Thorium and MSR Fuel Strategies

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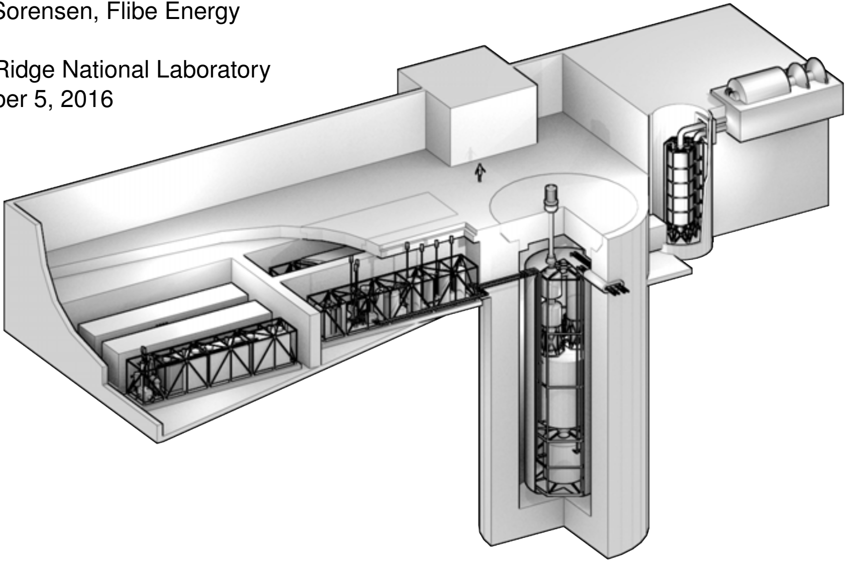
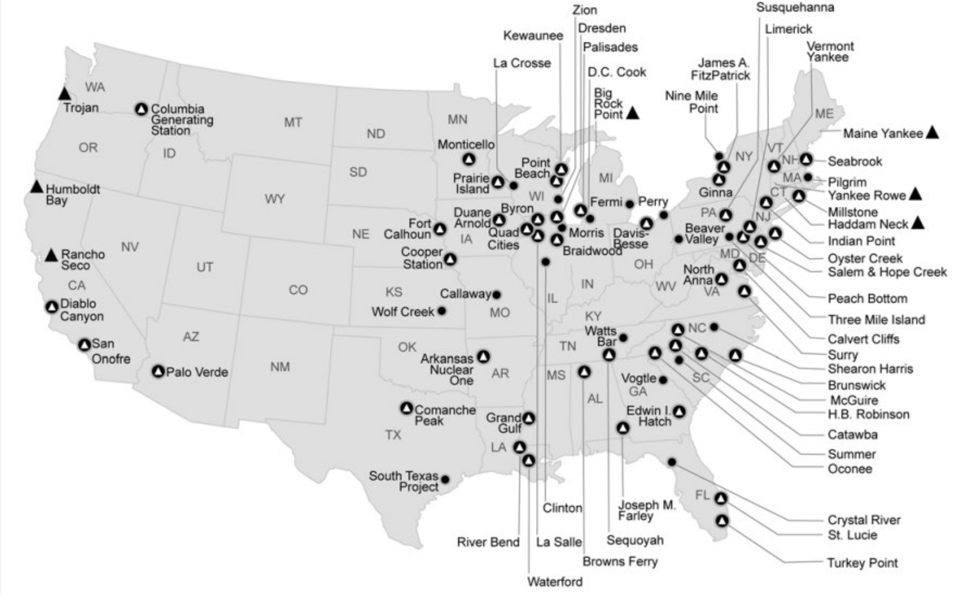


The production of long-lived nuclear waste has been a potent focus of opposition to nuclear power for many years.

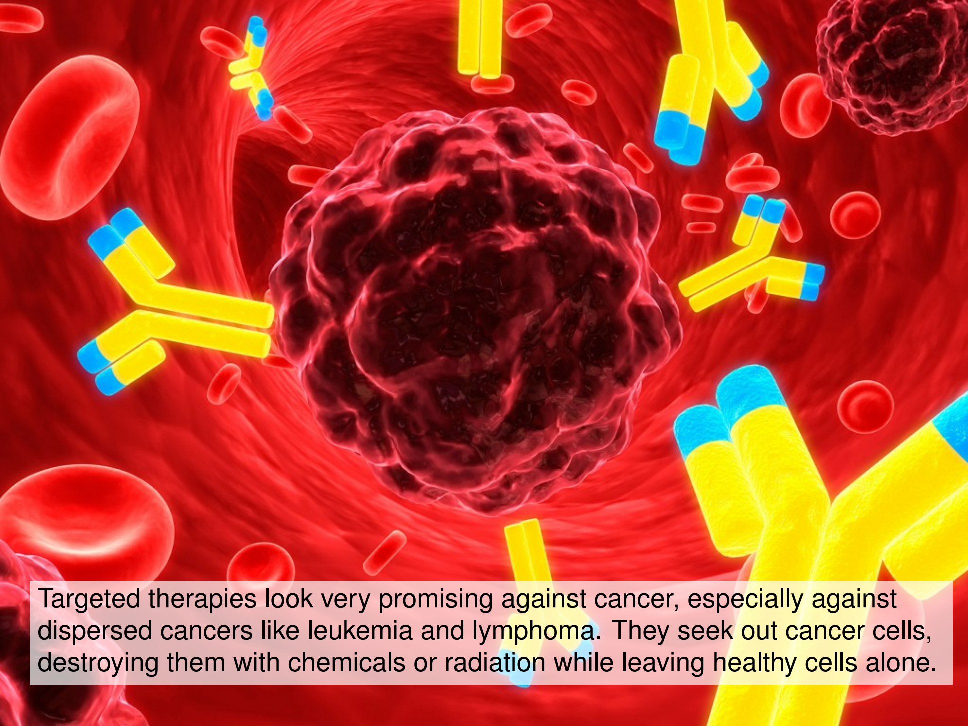


Because of the failure of the US government to take custody of spent nuclear fuel, it remains at the same site at which it was produced.

This was once the site of the Connecticut Yankee reactor. Even after a nuclear power plant site has been decommissioned, the "orphaned" spent nuclear fuel remains on site in casks.

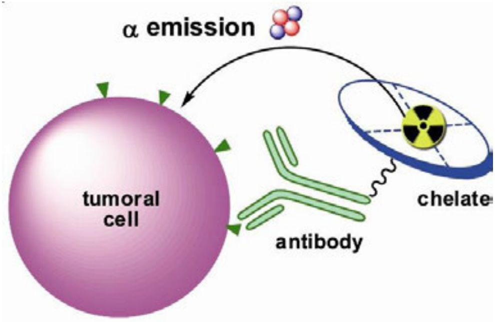
These spent fuel casks cannot legally be moved from the decommissioned reactor site and prevent its release for unlimited use. They also require continuous security.

For millions of people each year, receiving a diagnosis of cancer is a terrifying moment that leads to profound uncertainty.



Targeted therapies look very promising against cancer, especially against dispersed cancers like leukemia and lymphoma. They seek out cancer cells, destroying them with chemicals or radiation while leaving healthy cells alone.

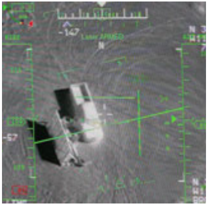
Targeted Alpha Therapy using Bismuth-213



Bismuth-213 has a 45-minute half-life (perfect) and decays from actinium-225, which has a 10-day half-life (perfect). It is near the end of its decay chain, and can be suitably chelated (wrapped in a chemical cage) and attached to an antibody that will hunt down and attach to a bloodborne cancer cell. When it decays, the alpha particle it emits will kill the cancer cell.

This is called targeted alpha therapy (TAT).

TAT is a Smart Bomb Against Cancer



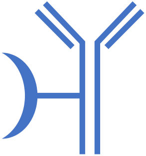
Explosive Payload

Precision Guidance & Delivery System

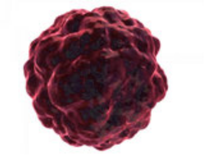
Specific Target

Target Destruction

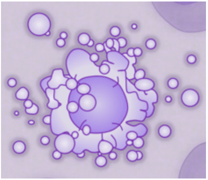
^{213}Bi



monoclonal antibody



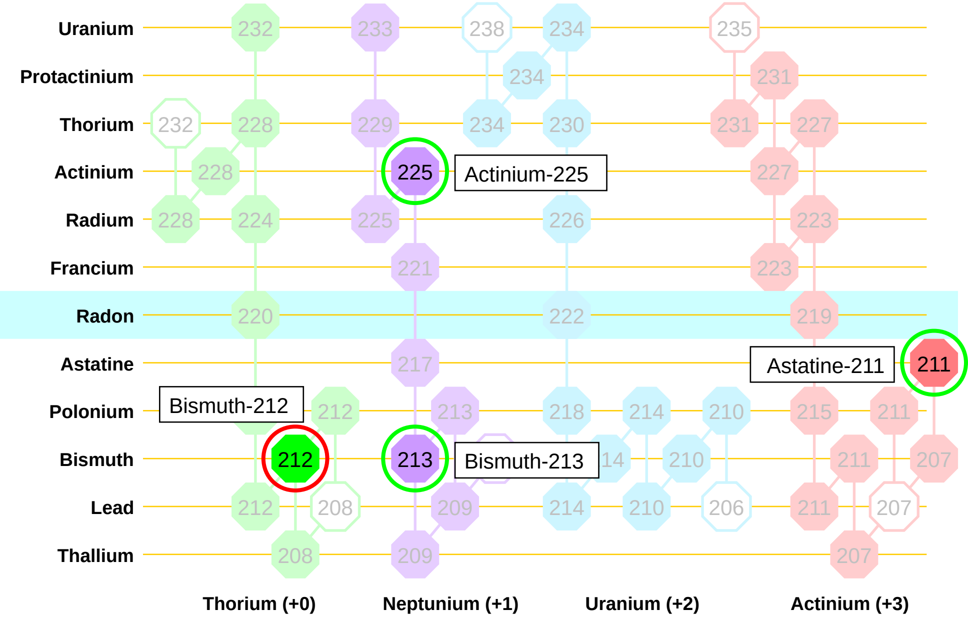
cancer cell



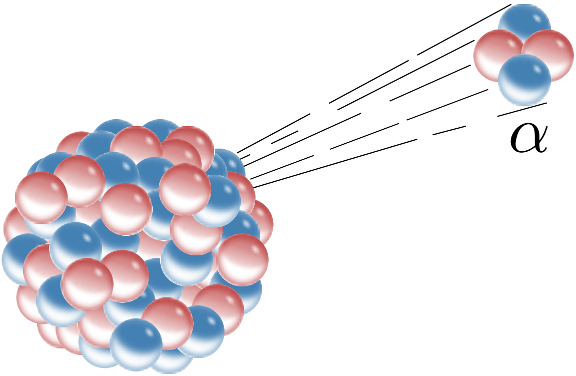
programmed cell death (apoptosis)

Glenn Seaborg first created uranium-233 from thorium in April 1941 and correctly predicted that it was the first of a new family of radioactive materials.

Candidate Alpha Emitters on the Decay Chains

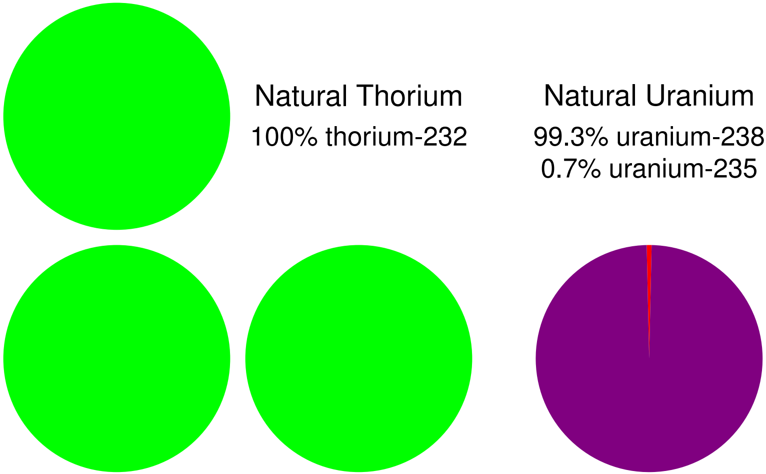


Bismuth-213 is formed from the decay of Uranium-233



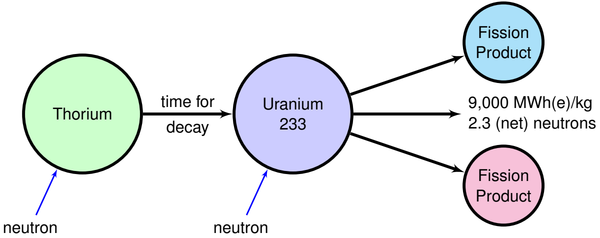
A million grams of uranium-233 will produce about 4 grams of thorium-229 each year. This thorium-229 will then produce alpha-emitting medicines (actinium-225 and bismuth-213) for thousands of years.

Possible Nuclear Fuels

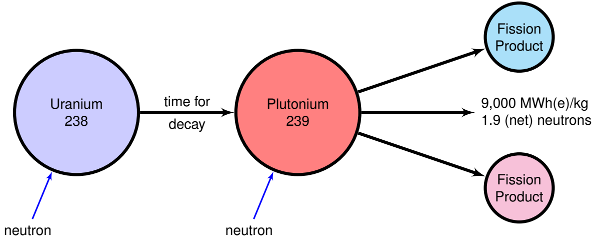


Only a small fraction of natural uranium is fissile. Most uranium and all thorium is "fertile" and can be converted to fissile material through neutron absorption.

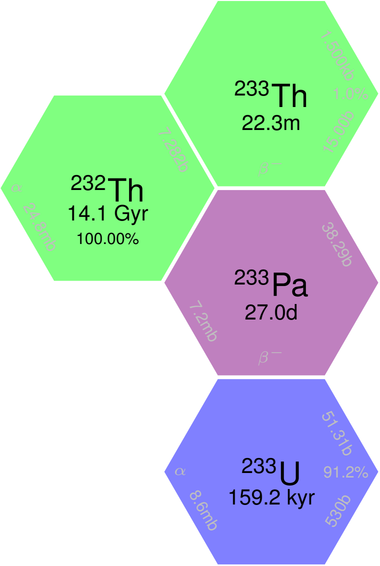
Nuclear Conversion Reactions



Thorium and uranium-238 both require two neutrons to release their energy: one to convert them to fissile fuel and another to release their energy through fission. But only thorium produces sufficient neutrons (2.3) in thermal reactors to sustain energy release.

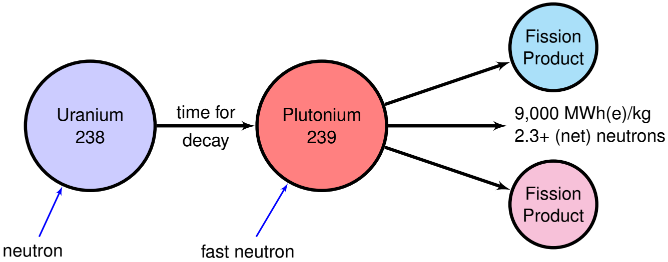


Energy from thorium



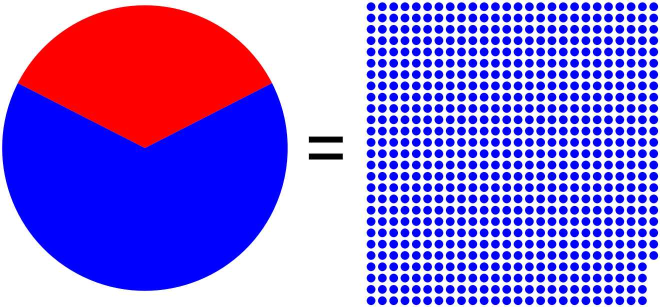
- Abundant, natural thorium is the starting point in the process
- Thorium absorbs a neutron, forming short-lived thorium-233.
- Thorium-233 quickly decays in protactinium-233, which is chemically distinct from thorium.
- After a little more than a month, protactinium-233 will decay into uranium-233, which is the best nuclear fuel.
- The fission of uranium-233 releases energy and sufficient neutrons to continue the process.

Nuclear Conversion Reactions



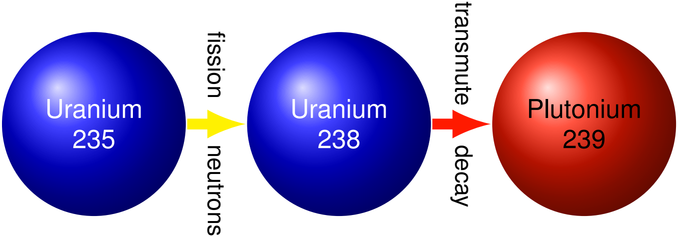
Using fast neutrons improves the performance of the uranium fuel cycle sufficiently to allow sustained further conversion and fission reactions. This has been the basis of global interest in fast-spectrum reactors for nearly 70 years.

Thermal vs. fast neutron cross-sections



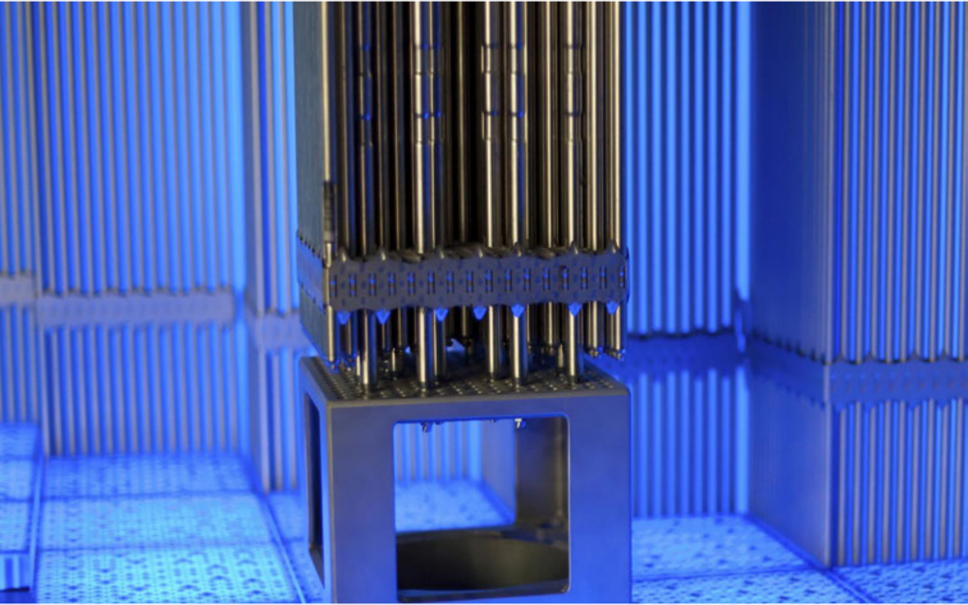
Uranium can be a sustainable fuel in a fast reactor, but using fast neutrons comes at a substantial price. Neutron cross-sections are much smaller for fast neutrons than for thermal (slowed-down) neutrons. To a thermal neutron, one atom of plutonium-239 is the equivalent of nearly 700 atoms of plutonium-239 to a fast neutron. **This is why thermal reactors have a far lower fuel inventory than fast reactors, and why almost every reactor in the world today is a thermal reactor.**

Starting with Uranium is Inevitable



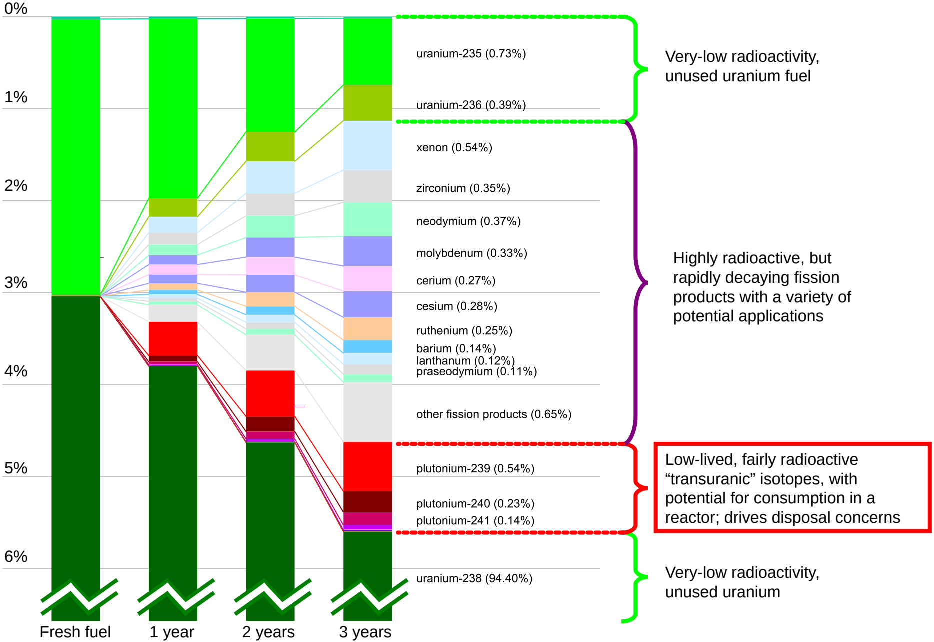
Starting with uranium is inevitable since uranium-235 is the only natural fissile material. A well-designed reactor will essentially "burn out" its uranium-235 inventory while producing chemically-separable plutonium. Depending on the exposure duration small amounts of other transuranics will also form.

Today’s nuclear fuel is fabricated with extraordinary precision, like a fine watch.

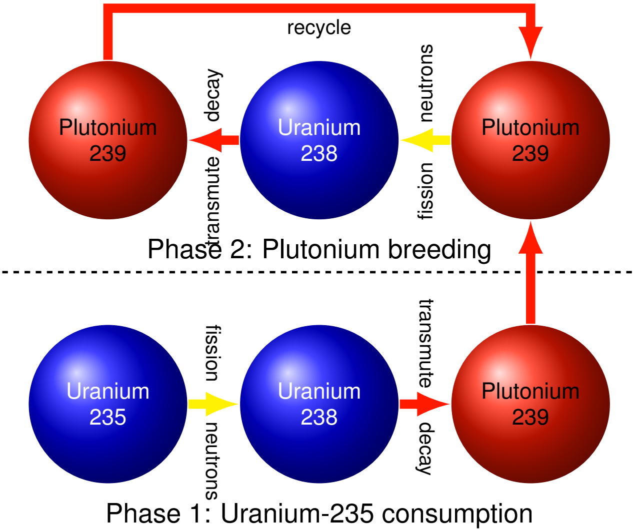


But it is that precision that makes it difficult to recycle and to refabricate. A new approach is needed that is more versatile and less expensive.

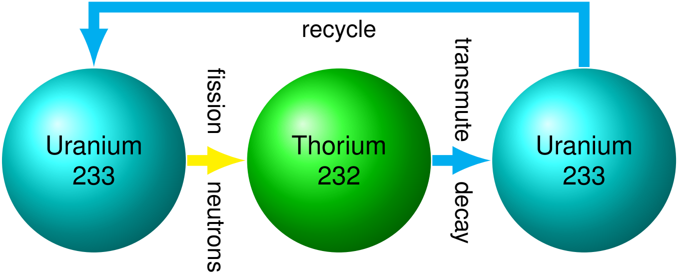
Spent Nuclear Fuel Composition



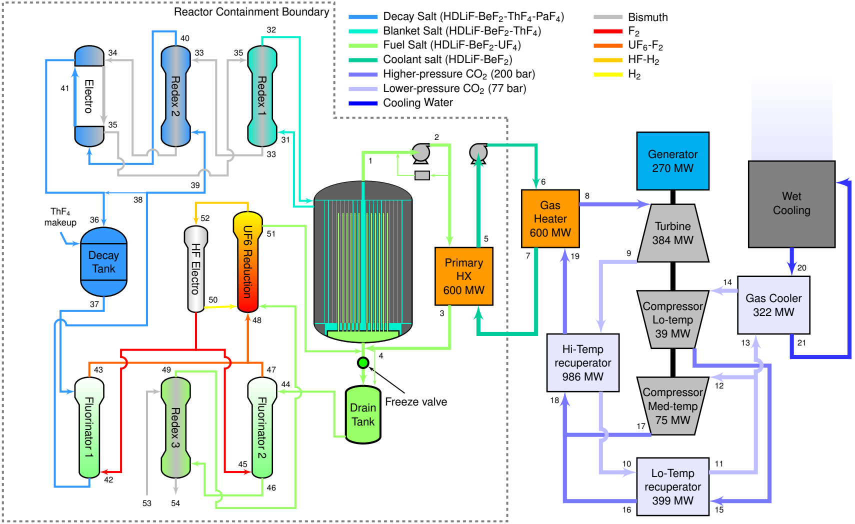
The Traditional Plan for Nuclear Utilization



Sustainable Use of Thorium is the Ultimate Goal



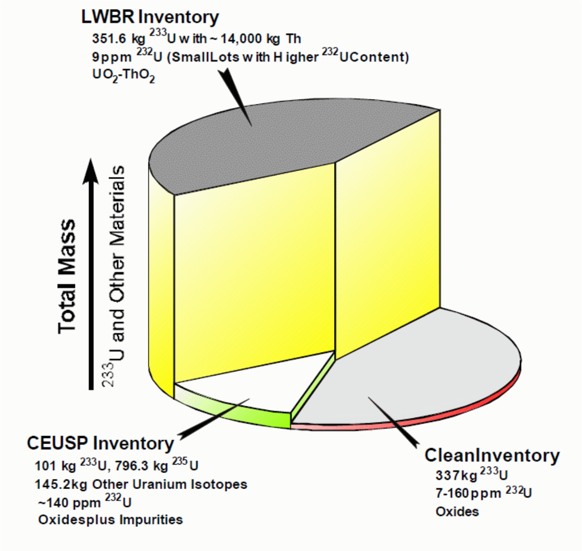
Uranium-233 alone produces sufficient neutrons per thermal neutron to match or exceed its consumption. In this way, U-233 is the "catalyst" to sustainable energy production from thorium and can almost eliminate transuranic production. But very little U-233 presently exists, and not enough for a major rollout of thorium reactors.



Liquid-Fluoride Thorium Reactors (LFTR) are reactors that use uranium-233 as their fuel, generated from abundant natural thorium. By using uranium-233, they also form the medicinal precursors needed for targeted alpha therapy.

Under the leadership of Alvin Weinberg, Oak Ridge National Laboratory led the effort to develop thorium as an energy source. Uranium-233 generated from thorium was first used to power a reactor in 1968, and ORNL has been the home to the US supply of uranium-233 every since.

Uranium-233 Inventories in DOE

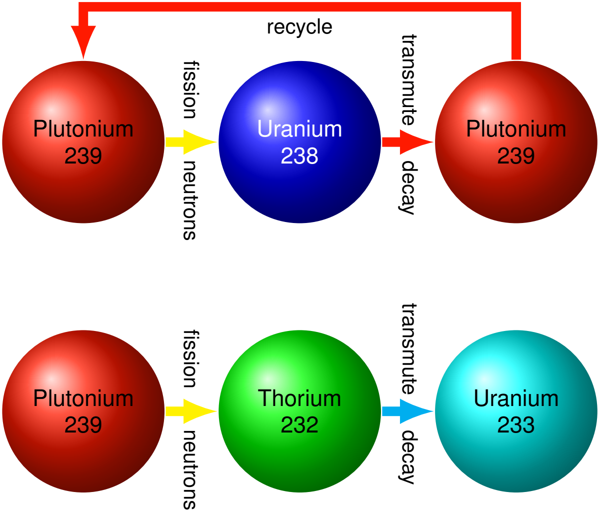


There are valuable materials at INL and ORNL that could greatly accelerate thorium reactor development. In particular, the inventory of $ThO_2/^{233}UO_2$ fuel developed for the 1978 "Light Water Breeder Reactor" contains:

- 351 kg of ^{233}U
- 14,000 kg of thorium

This fuel could be fluorinated into ThF_4 and UF_4 and combined with LiF-BeF_2 salts to form the fuel and blanket salts of a reactor that would thereafter produce ~300 MWe of sustainable power generation.

Consume Plutonium or Generate More Plutonium?

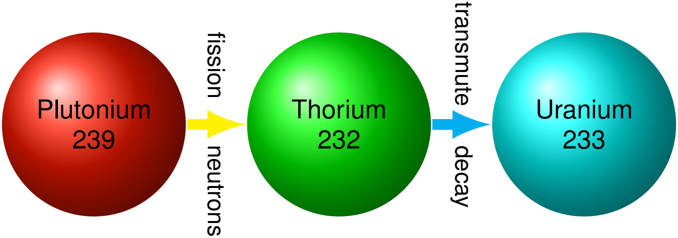


Plutonium is the inevitable result of the first stage of nuclear utilization.

WIth uranium, it cannot make more fissile than it consumes (in thermal reactors).

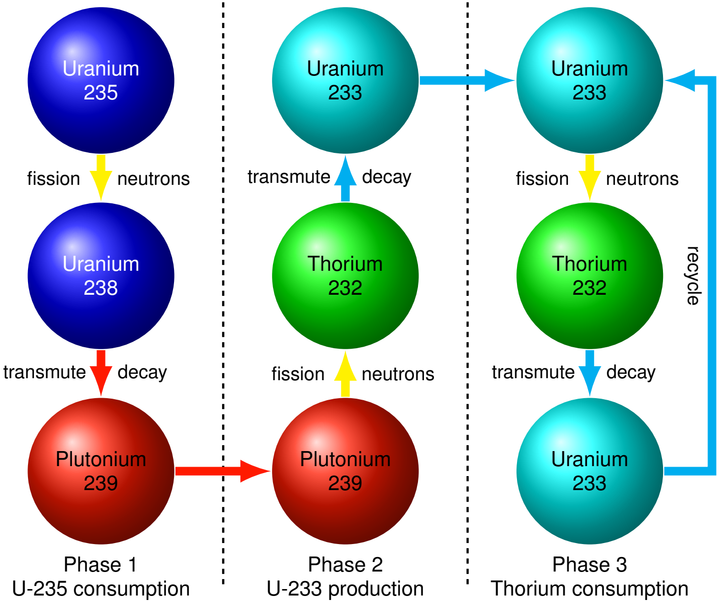
But with thorium, plutonium fission generates the U-233 that is the key to sustainability.

Use Thorium for Transition from Plutonium

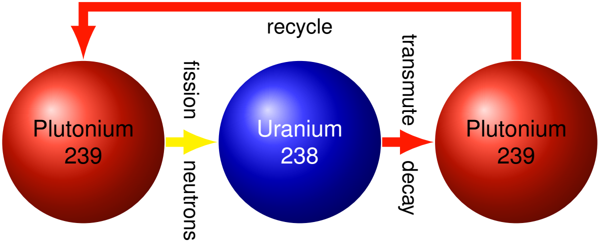


So consuming plutonium as fuel in a reactor with thorium can produce the uranium-233 needed to "bridge" to sustainable thorium-fueled reactors.

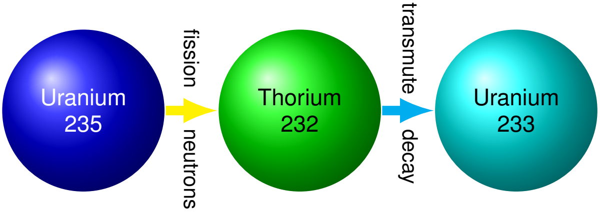
Three-Phase Plan to Sustainability



Better Fuel Strategies for MSRs

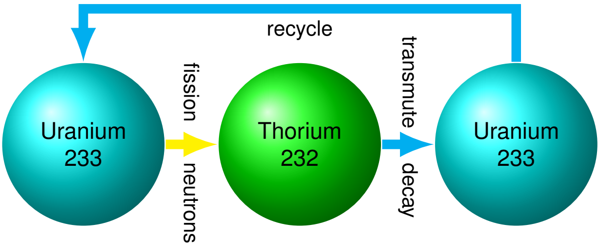


A chloride MSR (fast spectrum) could breed more fuel than it consumes, using the U-Pu cycle. **This has been proposed for fast chloride MSRs.**

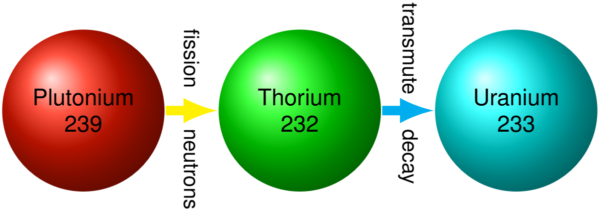


Fission of U-235 (essentially HEU) could permanently consume it while the neutrons form U-233 from thorium. **This approach could skip to Phase 3.**

Best Fuel Strategies for MSRs

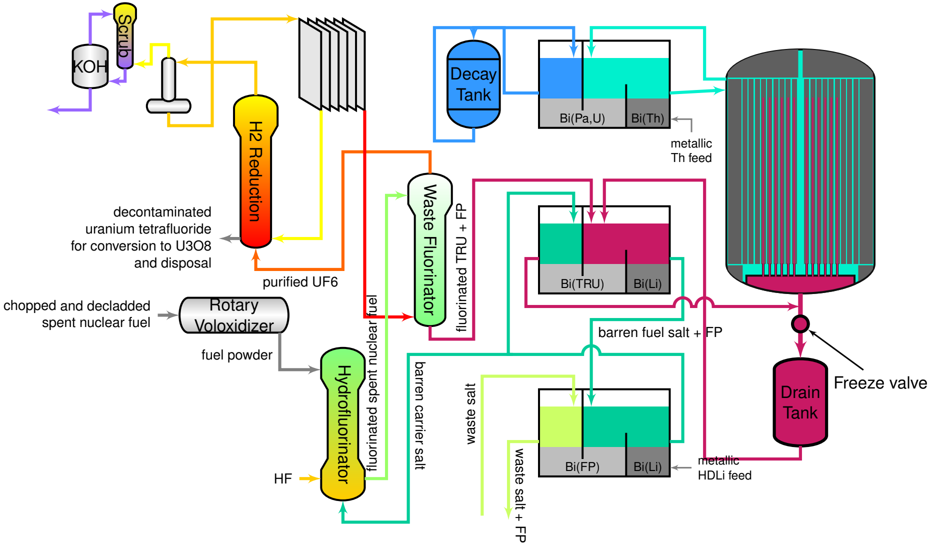


U-233 fuel irradiating Th-232 can breed in the thermal spectrum and almost eliminate transuranic production. **This is Phase 3.**



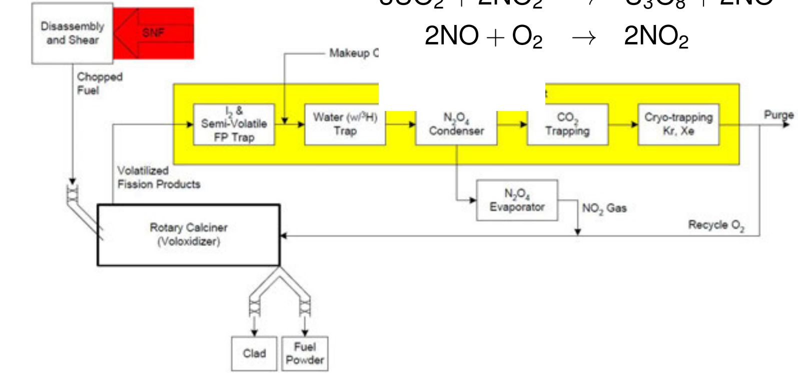
Consuming TRU in the presence of Th-232 forms U-233 while permanently destroying TRU. **This is Phase 2.**

LFLEUR chemical processing



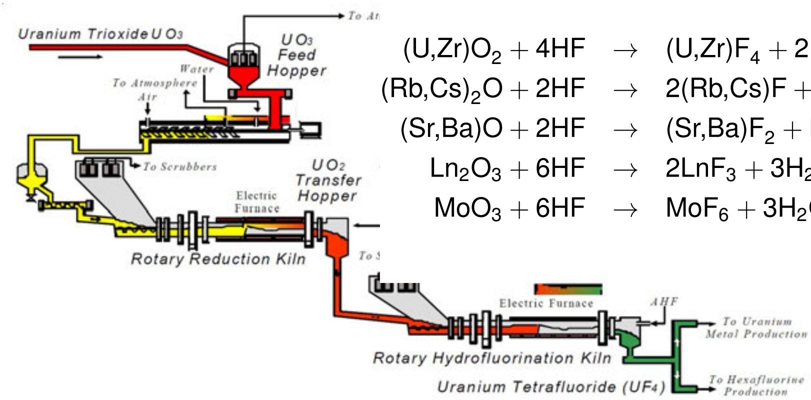
Voloxidation

$$3UO_2 + 2NO_2 \rightarrow U_3O_8 + 2NO$$
$$2NO + O_2 \rightarrow 2NO_2$$



Spent nuclear fuel is first oxidized with nitrogen dioxide which causes it to pulverize into a fine powder. Xenon, krypton, tritium, iodine, and CO2 are removed as gases and purified and separated.

Hydrofluorination



$$
\begin{aligned}
(U,Zr)O_2 + 4HF &\rightarrow (U,Zr)F_4 + 2H_2O \\
(Rb,Cs)_2O + 2HF &\rightarrow 2(Rb,Cs)F + H_2O \\
(Sr,Ba)O + 2HF &\rightarrow (Sr,Ba)F_2 + H_2O \\
Ln_2O_3 + 6HF &\rightarrow 2LnF_3 + 3H_2O \\
MoO_3 + 6HF &\rightarrow MoF_6 + 3H_2O
\end{aligned}
$$

Next the powdered fuel is reduced with hydrogen and hydro-fluorinated to replace all oxides with fluorides. The constituent materials change from oxides (ceramics) to fluorides (salts) as oxygen in the spent fuel is removed as water vapor.

Fluorination

Uranium is removed from the salt mixture through fluorination to gaseous uranium hexafluoride. Several other constituents also form gaseous hexafluorides, but most do not. Fluorination is one of the most challenging chemical processes because of its severity on any container material.

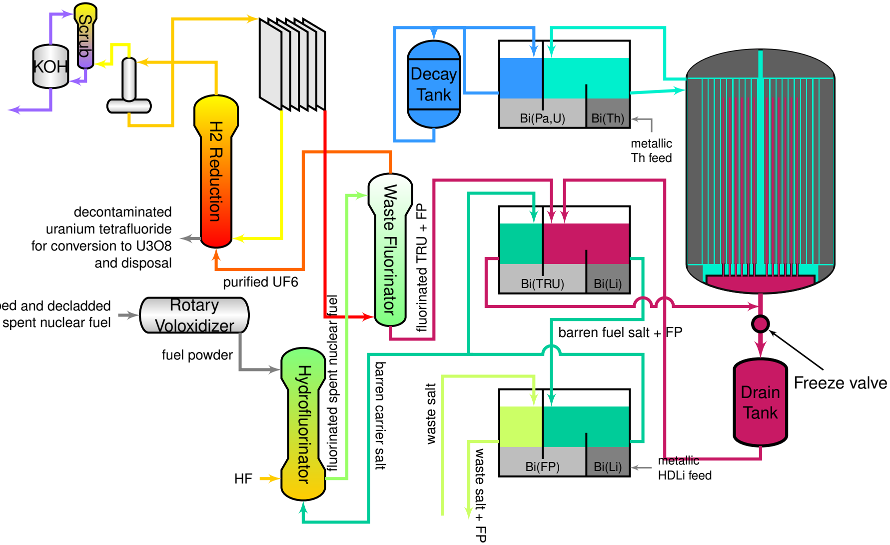
$$\begin{aligned} UF_4 + F_2 &\rightarrow UF_6 \\ NpF_4 + F_2 &\rightarrow NpF_6 \end{aligned}$$

Fluorination using NF3

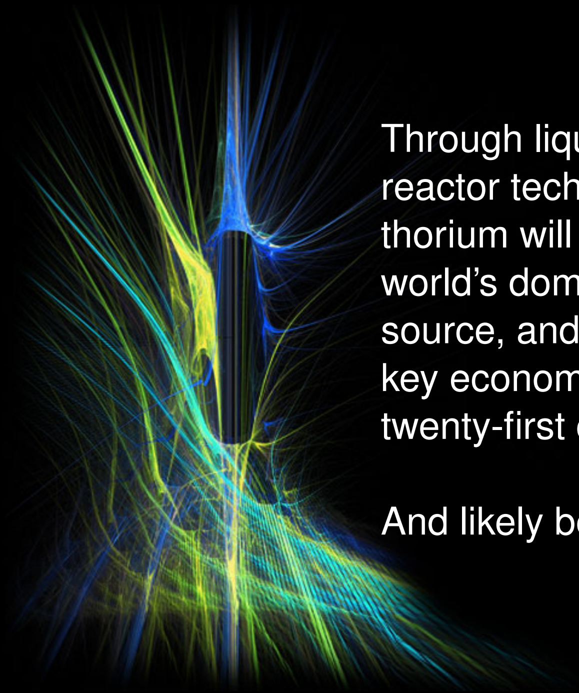
Alternatively, nitrogen trifluoride (NF3) might be used for fluorination instead of gaseous fluorine (F2). NF3 is much less aggressive towards container materials.

$$
\begin{aligned}
2UO_3 + 4NF_3 &\rightarrow 2UF_6 + 2N_2 + 3O_2 \\
3NpO_2 + 4NF_3 &\rightarrow 3NpF_4 + 2N_2 + 3O_2 \\
2Ln_2O_3 + 4NF_3 &\rightarrow 4LnF_3 + 2N_2 + 3O_2 \\
2MoO_3 + 4NF_3 &\rightarrow 2MoF_6 + 2N_2 + 3O_2
\end{aligned}
$$

LFLEUR chemical processing



Flibe Energy was formed in order to develop liquid-fluoride reactor technology and to supply the world with affordable and sustainable energy, water and fuel.



Through liquid-fluoride reactor technology, thorium will become the world's dominant energy source, and this will be the key economic driver of the twenty-first century.

And likely beyond.