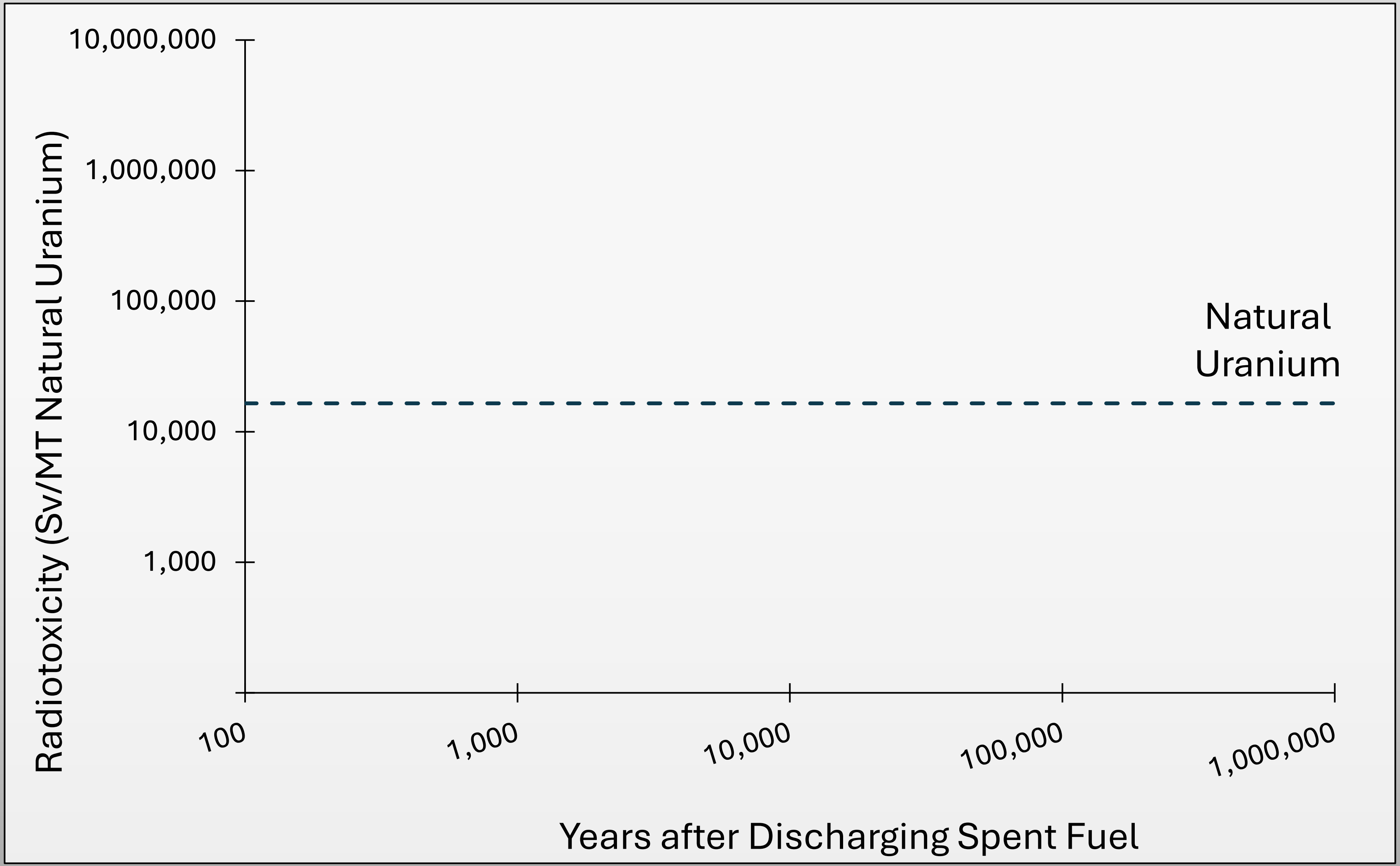

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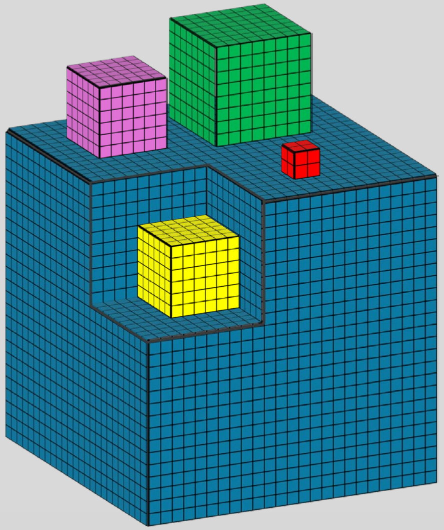

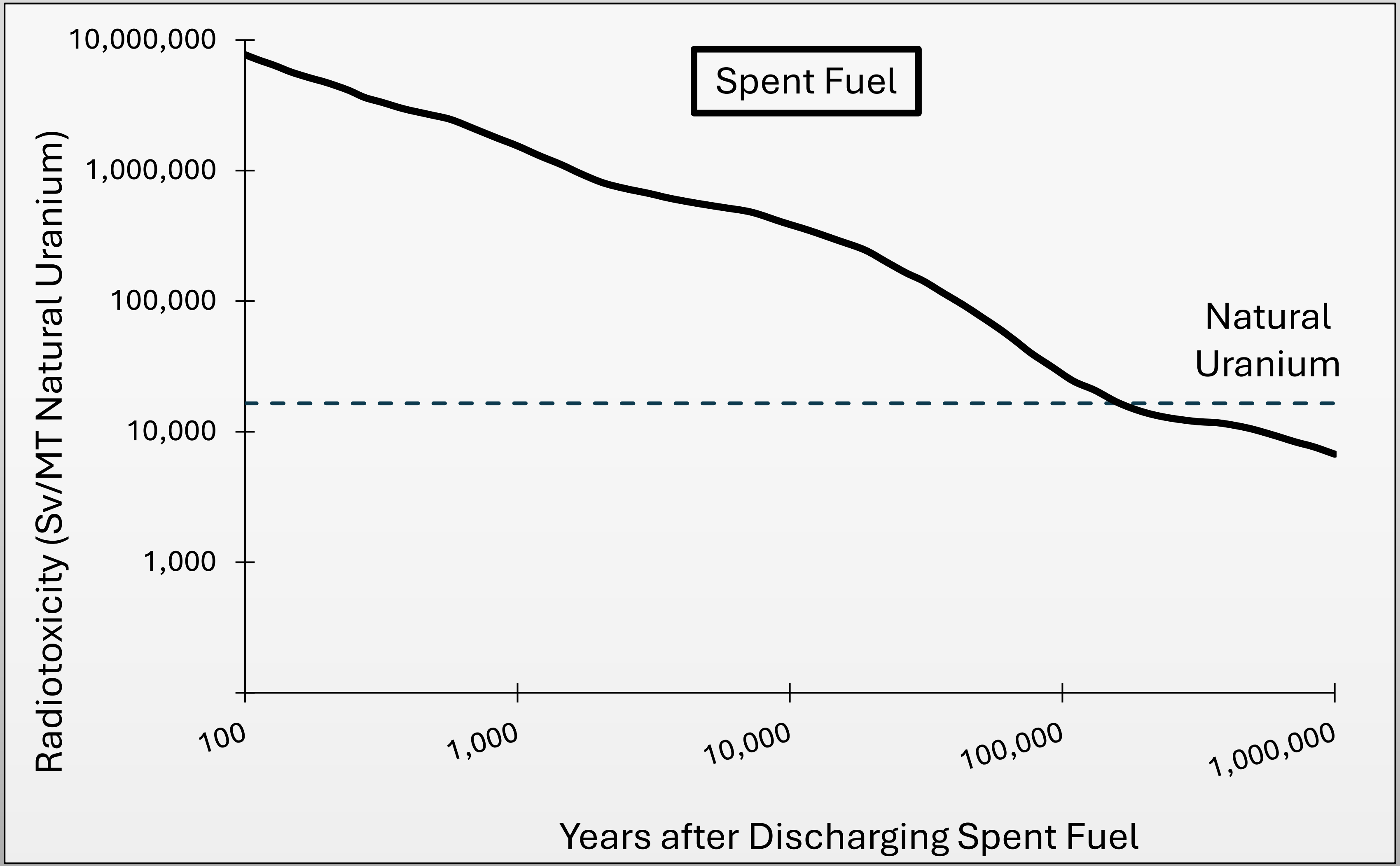

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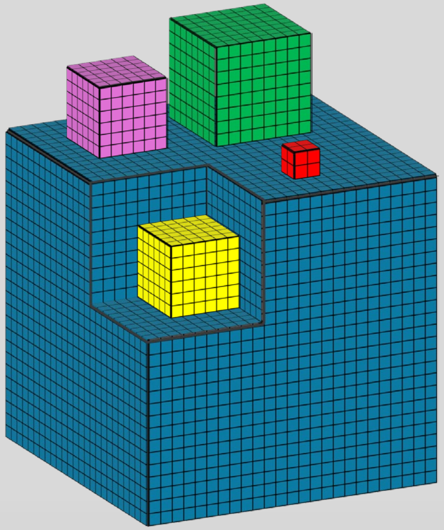

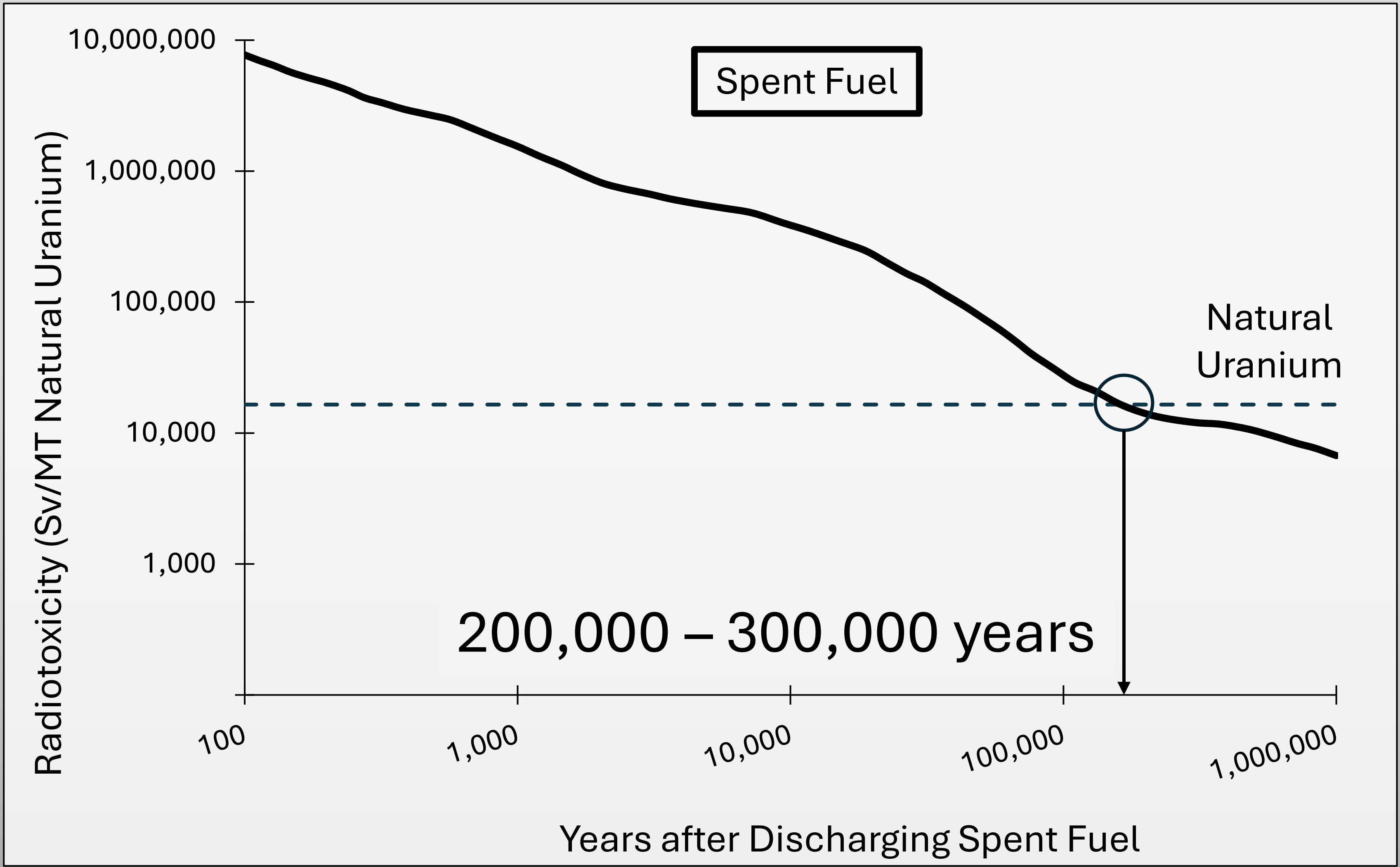

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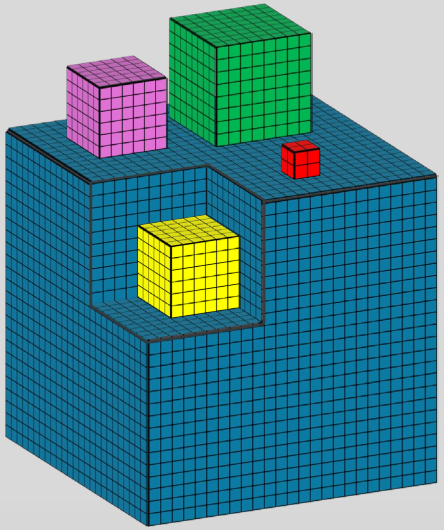
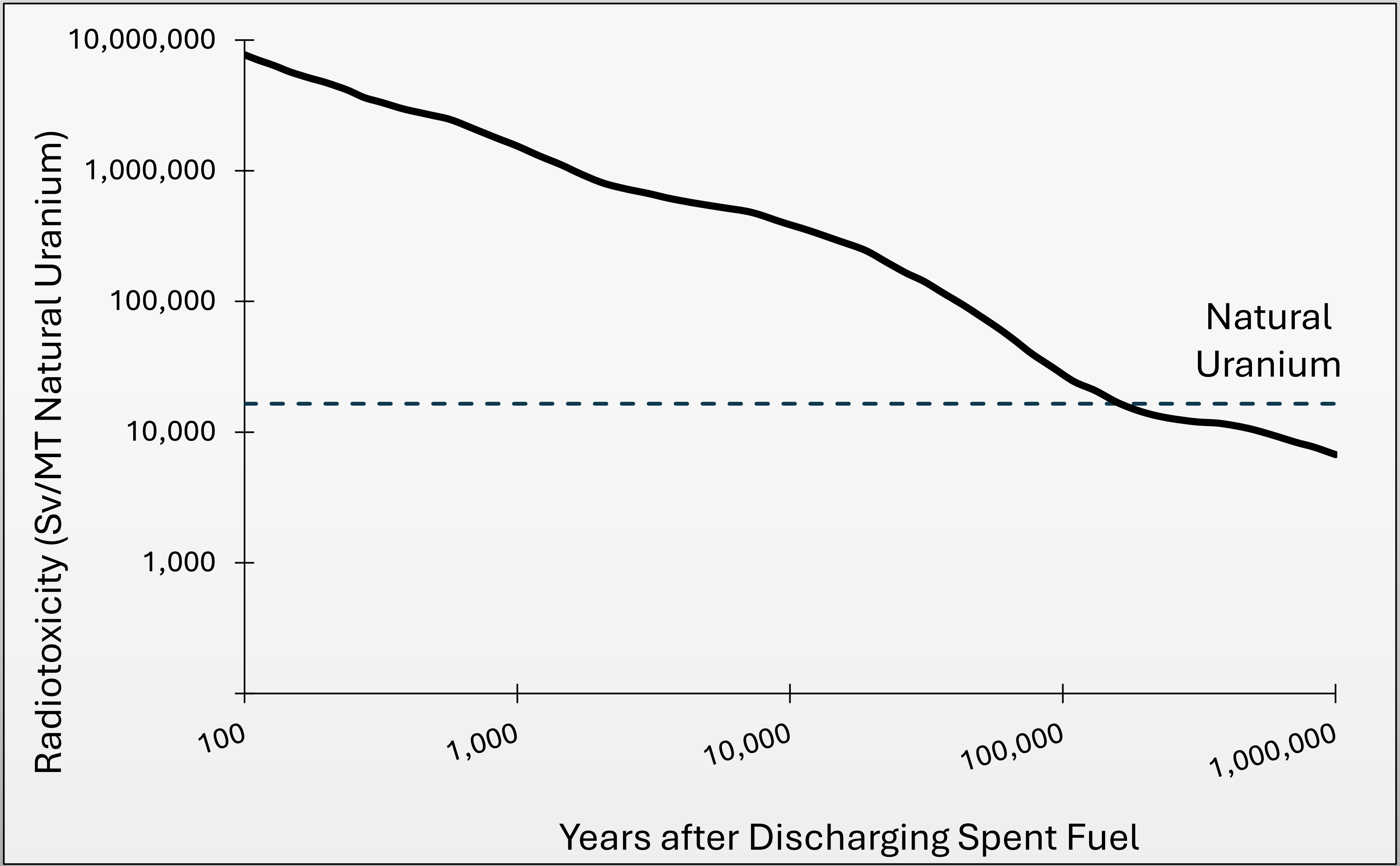


Spent Fuel 200,000 – 300,000 years



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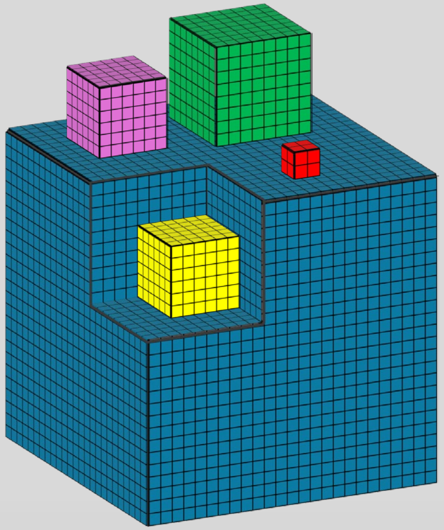

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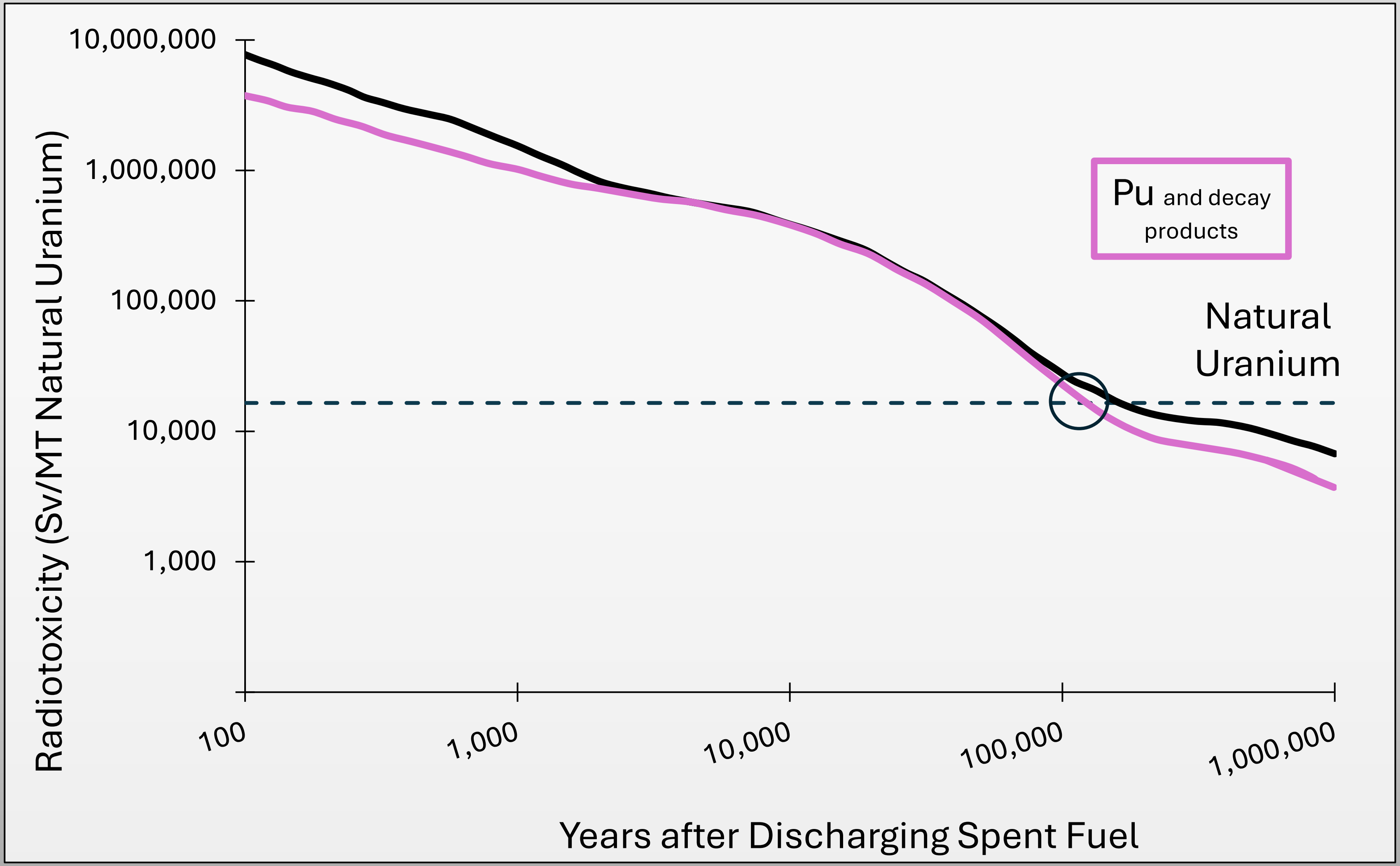

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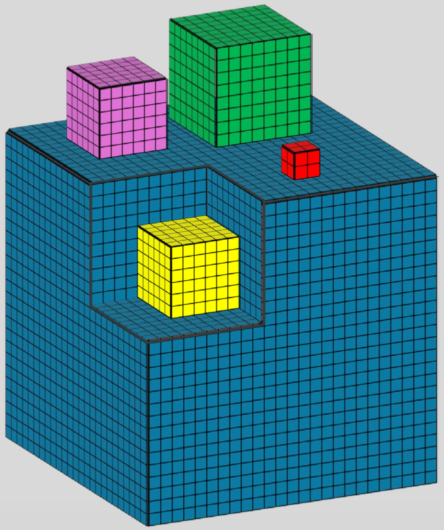

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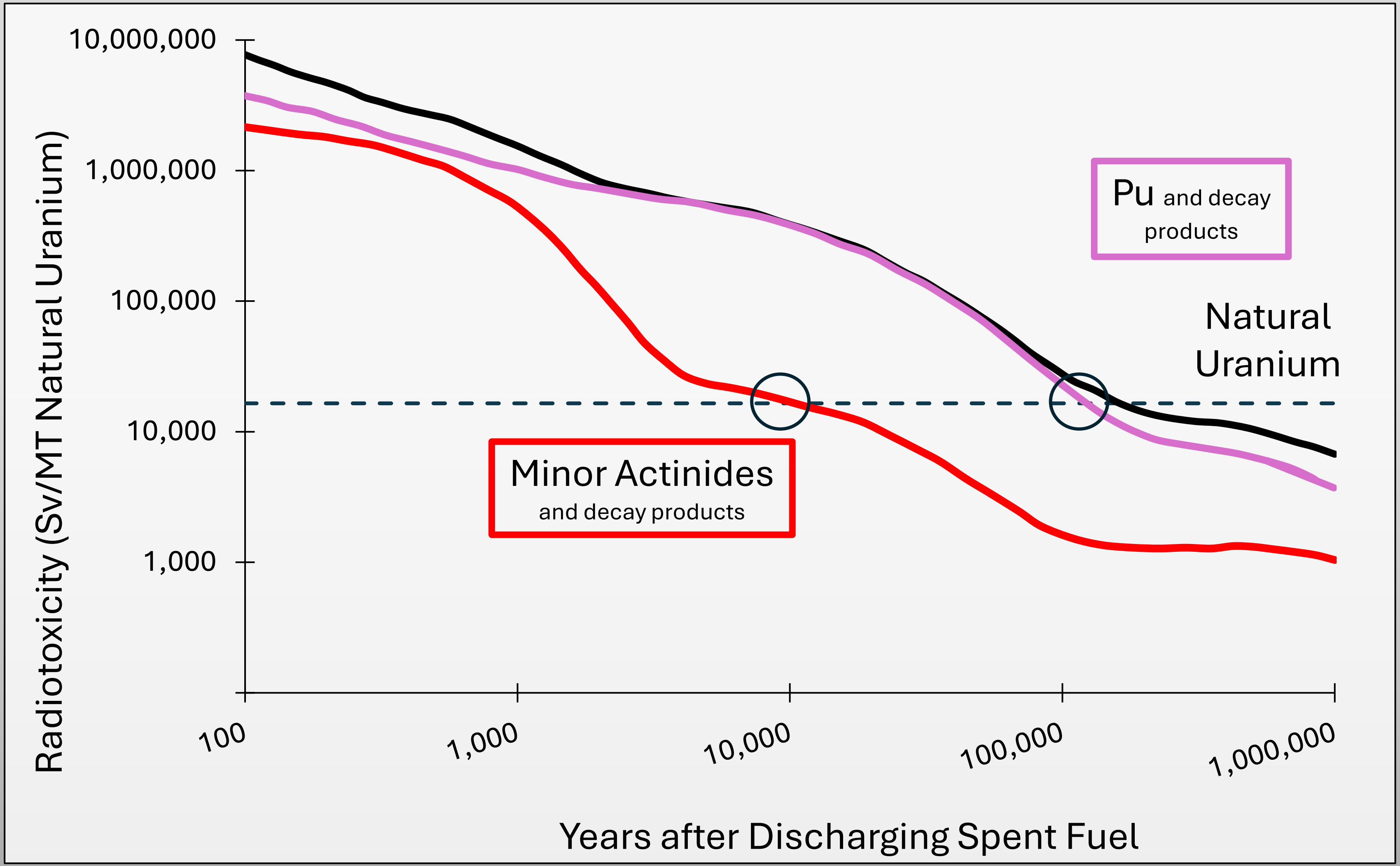

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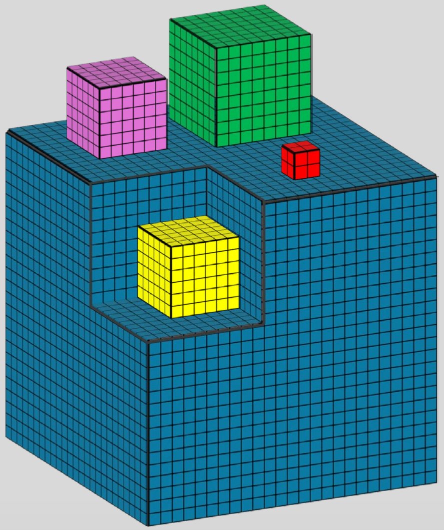

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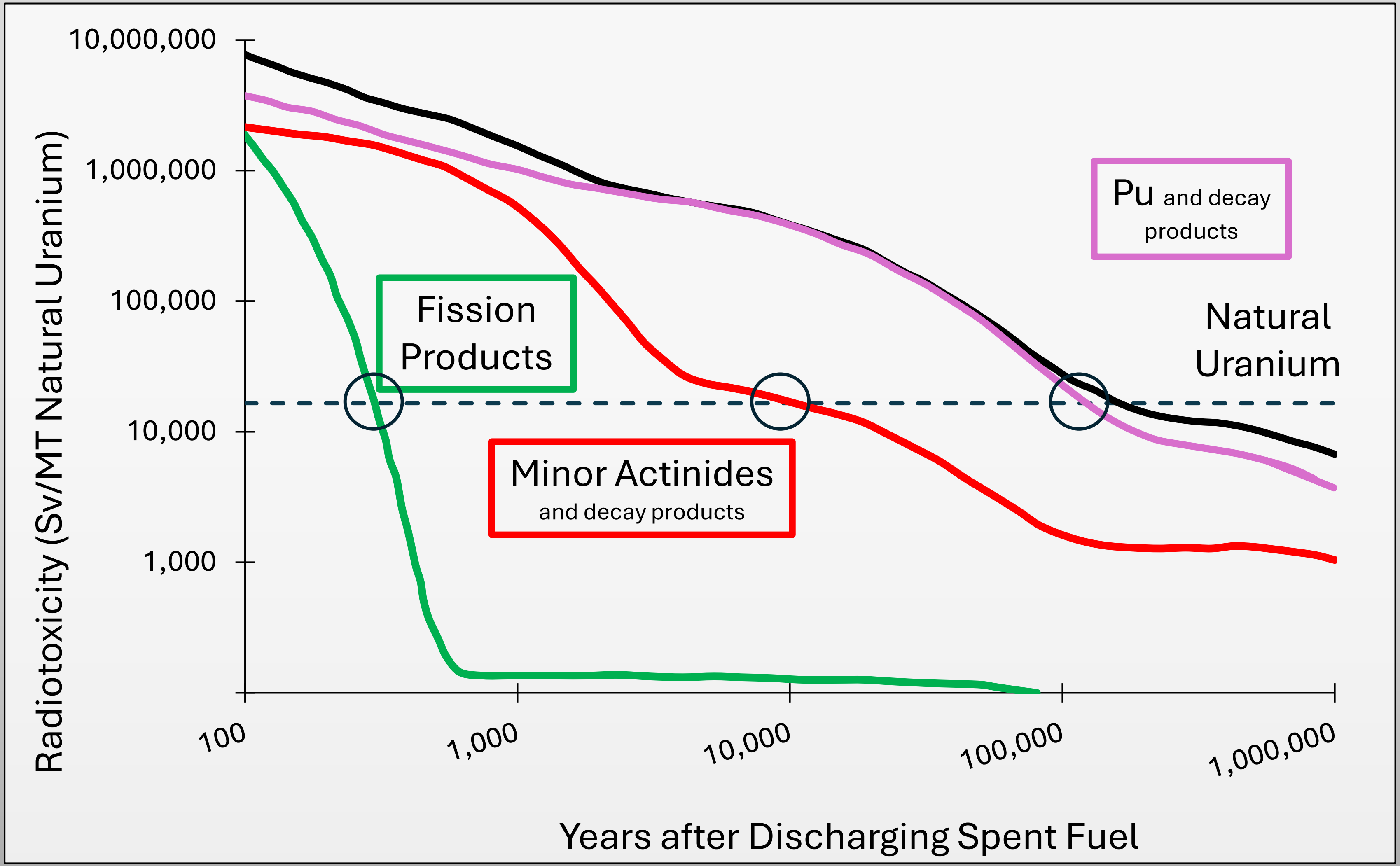

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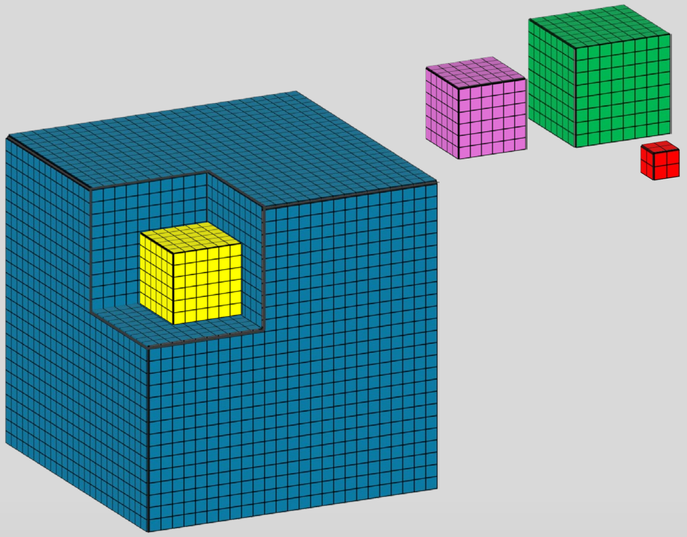

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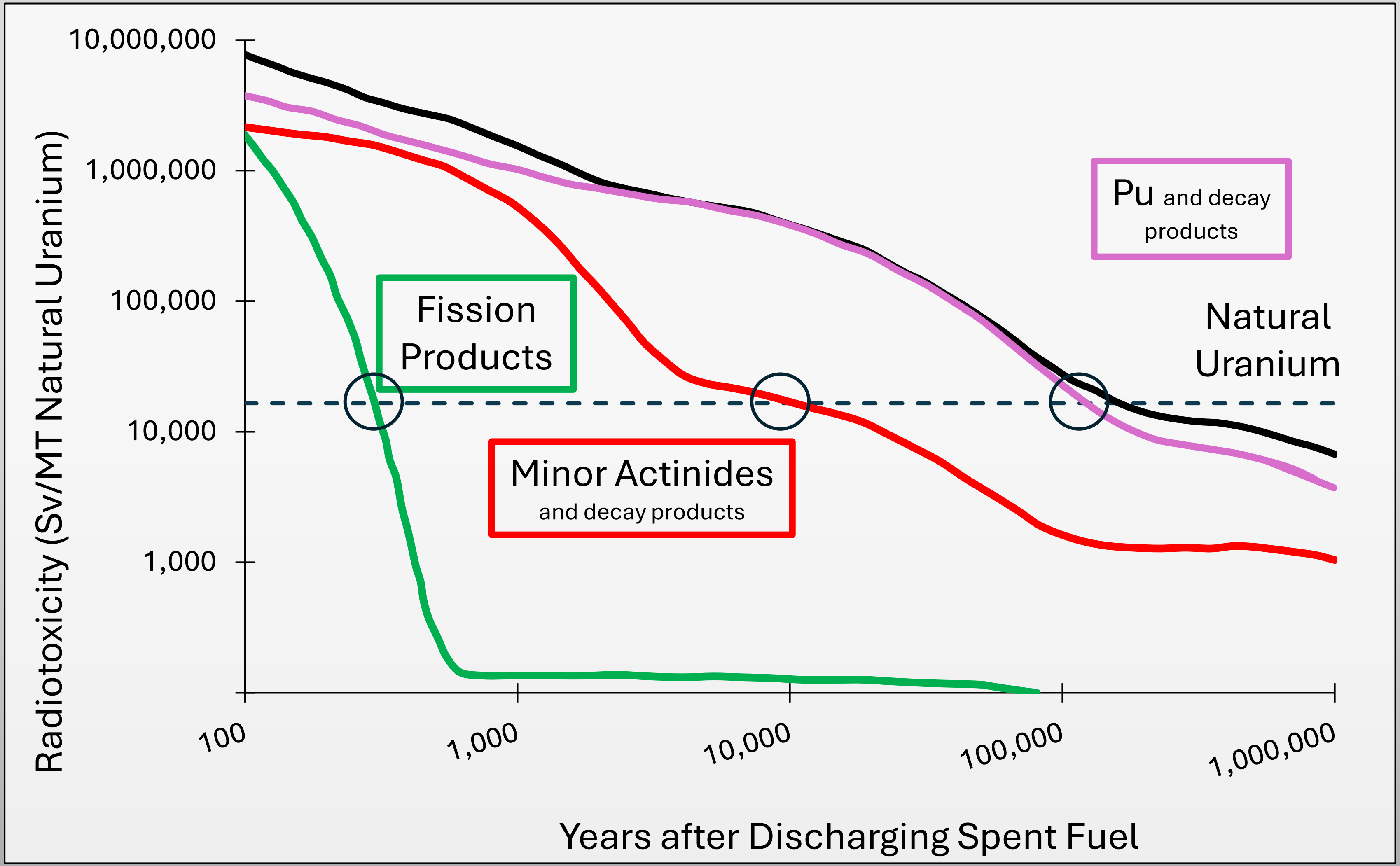

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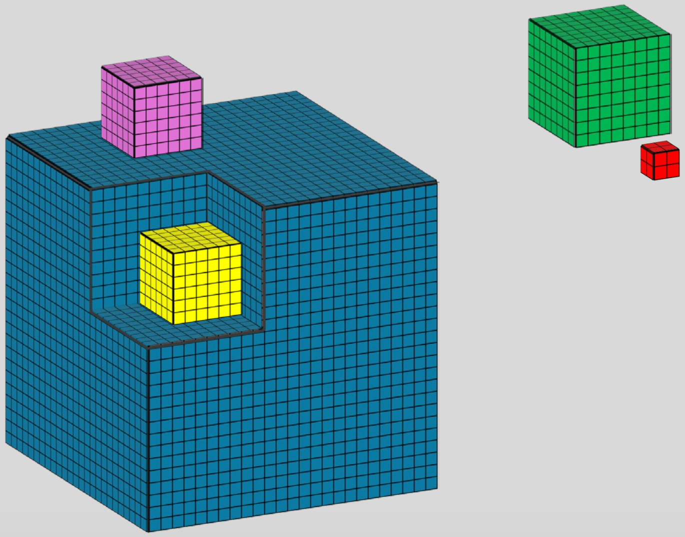
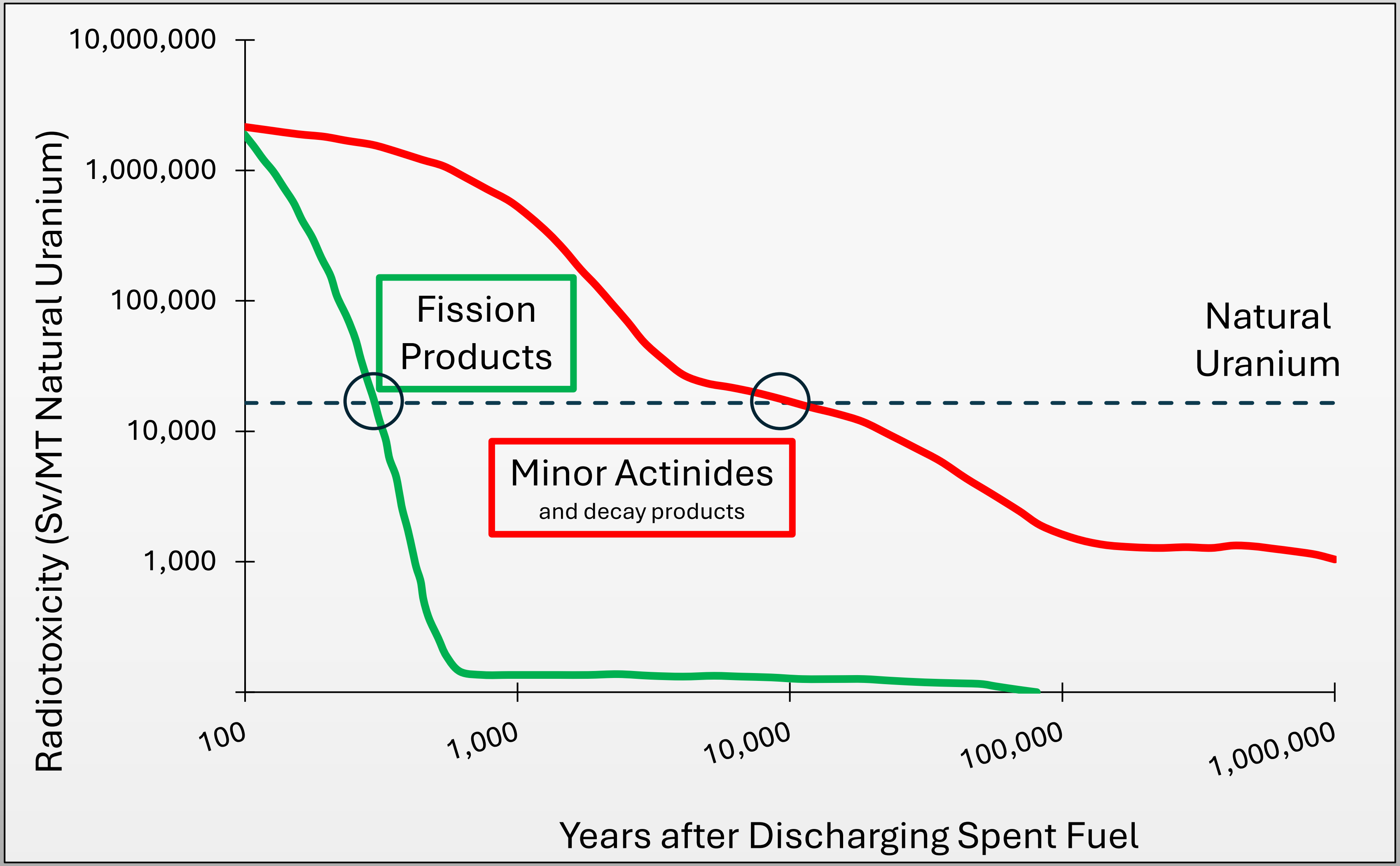


Spent Fuel 200,000 – 300,000 years

Pu and decay products



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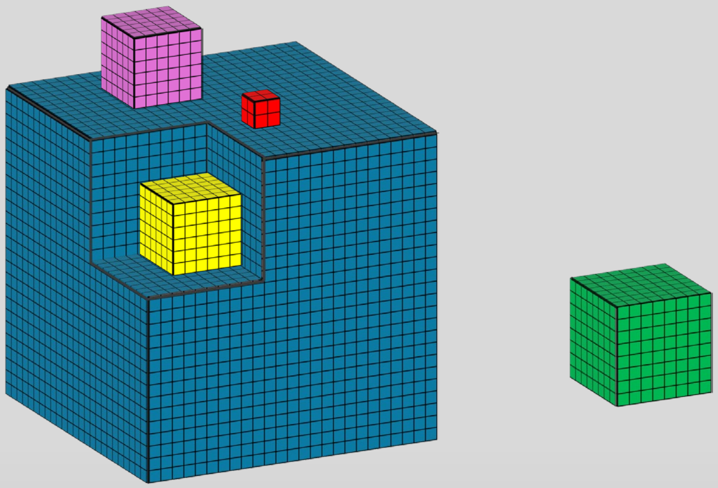

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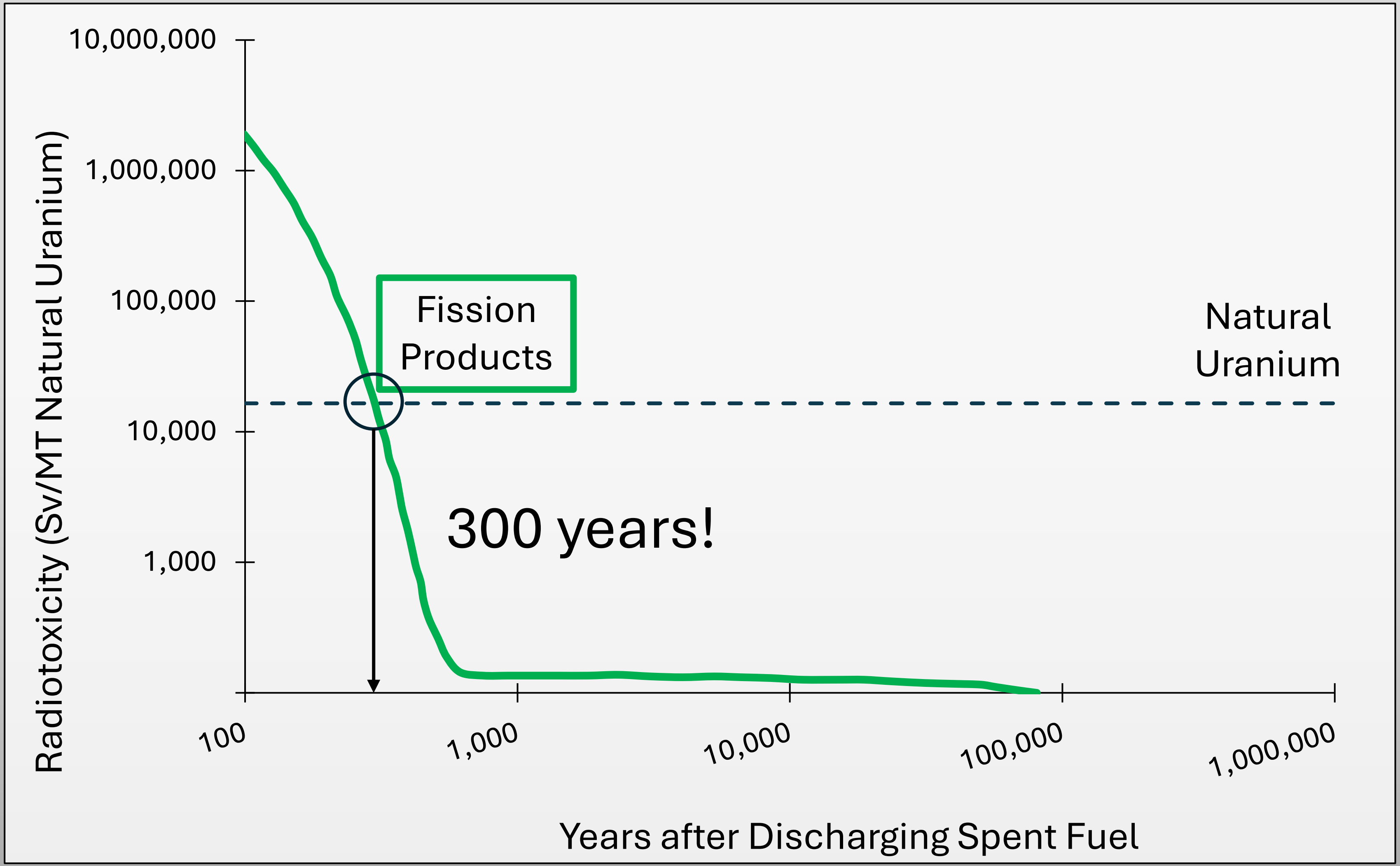
Pu and decay products

Minor Actinides and decay products



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Anything else of value?

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Medical Isotopes

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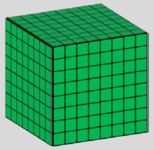
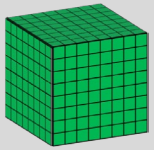


Fission Products

Tumor treatment	cesium-137 strontium-90 ruthenium-106
Liver cancer therapy	yttrium-90

Anything else of value?

Medical Isotopes

 Fission Products

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Minor Actinides

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iodine-131

lead-212

strontium-89

radium-223

thorium-227

actinium-225

bismuth-213

molybdenum-99

How is it done?

Commercial Reprocessing

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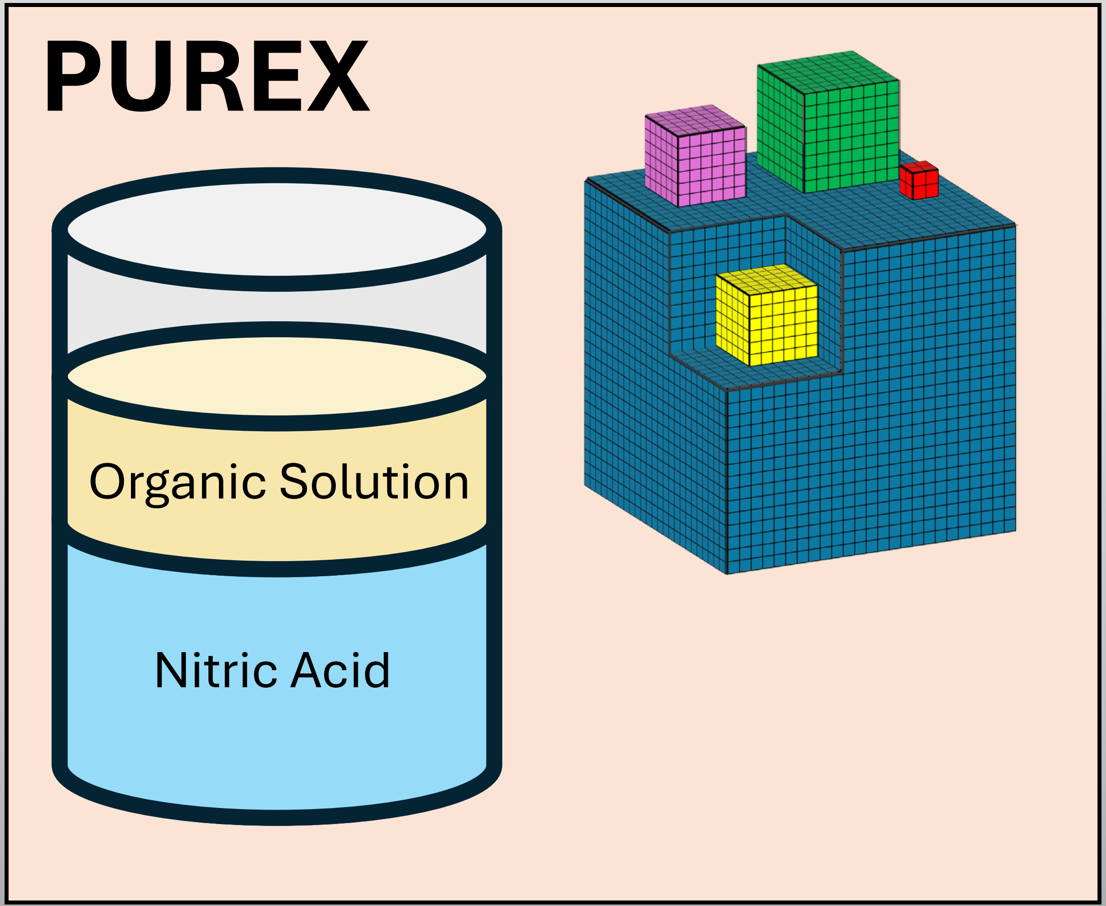

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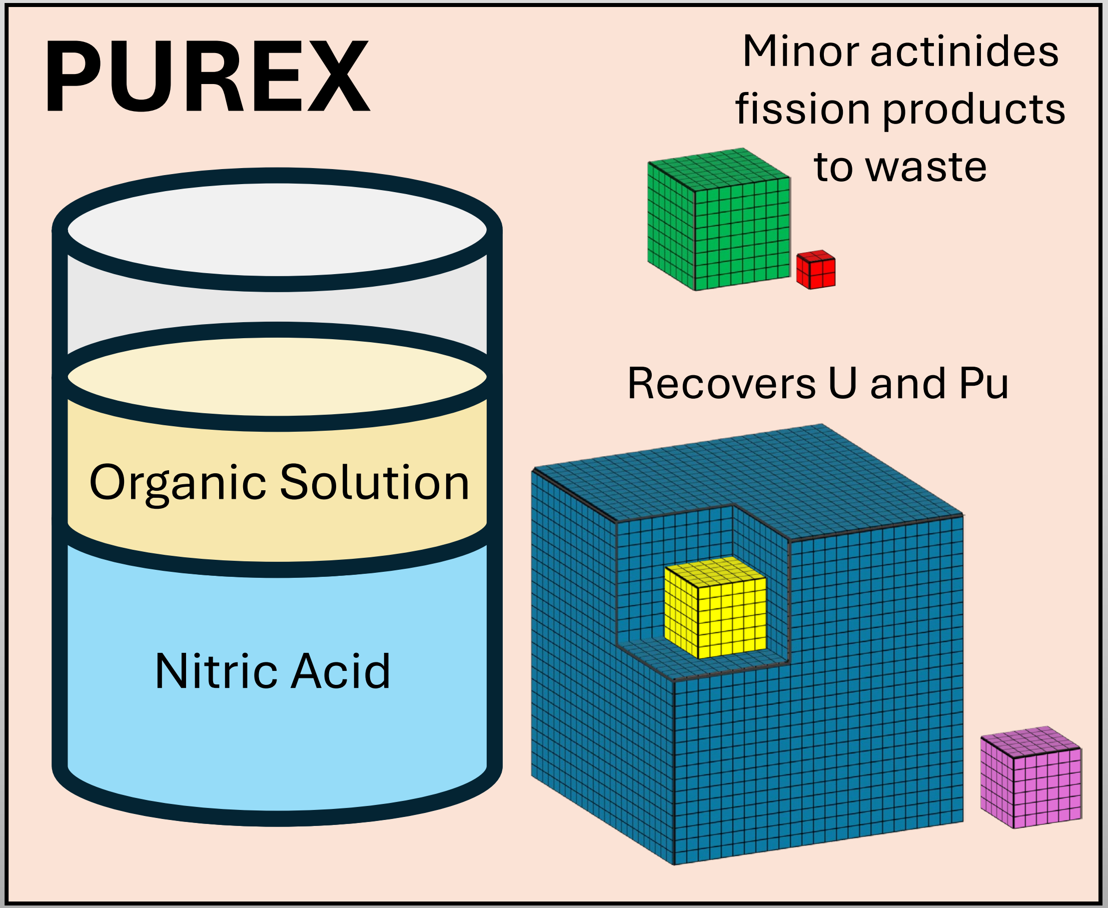

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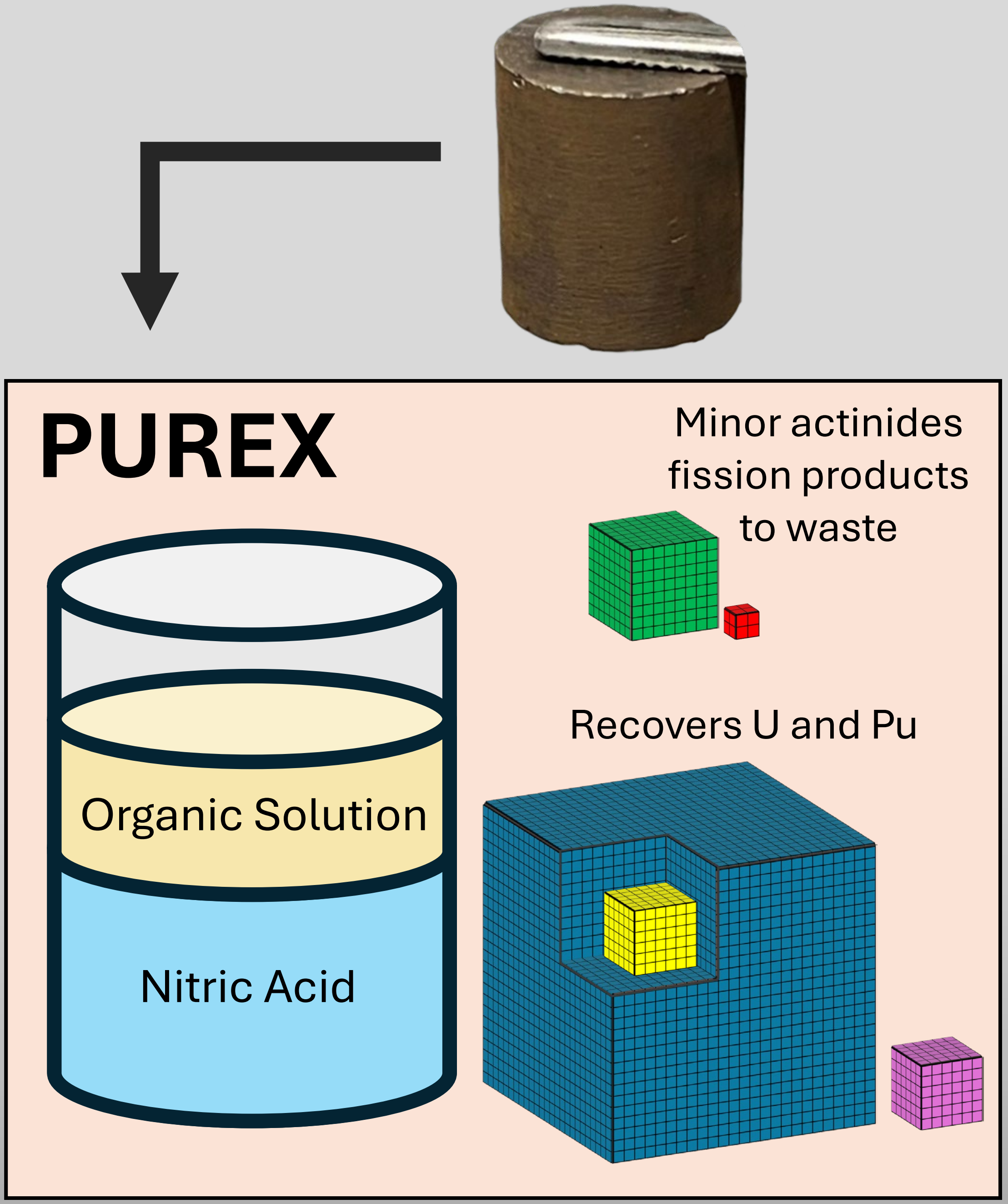

Commercial Reprocessing

PUREX is the only process to be implemented on a commercial level

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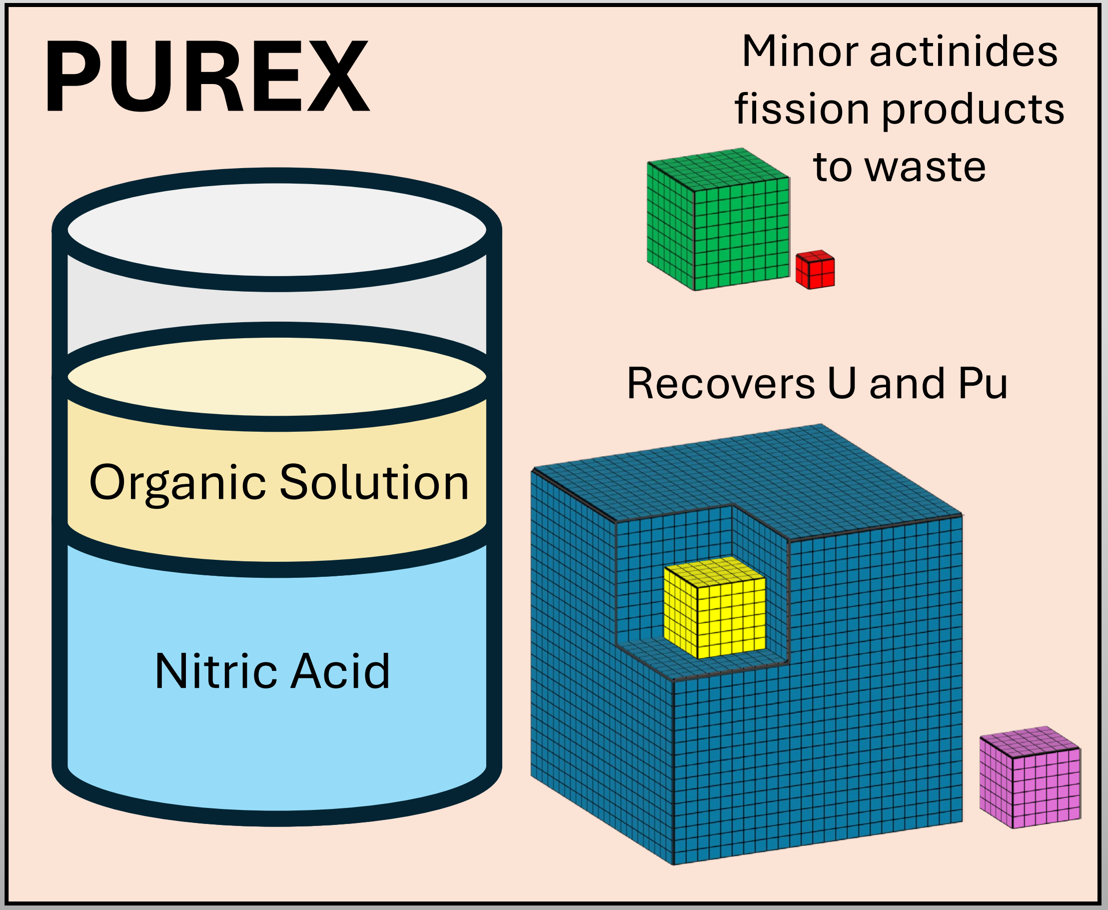
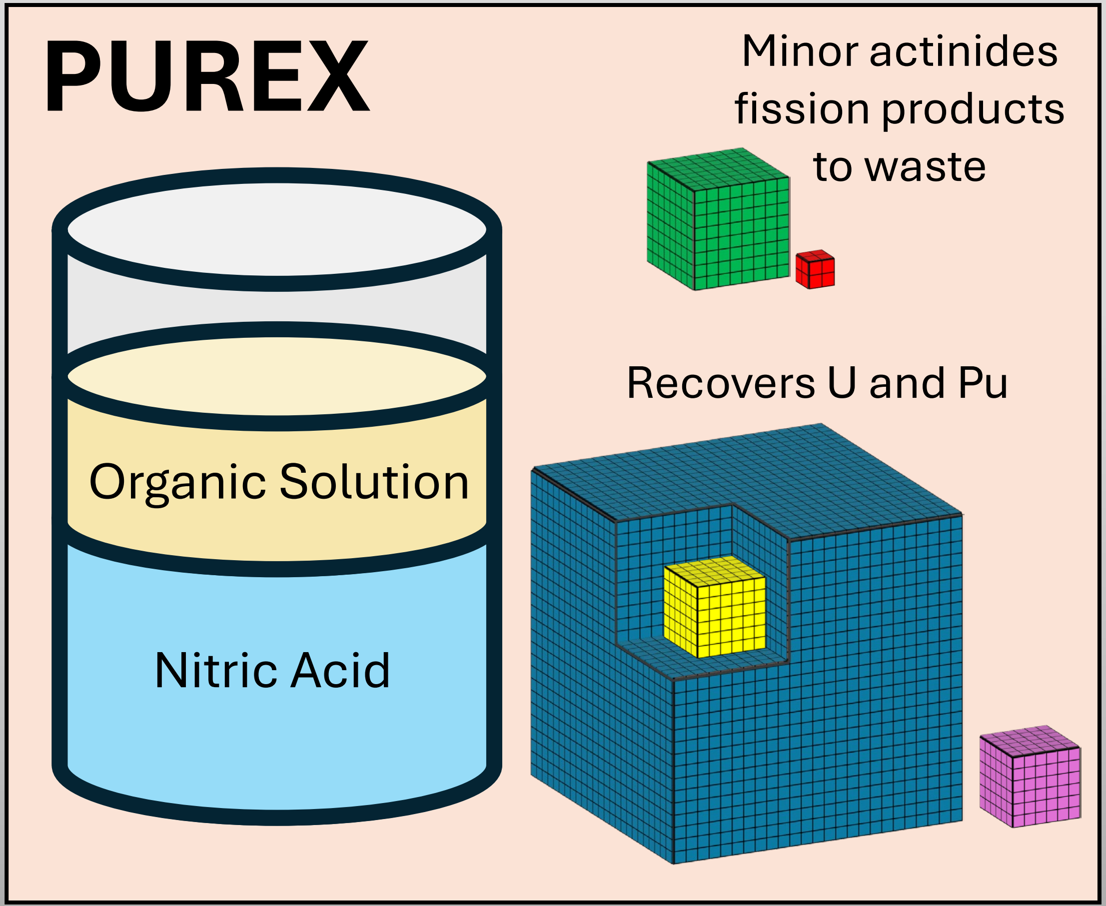


Commercial Reprocessing

PUREX is the only process to be implemented on a commercial level

uranium
(oxide or nitrate form)

How is it done?



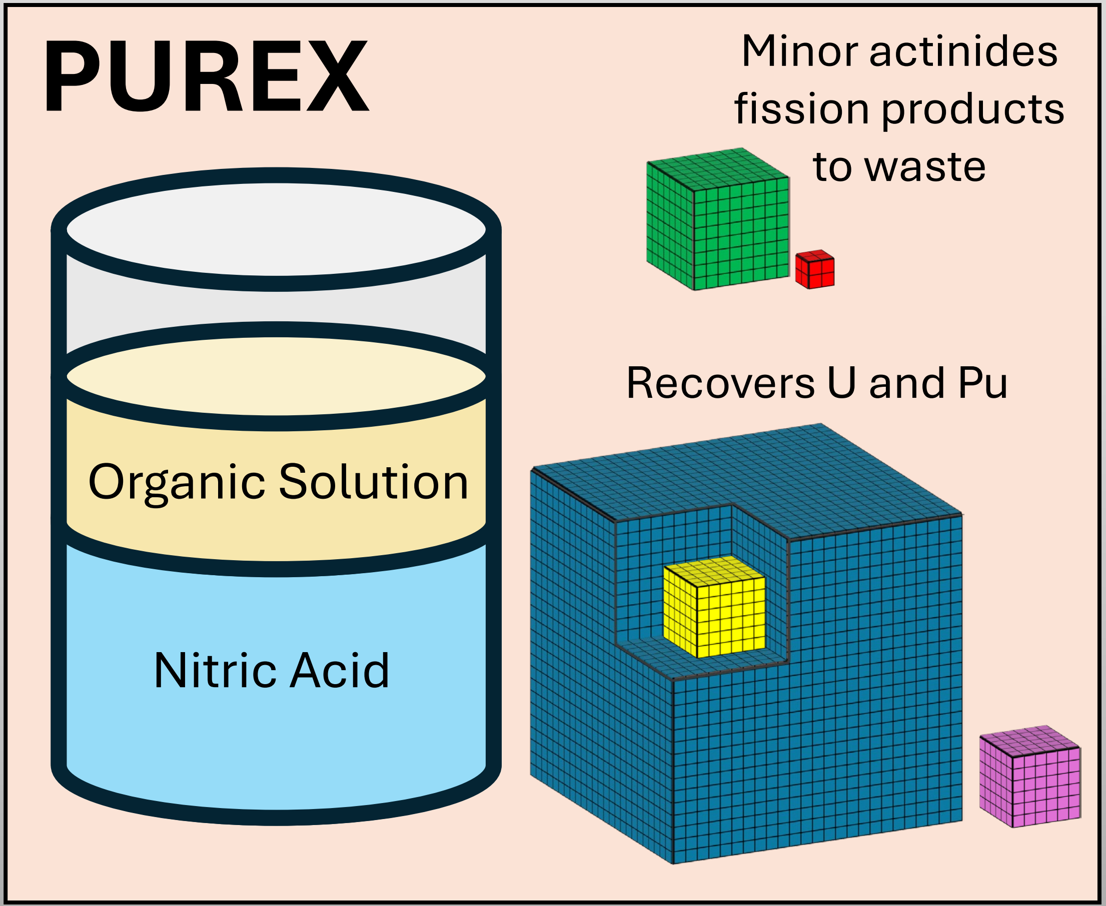
Commercial Reprocessing

PUREX is the only process to be implemented on a commercial level

uranium
(oxide or nitrate form)

plutonium
(oxide or nitrate form)

How is it done?



Commercial Reprocessing

PUREX is the only process to be implemented on a commercial level

uranium
(oxide or nitrate form)

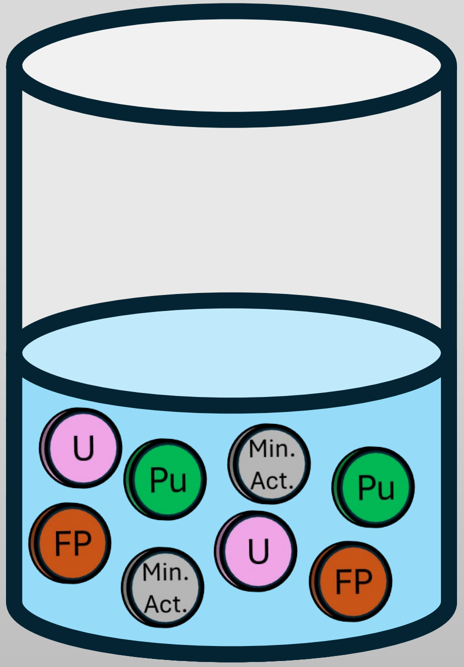
plutonium
(oxide or nitrate form)

Newer processes designed to never isolate pure plutonium

- GANEX (Group Actinide Extraction)
- UREX+ (Uranium Extraction Plus)

PUREX

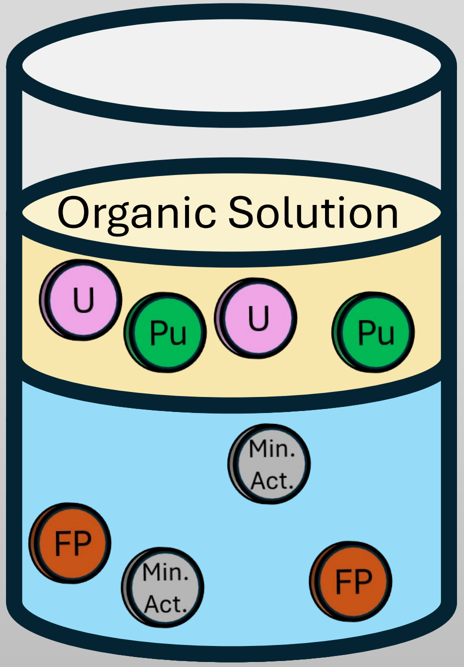
Nitrates



Nitric Acid

Dissolution of spent fuel in nitric acid

PUREX

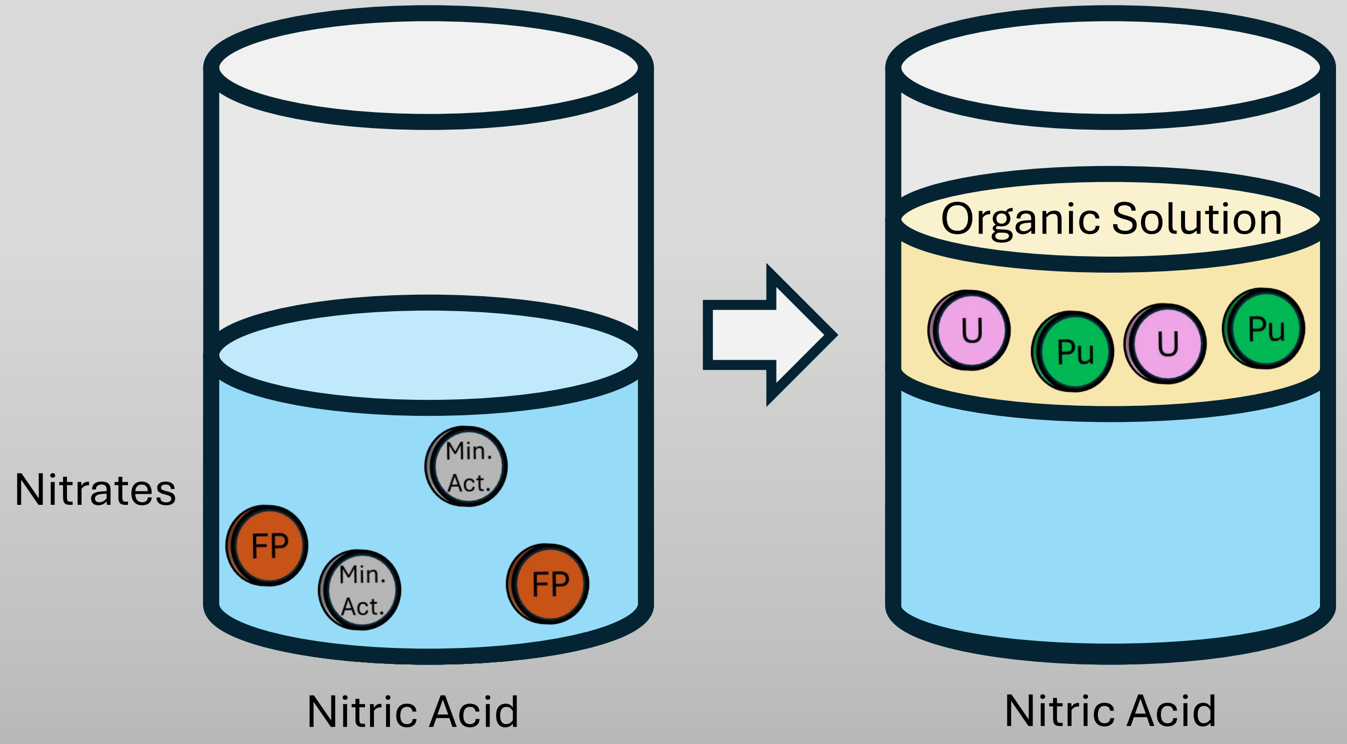


Nitrates

Nitric Acid

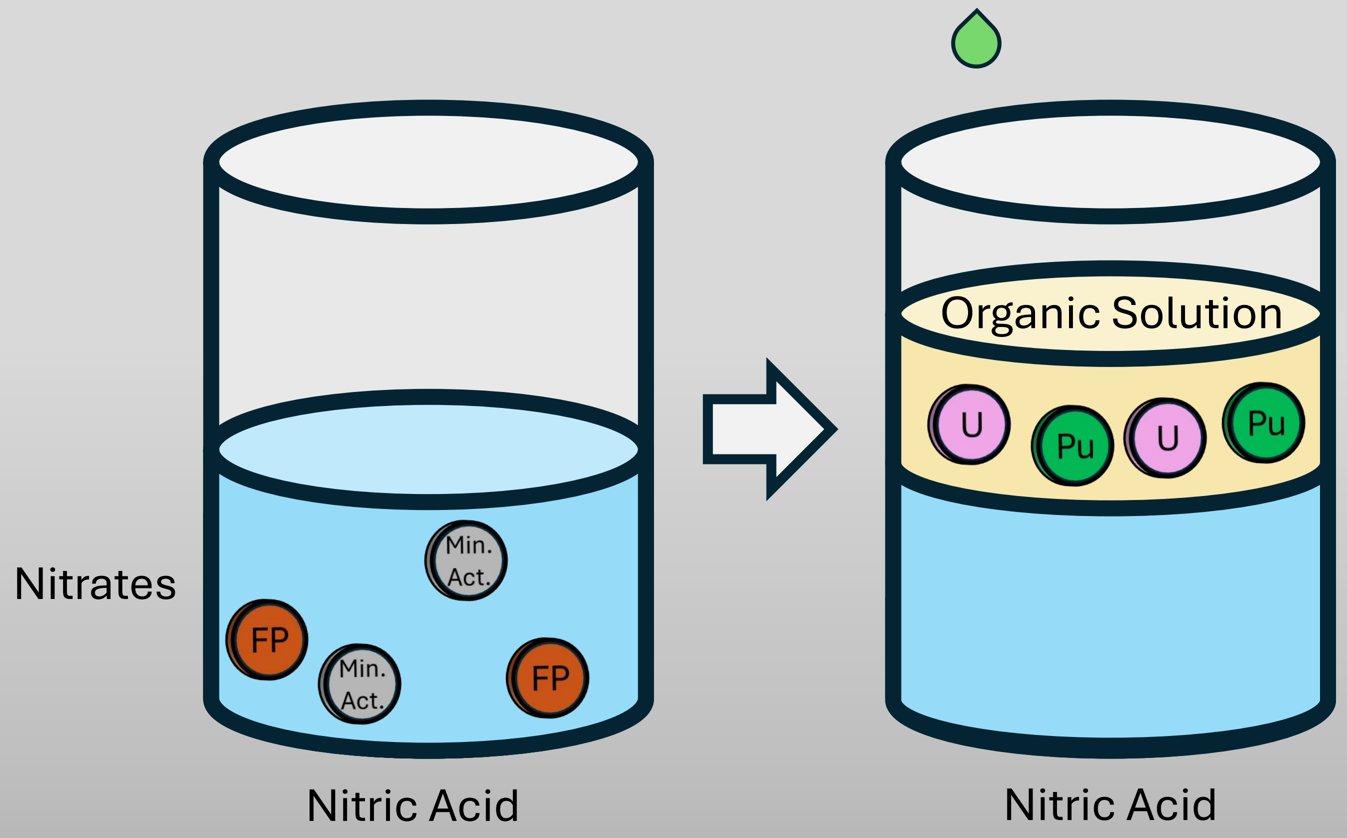
Extraction of
U/Pu into
organic solution

PUREX



Separation of U and Pu

PUREX



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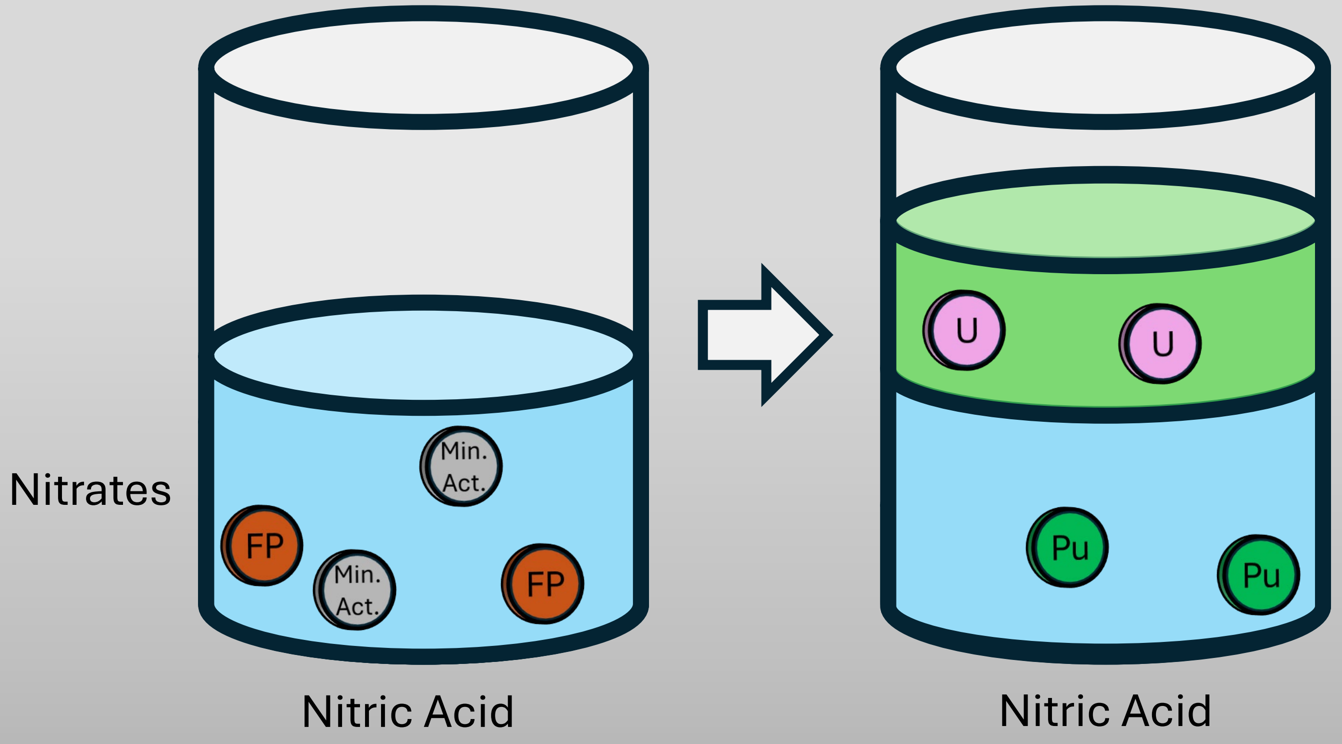
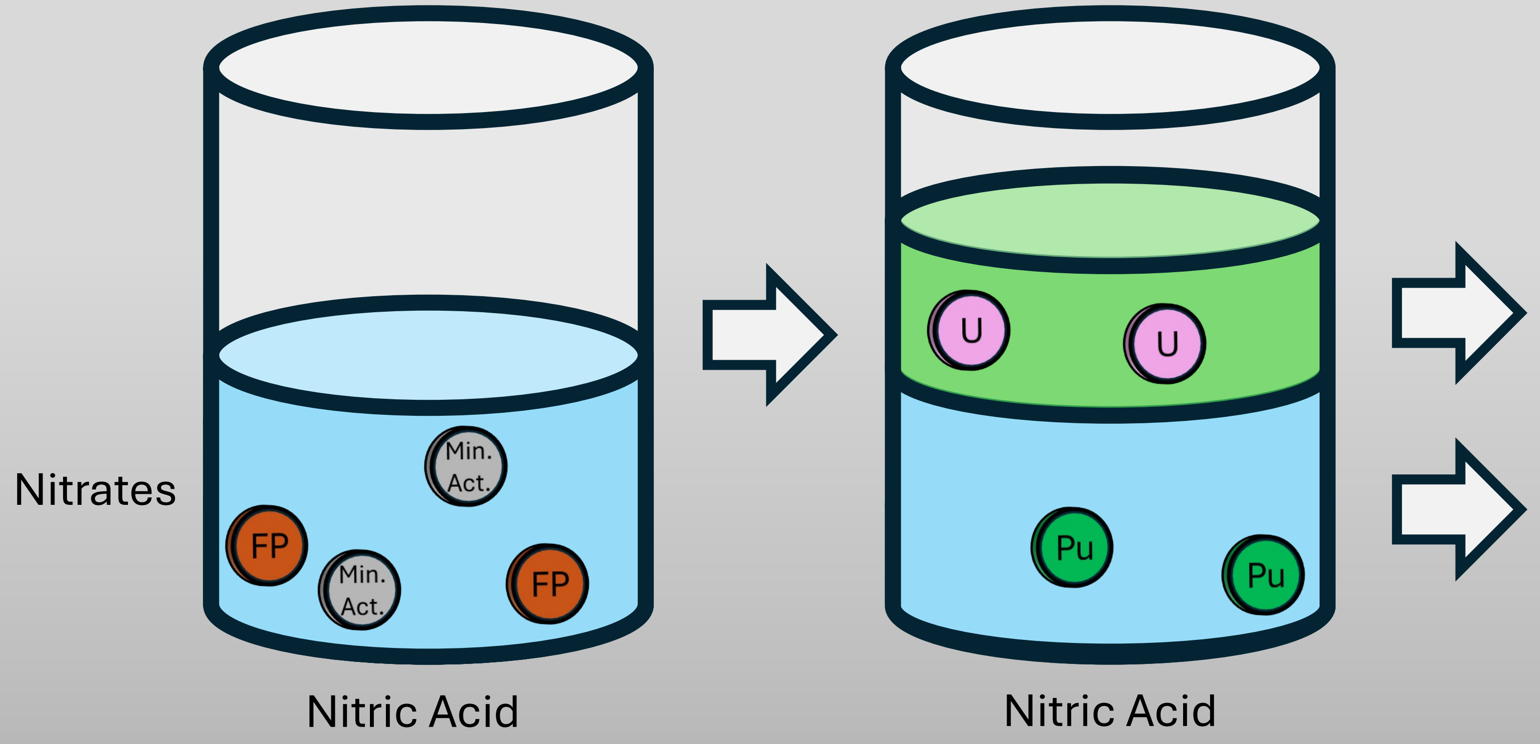
PUREX


Nitrates
Min.
Act.
FP
Min.
Act.
FP
Nitric Acid
U
U
Pu
Pu
Nitric Acid

PUREX



Pure uranium
(oxide or nitrate form)

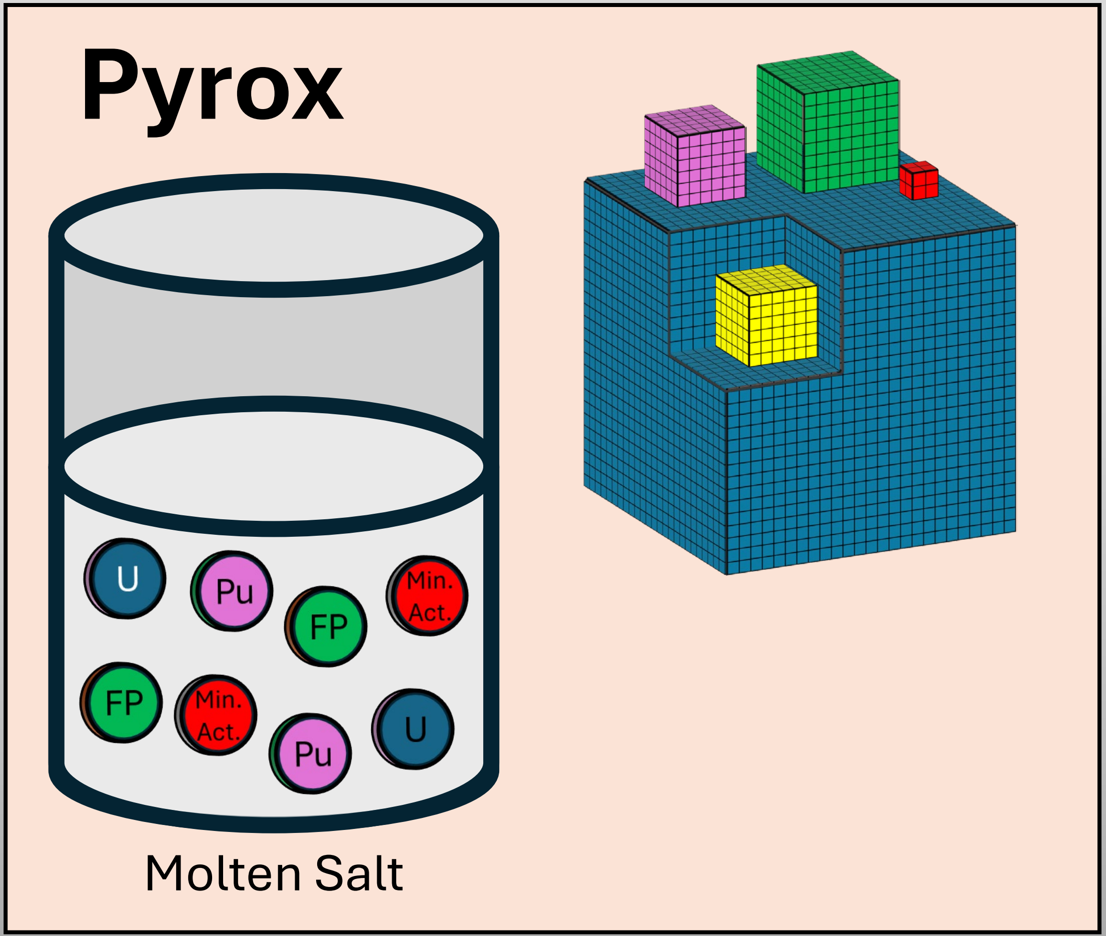
Pure plutonium
(oxide or nitrate form)

Other ways to prevent making pure plutonium?

Reprocessing using Molten Salts

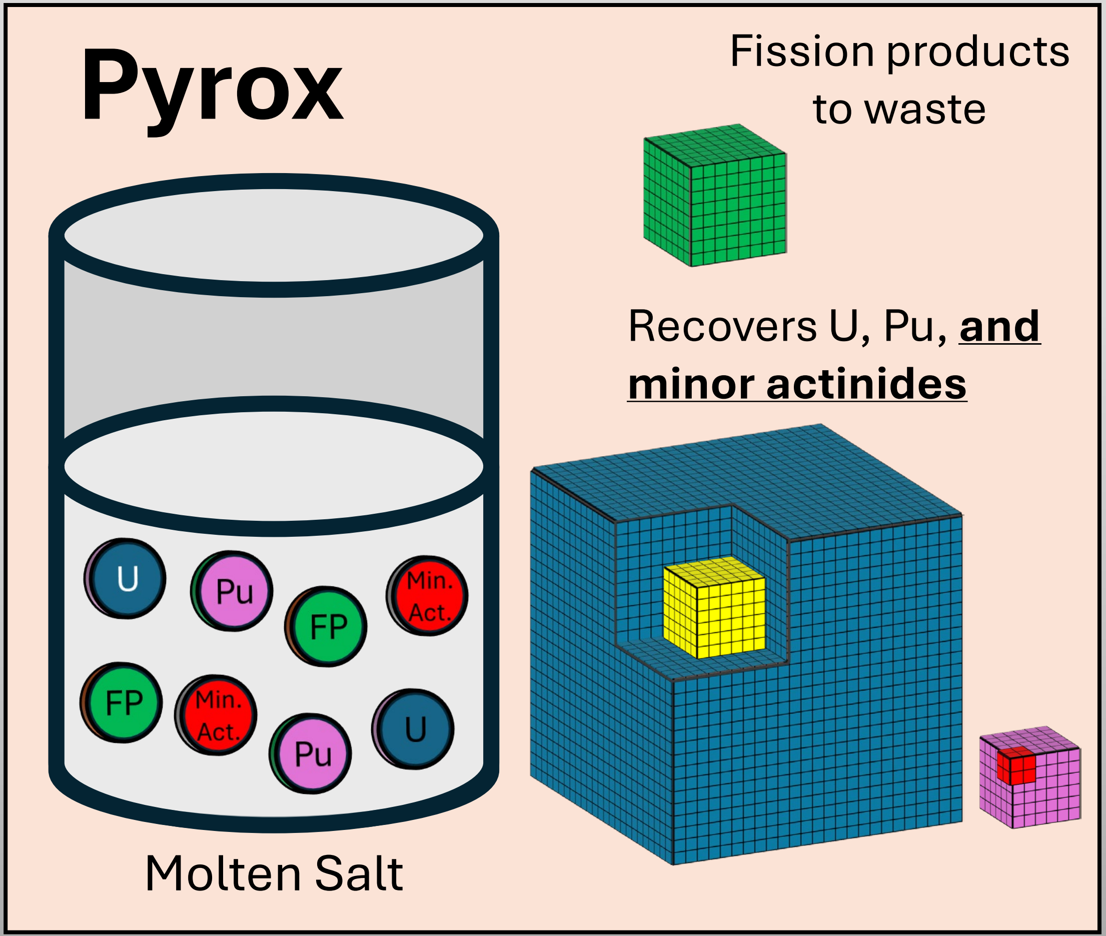
Other ways to prevent making pure plutonium?

<u>Reprocessing using Molten Salts</u>



Other ways to prevent making pure plutonium?

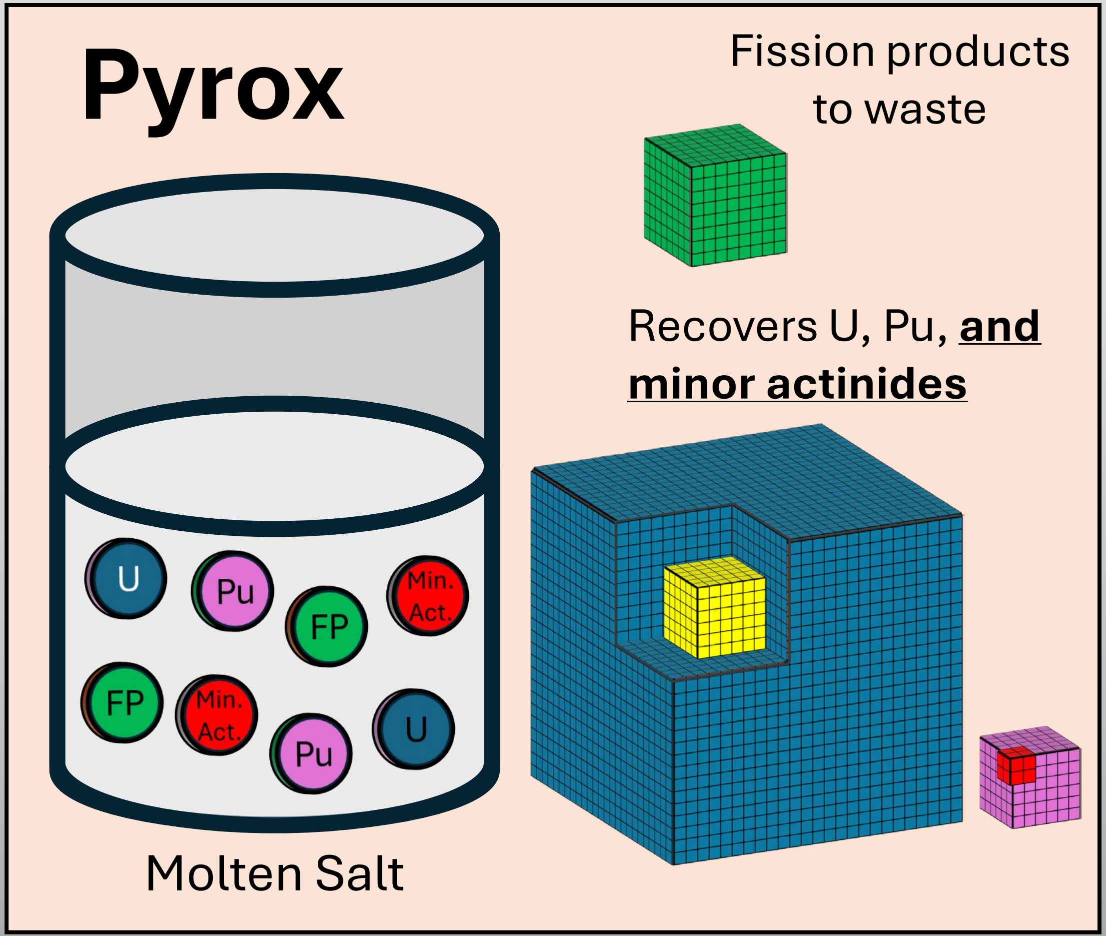
Reprocessing using Molten Salts



Other ways to prevent making pure plutonium?

<u>Reprocessing using Molten Salts</u>

Pyroprocessing and technologies like **Pyrox** are built to maximize proliferation resistance



Other ways to prevent making pure plutonium?

Reprocessing using Molten Salts

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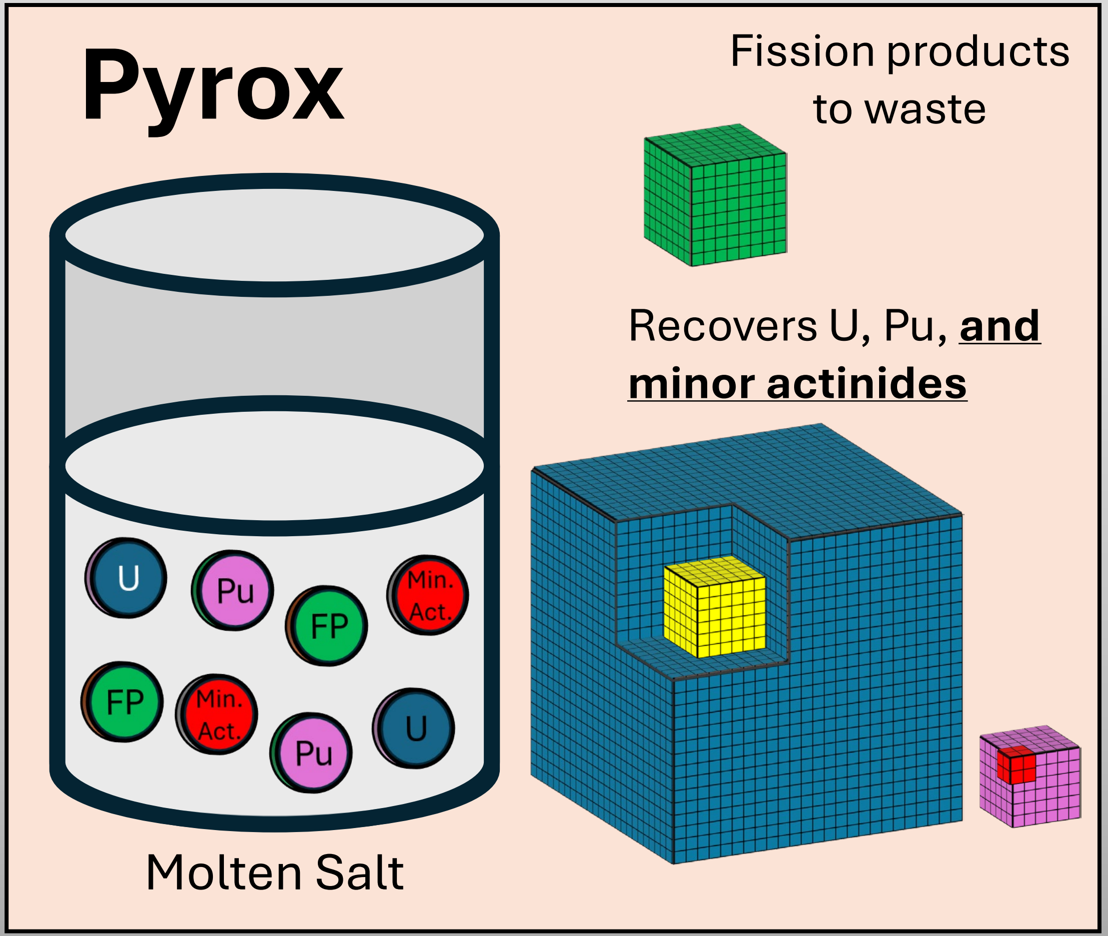
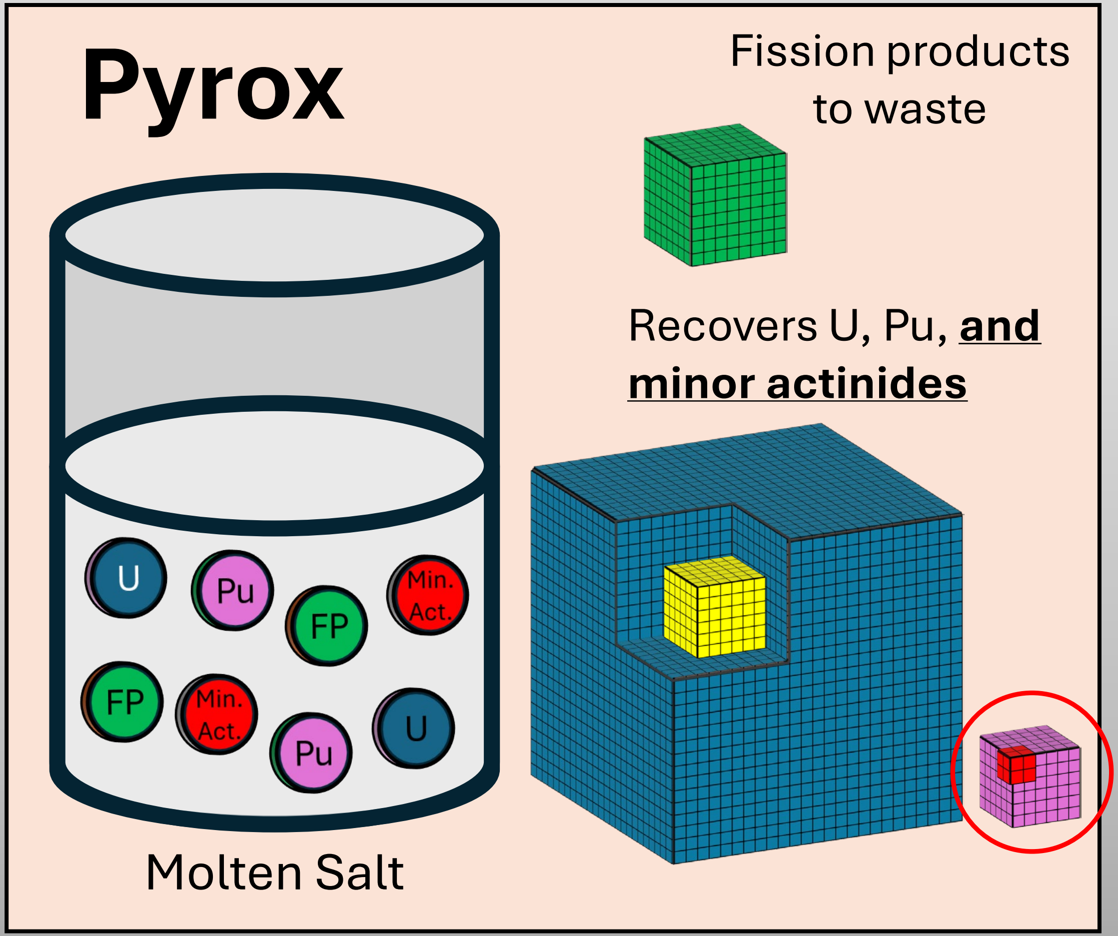


uranium
(metal)

Other ways to prevent making pure plutonium?



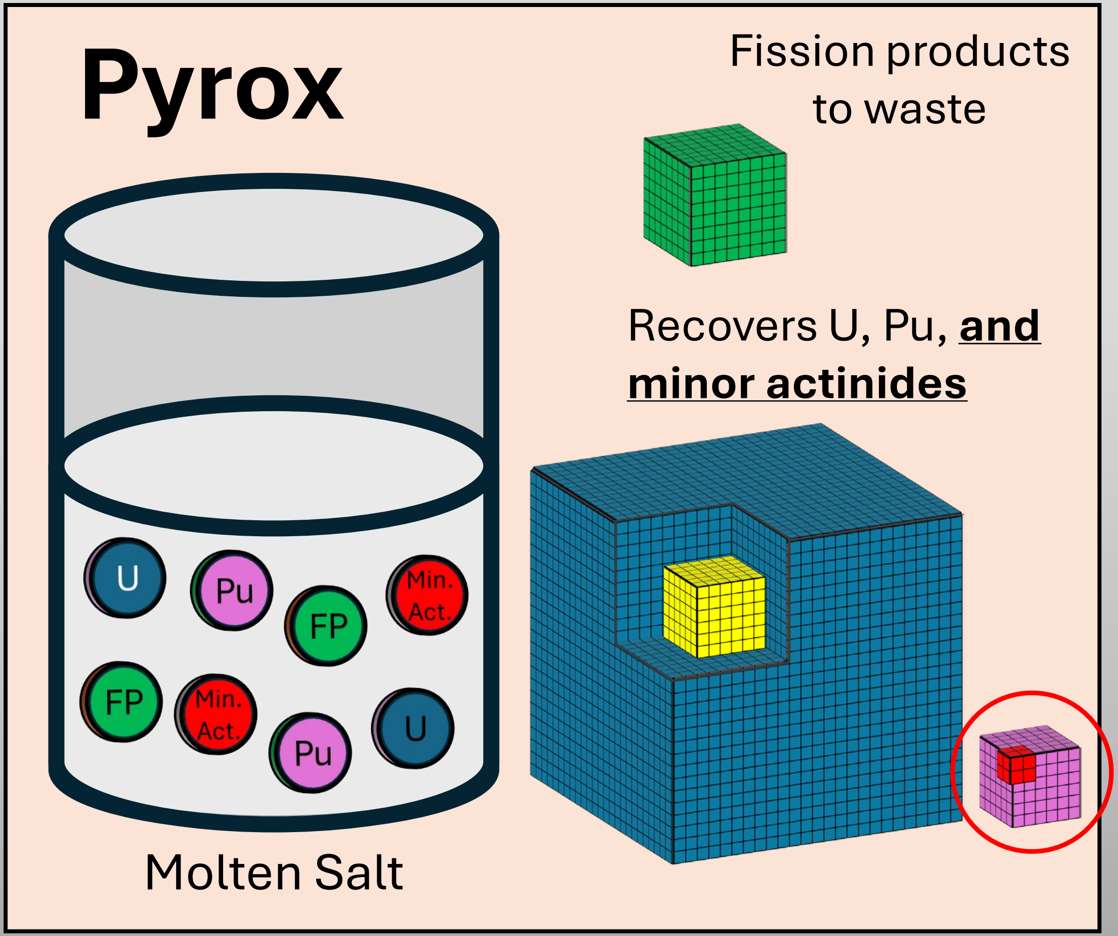
Reprocessing using Molten Salts

Pyroprocessing and technologies like **Pyrox** are built to maximize proliferation resistance

uranium
(metal)

mixed plutonium & minor actinides
(metal)

Other ways to prevent making pure plutonium?



Reprocessing using Molten Salts

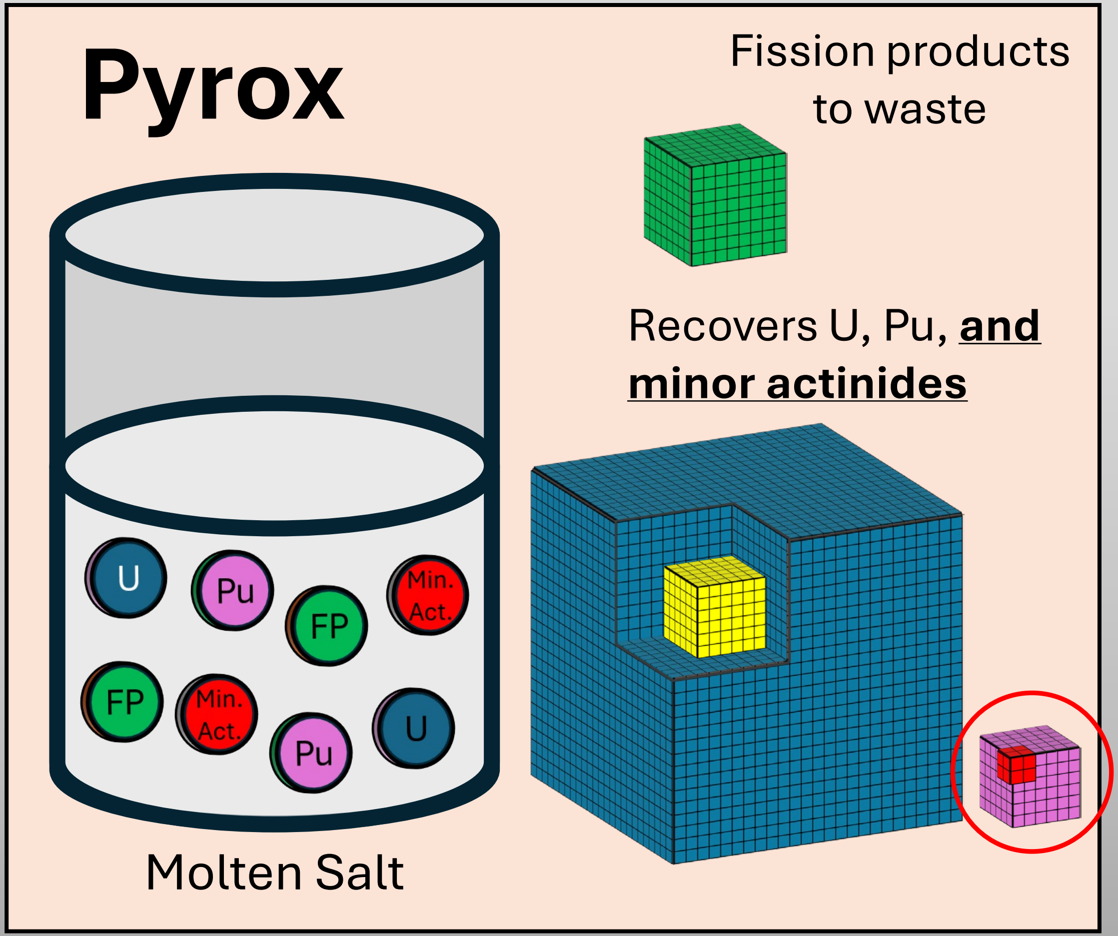
Pyroprocessing and technologies like **Pyrox** are built to maximize proliferation resistance

uranium
(metal)

mixed plutonium & minor actinides
(metal)

Designed to recover a mixed plutonium & minor actinide product

Other ways to prevent making pure plutonium?



Reprocessing using Molten Salts

Pyroprocessing and technologies like **Pyrox** are built to maximize proliferation resistance

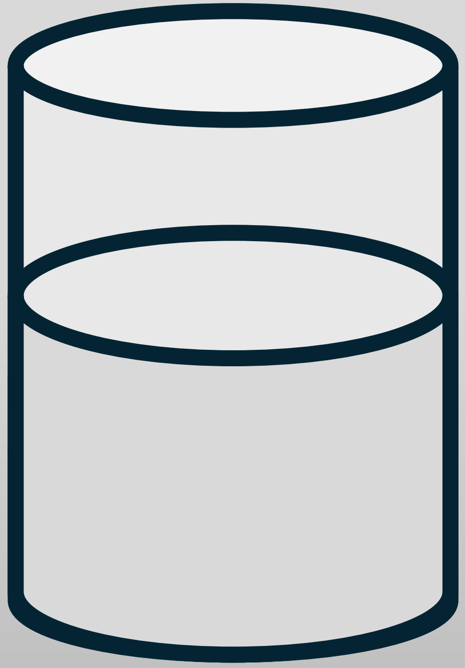
uranium
(metal)

mixed plutonium & minor actinides
(metal)

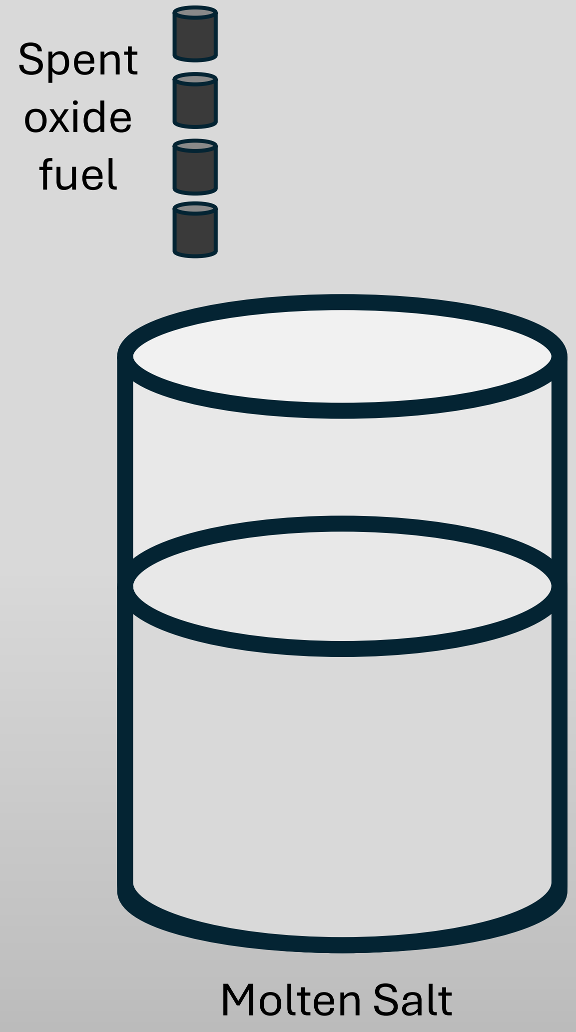
Fuel for fast reactors

Designed to recover a mixed plutonium & minor actinide product

Pyrox

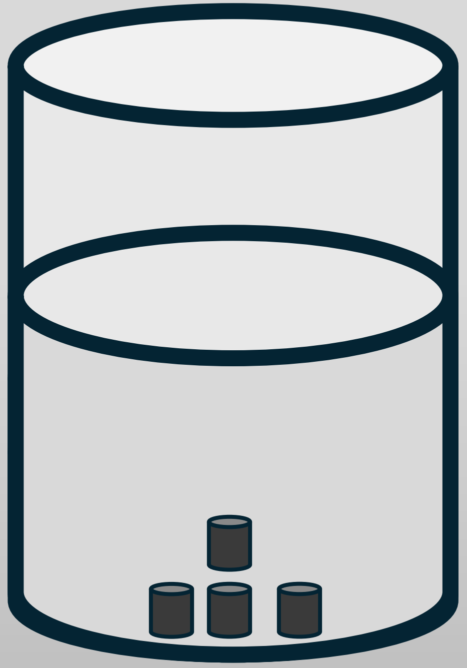

Molten Salt

Pyrox



Reactive dissolution

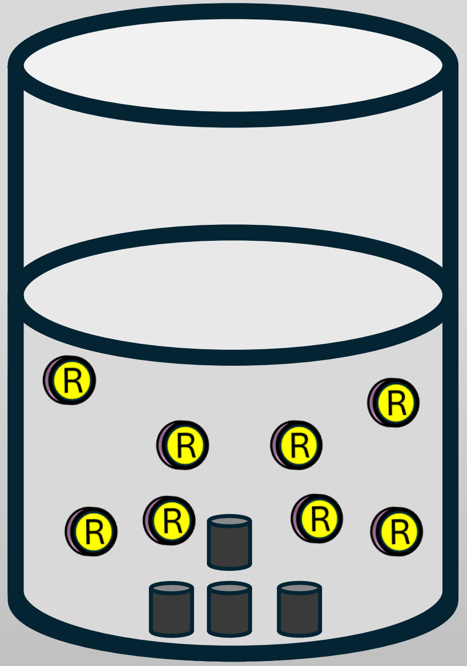
Pyrox



Molten Salt

Reactive dissolution

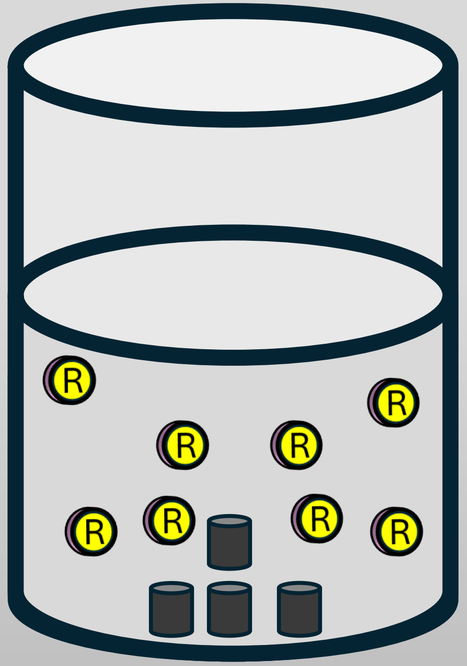
Pyrox



Molten Salt

Reactive dissolution

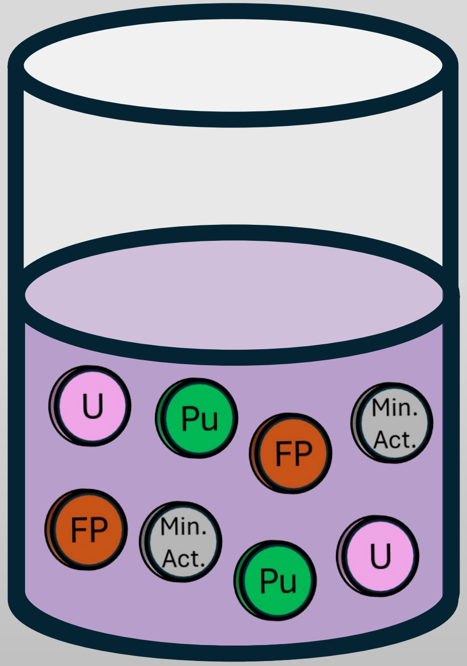
Pyrox



Molten Salt

Conversion to actinide/fission product chlorides

Pyrox

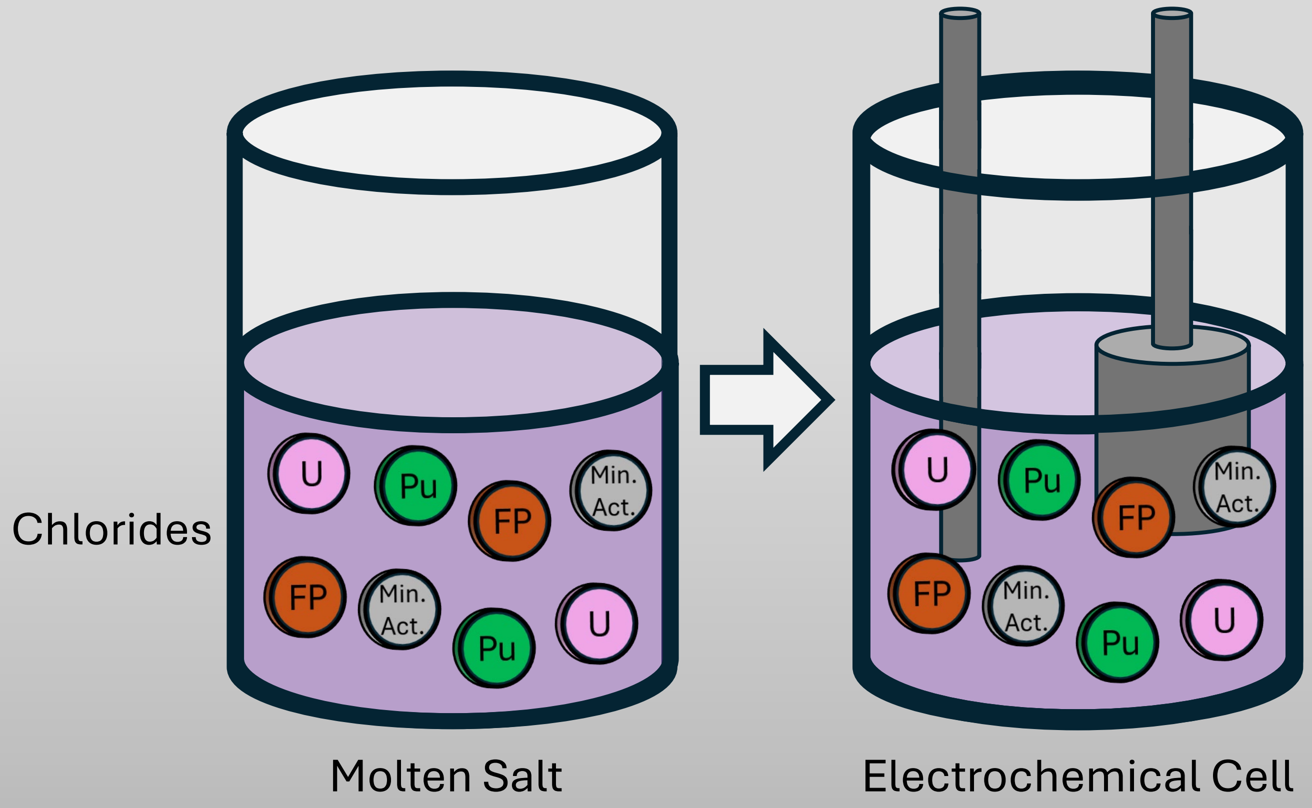


Chlorides

Molten Salt

Conversion to actinide/fission product chlorides

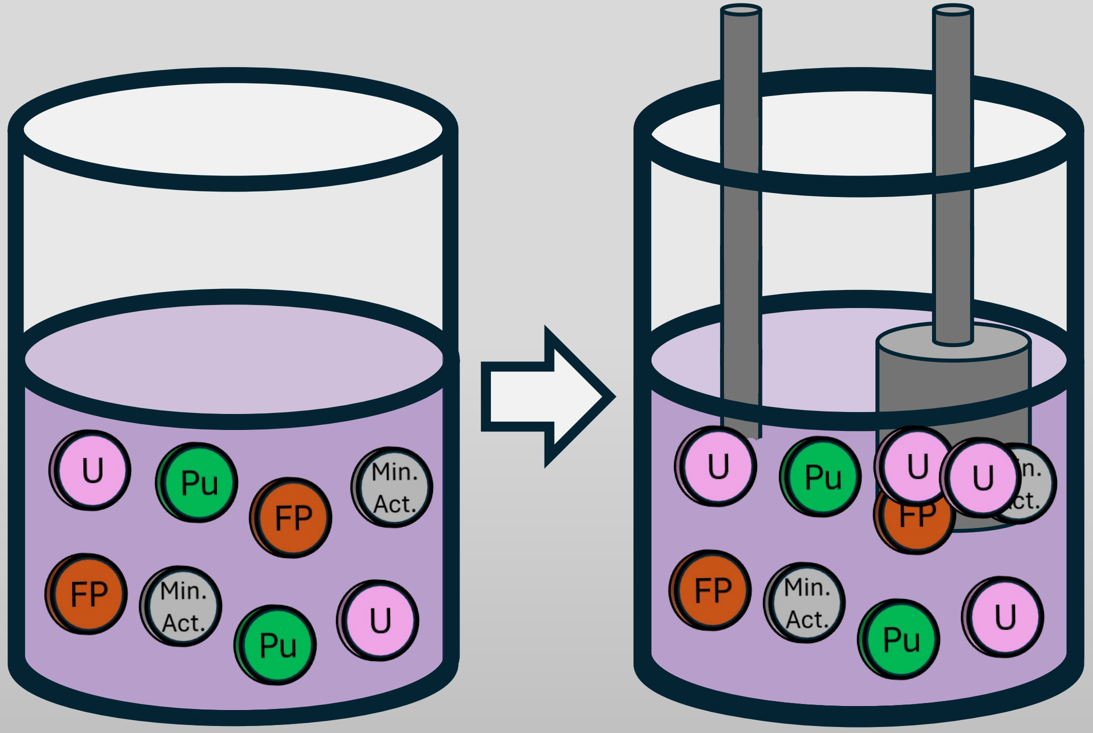
Pyrox



Uranium removal

Pyrox

Chlorides

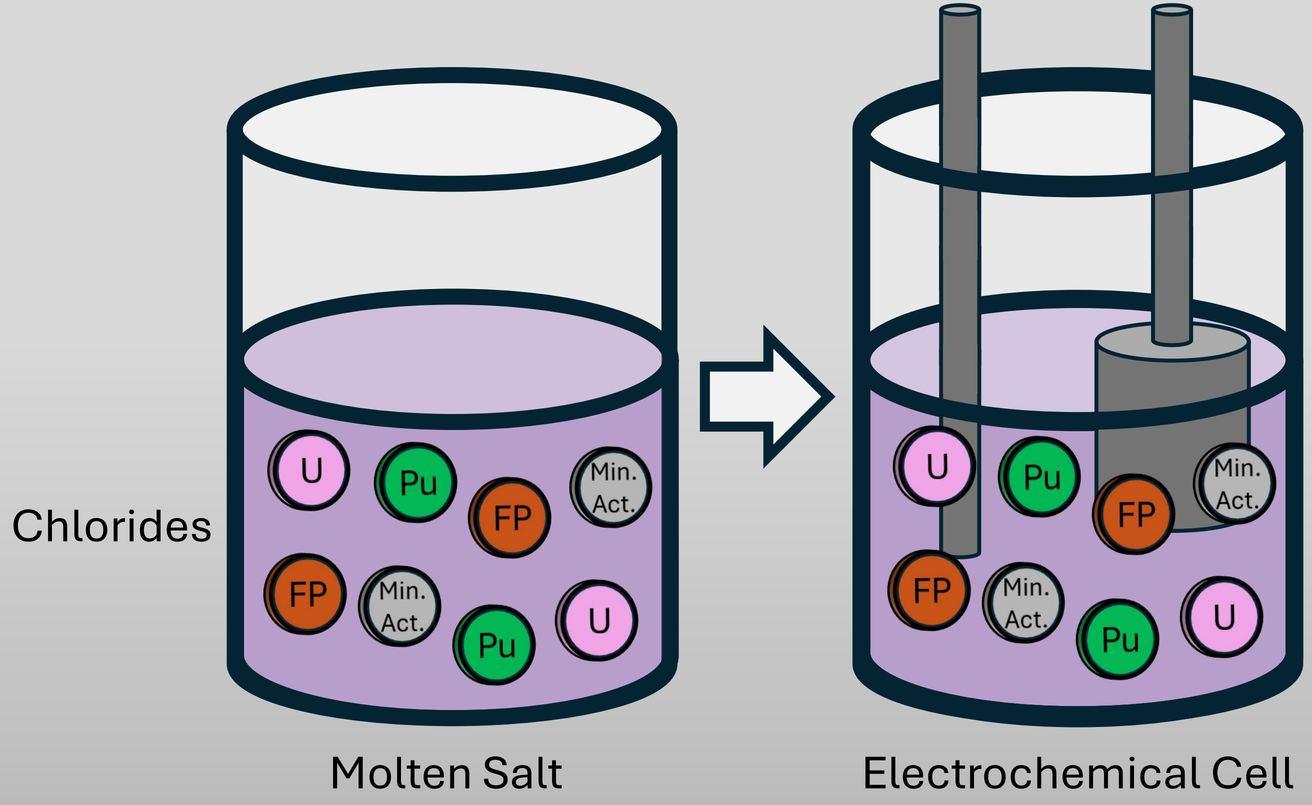


Molten Salt

Electrochemical Cell

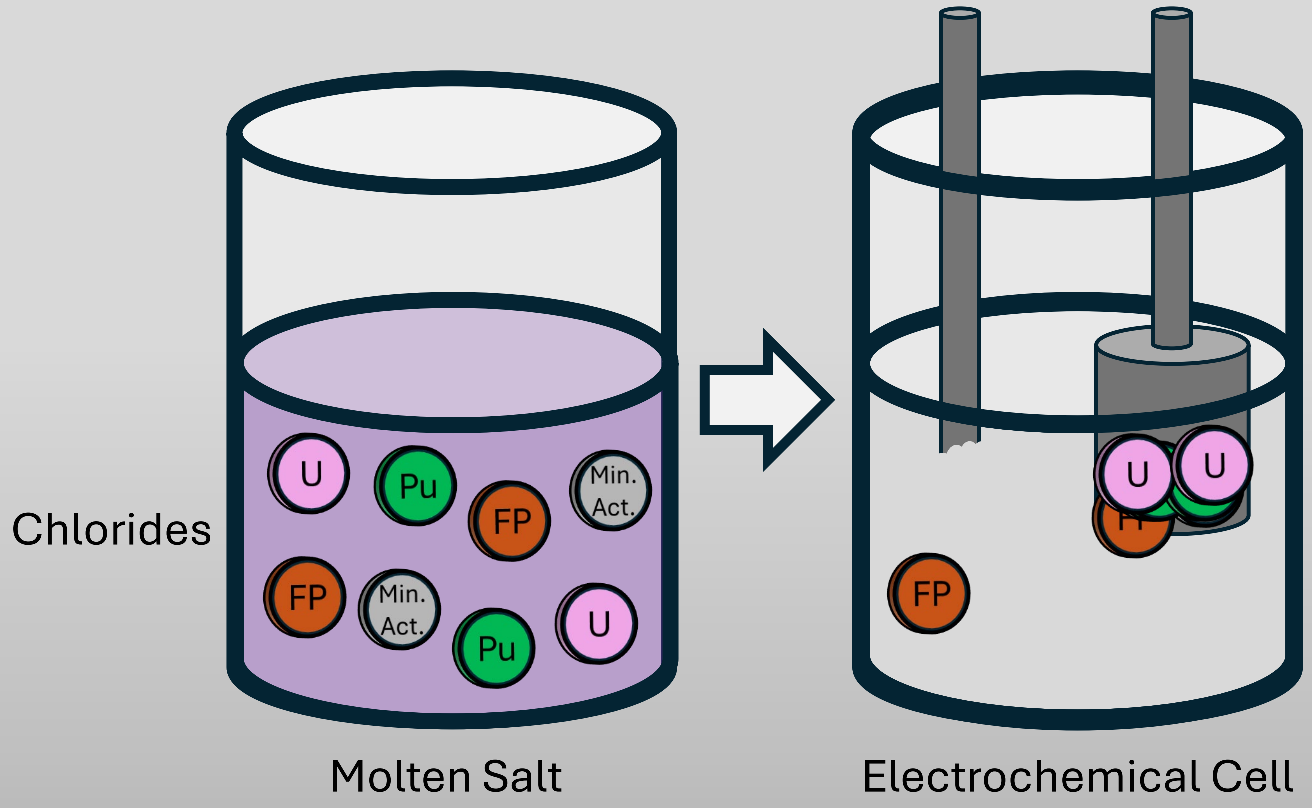
Uranium removal

Pyrox



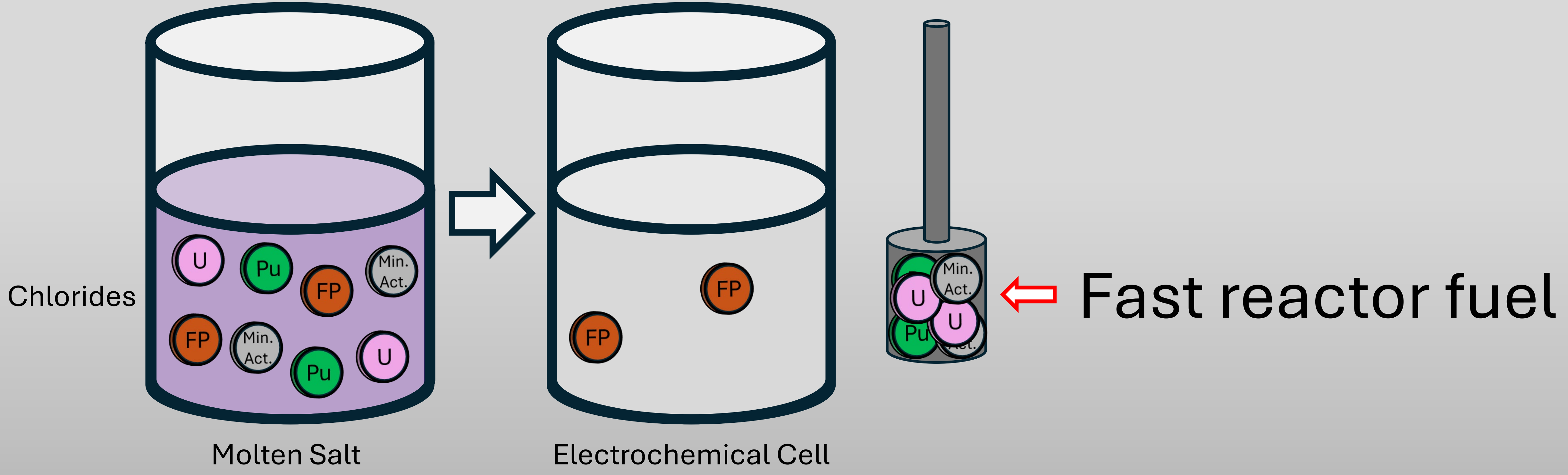
Group actinide removal

Pyrox



Group actinide removal

Pyrox



Chlorides
U
Pu
FP
Min. Act.
Molten Salt
Electrochemical Cell
Fast reactor fuel

Safeguards and security beyond process design?

Safeguards and security beyond process design?

Prevent diversion, theft, and misuse

International Verification

- material accountancy
- inspections
- seals, cameras, and monitoring

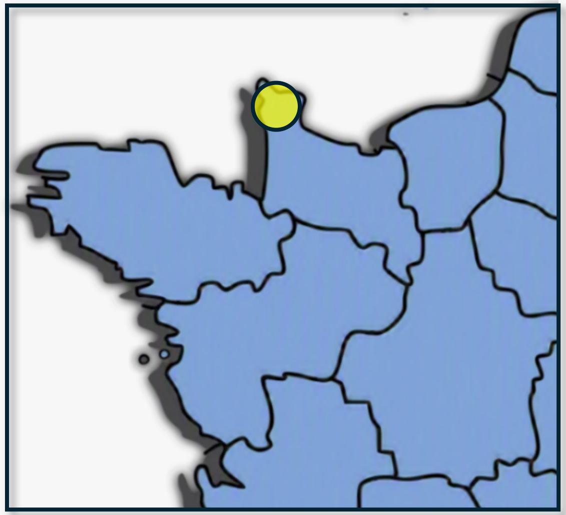
Facility Protection

- physical protection
- material control and accounting
- Timely detection

Where is reprocessing happening?

Where is reprocessing happening?

<u>World Leader in Nuclear Fuel Reprocessing</u>

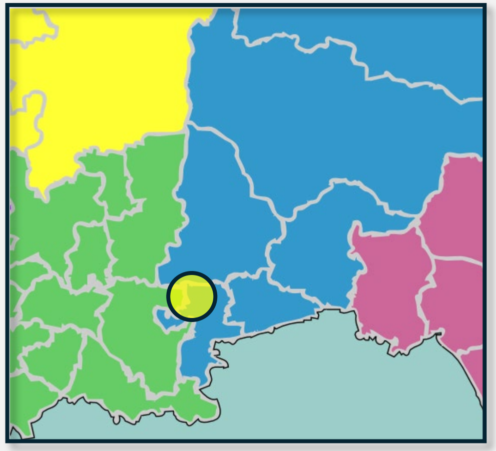


ORANO

La Hague, France

- PUREX
- Over 40,000 metric tons processed
- Processed fuel from: *Belgium, Germany, Italy, Japan, Netherlands, Switzerland, Australia*

Mayak (*Russia)*



- PUREX
- ~ 6,000 metric tons processed
- Processed fuel from: *Bulgaria, Czech Rep., Finland, Hungary, Slovakia, Ukraine*

Tarapur/Kalpakkam (*India)*

- PUREX
- ~ 250 metric tons processed
- Domestic reprocessing only

Rokkasho (*Japan)*

Planned for 2027

Designed for 800 MT/yr

Why did the U.S. stop reprocessing?

Why did the U.S. stop reprocessing?

<u>Three early reprocessing plants:</u>

<u>West Valley, NY</u>	<u>Morris, IL</u>	<u>Barnwell, SC</u>
1966 -1972	Never operated	Never operated
economics	*did not meet regulations*	*policy shift*

1974	**1976**	**1977**	**1981**
India tests bomb built with plutonium	Henry Ford suspends reprocessing	Jimmy Carter defers it indefinitely	Ronald Reagan reverses policy
Used civilian reprocessing program	Cites proliferation risk	*“A viable nuclear program can be sustained without it”*	Pushes for safeguards to manage proliferation risk

But

it’s “cheaper” to mine

Where are we now?

Where are we now?

Proliferation-resistant Processes

- UREX
- GANEX
- Pyroprocessing
- Pyrox

No recovery of isolated Pu

New Reactor / Fuel Types

- MSRs
- Fast Reactors
- U/TRU
- TRISO

Designed for proliferation resistance

Mined Uranium Price Increase

- LEU - $4,000/kg
- HALEU - $25,000/kg

Economics becoming more favorable

More importantly: Lets us make the case for more environmentally conscious fuel production

U.S. Energy Independence

- <5% of uranium used is domestic
- Push to reduce reliance on foreign sources

Less waste for **less time**