

Chemical Engineering 412

Introductory Nuclear Engineering

Lecture 22

Nuclear Power Plants II

Other Nuclear Systems



Spiritual Thought

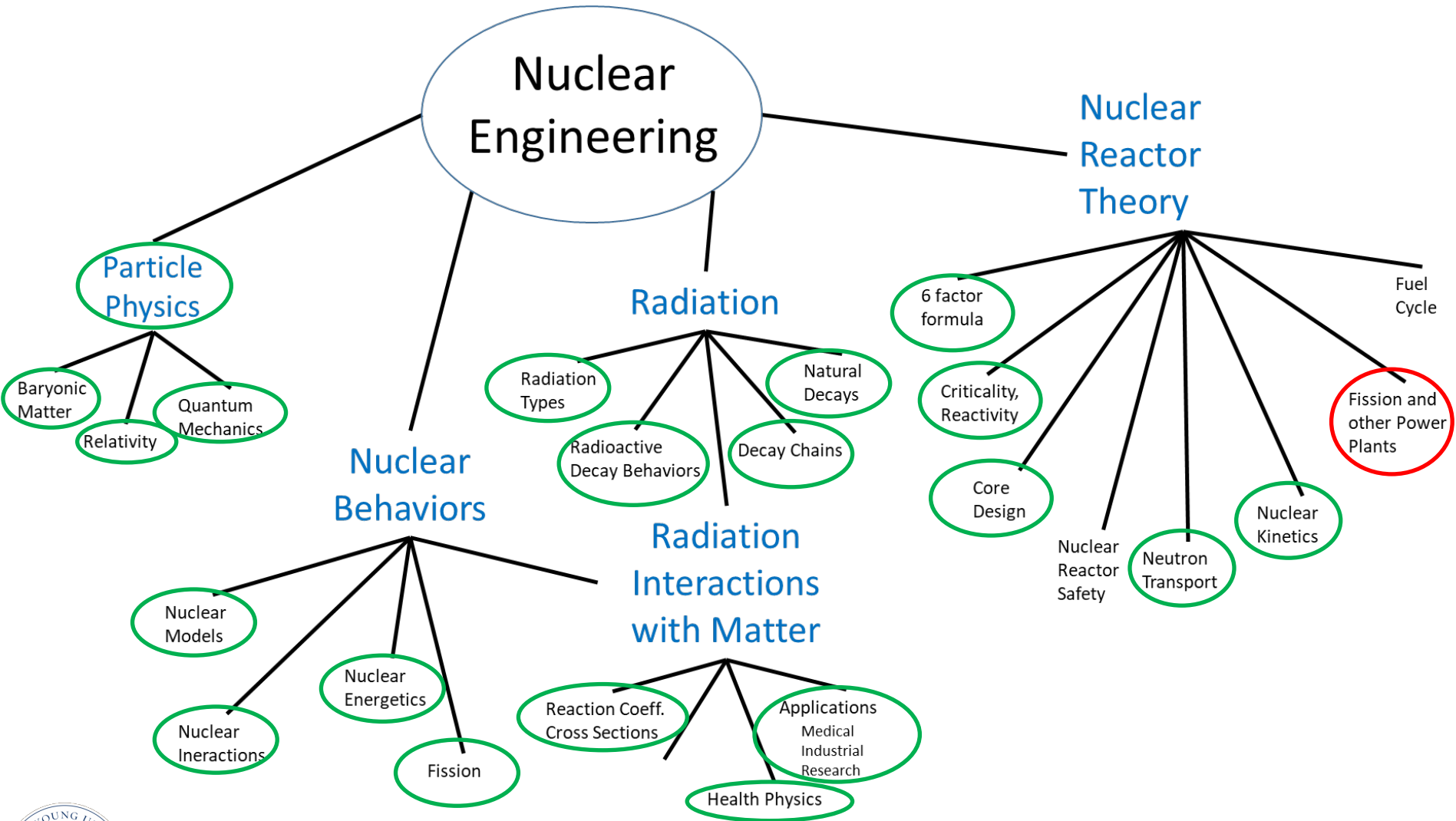
“...Each of us on earth, living under the stress and strain of this telestial climate, will have reason—real or perceived—to take offense. How will we react? Will we take offense? Will we find fault? Will we let the passions of the moment overcome us?

...When someone has hurt us or those we care about, that pain can almost be overwhelming. It can feel as if the pain or the injustice is the most important thing in the world and that we have no choice but to seek vengeance. But Christ, the Prince of Peace, teaches us a better way. It can be very difficult to forgive someone the harm they’ve done us, but when we do, we open ourselves up to a better future. No longer does someone else’s wrongdoing control our course. When we forgive others, it frees us to choose how we will live our own lives.”

– Elder David E. Sorensen



Roadmap



Generations I-IV

Generation I



Early Prototype Reactors

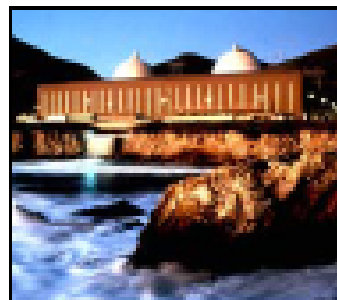


- Shippingport
- Dresden, Fermi I
- Magnox

Generation II



Commercial Power Reactors



- LWR-PWR, BWR
- CANDU
- AGR

Generation III



Advanced LWRs



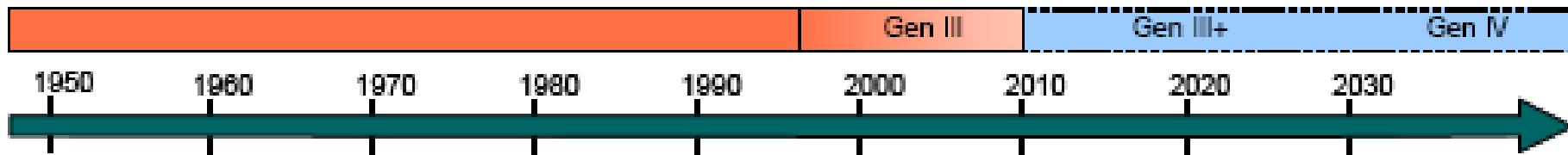
- ABWR
- System 80+

Generation III +

Evolutionary Designs Offering Improved Economics for Near-Term Deployment

Generation IV

- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant



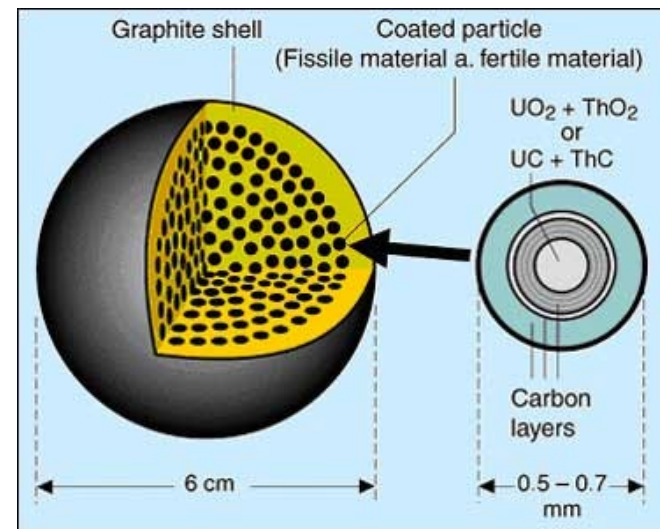
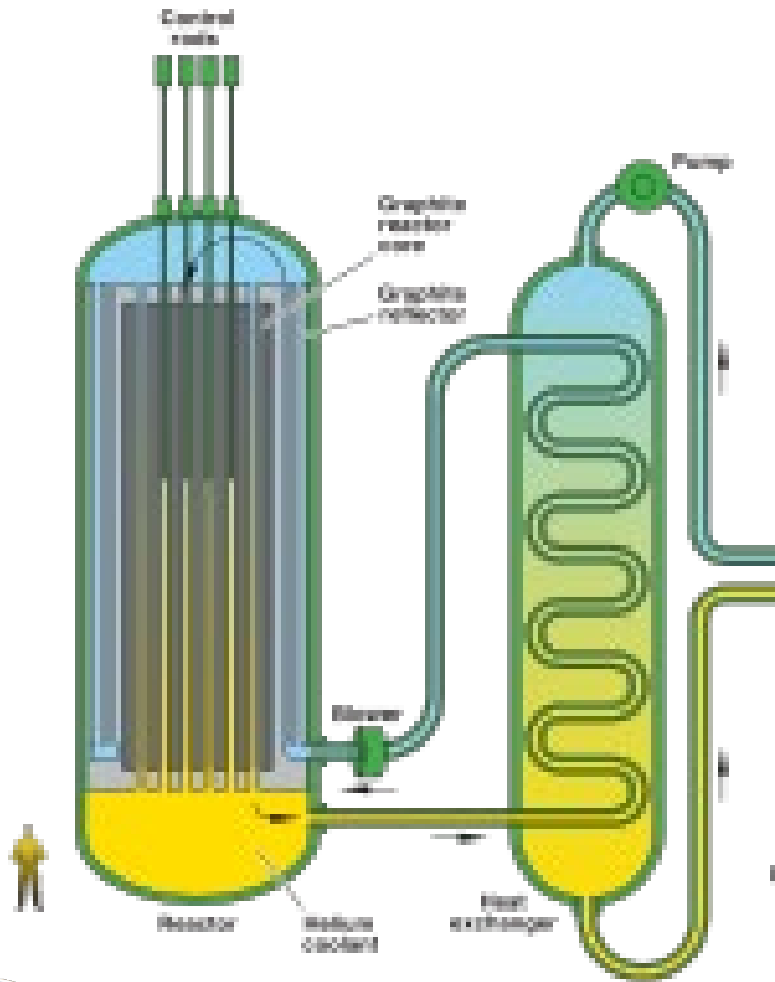
Generation IV

- Advanced reactors
 - Address and solve key issues of Gen III
- 6 primary types:
 - Gas Cooled Fast Reactors
 - Supercritical Water Reactors
 - Sodium Fast Reactors
 - Lead Fast Reactors
 - High Temperature Gas Reactors (Pebble Bed)
 - Molten Salt Reactors

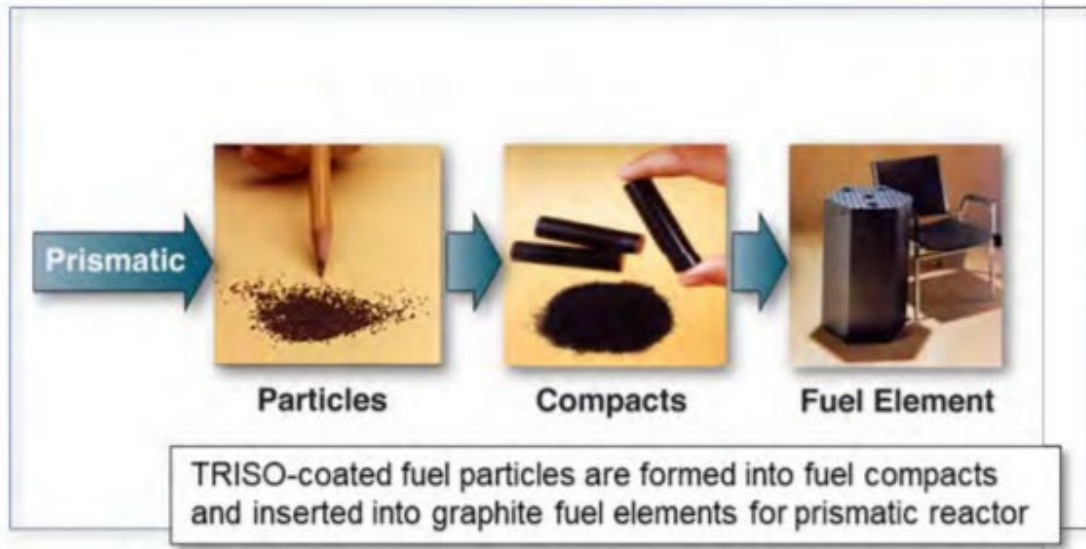
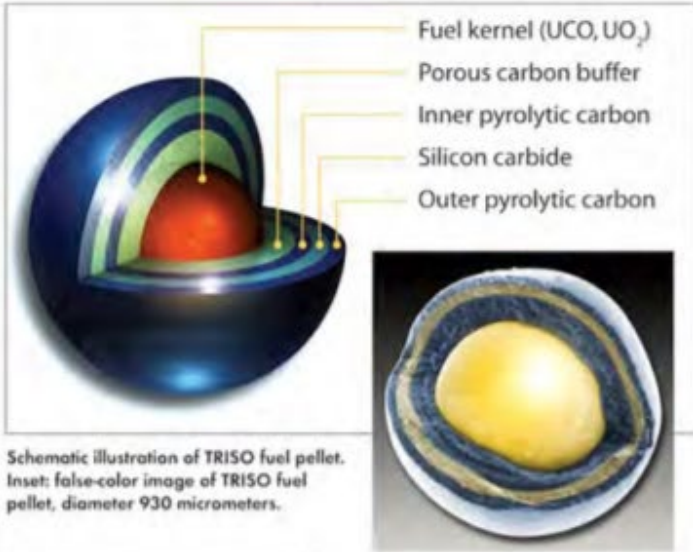


Very High Temperature Reactor

- $T_{\text{out}} = 1000^{\circ} \text{ C}$
- Gas cooled (He)
- Inherently safe
- Low Power Density
- Brayton Cycle



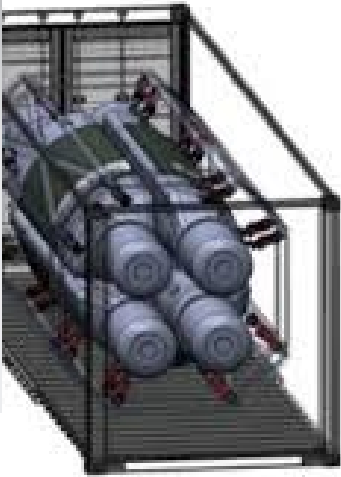
New fuel form - TRISO



X Energy Xenith Mobile Unit, 100MW



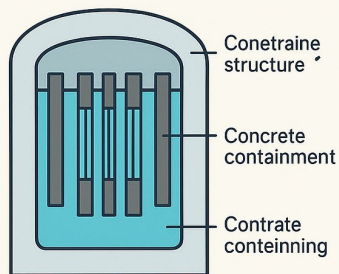
Radiant Energy – Kaleidos



Valar Atomics – Ward 250 100kW_{th}

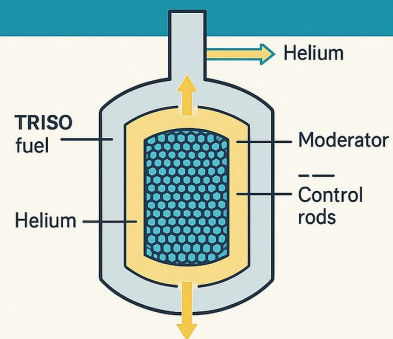


TRADITIONAL REACTOR



- Large, custom-built plant
- Water-cooled design

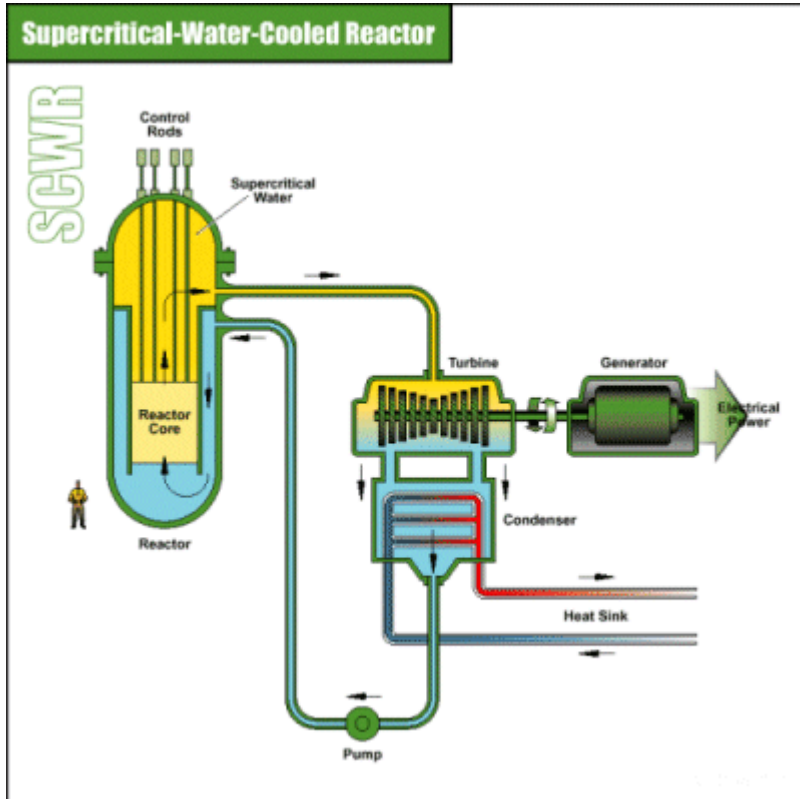
VALAR REACTOR



- Factory-manufactured modules
- Gas-cooled design

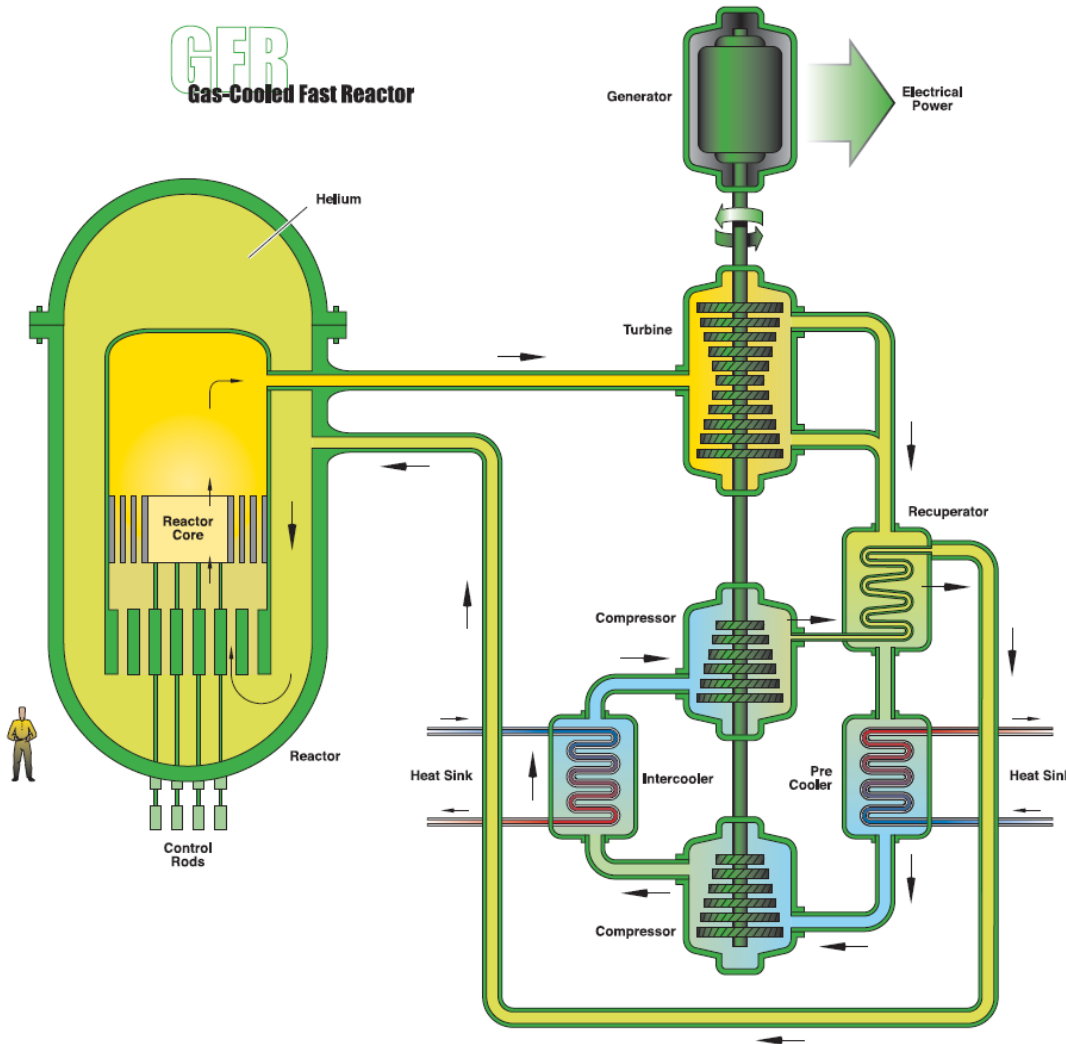


Supercritical-Water-Cooled Reactor



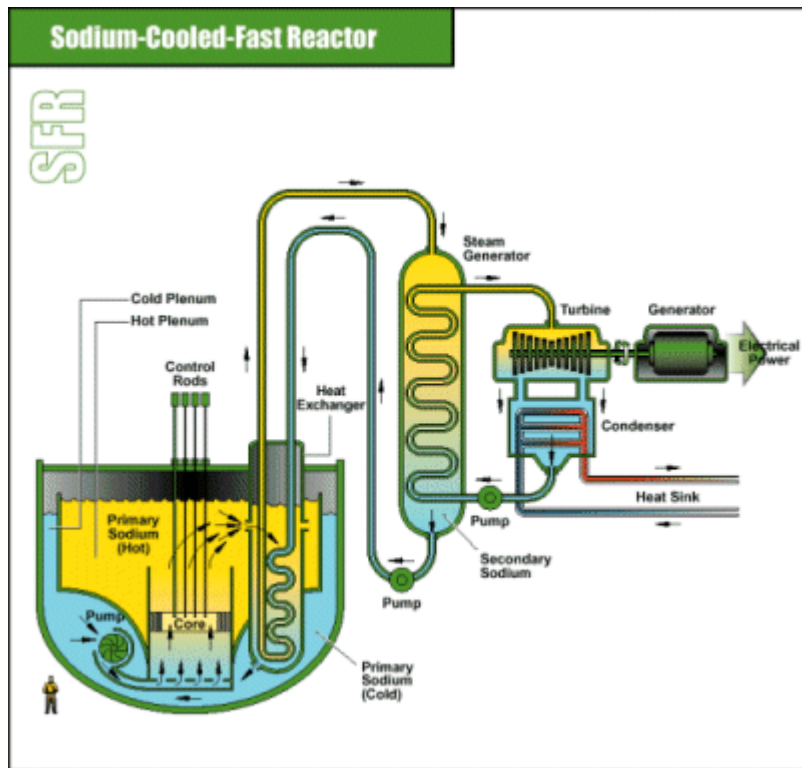
- SC Water (> 240 atm) for working fluid (similar to most modern coal boilers)
- 45% efficiency (compared to 33% in most current technologies)
- Combines LWR and fossil technology.

Gas-cooled Fast Reactor



- He cooled with direct Brayton cycle for high efficiency
- Closed fuel cycle
- Low Power Density
- Fuel Rods, ^{239}Pu

Sodium-Cooled Fast Reactor



- Eliminates the need for transuranic (Pu) isotopes from leaving site (by breeding and consuming Pu)
- Liquid sodium cooled reactor
- Fueled by U/Pu alloy
- Fuel Rods (Zr-Pu-U metallic fuel), ^{239}Pu

Fast Reactors - Advantages

- Most transuranics act as fuel
 - Reduces waste toxicity
 - Reduces waste lifetime (dramatically)
- Expand potential fuel –
 - Thermal is primarily odd-numbered actinides (^{235}U)
 - Fast is all actinides, including ^{238}U , Th, etc.
 - In waste
 - Depleted uranium
 - Actinides generated in the fuel
- When operated in breeder (as opposed to burner) mode, creates more fissionable fuel than it consumes, extending total available fuel.



Fast Reactors – Disadvantages

- Low response time
 - complicates control!
 - control rods less effective, other means must be used:
 - Fuel thermal expansion
 - Doppler broadening
 - Absorbers
 - Reflectors
 - Small cross sections – large critical mass
 - Leads to either large cores or high enrichment.
 - Sodium and sodium/potassium highly reactive!
 - Lead, salts and gases avoid this problem, but more absorption
 - Liquid metals and salts can become radioactive
 - (n, γ) reactions
 - ^4He avoids this problem (absorption cross section near zero).
- Potential positive void coefficient of liquids – not He.

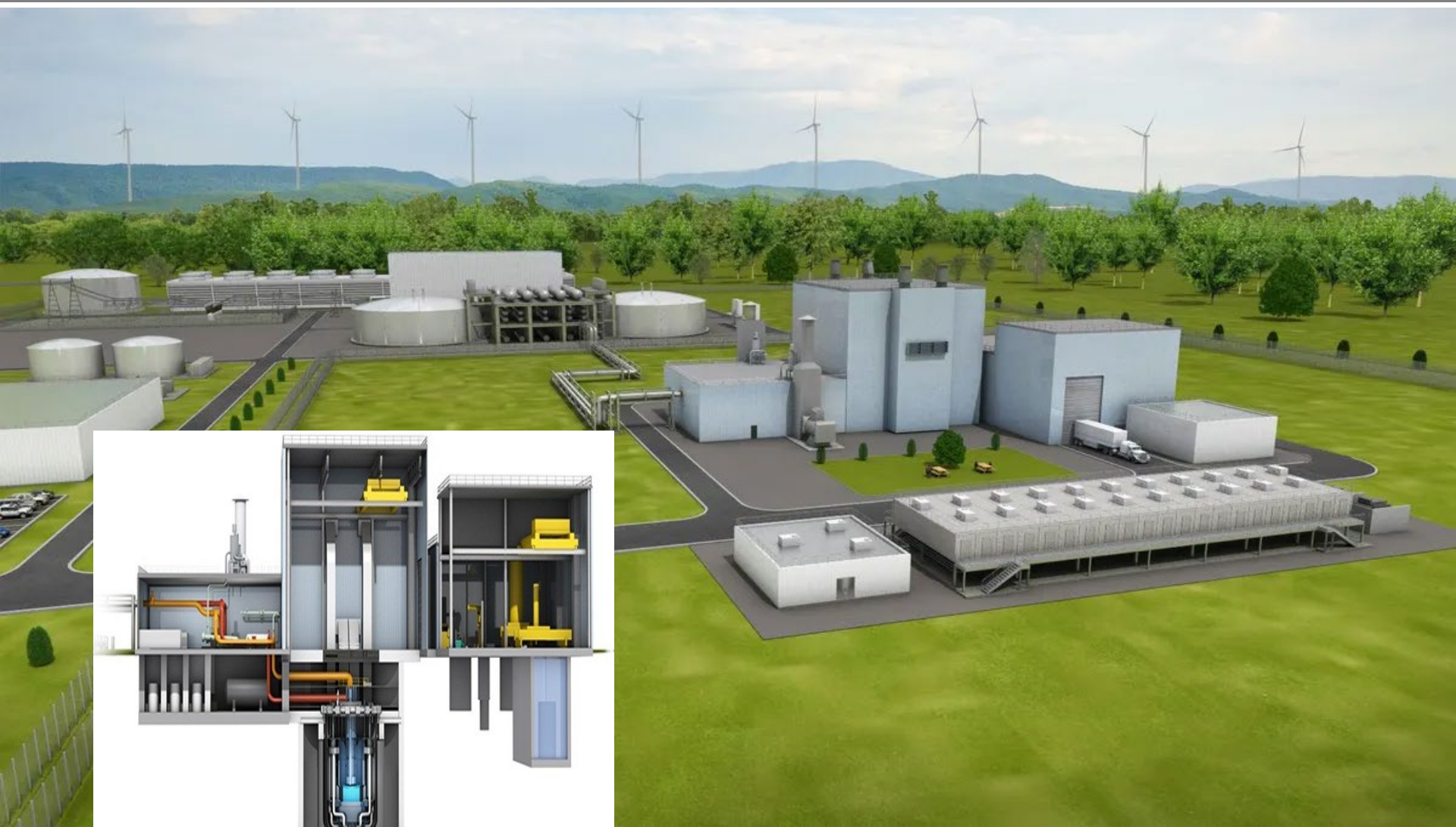


Conversion Ratio

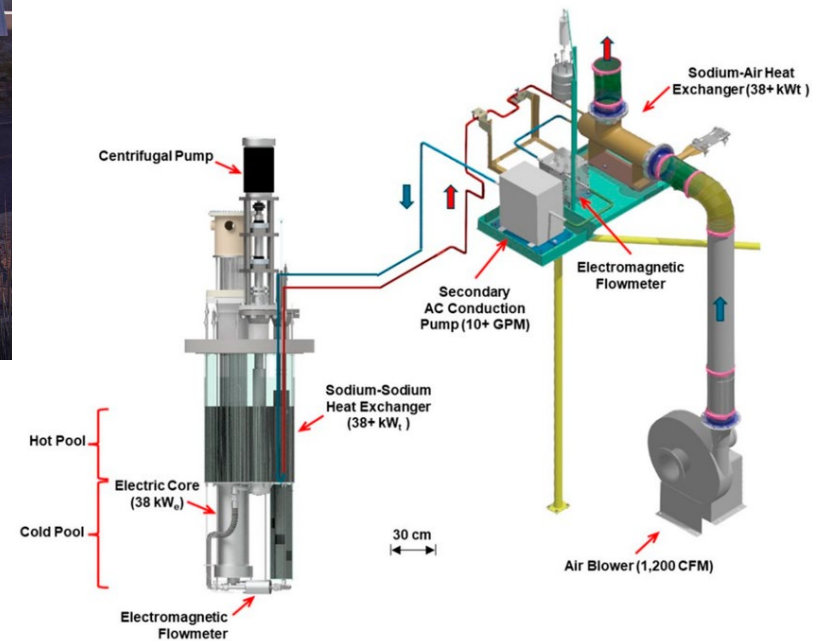
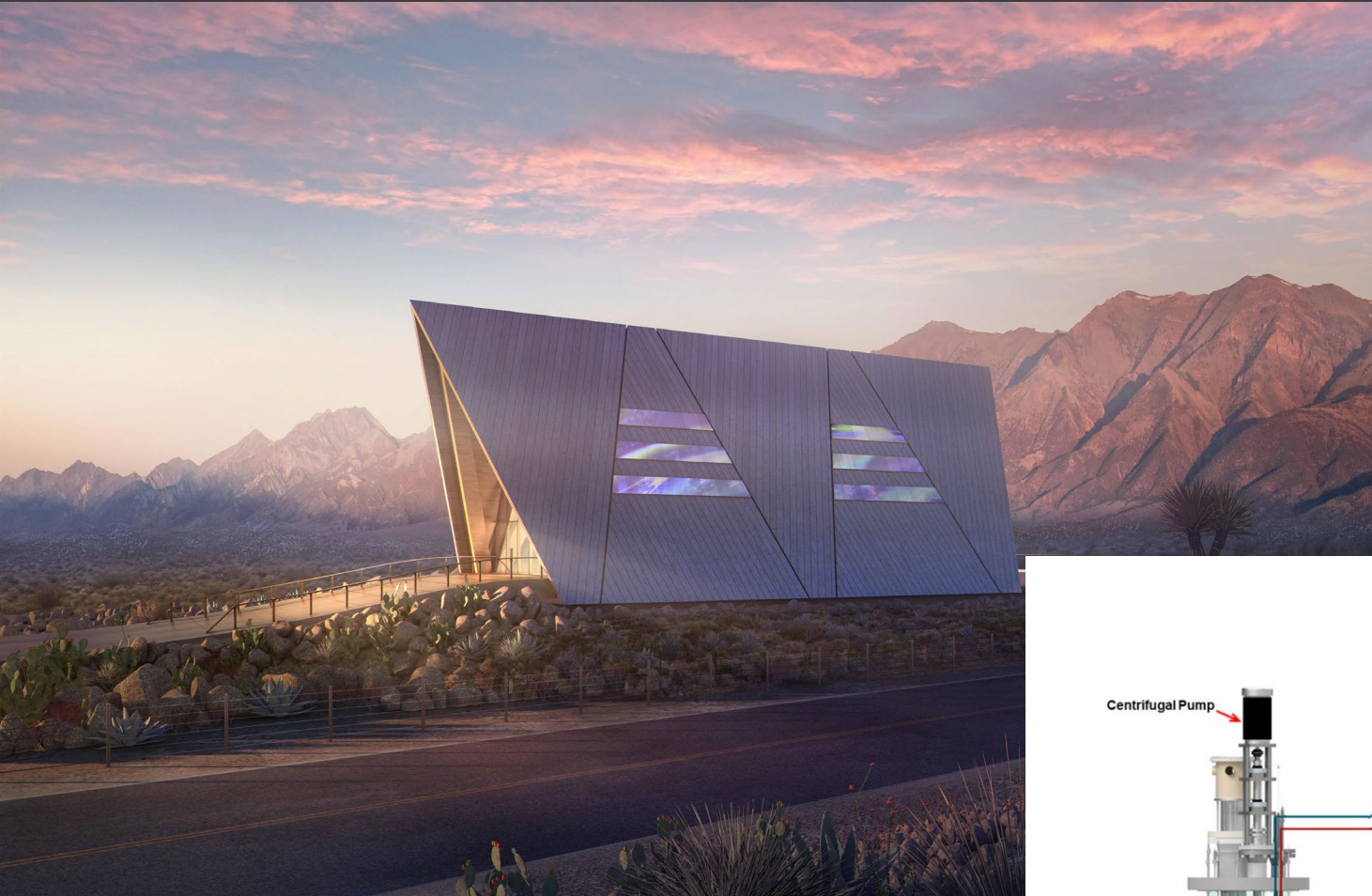
- Ratio of Created fuel to burned fuel
 - Breeder reactors 1.01 up to ~ 1.21
 - Burner reactors $\sim 0.1-0.2$
 - Example:
 - In a critical reactor fueled with natural uranium, it is observed that, for every neutron absorbed in ^{235}U , 0.254 neutrons are absorbed in resonances of ^{238}U and 0.640 neutrons are absorbed by ^{238}U at thermal energies. There is essentially no leakage of neutrons from the reactor.
 - What is the conversion ratio?
 - How much ^{239}Pu in kg is produced when 1 kg of ^{235}U is consumed?



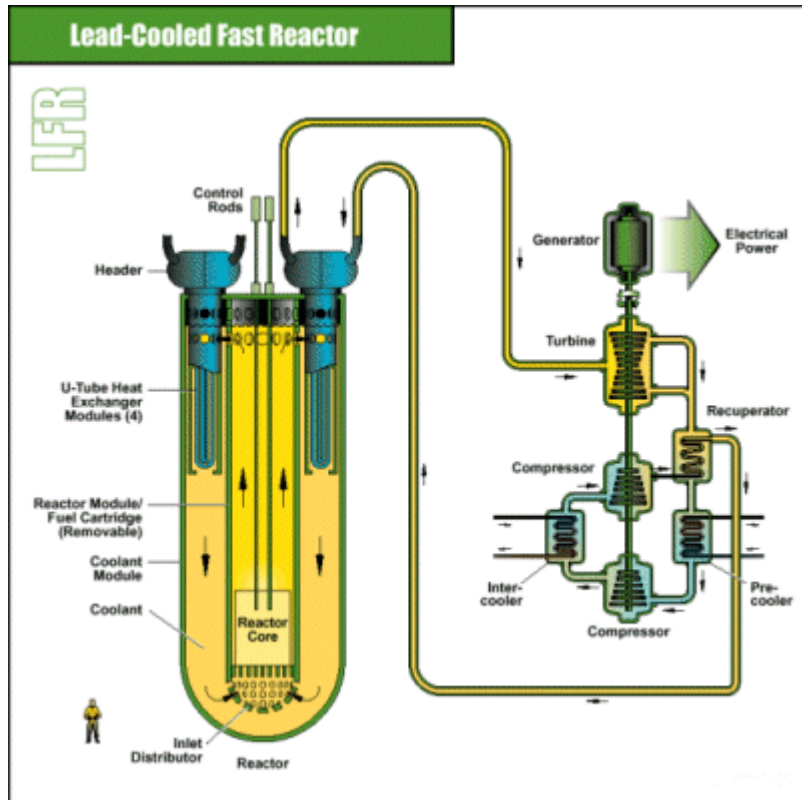
TerraPower – Sodium Reactor



Oklo – Aurora Microreactor



Lead-cooled Fast Reactor



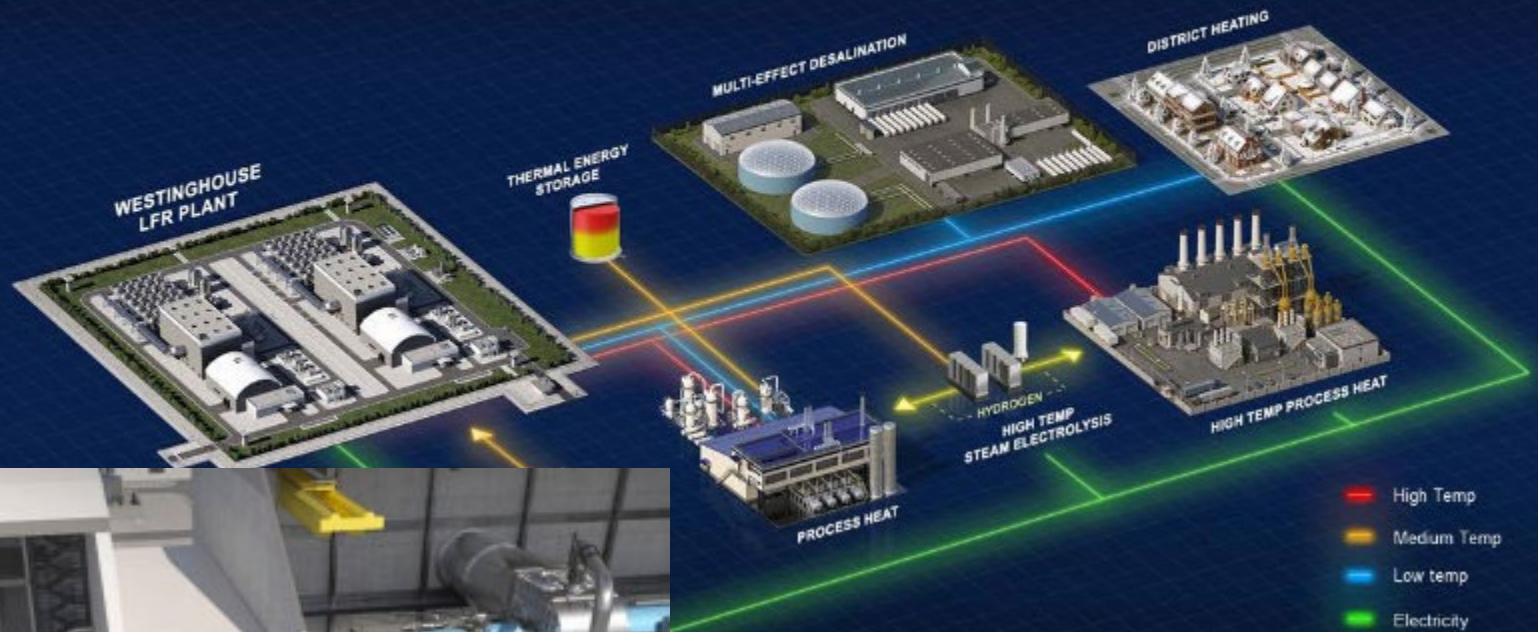
- Molten lead or lead-eutectic as core coolant
- Heat exchanged to gas-driven turbine
- Natural convection core cooling (cannot fail unless gravity fails)
- WEC Choice
- Fuel Rods (Zr-Pu-U metallic fuel), ^{239}Pu

Westinghouse Lead Fast Reactor

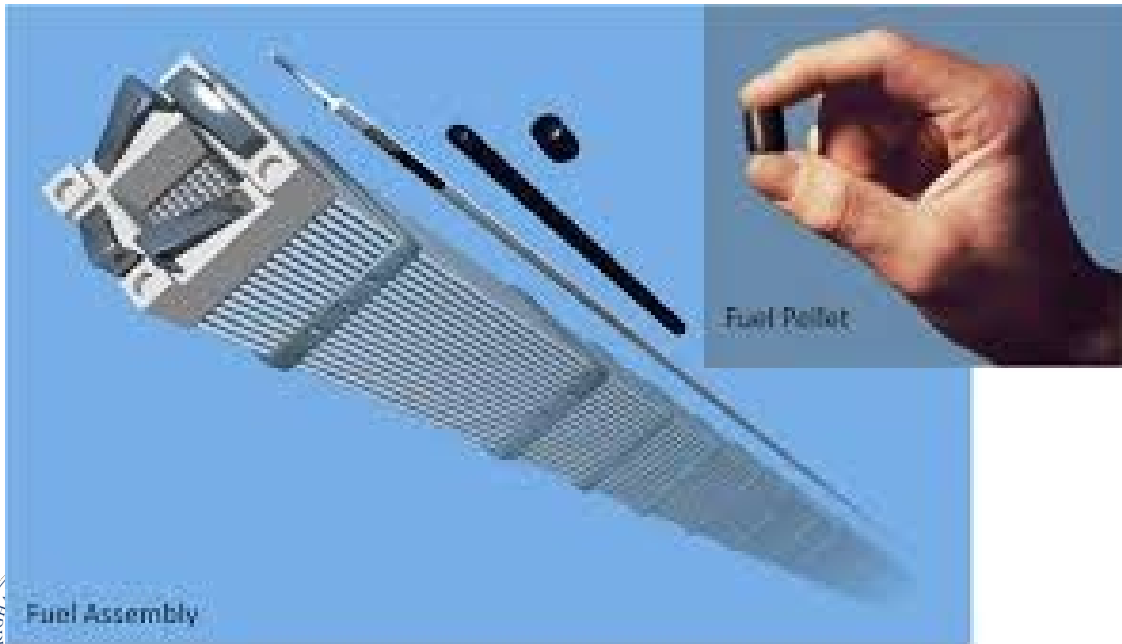
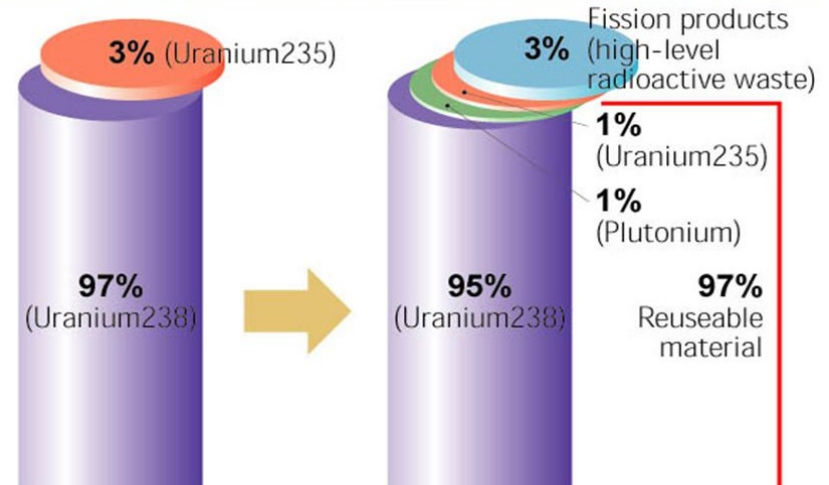


Versatility of Application

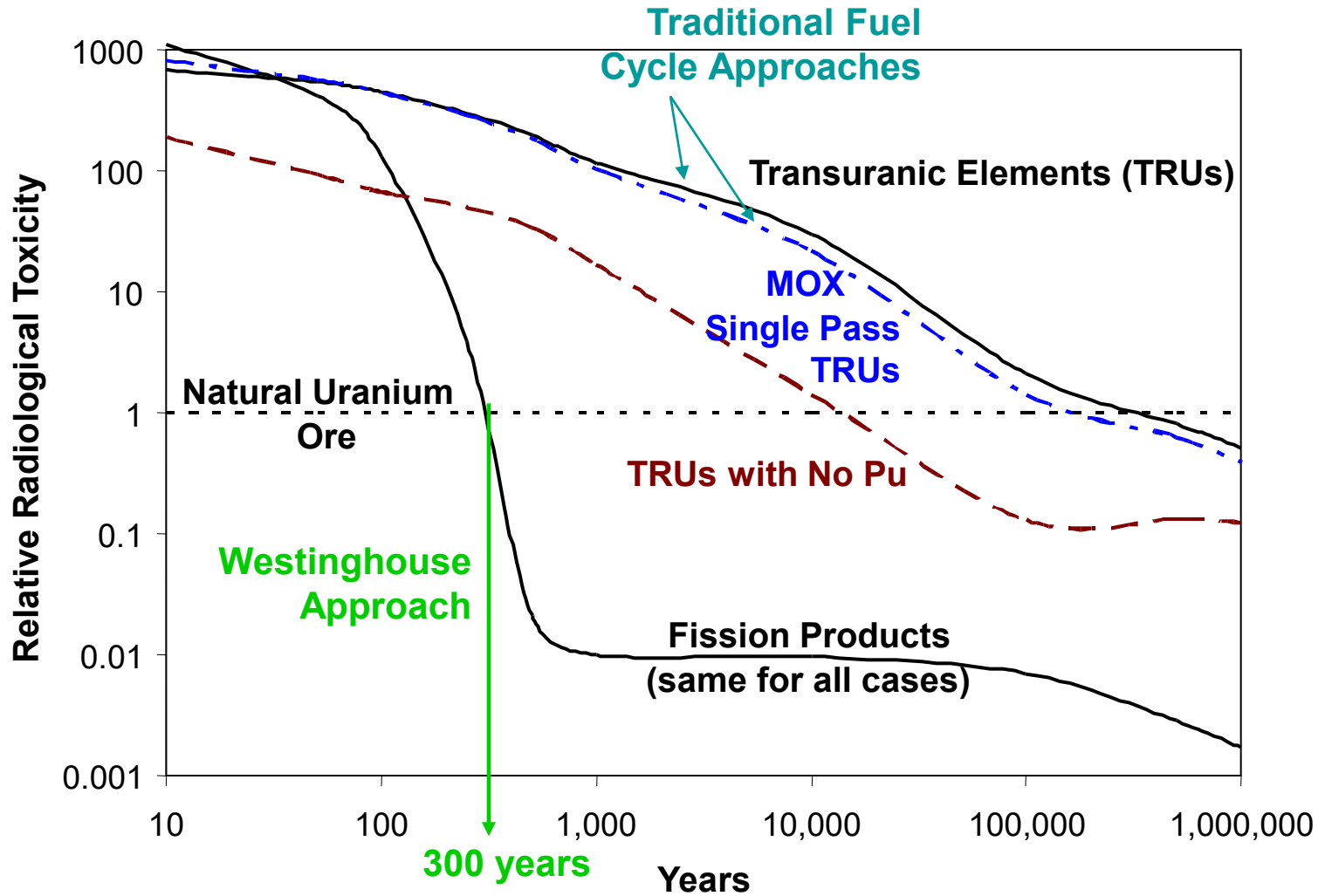
LFR Serves a wide variety of Decarbonizing Initiatives beyond Low-Cost Electricity



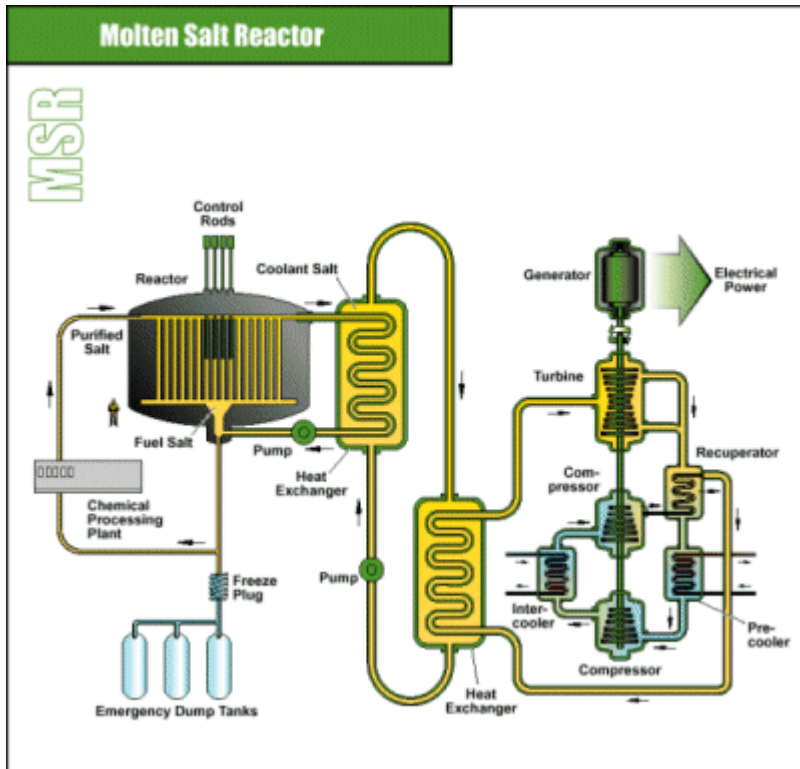
Waste Challenges



Waste

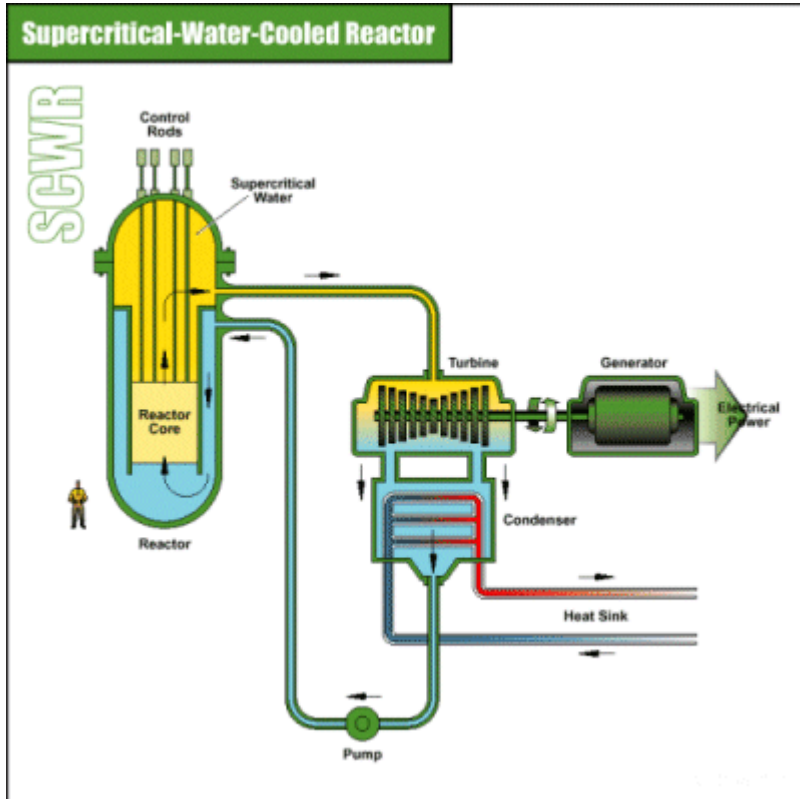


Molten Salt Reactor



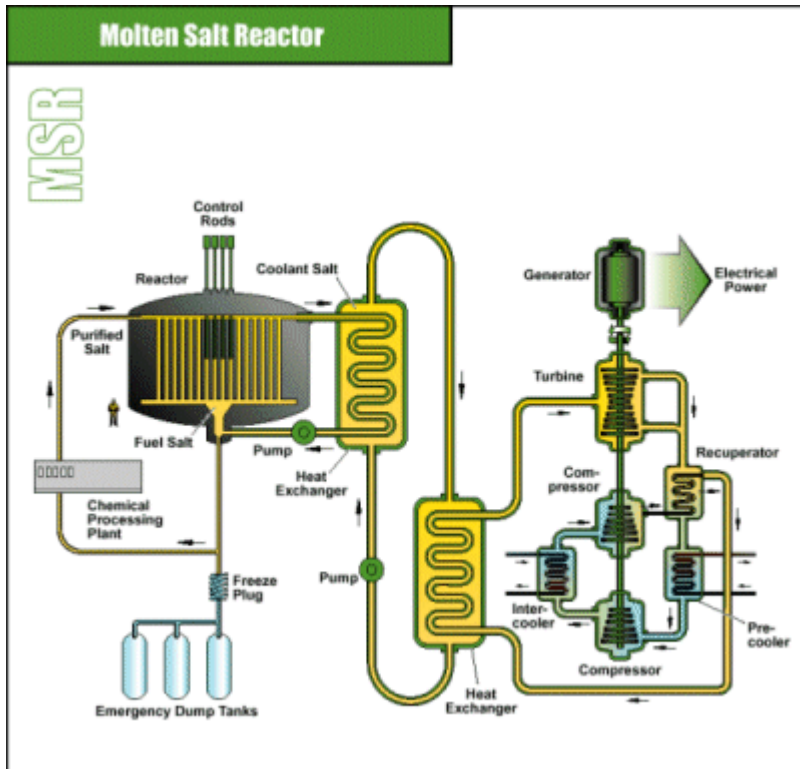
- Low-pressure, high-temperature core cooling fluid
- Fuel either dissolved in salt (typically as UF_4) or dispersed in graphite moderator.
- Perhaps gas-driven (S-CO₂) turbine.
- Liquid Fuel, ^{235}U or ^{233}U

Supercritical-Water-Cooled Reactor



- SC Water (> 240 atm) for working fluid (similar to most modern coal boilers)
- 45% efficiency (compared to 33% in most current technologies)
- Combines LWR and fossil technology.

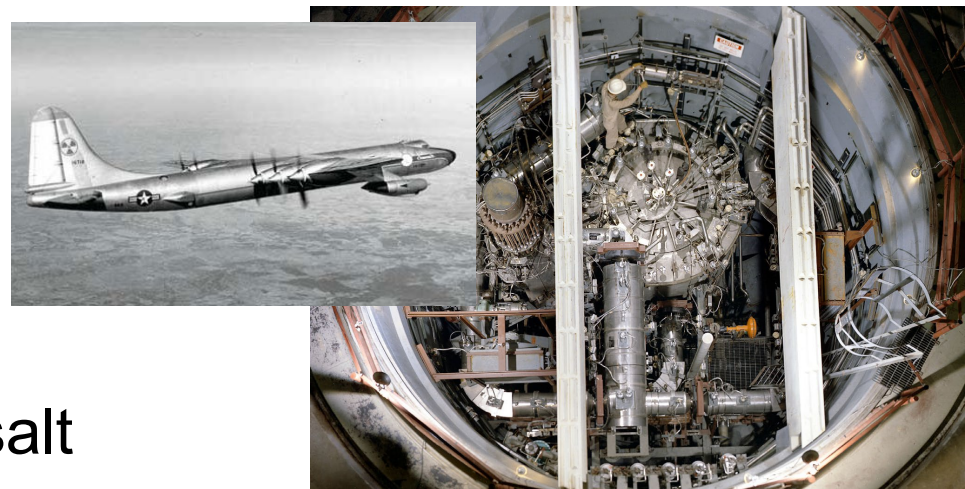
Molten Salt Reactor



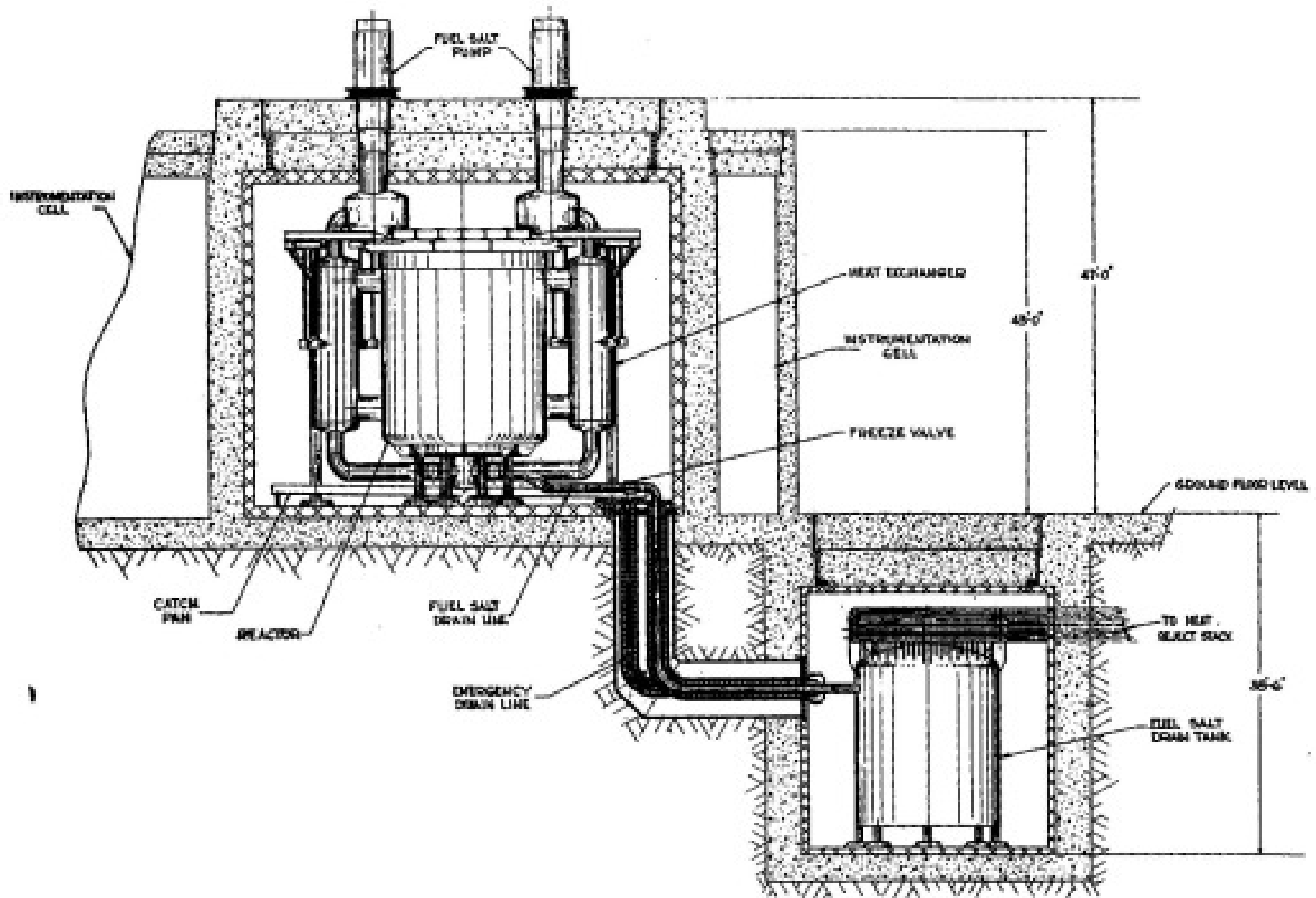
- Low-pressure, high-temperature core cooling fluid
- Fuel either dissolved in salt (typically as UF_6) or dispersed in graphite moderator.
- Perhaps gas-driven (He) turbine.

MSR Fuel

- Liquid fuel
 - UF₄
 - Suspended Directly in Salt
- No melt-down (already liquid)
- Fission products in coolant
 - COMPLEX chemistry
 - Online separation
 - Unknown behavior of salt

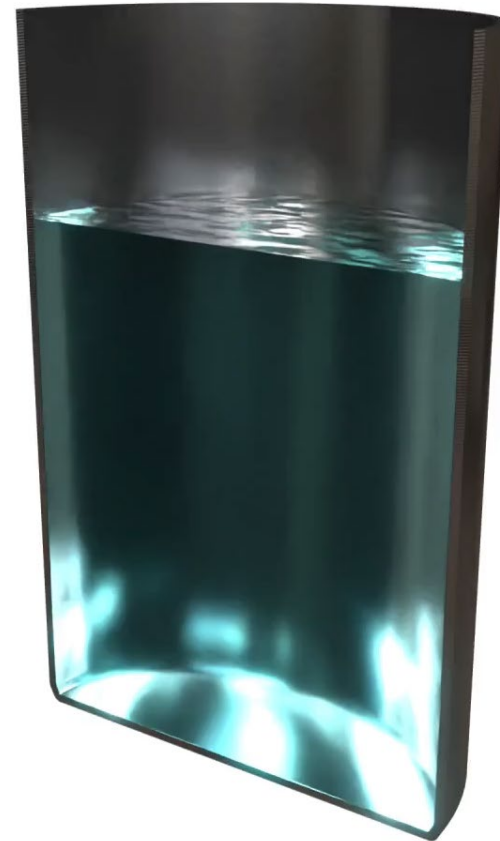


Safety



MSR Safety Advantages

- Atmospheric Pressure
- Strong Negative Reactivity Feedback
- Chemically binds to fission products
- High salt boiling point
 - $\sim 1500^{\circ}\text{C}$
- High structural melting point
 - $\sim 1200^{\circ}\text{C}$ to 1500°C



Fission Product Removal



MSR Weapons advantages

- No Pu-239
- U-233
 - Contaminated with U-232
 - High Energy Gammas
 - Human handling
 - Electronics busting



FLiBe Energy

LFLEUR

Lithium Fluoride Low Enriched Uranium Reactor

LFLEUR is designed to run on a commercially available fuel cycle that is accessible today. This provides an important step in accelerating the deployment of molten salt reactors across the world.



[Learn More >](#)

LFTR

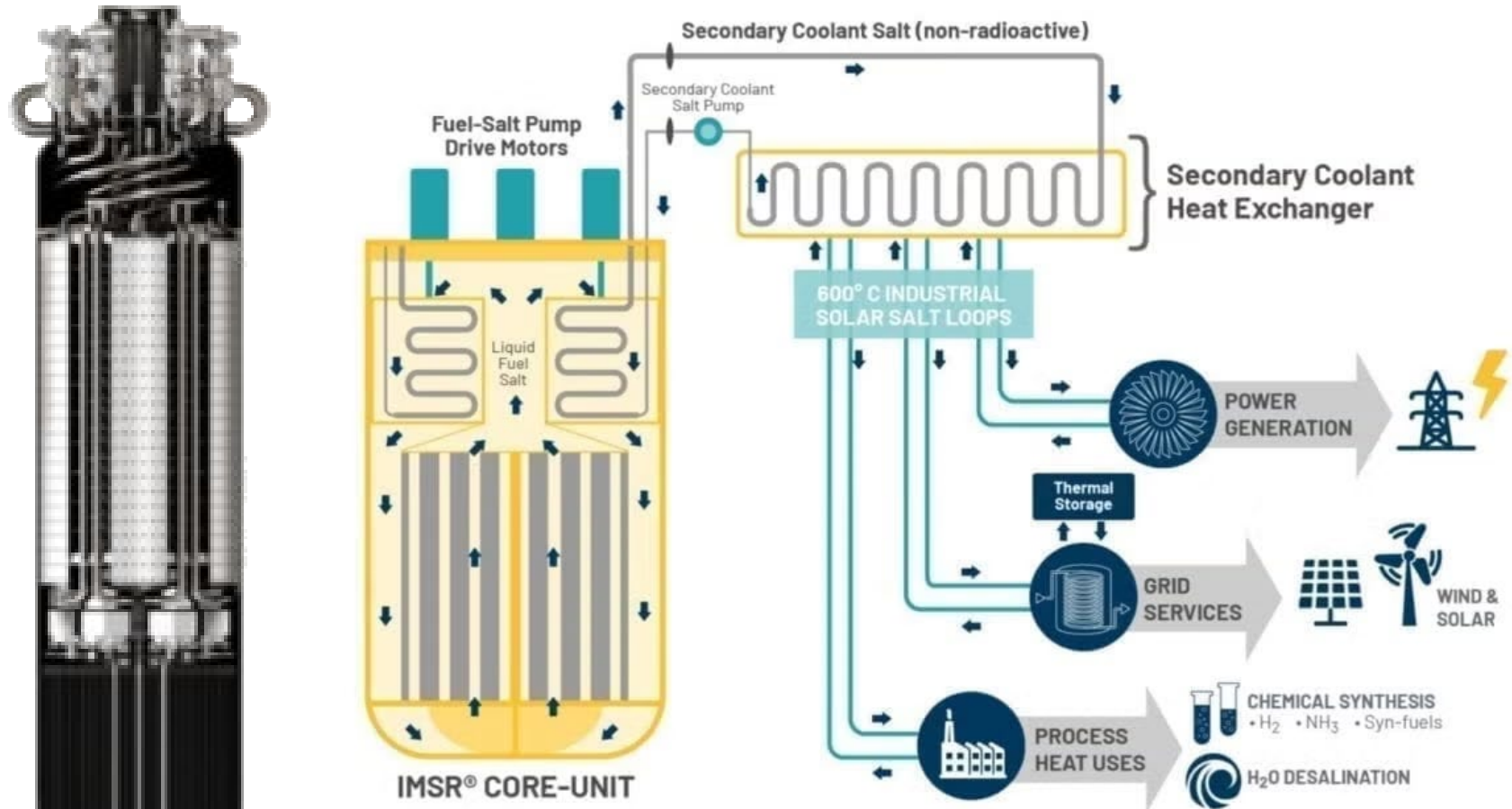
Lithium Fluoride Thorium Reactor

LFTR is designed to take full advantage of the thorium fuel cycle, bringing many benefits over competing designs. LFTR is the long-term solution for a scalable nuclear future.



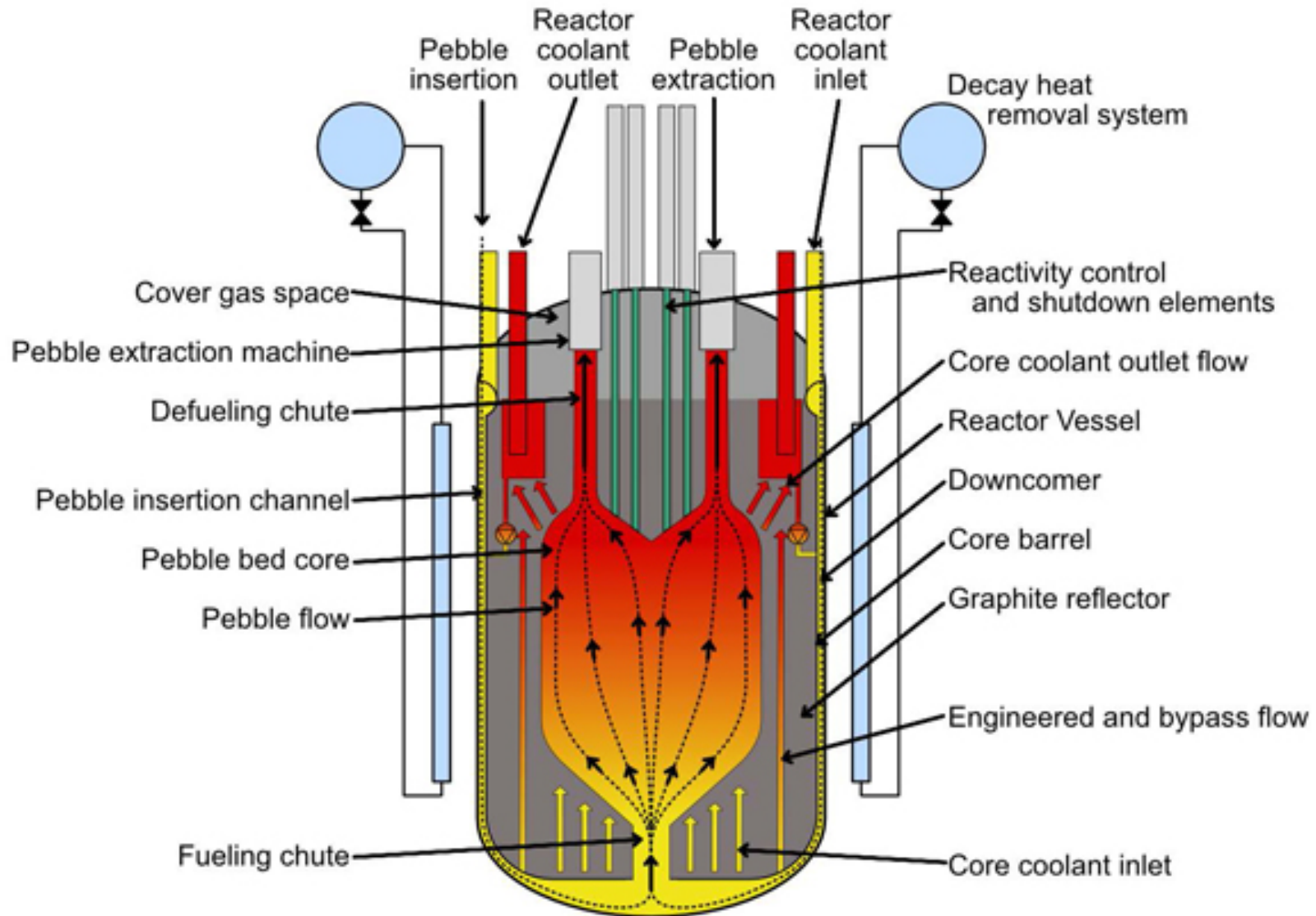
[Learn More >](#)

Terrestrial Energy – IMSR



The Replaceable IMSR® Core-unit

Kairos Power – Hermes



AlphaTech – ARC Reactor

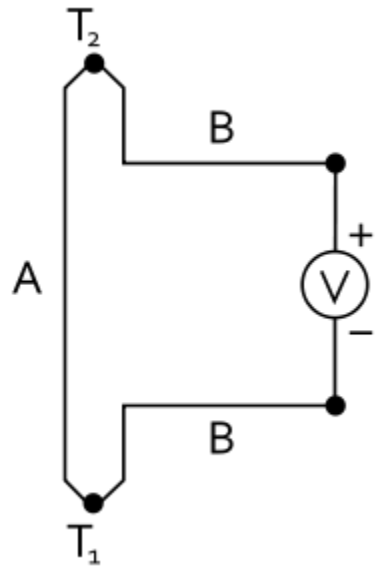


Thermoelectric Generators

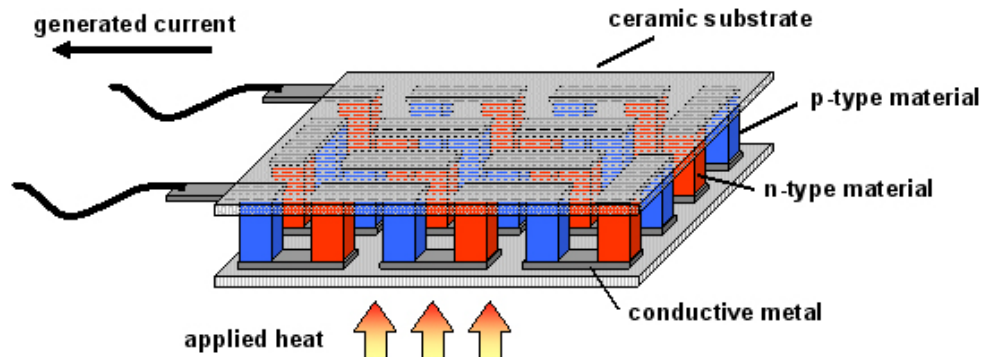
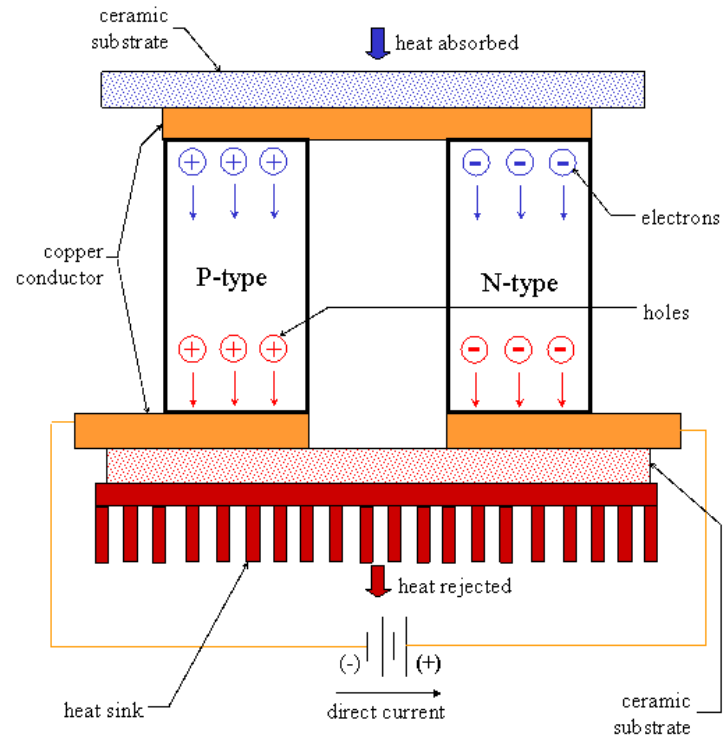
- Low-efficiency (5-10%) and high cost conversion of heat to electricity.
- Applicable primarily where traditional heat engines, which are more efficient and less costly but bulkier, will not work (space, remote locations, etc.).
- Based on the Seebeck effect, the same principle as a thermocouple, except most commonly use p-n junctions instead of dissimilar metals.
- Connected in series in thermopiles.



Thermoelectric Generators



Thermocouple (10s of microvolt/K potential)



Advantages and Disadvantages

Advantages

- No moving parts (except possibly a fan or pump)
- Works with relatively low-grade heat (up to 300 °C for consumer use, higher for industrial use).
- Reasonably compact and simple.

Disadvantages

- High cost
- Inefficient – Stirling cycles or other heat engines less costly and more efficient
- High source impedance (can only supply small current before source decreases voltage).
- Poor conductivity/heat sink.

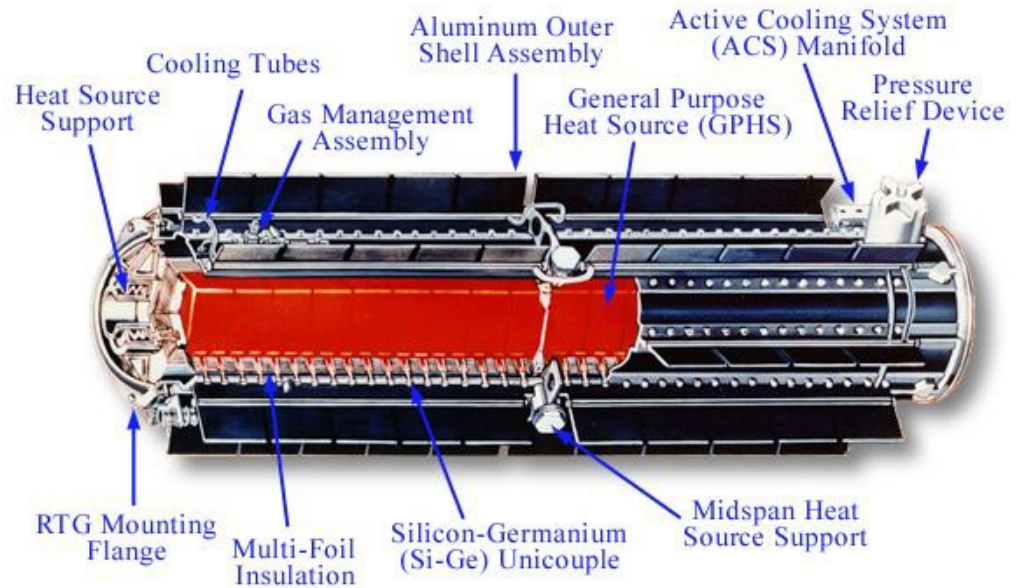


Radionuclide Thermoelectric Generators

Use decay heat from radionuclides on hot side and ambient (or space) temperature on cold side.

- ^{90}Sr and $\frac{1}{2}$ -
 - 1 ton total mass (1-2 kg fuel)
 - Common on earth
- ^{238}Pu and 2-60 kg total
 - (1-8 kg fuel)
 - common in space
 - 2-60 W_e typical output.

GPHS-RTG



GPHS-RTG for many space probes (Viking, Pioneer, Voyager, Galileo, Ulysses, Cassini, New Horizons)
Initial $300 W_e$, $4.4 kW_{th}$, 6.8% efficient

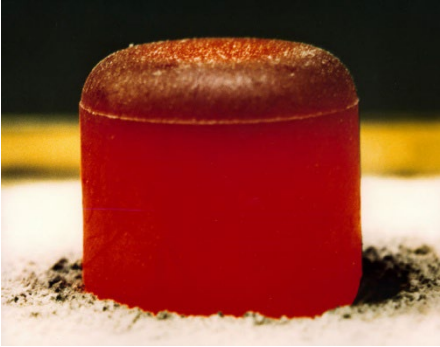
^{238}Pu

1 x $\frac{1}{2}$ m

57 kg ($5.2 W_e/\text{kg}$)

SiGe elements

GPU components



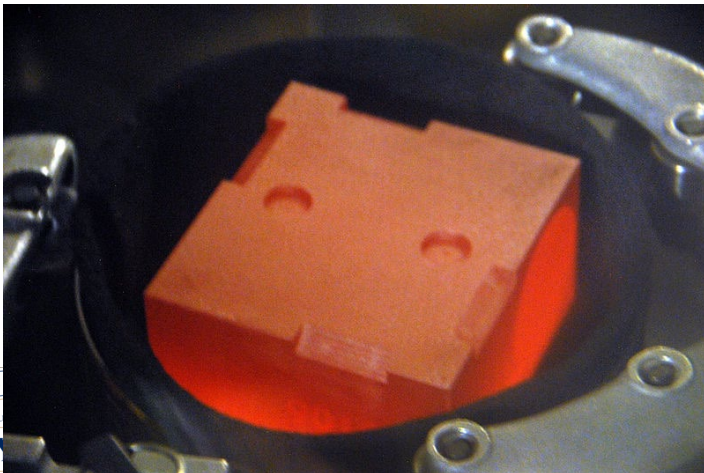
^{238}Pu pellet



Ir cladding

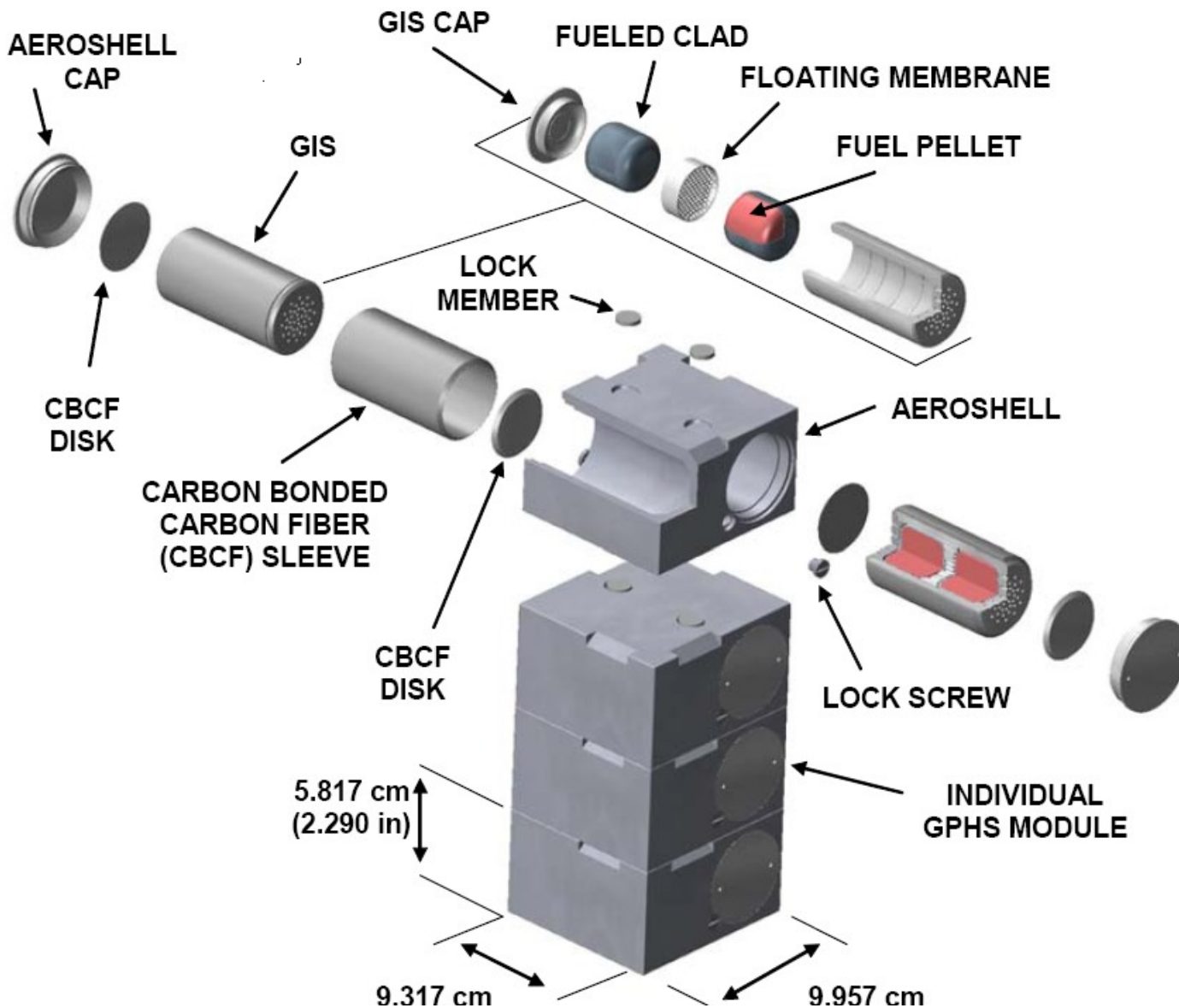


Graphite Impact Casing

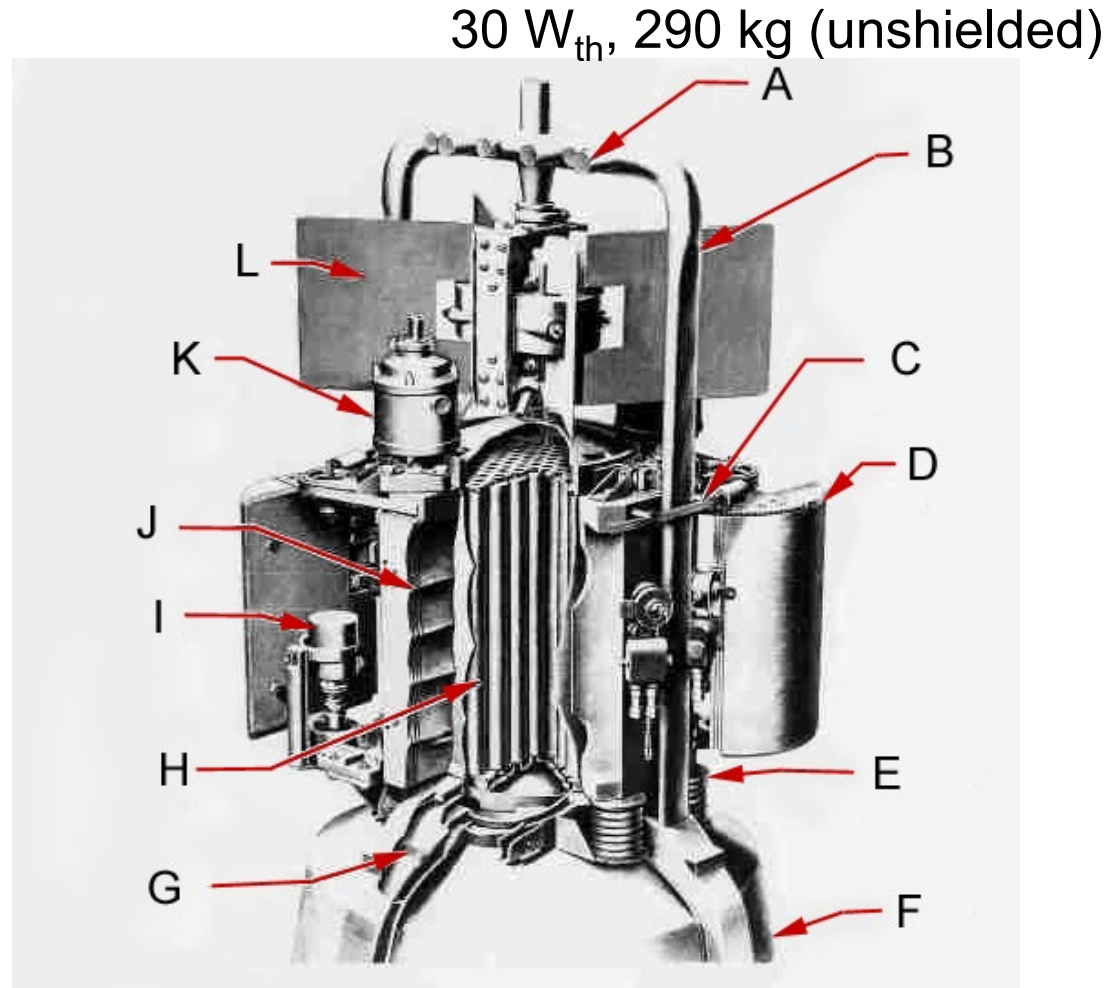


Assembled GPH cell

General Purpose Heat Source



Reactor Thermoelectric Generator



SNAP-10a – K/Na reactor and TE generator – known launch 4/3/1965 in low-earth orbit – design: 500 W_e for 1 year – satellite (not reactor) failed after 43 days – placed in 4000 year (1300 km) orbit – broke up in 1979

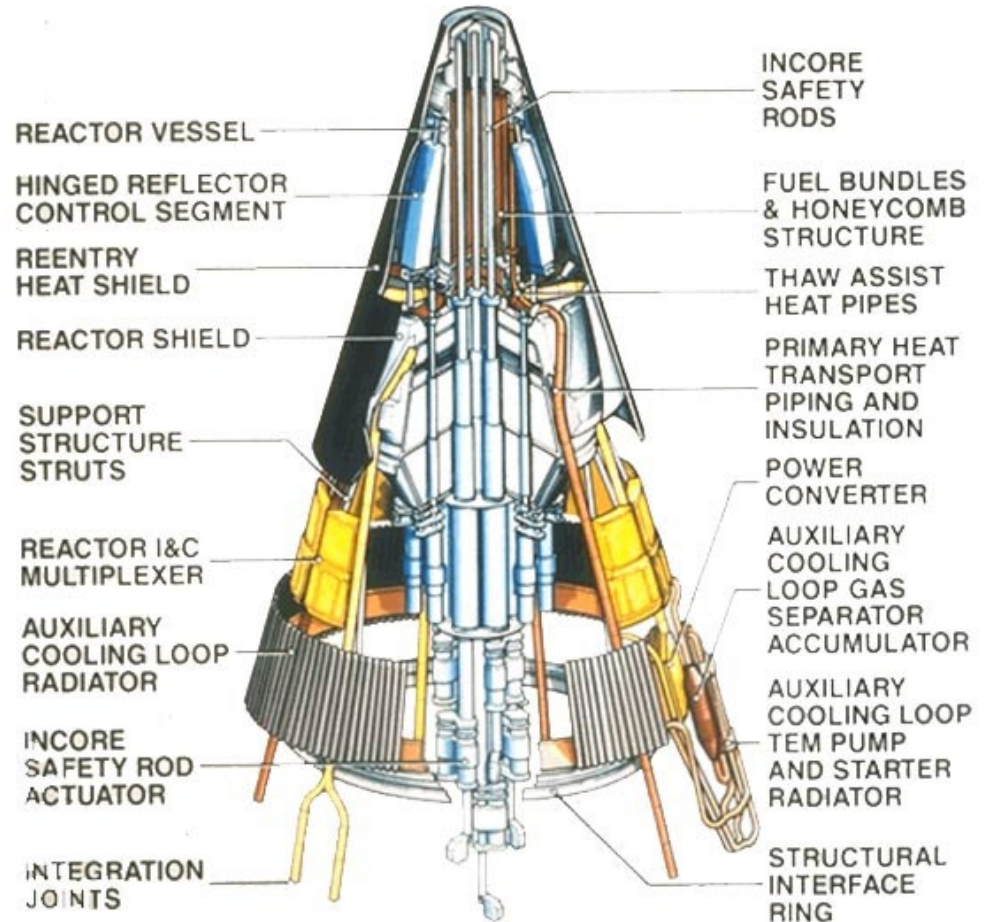
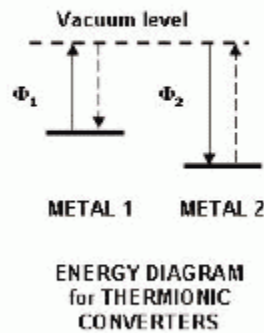
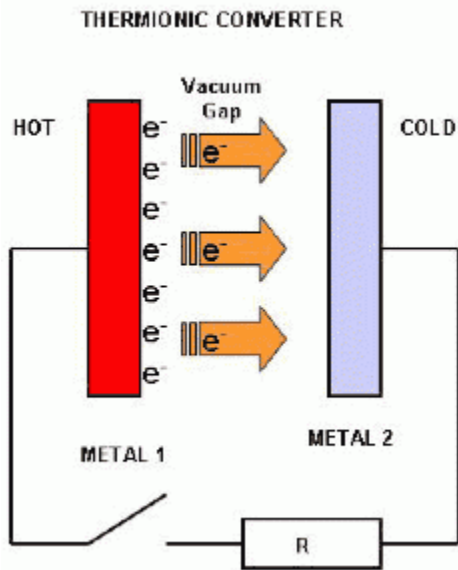


Topaz systems



Soviet BES-5 (US-A/Rorsat satellites) 33-38 known launches – 5 known failures and 16 spurts of NaK-78 – US bought Topaz-II technology for further development

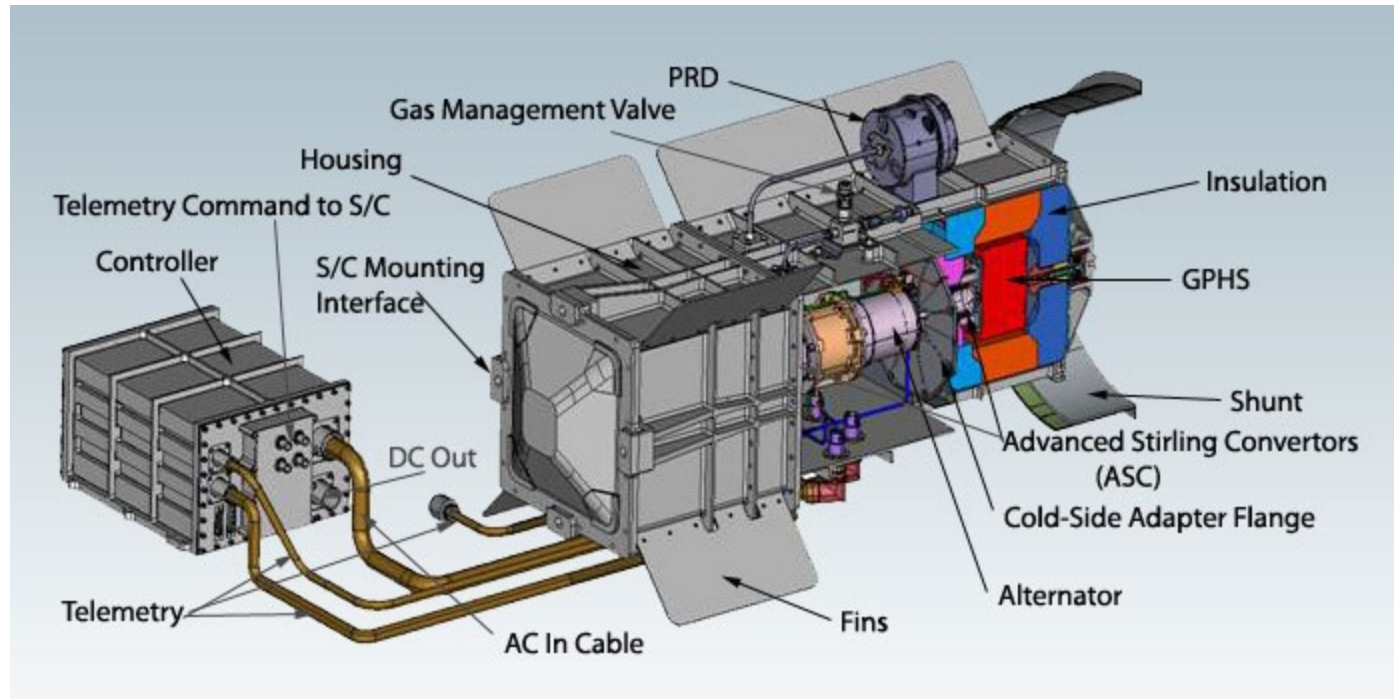
Thermionic Emission



Requires high temperature and detailed construction – 2 known Soviet-designed systems orbited – US bought Topaz-II technology for further development



Advanced Sterling Radioisotope Generator



≥14 year lifetime

Nominal power : $140 W_e$

Mass ~ 20 kg ($7 W_e/\text{kg}$)

System efficiency: ~ 30 %

2 General Purpose Heat Source (“Pu238 Bricks”) modules

Uses 0.8 kg plutonium-238

Example

- You friend wants to power his private island (96 kW) using ^{137}Cs , and he asks you to make the RTG ($\eta=10\%$) for him. How much ^{137}Cs is required? Assuming you use enough for 192 kW initially, how long will this power source power his island sufficiently?

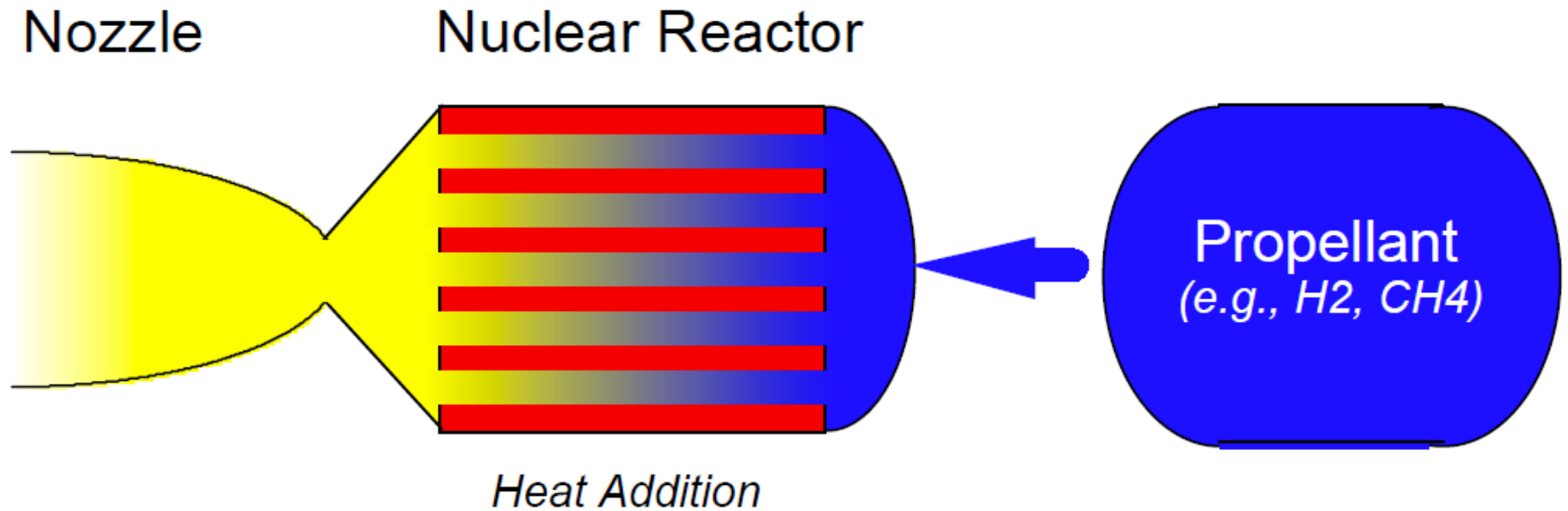


SAFE

- Safe Affordable Fission Engine (SAFE) are small experimental fission reactors.
- The SAFE-400 reactor produces 400 kW thermal power, giving 100 kW of electricity using a Brayton cycle gas turbine.
- Uranium nitride fuels the reactor in a core of 381 rhenium-clad pins clad with rhenium.
- The reactor is about 50 centimeters (20 in) tall, 30 centimeters (12 in) across and weighs about 512 kilograms (1,129 lb).
- It was developed at the Los Alamos National Laboratory and the Marshall Space Flight Center.



SAFE



SAFE Demonstration



Direct Devices

- Not heat engines
- Use radiation directly, called betavoltaic cell
- Low efficiency and low capacity, but relatively maintenance free
- Used in medical and some space research applications

