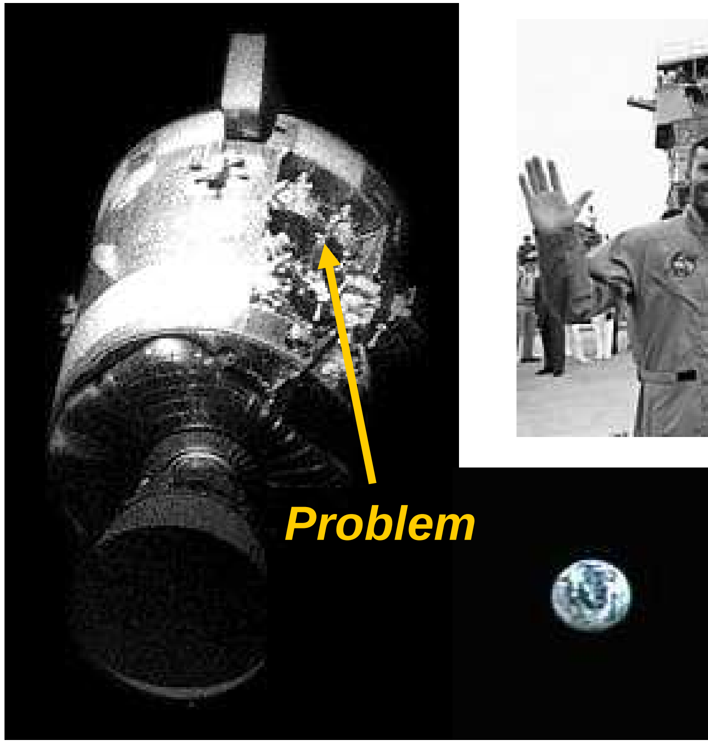
# Nuclear-Power Waste and the Thorium-Fuel Option

Dr. A. Cannara, *Thorium Energy Alliance* (thoriumenergyallinance.com),
North Sea Council & Journal, ECMA6, 15 August 2016 ***Extended (p 3,4,26,52)***

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

*Gene Kranz, Apollo 13 Flight Director, April 1970.*




***Result***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**10 Sept 2016**

# Scales of Reality

Nuclear 'Strong' Force

**All atoms are same size <=> Avogadro's Number (good news for nuclear-fission energy)**

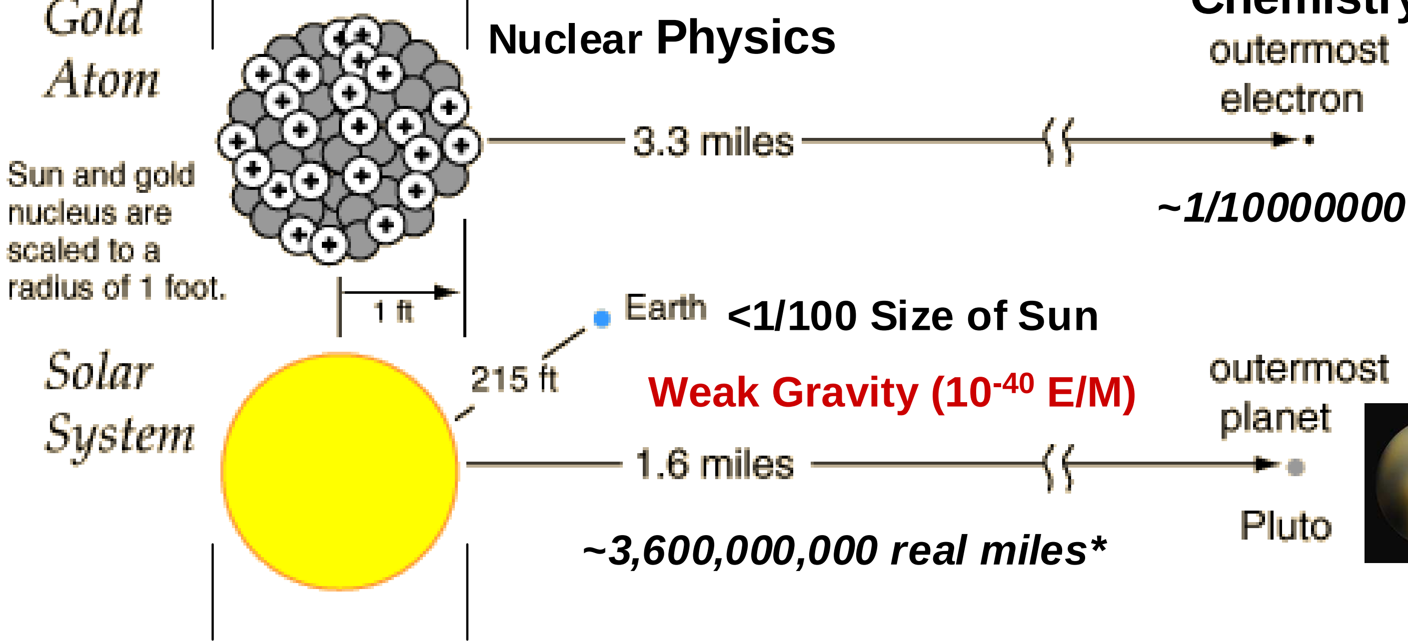
*~1/1000000000000"*

Electromagnetic Force

79p + 118n

Nuclear Physics

Chemistry




*~1/100000000 inch*

<1/100 Size of Sun

Weak Gravity ($10^{-40}$ E/M)

*~3,600,000,000 real miles**

x2 → Oort Cloud

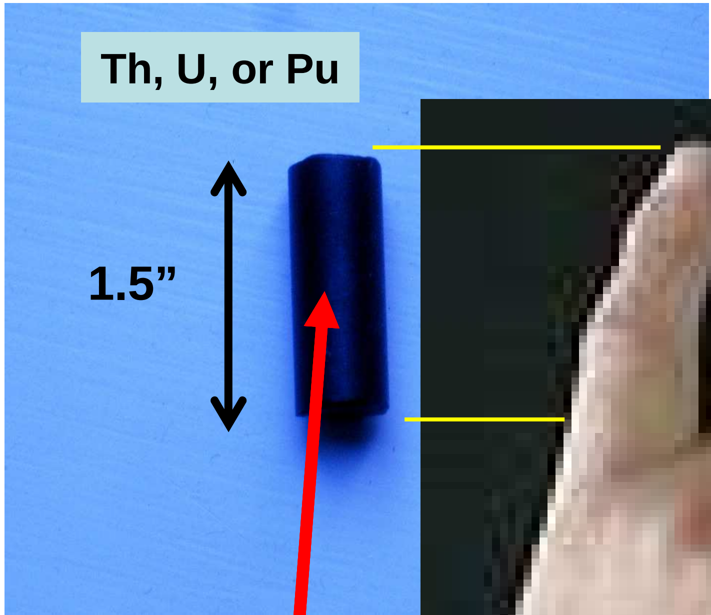
*~900,000 miles*

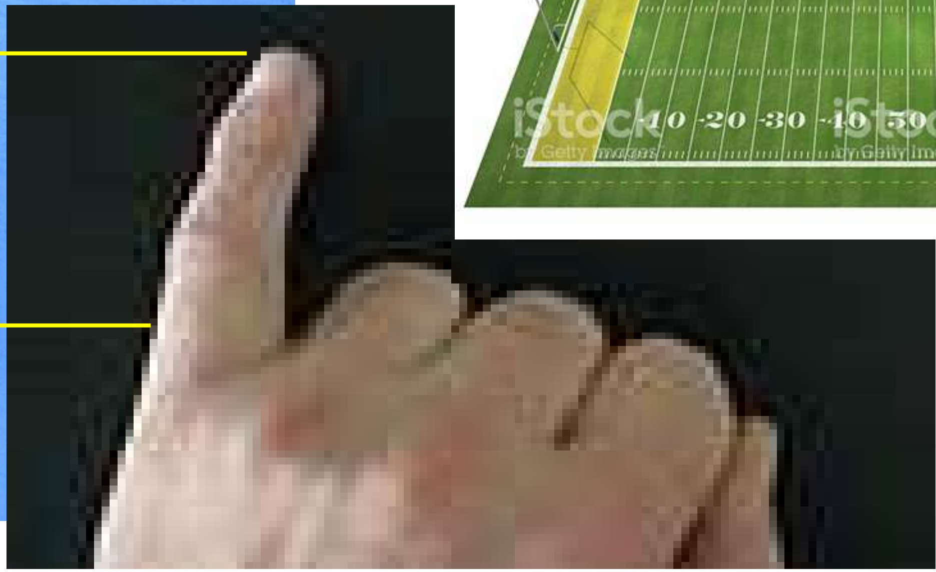
Nearest Star, 10,000 scale miles

*4 Light-Years, ~24,000,000,000,000 real miles**

Proxima Centauri

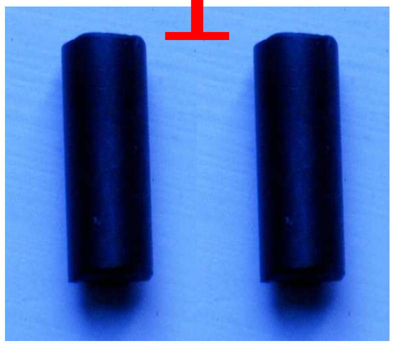
# Nuclear Waste



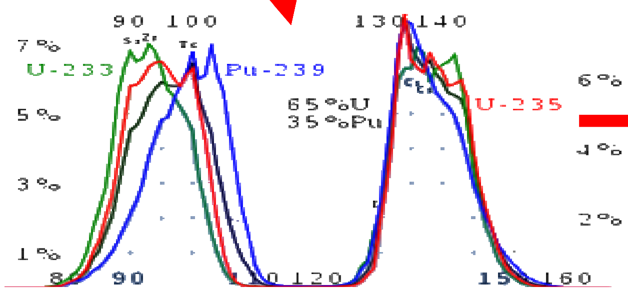



All US fission waste

All 57 years of US nuclear power’s true waste

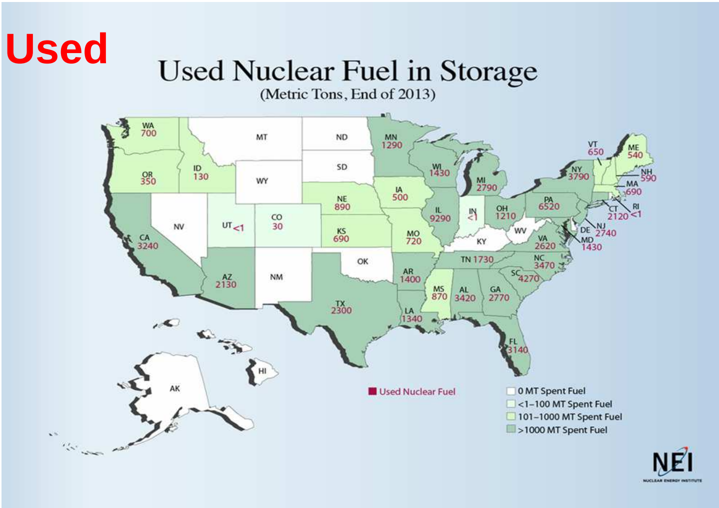


This <15g of fissile, whether fromThorium, Uranium or Plutonium, releases all the energy needed by a US citizen for a decade – <u>all energy needs for 10 years</u>.




The result is two ‘pinkies’ of fission products, (per Avogadro) which are already stable, or mostly radioactive for hundreds of years, not thousands.

# Used 'Spent' Fuel = Not Waste



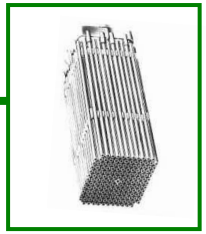

**>74,000 tons = 1 football field**


**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…)***

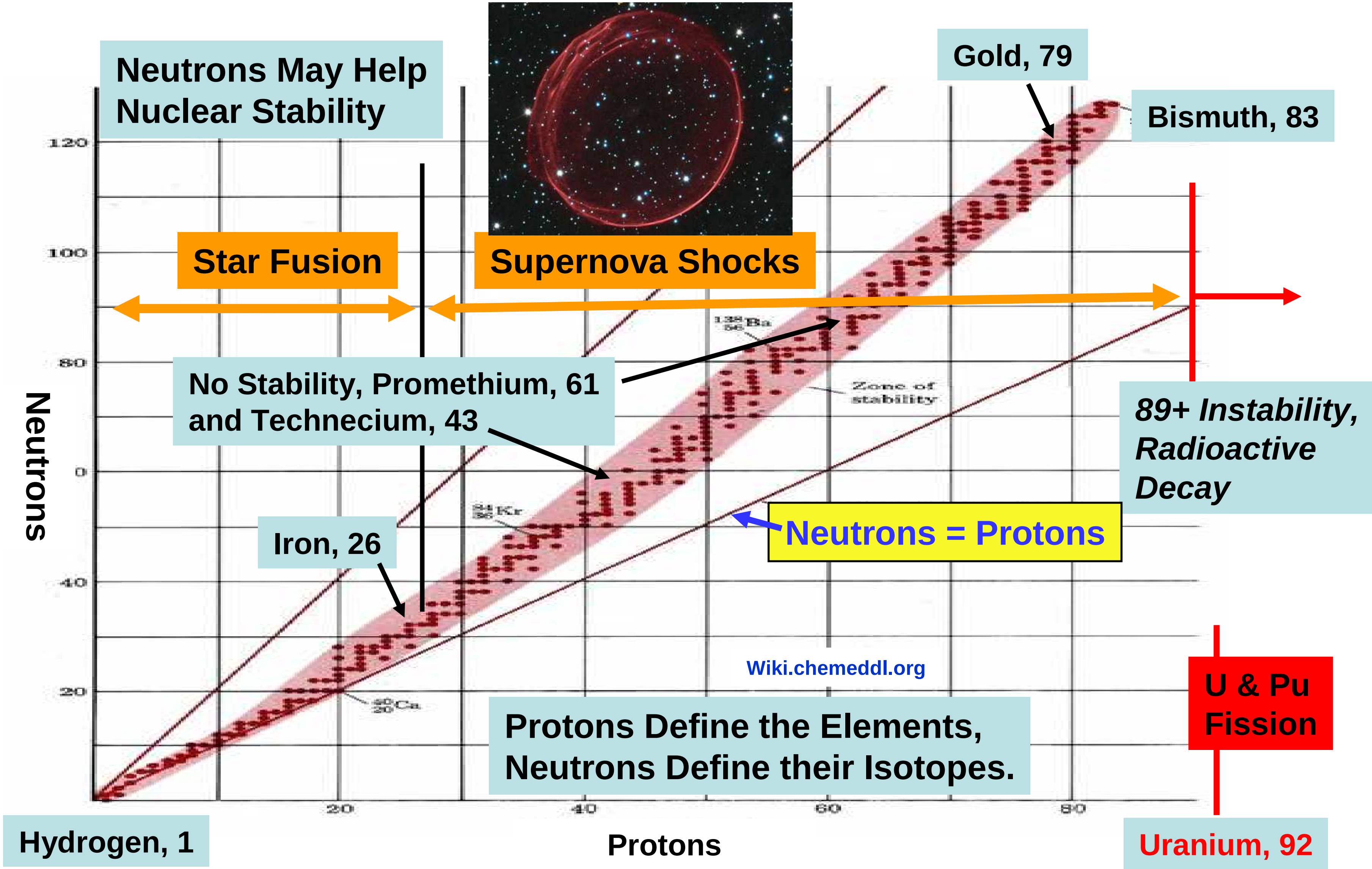
***"…and…make possible the exploitation of the vast energy resources latent in the fertile materials, uranium-238 and thorium." – Glenn Seaborg to JFK, 1962.***


**Used LWR Fuel Bundle**

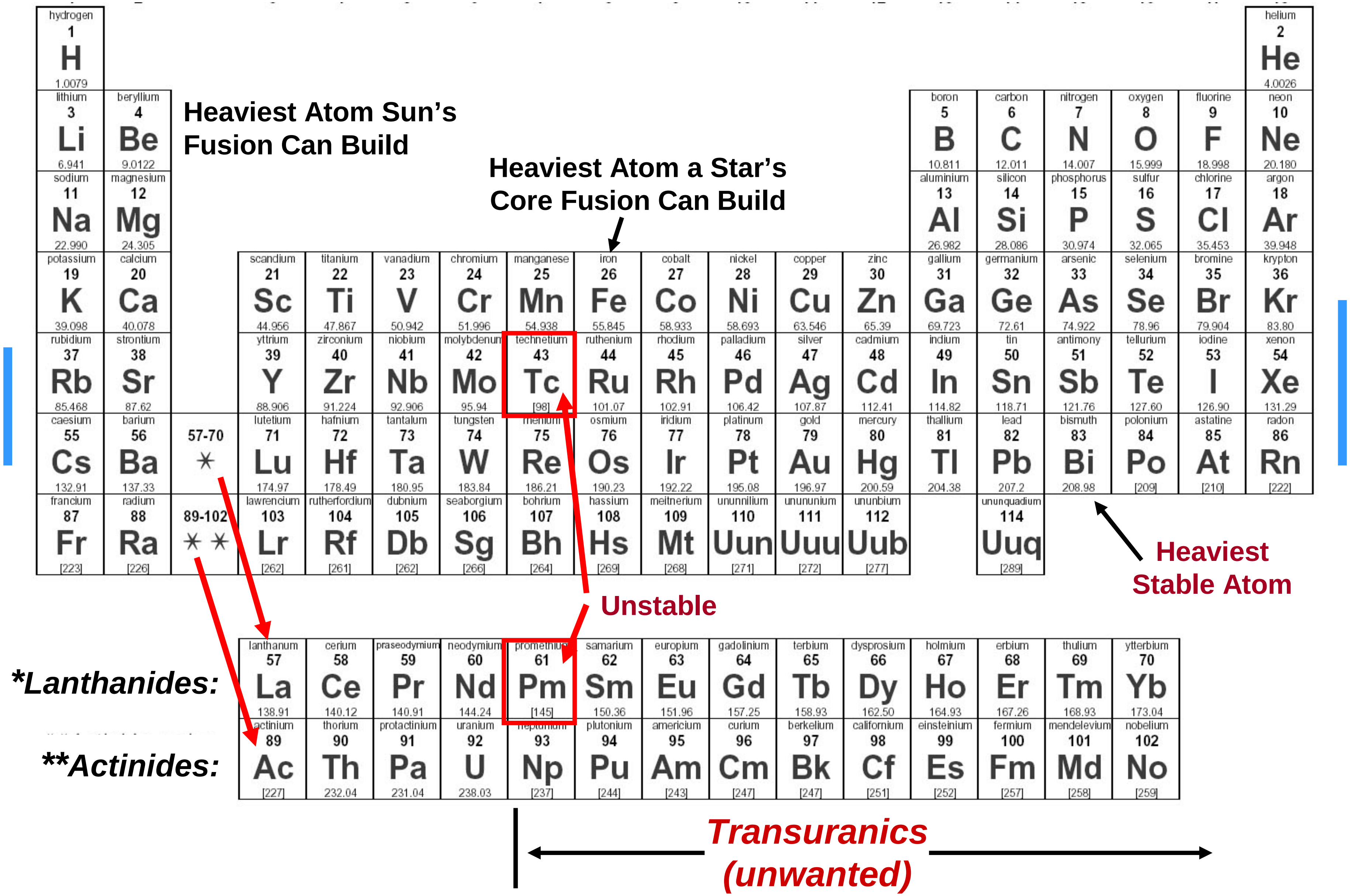


**>95% Not Waste:** ~2% unused fissile fuel, ~4% fission products, ~95% Uranium, and <1% transuranics.

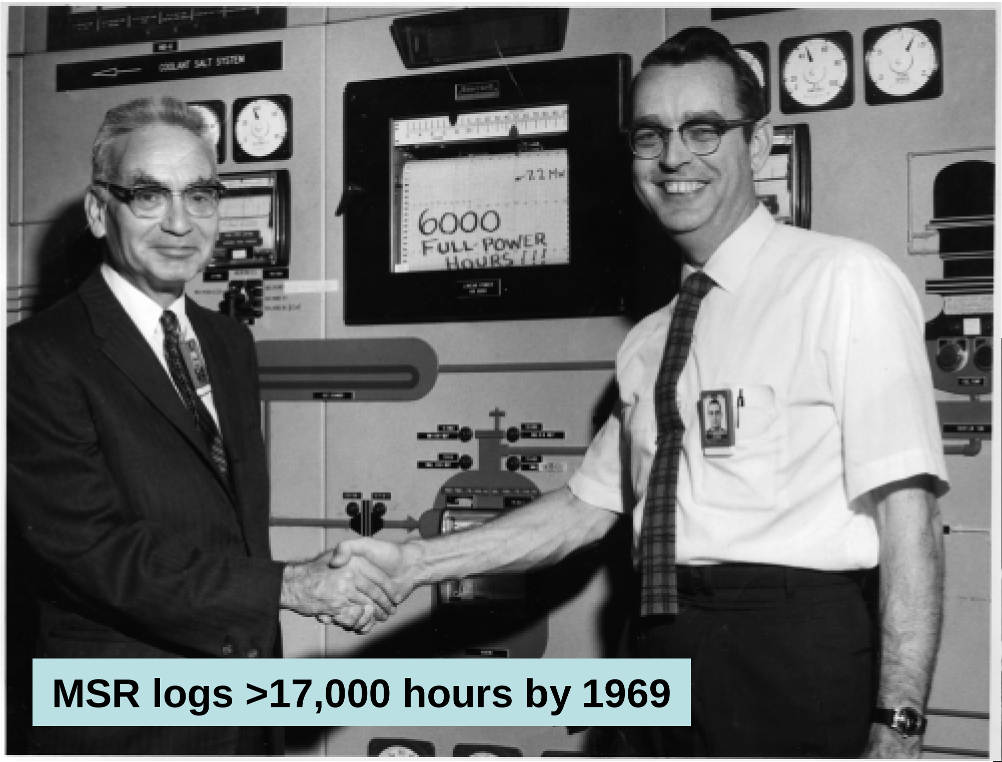
# Elements & Origins



# The Elements



# Molten-Salt Reactor Experiment (MSRE)




MSR logs >17,000 hours by 1969

**6000 Hours of Full-Power operation: Weinberg & Haubenreich**

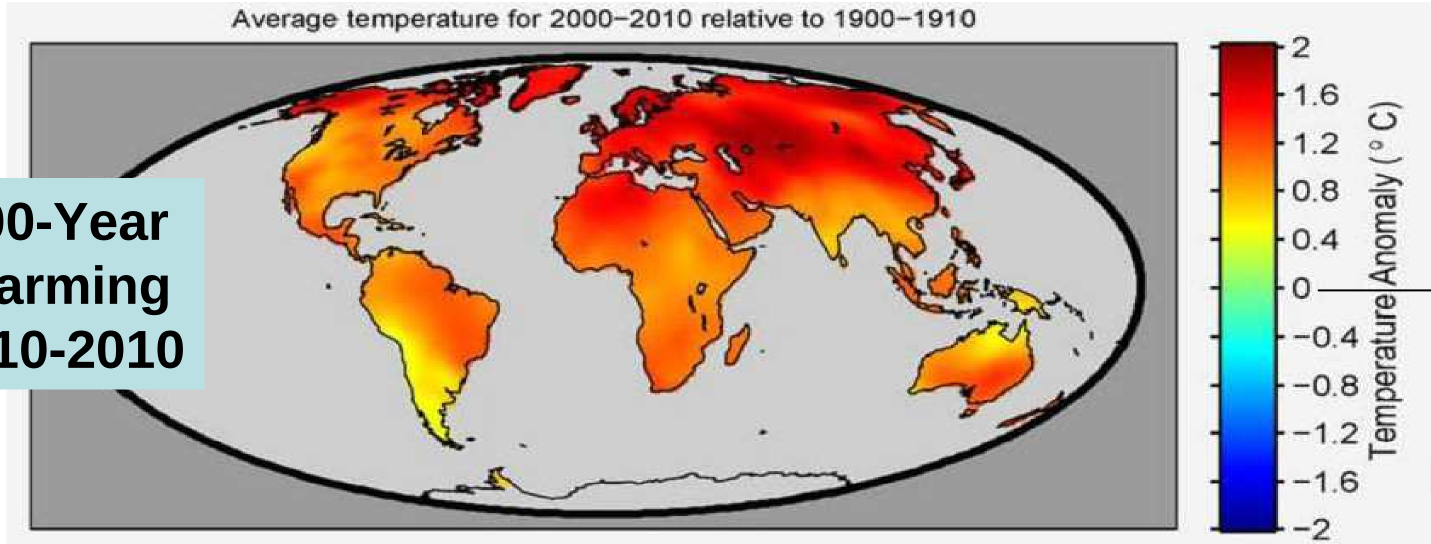
**www/energyfromthorium.com/pdf**

JFK Touring ORNL Before MSRE Start

**http://tinyurl.com/6xgpkfa** - **JFK:** ***"The development of civilian nuclear power involves both national and international interests of the United States."***

**1962, AEC Head, Seaborg:**
***"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."***

# Emissions Effects – Land & Sea



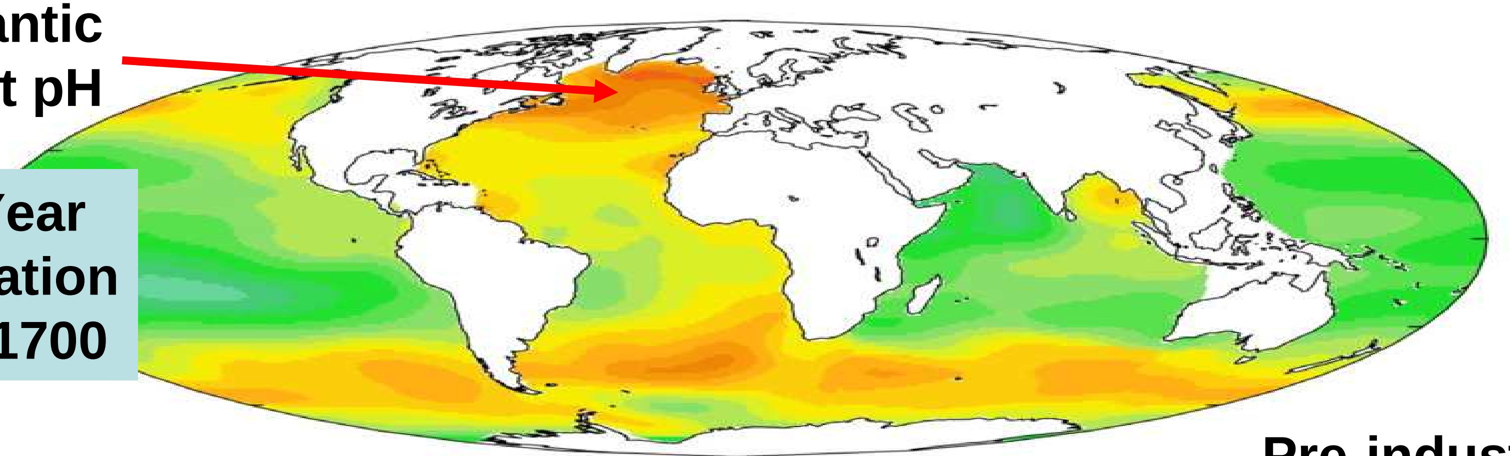

**Hotter**

**100-Year Warming 1910-2010**

**>10,000-Year Holocene Range**

**N. Atlantic Worst pH**

**~300-Year Acidification From ~1700**



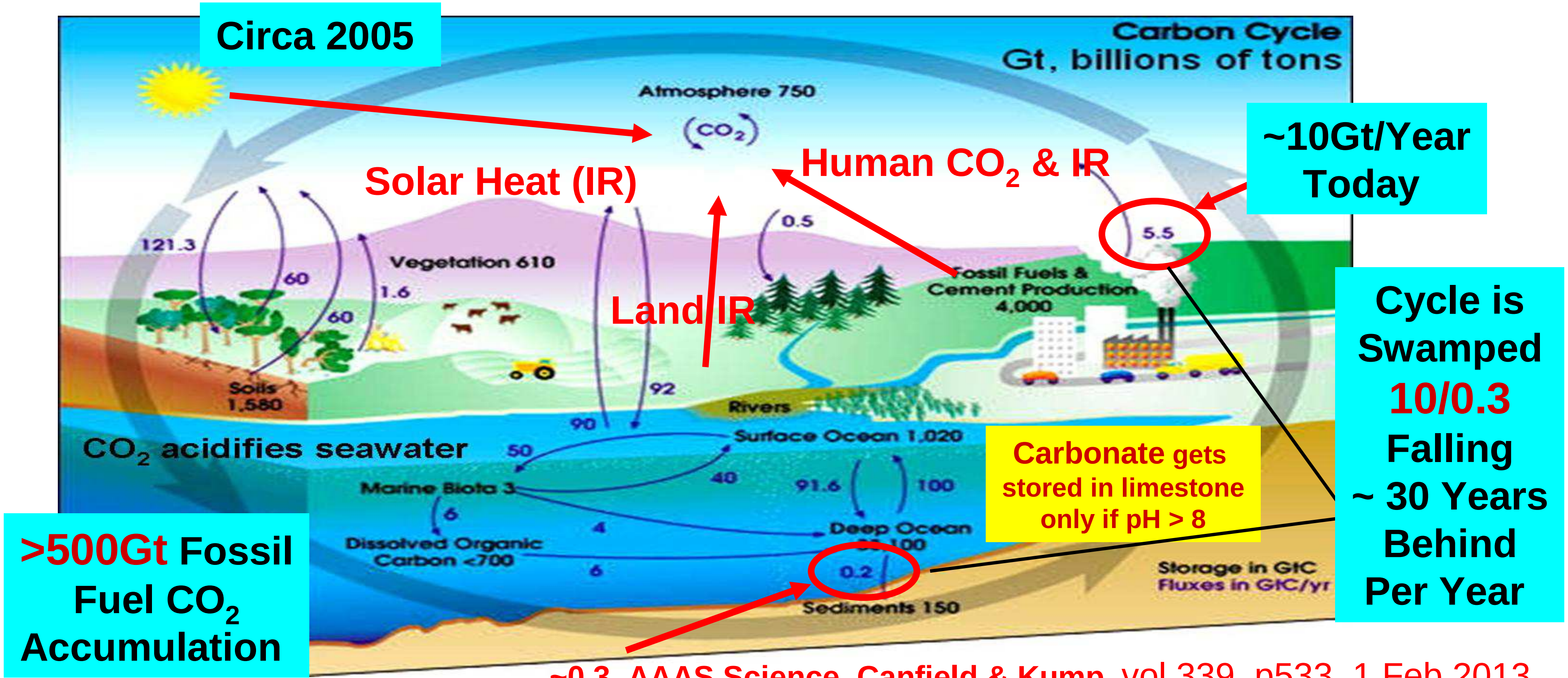
**Today ~8.1 (lowest in >200,000,000 years)**

**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. <u>All fossil fuels we dig up were made this way</u>. Carbon emissions today are **~10Gt** (>30Gt $CO_2$)

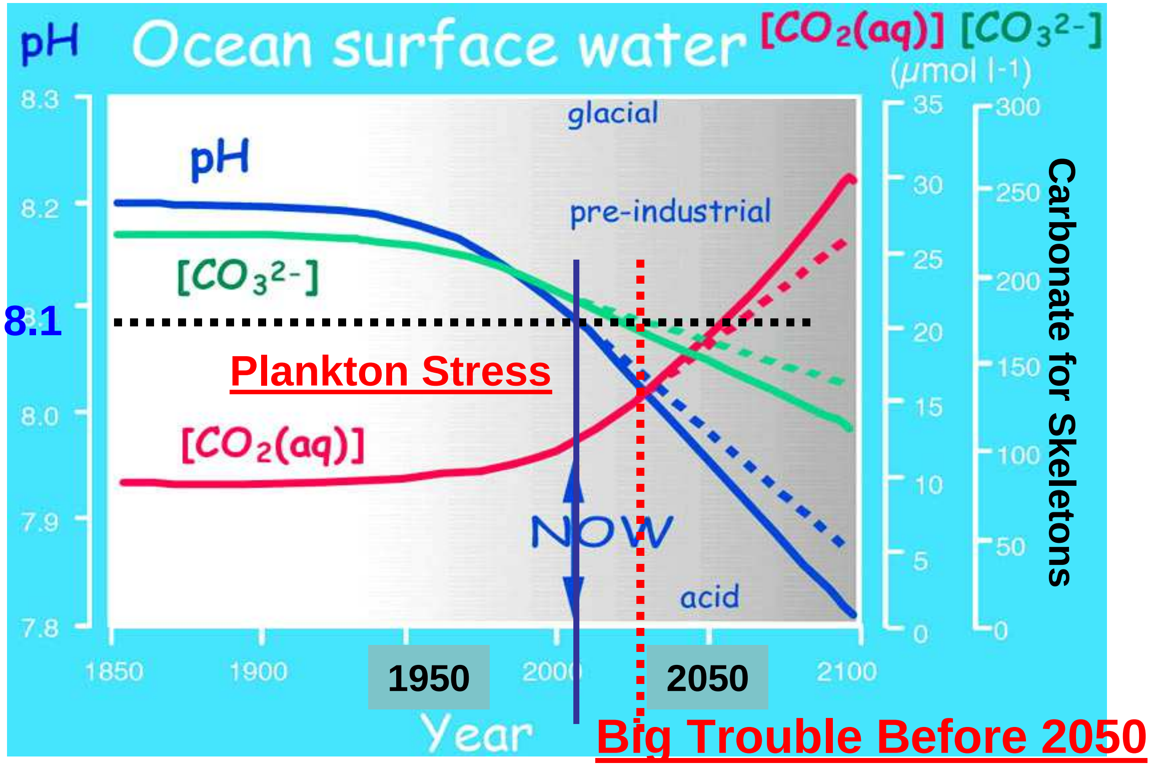
**www3.geosc.psu.edu/~jfk4/PersonalPage/Pdf/annurev_03.pdf**
**www.atmo.arizona.edu/courses/fall07/atmo551a/pdf/CarbonCycle.pdf**
**www.annualreviews.org/doi/abs/10.1146/annurev.earth.031208.100206?journalCode=earth**

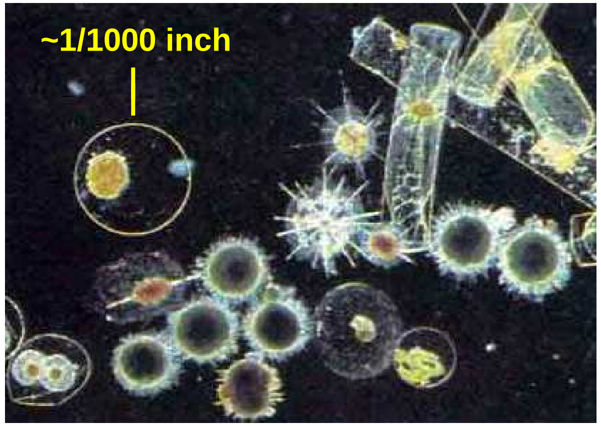



**~0.3, AAAS Science, Canfield & Kump,** vol 339, p533, 1 Feb 2013

# Acidification

**~30% of all ~1.8 trillion tons of $CO_2$ emissions are now in oceans creating less alkaline seawater, affecting entire sea food chains -- <u>sea life provides ~15% of all human food protein</u> – *"The Sixth Extinction"* by Kolbert 2014; "*A short history of ocean acidification science in the 20th century*" by Brewer 2013**




**Deformed Larvae**

**Normal Larvae:**

**Warmer, acidifying North Atlantic**

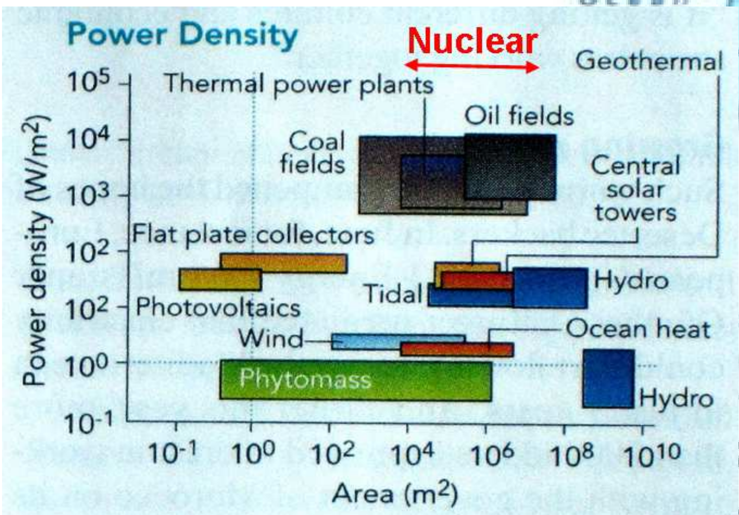
**www.ocean-acidification.net/**
**http://tinyurl.com/6mtd8db**
**www.noaa.gov/video/administrator/acidification/index.html**
**www.bbc.co.uk/news/science-environment-18938002**

# 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**

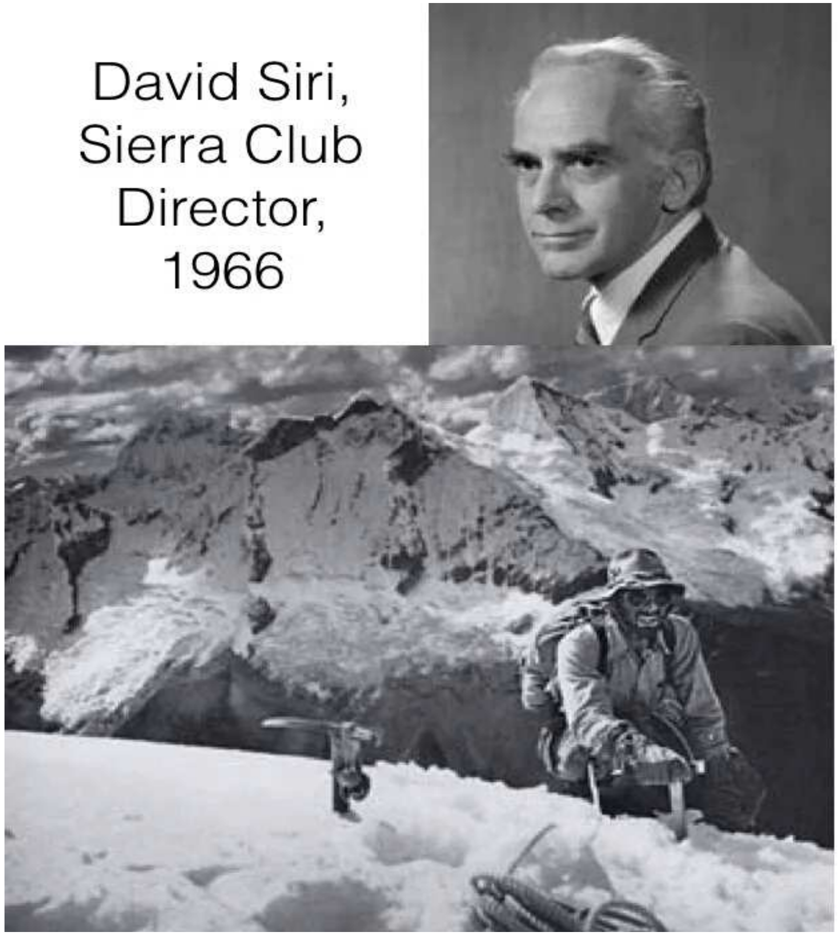

$10^{13}$ **J/kg**

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

**~10kWattHr/lb** *X1,000,000* → **>3GWHr/lb** *x100* → **>$10^{11}$ WHr/lb**

# Nuclear's Environmental Value

David Siri,
Sierra Club
Director,
1966



"Nuclear power is one of the chief long-term hopes for conservation…Cheap energy in unlimited quantities is one of the chief factors in allowing a large rapidly growing population to preserve wildlands, open space, and lands of high scenic value… With energy we can afford the luxury of setting aside lands from productive uses."

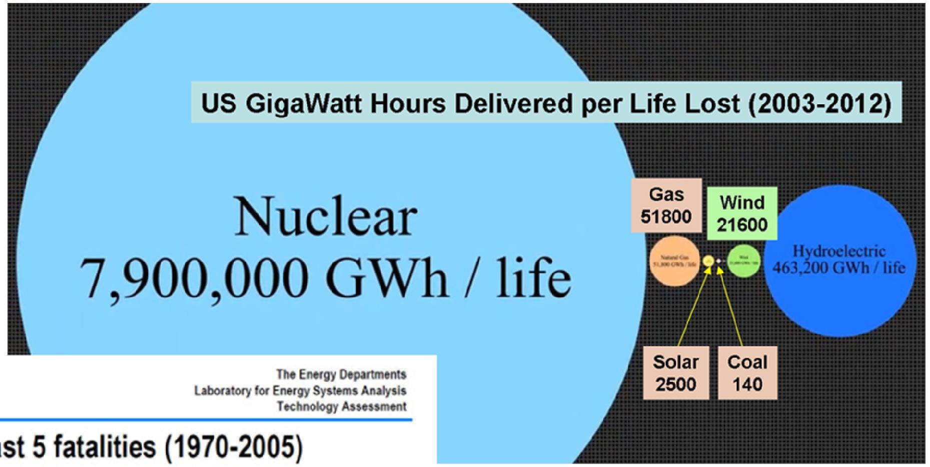
The Sierra Club's motto was wisely: "Atoms, not dams", and Ansel Adams said: ***"Nuclear energy is the only practical alternative that we have to destroying the environment with oil and coal."*** And, now we know, all 'renewables' require oil, coal, or gas to make up for more energy than they deliver.

# Nuclear Power Safety

**Present Civilian & Naval Nuclear Power is the Safest Form of Power Generation Ever Deployed by Humanity:** **PSI ENSAD 1998;**
**www.scientificamerican.com/article.cfm?id=the-human-cost-of-energy (2013)**
**http://cen.acs.org/articles/91/web/2013/04/Nuclear-Power-Prevents-Deaths-Causes.html**

**Comparative Power Source Safety**

**http://thoriumremix.com/th/**

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The Energy Departments
Laboratory for Energy Systems Analysis
Technology Assessment

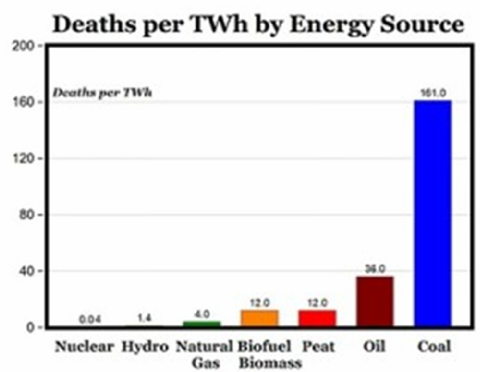
**Severe accidents with at least 5 fatalities (1970-2005)**

| | OECD | | EU 27 | | non-OECD | |
|---|---|---|---|---|---|---|
| Energy chain | Accidents | Fatalities | Accidents | Fatalities | Accidents | Fatalities |
| Coal | 81 | 2123 | 41 | 942 | 144<br>1363 (a) | 5360<br>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



# Relative Power Dangers

**Burgherr & Hirshberg, 2008**

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

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**http://tinyurl.com/kqce99w**
www.forbes.com/sites/jamesconca/2013/09/29/forget-eagle-deaths-wind-turbines-kill-humans/

**OECD = Org. for Econ. Co-operation & Dev.**

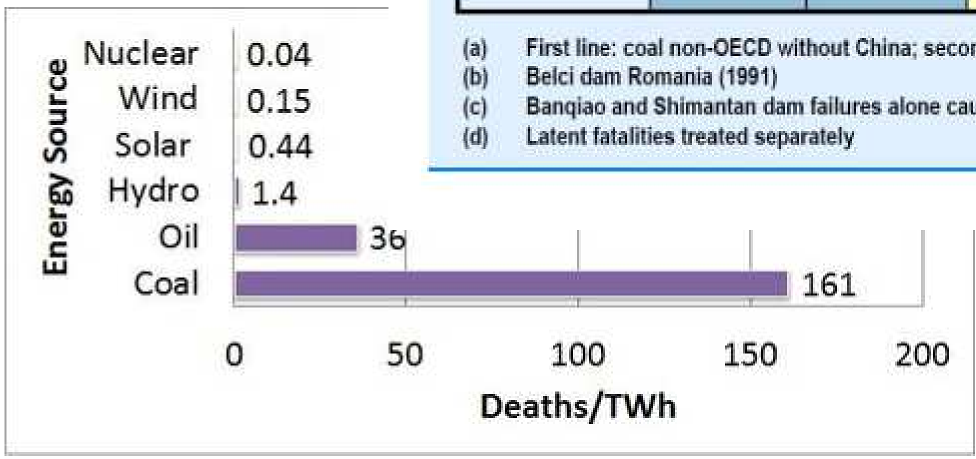
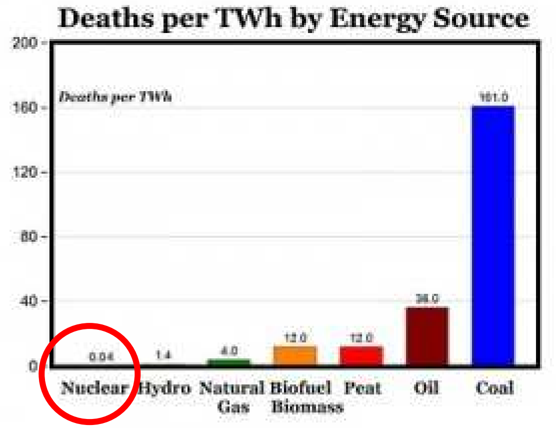
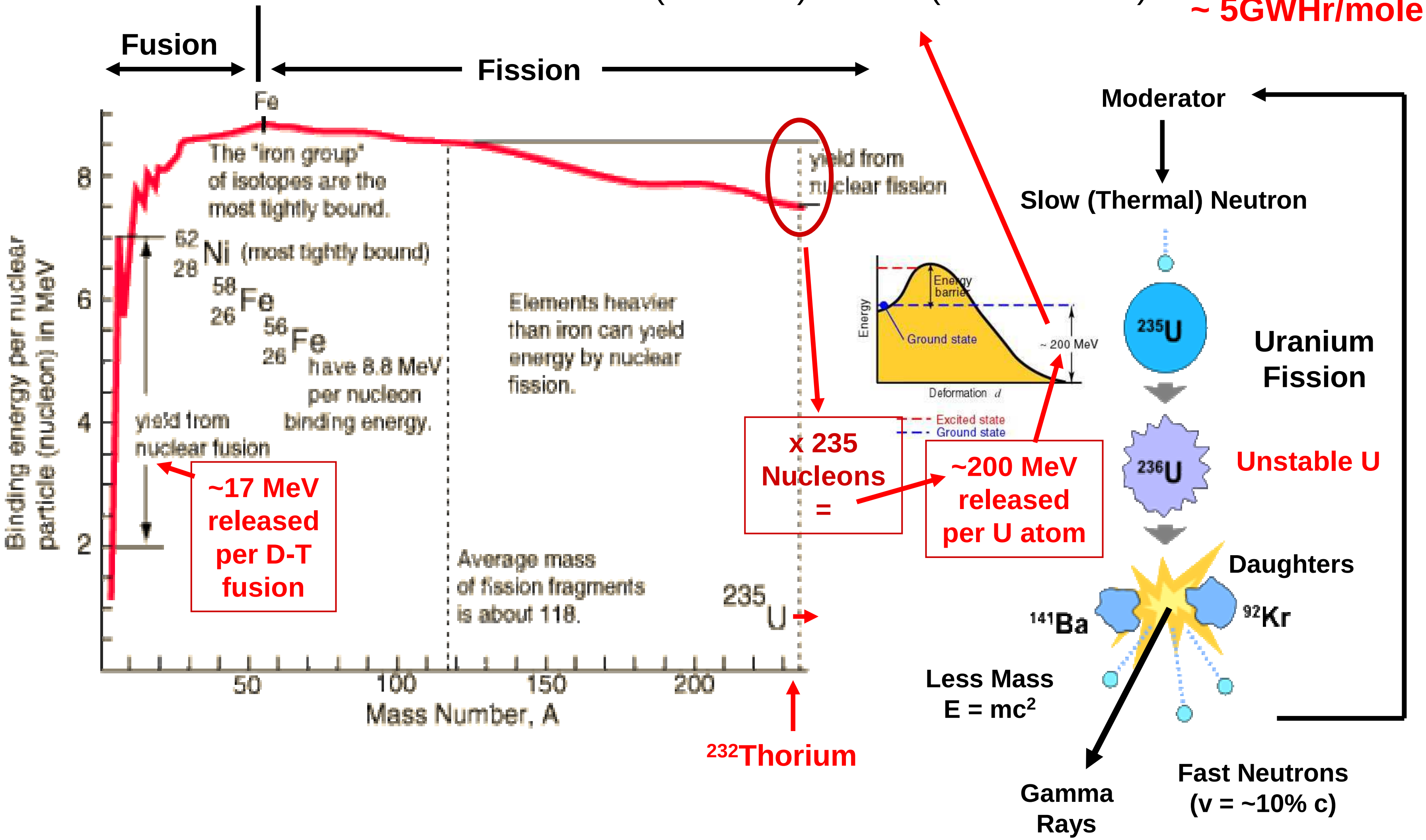



Figure 4: Life Cycle Deaths of Various Energy Sources (Wang 2012)



# Nuclear Energy

$$\frac{602000000000000000000000 \text{ (atoms/mole)} \times 200000000 \text{ (eV/atom)}}{6250000000000000000 \text{ (eV/Joule)} \times 3600 \text{ (Joule/WattHr)}}$$



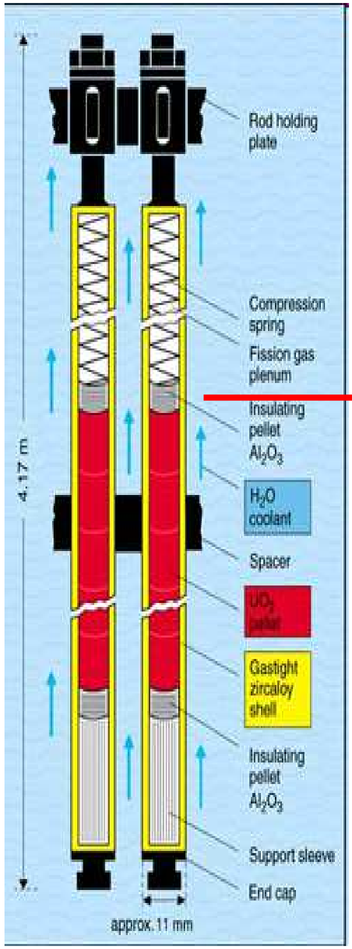
# Natural Fission

**The mountains in Oklo, south-eastern Gabon are home to several <u>natural $^{235}$Uranium fission reactors</u>. 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.**

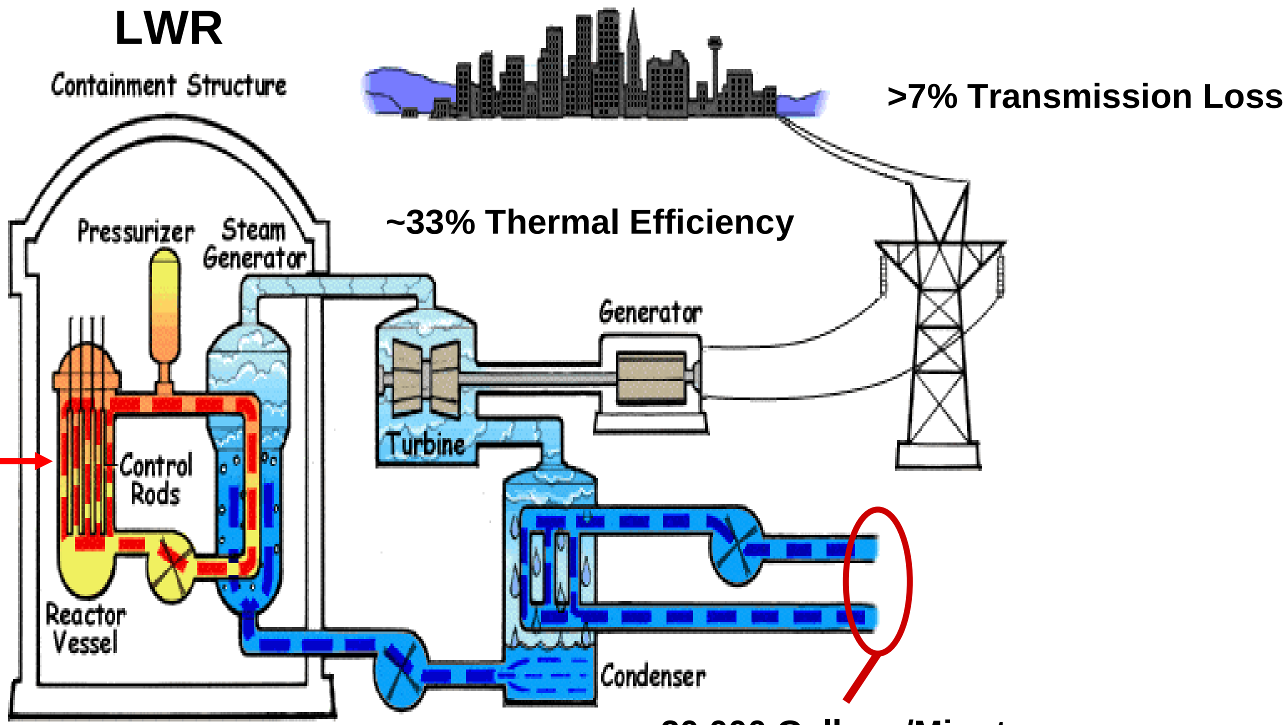

**http://www.ans.org/pi/np/oklo/**
**http://www.ans.org/pi/np/oklo/**
**http://en.wikipedia.org/wiki/Natural_nuclear_fission_reactor**
**www.physics.isu.edu/radinf/Files/Okloreactor.pdf**

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

**Fuel Rods**




**LWR**




**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**

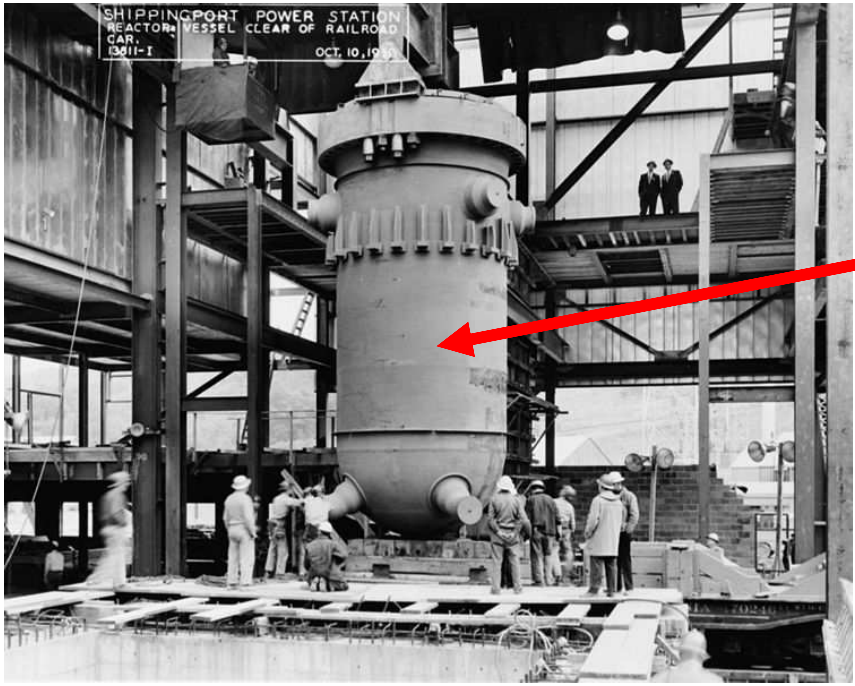
# $^{235/238}$Uranium Light-Water Reactors

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

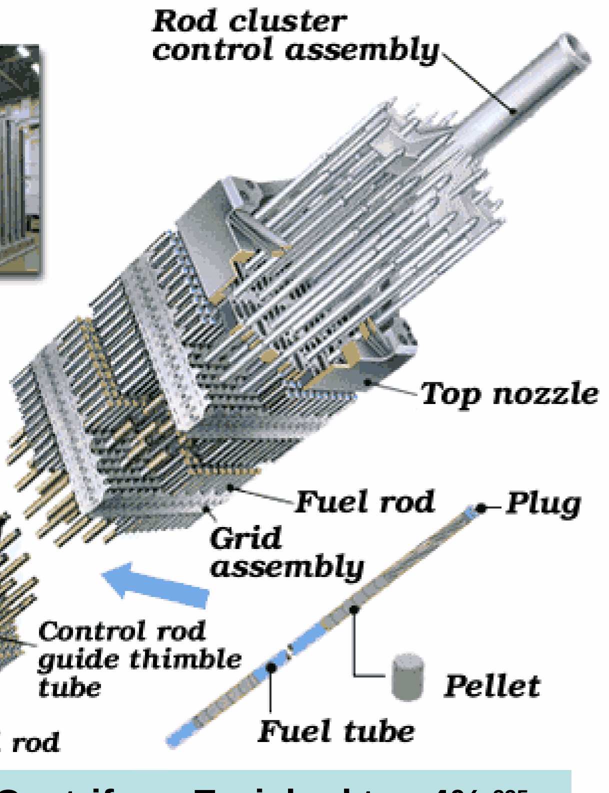
**Modern U235/238 Centrifuge**

**Workers**


**First Commercial US Reactor (60MW)**



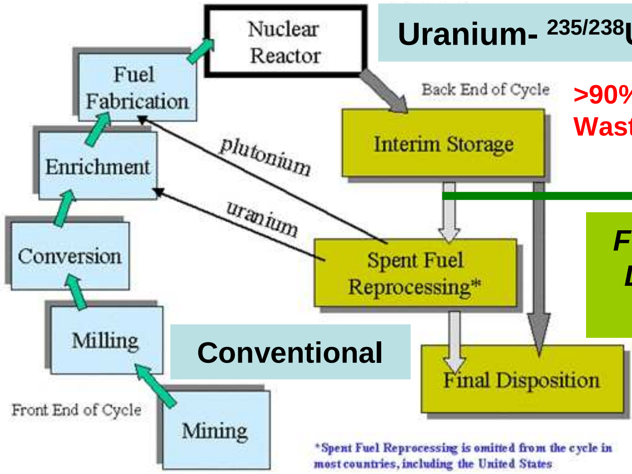

**Shippingport, Penn, 1954-56**




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

**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



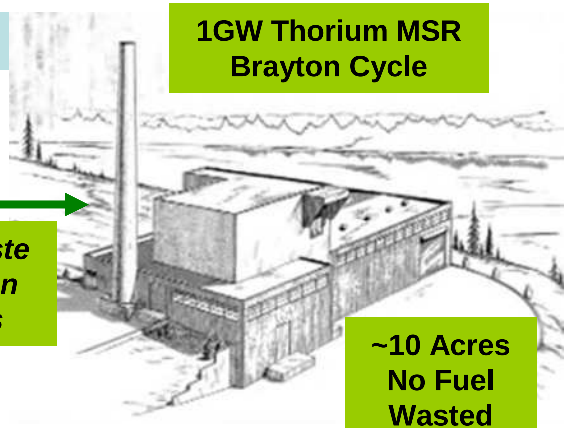

**Uranium- $^{235/238}$U Cycle**

**>90% U Wasted**

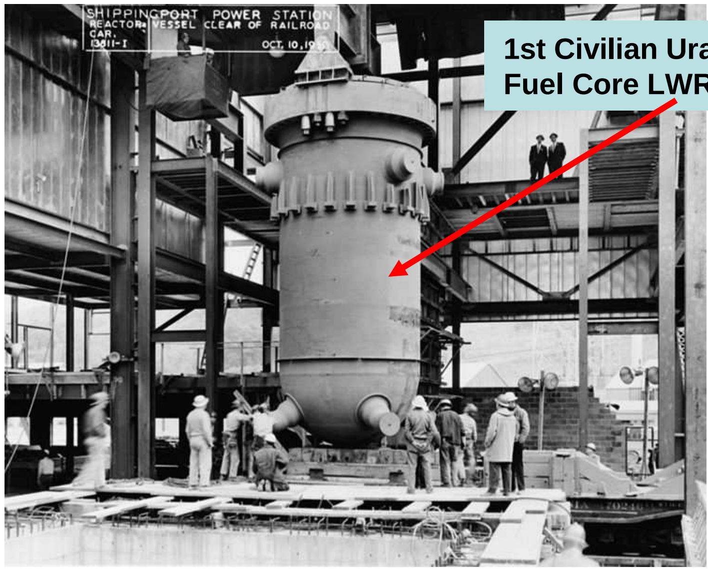
**Conventional**

***Future Waste Destruction Via MSRs***

**1GW Thorium MSR Brayton Cycle**

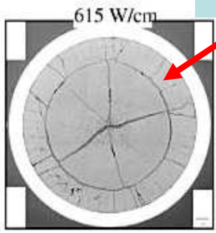


**~10 Acres No Fuel Wasted**




**1st Civilian Uranium Solid-Fuel Core LWR, 60MW**

**Normal Solid-Fuel Pellet Damage In <5 Years, Cladding Must Hold Unused Fuel + Wastes For Millennia**




**~10mm Dia.**

**Equivalent 60MW Thorium MSR Core**

***Equal Scales***

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

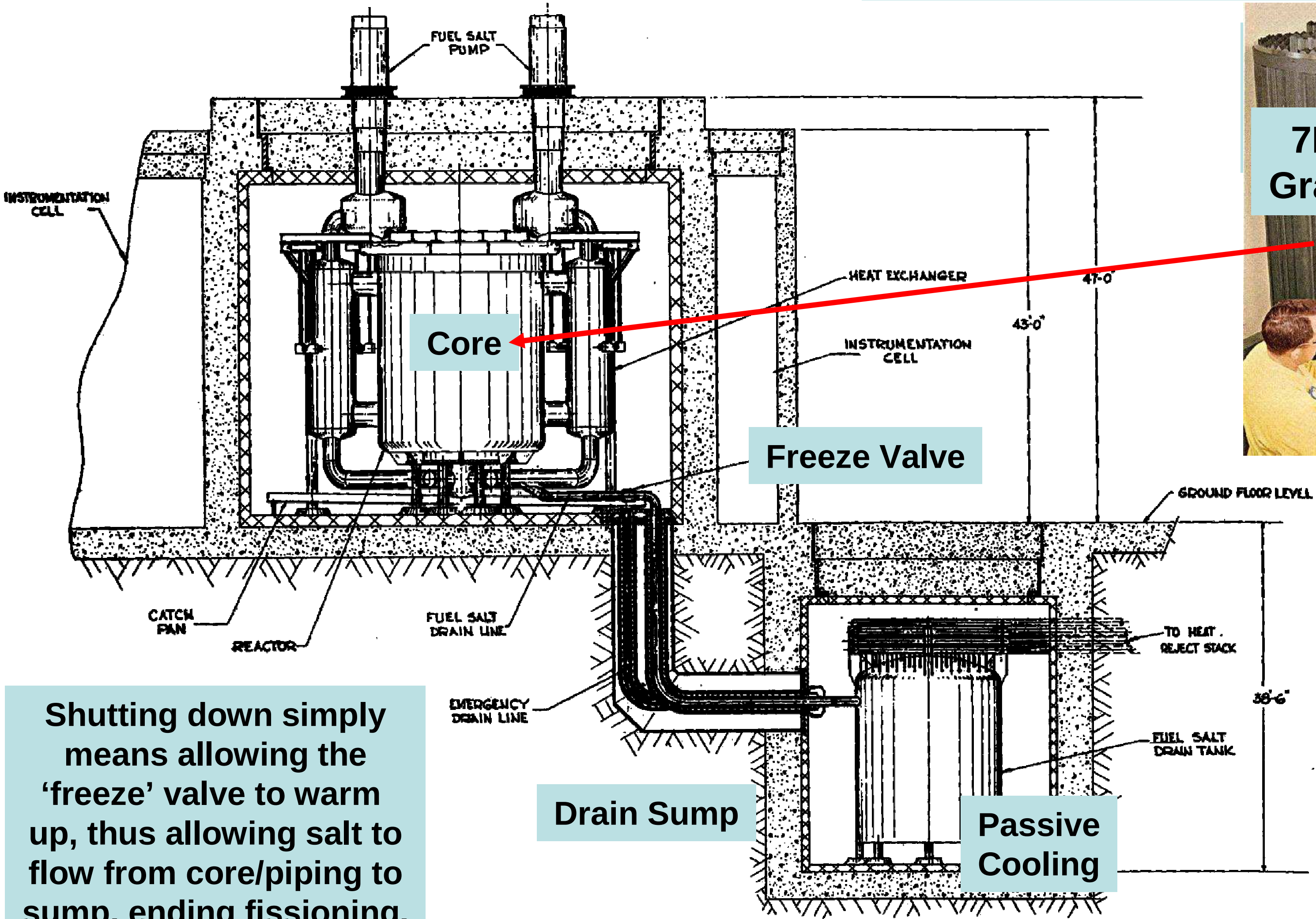
# Molten-Salt Reactors, Thorium Optional

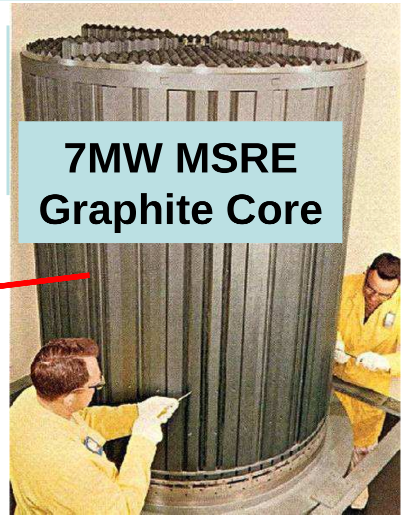
- **Thorium is more common & cheaper than Uranium**…
  - **No 'enrichment'** $ or energy wasted – **$^{232}$**Th is just a metal common in "rare-earth" ores.
  - **All Thorium is consumed** – no 'spent' fuel (>90% of BWR/PWR Uranium goes unused).
- Thorium-Fluoride salt is the 'fertile fuel' input ($ThF_4$ 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** -- if 100% breeder (iso-breeder).
  - **$^{233}$**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 & MSFR 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 & modular** from MW to GW – siting anywhere on Earth or in space.
  - **See**: **http://tinyurl.com/nu5o7k5** plus Terrestrial Energy, Thorcon, EVOL MSFR.

# The MSR (Molten-Salt Reactor)

**Molten-Salt Reactor & Shutdown Sump Structure…**

**1965-69 MSRE**
**www.energyfromthorium.com/pdf**



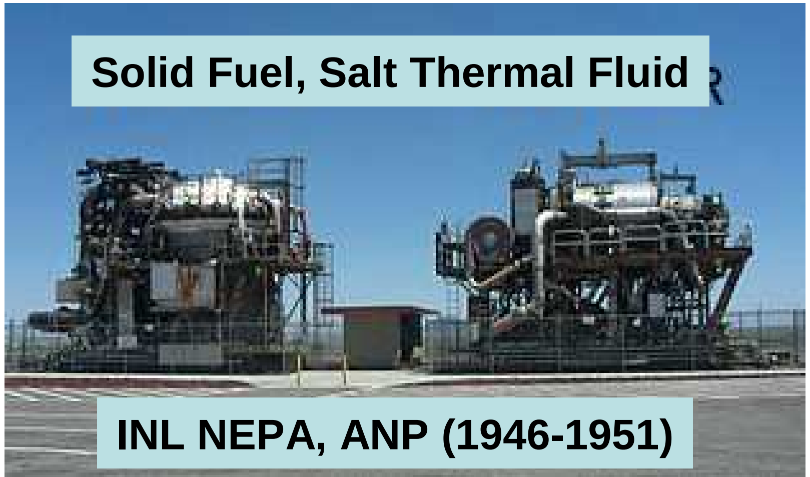



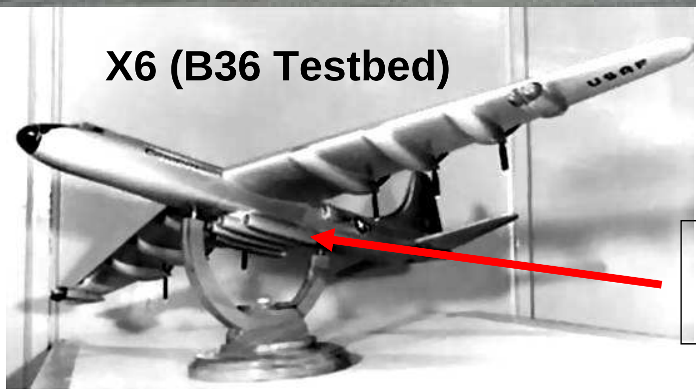

**Shutting down simply means allowing the 'freeze' valve to warm up, thus allowing salt to flow from core/piping to sump, ending fissioning.**

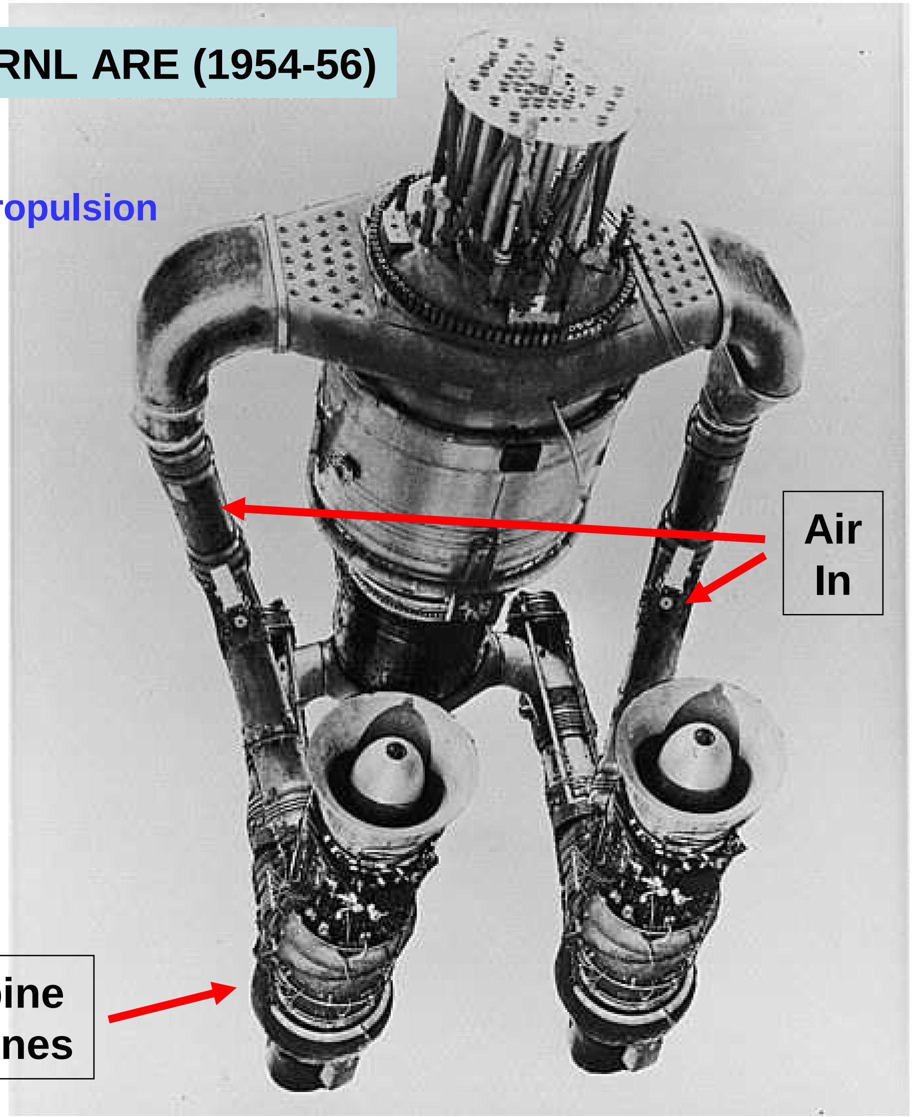
# Aircraft Reactor Experiments

**HTR-1 was operated for >5 GWHrs.**

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



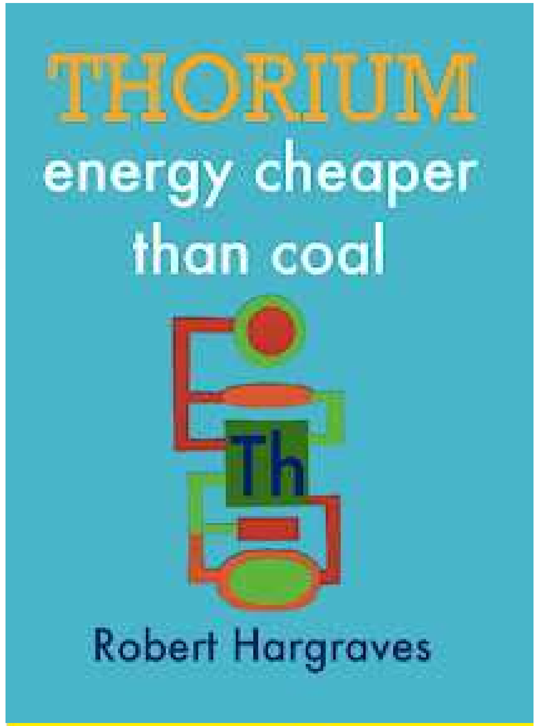



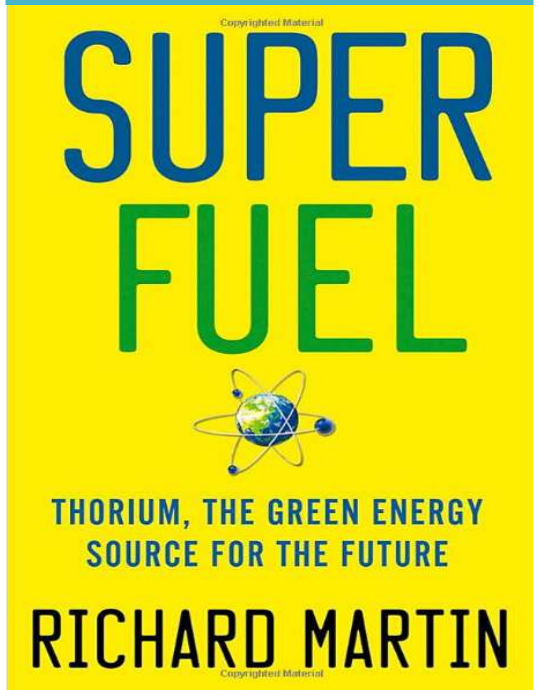

http://moltensalt.org/references/static/downloads/pdf/NSE_ARE_Operation.pdf
http://large.stanford.edu/courses/2012/ph241/omar2/

**See movie “Pandora’s Promise”**
**http://pandoraspromise.com/**
**by Richard Stone**

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

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



# Fission Choices

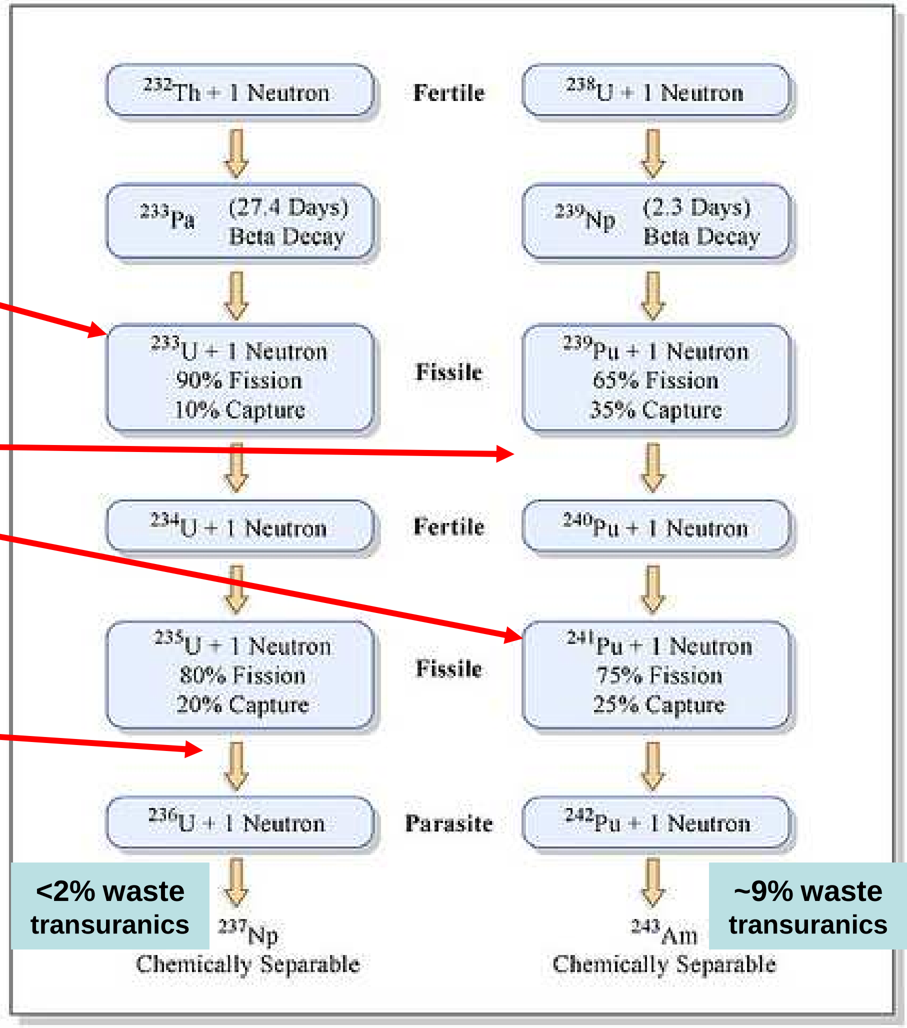
**Thorium bred to $^{233}$U with a neutron (via Protactinium decay), or via proton-beam & spallation**

**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**

**Graphics Courtesy of Wikipedia**

**Starting Fission with Thorium vs $^{238}$Uranium**



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

**Indian Point NY (~2GWe)**

**Enrichment 'Waste', U235-Depleted Below Ore**


**Fertile >99% of U Ore** — $^{238}$U + 1 Neutron

↓

$^{239}$Np (2.3 Days) Beta Decay

↓

**Fissile** — $^{239}$Pu + 1 Neutron, 65% Fission, 35% Capture

↓

**Fertile** — $^{240}$Pu + 1 Neutron

↓

**Fissile** — $^{241}$Pu + 1 Neutron, 75% Fission, 25% Capture

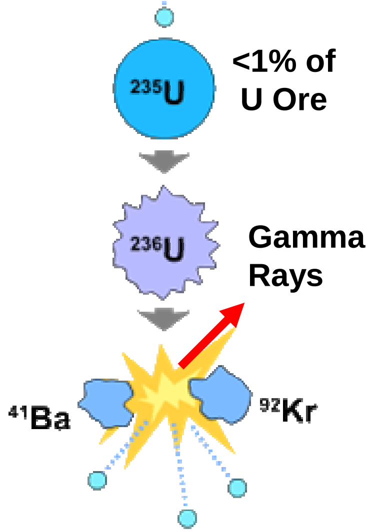
**~8% Waste** → ↓

**Parasite** — $^{242}$Pu + 1 Neutron

↓

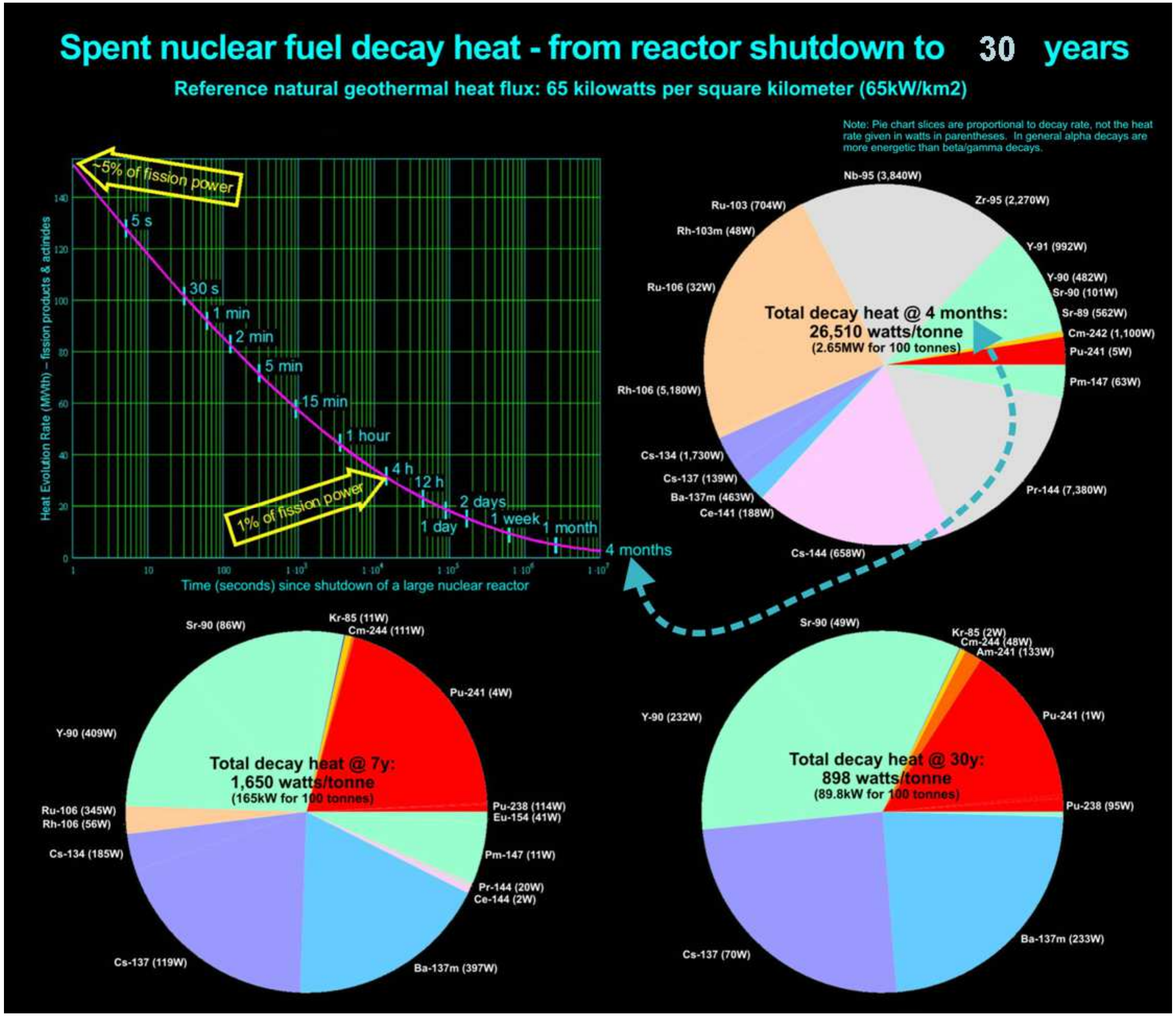
$^{243}$Am Chemically Separable

**Slow Neutron**



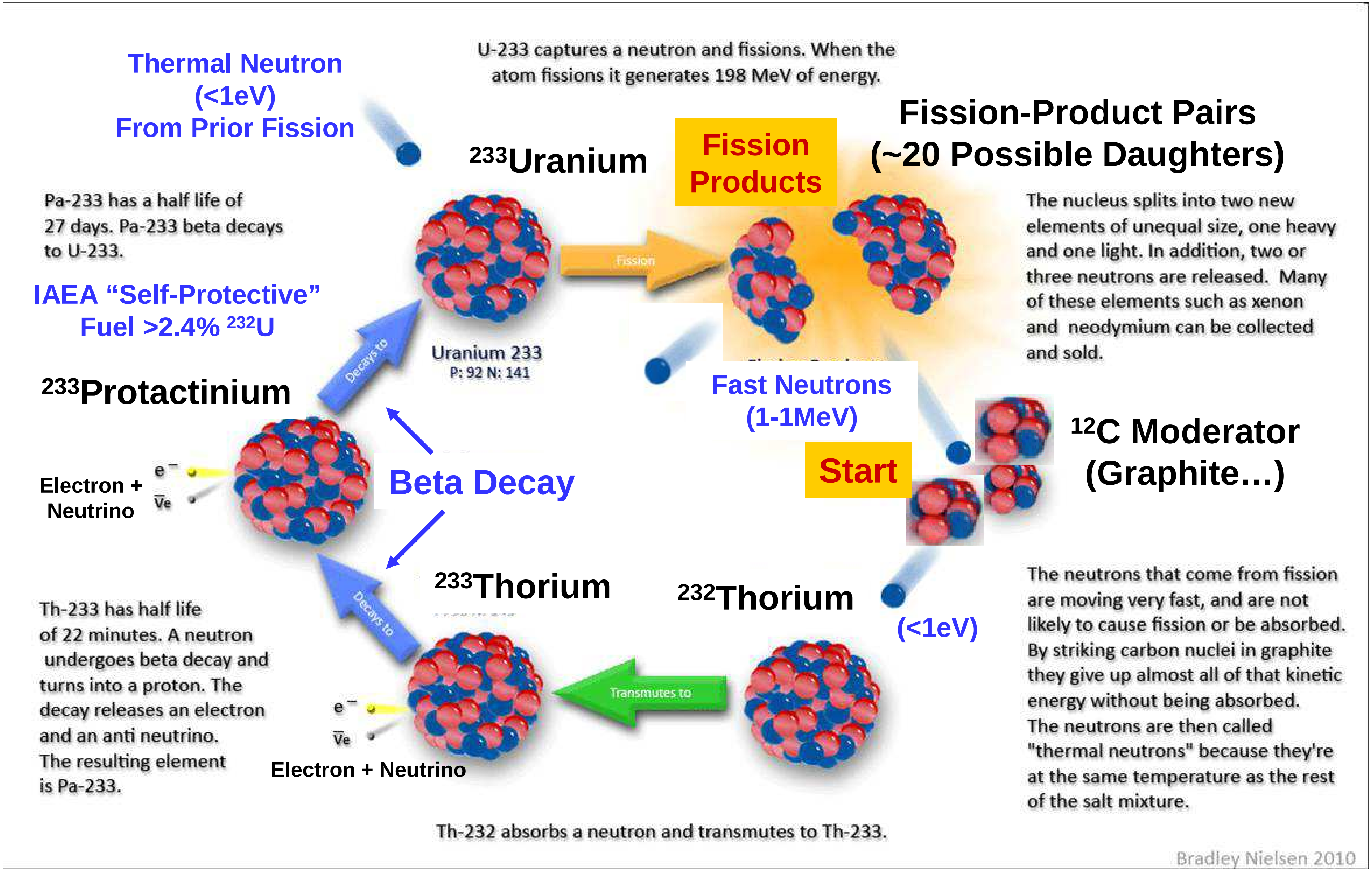

**1-4 Neutrons + pairs of ~20 other possible Fission fragments like: Rb, Cs, Sr, Xe… Plus ~200MeV or ~176 years of an American's energy use, per kilogram of U235.**

# $^{235/238}$U Reactor Decay Heat *(notes)*



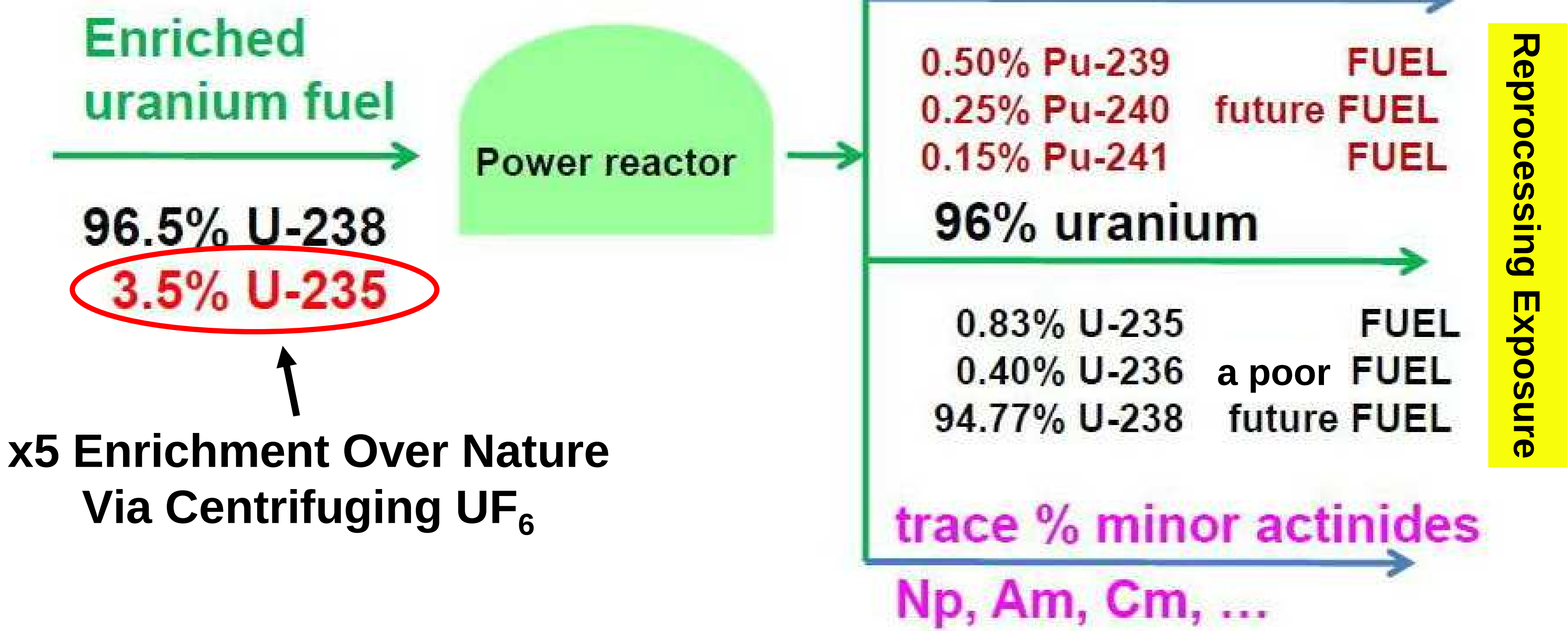

**After 3 Years, Solid Used Fuel Can Be Stored in Air**

# Thorium Breeding Cycle

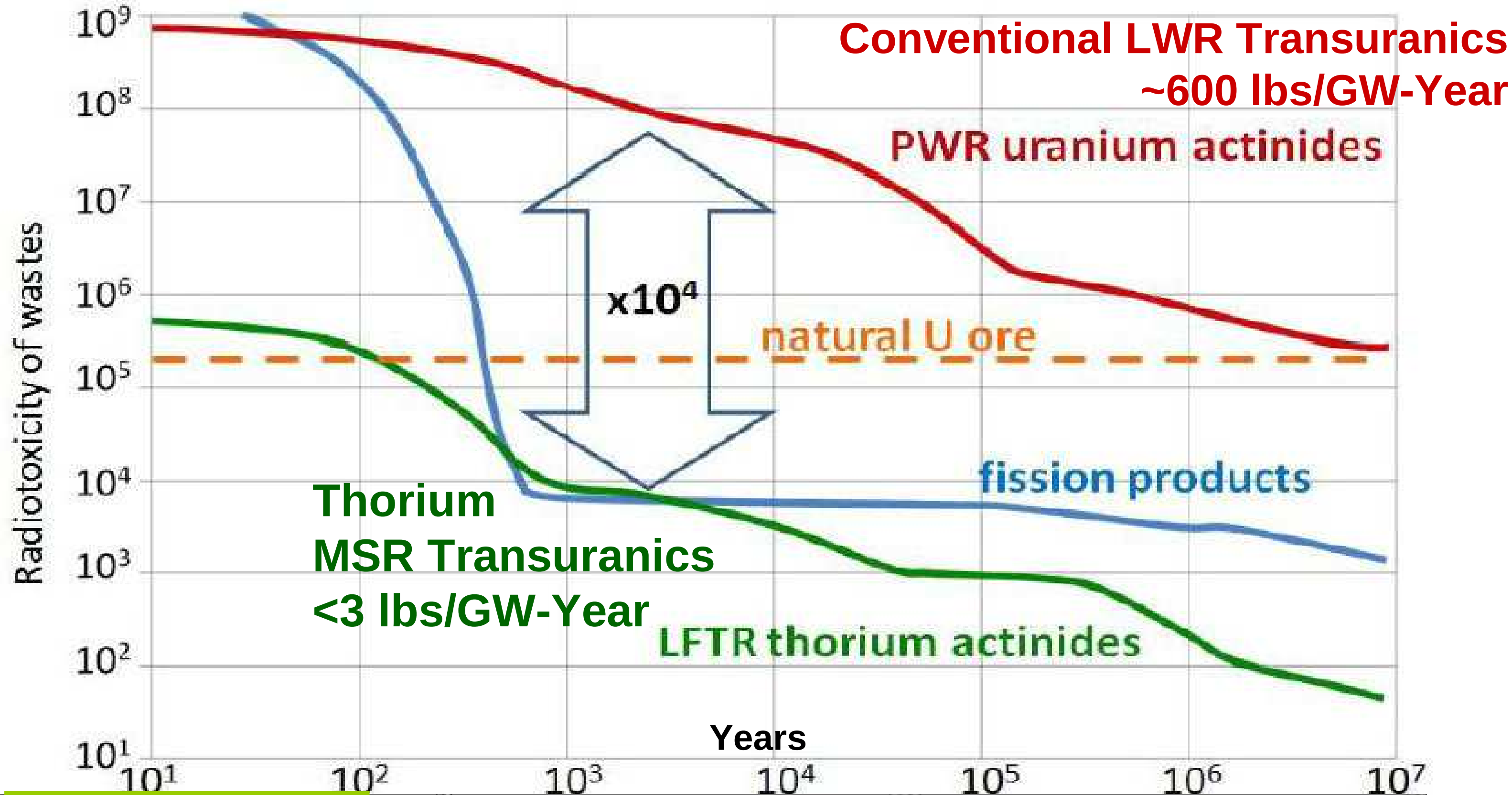


# Waste Comparisons

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



# Waste Comparisons

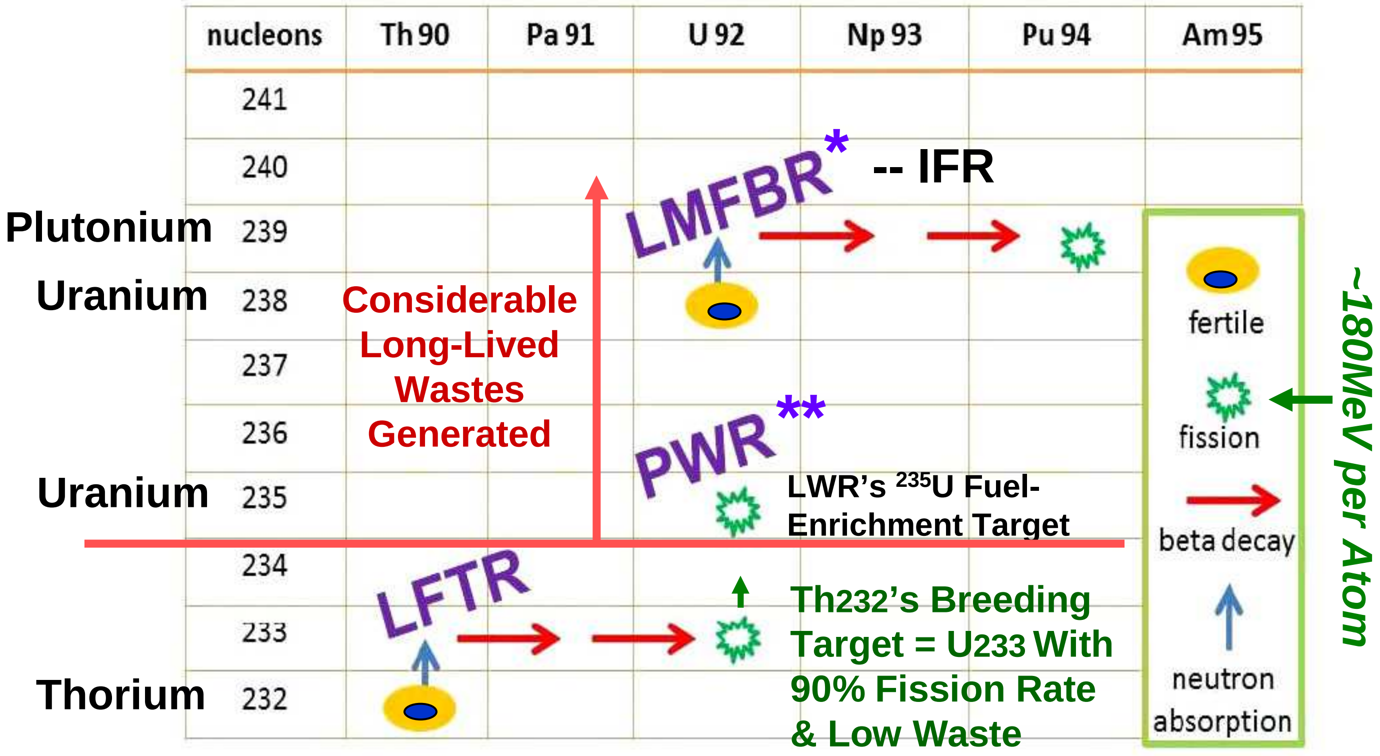



| For 30 years total: | FUJI-U3 (1GWe) | Relative to 1GWe BWR |
|---|---|---|
| Fissile requirement | 7.8 t (reusable) | 32% |
| Pu production | 4 kg | 0.1% |
| MA (Np/Am/Cm) production | 23 kg | 4 % |

Japanese Example ~60 lbs in 30 GW yrs

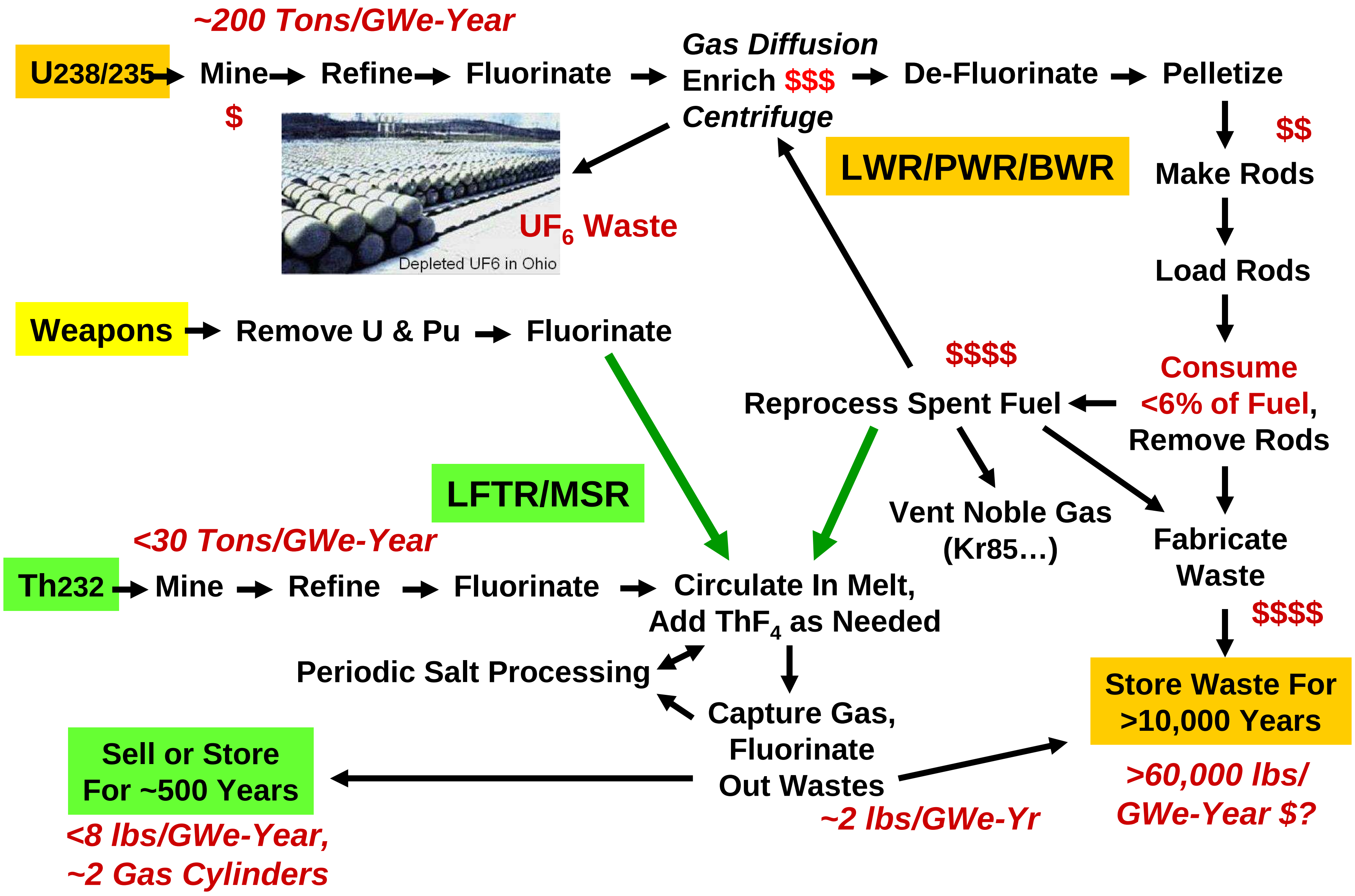
# The Thorium Solution

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




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

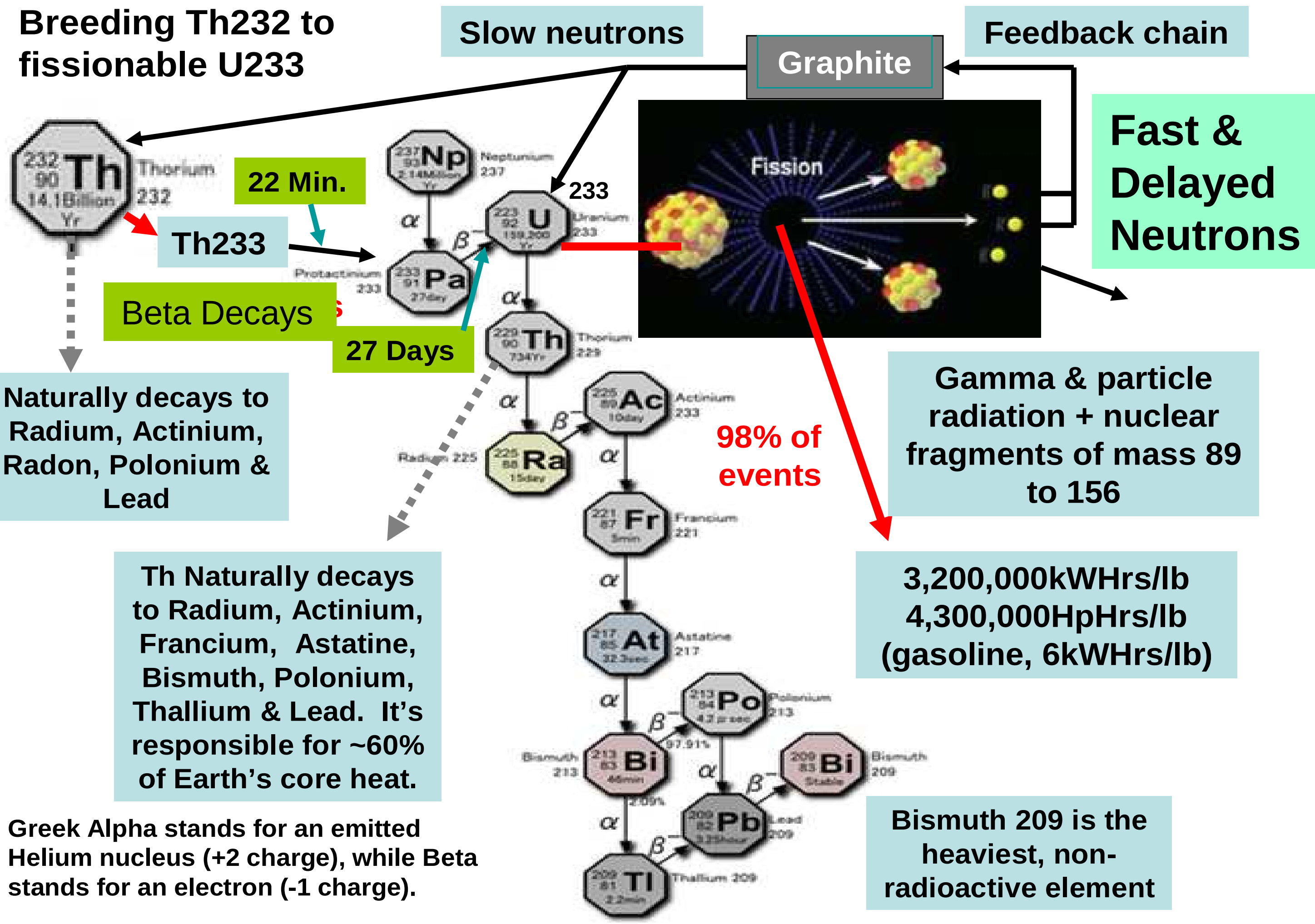
# Thorium MSR & Uranium LWR Cycles



# Thorium to $^{233}$U Based Fission

**Abundant, Cheap, low radioactivity**

**Breeding Th232 to fissionable U233**




**Naturally decays to Radium, Actinium, Radon, Polonium & Lead**

**Th Naturally decays to Radium, Actinium, Francium, Astatine, Bismuth, Polonium, Thallium & Lead. It's responsible for ~60% of Earth's core heat.**

**Greek Alpha stands for an emitted Helium nucleus (+2 charge), while Beta stands for an electron (-1 charge).**

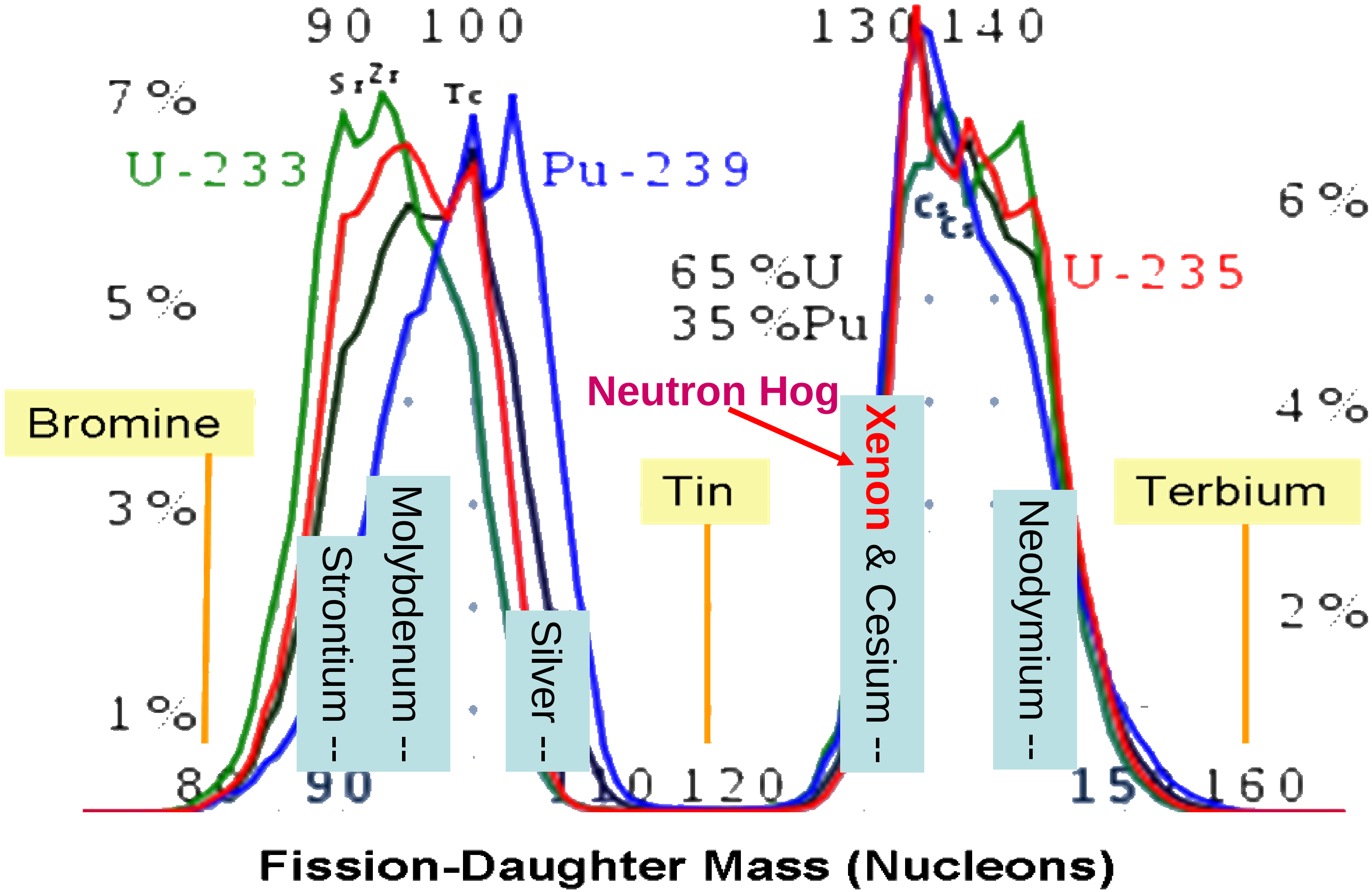
**Gamma & particle radiation + nuclear fragments of mass 89 to 156**

**3,200,000kWHrs/lb**
**4,300,000HpHrs/lb**
**(gasoline, 6kWHrs/lb)**

**Bismuth 209 is the heaviest, non-radioactive element**

***For proliferation protection, U233 can be made "Self-Protective" per IAEA, if it is bred to be >2.4% U232 by inclusion of Th230 or similar source isotope.***

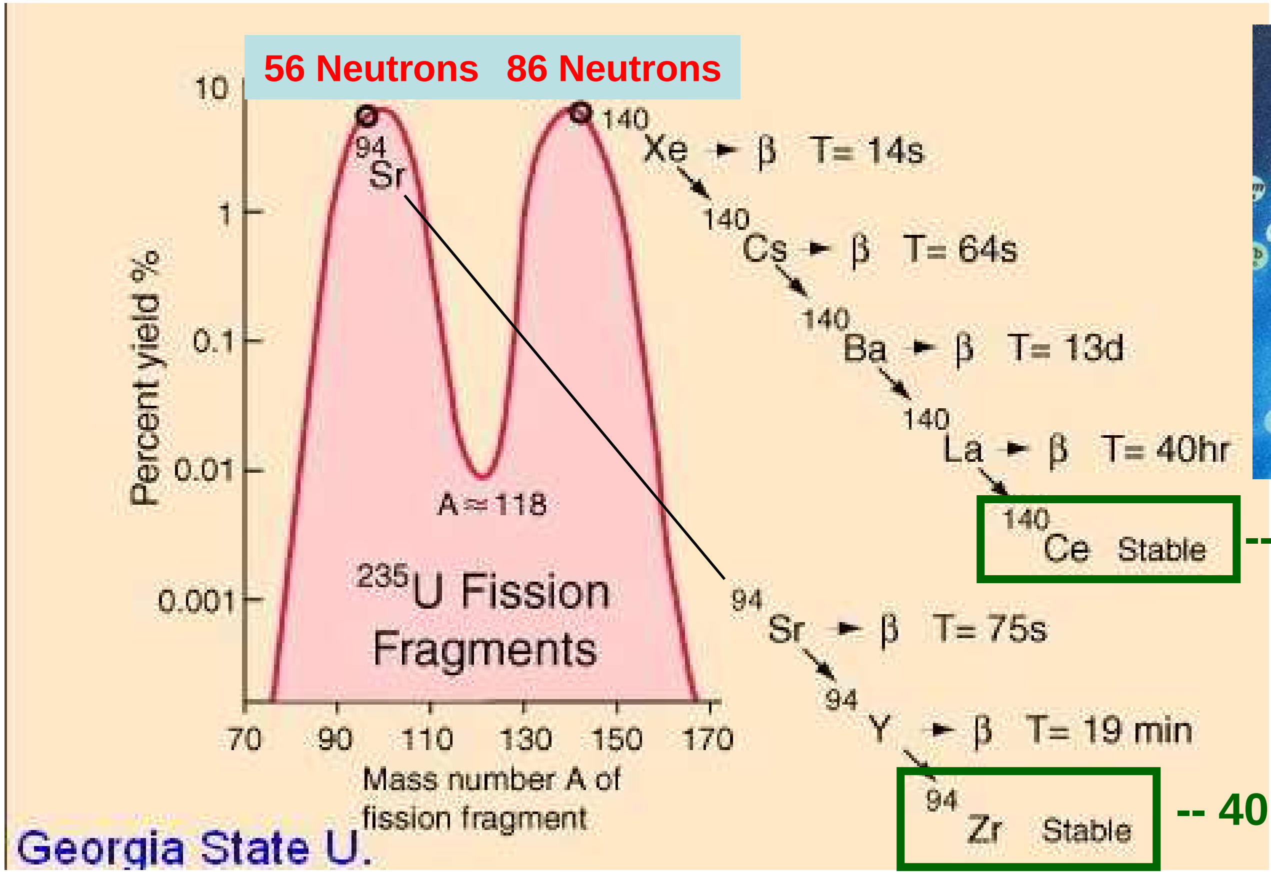
# Fission Products

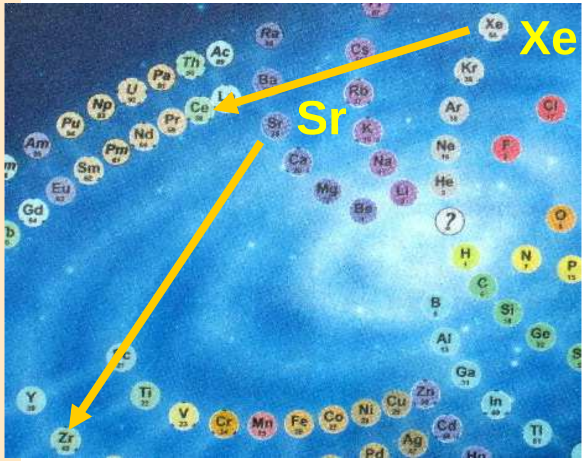



**Asymmetrical yields of thermal-fission-product pairs versus fissile element**

# 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..



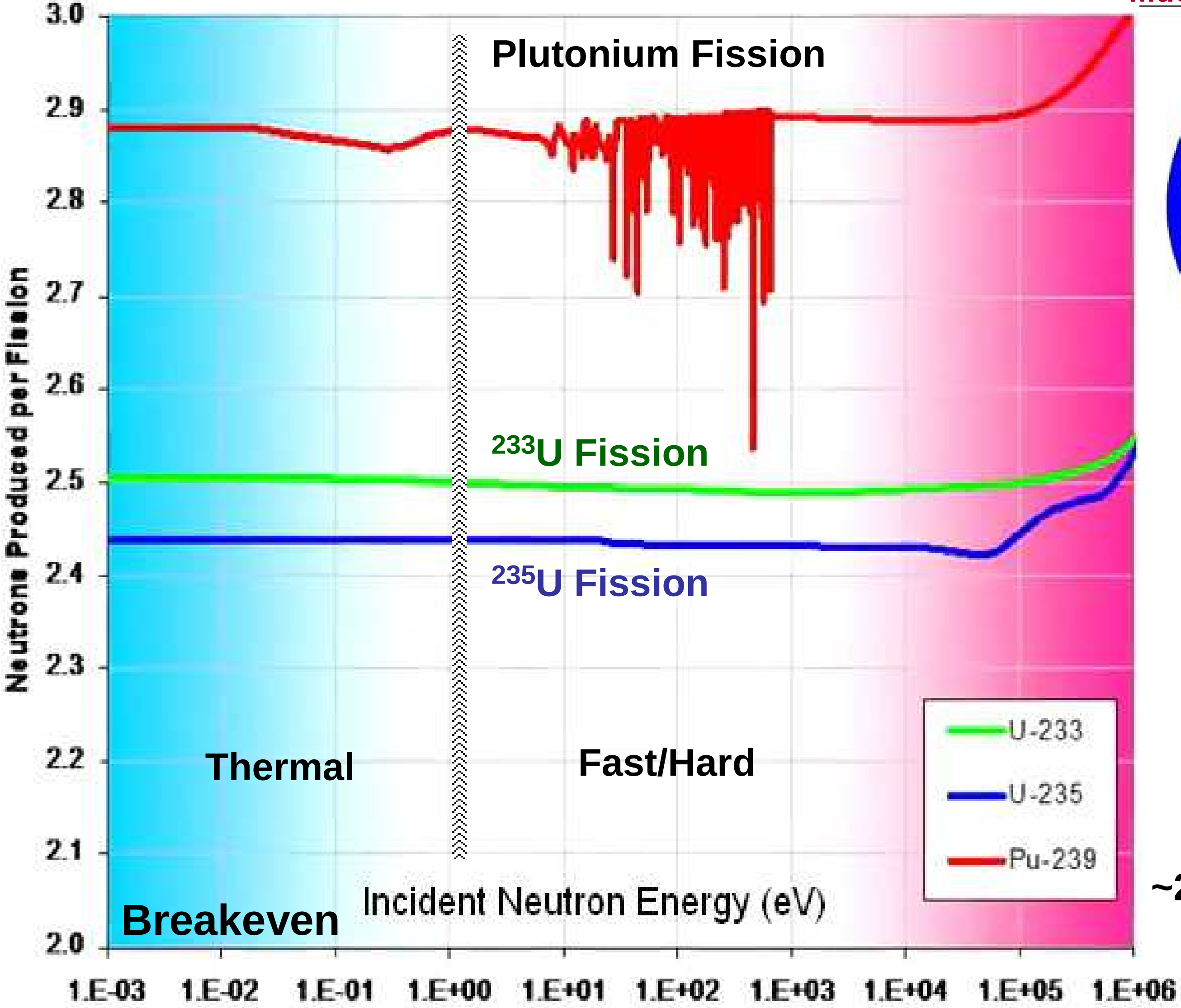



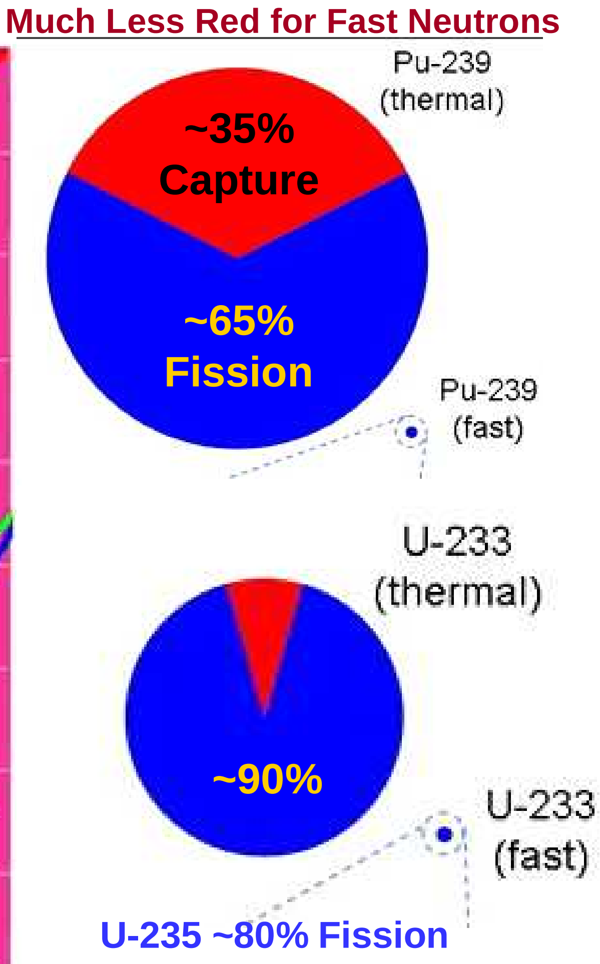

**-- 58 Protons, 82 Neutrons**

**-- 40 Protons, 54 Neutrons**

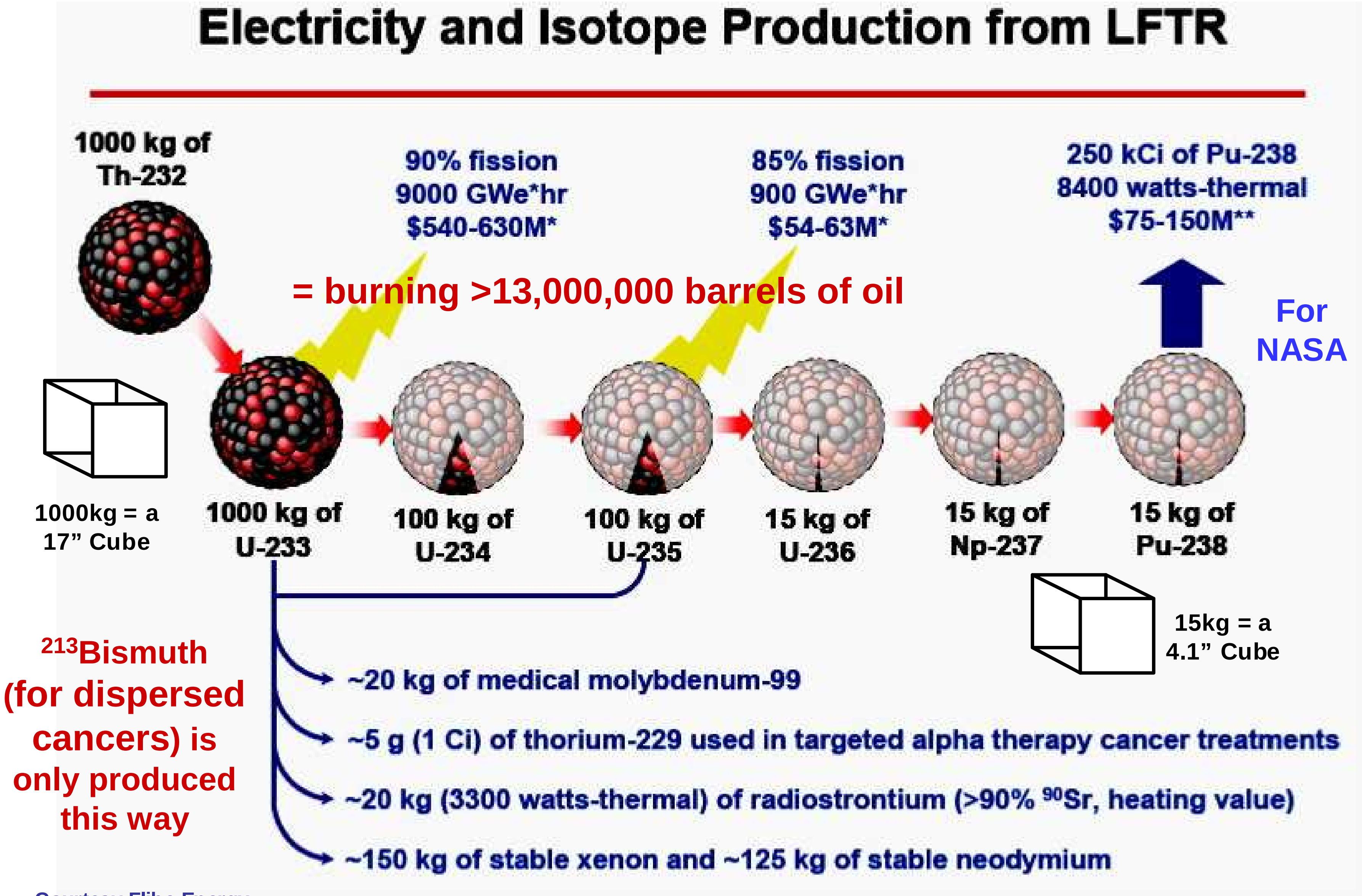
# Fission Neutron Economy

**Neutrons: Immediate + Delayed**



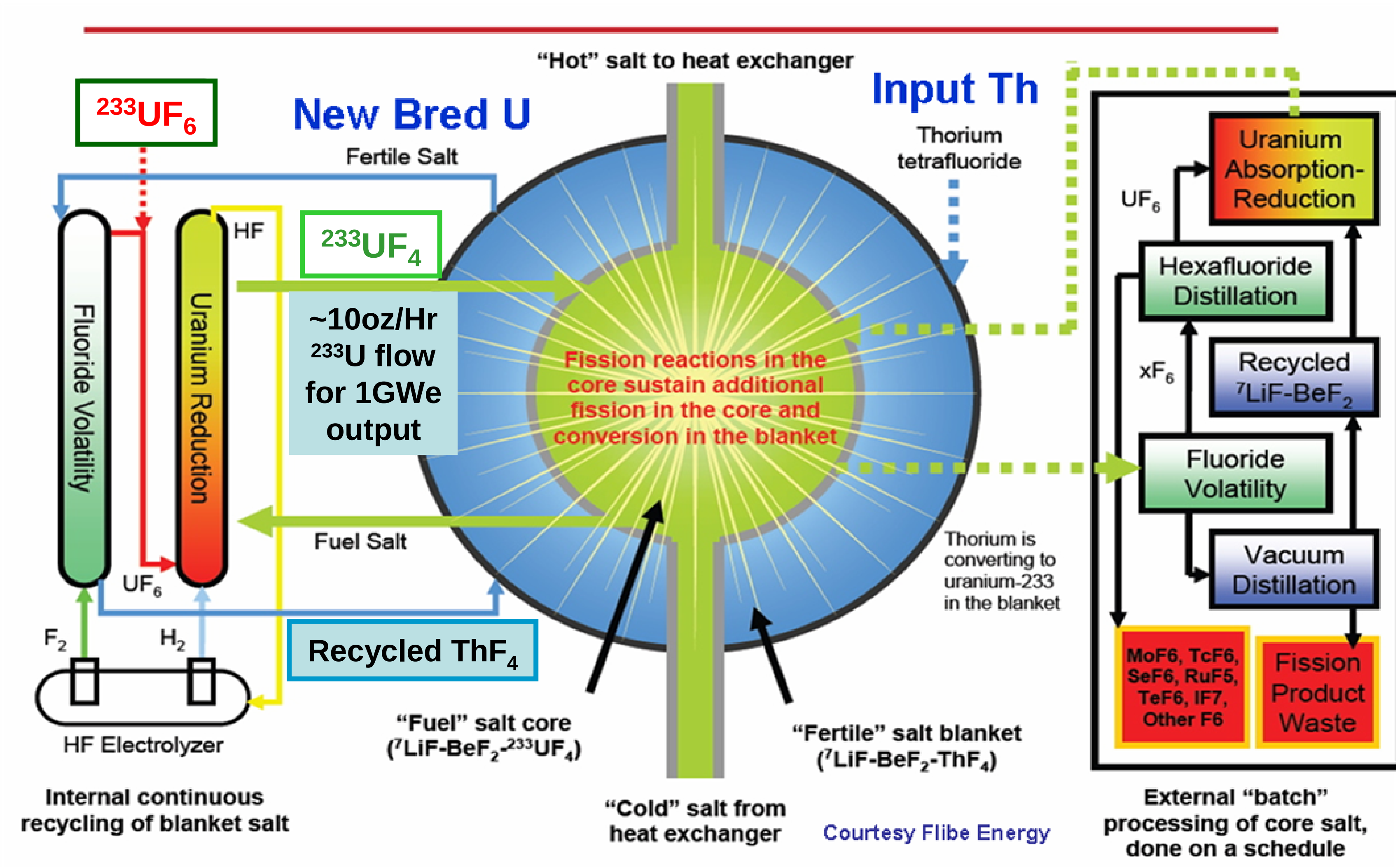

**~25:1 Thermal:Fast Cross-Section Ratio**




Courtesy Flibe Energy

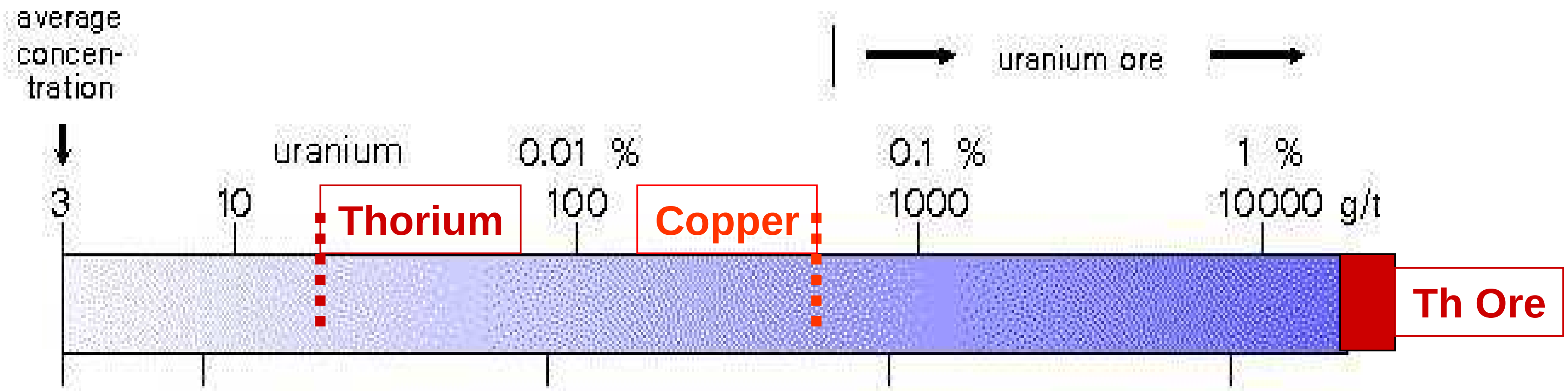
½ Oz. Thorium runs 1 American’s life for 1 decade

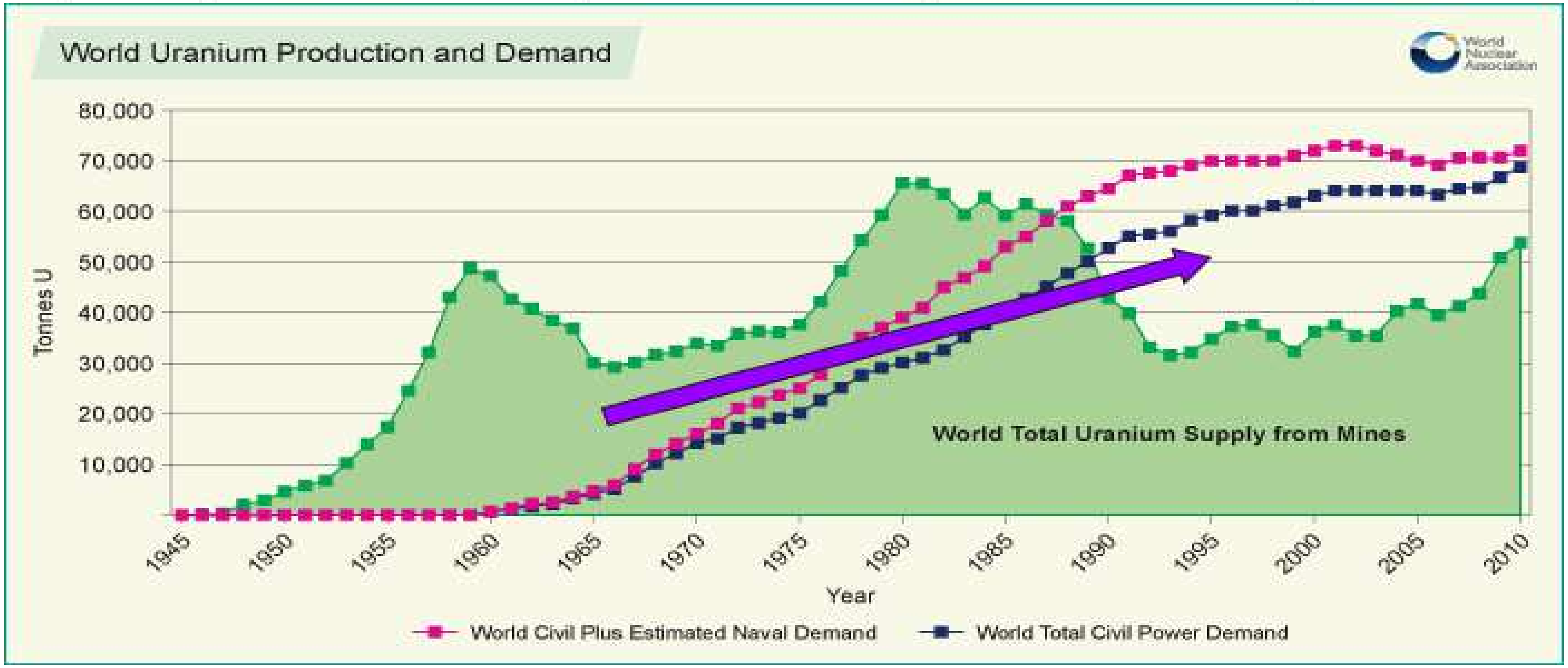
# Thorium Molten-Salt Reactor (LFTR)




**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.**

# Uranium Concentrations in Rock



# 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.

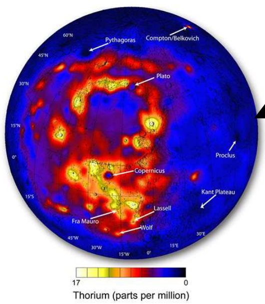
| | Mt. Pass Bastansite | China Byan Obo | HRE-China Laterite | Selected Monazite | Pea Ridge* Breccia | Pea Ridge** RE-Apatite |
|---|---|---|---|---|---|---|
| Lanthanum | 33.8 | 27.1 | 1.8 | 17.5 | 27.5 | 18.6 |
| Cerium | 49.6 | 49.8 | 0.4 | 43.7 | 38.8 | 34.6 |
| Praseodymium | 4.1 | 5.15 | 0.7 | 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** (Terbium through Yttrium)

Courtesy Wings/Pea-Ridge

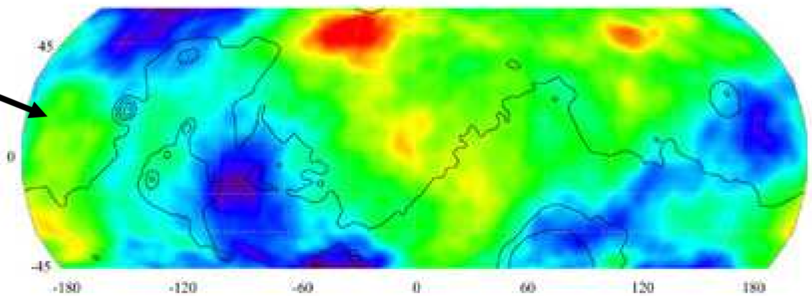
In order of Geologic Occurrence – Bastansite, Monazite, HRE Laterite

**Th on**




**Moon**

**Mars**



# Thorium & Rare Earths

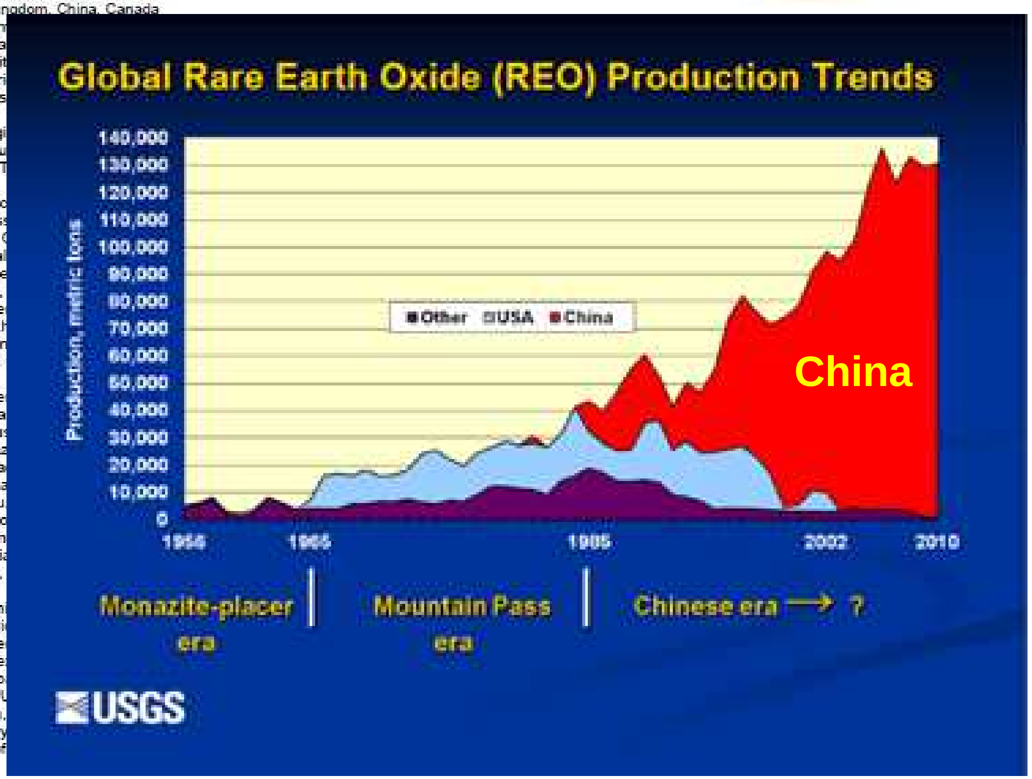
See: "***Rare Earths Industry***", Elsevier 2016, I. de Lima & W. Filho editors.

Monazite
~4-10% Th

Atomic Energy Act of 1946 designates Th as "source material"

**2012 U.S. NET IMPORT RELIANCE**

| Commodity | Percent | Major Import Sources (2008–11) |
|---|---|---|
| ARSENIC (trioxide) | 100 | Morocco, China, Belgium |
| ASBESTOS | 100 | Canada, Zimbabwe |
| BAUXITE and ALUMINA | 100 | Jamaica, Brazil, Guinea, Australia |
| CESIUM | 100 | Canada |
| FLUORSPAR | 100 | Mexico, China, South Africa |
| GRAPHITE (natural) | 100 | China, Mexico, Canada, Brazil |
| INDIUM | 100 | China, Canada, Japan, Belgium |
| MANGANESE | 100 | South Africa, Gabon, Australia, China |
| MICA, sheet (natural) | 100 | China, Brazil, Belgium, India |
| NIOBIUM (columbium) | 100 | Brazil, Canada, Germany |
| QUARTZ CRYSTAL (industrial) | 100 | China, Japan, Russia |
| RUBIDIUM | 100 | Canada |
| SCANDIUM | 100 | China |
| STRONTIUM | 100 | Mexico, Germany, China |
| TANTALUM | 100 | China, Estonia, Germany, Kazakhstan |
| THALLIUM | 100 | Germany, Russia |
| THORIUM | 100 | India, France |
| GALLIUM | 99 | Germany, United Kingdom, China, Canada |
| GEMSTONES | 99 | Israel, India, Belgium |
| VANADIUM | 96 | Rep. of Korea, Cana |
| BISMUTH | 92 | China, Belgium, Unit |
| PLATINUM | 91 | Germany, South Afri |
| GERMANIUM | 90 | China, Belgium, Rus |
| IODINE | 88 | Chile, Japan |
| ANTIMONY | 87 | China, Mexico, Belgi |
| DIAMOND (dust, grit, and powder) | 85 | China, Ireland, Repu |
| STONE (dimension) | 85 | China, Brazil, Italy, T |
| POTASH | 81 | Canada, Russia |
| BARITE | 80 | China, India, Morocc |
| COBALT | 78 | China, Norway, Russ |
| RHENIUM | 78 | Chile, Netherlands, |
| TITANIUM MINERAL CONCENTRATES | 77 | South Africa, Austral |
| TIN | 75 | Peru, Bolivia, Indone |
| SILICON CARBIDE (crude) | 73 | China, South Africa, |
| ZINC | 72 | Canada, Mexico, Pe |
| CHROMIUM | 70 | South Africa, Kazakh |
| GARNET (industrial) | 65 | India, Australia, Chin |
| TITANIUM (sponge) | 64 | Japan, Kazakhstan, |
| PEAT | 62 | Canada |
| SILVER | 57 | Mexico, Canada, Pe |
| PALLADIUM | 54 | Russia, South Africa |
| NICKEL | 49 | Canada, Russia, Aus |
| MAGNESIUM COMPOUNDS | 46 | China, Canada, Braz |
| TUNGSTEN | 42 | China, Bolivia, Cana |
| SILICON | 38 | Brazil, Russia, China |
| COPPER | 35 | Chile, Canada, Peru |
| NITROGEN (fixed), AMMONIA | 35 | Trinidad and Tobago |
| MAGNESIUM METAL | 31 | Israel, Canada, Chin |
| MICA, scrap and flake (natural) | 31 | Canada, China, India |
| VERMICULITE | 30 | South Africa, China, |
| PERLITE | 24 | Greece |
| ALUMINUM | 20 | Canada, Russia, Chi |
| SALT | 19 | Canada, Chile, Mexi |
| SULFUR | 19 | Canada, Mexico, Ve |
| PUMICE | 15 | Greece, Iceland, Me |
| GYPSUM | 12 | Canada, Mexico, Sp |
| IRON and STEEL | 11 | Canada, European U |
| BERYLLIUM | 10 | Russia, Kazakhstan, |
| IRON and STEEL SLAG | 9 | Japan, Canada, Italy |
| CEMENT | 7 | Canada, Republic of |
| PHOSPHATE ROCK | 5 | Morocco, Peru |

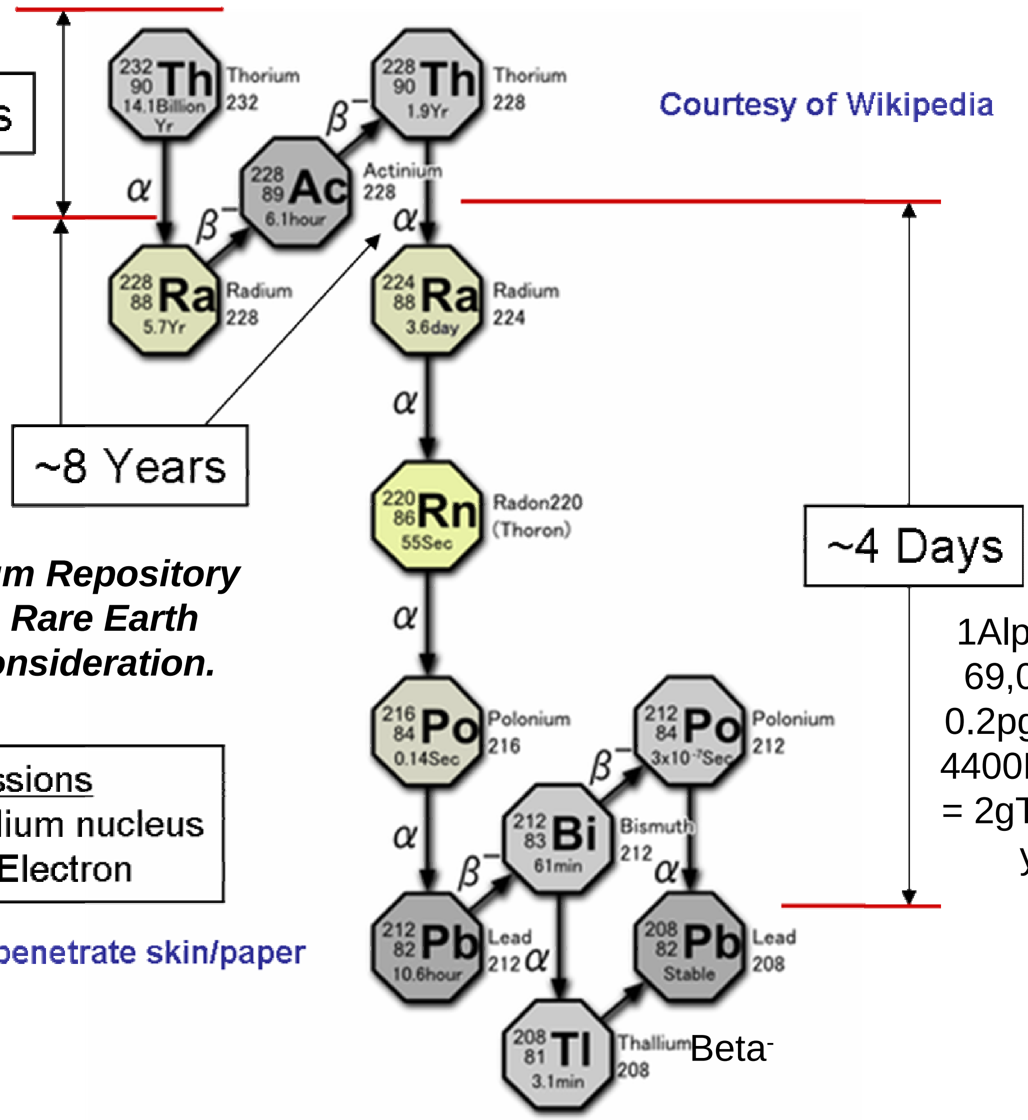


# Thorium’s Radiation Exposure (***notes***)

~14 Billion Years

Courtesy of Wikipedia

Times are half lives




***Legislation creating a Thorium Repository to remove Th liability from Rare Earth miners/ refiners is under consideration.***

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

# Molten-Salt Reactors (MSRE)

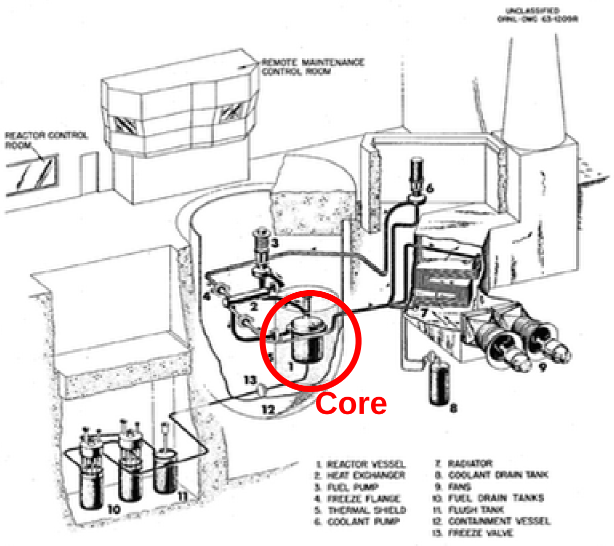
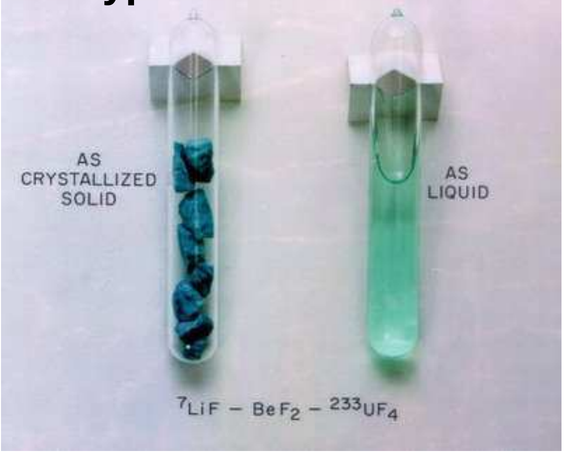



Fig. 7. Elevation of Part of MSRE Building.

**1960s MSRE**
**7MW, 17,000Hrs**

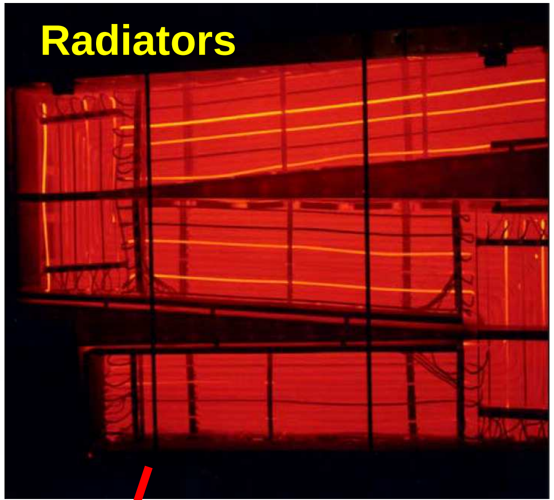
**Seaborg Turning It On**

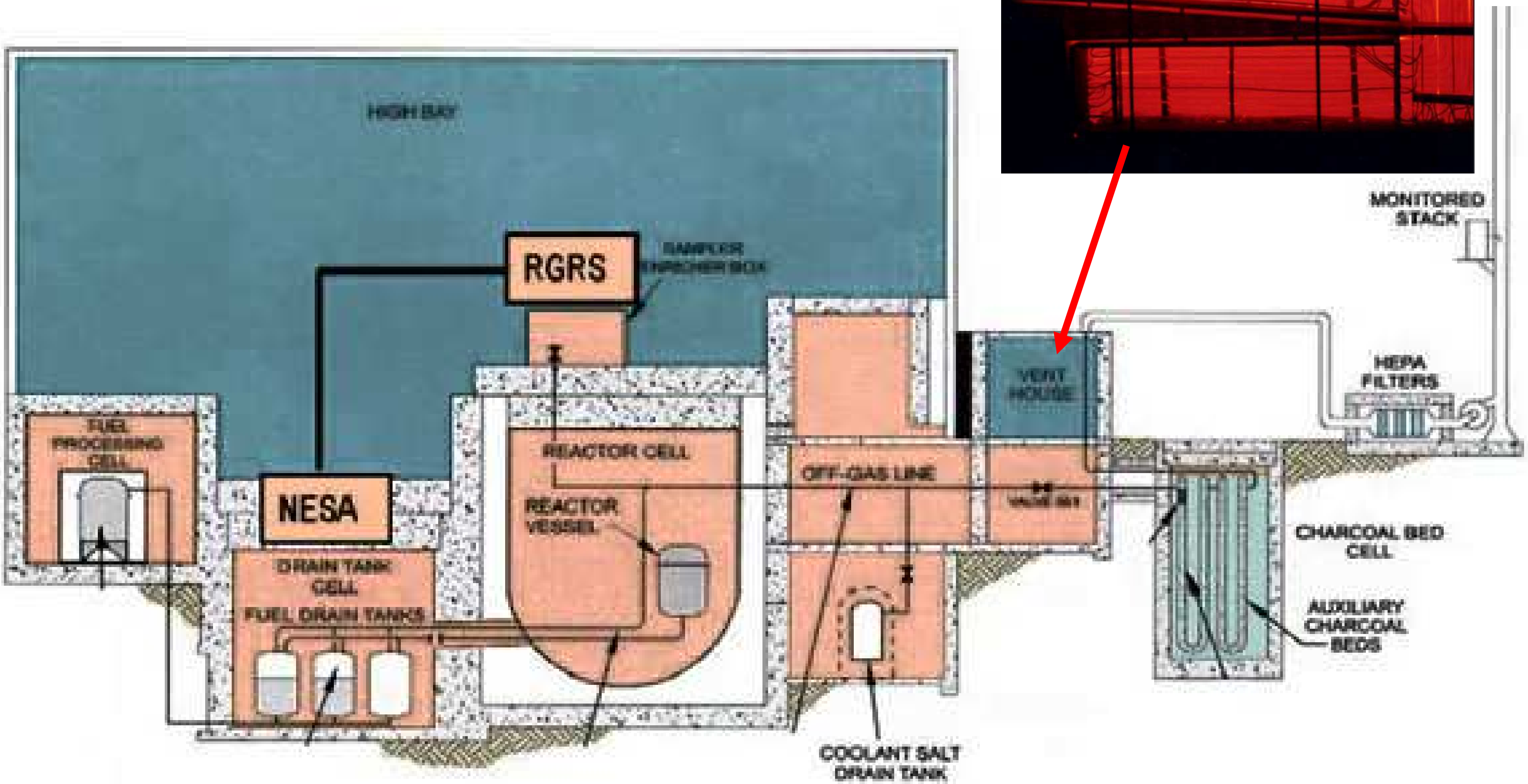
**Typical Fluoride Salt**




# 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



# 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.**

# MSR/MSBR/LFTR History

## What we were supposed to be doing by 2000

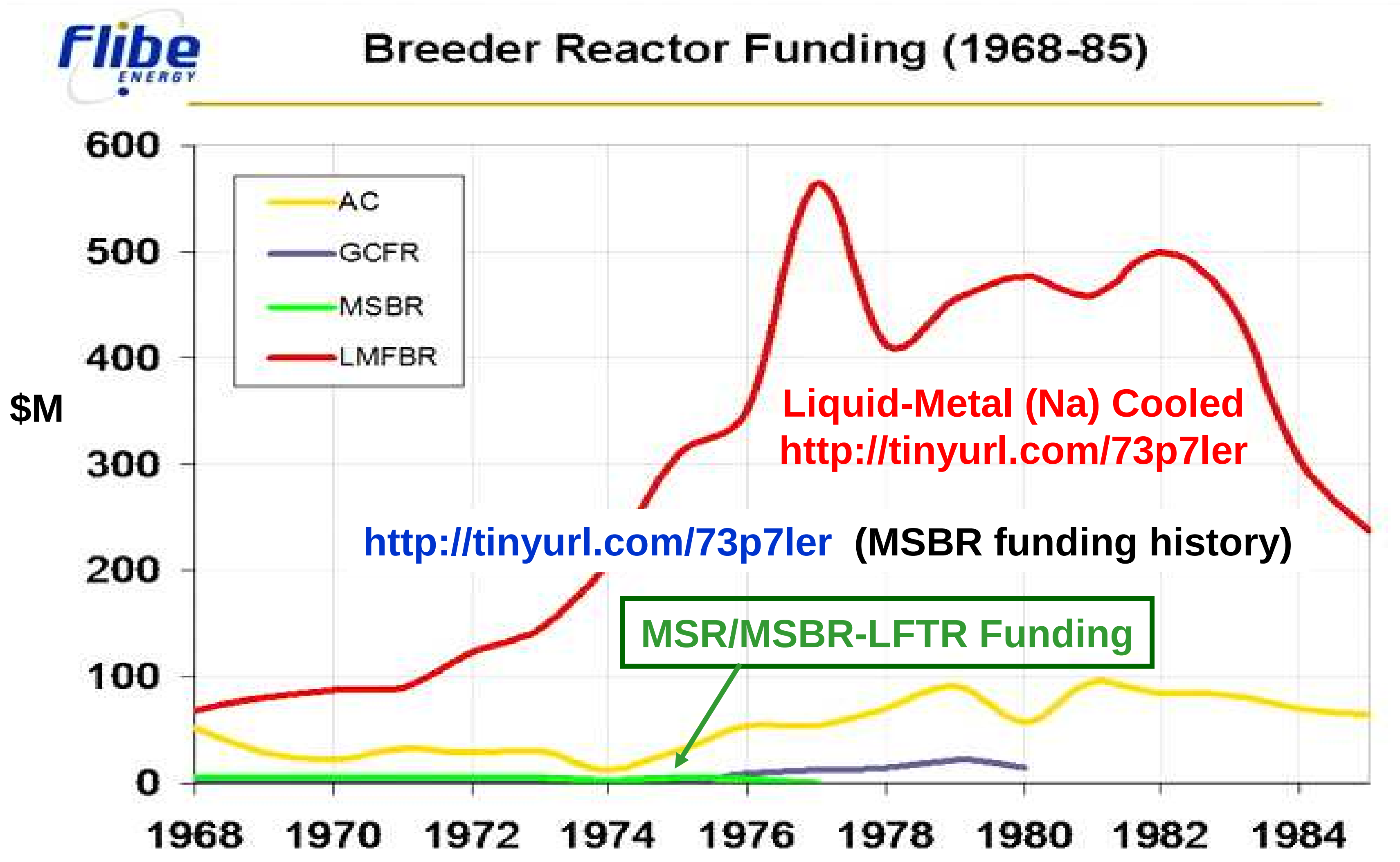
**In 1962, President Kennedy requested an AEC <u>civilian power study</u>…** *"**Your study should identify the objectives, scope and content of a nuclear power development program, in light of the nation's prospective energy needs and resources…recommend appropriate steps to assure the proper timing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

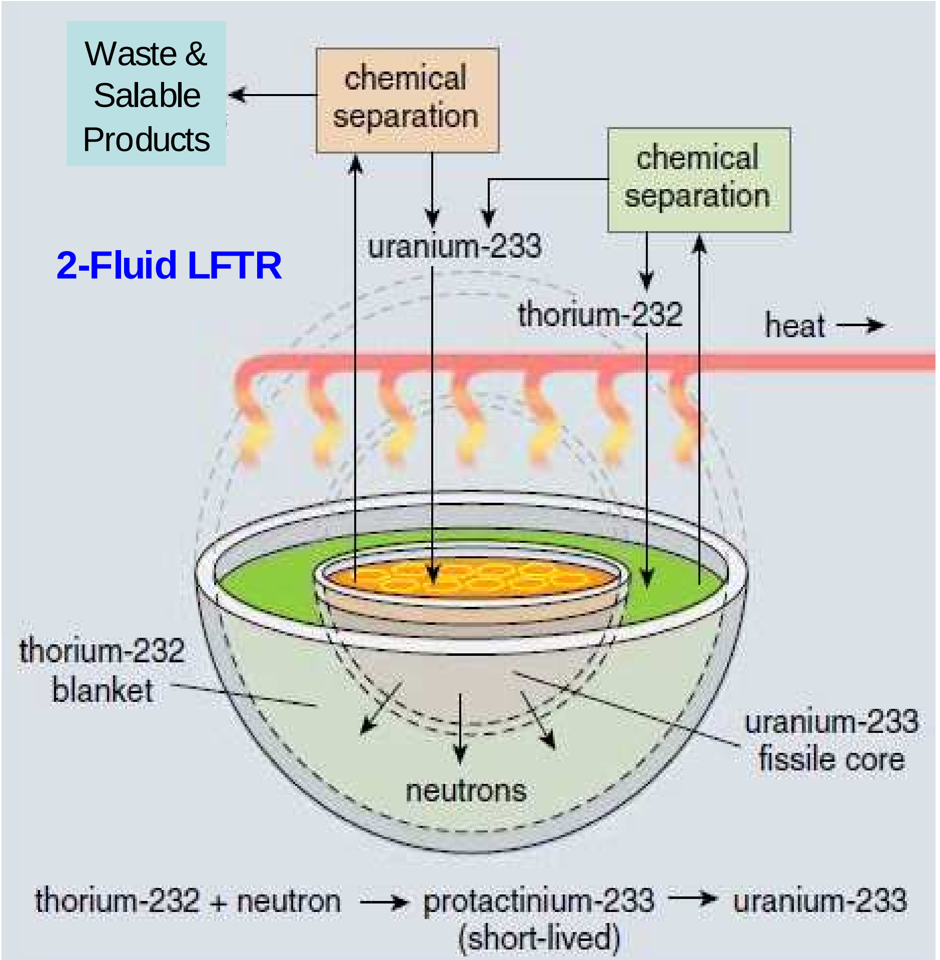
AEC Reactor Engineering Director, Shaw, a protégé of Adm. Rickover, but saw only the solid-fuelled, water-cooled designs used by the Navy as worthwhile. He asked MSR & MSBR engineers to "clear their desks into their wastebaskets" when '70s funding died: **http://tinyurl.com/al5hlap** especially due to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

# Funding History

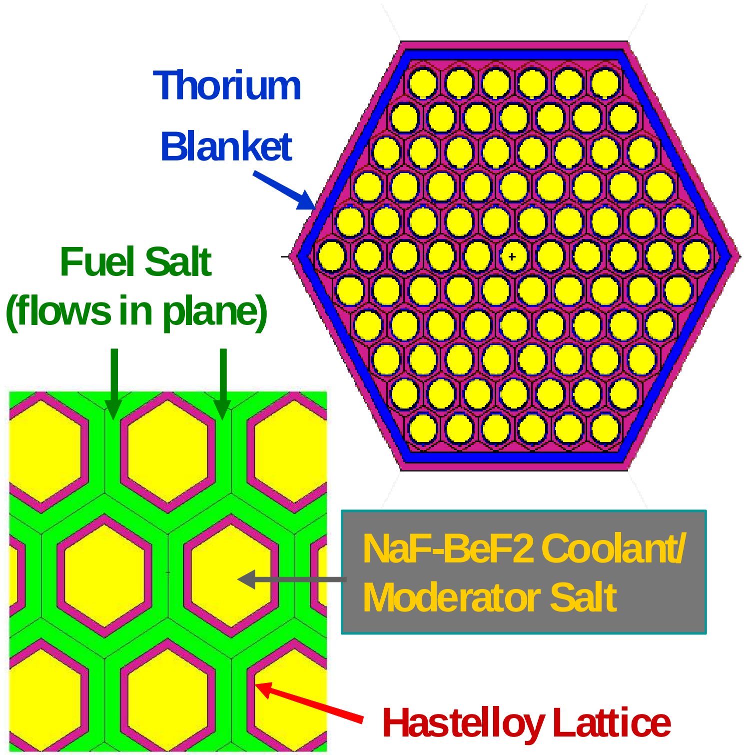


# LFTR Architectures

## 2-Fluid Pool & Solid Core Moderator



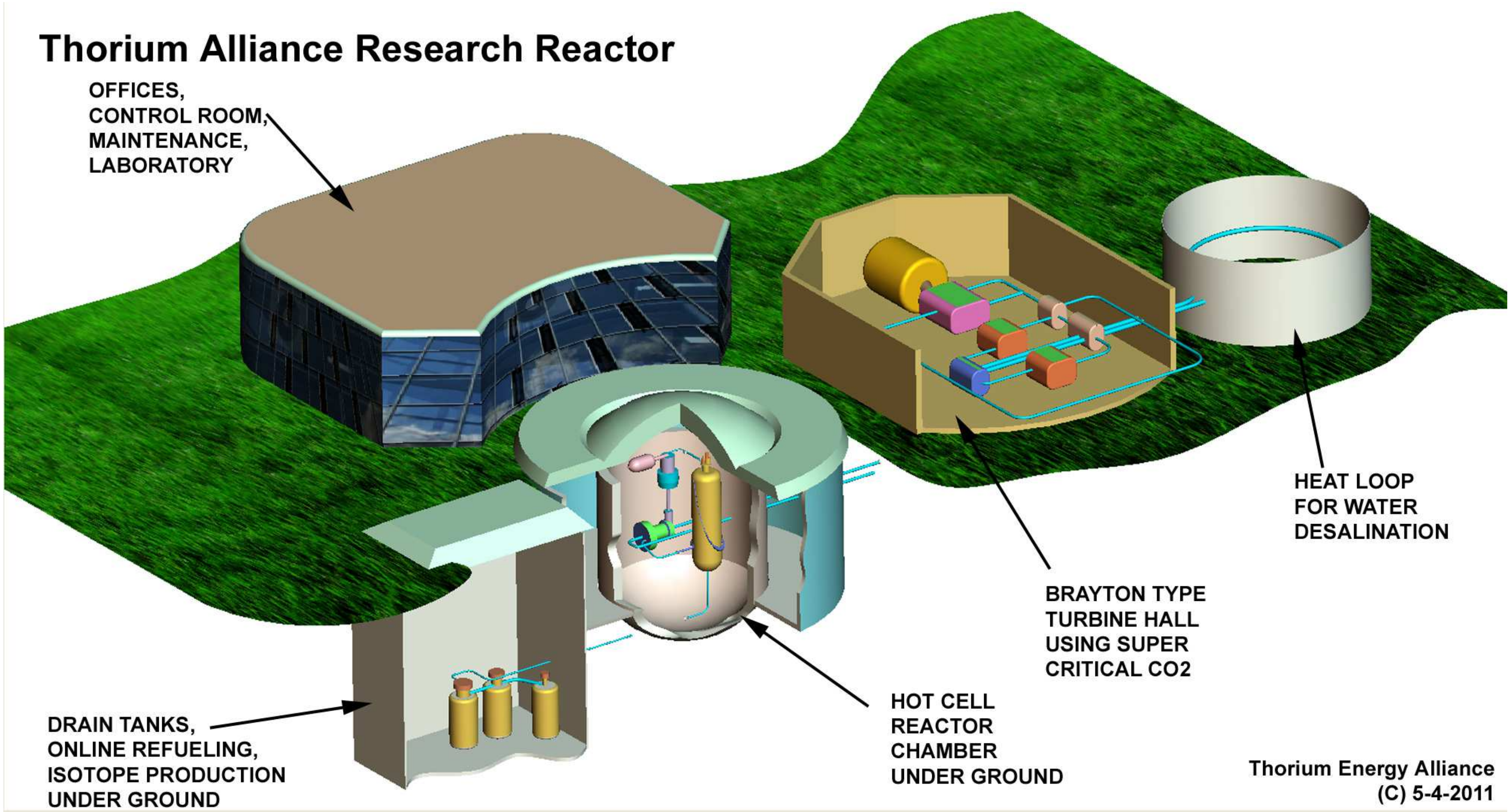

## 2-Fluid Lattice & Thorium Blanket




$BeF_2$ Moderator in Coolant & Fuel

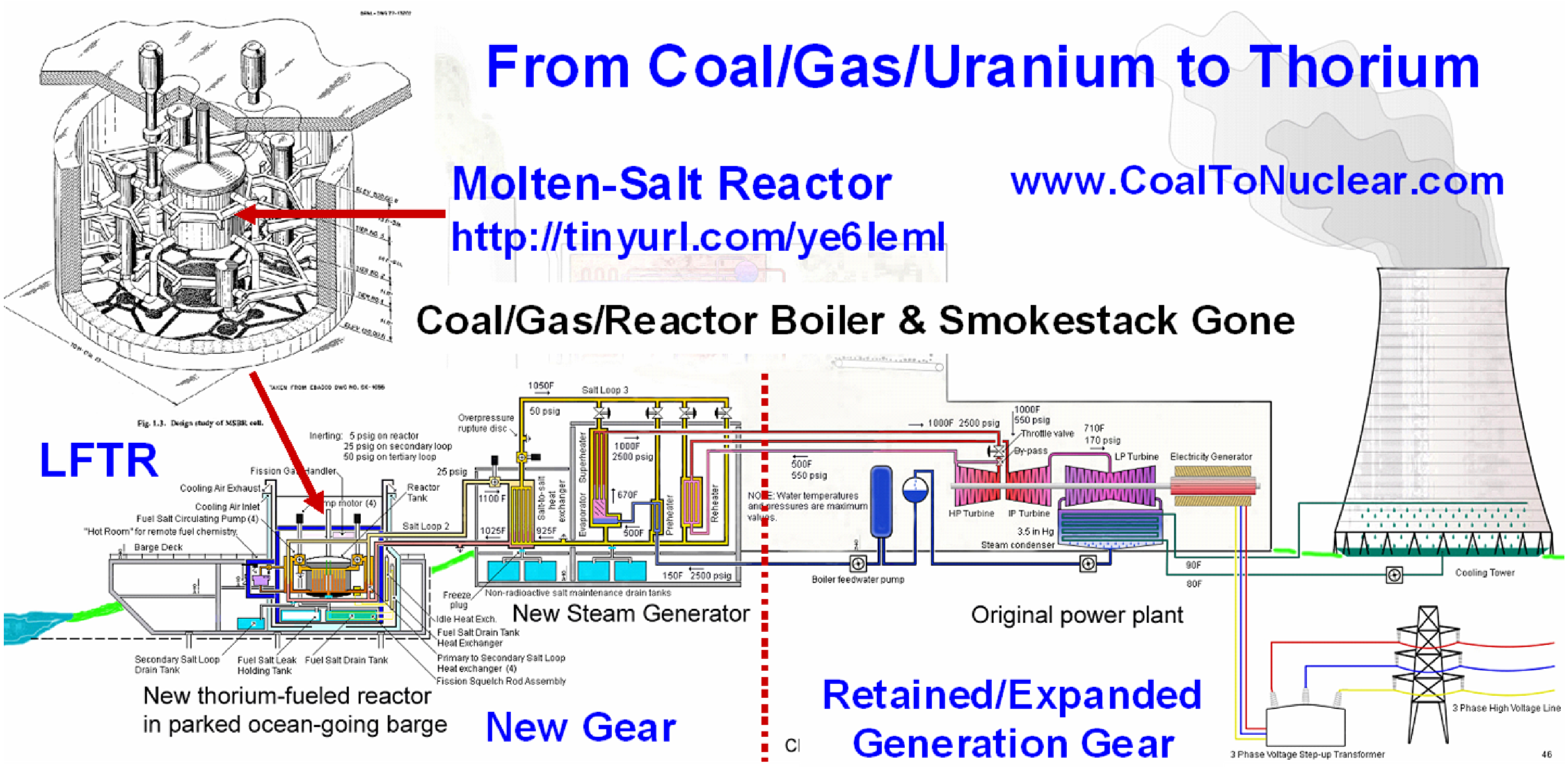
Courtesy Thorenco

# Molten-Salt Reactors

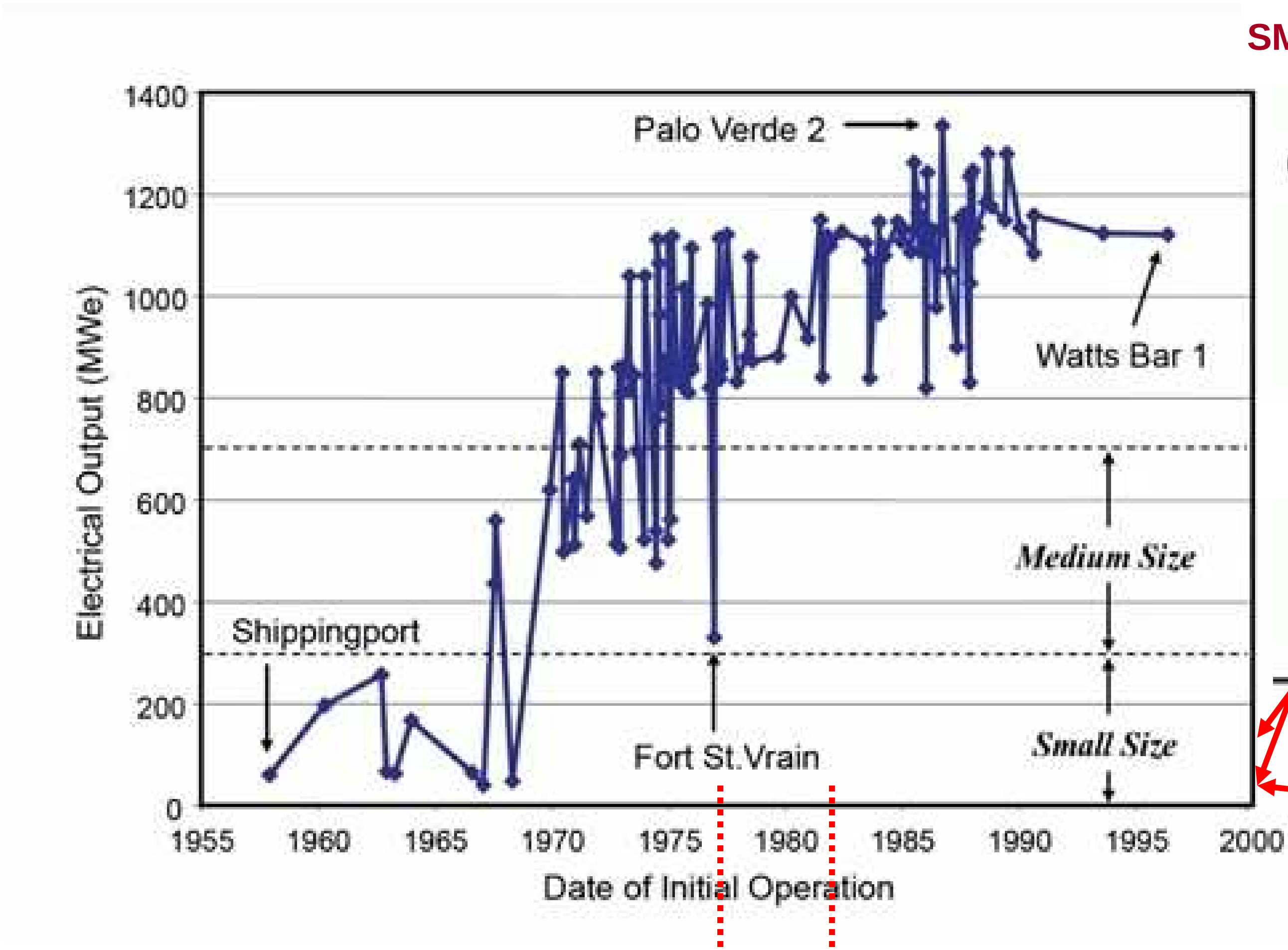



www.thoriumenergyalliance.com

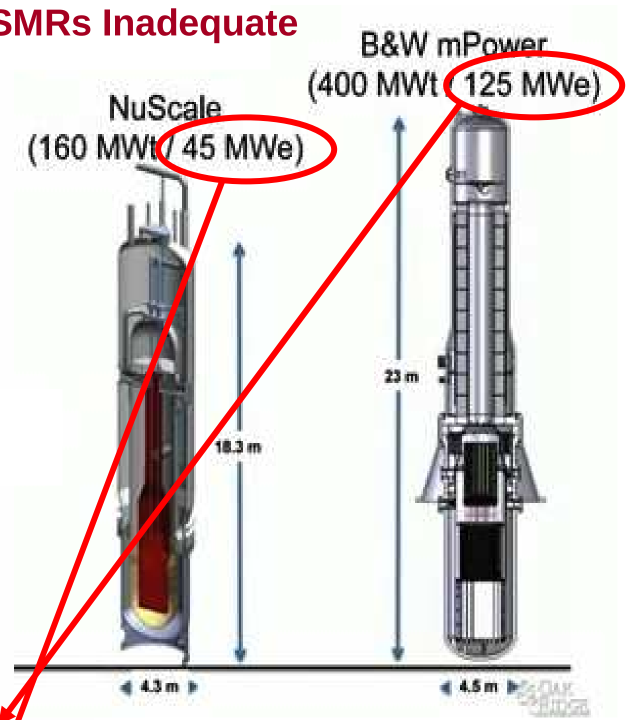
# Using MSR/LFTR Modules



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




**SMRs Inadequate**





**Salt Cooled**

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**1977-1982, >1% Fuel Gain in 5 Years**

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