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The Liquid Fluoride Thorium Paradigm

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This is a guest post by Charles Barton. Charles is a retired counselor who writes the Energy from Thorium blog. His father Dr. Charles Barton, Senior, worked at Oak Ridge National Laboratory for 28 years. He was a reactor chemist, who worked on the Liquid-Fluoride Thorium Reactor (LFTR) concept for about 2/3 of his ORNL career. Charles Barton, Junior gained his knowledge of the LFTR concept from his familiarity with his father's work. Neither his father nor Mr. Barton will gain financially from the advancement of this idea.

The Liquid Fluoride Thorium Paradigm

Excitement has recently been rising about the possibility of using thorium as a low-carbon way of generating vast amounts of electricity. The use of thorium as a nuclear fuel was extensively studied by Oak Ridge National Laboratory between 1950 and 1976, but was dropped, because unlike uranium-fueled Light Water Reactors (LWRs), it could not generate weapons' grade plutonium. Research on the possible use of thorium as a nuclear fuel has continued around the world since then. Famed Climate Scientist James Hanson, recently spoke of thorium's great promise in material that he submitted to President Elect Obama:

> The Liquid-Fluoride Thorium Reactor (LFTR) is a thorium reactor concept that uses a chemically-stable fluoride salt for the medium in which nuclear reactions take place. This fuel form yields flexibility of operation and eliminates the need to fabricate fuel elements. This feature solves most concerns that have prevented thorium from being used in solid-fueled reactors. The fluid fuel in LFTR is also easy to process and to separate useful fission products, both stable and radioactive. LFTR also has the potential to destroy existing nuclear waste.

> (The) LFTR(s) operate at low pressure and high temperatures, unlike today's LWRs. Operation at low pressures alleviates much of the accident risk with LWR. Higher temperatures enable more of the reactor heat to be converted to electricity (50% in LFTR vs 35% in LWR). (The) LFTR (has) the potential to be air-cooled and to use waste heat for desalinating water.
>
> LFTR(s) are 100-300 times more fuel efficient than LWRs. In addition to solving the nuclear waste problem, they can operate for several centuries using only uranium and thorium that has already been mined. Thus they eliminate the criticism that mining for

nuclear fuel will use fossil fuels and add to the greenhouse effect.

The Obama campaign, properly in my opinion, opposed the Yucca Mountain nuclear repository. Indeed, there is a far more effective way to use the $25 billion collected from utilities over the past 40 years to deal with waste disposal. This fund should be used to develop fast reactors that consume nuclear waste, and thorium reactors to prevent the creation of new long-lived nuclear waste. By law the federal government must take responsibility for existing spent nuclear fuel, so inaction is not an option. Accelerated development of fast and thorium reactors will allow the US to fulfill its obligations to dispose of the nuclear waste, and open up a source of carbon-free energy that can last centuries, even millennia.

It is commonly assumed that 4th generation nuclear power will not be ready before 2030. That is a safe assumption under "business-as-usual". However, given high priority it is likely that it could be available sooner. It is specious to argue that R&D on 4th generation nuclear power does not deserve support because energy efficiency and renewable energies may be able to satisfy all United States electrical energy needs. Who stands ready to ensure that energy needs of China and India will be entirely met by efficiency and renewables?

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Development of the first large 4 generation nuclear plants may proceed most rapidly if carried out in China or India (or South Korea, which has a significant R&D program), with the full technical cooperation of the United States and/or Europe. Such cooperation would make it much easier to achieve agreements for reducing greenhouse gases.

Uranium-235 is the only fissionable material that is observed in usable amounts in nature. Thus pioneering nuclear physicist like Enrico Fermi and Eugene Wigner had no other choice of but to use U-235 to create their first chain reaction under the bleachers of the University of Chicago's unused football field.

But Fermi and Wigner knew early on that once a reactor was built, it was possible to create other fissionable substances with the excess neutrons produced by a U-235 chain reaction. Thus if U-238 absorbed a neutron, it became the unstable U-239, which through a two stage nuclear process was transformed into plutonium-239. Plutonium-239 is very fissionable. The physicists also calculated that if thorium-232 was placed inside a reactor and bombarded with neutrons, it would be transformed into U-233. Their calculations also revealed that U-233 was not only fissionable, but had properties that made it in some respects a superior reactor fuel to U-235 and Pu-239.

During World War II, Fermi and Wigner, who were geniuses with active and far ranging minds, collected around themselves a group of brilliant scientists. Fermi, Wigner and their associates began to think about the potential uses of the new energy they were discovering--uses that would improve society rather than destroy it.

The capture of nuclear energy and its transformation into electrical energy became a central focus of discussions among early atomic scientists. They were not sure how long the uranium supply would last, so Fermi proposed that reactors be built that would breed plutonium from U-238. Wigner counted that thorium was several times as plentiful as uranium, and that it could produce an even better nuclear fuel than Pu-239.

The first nuclear era was dominated by uranium technology, a technology that was derived from military applications, and carried with it, rightly or wrongly, the taint of association with nuclear weapons. As it turned out, there was far more uranium available than Fermi or Wigner had originally feared, but other rationales propelled scientific interest in developing thorium fuel cycle reactors. First, Pu-239 was not a good fuel for most reactors. It failed to fission 1/3 of the time when it absorbed a neutron in a conventional Light Water Reactor (LWR). This led to the most difficult part of the problem of nuclear waste. Plutonium made excellent fuel for fast neutron reactors, but the fast neutron reactor that Fermi liked used dangerous liquid sodium as its coolant, and would pose a developmental challenge of enormous proportions.

Advocates of the thorium fuel cycle point to its numerous advantages over the uranium-plutonium fuel cycle. B.D. Kuz'minov, and V.N. Manokhin, of the Russian Federation State Science Centre, Institute of Physics and Power Engineering at Obninsk, write:

> Adoption of the thorium fuel cycle would offer the following advantages:
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> - Increased nuclear fuel resources thanks to the production of 233U from 232Th;
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> - Significant reduction in demand for the enriched isotope 235U;
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> - Very low (compared with the uranium-plutonium fuel cycle) production of long-lived radiotoxic wastes, including transuraniums, plutonium and transplutoniums;
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> - Possibility of accelerating the burnup of plutonium without the need for recycling, i.e. rapid reduction of existing plutonium stocks;
>
> - Higher fuel burnup than in the uranium-plutonium cycle;
>
> - Low excess reactivity of the core with thorium-based fuel, and more favourable temperature and void reactivity coefficients; . . .

Thorium could replace U-238 in conventional LWRs, and could be used to breed new nuclear fuel in specially modified LWRs. This technology was successfully tested in the Shippingport reactor during the late 1970's and early 1980's.

WASH-1097 remains a good source of information on the thorium fuel cycle. In fact, some major recent studies of the thorium fuel cycle rely heavily on WASH-1097. A recent IAEA report on Thorium appears to have been prepared without overt reliance on WASH-1097.

One of the first things physicists discovered about chain reactions was that slowing the neutrons involved in the process down, promoted the chain reaction. Kirk Sorensen discusses slow or thermal neutrons in one of his early posts.

Under low energy neutron conditions, Th232 can be efficiently converted to U233. The conversion process works like this. Th232 absorbs a neutron and emits a beta ray. A neutron switches to being a proton and the atom is transformed into Protactinium 233. After a period averaging a little less than a month, Pa 233 emits a second beta ray and is transformed into U233. U233 is fissionable, and is a very good reactor fuel. When a U233 atom encounters a low energy neutron, chances are 9 out of 10 that it will fission.

Since U233 produces an average of 2.4 neutrons every time it fissions, this means that each neutron that strikes U233 produces an average of 2.16 new neutrons. If you carefully control those neutrons, one neutron will continue the chain reaction. That leaves an average of 1.16 neutrons to generate new fuel.

Unfortunately the fuel generation process cannot work with 100% efficiency. The leftover U-234 that was produced when U-233 absorbed a neutron and did not fission will sometimes absorb another neutron and become U-235. Xenon-135, an isotope that that is often produced after U-233 splits, is far more likely to capture neutrons than U233 or Th232. This makes Xenon-135 a fission poison. Because Xenon in a reactor builds up during a chain reaction, it tends to slow the nuclear process as the chain reaction continues. The presence of Xenon creates a control problem inside a reactor. Xenon also steals neutrons needed for the generation of new fuel.

In conventional reactors that use solid fuel, Xenon is trapped inside the fuel, but in a fluid fuel Xenon is easy to remove because it is what is called a noble gas. A noble gas does not bond chemically with other substances, and can be bubbled out of fluids where it has been trapped. Getting Xenon 135 out of a reactor core makes generating new U233 from Th232 a whole lot easier.

It is possible to bring about 1.08 neutrons into the thorium change process for every U-233 atom that splits. This means that reactors that use a thorium fuel cycle are not going to produce an excess of U-233, but if carefully designed, they can produce enough U233 that burnt U233 can be easily replaced. Thus a well designed thorium cycle reactor will generate its own fuel indefinitely.

Research continues on a thorium cycle LWR fuel that would allow for the breeding of thorium in LWRs. There is however a problem which makes the LWR a less than ideal breeding environment for thorium. Elisabeth Huffer, Hervé Nifenecker, and Sylvain David note:

> Fission products are much more efficient in poisoning slow neutron reactors than fast neutron reactors. Thus, to maintain a low doubling time, neutron capture in the fission products and other elements of the structure and coolant have to be minimized.

India has only a small uranium supply, but an enormous thorium reserve. Millions of tons of thorium ore lie on the surface of Indian beaches, waiting to be scooped up by front loaders and hauled away to potential thorium reactors for a song. (For those of you who are interested in the EROEI concept, the EROEI for the recovery of thorium from Indian beaches would be almost unbelievably high, and the energy extracted could power the Indian economy for thousands of years, potentially making India the richest nation in the world.)

India has for 50 years been following a plan to gradually switch from uranium to thorium cycle reactors. That plan is expected to finally come to fruition by the end of the next decade. At that point India will begin the rapid construction of a fleet of thorium fuel cycle reactors.

A commercial business, Thorium Power, Limited, continues research based on the Shippingport Reactor experiment. Thorium Power plans to offer a thorium cycle based nuclear fuel with a starting charge of enriched U-235 for modified LWRs. Thorium Power has sponsored Throium fuel research at the Kurchatov Institute in Moscow, and a Russian VVER has been used to conduct thorium cycle fuel experiments.

Research on thorium cycle liquid fuel reactors is ongoing world-wide. The best-known effort is being performed in Grenoble, France at the Laboratoire de Physique Subatomique et de

Cosmologie. The Reactor Physics Group there is the only one in the world that has the resources and backing needed to actually develop a fluid core thorium cycle reactor that can be commercialized. In terms of organization size, the Thorium Molten Salt Reactor research group is much smaller than would be required to sustain a full-scale rapid development of thorium cycle reactor technology. The LPSC group thus is working in a business as usual time frame, and has no urgent motivation to do otherwise. After all, 80% of French electricity already comes from nuclear power plants.

Thorium fuel cycle research is also being carried on in the Netherlands, Japan, the Czech Republic. There is also presently a small-scale effort in the United States.

Thorium is extremely abundant in the earth's crust, which appears to contain somewhere around 120 trillion tons of it. In addition to 12% thorium monazite sands, found on Indian beaches and in other places, economically recoverable thorium is found virtually everywhere. For example, large-scale recovery of thorium from granite rocks is economically feasible with a very favorable EROEI. Significant recoverable amounts of thorium are present in mine tailings. These include the tailings of ancient tin mines, rare earth mine tailings, phosphate mine tailings and uranium mine tailings. In addition to the thorium present in mine tailings and in surface monazite sands, burning coal at the average 1000 MWe power plant produces about 13 tons of thorium per year. That thorium is recoverable from the power plant's waste ash pile.

One ton of thorium will produce nearly 1 GW of electricity for a year in an efficient thorium cycle reactor. Thus current coal energy technology throws away over 10 times the energy it produces as electricity. This is not the result of poor thermodynamic efficiency; it is the result of a failure to recognize and use the energy value of thorium. The amount of thorium present in surface mining coal waste is enormous and would provide all the power human society needs for thousands of years, without resorting to any special mining for thorium, or the use of any other form or energy recovery.

Little attention is paid to the presence of thorium in mine tailings. In fact it would largely be passed over in silence except that radioactive gases from thorium are a health hazard for miners and ore processing workers.

Thorium is present in phosphate fertilizers because fertilizer manufactures do not wish to pay the recovery price prior to distribution. Gypsum present in phosphate tailings is unusable in construction because of the presence of radioactive gasses associated with the thorium that is also present in the gypsum. Finally organic farmers use phosphate tailings to enrich their soil. This has the unfortunate side effect of releasing thorium into surface and subsurface waters, as well as leading to the potential contamination of organic crops with thorium and its various radioactive daughter products. Thus the waste of thorium present in phosphate tailings has environmental consequences.

The world's real thorium reserve is enormous, but also hugely underestimated. For example the USGS reports that the United States has a thorium reserve of 160,000 tons, with another 300,000 tons of possible thorium reserve. But Alex Gabbard estimates a reserve of over 300,000 tons of recoverable thorium in coal ash associated with power production in the United States alone.

In 1969, WASH-1097 noted a report that had presented to President Johnson that estimated the United States thorium reserve at 3 billion tons that could be recovered for the price of $500 a pound – perhaps $3000 today. Lest this sound like an enormous amount of money to pay for thorium, consider that one pound of thorium contains the energy equivalent of 20 tons of coal, which would sell on the spot market for in mid-January for around $1500. The price of coal has been somewhat depressed by the economic down turn. Last year coal sold on the spot market for as much as $300 a ton, yielding a price for 20 tons of coal of $6000. How long would 3 billion tons last the United States? If all of the energy used in the United States were derived from thorium for the next two million years, there would be still several hundred thousand years of thorium left that could be recovered for the equivalent of $3000 a pound in January 2009 dollars.

Nor would exhausting the USAEC's 1969 estimated thorium reserve exhaust the American thorium supply. Even at average concentrations in the earth's rocks, thorium can be recovered with a good EROEI, without making the cost of electricity impossibly expensive.