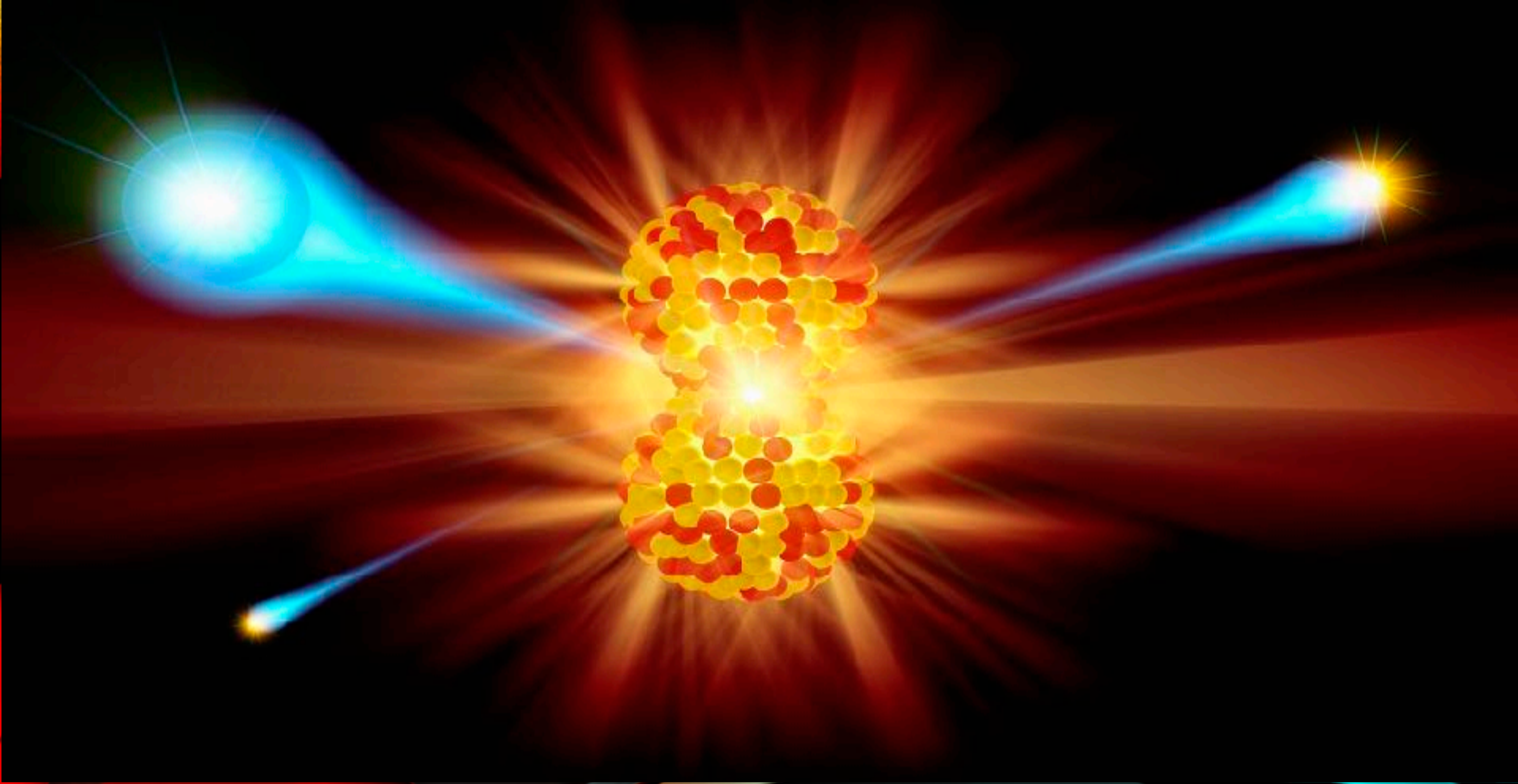
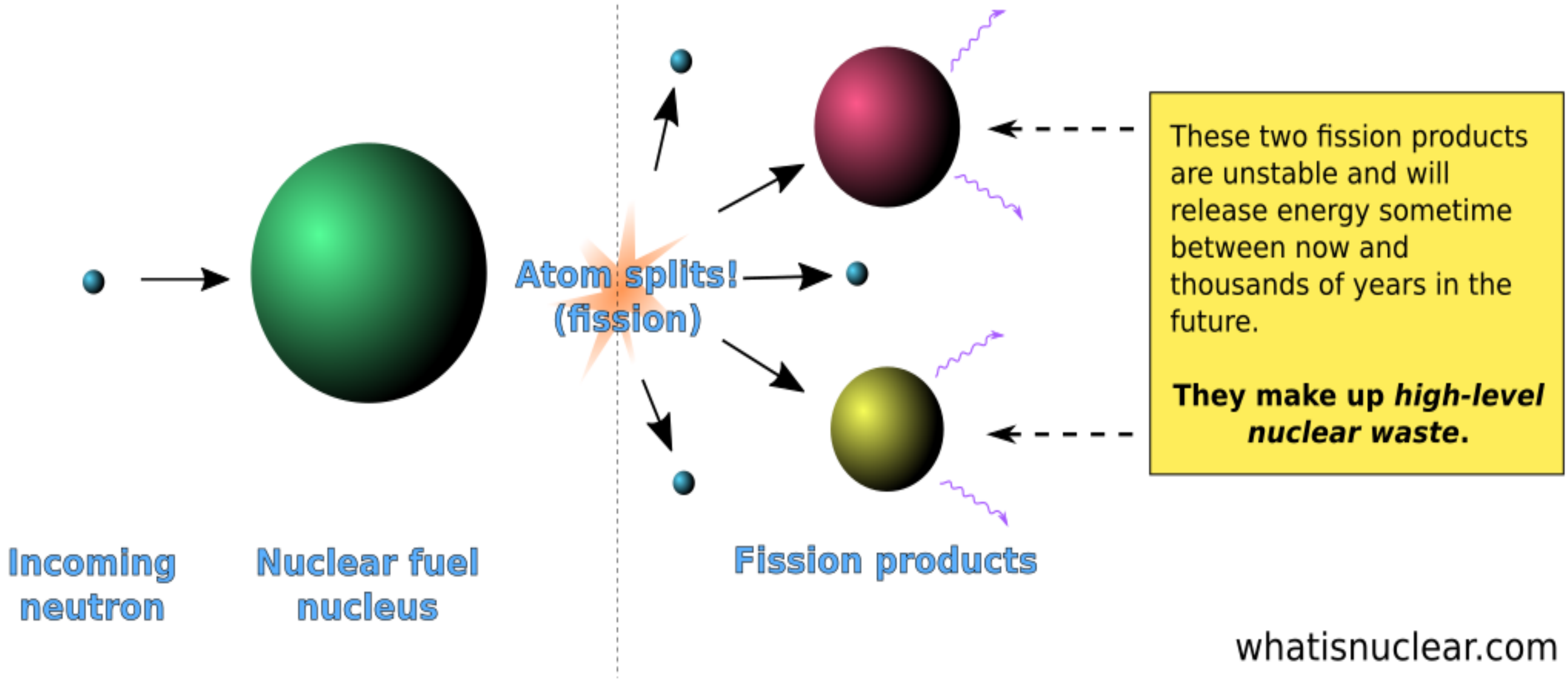


THORIUM and the Waste Issue…. by Richard Steeves March 21, 2019

FOUR GOOD BOOKS TO READ

THIS IS FISSION OF A FISSILE/FERTILE ATOM



Periodic Table of the Elements

Atomic Number
Symbol
Name
Atomic Mass

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Lanthanide Series	57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetal	Nonmetal	Halogen	Noble Gas	Lanthanide	Actinide

FROM WHERE DID OUR ELEMENTS COME?

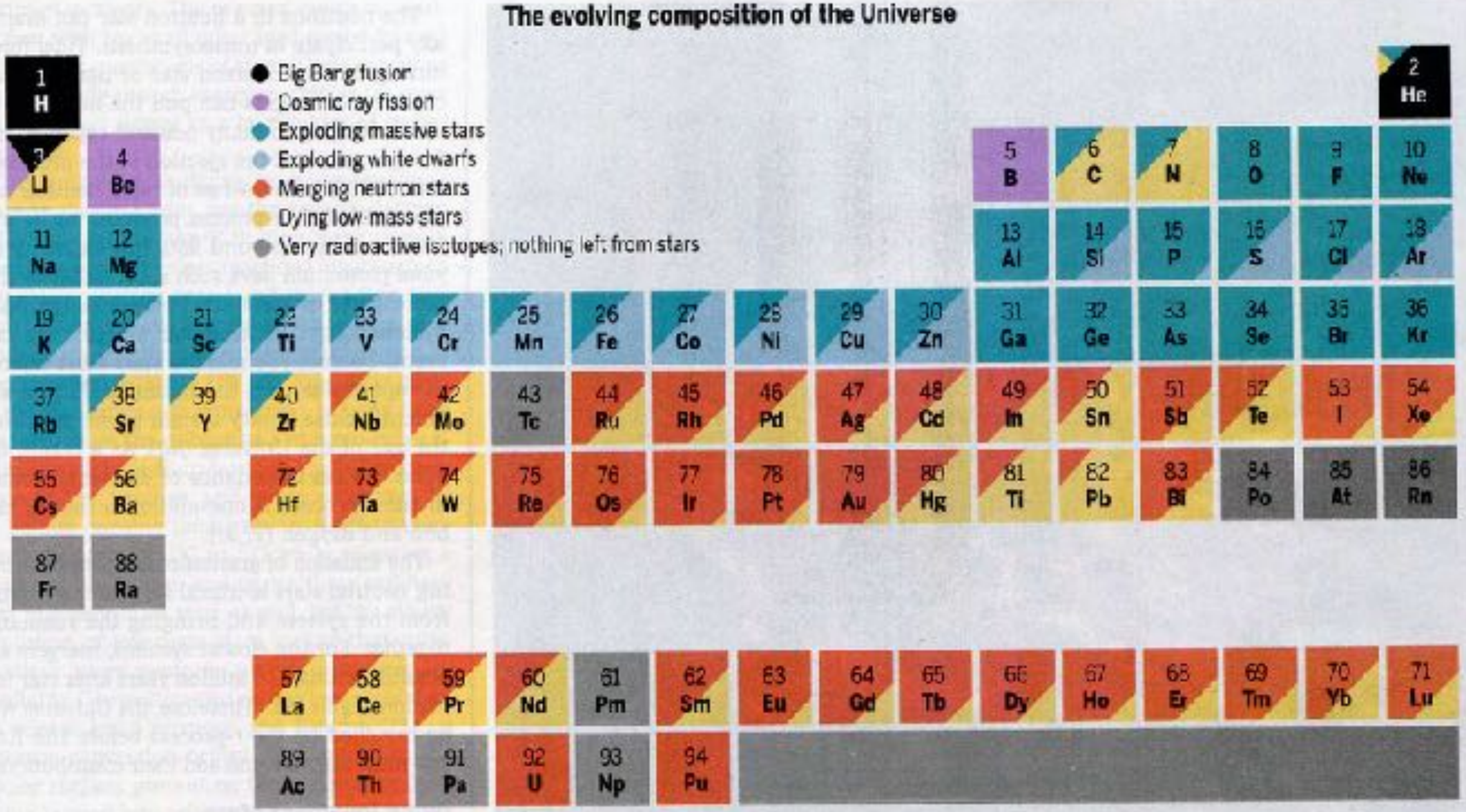
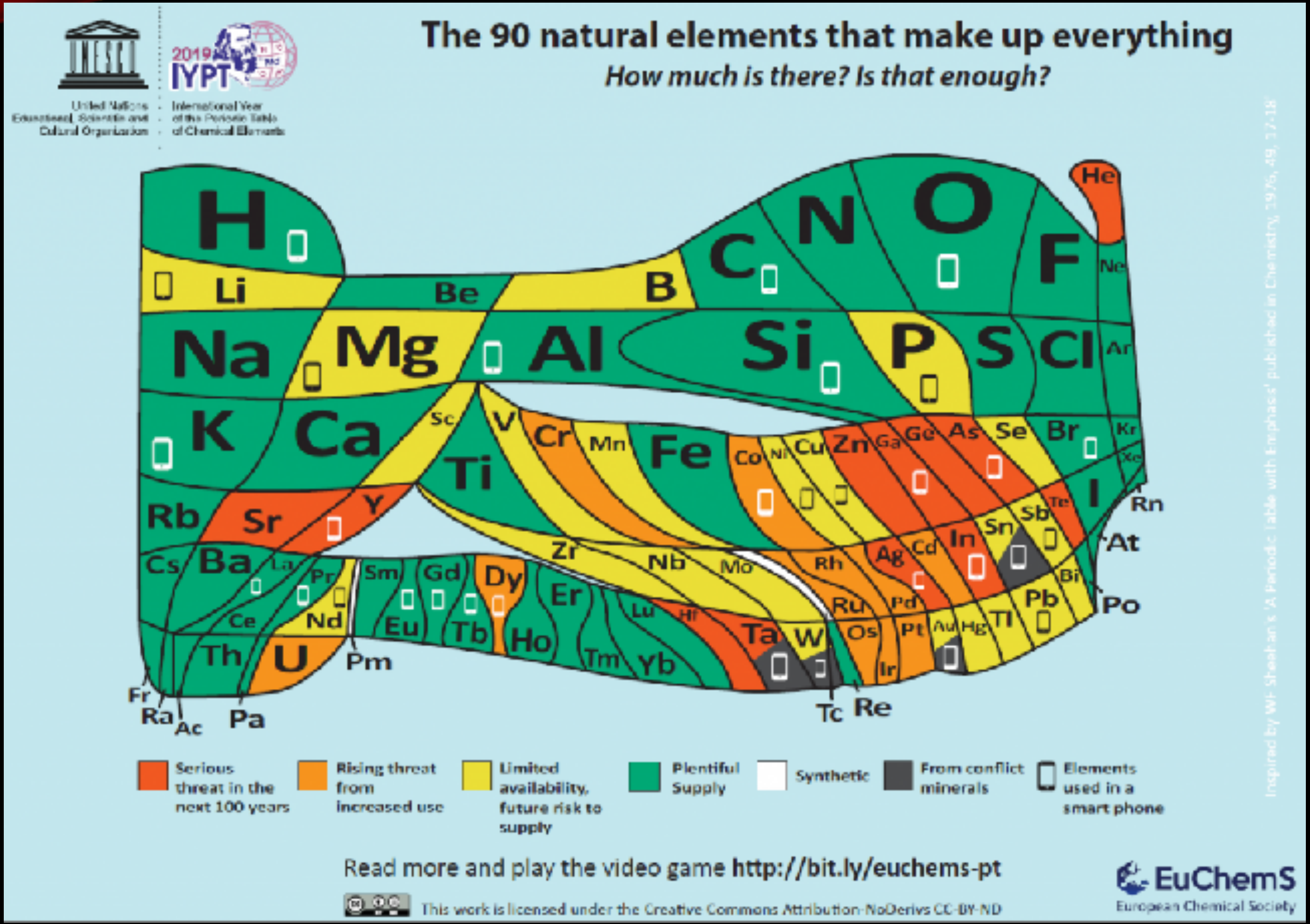
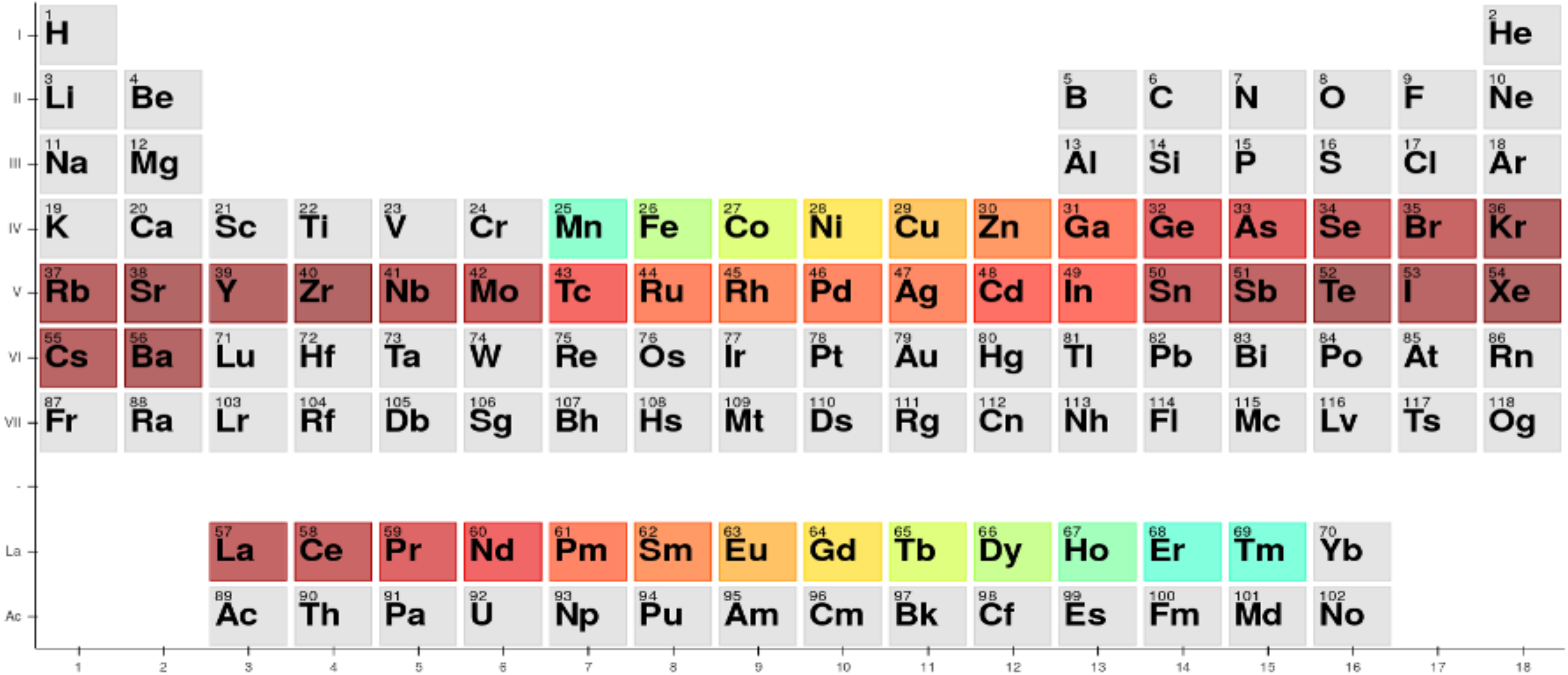


Fig. 1. Nucleosynthetic sources of elements in the Solar System. Each element in this periodic table is color-coded by the relative contribution of nucleosynthesis sources, scaled to the time of Solar System formation. Only elements that occur naturally in the Solar System are shown; artificially made elements and elements produced only through radioactive decay of long-lived nuclei are shown in gray. The data plotted in this figure are available in table S1.

THORIUM IS PLENTIFUL

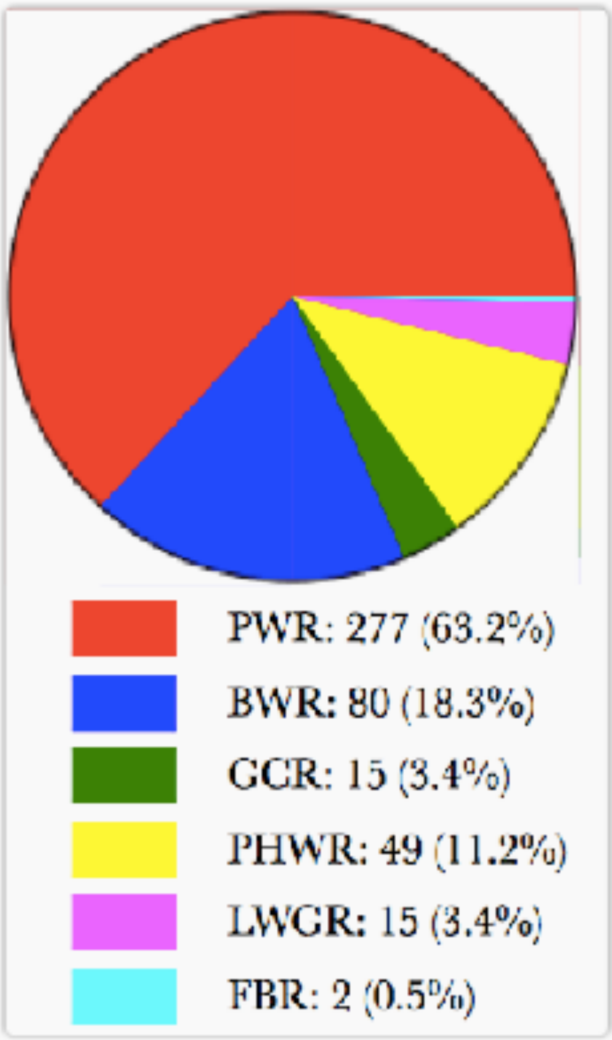


FISSION PRODUCT POSSIBILITIES

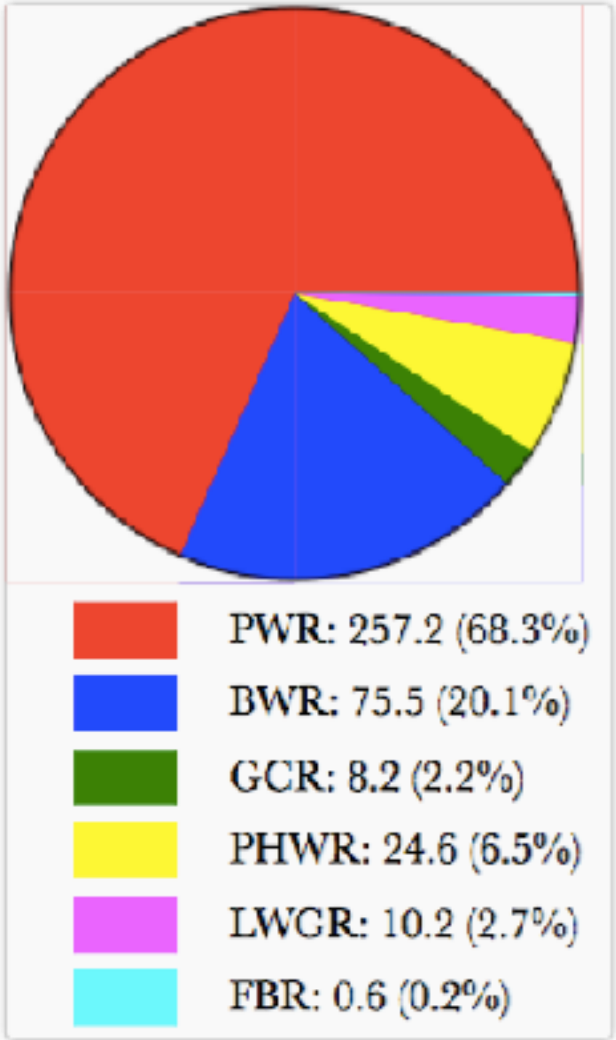


WORLD'S NUCLEAR REACTORS IN 2014

- **Abbreviations Defined:**
- PWR = Pressurized Water Reactor
- BWR = Boiling Water Reactor
- GCR = Gas-Cooled Reactor
- PHWR = Pressurized Heavy WR
- LWGR = Light Water-cooled, Graphite-moderated Reactor
- FBR = Fast Breeder Reactor

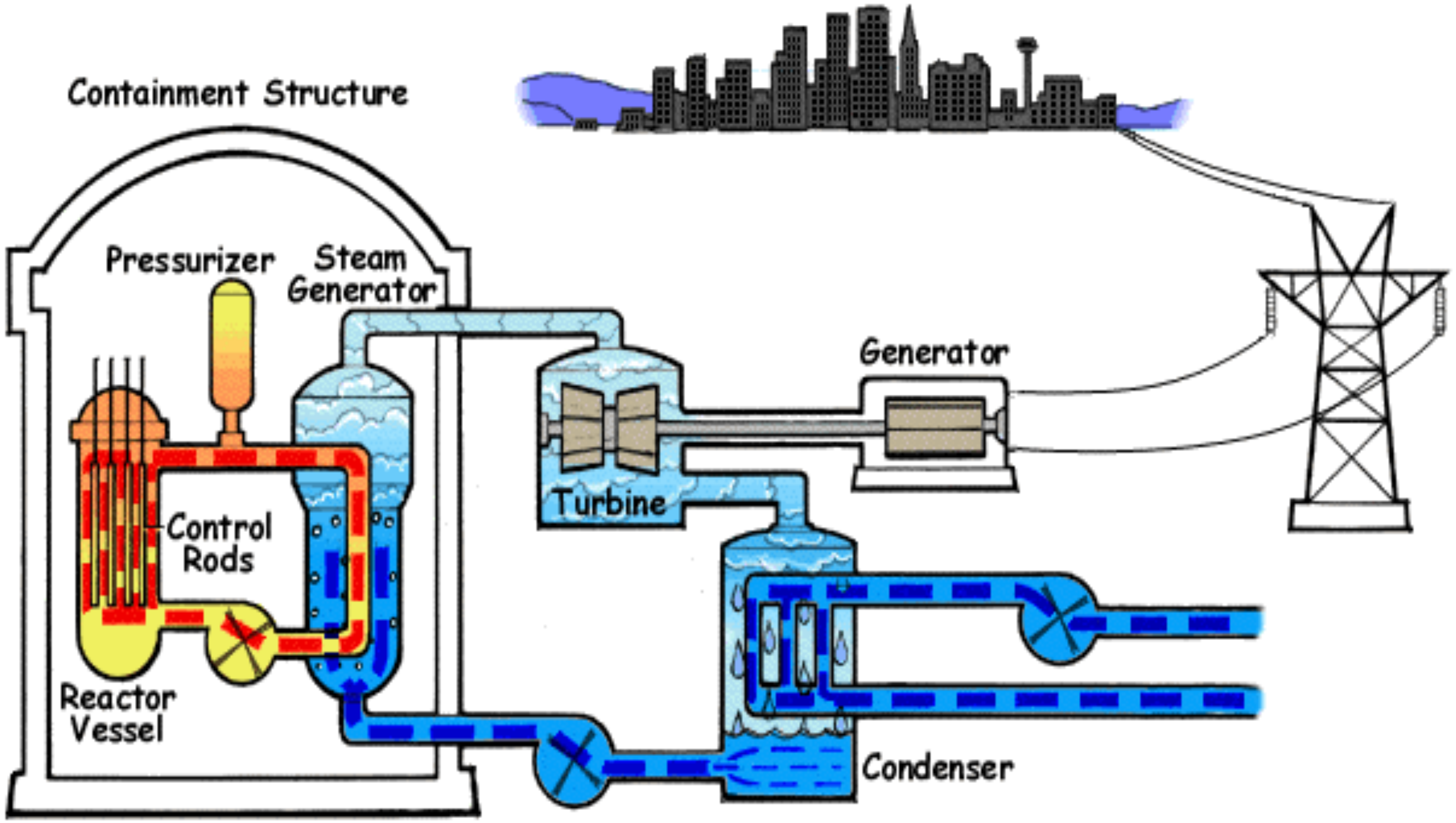


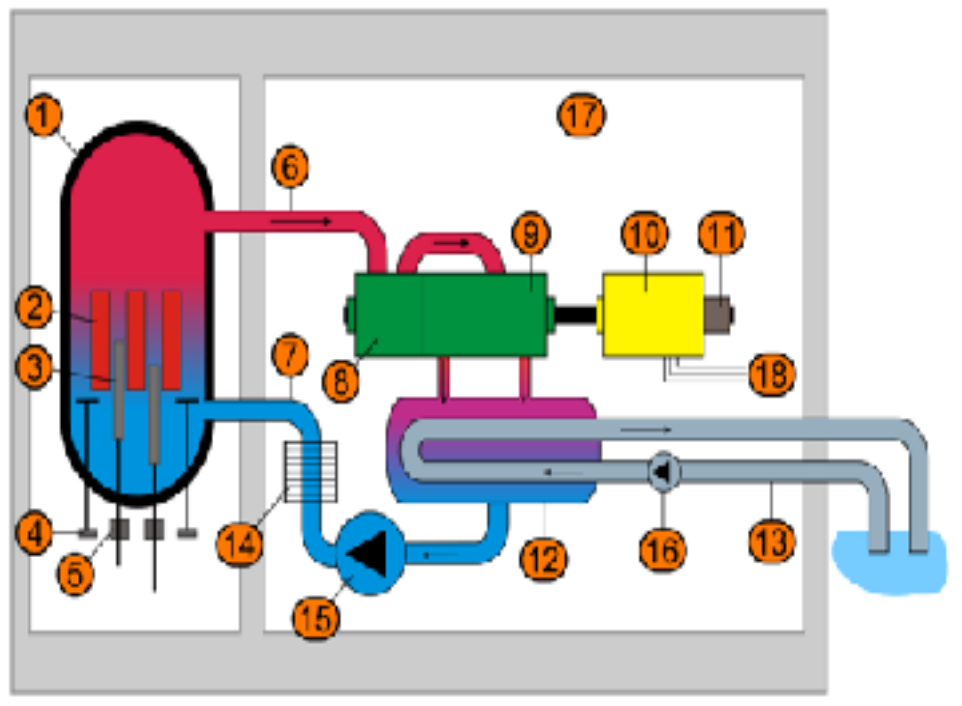
Number of reactors by type (end 2014)[21]



Net power capacity (GWe) by type (end 2014)[21]

URANIUM LIGHT WATER REACTORS PRESSURIZED vs BOILING TYPES





LIGHT WATER REACTORS (LWRS)

- Pressurized Water Reactor (PWR)
- PROs:
- Inherently safe: coolant=moderator.
- Easier maintenance; ”clean” turbine.
- Extensive operating experience.
- CONs:
- Can’t breed new fuel.
- Requires refueling every 2 years.
- Leaves 95% of fuel un-fissioned.

Boiling Water Reactor (BWR)

PROs:

Simpler plumbing reduces costs

Load-following is easier.

Extensive operating experience.

CONs:

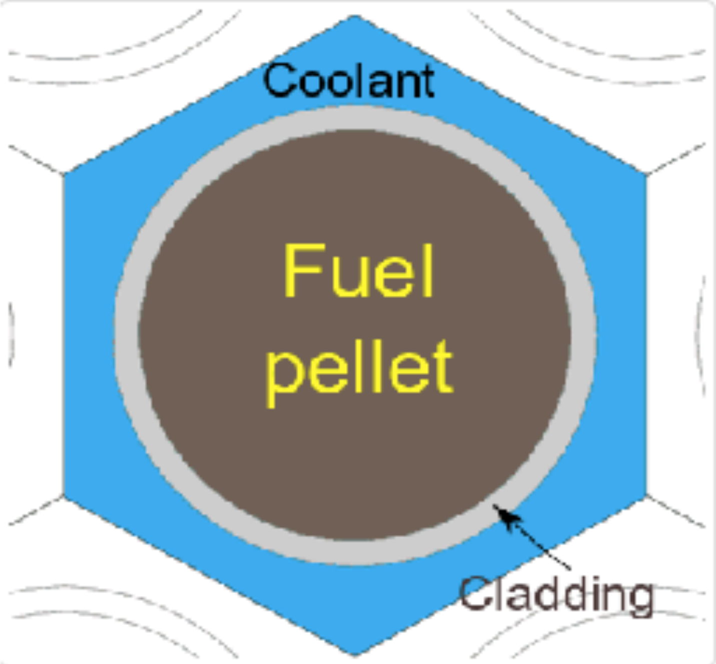
Can’t breed new fuel.

Requires refueling every 2 years.

Leaves 95% of fuel un-fissioned.

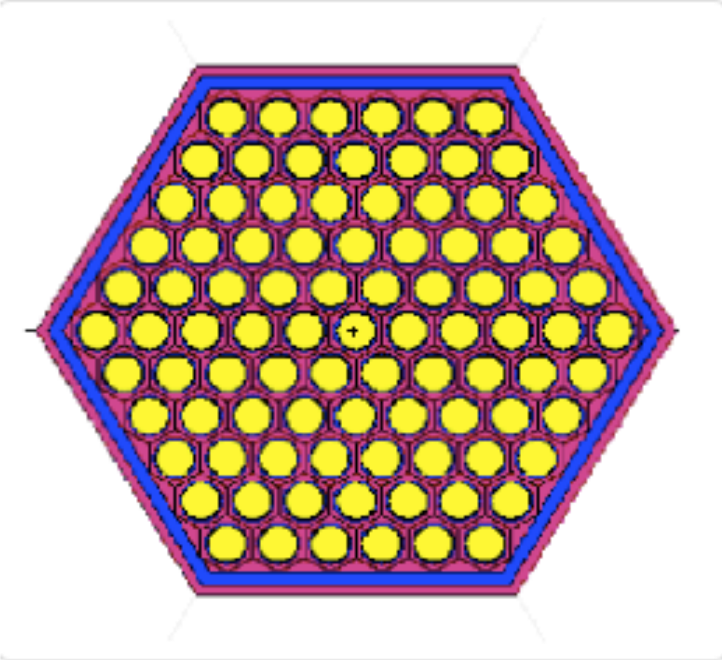
HOW THE FUEL RODS ARE ARRANGED

Fuel pins



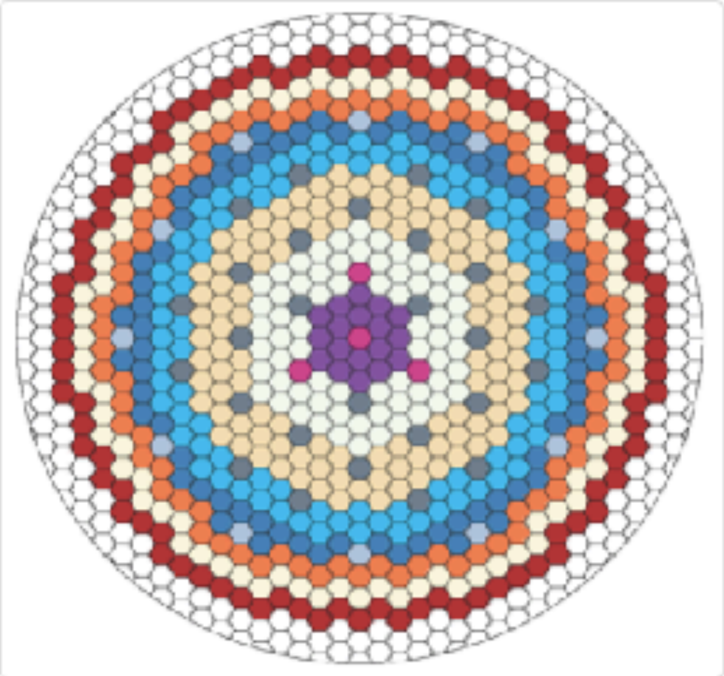
The smallest unit of the reactor is the fuel pin. These are typically uranium-oxide (UO_2), but can take on other forms, including thorium-bearing material. They are often surrounded by a metal tube (called the cladding) to keep fission products from escaping into the coolant.

Fuel assembly



Fuel assemblies are bundles of fuel pins. Fuel is put in and taken out of the reactor in assemblies. The assemblies have some structural material to keep the pins close but not touching, so that there's room for coolant.

Full core



This is a full core, made up of several hundred assemblies. Some assemblies are control assemblies. Various fuel assemblies around the core have different fuel in them. They vary in enrichment and age, among other parameters. The assemblies may also vary with height, with different enrichments at the top of the core from those at the bottom.

REVIEW OF PELLET TO REACTOR VESSEL

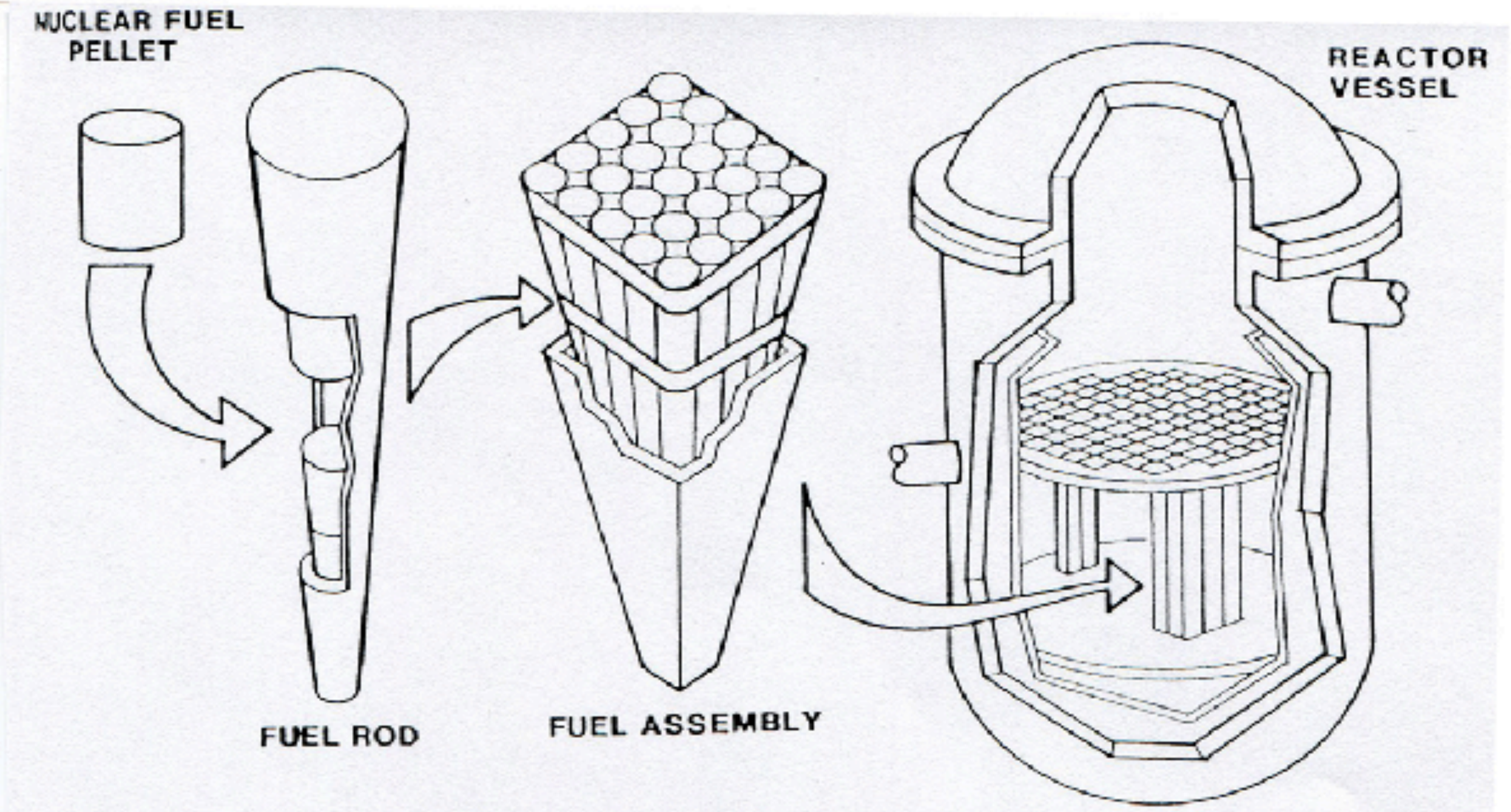


Figure 5.3 Assembly of the fuel into a core. COURTESY OF THE AMERICAN NUCLEAR SOCIETY.

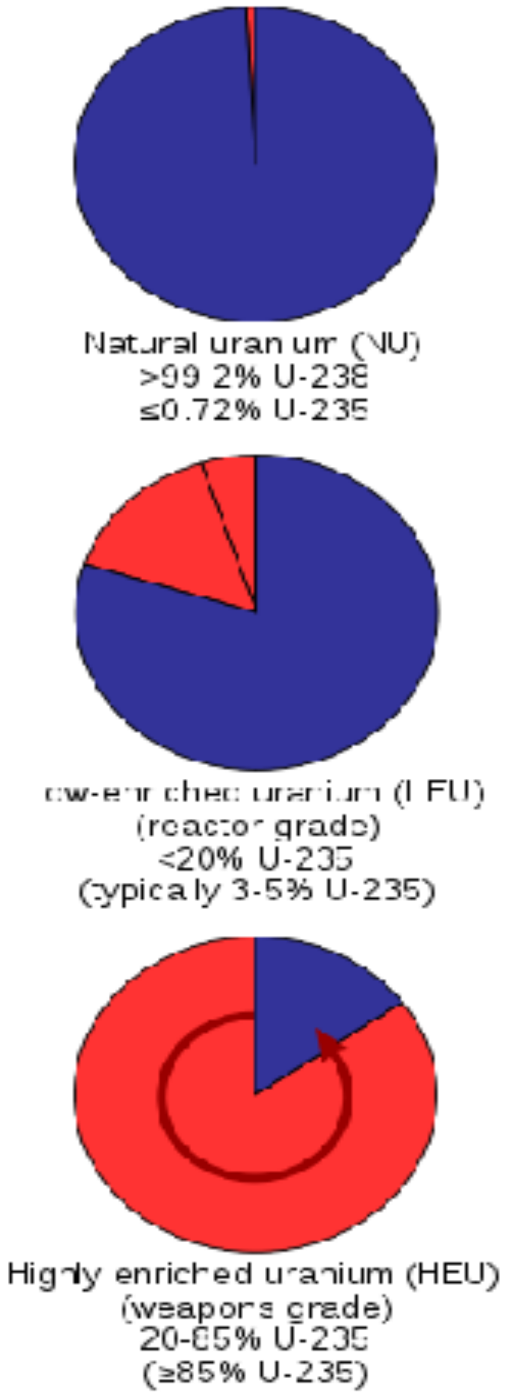
BEFORE/AFTER ENERGY HARVESTED

Table 1. Heavy metal composition of 4.2% enriched nuclear fuel before and after running for about 3 years (40,000 MWD/MT). Minor actinides include neptunium, americium, and curium. This table does not include structural material such as zirconium and stainless steel.

	Charge	Discharge
Uranium	100%	93.4%
Enrichment	4.20%	0.71%
Plutonium	0.00%	1.27%
Minor Actinides	0.00%	0.14%
Fission products	0.00%	5.15%

ENRICHMENT OF URANIUM

- There are 3 ways (including differential centrifugation) to enrich the tiny amount of ^{235}U that exists in natural uranium. (top→)
- The ^{238}U remaining after enrichment is known as depleted uranium (DU), and is considerably less radioactive than natural uranium, though still very dense.
- At present, 95% of the world's stocks of depleted uranium remain in secure storage.



GAS-COOLED REACTORS

- These types use graphite (instead of water) as a neutron moderator.
- Cooled by non-reactive gases, mostly CO_2, but can be He or N_2.
- Chief advantage is they can use natural (non-enriched) Uranium.
- Countries using them include UK, Italy & Japan (Magnox) as well as France and Spain (UNGG).
- There are also high and very high-temp helium-cooled reactors, such as prismatic and pebble-bed types.

CANDU (PHWR) REACTORS

- Canada Deuterium-Uranium Reactors (CANDUs)
- Designed in Chalk River, Ontario, they contain heavy water, in which the H in H2O (light water) is replaced by Deuterium, a heavier isotope of H.
- Deuterium absorbs many fewer neutrons than Hydrogen, allowing CANDUs to operate on non-enriched Uranium.
- PROs: CANDUs can be refueled while operating, since the cauldron is horizontal, and it can use many different types of fuel.
- CONs: Neutron absorption by Deuterium leads to Tritium production, which can leak in small quantities. Some variants have safety concerns or could be modified to produce weapons-grade plutonium more easily than LWRs.

CONVERSION RATIO

- A measure of a reactor's performance is the "conversion ratio," ie., the ratio of: newly produced fissile atoms/consumed fissile atoms. Most reactors experience some degree of conversion. When the conversion ratio > 1, it’s called the *Breeding Ratio*.
- Eg., commonly used LWRs have a conversion ratio of ~ 0.6.
- Pressurized heavy water reactors have a conversion ratio of 0.8.
- *Breeder reactors* have a conversion ratio of > 1.
- Break-even is achieved when the conversion ratio =1, and the reactor makes as much fissile material as it uses.

LIGHT WATER, GRAPHITE-MODERATED REACTORS

- All 15 of these early Gen-II reactors were built in Russia.
- Graphite moderation allows non-enriched uranium to be used as fuel.

FBR = FAST BREEDER REACTOR

- FBR=one type among 6 families of Generation IV reactors.
- China has one in Beijing.
- Experimental Breeder Reactor–1 (EBR-1) was built by O.R. in Idaho.
- The leading contender among Gen-IV reactors is the Molten Salt Reactor (MSR).
- MSR fuels are Uranium and/or Thorium, as liquid fluoride salts.

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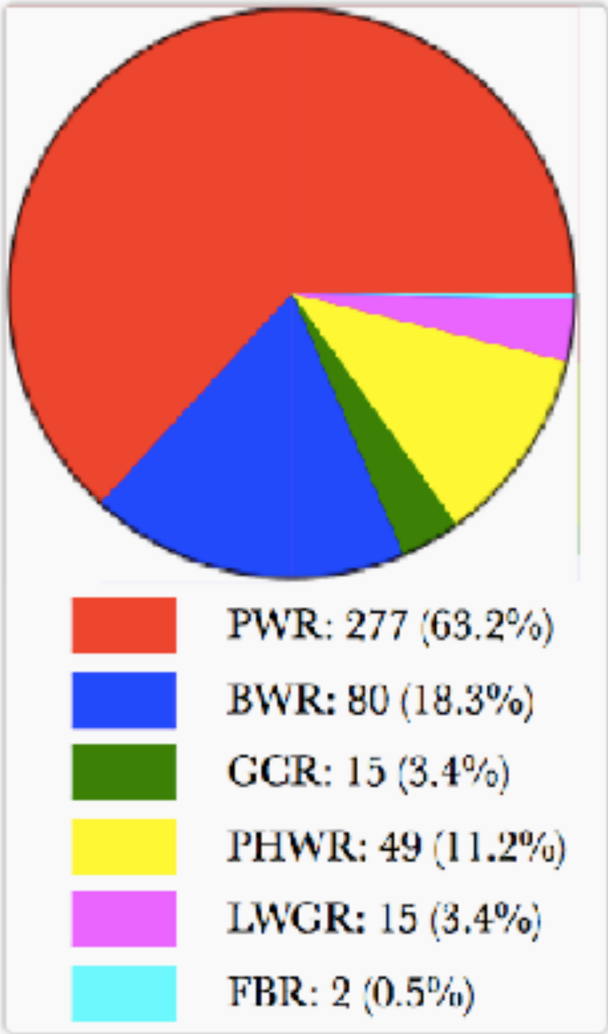
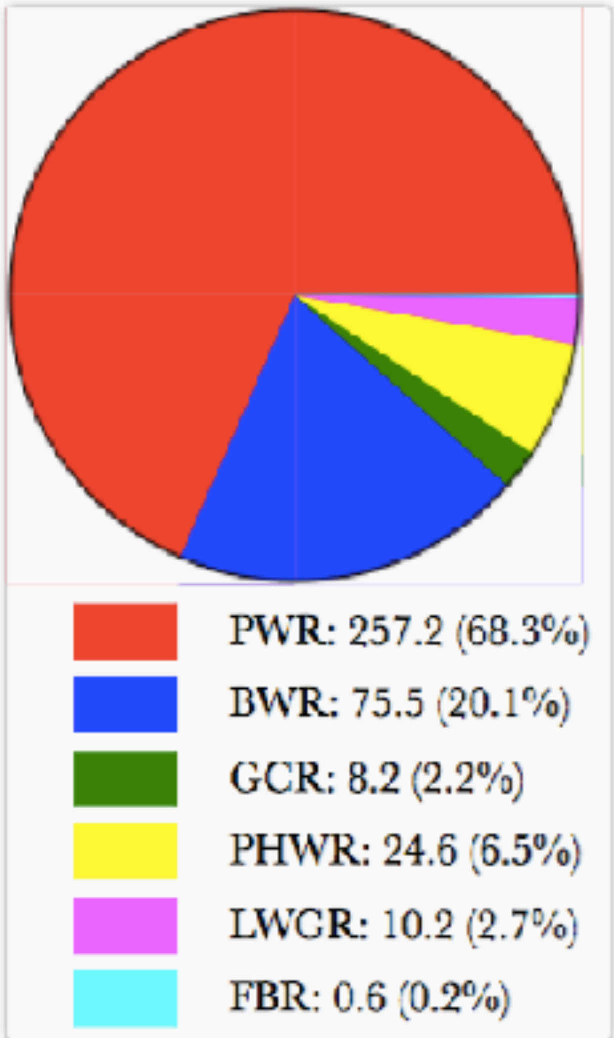


Number of reactors by type (end 2014)[21]



Net power capacity (GWe) by type (end 2014)[21]

SHORTCOMINGS OF URANIUM FUEL

- As an energy source, U has issues, long overshadowed by its advantages over coal.
- A tiny fraction (0.7%)of mined U is its fissile isotope, ^{235}U.
- Enrichment of ^{235}U from ^{238}U is difficult (isotopes are very similar).
- ^{235}U can be used to make nuclear weapons.
- Only ~4% of its energy is used for making electricity.

- <u>In contrast</u>: ^{238}U is fissionable but not fissile; it will split apart only when struck by a neutron traveling very, very fast. But breeder reactors have their own problems: big changes can happen very quickly, and liquid sodium coolant explodes in air/H20.

MY CANDID DISCLOSURE

Paul P.H. Wilson
@gonuke

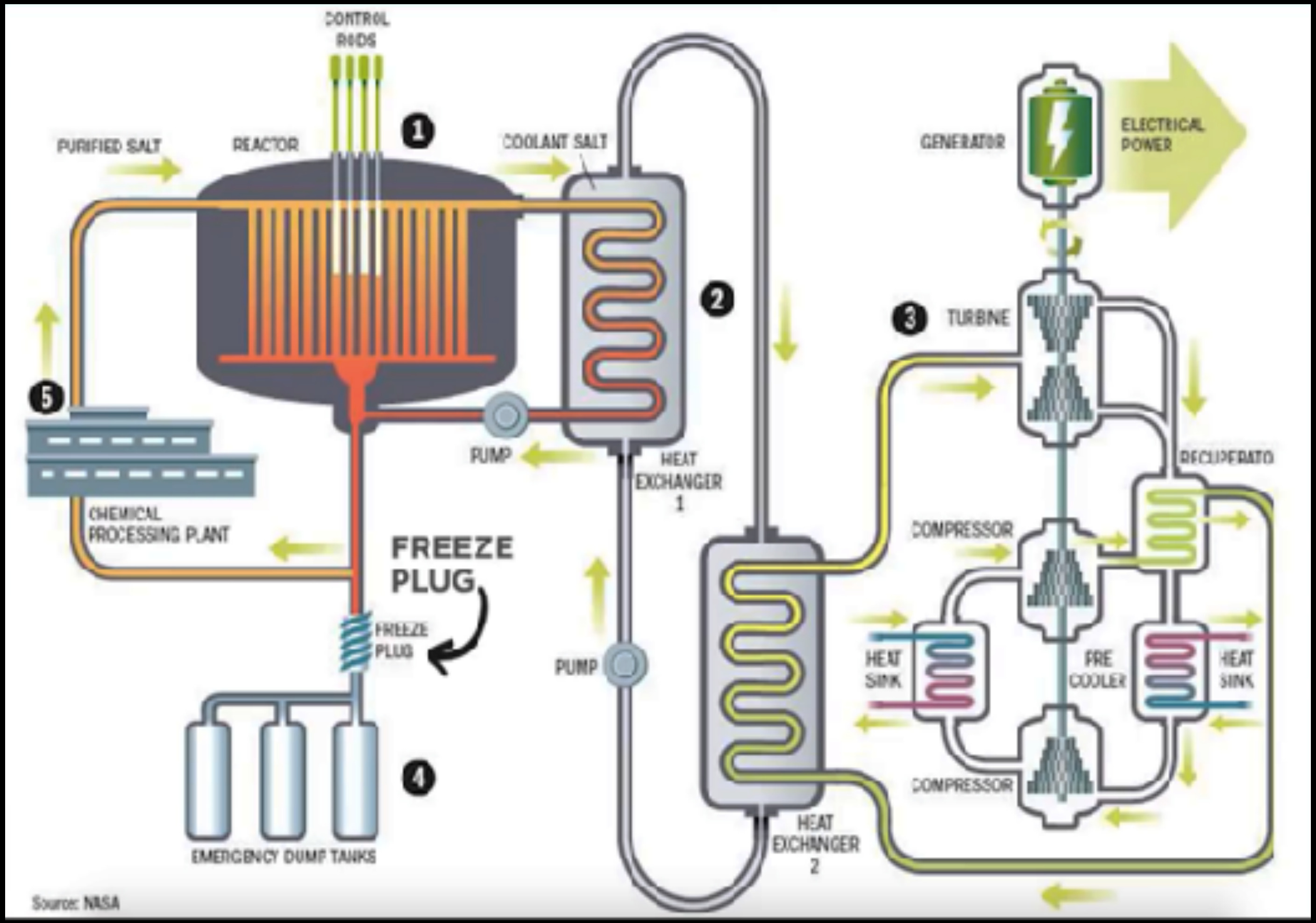
Following

Replying to @AchalHP @nuclear94

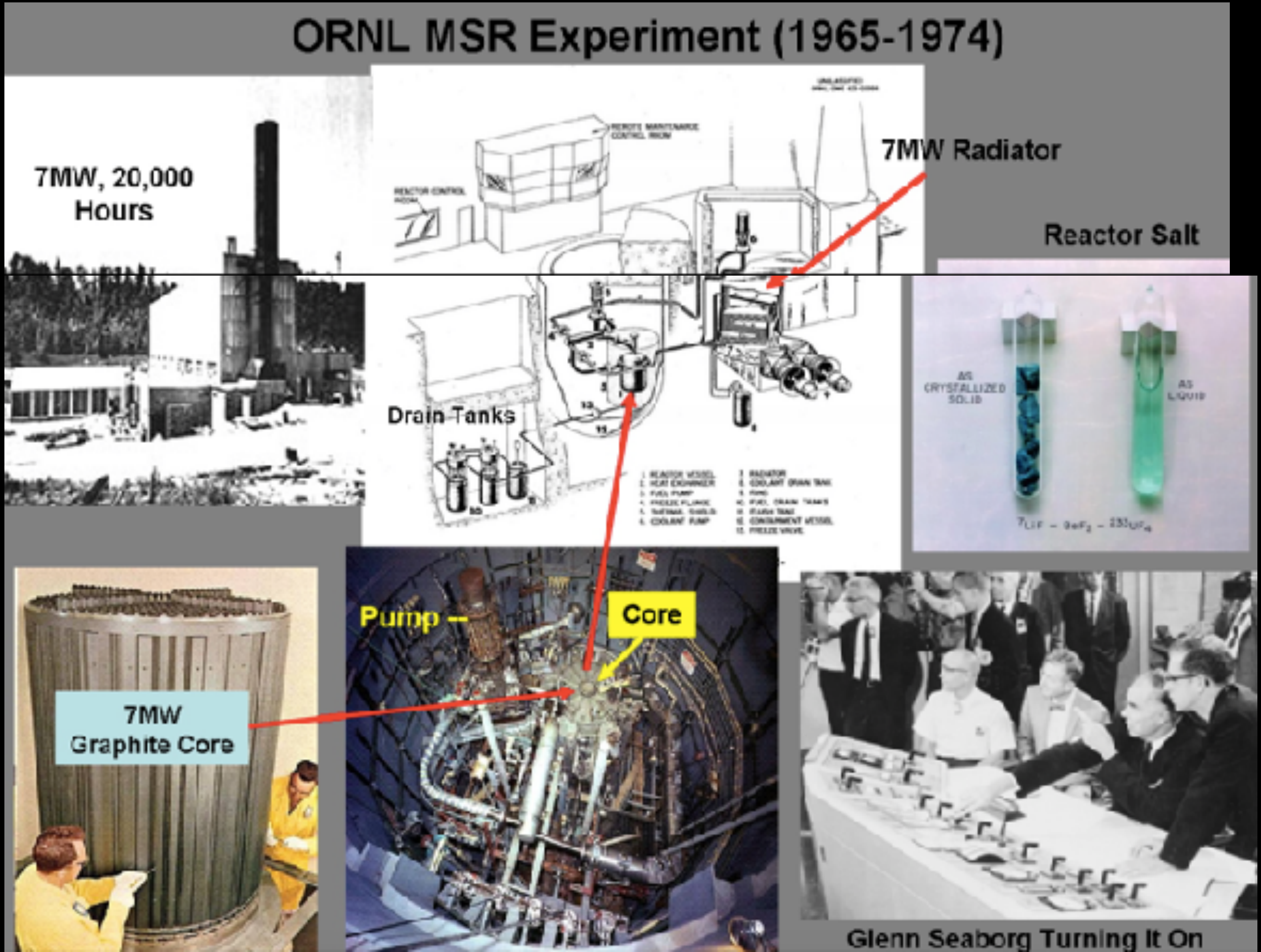
I don't have anything against Th fuel cycles, per se. It's just that when carefully assessed against a complete set of societal metrics, the benefits are marginal at best in most places in the world.... but many in the Th community have convinced lay audiences otherwise

THORIUM:
LFTR= LIQUID FLUORIDE THORIUM REACTOR

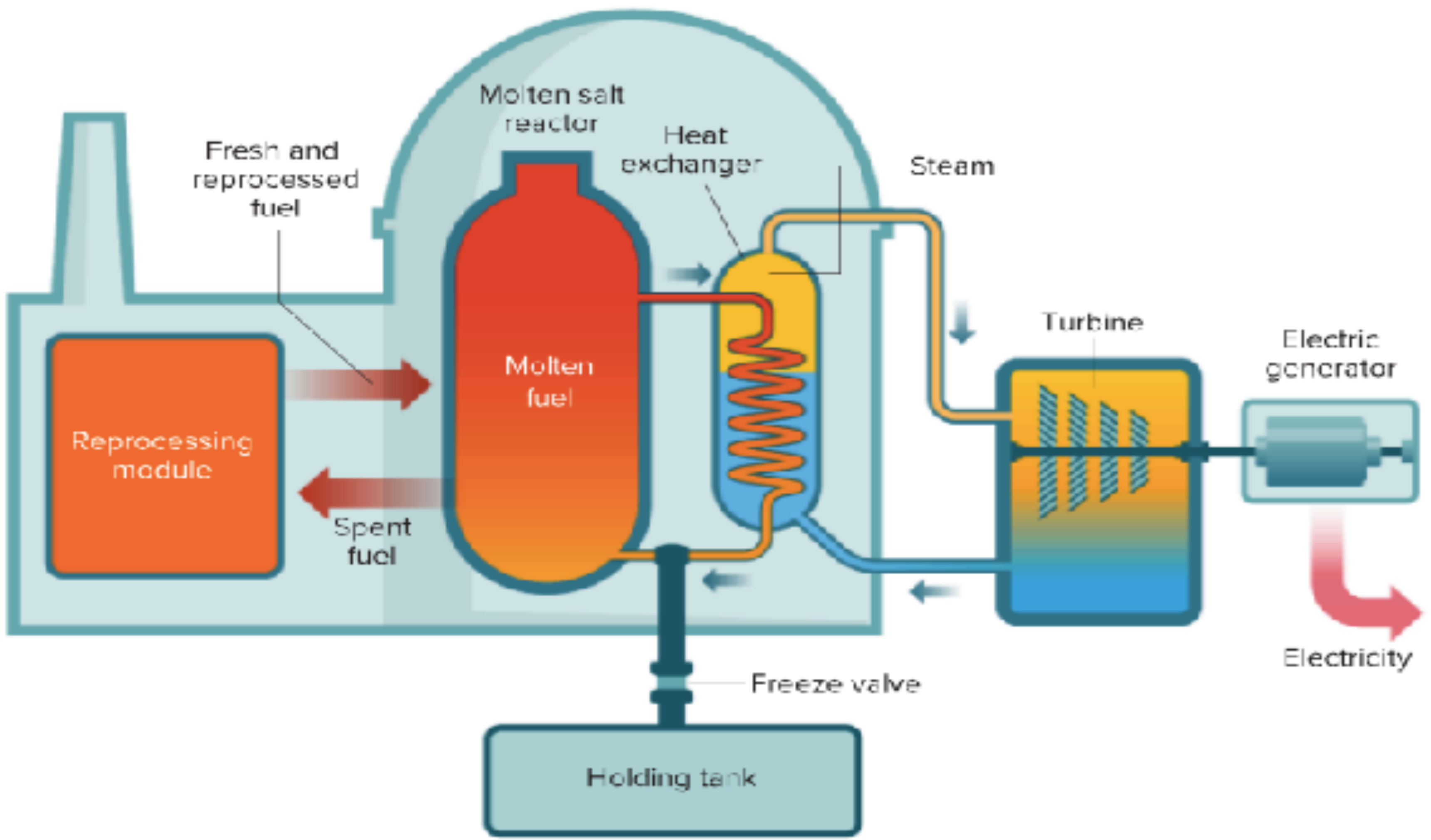
- Liquid: its fuel is dissolved in molten salt and circulated continuously to allow complete fuel burnup.
- Fluoride: such salts are very stable compounds, even when hot.
- Thorium: a very abundant element on Earth, not requiring enrichment.
- Reactor: operates at high temp but normal pressure, providing safe, compact, less expensive energy.



ORIGINAL MSR AT OAK RIDGE



How a molten salt reactor works



5W INFOGRAPHIC / KNOWABLE

A molten salt reactor differs from a conventional nuclear reactor in a number of ways, starting with the fact that it uses nuclear fuel that's liquid instead of solid. This has profound implications for safety. For example, meltdowns would be a non-issue: The fuel is already molten. And if temperatures in the fuel mix get too high for any reason, a plug of frozen salt below the reactor will melt and allow everything to drain into an underground holding tank for safekeeping. Long-lived nuclear waste would also be a non-issue: A chemical system would continuously extract reaction-slowing fission products from the molten fuel, which would allow plutonium and all the other long-half-life fissile isotopes to be completely consumed.

SCHEMATIC OF AN MSR

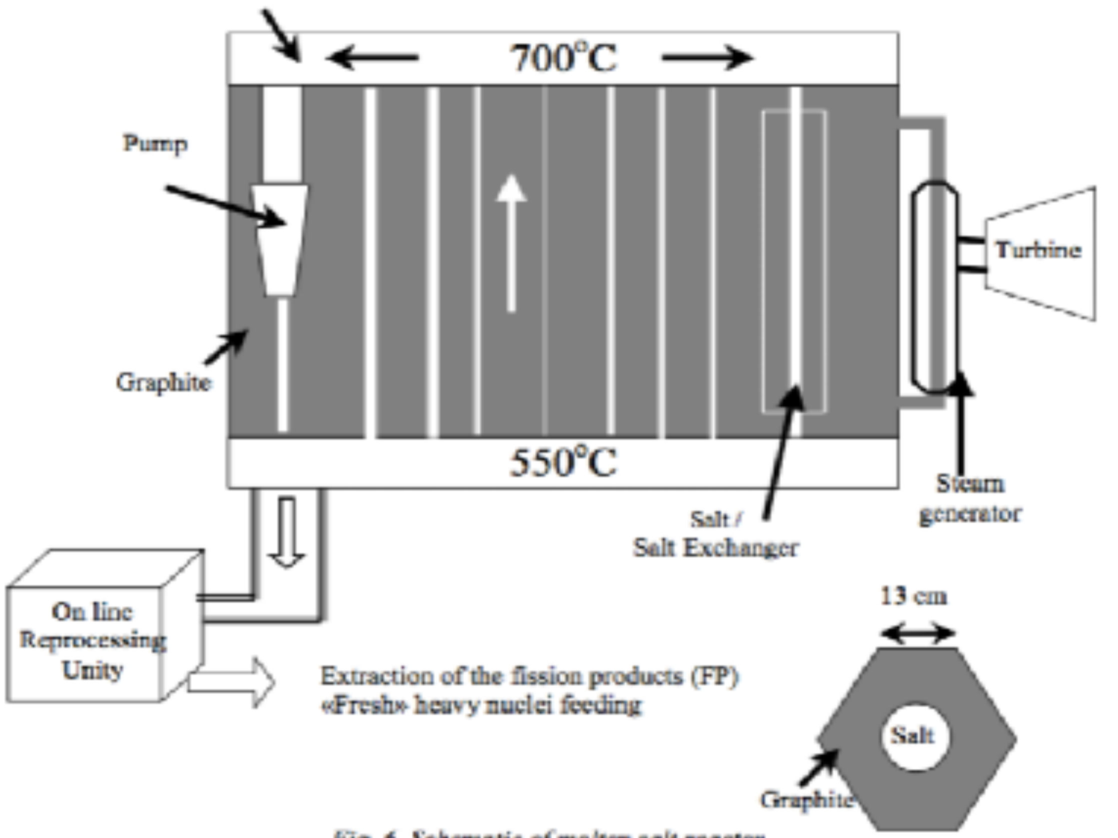
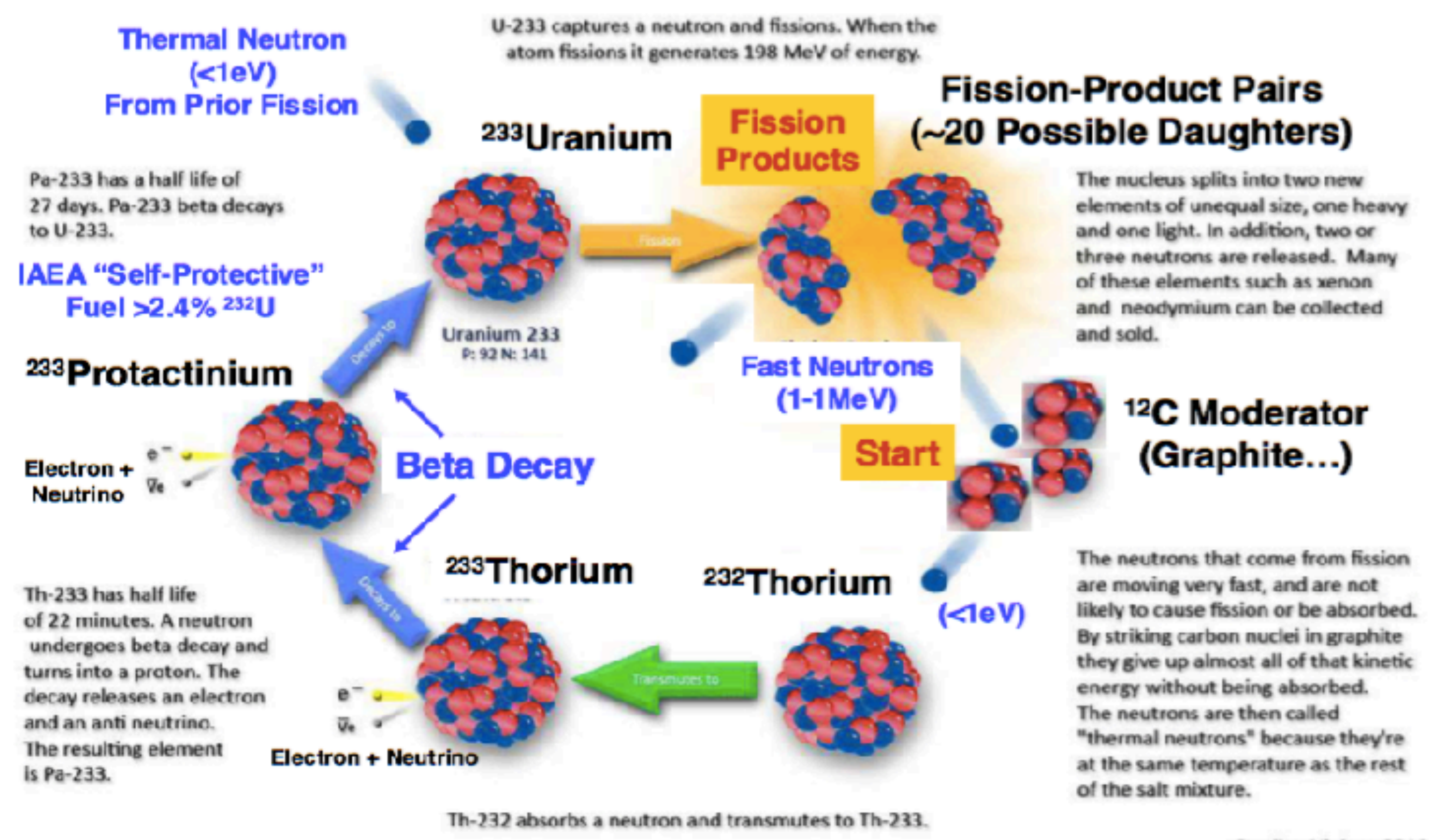


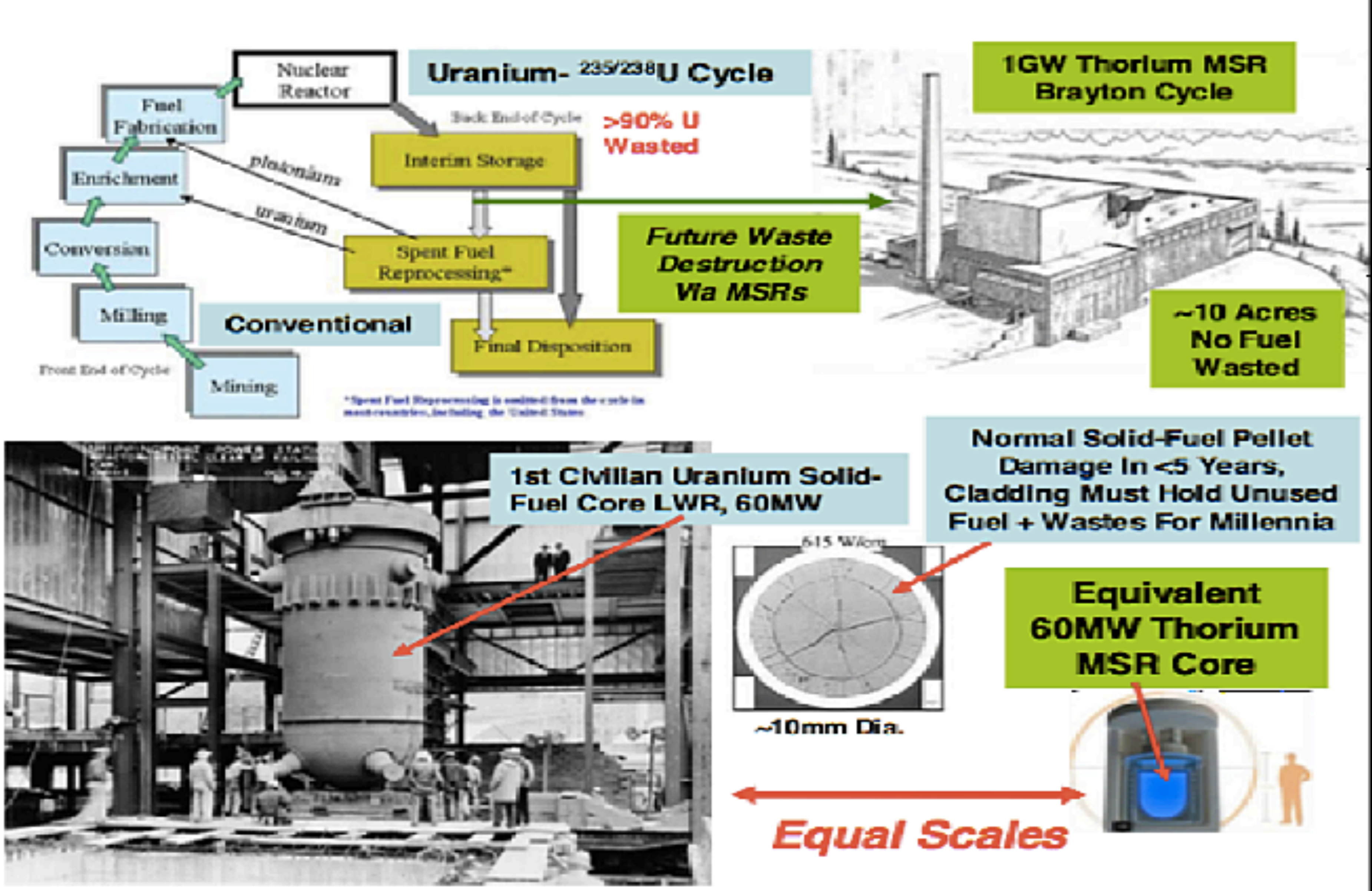
Fig. 6. Schematic of molten salt reactor.

Molten salt reactors (MSR) use graphite as moderator, molten fluoride salt of high boiling point (≥1400°C) with dissolved 'fissile' and 'fertile' materials as fuel and primary coolant and operate in an epithermal neutron spectrum. The core of MSR is usually a cylindrical graphite block that acts as moderator, through which holes are bored, in which the molten fluoride salt containing thorium uranium and plutonium circulates. The primary coolant, containing the fuel, flows to a primary heat exchanger, where the heat is transferred to a secondary molten salt coolant and then flows back to the graphite channel of the reactor core. The secondary coolant loop transfers the heat to the power cycle or hydrogen production facility. The operating temperature range of MSRs is between 450°C, the melting point of eutectic fluoride salts to around 800°C. In the secondary molten salt, the temperature is lower than the primary.

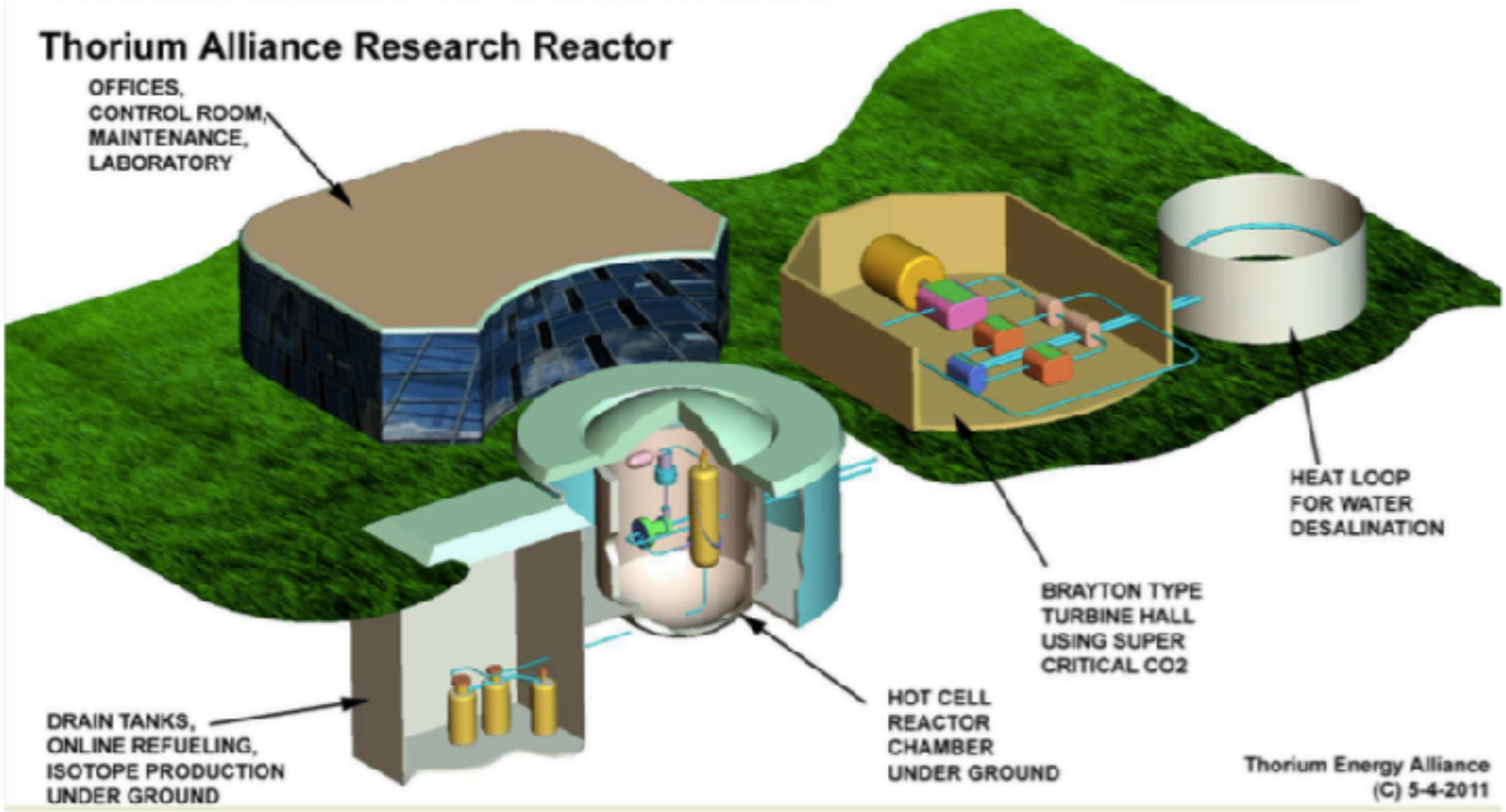
Thorium Breeding Cycle



LWR (BLUE) VERSUS MSR (GREEN)



Molten-Salt Reactors



www.thoriumenergyalliance.com

PROs & CONs OF MSRs

- PROs:
- No need to shut them down for refueling.
- Ability to breed more fuel at low neutron energies.
- Liquid fuel avoids cladding; more efficient.

- CONs:
- A containment breach might release more fission product gases than a single pin in water.
- On-line reprocessing is a potential "proliferation" concern.

HISTORY OF THE MSR AT OAK RIDGE

- Hyman Rickover applied for duty in submarines in 1929, but his only command, in 1937, lasted 3 months, after near-mutiny. By Dec 1941 he was chief of the Navy's electrical section. He oversaw building the largest submarine fleet in history, spurring his men to exhaustion, driving contractors into rages, but making a reputation for getting things done.
- Meanwhile at Oak Ridge, Alvin Weinberg showed that MSRs had proven advantages over LWRs. But by 1954, with the launching of the ***Nautilus***, Rickover had gained powerful influence over the AEC, helping to remove the government from atomic research, leaving GE and Westinghouse, already committed to LWRS, to dominate.

ALVIN WEINBERG (1915 – 2006)

- *"During my life, I have witnessed extraordinary feats of human ingenuity. I believe that this struggling ingenuity will be equal to the task of creating the Second Nuclear Era. My only regret is that I will not be here to witness its success." - 1994*

ADVANTAGES OF TH OVER U

- 1. Thorium is 4X more abundant than U in the earth's crust, and is easily found near the earth's surface.
- 2. Thorium does not need to be enriched, as uranium often does, before using it in a fission reactor.
- 3. Thorium is FERTILE, but not FISSILE, so it cannot be used by itself as a nuclear weapon.
- 4. Thorium's decay product, ^{233}U, fissions more completely, so there is much less waste.

8 WAYS TO COMPARE U VS TH

URANIUM vs. THORIUM in NUCLEAR REACTORS

Qualifier	U-235 Light Water	Th-232 Liquid Fluoride
Fuel State	Solid U oxide in rods is easily damaged by heat and irradiation. By-products like xenon-135 require careful reactor management.	Liquid fluoride salts of Th and U are not damaged, and readily yield their products for separation and recycling.
Fuel Element	Uranium is less common, is difficult to purify, and its by-products (Pu-239, Am, Np) are very long-lasting and highly toxic.	Thorium is 4X commoner in the earth and is more easily extracted. U-233 product is easily recovered after fluoridation and recycled.
Reactor Design	Needs large structures to contain pressurized water or steam, then a giant dome for tertiary containment.	Relatively simple vessels that can be mass-produced and assembled without requiring high pressures.
Operation	Fuel rods must be replaced every 18 months, requiring plant shutdowns. Thermal efficiency = 30% vs 45%→	Core of U-233 emits neutrons into a 'blanket' of Th-232. Latter burns to U-233, which is continuously separated and recycled into the core.
Safety	Spent fuel is highly radioactive and dangerous to handle, even remotely.	No structural stresses in liquids; less need to handle, no pressure increase.
Waste Management	After years of storage under water, it must be removed again, dried and stored in casks.	Easily removed by fluoridation or plating; less volume waste and less toxic.
Cost	Huge costs for infrastructure and fuel manufacturing, as well as loss of efficiency: 18-month shutdowns.	Less expensive to build both structure and fuel; few shutdowns and less need for shielding.
Proliferation Resistance	By-products remain active for many years, and require constant guarding to prevent abuse by terrorists.	Thorium technology is still poorly understood, less likely to be stolen; abuse is easy to detect.

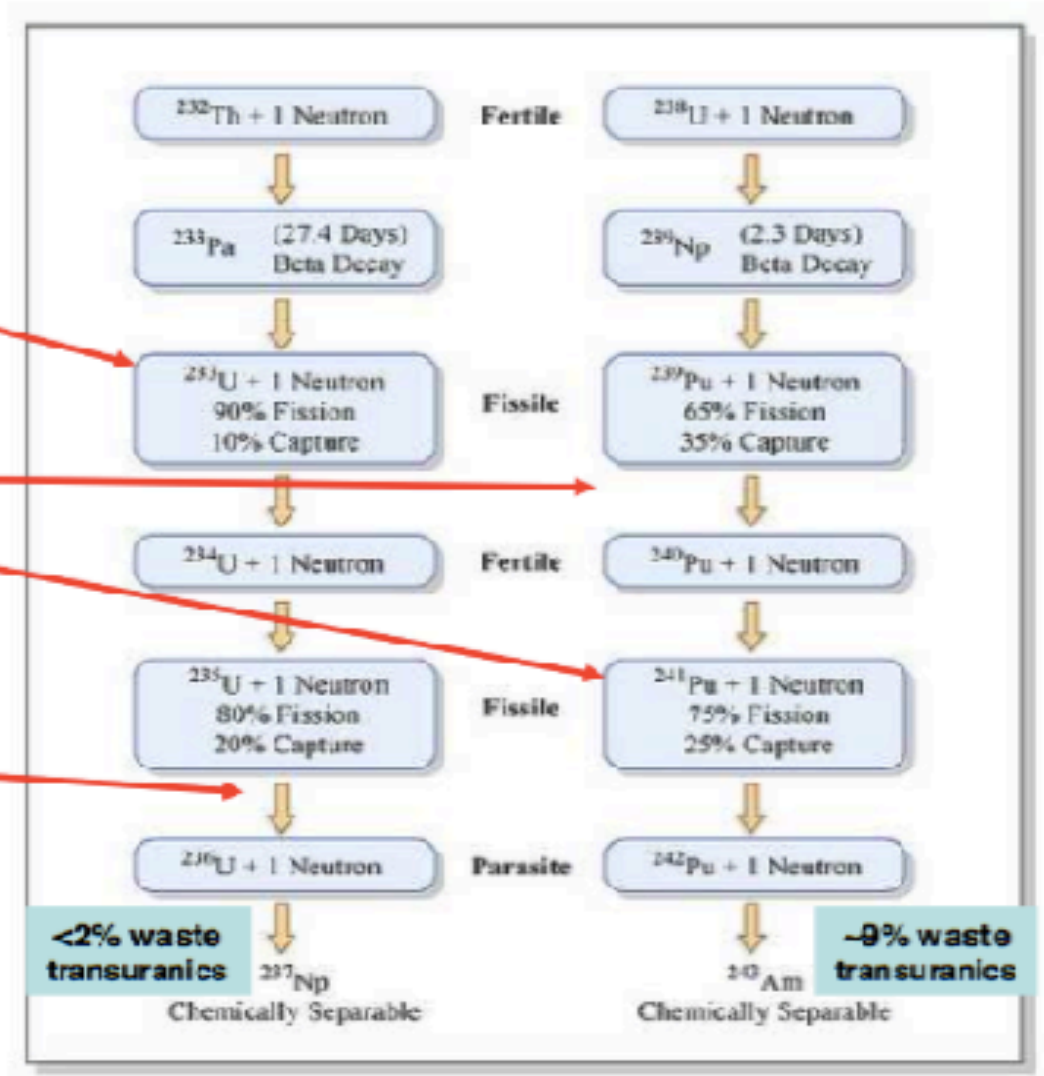
Fission Choices

Thorium bred to ^{233}U with a neutron (via Protactinium decay), or via proton-beam & spallation

Next neutron hitting ^{233}U has a very high probability of causing fission & releasing ~180MeV energy, but ^{238}U bred to Plutonium is much less likely to fission, thus building up higher-mass Pu, which has bomb-making potential, plus Am & other long-lived, <u>transuranic wastes</u>

Because Thorium starts at mass 232 & neutron captures rarely exceed 236 (< 20% of 10% = 2%), ^{238}U & Pu are rarely produced, but are consumed if fissile

Starting Fission with Thorium vs ^{238}Uranium



Graphics Courtesy of Wikipedia

IS “WASTE” DISPOSAL ALL THAT DIFFICULT?

- We’ve been disposing more toxic wastes than nuclear for decades.

- Spent nuclear fuel from LWRs is allowed to cool for ~ 5 years before storage, where it’s not as toxic as industrial wastes (formaldehyde, benzene or cyanides) 9 billion gallons of which we store annually.

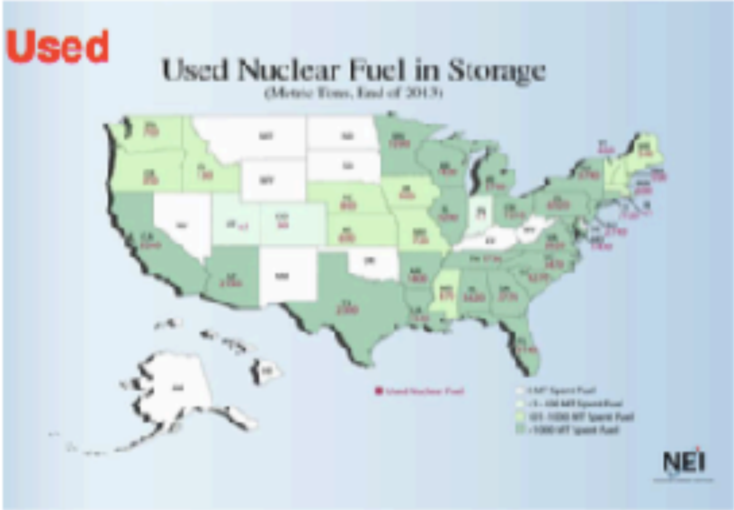
- EPA’s radiation standards for Yucca Mountain storage are too rigorous, 20X > the current “background” radiation we all receive.

- Spent nuclear fuel storage beside existing nuclear plants is sensible, and it could be used to fuel advanced reactors in future.

YUCCA MOUNTAIN IN SOUTHERN NEVADA

FEDERAL LANDS IN SOUTHERN NEVADA

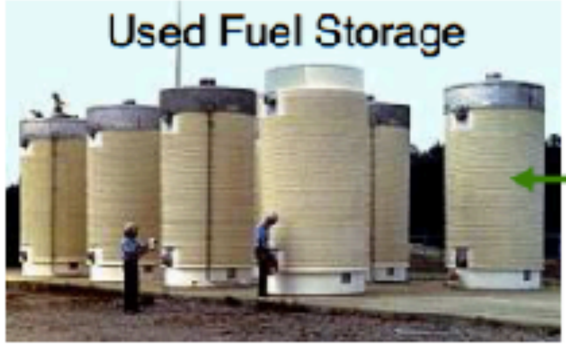
Used 'Spent' Fuel = Not Waste



>74,000 tons = 1 football field

Enrichment >500,000 tons pure U238

Used + unused Uranium = >570,000 GW-years of clean energy, when used to breed new fuel for fast-neutron reactors (IFR, EBR, MSFR…)
"…and…make possible the exploitation of the vast energy resources latent in the fertile materials, uranium-238 and thorium." – Glenn Seaborg to JFK, 1962.



Used LWR Fuel Bundle

>95% Not Waste: ~2% unused fissile fuel, ~4% fission products, ~95% Uranium, and <1% transuranics.

Solution to the Waste Problem

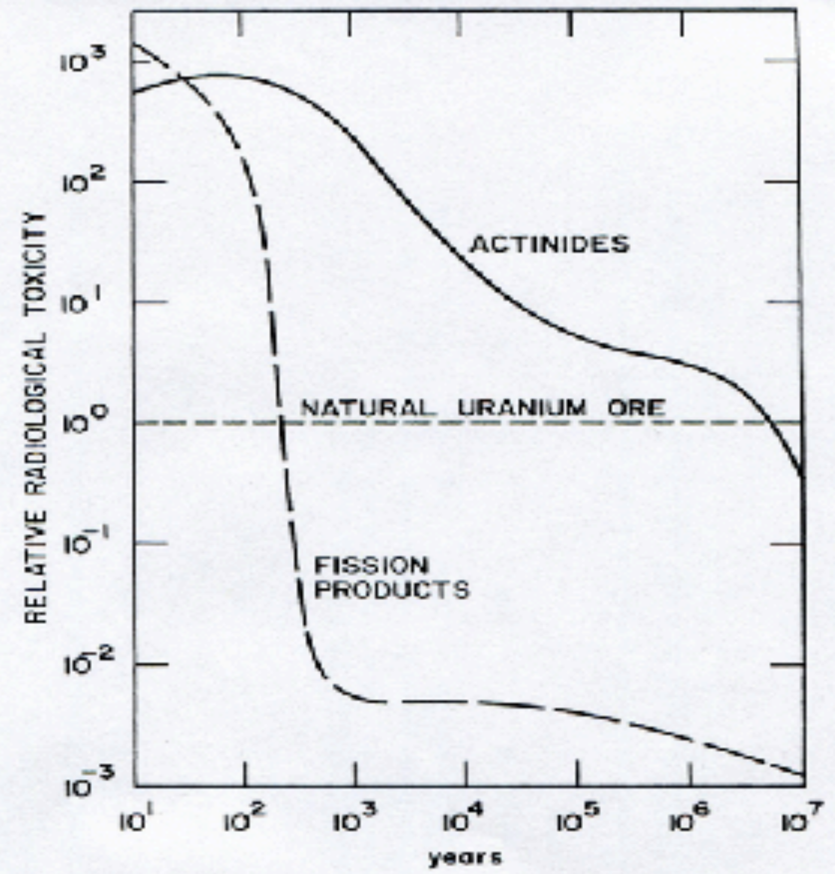


Figure 8.13 Relative radiological toxicity of high-level waste. COURTESY OF ARGONNE NATIONAL LABORATORY.

- Not a total solution, but if the original actinides are consumed, the toxicity of the remaining fission products drops by 5 logs to only 800 years.
- This is a powerful side-benefit of total “burn”.

WHY DO WE KEEP PLAYING WITH LEGOS?

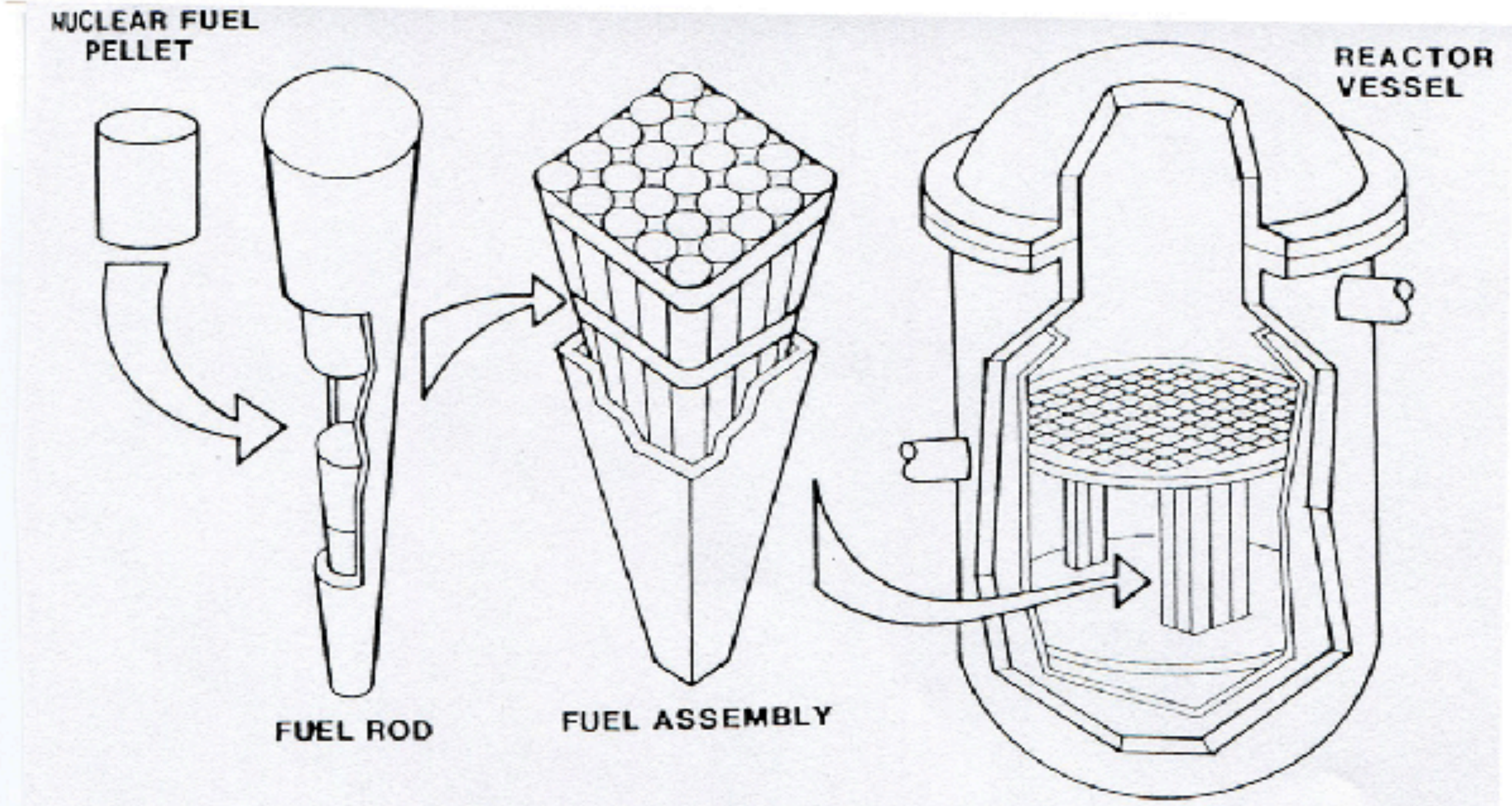
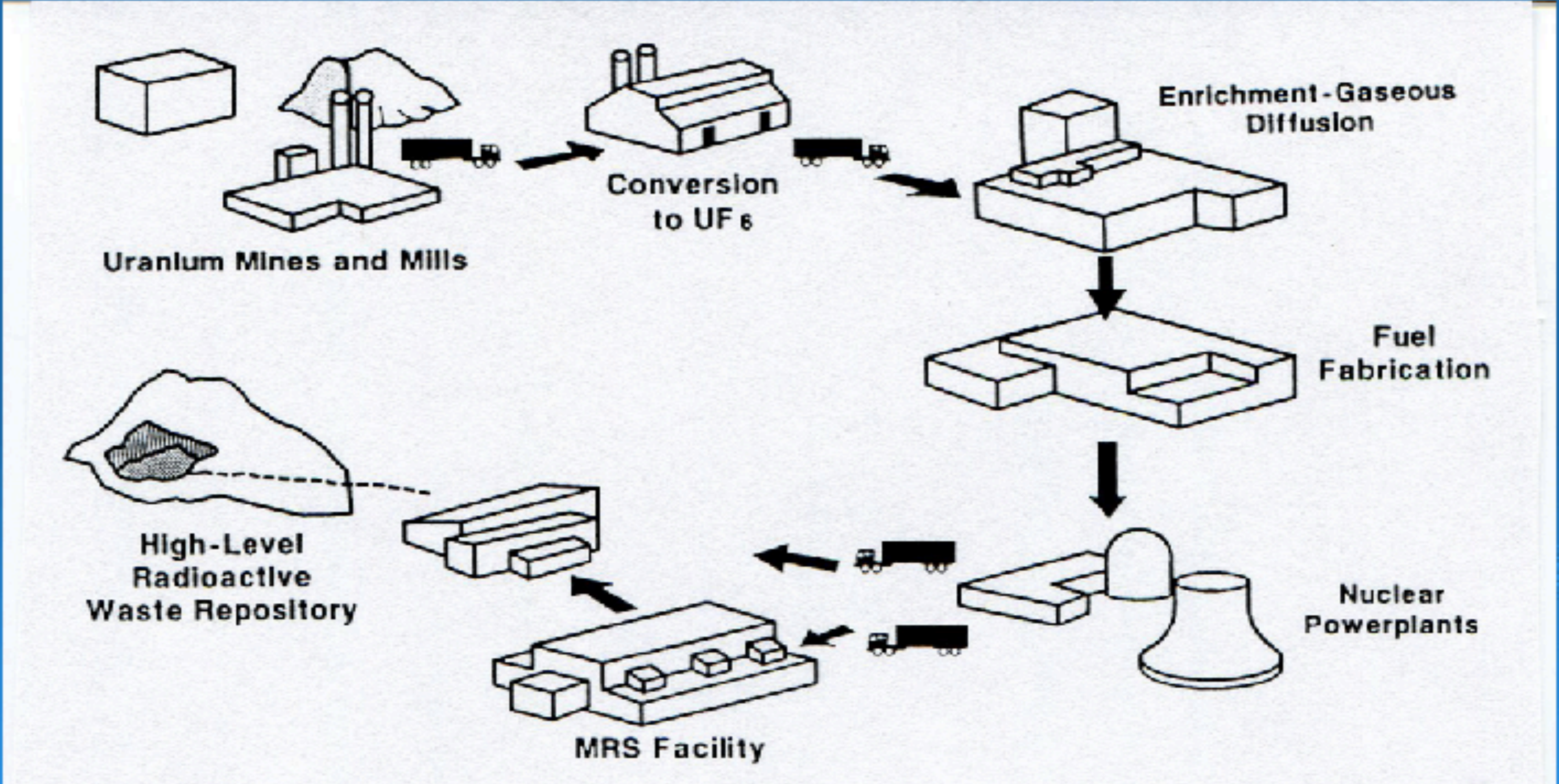


Figure 5.3 Assembly of the fuel into a core. COURTESY OF THE AMERICAN NUCLEAR SOCIETY.

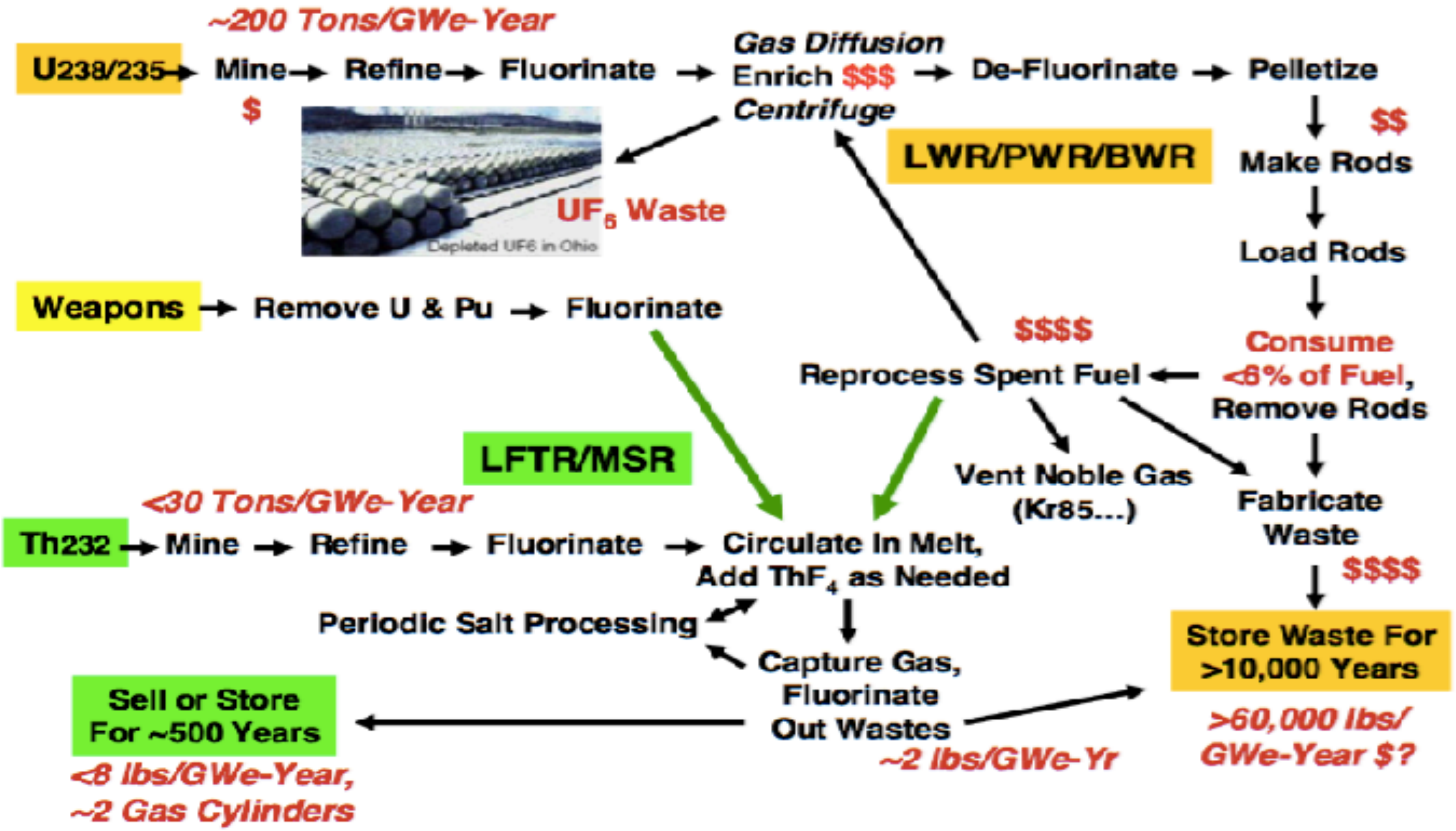
Uranium's Long Road to MRS (monitored retrievable storage)



MSRs can CONSUME EXISTING LWR WASTES

- Typical wastes from a 1 GWe LFTR, over 30 years, is < 100 lbs (<1/2 cubic ft).
- A 1 GWe LFTR makes 1/1000th the Plutonium made by an equivalent LWR.
- LFTR wastes are < wastes of fissioning U oxide pellets, with less fission products.
- OTHER MSR advantages are:
  - Higher temps give ~30% better thermal efficiency, and no pressurization.
  - MSRs automatically throttle via thermal expansion of atoms in fluid salt.
  - There is no "runaway" or "meltdown" with liquid fluoride salt reactors.
  - Expensive containment systems are avoided by using a "frozen plug" to release the fluid salts in the event of an electrical power failure.

Thorium MSR & Uranium LWR Cycles



Comparison with Fossils

1000 Mwe-yr Power Plant Emissions

Engineering Phy
College of Engineering
University of Wis

	COAL	GAS	NUCLEAR
Sulfur-oxide	~ 1000 mt		
Nitrous-oxide	~ 5000 mt	400 mt	
Particulates	~ 1400 mt		
CO_2	> 7million mt	3.5mill. mt	
Trace elements	< 1mt**	< 1 kg	
Ash (solids)	~ 1million mt		

** Volatilized heavy metals: e.g., Mercury, Lead, Cadmium, Arsenic

Spent Fuel			20-30 mt
Fission Products			~1 mt

TABLE 8.1 Fission Products Requiring Long-Term Isolation

Fission Product	*Half-Life (years)*	*Activity Discharged Annually from a 1000 MW PWR Reactor (Ci/y)*
Sr-90	28	2.1×10^6
Cs-137	30	2.9×10^6
Se-79	6×10^4	11
Sn-126	1×10^5	15
Tc-99	2.1×10^5	390
Zr-93	1.5×10^6	50
Cs-135	3.0×10^6	8
Pd-107	7×10^6	3
I-129	1.7×10^7	1.0

GEOMELT = VITRIFICATION

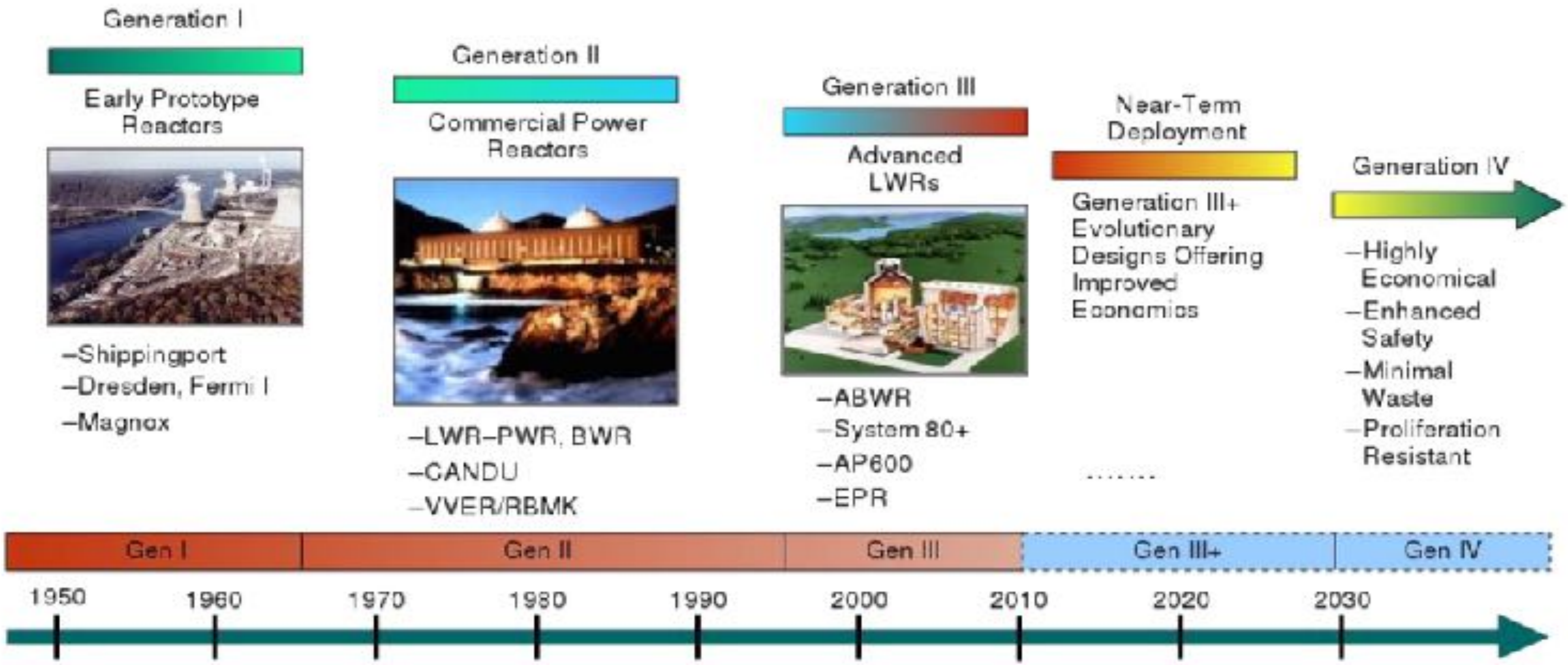
- Geomelting: dangerous contaminated material is mixed with clean soil, industrial waste and glass “grit”, and melted to create a very hard, leach-resistant glass. This vitrification immobilizes nearly all contaminants by incorporating them into a glass matrix. Organic wastes are destroyed by pyrolysis.
- Developed in 1980 by the US-DOE, the Geomelt process is conducted in situ (in place) or by In-Container Vitrification (ICV) in a special steel-lined container.

THE FACTS ABOUT "WASTE"

- Nuclear "waste" is Compact, Contained & Curated.
- Its dangers are greatly exaggerated by the oil lobby and by fearful, poorly informed environmentalists.
- Yucca Mountain and other waste sites need to be made operational for storing fission products.
- We need to consider Thorium as well as Uranium for future reactors, rather than remain limited by our current, uranium-based infrastructure.

EVOLUTION OF MORE INNOVATIVE REACTOR DESIGNS

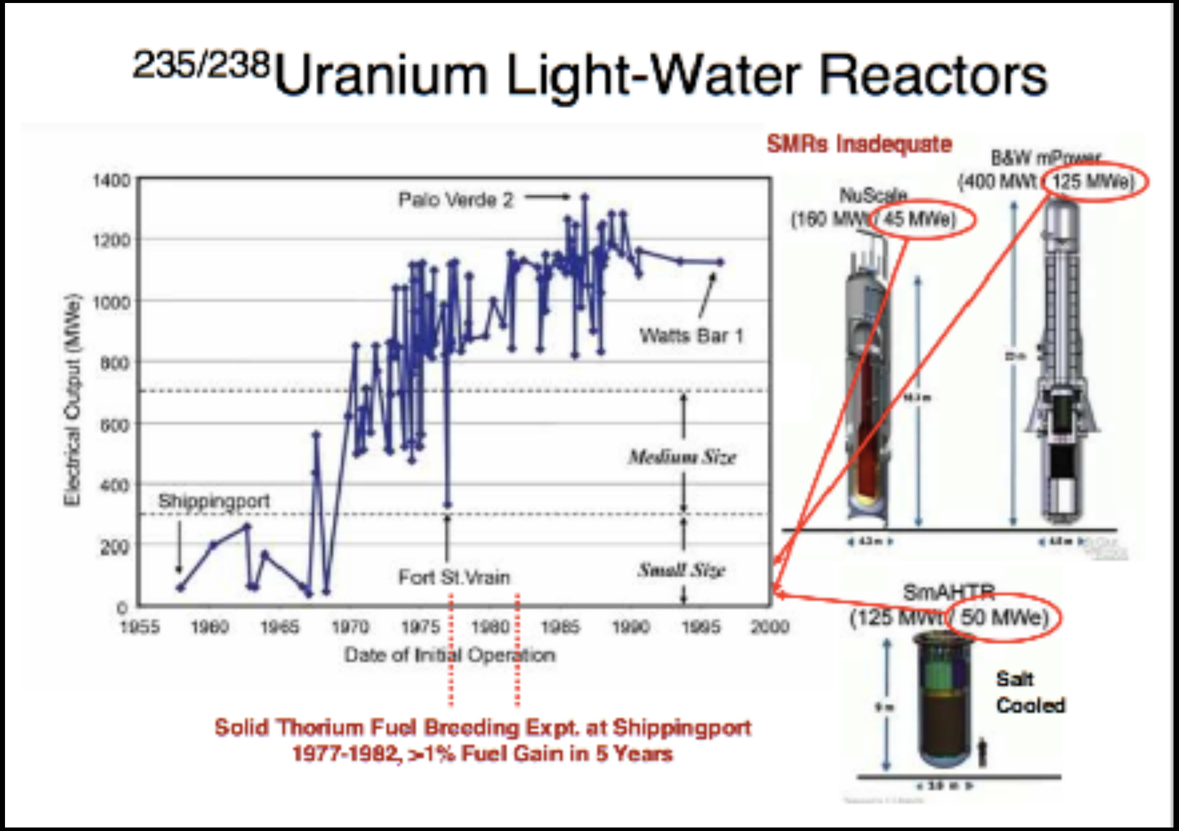
Generation IV: Nuclear Energy Systems Deployable no later than 2030 and offering significant advances in sustainability, safety and reliability, and economics



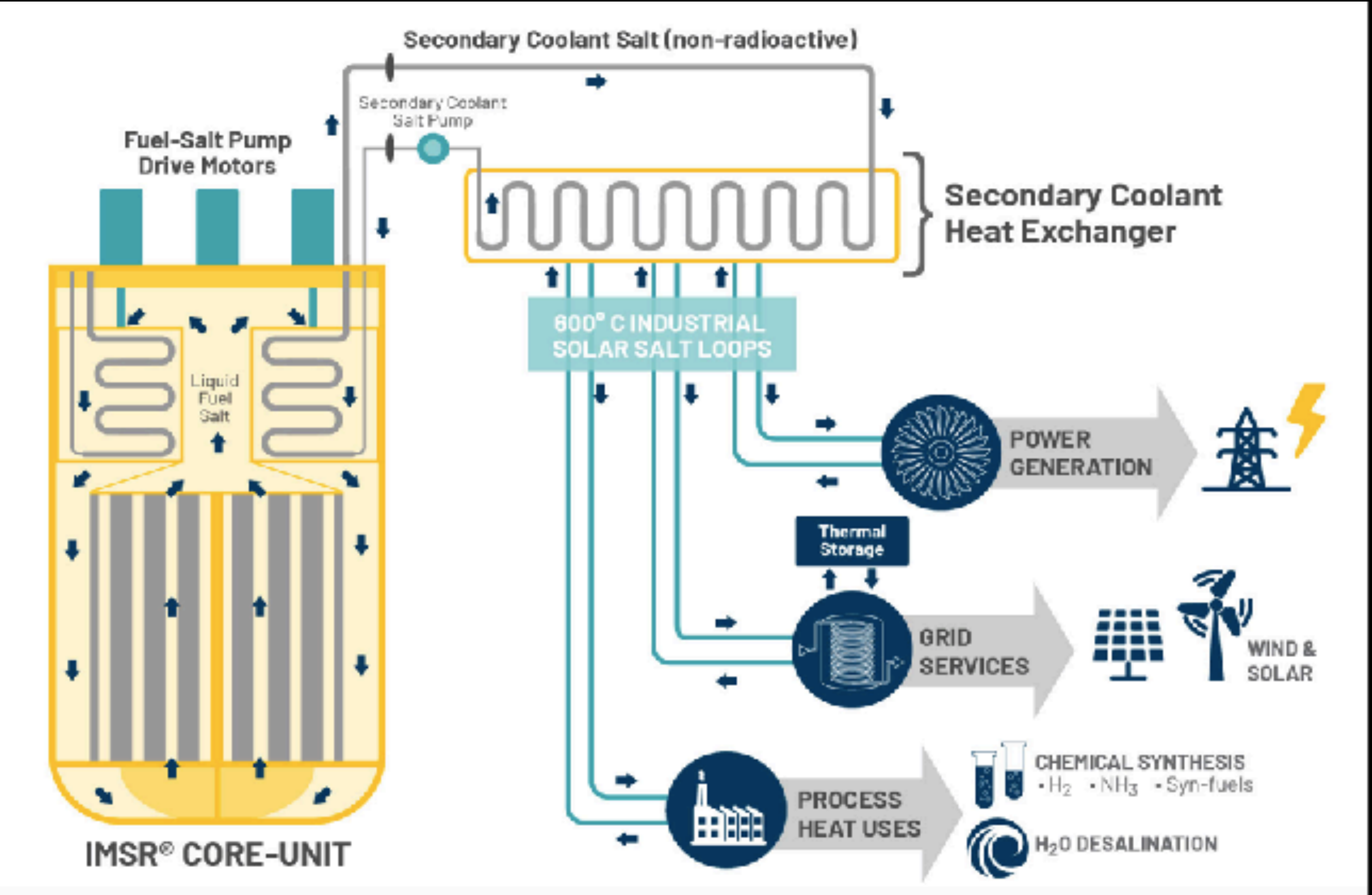
There is an urgent need to have safer, more efficient designs available as soon as the oldest of our fleet of mostly 2^{nd}-generation reactors are decommissioned.

AN ECONOMIC RESCUE?

- ***NuScale*** is a Small Modular Reactor (SMR) that might occupy the niche of III+ to save the beleaguered nuclear industry until Gen IV reactors enter the market.



TERRESTRIAL IMSR



The fight to rethink (and reinvent) nuclear power

MORE INFORMATION NEEDED?

- www.thoriumenergyalliance.com
- www.world-nuclear.org
- www.rethinkingnuclear.org