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Thorium – A Safe, Abundant and 'Fertile' Power Source

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1. Why Thorium?

This article describes why Thorium (Th), as a fertile precursor of certain nuclear fissiles (fission 'fuels'), has long been considered important to a future of safe, abundant, emissions-free energy for the United States and the world, especially given the extreme dangers posed by continued conversion of combustible hydrocarbons to thermal energy and greenhouse gasses over the last 100 or so years[(1)].

Thorium is about 4 times more abundant than Uranium and long considered a mining waste product of no value. Yet it solves many issues now associated with and limiting our climate-motivated build-out of present, Uranium-fuelled Light-Water Reactor (LWR) designs. Fission-reactor Neutrons 'breed' Thorium to the most efficient fissile isotope of Uranium (^{233}U) safely within the reactor itself – once started, no external Uranium fuel, spent-fuel storage or refueling is required for the life of a Thorium reactor, depending on its particular type (e.g., solid-blanket breeder, single-fluid MSR, DMSR, etc.).

Billions of years of natural decay now leave us but a low abundance of the fissile isotope, ^{235}Uranium, that conventional nuclear power depends on – only about 0.7% of purified Uranium is the fissile fuel ^{235}U, >99% is ^{238}U. Thorium not only has lasted billions of years more, but its useful fertile isotope, ^{232}Th, is nearly 100% of atomic Thorium refined from ore. Thus, we enjoy an immediate, per-ton advantage of >140:1 (100/0.7) in easily-accessible fission fuel, because nearly all Th can be converted to fissile ^{233}U, despite ^{233}U having long ago decayed from Nature. Thorium's advantage grows as well from Uranium enrichment savings and because only about ¾ of fissile ^{235}U solid fuel is consumed before its scheduled removal from an LWR core.

Thorium's total energy improvement (~4 x 140) over current un-reprocessed Uranium fuel thus provides great benefits of reduced Uranium-mining impact on the environment, as well as improved nuclear security. And, the bred isotope, ^{233}U, fissions more easily, with less higher-mass waste than from expensive, rare ^{235}U (used to fuel our existing LWR reactor fleet for >50 years). With certain, long-known reactor designs, this path, termed fuel breeding, also allows secure consumption of existing wastes, even weapons materials, all while generating power. Reactor designs capitalizing on Thorium and fuel breeding will be discussed, along with benefits summarized now as:

a) The abundant, inexpensive, Actinide metal Thorium is easily transmuted (bred) to the best fissile Uranium isotope, ^{233}U, inside typical reactor cores[(3)];
b) Thorium is non-weaponizable itself, and of all fissile and fertile materials, Thorium is by far the most difficult to re-purpose for weapons production.
c) Thorium's large nuclear transmutation distance from Plutonium greatly reduces long-term wastes[(4)] from breeder-reactor operation;
d) Thorium has large stockpiles, due to its natural occurrence in important ores;
e) Thorium's 4:1 abundance relative to Uranium on Earth and its 140:1 fuel potential, relative to common Uranium fuel, provide great economic and environmental benefits.
f) Thorium's salt chemistry, shared with Uranium's, encourages superior, safe reactor designs[(4, 5)];
g) Salt reactors can denature/destroy nuclear wastes/weapons materiel[(4)].
h) Salt reactors of any form operate at high temperatures, maximizing efficiency and gaining the extra advantage of water-independent site selection[(15)].

This paper highlights the report[(2)] to President Kennedy in 1962 and explains the recommended fuel/reactor paths (breeding) not taken that now should be completed, though too late to avoid tragic environmental consequences already built into our past emissions history and effects on world climate and chemistry.

Nuclear-fission reactors provide mankind with somewhat over 15% of all electricity production worldwide. They do so without significant climate-threatening emissions. The power density of fission is many hundreds of thousands of times that of our best, low-emissions fuels, including Hydrogen-Oxygen combustion, and ~6 million times better than coal. Plus, fission requires no additional reactive consumable, such as Oxygen, boosting its relative power density much further, by another factor >3.

Fission's energy was stored within heavy nuclei (e.g., beyond Fe – Iron, Fig. 12) many billions of years ago by shocks from large exploding stars (e.g., see: http://en.wikipedia.org/wiki/Supernova_nucleosynthesis), or collapsed Neutron remnants. Harvesting it now is many times better, in terms of MWe/acre or kW/m^2, than any alternatives referred to as "renewable" (solar, wind, tidal, etc.). However, it does not presently enjoy the explicit or implicit subsidies of our most common power sources (coal, oil and gas), nor of our presently popular, but low power-density 'renewable' sources. This unrealistic state will change as we realize that efficiency, conservation, localized emissions-free power generation and distribution are our only hopes for lasting success in addressing not just climate change, but environmental threats to food and water sources worldwide. Real teamwork is required of us all, in all nations. And, this is not new news(1).

Fission is essential to humankind's future, for energy, fresh-water production and medical purposes. Thorium provides a direct, inexpensive, low-waste path to fission's atom-by-atom cosmic energy store. This is also not news. In early 1962, President Kennedy requested an AEC civilian power study(2)…

> *"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…should recommend appropriate steps to assure the proper timing of development and construction of nuclear power projects, including the construction of necessary prototypes."*

Current LWR fuel/reactor designs impose large environmental burdens: from Uranium mining/refining through secure, energy-intensive fuel fabrication and handling, on to optional, secure waste processing and transport, and finally to storage of radioactive wastes in ways that must be safe for millennia. Most of these detriments derive directly from decisions made after WWII to continue civilian nuclear power from the Manhattan Project's vast Uranium-processing infrastructure -- encouraging solid, enriched-Uranium (LEU), fission-fuel cycles that create materials suitable for weapons (efficient or just 'dirty') and leave variously weaponizable wastes that decay over hundreds to tens of thousands of years. This history is explained in the AEC's Fall 1962 report(2), responding to the Presidential request above. For example…

> *"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."*

Fortunately, many scientists and engineers, who had helped develop current designs (e.g., Wigner and Weinberg), knew and were concerned about the limitations of solid Uranium-fuelled, water-cooled reactors (LWRs) for civilian use(2, 3). Other architectures for fission power were designed and tested, and the concept of "breeding" fissile fuel inside a secure reactor was developed, driven by the realization that Uranium mining, processing, shortages and wastes (e.g., Figs. 5, 6, 10 & 15) could be almost eliminated, while gaining orders-of-magnitude improvements in fuel efficiency and power longevity. The AEC report(2) continued…

"…it is important that the combination of breeders and converters reaches an overall net breeding capability…while relatively cheap fuel supplies are still available."

Breeding internal fuel could also eliminate many concerns about weapons proliferation, and with some reactor designs, actually allow destruction of existing wastes and weapons material. Today, these are essential properties of future, wisely-expanded, publicly-accepted dependence on fission reactors.

Enter an old idea – Thorium as a 'fertile', nuclear-fuel generator. Starting with abundant Thorium solves many LWR issues now associated with and limiting our build-out of present reactor designs. With Thorium and Thermal Neutrons, we breed ^{233}Uranium within the reactor itself (Figure 13), at about 140:1 total energy improvement over current, un-reprocessed LEU dependence. And, the isotope ^{233}U fissions with about 90% probability, compared to ^{235}U's 80% fission probability in present LEU fuels (e.g., center column in Fig. 4). This means far less reactor waste when starting from Thorium. The very first commercial LWR (Shippingport, Penn.) was, in fact, converted to use Thorium plus Uranium (oxides) upon its final refueling in 1977[(3)]. It produced more fissile fuel than it consumed over its next 5 years of operation, beating output expectations by 160%. Breeding fertile ^{238}U to fissile ^{239}Pu also nets a total energy benefit of about 100:1 by consuming all Uranium that is mined. The AEC's 1962 report[(2)] stated all this clearly (p14)…

"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."

Thus, if we had followed the 1962 recommendations, our ~440 LWRs might be history and we'd now supply world electric power with ~2400 safe, more efficient breeder reactors, consuming ~1/16 the total Uranium per reactor we now do as LEU, or none – we'd be using far more abundant, ordinary Thorium.

Thorium, like Uranium, Lithium, Beryllium and others, is easily converted to a salt, such as Thorium Fluoride (ThF_4). Salts are extremely stable under intense radiation, they melt at high, but industrial, temperatures and they have excellent thermal properties for heat transfer from reactor cores to thermal loads. This knowledge led to the design (from 1954-1974) of what are called Molten-Salt Reactors (MSRs)[(5)]. They were one of the two breeder designs recommended to be implemented quickly by the AEC in 1962. Unfortunately, only the LMFBR received sufficient support. But MSR today is one of DoE's six Generation-IV reactors slated for some support. This effort should be accelerated.

As Generation IV designs[(8)], MSRs directly address some key shortcomings of current LWRs and even offer a solution to present fusion-research reactors' inability to maintain their own Tritium budgets. They also address anti-proliferation concerns for nuclear weapons and, like Fast-Neutron reactors, provide means for destruction of weapons/waste material. Because of revived international R&D interest[(4)], the MSR, loaded with ThF_4 and known as LFTR (Liquid Fluoride Thermal Reactor), will be shown below to be a promising example of future, worldwide, cheap, safe nuclear power. Abundant, safe power also means abundant necessities, such as fresh water. High power

density and efficiency mean low environmental impacts and great flexibility in site selection. All those together address sustainability and economic progress.

2. Introduction

Thorium was discovered in 1828 by Berzellius and named for the Norse god of thunder -- Thor. It was known as a radioactive metal from the time of Madame Curie, who identified its mild radioactivity, along with Radium's and Polonium's stronger radiations in the natural Uranium ore Uraninite (Pitchblende). Relevant Thorium compounds here are the oxide (ThO_2) and fluoride (ThF_4), analogous to those of Uranium and Plutonium. Thorium melts at 1842^oC and has density (11.7g/cm^3) almost 12 times that of water. ThO_2 has the highest melting point of all oxides -- 3300^oC. ThF_4 melts at 1110^oC and its density is about ½ Thorium's – 6.3g/cm^3. When used in molten salt for breeder-reactor fluid, ThF_4 is typically mixed with fluorides of U, Be and Li, to achieve a low melting point (eutectic) while also including a fissile and/or Neutron moderating element (e.g., Be). Fluorides themselves are slightly moderating. A gift of Nature (discussed later) is that Thorium, unlike Uranium and Plutonium, forms no gaseous fluoride, like UF_6, thus allowing easy separation of bred Uranium fissiles from liquid fluoride salt via fluorination.

Early in the research on nuclear reactors, Thorium was considered a valuable, cheap alternative to Uranium, because it occurs as one isotope in nature, is much more common than Uranium, is easily purified from a variety of mining operations, and can breed highly fissile ^{233}Uranium under Thermal-Neutron bombardment. It, however, was not a good path to nuclear weapons made with Uranium and Plutonium. Thus, where we are today in civilian reactor design is about where we were in 1956, when the first commercial nuclear power plant was begun at Shippingport, PA[(3)]. That plant was wisely refueled in 1977 with Thorium and ^{233}U, making it the first, very successful test bed for Thorium-Uranium fuel breeding (see Atomic Insights)[(3)] and power generation Unfortunately, exigencies of the Cold War and its budgets made fuel-breeding R&D less important and fundable than production of nuclear weapons. Even Fast Breeder (e.g., LMFBR) work was limited.

The Shippingport LWR design, using standard Uranium fuel, was also chosen for Admiral Rickover's Nuclear Navy, being installed first in the submarine Nautilus, and subsequently in newer submarines and aircraft carriers -- the military did not want ships to be dependent on frequent refueling stops. Presently, nuclear submarines are fueled once or twice in their entire life, while carriers may receive an additional refueling (which actually consists of swapping out the entire reactor core as a single maintenance unit). Refueling cycles of 20-30-years are possible.

Because of the Cold War, all common reactors came to depend on the same fuel – enriched (to ~4% ^{235}U) Uranium. This fuel (LEU) can be further enriched for nuclear weapons (see HEU). And, the major isotope (^{238}U) breeds ^{239}Plutonium within a reactor, both fissioning it for energy and allowing its removal (via reprocessing) for extra fuel or for Pu fission bombs. At the end of the Cold War, our nuclear-power and weapons industries had cemented in their

technologies, so that the entire chain, from Uranium mining, through enrichment, fuel fabrication, reactor design, construction, operation, refueling, waste storage/reprocessing and decommissioning had attained industrial, economic and bureaucratic rigidity rarely matched by other human systems.

"…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." (Weinberg [5])

Today, for example, we in the US have limited support for better reactor designs. We even have little interest in utility-funded, standard reactor construction. It's not that alternate nuclear-power paths were never opened. It's that Cold War policies dampened our own research, leaving the world with few developed options now that they're essential. There is no source of power as dense and environmentally friendly as properly-chosen nuclear power. There's no fission source as cheap or as lasting as the Thorium breeder.

Yet, we in the US also have a regulatory agency, the NRC, holding just a few basic LWR power-plant designs for prospective builders to choose from, with some mix and match of components. And, each of those designs requires about $10 billion and many years to complete. No utility can invest that, which is why our present administration has promoted loan guarantees to get new plants built. Yet, even that hasn't worked.

Furthermore, the US NRC reports to Congress and can do only what that body mandates and funds. No work on alternative reactor designs, fuel cycles and rules can be expected from the NRC itself without new appropriations. Even a 1977 EPRI report[8] on the usefulness of Thorium in LWRs gained no industry action. Some new work has been funded by DoE[7], but not yet near the level needed, even if it continued from the excellent decades of work funded by the AEC and DoD at ORNL[5]. Similarly, private investors see no near-term return, but great risk, because nuclear reactors require extensive design for safety and regulation – the function of government agencies and research. The present situation is odd, yet with some hope, as will be explained.

"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 head] Ken Davis' insistence on a single line, the LWR, was premature." (Weinberg [5])

In this light, consider the reality all peoples of the world now share, though disproportioned by wealth. To meet just the internationally-estimated need to reduce greenhouse-gas (GHG) emissions now (January 2011) by a modest 4% per year, 2050 must see our (then) 9 billion souls emitting just 1 ton of CO_2 per capita per year[(1)]. And, with sea acidification and rise (see Rignot)[(1)] soon threatening over 100 million people, we need to be building and running one new, 1GWe emissions-free power plant each week for decades. A city-bound New Yorker currently causes emissions of 10 tons/year. A car-using Denver-ite causes twice that. And, an average California home causes 7 tons of CO_2 per year to be emitted, just from its internal energy use (see CEC reports). Only in remote, poor communities in Africa does any person now cause just 1 ton of CO_2 to be added to Earth's atmosphere each year. Sustainability, even at 1-ton per capita per year, is far from our reach.

Regardless of pro/con debates on climate change, we are collectively making a Pascal Wager against already evident climate change growing worse due to our emissions – we're "betting the farm" despite good hints as early as Nobel Laureate S. Arrhenius' 1896 and 1905 papers on possible effects of unnatural CO_2 emissions[(1)]. Later, we didn't listen to post-WWII analytical reports to governments; and our governments didn't even follow up on research we'd paid for that pointed the way to safe, non-emitting nuclear power -- 50 years before this writing. Some Generation IV[(8)] efforts are finally in motion, but another decade will pass before any demonstration system will run. The emissions-free power debt will then be 1GWe x 10 x 52 (a plant a week unbuilt) or more, just for US needs. Perhaps the new Chinese commitment[(4)] will be speedier, but the shortfall will remain stupendous, worldwide. We need serious efforts today, if we wish to leave a future to our descendents.

This article will explain why what has long been known about Thorium as a fertile nuclear fuel leads us to a viable future for Earth's power and water needs. And, it will use as example the complementary reactor architecture designed by the same people who gave us the LWR, but who knew better was needed. Thus, this article is dedicated to Alvin Weinberg, H. MacPherson and their ORNL teams, who were aware of global warming before Wikipedia and spent 20 years (1954-1974) designing and operating MSRs. They led the way to safely fuelling our future via Thorium [(3,4)]. And, it's our good fortune that a new foundation has just been established to give rebirth to their achievements: www.the-weinberg-foundation.org/ .

Nature's Way. Surface life on Earth would not be possible without radioactivity. Sea life would not likely have developed either. Earth's interior would have cooled soon after Earth's formation -- there'd not even have been volcanic vents in sea floors for archaic bacteria to chemically exploit. A billion or two years ago, about 6 million volcanoes were active in any year, now there may be 6. Nature's fortunate radioactivity (mostly from Uranium, ^{40}Potassium and Thorium), plus an abundance of Iron (fused in earlier stars) have made our modest planetary home safe for organic life.

Decaying nuclides have maintained a hot, molten-Iron-Nickel interior that generates Earth's magnetic field. Without that field, solar Protons, etc. would have swept away a developing atmosphere. Without the atmosphere, those

solar Protons, ultraviolet and X rays, and cosmic radiation from outside our solar system would have made hydrocarbon life as we know it impossible. When we visit Mars, we'll see what being on a planet with a cooled core means.

Thorium's slow decay today provides ~60% of Earth's internal heating. About 20% still comes from shorter-lived ^{40}K and Uranium isotopes, while the last 20% is left over heat from planetary formation almost 5 billion years ago. Not only is radioactivity a friend from Nature, Thorium has been our best nuclear friend for a few billion years, and still is working hard for us.

The work we need now from Thorium can help end our possibly fatal dance with combustion energy. In only a few generations, mankind has created an amazingly tough, now urgent, challenge – how to find sources of energy to replace burning a few cubic miles of petroleum, or equivalent, each year, not just to keep warm, but to support worldwide industry and economic progress. Emissions of such vast amounts of CO_2 have already been observed acidifying seas, threatening an entire food chain that supplies ~70% of humans' dietary protein. Climate Warming and sea rise may be the least of our problems in near decades.

Three other natural gifts work in our favor: a) Thorium is common, relatively useless and thus cheap; b) Nature has given us an exceedingly dense power source – nuclear fission; and c) Nature allows an excellent fissile material (^{233}U) to be bred from Thorium. If we listen to Nature, we can succeed in tapping a lasting, safe energy future,

Power Density -- measured in Watts per acre, per square kilometer, or per amount of a fuel, and energy density, measured in Watt-Hours per gram or pound, become essential parameters to scrutinize when evaluating long-term solutions to our energy needs – solutions that work without unrealistic financial/environmental subsidies. Any energy source comes with baggage – safety, environmental impacts, exploitation economics and useful longevity. How much of our surroundings is needed to exploit any power-generating technique relates not just to environmental impact, but to its fundamental value, long term.

Figure 1 illustrates the relative energy-density of combustible fuels, Uranium/Plutonium fission and Hydrogen fusion.

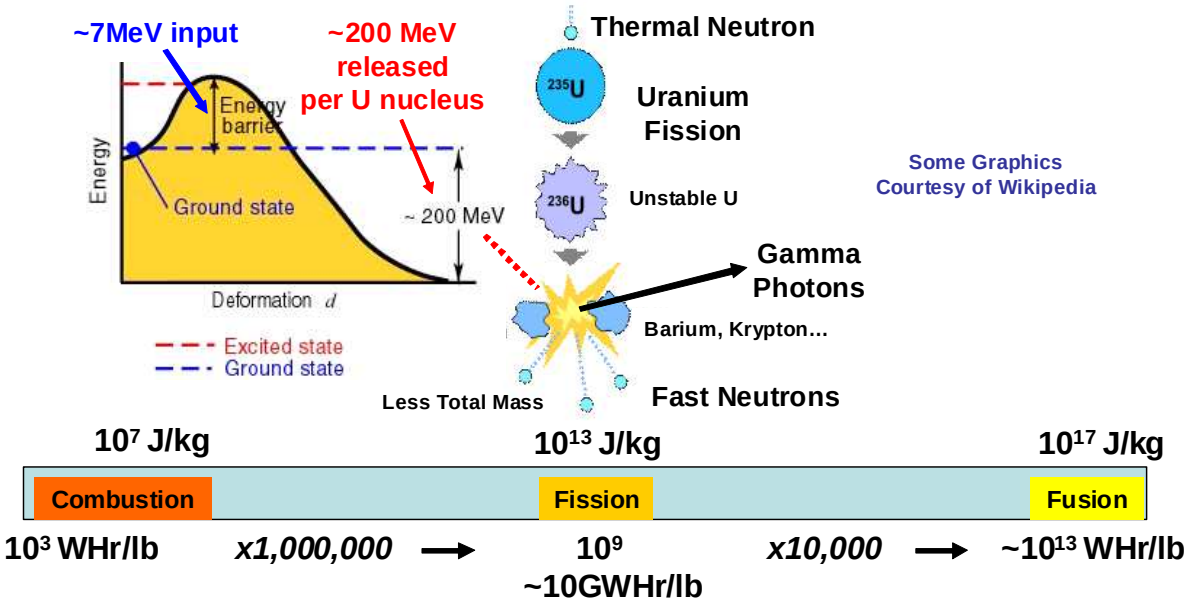


Figure 1. Energy Density for Hydrocarbon Combustion, Fission & Fusion.

Common English units are used to illustrate that about 1lb (~1/2 kg) of fissile U will run 2 typical utility-scale, 1GWe LWR power plants for an hour under full load – equivalent to over 3000 coal-train gondolas. On the combustion end, Hydrogen fuel would seem best at ~15kWHr/lb, but it loses a few kWHr to compress each pound to useful volume, as for a vehicle. This illustrates why gasoline/diesel, at ~6kWHr/lb, is so conveniently popular, and so challenging to replace, despite only yielding ~2kWe per hour per pound at the wheels due to engine inefficiency. H_2 also loses by failure to account for the needed reactant Oxygen, at 8:1 extra mass demand. This nets a Hydrogen vehicle 4kWHr/lb (counting both reactants) and only ~1kWHr/lb at wheels driven by a typical engine. All fossil fuels come out even worse, when accurate reactant and efficiency accounting is made. It's easy to see why fission energy, completely stored for us in heavy nuclei by stellar explosions billions of years ago, is so useful.

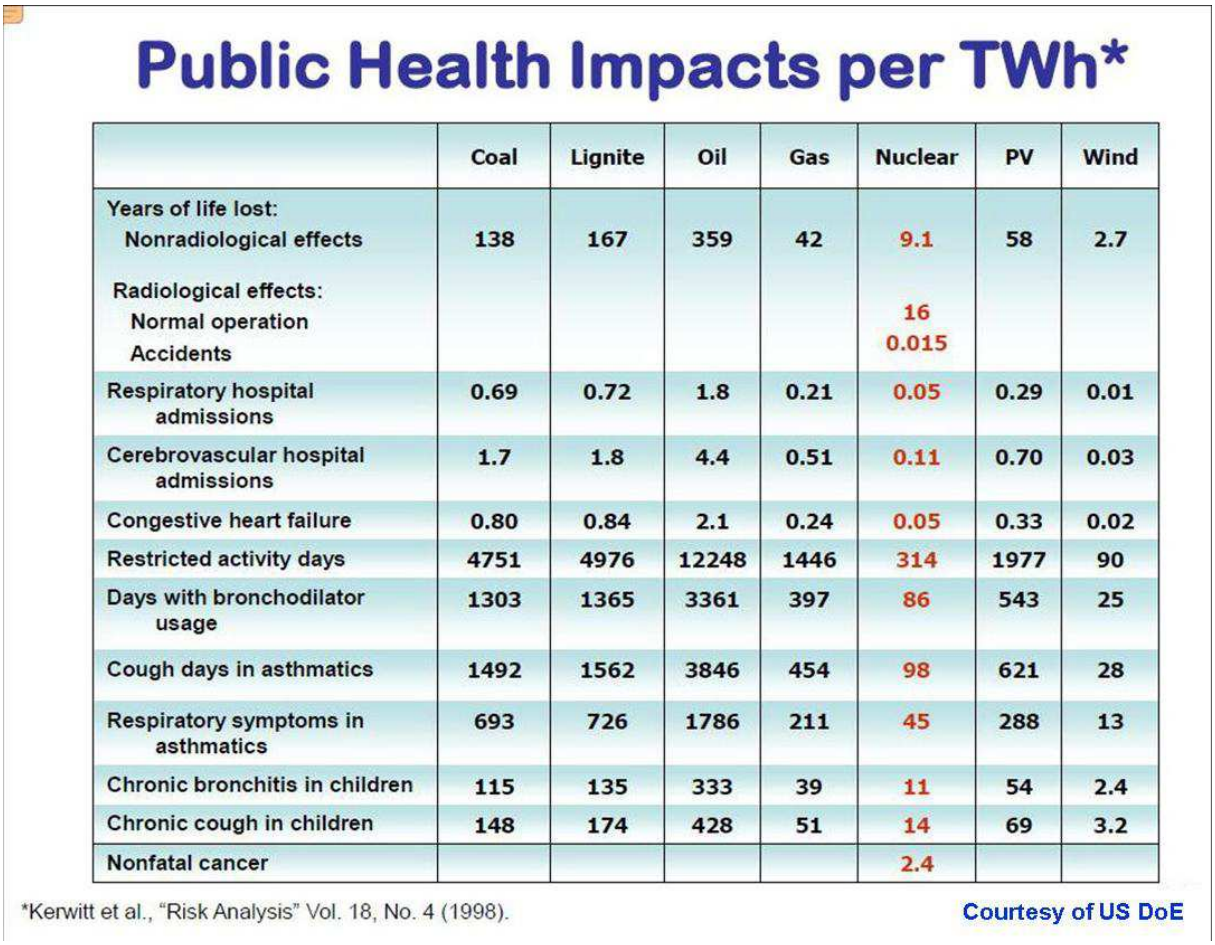
Figure 1 also illustrates how certain Actinide-element (Uranium, Plutonium…) fission nets a great energy surplus, once we've done something to a nucleus that drives it over the energy barrier from its ground state to instability (inset). All common Actinide fission events yield about 200MeV (~20GWHrs/kg) -- compare with gasoline/diesel fuel at 13kWHrs/kg (0.000013GWHrs/kg). The result for ^{232}Th bred to ^{233}U is that 10 grams of Thorium can support a typical American's or European's energy needs for years. In Nevada, we have a 3200-ton stockpile of Thorium Nitrate – Figure 2.

Figure 2. Thorium Nitrate Stockpile in Nevada, USA.

The Thorium in that pit can drive all US energy needs, including vehicular, for years. Four US pennies, minted of Thorium, would breed fissile fuel sufficient to supply a typical American with all his/her energy needs for several years. Just the 1400-acre Lemhi Pass mine, between Idaho and Montana, contains enough Thorium to supply all US electricity for 1000 years. Contrast this with the current BLM consideration of over 1000 claims for Uranium extraction via underground acidic leaching near the Grand Canyon, or with industry estimates that US natural gas reserves could last about 100 years.

Safety. Any energy source must be safe in use and safe throughout its entire environmental cycle – fuel discovery, production, processing, consumption, emissions, recycling and waste disposal. This requires accurate, complete accounting of effects and costs, without subsidy. Today, every energy source is subsidized in a variety of ways, especially the combustion sources -- input activities, combustion methods and waste disposal are all subsidized via tax law plus limited environmental law/enforcement – combustion plants are even allowed (the NORM rule) to emit radiation at ~100x what a nuclear power plant could ever emit. Unaccounted-for subsidies are largely responsible for civilization's daunting environmental problems today, and into the future. Such accounting failures are themselves unsustainable.

For nuclear power, obvious safety issues are radiation and chemical exposures in all parts of the fuel-to-waste path, explosive potential during fuel processing and use, and diversion of any materials for weapons, explosive or not. Figure 3 shows a 1998 international health comparison among power sources, from acquiring all raw materials, through fabrication, operation and all consequences of power output (see also the health references by Henriksen and Allison). Section 9 gives a more thorough discussion and reference list regarding radiation safety and health.



Public Health Impacts per TWh*

	Coal	Lignite	Oil	Gas	Nuclear	PV	Wind
Years of life lost: Nonradiological effects	138	167	359	42	9.1	58	2.7
Radiological effects: Normal operation					16		
Accidents					0.015		
Respiratory hospital admissions	0.69	0.72	1.8	0.21	0.05	0.29	0.01
Cerebrovascular hospital admissions	1.7	1.8	4.4	0.51	0.11	0.70	0.03
Congestive heart failure	0.80	0.84	2.1	0.24	0.05	0.33	0.02
Restricted activity days	4751	4976	12248	1446	314	1977	90
Days with bronchodilator usage	1303	1365	3361	397	86	543	25
Cough days in asthmatics	1492	1562	3846	454	98	621	28
Respiratory symptoms in asthmatics	693	726	1786	211	45	288	13
Chronic bronchitis in children	115	135	333	39	11	54	2.4
Chronic cough in children	148	174	428	51	14	69	3.2
Nonfatal cancer					2.4		

*Kerwitt et al., "Risk Analysis" Vol. 18, No. 4 (1998).

Courtesy of US DoE

Figure 3. Health Impacts per Thousand GWHrs (1 TWHr) by Source.

The performance of nuclear power over 50 years has been excellent, despite three serious civilian nuclear-power accidents – Three-Mile Island and Chernobyl, plus Fukushima (so far of intermediate severity – www.iaea.org) now developing in Japan[16]. Three-Mile Island and Chernobyl resulted from training and operational errors. Fukushima derives from even more serious mismanagement and planning errors that ignored the dual impacts of a large earthquake and tsunami[16], despite historical precedent Yet, as we hear all too often, coal, gas and oil extraction and transport have far more frequent, lethal events. In fact, an old joke says: "You can find a coal plant with a Geiger counter, but not a nuclear plant" – there's a great deal of Uranium in coal exhaust and ash (plus various toxics). Unregulated coal-fire emissions (Mercury, Lead, Radon, soot…) are identified by the National Institutes of Health (NIH) with over 10,000 US deaths per year. What Figure 3 suggests are the health effects of running 1000 full-scale (1GW) power plants each hour. Total world generation is >16 times that now (>16TW), so nuclear's advantage is even more dramatic. And Thorium can do still better.

Thorium, used as a fertile 'fuel', is safer than current LWR reactor cycles due to its abundance, its low radioactivity and its ability to efficiently breed fissile fuel at the lowest fissile mass – ^{233}Uranium. ^{233}U's Thermal-Neutron fission cross section (~90%) yields about ½ the probability (compared to ^{235}U) of transmutation to higher-mass Actinides – the realm where long-lived radioactive wastes present expensive safety problems (upper half of Fig. 31). Given that

the next fissile is ^{235}U, with 80% thermal-fission probability, higher wastes from the Th-to-^{233}U-to-^{235}U path are 1/10 of 20%, or 2%. This is far better than 20%, when starting with $^{235}U/^{238}U$, as in standard LWR fuel, inevitably breeding fissiles ^{239}Pu and ^{241}Pu – these Pu isotopes have even higher cross sections for transuranic production than does ^{235}U.

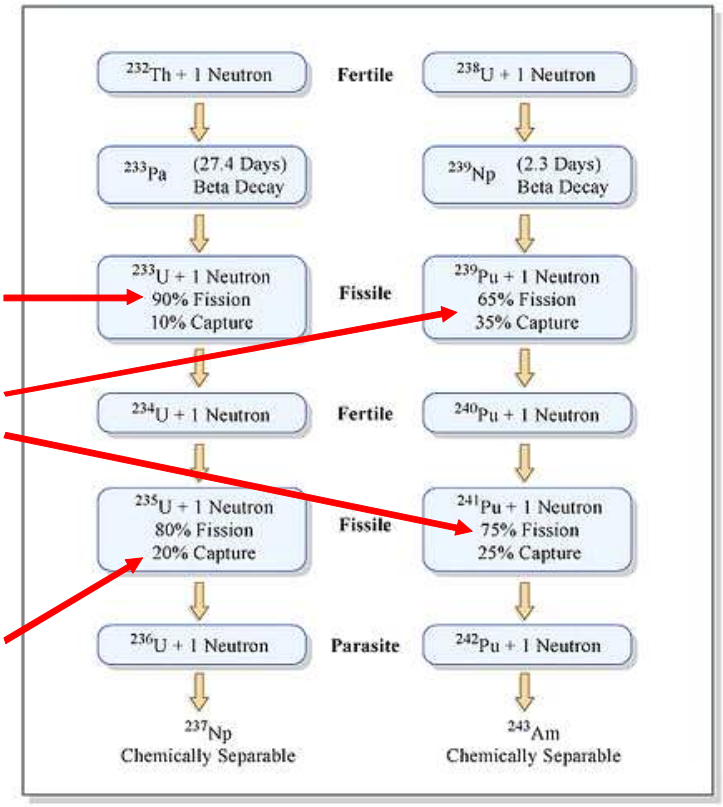
Then there are the weapons-proliferation and dirty-bomb issues, both of which are greatly reduced when Thorium is the fertile input to fission reactors. Figure 4 illustrates the key value of choosing the Th-^{233}U starting point for maintaining low-waste breeding and fission power.

Starting fission with Thorium vs ^{238}Uranium

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 energy, but ^{238}U bred to Plutonium is much less likely to fission, thus building up higher-mass Pu & waste, all of which has bomb-making potential

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

Figure 4. Thorium-to- ^{233}U, Versus ^{238}U-to- $^{239/241}Pu$ Breeding/Fission.

Figure 5 illustrates the issue of higher-Actinide (transuranic) wastes versus fission products for standard enriched-Uranium fuelling (1 on the logarithmic Hazard axis represents simply standing on average Uranium ore). A very useful graphical Java® application is available to see how fission products decay and change within typical LWR used fuel: SpentFuelExplorer[10].

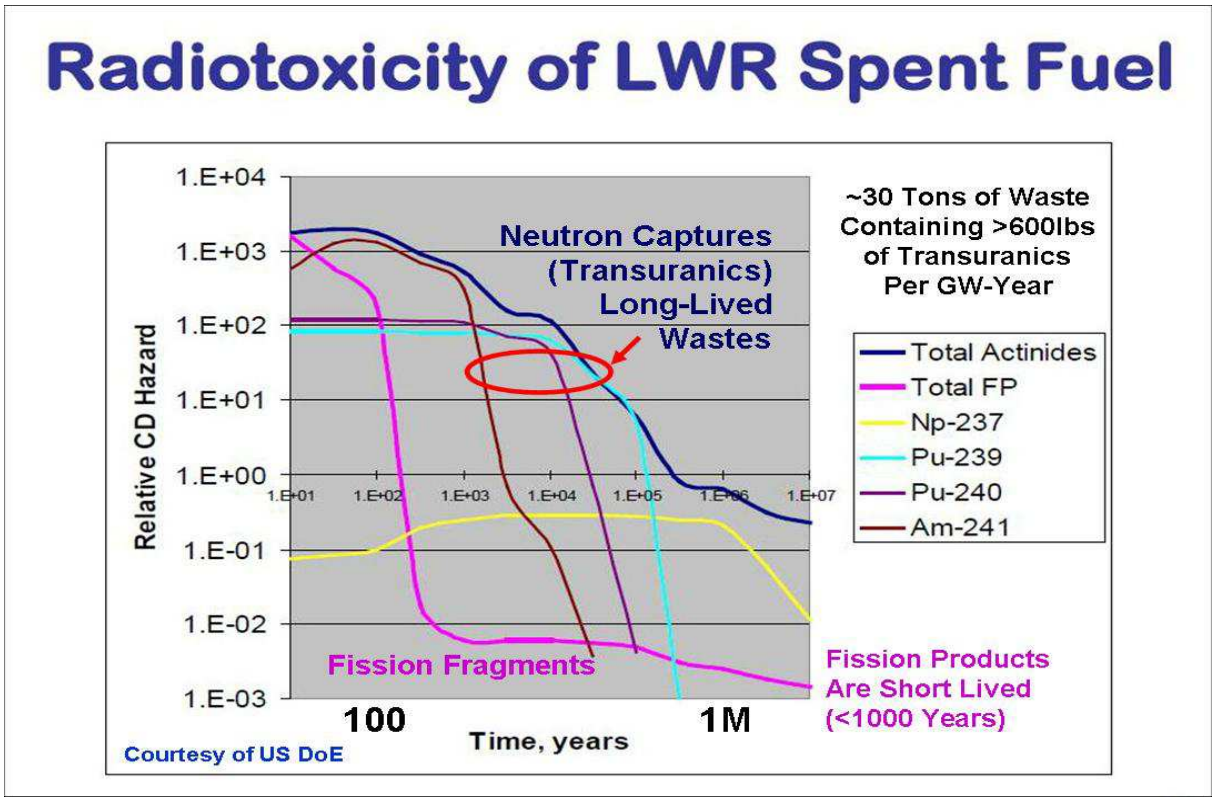


Figure 5. Typical LWR Fission Products & Transuranic Wastes.

Note the comparison with the relatively fast-decaying emissions from fission daughters (hot-pink curve). Being so abruptly created, they are all quickly reducing internal nuclear and electron-orbital energies by strong alpha, beta and gamma emissions across a naturally rich spectrum of strengths and half lives. These isotopes demand safe storage for a few hundred years, rather than tens of thousands, as for many transuranics. Thus, the safest fission cycles should be chosen to minimize all wastes, but should bias waste production as far toward fission products (daughters) as possible,

And, there are further reasons why long-term wastes from Th-to-^{233}U breeding can be greatly reduced. Figure 6 illustrates important comparisons, for breeding in Thorium salt reactors (e.g., LFTR[4]) – within a few hundred years, both fission products and transuranics are below Uranium ore in emissions, and the mass of transuranics is <1/10 that for standard solid fuel. The most important result of starting with ^{232}Th in liquid fuel is that waste radiotoxicity can be orders of magnitude below that of conventionally-fuelled LWRs. How the fuel is constituted and managed (processed) also has great influence on long-term waste production, as well as reactor efficiency.

Results from the Japanese FUJI reactor project (Furukawa)[4] illustrate just how much the higher-Actinide wastes can be reduced. However, reactor architecture also influences total waste, as when internal reactor structures need replacement and disposal. In any event, use of Thorium to breed ^{233}U has great potential for minimizing long-lived wastes, thus addressing large and expensive environmental and security impacts.

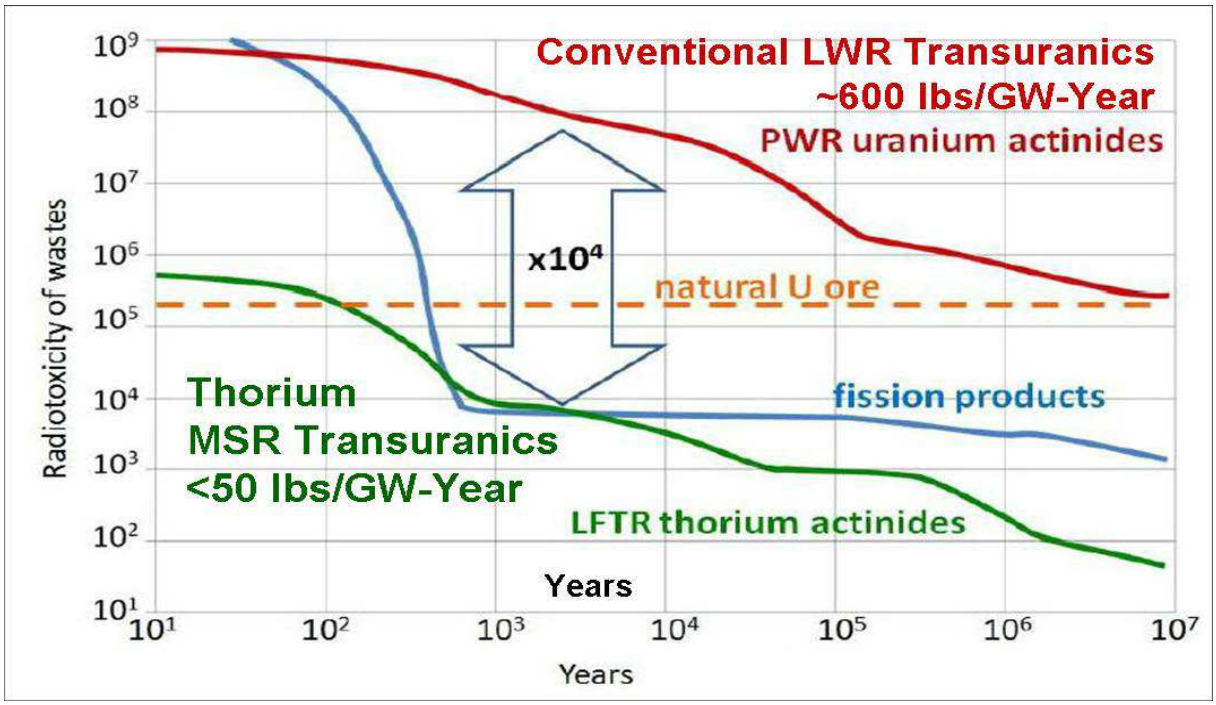


Figure 6. LWR Versus Thorium MSR Fission & Transuranic Wastes[#].

Abundance. The ease with which fissile elements can be found has great influence on both overall economy of the particular reactor cycle and its environmental impact (at least on the input side). Figure 7 illustrates the relative average atomic abundances (in % and grams/ton) of Uranium and Thorium on Earth (weathered or unweathered rock). Similar abundances appear on the Moon and Mars.

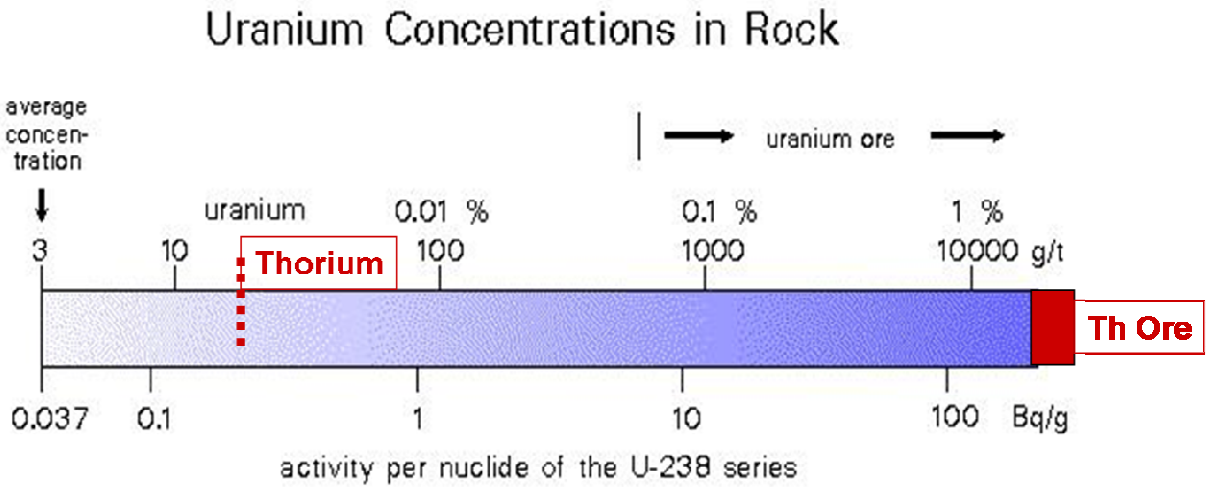
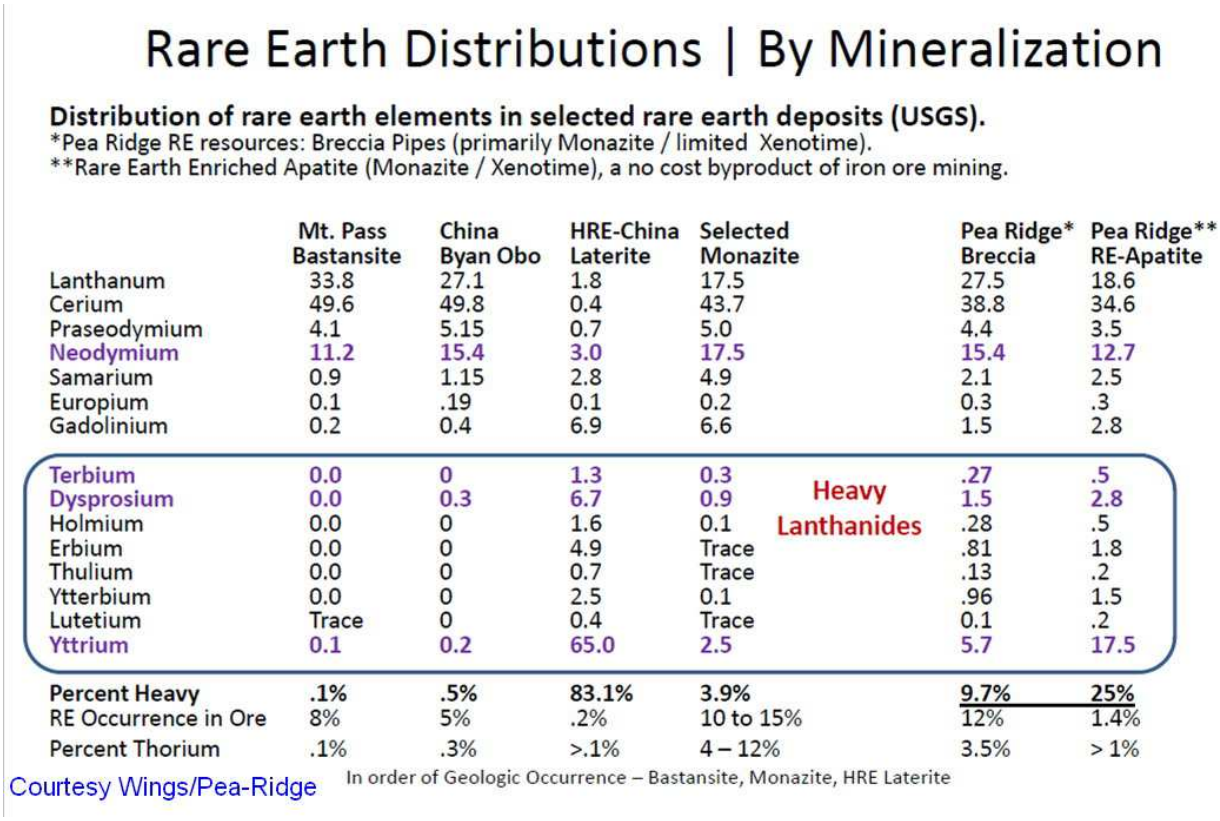


Figure 7. Average Uranium and Thorium Concentrations (DoE).

The figure illustrates that Thorium is about 4 times as abundant as Uranium (~12 grams/ton of earth vs ~3). A typical Thorium ore (Monazite) contains about 4% Thorium – also see Figure 8, last line. Uranium's fissile isotope is far rarer in any ore. Figure 7 also indicates ^{238}U's radioactivity. Since Thorium's

half life is several times that of ^{238}U, Thorium's natural radioactivity is much lower than Uranium's.



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	Heavy	.27	.5
Dysprosium	0.0	0.3	6.7	0.9	Lanthanides	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%

Courtesy Wings/Pea-Ridge

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

Figure 8. Example Rare-Earth Ores and Related Thorium Concentrations.

As Thorium is considered today, the Uranium ore Pitchblende was considered mining waste in Marie Curie's time, allowing easy access to the tonnage she needed to discover Polonium and Radium.

Wastes. The present LWR fuel cycle creates many tons of waste, from mining through fuel production, simply because of the fuel choice -- natural Uranium, which we choose not to breed to fissile Plutonium, as the 1962 AEC report advised. In addition, because of significant Thermal-Neutron capture cross sections for Actinides from ^{235}U through ^{241}Pu, much transuranic waste naturally accompanies current LWR operations. Starting reactor fuelling with ^{232}Th reduces final transuranic wastes by a factor of ~10 (see Jorgensen)[(10)].

Given how greatly our nuclear power sources must be expanded, long-lived (transuranic) nuclear waste production must be addressed and greatly reduced. This is understood at the highest levels of government…

> March 25, 2010, Nuclear News: *'US Energy Secretary Steven Chu told members of the President's Blue Ribbon Commission on radioactive waste that they must keep their sights set on the future. The 15-member commission co-chaired by Lee Hamilton and Brent Scowcroft is to conduct a comprehensive evaluation of waste-management alternatives to a Yucca Mountain repository and submit a final report with recommendations to Chu in January 2012. What the commission looks at does not have to be set in concrete, Chu told the panel, noting that it*

cannot be predicted what technologies would be available 50 or 150 years from now. But, he added, "The commission should look at all possible ways the amount of nuclear waste could be reduced."'

An LWR now produces about 250kg (550lbs) of transuranic waste per GWe-year. By 2050, given only modest additions to the worldwide reactor fleet, LWR use will have presented us with thousands of tons of such waste. We'll need some place to store this mass for tens of thousands of years, and we'll need to safely transport it among the countries generating it. Figure 9 presents an example, 2010 IAEA-ordered waste disposal of ~8000 Serbian used-fuel rods in Russia[10]. Security required elaborate, expensive, multi-modal transport:

Figure 9. Example Serbian LWR Waste-Fuel Transport (~2.75 tons).

Nuclear Power Daily (22 Dec. 2010): *"A convoy of 15 trucks carrying as many special containers holding the fuel left Vinca on November 19 under tight security provided by more than 3,000 policemen…"*

All this for just ~10GWe-years of power output, with >90% of fertile and fissile fuel left in the 'waste'. A breeder more than decimates the waste result.

On the less-dense, but environmentally-challenging input side of the Uranium fuel cycle, mining waste covers large areas, in comparison to the energy density of the fuel being sought (e.g., Scientific American)[10] -- Figure 10 illustrates unattended-to, abandoned mining wastes for which the US EPA has yet to establish clean-up efforts, despite confirmed cancer and other threats.

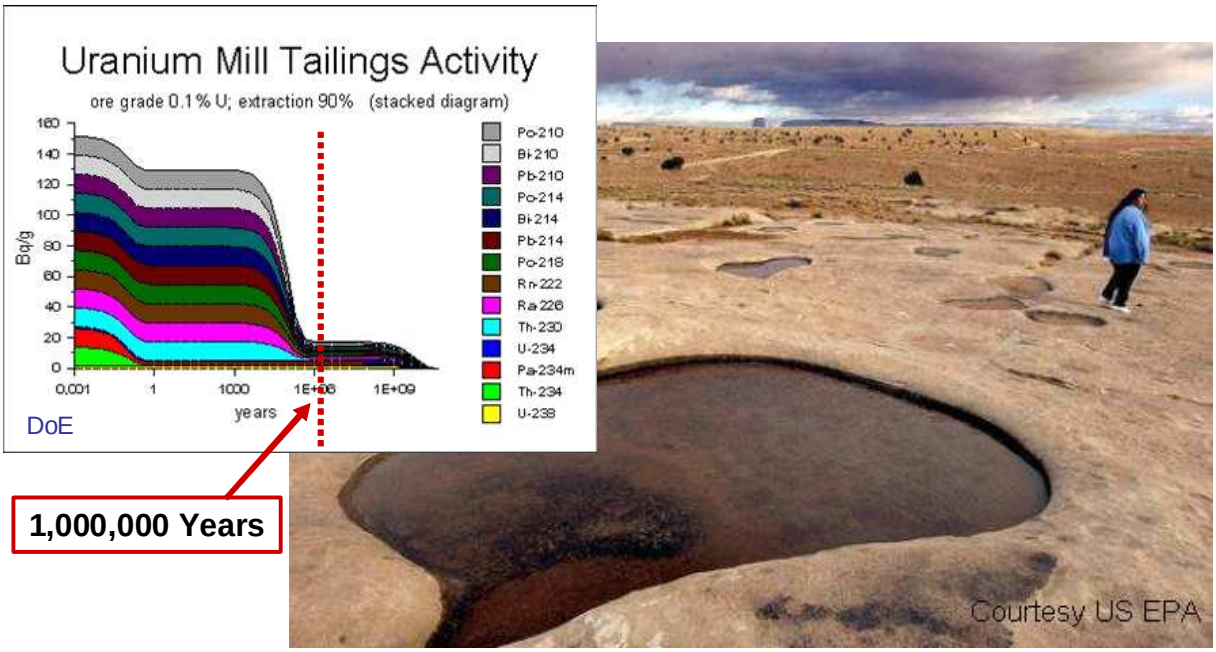


Figure 10. Example of Uranium Mining Waste (Navaho Nation).

Therefore, future reactor designs and fuel cycles directly impact our serious nuclear-waste problem, on input and output sides. These impacts must be reduced to gain hope for, and acceptance of, conversion from fossil fuels to non-emitting generation within as few decades as possible. This is why the President's 2010 Commission (see brc.gov)[9] was formed (arguably decades later than needed).

One way to reduce waste is to increase reactor thermal efficiency, and this is addressed by the various high-temperature designs under study (see AHTR[7]). But, this addresses just a modest part of the overall problem, which stems from two choices, initially made to support weapons – solid fuel and enriched Uranium. The body of this article concerns the relevant details of using Thorium to avoid as much of the natural-Uranium waste burden as possible. It mentions examples of reactor designs which couple with Thorium's fuel-breeding advantage to minimize transuranic wastes, giving a path forward to approach the green curve in Figure 6.

Weapons Anti-Proliferation & Nuclear Disarmament. The present LWR fuel cycle opens itself to redirection of incoming enriched ^{235}U fuel (and "depleted" fuel) to some weapons, and it produces ^{239}Pu via Thermal-Neutron breeding from the dominant natural isotope ^{238}U (this was, in fact, one of the breeder paths mentioned in the 1962 AEC report[2]). ^{238}U is but one Neutron capture away from fissile ^{239}Pu – WGP (weapons-grade Plutonium). Since ^{238}U's capture cross section is high in moderated reactors, Plutonium is an immediate product of normal operations. Of course, this was intended, when weapons were being constructed during WWII and the Cold War[8]. For peaceful reactor use, Plutonium indeed fissions, but has a large capture cross-section for Thermal Neutrons (~35%, Figure 4), thus creating many of the undesirable, long-lived Actinides (transuranics), along with fissile ^{241}Pu. With only a somewhat better capture cross section, ^{241}Pu leads upward to undesired

Americium etc. Fast-Neutron reactors can do better with these and other Actinides, but they incur other difficulties, such as control.

On the other hand, Thorium is 6 sequential and unlikely Neutron captures away from Plutonium, thus the very low production of Pu (~0.1% relative to LWR) over decades of operation, as shown in the FUJI[4] experiments (Figs. 26 & 31). And, Thorium's bred fissile ^{233}U has only ~10% capture-no-fission cross section (Figure 4). This immediately reduces total transuranic waste, in relation to how much Thorium is used within a thermal reactor and how the fuel itself is constituted – e.g., solid, 'pebble' or, better, liquid. Fuel constitution and core architecture relate strongly to how effective a reactor design is in utilizing fissiles as fully as possible, thus limiting waste and weapons material when fuel removal and reactor servicing are needed.

Since Plutonium fissions, and anti-proliferation aims are to reduce or eliminate ^{235}U-enriched Uranium and WGP from the world, it is possible to do that within reactors that minimize fuel highly-enriched in ^{235}U (HEU) and use Thorium to produce as little WGP as possible. This then allows secured WGP introduction into the fuel, destroying it over time, while generating useful power. The ORNL/Westinghouse-monitored program by the Russian Kurchatov Institute intends just that in its RTPI design[11] www.ltbridge.com/assets/14.pdf . The solid fuel (MOX) mix of Uranium and Plutonium oxides also allows WGP destruction, but subject to the same in-core limitations of normal solid fuel.

Because solid fuels must contain all fission products, including gasses, and survive continued radiation bombardment, fuel elements and structures need scheduled replacement. This forces their removal from the reactor and subsequent reprocessing or storage outside the reactor (perhaps far from the reactor site – Figure 9). This again exposes some weapons-grade fuel to diversion, plus large amounts of radioactive elements usable in a "dirty bomb". This used fuel actually still contains a great deal of useful, fertile & fissile fuel (typically >90%), so it can be reprocessed, as the French do,[8] or simply stored. Both options are expensive and must be secured.

One use of Thorium in solid fuel (e.g., by Lightbridge Corp.) is intended to not only reduce ^{239}Pu production, but to leave in the fuel U and Pu isotopes that would hinder weapons production from used fuel.

Ultimately, the goal should be to have a reactor generate as little WGP and long-lived waste as possible, require as little external reprocessing as possible, and be able to run continuously without frequent fuel-assembly replacements. Reactor-core architecture can help this, as by use of a Thorium Blanket around seed fuel elements containing both Thorium and either WGP or ^{235}U (destined for near destruction). Thermal Neutrons from fissioning fuel breed ^{233}U from the Thorium, which then also fissions (Figure 4). Thus the Neutron budget for the reactor is maintained while WGP and HEU are consumed. For advanced solid-fuel systems, the gain in waste reduction can be >25%. Fast-Neutron (unmoderated) reactors can also fission transuranics but high Neutron velocity makes their control more demanding, as discussed later. And, the reactor-population scale-up we need for the future means fractional waste reductions won't suffice.

Use of fluid or pseudo-fluid (e.g., 'pebble') fuels can go much farther down the road of consuming wastes and weapons material. This is where the example chosen for discussion here, the Molten-Salt Reactor[(5)], excels. It allows continuous operation with necessary fuel-chemistry management and waste-removal to be done within the reactor's secure hot cell. These features make it a boon to those negotiating weapons destruction and non-proliferation.

This also relates to a new, unfortunate technical reality – inexpensive Uranium enrichment via laser[(11)]. This allows parties to skip the presently time-consuming, expensive enrichment processes and even to avoid schemes for diversion of materials. Simply-processed Uranium ore (or used fuel) suffices as input to laser enrichment, yielding weapons materiel. But, if such material were found and confiscated, it at least could be destroyed efficiently via the MSR.

3. Fission-Reactor Details

This section describes in more detail important aspects of using Thorium as a fertile fuel element for fission reactors. The topics below cover details of reactor structure, fuel structure and processing that affect everything from thermal efficiency and wastes to safety and cost.

Fission/Fusion Energy.

As Figure 1 indicates, Uranium/Plutonium fission lies geometrically between fossil-fuel combustion and Hydrogen fusion, in terms of energy per unit mass used. Obviously, the combustion figure does not account for the additional mass of Oxygen we use when we burn a fuel, so the energy density per unit mass of the input substances will be much reduced (this is indeed "rocket science"). Nevertheless, there is about a 1 million-to-1 increase in energy density in proceeding from combustion to fission, then ~10:000:1 again from fission to fusion. This pair of extreme ratios illustrates why mankind can indeed find a far less environmentally-destructive energy future than from fossil fuels.

In each of the three sources, energy is extracted from reduction in mass – the input substances have more mass than what remains after their reaction. This is just Einstein's $E = mc^2$ (as Meitner & Hahn knew). For combustion, or all chemical reactions, the mass deficit per molecule, converted to energy, is miniscule. For a single Uranium/Plutonium nuclear fission, the deficit is about 200MeV, or about 390 Electron masses, which is less than ¼ a Proton's mass – still very tiny (~0.1%). For Hydrogen fusion (involving ^2H & ^3H), the fused nucleus is Helium. This event produces a Neutron as well, and about 17MeV is released, mostly to the Neutron's velocity. Other Hydrogen isotopes can fuse, but Deuterium-Tritium is the one chosen for fusion-power research due to good cross section and energy release. However, a 50-year-old joke in the fusion-research community is that fusion is always 20 years away (a recent Stanford Plasma-Physics group's 50^{th} reunion decided fusion is now 30 years away). Nonetheless, because only a few nucleons enter the reaction, the 17MeV derived from their fusing represents about 0.3% of the input mass and that input mass is so small that a vast number of 17MeV events can be derived from a

gram or pound of ^{2}H & ^{3}H, thus the 10,000-fold increase in mass power density beyond fission.

The problems we face with fusion, however, have remained daunting, despite many mechanisms for causing simple fusion of small nuclei, like Hydrogen – all to date consume far more energy than they release for any useful duration. Fusion has been essential to life, but fusion under our control demands detailed mastery of plasma confinement that we've yet to efficiently achieve.

The commonly-chosen plan is to fuse Deuterium and Tritium (D-T), because the former is abundant enough in Earth's seas (as 'heavy' water) to supply forever our most ambitious forecasts for energy consumption. Unfortunately, though Tritium is made in tiny amounts within fission reactors, it's half-life of only ~12 years means there's none in nature. We must make Tritium as fast as we fuse it. One way we know consumes a Neutron to fission ^{7}Li, which emits a Neutron which is then consumed fissioning ^{6}Li – Figure 11. The first Lithium fission is slightly endothermic, while the second releases about 5MeV. Together, 1 Neutron is lost, while two Tritium nuclei are formed.

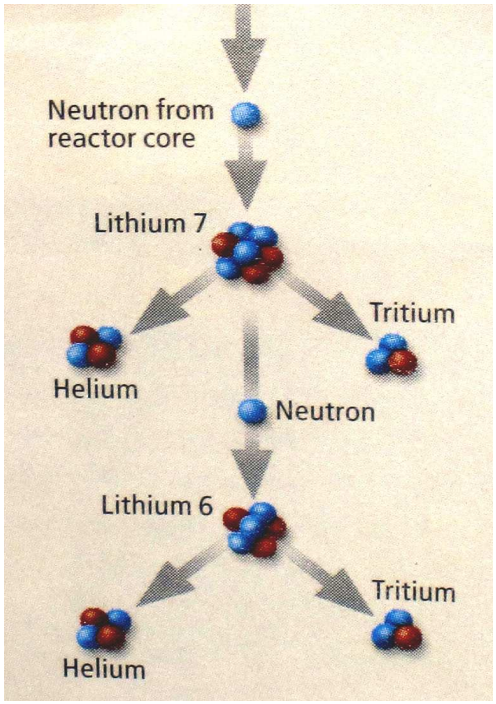


Figure 11. Example of Tritium Synthesis (Wikipedia)**.**

However, the majority of D-T fusion's energy (~14MeV) drives its lone exiting Neutron. If we use that Neutron to make two Tritium nuclei, we lose too much energy, despite netting one Neutron from two possible fusion events using two Tritium nuclei. The Neutron economics of the process leaves D-T fusion delivering less than the useful thermal energy we'd hope for, even if confinement to achieve fusion is mastered. Tritium can be supplied externally, but is currently in worldwide short supply, along with other crucial radio-nuclides[13]. These shortfalls can indeed be corrected in the same way breeding provides new fuel -- in salt reactors containing some LiF.

An alternate fusion system considers colliding Hydrogen and ^{11}Boron, yielding two Alpha particles (^{4}He) with high exit energies, plus one slower Alpha. This produces a positive electric current directly, with no emitted Fast Neutrons to cause radioactive transmutations of elements in chamber walls. The problem is that p-B fusion is about 1/3 that of D-T in reaction rate and requires several times the collision velocity (temperature), thus adding greatly to the challenge of plasma confinement (see focusfusion.org).

But, throughout the universe, fusion has indeed given us access to fission's energy. Because of reaction energetics, fusion is done in stars of our Sun's size only up to Be, in heavier stars up to Fe, and from then on only in shocks emanating from large exploding stars (supernovae). Figure 12 illustrates this and that the nuclei of elements beyond Bi are inherently unstable – they decay radioactively, and some may fission if driven to more instability. Yet all, including Uranium and Plutonium, are fusion products from stars' lives and deaths. Mastering fission means we can leave fusion to the cosmos.

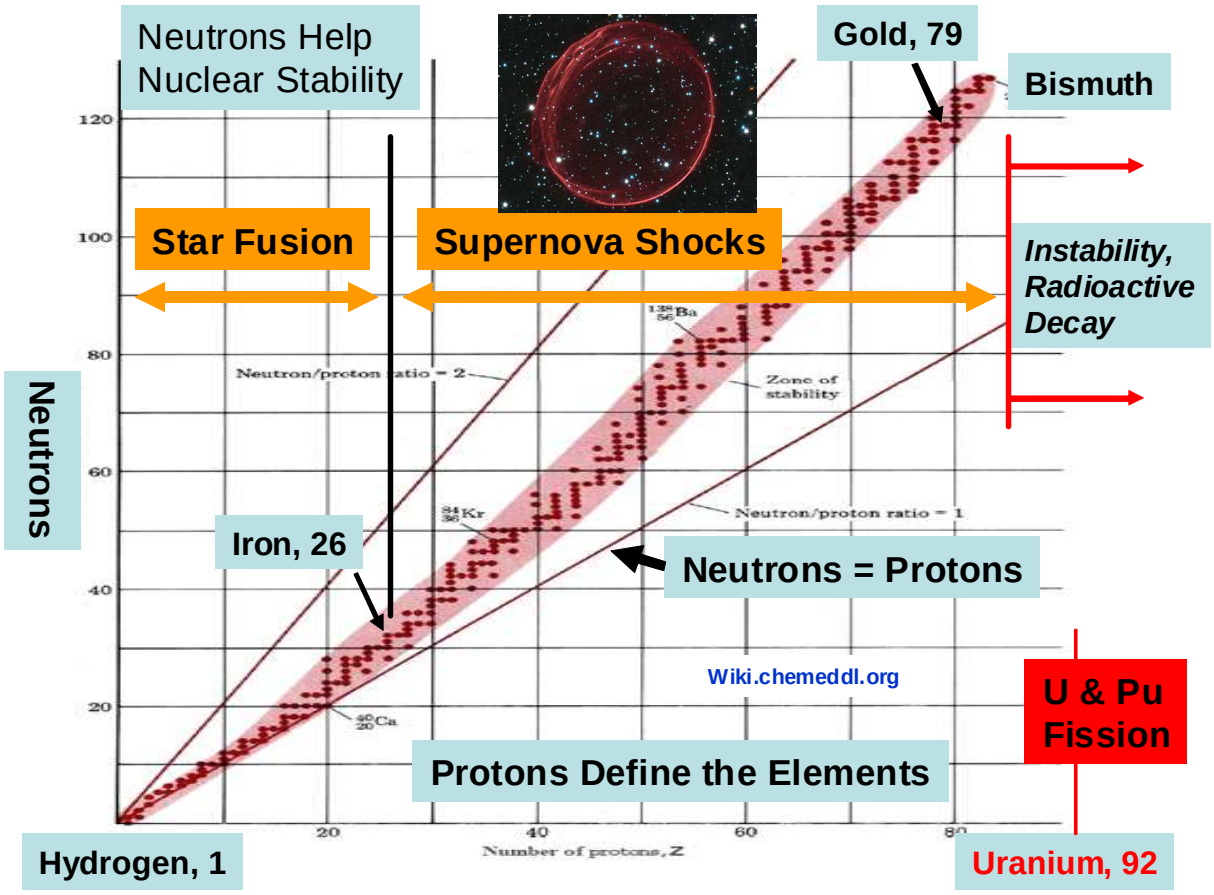


Figure 12. Nuclear Origins, Stability and Instability.**

The elements beyond Bismuth thus offer an opportunity to find nuclei that may not withstand energetic impacts by, or capture of, a Neutron. Fast Neutrons can, in fact, cause most any element to fission, without necessarily gaining energy from the event (e.g., making Tritium from ^{7}Lithium). Thermal Neutrons are easily captured by fissile elements, driving them to instability and fission with net energy gain. This is the basis for typical fission-power reactors.

Nature seems to require Neutrons in any stable nucleus beyond ^{1}Hydrogen, but only a few stable isotopes exist for each element – too many Neutrons induce Beta decay, moving a decayed nucleus rightward in Figure 12, to become a different element (too few Neutrons can induce Beta^{+} or Positron decay, moving to the next lower element). Decay via Alpha or Beta emission is generally dependent on two factors: evenness of Neutron & Proton totals, and certain counts of Neutrons or Protons (2, 8, 20, 28…) called "magic numbers" – the most stable elements have nucleon counts that are both magic numbers (the numbers reflect nucleon pairing possibilities and other features of the nuclear "strong force" that establish how tightly bound together nucleons are). Note that Alpha emission drops both Neutron and Proton counts by 2.

Thorium is of particular interest for fission-energy recovery because it exists in nature as just one, mildly radioactive, fertile isotope at the low end of Actinide masses, and it easily transmutes into the lowest-mass fissile isotope of Uranium (^{233}U) which, in fact, has a higher fission cross section than any other Uranium or Plutonium fissile. Nature is doubly kind to us, providing an abundant element giving fairly direct entry to the release of fission energy with less waste production than other choices we might make (and have made).

Breeding Thorium to Fissile Fuel.

To enter the fission realm from Thorium requires three steps, of which the first is our choice – hitting a Thorium nucleus with a Thermal Neutron. From then on, the path to ^{233}U is clear: ^{232}Th + n => ^{233}Th; ^{233}Th Beta decays quickly to ^{233}Protactinium ($_{91}$Pa), which more slowly Beta decays to ^{233}U, our target fissile. Then, Neutrons from prior fissions can cause the new ^{233}U to fission, releasing about 3 Fast Neutrons and typically a pair of daughter nuclei (e.g., Xe, Sr, Kr…) – see Figures 13 and 14.

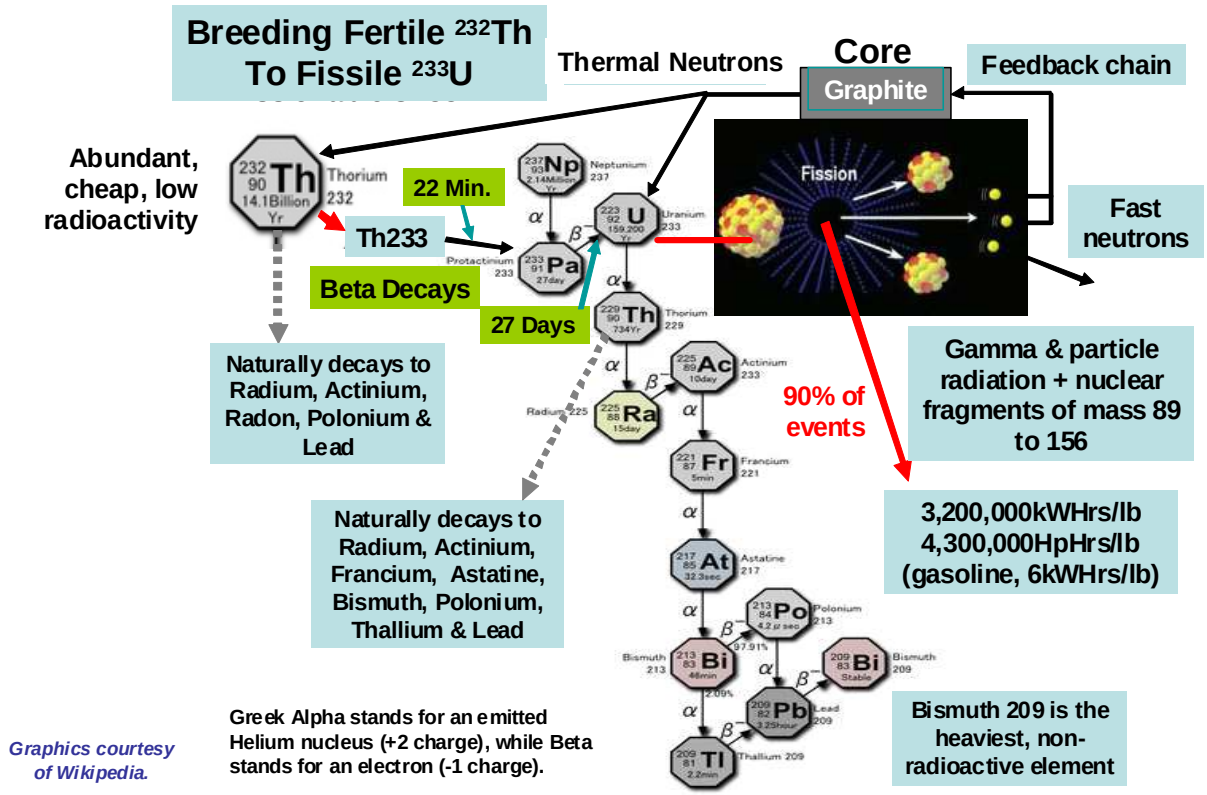


Figure 13. Thorium Breeding to Fissile ^{233}Uranium.

If the emitted Fast Neutrons are slowed by a moderator (water, graphite…), then they may impact other fissile Uranium or Plutonium nuclei in the fuel causing them to fission and release still more Neutrons and daughters. If the reactor is architected well, there will indeed be fissile nuclei awaiting these new, Thermal Neutrons along their paths – the Neutron economics of the reactor will sustain criticality and deliver net power to whatever heat-transfer material (liquid or gas) infuses the reactor core. And, if the fertile Thorium nuclei also see sufficient Thermal Neutrons, more fuel will be made than is consumed. This is fuel breeding, as demonstrated at Shippingport.

If the reactor contains a moderating liquid, such as water, its temperature will rise simply from fission-product and Neutron kinetic energy transfer. The same will occur if the moderator is solid, in which case the heat-transfer out of the reactor will generally be via liquid or gas, either of which may or may not be an effective moderator.

The in-reactor fuel-breeding process necessarily involves fission, daughter creation and production of the intermediate nuclide Pa. The Neutron-capture cross sections for all these must be known in order to confirm overall Neutron economics and criticality maintenance. This reality affects every type of reactor, but in somewhat different ways, to be described later. It certainly affects the schedule for fuel reprocessing and retirement. These create large differences among reactor designs and fuel phases. The next sections discuss key details of those differences.

A traditionally-fuelled LWR can be considered a breeder of fissile Plutonium (^{239}Pu & ^{241}Pu) fuel, via naturally fertile ^{238}U. When breeding is done for fuel via

Thorium, the desired product is ^{233}U, plus a fraction of a percent ^{232}U[12]. The latter is highly radioactive (half-life ~72 years), with very active Gamma-emitting daughters, such as Radium, Radon and Polonium. Thus, bred ^{233}U must be handled remotely if it must be removed from the reactor core and/or breeding blanket. For fluidic fuels and blankets, this process necessarily occurs within the reactor hot cell (e.g., Figure 29). Only if ^{233}U is to be used to fuel/start another reactor, would it be taken from that secure, remotely-accessed environment. US DoE currently has about ½ ton of bred ^{233}U (with minimal ^{232}U) in storage, which could be used to start, for instance, a Thorium MSR breeder (LFTR, Figs. 4 & 6), as described later in the example chosen for this article. The handling dangers associated with ^{232}U-polluted ^{233}U are flagged by some as advantageous in discouraging diversion for weapons (e.g., see Moir[11]).

As a footnote, Figure 14 illustrates the percentages of daughter elements (usually pairs) by mass, as produced by typical LWR thermal fissioning of ^{233}U, ^{235}U and ^{239}Pu. The very interesting point is the clearly bifurcated distribution of nuclide masses per event. It means that Actinide fissiles tend to break apart with limited, but clear asymmetry, due to how nucleons are bound by the "strong" nuclear force. Whether fissile nuclei were put together by cosmic stellar explosions acting inversely on daughters as precursors, or sequentially on populations of still smaller nuclei, isn't known.

An extremely important, non-power aspect of reactor operation is the production of useful isotopes, such as ^{99}Mo, which Beta decays to ^{99}Technetium, a key isotope for medical scanning. Serious supply shortages now exist[13], all of which can be corrected by safe reactors whose fuel is easily and promptly processed, especially if in liquid form, before short-lived precursor isotopes decay.

The graphs below also illustrate how often Thermal-Neutron poisons in the Lanthanide series plus Hafnium (140 to about 178 nucleons), appear as daughters. This is one nuclide region where fuel replacement or processing can be important to maintain power and criticality. Other fission poisons, like ^{131}Xenon, lie below the Lanthanide series.

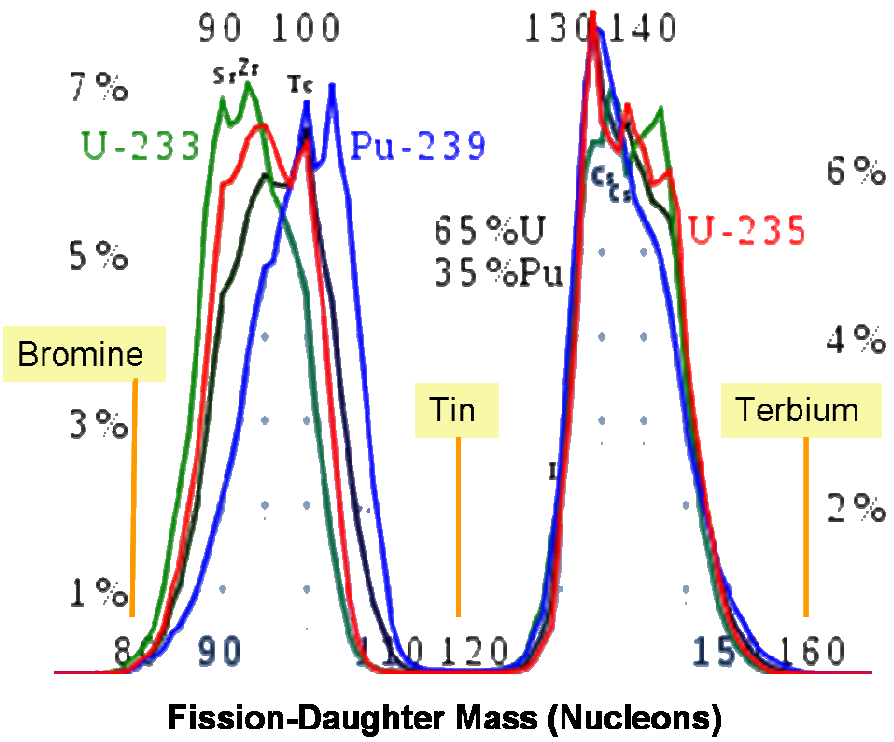


Figure 14. Fission-Daughter Mass Distributions (Wikipedia).

Thorium-^{233}U Breeding vs Direct Uranium/Plutonium Fission.

The pioneering Shippingport LWR[3] was converted in 1977 to contain a Uranium seed and Thorium blanket, both solid, for 5 years of fuel-breeding tests. When chemically analyzed in 1982, more than 1% new fissile fuel was present. Earlier tests done at the Indian Point (NY) LWR Number 1 in 1962, had been less successful, but led to breeder design improvements that allowed Shippingport to deliver ~160% of designed full-power-hours with less than usual enriched-Uranium fuel.

In these cases, solid fuel and Thorium, formed in plates or rods, composed seed and blanket structures. The key is to breed enough ^{233}U to reduce the need for mined and enriched Uranium in the Seed(s). This can be accomplished by using some Thorium in the Seed(s) as well as in the blanket, and choosing an architecture for each of the components and assemblies that maximizes Neutron economics, as well as thermal contact with reactor coolant/heat-transfer fluid (e.g., LWR water, AHTR liquid metal or salt).

For fluid-fuel designs (see ORNL Document Archive), such as an MSR, Thorium is added as a salt, which simply melts into the molten-salt fuel (or blanket fluid) in sufficient concentration to maintain breeding rate and optimal salt composition. Extensive work on salt-reactor chemistry was done at ORNL in the 1950s and 1960s, with detailed studies of optimal salt compositions (e.g., W. Grimes). This has led to an excellent fluid composition, based on a mix of Fluoride salts of Uranium, Beryllium, Lithium and optionally Plutonium, with Thorium Fluoride added in sufficient concentration to allow very good ^{233}U breeding. For Fast-Neutron reactors, as for fissioning non-fissile Actinides,

chloride salts can be used, since they are less moderating. Note that, unlike solid-fuelled reactors, liquid fuelling allows fertile and fissile concentrations to be just what is needed to maintain criticality, as opposed to what is needed to last until the next solid-fuel-element replacement (~2 years) without excessive Neutron-absorbing 'poison' (e.g., Xenon) buildup.

Liquid-metal fuels, such as a Bismuth-Uranium intermetallic solution, have long been considered for reactors, for thermodynamic reasons similar to those supporting the MSR choice. However, fuel breeding from Thorium or ^{238}U in such liquid metal is problematic because of those fertile elements' relatively low solubility in Bismuth. In addition, Bismuth breeds Polonium under Neutron bombardment, adding to the burden of fission-product radioactivity.

In solid- or fluid-fuel breeder reactors, continuous operation becomes a sophisticated, intriguing radio-chemistry effort. Fertile input must be added appropriately, the Neutron economy must be managed, as fission products that may poison reactivity accumulate, and transuranics must be removed, if the reactor operator wishes to avoid WGP and long-lived-waste production.

For solid-fuelled reactors, continuous operation from one fissile fuel load is not actually possible, because there's no path for gaseous 'poisons' to exit the fuel/core, and continued Neutron bombardment becomes detrimental to physical fuel structures. For breeding from solid Thorium (e.g.,ThO_2), the additional problem of Protactinium buildup exists – ^{233}Pa is the Beta-decay link to ^{233}U, but it also has a large Neutron-capture cross section (to ^{234}U), which hurts Neutron economics. And, it has a parasitic (N, 2N) path to ^{232}U that may not be desired. Thus solid-fuelled breeding suffers the same management needs standard LWR fuels do – peremptory fuel removal and/or mechanical/chemical reprocessing[(8)] or disposal of wastes along with much useful fertile/fissile fuel (typical, 4% ^{235}U LEU, when new, contains ~1% ^{235}U, ~95% ^{238}U and ~1% ^{239}Pu when removed after ~18 months for LWR refueling).

Chemists favor liquid operations, so even solid-fuel reprocessing deals largely with liquids, from which fluorination can extract Uranium and Plutonium as gasses (e.g., UF_6). Gaseous daughter products (e.g., Xe and Kr) evolve naturally from what was originally solid-fuel entrapment. Some of these are even valuable reactor byproducts now in short supply (Tritium, ^3He, etc.)[(13)].

In solid-fuelled breeder reactors, Thorium-bred fuel is typically left in the blanket structures longer than seed(s) are allowed to reside in the reactor. So the blanket generates a significant percentage of overall reactor thermal output, via ^{233}U fission. This is what occurred at Shippingport, but the bred fuel at shutdown in 1982 was not removed. Only sampling analyses were performed to verify how much breeding excess had occurred (~1.2%) and how well the core structures survived 5 years of operation (exceedingly well). Modern breeding designs for solid fuels use carefully-constructed core components to accomplish both efficient fuel breeding and thermal efficiency. These designs (e.g., by Lightbridge) will be discussed in the next section.

The problem presented by solid fuel, especially for breeding, is extraction of the new (or unused) fissiles, such as ^{233}U (or ^{235}U, ^{239}Pu and ^{241}Pu). So,

moving what chemists do for solid-fuel reprocessing (converting fuel/fission-product constituents to liquids) into the reactor itself makes great sense – run the reactor on liquid chemistry. This avoids the dangerous mechanical operations of reprocessing. It allows gasses to evolve directly. And, it allows easy addition of fertile Thorium. Figure 15 contrasts present LWR operation, from mine to waste, with that of a Molten-Salt reactor, breeding Thorium to ^{233}U. Note the key ratios (LWR/LFTR) for 1GWe-year of energy output for: a) purified ore – ~200/30; b) fuel consumed – ~0.06/100; and c) waste tonnage -- >1000/1. The last ratio worsens for LWR when no reprocessing occurs. And, this comparison ignores the very real effect of low Uranium ore concentrations on mining impacts and the great expense of conventional enrichment of LEU fuel to ~4% ^{235}U.

The Shippingport (and other) experiments verified that Uranium input tonnage and waste output tonnage could be significantly reduced by addition of Thorium in solid-fuel structures. Such fuel structures are indeed available to LWR operators, but liquid fuelling with Thorium breeding goes much farther down the economical and environmentally beneficial path.

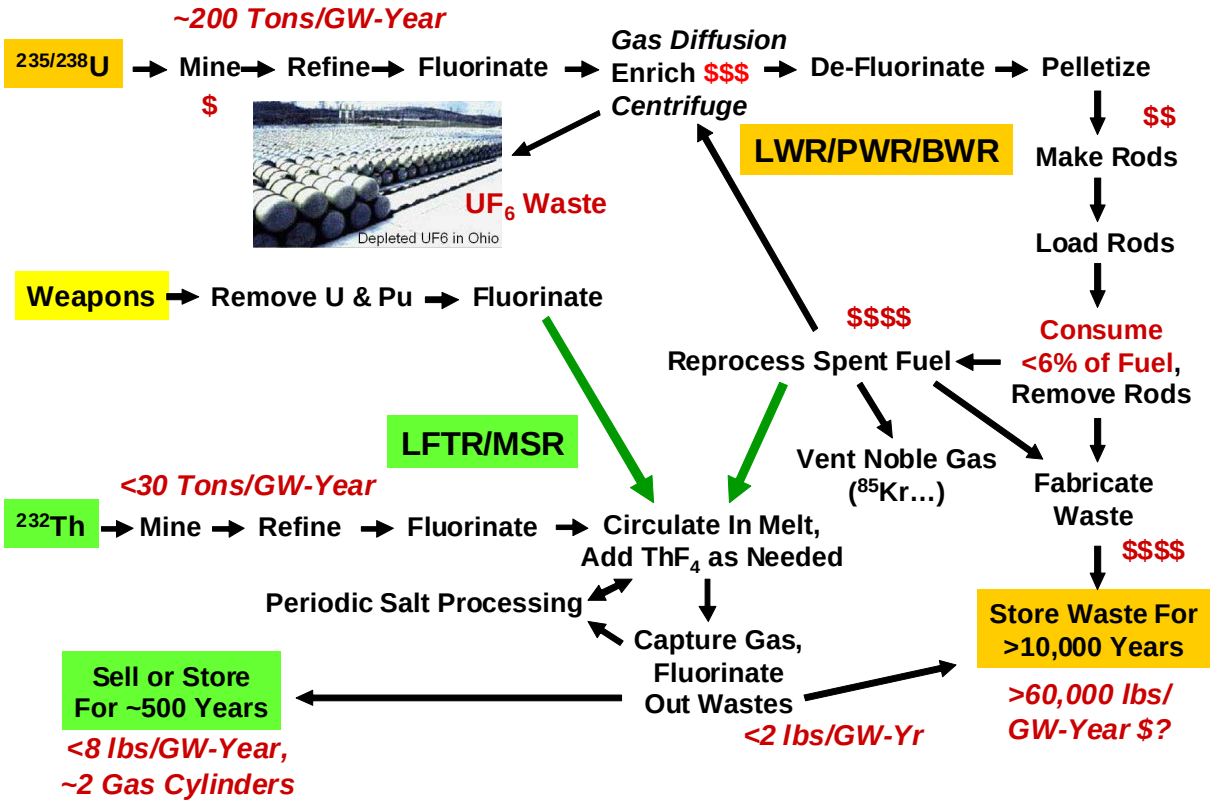


Figure 15. Liquid Thorium Salt vs Solid Uranium Fuels.

Figure 15 highlights how standard, non-breeding, LWR designs (yellow labels), with solid Uranium fuelling, suffer in comparison with fluidized Thorium breeding of fissile ^{233}U fuel (green labels). Both paths produce wastes, but the key differences of: a) breeding the lowest-mass fissile ^{233}U, and b) continued liquid-fuel residence in MSR cores, together allow far more complete consumption of fertiles and fissiles, as opposed to the once-through, solid LEU

path. Note that certain solid-fuel systems have used[3], and some today use (e.g., Lightbridge), Thorium to boost power and reduce transuranic wastes by tens of percentage points, but not by near as much as can be accomplished via the doubly-productive idea of using Thorium in a liquid-salt reactor. That combination not only reduces fuel costs, it reduces waste and security costs dramatically. And, it allows higher reactor temperatures than LWRs can use – AHTR (e.g., LMR/MSR/PBR) reactor-fluid temperatures above 700^{o}C can deliver ~15% more thermal output (to turbines, desalination gear, etc.

These are key contrasts between solid Uranium, a) to f), and Thorium, g), liquid-fuel/breeding choices:

a) Fissile ^{235}U is so rare (<1%) in natural ore that vast amounts must be mined and expensively (monetarily and energetically) processed to raise fissile content enough to establish an acceptable in-reactor Neutron economy.

b) Fuel-production facilities and transport add cost and security burdens (see NEI). Depleted UF_6 waste (inset) is considerable, but with lesser costs.

c) In-reactor and on-site fuel handling and storage add considerable cost.

d) If reprocessing is used, it adds great cost and further security issues[8].

e) If reprocessing isn't used, used fuel (e.g., rods) must be cycled out of the reactor and stored for several years (typically on site) until cooled sufficiently to go into costly long-term, dry storage (yet to be established)[10].

f) Net fuel consumption (burn-up) before becoming 'used' is typically under 3/4 of original input fertile/fissile fuel.

g) The fundamental benefit of avoiding natural Uranium for fuel is the great reduction in long-lived wastes via starting fission at ^{233}U bred from ^{232}Th (Figures 4-6).

Since breeding fuel from Thorium generates a significant Neutron absorber in Protactinium (Figure 13), the chemistry needed to maintain good Neutron economy and reactor criticality is easier when the fuel is already liquid. Thus operation of a Thorium MSR (LFTR) can include in its fluid-chemistry-management calendar periodic removal of reactor liquid to chemically separate Pa (Figure 29, righthand blocks). Such fluid batches then sit away from the core (but within the reactor hot cell) as Pa decays (with 27-day half-life) to ^{233}U. That new fuel is simply returned to the reactor's fluid fuel to produce power. If two separated reactor fluids are used, one for breeding, the same operation can move batches of new fuel to the main core fluid. ^{233}U recovery is accomplished by fluorinating the fissile out of fluid batches already set aside for Pa decay, just as fluorination in LWR fuel production creates UF_6 gas for enrichment systems. But, using the Isobreeder design, Pa can be left in the blanket, avoiding concerns for processing that might also expose access to ^{233}U.

Maintaining continuous operation, with all original fuel remaining in the core, as bred fuel is added, means as well that there is no more 'spent' fuel – all

fissiles can be consumed. Everything is on site and processing is all done within the reactor's hot cell (Figure 29). If elimination of higher Actinides (transuranics) is desired, most can be fluorinated out of the reactor fluid, either continuously or in the batching/continuous process managing Pa. Pu separation from fission products may, however, be subject to regulation that establishes only particular sites with monitored capability. In that event, used fuel would be stored and allowed to cool for some years before movement to such secured separation facilities. In any event, the fluidized Thorium breeder reactor severely limits long-lived waste production that has created such a barrier to proliferating traditional solid-fuel reactors (LWRs), even when they do incorporate some Thorium for extra fissile production.

Reactor Architectures and Safety.

A fission reactor generates Neutrons for two main purposes: 1) causing fission in fissile fuel nuclei (or non-fissiles via Fast Neutrons); and 2) transmuting elements within reach of the Neutrons being emitted. The latter can be for breeding new fuel (e.g., via Th & Pa), or for production of useful radio-nuclides. Most of a reactor's fission energy is delivered as daughter nuclei kinetics, with ~5% appearing as Neutron kinetic energy. All released energy ends up heating material thermally connected to external power loads (heaters, turbines…), or leaving the core, perhaps being trapped in shielding.

A successful power-reactor design must therefore consider fuel and Neutron budgets so that fission is self sustaining – criticality is achieved. If its purpose is to transmute elements for radio-isotope and/or new fuel production (breeding), then the reactor's fuel management must include loss of Neutrons to these purposes. Neutron economics of a reactor's design, along with its fuel behavior and alteration (physical or radiological) under continued operation, all play together. And, whether the reactor is to operate in Thermal- or Fast-Neutron realms is intimately related to all aspects of fuelling, architecture and control.

The physical structure of conventional LWRs is to have small solid-fuel (UO_2 or MOX) pellets encased in metal (e.g., Zircaloy) cylinders, which are in turn loaded into long metal rods. These fuel rods, plus possible Neutron-absorbing control rods, are then arrayed in a larger metal carrier to form a matrix sparse enough to allow adequate fluid (gas or liquid) circulation around all rods for external power delivery and cooling in case of emergency. Figure 16 illustrates a modern, solid-fuel array for present LWR core designs.

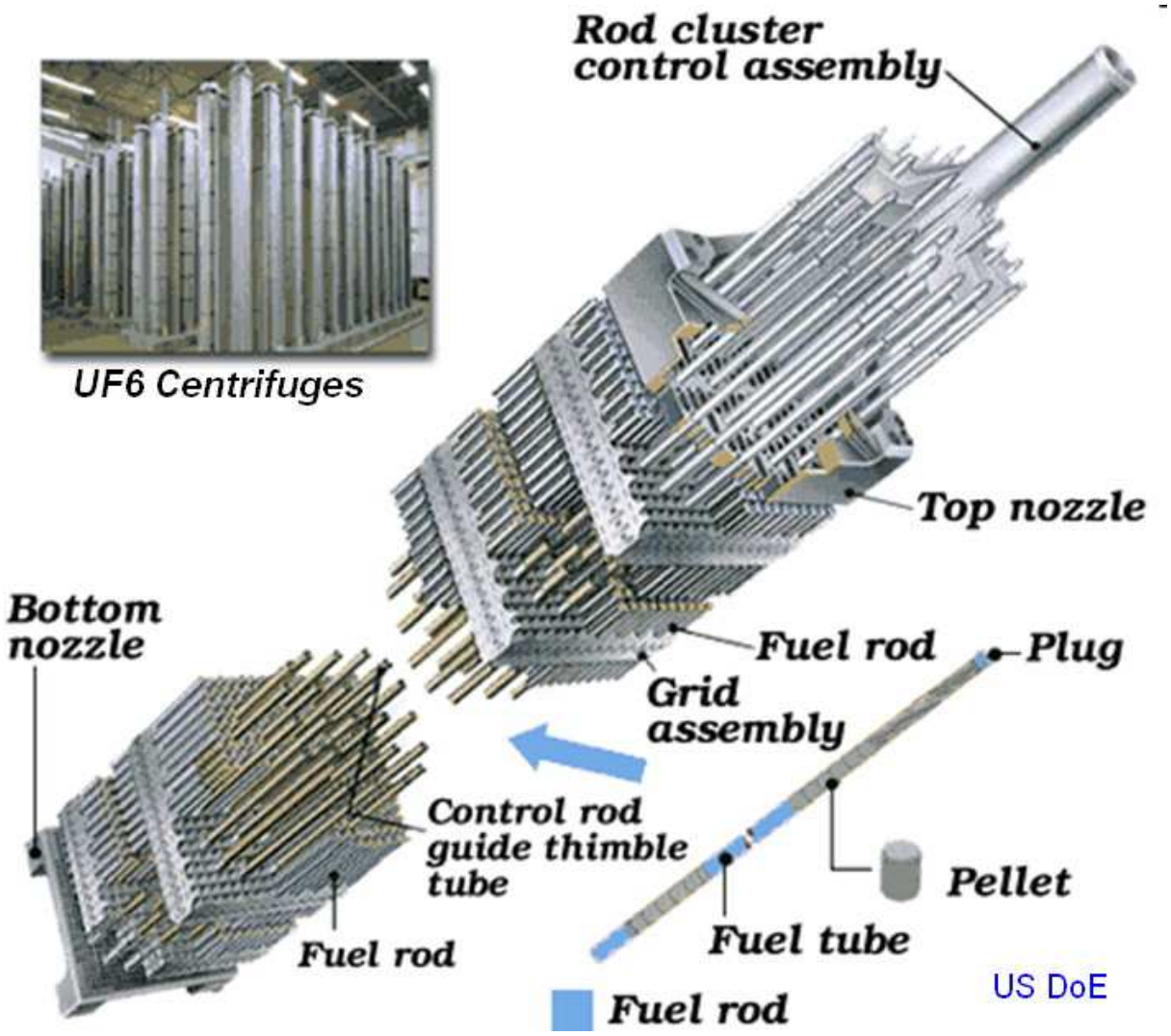


Figure 16. Modern LWR Solid-Fuel Array & Typical Centrifuge Hall.

Cooling water enters/exits the end apertures (nozzles) connecting coolant flow to external thermal power-generation systems. The figure also displays an inset from a centrifugation facility for ^{235}U enrichment – the centrifuge towers are each ~40ft high and ~3ft in diameter.

An LWR fuel array is lowered into a reactor vessel containing water or heavy water as both moderator and heat-transfer fluid. Heavy water (as in CANDU reactors) simply improves a reactor's Neutron economy. An auxiliary cooling system is usually plumbed into the array to handle any emergency need. Since water is used as both coolant and the agent for thermal power transfer, operating temperatures are limited to about 330^{o}C. Water dissociates into H_2 & O_2 at high temperatures, allowing oxidation from within the system's plumbing to do damage. Operating LWRs typically manage this by injecting Hydrogen directly into the water flow, in order to move the chemistry toward reducing rather than oxidizing. Unfortunately, this also introduces an explosive danger, which is worsened if Zirconium-clad fuel is overheated and the Zr reacts with water to release more H_2[16].

Control rods are needed to manage the Neutron economy when starting the reactor. Once operating, the thermal-expansion of moderating water (or evolution of steam) tends to reduce moderation, thus reducing the cross section for fissile nuclei, as Neutrons move beyond Thermal to epi-thermal speeds. This feedback mechanism aids reactor control, as does thermal fuel expansion, and is used in new designs that can avoid runaway conditions even upon loss of coolant/moderator. Being a better moderator, heavy water, though costly, provides a wider operating range and allows using natural (0.7% ^{235}U) Uranium.

A Fast-Neutron reactor (LMFBR[7, 8], etc.) can fission most of the transuranics and deliver energy to power generation. But, 'fast' reactors are harder to power modulate, because Fast Neutron flight times across a reactor core are exceedingly short – power fluctuations happen too quickly for typical control-rod manipulations and moderator/fuel thermal property changes. Relativistic behaviors (e.g., Time Dilation) come into play as well, on a per Neutron-nucleus event basis. The French have long intended to exploit fast-reactor technology (e.g., Phenix) to utilize fertile ^{238}U and fissile Plutonium surpluses from ordinary LWRs, but the result has not materialized and French Pu stockpiles are essentially valued at net zero -- *Spent Nuclear Fuel Reprocessing in France*[8]:

> *"France has reprocessed spent nuclear fuel since 1958. Originally the separation of plutonium was justified by military needs and later by the projected large-scale introduction of plutonium fuelled fast breeder reactors. The separation of plutonium for weapons ended in France in 1993 and the projected dozens fast breeder reactors never materialized."*

This is expanded on further in the next section on operational realities.

Since a fission reactor is essentially a heat and Neutron generator and those Neutrons carry away some of the ~200MeV released in a fission event, materials in and surrounding the reactor core should be designed to capture as much of the fleeing Neutrons' kinetic energy as possible, without ruining the Neutron economics of criticality. The production and consumption of fissiles must keep up with power-output demands and it must easily respond to varying demands. Architectural choices may interfere with this overall goal, thus limiting efficiency.

One issue for solid-fuel reactors is emergency cooling, should reactor behavior exceed safety bounds. An emergency-cooling system in cores, such as depicted in Figure 16, clearly occupies space within and around the core that might otherwise be used for power generation (via fissiles) or fuel breeding (from fertiles). Use of water for moderation also allows steam generation by the core, but then limits thermal efficiency to that of the Rankine Cycle[2, 14] – Figure 17 illustrates the standard LWR design.

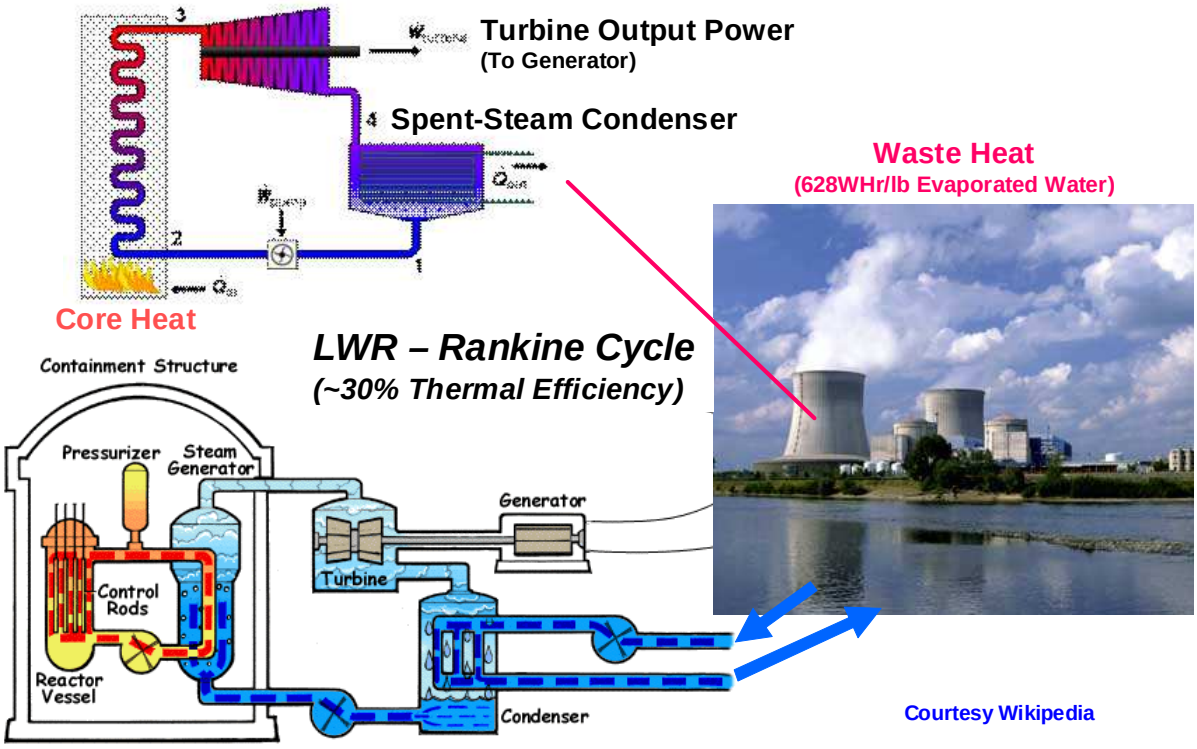


Figure 17. Rankine Thermal-Power Cycle -- LWR.

To increase efficiency, higher-temperature steam can be produced via maintaining the water plumbing under higher pressure to the steam generator-turbine stage (as in PWRs). Higher pressures mean higher reactor expense as well, especially for containment. Efficiency improvements can be made via core and fuel-structure design, as for example using long, cruciform fuel rods that maximize the surface area exposed to coolant (and to Neutron flux). When breeding from Thorium is used, core and fuel architectures can be chosen to allow longer residence-time for breeding structures than for seed structures. This results in somewhat better thermal/fuel efficiency, and significantly better waste generation (see Lightbridge Inc.).

Ultimately, however, much better reactor efficiency is the path to lowered Uranium demands and lower transuranic/waste production. LWR architecture limits how much can be gained, because the working fluid cannot operate at sufficiently high temperatures to gain the thermal efficiency of, for example, the gas turbine – the SCWR attempts this with very highly-pressurized water. This is where new reactor architectures (e.g., AHTR, LFTR) aim. And, their natural thermal cycle is the Brayton Cycle[15]. Figure 18 illustrates the use of very high temperature core coolant (molten salt) with subsequent heat transfer via inert gas (e.g., N_2, CO_2…) to sequential, preheated turbines. Each turbine utilizes heat left in the gas exiting from the prior turbine. Waste heat is used to preheat inlet gas for other turbines and the reactor's main, molten-salt-driven heat exchanger.

Remaining waste heat can be used for chemical processing, including fresh-water production from sea water and renewable combustible fuel production from atmospheric CO_2 and water. Thermal efficiencies near 60% can be

obtained and cooling does not require water – ambient air is sufficient. This is a very important environmental property and adds great flexibility to plant siting and modular-plant mobility. The combination of a reactor architected to use high-temperature (>700^{o}C) fluid and Brayton-Cycle turbine output brings a nuclear power plant's thermal efficiency up to ~60% -- that of the best coal- or gas-fired plants. Yet, the plant's undesirable emissions and water consumption are near zero (today >1/3 of all fresh water serving human needs is run through power-plant cooling systems).

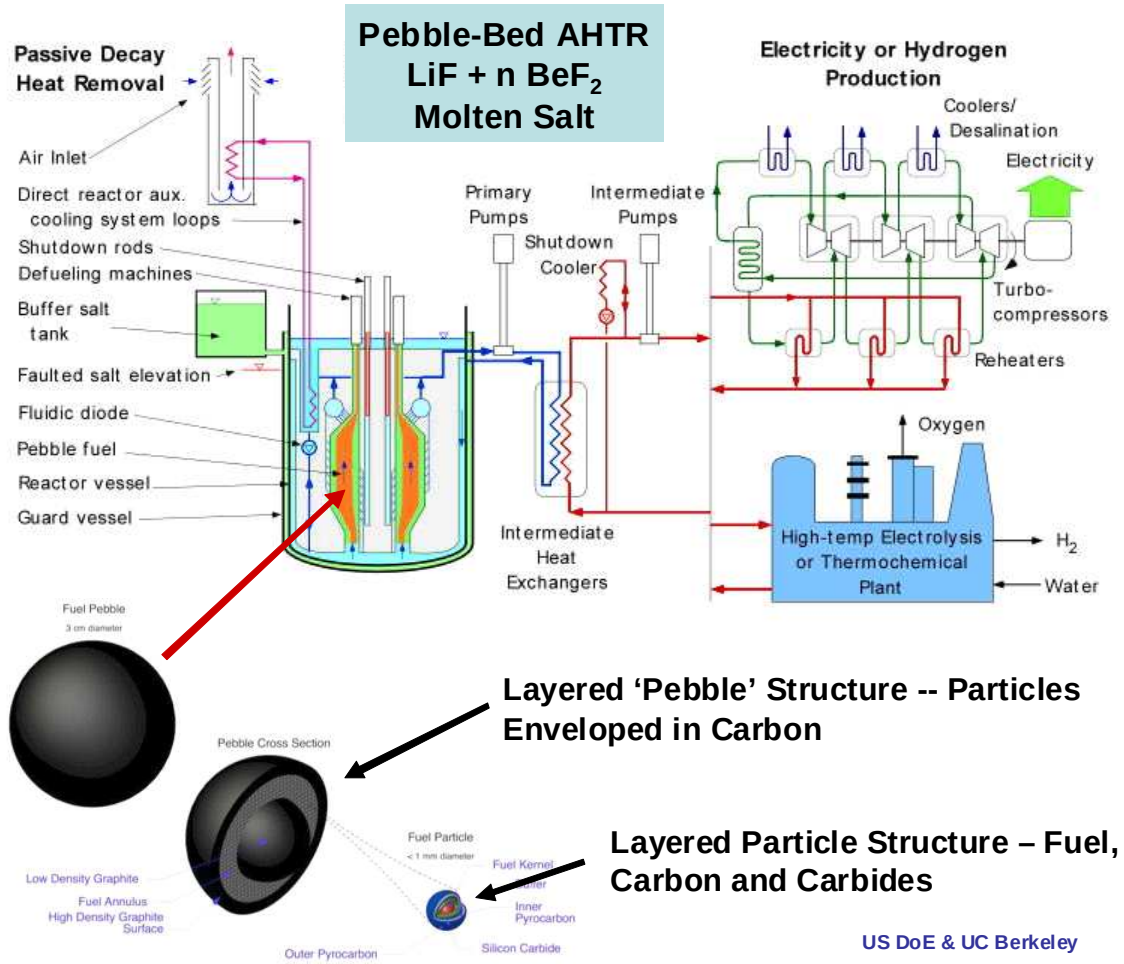


Figure 18. PBR with Brayton Thermal-Power Cycle.

Figure 18 also illustrates one AHTR[7] concept (PBR, pebble-bed reactor) for using conventional (or MOX) fuel more efficiently. By layering small fuel particles between graphite/carbide shells, designed to remain hermetically sealed both in use and when used, the reactor's self-moderating fuel load can be more fully consumed before removal. The system is fail safe when designed for a maximum temperature excursion, should all coolant flow stop – the Chinese (having acquired and re-assembled the German AVR), recently demonstrated this for reporters -- see[7] "pebblebedreactor.blogspot.com". This goes a long way toward waste reduction, but fuel construction and handling remain expensive.

Figure 19 shows the successful Molten-Salt Reactor[5] designed at ORNL for the 1960s MSRE (Molten-Salt Reactor Experiment) to determine details of fluid-

salt chemistry and fissile behaviors in such a design. The reactor shown ran for >17,000 hours, operating as a single-fluid, unpressurized thermal engine – no generation gear was connected. The reactor's 7MW output was simply delivered to red-hot, turbofan-cooled radiators.

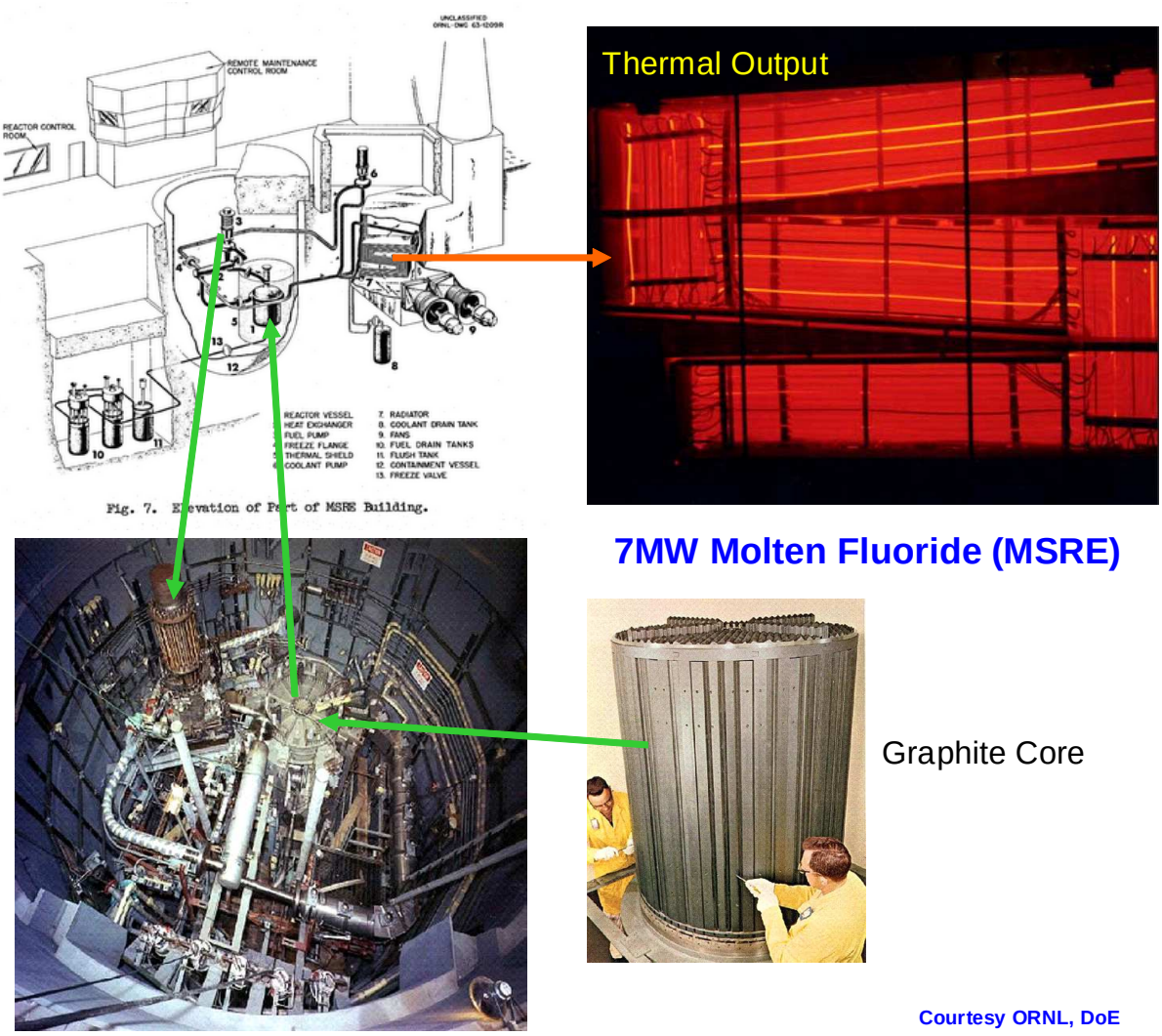


Figure 19. ORNL MSRE – Fissile Molten Salts (1965-1969).

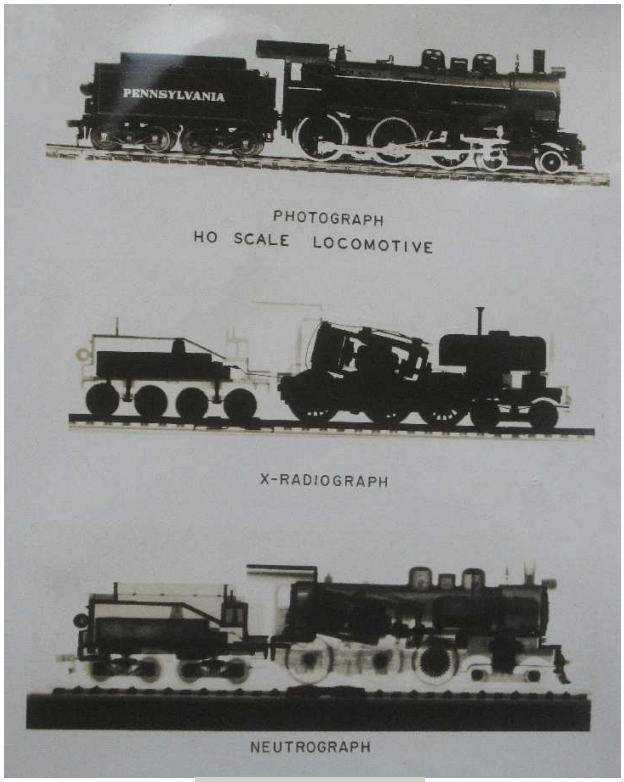
This success demonstrated the efficiency, safety and reliability of liquid salts as working fluids in unpressurized thermal reactors. The next two sections will describe its operational needs, ending with its direct application to Thorium-salt-based, internal fuel (^{233}U) breeding. Funding ran out before the MSRE could be extended to do breeding from thorium.

Safety issues are of two classes: reactor-site and fuel/waste handling. Clearly the goal of a reactor's core is to maximize Neutron flux to meet the highest power output demanded within design limits and to do it safely for as long as possible, as measured by full-power hours. The core is thus a continual source of great radiation, both from fission events and decay of fission products. Materials in and around the core stop Alpha, Beta and Gamma radiation and trap most fission products and transmuted elements in their own structures. Neutrons are not so easily confined, as Figure 20 illustrates for common metal

castings versus organic plastic. The world looks different to a Neutron, as compared to what a charged particle or electromagnetic wave/Photon sees.

Toy Locomotive

Visible Light --



Plastic body with metal parts

X-Rays --

X-Rays easily penetrate non-metals

Neutrons --

Neutrons easily penetrate metals, but not hydro-carbons

Personal collection.

Figure 20. Neutron vs X-Ray Radiation.

Neutrons react more with organic materials than with common metals. And, their biological damage increases with velocity. The lower picture in Figure 20 unfortunately exposes the rationale for the Neutron Bomb – targeting humans rather than machines. The figure's middle and lower pictures illustrate two different needs for shielding of typical reactor cores and hot cells. Alpha and Beta radiation, however, are easily stopped by most any thin material. Gamma radiation is stopped by materials (e.g., metals) possessing many free or valence electrons that couple to electromagnetic energy.

Fast-Neutron (fast-spectrum) reactors split essentially all Actinides, reducing long-lived waste, but they also need much greater shielding, to maintain a hot-cell boundary. For Fast MSRs the vessel would require an additional ½ meter or so of salt-blanket, plus a moderating shell of under ½ meter, both within the vessel itself. Other fast-reactor designs require similarly-effective Neutron shielding (e.g., containing Boron), all within whatever hot-cell shielding is acceptable for Thermal-Neutron systems.

On-Site Safety. The reactor and all its directly-connected heat-transfer plumbing must be secured from human access during operation. This means that shielding and access control are required for the reactor vessel, processing gear and initial coolant loop. And, provision must be made for leakage between

normally-isolated components. Liquid-liquid heat exchange is a key point where serious failure could expose those outside a reactor's hot cell. If water is the initial thermal medium, then planning for dissociation and/or Zircaloy corrosion, Hydrogen buildup and thus explosive dangers must be part of the reactor's design – this was one real threat in the Three-Mile Island failure that fortunately didn't materialize, but did occur at Fukushima(16).

LWR reactor-containment structures provide the strongest, close-in defense for serious failure events -- trapping steam, gas, liquid or solid releases at up to 160 atmospheres (>2400psi) of internal overpressure. NRC has very clear standards for all safety issues regarding LWRs, especially containment and emergency procedures. Site design also must take account of incoming fuel and used-fuel storage or removal. This is another reason why an exclusion zone is defined for every civilian power reactor. These zones dedicate about 100 acres per GWe, from which the public is excluded by monitored fencing. Note that this safety measure sets the LWR's power-density to about 10MWe/acre. Solar power is absolutely limited to 3.1MWe/acre peak (higher than any other 'renewable'), with diurnal average of <3/4MWe/acre. So, if safer fission reactors can be deployed, power density will be much higher than 'renewables' and present LWRs, even discounting Uranium mining, enrichment and waste operations, as the last sections here describe.

Containment must also handle the effects of total loss of reactor heat transfer to loads or emergency cooling. In the event of LWR core melting and possible breach of the vessel's base, molten fuel and fission products will reach the lower containment surface – typically many feet of concrete. This mass is termed Corium, for the mix of metals in typical LWR core structures. The continuing heating from some continuing fission, plus daughter decay, can create a long-term safety problem, since used fuel alone needs several years of actively-cooled storage, and any compact Corium mass will be harder to cool. Its radioactive gaseous releases (e.g., Kr, Xe…) must also be kept within the remaining containment.

For fluid reactors, fissioning will stop quickly when fuel is spilled or just dropped from the core to underground storage during a shutdown. Cooling demands will remain, as discussed below, and containment will still be needed to retain gaseous decay products. However, for salt reactors (MSR, LFTR…), processing the whole fuel melt every minute or so has already been going on, so there is no large inventory of radioactive gasses to defend against. This is important for ^{137}Xe, which, though an inert gas, decays in minutes to ^{137}Cs, which has a 30-year half-life and is biologically active. Having a safely-stored fuel melt already purged of most ^{137}Xe is a great advantage – compare with events at Fukushima(16).

An additional safety issue is storage of cooling masses, containing fuel and fission products. For example, typical LWR used fuel will have been in core for <2 years and when removed will be generating ~7% of its contribution to full thermal reactor power, just from decaying fission products. In a day, that decay heating will be ~0.5% of original in-core output. And, in 30 years, ~0.03%. So moving ~1/3 of a 1GWe reactor's fuel rods to storage will demand the ability to dissipate heat equivalent to ~0.8GW times the output percentages mentioned

above. That's about 60MW immediately and ~4MW at the end of day 1. This is why LWR used fuel rods can only be moved to air-cooled storage after about 6 years.

The safest storage method depends only on passive cooling, such as storing used fuel rods in spaced arrays within pools of circulating water somewhat above ambient temperature. Some LWR sites, however, have more active cooling systems, allowing NRC-approved, higher-density storage. This adds a safety and reliability burden of maintaining such stores actively cooled, despite major unforeseen events. The Fukushima experience warns of the need for comprehensive design. Other fuel phases, such as molten salt, will have similar decay-heating burdens, if fuel is removed for processing, as for Lanthanide/Actinide removal. But, with typically higher efficiency, there will be less fuel mass to cool. And continual removal of gasses, also means a lesser cooling demand from stored MSR fuel.

Operational and Environmental Realities.

Given the radiation and thermal fluxes within a reactor core, it's not surprising that solid-fuel systems suffer damage after months of use. This is one reason LWR cores are about 1/3 de-fuelled every 18-24 months, with removed fuel replaced and classified as "spent" (used). Figure 21 illustrates some test results for typical, Zircaloy-clad fuel pellets.

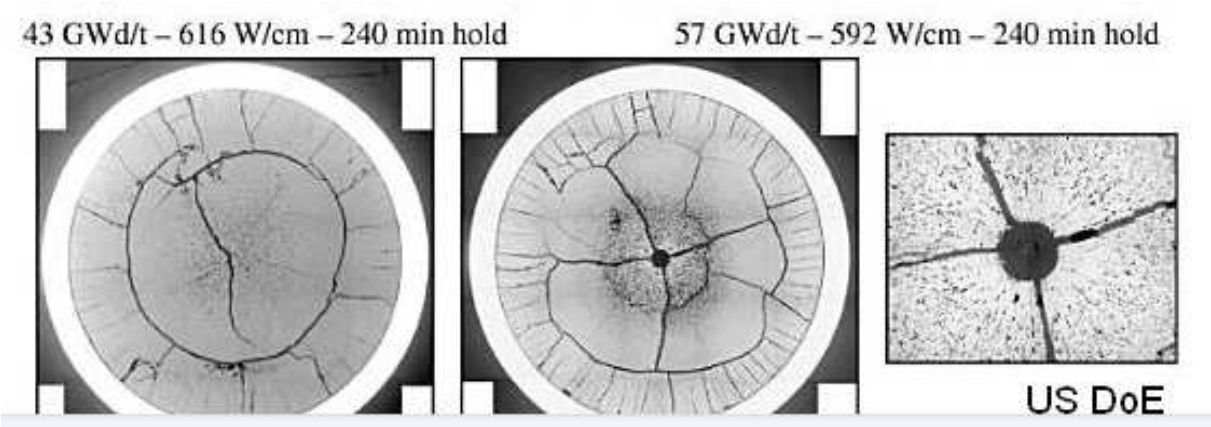


Figure 21. Thermal Rate-Stressed Fuel Pellets Showing Cracks (DoE).

Fuel reprocessing has long been considered as a way of regaining the enriched Uranium now wasted in used, solid fuel. And, it has been considered as a way of utilizing the dominant ^{238}U fertile isotope by Fast-Neutron breeding to fissile Pu[(2)]. However, little has come of these ideas, as the next section explains. Improved reactor designs can address both effectively.

Fission products affect both reactor efficiency and durability. For example, fission daughter ^{135}Te (half-life, 1/2 min) decays to ^{135}I (half-life, ~6 hr) and to ^{135}Xenon (half-life, ~9 hr), with its very high Neutron affinity (see Roggenkamp). The delay in reaching Xenon is itself problematic. When formed via U or Pu fisson daughters, this Xenon isotope gradually builds, hurting a reactor's Neutron economy, reducing fission events and breeding. As it decays, neutronics improve. If fuel is solid, Xenon is trapped within. A reactor's

operator must sense criticality loss and adjust any control rods so fission rates rebound. However, ^{135}Xe's short half-life allows its poisoning effect to dissipate within hours, allowing fission rates to increase beyond the rate just re-set by compensating control adjustments. The effect of this is that continual monitoring of power and control settings must occur to avoid undesired thermal excursions, particularly after refueling and when power-output changes are called for. Failure to mange this effect contributed to the Chernobyl disaster.

In fluid-fuelled reactors, gasses like Xenon simply evolve for capture at appropriate catch points in the plumbing (e.g., at pump plenums), avoiding related control actions. Other fission poisons are not so easily removed (e.g., Lanthanides and Hafnium), so provision is included to remove these chemically from reactor fluid. This is processing done within a reactor's hot cell, as opposed to removing fluid fuel from the site for centralized processing, as optionally done with solid fuels. However, the processing schedule is also dependent on Neutron velocity – a moderated core produces Thermal Neutrons which breed fissiles (e.g., in the surrounding fertile blanket) and fission them more quickly. Thus, to avoid excessive fission in the breeding blanket, its load must be processed more often. If the reactor is largely unmoderated, then its Fast or Epi-Thermal Neutron flux will both breed and fission blanket Actinides more slowly, but the hot-cell's shielding must be much heavier. In any case, fluid-fuelled reactors have little excess reactivity -- just enough fuel is put in at any time (Figure 29). A solid fuel reactor has to put in enough fuel to last until the next refueling.

Another advantage of fluid fuels is the response to catastrophic mechanical failure of core or blanket so that fluid runs out over the containment floor. The fissiles in the now spreading fuel will no longer fission and the fluid will spread over the floor, designed to present a large surface for safe, passive cooling. For salt reactors, the fuel will cool and solidify in place, over the floor area. The total cooling burden can be calculated as discussed above. The key safety features are: a) fission ceases immediately, so little gas evolution occurs; and b) salts are stable, especially fluorides, in binding fission products within the solidifying melt -- F is the most electro-negative of ions. Cleanup need not be so long delayed or as difficult, especially since containment hasn't been challenged by steam or Hydrogen explosions as can occur in LWRs. Even full breach of all containment would, for salt fuels, simply mean a small outside area, within the site's exclusion zone, would need to be protected until salt recovery could be accomplished.

Fuel Reprocessing & Fast (Pu) Breeding. As mentioned, France has provided the world with an excellent example of what really happens when a country decides to depend on nuclear-fission power and goes beyond simple LWR operations. The French pioneered fuel reprocessing and the idea that Plutonium breeding (from ^{238}U) can be an effective, safe use of Fast-Neutron reactors. They even contracted with other European nations (Figure 24) to accept their used fuel for reprocessing and Pu extraction. Figure 22 shows Plutonium-related generation and processing in France at the end of 2007.

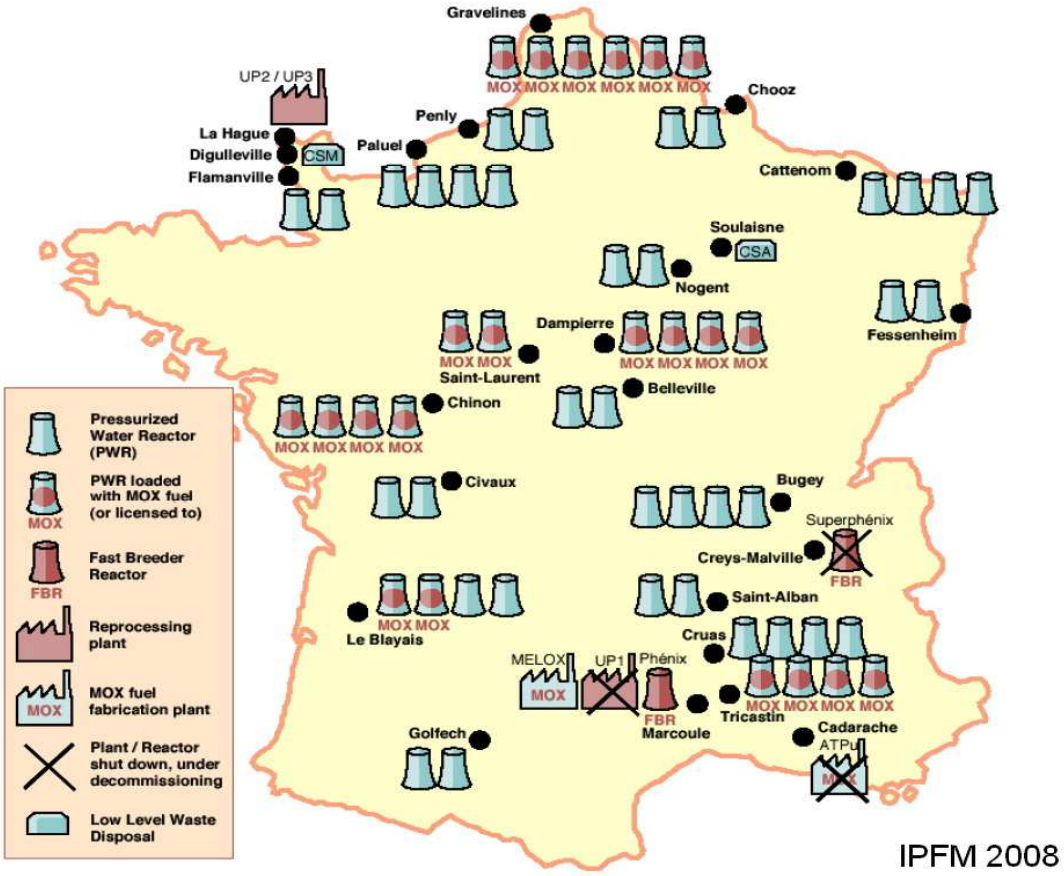


Figure 22. Main Plutonium Facilities – France, Dec. 2007.

Reactors loaded with MOX (PuO_2 + UO_2) fuel are indicated with red circles. Only one fast breeder reactor was then operating. PWRs operated with standard, LEU fuels. De-commissioned fuel and processing plants display an X. The French situation is best expressed by authors Schneider & Marignac[8], in 2008 (underlines and bold added for emphasis):

> *"The reprocessing-plutonium use strategy failed, however, as an adequate framework for spent fuel management in France. Large stocks of both spent fuel and of separated plutonium have been the result. The separation and use of plutonium in MOX fuel and the re-enriching of reprocessed uranium are both uneconomic activities…even in France, which has the most favorable political and industrial conditions. Consequently, since 1995 the state electricity utility EDF has assigned in its accounts a* ***zero value*** *to its stocks of separated plutonium, as well as to its stocks of reprocessed uranium…Under past and current industrial conditions, there is no clear advantage for the reprocessing option -- either in terms of waste volumes or repository area. …*
>
> *La Hague is currently the largest man-made source of radioactivity releases to the environment....Reprocessing…impacts in terms of safety and security… plutonium separated at La Hague results in…almost two truck shipments of separated plutonium per week from La Hague to…Marcoule, over 1000 km away. An overall cost-benefit analysis of used fuel reprocessing in France would find that the economic, environmental, health, safety and security costs clearly outweigh the benefit of minor savings of natural uranium."*

The La Hague processing plant is the size of a town – Figure 23.

Figure 23. La Hague Fuel Reprocessing Ctr., France (Google).

As of 2008, France was holding over 80 tons of Plutonium, derived from its own reactor sources and those in contracted countries – Figure 24. That's enough Pu, if isotopically purified, to fabricate thousands of fission weapons. But, it's also enough to start near 80, utility-scale Thorium breeders, as described later here, allowing near complete destruction of the Pu while generating civilian power.

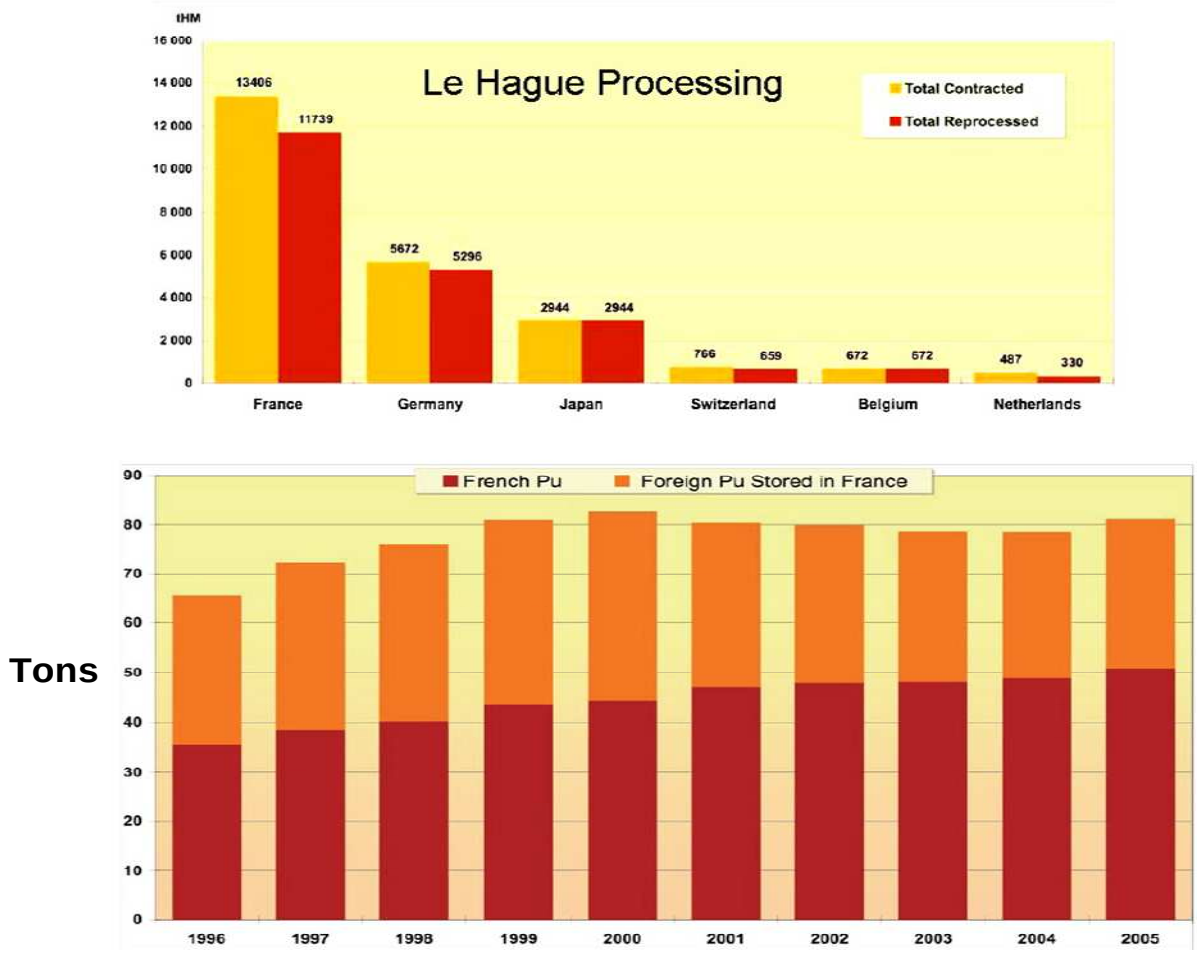


Figure 24. French Plutonium Processing & Storage (IPFM, 2008).

Processing for Thorium-based reactors indeed must occur, unless once-through fuel use is stipulated. The latter is the path chosen by Lightbridge, whose designs improve Uranium efficiency and reduce wastes via limited breeding, but still end up producing a significant fraction of LWR-like used fuel, polluted, however, with anti-proliferation quantities of isotopes such as ^{232}U. And, seed material can include Pu, thus providing a way of destroying some while generating power and less waste.

Processing in Thorium breeding of ^{233}U may require Protactinium separation so that its hunger for Neutrons doesn't affect criticality – for the fluidic Isobreeder, DMSR and any design allowing some fissile to be added over the years (to maintain Neutron economics), this may be avoided. When used, chemical separation within a reactor's hot cell allows Pa to decay to ^{233}U for ultimate return to the core. In the event the reactor has separate fuel and breeding elements or fluid paths, then the separation is done both to retrieve bred fuel from the blanket and to maintain the Neutron economics for the blanket's breeding function (see Figure 29). Some bred fuel may not actually be needed and so may be used to start/fuel another reactor. That raises some security issues associated with reprocessing, since the fuel now has to leave the reactor hot cell and perhaps the reactor site. But, this is likely avoidable, as explained in the next sections.

Economics of Thorium-Based Reactors.

Fuel. The economics of Thorium used as fertile source of fission energy is extraordinary. The availability of Thorium is 4 times that of Uranium ore and effectively 140 times that (if the breeding path ^{238}U-^{239}Pu isn't used), because ^{232}Th is the only significant Thorium isotope and it can nearly all be bred to fissile ^{233}Uranium within a reactor. Further, the stockpiles of Thorium around the world, as well as the tailings containing Thorium discarded from mining operations are so great that no new mining would be needed for many, many years. The environmental benefit of Thorium use is clear and immediate.

The economic benefit is just as clear – no significant competitive uses, no unusual or expensive ore processing, and no security issues in the fuel-supply chain. What could be cheaper than choosing as an energy source something relatively abundant and typically considered since its discovery as a 'waste' product? Contrast with an example from Exelon's 2010 Annual Report allocating $1 billion for yearly fueling of its ~17MWe reactor fleet (www.exeloncorp.com). LWR ^{235}U fuel's abundance falls between those of Silver and Platinum – LWRs 'burn' something rarer than Silver.

Estimates for providing pure Thorium oxide or salt to a reactor site top out at about $300,000/ton. Since a 1GWe reactor needs <30 tons (once-through) to run for a year, breeding ^{233}U, this means the yearly fuel cost is under $10 million. If processing retrieves most Th and bred ^{233}U, then only ~1 ton of Thorium is used per GWe-year. Compare that with about 200 tons/GWe-year for LWR fuelling at the price of enriched Uranium (www.nei.org). 500 tons of Thorium can run the whole USA for a year and 1 ton fits into the passenger seat of a car (a very tilted car). A GWe-year = 8.8TWHours, or ½ the world's entire, present electric-power generation for an hour. That's >250 million gallons of gasoline, in thermal energy content, or half a billion gallons, when correcting for typical thermal-electrical/mechanical conversion efficiency. Half a billion gallons for $10 million and no emissions, drilling, spilling, fighting…

So Thorium power is essentially free, from the fuelling standpoint. This mimics the initial 1950's view of Uranium-fission power as being "too cheap to meter" – but not correct then and not now, even with Th fueling. Figures 2, 7 & 8 have real meaning now. Figure 25 shows a piece of good (~4%) Thorium ore (Monazite) and a pan of refined, Thorium-oxide pellets (each pellet meets an American's energy needs for some years). Not pictured is the other major Thorium-bearing mineral -- Thorite. There are many lesser sources, because the complex mineralization of the rare earths often includes Thorium (Figure 8).

Monazite **Thorium Oxide Pellets**

Figure 25. Thorium Ore & Purified Oxide Pellets[#].

Reactor Choices. Clearly we still want to maximize the efficiency of each power plant, because that benefits overall environmental impact, despite fuel being almost free and on hand. This means we need to examine high-temperature systems and forgo water-cooled systems we've been accustomed to having a love-hate relationship with. This leads directly to the Generation IV proposals[(8)] and the 6 now chosen for further R&D[(8)].

However Thorium fuel is used (solid or liquid), we want to operate reactor cores at the highest industrial temperatures possible and we want output fluid to drive Brayton-Cycle output-power generation (as explained for AHTR, Figure 18). We want to approach the relative benefits Figure 15 showed for liquid Thorium-salt operation, relative to LWR operation. This means we want a fluid or pseudo-fluid reactor cycle, where the fluid directly or indirectly heats a gas for turbine drive.

Pebble-Bed reactors[(7)] (PBRs) are intended to operate above 1000^{o}C, which is very beneficial for efficiency, but perhaps challenging for reactor materials and plumbing. They also utilize solid-fuel components, which are intended to achieve higher fuel burn, but will still result in some unconsumed fuel and transuranics, to the extent they contain ^{238}U. So, while there will be much less waste on the output side, there will also be more fuel-fabrication expense and environmental impact on the input side – Uranium is still a major component. A recent test of such billiard-sized pebbles was summarized as:

> *"Idaho National Laboratory used its Advanced Test Reactor to expose these test fuel grains to radiation levels much higher than in an operational PBR, thus simulating years of exposure in a few months. The multiple, coated layers of silicon carbide and ceramic graphite contain the radioactive products of fission. These tested fuel grains have not failed, at the level of 9% burn-up of the uranium within. Tests will continue to see if a 12-14% burnup can be achieved by year-end."*

Even if this design meets the target “burnup”, large amounts of fuel and transuranics will remain in pebbles removed and considered used. So the burden of reprocessing and/or disposal is reduced, but only partly.

China also validated PBR technology at Tshingua university by running a test reactor and shutting off all cooling -- a foreign TV news crew recorded the event’s passive, stable response. Several Chinese PBRs are being built, though the Fukushima events[16] (beginning in March 2011) may delay them for safety reviews.

The goal for Thorium bred to fuel then appears to be more demanding – high temperature and near-complete fuel consumption while minimizing long-term wastes. That’s where the example chosen for this article excels – the Thorium-Fluoride Molten-Salt Reactor[4,5,6], or LFTR. As explained in the next section, and compared in Figure 15, it avoids solid fuel and optimizes reactor fluid via fluoride salts of Thorium, ^{233}Uranium and a few other metals -- this yields a near-ideal system[5] and a variety of reactor and fuel-processing designs:

a) Thorium is bred by Thermal Neutrons to ^{233}U, which fissions with higher probability than other U and Pu fissiles, potentially producing orders of magnitude less of all transuranics.

b) ThF_4, UF_4 and some additional fluorides are easily fabricated by standard industrial processes, providing an excellent heat-exchange fluid that’s also highly radiation resistant (see ORNL Document Library, esp. *Molten-Salt Reactor Chemistry* by Grimes[8]).

c) Such a salt mix melts at reasonably low temperatures and will operate above 700^{o}C as an efficient reactor coolant with low corrosivity on typical industrial plumbing (e.g., Hastelloy).

d) Processing of the salt melt is done within the reactor’s hot cell, to both maintain proper chemistry and to remove desired and undesired fission products (e.g., Tritium, Xenon, Lanthanides and Hafnium), desired bred products (e.g., Protactinium and ^{233}U) and undesired Actinides like Plutonium.

e) Fluorides are somewhat moderating, but also provide negative fission-rate feedback, because they expand with temperature -- reducing fission probability if fission rate were to increase. This adds a self-throttling feature to thermal output, since a lightly-loaded heat-exchanger will return warmer fluid to the reactor than will a heavily loaded one – warmer, less-dense returned fluid decreases fission probability, delivering cooler fluid back to the exchanger and less thermal power to the system’s load (e.g., turbines).

The LFTR choice thus provides for its own radio-chemical needs within the bounds of its hot cell, it produces desired products for removal and sale, and it creates so little waste that all can reside at the site. There is almost no used fuel, unless off-site processing is required for security, such as to remove the small amounts of Plutonium produced. Per the FUJI experiments[4], typical LWR-LFTR comparative results appear in Figure 26.

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 %

Figure 26. FUJI Experimental LFTR Wastes for 30GWe-Years[#].

Note from the figure that an LWR (BWR) needs ~3 times as much initial fuel, while the LFTR bred more than it needed from input Thorium, and after 30 years of full-power operation, LFTR had produced just 4% of the transuranics and 1/1000 the Plutonium that an LWR produced. Add to that at least 15% higher thermal efficiency and we see the attraction of the liquid-fluoride, Thorium-based breeder reactor. This will be discussed in more detail in the next section.

Reactor Construction. With fluid or pseudo-fluid core coolants, there's insignificant pressure associated with thermal transfer. And, since water (or other state-changing fluid) is not used, there's no explosive danger from rapid liquid-gas transitions or dissociation into flammables. If further heat-exchange is via inert gas (as for the Brayton Cycle), there may be violent rupture but not explosive potential or radiation release if generation equipment fails. This all means that the costly containment structure for LWRs is no longer needed. Gas-tight containment around the reactor's hot cell indeed is necessary, but its design and cost are greatly reduced (Figure 19 depicts the actual, modest MSRE[(5)] building and core containment). In addition, the higher power density of higher temperature operation means that greater reactor capacity can fit the same footprint. This even means that a de-commissioned LWR building can be used to house more powerful fluid/semi-fluid designs, at about 2:1 power-density advantage. The Examples section describes canonical LFTR construction.

Economic Estimates. Given an inexpensive fuel and higher efficiencies, the more Thorium is exploited in a reactor's fuelling, the more economical we might expect it to be. This is the tack companies like Lightbridge have taken – essentially providing upgraded LWR fuel assemblies that use both some Thorium for breeding and improved thermal design and geometries for fuel elements. As such, they explore the limits of the basic LWR design and advertise operational cost reductions of modest percentages.

Moving to higher-temperature systems, such as Pebble-Bed, only after Gen-IV[(9)] R&D proceeds further will we have good estimates for most AHTR economics. However, because of ORNL's work from 1954-1974 on the MSR, and the Shippingport Thorium experiment, we have good estimates for how much a utility-scale (1GWe) LFTR should cost to build – Figure 27.

Estimate	Year	$/watt	2009 $/watt
Sargent & Lundy	1962	0.650	4.64
Sargent & Lundy ORNL TM-1060	1965	0.148	1.01
ORNL-3996	1966	0.243	1.62
Engel et al, ORNL TM7207	1978	0.653	2.16
Moir	2000	1.580	1.98

Figure 27. LFTR Construction-Cost Estimates Over the Years[#].

ORNL used detailed construction and operation costs for three 1GWe plants: MSR, PWR and coal, to estimate competitiveness (see Moir[(9)]). Using pre-1980 plant standards, the $/KWHr results were: MSR ~.038; PWR ~.041; and Coal ~.042. Also, the net plant efficiency was estimated at 44% for MSR and coal, but 33% for PWR (due to its lower operating fluid temperatures). A similar analysis today, by Moir, shows the MSR/LFTR delivering power 7% cheaper than LWR and 9% cheaper than coal.

If we think conservatively and say $3/W for construction, including de-commissioning, then we see the LFTR path is actually cheaper than coal – now advertised near $2/W, yet not accounting for environmental burdens on the input (mining, fuel transport) and output (emissions, ash costs…) sides. For instance, we know that still-unregulated coal-plant emissions account for over 10,000 US deaths per year (per NIH and EPA), and coal-based generation is fully dependent on oil, for mining operations and coal transport to plants. These and the environmental costs of coal have not been dialed into the $2/W estimate, so amount to subsidies. Perhaps another way to compare costs is to credit LFTR with the value of all avoided emissions and environmental remediation (from ~6000 tons of coal burned per day per GWe).

Fluid reactors can even be credited with revenue from radio-nuclide sales. For example, the world now faces extreme shortages[(13)] of (among many) ^{3}He, Tritium and ^{99}Mo. The Helium isotope is key to both physics experimentation and international security tools. Tritium is essential to fusion research. The Molybdenum isotope's decay product ^{99m}Tc (isomer) is essential to millions of medical scans every year. These and many more products are all commercially valuable. Worldwide, reactors historically used for their production have fallen away, due to age, and other circumstances. At $4000-US/gram (6 liters), ^{3}He is a nice source of income. Tritium production from a salt reactor containing a bit of LiF would net about $4 million-US per year. Even if only the self-evolving gasses were trapped for sale, any LFTR would generate significant income (though a small percentage of actual sold-electricity revenue).

Fuelling needs, for the present ~400GWe worldwide nuclear generation, are about 400 tons of ^{235}U each year. Sufficient mining and enrichment exists to provide that 400 tons yearly (though worry about U resources partly motivated the AEC report[2] to the President that advised quick development of breeders). That 400 tons will start ~200 GWe worth of LFTRs per year – more than one utility-scale LFTR every 2 days. This addresses our desperate need for CO_2 emissions reduction -- in 50 years, 10,000 GWe (10TWe) of LFTRs can be started, even with no breeding. In addition, there's enough Plutonium around (and being created) to start much more than 500GWe of LFTRs. That means ~65% of all present worldwide generation can be met/replaced by 2061, displacing all present coal and petroleum for generation, plus about 1/2 of natural gas. Given just existing hydro-electric, plus the gradual rise of distributed solar-electric and efficiency gains from many sources, our goal can be met, with hard work. And, the necessary high-level education and jobs involved are a double economic benefit to countries so engaged.

The great economic benefit is that after starting, no further expensive Uranium need be supplied to an operating LFTR, little waste need be handled, and various reactor products can derive income -- all this while reducing environmental impacts many-fold, especially after most planned LFTRs are started (some within de-commissioned LWR structures) and Uranium mining is little needed. This realizes the goal presented to President Kennedy 49 years ago.

Processing needs include ongoing gaseous-product removal from reactor salt and periodic/continuous removal of Pa, reactor poisons (e.g., Lanthanides), ^{233}U, and various fission products and undesired Actinides such as Pu. All these, except perhaps Pu (per security needs), may be done within the reactor hot cell, and on schedules appropriate for the targets of removal and their rates/effects of production. This is where the most sophisticated radio-chemistry exists in LFTR design and operation, particularly subject to regulations, and where many opportunities arise for proprietary development of processes by the nuclear industry – the MSR documents are all public and the patent itself has expired[5] – so this is also a business activity that can derive revenue from more than just radio-nuclides.

Below is an illustrative list of processing needs and steps. Much is based on original ORNL research (see ORNL Document Archive, esp. Grimes on MSR chemistry). Some is based on current design efforts. It should be considered a guide, not a specification, because the need for any of the procedures depends on the specific architecture of the LFTR itself – single-fluid, 2-fluid, or 1.5-fluid (some breeding in core). A LFTR with separate core and blanket (2-fluid), for example, may only need blanket fluorination and batch reprocessing of the core through fluorination and distillation, plus just-in-time denaturing of core ^{233}U with external DU. This avoids fissile shipments to or from the site, other than at startup and perhaps shutdown. There are several choices for LFTR designs, which may be based on nuclear-cooperation treaties, and anti-proliferation needs. Some operations are not done for years after a LFTR is started:

a) Core moderator replacement – The graphite core in a Thermal-Neutron MSR will likely need removal on a semi-decadal basis. The molten salt is

drained into the sump tanks by opening the salt drain ("freeze plug", Figs. 29 & 30) – this is also the safe, emergency-shutdown mechanism. The core is flushed with gas and clean salt to remove residual radioactive particles. The reactor is cooled, its cover is removed and the old graphite (e.g., Figure 19) replaced by new. The cover is replaced. The core and plumbing are heated above the salt's melting point and sump-stored fuel salt is pumped back in, restoring fissioning and operation.

b) Sparge -- (gaseous flush of fuel/blanket salt) with Helium to remove Xe, Kr, etc., as well as related products, like Cs, before they form as daughters. This also removes some noble metals, since they do not form fluorides and will cling to He bubbles.

c) Settling -- particularly of noble metals, to avoid plating on internal reactor plumbing.

d) Fluorination – to remove Uranium before the fuel salt goes to further processing. U is the highest-value content in the used fuel salt, so should be put back to work as quickly as possible. Other fission products come out with fluorination as well, separable with cold traps at different temperatures

e) Vacuum distillation – (mild) to remove valuable ^{7}Li along with useful Be.

f) Aging -- Let fission products (in batches) cool down for a year or so.

g) Hard-vacuum distillation -- to remove most of the Thorium (there may be process differences among the 1-, 1.5- and 2-fluid designs).

h) Liquid-metal exchange -- with Al, to substitute Al for the Actinides (e.g., Pu & Am). Pu and Am precipitate. This may be subject to regulated, centralized secure processing.

i) More aging – then waste conversion to a solid, chemically-inert waste form (amounting to tens of pounds per GW-year, not tons).

j) Example options – for inclusion within above steps, or for additional scheduling: isolation of Iodine (^{129}I) for compounding in a particularly stable chemical form; isolation of ^{99}Mo, an isotope which has medical application; and others (e.g., Tc appears useful in packaging nuclear wastes). Zr will also need removal on a sub-decadal scale.

The above simply illustrates some opportunities and regulatory obligations related to a LFTR's normal operation over decades. In hourly-to-weekly operations, Pa, for example, can be processed out, returning its decay product ^{233}U to core fluid within a few weeks. For iso-breeding, 1.5- or 2-fluid designs, this would not be needed. For DMSR designs[8] (LeBlanc or Engel et al), denatured fluids increase anti-proliferation at the expense of periodically adding fissile to the core. Opportunities for innovative chemistry and technology abound.

It's well to remember, that when speaking of a 1GWe LFTR holding a few tons of ThF_4, UF_4, etc., that a ton (<3 cubic feet) of these salts fits easily on a car's front passenger seat (crushing it, and perhaps the car's suspension). With processing recovery of Th and U, that ton also produces ~1GWe for a year.

Thorium Reactor Examples.

Shippingport[3] provided the successful demonstration of breeding fissile ^{233}U from Thorium in solid fuel, using seed-and-blanket core structures, but no effort was made to continually extract the bred fuel for use as new. That reactor operation is called "once-through", since unused fuel and generated wastes are simply disposed of. Recent LWR solid-fuel designs incorporating Thorium (e.g., by Lightbridge) are also once-through, aiming for reduced Uranium input, somewhat better thermal efficiency, and a somewhat better waste (and proliferation) profile.

Reactor fuel and waste profiles change dramatically when the fuel is liquid and processing chemistry is continually available on site, during operation. Because Thorium dissolves poorly in liquid metal alloys, appropriate as fuels (e.g., Bismuth-Uranium), that path is not as open to ^{233}U breeding as it is in the salt reactors, such as MSR[5]. The MSRE served to elucidate molten-salt choices for high-temperature, Uranium-fission reactors, and in 1968 it was fuelled with $^{233}UF_4$. Though not using Thorium to internally breed that fissile, it demonstrated how effective ^{233}U was for limiting transuranic waste. Now, as part of Gen-IV reactor work, we can combine 20 years of MSR engineering results with Th-^{233}U breeding and gain a superior, safe reactor.

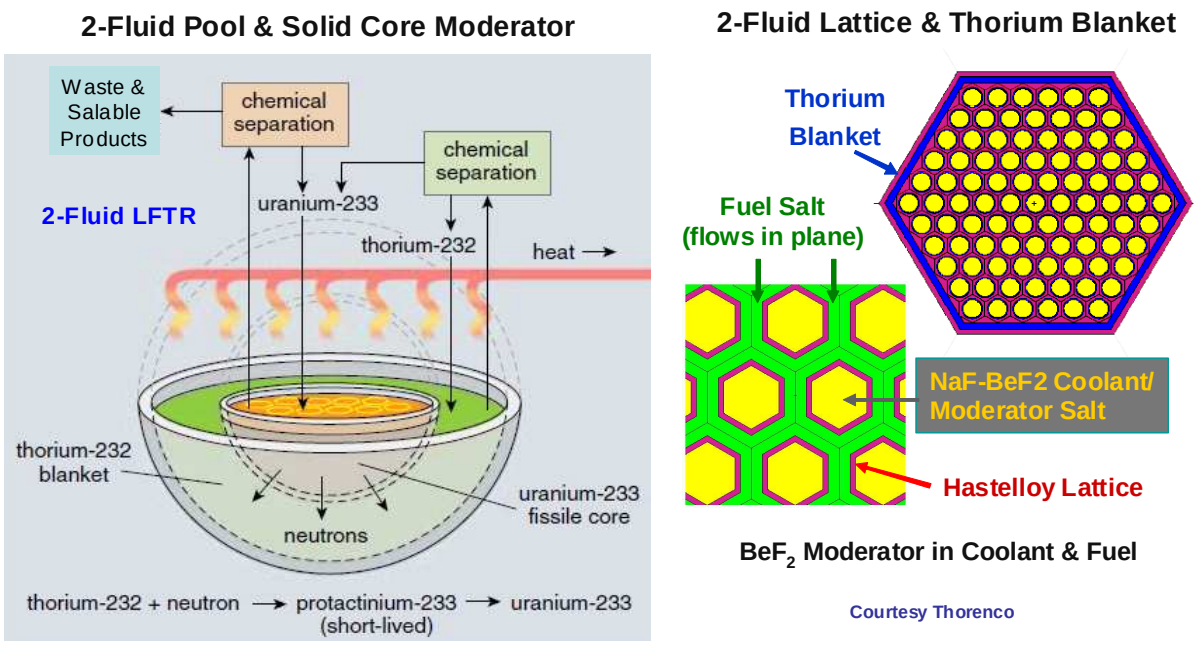


Figure 28. Conceptual Dual-Fluid LFTR*#.

Figure 28 illustrates concepts of a two-fluid breeder reactor, where the outer fluid layer (the blanket) serves to breed fissile ^{233}U from fertile Thorium (a "1.5-fluid" reactor has some fertile Thorium within the core). The inner liquid (fluoride salts) produces most of the thermal output via fission. The wall

between it and the blanket allows Thermal Neutrons to reach blanket Thorium (ThF_4) and transmute it to ^{233}U's precursor, ^{233}Protactinium. Pa's 27-day half life allows continuous, or scheduled taking, perhaps weekly, of fluid from the blanket so most Pa can decay to ^{233}U while being set aside in a hot cell, but not in the Neutron flux. Each such batch of fluid can then be fluorinated to remove $^{233}UF_6$ as gas, while other fission/capture products are removed chemically. $^{233}UF_6$ is converted back to $^{233}UF_4$ (Figure 29, Hydrogen reduction path) and re-dissolved in the core fluid to continue power generation. The flow rates are small: ~1/4kg per hour (of U or Th) for 1GWHr of reactor output.

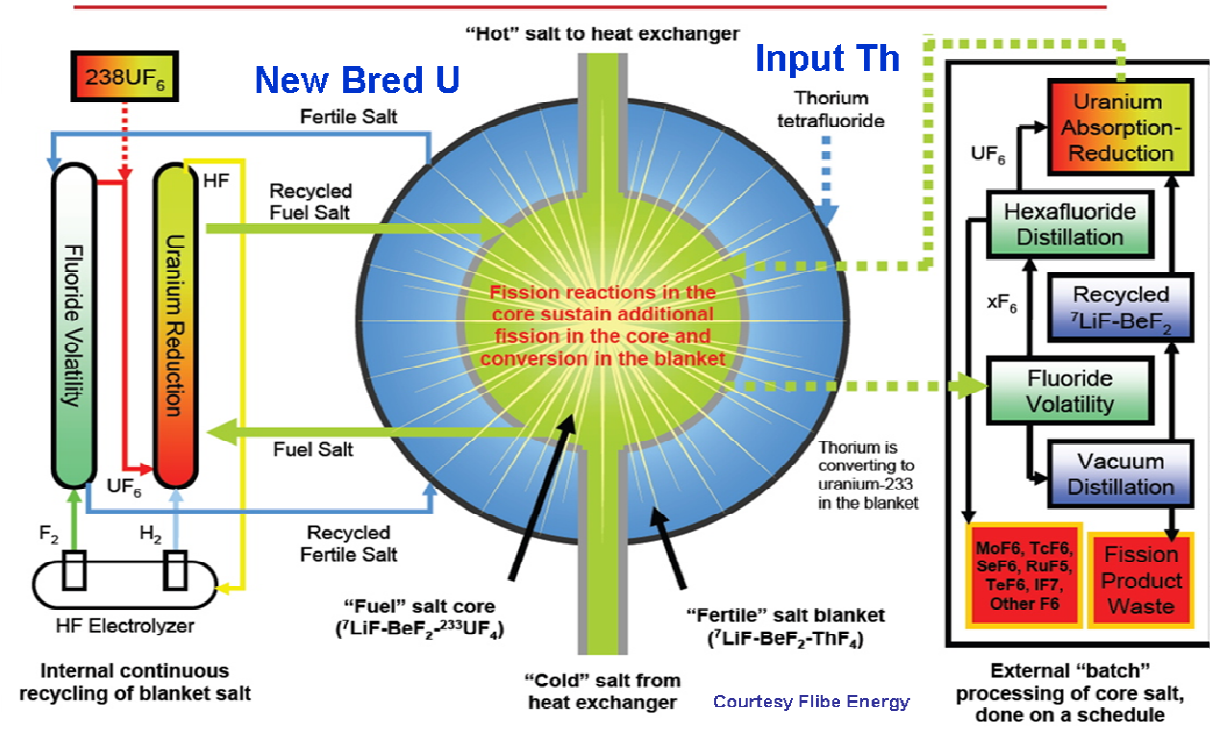


Figure 29. Dual-Fluid LFTR Fuel/Product Processing.

The lattice version also allows continuous fuel processing. Should the core not need additional fissile yet, the bred $^{233}UF_4$ can be securely stored or shipped to start another reactor. But, the latter is not significant, given how much existing LWR 'waste' used fuel exists (containing ~2% U & Pu fissiles, plus ~95% fertile ^{238}U), available for enriching and starting LFTR sites as they are built out.

The MSRE was a single-fluid reactor, Figures 19 & 30, so all processing was done with the same salt mix that flowed through the moderated core and the first heat exchanger. In either single- or two-fluid LFTR designs, all salts must be processed as the reactor runs. Since Neutron poisons (e.g., Xe) as well as wastes and valued products (e.g., Tritium) are often gasses, their separation is relatively straightforward, such as at the pump in the general MSRE diagram in Figure 30. For the majority of fission products and transuranics, liquid chemical processing is required, as described earlier.

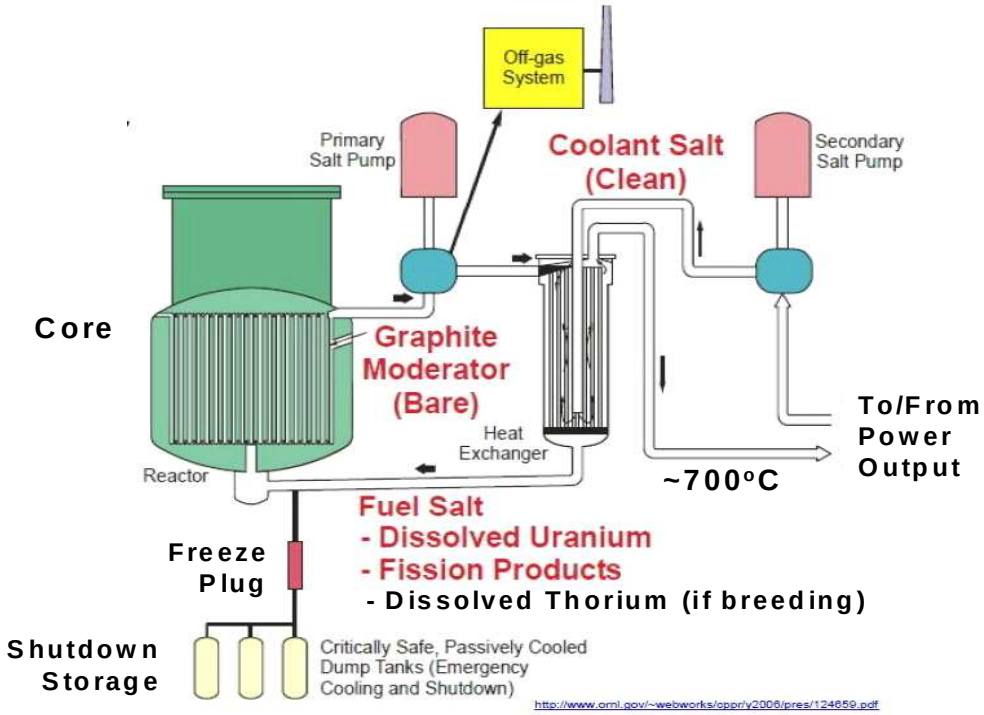


Figure 30. Single-Fluid MSRE Schematic (ORNL, DoE).

There are other variants for LFTR that include “tube-in-tube” designs for radial separation of fuel salt from breeding salt. And, there are fuel-mix choices, such as the DMSR, which denatures the melt for anti-proliferation purposes, but requires occasional additions of fissiles to make up for reduced breeding.

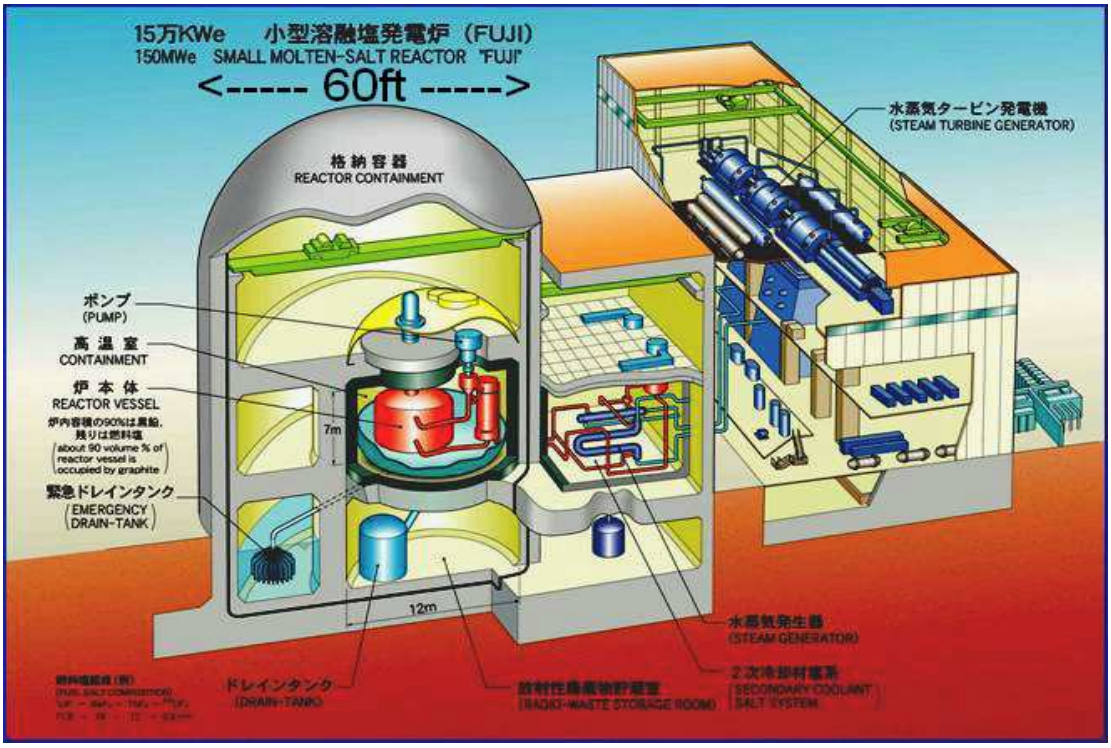


Figure 31. FUJI Experimental LFTR[#].

The FUJI design[4] appears in Figure 31. And Figure 32 graphically reviews the basic, beneficial physics of choosing to enter the realm of fission from the low-mass end, via ^{232}Th, using Thermal Neutrons for breeding and fission, thus keeping higher Actinides at bay (Figures 5 & 6) – all while greatly increasing efficiency and environmental benefit.

Anti-proliferation benefits also derive from Thorium and molten-fluoride salts, which may be used to destroy WGP. For example, the LFTR fuel salt needed to acquire 1 SQ (8 kg) of Pu or U weighs about 800kg (~1800lbs) and occupies a volume of about 250 liters (>60 gals). A very high barrier to theft (see Furukawa[4]), independent of the salt mass's extremely high temperature and radioactivity.

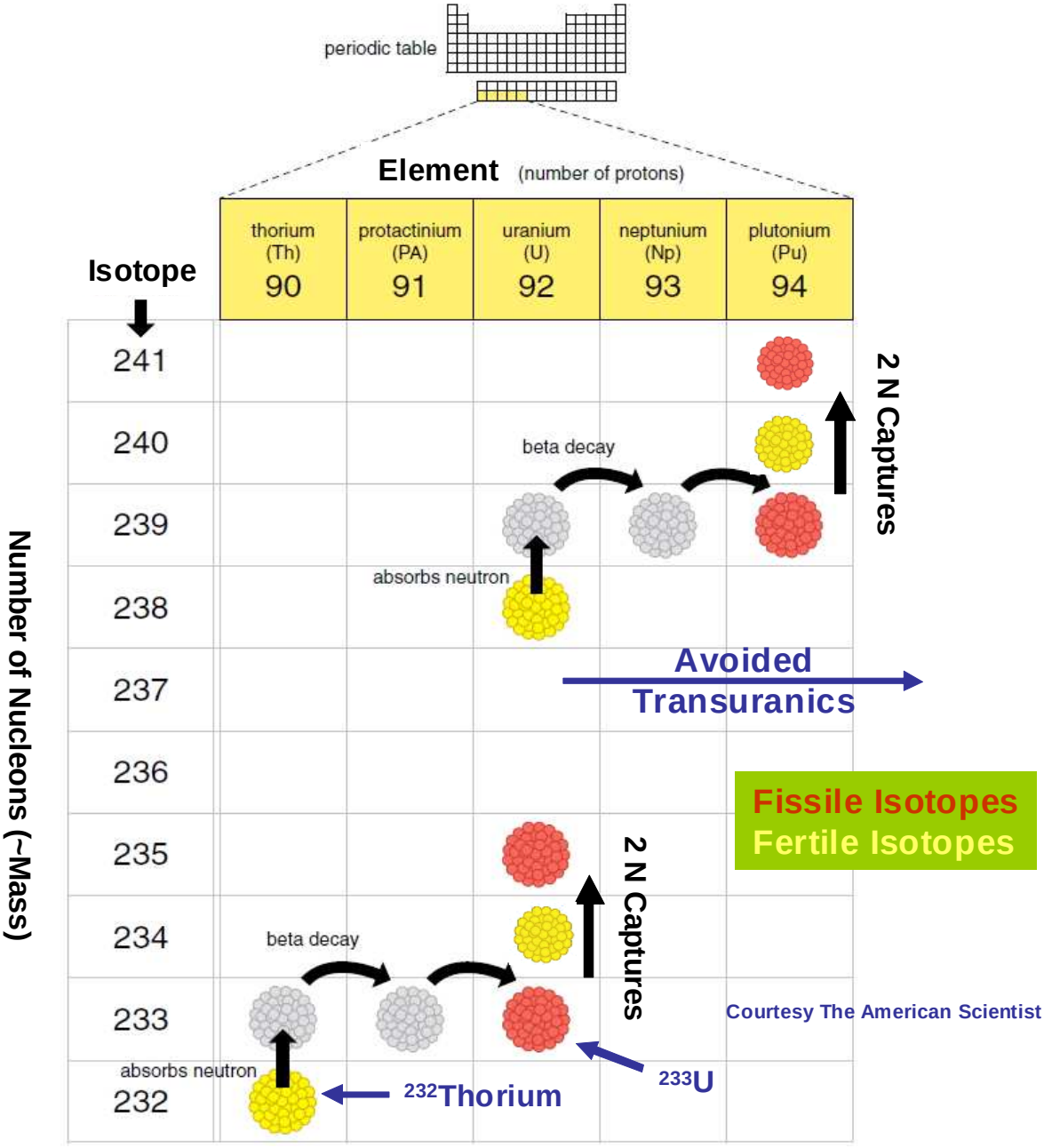


Figure 32. Review of Why Thorium & MSR (LFTR).

All the variants of LFTR share the same robustness in design: scalable power capacity, non-pressurized working fluid, self-throttling reactivity, direct Brayton-Cycle power conversion, easy rejection of fission-product gasses, prompt access to valuable radio-isotopes, continuous operation, ease of shutdown, and secured, on-site processing, with small waste-storage demands. The basic properties of the MSR, combined with fuel bred from Thorium means that power density goes up by a large factor and costs shrink. A 1GWe LFTR might look like Figure 33 and occupy 10 acres, not 100.

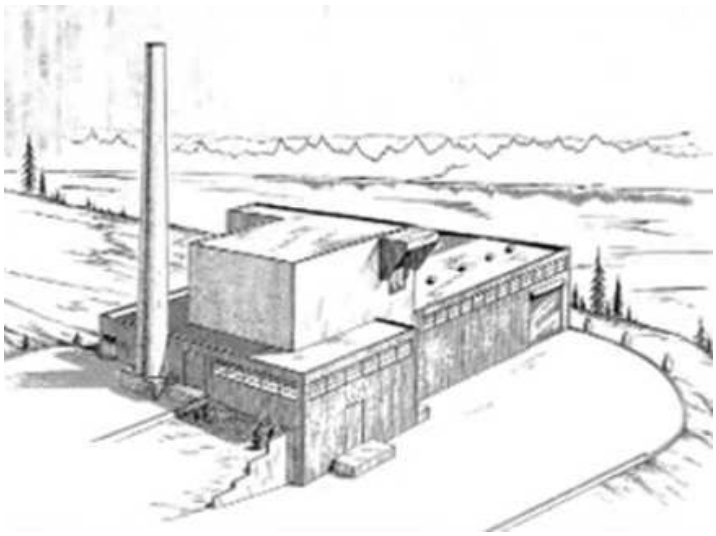


Figure 33. A Conceptual 1GWe LFTR[#].

Such a power plant can be located closer to loads, even modularized for smaller output as needed for remote, military, or emergency operations. The use of air cooling is made possible by higher efficiency from the reactor's high fluid temperature and multi-stage (Brayton-Cycle) turbine output. This adds great environmental benefit and siting flexibility – Figure 34 illustrates the huge size differences among steam, and inert-gas turbines of similar power outputs.

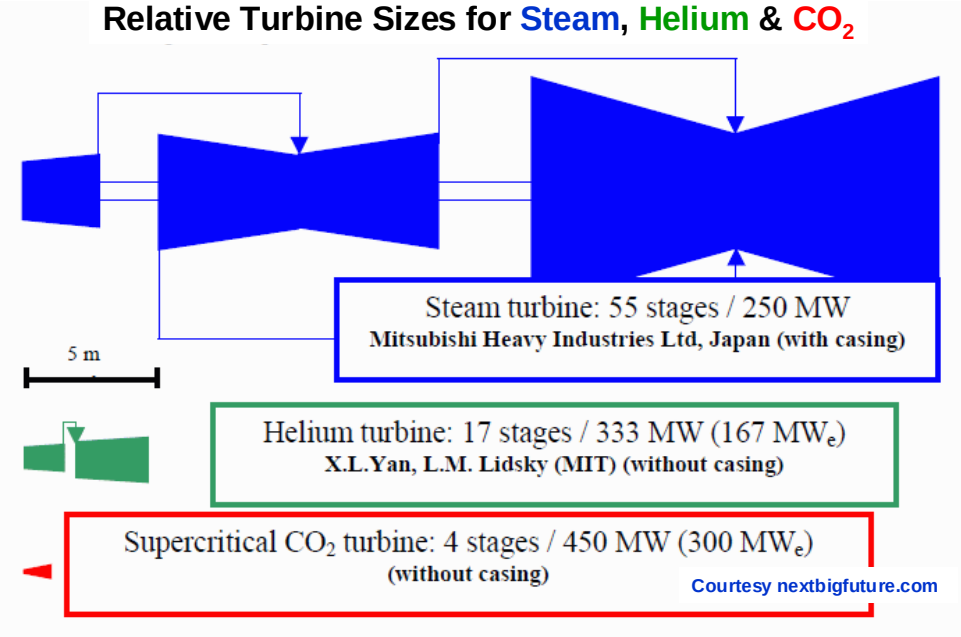


Figure 34. Size Efficiencies of Gas Turbines Relative to Steam.

Clearly, steam (blue) is to be avoided, when higher reactor-coolant temperatures are available, as in any AHTR (e.g., LFTR). Utility-scale steam turbines are very expensive – an LWR penalty. For fresh-water production, or industrial-process heat, just thermal output is needed, making the plant even more compact.

In fact, an economic way to proceed makes use of an existing coal/gas-fired plant's turbine-generator stages by simply substituting an MSR/LFTR for the burner – Figure 35.

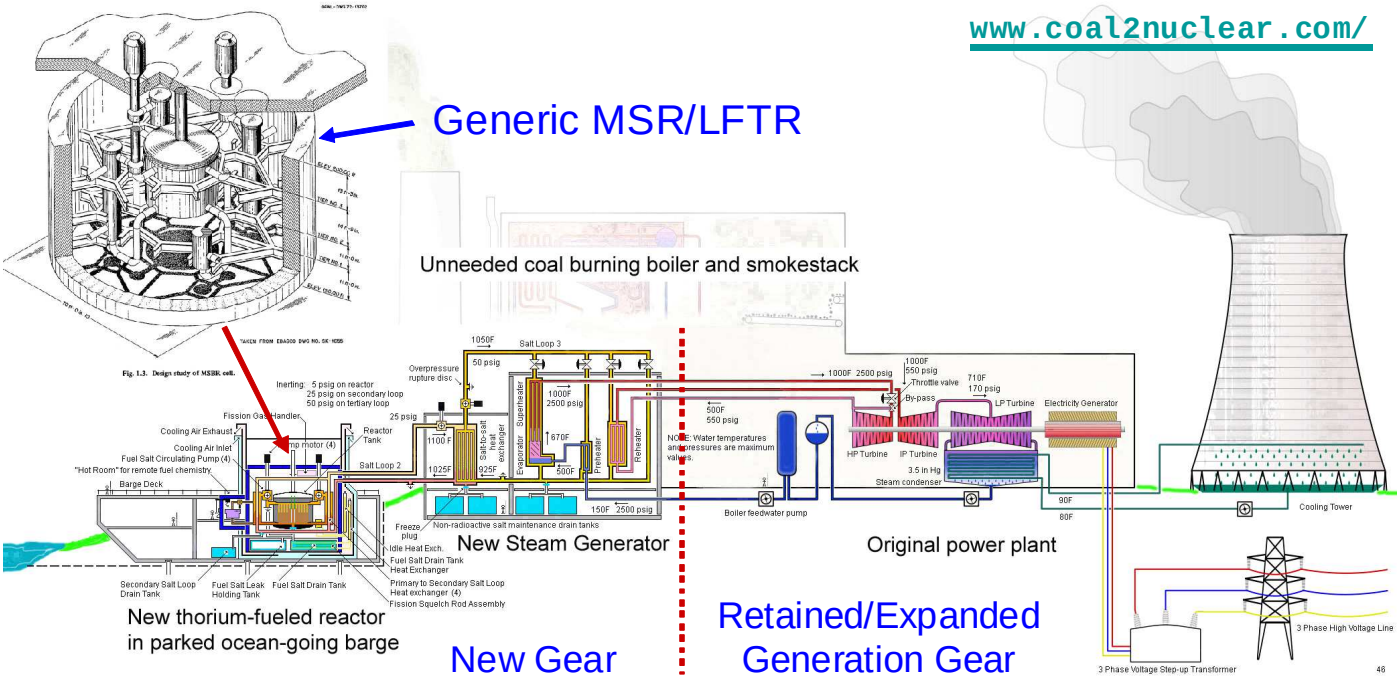


Figure 35. Rebirth of a Coal Plant as Emissions-Free LFTR.

For an existing coal/gas plant on a waterway, as typical for cooling needs, the LFTR module is simply barged in, the steam generator replaced, and the coal facilities simply decommissioned, typically freeing many acres of damaged land for remediation or new uses. Future site upgrades can include conversion to Brayton Cycle turbines and elimination of water needs for cooling.

4. Summary

Thorium by itself benefits nuclear-power generation by breaking our bonds to most, if not all, Uranium mining, enrichment and safeguarding. It nearly eliminates long-term waste production and expensive processing or storage. Because Thorium is already stockpiled, and is a 'waste' byproduct of essential mining operations, such as for rare earths, its cost is negligible for reactor operations. That it provides nearly direct access to the most fissile (yet unnatural) Uranium isotope (^{233}U), is a gift of Nature.

Thorium combined with standard, solid, enriched Uranium fuel, yields significant benefit, as commercialized by some (e.g., Lightbridge) for existing LWR designs. But, the full benefit of moving power generation to Thorium fuel is realized when that fuel is liquid. And, because of how metallic solubilities limit fissile density, we're naturally led to liquids formed from salts. These can easily be formed from Thorium and Uranium to constitute effective reactor fuel with superior thermal-power and safety characteristics.

The stability of salts under radiation and their good thermal properties then lead us to finding an optimal anion that will easily combine with Thorium and Uranium cations via industrial processes, both for fuel production and operational processing. That choice has been found to be Fluorine, as already used in gaseous Uranium enrichment (via UF_6).

Then, to make a reactor fluid that for operational safety remains liquid at the lowest feasible temperature, we choose a near-eutectic mix of fluorides containing ThF_4, BeF_2, UF_4, LiF and perhaps ZrF_4 (to prevent undesired UO_2 precipitation). The fluid is pumped for heat exchange, but is unpressurized, and allows gaseous fission products to directly evolve for capture. Other fission-products bind strongly with fluorine (the most electro-negative ion), trapping them within the salt. Chemical processing of the fluid is done within the reactor hot cell, whether in scheduled batches, or continuously. Desired products (e.g., Tritium, medical isotopes, etc.) are removed and contained for offsite shipment, while bred fuel ($^{233}UF_4$) is fluorinated to UF_6 gas, captured and de-fluorinated to salt for delivery back into the reactor's flow (Figure 29), or secured for shipment to another reactor. The reactor also never contains more fuel than it actually needs, unlike solid-fuelled systems, which must be loaded with enough fuel to last until the next refueling. The small amount (pounds) of fission-product and Actinide waste is removed for safe storage. This is a very great advantage over yearly tons of LWR waste and used-fuel burdens[10]. Another advantage is thermal efficiency, gained from high operating temperature, multi-stage inert-gas turbine generation, and end-cycle cooling via air, rather than water, avoiding many environmental impacts and allowing ultimate site flexibility and desalination opportunities (e.g., Figure 35).

The above knowledge is largely the work of the ORNL teams under MacPherson and Weinberg in the 1960s, for the Molten-Salt Reactor Experiment (MSRE)[5], and continued ORNL efforts[8, 9], even to this date (see ORNL Document Archive).

Semi-fluidic designs, such as the Pebble-Bed reactor (an AHTR), perhaps with inclusion of Thorium in the fuel particles for breeding, effectively distributes the blanket throughout the core. Like DMSR, this provides an intermediate between molten-salt and LWR behaviors, including high thermal efficiency, and perhaps better fuel consumption and waste reduction than even Thorium-seeded LWRs.

The six Generation-IV reactors slated for DoE research support now will not yield demonstration plants until about 2021 and even those will not be Uranium independent. Thus, it's imperative that concerned groups work to acquire funding to augment presently-committed US-government efforts and aim to fulfill the goal described in the AEC's report to President Kennedy[2]. However, in the USA, we still face the lack of funding provided the NRC for new fuel-cycle and processing certification. China is clearly working on this[4] for themselves (the *Chinese Academy of Science* funds and coordinates most aspects of the country's Liquid Fluoride "T" Reactor development). Other countries, such as India and Brazil seem poised to follow, because they have easier access to Thorium than Uranium. At an estimated $3/Watt for construction of a 1GWe Thorium-fluoride MSR (LFTR), this may well be the decade of Thorium and breeding for safe nuclear power. It may also herald an expansion of education and employment in nuclear engineering and radio-chemistry, creating good jobs around the world in reactor design and operation.

The tragic events in Japan (11 March 2011) have focused world attention on nuclear power, especially with regards to safety in natural disasters. In this light, known past problems with the Fukushima GE Mark-I reactor designs and management are presented here[16] in relation to known and expected behaviors of MSR/LFTR reactors when under similarly extreme stress (see last reference URL[16]). One key to safe behavior is liquid fuelling, which allows immediate, gravity-driven core unloading upon triggered shutdown, as by earthquake detection. The MSRE design, in particular, automatically shut down upon auxiliary power failure, with no human intervention. And, lack of water, oxidizable fuel components (e.g., Zircaloy casings) and any significant fuel pressurization mean that an MSR/LFTR will not incur explosive damage, or dispersal of fuel and fission products. This amounts to what is viewed as an essential property of next generation of reactor designs – "walk-away safe".

Safe nuclear power also means abundant fresh water anywhere water of any source can be tapped. This reality is no less important than basic electrical generation without GHG emissions. LFTR also gives access to abundant radio-isotopes, now in critical need for medicine. Fertile Thorium makes all this a reality at minimal cost and environmental impact, and can do so for millennia, much as its slow decay has helped keep our planet safe from external radiation for billions of years. Figure 36 summarizes what LFTR can do for us all.

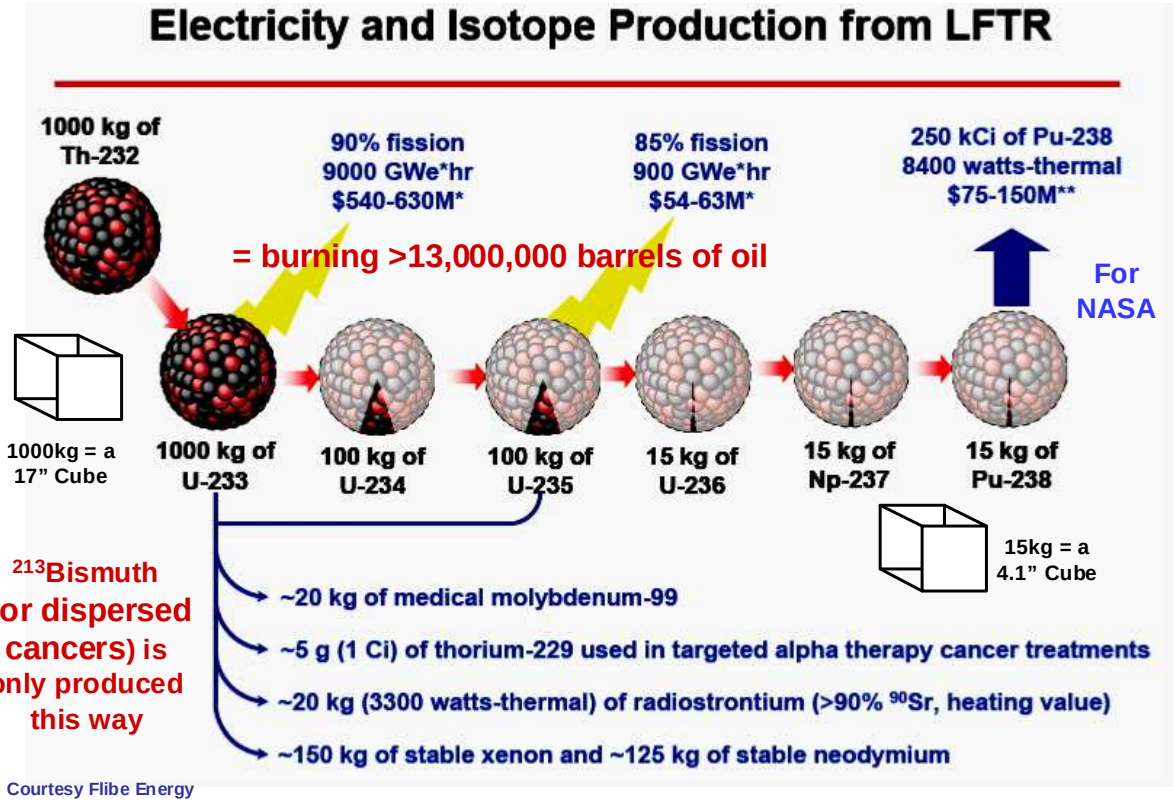


Figure 36. LFTR Products.

A unique medical example is ^{213}Bismuth, only produced by ^{233}U decay, and the only isotope whose decay to stability emits an Alpha particle that can kill a cancer cell when the Bismuth is attached to an ingested antibody – a magic anti-cancer bullet, only from LFTR.

5. The Future

"There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things, because the innovator has for enemies all those who have done well under the old order of things, and lukewarm defenders in those who may do well under the new." – Niccolo Machiavelli

Machiavelli gets a bum rap -- he was in fact a learned, serious student of man and cared for mankind. His words above just signal his awareness and sharing of real human weaknesses. We're the species with both opposable thumbs and obdurate minds – the "not invented here" syndrome, for instance.

Future directions for US reactor research are somewhat dependent on the DoE's Advanced Reactor program, specifically the 6 Gen-IV choices for R&D. However, the rest of the world doesn't sleep and needs power and water at least as much as we do (e.g., China builds a new city the size of Chicago every several months). So, given China's recent (March 2011) announcement[4] of clear plans to follow on from ORNL's MSR research, we may well see India,

Brazil, Japan and others quickly follow. The tragic events in Fukushima Japan[16], in fact, augur for new directions in nuclear-power system design, as advised in 1962[2]. Perhaps US Congress and DoE will change course and emphasis a bit, to accelerate the Gen-IV MSR plan. It will serve all countries well to quickly move to LFTR demonstration projects. Economists often talk about our world's imbalances (food, water, energy, incomes…). Access to abundant power (and water) is an agreed-upon key to bettering those imbalances.

Moving something important, efficient, inexpensive and novel to the forefront in a complex world's markets is challenging. There are so many interests that would have to begin sharing their current benefits with developers of the new. There are so many forces with set minds about nuclear power, despite the reality that none of us would exist without nuclear phenomena, and that safety is indeed built into alternative designs we failed to complete decades ago. To interfere so seriously with established ideas and incomes, as LFTR will, is likely the biggest challenge facing us.

Yet, we've no choice. ORNL's old, scanned documents alone stand as such a clear, complete map to a safe energy and water future, that we cannot face yet another generation and say we couldn't complete the work laid out for us in 1962. The amazing story of Weinberg's tireless MSR team and Nature's gifts of Thorium and fission speak too clearly to ignore. So plans are afoot to fulfill ORNL's dedication with real demonstrations, like the one in the final figure.

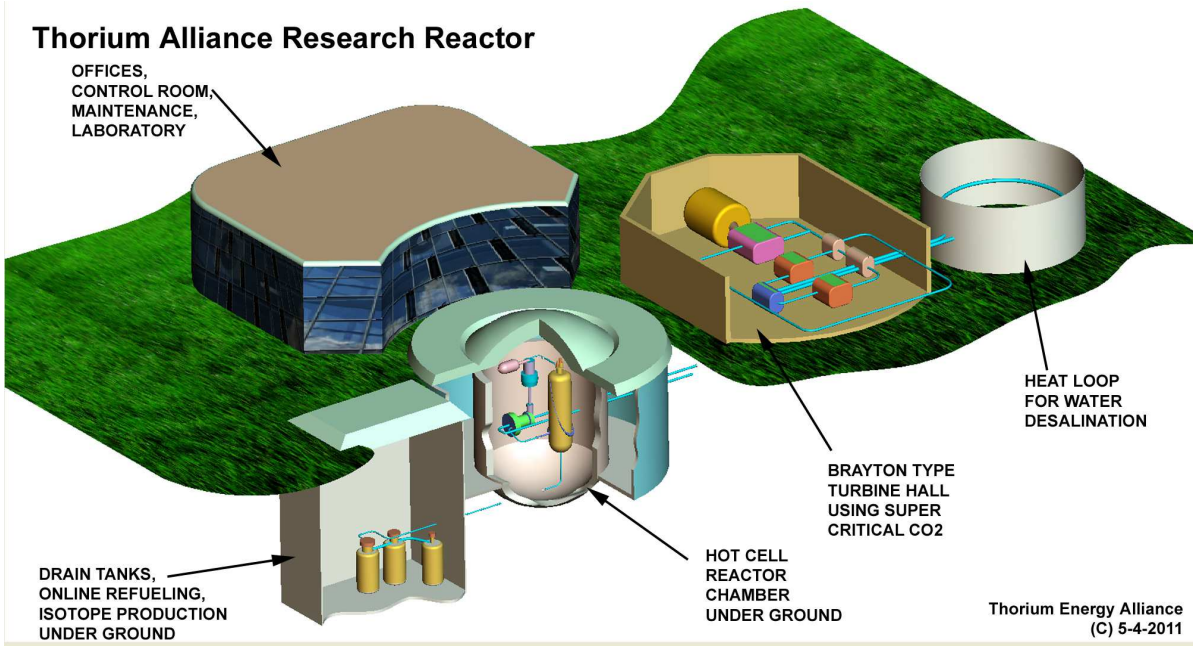


Figure 37. A LFTR Demonstration Reactor[#].

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And, many nuclear researchers around the world deserve our gratitude for their dedication over decades to bring us so close to solving the world's safe-energy and thus fresh-water needs. A special debt is owed those of Oak Ridge National Labs, for their extraordinary, dedicated work from 1945 on, which is clearly evidenced in the unmatched volume and competence of their research and reports (see ORNL Document Archive).

Finally, my wife deserves unlimited thanks for her patience, while this writing slowed needed household projects.

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8. Glossary

A: Atomic mass -- the number of Protons and Neutrons in any nucleus.

Actinides: The heavy elements of the Periodic Table after Radium, starting with Actinium ($_{89}$Ac), then Thorium and continuing past Uranium and Plutonium to Nobellium ($_{102}$No). They are typically Alpha emitters. See also Trans-Uranics.

AEC: Atomic energy Commission, established in 1946, then functionally split into the NRC and part of DoE after 1975.

AHTR/VHTR: Advanced/Very High-Temperature Reactor[7]. A variety of designs using LWR core architectures with molten-salt or liquid-metal cooling/heat-transfer loops for higher thermal efficiency. See also Generation IV Reactors[8].

Alpha Particle (^{4}He ion): A freely-moving, energetic Helium nucleus (2 Protons, 2 Neutrons) with +2 charge. Emission of an Alpha Particle moves an element 2 positions down the Periodic Table, to become a lighter element. Radioactive decay produces Alpha emissions in the several eV range, typically unable to penetrate paper or skin. Interstellar mechanisms provide

much higher Alpha energies (e.g., >1GeV), as in Cosmic Rays, ~10% of which are Alpha Particles.

Anti Particle: An atomic particle whose properties are conjugate to those of the 'normal' particle it's named for. For example, a Positron (Anti-Electron) has the same mass, but opposite charge (positive) to that of an Electron. Particles and their Anti-Particle twins annihilate each other to produce energetic photons (electromagnetic waves). Fission, fusion and decay reactions can produce Positrons and other Anti-Particles.

Beta Particle: A freely-moving, energetic Electron. Nuclear Beta emission releases some nuclear energy and effectively converts a Neutron to a Proton, thus creating an isotope of the next element (Z+1) in the Periodic Table. The opposite move occurs by emission of a Positron (a Beta^{+} emission). Electrons & Positrons constitute ~1% of Cosmic Rays and are easily shielded. An excellent animation of both Beta and Beta^{+} emissions from nuclei appears here…
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Blanket: An fully/partially-enclosed region surrounding a reactor core (or fuel Seed), into which fertile (or other) material is loaded to become irradiated by Neutron flux from the core, for the purposes of breeding fissile elements (or useful isotopes, as for medicine). In the case of fuel breeding, the blanket may be continuously or batch processed chemically to separate target materials and wastes. A 2-fluid MSBR/LFTR has a blanket containing a molten Thorium salt.

Breeder: Any reactor that creates more fissile fuel (via Neutron absorption) than it consumes and was originally loaded into the reactor from the outside world[2, 3]. Its starting fuel load typically includes both fertile and fissile elements (e.g., ^{232}Th & ^{233}U and/or ^{238}U & ^{239}Pu). Breeding may occur via internal Neutron flux, or by external tools, such as a Proton accelerator aimed at a target that produces many spallation neutrons (see G. Myneni)[8]. Excess fissiles may be removed periodically for use in other reactors.

BWR: See LWR.

CEC: California Energy Commission.

Containment: A nuclear reactor has components that vary from exceedingly radioactive to benign (at natural or background) levels. In addition, the nature of operating emissions varies, such as from the high Neutron and Gamma fluxes in the core, to milder Alpha and Beta emissions from unused fuel. Any material for reprocessing or sale (e.g., used fuel, Tritium, medical radio-nuclides, etc.) will produce emissions and solid/gaseous daughter elements. Release to the environment of most any of these (except perhaps ^{85}Kr) must be prevented. In addition, depending on the reactor's architecture and heat-transfer fluid(s), risk of a non-nuclear explosive event could exist – an LWR steam explosion or overheated Zircaloy oxidation and Hydrogen release[16], or a combustive coolant reaction with air/water in an alkali-metal-cooled system.

Thus, reactor design and fuel-cycle choices greatly influence overall site location, size, construction and cost. For example, a standard, civilian LWR (BWR-PWR) must be contained in a sealed structure capable of withstanding about 60-160 Atmospheres (~900-2400psi) of internal overpressure without cracking or otherwise allowing solids/liquids/gasses to escape. These are the large, expensive dome-like structures we see and associate with nuclear power. NRC inspections concentrate a great deal on how they are maintained. In contrast, containment for reactor designs that have no similar failure modes require much less dramatic physical containment – an MSR is such an example, since it runs unpressurized, using non-combustive fuels and coolants that simply cool and solidify upon leaking. Containment size and cost vary greatly with reactor design choices, but always share the purpose of maintaining radiation and decaying gaseous/liquid/solid material within a sealed volume.

Core: The region of a reactor whose structure and material allows encouragement and control of nuclear fission, typically induced by Neutrons from fissile elements in a chain reaction. Moderator adjustments and/or control rods of Neutron-absorbent material(s) (e.g., Hafnium or Boron) may be used within a core to adjust power output and maintain or dampen criticality. Varying moderator mixtures of normal and heavy water have been used for control in some LWRs. The core may be movable and include vias for gas/liquid coolant to capture reaction energy for thermal transfer to external control and power systems (e.g., see Clayton[3]).

Corium: The metallic mix of molten LWR fuel-structure components that's created upon partial or full core meltdown. It will rest on the containment's protective floor, perhaps vaporizing floor materials (e.g., within concrete).

Criticality: The desirable reactor condition achieved when core architecture and Neutron production are sufficient to maintain a continuous series of fissions without external intervention. This implies both exposure of enough fissile nuclei and enough Neutrons of appropriate velocities to exploit the fuel's fission cross section. It does not imply a nuclear explosion.

Cross-Section: A probabilistic measure of any particle-nucleus interaction. For example, the cross-sections for Thorium or Uranium nuclei to capture a Thermal Neutron are about the same, but each is far smaller than that of Gadolinium (the king of Neutron capture). Fission cross-sections for common fissiles in Thermal-Neutron fluxes are: 90% for ^{233}U, 80% for ^{235}U & 65% for ^{239}Pu. Other elements may be fissioned by Neutrons of energies ranging from Thermal to Fast.

Delayed Neutron: A chain fission reaction could blow the fissiles apart if all Neutrons from each fission were immediately available for more fission events. However, each fission produces daughter nuclei which are themselves Neutron rich and typically Beta decay to the next element (Z+1). The more Neutron rich the fragment, the faster its Beta decay. In cases where the potential Beta decay energy is very high, a Neutron may be emitted instead of Beta and Gamma, especially for certain nuclei with odd-

valued Neutron counts, where Neutron binding energy is low. Delays before such emissions occur range from milliseconds to minutes. Probabilities for Delayed Neutron emissions are typically less than 1% per fission event. Stable reactor operation depends on some sufficiently-delayed Neutrons, so that control mechanisms and/or thermal effects in fuel/moderator have time to provide negative reactivity feedback. Salt reactors like MSR/LFTR are very good this way. Fast reactors like IFR require more elaborate controls, even dependence on relativistic effects.

DMSR: Denatured (anti-proliferation fuel mix) MSR[8]. DMSRs end up slightly reducing radioactivity in the world, after fission fragments decay.

DoE: Department of Energy: http://energy.gov/

DU: Depleted Uranium -- what's left over after natural Uranium has been enriched (e.g., via centrifugation) – see Fig. 15 inset and below, showing thousands of UF_6 DU waste canisters in Kentucky. DU contains ~0.25 % ^{235}U, down from ~0.7% in natural uranium. UF_6 is a gas above ~100^{o}F.

Electron-Volt (eV): A tiny energy measure equal to the kinetic energy gained by an electron falling through a potential difference of 1 Volt. Thus 1eV = .00000000000000000016 Joules (Watt-seconds). 1keV = 1000eV, 1MeV = 1000keV = 1.602×10^{-13} Joules. Kinetic energy of any particle can be expressed in eV, such as a Neutron's velocity exiting a Deuterium-Tritium fusion event – 14.1 MeV, or 17% the speed of light (fastest of the Fast Neutrons). Via Einstein's mass-energy equivalence ($m = E/c^2$), rest masses can be written in eV as well. By this measure, an Electron's mass is 511keV, while a Proton's is 938MeV (about 1800 times the rest mass of an Electron).

Enrichment (Uranium): Natural Uranium no longer contains sufficient fissile (i.e., only ~0.7% ^{235}U) to easily maintain criticality in a reactor core, so means have been developed since the Manhattan Project to selectively increase fissile concentration. Methods include electromagnetic, gaseous diffusion, centrifugation, and today, laser: laser: www.world-nuclear.org/info/inf28.html

~2 billion years ago, ^{235}U was common enough that natural reactors, moderated by rainwater, reached criticality in some ore deposits, as in Oklo, Gabon (see Uranium entry).

EPRI: Electric Power Research Institute – utility-industry-financed R&D.

Fast Neutron: A Fast Neutron (from fission) is essentially un-moderated, moving at a modest percentage of the speed of light (in the keV range).

Fast Reactor: A Fast (Neutron) Reactor generates essentially un-moderated Neutron flux within its core, thus demanding other, faster means than mechanical/thermal effects on fuel for managing criticality. Fast Neutrons fission most nuclides. . Transmuted odd-numbered Actinides split more easily, forming pairs of fission products with lower total radio-toxicity. These have half lives under 30 years, reducing transuranic waste burdens to small percentages and from millennia to centuries. The transmuted even Actinides (e.g., ^{240}Pu) also become fuel (e.g., ^{241}Pu), extending the power capability of the reactor.

Fertile: An element, transmutable via Neutron capture, into a fissile. Thorium is fertile, in that Thermal-Neutron impacts (and subsequent Beta decays) can transmute it to highly fissile ^{233}U. Natural Uranium (99% ^{238}U) is also fertile, producing fissile isotopes ^{239}Pu & ^{241}Pu. See also Breeder and Protactinium.

Fissile: An element whose nucleus may fission into smaller, daughter nuclei, upon capture of a Thermal Neutron. ^{233}U, ^{235}U, ^{239}Pu, and ^{241}Pu are fissile.

Fission: The breaking apart of any nucleus heavier than ordinary Hydrogen, into smaller nuclei. A typical fission event yields about 200MeV of energy, plus a pair of smaller nuclei, plus some Neutrons (e.g., Figure 14), which can support a chain reaction. The fission products are generally themselves radioactive, decaying relatively quickly down a chain of lighter 'daughter' elements until stable nuclei, such as Bismuth or Lead are reached. These decays produce the whole gamut of emissions (Alpha, Beta & Gamma), usually intense, as the unstable elements reduce their nuclear energies. Each unstable nucleus experiences its own decay chain, like a fingerprint, of daughter elements, until a stable nucleus is reached. This may take micro-seconds or millennia. Faster decays typically emit more intense radiation, exhibiting shorter Half-Lives.

In 1934, German chemist Ida Noddack suggested: "it is conceivable that the nucleus breaks up into several large fragments." In 1938, Lise Meitner, Otto Hahn, and Fritz Strassmann proved that one product of bombarding Uranium with Neutrons was lighter Barium, thus confirming nuclear fission. They also computed the energy released as equal to ~1/5 Proton mass, or ~200MeV.

A lightweight fission example is Tritium breeding (Fig. 11) -- a Neutron impacts a $^{7}Lithium$ nucleus, producing Helium, Tritium (^{3}H) and a Neutron, which then impacts a $^{6}Lithium$ nucleus, again producing Helium and

Tritium. The first fission is mildly exothermic; the second endothermic. Tritium then Beta decays (half-life ~12 years) to ^{3}Helium, releasing over 18keV of energy per event. Uranium fission provides a heavyweight example, typically yielding pairs of fission products whose nuclei are drawn from a pool of about 20 possible 'daughters' (radioactive isotopes of elements like Krypton, Strontium, Barium and Lanthanum). The key value of Uranium fission is its exothermicity (~200MeV per event) and Neutron economics – more energy and Neutrons are released per fission than consumed (e.g., Figure 1, energy-barrier inset). This is what offers the potential for a sustained (chain) reaction to deliver useful power to reactor coolant.

Fluorination: A very common chemical process -- compounding an element into a fluoride salt or gas. For enrichment, Uranium is converted to the gas UF_6, to support diffusion or centrifuge processing. For salt reactors, UF_4 is the fissile charge, or the result of breeding fertile ThF_4 to $^{233}UF_4$. Fluorination also serves to remove, as gasses, potential fuels, fission products or wastes from liquid-fuelled reactors, such as MSRs, LMFBRs, or from reprocessed solid-fuel wastes.

Fuel (Reactor): Solid assemblies or fluids containing fissile and perhaps fertile elements. Common solid fuels are composed of Actinide-oxide ceramics (e.g., PuO_2, UO_2,ThO_2, ThO_2-UO_2, or ZrO_2-UO_2) or carbides. Some newer designs use metal alloys of Zirconium with either Uranium or Plutonium. Various fuels have been formed into plates, rods and complex geometries, iterated to serve the needs of criticality, power output, thermal transfer, maintenance, and, perhaps, breeding. Pseudo solids have also been designed, such as ellipsoidal 'pebbles' (e.g., TRISO, golf-ball sized), whose internal structure includes solid fuel with moderator shell(s), such as graphite. Such reactors (VHTR/AHTR) are gas, salt or molten-metal cooled and operate at very high temperatures, with high efficiency and safety (see AHTR & Generation IV Reactors). True fluid reactors have used water-soluble fissile compounds, or pure salts, melted at high temperature (see MSR) to achieve advantages of efficiency and safety.

Gamma Ray: Photons of electromagnetic radiation whose energy exceeds that of Xray photons (roughly >100keV), with frequencies (nu or f) above 1000 Peta Hz and wavelengths less than an Angstrom (the scale of an atom). Photon energies are proportional to their frequency times Planck's constant ($E/f = \sim 6.6 \times 10^{-34}$ Joule/Hz). Thus Gamma rays have exceedingly high frequencies and are highly-ionizing radiation. Ultraviolet light, for example, can deliver 3eV or more, while Gamma photons deliver at least 50,000 times as much energy, freeing even innermost electrons from an atom. Gamma radiation above 10MeV occurs not from nuclear processes but from extremely energetic environments, such as those near Black Holes, Magnetars, etc. Gamma rays can be emitted by fission or fusion of nuclei, by interactions of particles and Anti-Particles, or by interaction of energetic, charged particles with extreme magnetic fields. Gamma radiation exposure is measured by the Gray or Sievert, which both correspond to 1 Joule (1 Watt-second) of energy delivered to 1 kilogram of target material (also equivalent to an exposure of 100 Rem). But, the Sievert is intended to

measure biological effect, thus different types of radiation are rated in “dose equivalents”, using multipliers (e.g., Photons/Electrons = 1, Protons = 2, Alpha particles or fission fragments = 20, thermal-fast Neutrons = 1-30…). Living targets depend on DNA-repair mechanisms to correct for natural Gamma exposures (<1/2 Rem), chemical insults, etc. Thus dose equivalents depend on not just the form of radiation, but the target tissue as well (http://en.wikipedia.org/wiki/Sievert).

Generation IV Reactors: Over recent decades, efforts have been made to address nuclear-fuel cycles with regard to safety and efficiency improvements to the traditional LWR cycle. Six categories are presently noted by DoE: VHTR, MSR, SCWR (Super-Critical Water-cooled Reactor) and 3 Fast-Neutron reactors: GFR, LFR, SFR, using gas, Lead or Sodium cooling, respectively. A VHTR design is expected to be complete within a decade of this writing: http://en.wikipedia.org/wiki/Generation_IV_reactor

GWe: Giga-Watt (electric) = 1000MWe.

HEU: Highly-Enriched Uranium (>20% ^{235}U), with bomb potential if enriched further to >90%.

Half-Life: A pure radioactive-isotope mass decays exponentially, as individual nuclei emit radiation and become daughter elements. The time (picoseconds to billions of years) taken for half of an original mass of nuclei to decay to daughter elements is termed that isotope’s half life. The shorter a half life, the more radioactive an isotope is.

Hastelloy: A Nickel-bearing stainless steel used in industry for its temperature and corrosion resistance. It was used in ORNL MSR designs.

Hot Cell: The part of a reactor or fuel-processing system that excludes operators from contact with both operational heat and radiation. Remote manipulation of materials is used.

IAEA: International Atomic Energy Agency, www.iaea.org

IFR: Integral Fast (breeder) Reactor, typically cooled by liquid Sodium. Intended to breed ^{238}U to Pu and fission that (and other Actinides) via Fast Neutrons. Initial fissile need is higher than for Thermal-Neutron reactors. Fuel reprocessing and fabrication are integral to the plant. Waste, instability and proliferation dangers may increase. See also LMFBR.

Ionizing Radiation: Energetic emissions of charged particles, photons (UV, X or Gamma), or Neutrons (by indirect action), that can strip Electrons from atoms, leaving positively-charged ions and broken molecular bonds. Alpha particles (Helium ions) are, easily stopped, but especially dangerous to life when emitted internally by ingested materials. External Alpha and Beta (Electron or Positron) radiation typically cannot penetrate skin, but can cause burns. Evolution under natural radiation and far more frequent chemical insult has given normal cells DNA-repair mechanisms that can correct errors caused by radiation, up to an exposure limit of a few milli-Sieverts. Sieverts

account for the biological damage of the radiation's type and energy, while a Gray is the radiological energy delivered to any given mass -- 1 Gray = 1 Joule/kg. So, 1 Gray = 1 Sievert for Gamma and Beta; 5-20 Sieverts per Gray of Neutrons; and for Alpha particles and fission fragments, ~20 Sieverts per Gray: http://en.wikipedia.org/wiki/Sievert Typical human radiation doses are illustrated here: http://imgs.xkcd.com/blag/radiation.png

Iso-Breeder: A reactor that generates just enough fissile (from fertile) material to replace the fissile being consumed.

Isomer (Nuclear): A different configuration of the nucleons in a given isotope, with perhaps usefully different nuclear/decay characteristics, as ^{99m}Technetium is is for medical imaging.

Isotope: A nucleus of an element containing the proper number of Protons (Z), but a number of Neutrons that differs from the typical (common) form(s) of the element found in nature (see vertical spreads for each Z in Figure 12). Thus, an element's isotopes all share one Z but have different mass numbers (A) and may be stable or radioactive. They are all nearly identical at the electronic (chemistry) level, but their nuclear mass differences allow for separation (as for ^{235}U & ^{238}U) via inertial means (e.g., via centrifuge), even via laser[11]. Many radioactive isotopes (e.g., ^{99}Mo) are important to medicine and industry. Nuclear Isomers are different configurations of the nucleons in a given isotope, and so may have usefully different decay characteristics, as ^{99m}Technetium is for medical imaging.

Lanthanides: Elements from Lanthanum through Ytterbium, often undesirably produced within reactor fuels. Their general hunger for Neutrons (high capture Cross Sections) hurts a reactor's Neutron economy.

LEU: Low-enriched Uranium – an isotopic mix typically under 20% ^{235}U (~4% is typical of LWR fuel).

LFTR: Liquid Fluoride (or Fuel) Thermal (or Thorium) Reactor[4] (typically a Thorium-Fluoride MSR). It breeds fissile ^{233}Uranium from Thorium. Alternatives include 1-, 1.5- and 2-fluid designs (e.g., Figure 28). Chloride salts are also usable, thus the 2nd acronym version.

LMFBR[7, 8]: Liquid-Metal (Fuelled) Fast-Breeder Reactor. A molten metal solution (e.g., Uranium and Bismuth) whose fissile component may be bred within the melt, but the melt provides excellent thermal characteristics and power efficiency by operating at temperatures much higher than LWRs can. The ***LMFR*** similarly gains thermal efficiency, but isn't intended to breed fuel.

LWR: Light-Water Reactor. Common forms are Boiling-Water and Pressurized-Water reactors (BWRs & PWRs). Water acts both as Neutron velocity moderator and heat-transfer fluid (~300^{o}C) for power generation.

LWBR: Light-Water Breeder Reactor – an LWR loaded with a fertile element like Thorium which can be transmuted by the core's Neutron flux into a fissile element which, under criticality, creates more fuel than is consumed [2, 3].

Manhattan Project: The US effort in WWII to design the first atomic bomb.

Moderator: A reactor structure/material that slows Neutrons to velocities appropriate to desired reactions, such as for Thermal Neutrons causing fission of fissile nuclei. Graphite and water are common moderators. A moderator should not capture significant numbers of Neutrons, hurting the reactor's Neutron economics, while undesirably transmuting its own element(s). For salt reactors, fluorides are somewhat moderating while chlorides are less so. Thus the latter are chosen for Fast-Neutron systems.

MOX: Mixed-Oxide reactor fuel, commonly depleted or natural Uranium and Plutonium in oxide form (PuO_2+UO_2). One purpose is to dispose of WGP. Fuel forms may be ceramic pellets loaded into metallic rods, arrayed to maximize thermal efficiency. Its characteristics are similar to those of enriched Uranium used in standard UO_2 fuels.

MSR: Molten-Salt Reactor[5]. A liquid-fuelled, non-pressurized fission reactor using salts, some fissile, heated above their melting point (~700^{o}C) to carry energy efficiently from reactor core to load (e.g., a heat exchanger). Inclusion of fertile nuclei, such as ^{232}Th, allows the reactor ***(MSBR**, or **DMSR)*** to breed its own fuel within the salt melt, eliminating/reducing many costs and dangers of solid fuels and water/steam thermal power transfer.

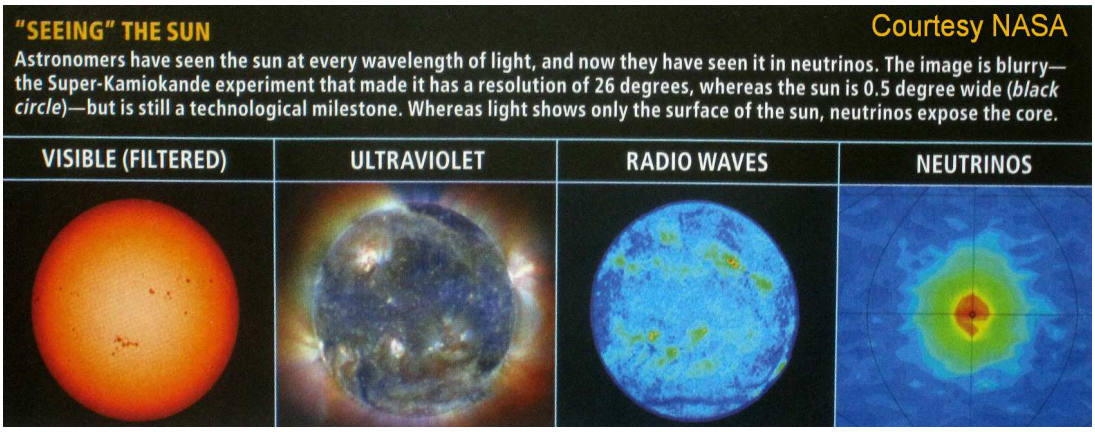
MWe: Mega-Watt-electric – net power output after thermal efficiency losses in an electrical power plant, regardless of raw thermal source (combustion, solar, nuclear…). For typical combustion, working-fluid temperatures exceed 600^{o}C, allowing about 40% thermal efficiency. LWRs operate at lower temperatures, MSRs at higher, thus spanning efficiencies from about 30% to 50%. Much effort goes into designing multi-stage (e.g., Brayton-Cycle) turbine-generator drives to extract as much thermal energy as possible. For example, a barrel (42 US gallons) of oil represents ~1.5MWHrs of energy if burned with Oxygen, but a gasoline/diesel engine will only extract about 0.45MWHrs, due to its thermal efficiency of about 30%. Any thermal energy convertor will always deliver significantly less output (mechanical/electrical) energy than is stored in the input fuel (combustible/nuclear).

NEI, Nuclear energy Institute, www.nei.org

Neutron: An uncharged nuclear particle of about the same mass as a Proton, but unstable outside a nucleus – it Beta decays to a Proton, Electron and Anti-Neutrino within minutes. Its electromagnetic neutrality delayed its discovery until 1932, long after Alpha, Beta and Gamma discoveries.

Neutrino: An uncharged nuclear particle of so small mass that it was considered massless for decades, but served the need to explain how some reactions' (e.g., fusion's) energy balances are maintained. It appears to have 3 varieties which can cycle among themselves as a Neutrino propagates away from a nuclear reaction. Current theory also suggests Neutrino as a possible component of the Dark Matter that dominates the universe. And, it may be related to the Tachyon of Quantum Field theory. So many Neutrinos

are produced by stellar fusion that billions pass safely through our bodies every second, rarely interacting with matter in an entire planet. The pictures below show our Sun as seen in different 'lights', ending with Neutrino light from the Sun's core where fusion is taking place:



NNSA: National Nuclear Security Administration – the agency responsible for tracking and collecting rogue nuclear materials: http://nnsa.energy.gov/

NORM: Naturally-Occurring Radioactive Materials – allowed emissions from combustion plants, whose fuels inevitably contain contaminants, like Uranium, Radon, etc. Without this exception, all combustion plants would be closed by radiation standards that nuclear plants must already meet.

NRC: Nuclear Regulatory Commission -- the US agency responsible for civilian nuclear power and materiel regulation. www.nrc.gov/reactors.html Created out of the former AEC in 1975. Its standards and methods affect worldwide nuclear-power regulation.

Nuclear Stability: Atomic nuclei must contain Protons, whose number (Z) defines each element and its chemistry, via its bound shell electrons. Beyond Hydrogen's one Proton, nuclei must contain Neutron(s). The count of nuclear Neutrons (N) determines an element's Isotope. Neutrons appear to increase stability of nuclei containing more than one Proton. Thus, a plot of Neutrons versus Protons for most all observable elements and isotopes falls above a line for which Neutrons and Protons are equal in number (see Fig. 12 and http://wiki.chemeddl.org/index.php/19.3_Nuclear_Stability **). ^{3}Helium is the only stable nucleus where Z > N. However, too many Neutrons also leads to nuclear instability. Beyond ^{209}Bismuth, all elements and isotopes are unstable – decaying via Gamma and particle emissions. The addition of Protons (or Beta emission) thus transmutes any element to another, perhaps unstable, but of higher Z. The addition of Neutrons creates elemental isotopes, some or all of which are unstable, leading to decay either down in Z by 2 (Alpha emission), up in Z by 1 (Beta), or even by fission. Electron capture or Positron emission are also possible, moving Z down by 1. There could be a Z=0 element (Neutronium), if lone Neutrons were stable.

Nucleon: A Neutron or Proton. A nucleus (nuclide) contains nucleons.

ORNL: Oak Ridge National Labs. A DoE facility, formerly under the AEC. Home to reactor research from the Manhattan Project to today, including MSR development and operation from 1954-1974[3,4] -- www.ornl.gov .

Poison (Neutron): Boron, Xenon, Hafnium and many Lanthanides have such significant cross sections for Neutron capture that their presence within a reactor core/fuel can seriously reduce fission rates (e.g., for Xenon, see Roggenkamp). In a solid-fuelled reactor, this is one reason why fuel pellets must periodically be removed and reprocessed or discarded external to the reactor. In liquid-fuelled reactors, Neutron-hungry gasses like Xenon simply bubble out continuously, while liquid poisons are chemically processed out, possibly on a continuous basis within the reactor's own containment. Poisons, however, are useful for reactor control (e.g., as in control rods). See also Reprocessing.

Power Density: The number of Watts available from any energy source, divided by the amount (mass, area or volume) of that source needed to generate that power (e.g., the power density of sunlight at Earth orbit is 1366W/m^2).

Protactinium: The element ($_{91}$Pa) between Thorium and Uranium. It Beta decays to ^{233}Uranium with a 27-day half life. This is one path to breed ^{233}U from ^{232}Th, because Neutron capture by Thorium creates ^{233}Th, which Beta decays to ^{233}Pa with a 22-minute half life. Essentially, this adds 2 Protons to a Thorium nucleus in 2 steps[1,3,4]. Pa creation within solid or liquid fuel influences Neutron behavior and so is dealt with in variety of ways by reactor designers[8]. See also Reprocessing.

Proton: A fundamental nuclear particle with electric charge +1, equal but opposite that of an Electron. Protons are apparently stable for at least the life of the universe, being created about 1 micro-second after the Big Bang. They constitute most of the Solar-Wind and Cosmic-Ray particles reaching Earth's atmosphere.

PWR: See LWR.

Radiation (Nuclear): Energetic particles or electromagnetic waves produced as naturally-decaying atoms reduce their internal energy. Basic types are: Alpha, Beta, Gamma, Neutrons and fission products. Each type has characteristic properties and safe exposure levels (see Gamma Ray & Sievert).

Reactor (Nuclear-Fission): A structure capable of encouraging and containing localized fissioning of fissile elements (e.g., ^{235}U) continuously and controllably, so that heat can be efficiently extracted from the kinetic and radiative energy released by each fissioning nucleus in the fuel. See also Breeder.

Reflector (Neutron): Any reasonably moderating material thick enough to slow impinging Neutrons so they generally assume random internal paths

and diffuse back toward their source. Such a reflector can help maintain a reactor's Neutron economy.

Reprocessing: For typical LWRs, solid-fuel assemblies cannot remain in a reactor core for more than about 5 years, due to trapped fission-product buildup, stress cracking and other damage. Some fission products (e.g., Xenon) 'poison' the fission rate by easily absorbing Neutrons. The convention is to remove ~1/3 the fuel assemblies from such a core every 18 months or so, replacing them with new ones. The used (spent) assemblies still contain about 1/2 their original fissile load, but are either stored forever as waste (in the US), or torn apart (in France) and separated chemically into potential new fuel or salable isotopes and long-term wastes (e.g., heavier Actinides and physical reactor components). A few elements, such as ^{85}Krypton, are simply vented to the air because they are biologically inert, with safe daughters, despite being radioactive.

For liquid-fuelled reactors, like the MSR, any products of value or waste bubble out (e.g., Xenon and Krypton), or can be fluorinated continuously out of the melt as gasses. Still others can be chemically separated in batch or continuous procedures at the reactor, within its containment. Continuous operation means the typical liquid-fuel design can run until all originally-loaded fissiles are consumed. Those could have been weapons or waste material, with the reactor's power level maintained via breeding (e.g., via Thorium), as the undesired fissiles were destroyed.

Seed: A special portion of a reactor's core into which highly fissile fuel is loaded. Such Seeds may be surrounded by, or even contain, fertile materials, so that breeding of new fuel can occur while the reactor operates – see Blanket. Multiple Seed-Blanket structures may be stacked into a core to meet the desired power output and breeding capacity[1, 6].

Spallation: (Nuclear) a particle accelerator may produce a beam of Fast Neutrons via impacts of its own beam particles (e.g., Protons) on heavy-nuclei (Z>50) targets (e.g., Mercury, Tantalum...). Smaller nuclei plus the emission of several Neutrons occur for each such impact.
http://en.wikipedia.org/wiki/Spallation

Spent Fuel: Reactor fuel, typically solid, that can no longer be used efficiently because of internal fission-product buildup. Another term is "used fuel" and, for LWRs, it contains about ¼ its original ^{235}U enrichment:
www.energyfromthorium.com/javaws/SpentFuelExplorer.jnlp

SQ: Significant Quantity an amount (~8kg) of pure fissile material (e.g. Uranium or Plutonium) sufficient for a minimal nuclear weapon.

Thermal Neutron: A Neutron moving about 2km/s (~1 mi/s or <1eV), rather than thousands of miles per second, as "Fast" Neutrons (directly from fission/fusion reactions) do. There are some speed categories: "Slow" Neutrons fly about 20 times faster than Thermal. Between Slow and Fast is "Epi-Thermal". Fast Neutrons are un-moderated and can fission most nuclei.

Thermal Neutrons have good probabilities of causing fissile nuclei to fission. See also Moderator.

Thorium: Element 90 (Z=90), whose natural mass A is 232 (90 Protons, 142 Neutrons). It is mildly radioactive, as discovered by Schmidt and Curie, decaying via Alpha emission to Radium then, via other daughters, to Lead. ^{232}Th has a half-life of over 14 billion years, about the age of the known universe. It is about 4 times as abundant as Uranium (on Earth, Moon & Mars) and often occurs in rare-earth ores. Thorium is considered a mining waste product. Its slow decay is now responsible for about 60% of the heat maintaining Earth's core molten. The picture# below shows ~200 grams of Thorium – enough to breed, within a reactor, fissile fuel (and thus energy) sufficient to run a person's entire life…

Transuranics: Actinides heavier than Uranium (Neptunium…), which are all radioactive, typically with long half lives and so to be avoided as components of reactor wastes. They pose the largest problem for current LWRs -- waste storage to be safe for millennia. Use of Thorium reactors to breed and fission ^{233}U avoids most of these wastes. Fast Breeders serve similar purposes via transuranic destruction.

Uranium: Element 92 (Z=92). As mined, Uranium is typically in its solid, oxidized state – UO_2 or U_3O_8 or as a silicate. Three isotopes are found in nature, ^{238}U (99.3 %), ^{235}U (0.711%), and ^{234}U (5.7x10-3%). It is naturally radioactive, Alpha decaying to ^{234}Th, then Beta decaying back to ^{234}U, which decays to ^{230}Th and eventually to Lead. ^{238}U can be bred to Plutonium (^{239}Pu) via Thermal Neutrons, whereupon further Neutrons can induce fission (for power or weapons). ^{235}U, however, is the fuel for typical fission reactors and weapons, since it fissions about 80% of the time in Thermal Neutron flux, producing more Neutrons that can establish a chain reaction. Unfortunately, despite being many more times abundant than Silver or Gold, Uranium ore is less than 1% fissile ^{235}U, so extreme measures are taken (fluorination and gas diffusion or centrifugation) to enrich ^{235}U's concentration up to about 4% (for useful reactor fuel). The desired result is called "enriched" Uranium. The leftover is "depleted" Uranium and stored as vast amounts of Uranium Hexafluoride (UF_6) waste. Cheaper laser enrichment is in development(11), but constitutes a proliferation risk.

Other Uranium isotopes have usefulness: ^{232}U, ^{233}U, ^{234}U, etc. Of these, ^{233}U is excellent for power production, having a 90% fission probability upon a Thermal-Neutron strike. Unlike other Uranium isotopes, it's superior across the Thermal-to-Fast Neutron spectrum, thus supporting a variety of reactor designs. However, its 160,000-year half life means it's no longer found in nature. It is, however, exactly what ^{232}Th can be bred to -- again via Thermal Neutrons within a reactor. Along with ^{233}U production via Neutron transmutation of Thorium, a very small amount of ^{232}U is created (via rare parasitic reactions). ^{232}U's half life of ~72 years, decaying to very strong Gamma emitters, means that ^{233}U breeders produce tainted fuel that is difficult to divert and weaponize.

The picture below shows a ~2-billion-year-old, natural Uranium reactor, moderated cyclically by rain/ground water to criticality so long ago because of ^{235}U's ~700-million-year half life – there was much more of that fissile then:

The natural reactor consumed its fissile isotope and left the typical Uranium-fission products. Thus these sites (more than one) allow us now to estimate the movement of long-lived (e.g., transuranic) products in rock and groundwater, over many millennia. Estimates from these Gabon sites show little waste migration.

Uranium Hexafluoride (UF_6): The only gaseous uranium compound at almost room temperature. Thus, it's the only compound that may used for Uranium enrichment by laser, gaseous diffusion or centrifugation. Since ^{235}U is the desired fissile, but below 1% in ore, Uranium oxide is converted to UF_6. for ease of isotopic separation. The separation waste is depleted in ^{235}U, in relation to original ore. Thus, a large amount of waste UF_6 is stored in gas canisters around the US (Fig. 15 inset), having no use in conventional LWR fuels. It does have use for military projectiles needing high densities, and it likely has use in Fast and advanced reactors, such as LMFBR and LFTR, which can fission ^{238}U and/or breed it to fissiles ^{239}Pu or ^{241}Pu.

WGP: Weapons-grade Plutonium.

WANO: World Association of Nuclear Operators (www.wano.info/).

WNA: World Nuclear Association (www.world-nuclear.org).

Z: The atomic number -- the count of Protons in any nucleus (e.g., horizontal axis in Figure 12).

Zircaloy: A Zirconium alloy developed for containing Uranium fuel pellets in LWRs. It was used in the first civilian LWRs, including Shippingport[3].

9. Health *(in progress)*

www.neimagazine.com/story.asp?storyCode=2061350

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http://lowdose.energy.gov/radiobio_slideshow.aspx

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