The era of Ultra Safe Nuclear Micro Modular Reactors

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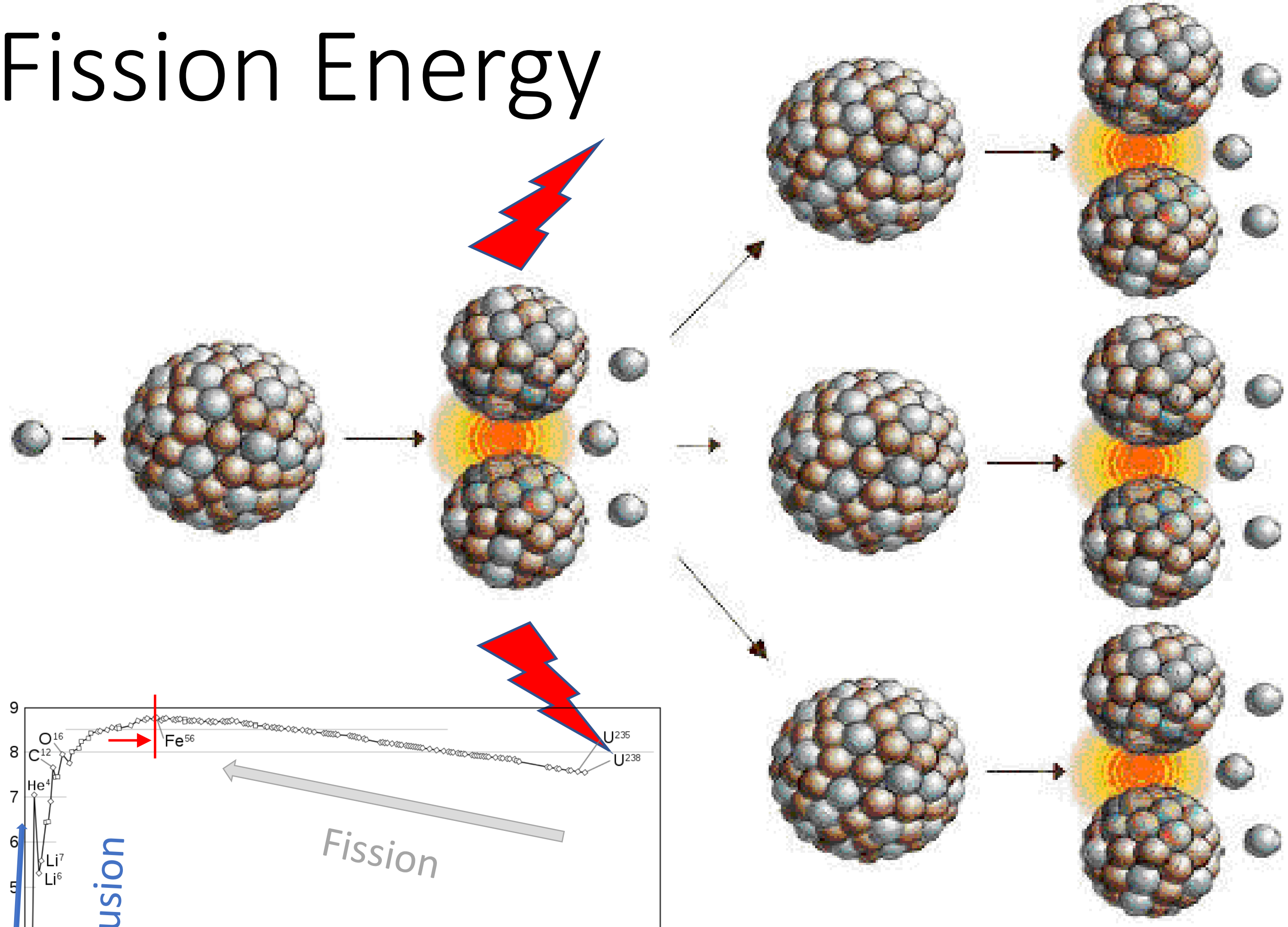
The need for decarbonization of industry and transportation first, and then the Russian invasion of Ukraine and the energy crisis it caused, are bringing nuclear energy back.
The Micro Modular Reactors (MMR) and the achievement of intrinsically safe reactors are bringing nuclear power directly where is needed, in factories, near cities and along highways.

Nuclear Fission Energy

- Fission of ^{235}U produces:
  - energy,
  - fission products and
  - neutrons
- Chain reaction if there is:
  - Sufficient ^{235}U density to catch most neutrons
  - Sufficient neutron confinement
  - Sufficiently low neutron absorption ^{238}U, B^{10}, . . . (reactor poisoning)



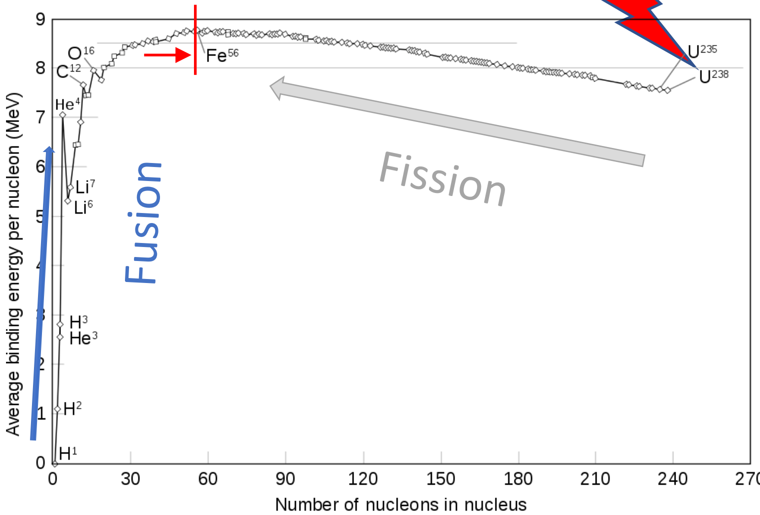
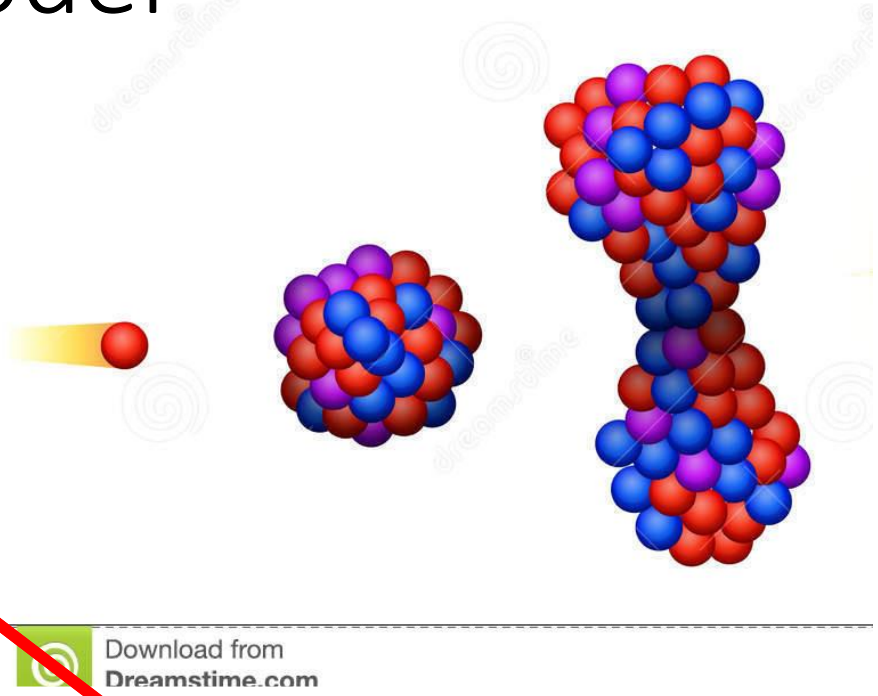
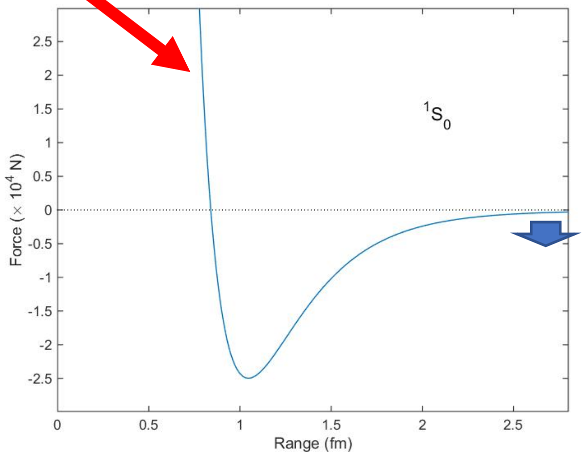


Figure: Altervista

The droplet model

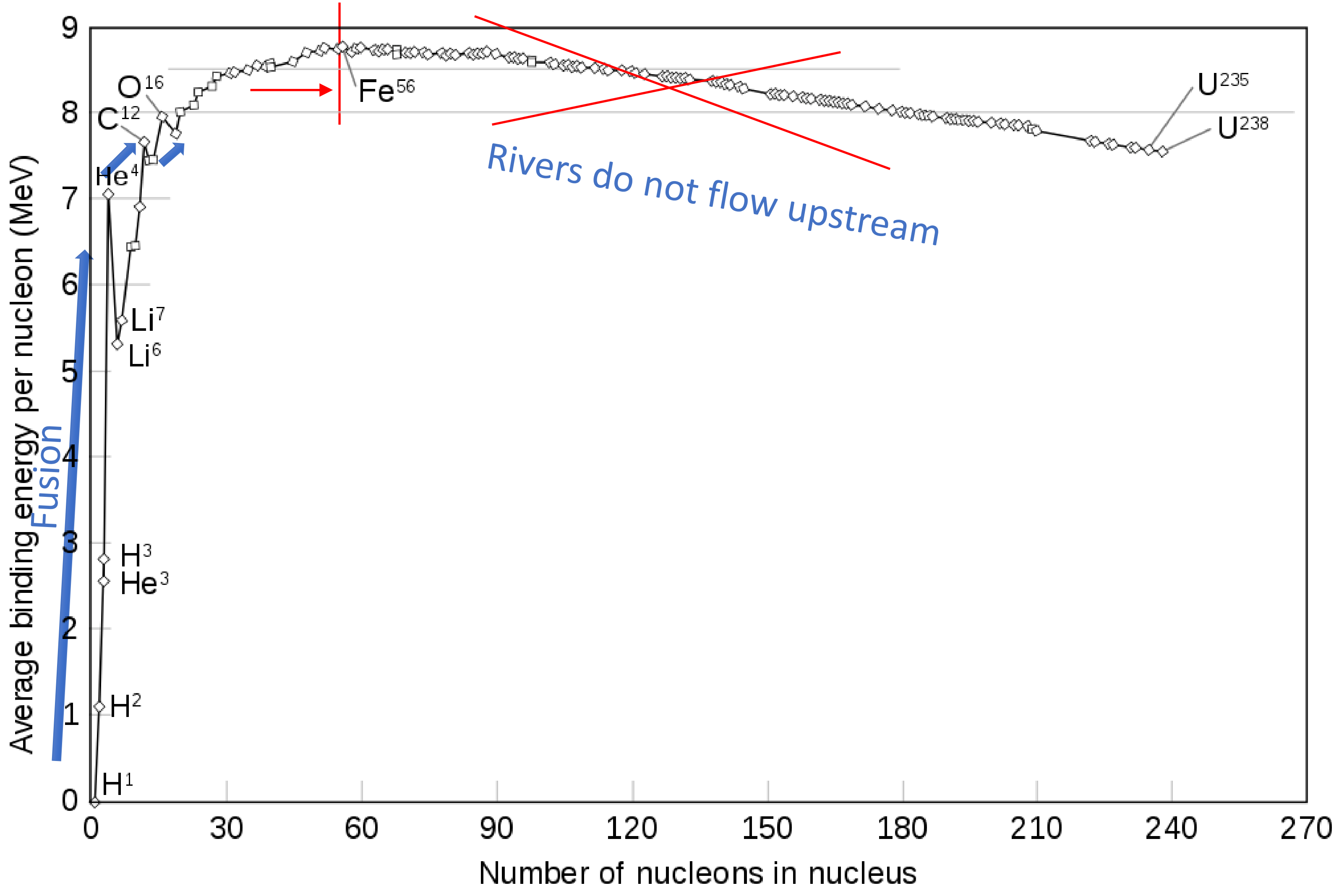
- Proton/Neutron are like hard spheres 10^{-15} m in size subject two forces
- Strong force, acts between protons and neutrons, and only on closest neighbors, produce surface tension proportional to n_{proton}
- Electromagnetic repulsion proportional to n^2_{proton} that eventually dominates
- Crossover at Uranium
  - Electromagnetic repulsion makes all transuranic nuclei unstable (including ^{235}U)





Where does Uranium come from?

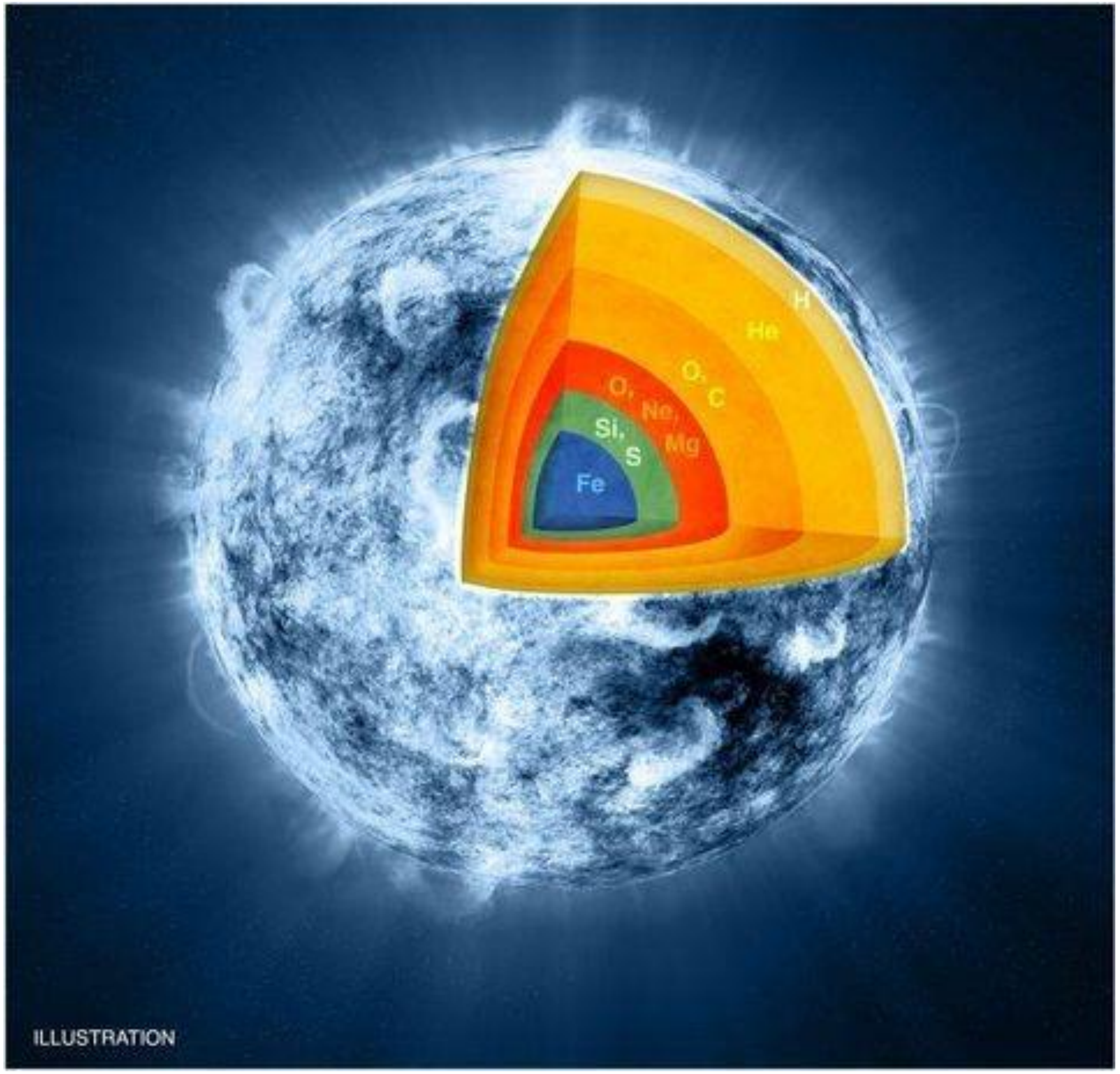
- The big bang made lots of hydrogen
- Stars burn hydrogen into elements of the periodic table down to Iron and vicinity
- And the heavy elements?



- When in a large star a core of ~ 1.5 solar masses of Iron (Fe) is formed, the Iron in the core suddenly collapses into neutrons, emitting a large number of gamma rays and neutrinos

- The explosion blows the rest of the star back into the galaxy gas

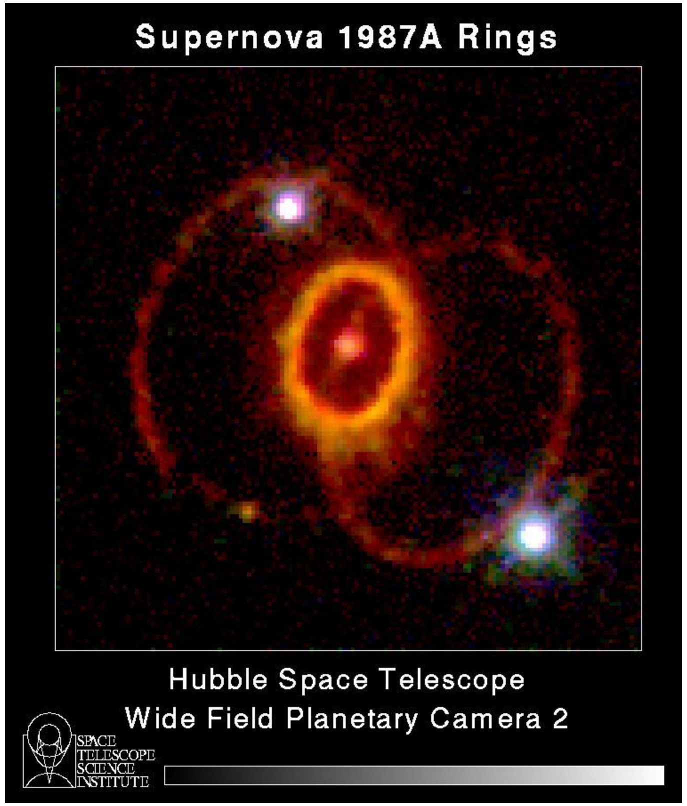
- This is called a SuperNova

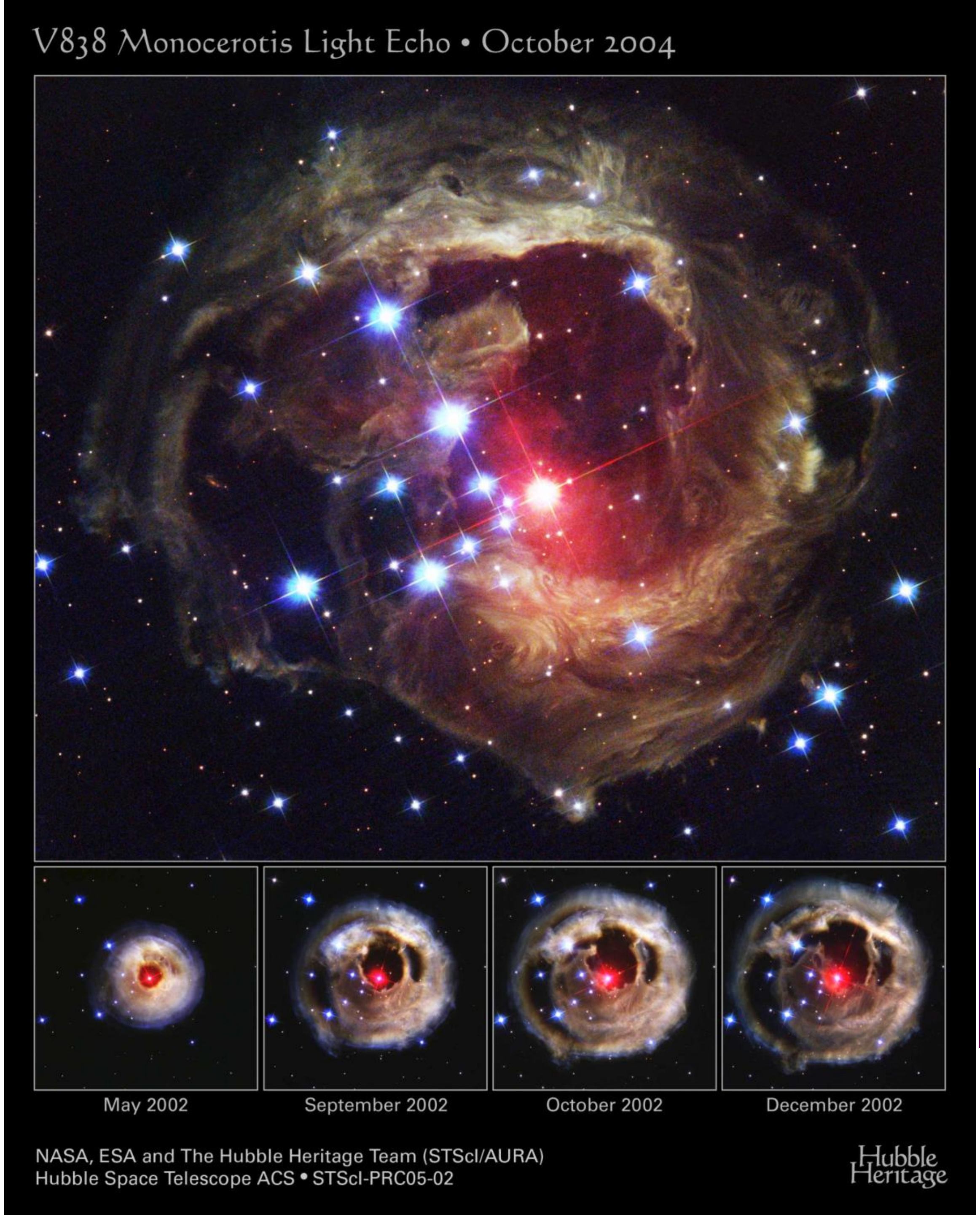


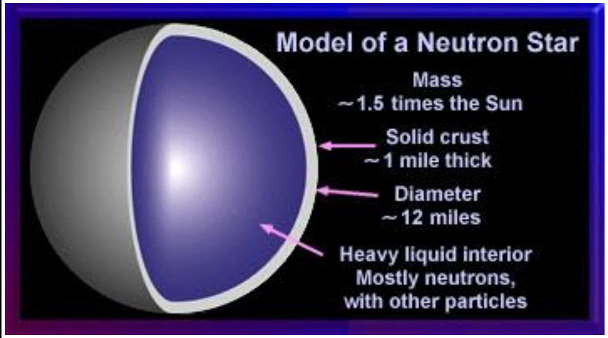
NASA/CXC/M.Weiss

SuperNova Explosions

Some powerful and spectacular shows of nature's power

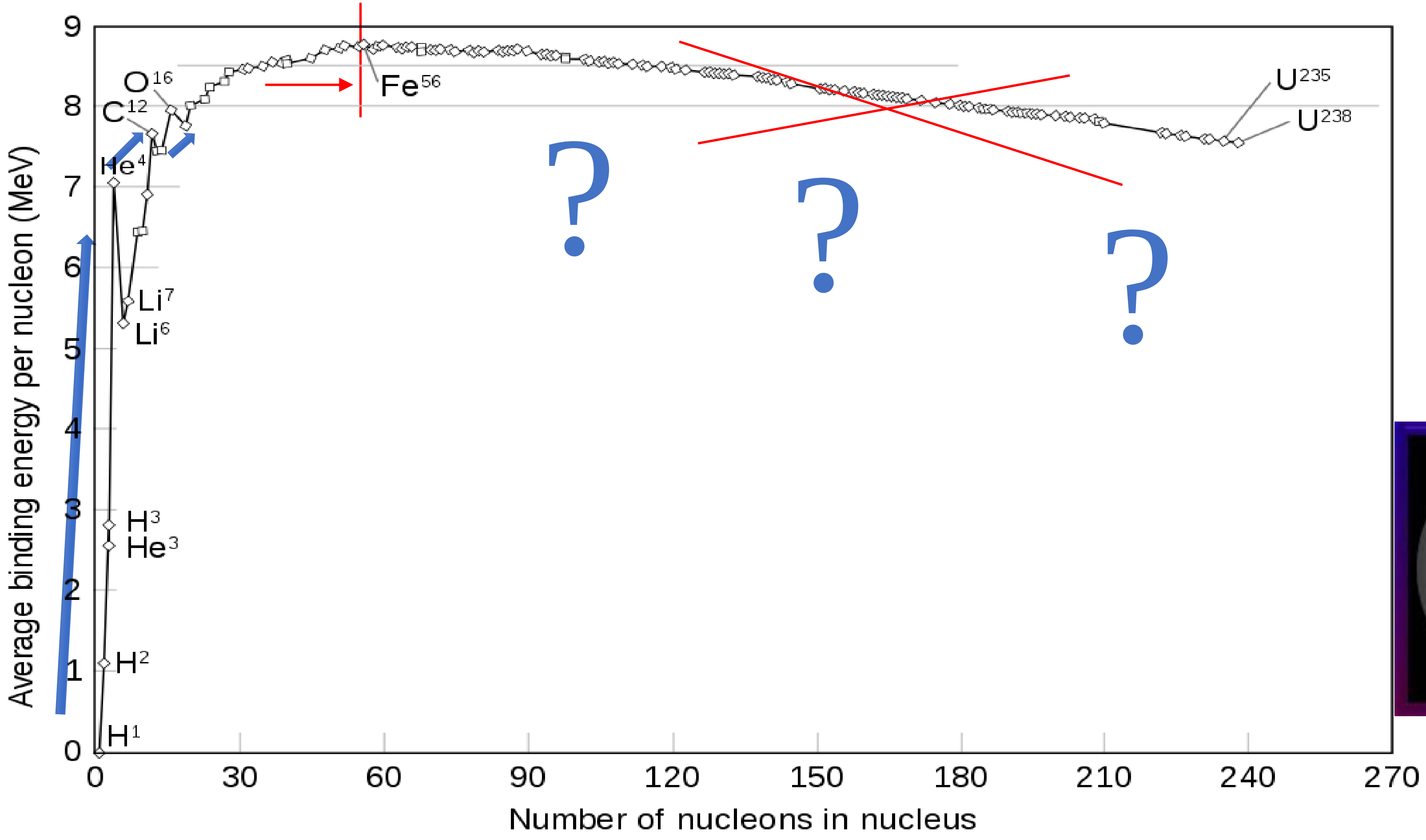


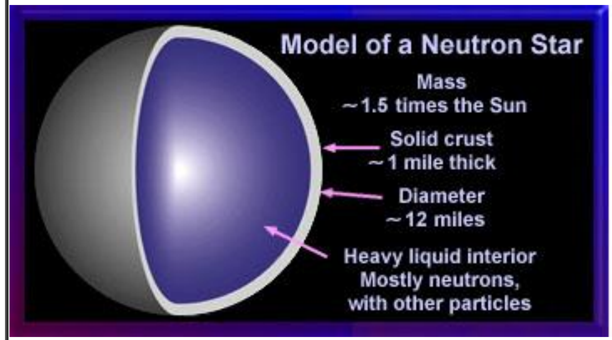




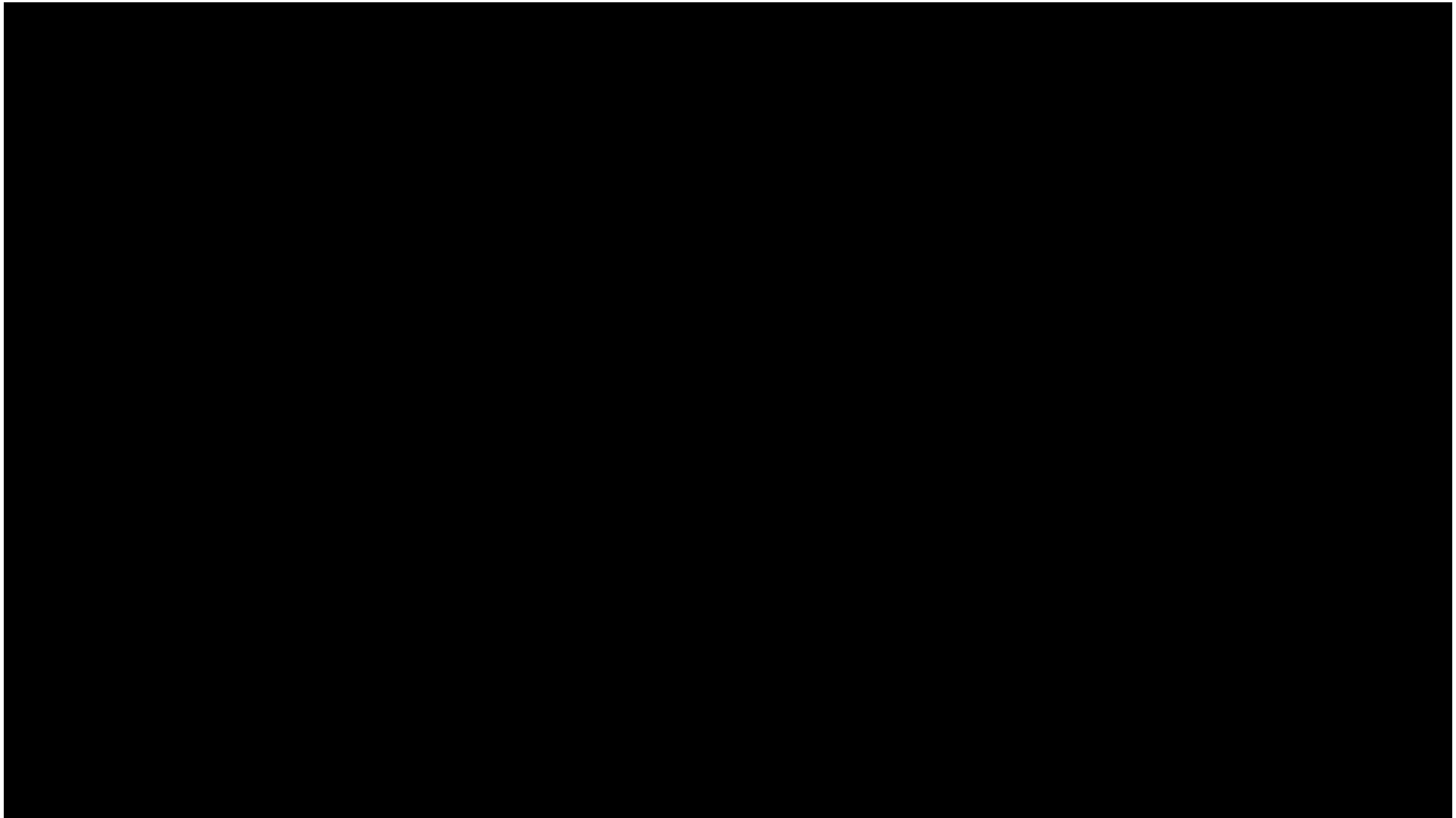
Where are the Gold galactic factories?

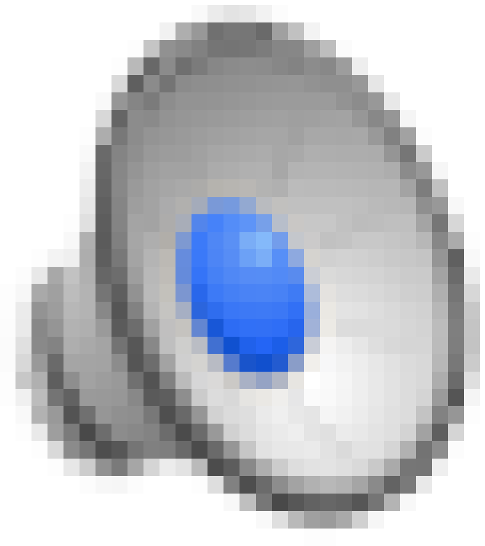
And, Lead, Tungsten, Uranium . . .





During inspiral of two Neutron Stars into a black hole, the outer mass try to go faster than light between 0.1% and 10% of the mass is ejected

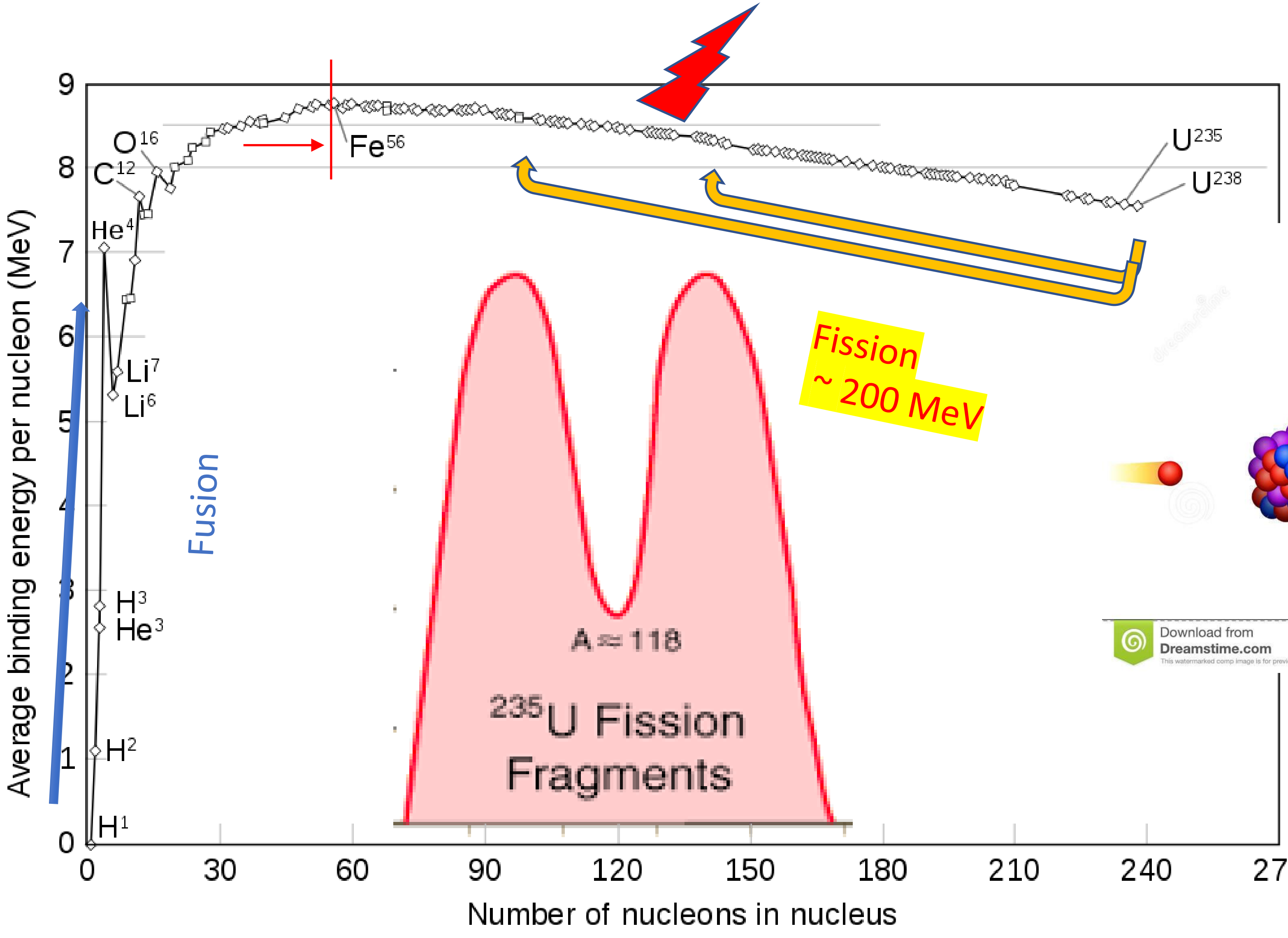


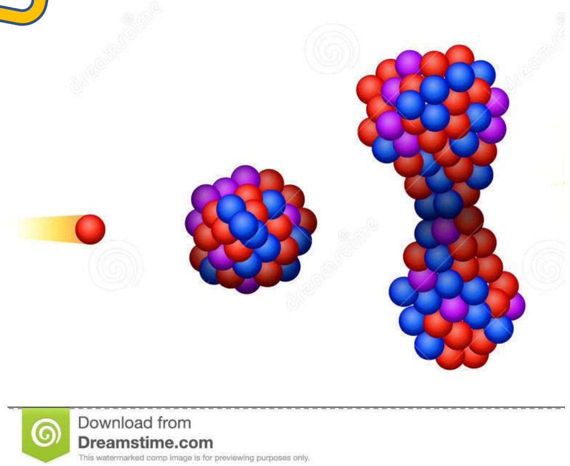


r-Process Lanthanide Production and Heating Rates in Kilonovae, **Jonas Lippuner and Luke F. Roberts**

[The Astrophysical Journal 815, 18 (2015)]

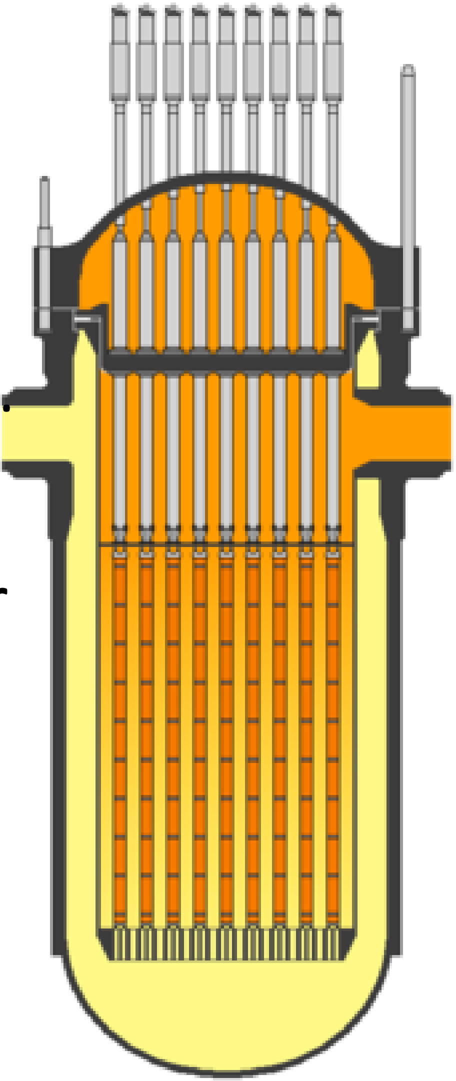
Nuclear Power and Fission products





3rd generation nuclear reactors

- Mostly Water cooled
- Metal fuel rods
- Gigantic:
  - ~ 1-1.5 GW-el.   ~ 3-4.5 GW-therm.
- Semi-Passive cooling features
- Large steel pressurized container vessel
- Large concrete containment building



3rd generation reactors

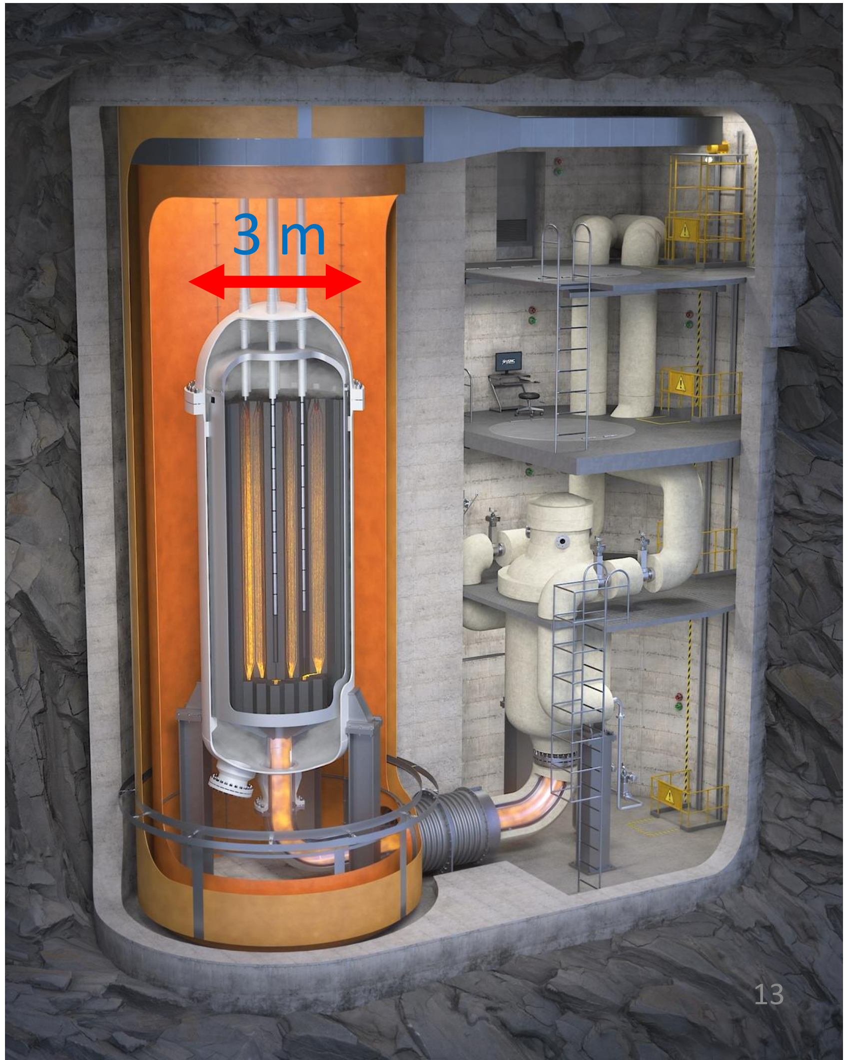
- 2^{nd} gen. were quite safe, (include Fukushima and three Mile Island)
  - Managed to self damage (meltdown)
  - scared the world (mostly due to media hype),
  - but caused little or no harm to people
- 3^{rd} gen. reactors are substantially safer due to backup systems
  - Mostly same working concepts
  - Cannot harm people with radiation release
  - But can self damage in accidents

- Chernobyl was a criminal design, with no containment vessel nor containment building to allow for easy plutonium production for bombs

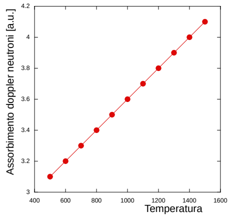
4th generation nuclear reactors

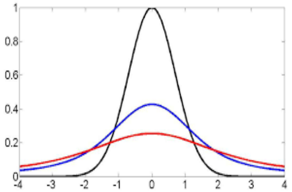
- Numerous (>60) 4th generation nuclear reactor designs are being developed
- Few already being reviewed for licensing
- All smaller in size and modular
- Factory built, truck installed.
- All seeking even higher safety level than 3rd generation reactors
- Some are intrinsically safe
- Including

Ultra-Safe Micro Modular Reactors



Why USNC MMR are Ultra Safe?



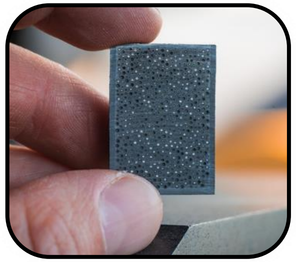


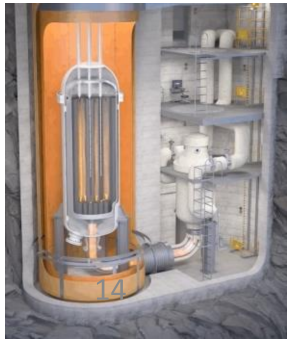
- Five physical reasons:

    1. Self arresting nuclear reaction 300°C above design temperature due to Doppler effect of the chain reaction
    2. Working temperature less than 1000°C
    3. All ceramic construction with melting points above 2300°C thus making meltdown and even any damage to the plant physically impossible
    4. Permanent confinement of fission products at millimetric scale

       Reactor damage or escaping radionuclides are impossible

    5. Helium cooled. The elimination of water as a heat extracting fluid makes steam or hydrogen explosions impossible
    6. Low power(<50 MW-thermal ~ 1.% of traditional reactors)

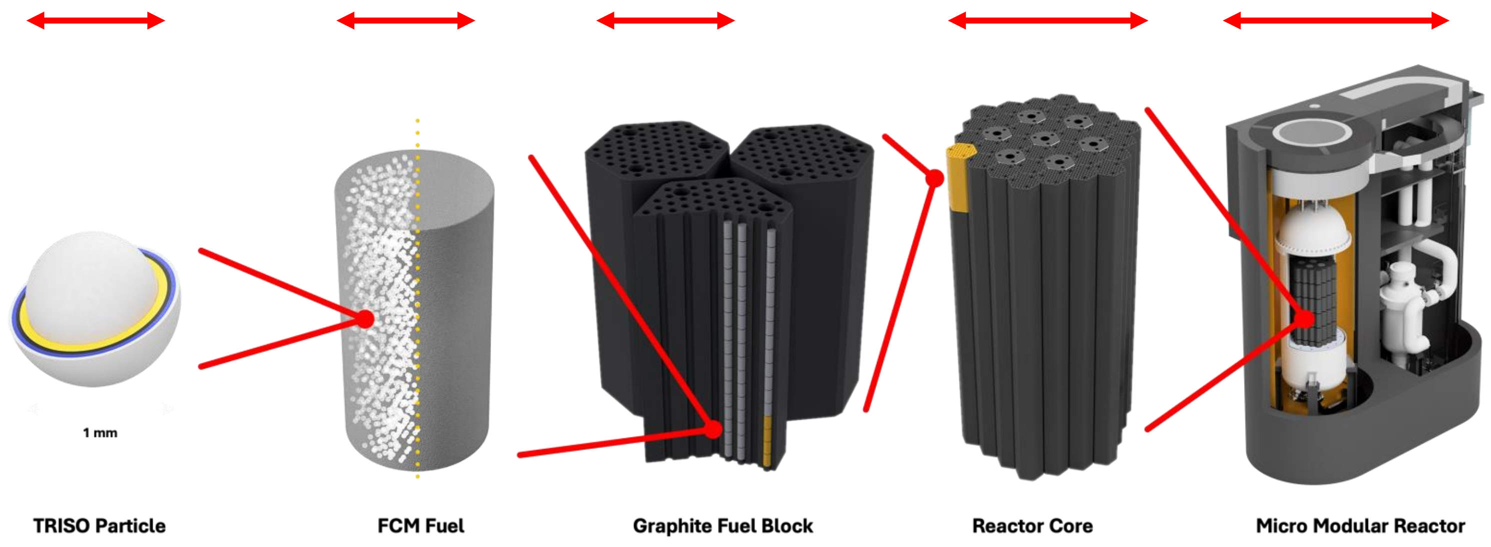




Building up a micro modular reactor

- TRISO fuel bead
- SiC fuel cartridge
- Hexagonal Graphite moderator module
- Hexagonal assembly of modules into a reactor core
- Graphite neutron reflector
- Helium pressure tank for heat extraction
- Helium pump and heat exchanger in a separate volume

TRISO Bead 1 mm | Fuel Cartridge 2 cm | Graphite Moderator 30 cm | Reactor Core 2 m | Reactor Well 5x10 m

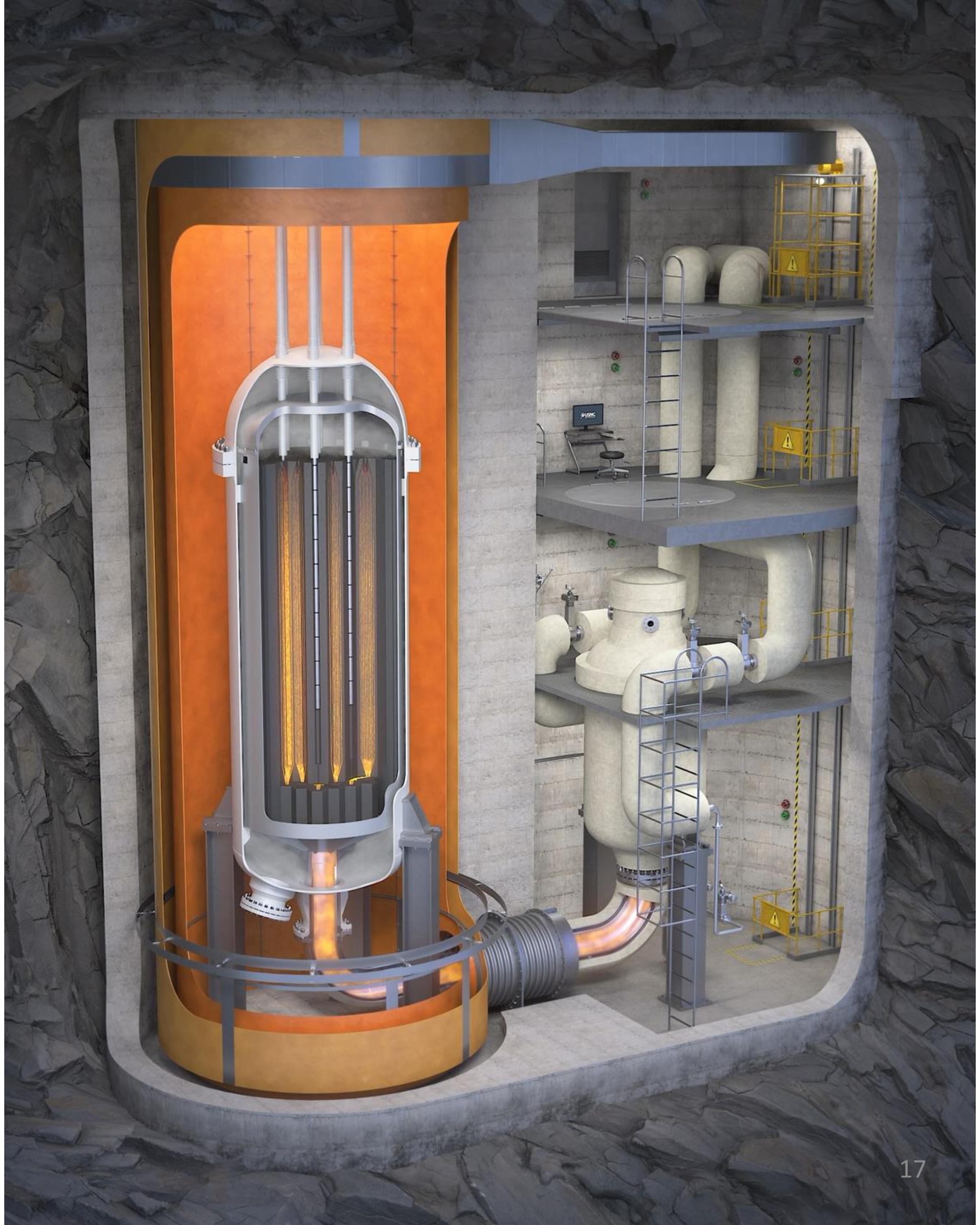


The micro reactor assembly

- Fully modular construction
- The first metal component is the 3 m diameter sleeve enveloping the neutron reflector outside the core
- Outside the reflector the temperature remains at safe levels even in case of full loss of cooling power.

The micro reactor heat extraction

- No moving parts in the reactor
- Helium circulation is used to extract heat
- Pumps and all moving parts are separated by a thick concrete wall and stay away from neutron flow
- The heat exchanger transfers the heat to a molten salt circuit that separates the nuclear from the traditional plant.



The TRISO fuel bead

- Developed in the 50s-60s
- Completely built with refractory materials stable up to >2300ºC
- The outer shell of dense pyrolithic Graphite and the Silicon Carbide effectively seal all decay products at a microscopic level

The TRISO fuel bead structure

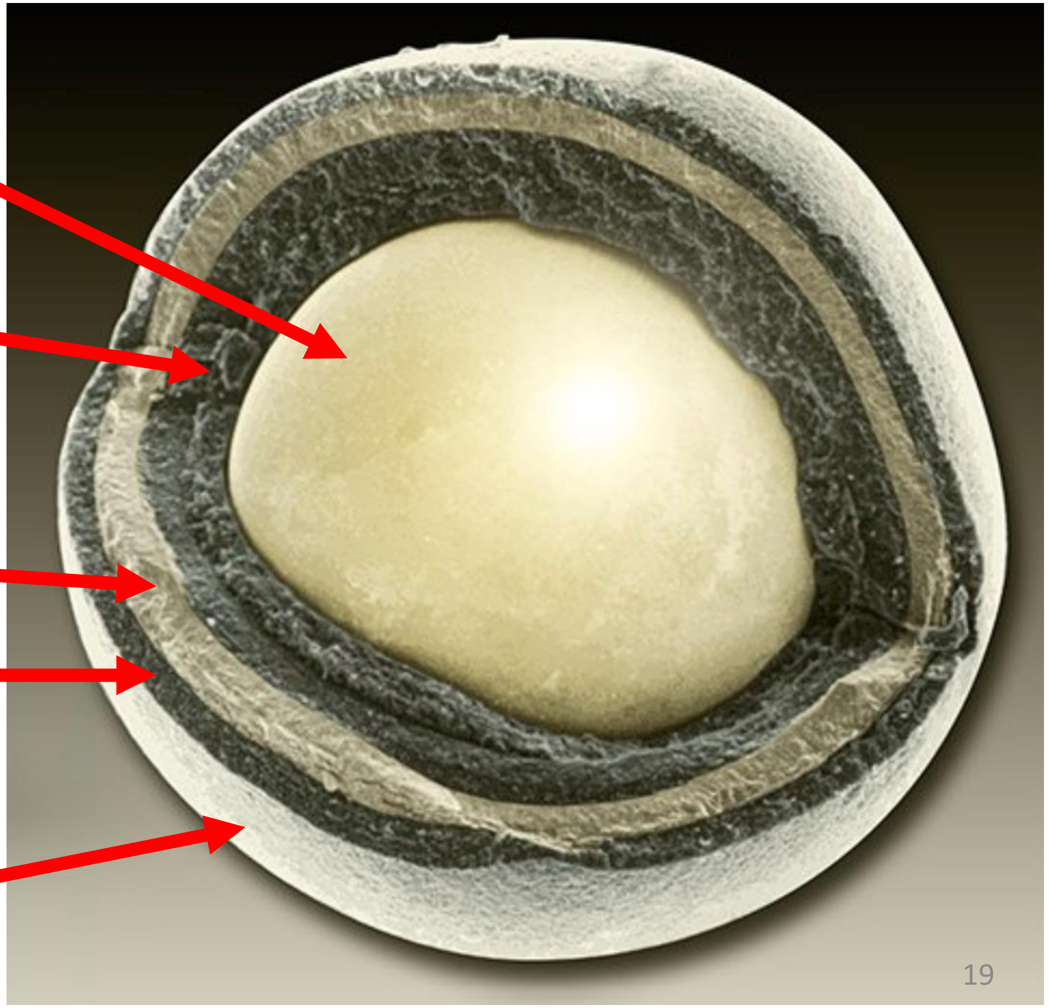
- Uranium dioxide (UO_2) core ~1/2 mm diameter
- Low density carbon (~active carbon) absorb all volatile fission and decay product, allows for UO_2 expansion

Sealing layers:

- High density pyrolithic graphite
- PVD Silicon Carbide

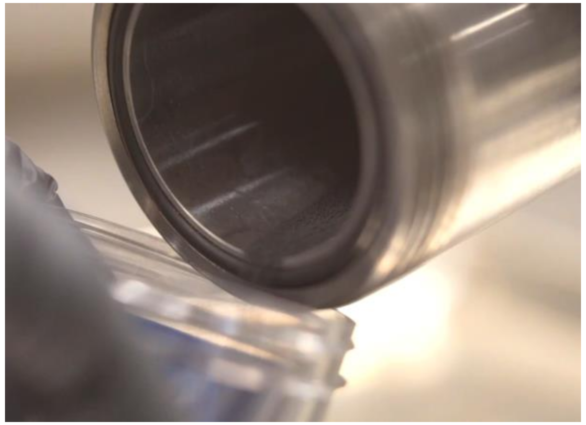
~1 mm outer diameter

  - Extremely dense ceramics
  - Lowest melting temperature 2350ºC



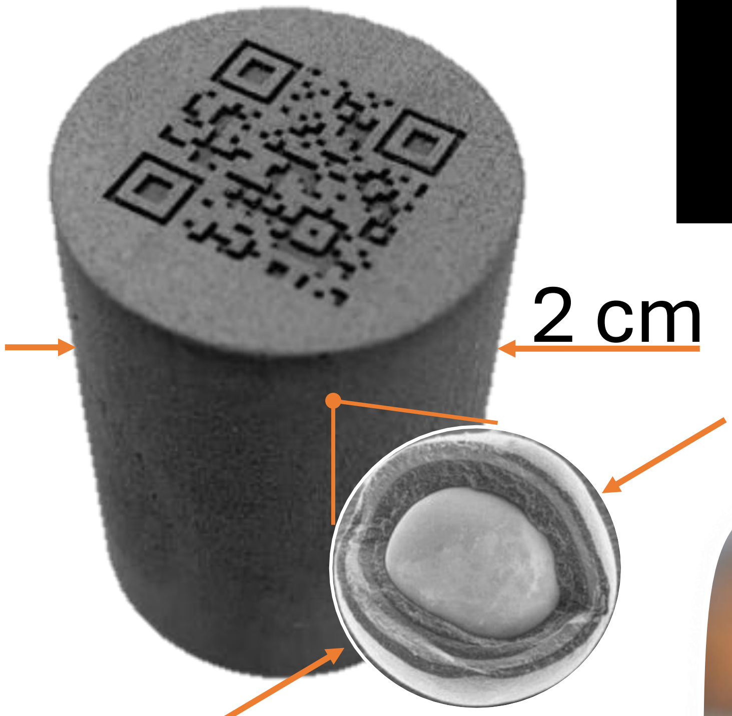
Fluidized bed coating TRISO beads with pyrolithic graphite and Silicon carbide

- Methane and silane gases are decomposed at high pressure and temperature to form dense coatings films



The Silicon Carbide fuel cartridge

- 3D printed SiC canister
- Contains hundreds of TRISO beads
- The interstices are refilled with SiC infiltration (~CVD)



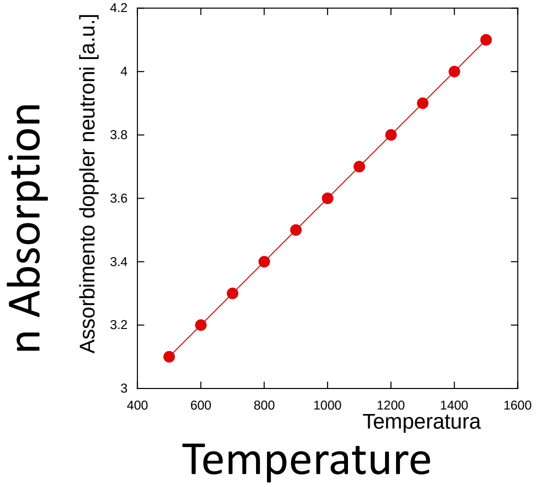
- The cartridge becomes a compact stone as hard as diamond
- Produce a redundant confinement layer for decay product

Hexagonal moderator modules

- Hexagonal graphite modules form the reactor core
- Graphite is a refractory material that melts at 3600^{o}C

- Visible in the picture are the channels for :
  - Stacks of fuel cartridges
  - Helium flow for heat extraction, and
  - Shut-down control rods

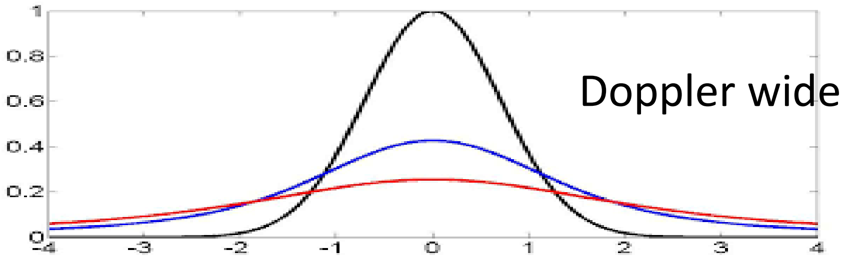
Intrinsic safety: Negative Thermal Reactivity Coefficient from ^{238}U

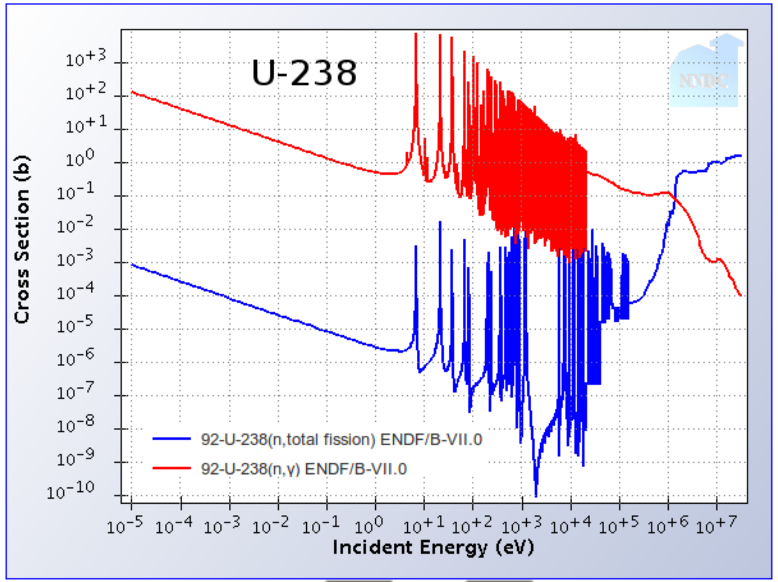


- Uranium has a forest of extremely narrow neutron absorption lines
- Due to their tightness, at room temperature they are

weakly effective in capturing neutrons

- The resonances widen up by Doppler effect as temperature raises and
- become more effective to capture neutrons and stop the chain reaction





Fission product confinement
Spent fuel disposal

- The Silicon Carbide and graphite layers of the TRISO bead and the Silicon Carbide cartridge are dense ceramics impervious to liquids and gases

- The Silicon Carbide is strong stable and not reactive

- Confine all fission products

Fission product confinement

- Diffusion is an Arrhenius process, i.e.
  - the diffusion depth is logarithmic with time and
  - the diffusion speed decrease exponentially with temperature

- Diffusion through the 35 µm thickness of the SiC layer of the TRISO beads

was observed to start only after many days

at very high (>1250^{o}C) temperature.

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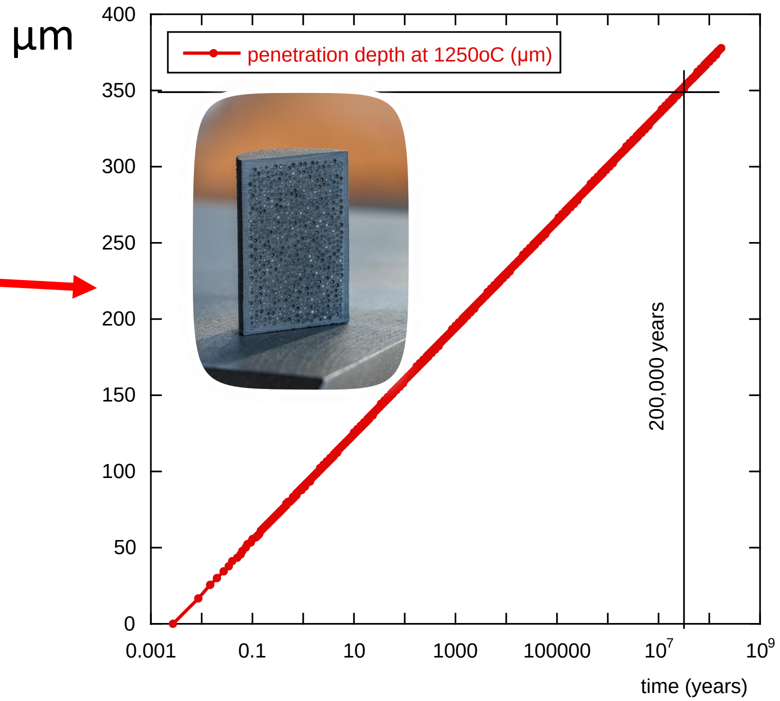
Fission product confinement

- It would take more than 100,000 years to penetrate 1/6 of the 2 mm thick canister walls even at high temperature
- Every 100°C drop in temperature will reduce the diffusion speed by orders of magnitude
- In a geological repository, the temperature would be low
- It would take about the age of the Universe to penetrate the wall thickness !

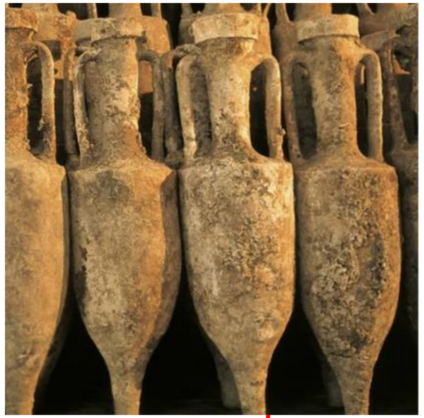


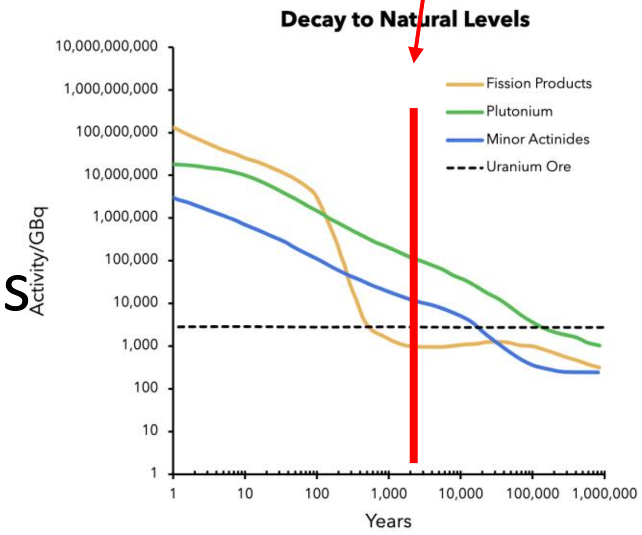
Confinement of fission products

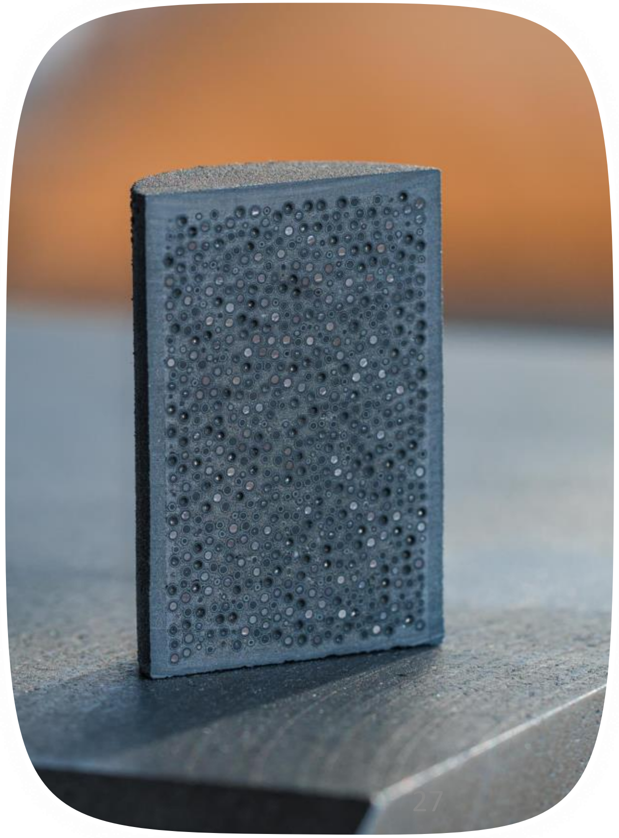
- SiC is thousands of times more compact than the earthenware used by the Romans, which stored wine for 2000 years at the bottom of the sea

- All fission products confined for millions of years

- Well over the 200,000 years it takes for plutonium to decay

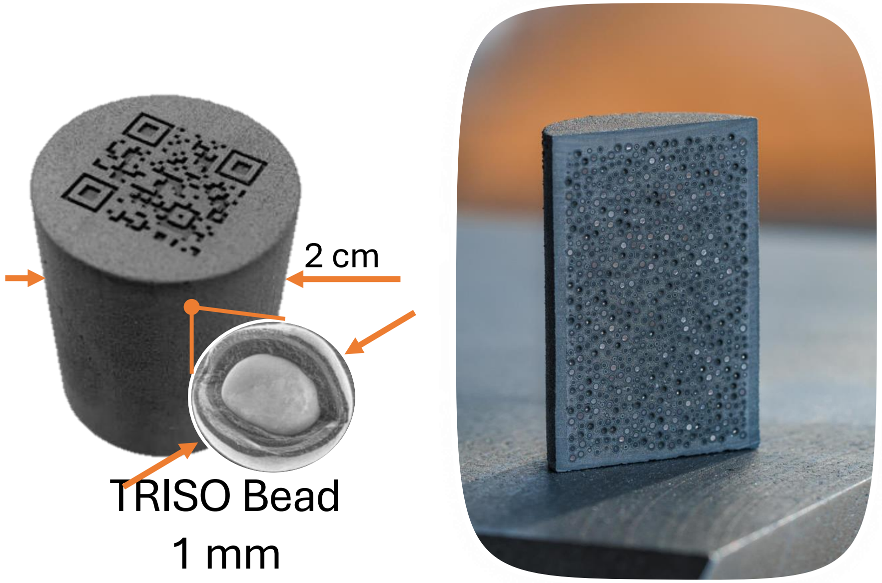


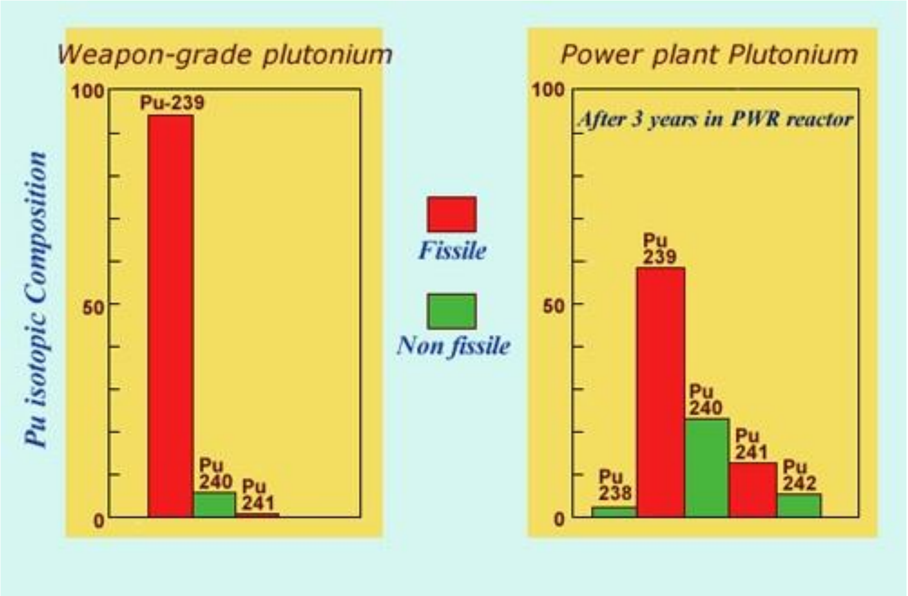




Non proliferation

- Confinement of fission materials within the silicon carbide cartridge makes plutonium nearly unattainable for military uses
- Long exposure to neutron flux transmutes ^{239}Pu into ^{240}Pu and ^{241}Pu rendering it not useful for making bombs
- The Quad code printed directly into the silicon carbide makes for easy tracking and proof of forgery

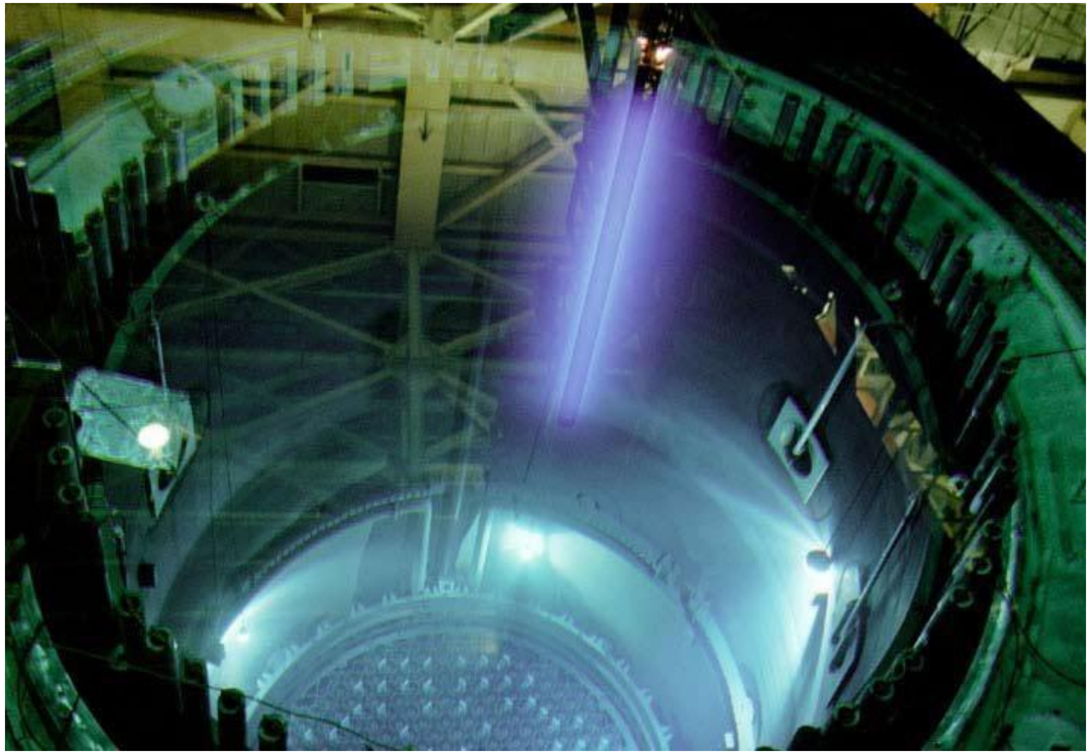




https://radioactivity.eu.com/phenomenon/plutonium_239

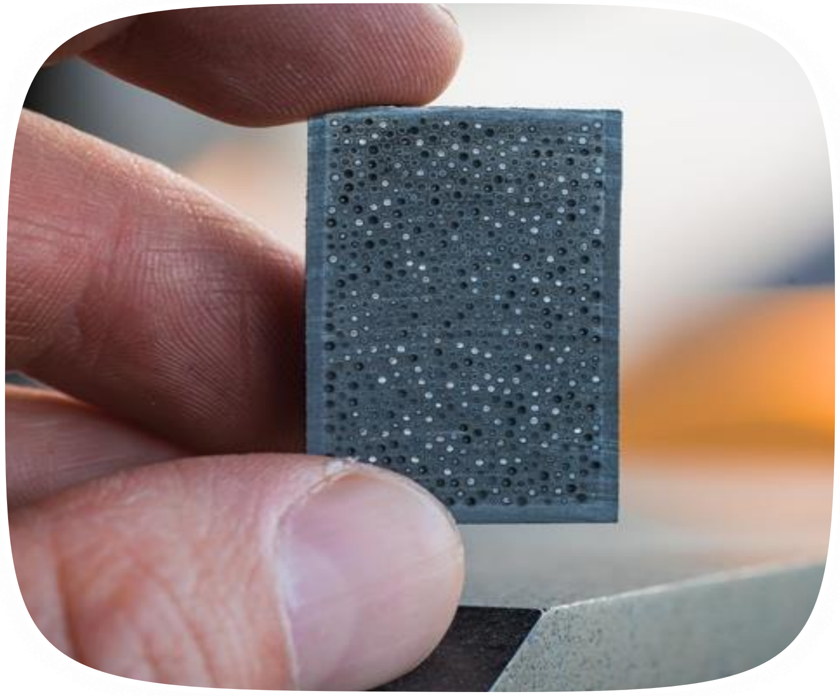
Operational lifetime of older reactors

- All reactors must be loaded just ~1% above unitary reactivity
- After consuming ~1% of ^{235}U , refueling is necessary, typically every 1.5 years
- Cost, downtime and risk



Boron to extend MMR operational lifetime

- ^{10}B absorbs neutrons and reduce the reactivity (a reactor poison).
- A calibrated number of Boron beads are interleaved with the UO_2
- More ^{235}U is loaded to reach criticality
- ^{10}B But is burned into ^{11}B in the same proportion of ^{235}U
- The reactivity remains stable for as much as 20 years without refueling



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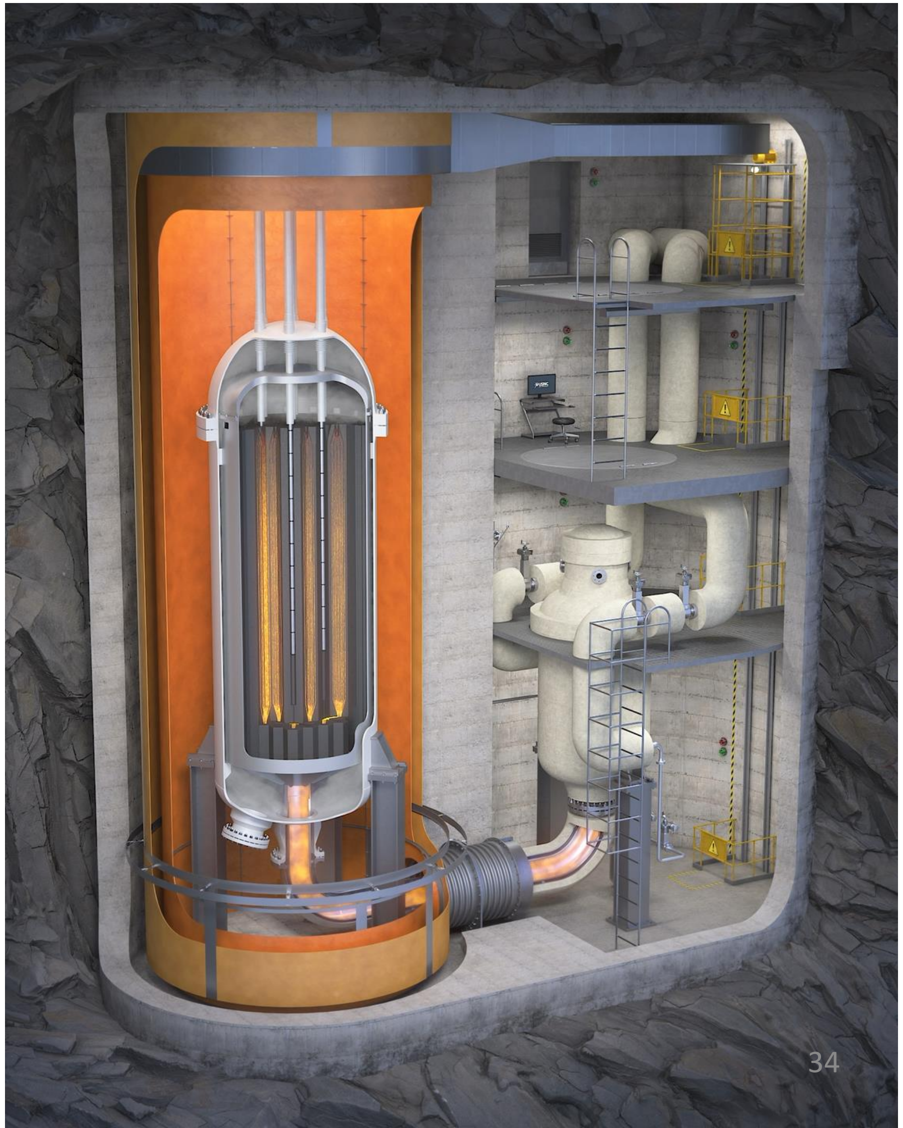
Factory power plants

- The vocation of the nuclear batteries is to be sited inside factories
- To provide heat directly where needed
- Or provide electrical power without reliably and without transmission losses

Energy for Italian factories

- A USNC MMR occupies only 50 m^2
- In a well ~ 10 m deep
- They can directly fit inside factories
- Eliminate transmission and transportation losses (~50%)
- Larger reliability and stable prices
- Allow for direct heat delivery



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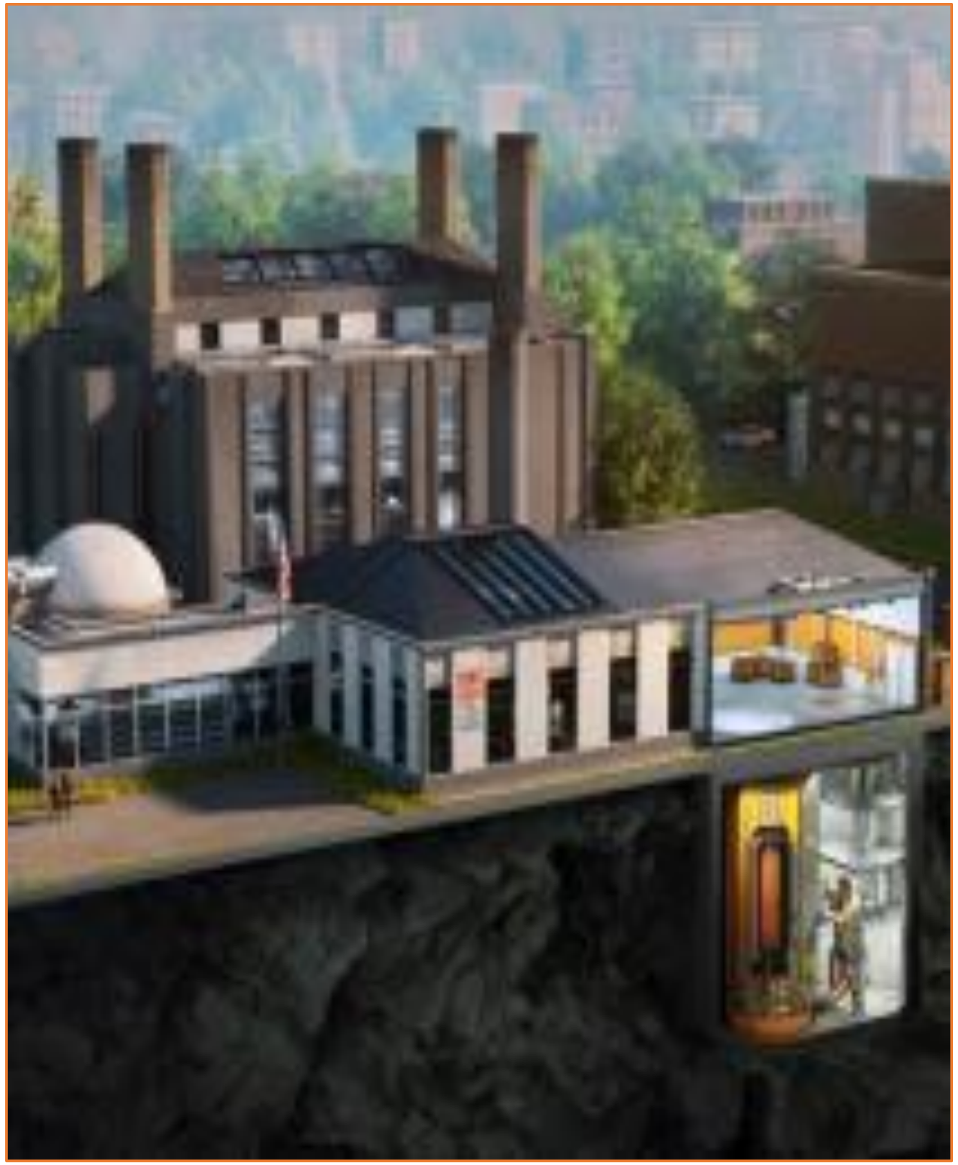
City power

- City power
- Ultra safe means it can be located near people
- Example: Urbana Champaign University campus installation
- Repowering an old plant
- To provides heat and electricity
-                                In 2027 !

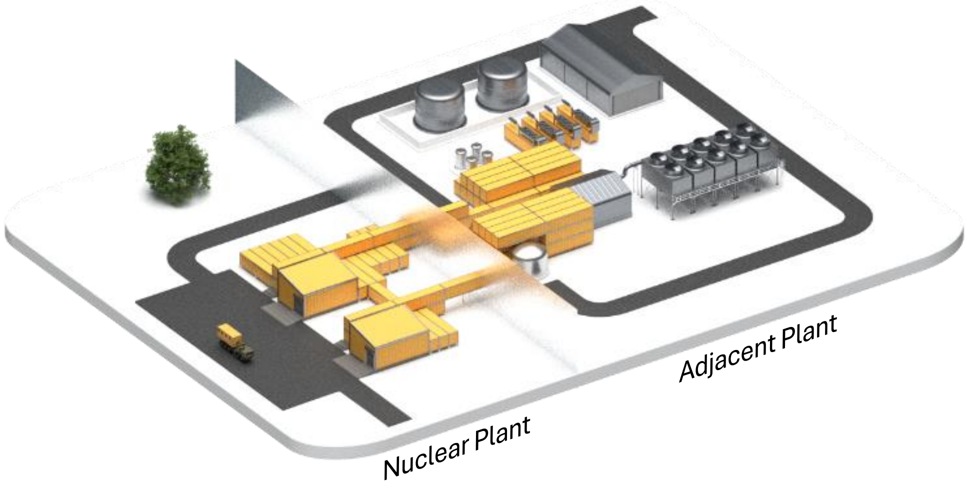


Peak-catcher power plants

- The Output Power produced is accumulated in hot molten salt
- Very large power levels can be drawn from the salts to energize the electricity generators
- Can compensate for power surges with negligible delay

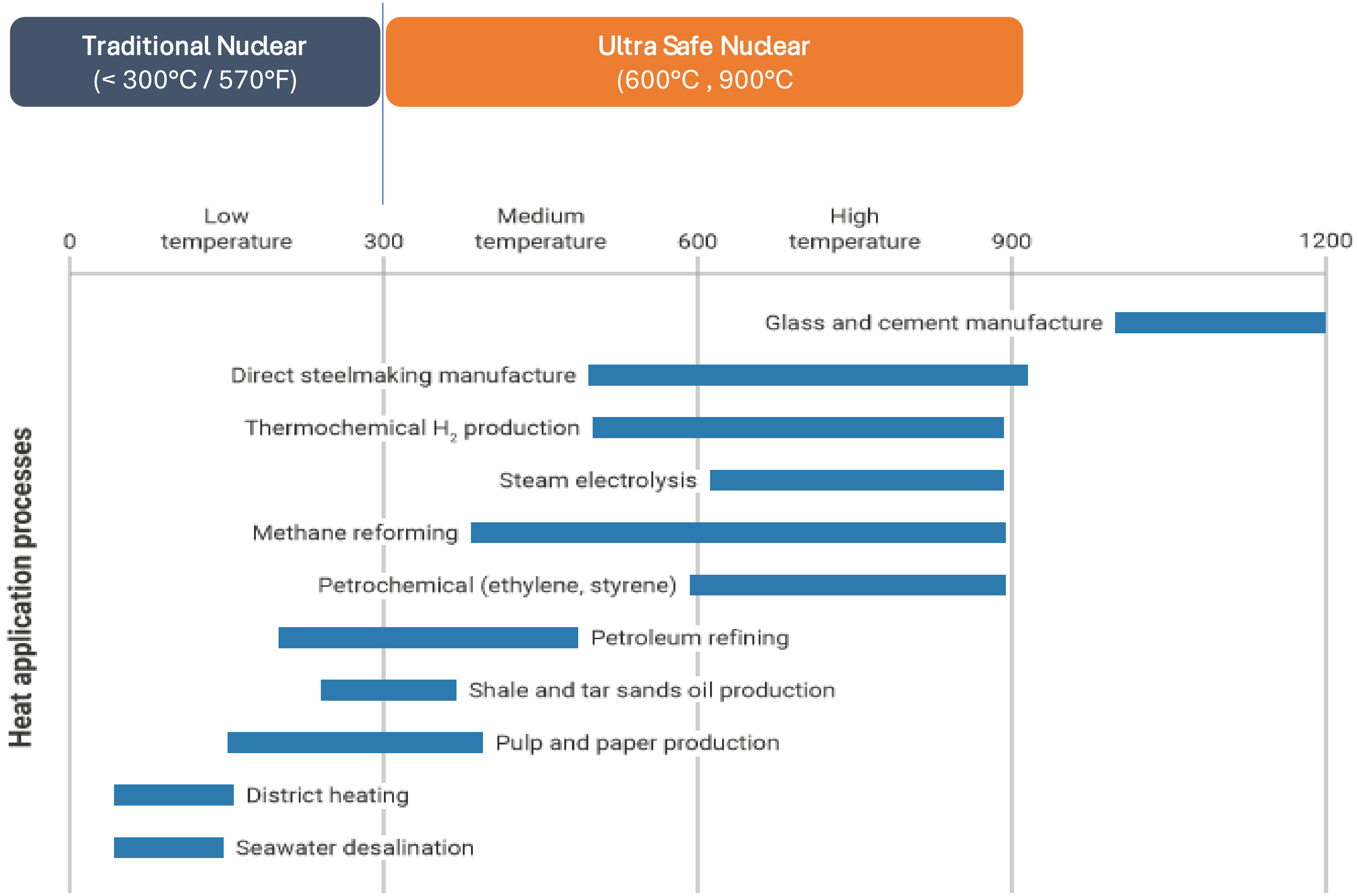
Advantages from high temperature heat

- High temperature (600-900^{o}C) heat delivery
- Waste heat can be disposed at higher temperature with relatively small waste
- Low temperature heat useful for district heating or disposed in air when not useful
- No need to use water or cooling towers; no interruption during droughts



Advantages of high temperature

- Cheap hydrogen
- Steel processing
- Hydrocarbon processes
- Polymer production

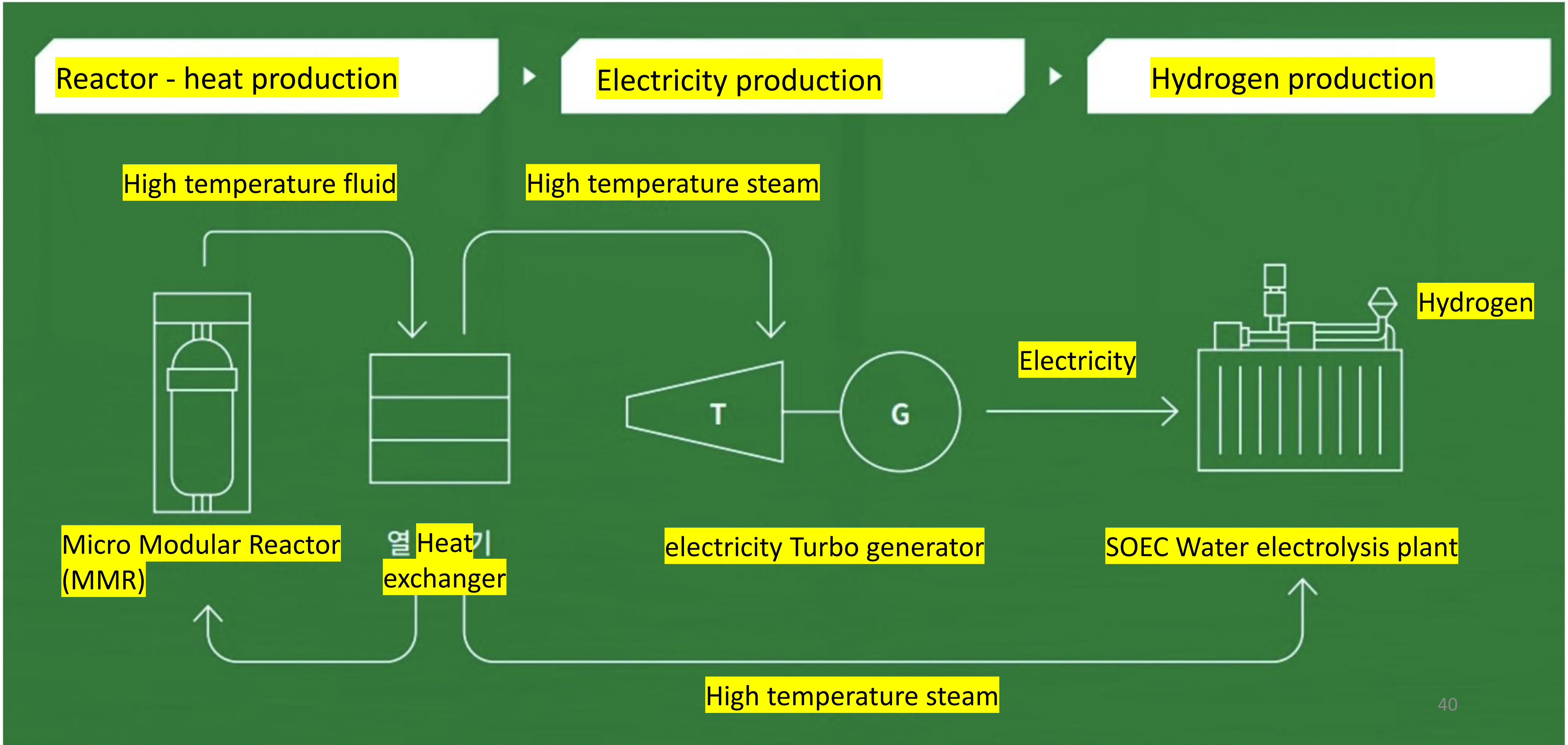


Inexpensive Hydrogen production

- In high temperature steam the Hydrogen-Oxygen bond is weakened
- Less energy is necessary to separate hydrogen
- Electrical cost reduction factors of 2 to 4 are possible with electrolysis applied on superheated steam

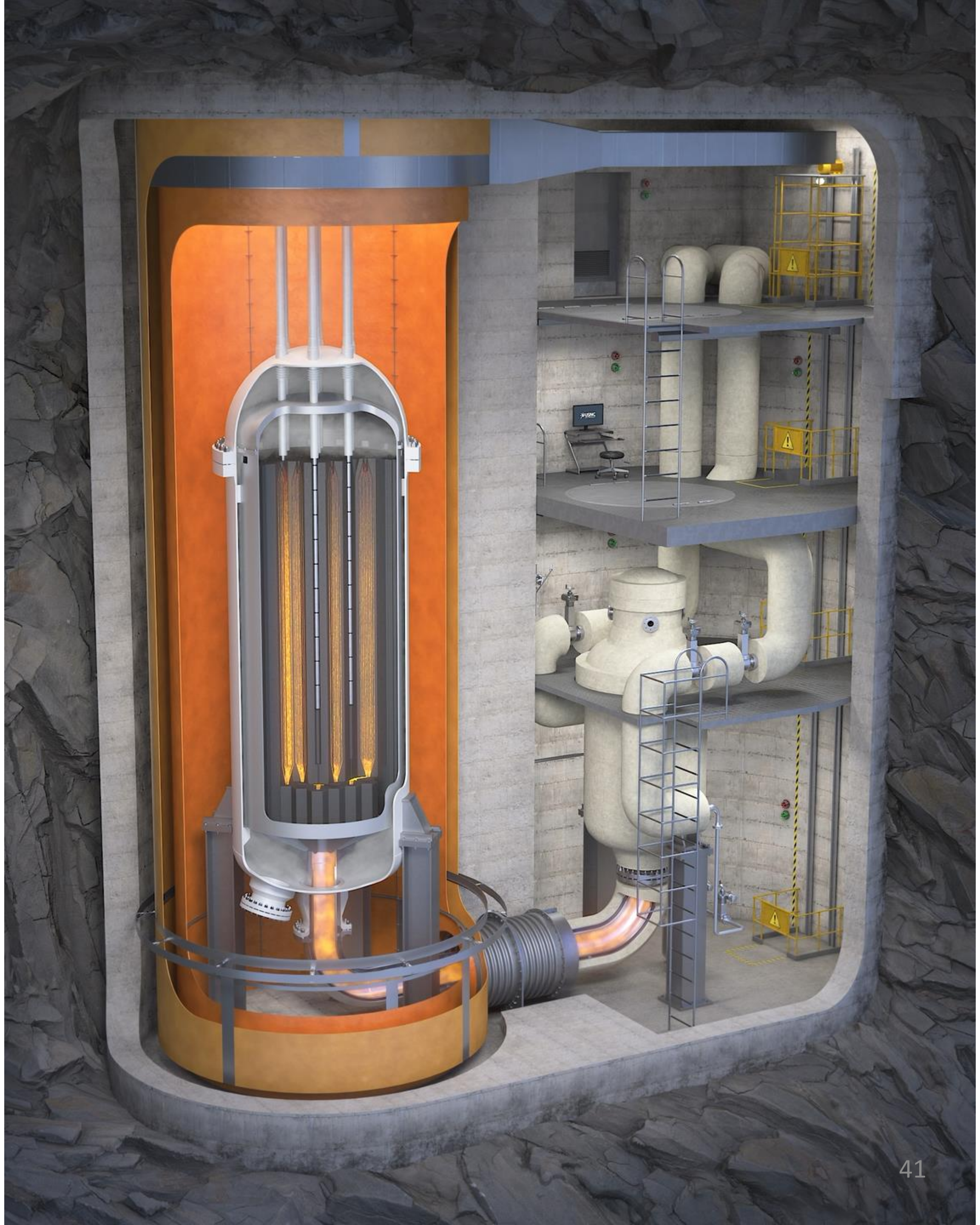
Hyundai Engineering – SK ecoplant – Ultra Safe Nuclear

MOU Signed for Clean Hydrogen Production



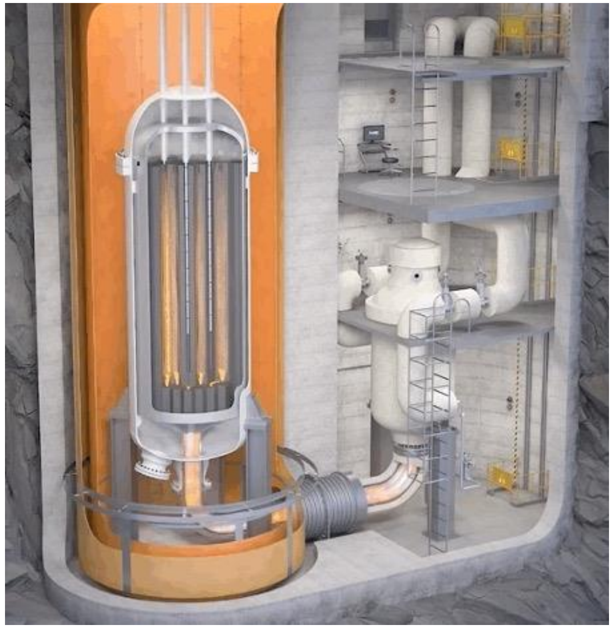
Inexpensive chemical Hydrogen generation

- HSO$_4$@~900^{o}C-HI@~600^{o}C chemical process also used to economically produce H_2



Decarbonization

- A reactor contains 3 milions of MWh
- Equal to 240,000 t of oil (a supertanker)
- Eliminate the production of 750,000 t of CO_2
- Also equal to 370,000 t of coal.



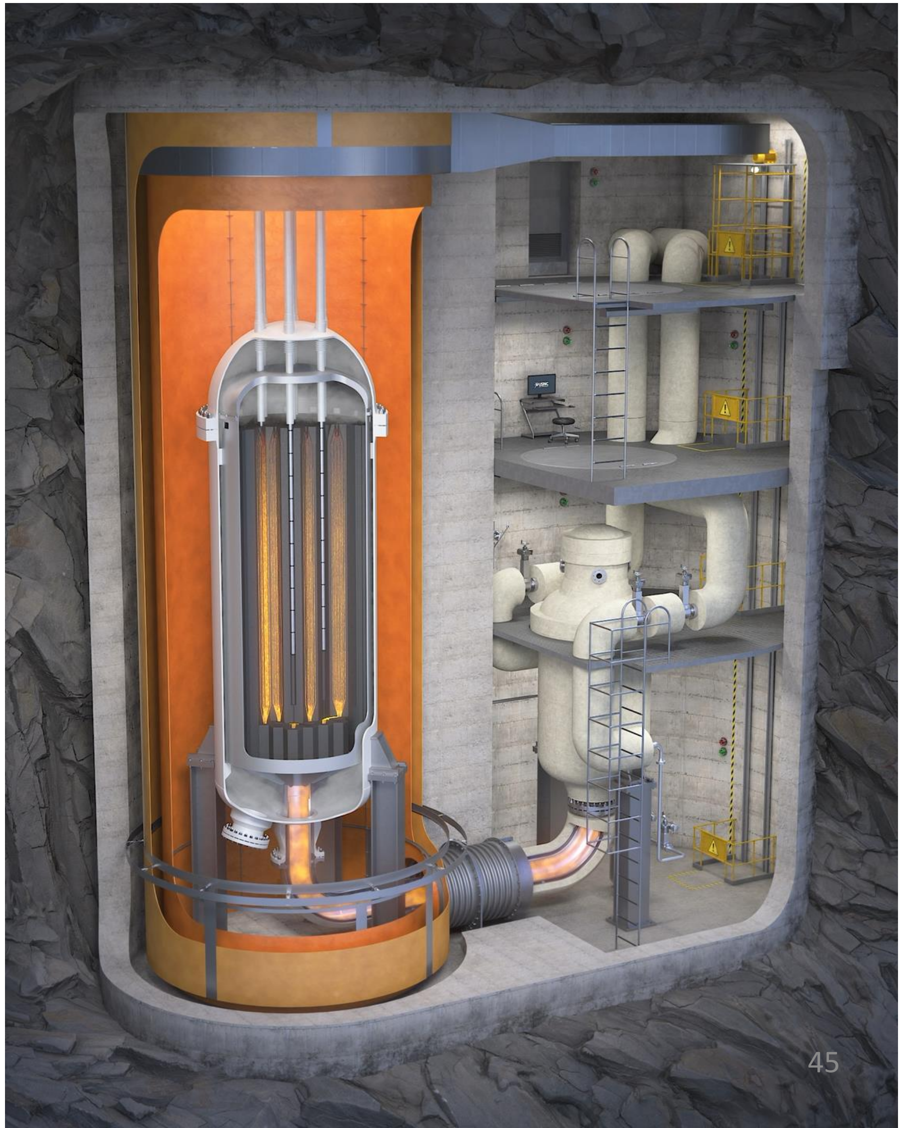
Carbon footprint di impianti di produzione energetica	
Sorgente di energia	Footprint CO_2 g/kWh-e
Batterie MMR USNC prodotte in fabbriche utilizzanti Potenza da MMR	1.5
Nucleare Convenzionale	5.0
Batterie MMR USNC	11.5
Eolico	17.0
Solare	34.0
Metano	500.0

Italian annual Energy Needs

- Italy consumes 700 TW-h of energy per year (including transportation)
- Equivalent to 80 GW of power plants working with 100% efficiency
- Considering that renewables work with 30% efficiency one would need 240 GW of installed power plants, assuming enough energy storing capability
- The requirements from renewable power plants are further increased to 1330 GW because energy storage has an average 30% efficiency, and transmission losses are typically 40%
- The gap can be filled by nuclear power plants

Italian annual Energy Needs

- 700 TW-h of energy is equivalent to the energy content of ~250 USNC MMRs
- An MMR load lasts 10 years
- 80 GW of electrical power can be covered with 2000 MMR
- Or a lower number of larger brothers



Desalinization of sea water

- Surplus electricity produced can be dispatched through the electric grid to a seaside location for inverted osmosis desalinization

- The produced drinking water can be dispatched back using the water distributing system

- For batteries located near the sea, the waste heat from producing electricity can be used for evaporative desalinization

Costs

- A loaded nuclear battery costs ~ 90 Million $
  - Including installation and eventual de-installation costs
- It contains 3 Million of MW-h of heat (3 TW-h) delivered @ 600^{o}C
  - Operating at a power of 30 MW, the 3 TW-h are delivered over 10 years
- The cost of a MW is therefore 30$/MW-h + 10-year financing costs
- A recharge costs ~ 30 Million $ and also contains 3 TW-h of heat
- Starting from the second recharge the cost of a MW is 10$/MW-h

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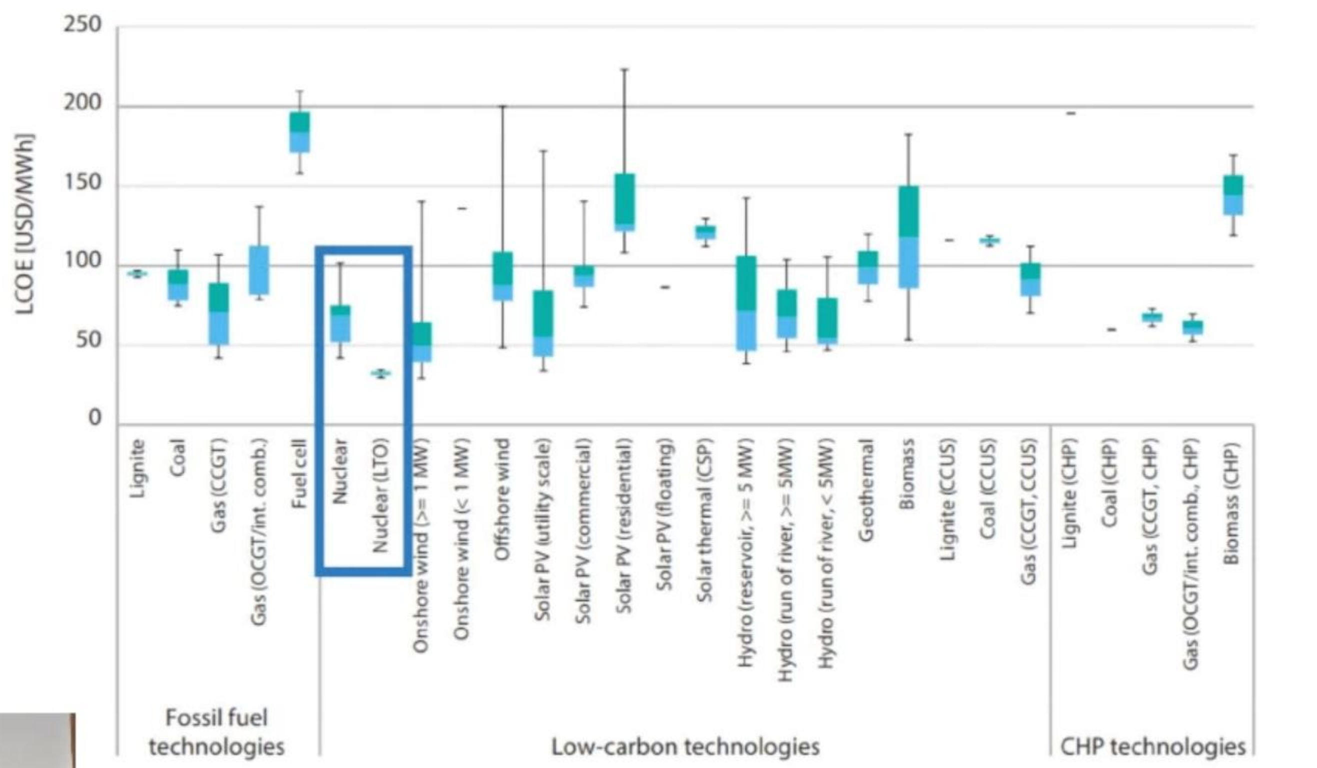
Costs

- The projected costs of electricity using MMRs is more or less in line with the of other nuclear energy, both in initial and extended lifetime regime
- i.e. cheaper than most other energy sources

Nuclear : LCOE costs



lues at 7% discount rate. Box plots indicate maximum, median and minimum values. The boxes indicate the central 50% of values, i.e. nd and the third quartile.

nttps://www.oecd-nea.org/upload/docs/application/pdf/2020-12/egc-2020_2020-12-09_18-26-46_781.pdf

Costs

- Available starting after 2030
- Batteries contains 4.5 Million of MW-h of heat (4.5 TW-h)
  - Operating at a power of 45 MW, the 3 TW-h are delivered over 10 years
- A loaded 45 MW nuclear battery would cost ~ 100 Million $
  - Including installation and eventual de-installation costs
- The cost of a MW is therefore ~22 $/MW-h + 10-year financing costs
- Working at higher temperature
- Conversion to electric energy with super-critical CO_2 turbine with 42-43% efficiency leading to ~ 50 $/MW-el + 10-year financing costs

Example of cost estimate for the Ostiglia power plant

Annual cost of required heat (expanded to 2 GW)	
Source	EURO/year
30 MW USNC batteries for the first 10 years	650.000.000
USNC top-ups after first 10 years	220.000.000
Gas at €50/MWh without carbon tax	905.000.000
Gas at €100/MWh without carbon tax	1.800.000.000
Gas at €50/MWh with a €50/MWh carbon tax	1.800.000.000
Gas at €100/MWh with a €50/MWh carbon tax	2.700.000.000

When?

- First battery installed and certified in Canada in 2026
- First certified batteries in USA, Finland and Poland in 2027
- Batteries available to industrial buyers from 2028
- Certification battery for Italy reserved for 2027
- If Italy will be ready

How many?

- Italy consumes 7-800 TW-h of energy per year
  - Of which 300 TW-h elettricity (TERNA)

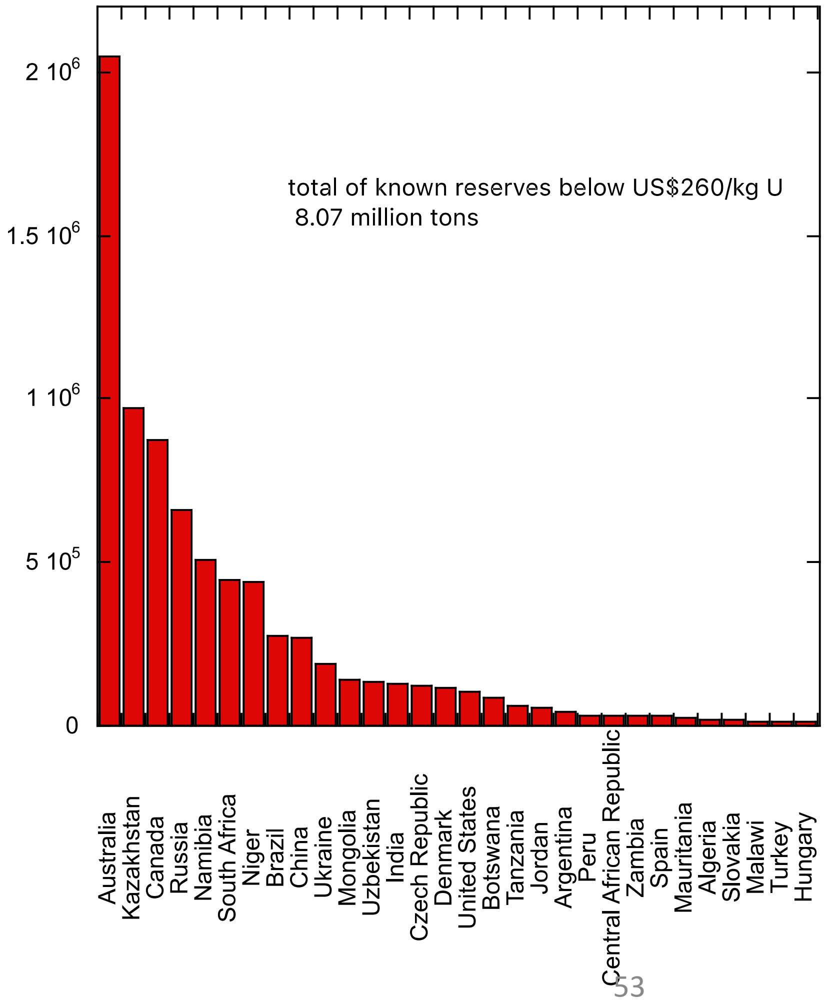
- A battery contains 3 TW-h of energy
- It would be necessary to build ~250 batteries / year
  - (one/day)
- Each batteries eliminated the arrival of a super oil tanker
  - (one battery a day keeps the CO_2 away)

Uranium availability

- Cost of Uranium
- From mining U 60 - 300 $/kg
- Extracting from seawater 250 - 300 $/kg

- Availability
- U minable below 260 $/kg 8 Mt
- U in seawater 4,500 Mt

- Cost Impact
- The cost of fuel is <=5% of the cost of energy
- produced

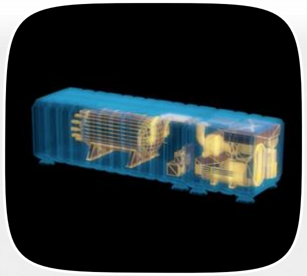


ULTRA SAFE NUCLEAR

RELIABLE ZERO-CARBON ENERGY ANYWHERE

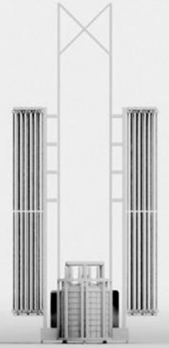
MILLIWATT to GIGAWATT
EARTH to SPACE

- Family of nuclear energy products and services
- Zero-carbon power. Minimal infrastructure required
- From Watts to Mega Watts
- All based on Ultra Safe principles & technologies
- Shared design and fabrication resources



Micro-grid
Off-grid
Defense
Grid Scale

EmberCore
Earth & Space
1mW and up



PYLON
Earth & Space
10kWe to MWe

NTP
Space
Propulsion Engine

MMR
Earth
5MWe+ & GW scaled

usnc.com

Nuclear Thermal Propulsion

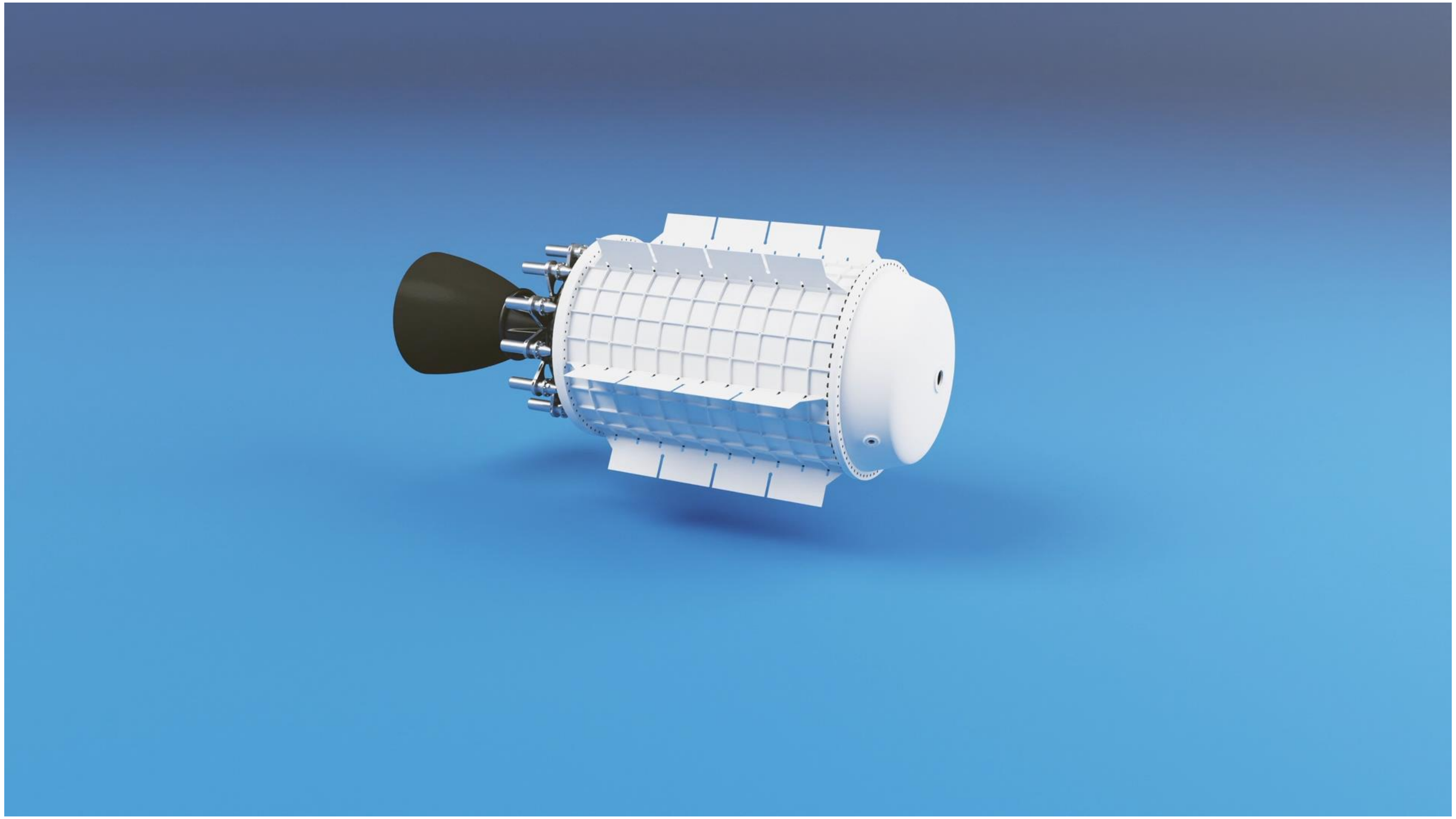
- ZrC core (3800K)

and graphite (3900K)

- 19% ^{235}U

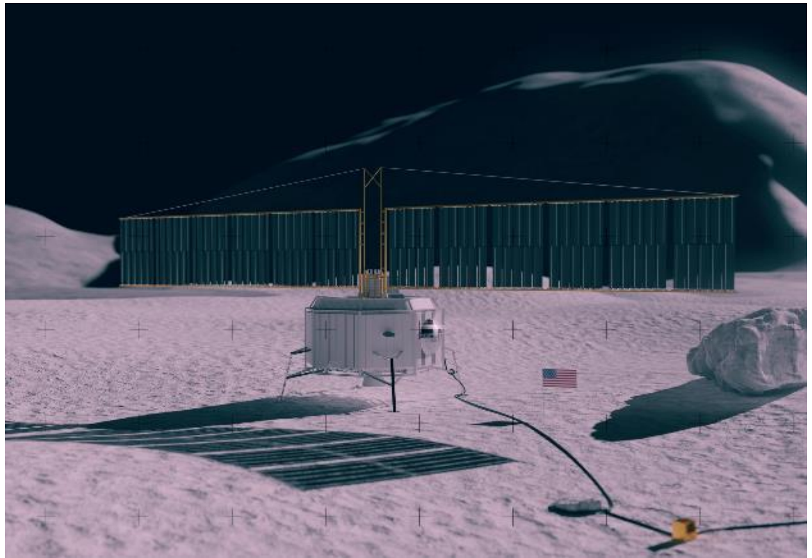
- No control rods >
- Control N reflectors

- NH_3 propellant
- 2x specific impulse than chemical rockets



- rocket propulsion reactor

- Lunar/Mars power reactors



Electro-Nuclear Proepulsion

- A reactor produces high temperature heat
- Turbines generate MW of electricity
- Waste Heat is radiated to space (very difficult)

- Ions are accelerated at ~ MV of kinetic energy and ejected

- 100,000 more specific impulse
- Need 1/100,000 reaction mass
- But very slow acceleration

Thank you

-
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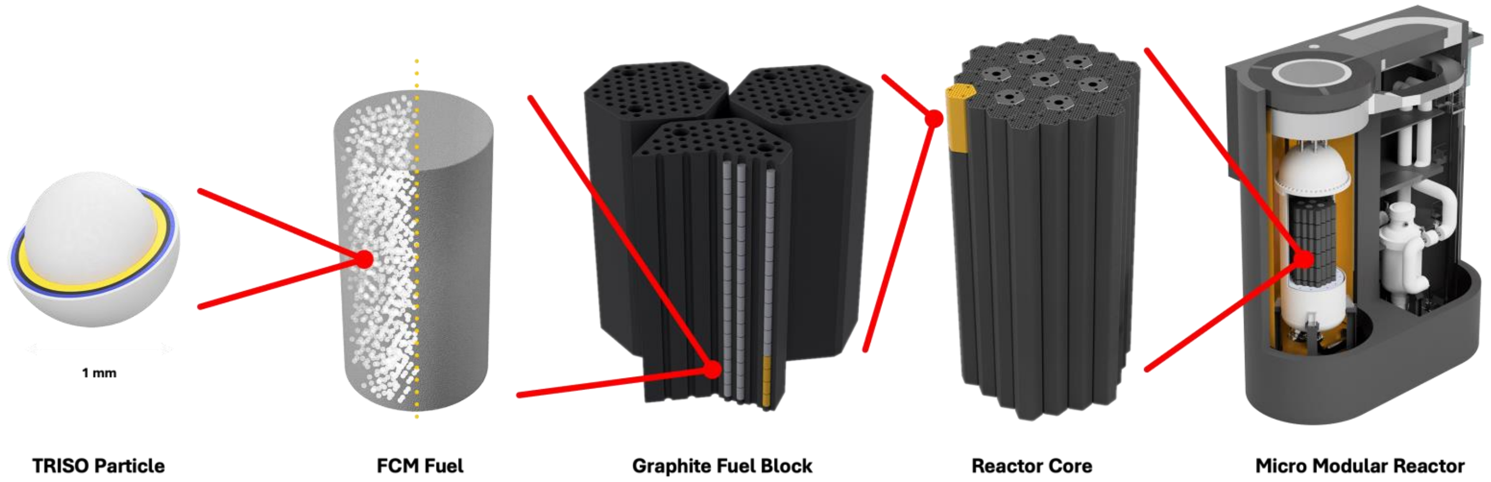
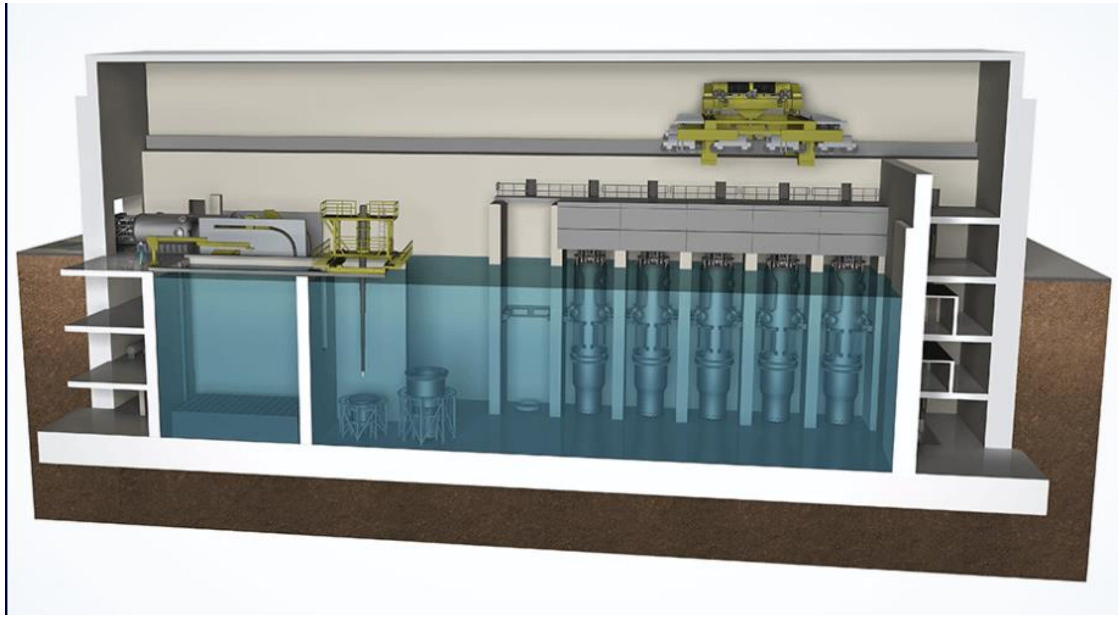
  - **Senior Advisor**
  - Ultra Safe Nuclear
  - Email: riccardo.desalvo@ultrasafe-nuclear.com Tel +1 626 246 4005

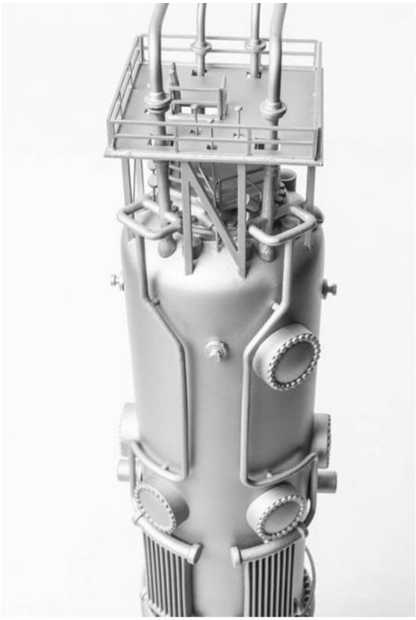


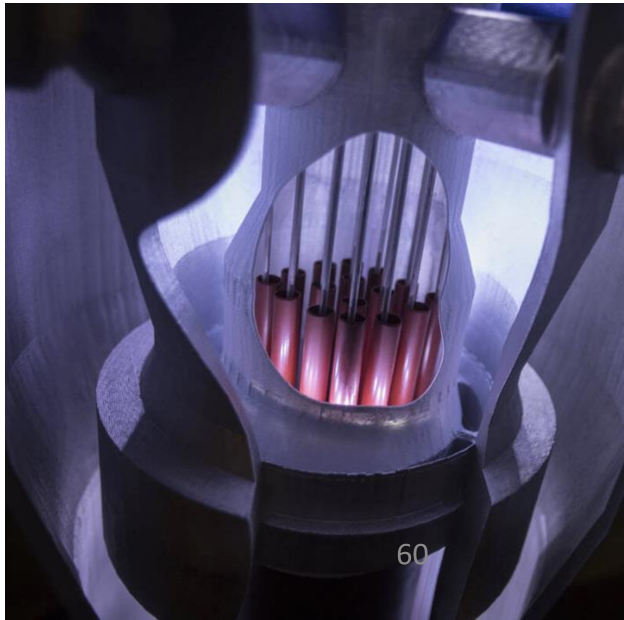
Additional slides
Other 4th generation reactors

Nu-Scale VOYGR-12

- Water cooled slow neutron
- Similar to gen 3
- Many SMR in a common pool to reach high power levels
- Passive cooling to pool in case of cooling stoppage



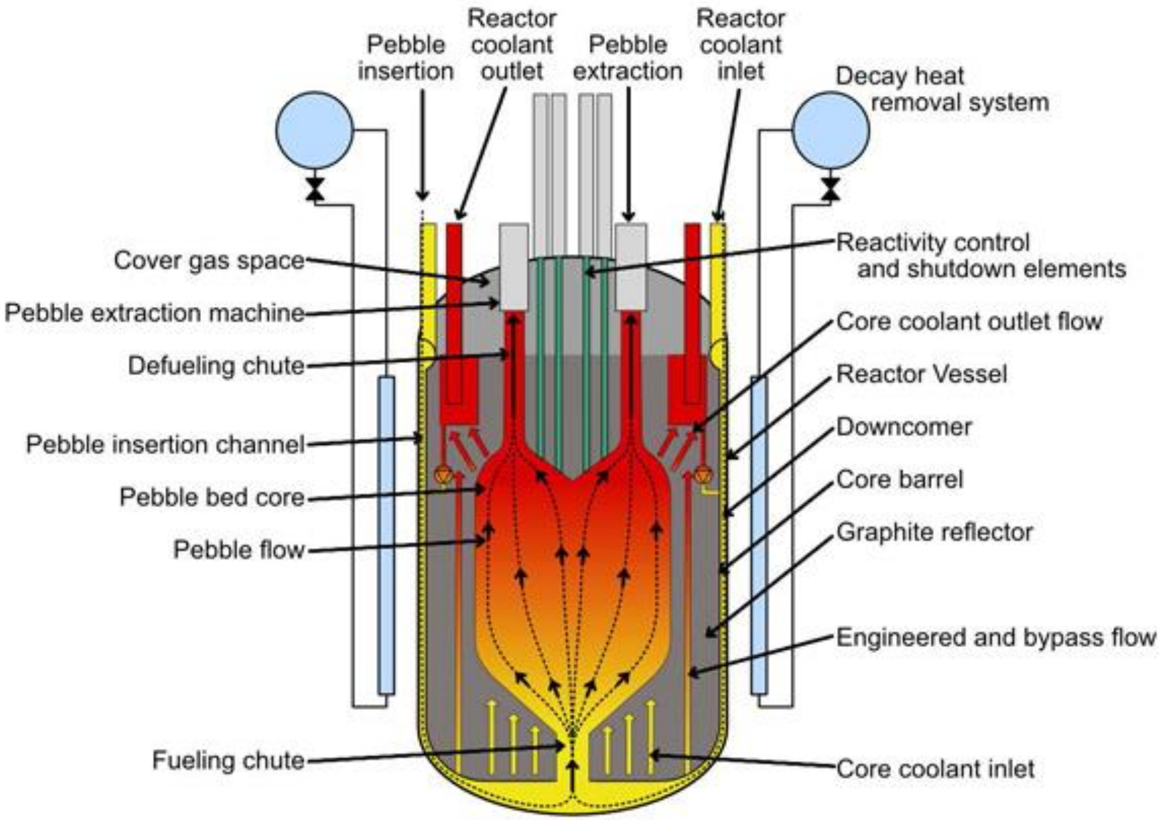




Water free, high temperature reactors

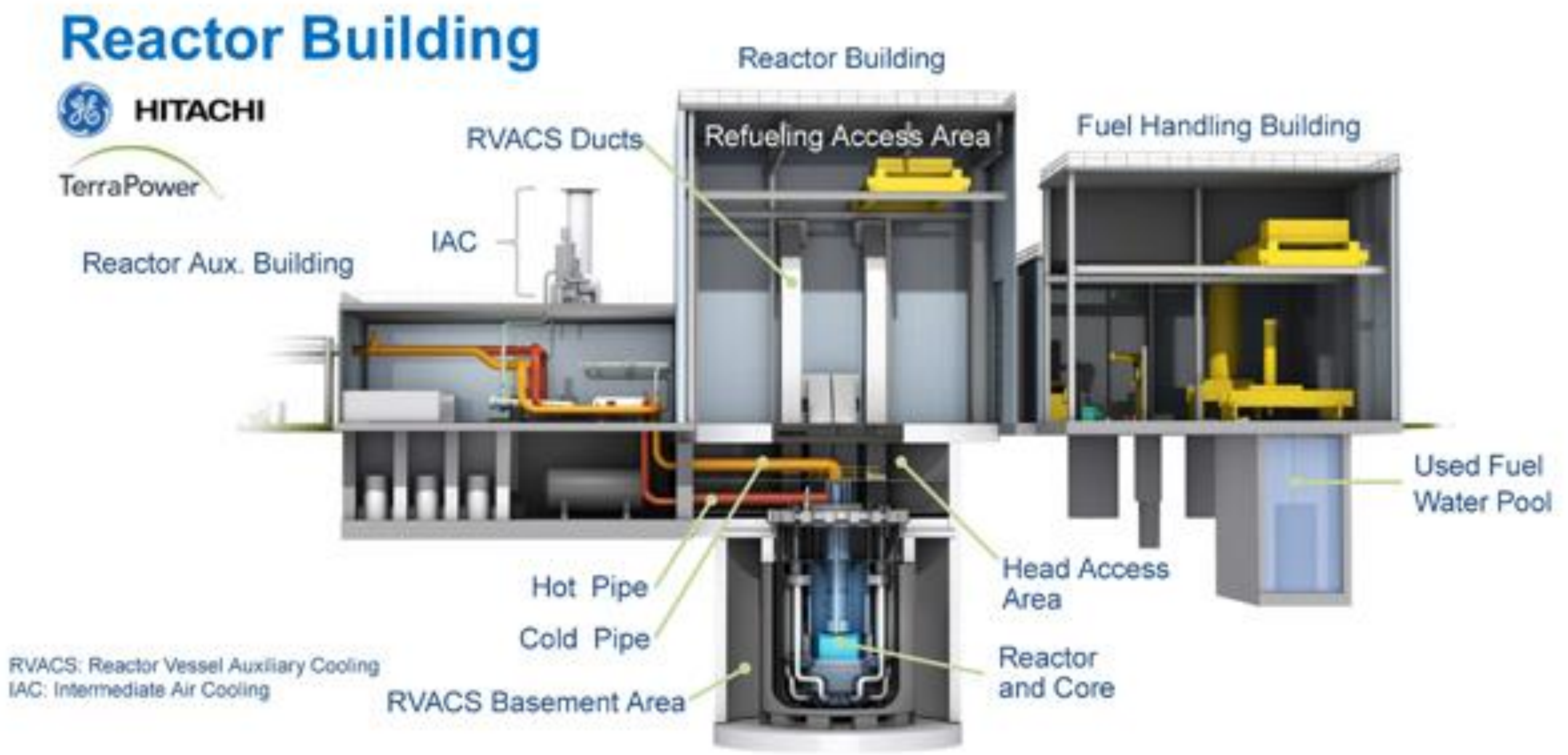
Kairos

- Fluoride salt-cooled
- Fast neutron
- TRISO fuel floating in a pebble bed configuration.



Natrium

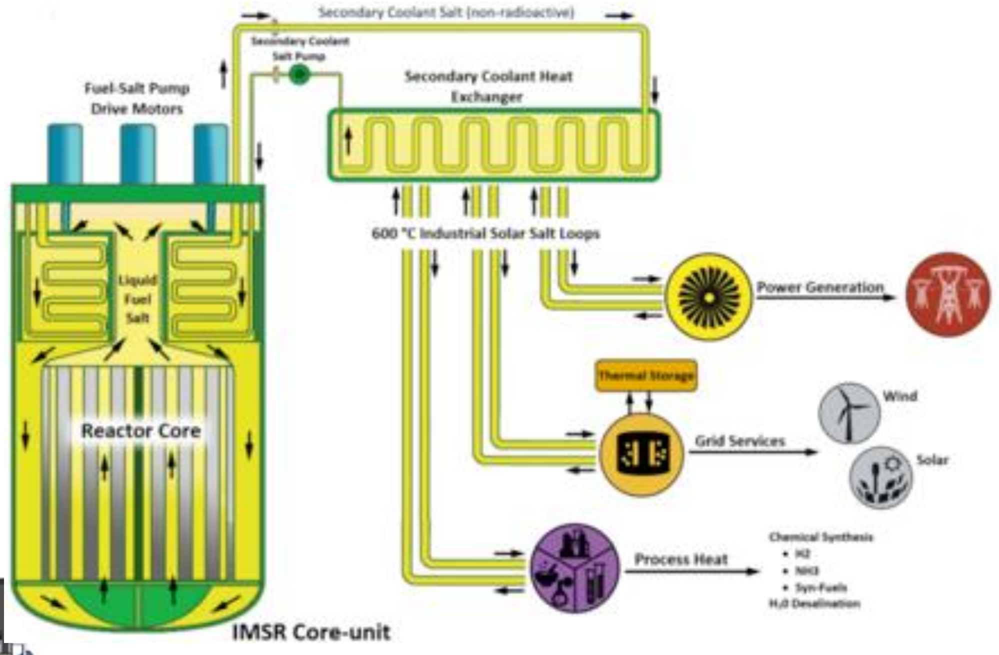
- Molten sodium
- Metal fuel rods
- Fast reactor

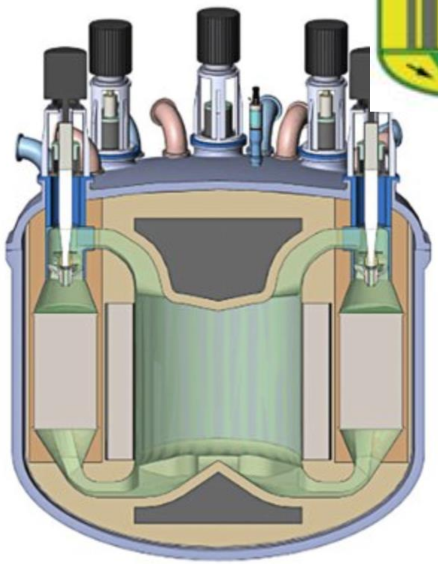


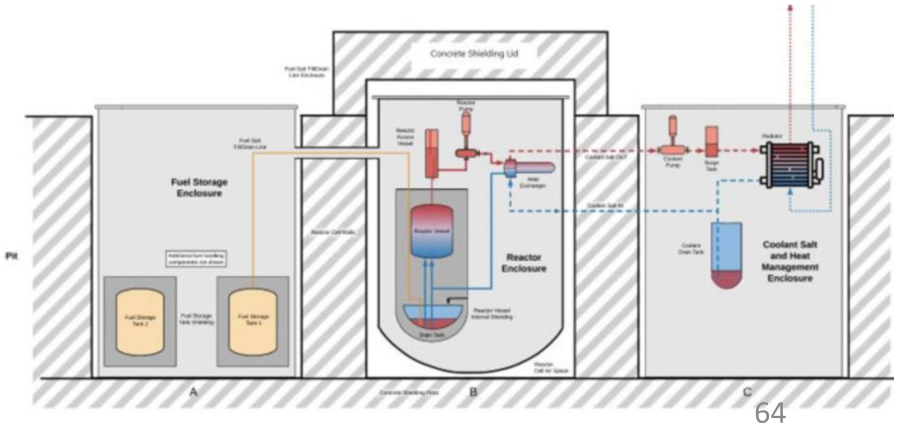
Terrestrial energy and Terra-power

- Molten fuel
- Uranium tetrafluoride dissolved in molten salts
- Or
- Molten chlorides fuel and coolant

- Fast reactors

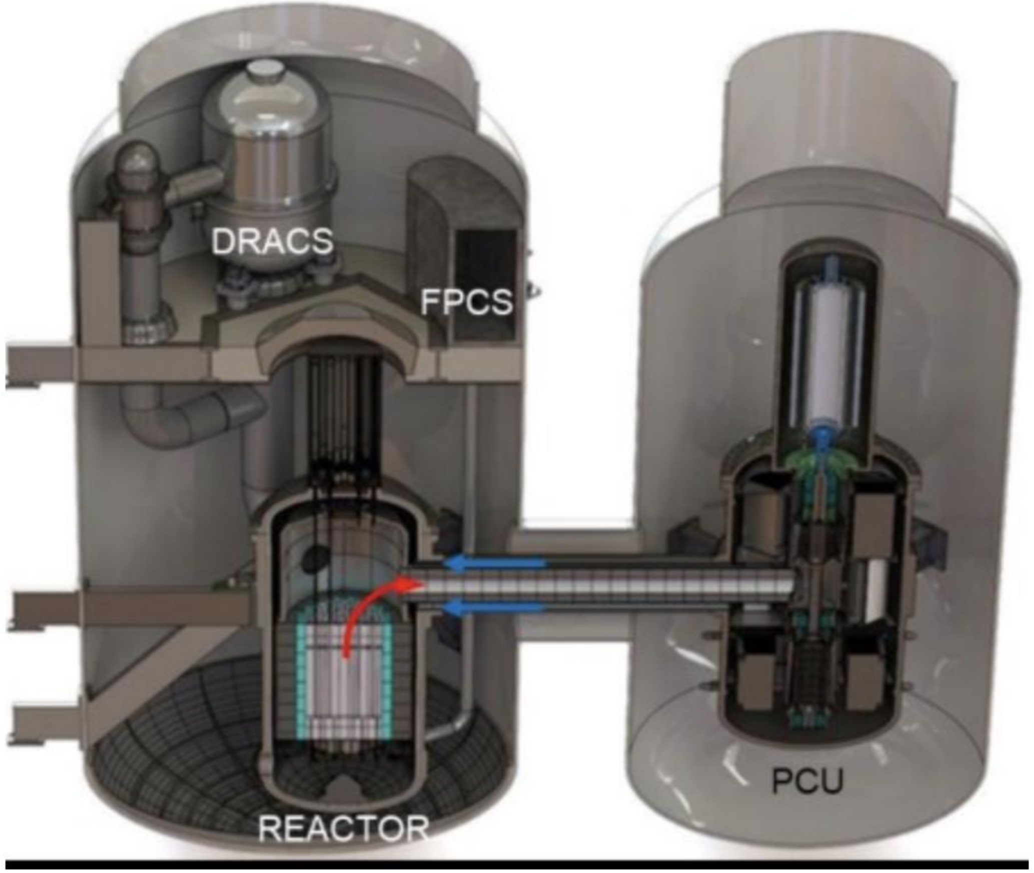






General Atomics - Energy Multiplier

- Helium cooled
- Ceramic fuel
- Fast reactor



Water free, slow neutron reactors

- All the reactors presented next are High Temperature Reactors, free of the limitations and dangers involved in using water to extract the heat

- Being able to survive overheating of few hundred degrees they can take advantage of the

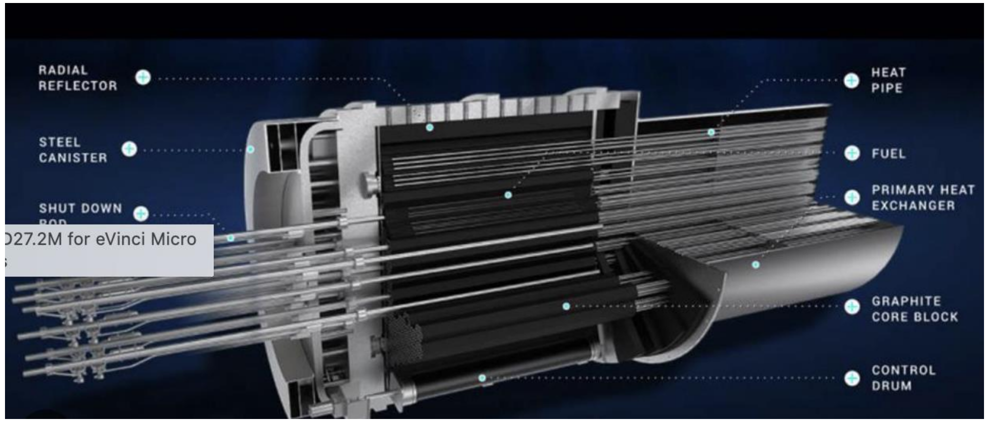
  Uranium-238's natural chain reaction quenching

  - i.e. self shut down of the reactor if overheating

- Uranium-238 is always at least 80% of the nuclear fuel

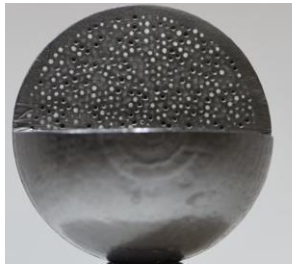
eVinci Westinghouse

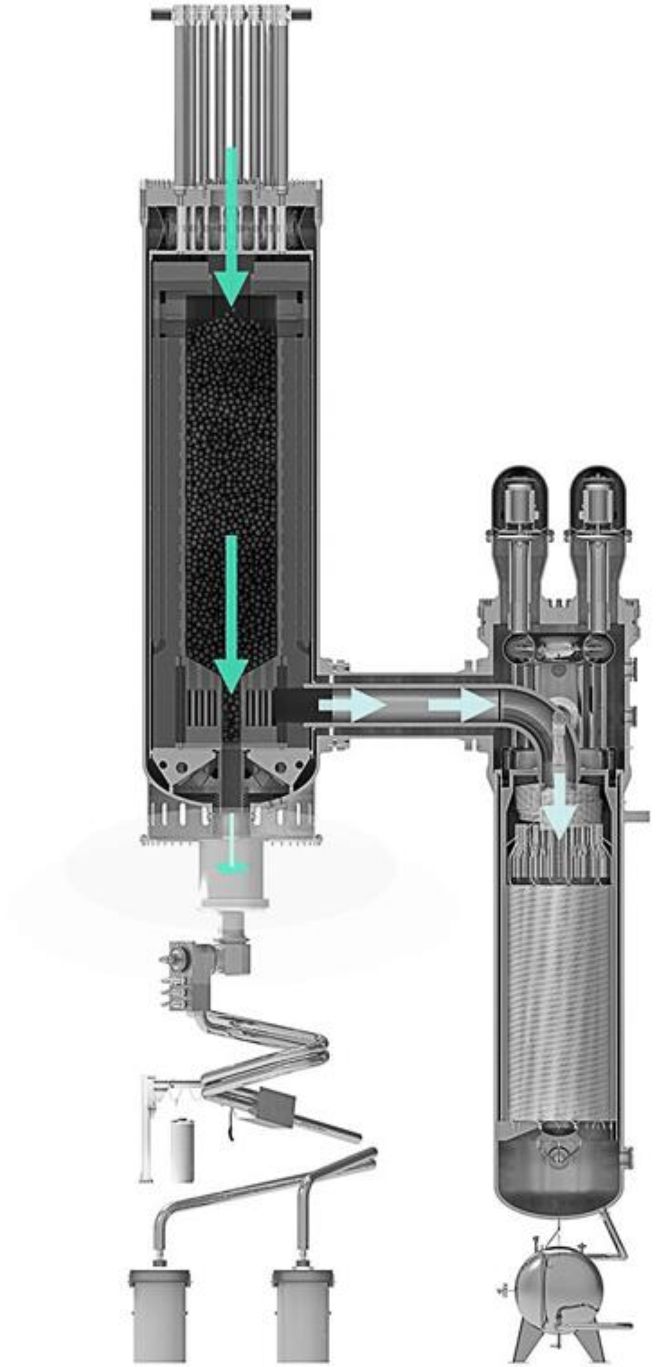
- Graphite moderator
- STEEL channels for both
- heat pipes and fuel
- Using USNC fuel pellets



X-Energy X

- TRISO into graphite balls (pebbles)
- pebble-stack,
- gas-cooled reactor





Ultra-Safe Micro Modular Reactors

- All ceramics core
- Graphite core moderator
- Helium cooled