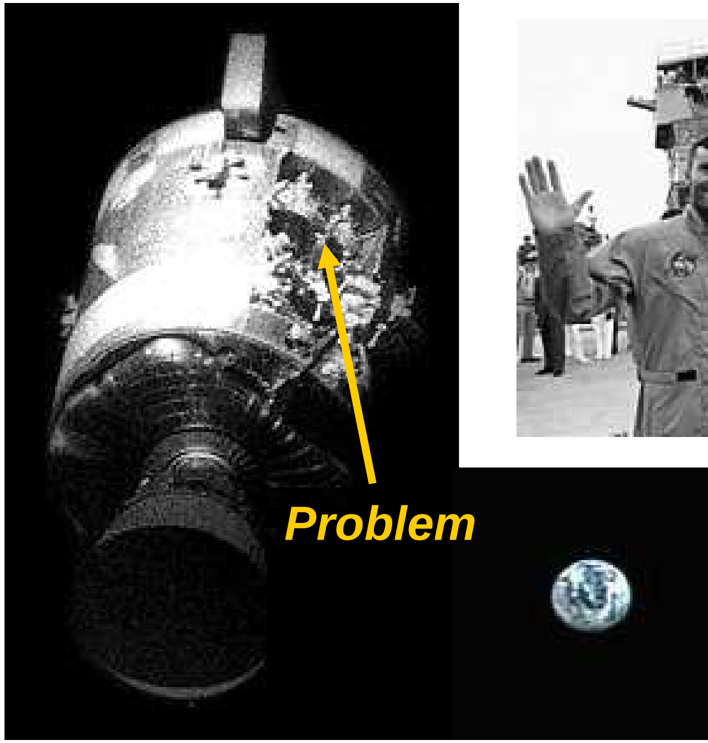
Safe Nuclear Energy

(15 Nov 2012, Lockheed ATC, 6 Feb 2013 EDF, 18 Apr OAEP, 8 May ASM, 7 Oct SRI)

"Let's work the problem.
Let's not make things worse by guessing."

Eugene Kranz, Apollo 13 Flight Director, April 1970.



Result

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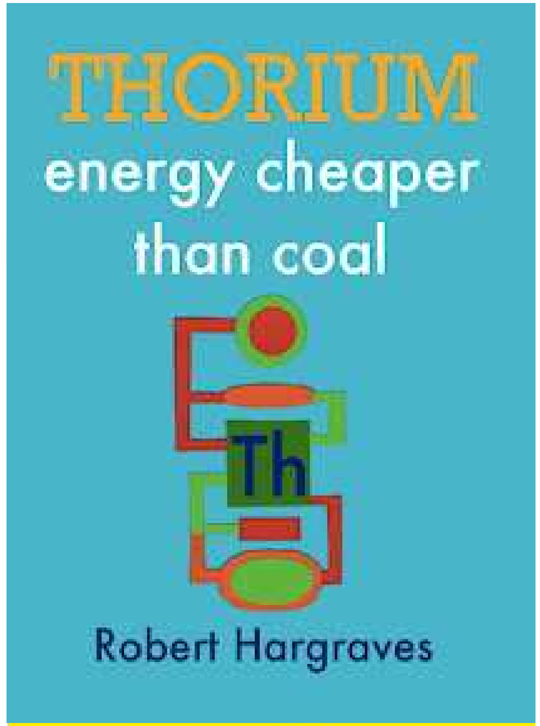
Thorium-Based Molten-Salt Reactors

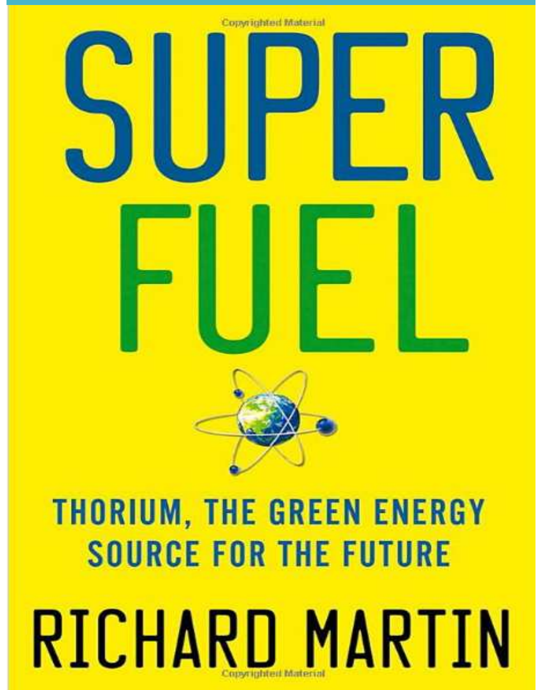
- Thorium is far more common & cheaper than Uranium...
  - **No 'enrichment'** $ or energy wasted – ^{232}Th is just a metal common in "rare-earth" ores.
  - **All Thorium is consumed** – no 'spent' fuel (>90% of BWR/PWR Uranium goes unused).
- Thorium-Fluoride salt is the 'fertile fuel' input (ThF_4 MSR -- LFTR)…
  - Exceedingly stable inexpensive salt, of **no weapons value**.
  - **No refuelling shutdowns** needed, **no excess fuel** in core.
  - ^{232}Th is neutron-bred in core to ^{233}Uranium within the molten salt – **no external fissiles after startup**.
  - ^{233}U fissions better than higher U isotopes, so **far less Actinide waste**.
- <u>MSRs automatically throttle</u> via thermal expansion of salt…
  - As thermal load changes, **fission rate tracks salt density**.
  - **No runaway or 'meltdown'** -- salts are radiation stable, gravity removes melt from core.
- MSRs have higher temp & power density so ~30% <u>better thermal efficiency</u>
  - ~1000^{o}C **unpressurized** temp range from solid to vapor – water only has 100C.
  - De-commissioned BWRs/PWRs can become ~3x more potent MSR/LFTRs.
  - Gas (Brayton) or steam-turbine cycles possible – **no water needed for cooling.**
- MSRs <u>can</u> <u>consume existing BWR/PWR fissile/fertile wastes</u>...
  - Typical **wastes** from a 1GWe LFTR, over 30 years, is under 100lbs (<1/2 cubic foot).
  - A 1GWe LFTR makes 1/1000 the Plutonium of a BWR/PWR & MSR can consume that.
  - **Reduction of wastes onsite**, down to whatever low level is desired – **no 'spent' fuel**.
- MSRs have <u>no expensive control/containment</u> or emergency systems.
  - **LFTR cost ~$3/Watt** (far less than current ^{235}U LWRs) – **less than coal**.
  - **Scalable** from 1MW to multiple GW – siting anywhere on Earth or in space.
  - Initial working MSR was for the 1960s DoD Atomic Plane – had to be **small & safe**.

"I'm sure you're a nice man, but I'm not interested in hearing about Thorium."

See movie "Pandora's Promise"
http://pandoraspromise.com/
by Richard Stone

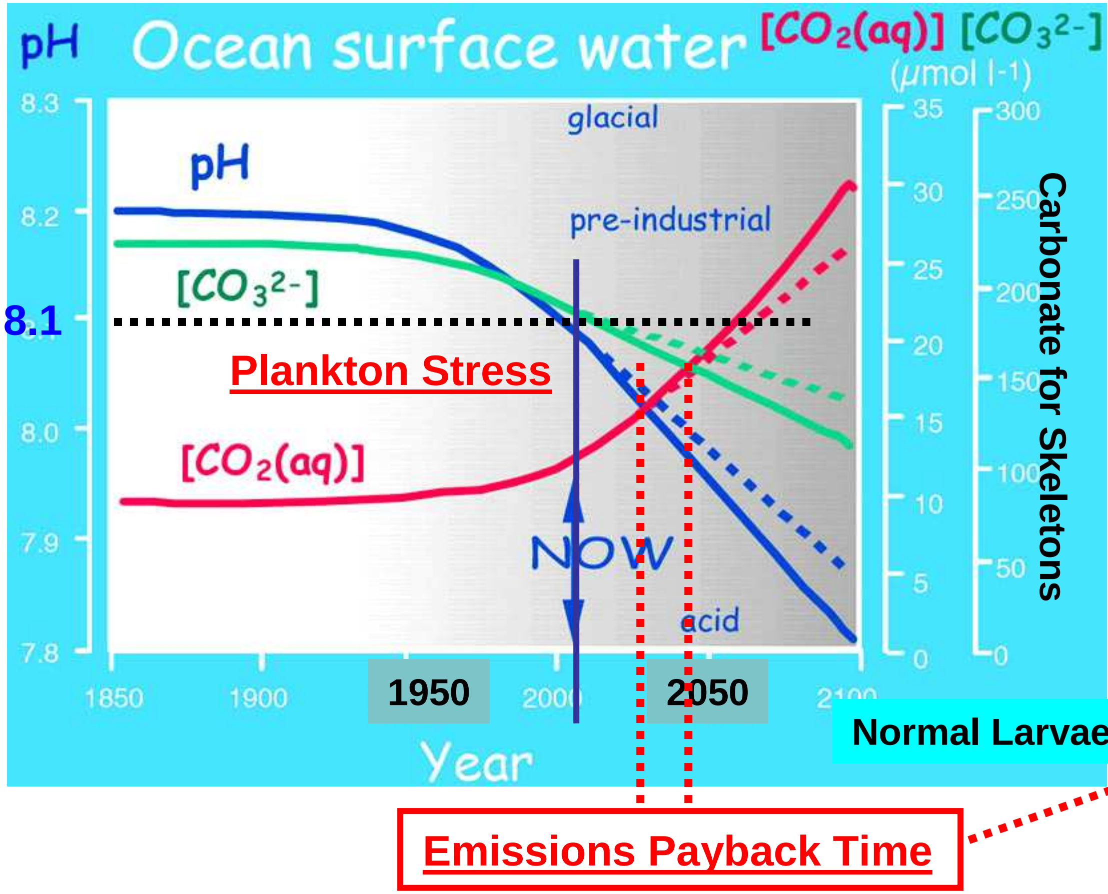
https://www.youtube.com/watch?v=nQpuGwWyFQ0

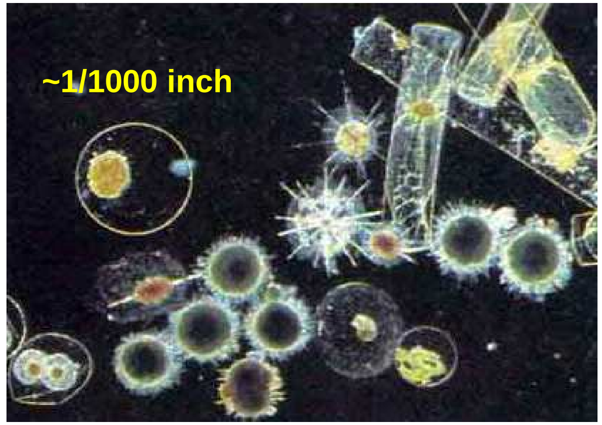


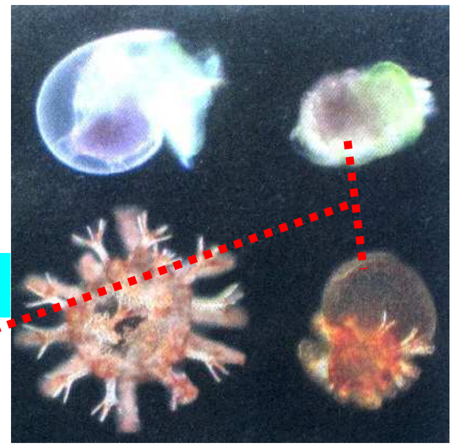


Why? -- Emissions Effects

~40% of all CO_2 emissions are now in oceans creating more acidic seawater, preventing plankton growth, affecting entire sea food chain --- <u>sea life provides 20% of human food protein</u>…

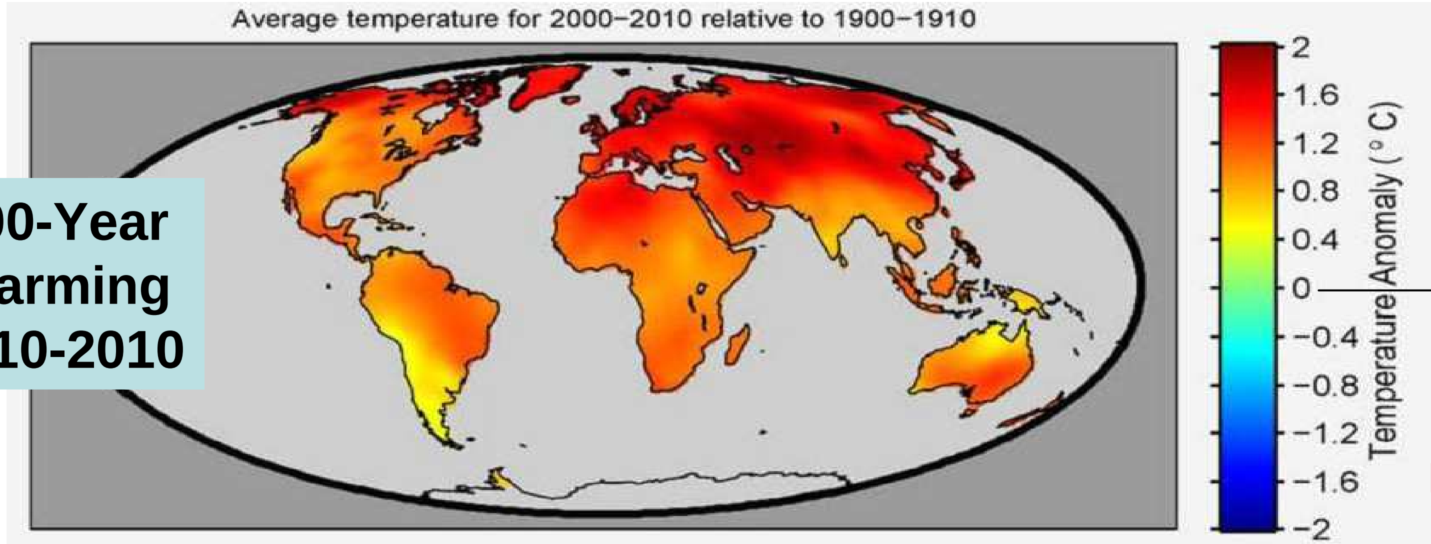






http://tinyurl.com/m6gvgp4 (2013)

Emissions Effects – Land & Sea

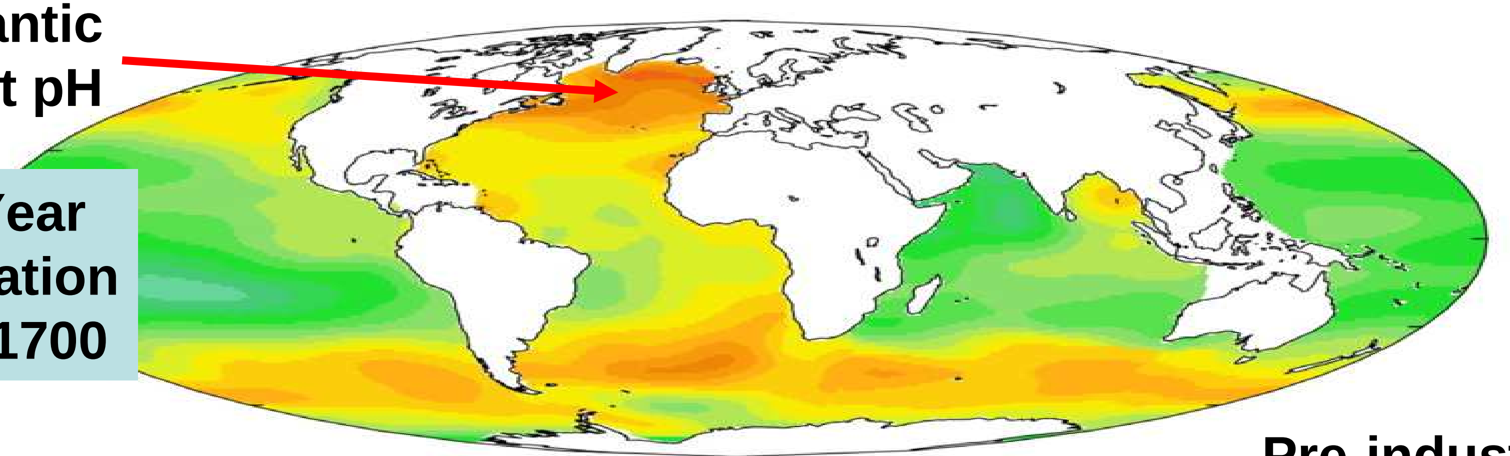


100-Year Warming 1910-2010

Hotter

>10,000-Year Holocene Range

N. Atlantic Worst pH



~300-Year Acidification From ~1700

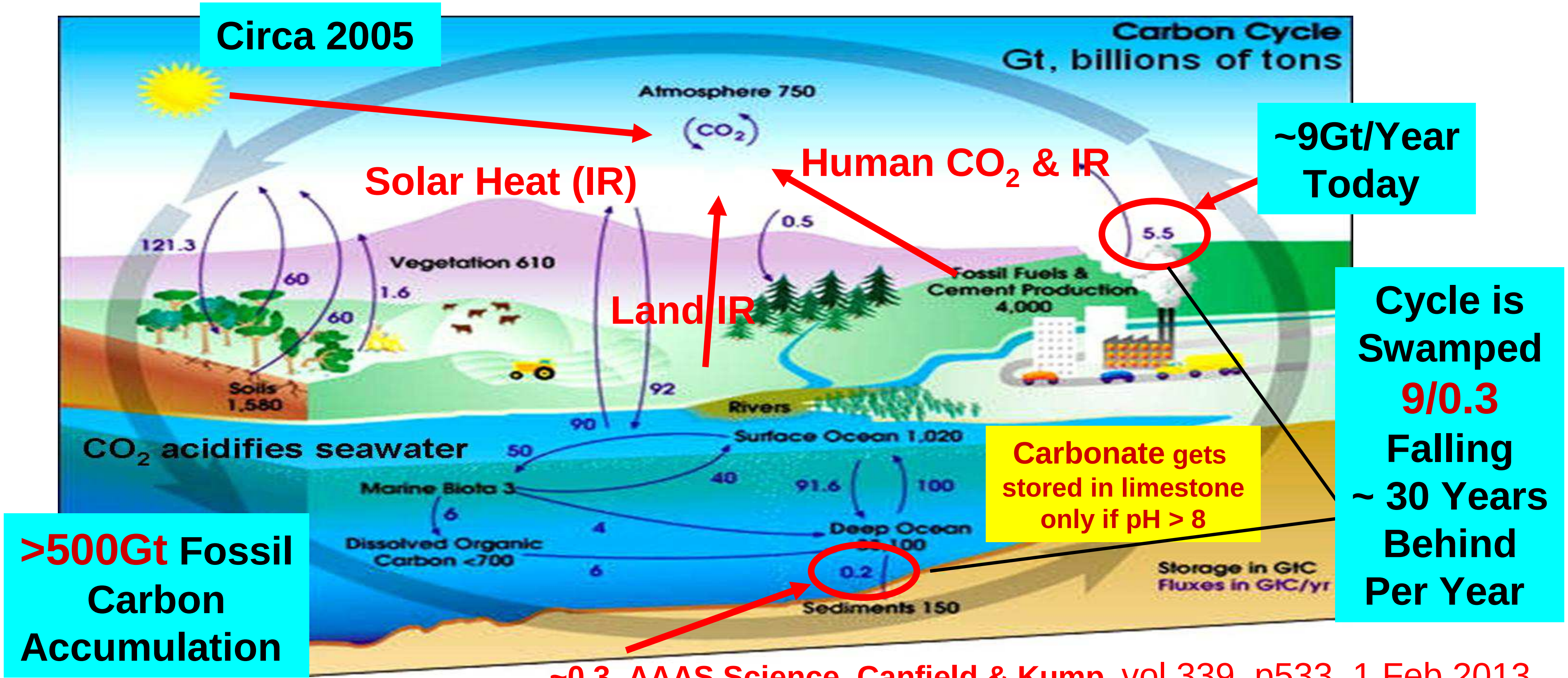
Today ~8.1 (lowest in >200,000,000 years)

Pre-industrial ~8.2 pH

The Carbon Cycle (**3 Numbers**)

Cyanobacteria, plankton & algae produced most of the Oxygen we have to breathe & use, starting ~2 billion years ago, with the earliest photosynthesizing ocean life. Land plants later evolved & helped. All fossil fuels we dig up were made this way. Carbon emissions today are **~9Gt** (>30Gt CO_2)

www3.geosc.psu.edu/~jfk4/PersonalPage/Pdf/annurev_03.pdf http://tinyurl.com/m6gvgp4
www.atmo.arizona.edu/courses/fall07/atmo551a/pdf/CarbonCycle.pdf
www.annualreviews.org/doi/abs/10.1146/annurev.earth.031208.100206?journalCode=earth



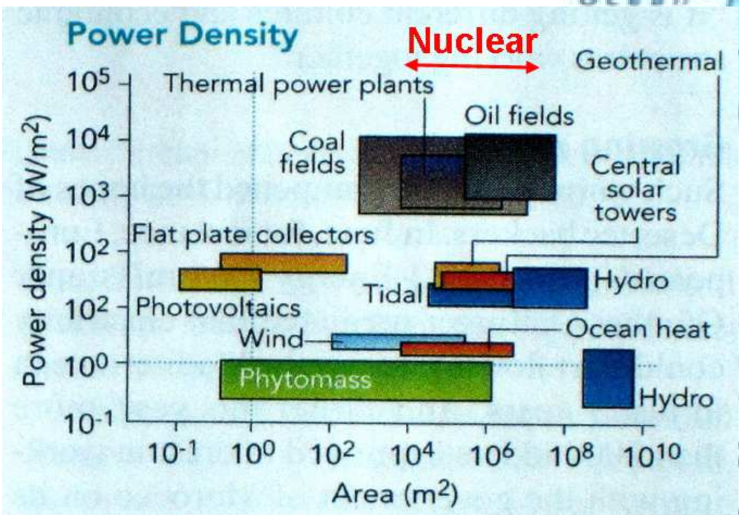
~0.3, AAAS Science, Canfield & Kump, vol 339, p533, 1 Feb 2013

Areas Needed to Replace US Fossil Fuels

Area Needed for Nuclear* •

Area Needed for Solar PV*
(Wind is much larger)

*** All mining, construction, power & vehicular uses included in nuclear & solar.**



It takes ~100 times more water to produce 1 gal of 'biofuel' than to produce 1 gal of diesel

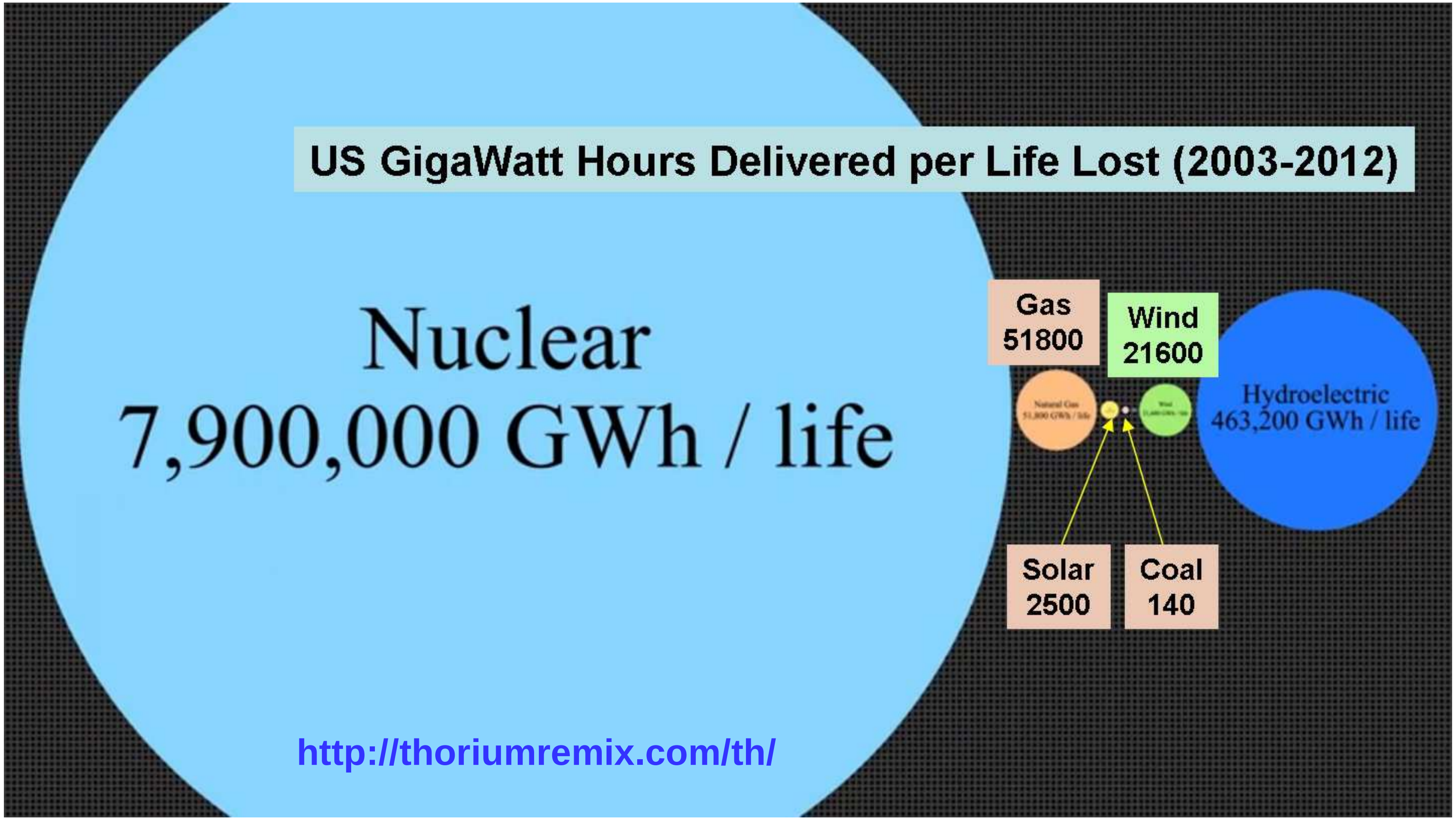
10^{13} J/kg

Combustion	Fission	Fusion

~10kWattHr/lb *x500,000* → **>3GWHr/lb** *x100* → **>10^{11} WHr/lb**

Nuclear Power Safety

Present Civilian & Naval Nuclear Power is the Safest Form of Power Generation Ever Deployed by Humanity: http://tinyurl.com/42wvr9l **(1998)**
www.scientificamerican.com/article.cfm?id=the-human-cost-of-energy **(2013)**



Relative Power Dangers

PAUL SCHERRER INSTITUT PSI

The Energy Departments
Laboratory for Energy Systems Analysis
Technology Assessment

Severe accidents with at least 5 fatalities (1970-2005)

	OECD		EU 27		non-OECD	
Energy chain	Accidents	Fatalities	Accidents	Fatalities	Accidents	Fatalities
Coal	81	2123	41	942	144 1363 (a)	5360 24'456 (a)
Oil	174	3388	64	1236	308	17'990
Natural Gas	103	1204	33	337	61	1366
LPG	59	1875	20	559	61	2636
Hydro	1	14	1	116 (b)	12	30'007 (c)
Nuclear	—	—	—	—	1	31 (d)

(a) First line: coal non-OECD without China; second line: coal China
(b) Belci dam Romania (1991)
(c) Banqiao and Shimantan dam failures alone caused 26'000 fatalities
(d) Latent fatalities treated separately

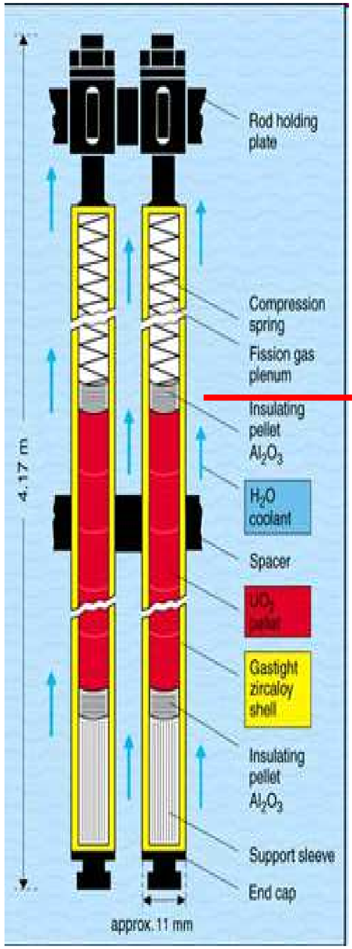
Burgherr & Hirschberg, 2008

IDRC, 25 – 29 August 2008, Davos, Switzerland

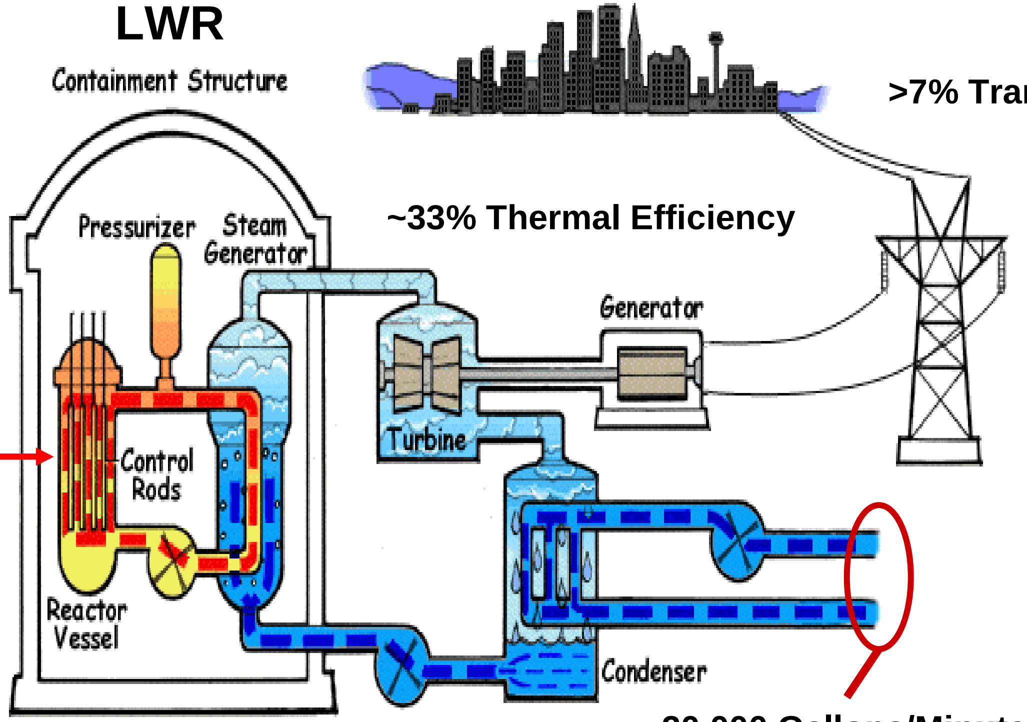
OECD = Organisation for Economic Co-operation and Development

$^{235/238}$Uranium Light-Water Reactors

Fuel Rods



LWR



>7% Transmission Loss

Must Contain 60-160 Atmospheres (>900psi) of Pressure in Event of Reactor Runaway

~20,000 Gallons/Minute To/From Cooling Tower, Lake or Sea

www.thoriumremix.com/2011

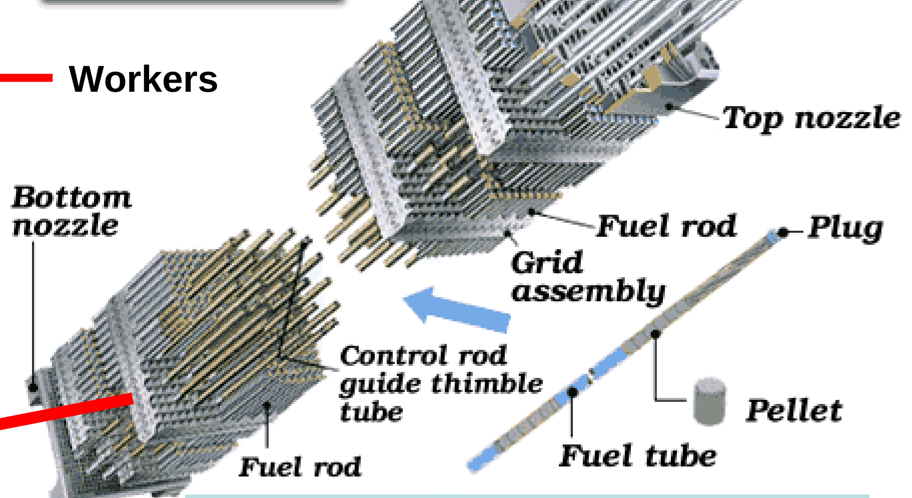
11/30/2011, Dr. A. Cannara; cannara@sbcglobal.net

$^{235/238}$Uranium Light-Water Reactors

2 types: Pressurized-Water (PWRs) & Boiling-Water Reactors (BWRs)

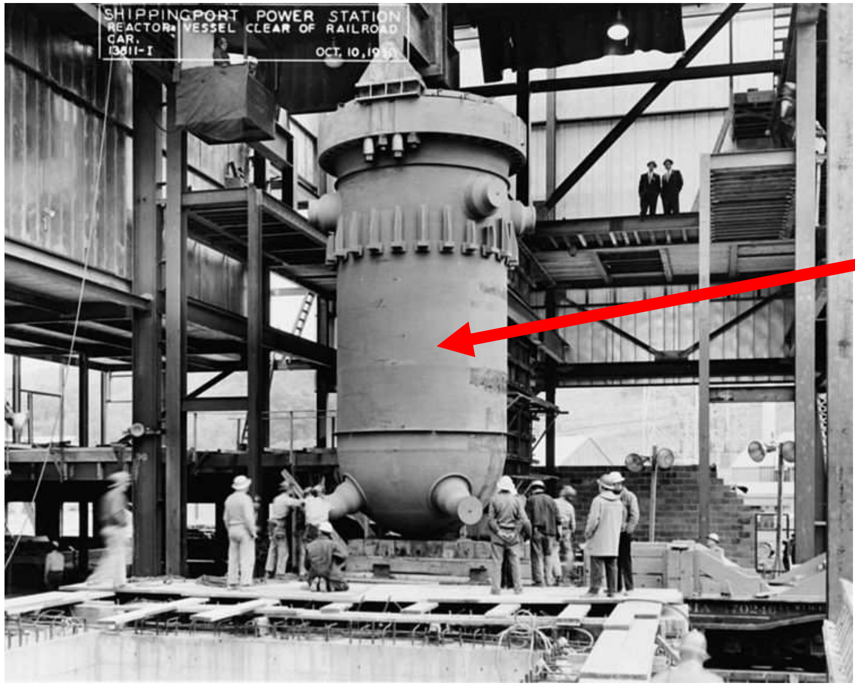
Modern U235/238 Centrifuge

Workers



Fuel Centrifuge-Enriched to ~4% ^{235}U

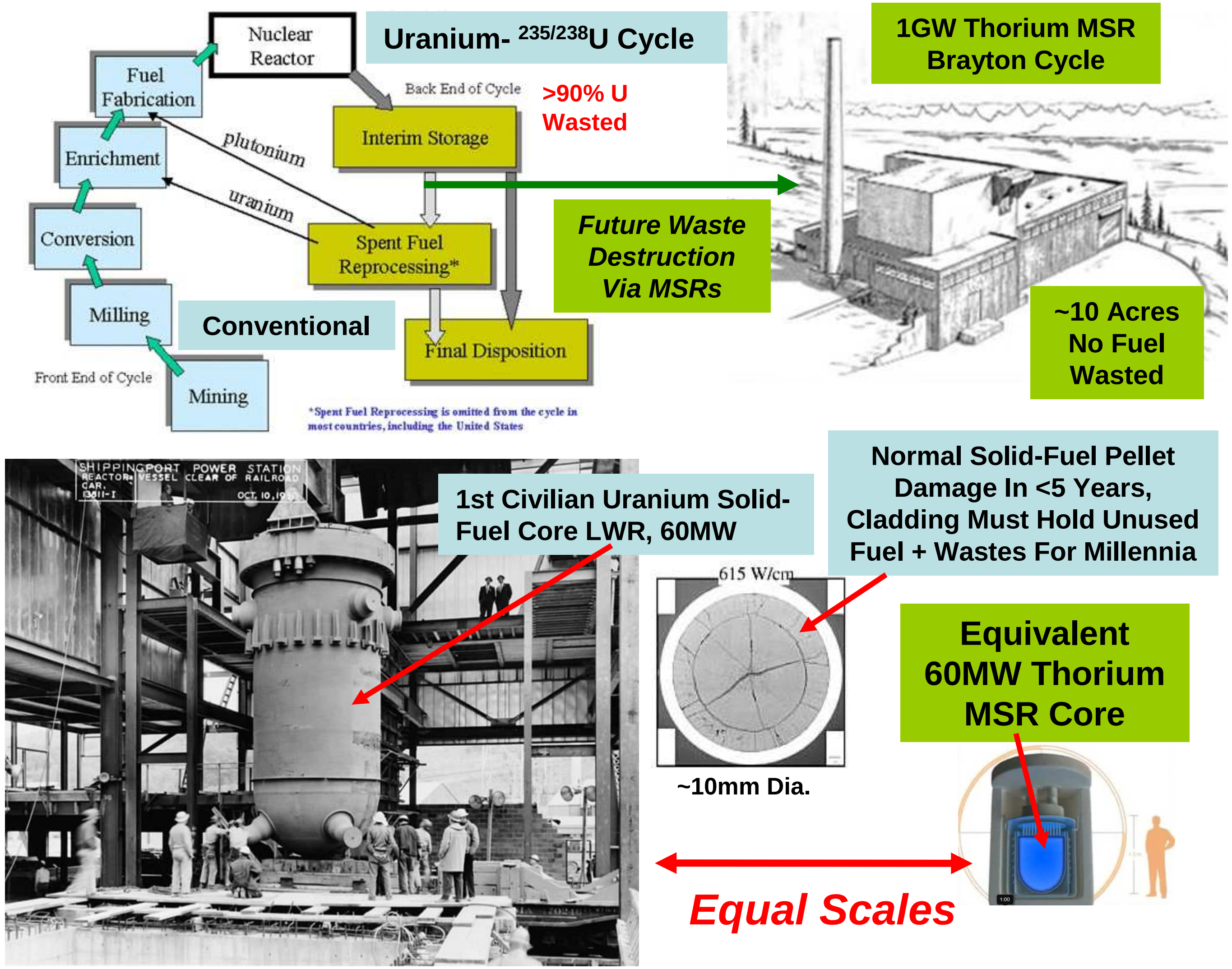
First Commercial US Reactor (60MW)



Shippingport, Penn, 1954-56

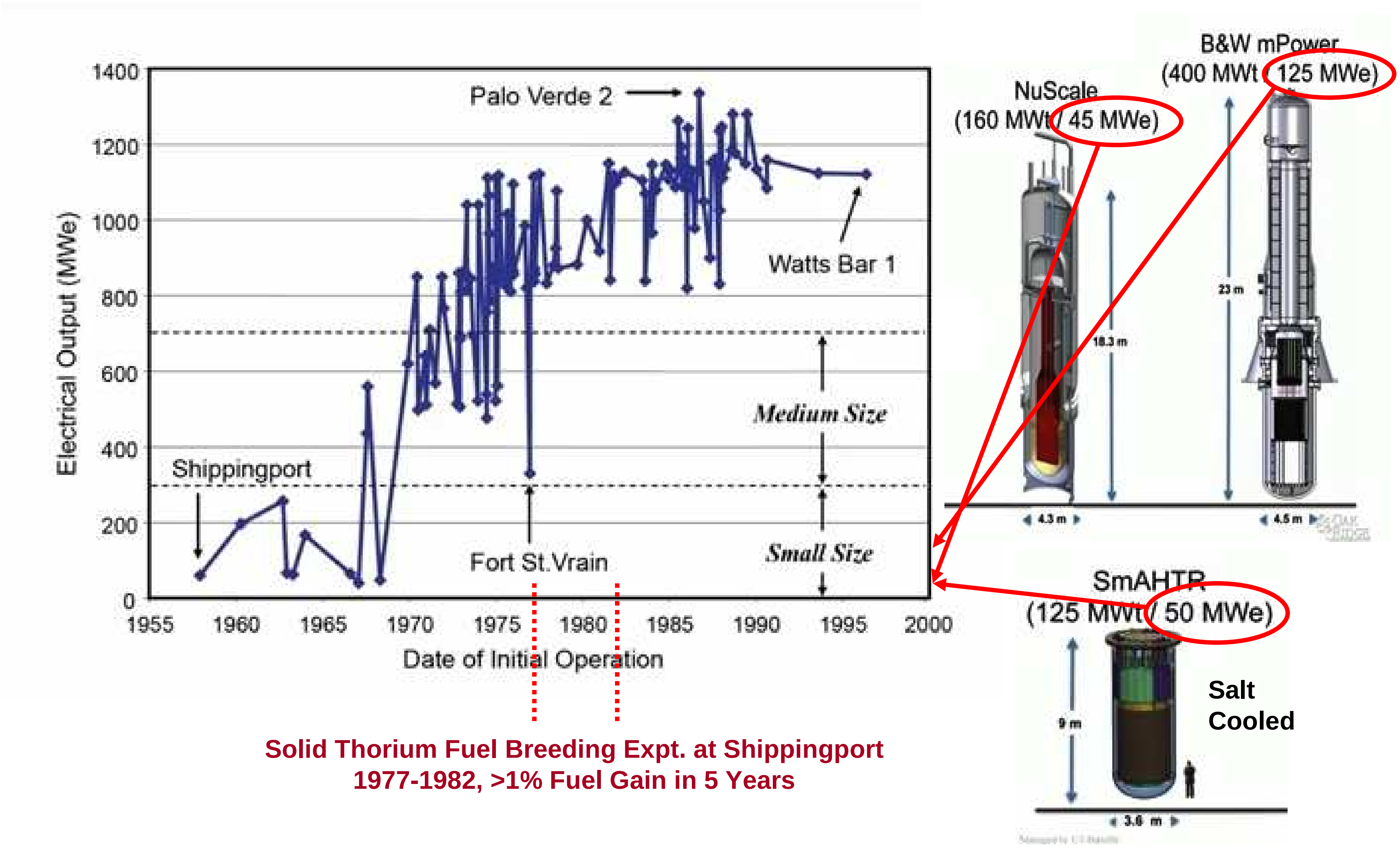
Modern Fuel Assemblies. Only ~4% of Uranium is fissioned before rods must be removed & stored or reprocessed – ~200 tons Uranium needed per GWe-Year.

MSR Versus LWR



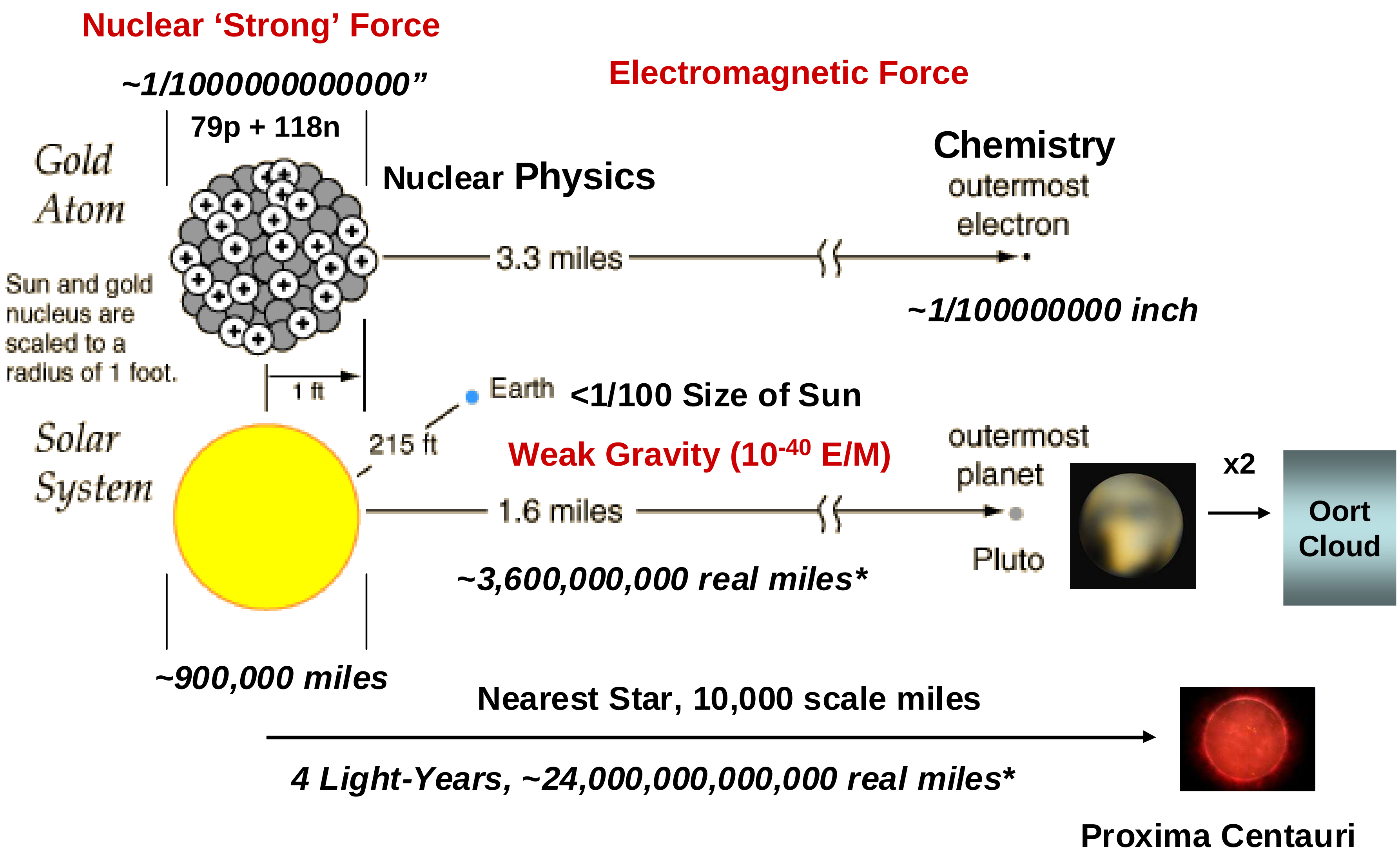
General MSR design: http://tinyurl.com/8xmso5v

$^{235/238}$Uranium Light-Water Reactors

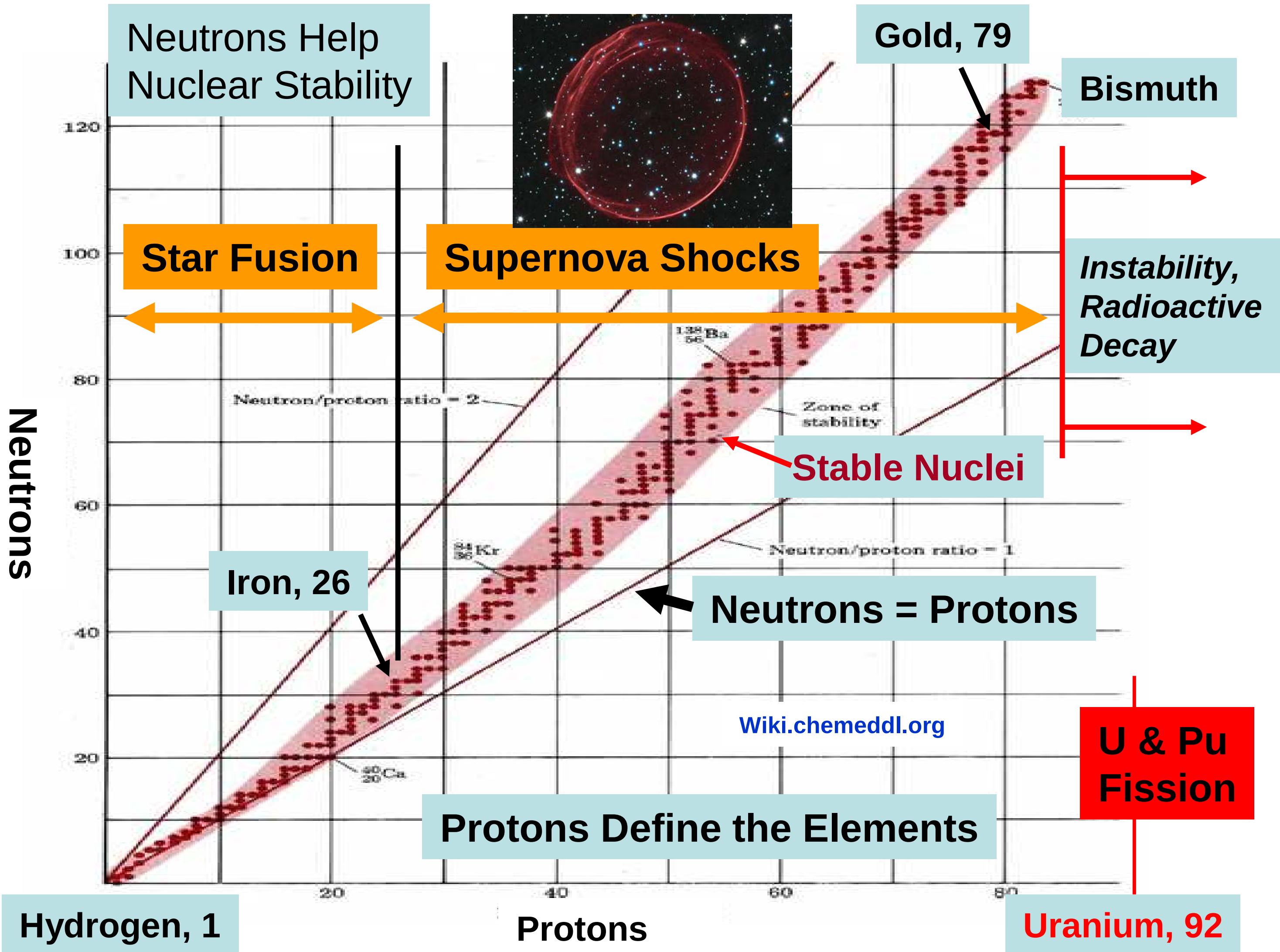


Solid Thorium Fuel Breeding Expt. at Shippingport
1977-1982, >1% Fuel Gain in 5 Years

Scales of Reality



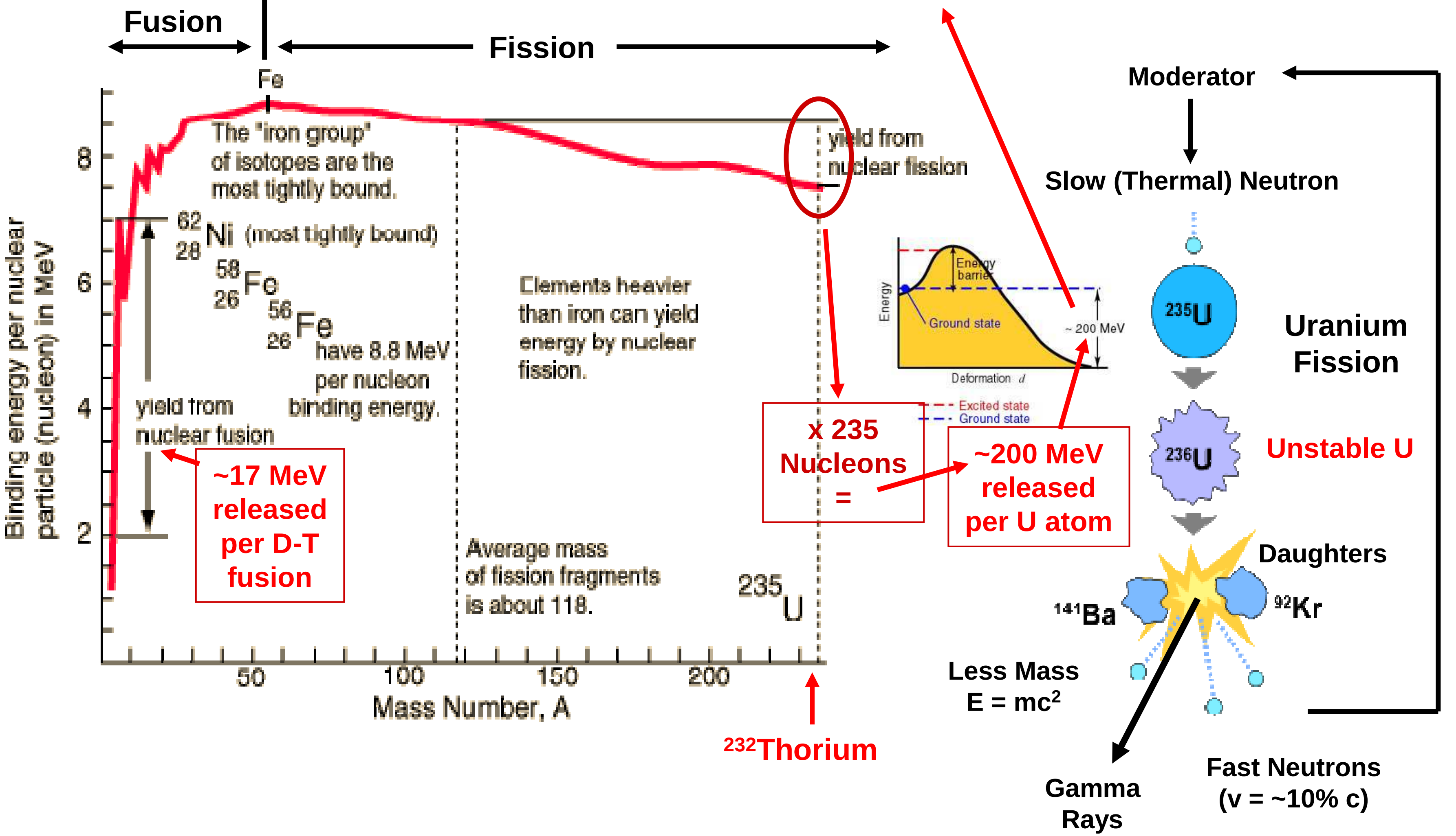
Elements & Origins



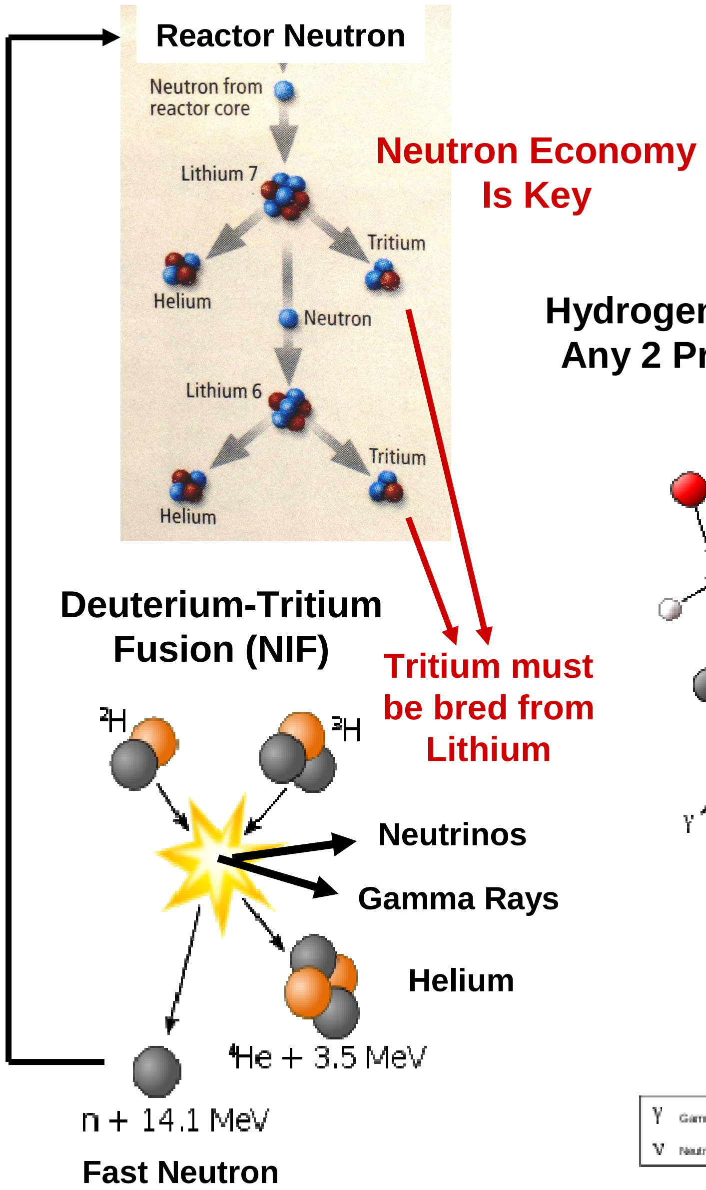
Nuclear Energy

602000000000000000000000 (atoms/mole) x 200000000 (eV/atom)
6250000000000000000 (eV/Joule) x 3600 (Joule/WattHr)

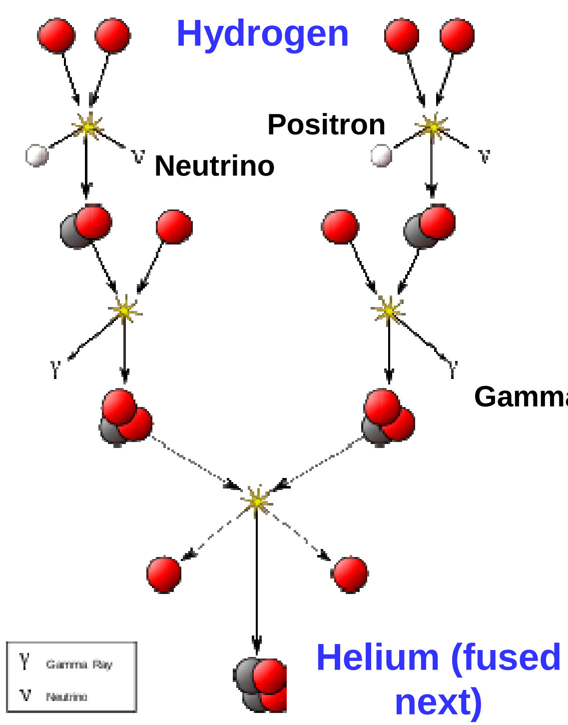
~ 5GWHr/mole



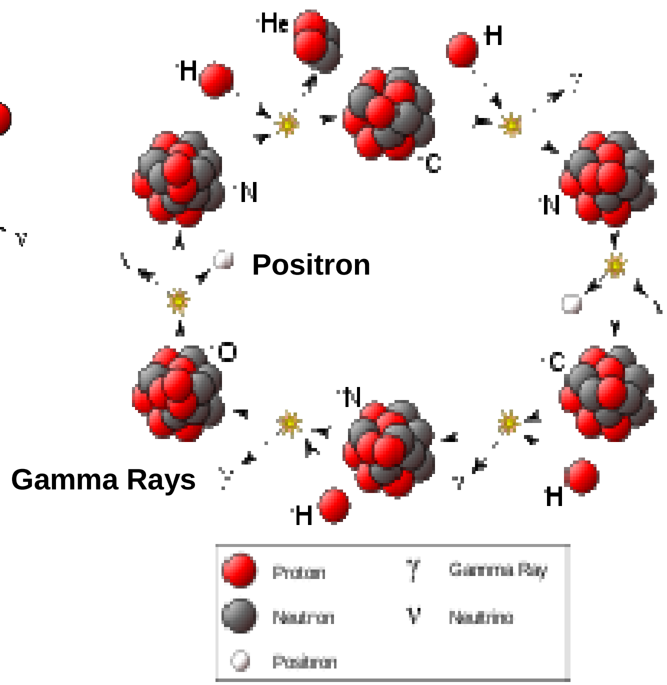
Fusion



Hydrogen-Hydrogen Fusion (Our Sun)
Any 2 Protons Take ~8 billion Years Before Fusing



Carbon-Nitrogen-Oxygen Fusion Cycle (big stars)



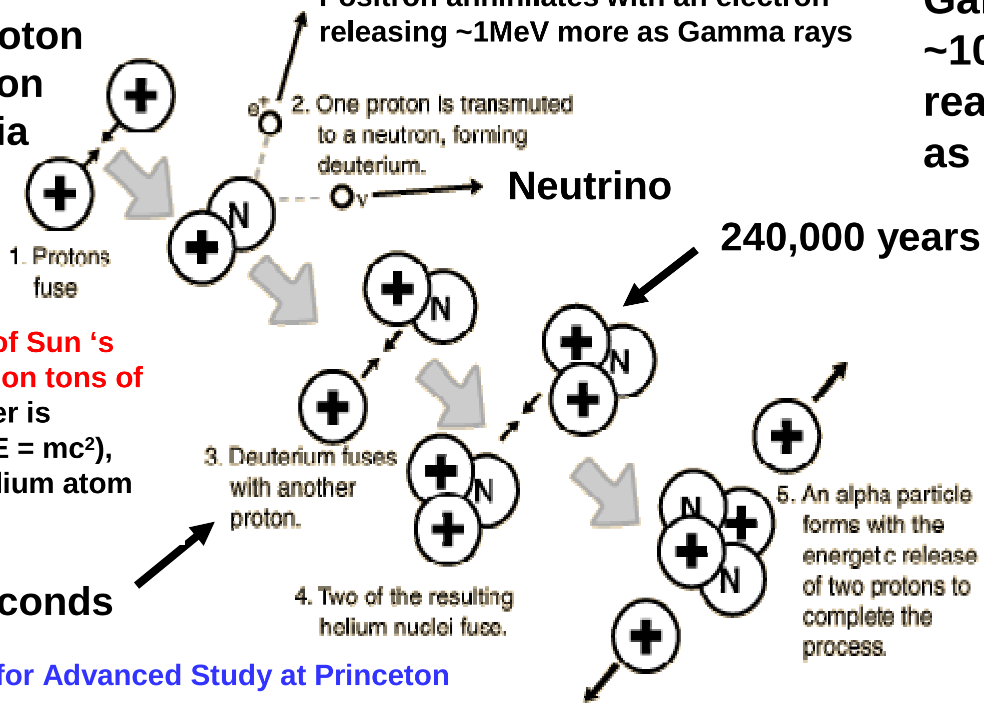
Natural Radiation – Solar Fusion

Sun's energy density is low – about ¼ that of a resting human's body heat: 260uW/cm3) -- lower than a candle's -- why it's been around for over 4 billion years, turning Hydrogen into Helium, then Beryllium, plus neutrinos and gamma rays (light).

Sun's average proton pair waits ~8 billion years to fuse & via this chain, emit ~27 MeV

Positron annihilates with an electron releasing ~1MeV more as Gamma rays

Gammas take ~10^6 years to reach surface as light



Neutrino

240,000 years

Each second, 600 million tons of Sun 's Hydrogen fuse to form 596 million tons of Helium -- 4 million tons of matter is converted into 3.9x10^{26} Watts ($E = mc^2$), which is just 1 picoWatt per Helium atom produced.

< 2 seconds

Next is $_4$Be ~10^6 years

Courtesy Wikipedia & Institute for Advanced Study at Princeton

~10^7 Joule/kg | >10^{13} J/kg | ~10^{15} J/kg

Combustion | **Fission** | **Fusion**

~10kWattHr/lb *X>500,000* → **~3GWHr/lb** *x100* → **~10^{11} WHr/lb**

Fission Choices

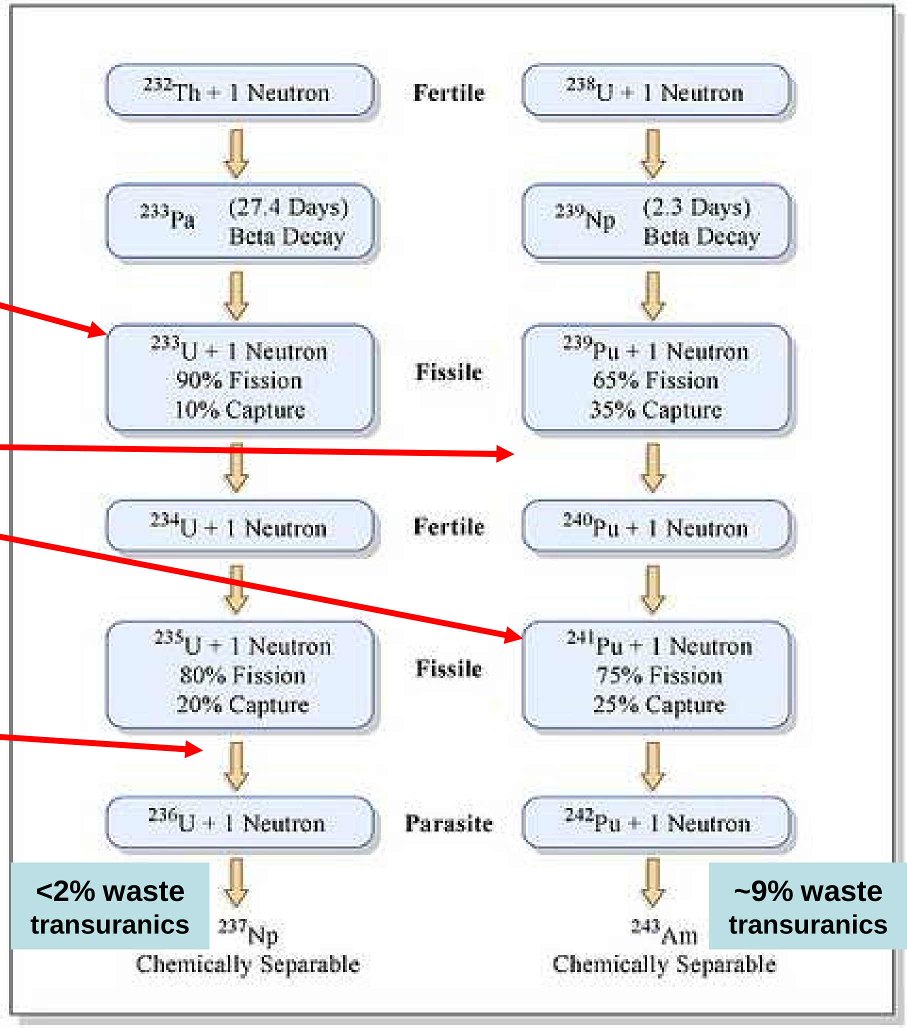
Thorium bred to ^{233}U with a neutron (via Protactinium decay), or via proton-beam spallation

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>

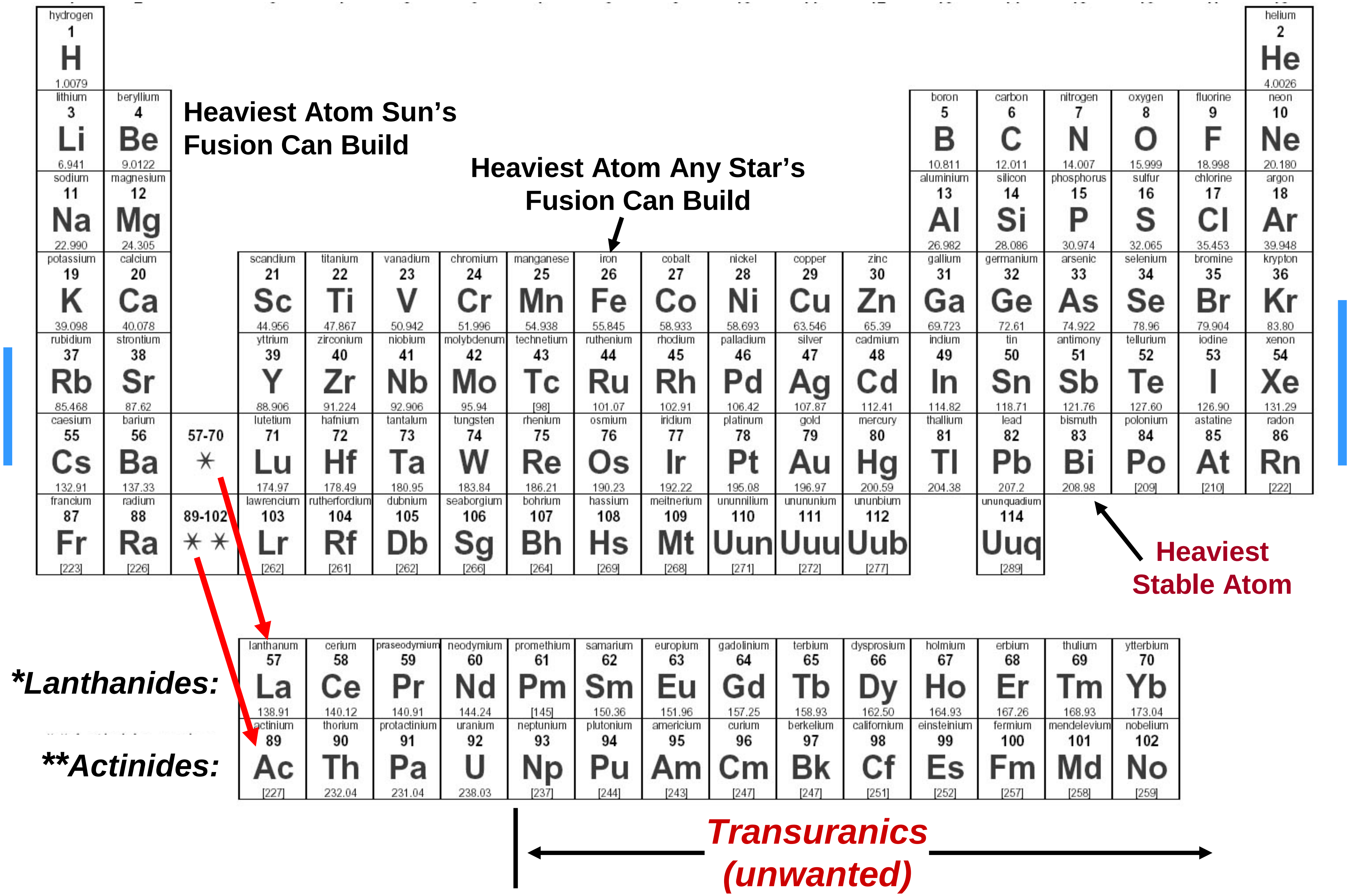
Because Thorium starts at mass 232 & neutron captures rarely exceed 236 (< 20% of 10% = 2%), ^{238}U & Pu are rarely produced, but are consumed if fissile

Graphics Courtesy of Wikipedia

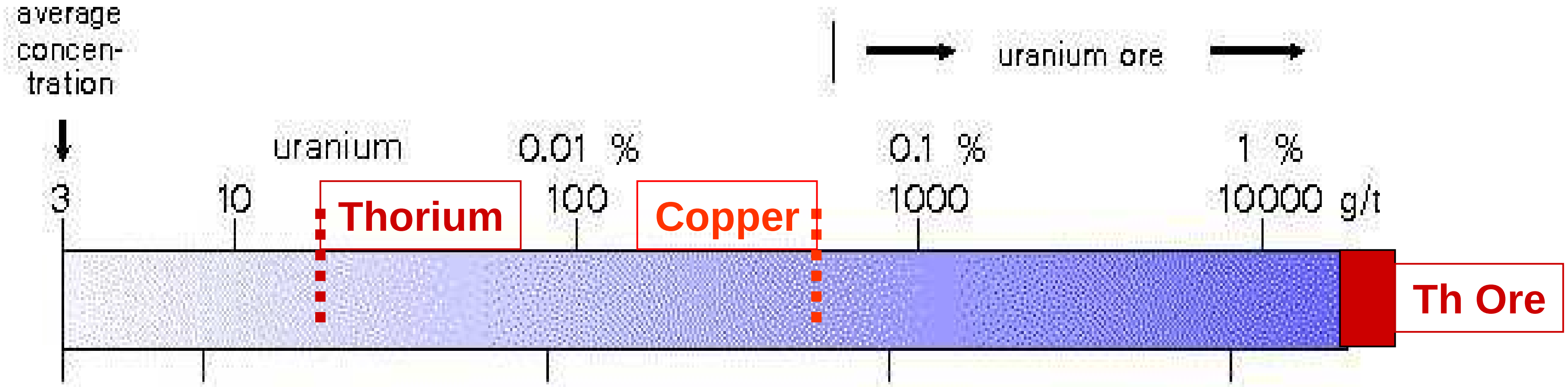
Starting Fission with Thorium vs ^{238}Uranium

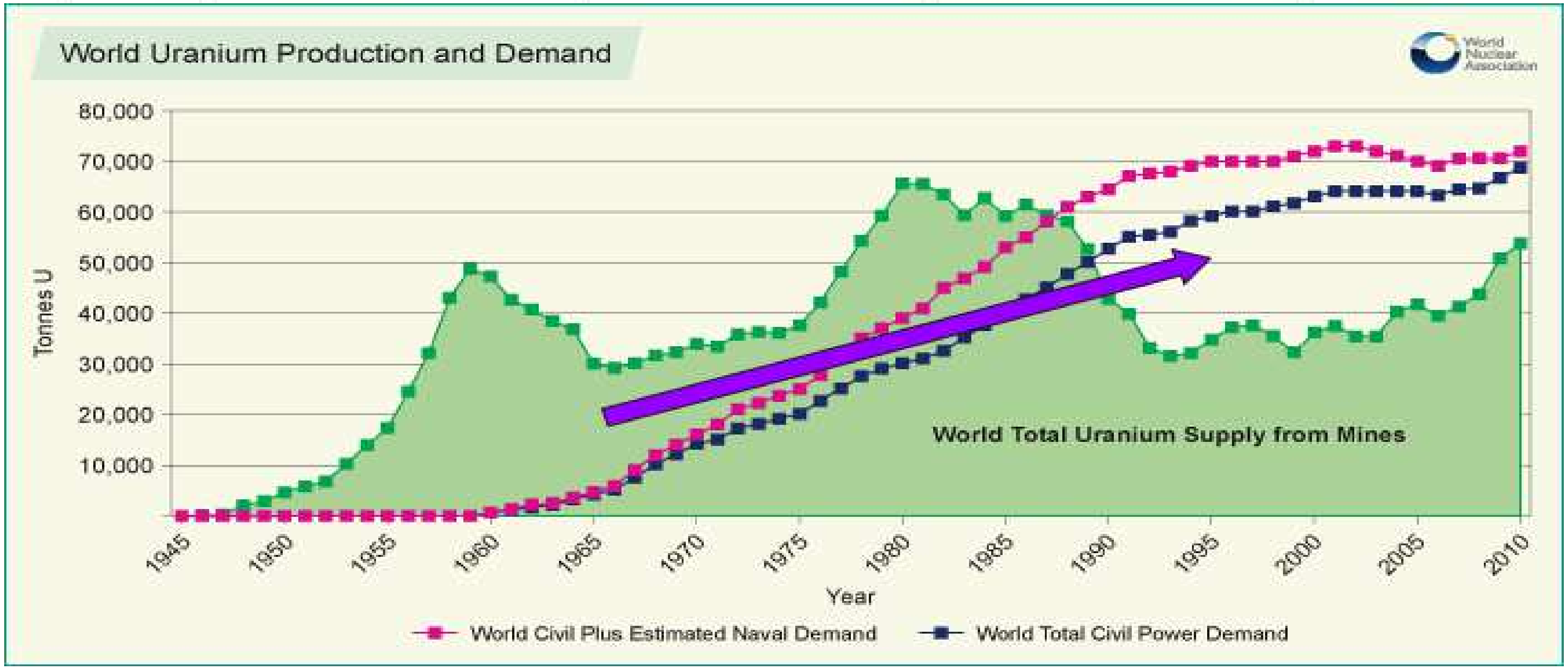


The Elements

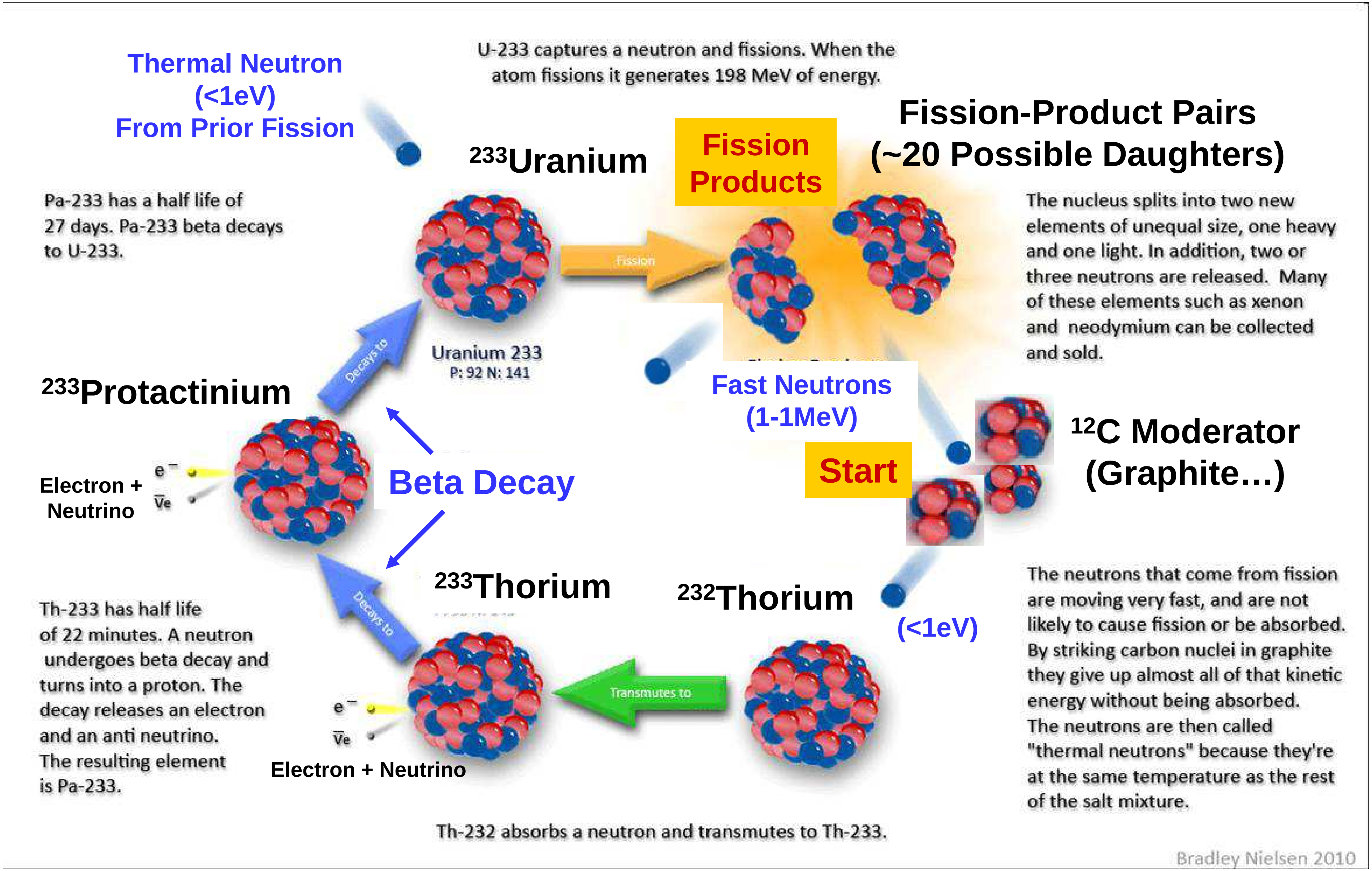


Uranium Concentrations in Rock





Thorium Breeding Cycle



Thorium Abundance

Rare Earth Distributions | By Mineralization

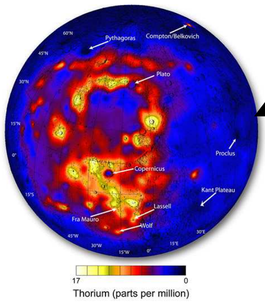
Distribution of rare earth elements in selected rare earth deposits (USGS).
*Pea Ridge RE resources: Breccia Pipes (primarily Monazite / limited Xenotime).
**Rare Earth Enriched Apatite (Monazite / Xenotime), a no cost byproduct of iron ore mining.

	Mt. Pass Bastansite	China Byan Obo	HRE-China Laterite	Selected Monazite	Pea Ridge* Breccia	Pea Ridge** RE-Apatite
Lanthanum	33.8	27.1	1.8	17.5	27.5	18.6
Cerium	49.6	49.8	0.4	43.7	38.8	34.6
Praseodymium	4.1	5.15	0.7	5.0	4.4	3.5
Neodymium	11.2	15.4	3.0	17.5	15.4	12.7
Samarium	0.9	1.15	2.8	4.9	2.1	2.5
Europium	0.1	.19	0.1	0.2	0.3	.3
Gadolinium	0.2	0.4	6.9	6.6	1.5	2.8
Terbium	0.0	0	1.3	0.3	.27	.5
Dysprosium	0.0	0.3	6.7	0.9	1.5	2.8
Holmium	0.0	0	1.6	0.1	.28	.5
Erbium	0.0	0	4.9	Trace	.81	1.8
Thulium	0.0	0	0.7	Trace	.13	.2
Ytterbium	0.0	0	2.5	0.1	.96	1.5
Lutetium	Trace	0	0.4	Trace	0.1	.2
Yttrium	0.1	0.2	65.0	2.5	5.7	17.5
Percent Heavy	**.1%**	**.5%**	**83.1%**	**3.9%**	**9.7%**	**25%**
RE Occurrence in Ore	8%	5%	.2%	10 to 15%	12%	1.4%
Percent Thorium	.1%	.3%	>.1%	4 – 12%	3.5%	> 1%

Heavy Lanthanides

Courtesy Wings/Pea-Ridge

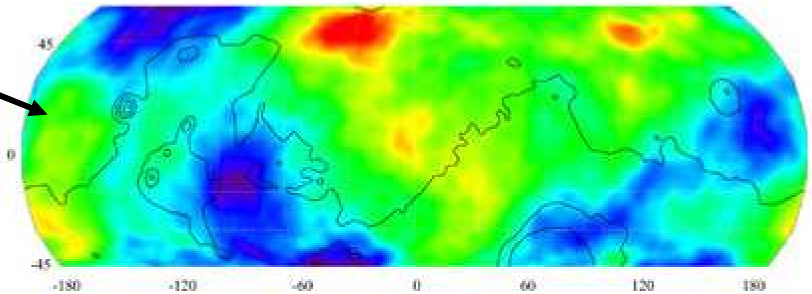
In order of Geologic Occurrence – Bastansite, Monazite, HRE Laterite



Th on

Moon

Mars



MSR/MSBR/LFTR History

What we were supposed to be doing by 2000

In 1962, President Kennedy requested an AEC <u>civilian power study</u>… *"**Your study should identify the objectives, scope and content of a nuclear power development program, in light of the nation's prospective energy needs and resources…recommend appropriate steps to assure the proper timing of development and construction of nuclear power projects**, including the construction of necessary prototypes."*

The AEC report concluded… **http://tinyurl.com/6xgpkfa** *"The overall objective of the [Seaborg] Commission's [AEC's] nuclear power program should be to foster and support the growing use of nuclear energy and…**make possible the exploitation of the vast energy resources latent in the fertile materials, uranium-238 and thorium."***

Why did we fail?... *"…[enriched, natural U] **pressurized water had been chosen to power submarines** because such reactors are compact and simple. Their advent on land was entirely due to Rickover's dominance in reactor development in the 1950s, and once established, the light-water reactor could not be displaced by a competing reactor. **To claim that light-water reactors were chosen because of their superior safety belied an ignorance of how the technology had actually evolved… Although the AEC established an office labeled 'Fast Breeder,' no corresponding office labeled 'Thermal Breeder' was established**." (A. Weinberg,1994).*

AEC Reactor Engineering Director, Shaw, a protégé of Adm. Rickover, but saw only the solid-fuelled, water-cooled designs used by the Navy as worthwhile. He asked MSR & MSBR engineers to "clear their desks into their wastebaskets" when '70s funding died: **http://tinyurl.com/al5hlap** especially due to Nixon: **http://tinyurl.com/73p7ler**

Aircraft Reactor Experiments

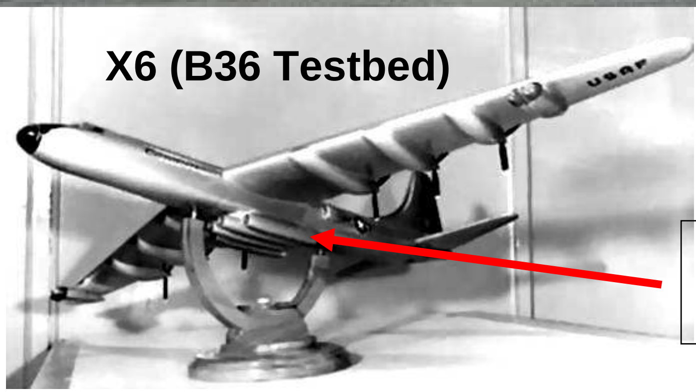
HTR-1 was operated for >5 GWHrs.

ORNL ARE (1954-56)

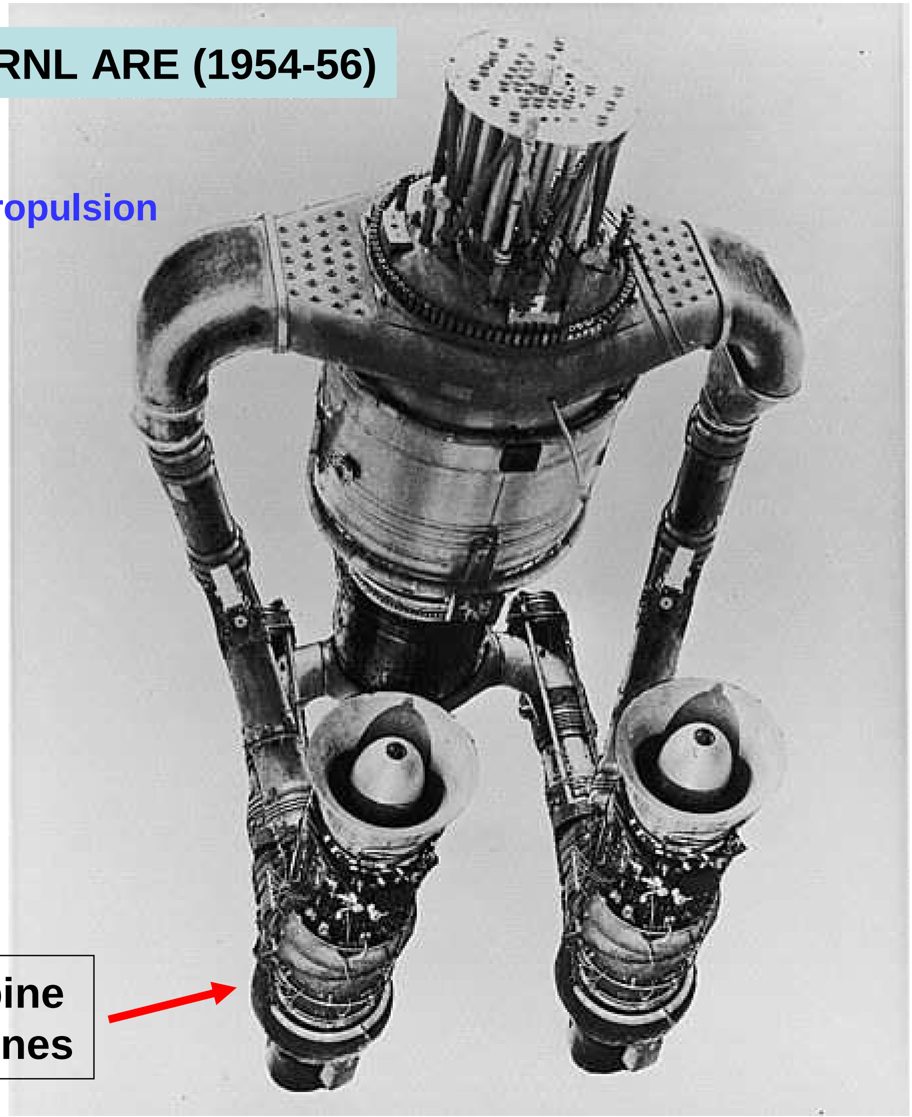
Salt: Sodium, Ziconium, Uranium Fluorides
http://en.wikipedia.org/wiki/Aircraft_Nuclear_Propulsion

INL NEPA, ANP (1946-1951)

X6 (B36 Testbed)



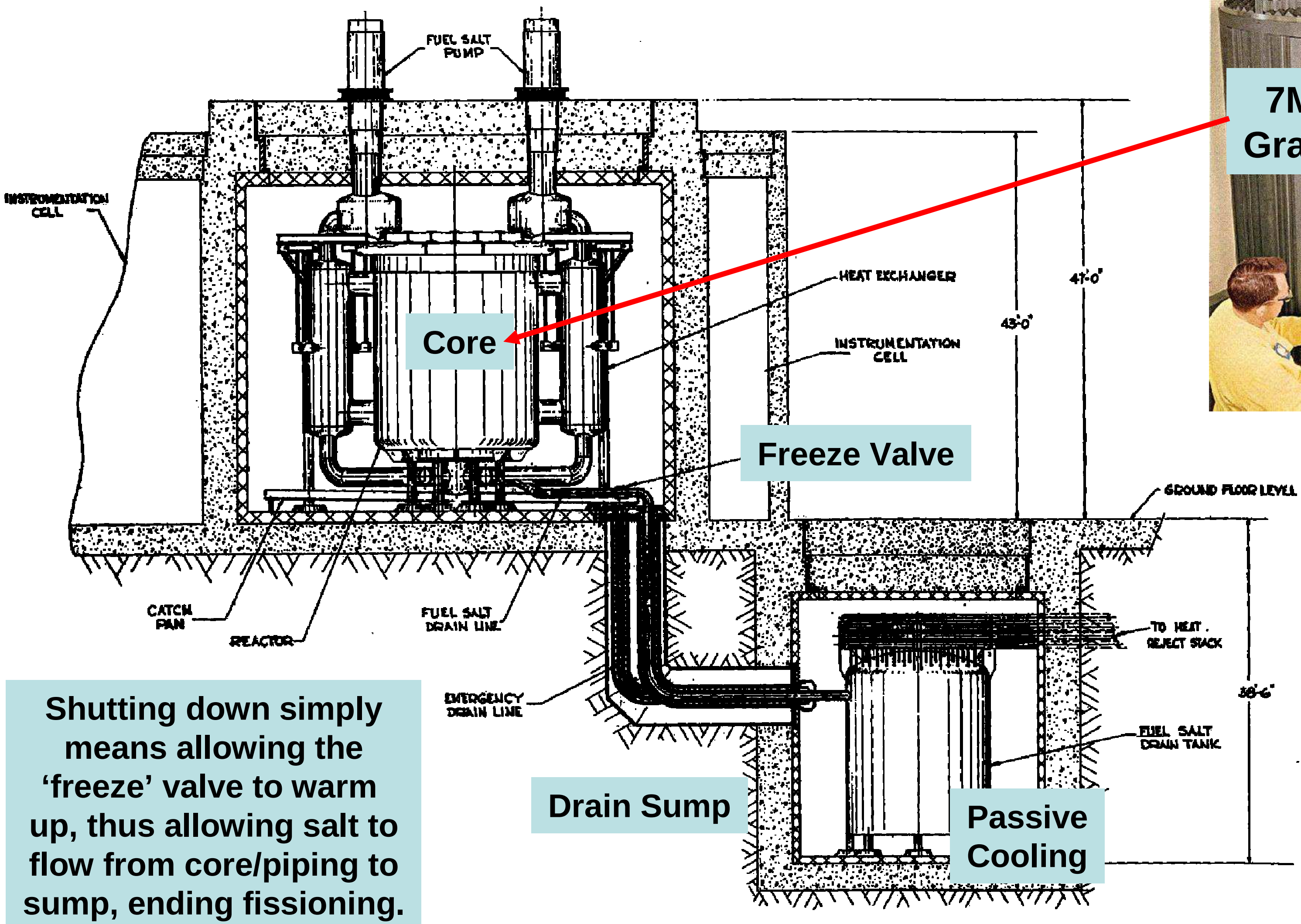
Turbine Engines

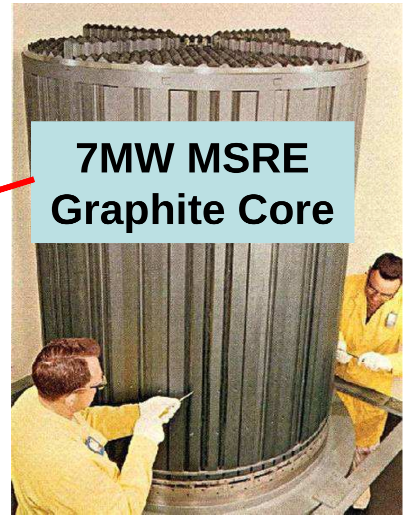


http://moltensalt.org/references/static/downloads/pdf/NSE_ARE_Operation.pdf
http://large.stanford.edu/courses/2012/ph241/omar2/

The MSR (Molten-Salt Reactor)

Molten-Salt Reactor & Shutdown Sump Structure…





Shutting down simply means allowing the 'freeze' valve to warm up, thus allowing salt to flow from core/piping to sump, ending fissioning.

Molten-Salt Reactors (MSRE)

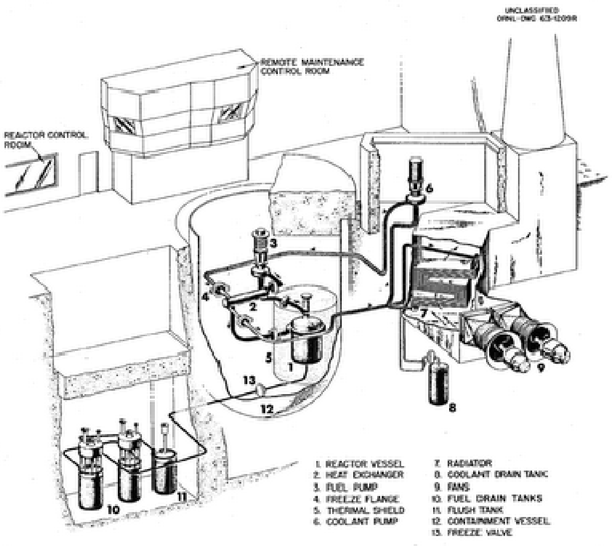
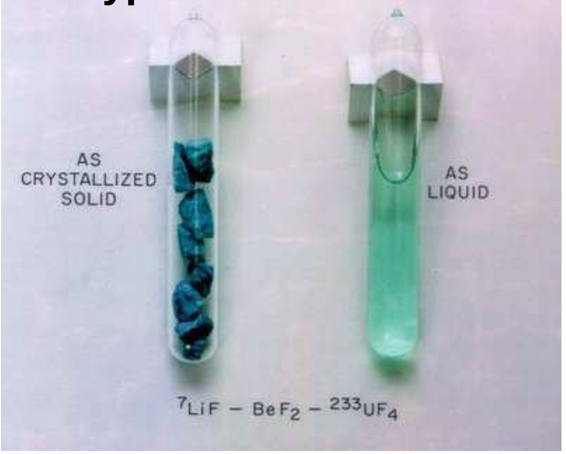


Fig. 7. Elevation of Part of MSRE Building.

1960s MSRE
7MW, 17,000Hrs

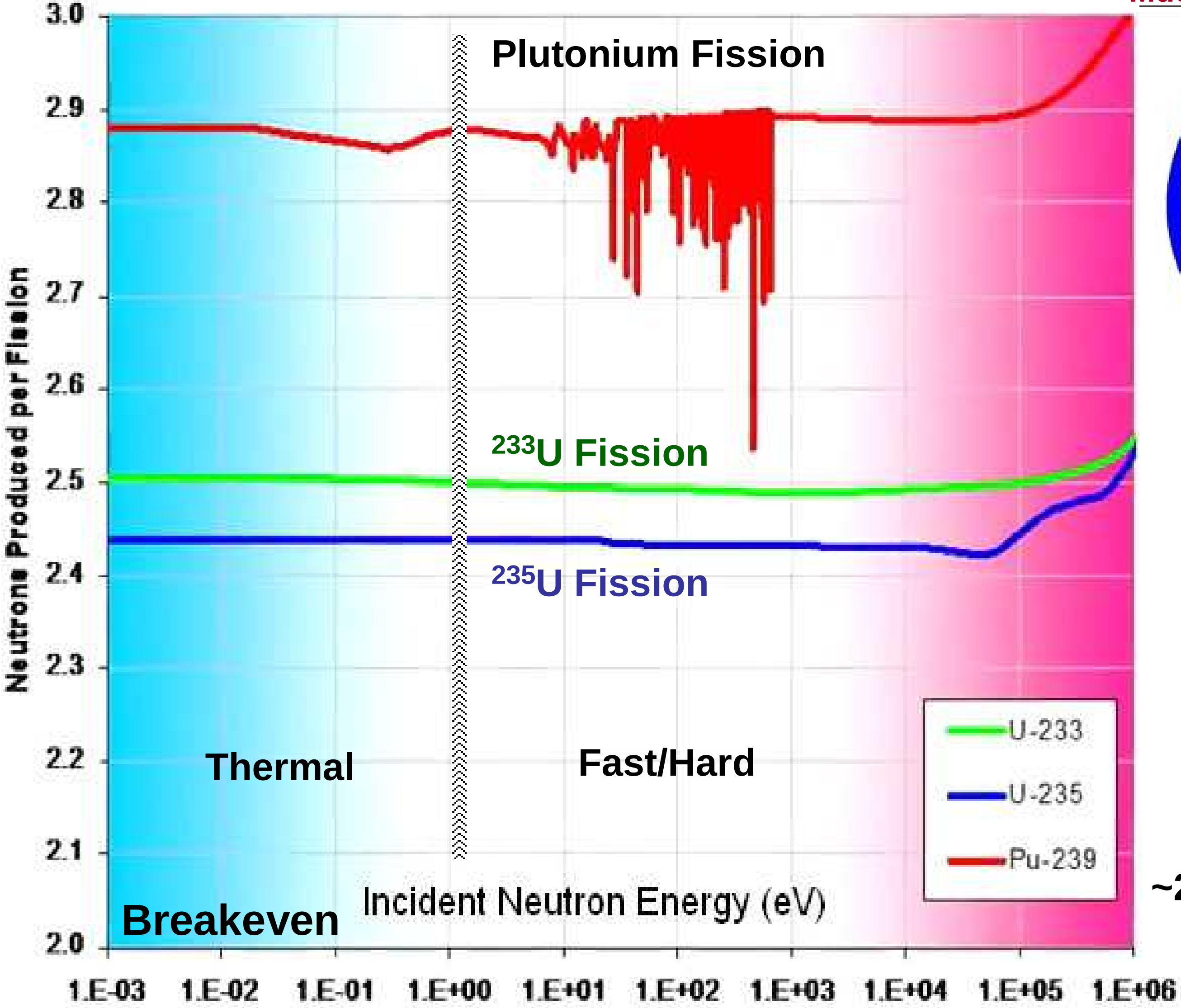
Seaborg Turning It On

Typical Fluoride Salt

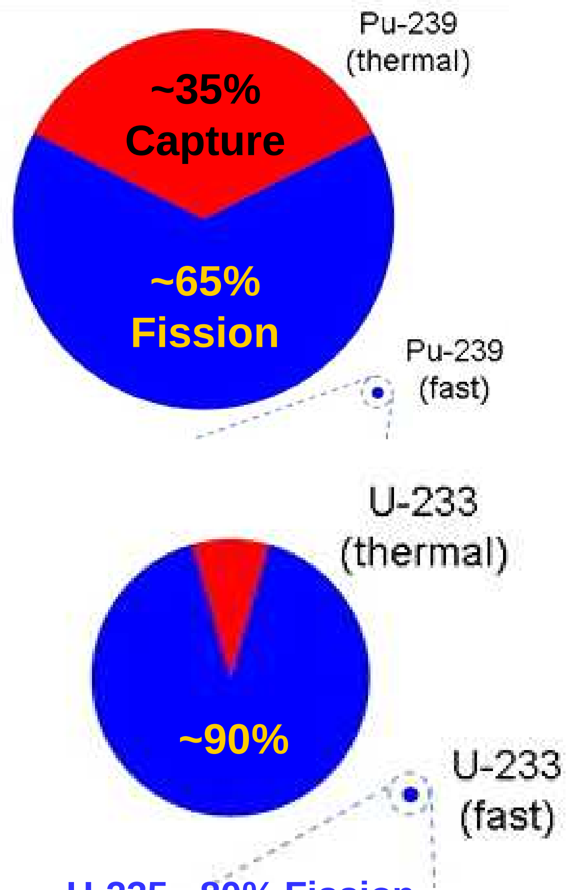


Fission Neutron Economy

Neutrons: Immediate + Delayed



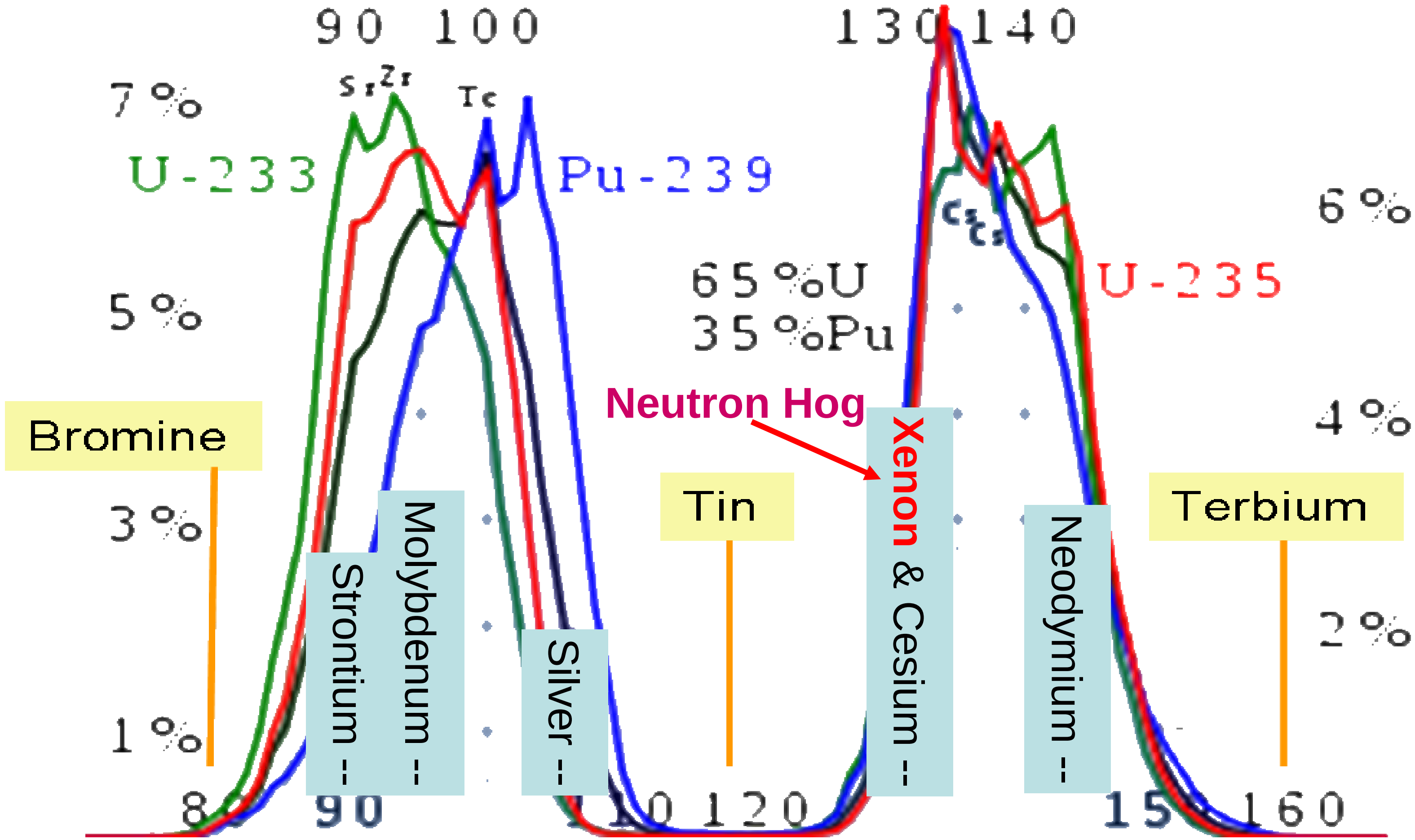
Much Less Red for Fast Neutrons



U-235 ~80% Fission

~25:1 Thermal:Fast Cross-Section Ratio

Fission Products

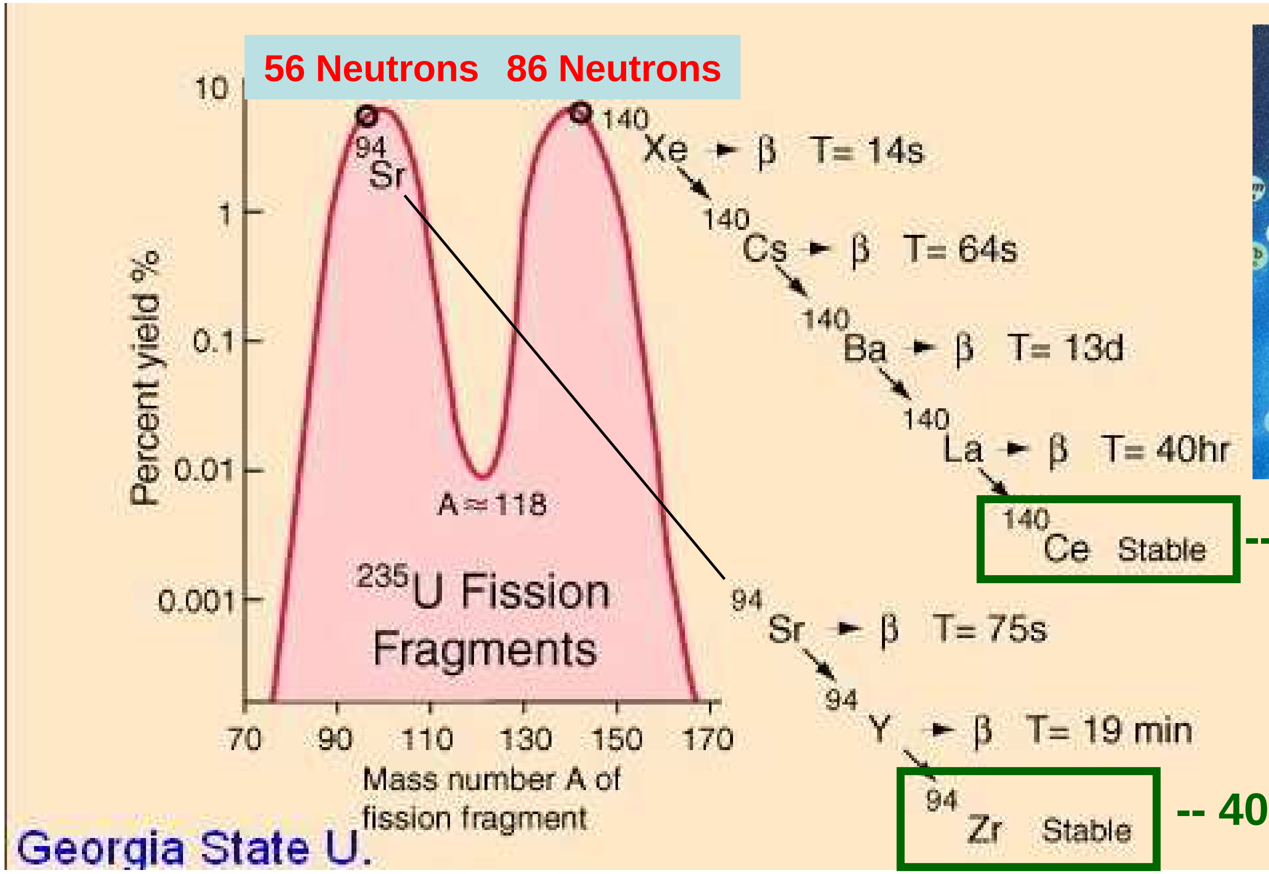


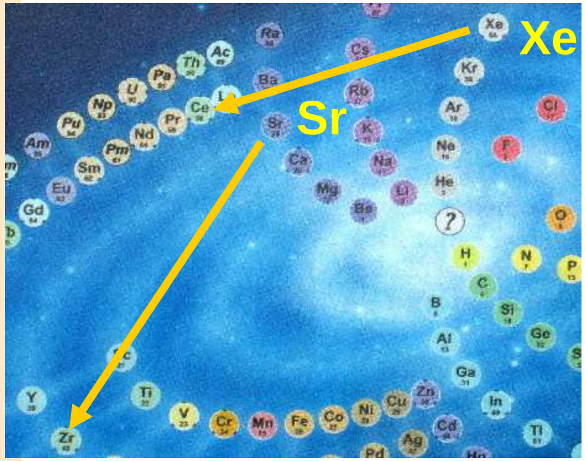
Fission-Daughter Mass (Nucleons)

Asymmetrical yields of thermal-fission-product pairs versus fissile element

Fission-Product Radiation

^{235}U fission can result in the FP pair **^{94}**Strontium and **^{140}**Xenon, which are Highly radioactive, due to excess of several neutrons each. They decay within minutes or days to stable Zirconium and Cerium, by shedding Beta particles (electrons), thus moving up the Periodic Table to higher Proton/Neutron ratios..





-- 58 Protons, 82 Neutrons

-- 40 Protons, 54 Neutrons

Natural Radiation -- Fission

The mountains in Oklo, south-eastern Gabon are home to several natural ^{235}Uranium fission reactors. They operated about 2 billion years ago, when the 700-million-year half life of that isotope would have meant it was about 8 times as abundant in typical rock containing Uranium ore. The Earth's growing *atmospheric Oxygen content, water & bacteria concentrated UO_2 enough that rainfall & groundwater acted as a neutron moderator to enhance fission* by slowing neutrons to 'thermal' speeds, making their capture by ^{235}U nuclei more probable. When water stopped flowing, the reactors stopped fissioning. When it flowed again, they restarted. The site is now useful to judge stability of fission wastes. Niger & Gabon have very significant U deposits.

http://www.ans.org/pi/np/oklo/
http://www.ans.org/pi/np/oklo/
http://en.wikipedia.org/wiki/Natural_nuclear_fission_reactor
www.physics.isu.edu/radinf/Files/Okloreactor.pdf

The Molten-Salt Breeder

"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." -- Alvin Weinberg (1915-2006)

1962 AEC Seaborg Commission Report to the President (JFK)…
*"This [AEC civilian reactor] program… leaned heavily upon, indeed it started from, knowledge gained from other reactor programs, notably…reactors for making plutonium, naval propulsion reactors and research and test reactors…Certain classes…notably water-cooled converters [LWRs]…are now on the threshold of economic competitiveness…it is important that the combination of breeders and converters reaches an overall net breeding capability...**The overall objective of the Commission's nuclear power program should be to foster and support the growing use of nuclear energy and…make possible the exploitation of the vast energy resources latent in the fertile materials, uranium-238 and thorium."*** **-- http://energyfromthorium.com/pdf/CivilianNuclearPower.pdf**

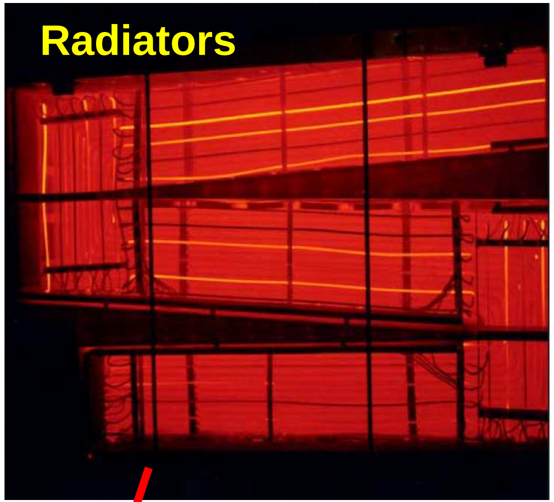
Nowadays [1994], I often hear arguments about whether the decision to concentrate on the LWR was correct. I must say that at the time I did not think it was; and 40 years later we realize, more clearly than we did then, that **safety must take precedence even over economics** — that no reactor system can be accepted unless it is first of all safe. However, in those earliest days we almost never compared the intrinsic safety of the LWR with the intrinsic safety of its competitors. We used to say that every reactor would be made safe by engineering interventions. We never systematically compared the complexity and scale of the necessary interventions for [different] reactors. So in this respect, **I would say that [AEC's reactor-development director in 1955] Ken Davis' insistence on a single line, the LWR, was premature.**

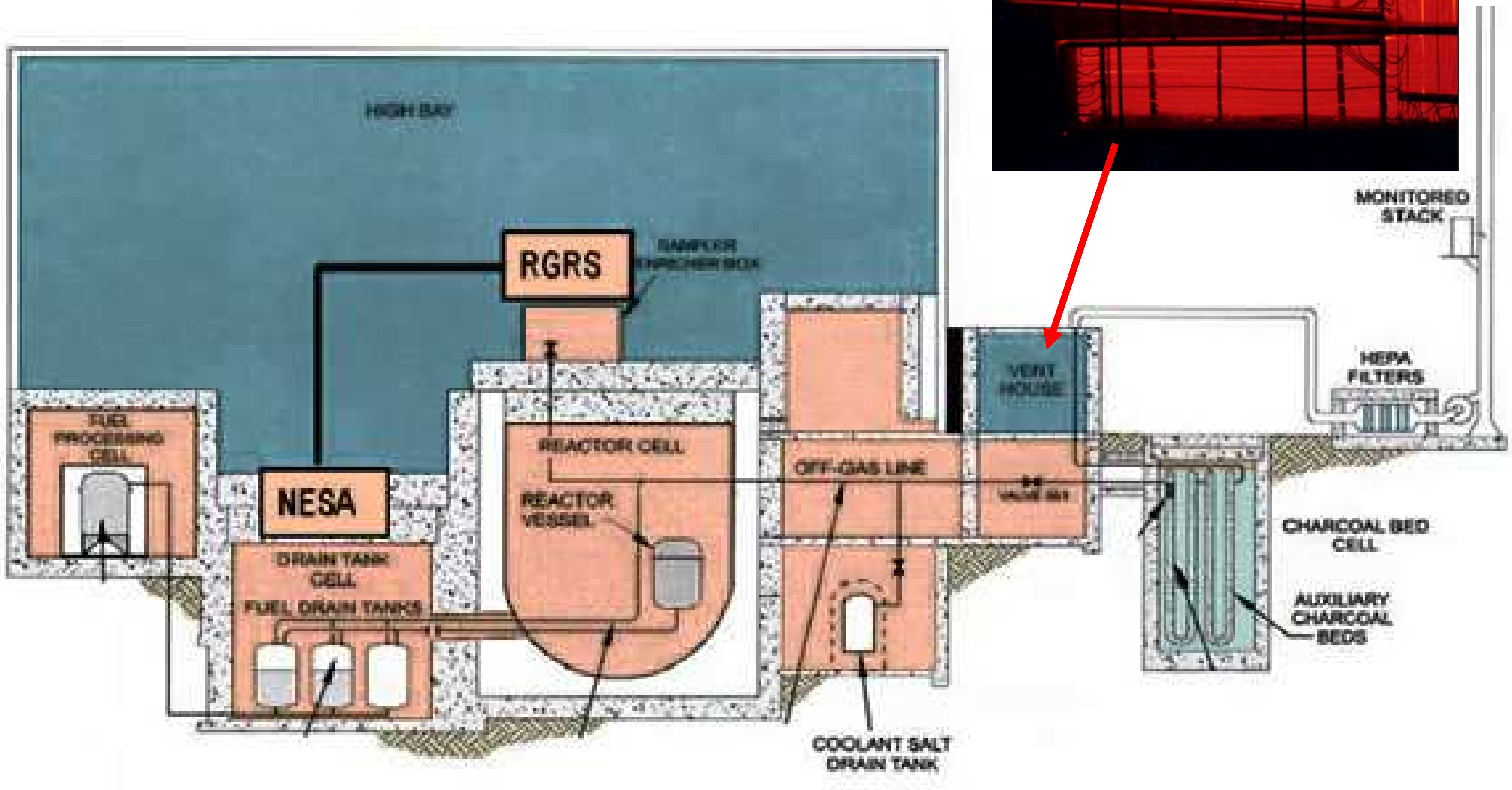
***…The Second Nuclear Era* – A. Weinberg, 1994…**

One publicist claimed that the light-water reactor had been chosen after long and careful analysis because it possessed unique safety features. I knew this was untrue: **pressurized water had been chosen to power submarines because such reactors are compact and simple. Their advent on land was entirely due to Rickover's dominance in reactor development the 1950s,** and once established, the light-water reactor could not be displaced by a competing reactor. **To claim that light-water reactors were chosen because of their superior safety belied an ignorance of how the technology had actually evolved…the Army finally decided that even small light-water reactors were too difficult and costly to maintain, and they were all eventually decommissioned.**

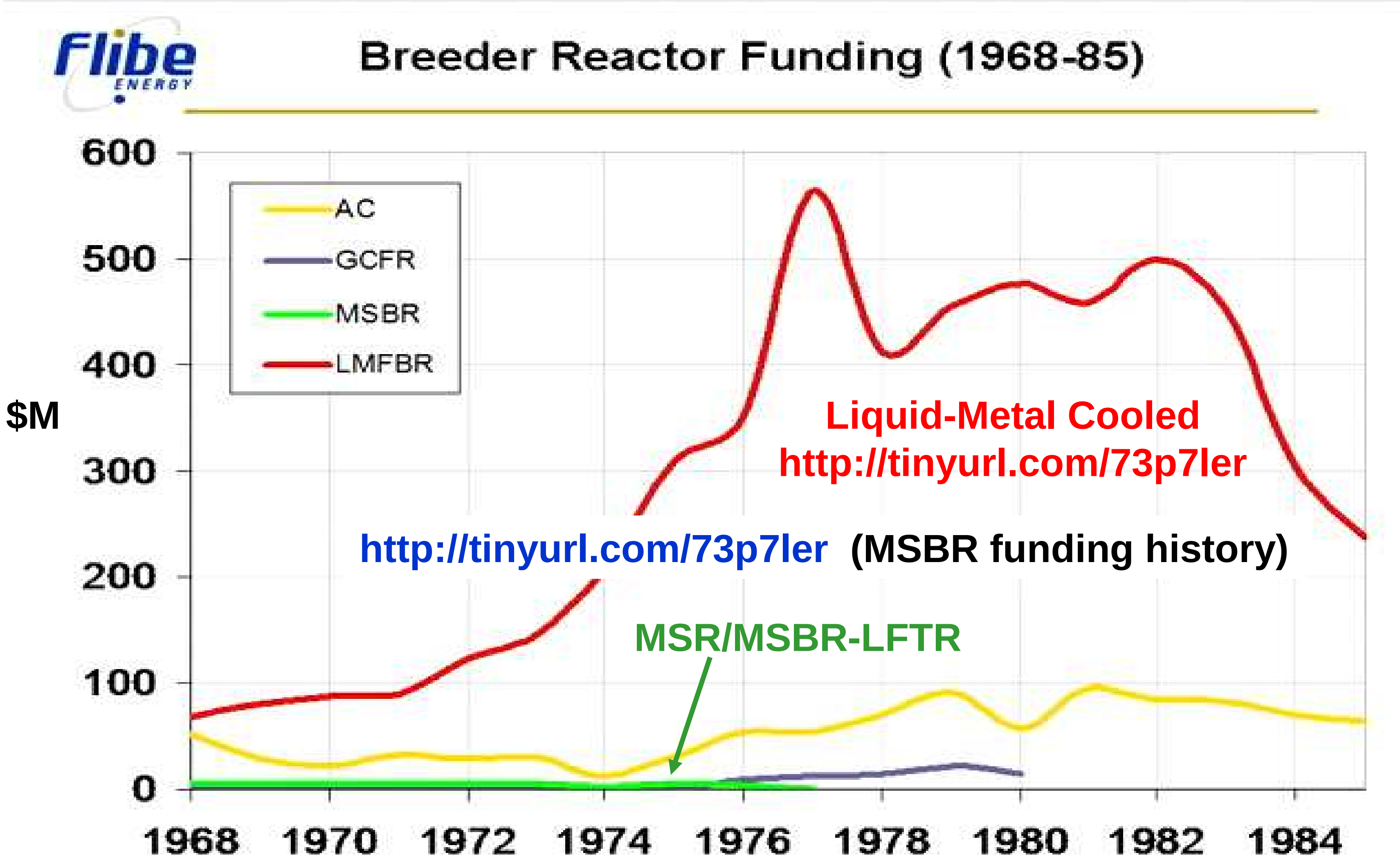
Molten-Salt Reactors (MSRE)

- Operated from June 1965 to December 1969
- 8MW Thermal Power
- Started with 227kg $^{235/238}$Uranium
- In 1968, Fuel Changed to $^{233/235}$Uranium & ^{239}Plutonium
- Salts: Lithium, Beryllium, Zirconium & Fuel Fluorides

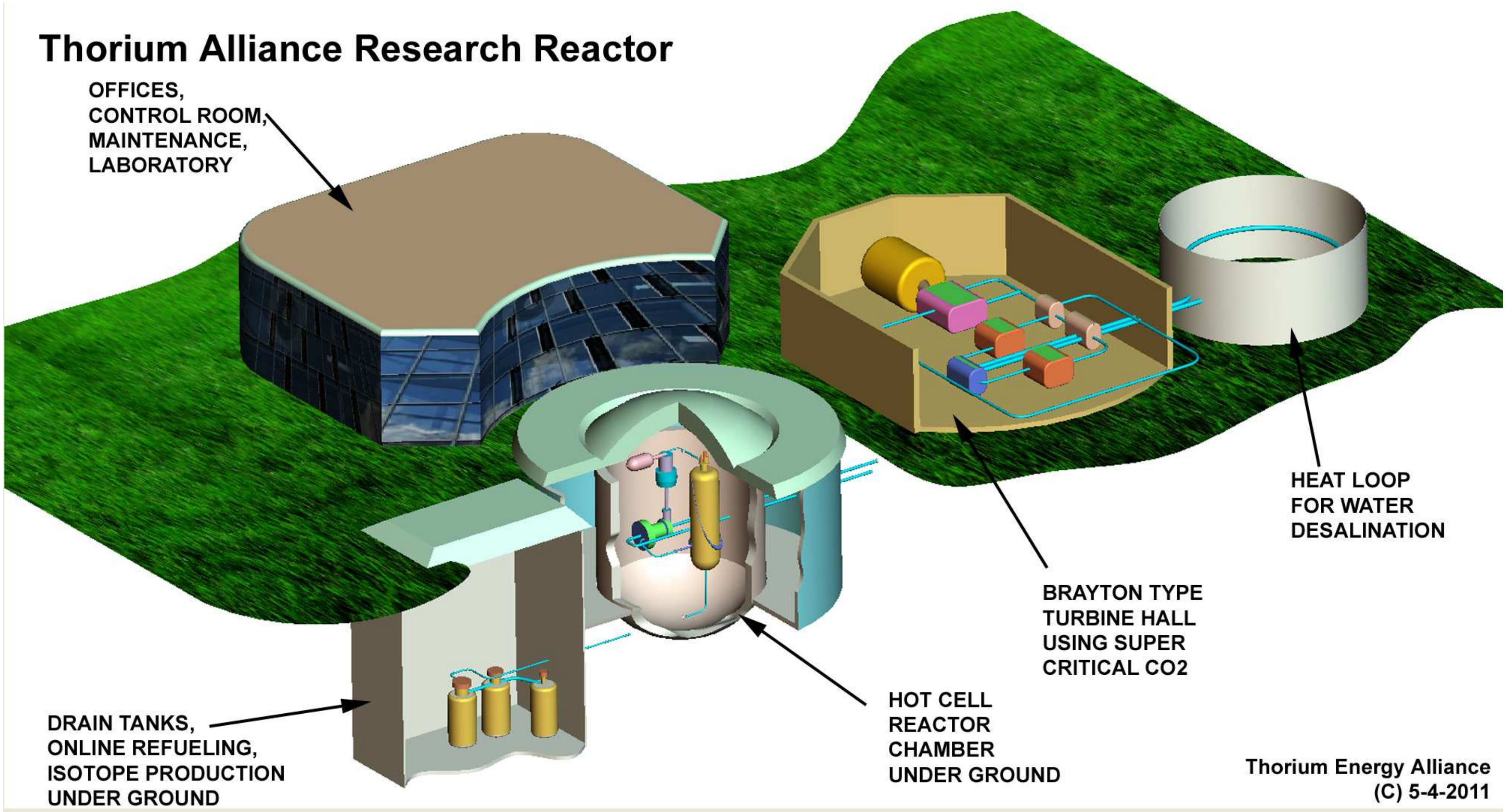




Funding History



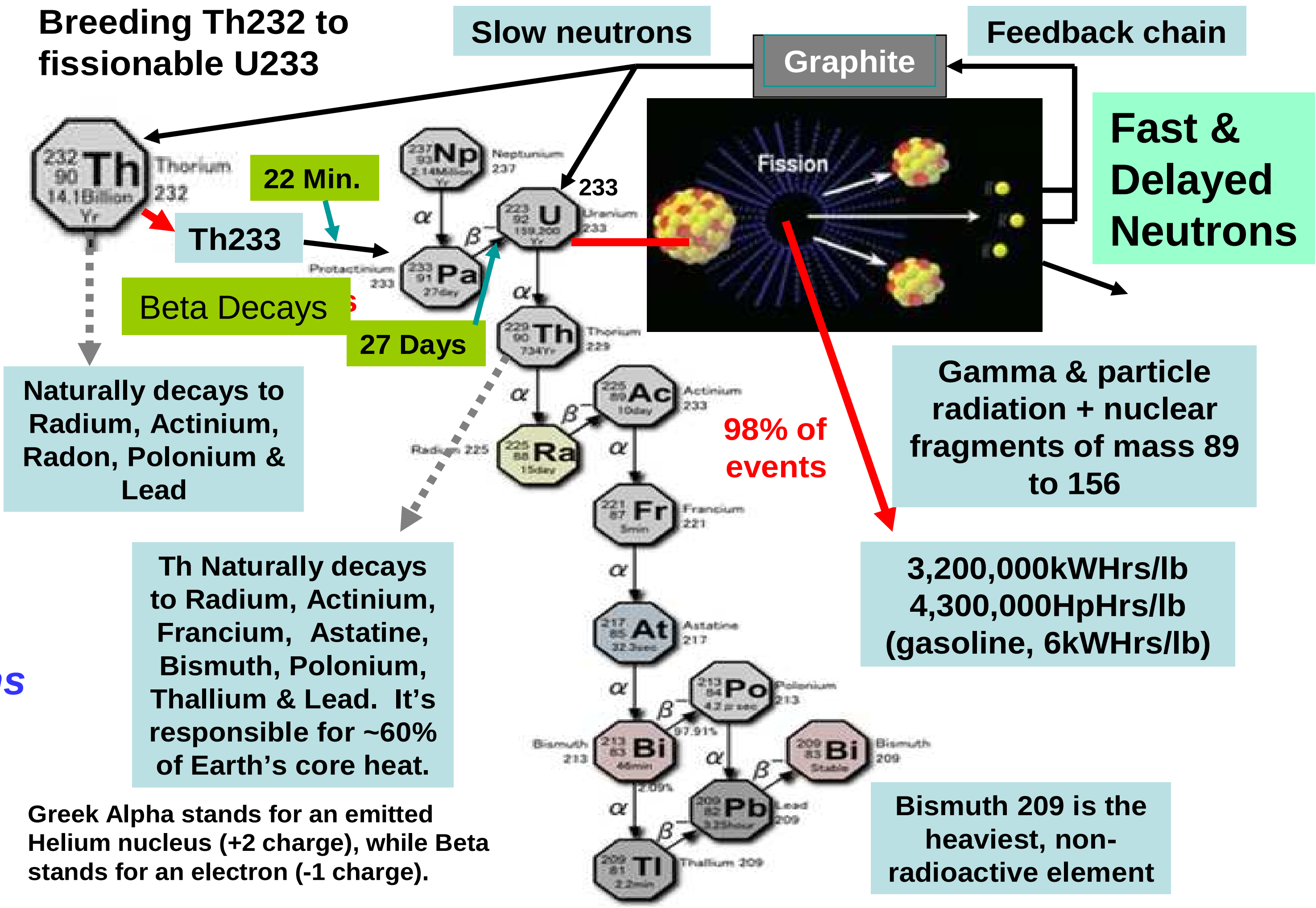
Molten-Salt Reactors



www.thoriumenergyalliance.com

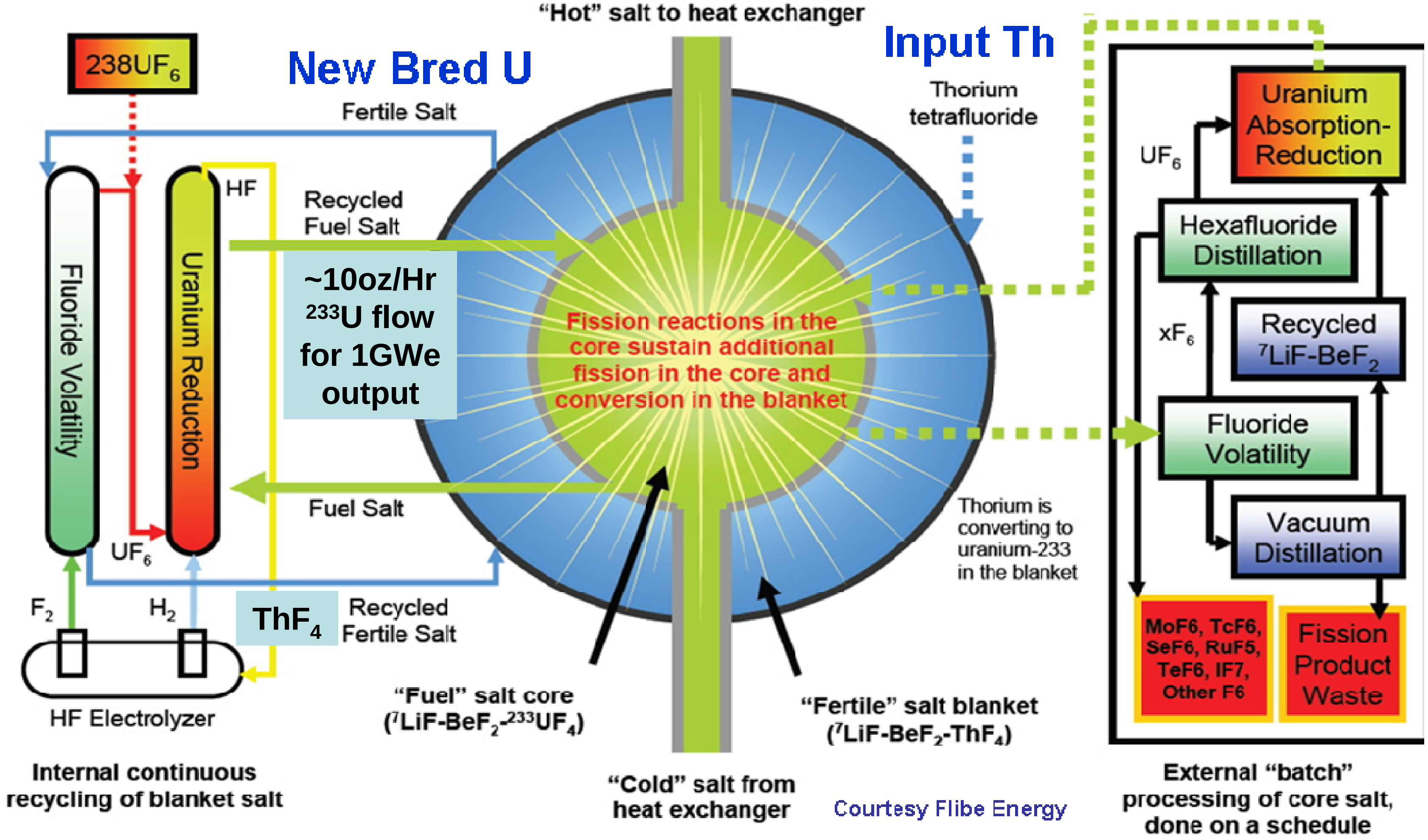
Thorium-^{233}U Based Fission

Abundant, Cheap, low radioactivity



Alternatively, accelerator-injected neutrons can breed Th_{232} to U_{233}

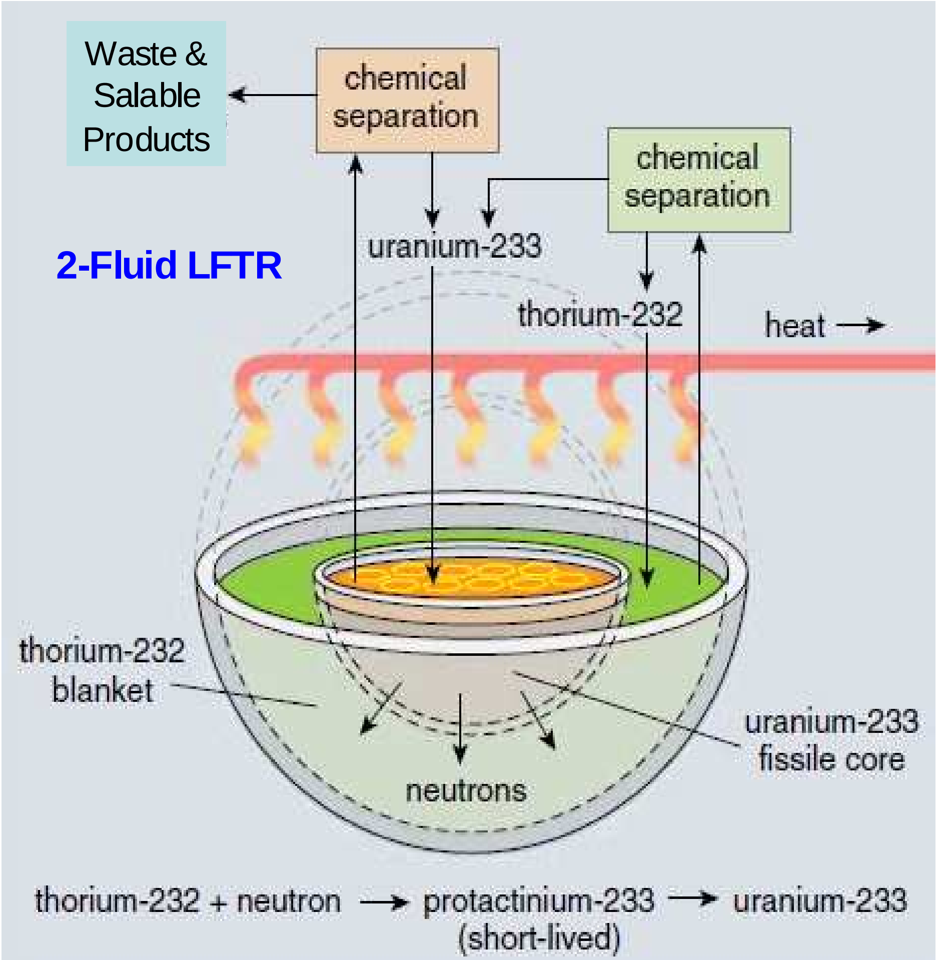
Thorium Molten-Salt Reactor (LFTR)



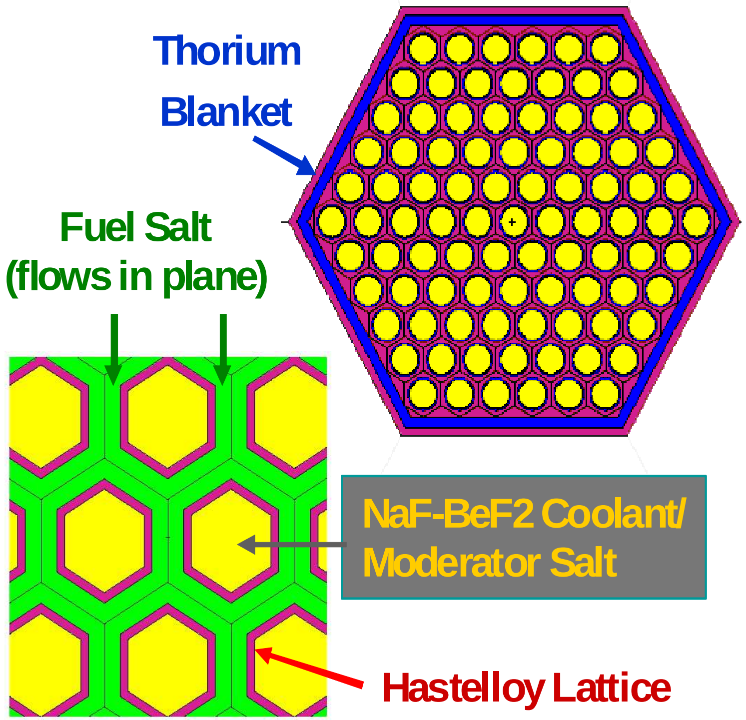
Thorium is 4x as abundant as Uranium & nearly free 'waste' product of rare-earth mining. Inside the reactor it breeds ^{233}Uranium, which fissions easily, with low waste & valuable products.

LFTR Architectures

2-Fluid Pool & Solid Core Moderator



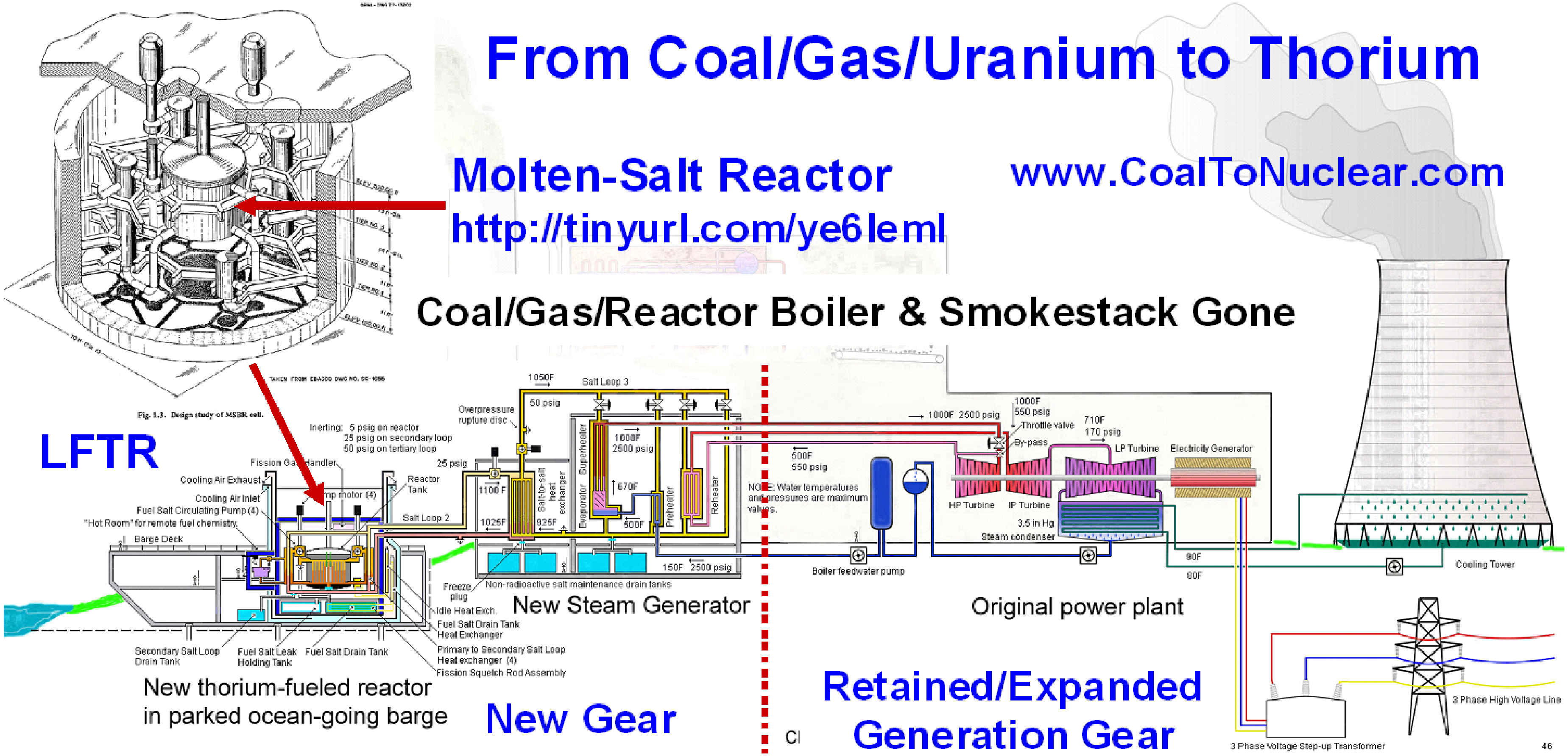
2-Fluid Lattice & Thorium Blanket

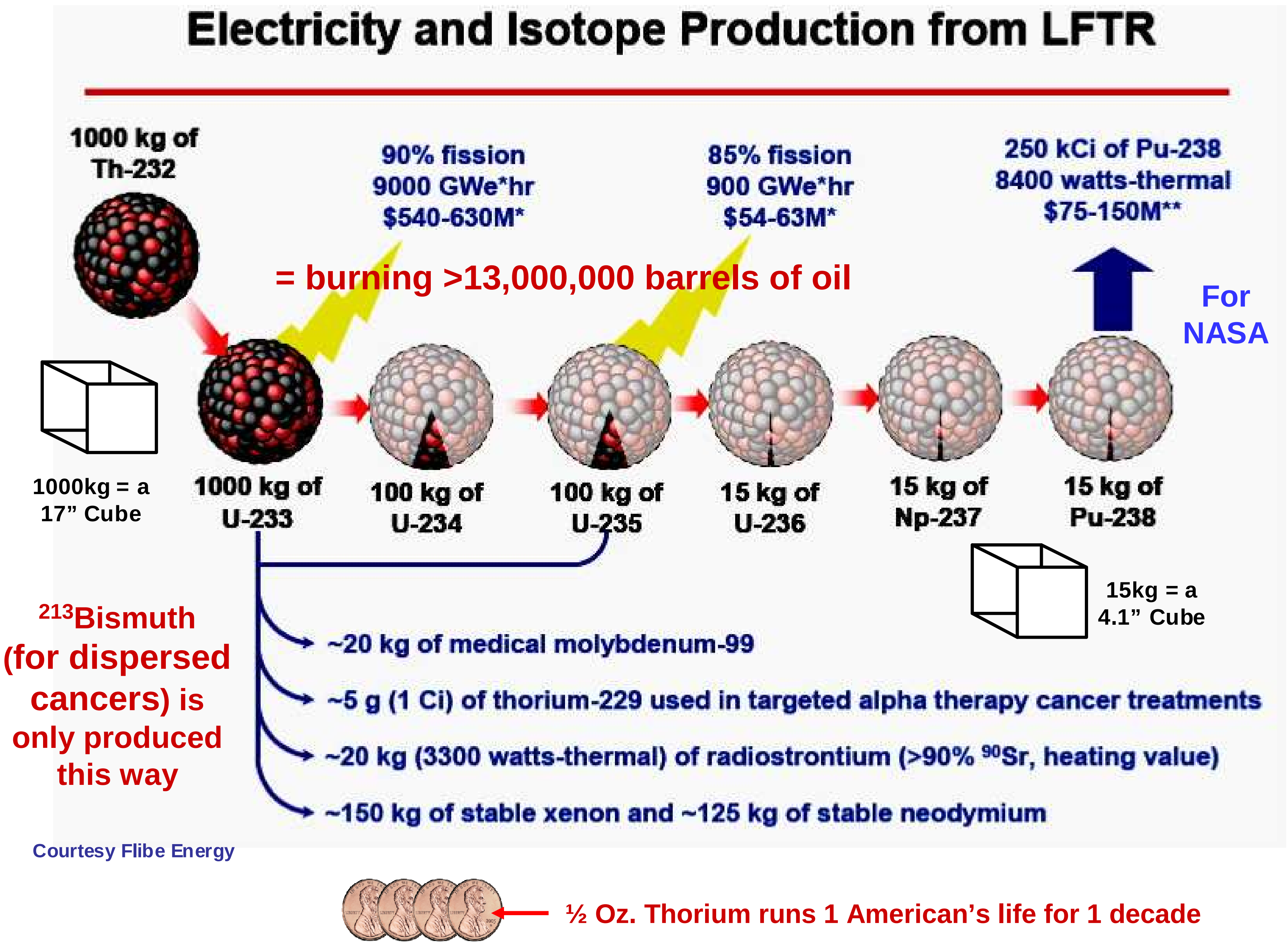


BeF_2 Moderator in Coolant & Fuel

Courtesy Thorenco

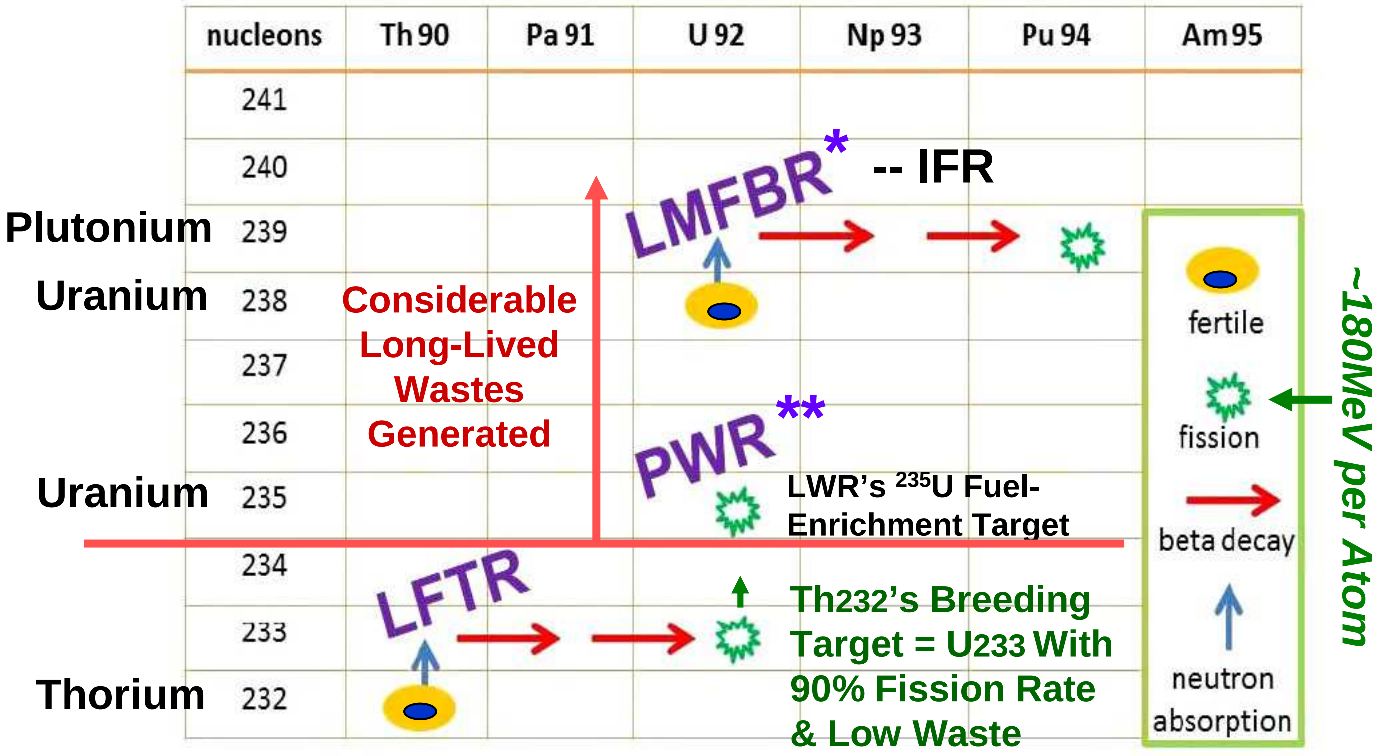
Using MSR/LFTR Modules




Electricity and Isotope Production from LFTR
1000 kg of Th-232
90% fission
9000 GWe*hr
$540-630M*
85% fission
900 GWe*hr
$54-63M*
250 kCi of Pu-238
8400 watts-thermal
$75-150M**
= burning >13,000,000 barrels of oil
For NASA
1000kg = a 17" Cube
1000 kg of U-233
100 kg of U-234
100 kg of U-235
15 kg of U-236
15 kg of Np-237
15 kg of Pu-238
15kg = a 4.1" Cube
213Bismuth (for dispersed cancers) is only produced this way
~20 kg of medical molybdenum-99
~5 g (1 Ci) of thorium-229 used in targeted alpha therapy cancer treatments
~20 kg (3300 watts-thermal) of radiostrontium (>90% 90Sr, heating value)
~150 kg of stable xenon and ~125 kg of stable neodymium
Courtesy Flibe Energy
½ Oz. Thorium runs 1 American's life for 1 decade

The Thorium Solution

Two breeding technologies provide 10^2 X more energy than 0.7% U-235.



** Liquid-Metal Fast Breeder Reactor , ** Pressurized-Water Reactor (an LWR)*

Thorium MSR & Uranium LWR Cycles

~200 Tons/GWe-Year

U238/235 → Mine → Refine → Fluorinate → *Gas Diffusion* Enrich $$$ *Centrifuge* → De-Fluorinate → Pelletize

$

UF$_6$ Waste

LWR/PWR/BWR

Pelletize → $$ Make Rods → Load Rods → Consume <6% of Fuel, Remove Rods

Weapons → Remove U & Pu → Fluorinate

$$$$

Reprocess Spent Fuel ←

Vent Noble Gas (Kr85…)

Fabricate Waste

$$$$

Store Waste For >10,000 Years

>60,000 lbs/ GWe-Year $?

LFTR/MSR

<30 Tons/GWe-Year

Th232 → Mine → Refine → Fluorinate → Circulate In Melt, Add ThF$_4$ as Needed

Periodic Salt Processing

Capture Gas, Fluorinate Out Wastes

~2 lbs/GWe-Yr

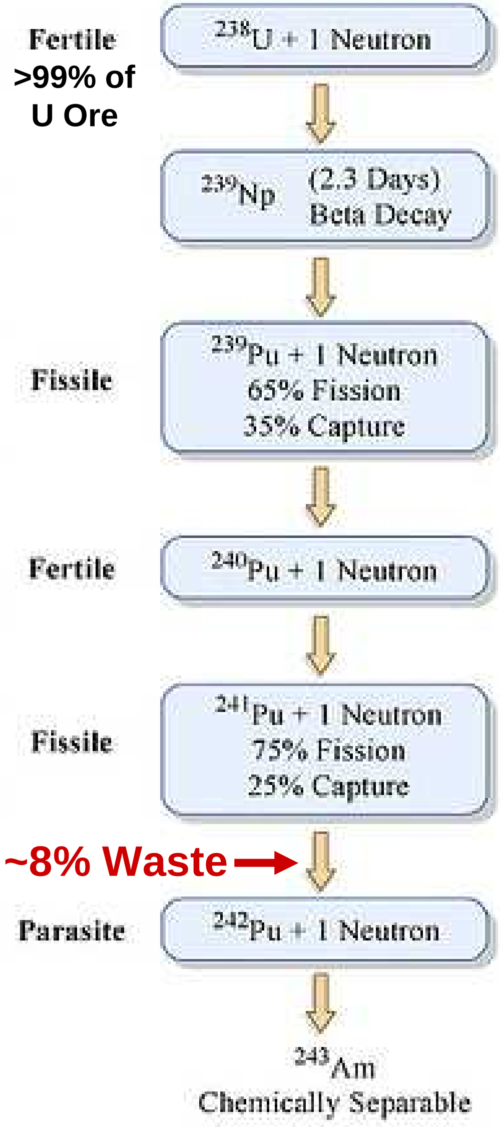
Sell or Store For ~500 Years

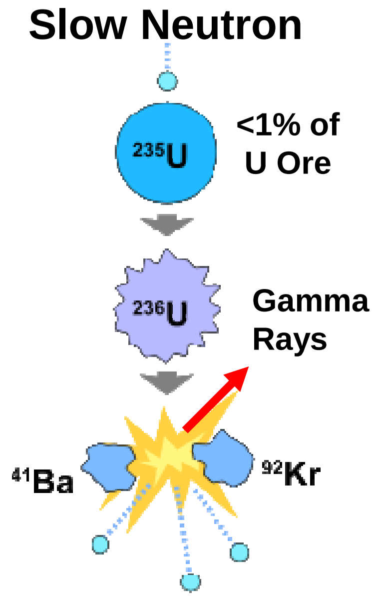
<8 lbs/GWe-Year, ~2 Gas Cylinders

$^{235/238}$Uranium Reactor Wastes (*notes*)

Indian Point NY (~2GWe)

Enrichment Waste, U235-Depleted Below Ore

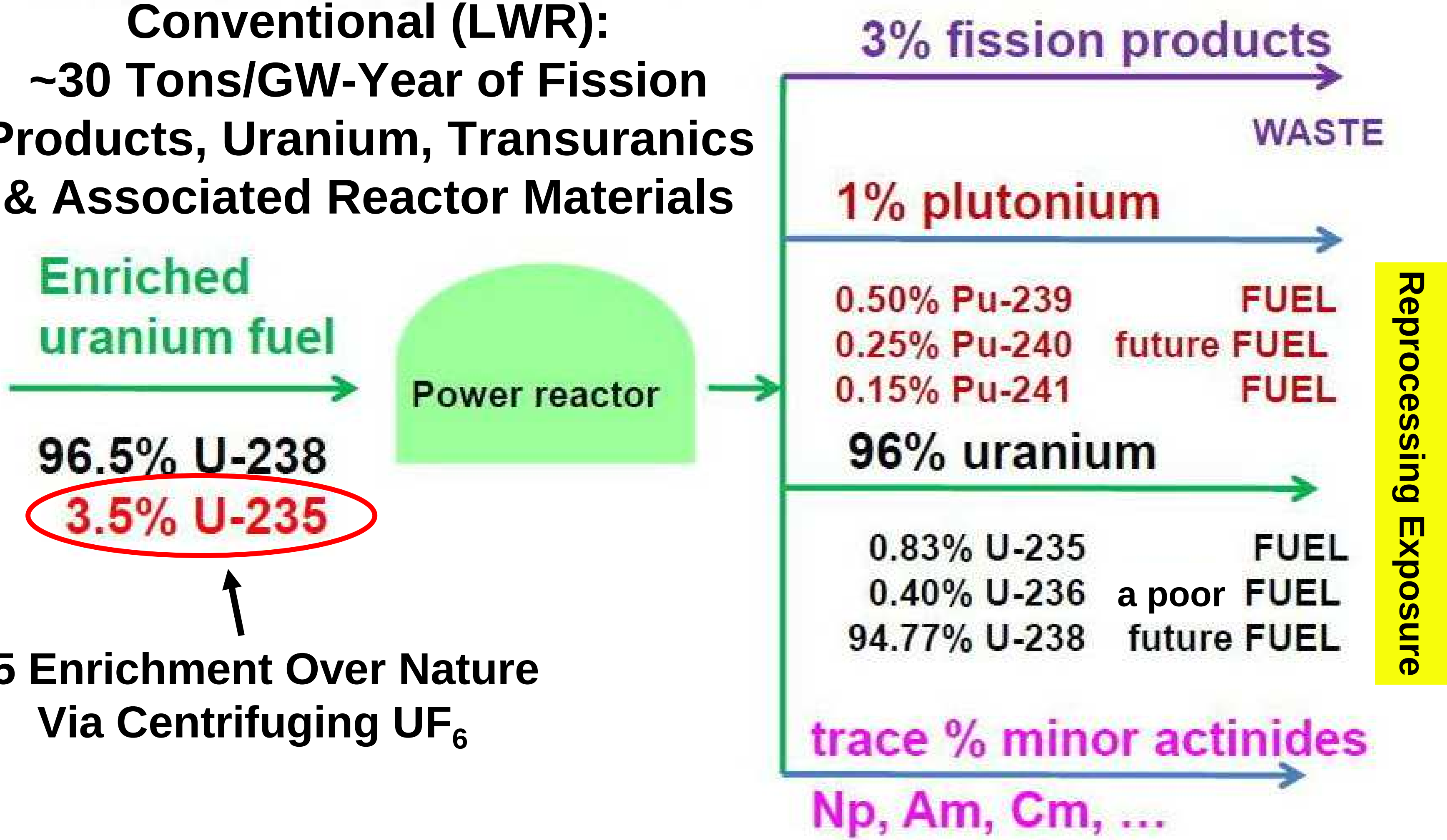




1-4 Neutrons + pairs of ~20 other possible Fission fragments like: Rb, Cs, Sr, Xe… Plus ~200MeV or ~176 years of an American's energy use, per kilogram of U235.

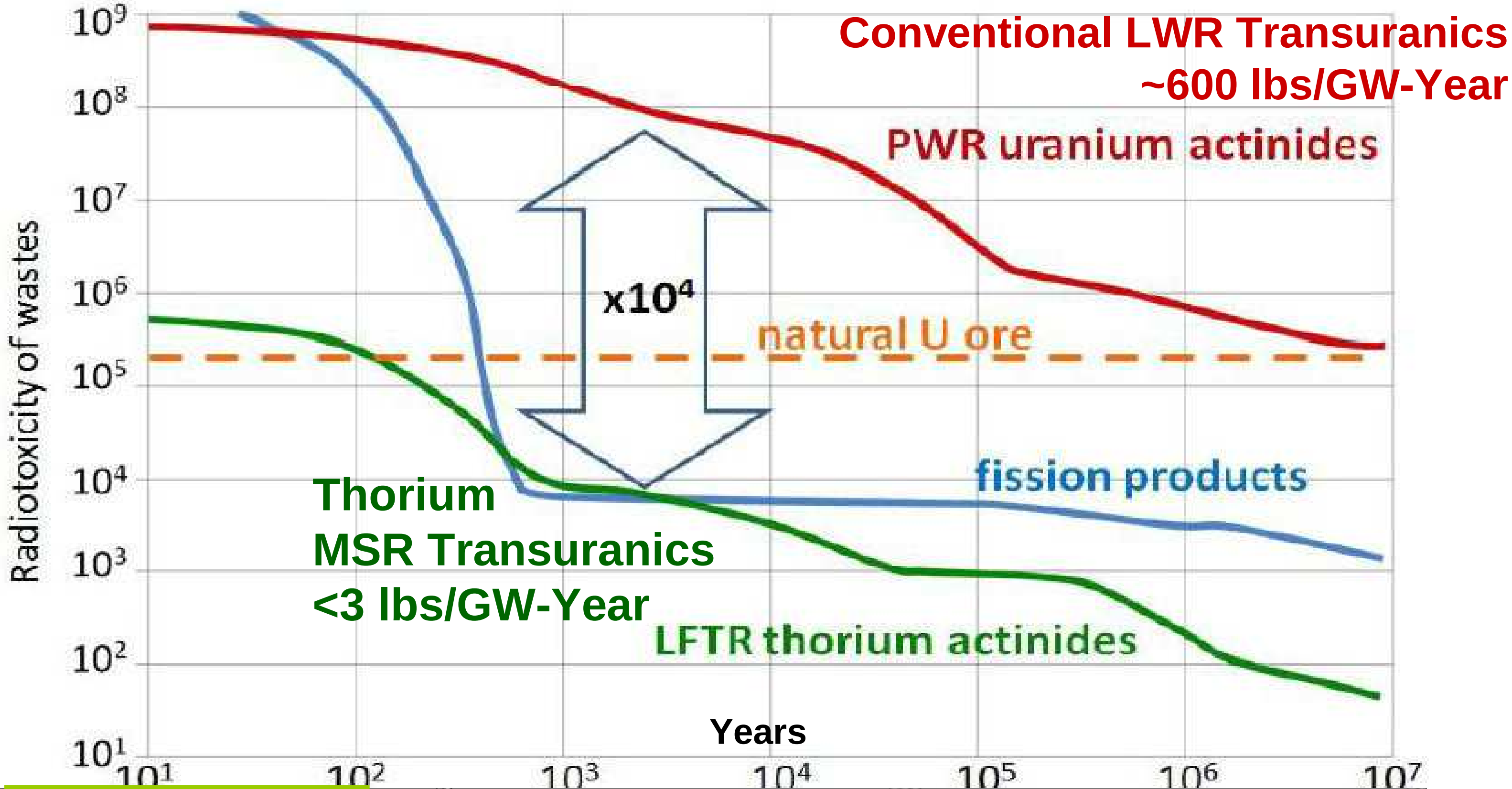
Waste Comparisons

Conventional (LWR):
~30 Tons/GW-Year of Fission Products, Uranium, Transuranics & Associated Reactor Materials



x5 Enrichment Over Nature
Via Centrifuging UF_6

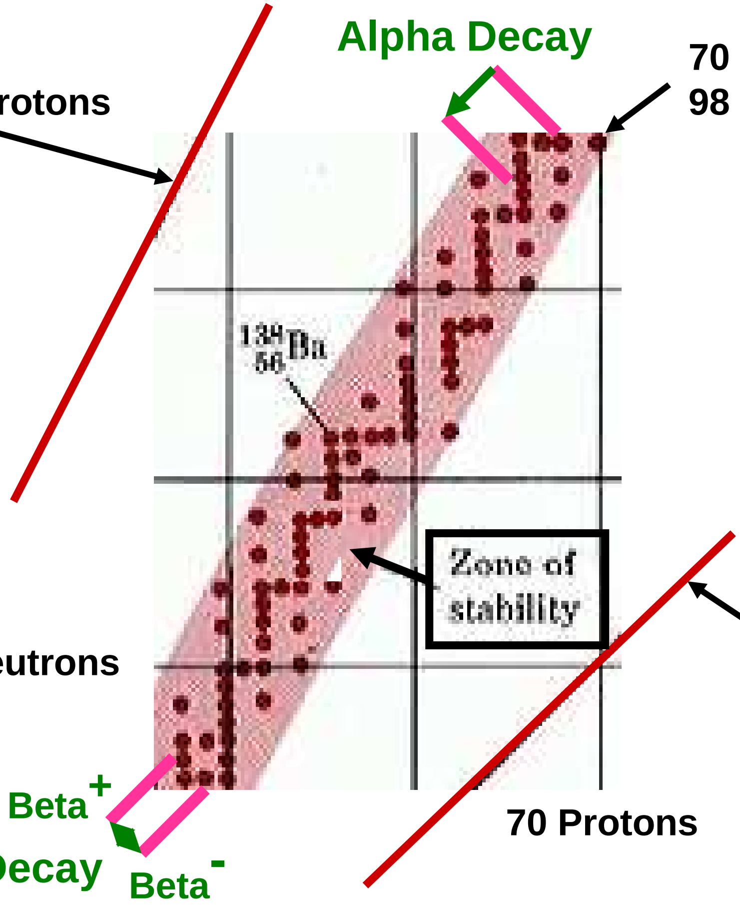
Waste Comparisons



For 30 years total:	FUJI-U3 (1GWe)	Relative to 1GWe BWR
Fissile requirement	7.8 t (reusable)	32%
Pu production	4 kg	0.1%
MA (Np/Am/Cm) production	23 kg	4 %

Japanese Example
~60 lbs in
30 GW yrs

Alpha & Beta Decay Detail



Emitted Radiation

Alpha .. Helium ion
$Beta^+$ .. Positron
$Beta^-$ .. Electron
EC .. X& Gamma rays

(EC = inner electron capture by a nuclear Proton)

Decay Result

Alpha .. -2P –2N
$Beta^+$ .. -1P +1N
$Beta^-$ .. -1N +1P
EC .. -1e -1P +1N

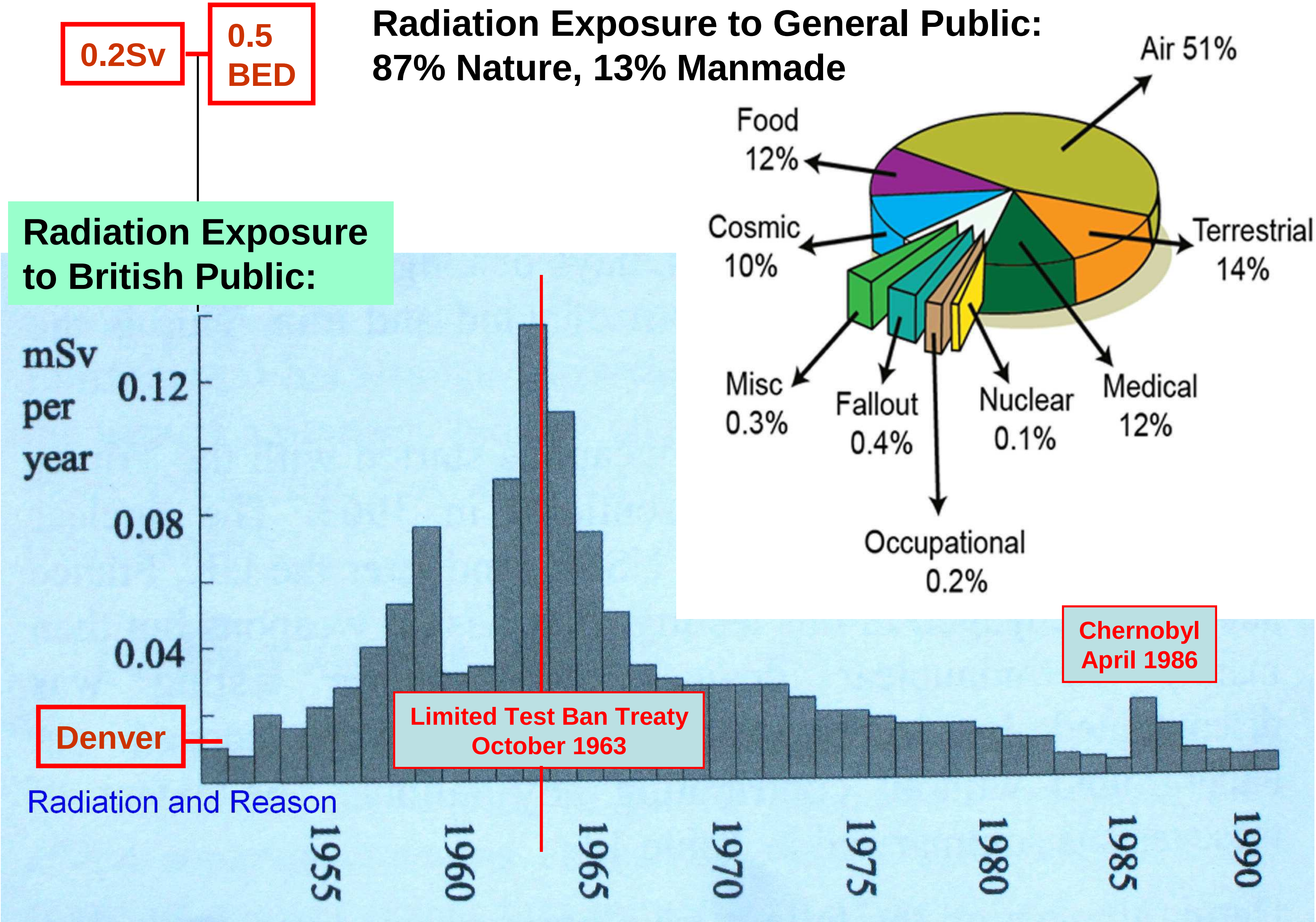
Protons Define Elements
Neutrons Define Isotopes

Note 1: Illustrated decays would only occur outside the Zone of Stability, or for isotopes not indicated by red dots, e.g., ^{139}Ba.

Note 2: Decays are accompanied by Gamma or X radiation at some energies reflecting needed nucleon reshufflings.

Relative Radiation Dangers

Radiation Exposure to General Public:
87% Nature, 13% Manmade

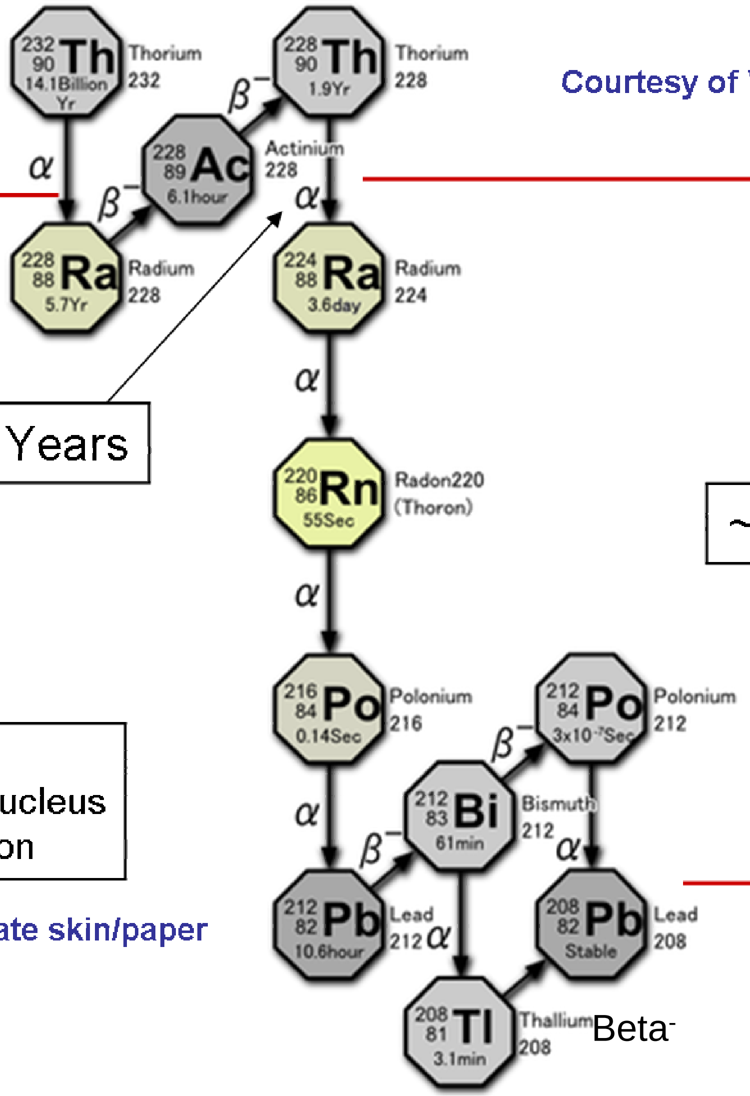


Thorium's Radiation Exposure (*notes*)

~14 Billion Years

Courtesy of Wikipedia

Times are half lives



~8 Years

~4 Days

1Alpha every 69,000 sec.
0.2pg Th = ^{40}K
4400Bq In body = 2gTh for 14B years

Emissions
Alpha = Helium nucleus
Beta = Electron

Alpha & Beta can barely penetrate skin/paper

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