The promise of thorium in meeting future world energy demand

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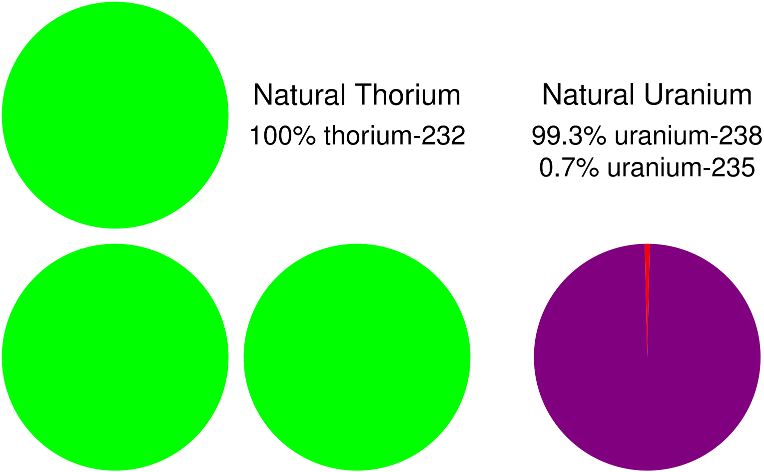
Dates and Discoveries

- Glenn Seaborg, UC Berkeley and University of Chicago
  - 1941: U-233 is formed from neutron absorption on thorium
  - 1942: U-233 is fissile with an appreciable cross-section
  - 1944: thorium can breed in a thermal-spectrum reactor
  - 1944: U-232 contamination renders U-233 worthless for practical weapons
- Oak Ridge National Laboratory
  - 1951, conception of molten-salt reactor
  - 1954, MSRs are chemically and operationally stable
  - 1956, thorium tetrafluoride is soluble in MSR
  - 1958, INOR-8 is a suitable alloy for fluoride salts in MSR
  - 1960, unclad graphite can be used in MSR
  - 1965, LiF-BeF2 salt suitable for MSRE
  - 1968, two-fluid design challenging (core design)
  - 1972, one-fluid design challenging (chem processing)

Technology Realizations

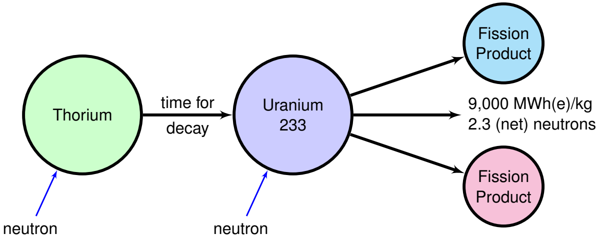
- Political mistakes and poor information led to MSR cancellation
- Key materials compatibility questions were answered to satisfaction in the operation of the MSRE
- MSR technology was unique in what it offered and has not been surpassed in the decades since by another class of reactor technology
- Safety was important at the time of MSR cancellation and has only grown in significance
- The public will never accept a nuclear technology in the long term that does not have a strong and defensible safety basis, in other words, engineered safety features are not sufficient for public acceptance
- MSR offers the best confluence of safety, performance, and technological readiness of any reactor technology known

Possible Nuclear Fuels

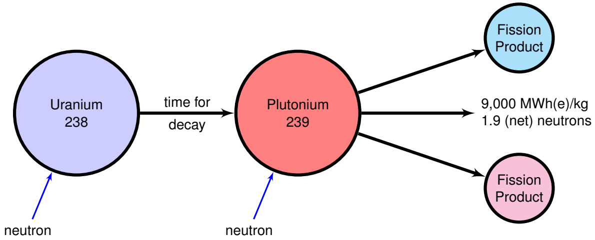


Only a small fraction of natural uranium is fissile. Most uranium and all thorium is "fertile" and can be converted to fissile material through neutron absorption.

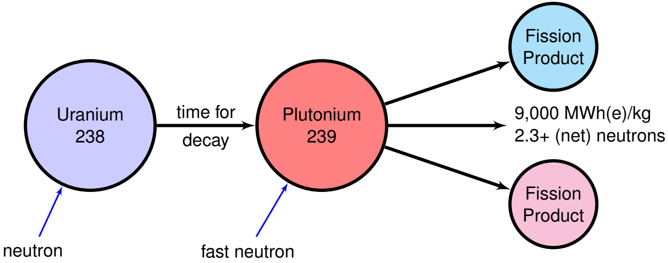
Nuclear Conversion Reactions



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.

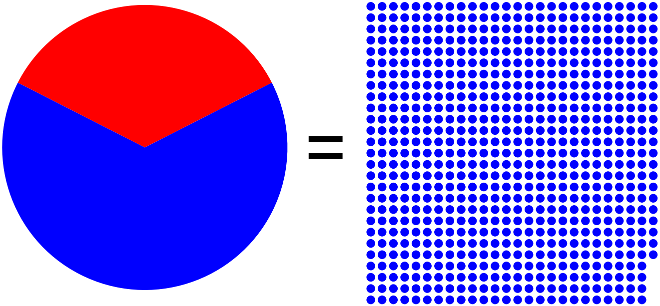


Nuclear Conversion Reactions



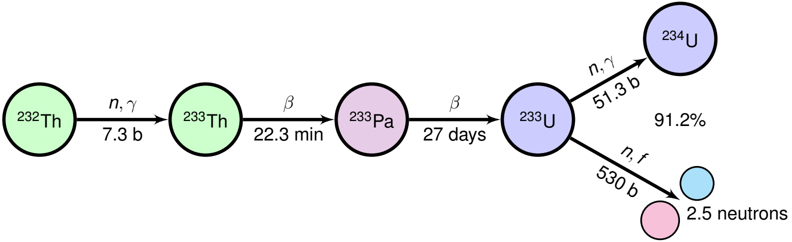
Using fast neutrons improves the performance of the uranium fuel cycle sufficiently to allow sustained further conversion and fission reactions. This has been the basis of global interest in fast-spectrum reactors for nearly 70 years.

Thermal vs. fast neutron cross-sections



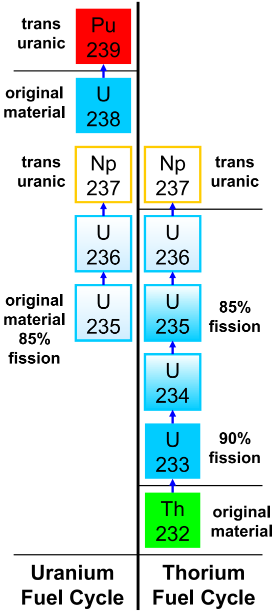
Uranium can be a sustainable fuel in a fast reactor, but using fast neutrons comes at a substantial price. Neutron cross-sections are much smaller for fast neutrons than for thermal (slowed-down) neutrons. To a thermal neutron, one atom of plutonium-239 is the equivalent of nearly 700 atoms of plutonium-239 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.**

Thorium enables an efficient thermal-spectrum reactor

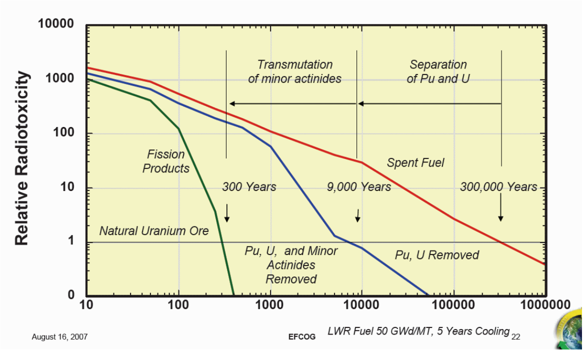


The central advantage of thorium as a nuclear fuel is its unique ability to be sustainably consumed in a thermal-spectrum reactor, maximizing the production of energy while minimizing the production of wastes.

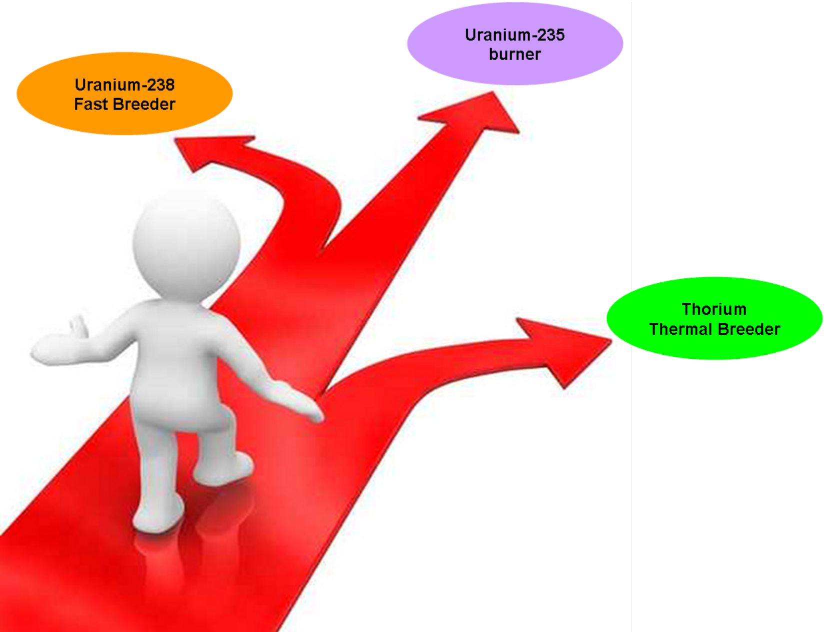
Reducing Long-Lived Waste



- Today's approach to nuclear energy consumes only a small amount of the energy content of uranium while producing "transuranic" nuclides that complicate long-term waste disposal.
- Using thorium/U-233 in a liquid-fueled reactor can more nearly approach the ideal of a fission-product-only waste stream that reaches the same radioactivity as uranium ore in 300 years.



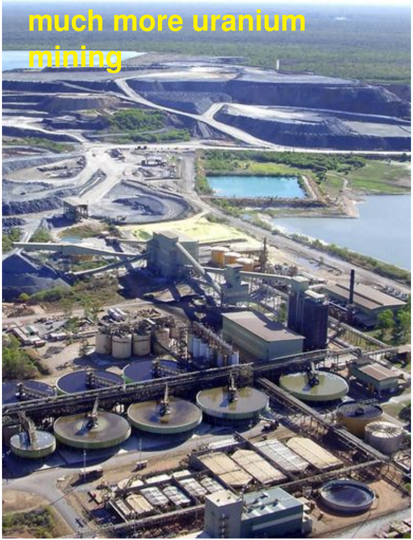
Three Nuclear Options



Three fuel options viewed through MSR technology

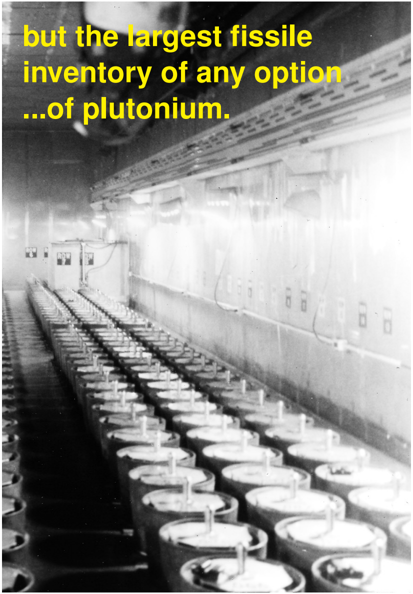
- Assume a molten-salt reactor in each case:
- Option 1: LEU-fueled MSR:
  - Uranium mining and enrichment comparable to current LWR
  - Challenge to add ^{235}U and discard ^{238}U while retaining plutonium and other TRU
- Option 2: ^{238}U-fueled fast-spectrum MSR:
  - No uranium mining or enrichment necessary in steady state
  - Highest fissile inventory (^{239}Pu)
  - Chemical separation of fissile plutonium from fertile uranium in fluoride media appears challenging (chloride still another unknown)
- Option 3: ^{232}Th-fueled thermal-spectrum MSR:
  - No uranium mining or enrichment necessary in steady state
  - Lowest fissile inventory (^{233}U)
  - Chemical separation of fissile uranium from fertile thorium straightforward in fluoride media
- In each case, waste profile very strongly dependent on chemical processing efficiency

A world fueled by LEU MSR will require...



A world fueled by uranium MSR will require...

- fast-spectrum reactors
- no uranium mining
  - (for the foreseeable future due to depleted uranium inventories)
- no uranium enrichment
- efficient chemical processing
- fissile recovery from spent fuel, and
- significant breeding ratio



A world fueled by thorium MSR will require...

- thermal-spectrum reactors
- no uranium mining
- no uranium enrichment
- no thorium mining
  - (for the foreseeable future due to thorium recovered from rare-earth mining operations)
- efficient chemical processing
- fissile recovery from spent fuel converted to ^{233}U in modified LFTRs

Choose your fissile "currency" wisely

- Ultimately, in a world powered predominantly by nuclear fission, the choice will have to be made as to where the majority of the nuclear fuel originates:
  1. ^{235}U from natural uranium via enrichment
  2. plutonium bred from natural uranium in a fast-breeder
  3. ^{233}U bred from thorium in a thermal-breeder
- the first path was been weaponized and continues to pose international concern (Iran)
- a variation of the second path was weaponized (production reactors) and continues to pose international concern (North Korea)
- the third path was not weaponized (unavoidable ^{232}U contamination) and would not be weaponized
  - by a nation-state (simpler alternatives)
  - by a subnational group (design and testing necessary)

Plutonium or thorium?

- Whether thermal-spectrum LEU or fast-spectrum plutonium is the fuel, plutonium will be produced, used, and likely disposed.
- Plutonium cannot be isotopically diluted like uranium
- Only thermal-spectrum thorium/U233 avoids plutonium production
- Which poses the greater threat in the long term, plutonium or U-233?
- It can be debated, but there are good reasons why U-233 represents the safer option, and why it was never used in production weapons (and only a handful of experiments)

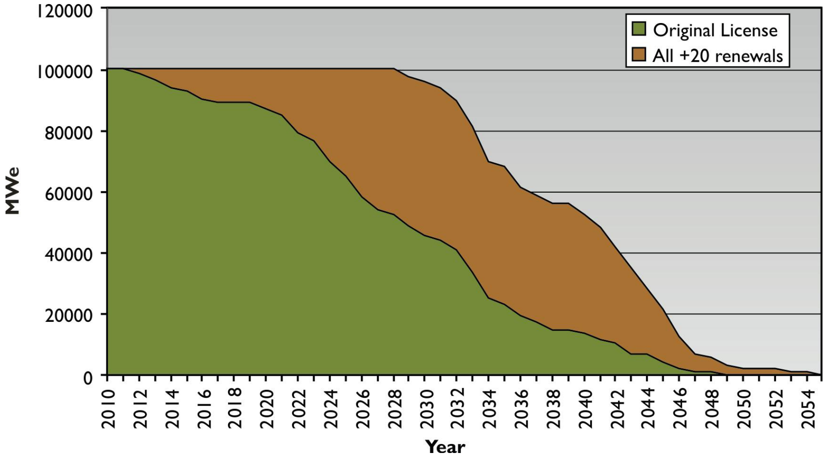
Section 1

Liquid-Fluoride Thorium Reactor (LFTR) Technology Option

Technology Realizations

- Although molten-salt reactors were studied for decades at ORNL, the detailed consideration of molten-salt "breeder" reactors (those that would implement the thorium fuel cycle) was confined to a relatively short period:
  - 1965-1971, with reference design concluded by February 1969; MSRP program director Murray Rosenthal: "we were trying to show technical feasibility"
- Optimism about chemical processing techniques (particularly reductive extraction) led to reactor simplifications at the expense of processing complexity
  - A more complex reactor (two-fluid design) offered better safety, performance, and chemical processing simplification than a one-fluid reactor (reference design)
- Since 2004, I have worked to develop a two-fluid molten-salt reactor design that addresses the concerns that led to its cancellation in late 1967

The US Nuclear Retirement "Cliff"

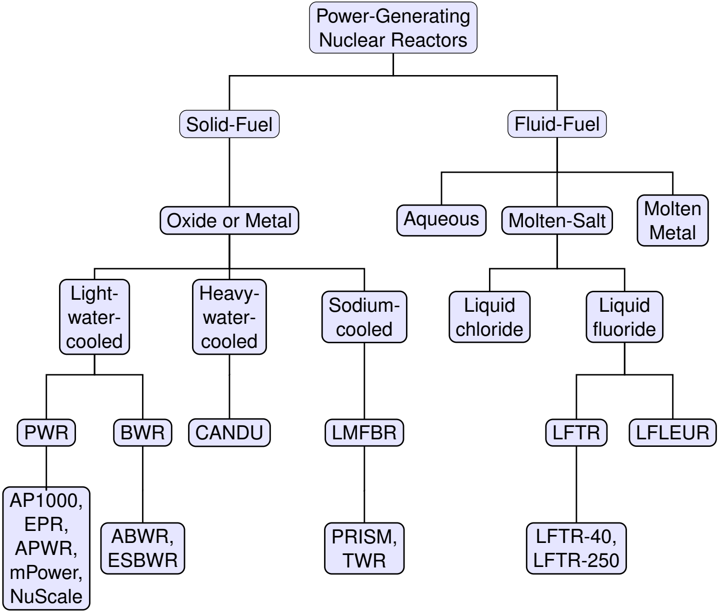


The challenge will soon grow much worse.

Media Diagnostic Error

It is commonly believed that nuclear energy is a failed technology. This is not true. Nuclear energy is the best hope for humanity's future. But for this to happen, better nuclear technology must be developed and deployed.

Nuclear Reactor Families

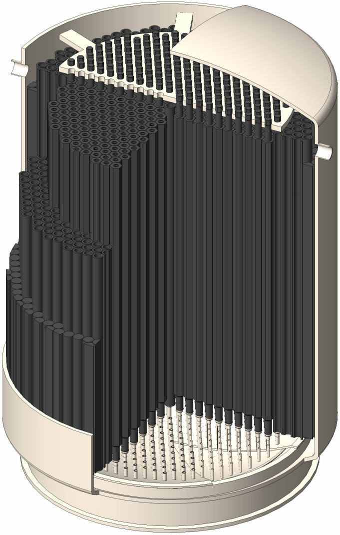



We believe in the vision of a sustainable, prosperous future enabled by liquid-fluoride reactors producing electricity and desalinated water.

Flibe ENERGY

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.

Modular LFTR design parameters



Materials and fluids:

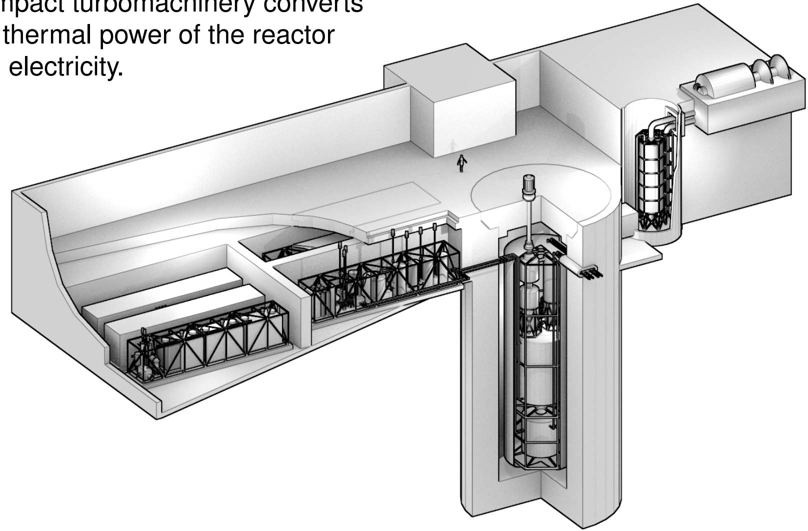
- HDLiF-BeF_2-UF_4 fuel salt
- HDLiF-BeF_2-ThF_4 blanket salt
- HDLiF-BeF_2 coolant salt
- Graphite moderator and reflector
- Hastelloy-N reactor vessel and piping

Design objectives:

- 250 MWe / 600 MWt modular core
- conversion ratio $\geq$ 1.0
- design life to be determined
- fuel salt separated from blanket by graphite tubes
- graphite reflector and thorium blanket shield reactor vessel from neutron flux

250 MWe LFTR facility concept

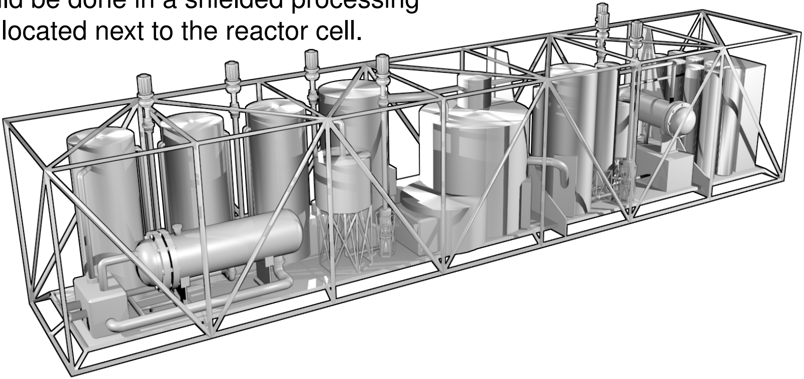
Compact turbomachinery converts the thermal power of the reactor into electricity.



The reactor cell is located below ground in a shielded containment structure.

LFTR chemical processing concept

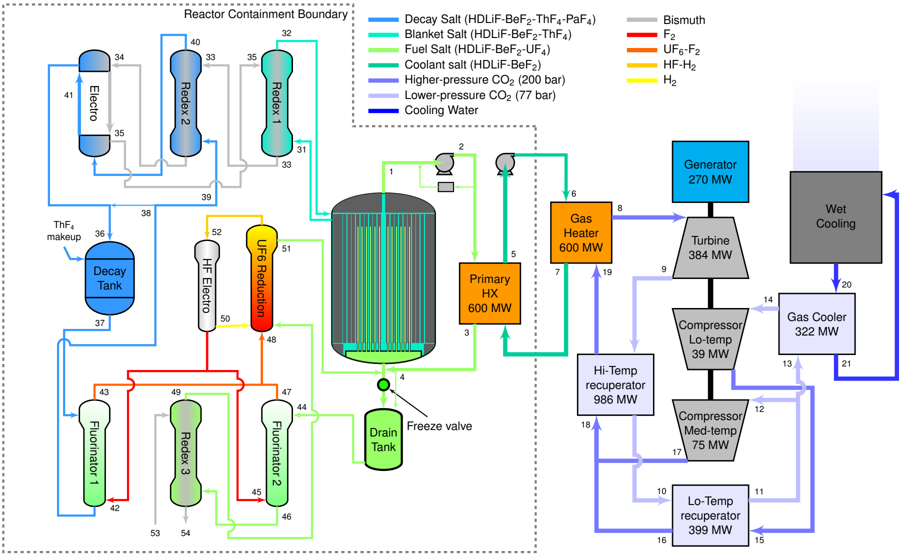
Chemical processing of the fluoride salts would be done in a shielded processing cell located next to the reactor cell.



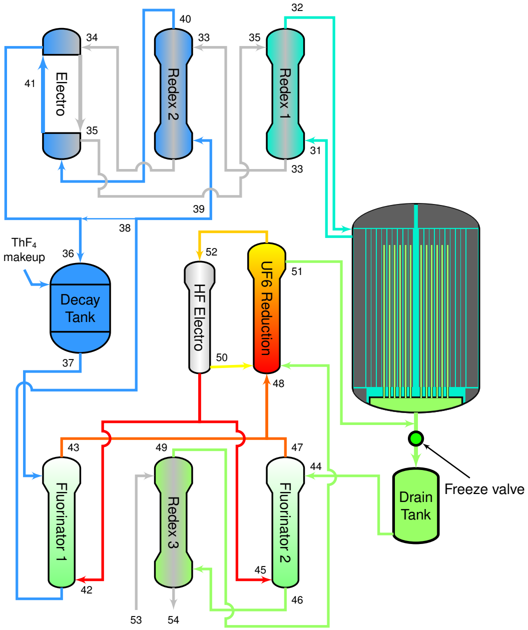
LFTR chem processing objectives

1. Reductive extraction of metals from a salt into metallic bismuth, using a dissolved metal in the bismuth as the reduction agent.
2. Fluorination of salt using fluorine gas to remove materials that form gaseous hexafluoride compounds, most notably uranium.
3. Reduction of gaseous hexafluoride compounds, most notably uranium, using hydrogen gas in the presence of salt.
4. Electrolytic cells that reduce salt compounds to metals and free fluorides, using bismuth as both anode and cathode of these cells.
5. Electrolytic cells that reduce hydrogen fluoride to hydrogen gas and fluorine gas.

LFTR 250 MWe overall processing flow diagram



LFTR chemical processing flow diagram



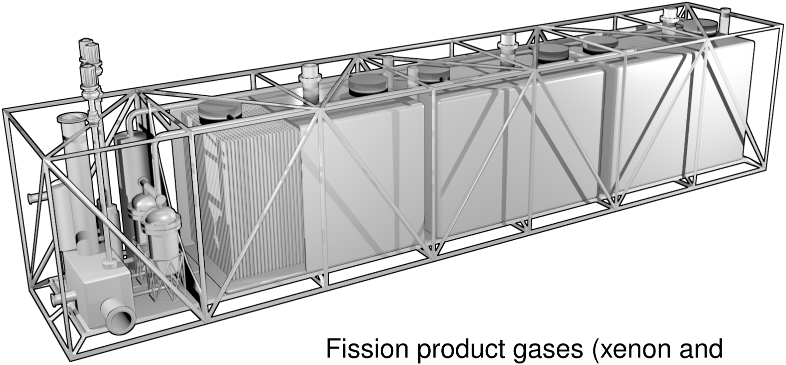
250 MWe LFTR chemical processing fluid properties

idx	Fluid	Temp (°C)	Press (bar)	Density (kg/m^3)	Flow Rates mass (g/s)	molar (mol/s)	volume (cc/s)	Concentrations Li (ppm)	Th (ppm)	Pa (ppm)	U (ppm)
31.	HDLiF-BeF2-ThF4	600.0	1.0	4475.6	378.27	3.6876	84.519	71.0%	27.0%	15.0	1.9
32.	HDLiF-BeF2-ThF4	605.0	1.0	4471.7	378.27	3.6876	84.593	71.0%	27.0%	5.8	0.7
33.	Bismuth	640.0	1.0	9585.7	24.305	0.1163	2.5356	3689.	2670.	293.4	36.7
34.	Bismuth	640.0	1.0	9585.7	24.305	0.1163	2.5356	3689.	2657.	306.2	36.8
35.	Bismuth	640.0	1.0	9585.7	24.305	0.1163	2.5356	3689.	3000.	0.5	-
36.	HDLiF-BeF2-ThF4-PaF4	550.0	1.0	4680.9	0.4104	0.0040	0.0877	67.9%	29.1%	8901.	1068.
37.	HDLiF-BeF2-ThF4-PaF4	550.0	1.0	4684.4	0.4104	0.0040	0.0876	67.9%	29.1%	382.3	9587.
38.	HDLiF-BeF2-ThF4-PaF4	550.0	1.0	4520.2	0.0	0.0	0.0	-	-	-	-
39.	HDLiF-BeF2-ThF4-PaF4	550.0	1.0	4644.6	0.4064	0.0040	0.0875	68.6%	29.4%	386.0	2.2
40.	HDLiF-BeF2-ThF4-PaF4	550.0	1.0	4644.6	0.4064	0.0040	0.0875	68.6%	29.4%	14.5	-
41.	HDLiF-BeF2-ThF4-PaF4	550.0	1.0	4520.2	0.3306	0.0032	0.0731	71.0%	-	0.0	-
42.	F_2	550.0	2.0	1.1095	0.0022	0.0001	1.9701	-	-	-	-
43.	UF_6-F_2	550.0	2.0	7.1289	0.0140	0.0001	0.0140	-	-	-	66.7%
44.	HDLiF-BeF2-UF4	550.0	1.0	1987.8	0.8328	0.0251	0.4189	68.5%	-	-	2000.
45.	F_2	550.0	2.0	1.1095	0.0029	0.0001	2.5810	-	-	-	-
46.	LiF-BeF2-(FP)Fx	550.0	1.0	1987.8	0.8327	0.0251	0.4189	68.5%	-	-	2.2
47.	UF_6-F_2	550.0	2.0	7.1237	0.0184	0.0001	0.0184	-	-	-	66.6%
48.	UF_6-F_2	550.0	2.0	7.1237	0.0324	0.0001	4.5472	-	-	-	66.6%
49.	LiF-BeF2 (68.5-31.5)	600.0	1.0	1987.8	0.8327	0.0251	0.4189	68.5%	-	-	-
50.	H_2	550.0	2.0	0.0589	0.0004	0.0002	6.7703	-	-	-	-
51.	HDLiF-BeF2-UF4	600.0	1.0	1970.5	0.8327	0.0251	0.4226	68.5%	-	-	3518.
52.	HF-H_2	550.0	2.0	1.1461	0.0130	0.0003	0.0130	-	-	-	-
53.	Bismuth	640.0	1.0	9585.7	0.0321	0.0002	0.0034	-	-	-	-
54.	Bismuth	640.0	1.0	9585.7	0.0321	0.0002	0.0034	-	-	-	-

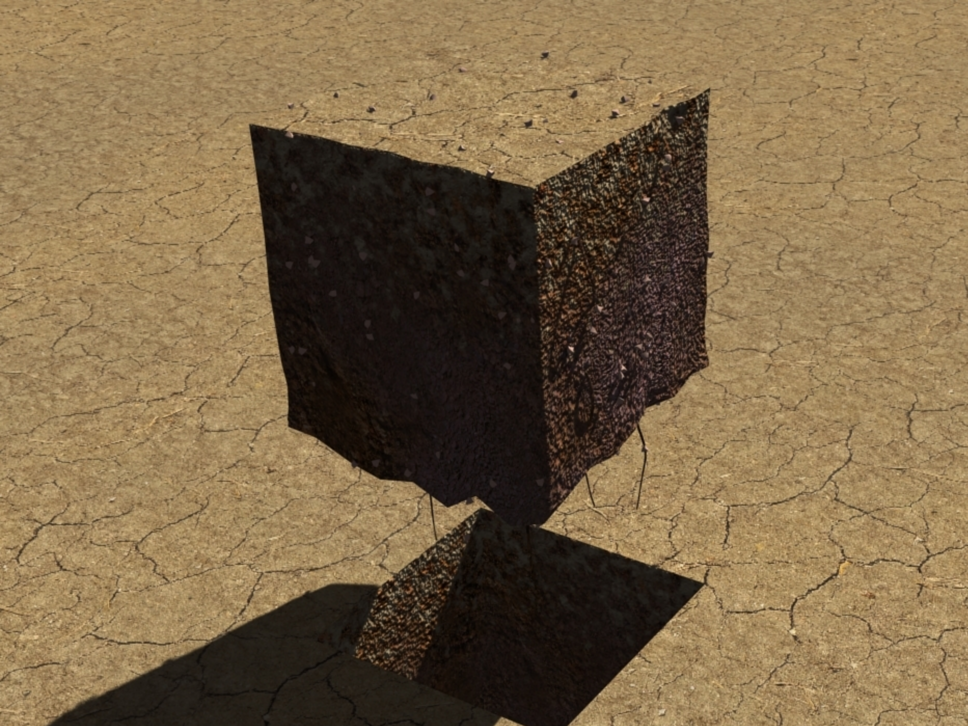
LFTR chem processing objectives

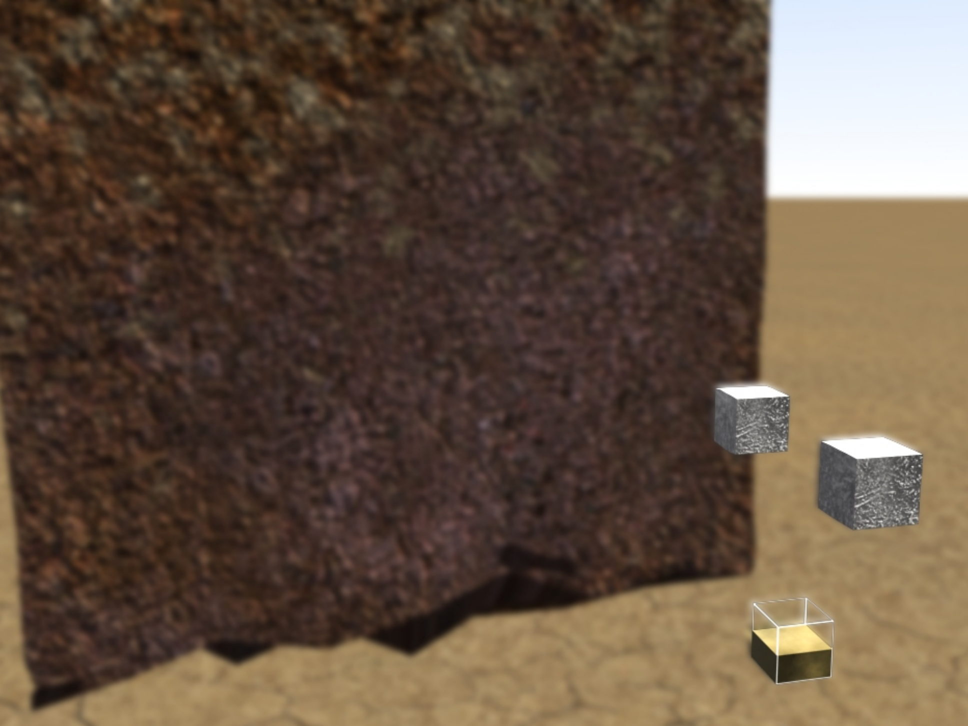
1. Three reductive extraction columns
   - extract protactinium and any uranium from blanket salt
   - extract protactinium and any uranium from decay salt
   - extract fission products from fuel salt
2. Two fluorinators
   - extract uranium from decay salt (as UF_6)
   - extract uranium from fuel salt (as UF_6)
3. One hydrogen reduction column
   - add uranium to fuel salt (as UF_4)
4. Two electrolytic cells
   - electrolyze decay salt to generate metallic reductants
   - electrolyze HF to generate hydrogen and fluorine

LFTR offgas handling concept

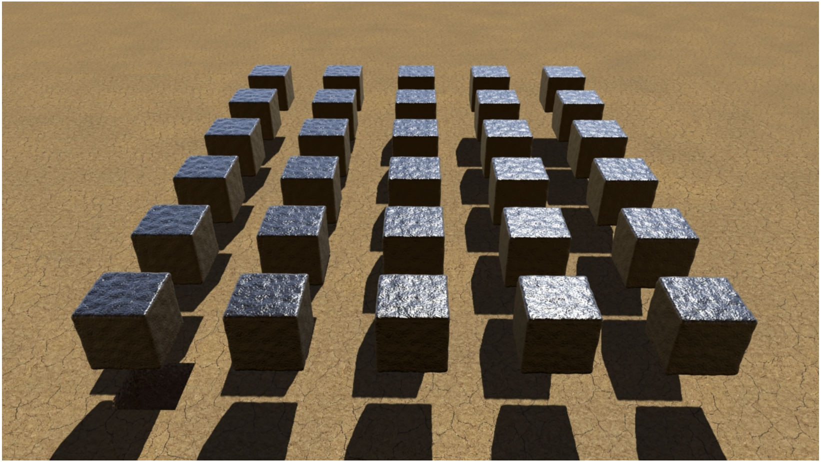


Fission product gases (xenon and krypton) would be held up until they decayed to stable isotopes in a shielded cell close to the reactor cell.





The Energy Value of Thorium in a m^3 of dirt



If the small amount of thorium in a cubic meter of average "dirt" were converted to U-233 and fissioned, the value of the electricity that could be produced would be worth more than 30 cubic meters of light sweet crude oil!

Near-term technology challenges

- ASME code-qualification of Hastelloy-N
- better noble gas removal system than MSRE used
- better pump designs
- better heat exchanger designs
- development of fluorination and H2 reduction colums
- lithium isotope separation / tritium capture
- preservation of existing U-233 inventory
- more investigation of fuel cycle safeguards

Medium-term technology challenges

- power conversion system development
- development of reductive extraction system
- development of hydrofluorination columns
- increasing U-233 inventory
- development of hydrogen generation system
- development of integrated desalination cooling system

Longer-term technology challenges

- development of materials lifetime database
- plutonium burning in MSRs for waste reduction and U233 generation
- mobile MSRs for remote sites and cargo ships

Summary

- Only thorium MSR permits the generation of nuclear power without plutonium
- In the 43 years since 1972, the potential of MSR has not diminished, but we are faced with the consequences of our inaction
    - Technology does not advance on its own!
    - Need to restart technology development
    - Solutions to technological challenges exist but must be pursued through real research, and real research requires funding
- My personal confidence is high that we will find acceptable solutions to the residual challenges of MSR technology and will be able to realize its incredible advantages