Thorium-based Nuclear Power:
The Road to Green, Sustainable Nuclear Power

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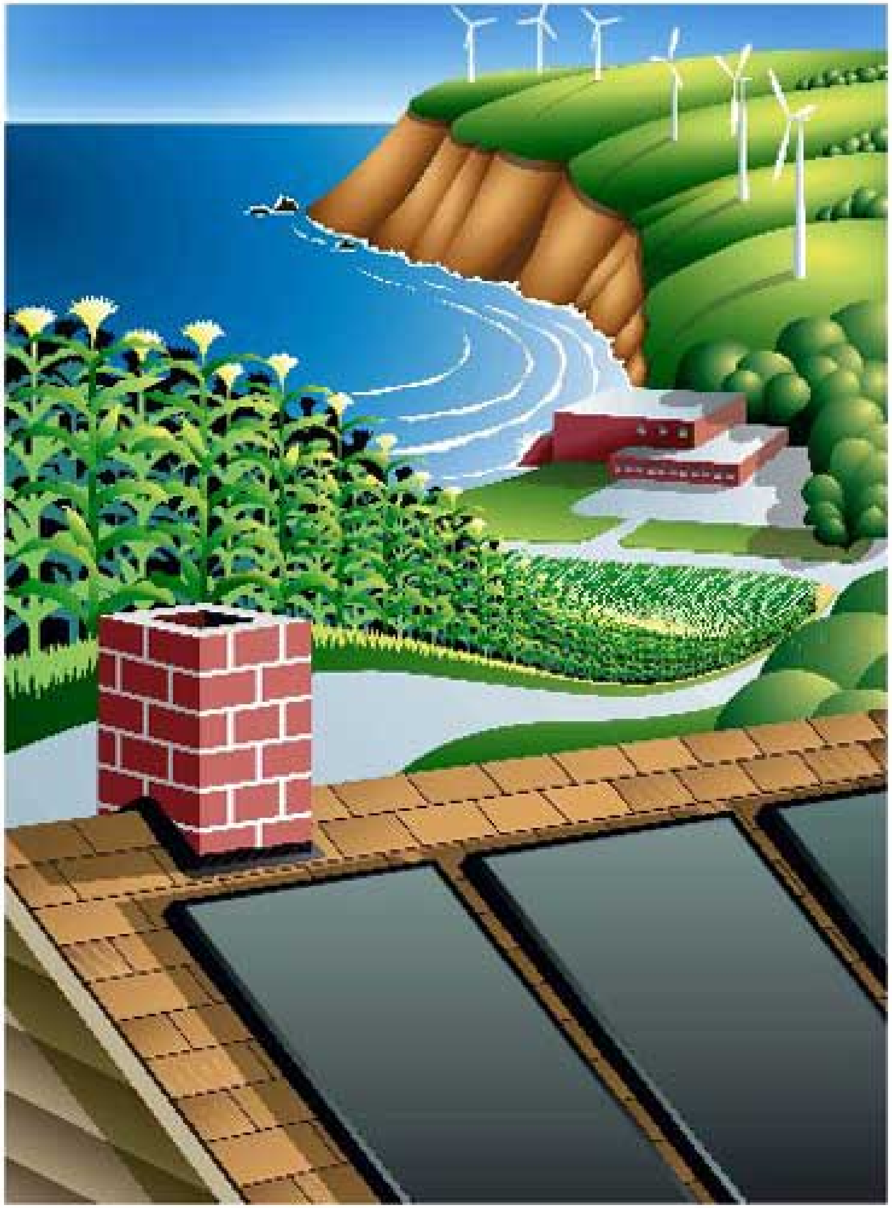
Friday, July 25, 2007

What does it mean to be “green”?

- **Minimal impact to the environment**
  - Material inputs
  - Material outputs
  - Waste amount and toxicity
- **Sustainability of the technology**
  - Resource depletion rate
- **Social and political acceptability?**

How do we imagine “green” energy?

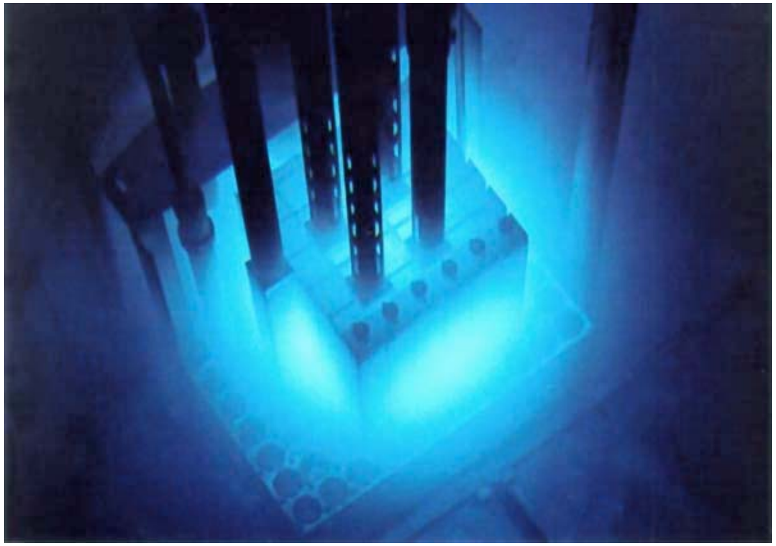


Who's "green" now?

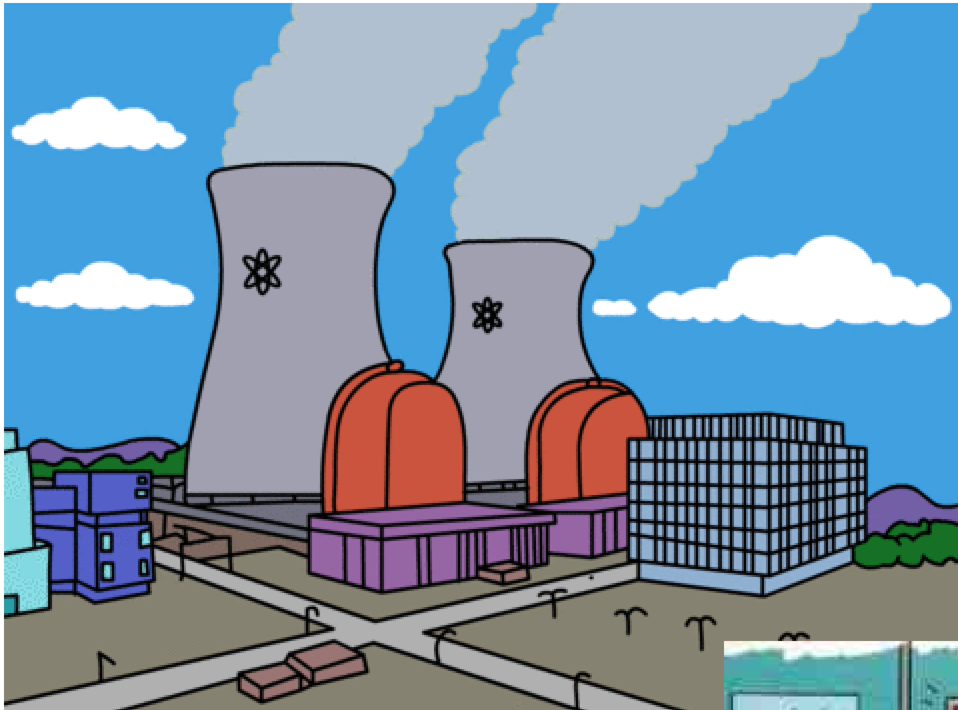
- **Solar and wind energy are generally considered "green", but are they capable of shouldering the requirements of powering the planet?**
  - They are diffuse and intermittent energy sources.
  - They require large amounts of land and large resource requirements per megawatt of generation capability.
  - To overcome intermittency, vast amounts of inexpensive energy storage will be required.

- **What about nuclear energy? Why is nuclear energy generally not considered "green"?**
  - Concern about nuclear waste
  - Concern about nuclear security (terrorism, dirty bombs, proliferation)
  - Concern about nuclear safety (meltdown, radiation release).
  - Concern about cooling water supplies for nuclear reactors
  - Concern about the fuel requirements (uranium) of nuclear reactors

How do we imagine nuclear energy?



Or maybe like this?



Can Nuclear Power be "Green"?

- **Yes!**
  - Long-term nuclear waste generation can be essentially eliminated.
  - Nuclear reactors can be made INHERENTLY safe against large radiation release (no meltdown).
  - Nuclear proliferation can be addressed.
  - Nuclear power can be distributed and decentralized to a much greater degree than is done today.
  - Large reductions in construction and operation costs can be realized.
  - Cooling water requirements can be reduced and even eliminated.
- **But…this is not going to happen with the currently existing type of nuclear reactors.**
- **It will require a new nuclear fuel, a new nuclear design, and a new approach to nuclear safety.**

How can we do this?

- **How can we get rid of nuclear waste?**
  - Burn our fuel up completely.
  - Destroy the waste already created.
- **How can we improve safety?**
  - Design reactors with INHERENT safety rather than engineered safety.
- **How can we address proliferation?**
  - Use nuclear fuel that is unsuitable for nuclear weapons.
- **How can we reduce fuel and mining requirements?**
  - Use a more abundant nuclear fuel (thorium) and use it all.
- **How can we reduce cooling water requirements?**
  - Use high-temperature reactors and power conversion cycles that can be effectively air-cooled.
- **How can we build reactors cheaper?**
  - Use reactors whose core operate at ambient pressure to reduce the size of the vessel.
  - No pressurized water that can evolve to steam in an accident.
  - Use compact gas turbines instead of steam cycles for power conversion

Reducing Waste

Waste generation from 1000 MW*yr uranium-fueled light-water reactor

Mining 800,000 MT of ore containing 0.2% uranium (260 MT U)

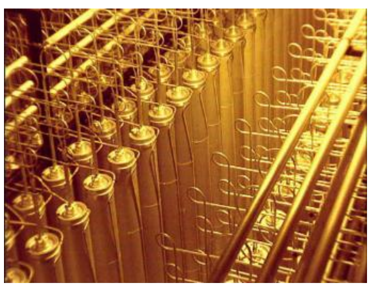
Generates ~600,000 MT of waste rock

Milling and processing to yellowcake—natural U_3O_8 (248 MT U)

Generates 130,000 MT of mill tailings

Conversion to natural UF_6 (247 MT U)

Generates 170 MT of solid waste and 1600 m^3 of liquid waste



Enrichment of 52 MT of (3.2%) UF_6 (35 MT U)

Generates 314 MT of depleted uranium hexafluoride (DU); consumes 300 GW*hr of electricity

Fabrication of 39 MT of enriched (3.2%) UO_2 (35 MT U)

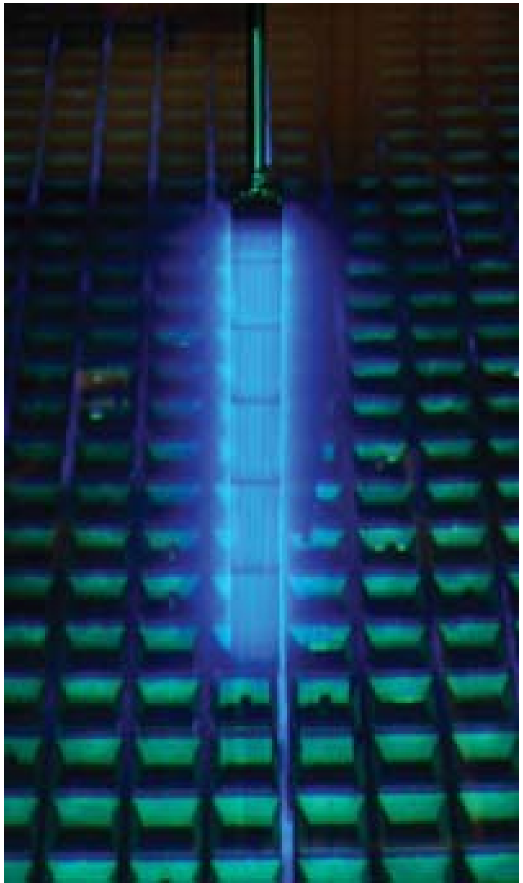
Generates 17 m^3 of solid waste and 310 m^3 of liquid waste

Irradiation and disposal of 39 MT of spent fuel consisting of unburned uranium, transuranics, and fission products.

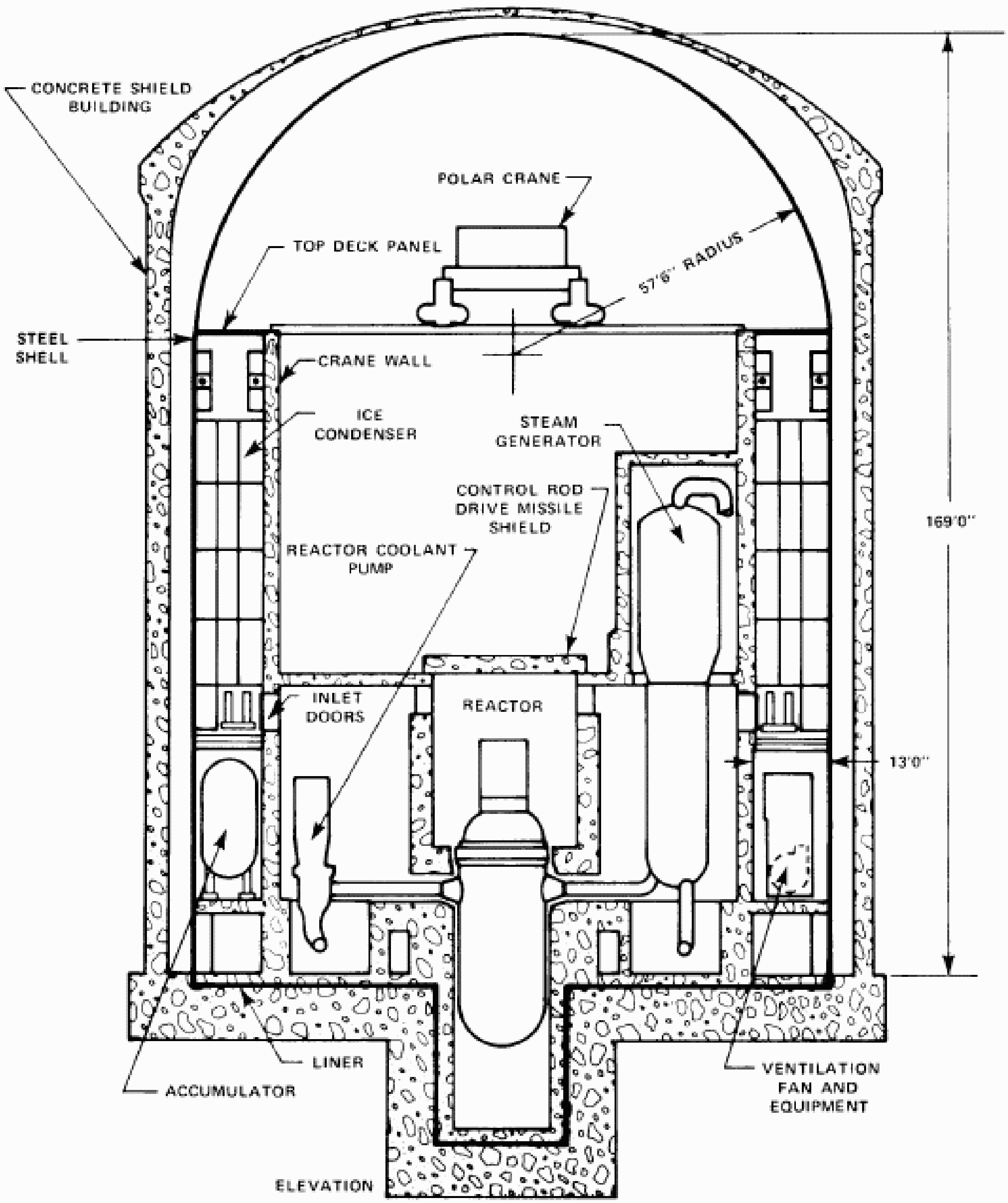
Uranium fuel cycle calculations done using WISE nuclear fuel material calculator: http://www.wise-uranium.org/nfcm.html

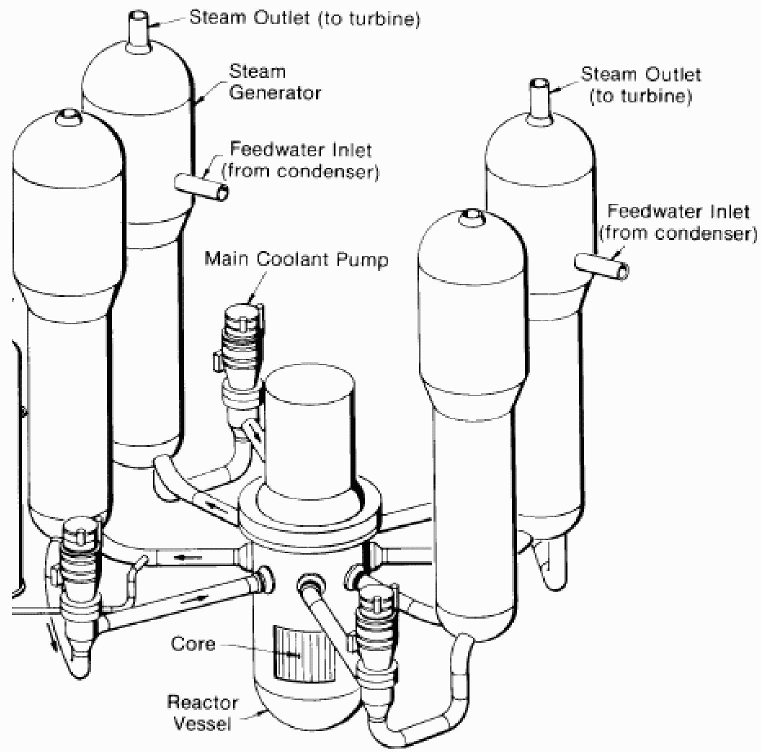
Lifetime of a Typical Uranium Fuel Element

- Conventional fuel elements are fabricated from uranium pellets and formed into fuel assemblies
- They are then irradiated in a nuclear reactor, where most of the U-235 content of the fuel "burns" out and releases energy.
- Finally, they are placed in a spent fuel cooling pond where decay heat from radioactive fission products is removed by circulating water.

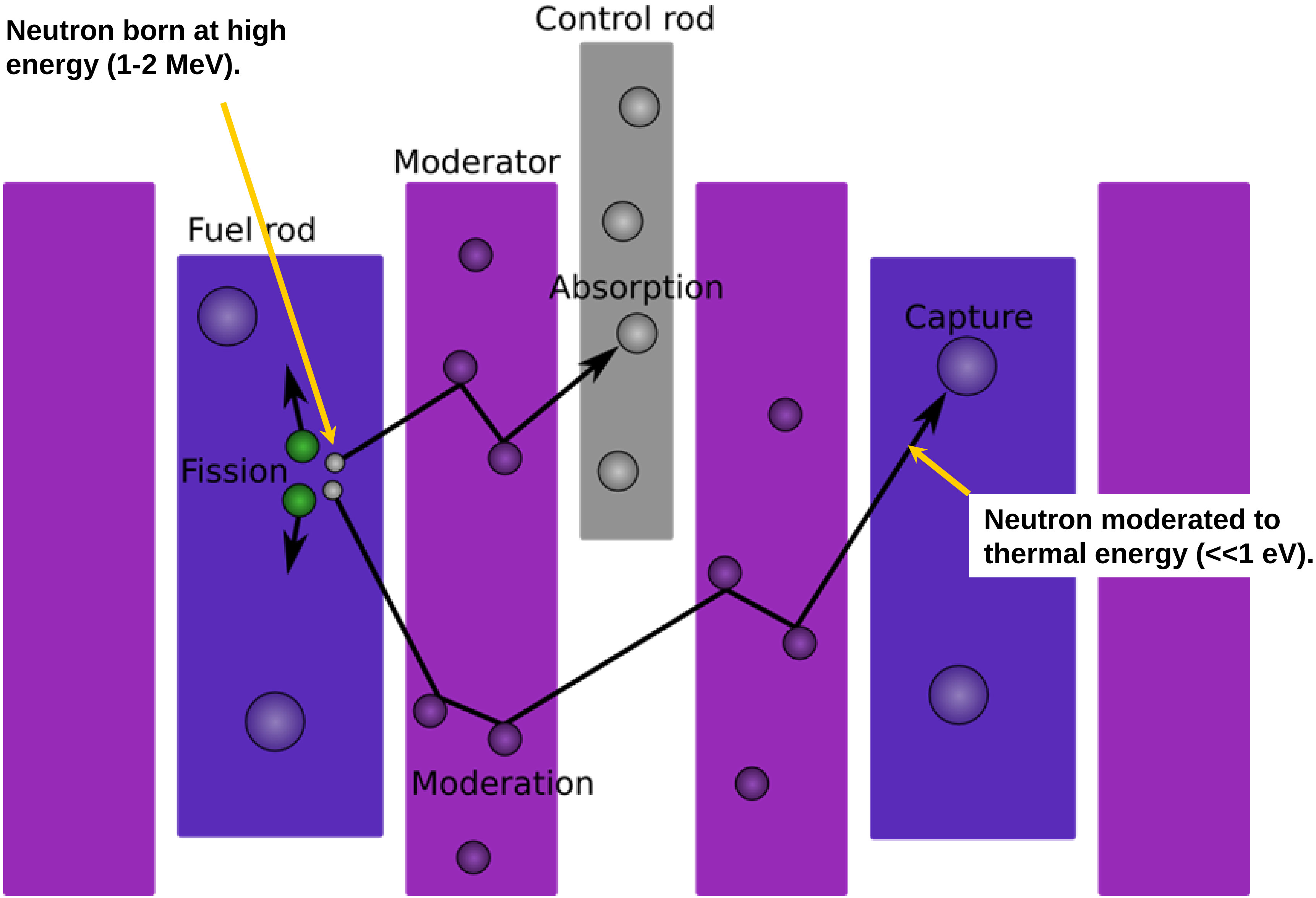


A Pressurized-Water Reactor





Neutrons are moderated through collisions



The Current Plan is to Dispose Fuel in Yucca Mountain

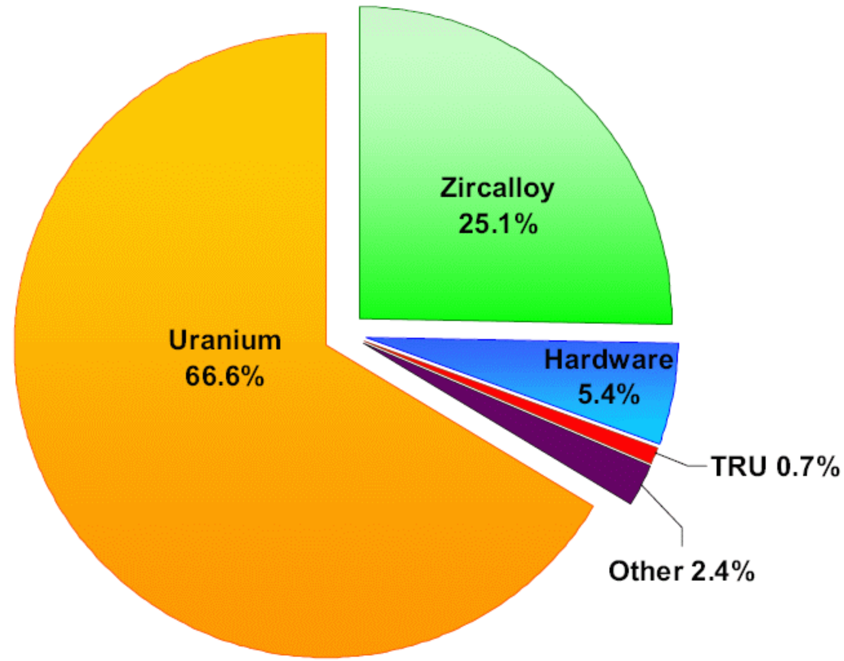
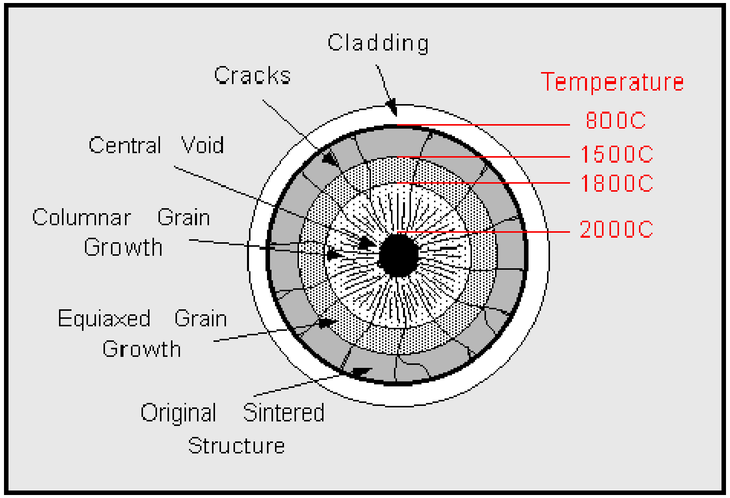


Fig. 1 Average composition of U.S. spent fuel (1968 to 2002).

Radiation Damage Limits Energy Release

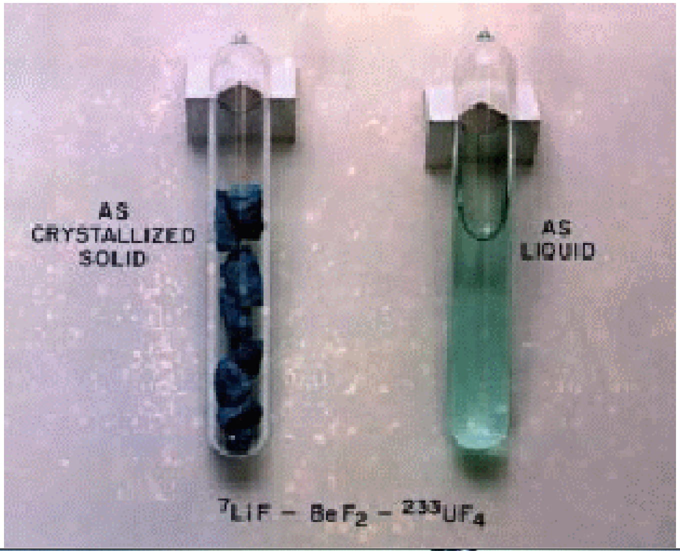
- **Does a typical nuclear reactor extract that much energy from its nuclear fuel?**
  - No, the "burnup" of the fuel is limited by damage to the fuel itself.
- **Typically, the reactor will only be able to extract a portion of the energy from the fuel before radiation damage to the fuel itself becomes too extreme.**
- **Radiation damage is caused by:**
  - Noble gas (krypton, xenon) buildup
  - Disturbance to the fuel lattice caused by fission fragments and neutron flux
- **As the fuel swells and distorts, it can cause the cladding around the fuel to rupture and release fission products into the coolant.**

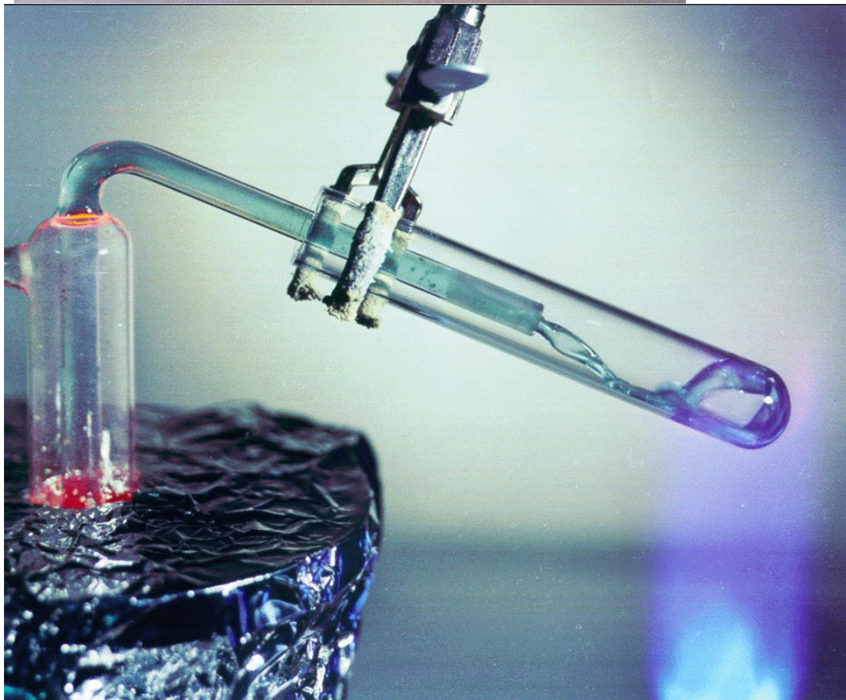


Ionically-bonded fluids are impervious to radiation

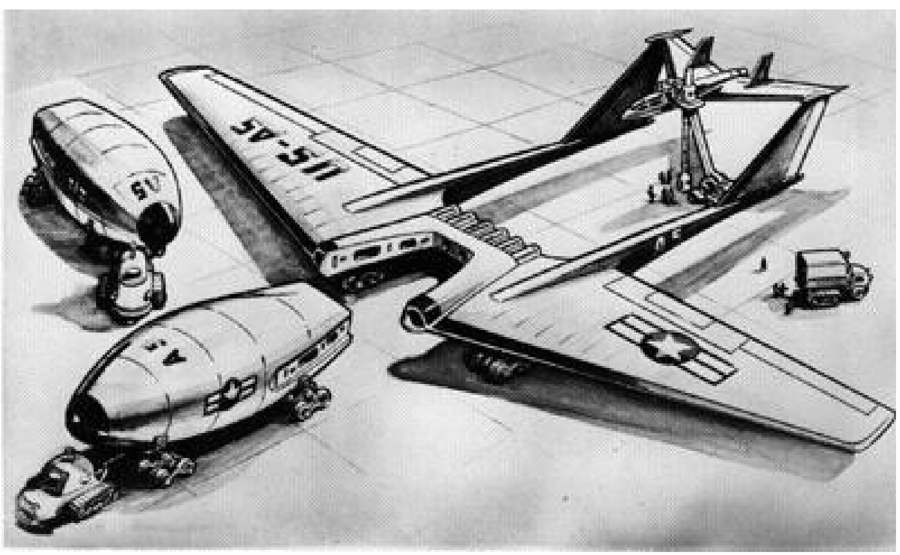
- The basic problem in nuclear fuel is that it is covalently bonded and in a solid form.

- If the fuel were a fluid salt, its ionic bonds would be impervious to radiation damage and the fluid form would allow easy extraction of fission product gases, thus permitting unlimited burnup.





Aircraft Nuclear Program

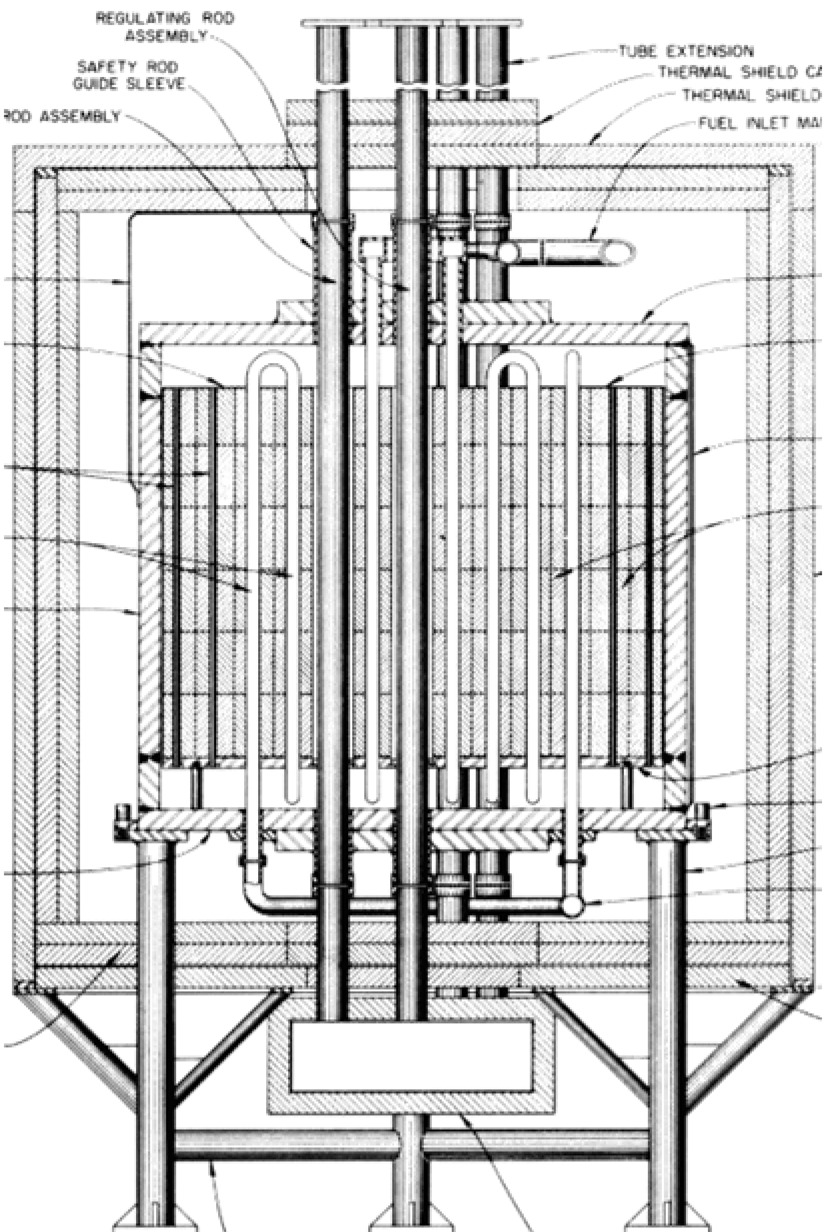


Between 1946 and 1961, the USAF sought to develop a long-range bomber based on nuclear power.

The Aircraft Nuclear Program had unique requirements, some very similar to a space reactor.

- High temperature operation (>1500° F)
  - **Critical for turbojet efficiency**
  - **3X higher than sub reactors**
- Lightweight design
  - **Compact core for minimal shielding**
  - **Low-pressure operation**
- Ease of operability
  - **Inherent safety and control**
  - **Easily removeable**

The Aircraft Reactor Experiment (ARE)



In order to test the liquid-fluoride reactor concept, a solid-core, sodium-cooled reactor was hastily converted into a proof-of-concept liquid-fluoride reactor.

The Aircraft Reactor Experiment ran for 100 hours at the highest temperatures ever achieved by a nuclear reactor (1150 K).

- Operated from 11/03/54 to 11/12/54
- Molten salt circulated through beryllium reflector in Inconel tubes
- $^{235}UF_4$ dissolved in $NaF\text{-}ZrF_4$
- Produced 2.5 MW of thermal power
- Gaseous fission products were removed naturally through pumping action
- Very stable operation due to high negative reactivity coefficient
- Demonstrated load-following operation without control rods

Molten Salt Reactor Experiment (1965-1969)

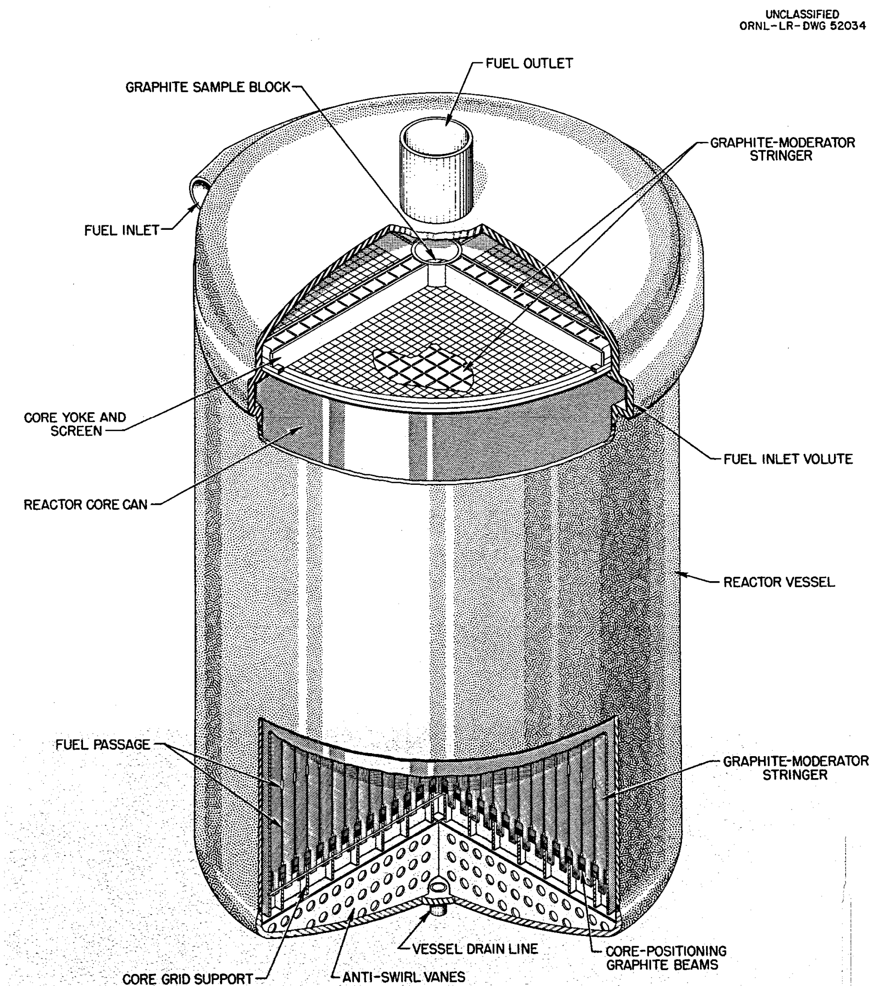
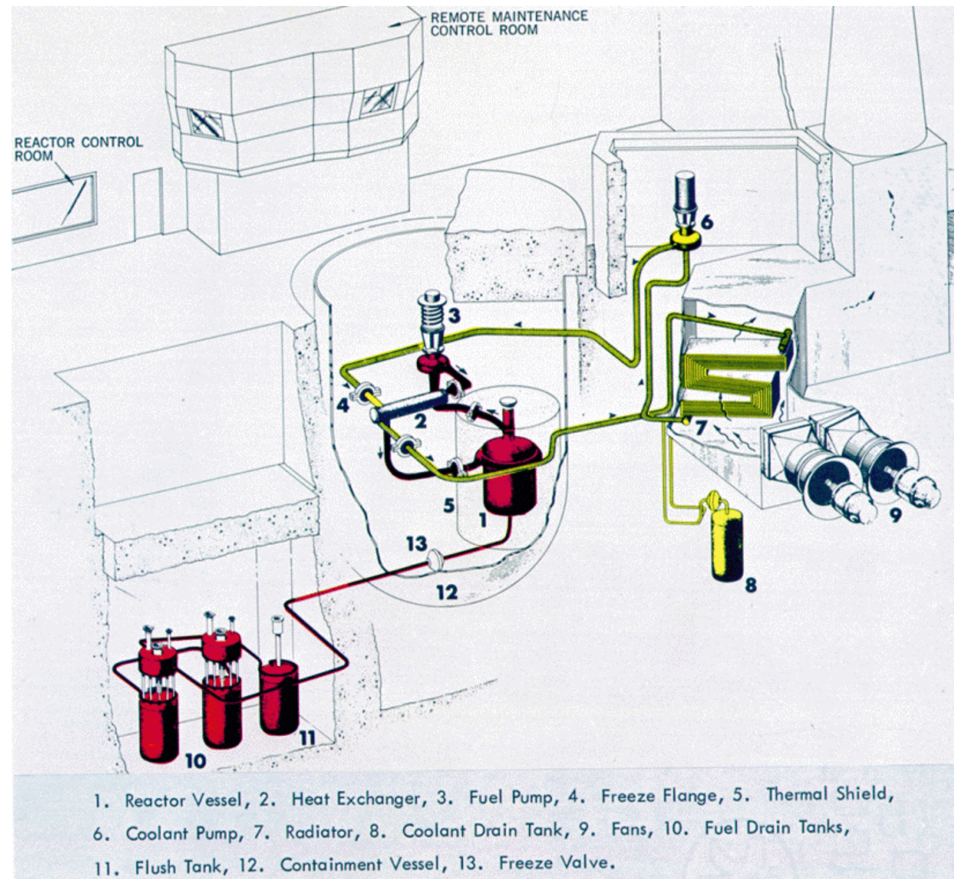
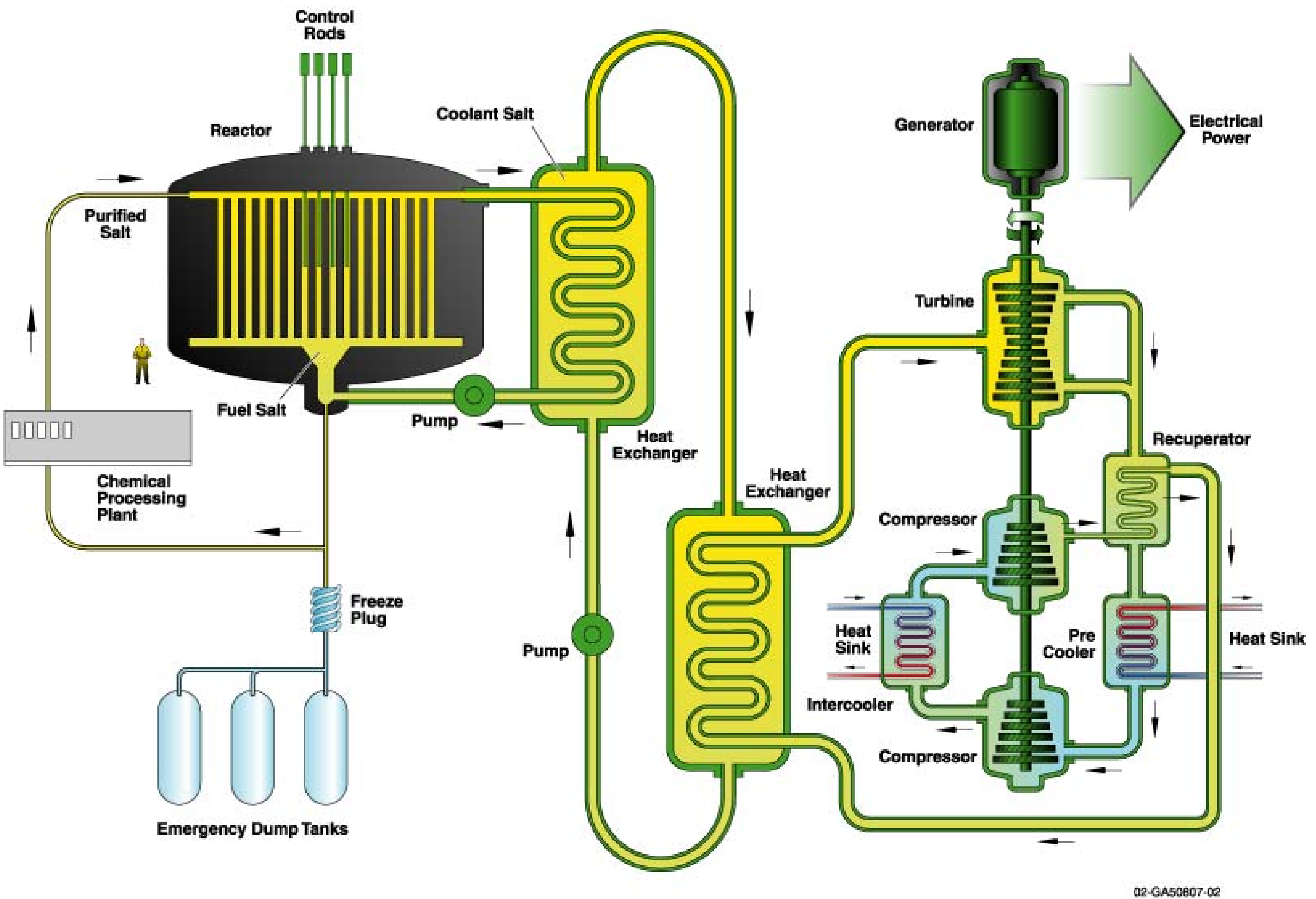


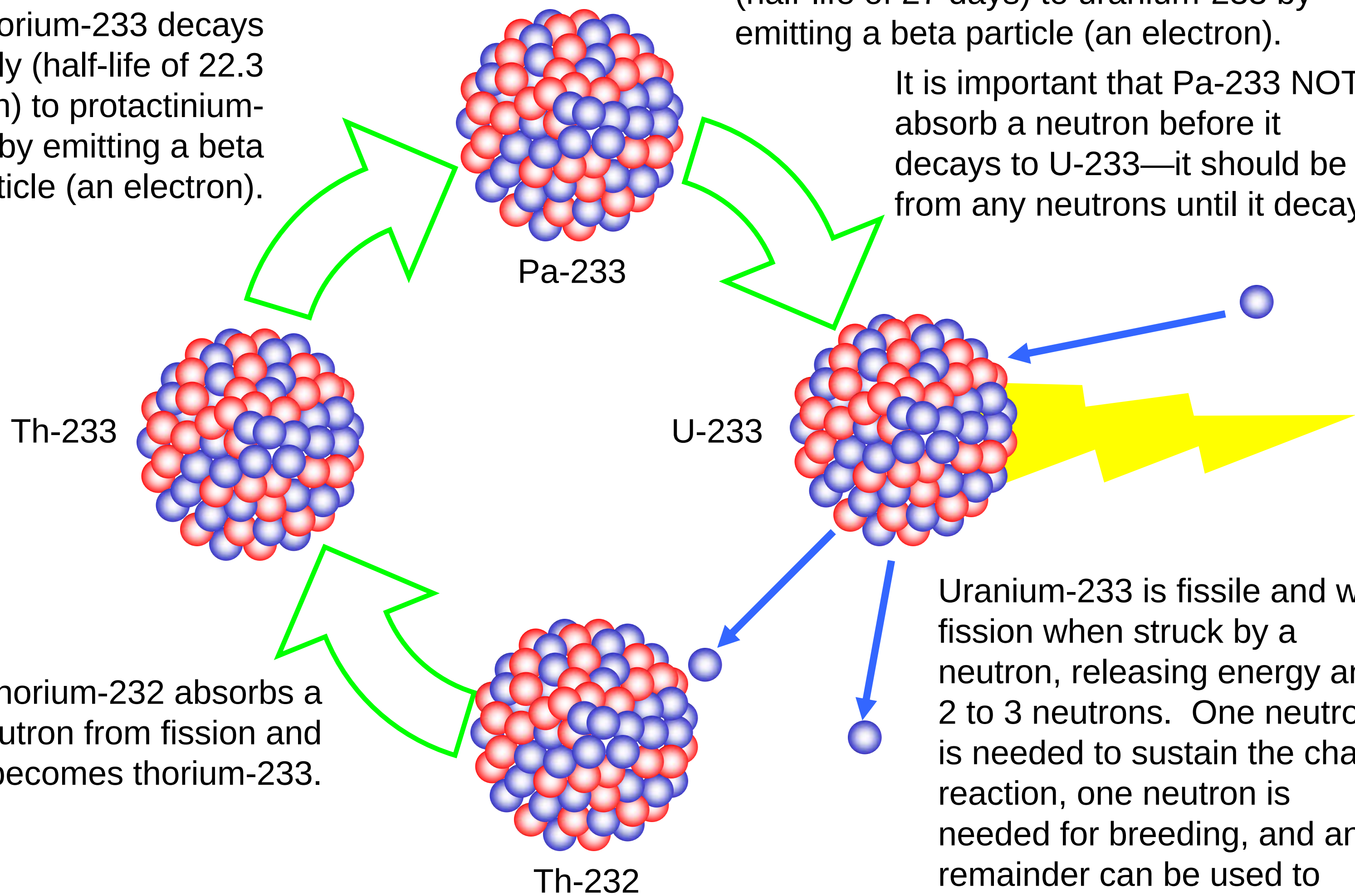
Fig. 1.2. MSRE Reactor.



Liquid-Fluoride Reactor Concept



Thorium-Uranium Breeding Cycle



Thorium-233 decays quickly (half-life of 22.3 min) to protactinium-233 by emitting a beta particle (an electron).

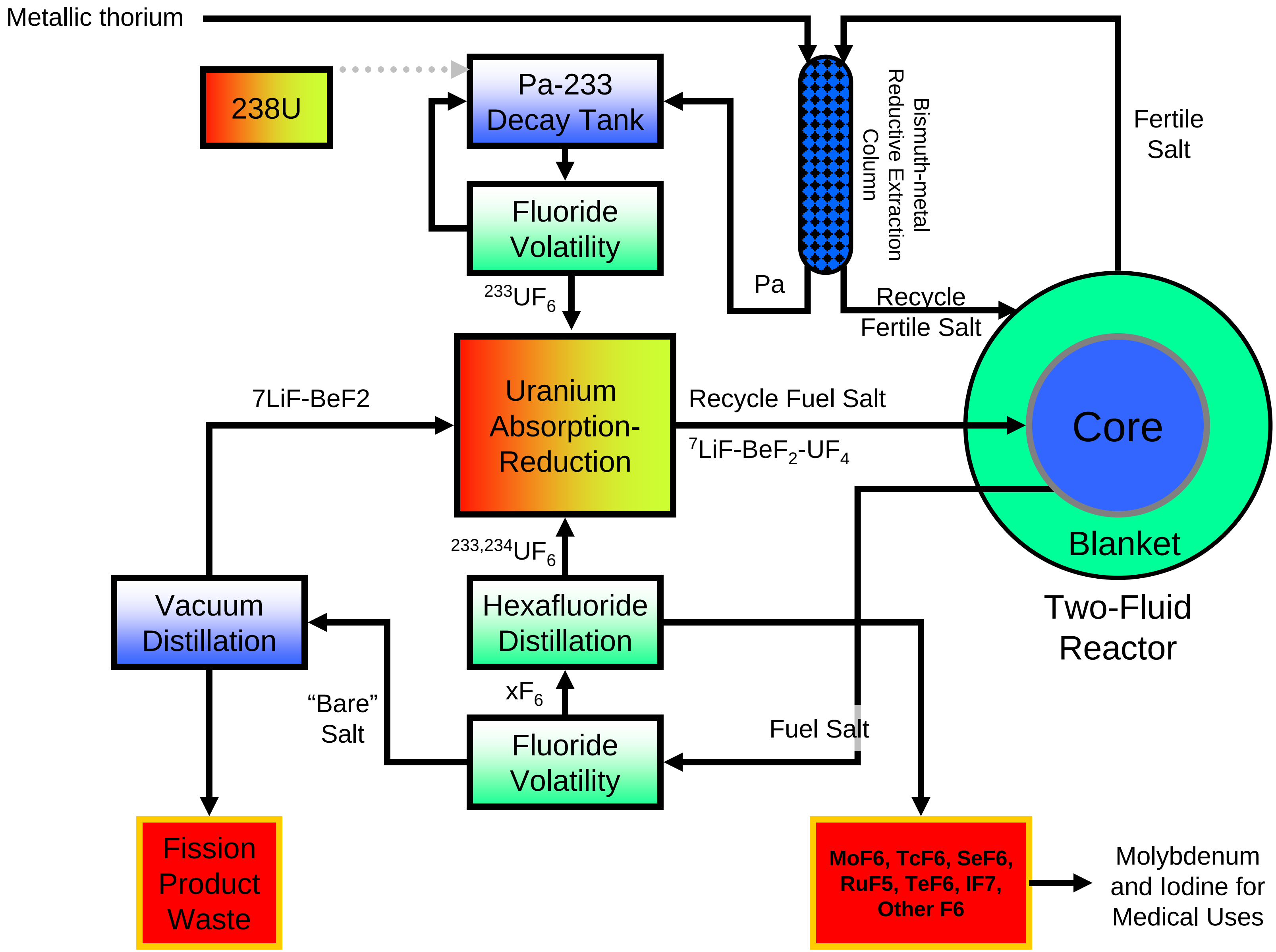
Protactinium-233 decays more slowly (half-life of 27 days) to uranium-233 by emitting a beta particle (an electron).

It is important that Pa-233 NOT absorb a neutron before it decays to U-233—it should be from any neutrons until it decays.

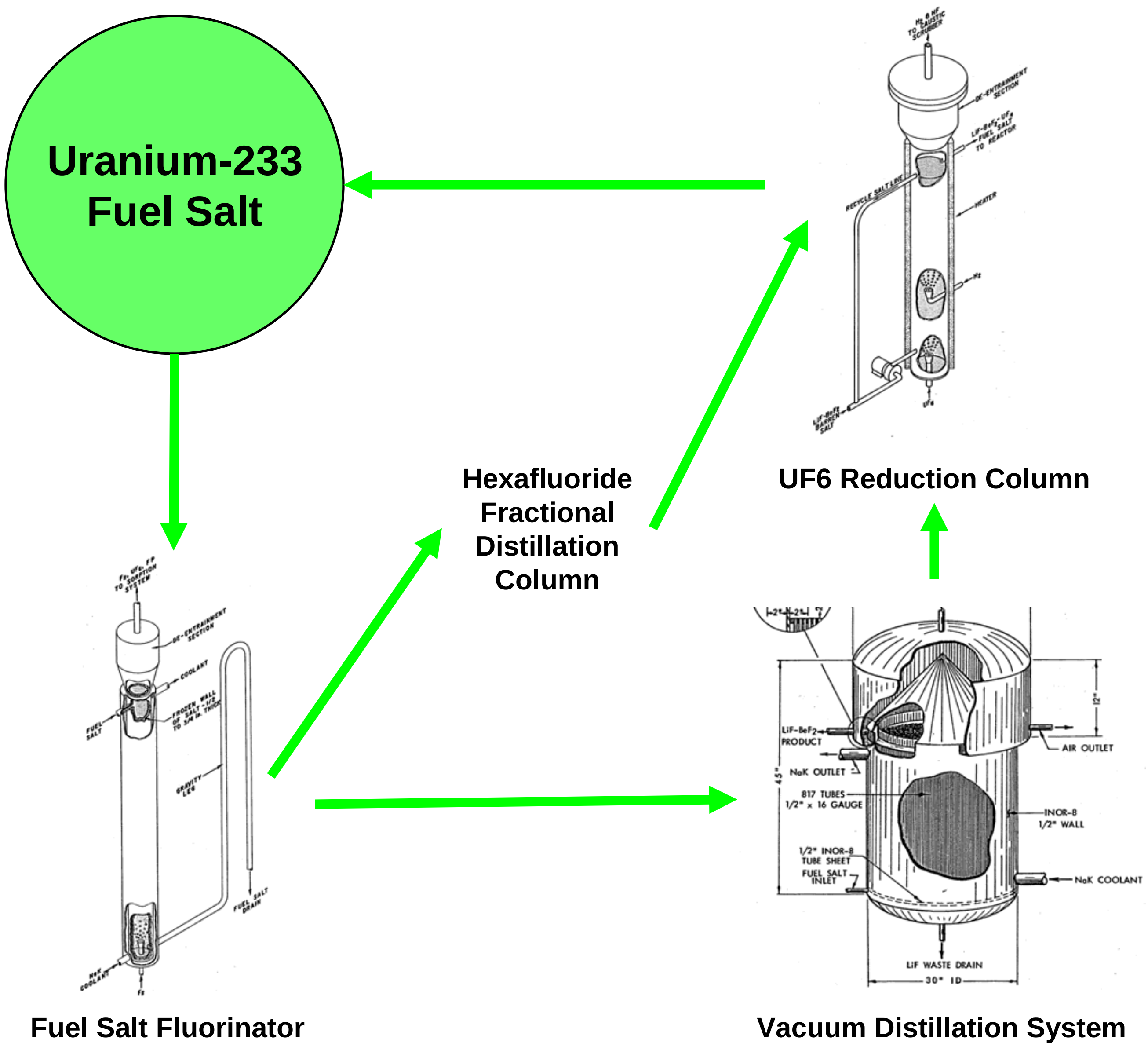
Uranium-233 is fissile and will fission when struck by a neutron, releasing energy and 2 to 3 neutrons. One neutron is needed to sustain the chain-reaction, one neutron is needed for breeding, and any remainder can be used to breed additional fuel.

Thorium-232 absorbs a neutron from fission and becomes thorium-233.

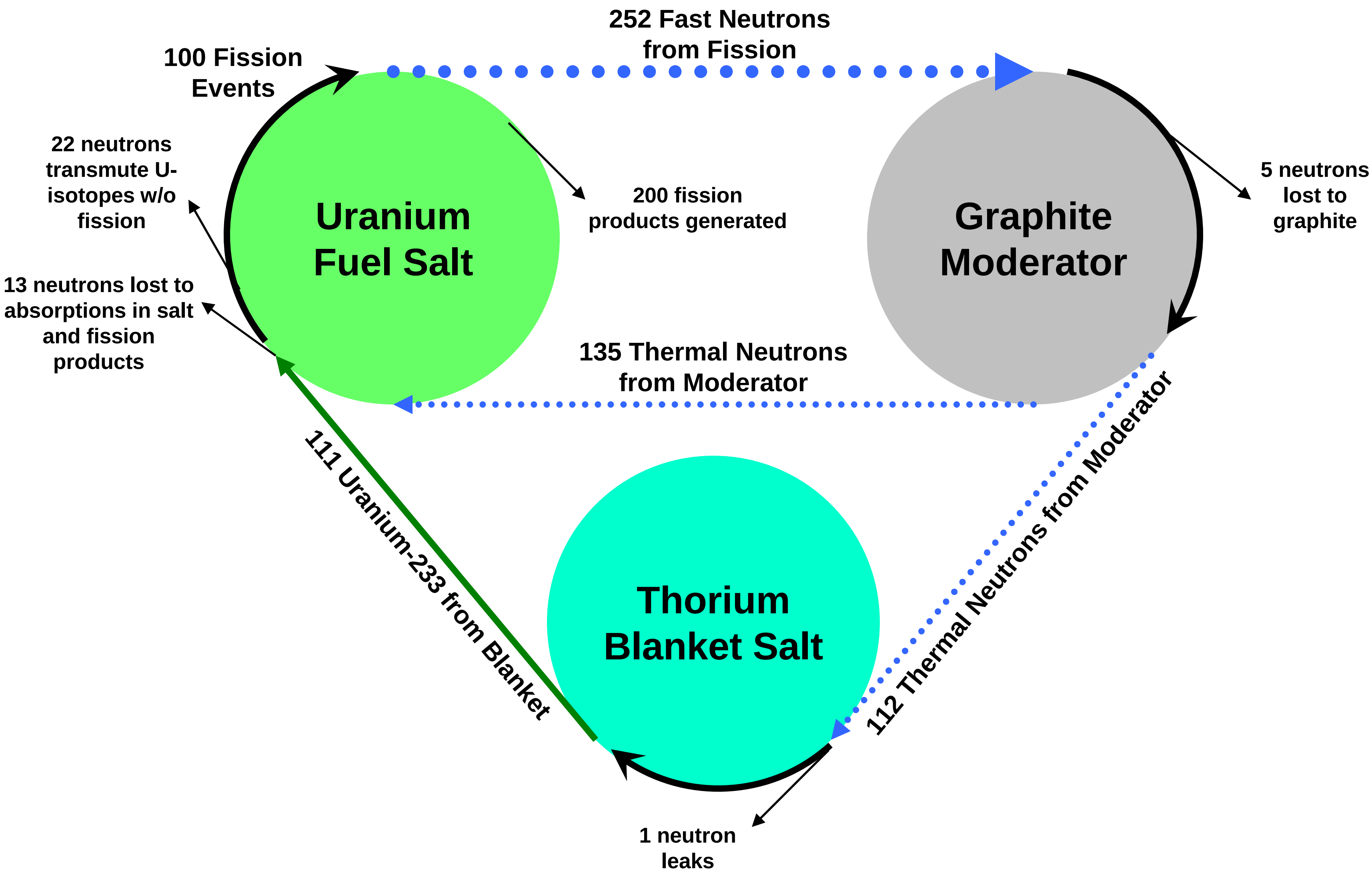
How does a fluoride reactor use thorium?



Simplified Reprocessing of Fuel Salt



Simplified Neutron Balance



Fluoride Reactor Advantages

- **Inherent Safety**
  - Chemically-stable nuclear fuels and coolants (fluoride salts)
  - Stable nuclear operation
  - Passive decay heat removal
- **Efficiency**
  - Thermal efficiency of 50% vs. 33%
  - Fuel efficiency up to 300x greater than uranium LWRs with once-through fuel cycle
- **Waste Disposal**
  - significantly reduces the volume and radioactivity of wastes to be buried while enabling “burning” of existing waste products
- **Proliferation**
  - not attractive bomb material
  - resistive to threats
  - eliminates the fuel cycle processing, storage, & transportation vulnerabilities
- **Scalability**
  - no conventional reactor can scale down in size as well or as far

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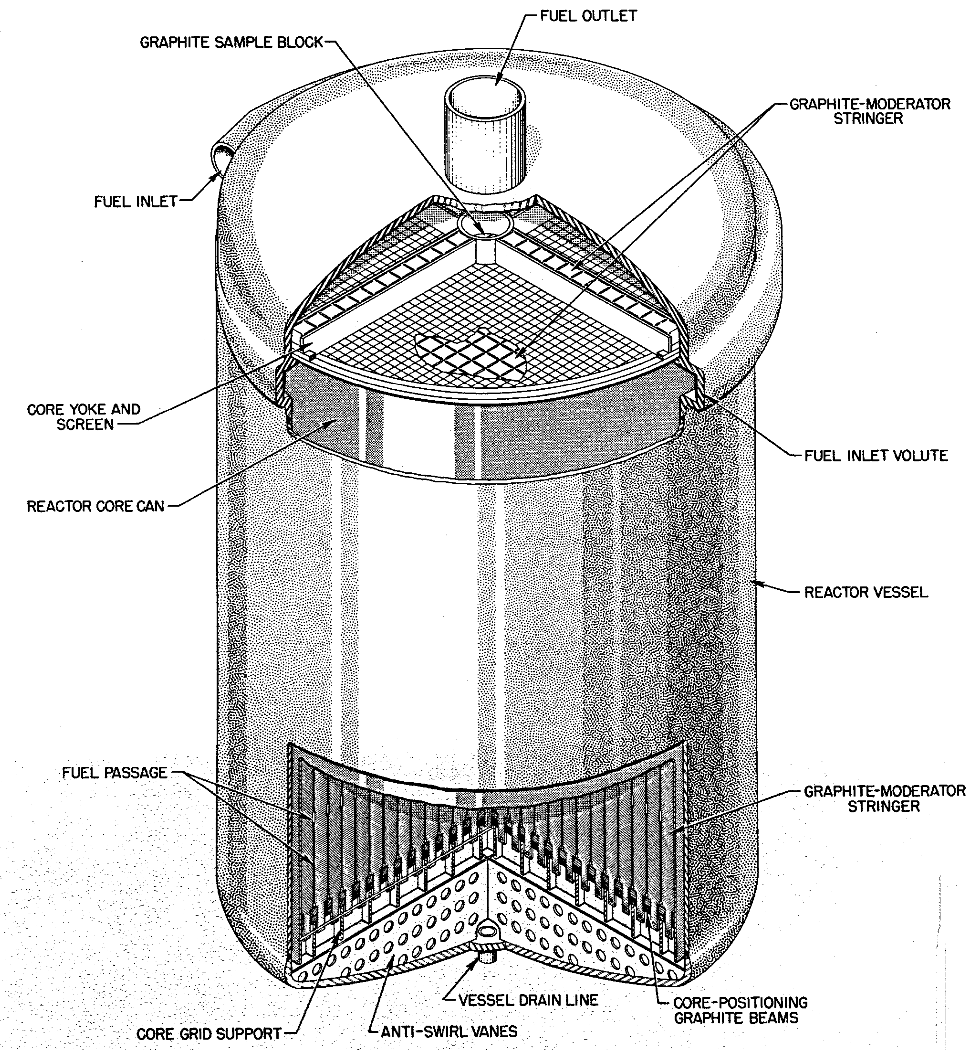

Fig. 1.2. MSRE Reactor.

Thorium energy produces far less mining waste

1 GW*yr of electricity from a uranium-fueled light-water reactor

Mining 800,000 MT of ore containing 0.2% uranium (260 MT U)

Generates ~600,000 MT of waste rock

Milling and processing to yellowcake—natural U_3O_8 (248 MT U)

Generates 130,000 MT of mill tailings

Conversion to natural UF_6 (247 MT U)

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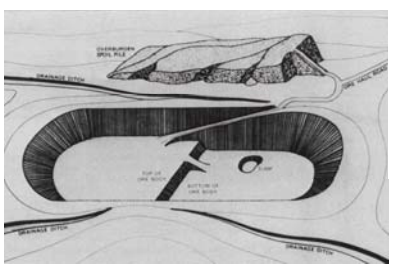
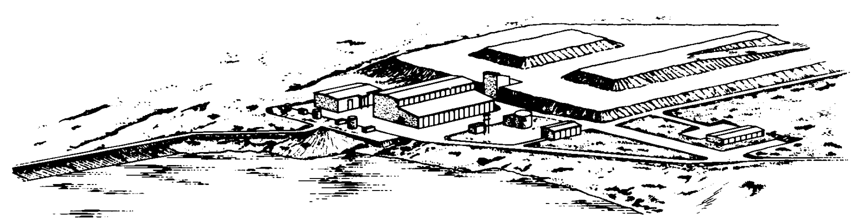
1 GW*yr of electricity from a thorium-fueled liquid-fluoride reactor



Mining 200 MT of ore containing 0.5% thorium (1 MT Th)

Generates ~199 MT of waste rock



Milling and processing to thorium nitrate $ThNO_3$ (1 MT Th)

Generates 0.1 MT of mill tailings and 50 kg of aqueous wastes

Uranium fuel cycle calculations done using WISE nuclear fuel material calculator: http://www.wise-uranium.org/nfcm.html

…and far less operation waste than a uranium reactor.

1 GW*yr of electricity from a uranium-fueled light-water reactor

Enrichment of 52 MT of (3.2%) UF_6 (35 MT U)

Generates 314 MT of DUF_6; consumes 300 GW*hr of electricity

Fabrication of 39 MT of enriched (3.2%) UO_2 (35 MT U)

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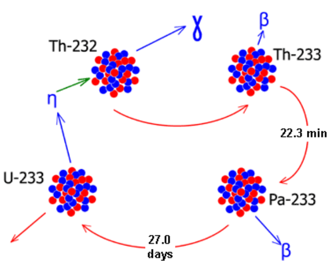
Irradiation and disposal of 39 MT of spent fuel consisting of unburned uranium, transuranics, and fission products.

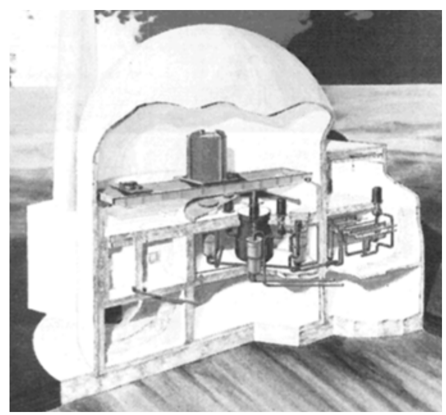
1 GW*yr of electricity from a thorium-fueled liquid-fluoride reactor



Thorium Fuel Cycle

Conversion to metal and introduction into reactor blanket

No costly enrichment!



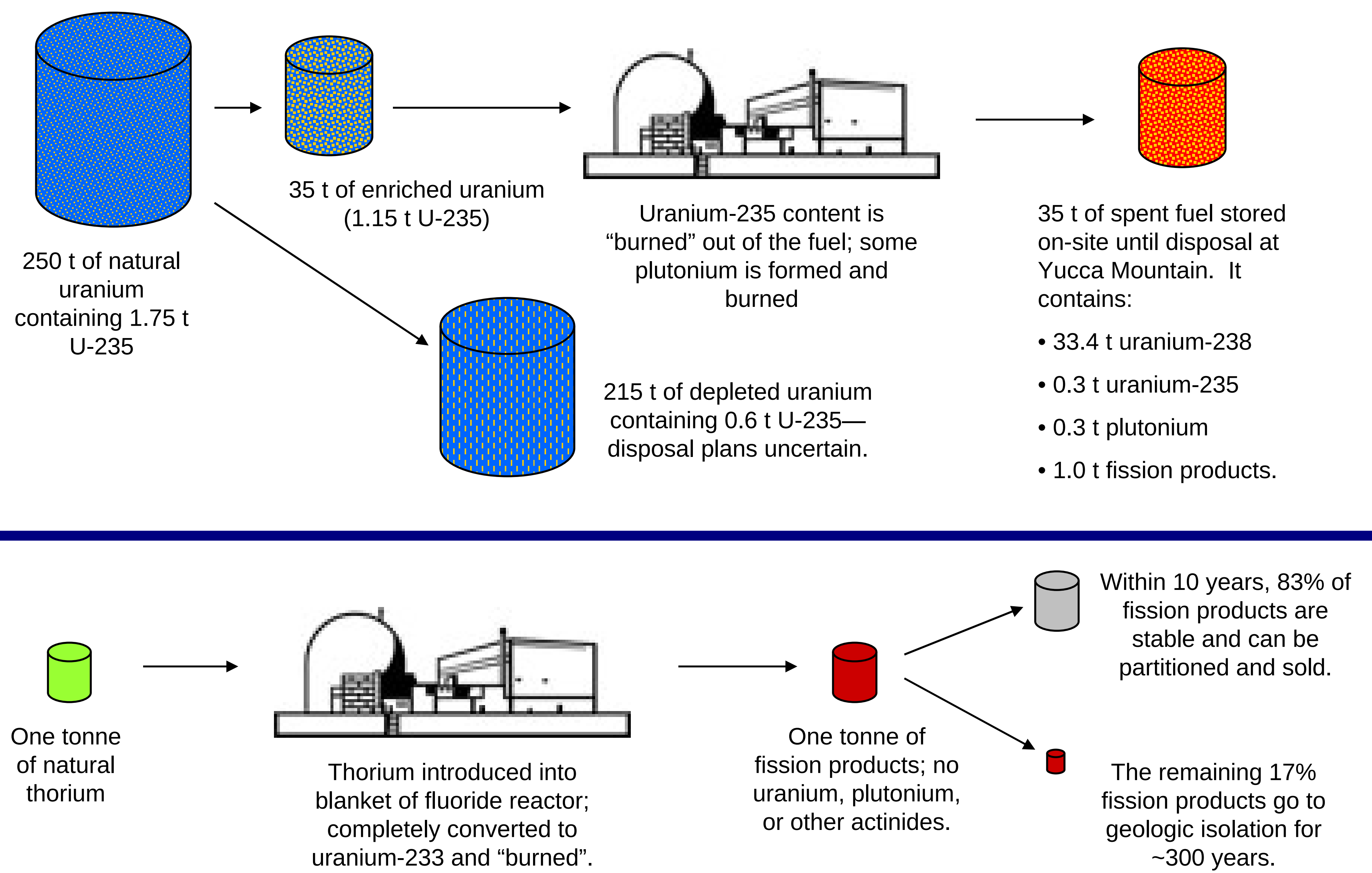
Breeding to U233 and complete fission

Disposal of 0.8 MT of spent fuel consisting only of fission product fluorides

Uranium fuel cycle calculations done using WISE nuclear fuel material calculator: http://www.wise-uranium.org/nfcm.html

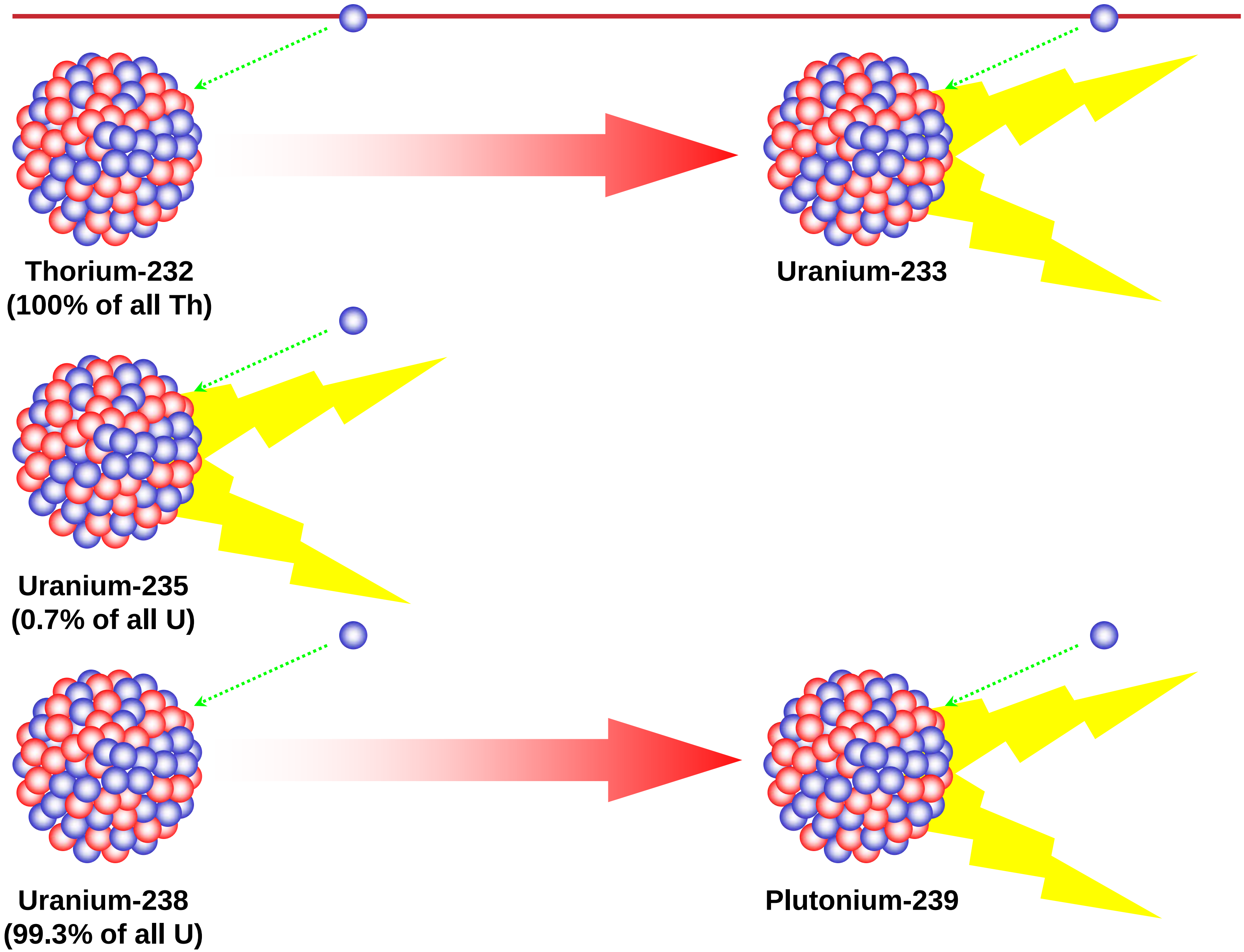
Today's Uranium Fuel Cycle vs. Thorium

mission: make 1000 MW of electricity for one year



Breaking the Weapons Connection

Three Basic Nuclear Fuels



Is the Thorium Fuel Cycle a Proliferation Risk?

- **When U-233 is used as a nuclear fuel, it is inevitably contaminated with uranium-232, which decays rather quickly (78 year half-life) and whose decay chain includes thallium-208.**
- **Thallium-208 is a “hard” gamma emitter, which makes any uranium contaminated with U-232 nearly worthless for nuclear weapons.**
- **There has never been an operational nuclear weapon that has used U-233 as its fissile material, despite the ease of manufacturing U-233 from abundant natural thorium.**
- **U-233 with very low U-232 contamination could be generated in special reactors like Hanford, but not in reactors that use the U-233 as fuel.**

U-232 Formation in the Thorium Fuel Cycle

$$^{232}\mathrm{Th} \xrightarrow{n,2n} {}^{231}\mathrm{Th} \xrightarrow[25.5\ \mathrm{h}]{\beta^-} {}^{231}\mathrm{Pa} \xrightarrow{n,\gamma} {}^{232}\mathrm{Pa} \xrightarrow[1.31\ \mathrm{days}]{\beta^-} {}^{232}\mathrm{U}$$

$$^{233}\mathrm{U} \xrightarrow{n,2n} {}^{232}\mathrm{U}$$

$$^{230}\mathrm{Th} \xrightarrow{n,\gamma} {}^{231}\mathrm{Th} \xrightarrow[25.52\ \mathrm{h}]{\beta^-} {}^{231}\mathrm{Pa} \xrightarrow{n,\gamma} {}^{232}\mathrm{Pa} \xrightarrow[1.31\ \mathrm{days}]{\beta^-} {}^{232}\mathrm{U}$$

Table 2: Unshielded working hours required to accumulate a 5 rem dose (5 kg sphere of metal at 0.5 m one year after separation)

Metal	Dose Rate (rem/hr)	Hours
Weapon-grade plutonium	0.0013	3800
Reactor-grade plutonium	0.0082	610
U-233 containing 1ppm U-232	0.013	380
U-233 containing 5ppm U-232	0.059	80
U-233 containing 100 ppm U-232	1.27	4
U-233 containing 1 percent U-232	127	0.04

Why wasn't this done? No Plutonium!

Alvin Weinberg:

"Why didn't the molten-salt system, so elegant and so well thought-out, prevail? I've already given the political reason: that the plutonium fast breeder arrived first and was therefore able to consolidate its political position within the AEC. But there was another, more technical reason. [Fluoride reactor] technology is entirely different from the technology of any other reactor. To the inexperienced, [fluoride] technology is daunting…

"Mac" MacPherson:

The political and technical support for the program in the United States was too thin geographically…only at ORNL was the technology really understood and appreciated. The thorium-fueled fluoride reactor program was in competition with the plutonium fast breeder program, which got an early start and had copious government development funds being spent in many parts of the United States.

Alvin Weinberg:

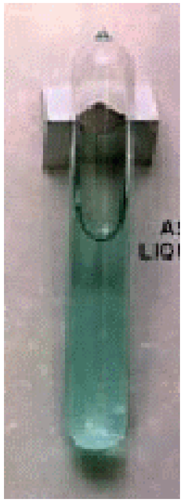
"It was a successful technology that was dropped because it was too different from the main lines of reactor development… I hope that in a second nuclear era, the [fluoride-reactor] technology will be resurrected."

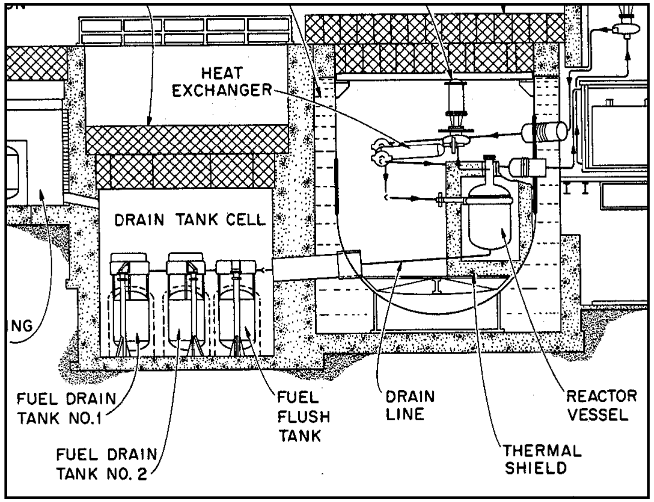
Inherent Safety

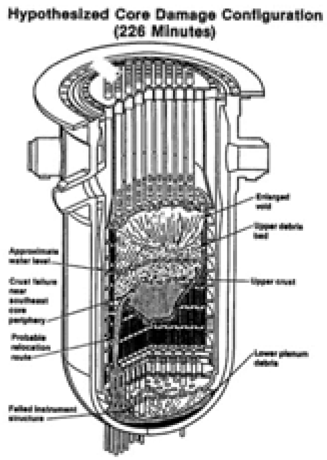
Fluoride Reactors can be Inherently Safe

- The liquid-fluoride thorium reactor is incredibly stable against nuclear reactivity accidents—the type of accident experienced at Chernobyl.

- It is simply not possible because any change in operating conditions results in a reduction in reactor power.





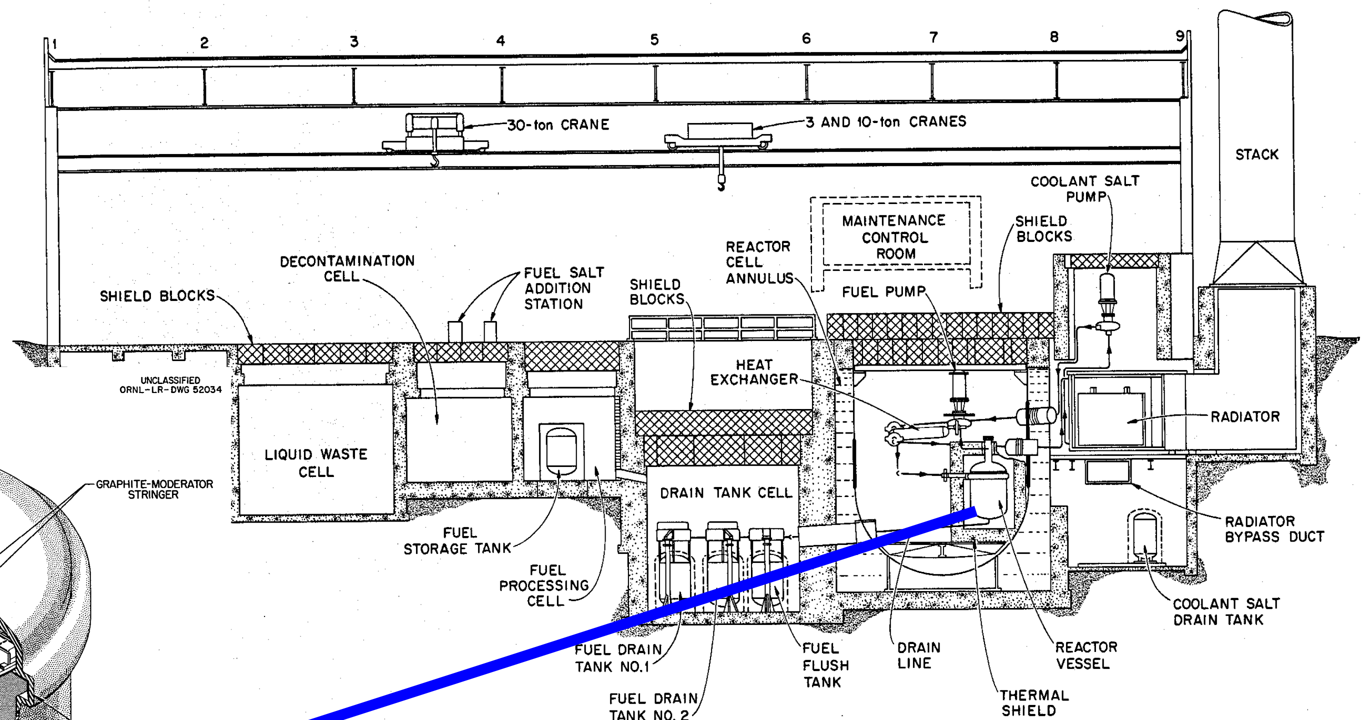


- The LFTR is also totally, passively safe against loss-of-coolant accidents—the type of accident that happened at Three Mile Island.

- It is simply not possible because in all cases the fuel drains into a passively safe configuration.

Accident, attack, or sabotage cannot create a radiation release hazard.

“Freeze Plug” approach is totally automatic



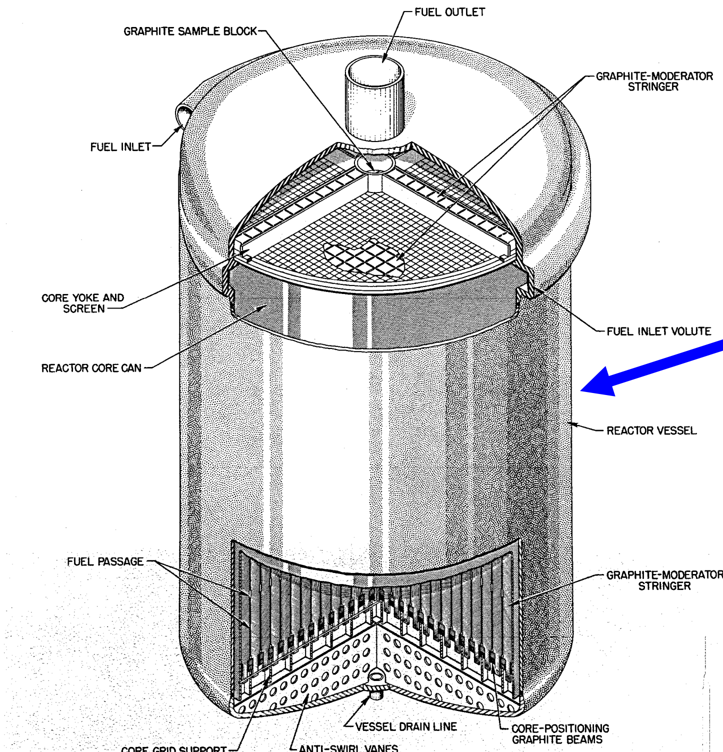
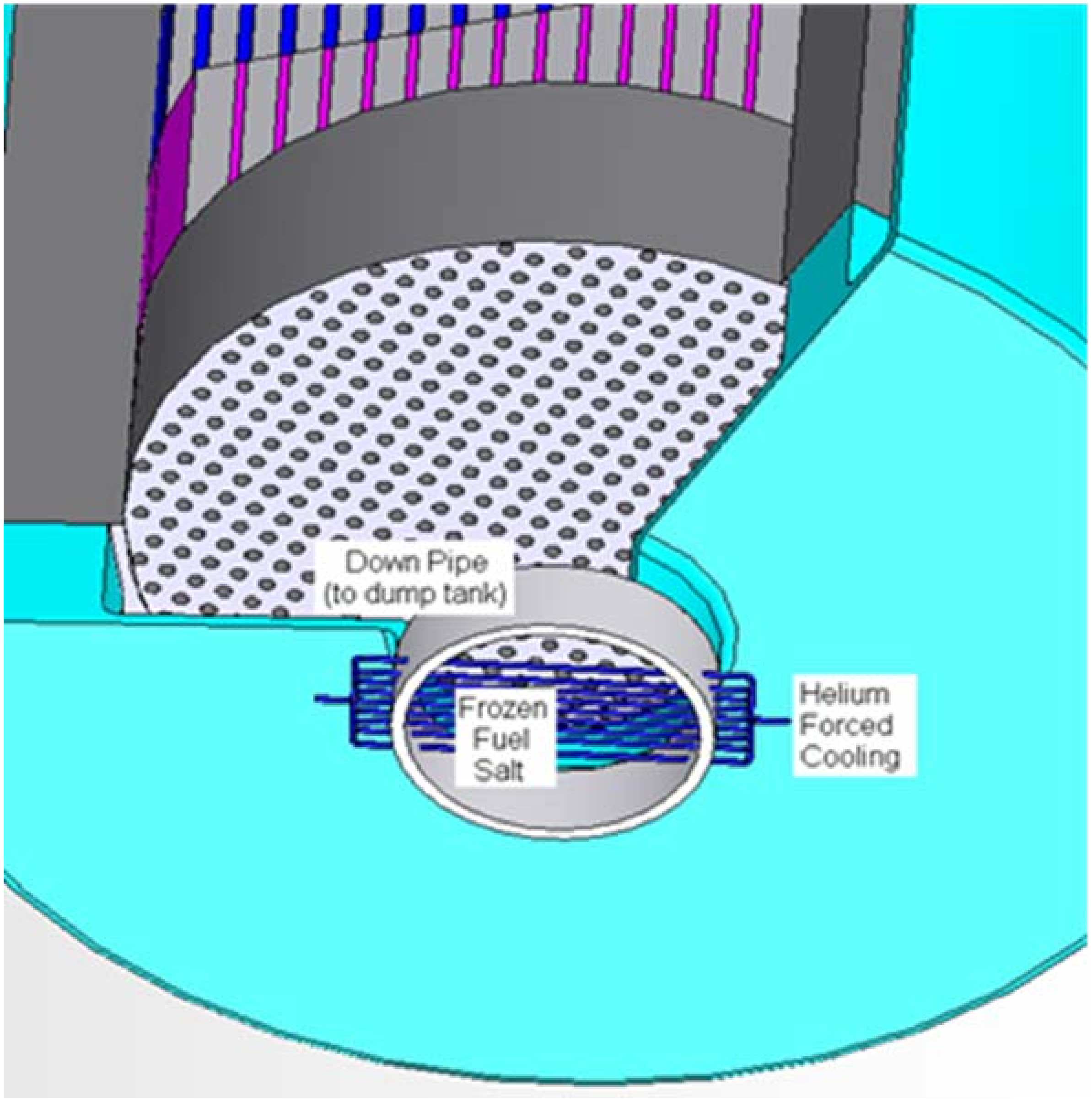


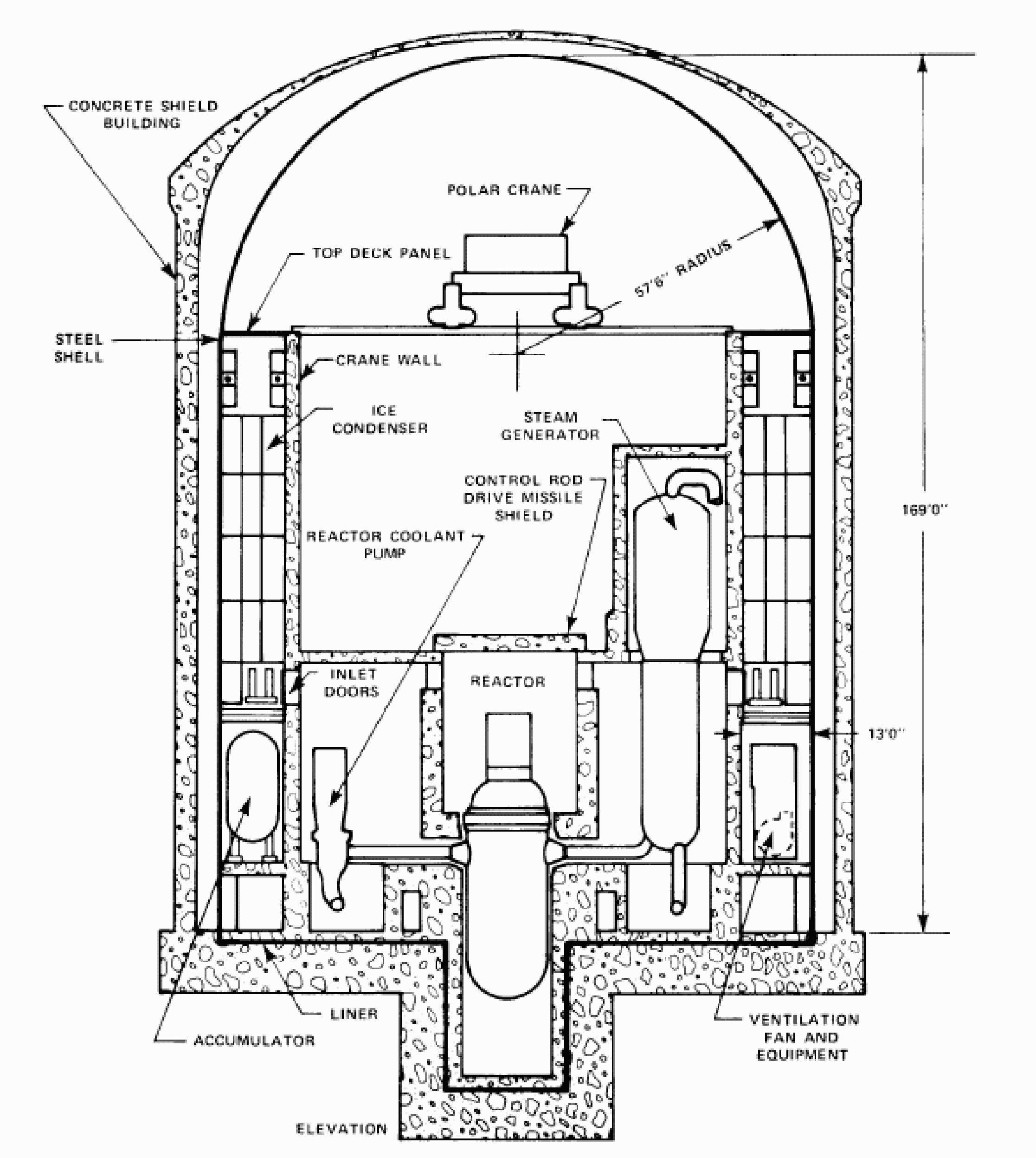
Fig. 1.2. MSRE Reactor.

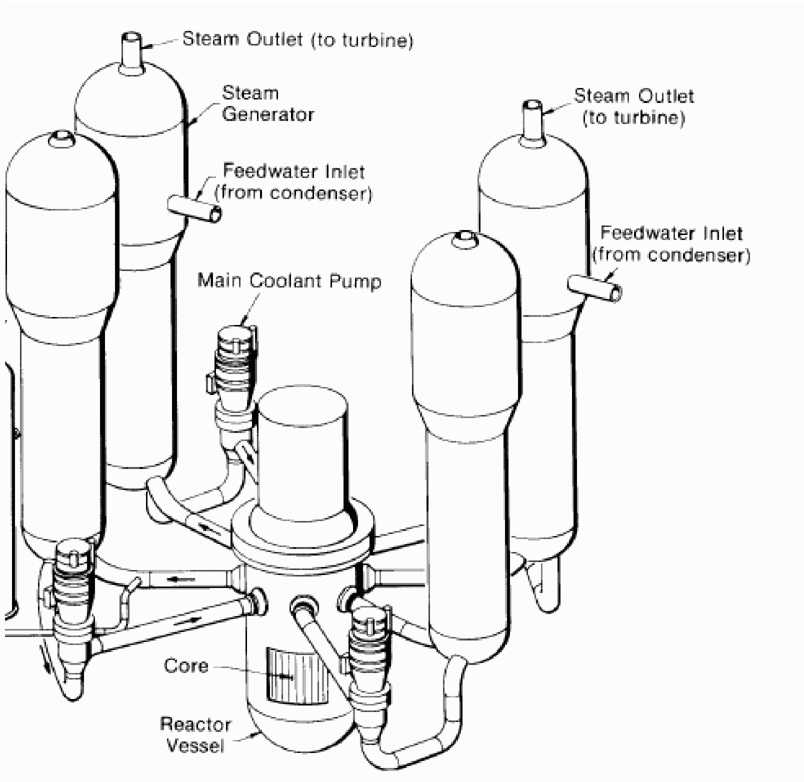
- **In the event of TOTAL loss of power, the freeze plug melts and the core salt drains into a passively cooled configuration where nuclear fission is impossible.**

Passive Decay Heat Removal thru Freeze Valve



A Pressurized-Water Reactor





Availability of Fuel

"We Americans want it all: endless and secure energy supplies; low prices; no pollution; less global warming; no new power plants (or oil and gas drilling, either) near people or pristine places. This is a wonderful wish list, whose only shortcoming is the minor inconvenience of massive inconsistency."

—Robert Samuelson

2007 Energy Consumption: 467 quads

- **In 2007, the world consumed:**

5.3 billion tonnes of coal (128 quads*)

31.1 billion barrels of oil (180 quads)

2.92 trillion m^3 of natural gas (105 quads)

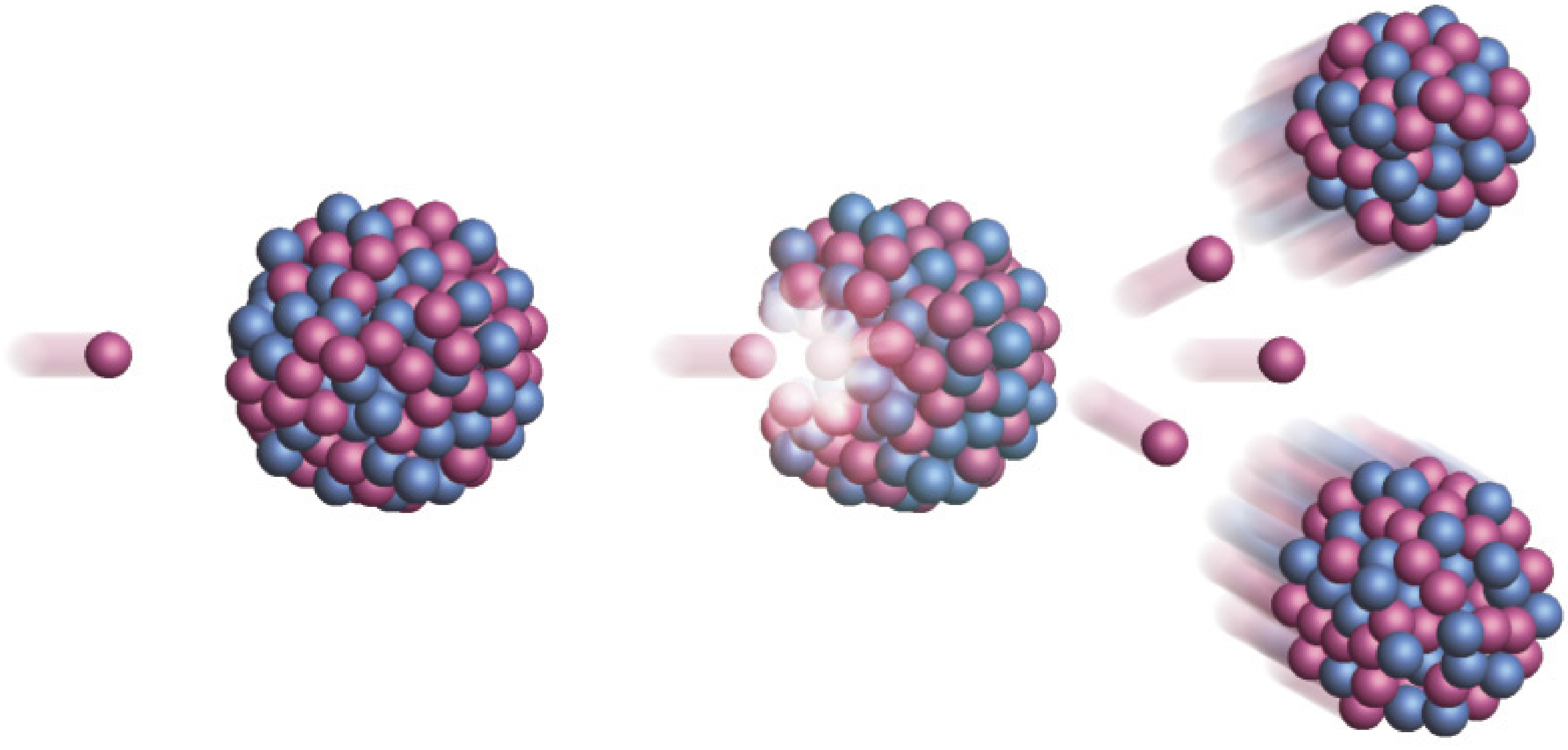
65 million kg of uranium ore (25 quads)

29 quads of hydroelectricity

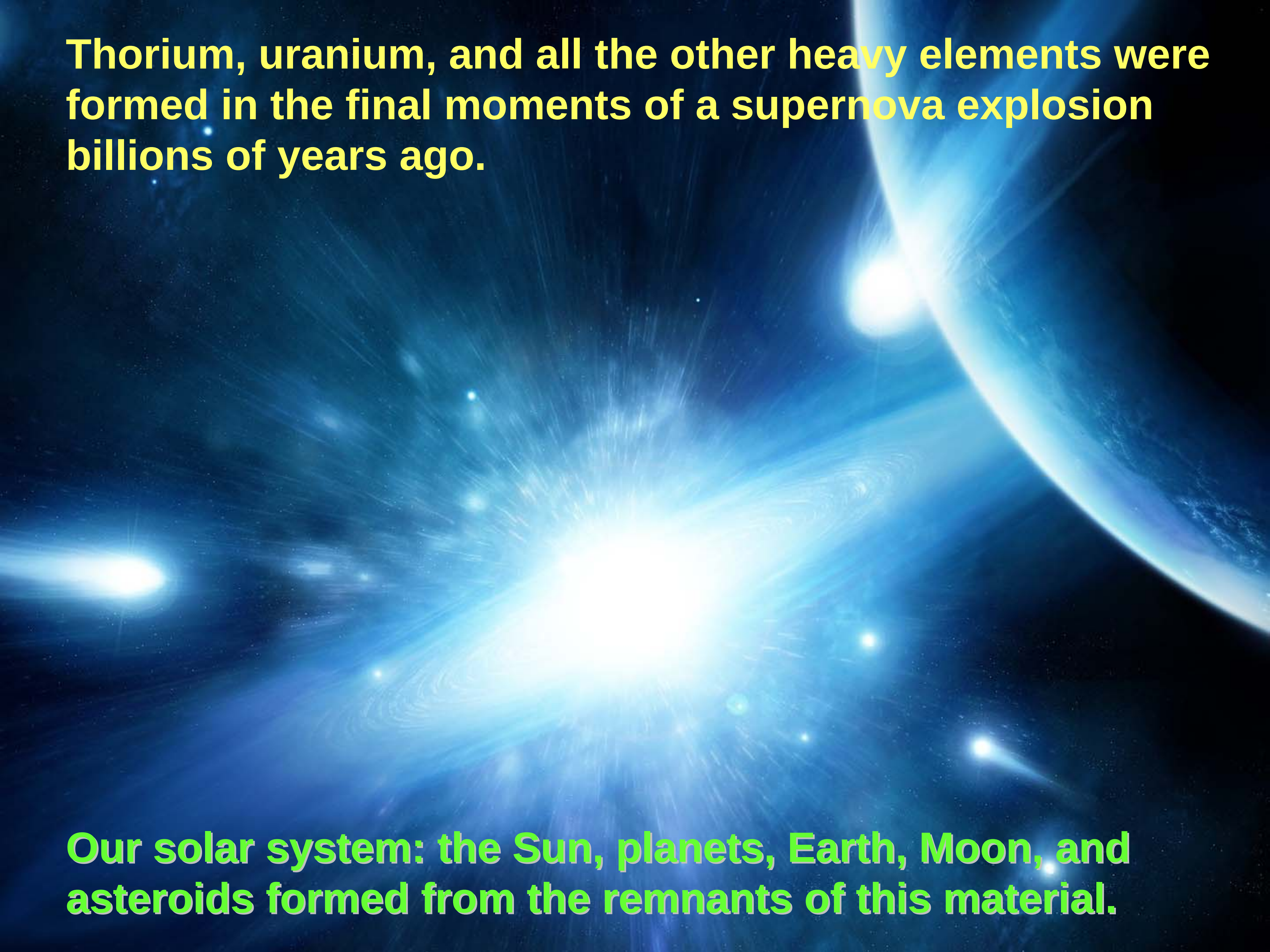
Source: BP Statistical Review of World Energy 2008

***1 quad = 1 quadrillion BTU ~ 1.055e18 J = 1.055 exajoule**

Each Fission Reaction Releases ~200 MeV



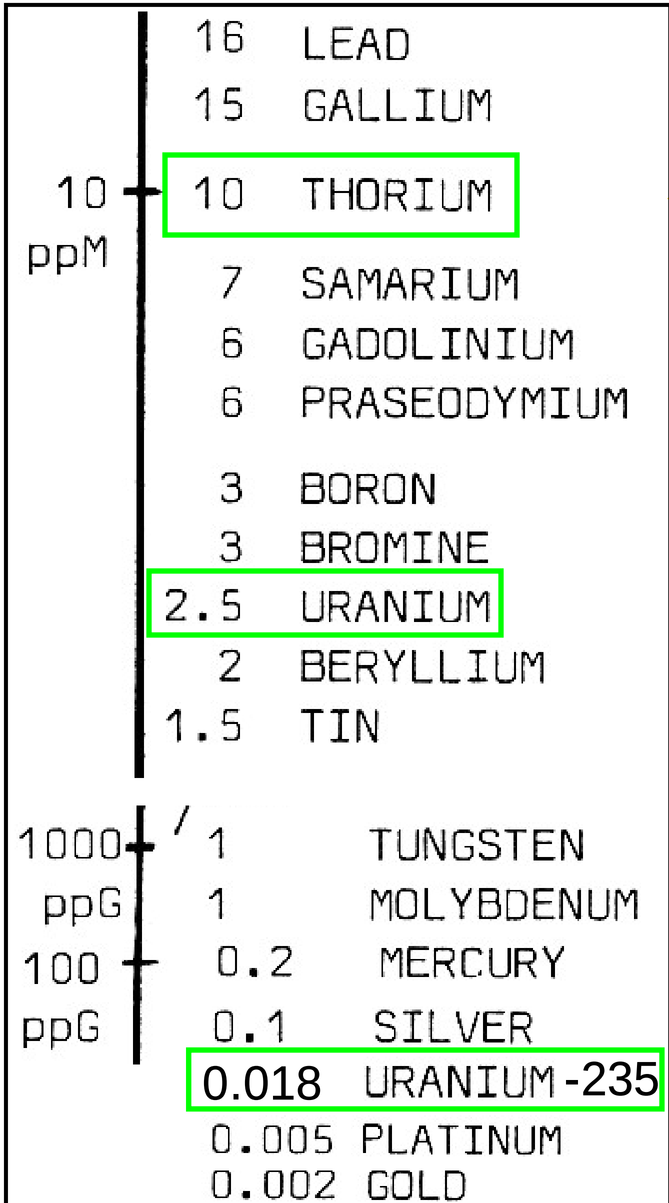
200 MeV/235 amu = 35 billion BTU/lb = 23 million kW*hr/kg



Thorium, uranium, and all the other heavy elements were formed in the final moments of a supernova explosion billions of years ago.

Our solar system: the Sun, planets, Earth, Moon, and asteroids formed from the remnants of this material.

Thorium and Uranium Abundant in the Earth’s Crust



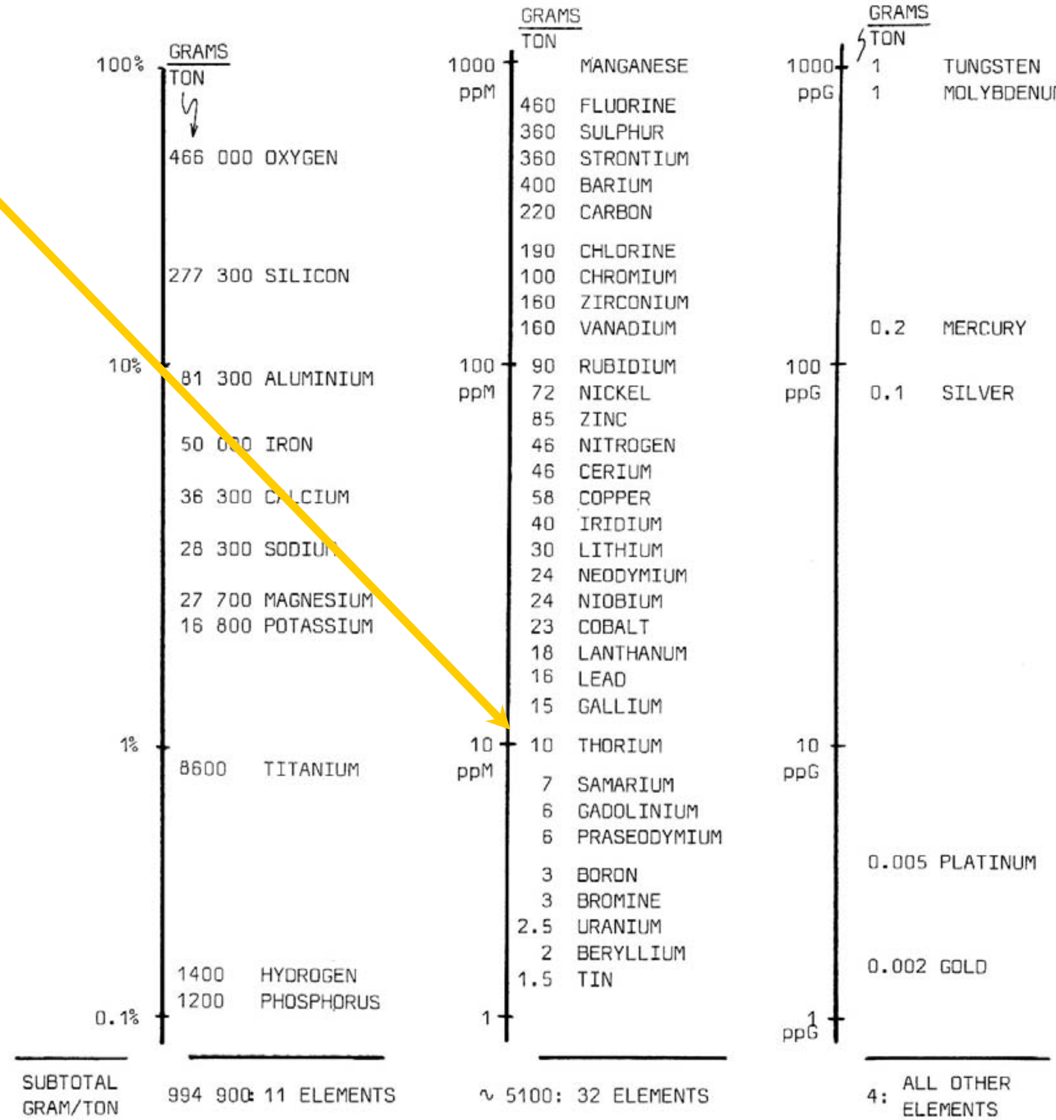


Fig. 5.13. The chemical composition of the Earth’s crust.

Thorium is virtually limitless in availability,

- **Thorium is abundant around the world**
  - 12 parts-per-million in the Earth's crust
  - India, Australia, Canada, US have large resources.
- **There will be no need to horde or fight over this resource**
  - A single mine site at the Lemhi Pass in Idaho could produce 4500 MT of thorium per year.
  - 2007 US energy consumption = 95 quads = 2580 MT of thorium

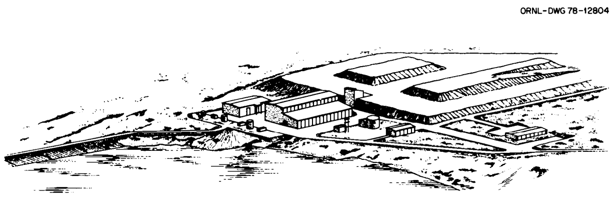
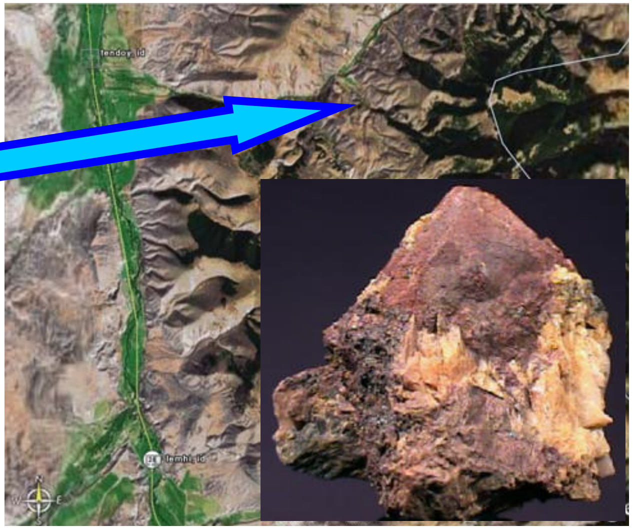
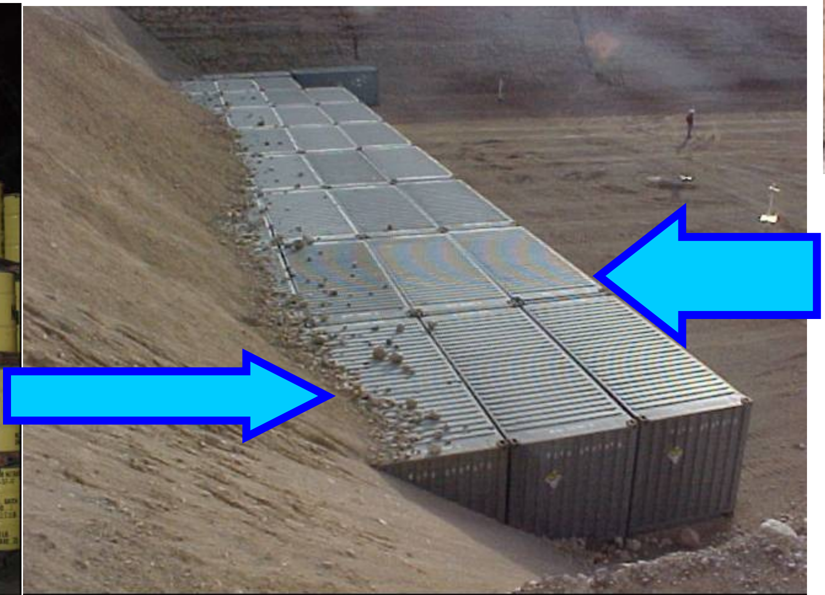


Fig. 3.3. Artist's rendition of ore-treatment mill. (Taken from U.S. Nuclear Regulatory Commission, Final Environmental Statement Bear Creek Project, NUREG-0129, Docket No. 40-8452, June 1977.)



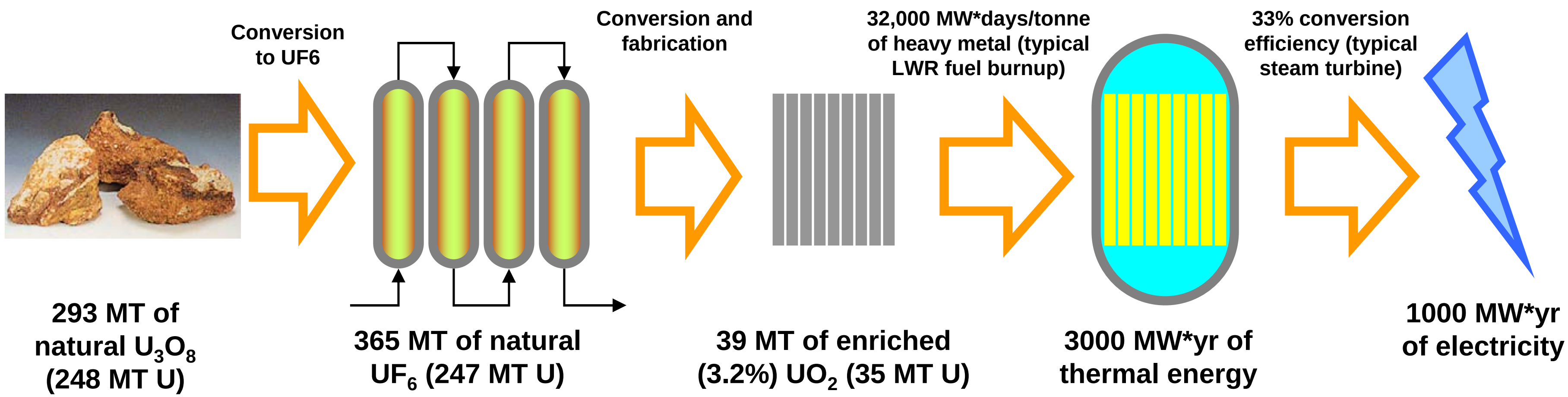


The United States has buried 3200 metric tonnes of thorium nitrate in the Nevada desert.

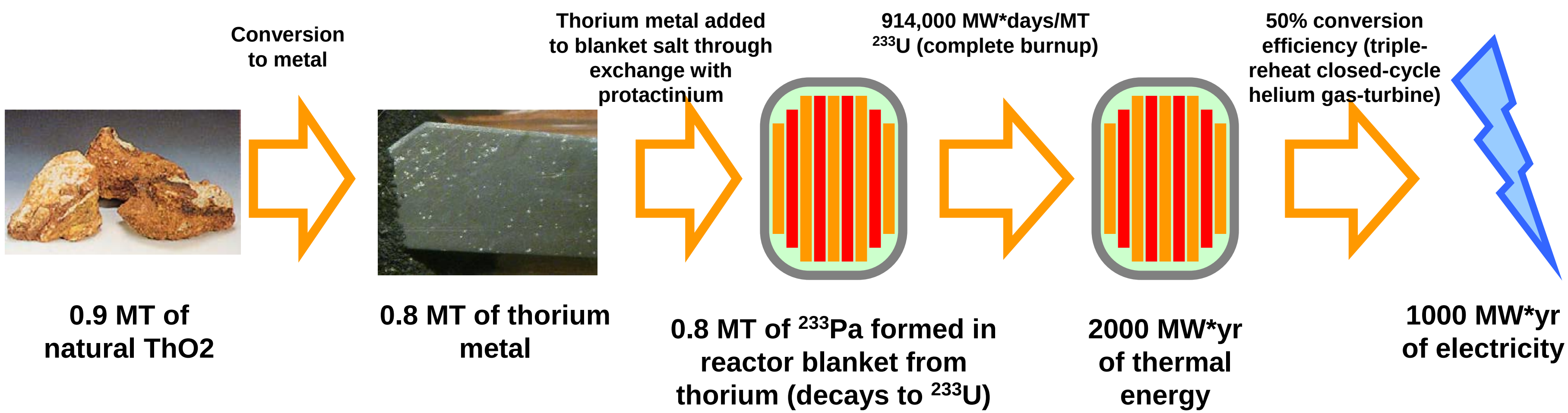
There are 160,000 tonnes of economically extractable thorium in the US, even at today's "worthless" prices!

100% of thorium's energy is extractable, ~0.7% for uranium

Uranium-fueled light-water reactor: 35 GW*hr/MT of natural uranium

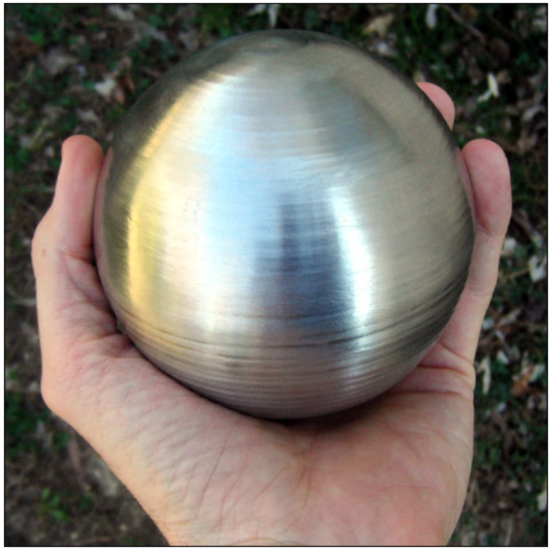


Thorium-fueled liquid-fluoride reactor: 11,000 GW*hr/MT of natural thorium



Uranium fuel cycle calculations done using WISE nuclear fuel material calculator: http://www.wise-uranium.org/nfcm.html

Energy Comparison



6 kg of thorium metal in a liquid-fluoride reactor has the energy equivalent (66,000 MW*hr) of:

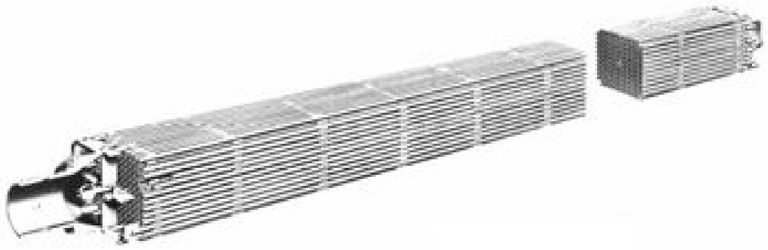
=

230 train cars (25,000 MT) of bituminous coal or,

600 train cars (66,000 MT) of brown coal,

(Source: World Coal Institute)

or, 440 million cubic feet of natural gas (15% of a 125,000 cubic meter LNG tanker),



or, 300 kg of enriched (3%) uranium in a pressurized water reactor.

Economy of Construction

Power Generation Resource Inputs

- **Nuclear: 1970's vintage PWR, 90% capacity factor, 60 year life [1]**
  - 40 MT steel / MW(average)
  - 190 m3 concrete / MW(average)

- **Wind: 1990's vintage, 6.4 m/s average wind speed, 25% capacity factor, 15 year life [2]**
  - 460 MT steel / MW (average)
  - 870 m3 concrete / MW(average)

- **Coal: 78% capacity factor, 30 year life [2]**
  - 98 MT steel / MW(average)
  - 160 m3 concrete / MW(average)

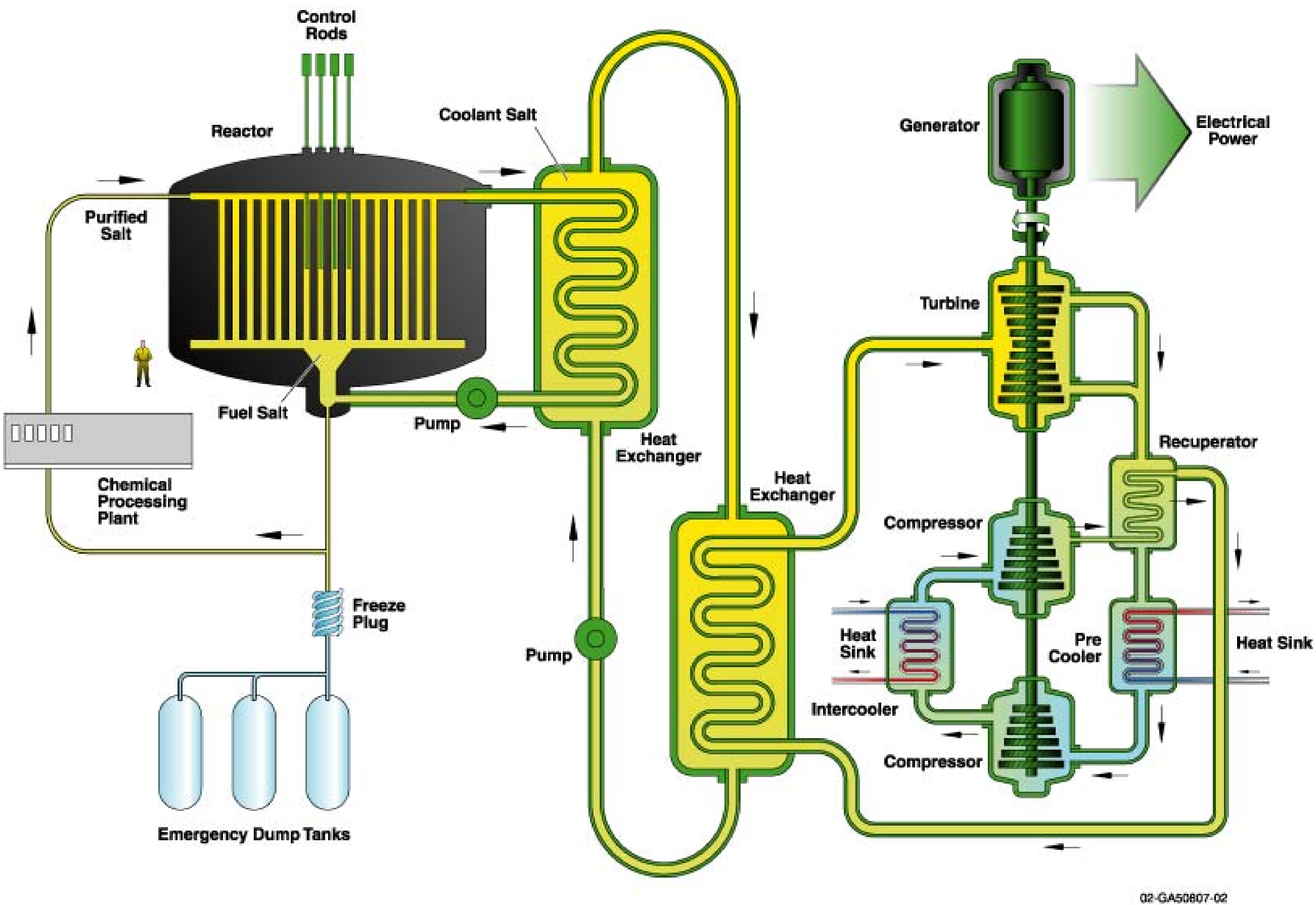
- **Natural Gas Combined Cycle: 75% capacity factor, 30 year life [3]**
  - 3.3 MT steel / MW(average)
  - 27 m3 concrete / MW(average)

1. R.H. Bryan and I.T. Dudley, "Estimated Quantities of Materials Contained in a 1000-MW(e) PWR Power Plant," Oak Ridge National Laboratory, TM-4515, June (1974)

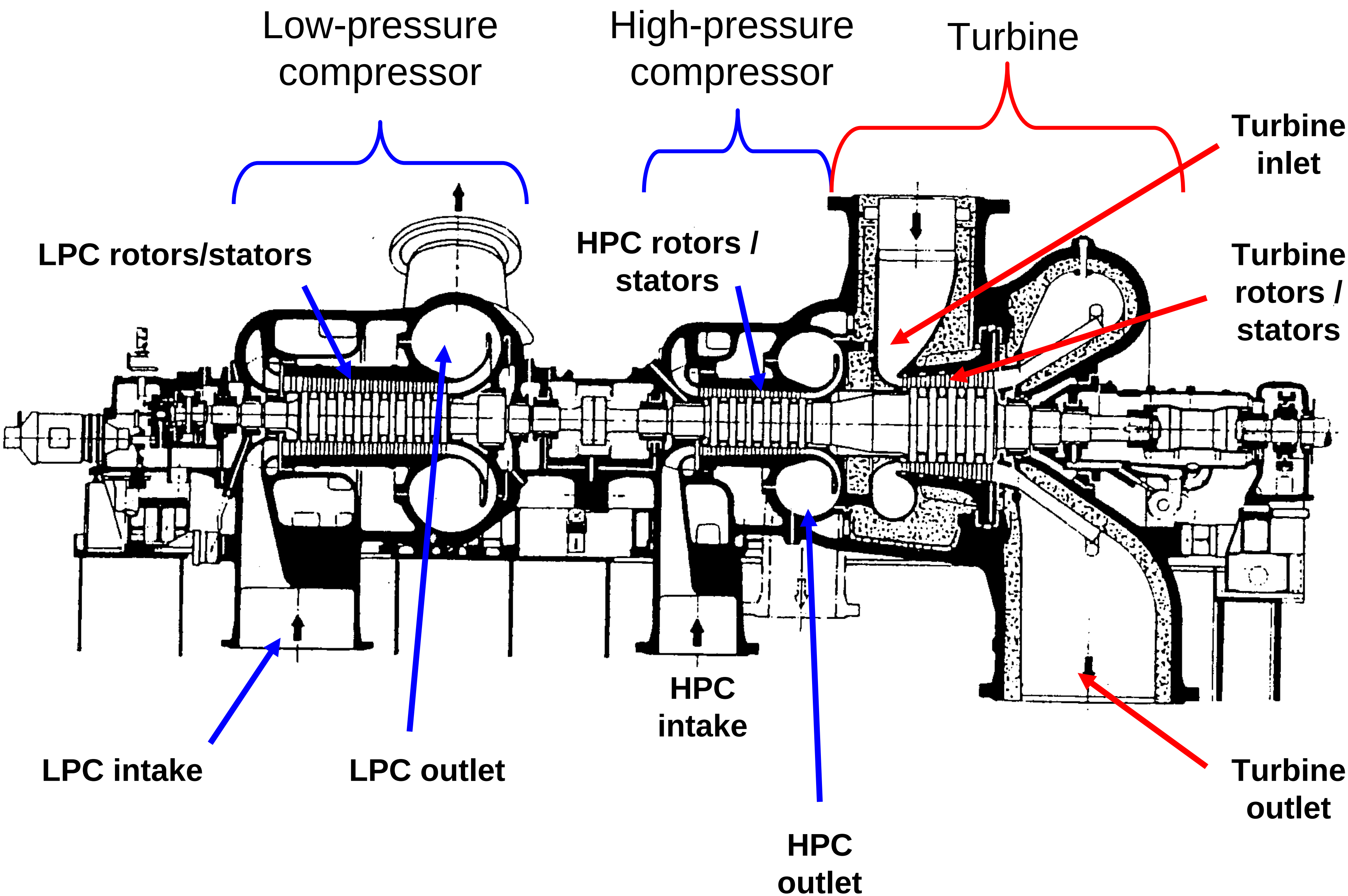
2. S. Pacca and A. Horvath, Environ. Sci. Technol., 36, 3194-3200 (2002).

3. P.J. Meier, "Life-Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis," U. WisconsinReport UWFDM-1181, August, 2002

Liquid-Fluoride Reactor Concept

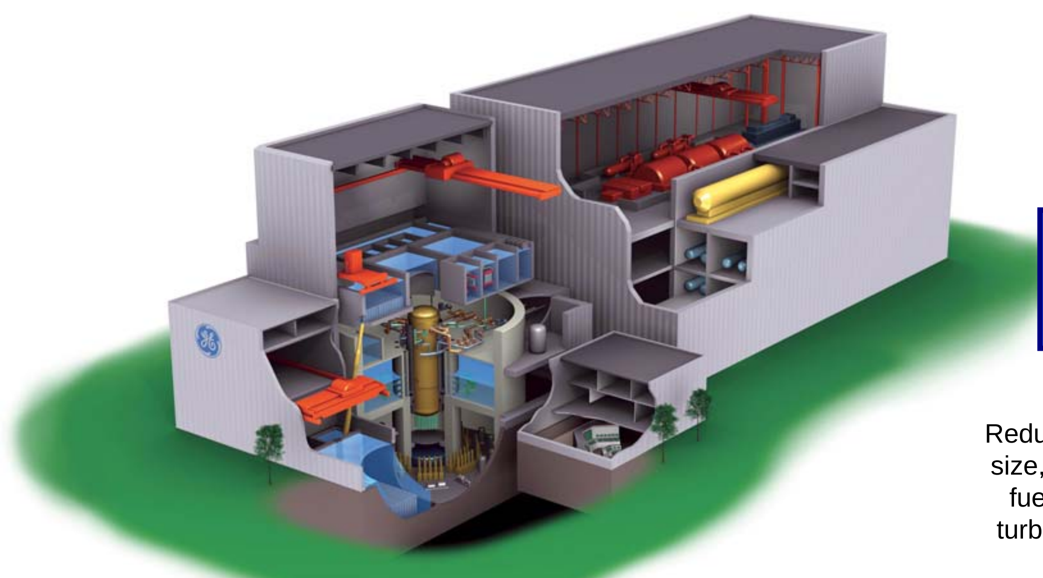


Closed-Cycle Turbomachinery Example

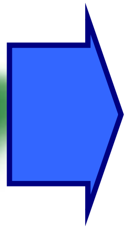


Cost advantages come from size and complexity reductions

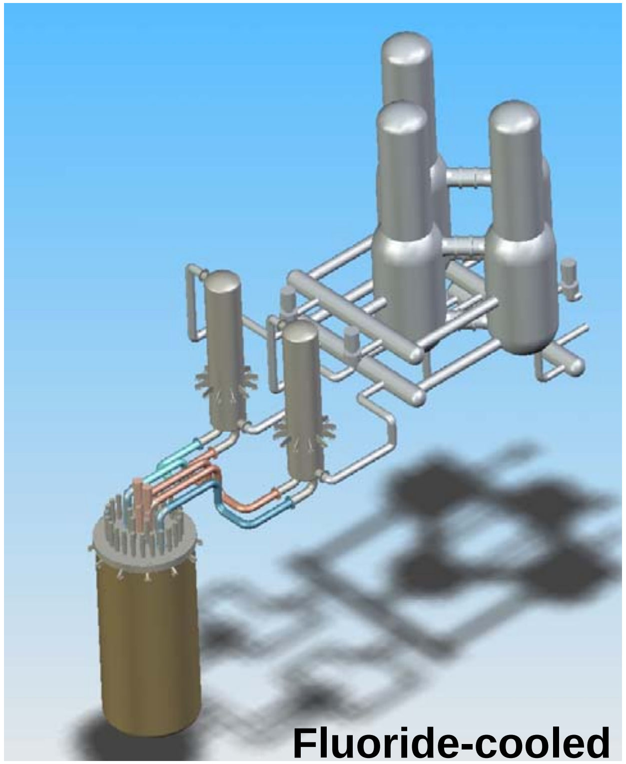
- **Cost**
  - Low capital cost thru small facility and compact power conversion
    - Reactor operates at ambient pressure
    - No expanding gases (steam) to drive large containment
    - High-pressure helium gas turbine system
  - Primary fuel (thorium) is inexpensive
  - Simple fuel cycle processing, all done on site



GE Advanced Boiling Water Reactor (light-water reactor)

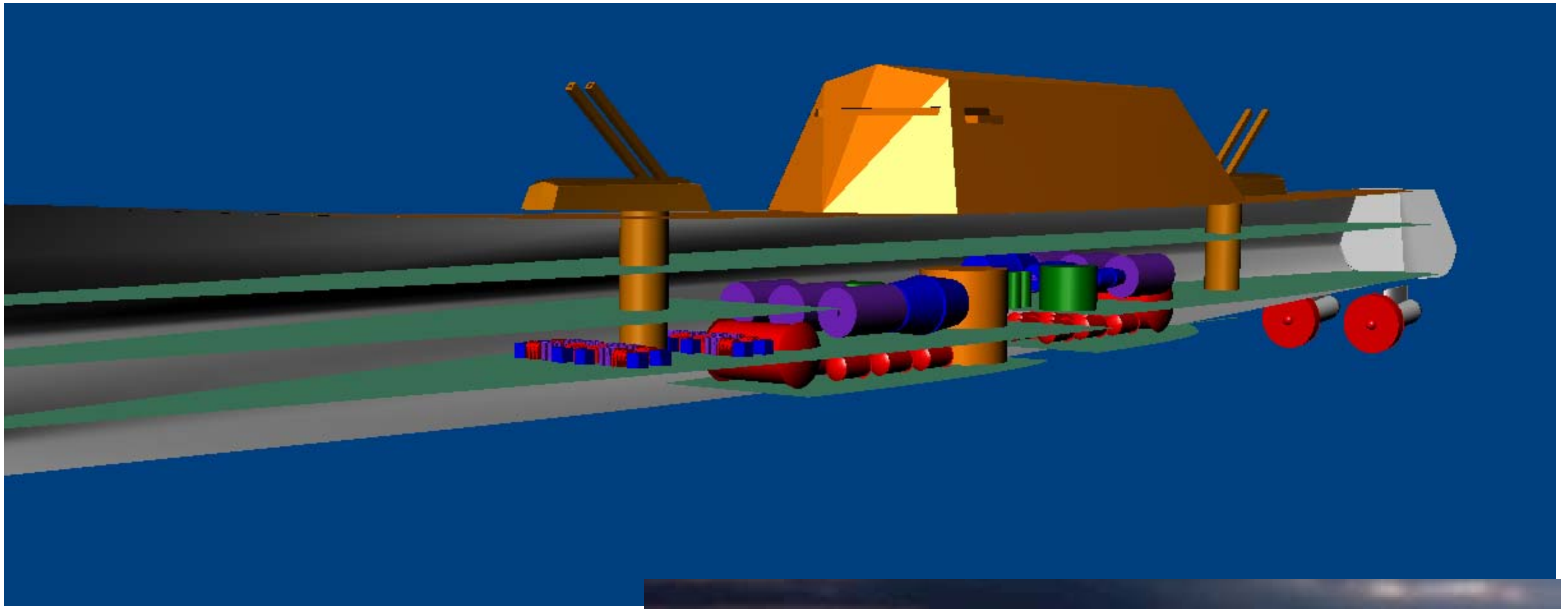


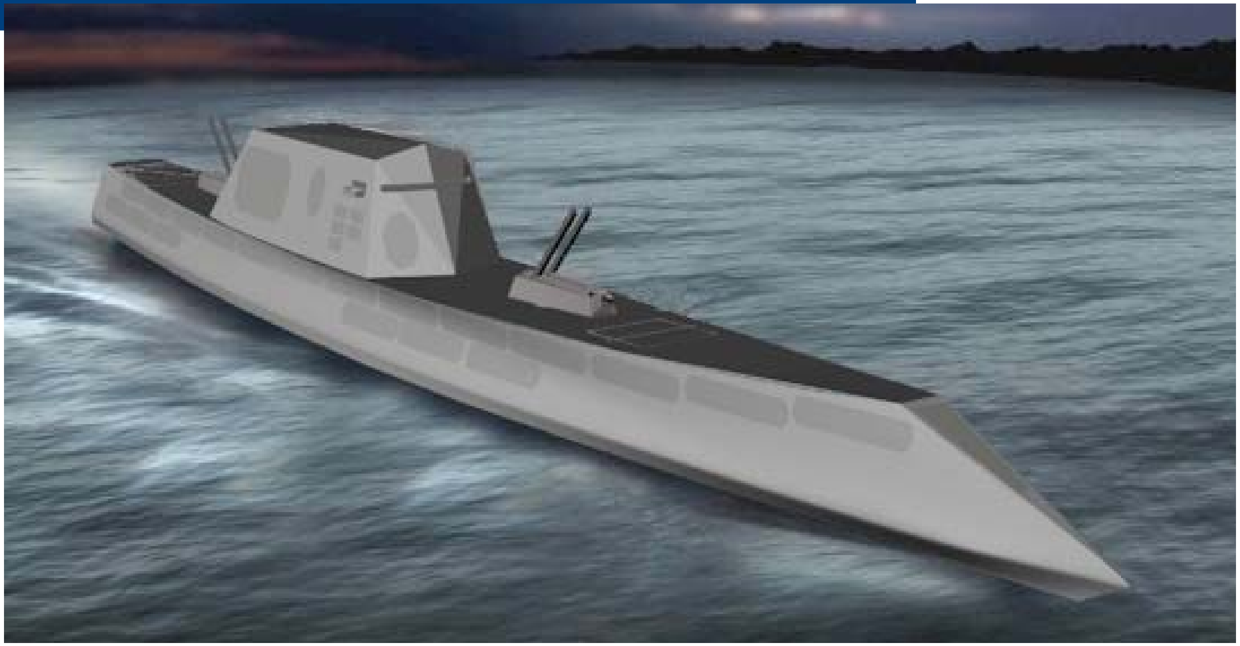
Reduction in core size, complexity, fuel cost, and turbomachinery



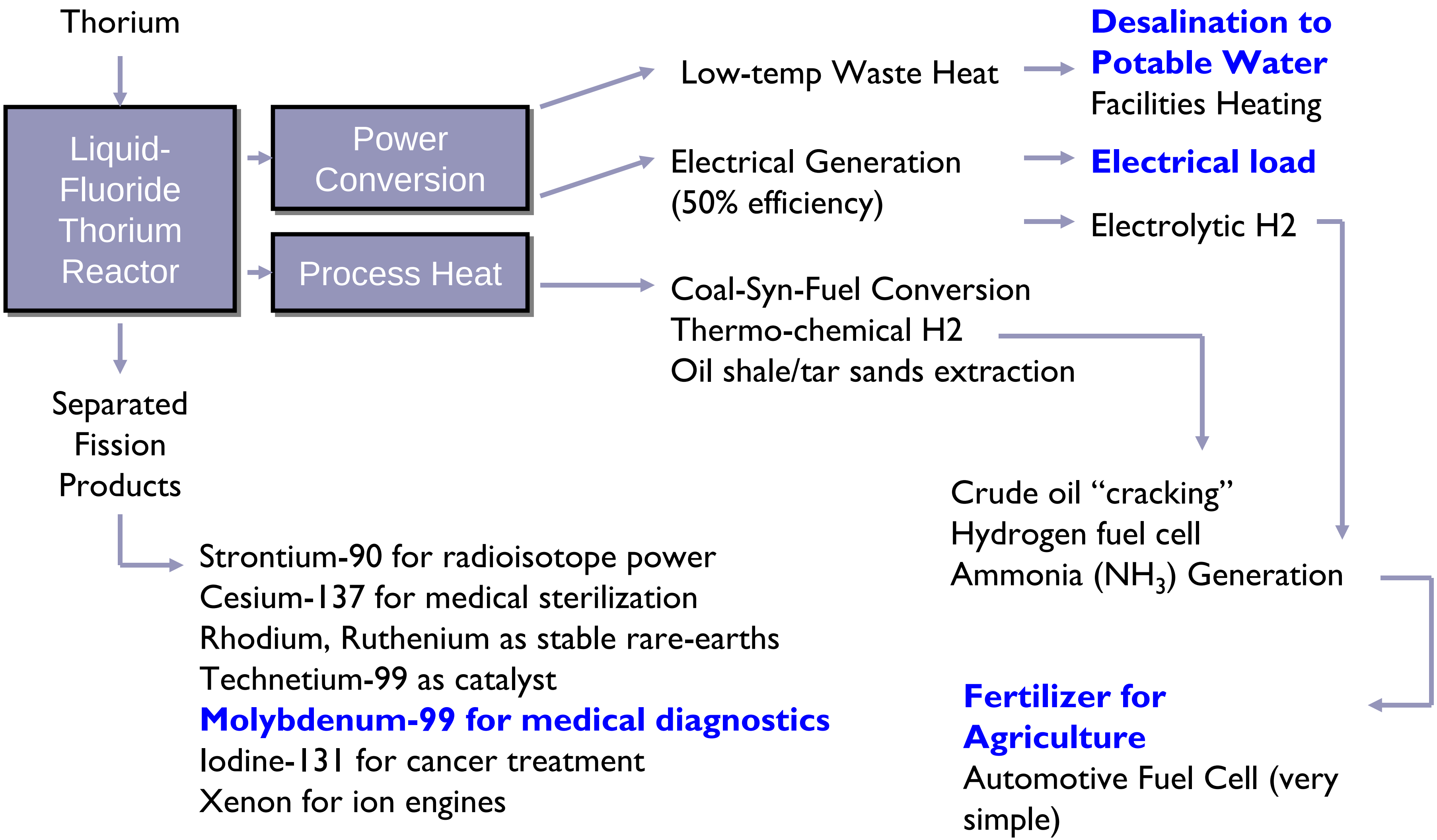
Fluoride-cooled reactor with helium gas turbine power conversion system

Recent Ship Designs at NPS have incorporated fluoride reactors



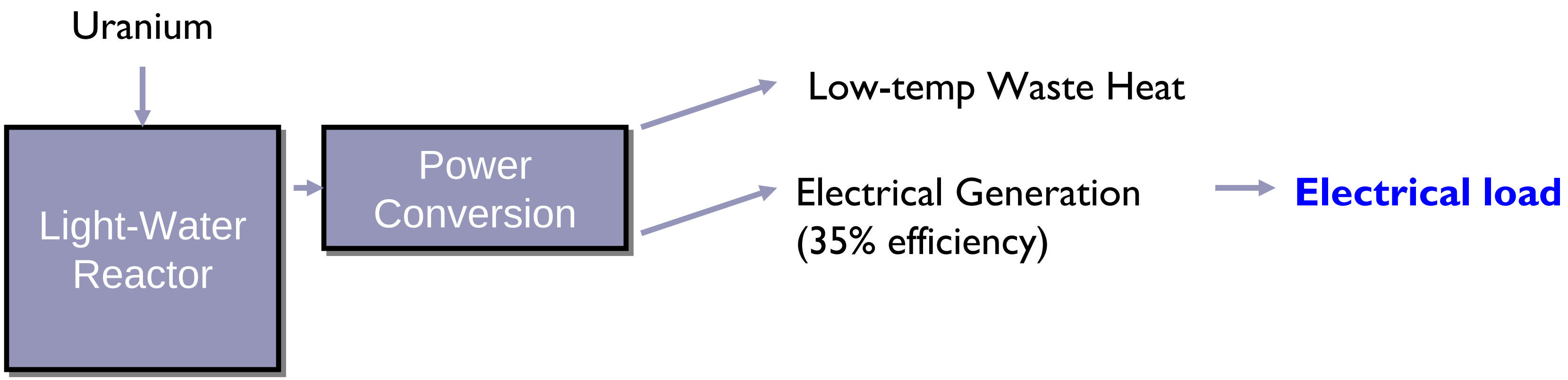


LFTR can produce many valuable by-products



These products may be as important as electricity production

The byproducts of conventional reactors are more limited



The New Era in Nuclear Energy Will be Led by Thorium

2008 → **2050**

- **Abundant, cost effective electricity**
- **Other products**
  - Hydrogen Production } Fuel/fuel cells
  - Ammonia Production } Fuel/fuel cells
  - Seawater Desalinization
  - Burnup Actinides

Present ~100 LWR In US

Thorium Based

- **~ 2000 LFTRs**
- **< 10% Coal**
- **< 10% Petroleum (electric cars)**
- **No Yucca Mtn**
- **Electricity and other products**

Current Trend

- **~ 150 LWRs**
- **> 70% Coal**
- **> 95% Petroleum (transportation)**
- **~2+ Yucca Mtn**

Ambitious Conventional Nuclear

- **~ 2000 LWRs (Not enough uranium!)**
- **< 10% Coal**
- **< 10% Petroleum (transportation)**
- **10+ Yucca Mtns**
- **Electricity Only**

2007 World Energy Consumption

5.3 billion tonnes of coal (128 quads)

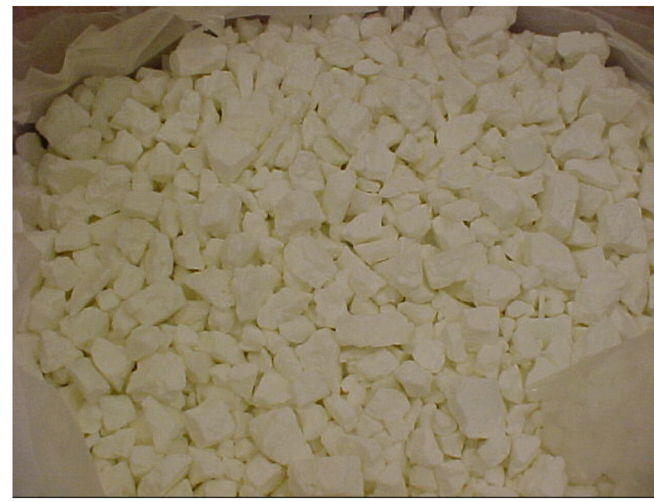
31.1 billion barrels of oil (180 quads)

2.92 trillion m^3 of natural gas (105 quads)

65,000 tonnes of uranium ore (24 quads)

The Future:

Energy from Thorium



6600 tonnes of thorium (500 quads)

Learn more at:

http://thoriumenergy.blogspot.com/

http://www.energyfromthorium.com/

Reference Material

Are Fluoride Salts Corrosive?

- **Fluoride salts are fluxing agents that rapidly dissolve protective layers of oxides and other materials.**
- **To avoid corrosion, molten salt coolants must be chosen that are thermodynamically stable relative to the materials of construction of the reactor; that is, the materials of construction are chemically noble relative to the salts.**
- **This limits the choice to highly thermodynamically-stable salts.**
- **This table shows the primary candidate fluorides suitable for a molten salt and their thermo-dynamic free energies of formation.**
- **The general rule to ensure that the materials of construction are compatible (noble) with respect to the salt is that the difference in the Gibbs free energy of formation between the salt and the container material should be >20 kcal/(mole ºC).**

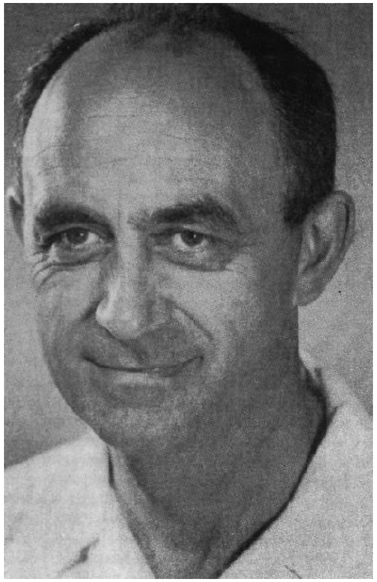
Table 2. Properties of Fluorides for Use in High-Temperature Reactors

Compound	Free Energy of Formation at 1000°K (kcal/F atom)	Melting Point (°C)	Absorption Cross Section[a] for Thermal Neutrons (barns)
Structural metal fluorides			
CrF_2	−74	1100	3.1
FeF_2	−66.5	930	2.5
NiF_2	−58	1330	4.6
Diluent fluorides			
CaF_2	−125	1330	0.43
LiF	−125	870	0.033[b]
BaF_2	−124	1280	1.17
SrF_2	−123	1400	1.16
CeF_3	−118	1324	0.7
YF_3	−113	1144	1.27
MgF_2	−113	1270	0.063
RbF	−112	790	0.70
NaF	−112	1000	0.53
KF	−109	880	1.97
BeF_2	−104	545	0.010
ZrF_4	−94	912	0.180
AlF_3	−90	1040	0.23
ZnF_2	−71	872	1.06
SnF_2	−62	213	0.6
PbF_2	−62	850	0.17
BiF_3	−50	727	0.032
Active fluorides			
ThF_4	−101	1115	
UF_4	−95.3	1035	
UF_3	−100.4	1495	

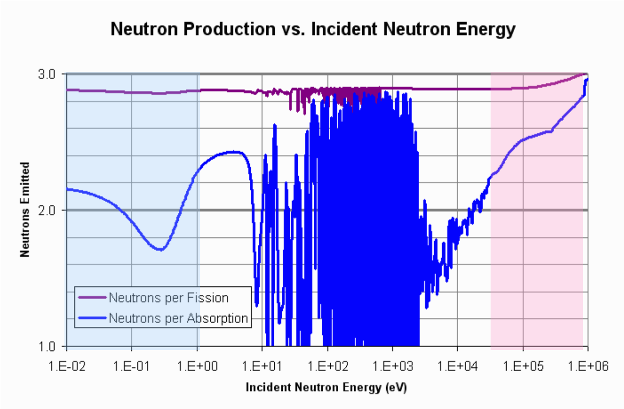
[a]Of metallic ion.

[b]Cross section for ^{7}Li.

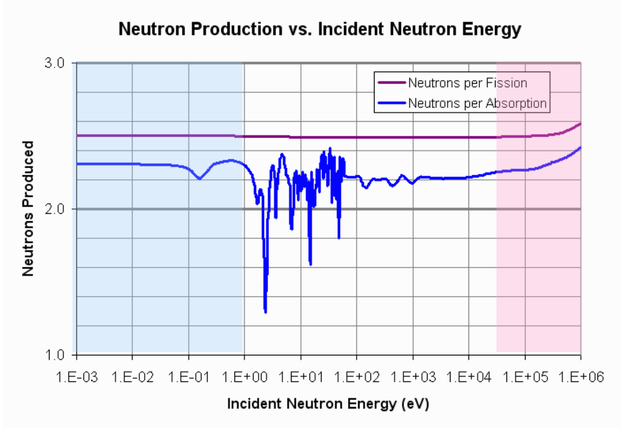
1944: A tale of two isotopes…



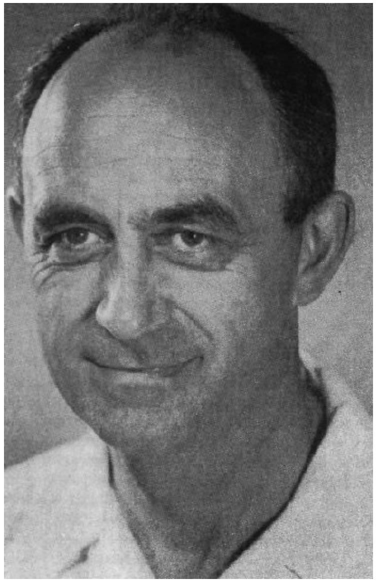
- Enrico Fermi argued for a program of fast-breeder reactors using uranium-238 as the fertile material and plutonium-239 as the fissile material.
- His argument was based on the breeding ratio of Pu-239 at fast neutron energies.
- Argonne National Lab followed Fermi's path and built the EBR-1 and EBR-2.



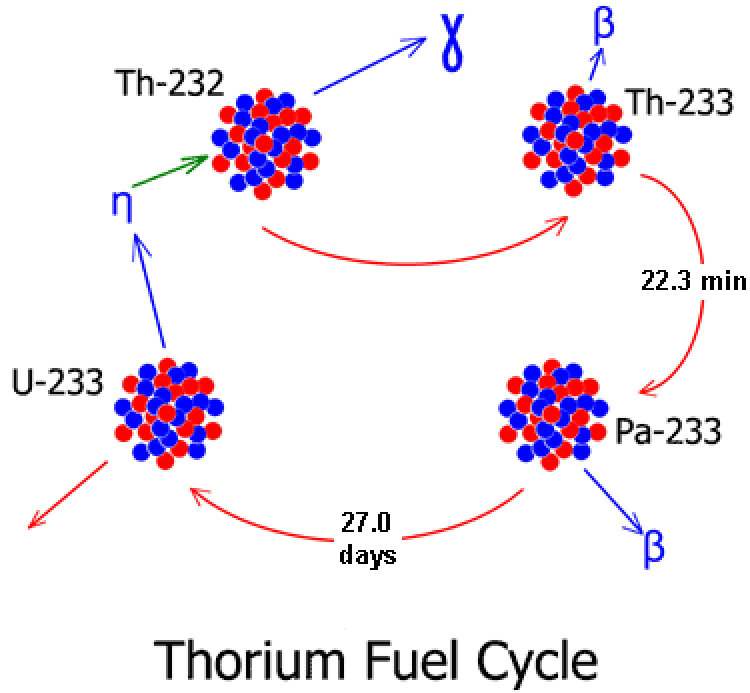
- Eugene Wigner argued for a thermal-breeder program using thorium as the fertile material and U-233 as the fissile material.
- Although large breeding gains were not possible, THERMAL breeding was possible, with enhanced safety.
- Wigner's protégé, Alvin Weinberg, followed Wigner's path at the Oak Ridge National Lab.



1944: A tale of two isotopes…

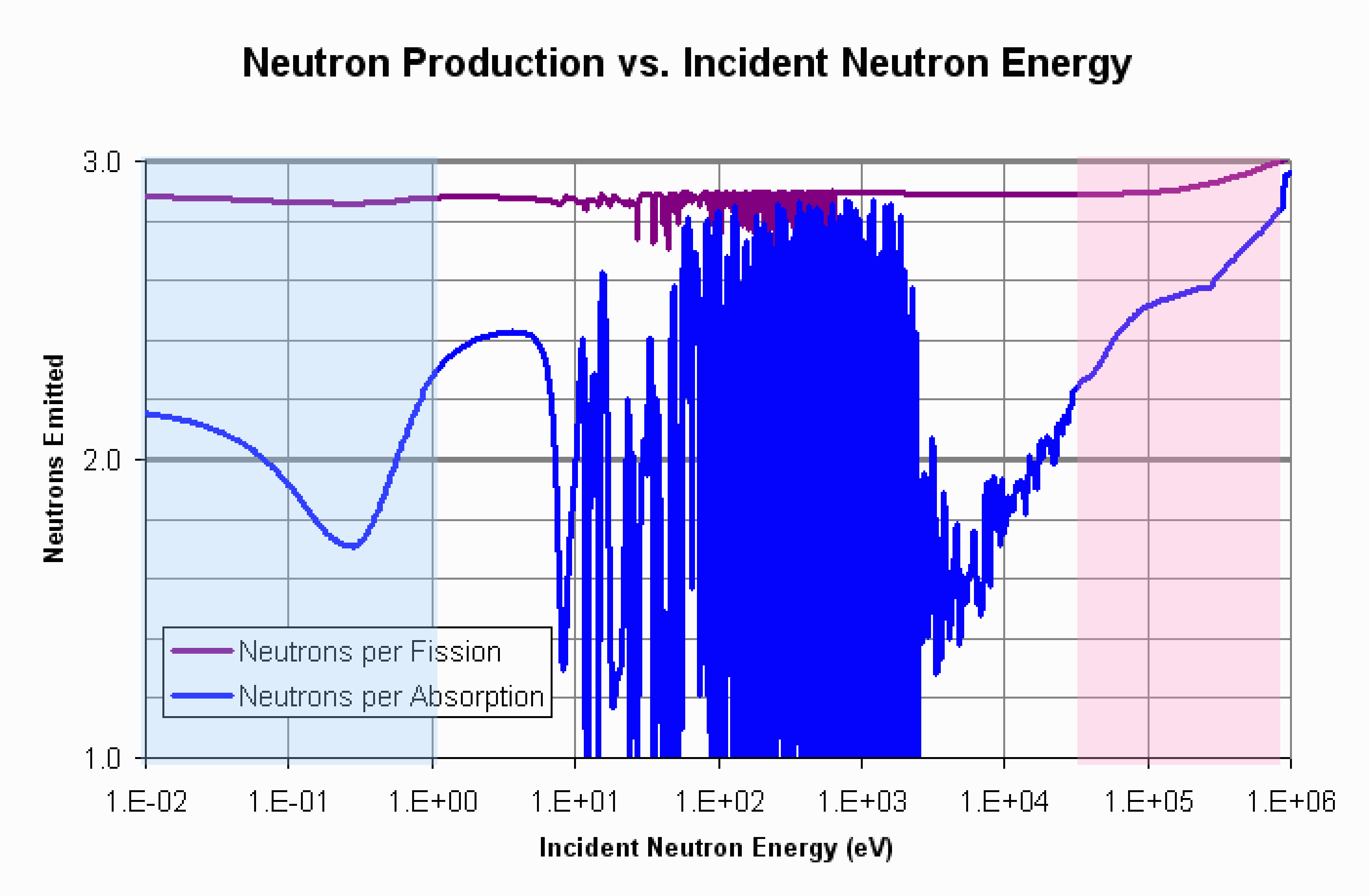


"But Eugene, how will you reprocess the fuel fast enough to prevent neutron losses to protactinium-233?"



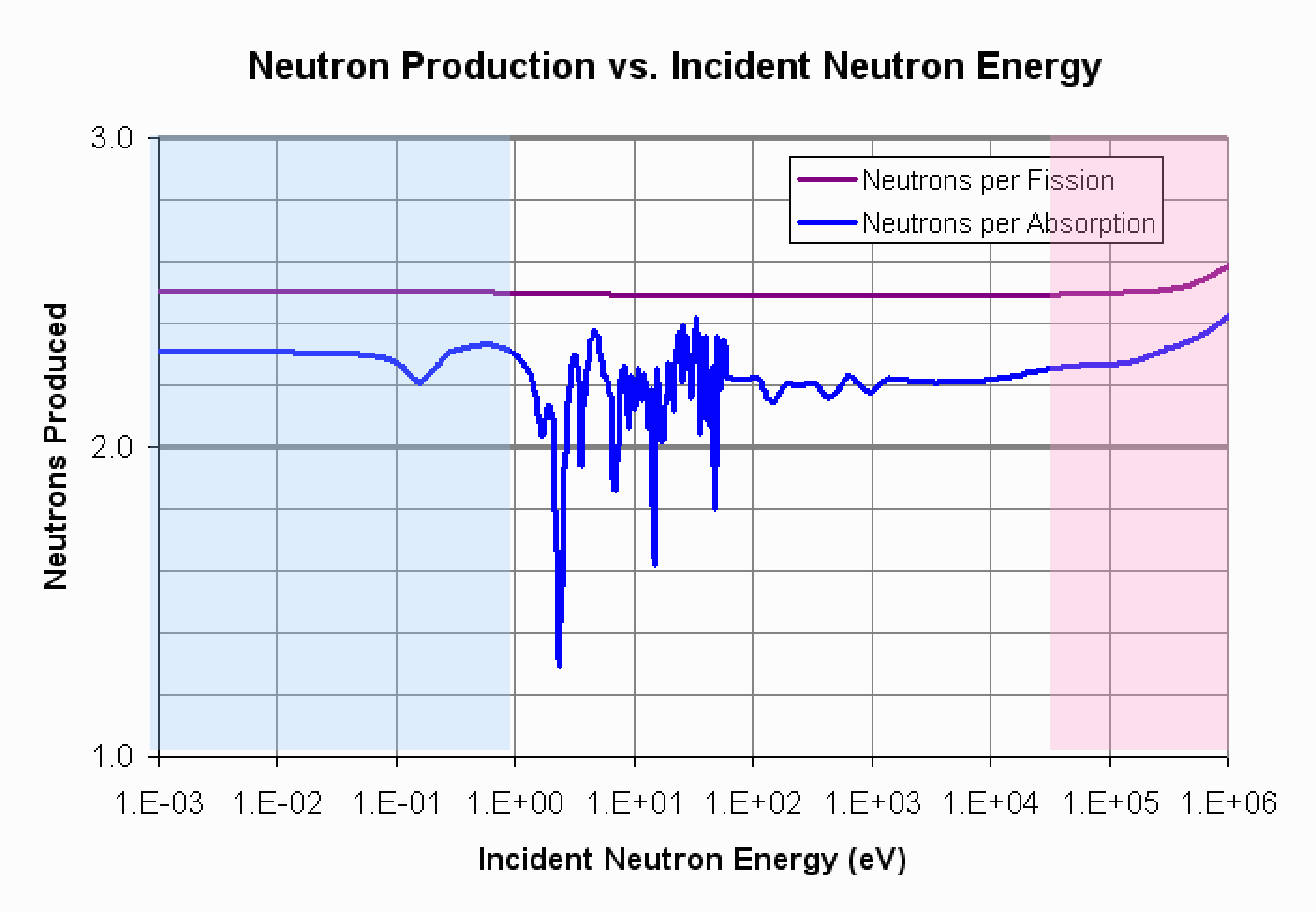
"We'll build a fluid-fueled reactor, that's how…"

Can Nuclear Reactions be Sustained in Natural Uranium?



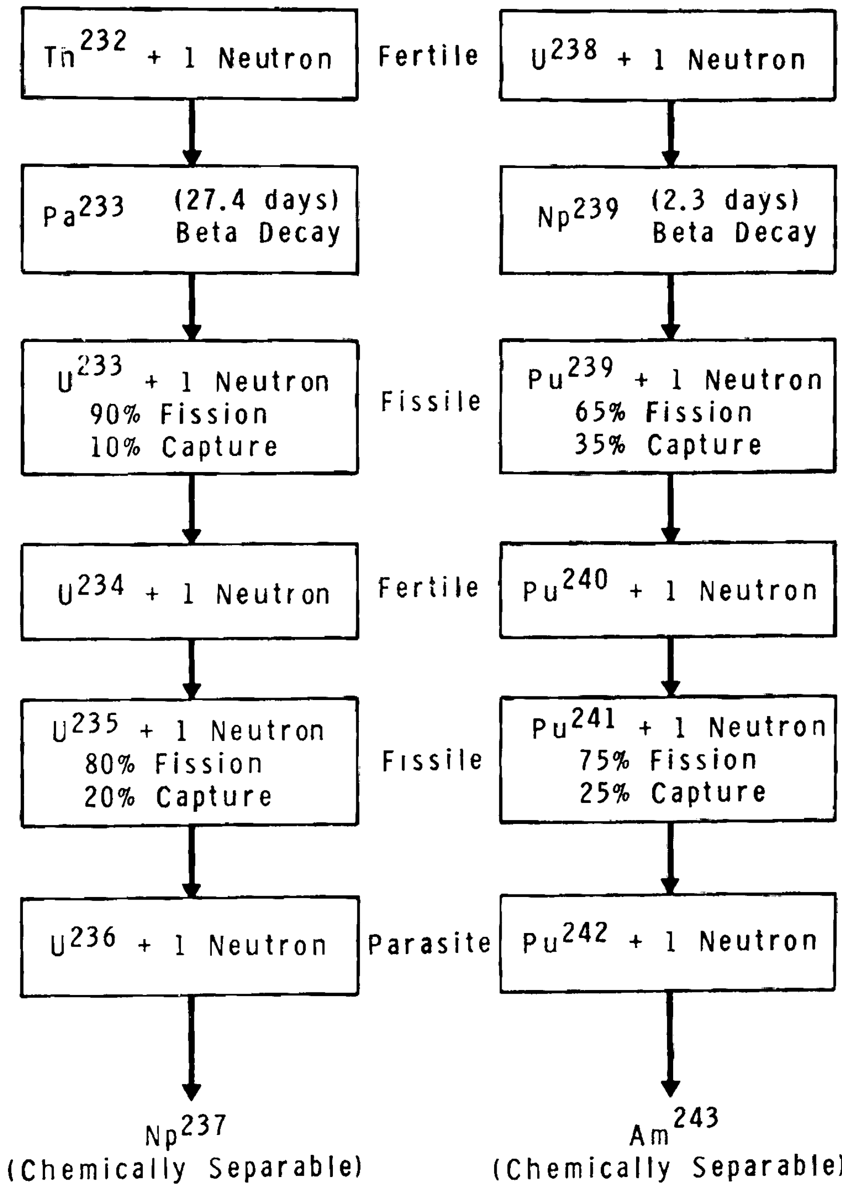
Not with thermal neutrons—need more than 2 neutrons to sustain reaction (one for conversion, one for fission)—not enough neutrons produced at thermal energies. Must use fast neutron reactors.

Can Nuclear Reactions be Sustained in Natural Thorium?

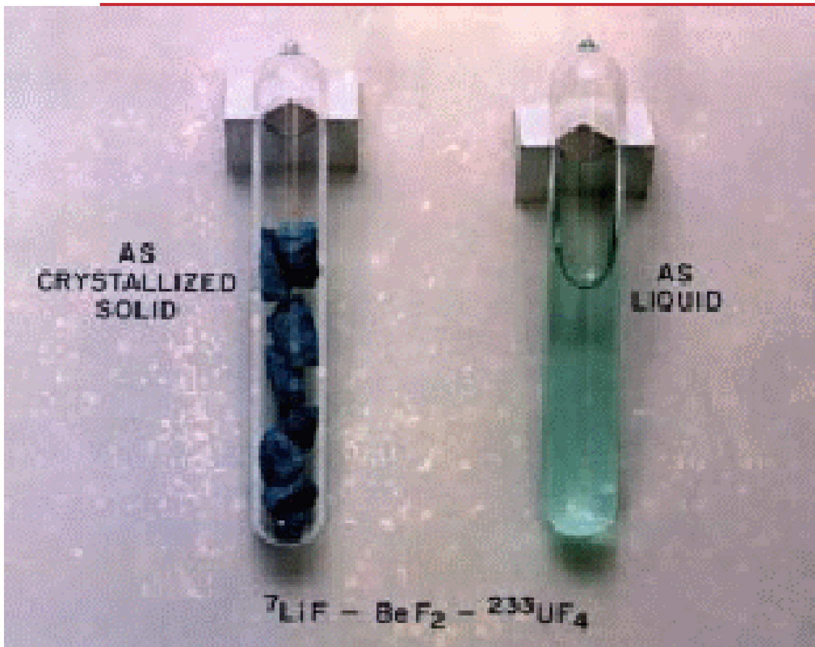


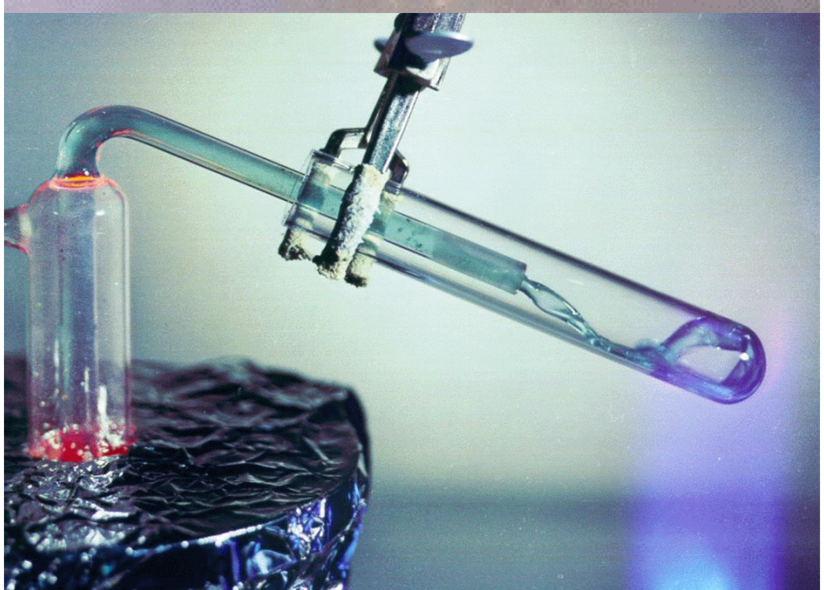
Yes! Enough neutrons to sustain reaction produced at thermal fission.
Does not need fast neutron reactors—needs neutronic efficiency.

"Incomplete Combustion"



The Birth of the Liquid-Fluoride Reactor





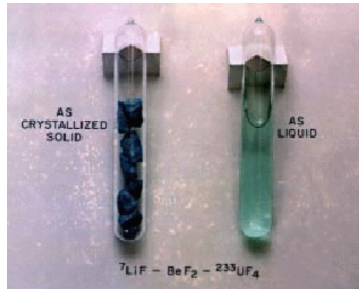
The liquid-fluoride nuclear reactor was invented by Ed Bettis and Ray Briant of ORNL in 1950 to meet the unique needs of the Aircraft Nuclear Program.

Fluorides of the alkali metals were used as the solvent into which fluorides of uranium and thorium were dissolved. In liquid form, the salt had some extraordinary properties!

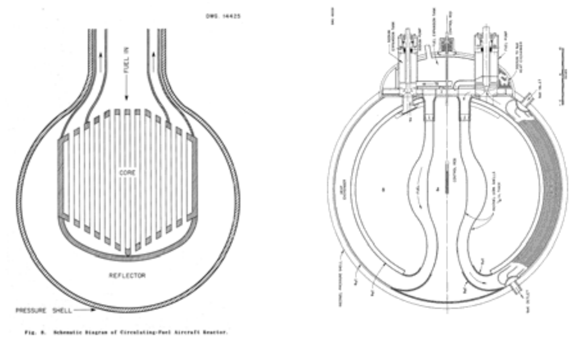
- **Very high negative reactivity coefficient**
  - **Hot salt expands and becomes less critical**
  - **Reactor power would follow the load (the aircraft engine) without the use of control rods!**
- **Salts were stable at high temperature**
  - **Electronegative fluorine and electropositive alkali metals formed salts that were exceptionally stable**
  - **Low vapor pressure at high temperature**
  - **Salts were resistant to radiolytic decomposition**
  - **Did not corrode or oxidize reactor structures**
- **Salts were easy to pump, cool, and process**
  - **Chemical reprocessing was much easier in fluid form**
  - **Poison buildup reduced; breeding enhanced**
  - **"A pot, a pipe, and a pump…"**

ORNL Aircraft Nuclear Reactor Progress (1949-1960)

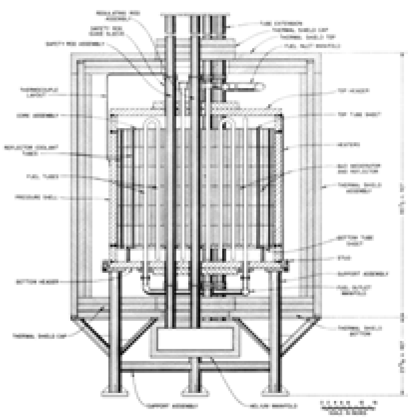
1949 – Nuclear Aircraft Concept formulated



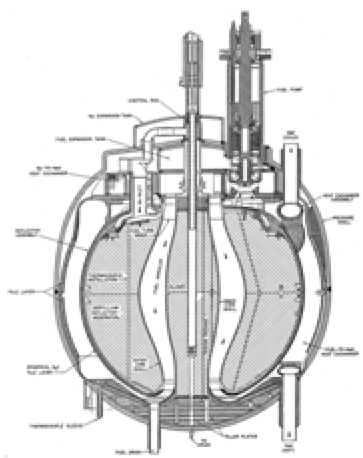
1951 – R.C. Briant proposed Liquid-Fluoride Reactor



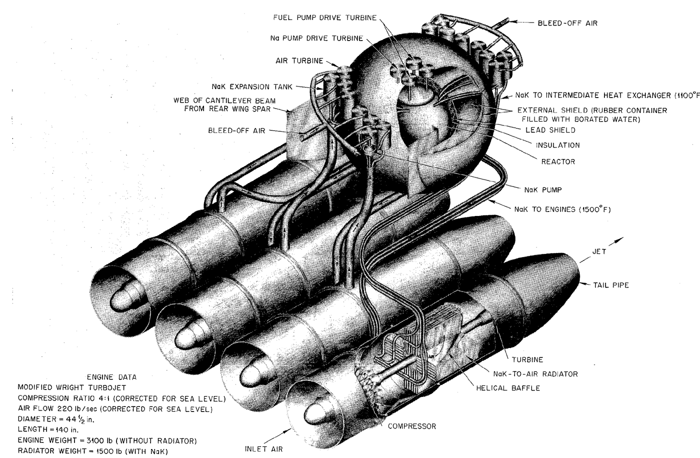
1952, 1953 – Early designs for aircraft fluoride reactor



1954 – Aircraft Reactor Experiment (ARE) built and operated successfully (2500 kWt, 1150K)



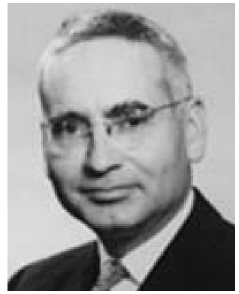
1955 – 60 MWt Aircraft Reactor Test (ART, "Fireball") proposed for aircraft reactor



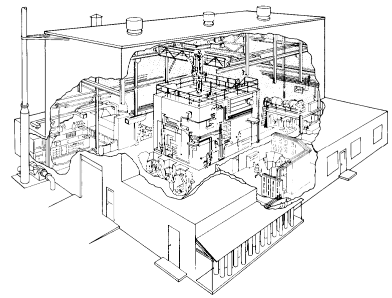
1960 – Nuclear Aircraft Program cancelled in favor of ICBMs

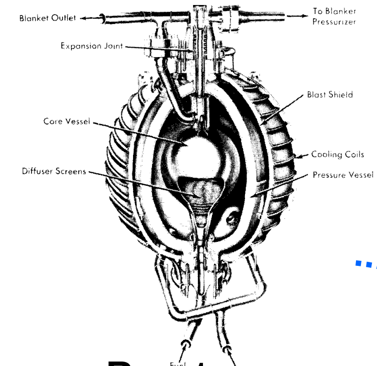
ORNL Fluid-Fueled Thorium Reactor Progress (1947-1960)

1947 – Eugene Wigner proposes a fluid-fueled thorium reactor



1950 – Alvin Weinberg becomes ORNL director





1952 – Homogeneous Reactor Experiment (HRE-1) built and operated successfully (100 kWe, 550K)

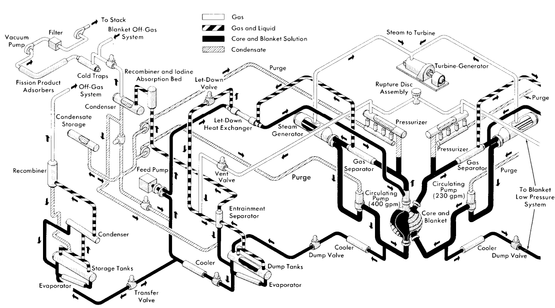


Fig. 7-7. Flowsheet of HRE-2.

1958 – Homogeneous Reactor Experiment-2 proposed with 5 MW of power

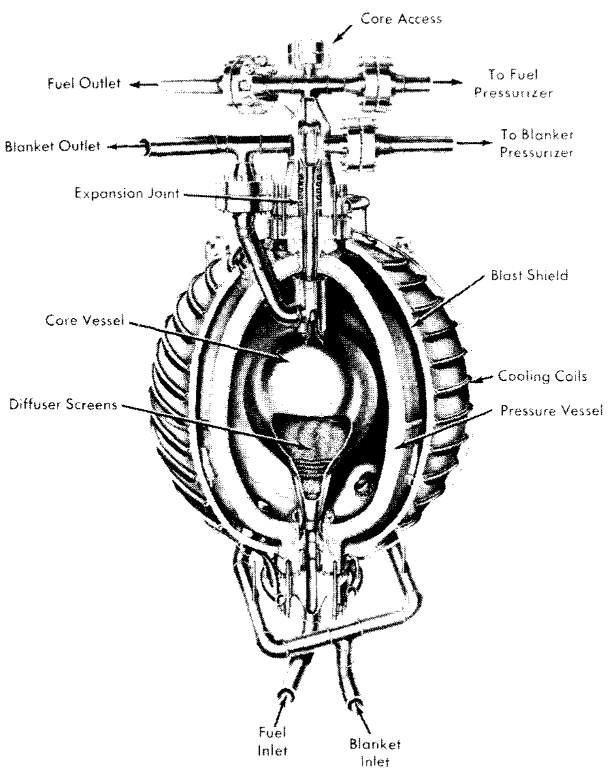
1959 – AEC convenes “Fluid Fuels Task Force” to choose between aqueous homogeneous reactor, liquid fluoride, and liquid-metal-fueled reactor. Fluoride reactor is chosen and AHR is cancelled.

Weinberg attempts to keep both aqueous and fluoride reactor efforts going in parallel but ultimately decides to pursue fluoride reactor.

Fluid-Fueled Reactors for Thorium Energy

Aqueous Homogenous Reactor (ORNL)

- Uranyl sulfate dissolved in pressurized heavy water.
- Thorium oxide in a slurry.
- Two built and operated.



Liquid-Fluoride Reactor (ORNL)

- Uranium tetrafluoride dissolved in lithium fluoride/beryllium fluoride.
- Thorium dissolved as a tetrafluoride.
- Two built and operated.

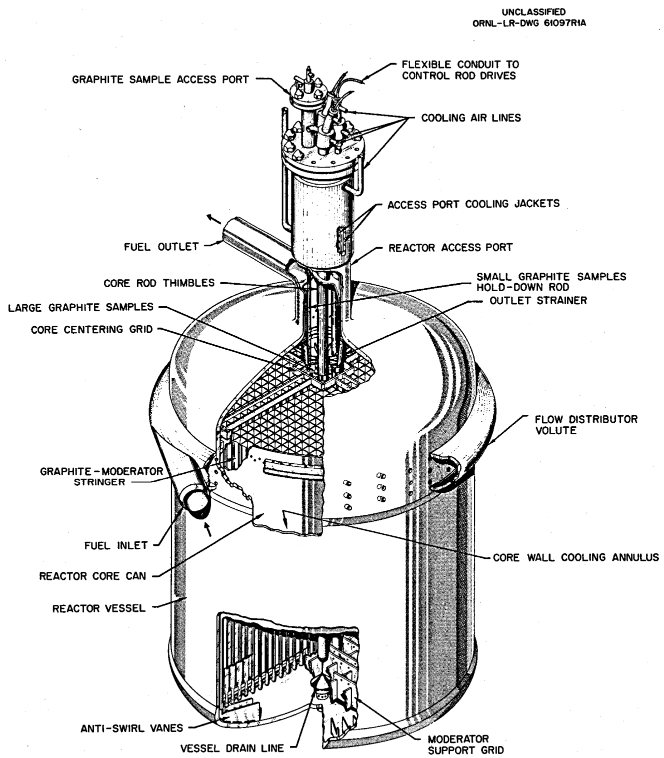
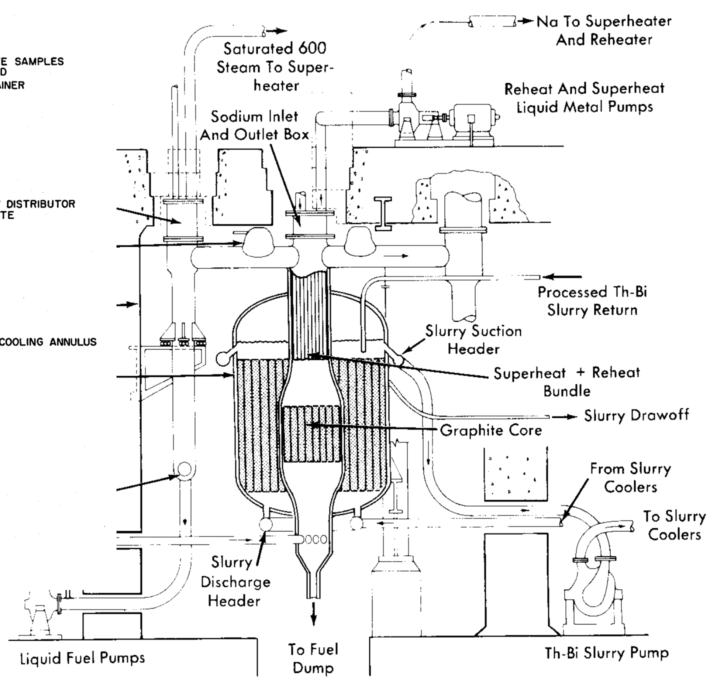


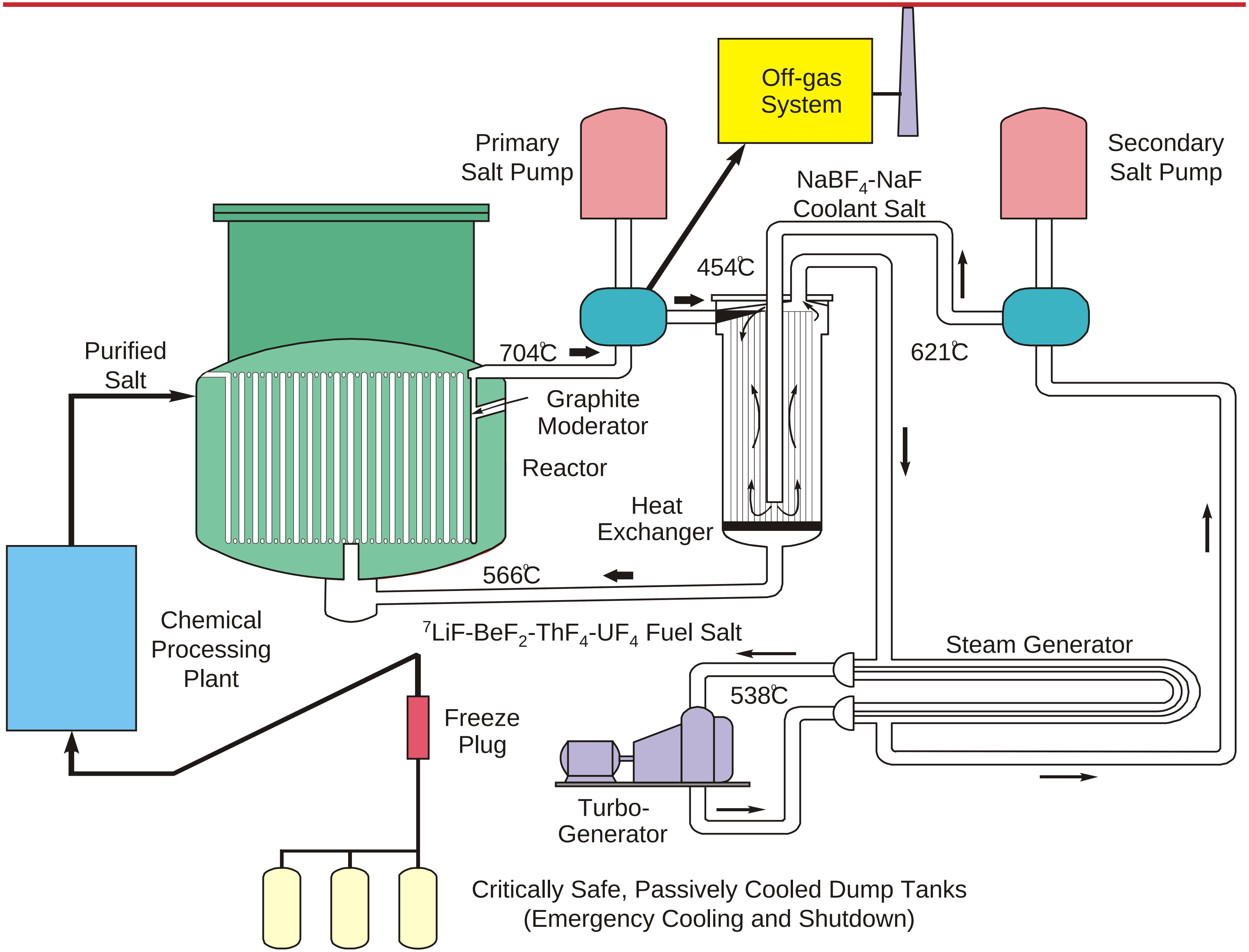
Fig. 6. MSRE Reactor Vessel.

Liquid-Metal Fuel Reactor (BNL)

- Uranium metal dissolved in bismuth metal.
- Thorium oxide in a slurry.
- Conceptual—none built and operated.



1972 Reference Molten-Salt Breeder Reactor Design



A single mine site in Idaho could recover 4500 MT of thorium per year

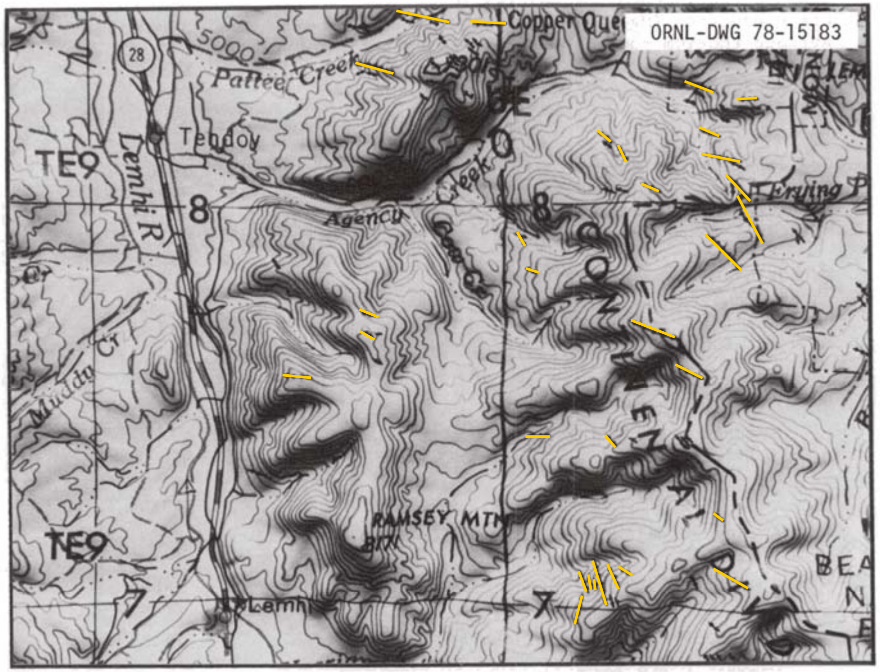


Fig. 3.1. Identified vein deposits of thorium ore in the vicinity of the Lemhi Pass. (Photograph of selected portion of relief map titled Dubois, Idaho, NL12-10, Hubbard Co., Northbrook, Illinois 60062.) Deposit locations identified by (●–●–●).

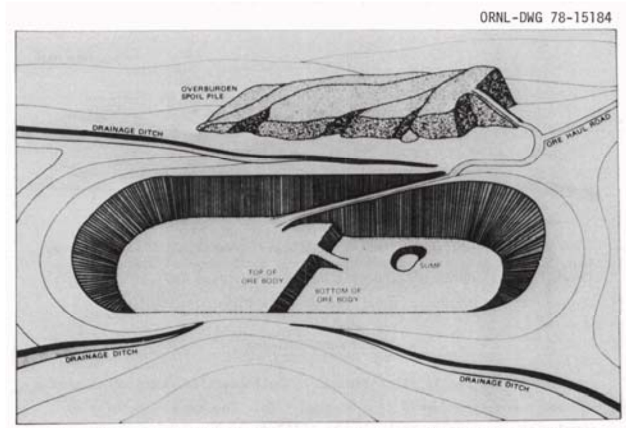


Fig. 3.2. Typical features of open-pit mine. (Taken from Tennessee Valley Authority Final Environmental Statement, Morton Ranch Uranium Mine.)

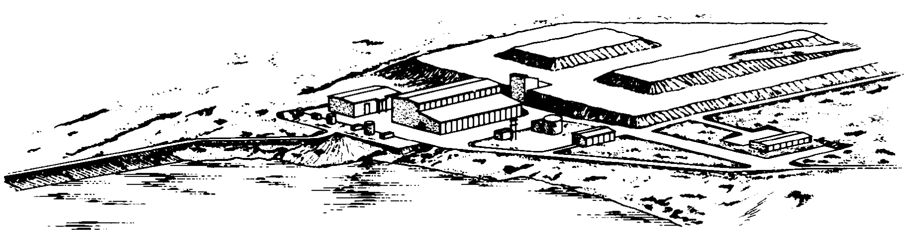


Fig. 3.3. Artist's rendition of ore-treatment mill. (Taken from U.S. Nuclear Regulatory Commission, Final Environmental Statement Bear Creek Project, NUREG-0129, Docket No. 40-8452, June 1977.)

ANWR times 6 in the Nevada desert

- Between 1957 and 1964, the Defense National Stockpile Center procured 3215 metric tonnes of thorium from suppliers in France and India.
- Recently, due to "lack of demand", they decided to bury this entire inventory at the Nevada Test Site.
- This thorium is equivalent to 240 quads of energy*, if completely consumed in a liquid-fluoride reactor.

*This is based on an energy release of ~200 Mev/232 amu and complete consumption. This energy can be converted to electricity at ~50% efficiency using a multiple-reheat helium gas turbine; or to hydrogen at ~50% efficiency using a thermo-chemical process such as the sulfur-iodine process.