THORIUM ENERGY & LFTR

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ABSTRACT:

Element 90, found as Thorium 232 in nature, is 4 times more common than Uranium and about 200-400x more common than U-235, the fuel we burn in Light Water Reactors (LWRs) in the US and much of the world.

Thorium is naturally radioactive like uranium, and has a half-life equal to the age of the universe (about 15 billion years) so it will be with us for a long time

It is found in large quantities in “Rare Earth” mines, which are rare in the US *because* they dig up Thorium. Thorium is (weakly) radioactive, and US law requires it be treated as a radioactive waste and buried.

Too much Thorium in a rare earth mine makes it unprofitable, but it is these rare earth mines that bring up the high technology metals we need in society today, such as Neodymium for magnets (think generators and motors).

A LWR (Light Water Reactor) in the US burns about 0.5%-5% of the fuel put in it, the remaining is disposed of as unburned fuel as part of the radioactive waste. A LFTR on the other hand, running from Thorium could burn 100% of the fuel

LIQUID FLUORIDE THORIUM REACTOR (LFTR) IS AN INNOVATIVE DESIGN FOR THE THERMAL BREEDER REACTOR THAT HAS IMPORTANT POTENTIAL BENEFITS OVER THE TRADITIONAL REACTOR DESIGN. LFTR IS FLUORIDE BASED LIQUID FUEL, THAT USE THE THORIUM DISSOLVED IN SALT MIXTURE OF LITHIUM FLUORIDE AND BERYLLIUM FLUORIDE. THEREFORE, LFTR TECHNOLOGY IS FUNDAMENTALLY DIFFERENT FROM THE SOLID FUEL TECHNOLOGY CURRENTLY IN USE. ALTHOUGH THE TRADITIONAL NUCLEAR REACTOR TECHNOLOGY HAS BEEN PROVEN, IT HAS PERCEPTUAL PROBLEMS WITH SAFETY AND NUCLEAR WASTE PRODUCTS. THE AIM OF THIS PAPER IS TO DISCUSS THE POTENTIAL ADVANTAGES OF LFTR IN THREE ASPECTS SUCH AS SAFETY, FUEL EFFICIENCY AND NUCLEAR WASTE AS AN ALTERNATIVE ENERGY GENERATOR IN THE FUTURE. COMPARISONS BETWEEN LFTR AND LIGHT WATER REACTOR (LWR), ON GENERAL PRINCIPLES OF FUEL CYCLE, RESOURCE AVAILABILITY, RADIOTOXICITY AND NUCLEAR WEAPON PROLIFERATION SHALL BE ELABORATED.EASE OF USE

Robert Hargraves and Ralph Moir:

Today’s familiar pressurized water nuclear reactors use solid fuel -- pellets of uranium dioxide in zirconium fuel rods bundled into fuel assemblies. These assemblies are placed within the reactor vessel under water at 160 atmospheres pressure and a temperature of 330°C. This hot water transfers heat from the fissioning fuel to a steam turbine that spins a generator to make electricity. Alvin Weinberg invented the pressurized water reactor (PWR) in 1946 and such units are now used in over 100 commercial power-producing reactors in the US as well as in naval vessels.

Weinberg also pursued research on liquid fuel-reactors, which offer a number of advantages over their solid-fueled counterparts. In this article we review some of the history, potential advantages, potential drawbacks, and current research and development status of liquid-fueled reactors. Our particular emphasis is on the Liquid Fluoride Thorium Reactor (LFTR).

Before describing the characteristics of liquid-fuel reactors we review briefly in this paragraph the situation with PWRs. In a conventional PWR the fuel pellets contain UO_2 with fissile U-235 content expensively enriched to 3.5% or more, the remainder being U-238. After about 5 years the fuel must be removed because the fissile material is depleted and neutron-absorbing fission products build up. By that time the fuel has given up less than 1% of the potential energy of the mined uranium, and the fuel rods have become stressed by internal temperature differences, by radiation damage that breaks covalent UO_2 bonds, and by fission products that disturb the solid lattice structure (Figure 1). As the rods swell and distort, their zirconium cladding must continue to contain the fuel and fission products while in the reactor and for centuries thereafter in a waste storage repository.

Courtesy of Japan Atomic Energy Agency R&D Review 2008

Solid fuel rods are stressed by fission products, radiation, and heat.

In contrast, fluid fuels are not subjected to the structural stresses of solid fuels: liquid-fuel reactors can operate at atmospheric pressure, obviating the need for containment vessels able to withstand high-pressure steam explosions. Gaseous fission products like xenon bubble out while some fission products precipitate out and so do not absorb neutrons from the chain reaction. Like PWRs, liquid-fuel reactors can be configured to breed more fuel, but in ways that make them more proliferation resistant than the waste generated by conventional PWRs. Spent PWR fuel contains transuranic nuclides such as Pu-239, bred by neutron absorption in U-238, and it is such long-lived transuranics that are a core issue in waste storage concerns. In contrast, liquid-fuel reactors have the potential to reduce storage concerns to a few hundred years as they would produce far fewer transuranic nuclides than a PWR.

History of liquid fuel reactors:

The world’s first liquid fuel reactor used uranium sulphate fuel dissolved in water. Eugene Wigner conceived this technology in 1945, Alvin Weinberg built it at Oak Ridge, and Enrico Fermi started it up. The water carries the fuel, moderates neutrons (slows them to take advantage of the high fission cross-section of uranium for thermal-energy neutrons), transfers heat, and expands as the temperature increases, thus lowering moderation and stabilizing the fission rate. Because the hydrogen in ordinary water absorbs neutrons, an aqueous reactor, like a PWR, cannot reach criticality unless fueled with uranium enriched beyond the natural 0.7% isotopic abundance of U-235. Deuterium absorbs few neutrons, so, with heavy water, aqueous reactors can use unenriched uranium. Weinberg’s aqueous reactor fed 140 kW of power into the electric grid for 1000 hours. The intrinsic reactivity control was so effective that shutdown was accomplished simply by turning off the steam turbine generator.

In 1943, Wigner and Weinberg also conceived a liquid fuel thorium-uranium breeder reactor, for which the aqueous reactor discussed above was but the first step. The fundamental premise in such a reactor is that a blanket of thorium Th-232 surrounding the fissile core will absorb neutrons, with some nuclei thus being converted (“transmuted”) to Th-233. Th-233, in turn, beta decays to protactinium-233 and then to U-233, which is itself fissile and can be used to refuel the reactor. Later, as Director of Oak Ridge, Weinberg led the development of the liquid fluoride thorium reactor (LFTR), the subject of this article. Aware of the future effect of carbon dioxide emissions, Weinberg wrote “humankind's whole future depended on this.” The Molten Salt Reactor Experiment, powered first with U-235 and then U-233, operated successfully over 4 years, through 1969. To facilitate engineering tests, the thorium blanket was not installed; the U-233 used in the core came from other reactors breeding Th-232. The MSRE was a proof-of-principle success. Fission-product xenon gas was continually removed to prevent unwanted neutron absorptions, online refueling was demonstrated, minor corrosion of the reactor vessel was addressed, and chemistry protocols for separation of thorium, uranium, and fission products in the fluid fluorine salts were developed. Unfortunately, the Oak Ridge work was stopped when the Nixon administration decided instead to fund only the solid fuel Liquid sodium Metal cooled Fast Breeder Reactor (LMFBR), which could breed plutonium-239 faster than the LFTR could breed uranium-233.

The Liquid Fluoride Thorium Reactor:

A significant advantage of using thorium to breed U-233 is that relatively little plutonium is produced from the Th-232 because six more neutron absorptions are required than is the case with U-238. The U-233 that is bred is also proliferation-resistant in that the neutrons that produce it also produce 0.13% contaminating U-232 which decays eventually to thallium, which itself emits a 2.6 MeV penetrating gamma radiation that would be obvious to detection monitors and hazardous to weapons builders. For example, a year after U-233 separation, a weapons worker one meter from a subcritical 5 kg sphere of it would receive a radiation dose of 4,200 mrem/hr; death becomes probable after 72 hours exposure. Normally the reactor shielding protects workers, but modifying the reactor to separate U-233 would require somehow adding hot cells and remote handling equipment to the reactor and also to facilities for weapons fabrication, transport, and delivery. Attempting to build U-**233-based nuclear weapons by modifying a LFTR would be** more hazardous, technically challenging and expensive than creating a purpose-built weapons program using uranium enrichment (Pakistan) or plutonium breeding (India, North Korea).

Work on thorium-based reactors is currently being actively pursued in many countries including Germany, India, China, and Canada; India plans to produce 30% of its electricity from thorium by 2050. But all these investigations involve solid fuel forms. Our interest here is with the liquid-fueled form of a thorium-based U-233 breeder reactor.

The configuration of a LFTR is shown schematically in Figure 2. In a “two-fluid” LFTR a molten eutectic mixture of salts such as LiF and BeF_2 containing dissolved UF_4 forms the central fissile core. (“Eutectic” refers to a compound that solidifies at a lower temperature than any other compound of the same chemicals.) A separate annular region containing molten Li and Be fluoride salts with dissolved ThF4 forms the fertile blanket. Fission of U-233 (or some other “starter” fissile fuel) dissolved in the fluid core heats it. This heated fissile fluid attains a noncritical geometry as it is pumped through small passages inside a heat exchanger. Excess neutrons are absorbed by Th-232 in the molten salt blanket, breeding U-233 which is continuously removed with fluorine gas and used to refuel the core. Fission products are chemically removed in the waste separator, leaving uranium and transuranics in the molten salt fuel. From the heat exchanger a separate circuit of molten salt heats gases in the closed cycle helium gas turbine which generates power. All three molten salt circuits are at atmospheric pressure.

In a two-fluid liquid fluoride thorium reactor the fission of U-233 in the core heats molten carrier salt (yellow). It attains a noncritical geometry as it is pumped through small passages in a heat exchanger. A separate circuit of molten salt (red), with no radioactive materials, heats gases in the closed cycle helium gas turbine which spins to generate power. Excess neutrons are absorbed by Th-232 in the molten salt blanket (green), breeding U-233 which is removed with fluorine gas. Fission products are chemically removed in the waste separator, leaving uranium and transuranics in the molten salt fuel. All three molten salt circuits are at atmospheric pressure.

Merits of LFTR:

Existing PWR spent fuel can be an asset. A 100 MW LFTR requires 100 kg of fissile material (U-233, U-235, or Pu-239) to start the chain reaction. The world now has 340,000 tonnes of spent PWR fuel, of which 1% is fissile material that could start one 100 MW LFTR per day for 93 years.

A commercial LFTR will make just enough uranium to sustain power generation, so diverting uranium for weapons use would stop the reactor, alerting authorities. A LFTR will have little excess fissile material; U-233 is continuously generated to replace the fissioned U-233, and Th-232 is continuously introduced to replace the Th-232 converted to the U-233. Terrorists could not steal this uranium dissolved in a molten salt solution along with lethally radioactive fission products inside a sealed reactor, which would be subject to the usual IAEA safeguards of physical security, accounting and control of all nuclear materials, surveillance to detect tampering, and intrusive inspections.

It is also possible to configure a liquid-fuel reactor that would involve no U-233 separation. For example, the single fluid denatured molten salt reactor (DMSR) version of a LFTR with no U-233 separation is fed with both thorium and < 20% enriched uranium. It can operate up to 30 years before actinide and fission product build-up requires fuel salt replacement, while consuming only 25% of the uranium a PWR uses.

Starting up LFTRs with plutonium can consume stocks of this weapons-capable material. Thorium fuel would also reduce the need for U-235 enrichment plants, which can be used to make weapons material as easily as power reactor fuel. U-233, at the core of the reactor, is important to LFTR development and testing. With a half-life of only 160,000 years, it is not found in nature. The US has 1,000 kg of nearly irreplaceable U-233 at Oak Ridge. It is now slated to be destroyed by diluting it with U-238 and burying it forever, at a cost of $477 million. This money would be far better invested in LFTR development.

Can LFTR power be cheaper than coal power?

Burning coal for power is the largest source of atmospheric CO_2, which drives global warming. We seek alternatives such as burying CO_2 or substituting wind, solar, and nuclear power. A source of energy cheaper than coal would dissuade nations from burning coal while affording them a ready supply of electric power.

Pressure. The LFTR operates at atmospheric pressure, obviating the need for a large containment dome. At atmospheric pressure there is no danger of an explosion.

Safety. Rather than creating safety with multiple defense-in-depth systems, LFTR's intrinsic safety keeps such costs low. A molten salt reactor cannot melt down because the normal operating state of the core is already molten. The salts are solid at room temperature, so if a reactor vessel, pump, or pipe ruptured they would spill out and solidify. If the temperature rises, stability is intrinsic due to salt expansion. In an emergency an actively cooled solid plug of salt in a drain pipe melts and the fuel flows to a critically safe dump tank. The Oak Ridge MSRE researchers turned the reactor off this way on weekends.

Heat. The high heat capacity of molten salt exceeds that of the water in PWRs or liquid sodium in fast reactors, allowing compact geometries and heat transfer loops utilizing high-nickel metals.

Energy conversion efficiency. High temperatures enable 45% efficient thermal/electrical power conversion using a closed-cycle turbine, compared to 33% typical of existing power plants using traditional Rankine steam cycles. Cooling requirements are nearly halved, reducing costs and making air-cooled LFTRs practical where water is scarce.

Mass production. Commercialization of technology lowers costs as the number of units produced increases due to improvements in labour efficiency, materials, manufacturing technology, and quality. Doubling the number of units produced reduces cost by a percentage termed the learning ratio, which is often about 20%. In *The Economic Future of Nuclear Power*, University of Chicago economists estimate it at 10% for nuclear power reactors. Reactors of 100 MW size could be factory-produced daily in the way that Boeing Aircraft produces one airplane per day. At a learning ratio of 10%, costs drop 65% in three years.

Ongoing research. New structural materials include silicon-impregnated carbon fiber with chemical vapour infiltrated carbon surfaces. Such compact thin-plate heat exchangers promise reduced size and cost. Operating at 950°C can increase thermal/electrical conversion efficiency beyond 50% and also improve water dissociation to create hydrogen for manufacture of synthetic fuels such that can substitute for gasoline or diesel oil, another use for LFTR technology.

Development Status of LFTR:

A number of LFTR initiatives are currently active around the world. France supports theoretical work by two dozen scientists at Grenoble and elsewhere. The Czech Republic supports laboratory research in fuel processing at Rez, near Prague. Design for the FUJI molten salt reactor continues in Japan. Russia is modelling and testing components of a molten salt reactor designed to consume plutonium and actinides from PWR spent fuel, and LFTR studies are underway in Canada and the Netherlands. US R&D funding has been relatively insignificant, except for related studies of solid fuel, molten salt cooled reactors at UC Berkeley and Oak Ridge, which hosted a conference to share information on fluoride reactors in September 2010.

Developing LFTRs will require advances in high temperature materials for the reactor vessel, heat exchangers, and piping; chemistry for uranium and fission product separation; and power conversion systems. The International Generation IV Forum budgeted $1 billion over 8 years for molten salt reactor development. We recommend a high priority, 5-year national program to complete prototypes for the LFTR and the simpler DMSR. It may take an additional 5 years of industry participation to achieve capabilities for mass production. Since LFTR development requires chemical engineering expertise and liquid fuel technology is unfamiliar to most nuclear engineers today, nuclear engineering curricula would have to be modified to include exposure to such material. The technical challenges and risks that must be addressed in a prototype development project include control of salt container corrosion, recovery of tritium from neutron irradiated lithium salt, management of structural graphite shrinking and swelling, closed cycle turbine power conversion, and maintainability of chemical processing units for U-233 separation and fission product removal. Energy Secretary Chu expressed historical criticism of the technology in a letter to Senator Jeanne Shaheen (D-NH) answering questions at his confirmation hearings, "One significant drawback of the MSR technology is the corrosive effect of the molten salts on the structural materials used in the reactor vessel and heat exchangers; this issue results in the need to develop advanced corrosion-resistant structural materials and enhanced reactor coolant chemistry control systems", and

“From a non-proliferation standpoint, thorium-fueled reactors present a unique set of challenges because they convert thorium-232 into uranium-233 which is nearly as efficient as plutonium-239 as a weapons material.” He also recognized, however, that “Some potential features of a MSR include smaller reactor size relative to light water reactors due to the higher heat removal capabilities of the molten salts and the ability to simplify the fuel manufacturing process, since the fuel would be dissolved in the molten salt.”

Other hurdles to LFTR development may be the regulatory environment and the prospect of disruption to current practices in the nuclear industry. The Nuclear Regulatory Commission will need funding to train staff qualified to work with this technology. The nuclear industry and utilities will be shaken by this disruptive technology that changes whole fuel cycle of mining, enrichment, fuel rod fabrication, and refueling. Ultimately, the environmental and human development benefits will be achieved only when the cost of LFTR power really proves to be cheaper than from coal.

The important agenda “NUCLEAR WASTES”:

Thorium mixed with plutonium and other actinide “waste” could continuously power modified conventional reactors almost forever in a reusable fuel cycle,

Ideally, the reactors would be “reduced-moderation water” reactors that work on the same solid-fuel, water-cooled principles of conventional reactors but that do not slow down neutrons as much and thus also offer some of the advantages of fast reactors.

It bodes well for the use of thorium not only as a safe, efficient and clean power source, but also as one that addresses the vexing problem of what to do with nuclear waste from the 430-some conventional light water reactors that make up almost all of the commercial power reactors operating in the world today and that run on uranium.

By mixing thorium with “waste” in a solid fuel, the nuclear industry could eliminate the need to bury long-lived plutonium and other actinides.

INDIA’s nuclear plans & Contribution of Thorium:

World Thorium Resources

(economically extractable):

Country	Reserves (tonnes)
Australia	300 000
India	290 000
Norway	170 000
USA	160 000
Canada	100 000
South Africa	35 000
Brazil	16 000
Other countries	95 000
World total	1 200 000

Scope for INDIA:

- **India has a flourishing and largely indigenous nuclear power programme and expects to have 14.6 GWe nuclear capacity on line by 2024 and 63 GWe by 2032. It aims to supply 25% of electricity from nuclear power by 2050.**
- **Because India is outside the Nuclear Non-Proliferation Treaty due to its weapons programme, it was for 34 years largely excluded from trade in nuclear plant or materials, which has hampered its development of civil nuclear energy until 2009.**
- **Due to earlier trade bans and lack of indigenous uranium, India has uniquely been developing a nuclear fuel cycle to exploit its reserves of thorium.**
- **Since 2010, a fundamental incompatibility between India’s civil liability law and international conventions limits foreign technology provision.**
- **India has a vision of becoming a world leader in nuclear technology due to its expertise in fast reactors and thorium fuel cycle.**

India’s primary energy consumption more than doubled between 1990 and 2011 to nearly 25,000 PJ. India's dependence on imported energy resources and the inconsistent reform of the energy sector are challenges to satisfying rising demand.

The 2015 edition of BP’s Energy Outlook projected India’s energy production rising by 117% to 2035, while consumption grows by 128%. The country’s energy mix evolves very slowly over the next 22 years with fossil fuels accounting for 87% of demand in 2035, compared with a global average of 81% (down from 92% today). Oil remains the dominant fuel (36%) followed by gas (30%) and coal (21%). CO_2 emissions from energy consumption increase by 115%.

Electricity demand in India is increasing rapidly, and the 1287 TWh gross produced in 2014 was more than triple the 1990 output, though still represented only some 1000 kWh per capita for the year. With large transmission losses – 250 TWh (19.4%) in 2014 – this resulted in only about 947 TWh consumption. Overall transmission and distribution losses have been put at 26% by the Power Engineers Society. Gross generation in 2014 comprised 850 TWh from black coal, 36 TWh from brown coal, 63 TWh from gas, 23 TWh from oil, 36 TWh from nuclear, 132 TWh from hydro and 67 TWh from other renewable. There was net import of 5 TWh. Coal provides almost three-quarters of the electricity at present, but reserves are effectively limited* – in 2013, 159 million tonnes was imported, and 533 million tonnes produced domestically.

* Quoted resources are 293 billion tonnes, but much of this is in forested areas of eastern India – Jharkhand, Orissa, Chhattisgarh, and West Bengal. While the first three of these are the main producing states, nevertheless permission to mine is problematical and infrastructure limited.

The per capita electricity consumption figure – 1000 kWh/yr in 2014 – is expected to double by 2020, with 6.3% annual growth, and reach 5000-6000 kWh/yr by 2050, requiring about 8000 TWh/yr then. There is an acute demand for more reliable power supplies. One-third of the population is not connected to any grid, and in 2013, 19% was without any electricity.

Prospects of Thorium:

According to the UN nuclear agency IAEA there are many benefits with thorium compared to uranium, which is currently used in nuclear reactors.

To begin with, there is limited radioactive debris when thorium is used. And in terms of chemical stability and resistance to radioactivity thorium is a safer alternative compared to uranium.

Depending on the core process utilized, thorium leads to more energy that can be recovered from this cheap, available and relatively safe energy.

One of the major drawbacks of nuclear power is the fear that countries that have the technology will use it to acquire nuclear weapons.

This is much more difficult to do with the material that is created in nuclear reactors fueled with thorium compared to those that run on uranium.

1) Investments in India and China

The obvious advantages of using thorium in core processes have been particularly interesting to India and China. Both countries have invested in a new generation of thorium-based nuclear power plants.

The Indian reactors Kakrapar-1 and Kakrapar-2 were the first in the world to use thorium on a large scale. Already in 1995, the reactors succeeded to operate 400 days at full strength based on thorium. India's long-term interest in thorium is not just about its environmental benefits. India has only one percent of the world's uranium resources, but about 30 percent of the world's thorium resources. Canada, the U.S., Germany, UK and the Netherlands have also tested thorium as an alternative fuel.

2) Technical challenges to be solved

Although thorium can already be used, a number of technical challenges need to be resolved before this new technology can reach its full potential.

For example, higher temperatures are required to produce thorium-based fuels. Residual materials from thorium-based nuclear power lose their radioactivity faster than residual materials from uranium-based nuclear fuels. In the short term, however, thorium's residual materials emit stronger radiation and this increases the cost of the immediate handling.

3) Will Thorium replace uranium?

As experience is gained from thorium-based nuclear power plants, and from the research done in the field, we will most likely become aware of the pros and cons of this relatively new energy source.

Perhaps the biggest challenge when moving from uranium to thorium is the time and the investments that are required. Many countries, because of these high investment costs, cling to the uranium that is already used as a nuclear fuel. Given that thorium is regarded as a less dangerous, less expensive, more accessible and more environmentally friendly alternative to uranium, there are good reasons to keep an eye on developments.

Conclusion:

Thorium will be a promising alternative for Uranium .It will serve India and as well as the whole world on power production and can make a revolution in power production.

Thorium energy has a very enormous amount of scope in INDIA and as well as for the other giants in Nuclear power such as France, United States and China.

LFTR reactor will reduce the essential threat of "Nuclear Meltdown" in the minds of the public.

The nuclear wastes from Thorium-fueled reactors can be easily treated and recycled.

INDIA being one amongst the largest reserves of thorium is having a great scope for marketing thorium to the country interested in Thorium energy

The Thorium reactor would be a promising source of power in the future and it could possibly replace Uranium as fuel and produce safe and clean nuclear energy.

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