Uranium vs Thorium for Power Production—an Overview

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Definitions and Background Information

- A nucleus has an *atomic number* and a *mass number*.
- The *atomic number* (number of protons) determines the *element*; e.g., 90, 92, and 94 are the atomic numbers of thorium, uranium, and plutonium, respectively.
- The *mass number* is the number of *nucleons* (protons plus neutrons) in the nucleus.
- For a given element, the number of neutrons determines the *isotope*; e.g., the two main isotopes of uranium (U-238 and U-235) have 146 and 143 neutrons, respectively (238 and 235 being the mass numbers).
- Heavy-metal nuclei ("actinides" – thorium and above) are either *fissile* (the ones with odd mass numbers) or *fertile* (even mass numbers).
- A *fissile* nucleus has a good probability of *fissioning* (splitting into two lighter nuclei) when struck by a neutron of any energy; but sometimes it just absorbs the neutron and is transmuted into a fertile nucleus.
- A *fertile* nucleus is transmuted into a fissile nucleus upon absorbing one neutron. However, fertile nuclei are said to be *fissionable*, since they sometimes fission if struck by a fast neutron.
- The most important fissile nuclei are U-233, U-235, Pu-239, and Pu-241.
- The most important fertile nuclei are Th-232 (becomes U-233 after absorbing a neutron), U-238 (becomes Pu-239), and Pu-240 (becomes Pu-241).
- A *thermal reactor* is one whose neutrons are *moderated* (slowed down) to improve their chances of causing fissions in the fissile isotopes. Most of the thermal reactors use water (heavy or light) as the moderator, but some use carbon.
- In a *fast reactor*, the neutrons remain fast—i.e., the coolant is a non-moderating fluid.
- Each type of reactor needs a certain minimum fissile enrichment in order to function (achieve and maintain *criticality*).
- Each type of reactor also has a minimum fissile *loading* (amount of fissile per GWe of capacity).
- Today's reactors are almost exclusively Gen-II (Generation 2) or Gen-III *thermal* reactors. Most of them are fueled with low-enrichment uranium (~4% U-235) and cooled and *moderated* (moderation slows the neutrons) by light water, but some (CANDUs) use heavy water and natural uranium (which is 0.7% U-235).
- Today's thermal reactors use less than 1% of the energy in the mined uranium, and cannot exceed 1% even when the plutonium is recycled, as is done by the French.
- To get almost all the energy out of the mined uranium, a *fast* reactor (whose neutrons are unmoderated) must be used, not a thermal or epithermal reactor (one in which the energy of the neutrons is reduced considerably, but not all the way down to thermal levels).
- With fast reactors, enough uranium has already been mined to power the world for several centuries.

Facts about Uranium and Thorium

- There's enough uranium ***or*** thorium to power civilization for as long as it lasts.
- There are designs for passively safe reactors using either thorium fuel ***or*** uranium fuel.
- For now, most of the reactors built in the next decade or two will be today's types of thermal reactors, which are water-moderated and uranium-fueled.
- However, Gen-IV reactors are being actively developed in several countries—notably India, China, South Korea, Japan, and France (but not in the United States, which abdicated its leadership in that area in 1994 with the aborting of the eminently successful IFR development program).
- Various types of thorium-based reactors are being discussed currently, with no consensus yet in the thorium community regarding which types are the best ones to pursue.
- Thorium enthusiasts usually cite the advantages that their reactor concept offers *over today's thermal reactors*. The problem there is that theirs is really a Gen-IV (or Gen-V) reactor, whose competition will not be today's variety of thermal reactors. There's at least one uranium-based Gen-IV concept that offers very similar improvements, whose existence the thorium community rarely acknowledges voluntarily.
- The Gen-IV concept that is closest to commercialization is the uranium-based IFR (Integral Fast Reactor). It's embodied in General Electric Hitachi's PRISM proposal, and the company is ready to build a commercial demonstration plant if given the go-ahead.
- The thorium-based reactor concept that seems to attract the most enthusiastic support is the LFTR (Liquid Fluoride Thorium Reactor).
- In 2002, a 242-person DOE task force ranked the Argonne-developed IFR (referred to as "Na Metal Pyro") the most promising, overall, of 19 next-generation (Gen-IV) reactor concepts. Of the other concept categories, the closest to the LFTR was the "molten-salt cooled" reactor (MSR), which ranked sixth.
- The LFTR's state of maturity is about where the IFR's was in the 1970s—a promising concept with some significant technological questions to be answered before commercialization can be considered. Nevertheless, this essay will proceed as though the LFTR's state of development is comparable with the IFR's—i.e., *the technical challenges still to be encountered in commercializing the LFTR are assumed to have been satisfactorily resolved, so that LFTRs perform as predicted by their supporters.*

LFTR Claims, the IFR, and Related Facts

Thorium-fueled reactors are viable energy producers, destined, it seems likely, to be part of the next-generation mix of reactor types in some countries (India for one). In comparing thorium and uranium as reactor fuels, however, the promoters of thorium-based reactors almost always emphasize their potential advantages with respect to today's Generation-II and -III (uranium-fueled) thermal reactors. *But that is not a relevant comparison,* because, by the time a thorium cycle has been developed to commercial readiness, the main competition will not be from Gen-III, but from Gen-IV—primarily uranium-fueled—*fast* reactors.

At least one revolutionary, uranium-based Gen-IV reactor (the IFR) is now ready for commercial demonstration, and its closed fuel cycle has virtually all the advantages *over Gen-III* that are claimed for the thorium cycle:

- passive safety
- waste minimization
- resource utilization
- sustainability
- cost of fuel
- proliferation resistance

Passive Safety

- **Claim**: LFTRs have a number of design features and physical properties that make them exceptionally immune to accidents that could cause dangerous radioactivity to be dispersed off-site. One of those features is the fact that the LFTR's coolant is not pressurized, so there can be no "blowdown" if a pipe breaks.

  Fact: That's true. And the same can be said of the IFR (its coolant too runs at atmospheric pressure).

  Fact: However, in terms of public health, the safety record of civilian nuclear power is already better than that of any other heavy industry, and further improvement in accident resistance is icing on the cake.

Waste Minimization

- **Claim**: Because the LFTR does not use U-238 for its fertile isotope, its used fuel does not contain appreciable amounts of the long-lived transuranics (an advantage with respect to LWRs).

  Fact: True. And the IFR has the same advantage: although it does use U-238, it consumes the long-lived transuranics that are produced.

- **Claim**: LFTRs can consume the long-lived transuranics that are left in the used fuel from today's thermal reactors, thereby greatly simplifying the task of managing the long-term waste.

Fact: True—and the same can be said of the IFR.

Fact: While LFTRs would consume the bulk of the plutonium in the used thermal-reactor fuel, they would not use very much of the uranium that's left (some 94% of the fuel's original uranium remains). That left-over uranium, plus about ten times as much depleted uranium, would be treated as radioactive waste (although its activity would be quite low).

Fact: That already-mined uranium could fuel a global fleet of IFRs for the better part of a millennium, and such a fleet could grow exponentially for as long as the energy demand was growing.

Resource Utilization

- **Claim**: The LFTR consumes almost 100% of its thorium fuel (an advantage with respect to LWRs).

  Fact: True. Similarly, the IFR consumes almost 100 percent of its uranium-plus-plutonium fuel.

  Fact: With IFRs, when all the plutonium from used thermal-reactor fuel has been recycled, the remaining uranium from that fuel plus the depleted uranium left over from the enrichment process can continue powering the globe for centuries.

Sustainability

- **Claim**: Once a LFTR has been fueled (with its initial loading of Th-232 plus the needed fissile (probably Pu from the weapons inventory or from used thermal-reactor fuel), it will generate its own replacement fissile (U-233). Only one tonne of thorium per GWe-year will be needed to keep the reactor running indefinitely.

  Fact: True. Similarly, once an IFR has been fueled with its initial loading of uranium plus the needed fissile (probably Pu from the weapons inventory or from used thermal-reactor fuel), it will generate its own replacement fissile (Pu239, mainly), needing only one tonne of uranium per GWe-year to keep the reactor running indefinitely.

  Furthermore:

  Fact: IFRs can be configured to have a breeding ratio as high as 1.5 or more, leading to self-sustained doubling times of 15 years or less.

  Fact: The LFTR people do not claim a breeding ratio significantly greater than unity, which means that the growth of a LFTR fleet (and of nuclear power in general) would be seriously constrained once all of the easily available fissile had been committed, unless a prolific source of new fissile had come into play. (The self-sustained doubling time for a fleet of LFTRs is essentially infinite.)

- **Claim**: The fissile inventory needed to prime (start up) one IFR could prime five or more LFTRs with the same generating capacity.

  Fact: That is true. However:

Fact: There will be enough fissile plutonium to prime all the IFRs ***or*** LFTRs that will be needed in the next 4 or 5 decades.

Fact: However, if we were to dispose of the used thermal-reactor fuel permanently, that would (a) guarantee the continued operation and expansion of enrichment facilities and uranium mining, and also (b) seriously limit the expansion rate of nuclear power by severely restricting the number of advanced reactors—LFTRs *or* IFRs—that could be deployed.

Fact: The larger fissile inventory in an IFR is an advantage when, as currently in the U.K., the desire is to sequester existing plutonium inventory as quickly as possible.

- **Claim**: There is enough accessible thorium in the world that LFTRs could power civilization for as long as it lasts.

  Fact: True, but with the caveat that the sources of readily available fissile material must remain adequate to seed the needed growth in capacity. And the same claim is true of IFRs—but without the caveat.

- **Claim**: After the available plutonium runs out, new LFTRs could be primed with uranium enriched to approximately 20% U-235 (80% U-238).

  Fact: True, in principle. However, this approach has a number of problems, as follows:

  Fact: These starting-up reactors would produce transuranics (plutonium and up) until all the U-238 in the enriched uranium had been transmuted to plutonium and fissioned (replaced by Th-232).

  Fact: Therefore startup uranium with a much higher enrichment would be desirable, but uranium enriched to more than 20% is currently ruled out because it is considered a proliferation hazard.

  Fact: Enriching to 20% leaves behind some 97% of the mined uranium atoms as depleted uranium (DU), which is useless as a LFTR fuel (but is a good makeup fuel for IFRs).

  Fact: Possession of enrichment facilities provides a nation with an easy path to fission weapons. A fleet of IFRs could grow indefinitely with never any need for enriched uranium, so that a nation that only had IFRs would have no legitimate need for an enrichment capability.

- **Claim**: With LFTRs there would be no need for enriched uranium as long as there's a supply of plutonium from used fuel from thermal reactors.

  Fact: True. However, once that supply was gone (some decades hence), further expansion of nuclear power—LFTR ***or*** IFR—would be stymied without a source of fresh fissile material that is acceptable economically, environmentally, and proliferation-wise.

  Fact: To expect that source to be uranium is arguably unrealistic, since a lot of uranium would have to be mined (~30 tons of natural uranium for every ton of U-235). But—and this is important—a large enrichment capacity would have to be resuscitated, with its proliferation implications.

Fact: With IFRs, no enrichment of uranium would ever again be needed.

Cost of Fuel

- **Claim**: Thorium is produced in abundance as a waste product from the mining of rare-earth metals, and so the raw thorium would be essentially free for the indefinite future.

  Fact: True. Similarly, the IFR's fertile material (from used LWR fuel for a number of decades, followed by existing depleted uranium for the next few centuries) will also be essentially free for the better part of a millennium, and after that only one tonne of uranium per year per GWe of capacity would have to be procured. (For an LWR it's closer to 150 tonnes per GWe-yr.)

  Fact: An operating IFR should function equally well if adapted to be refueled with thorium instead of uranium, so a commitment to IFRs would not rule out eventual conversion to a thorium/U-233 cycle if that should ever become economically or otherwise desirable.

Proliferation Resistance

- **Claim**: LFTRs are proliferation resistant because the fissile U-233 in them is too contaminated with U-232.

  Fact: That's very misleading—and not all LFTR supporters make the claim. Pure U-233 is an excellent material for bombs, and it can be produced by chemically separating from the LFTR fuel some of the intermediate Pa-233 (27-day half-life) before it decays into U-233.

- **Claim**: But the reactor cannot spare that U-233, because it is needed to keep the fission chain reaction going.

  Fact: The extracted U-233 can be replaced with poor-quality Pu-239 from used LWR fuel—after all, that's what was probably used as the fissile material for starting up the LFTR in the first place. Thus a LFTR can be a good device for converting lousy Pu into good-quality U-233 for bombs.

- **Claim**: The LFTR eliminates the need for aqueous reprocessing (such as PUREX), which is required if plutonium bombs are to be made.

  Fact: True. And so does the IFR.

  Fact: In addition, the IFR also permanently eliminates the need for U enrichment, which is the path to U-235 bombs.

  Fact: To achieve anything near their maximum fuel-use efficiency, both IFR and LFTR have to have their fuel processed regularly to remove the fission products.

- **<u>Claim</u>**: An IFR can make good-quality Pu-239 by being run with some special U-238 fuel elements.

  <u>Fact</u>: True. *Any* <u>unsafeguarded</u> reactor can be adapted to do that, including a LFTR.

  <u>Fact</u>: In normal operation *with international safeguards,* neither fuel cycle ever contains bomb-usable uranium or plutonium.

  <u>Fact</u>: As mentioned above, Pa-233 can be chemically extracted from a LFTR's molten fuel—and in some of the proposed thorium cycles that would be routinely done. Pa-233 decays with a 27-day half-life into pure U-233 (an excellent bomb material, as mentioned above).

  <u>Conclusion</u>: The LFTR has no meaningful proliferation-related advantage over the IFR: both would have to be subject to international inspection to assure that they were not being diverted for weapons production.

SUMMARY

Provided the LFTR works as expected, in almost every case the comparison with IFR comes out a wash. Relevant to energy policy, therefore, the question is whether commercial demonstration of a technology that is ready now (the IFR) should be delayed for two decades or more while waiting for R&D to bring to maturity a technology (such as the LFTR) that might have some advantages that cannot be more than marginal in any event—keeping in mind that R&D can proceed regardless, and new technology can always be deployed when commercially ready. The most important differences between the two systems discussed here are (a) the degree of readiness for commercialization, (b) the fissile inventory needed, and (c) the potential breeding rate.

In category (a), currently the advantage is clearly with the IFR, since construction of a commercial demonstration could start tomorrow. Meanwhile, R&D on advanced thorium systems can continue, on the way to seeing whether there are applications where thorium has an economic advantage over uranium.

Assuming equal readiness for commercialization, considerations in categories (b) and (c) favor one system or the other, depending on circumstances. A large fissile inventory in the plant is an advantage for segregating a lot of plutonium in a hurry (advantage IFR), but it's a disadvantage if extremely rapid *early* growth of nuclear energy is wanted (advantage LFTR).

However, if the lion's share of global energy by the end of the century is to be supplied by nuclear power, the IFR can grow into that in an orderly manner, whereas deployment of a large number of LFTRs would preempt the readily available fissile material, putting serious constraints on continued growth of nuclear energy after mid-century.