Chemical Engineering 412

Introductory Nuclear Engineering

Lecture 22

Nuclear Power Plants II

Other Nuclear Systems

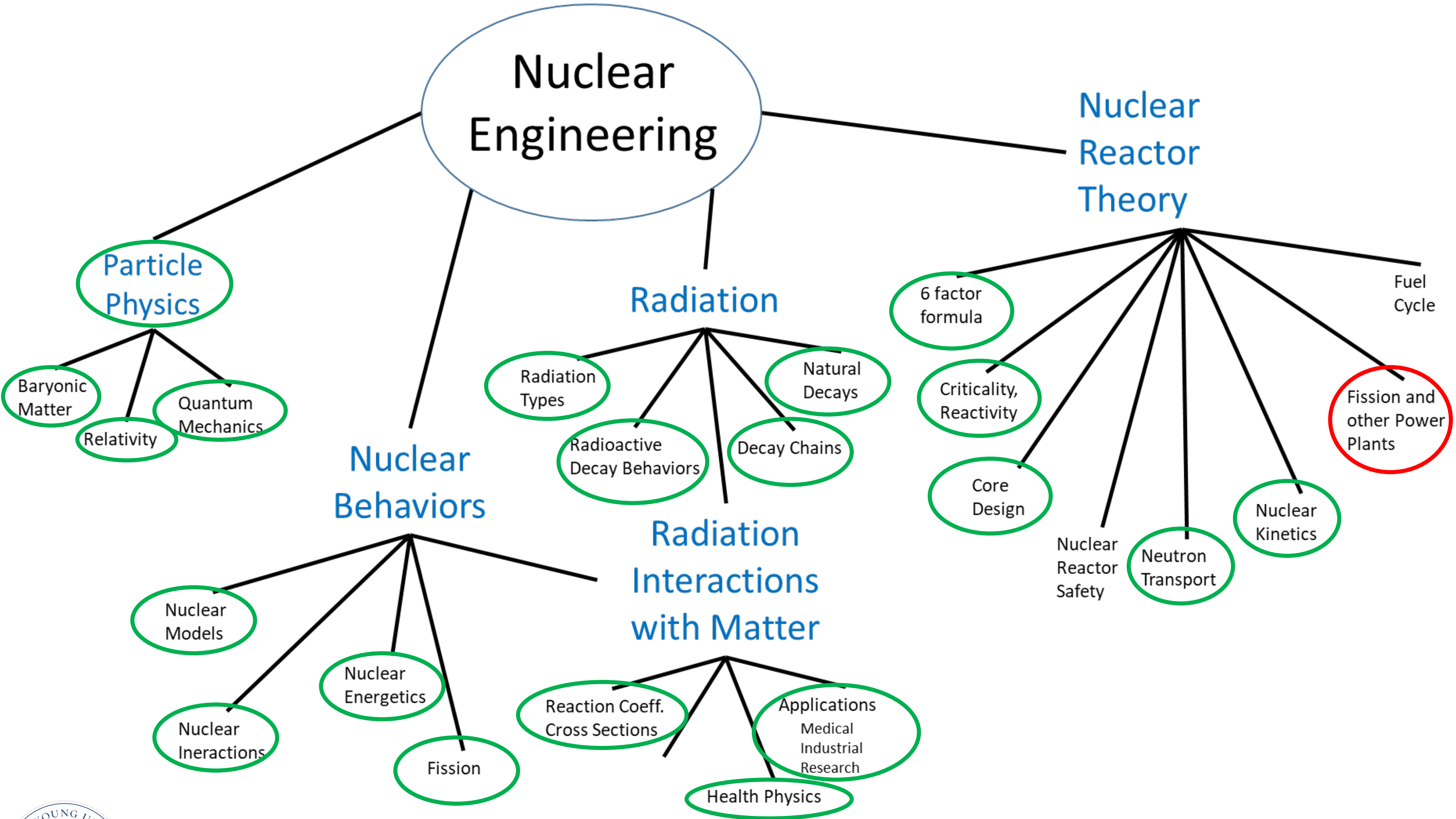
Spiritual Thought

D&C 76:22-23

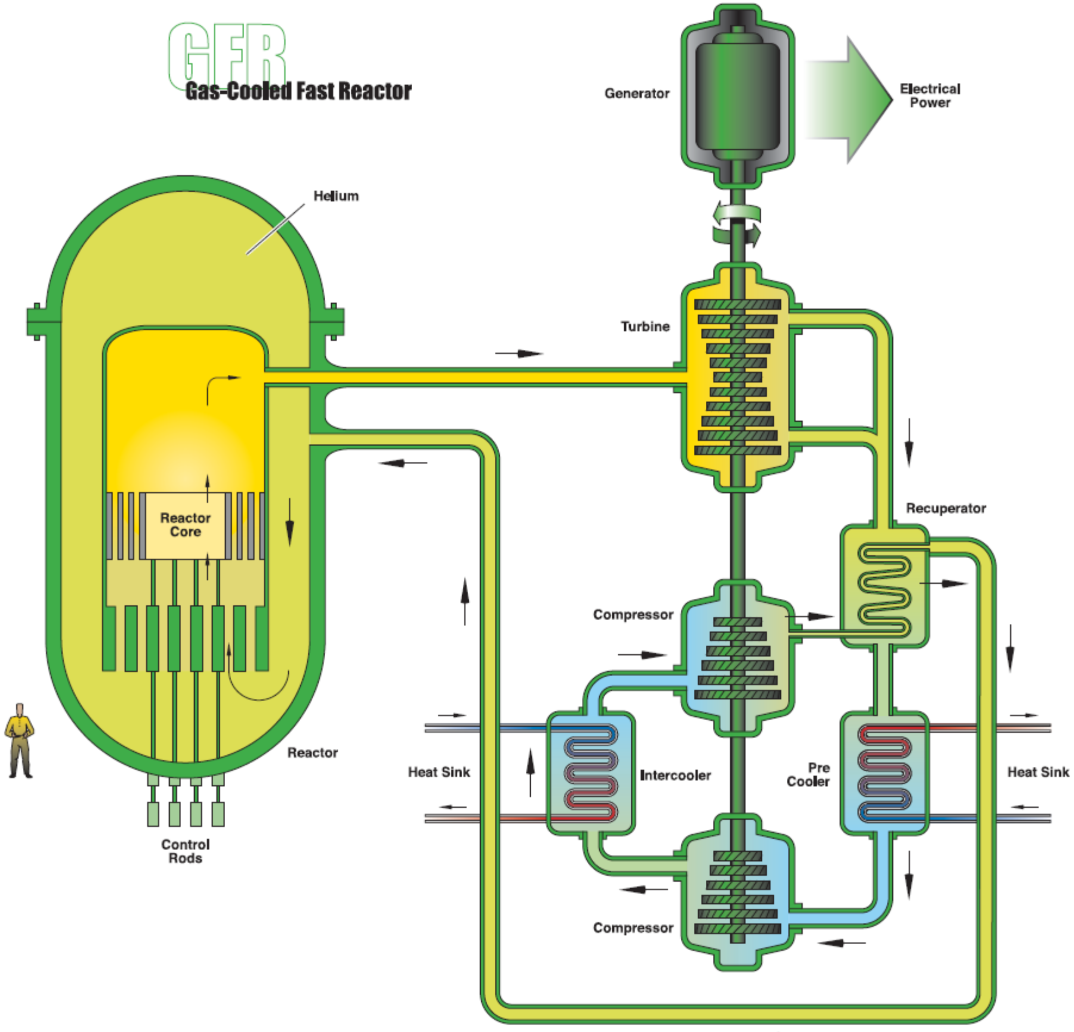
22…this is the testimony, last of all, which we give of him: That he lives!

23 For we saw him, even on the right hand of God; and we heard the voice bearing record that he is the Only Begotten of the Father

Roadmap

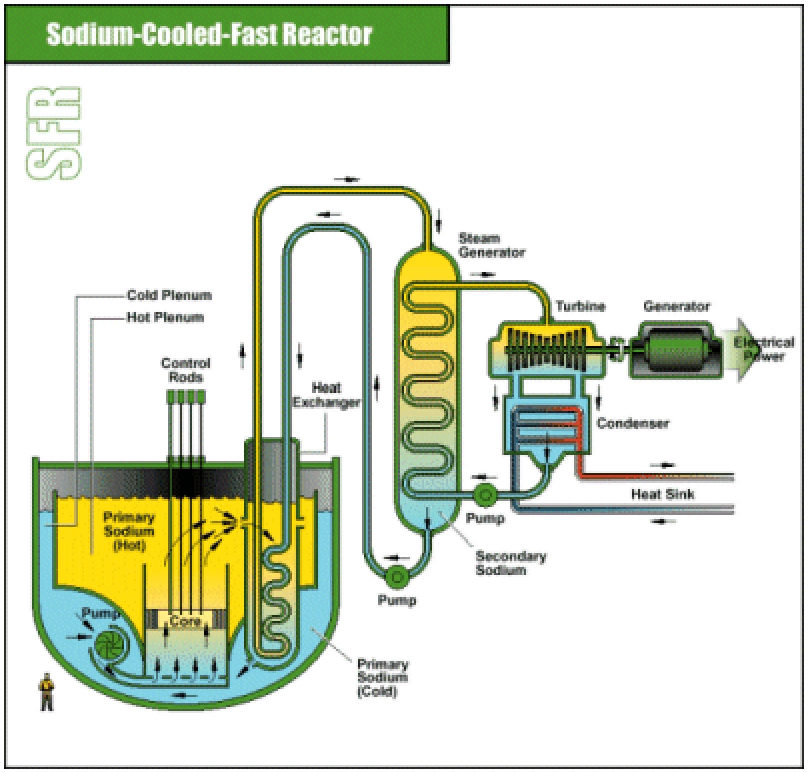

Nuclear Engineering
Particle Physics
Baryonic Matter
Relativity
Quantum Mechanics
Nuclear Behaviors
Nuclear Models
Nuclear Ineractions
Nuclear Energetics
Fission
Radiation
Radiation Types
Radioactive Decay Behaviors
Natural Decays
Decay Chains
Radiation Interactions with Matter
Reaction Coeff. Cross Sections
Applications
Medical
Industrial
Research
Health Physics
Nuclear Reactor Theory
6 factor formula
Criticality, Reactivity
Core Design
Nuclear Reactor Safety
Neutron Transport
Nuclear Kinetics
Fission and other Power Plants
Fuel Cycle

Gas-cooled Fast Reactor



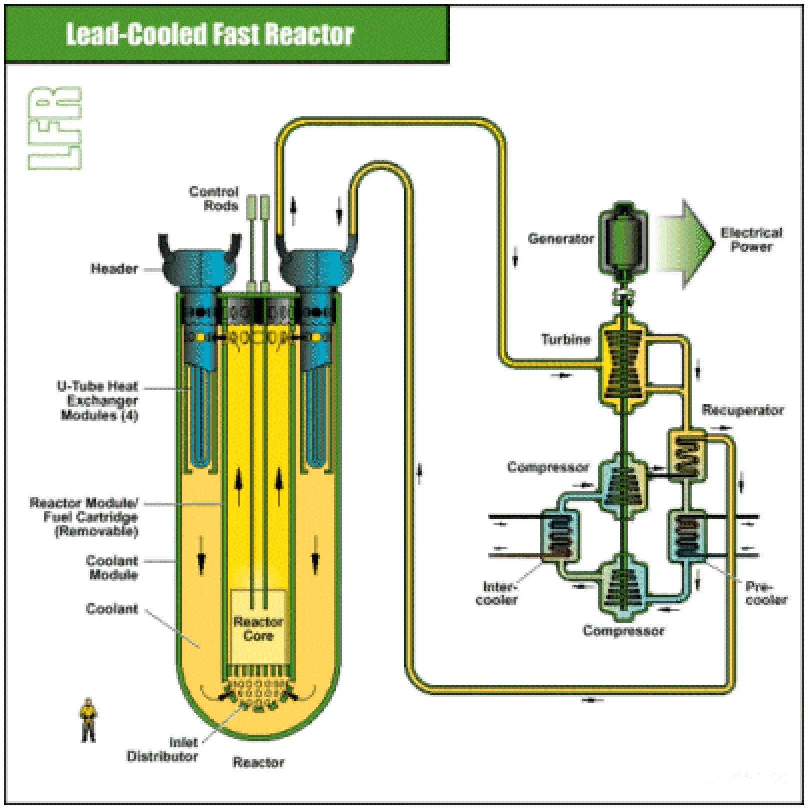
- He cooled with direct Brayton cycle for high efficiency
- Closed fuel cycle
- Low Power Density
- Fuel Rods, ^{239}Pu

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

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

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.

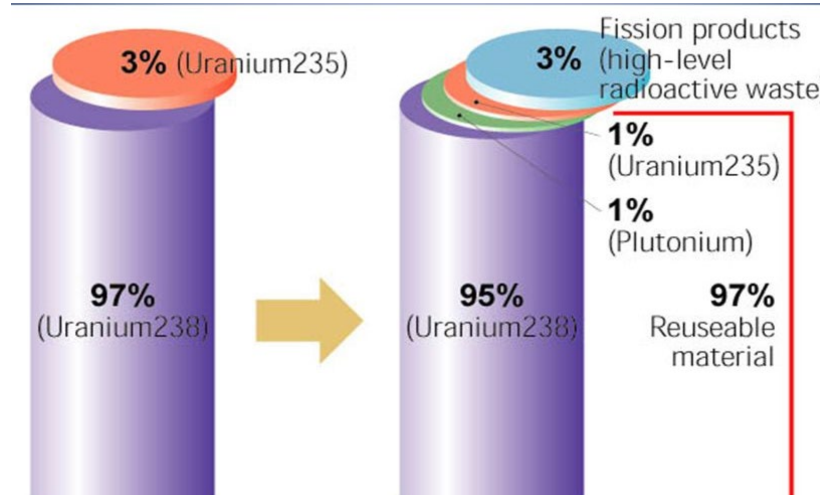
Conversion Ratio

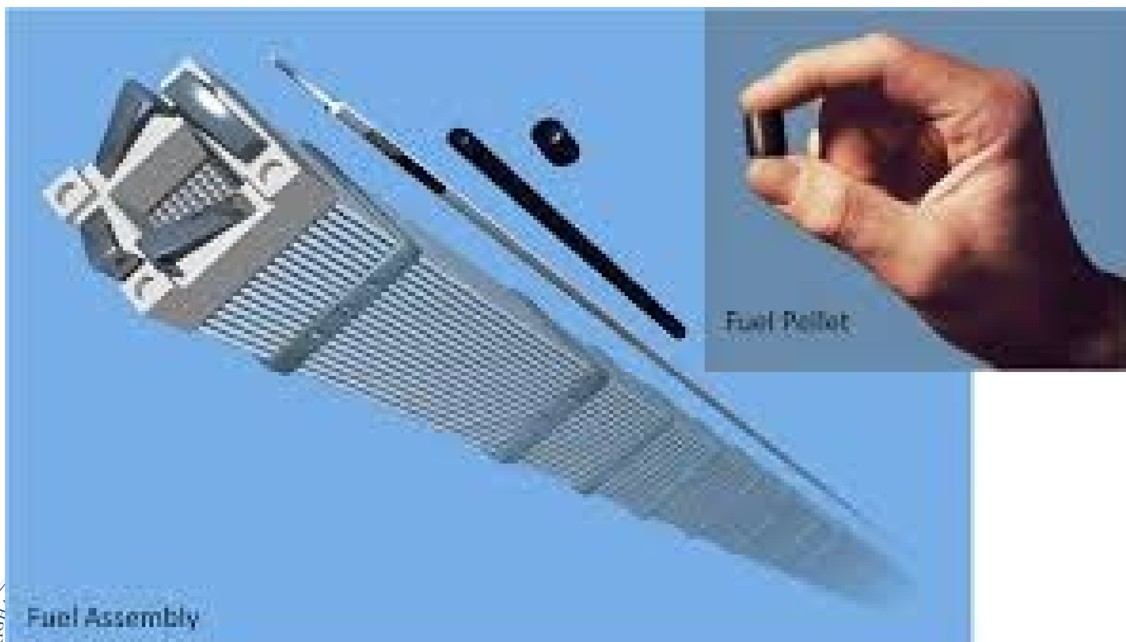
- Ratio of Created fuel to burned fuel
  - Breeder reactors 1.01 up to ~1.21
  - Burner reactors ~0.1-0.2
    - Example:
    - In a critical reactor fueled with natural uranium, it is observed that, for every neutron absorbed in 235U, 0.254 neutrons are absorbed in resonances of 238U and 0.640 neutrons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

Fast Reactors – Disadvantages

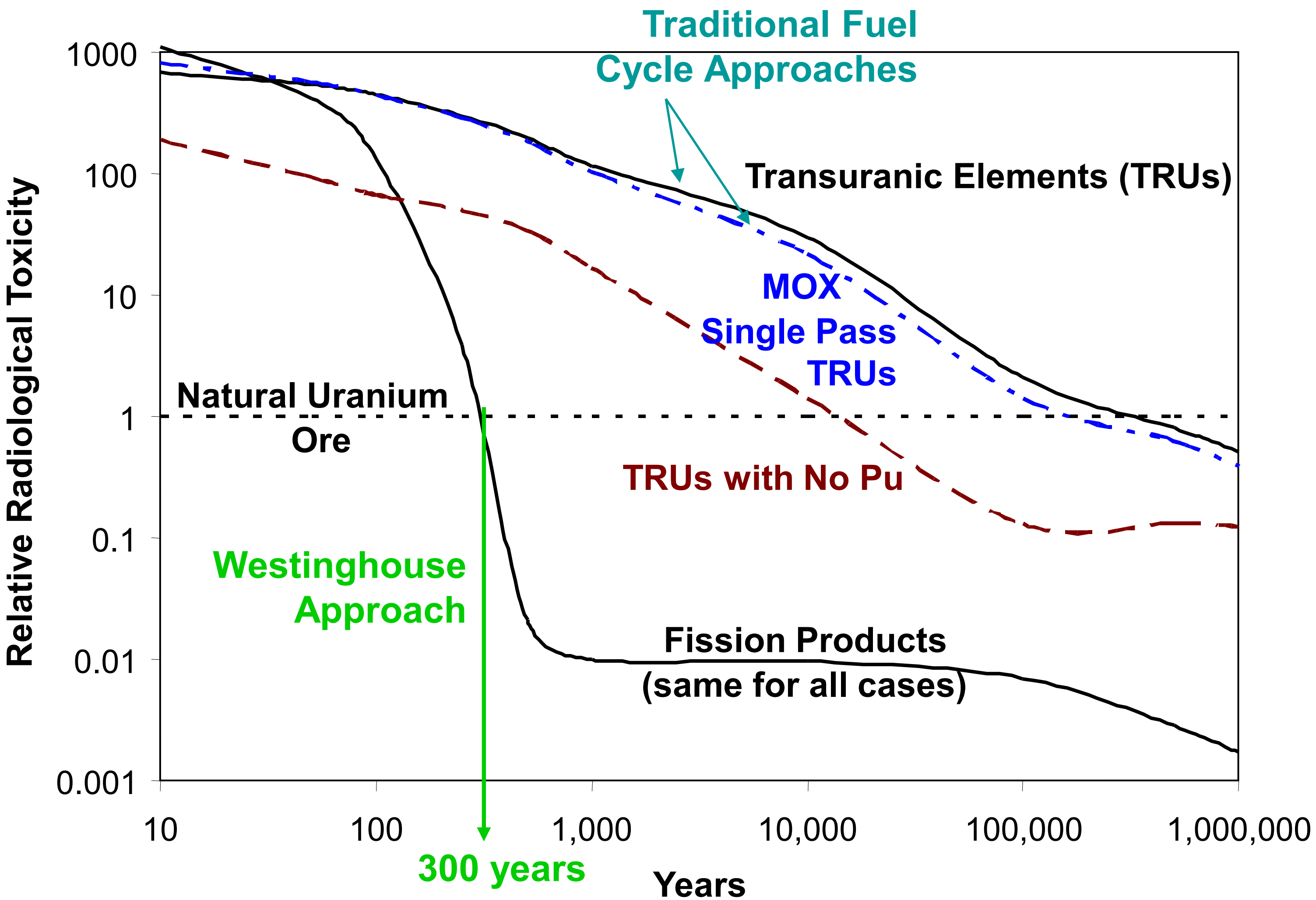
- Low response time
  - complicates control!
  - control rods less effective, other means must be used:
    - Fuel thermal expansion
    - Doppler broadening
    - Absorbers
    - Reflectors
- Small cross sections – large critical mass
  - Leads to either large cores or high enrichment.
- Sodium and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

Waste Challenges

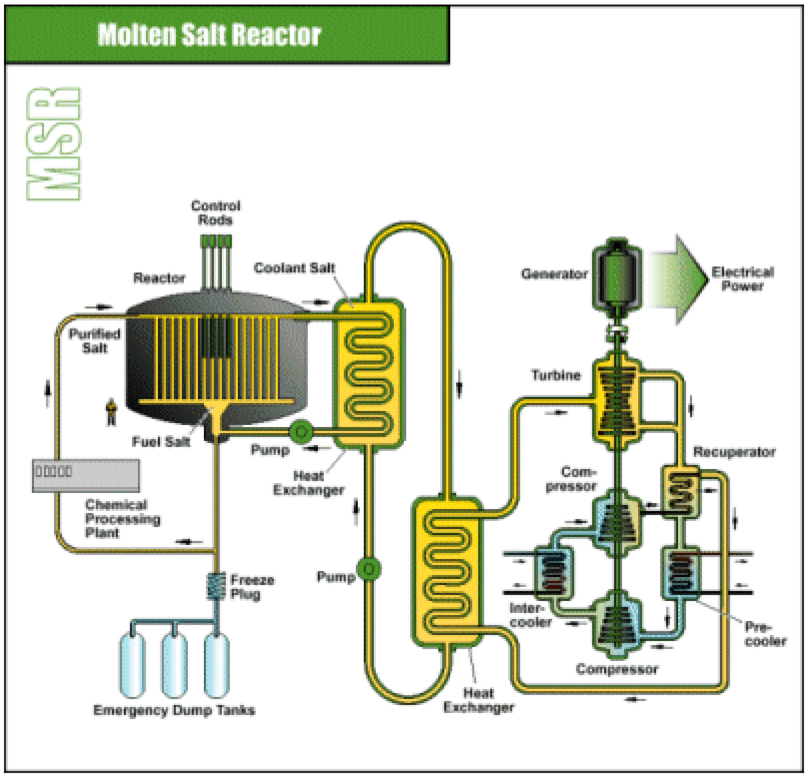




Waste

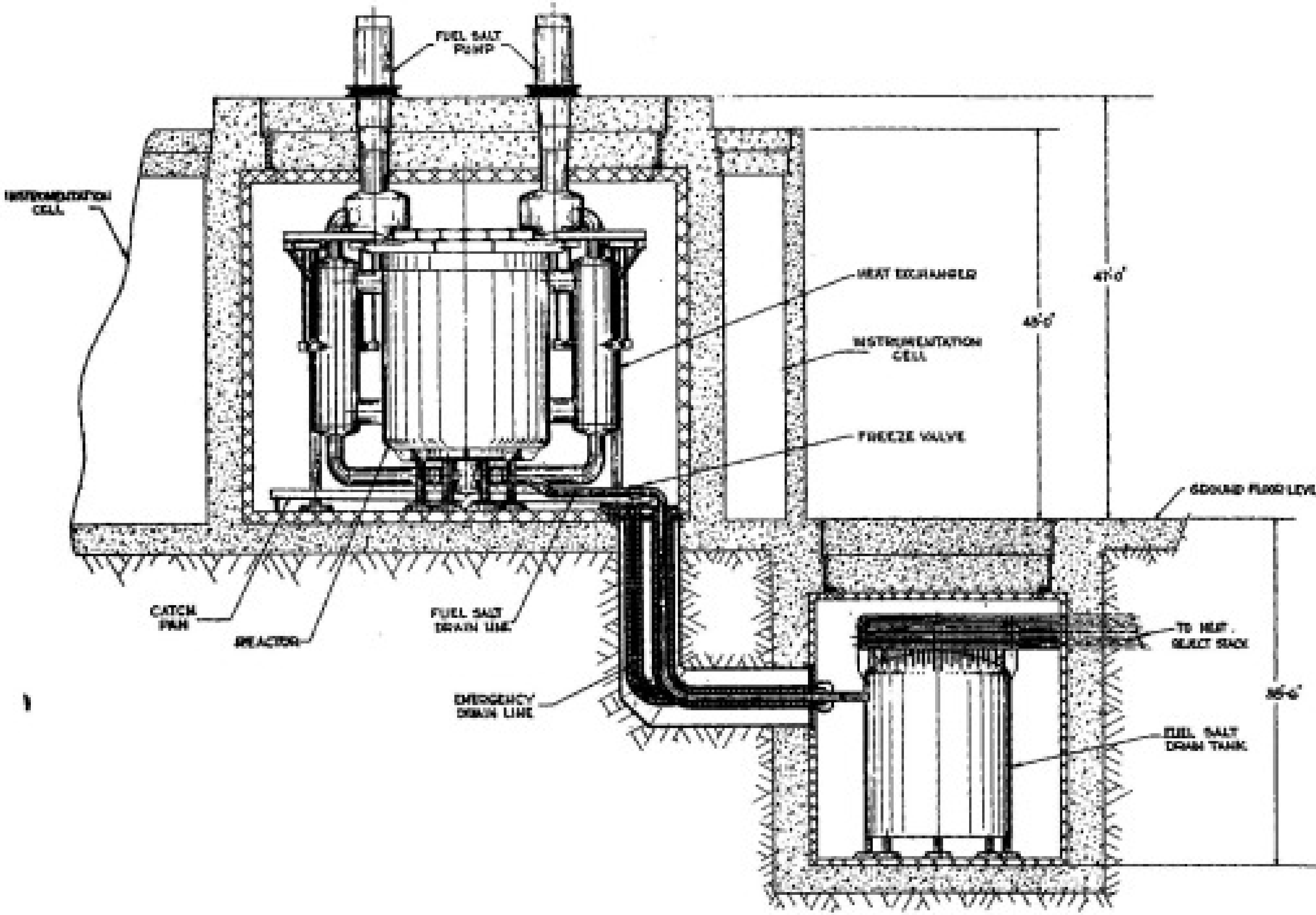

Traditional Fuel
Cycle Approaches
Transuranic Elements (TRUs)
MOX
Single Pass
TRUs
Natural Uranium
Ore
TRUs with No Pu
Westinghouse
Approach
Fission Products
(same for all cases)
Relative Radiological Toxicity
1000
100
10
1
0.1
0.01
0.001
10
100
1,000
10,000
100,000
1,000,000
300 years
Years

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

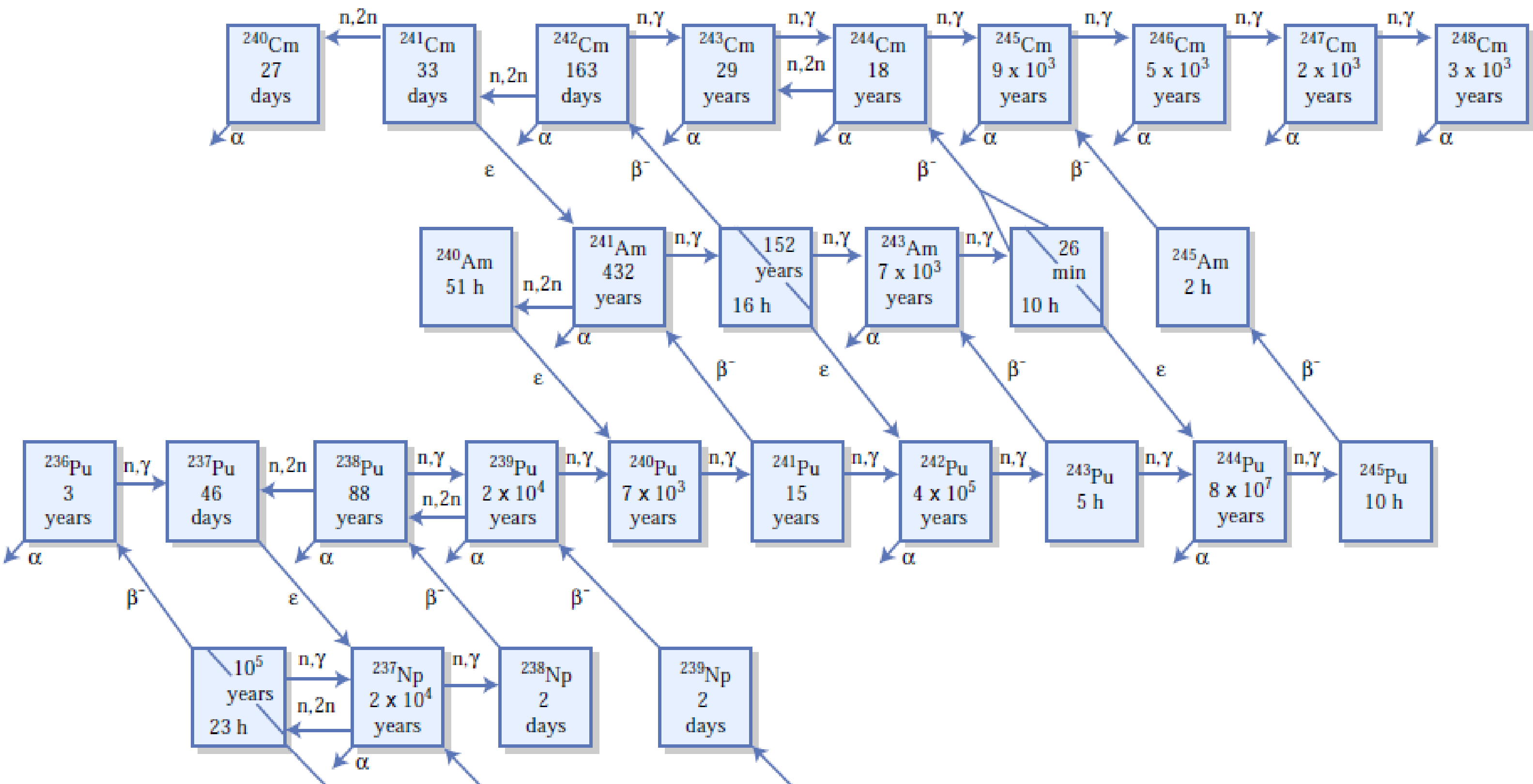
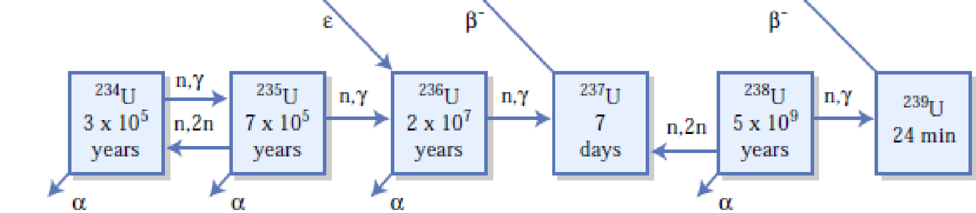
Safety


FUEL SALT PUMP
INSTRUMENTATION CELL
HEAT EXCHANGER
INSTRUMENTATION CELL
FREEZE VALVE
CATCH PAN
REACTOR
FUEL SALT DRAIN LINE
EMERGENCY DRAIN LINE
FUEL SALT DRAIN TANK

MSR Safety Advantages

- Atmospheric Pressure
- Strong Negative Reactivity Feedback
- Chemically binds to fission products
- High salt boiling point
  - ~1500°C
- High structural melting point
  - ~1200 °C to 1500 °C

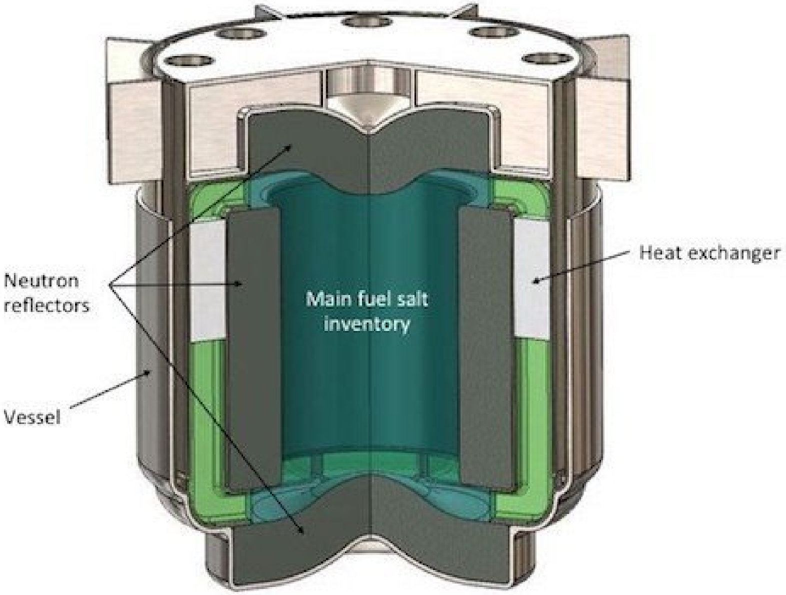
MSR Waste Advantages

Fission Product Removal

MSR Cost Advantages

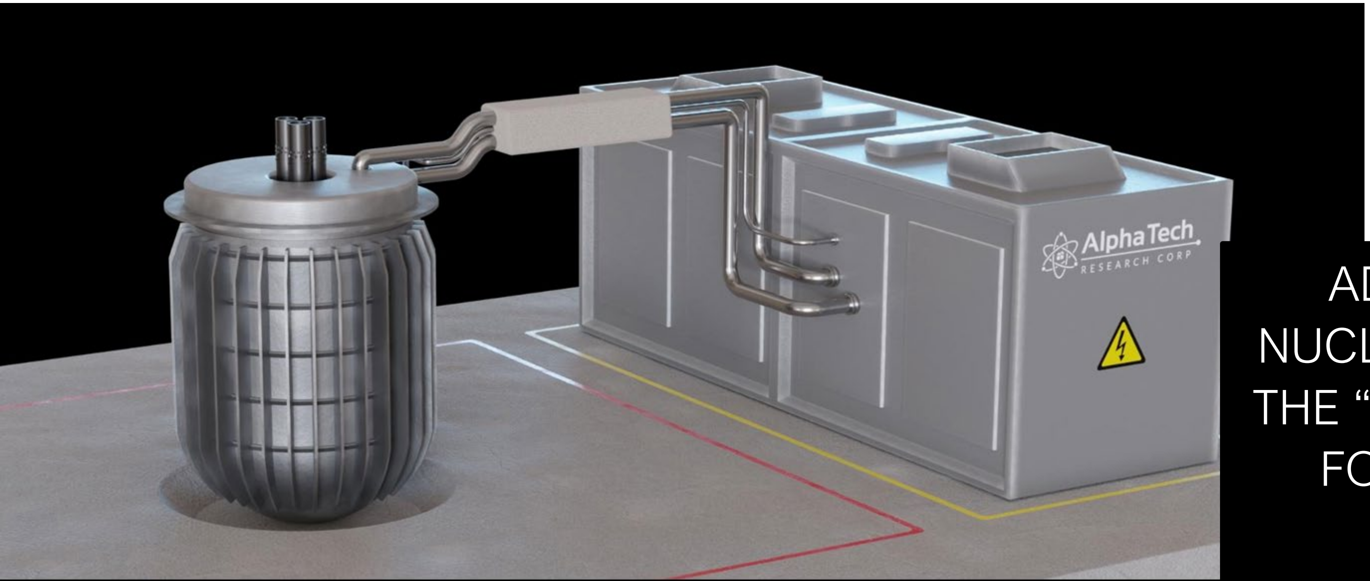
- Atmospheric
- Utilize ALL fuel
- Less Material
- Less safety systems
- No fuel melting
- More simplicity= lower cost
- Increased safety = lower costs
- Caveat: NRC licensing unknowns

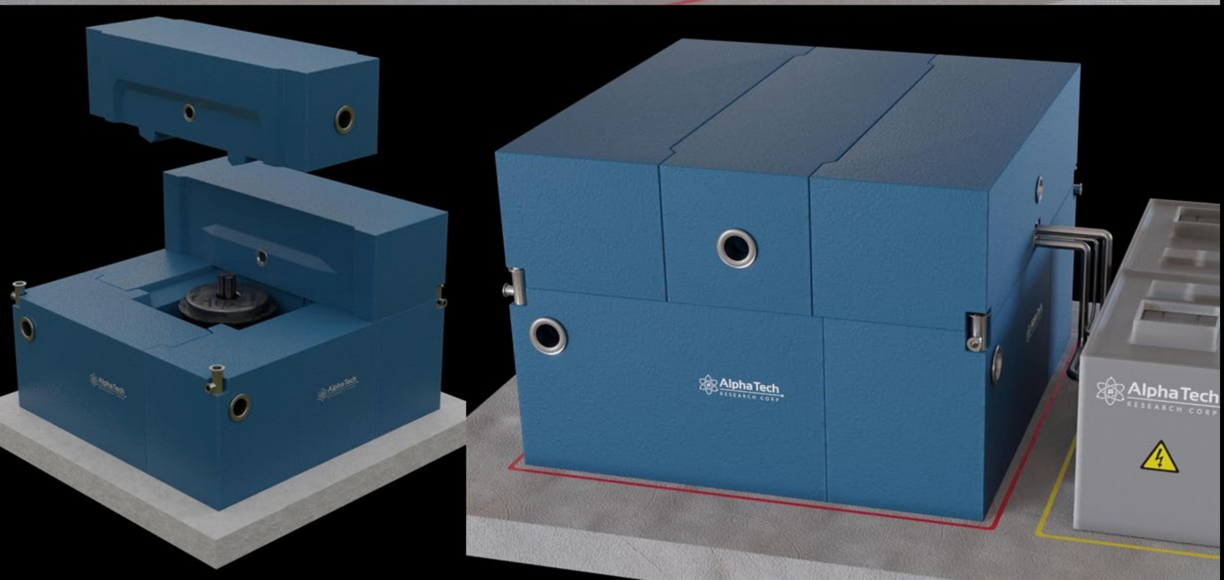


MSR Weapons advantages

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

Molten Salt Microreactor (ARC)





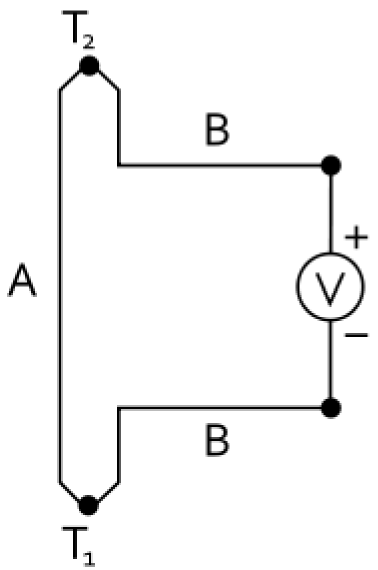
ADVANCED MICRO-NUCLEAR POWER CAN BE THE “MODEL T” SOLUTION FOR CLEAN ENERGY

- Micro-Reactors:
  - Mass produced;
  - Low cost to install and operate;
  - Reduced complexity for licensing.
- Plentiful & widely available.
- Game changer.

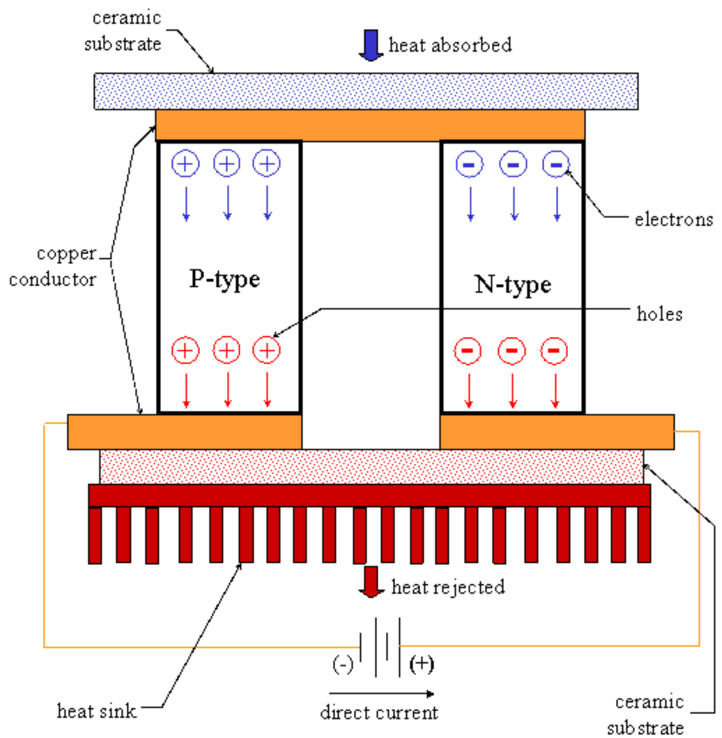
Thermoelectric Generators

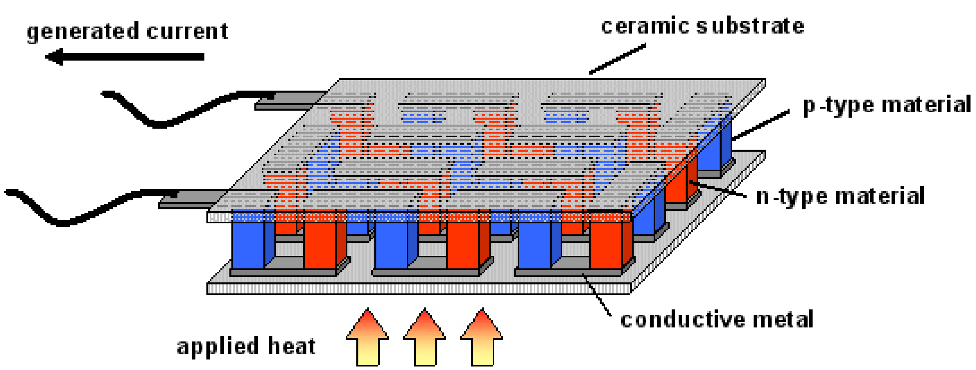
- Low-efficiency (5-10%) and high cost conversion of heat to electricity.
- Applicable primarily where traditional heat engines, which are more efficient and less costly but bulkier, will not work (space, remote locations, etc.).
- Based on the Seebeck effect, the same principle as a thermocouple, except 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.

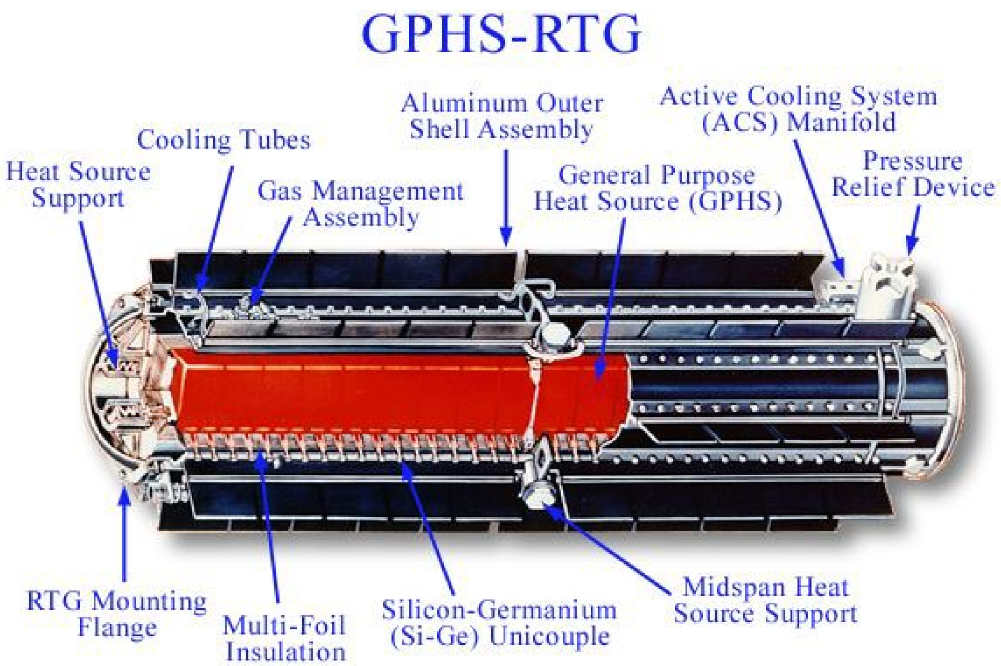
Disadvantages

- 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

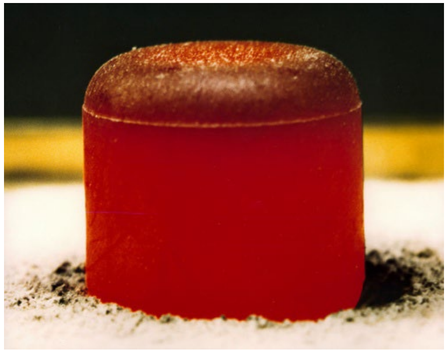
Use decay heat from radionuclides on hot side and ambient (or space) temperature on cold side.

- ^{90}Sr and ½ -
  - 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.



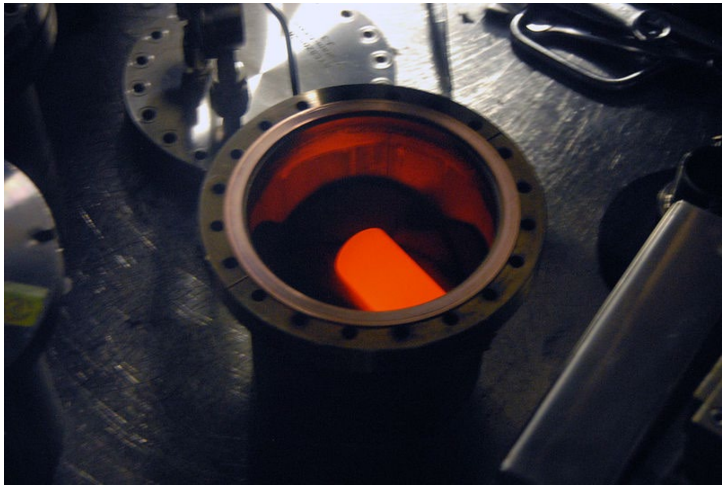
GPHS-RTG for many space probes (Viking, Pioneer, Voyager, Galileo, Ulysses, Cassini, New Horizons)
Initial 300 W_e, 4.4 kW_{th}, 6.8% efficient
^{238}Pu
1 x ½ m
57 kg (5.2 W_e/kg)
SiGe elements

GPU components

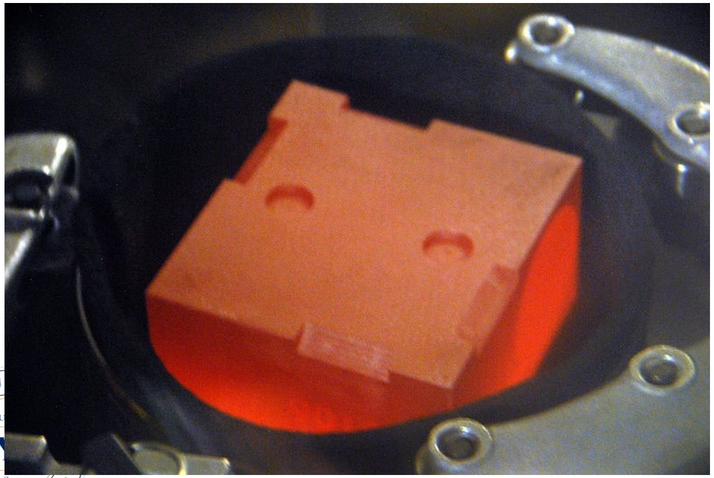


^{238}Pu pellet

Ir cladding

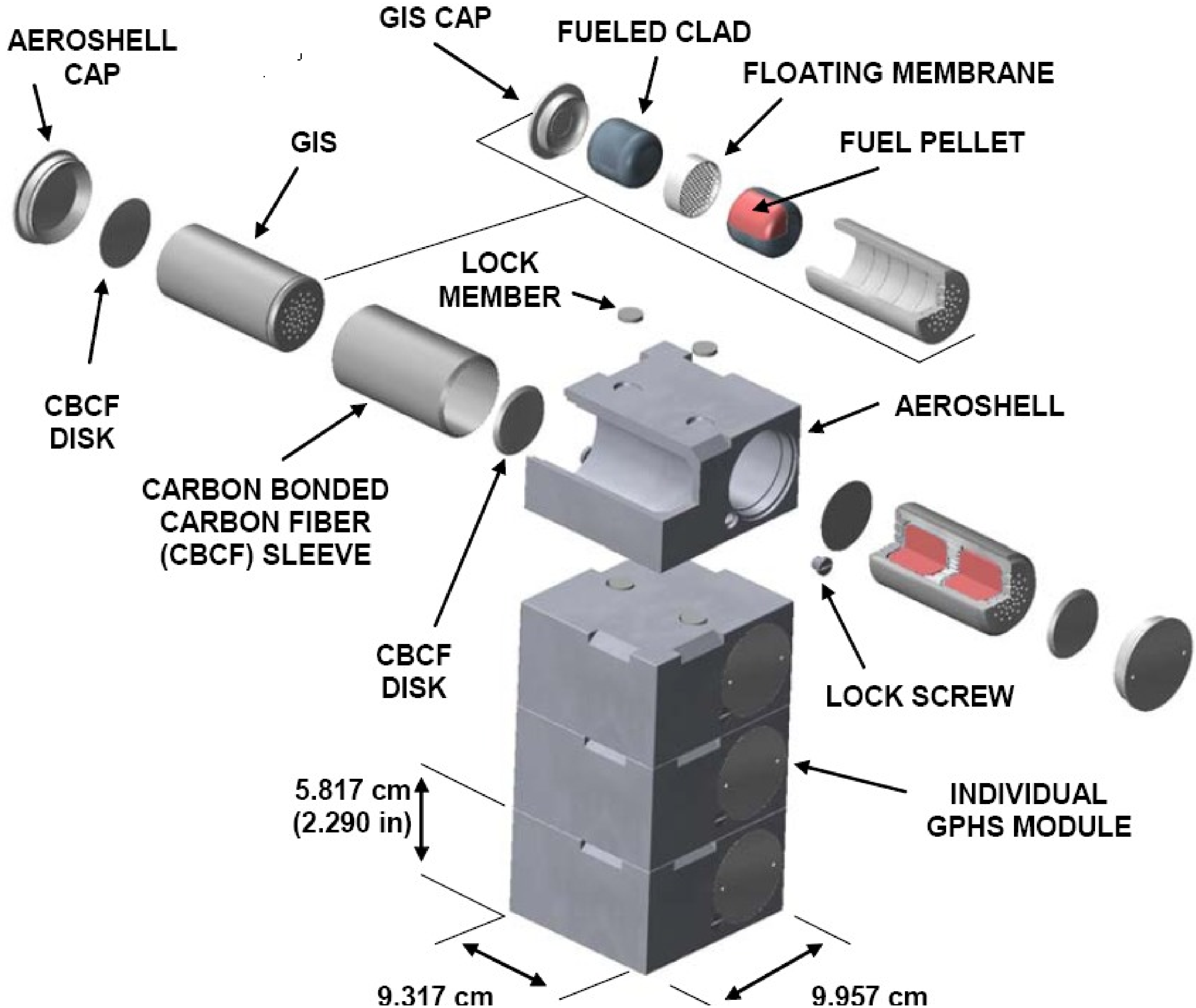


Graphite Impact Casing



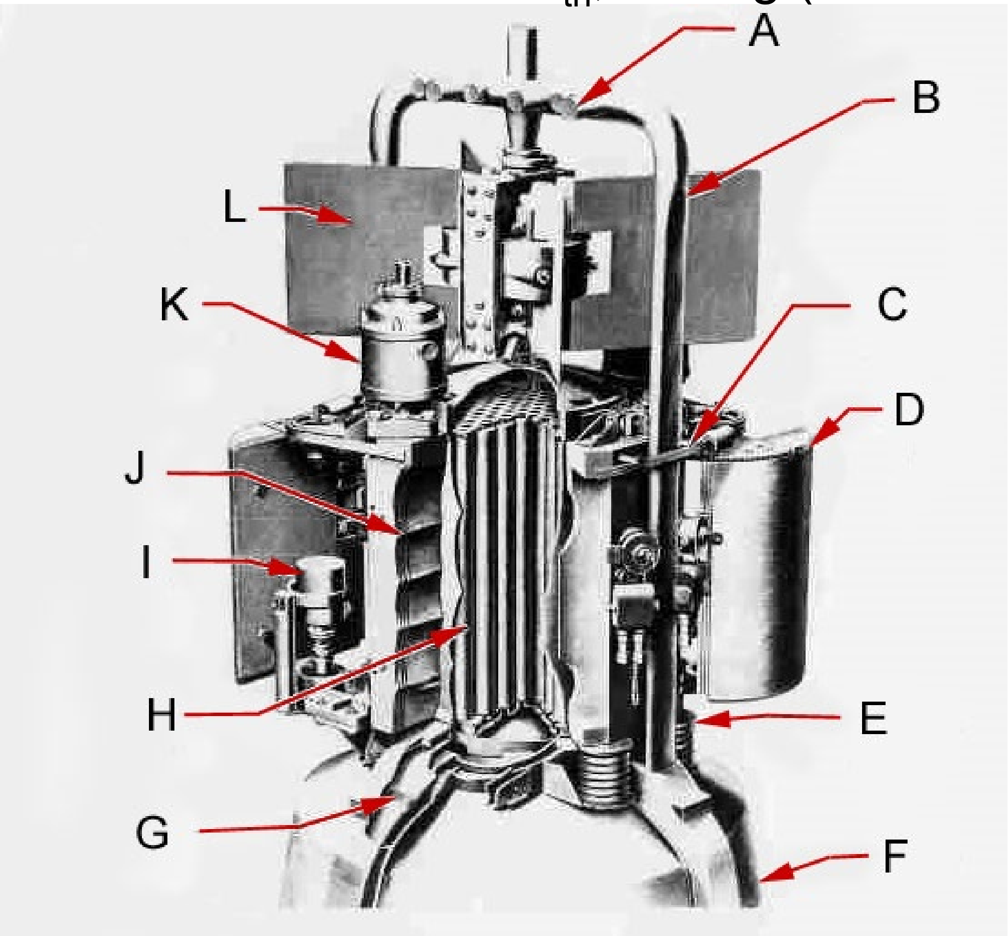
Assembled GPH cell

General Purpose Heat Source



Reactor Thermoelectric Generator

$30\ W_{th}$, 290 kg (unshielded)

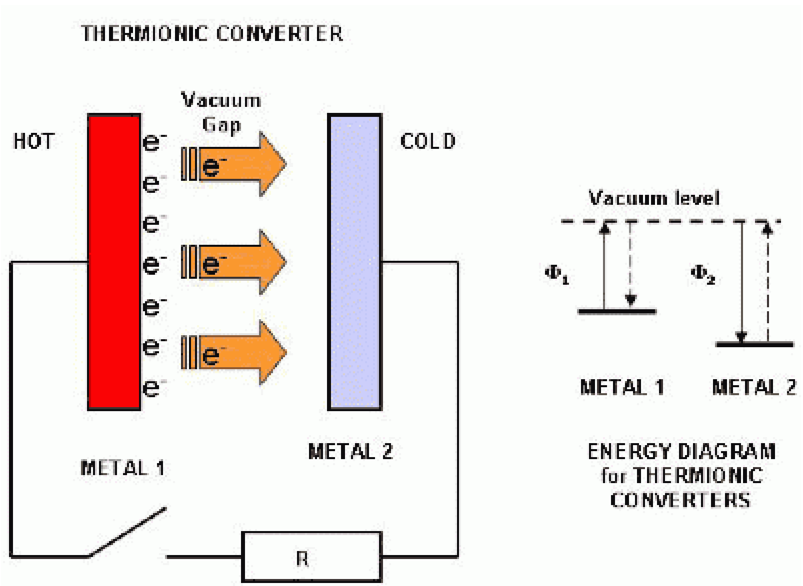


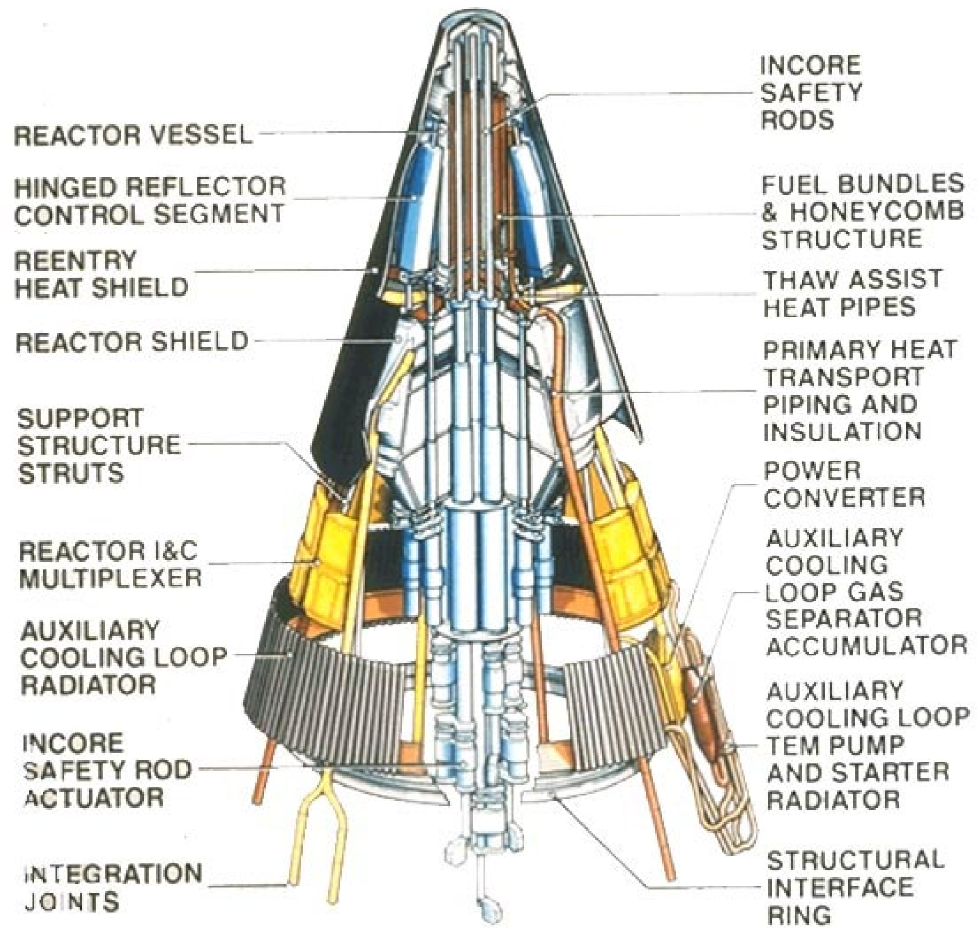
SNAP-10a – K/Na reactor and TE generator – known launch 4/3/1965 in low-earth orbit – design: 500 W_e for 1 year – satellite (not reactor) failed after 43 days – placed in 4000 year (1300 km) orbit – broke up in 1979

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

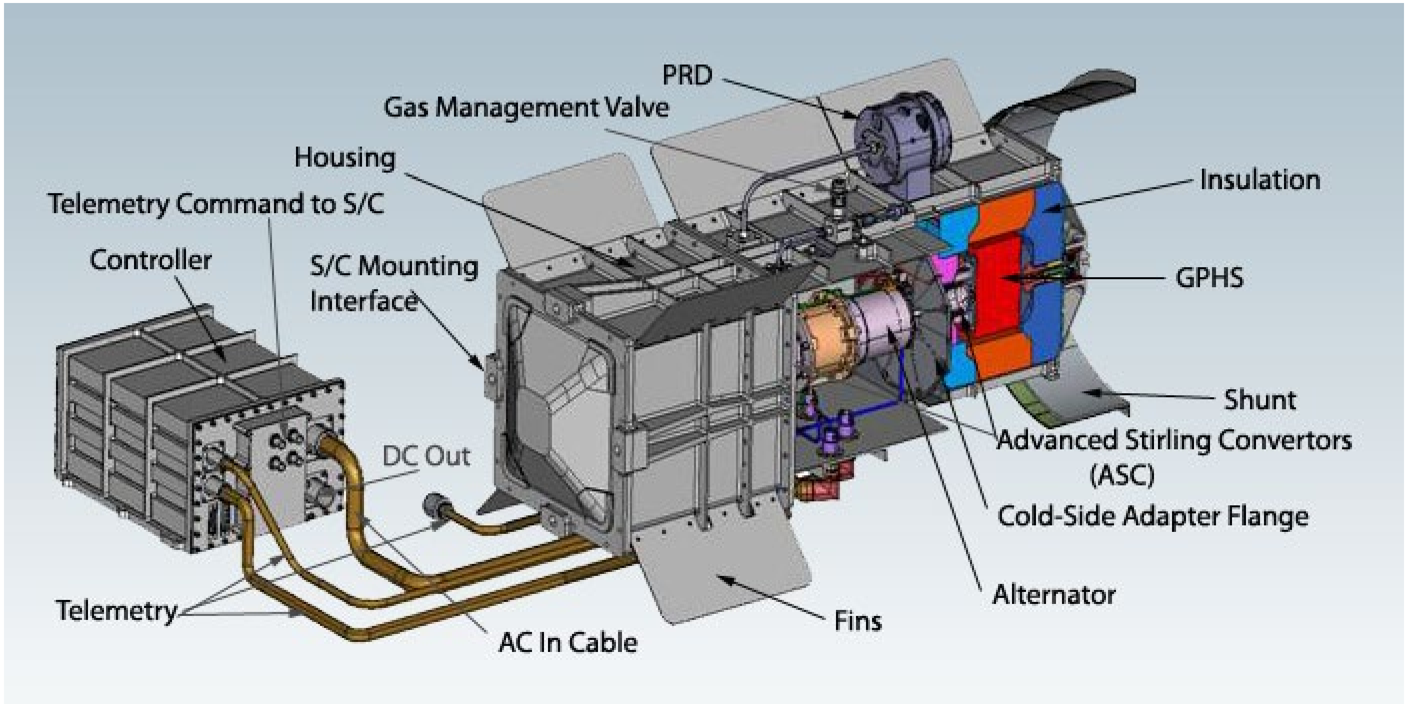
Thermionic Emission





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/kg)

System efficiency: ~ 30 %

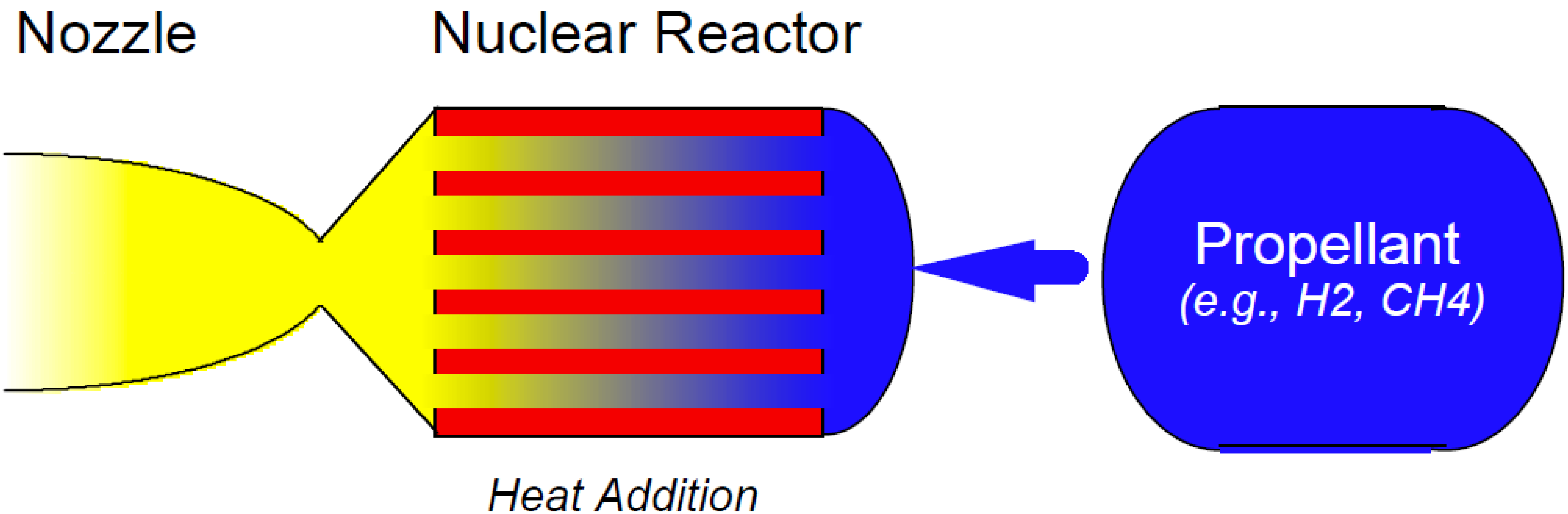
2 General Purpose Heat Source (“Pu238 Bricks”) modules

Uses 0.8 kg plutonium-238

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.

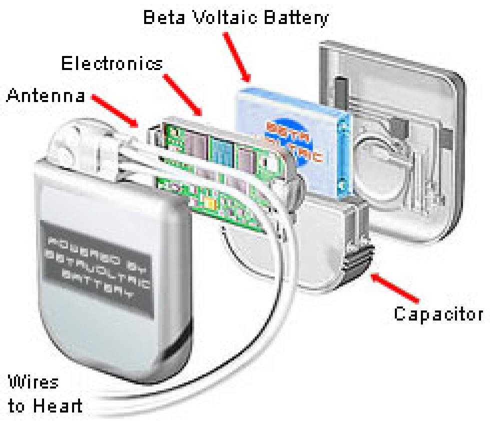
SAFE



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



Example

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