Molten Salt Reactors

If one were to fantasize about an ideal solution to replacing fossil fuels with renewable energy some of the requirements would be:

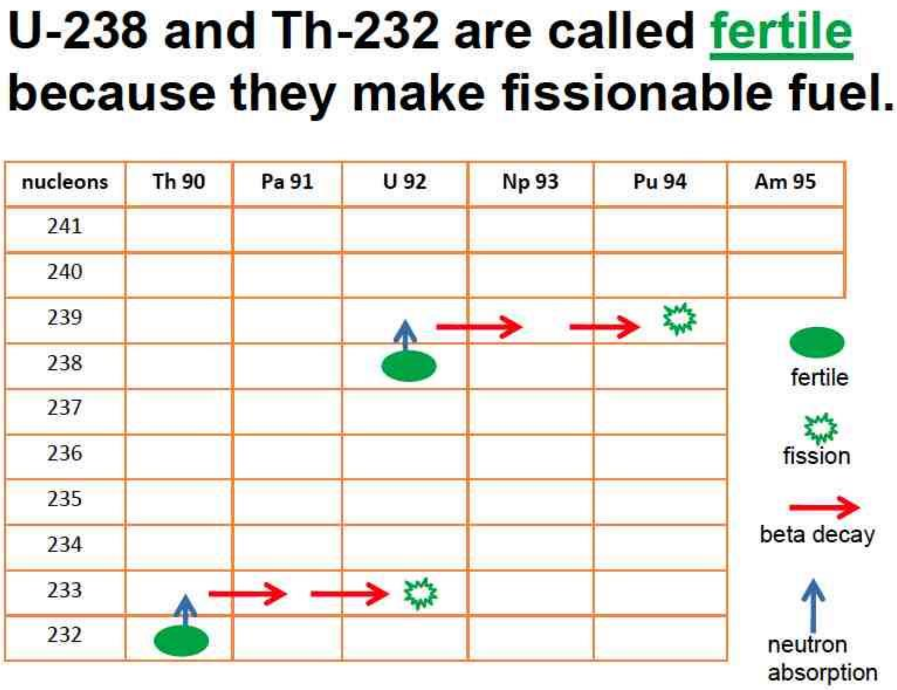
- zero carbon footprint,
- able to burn up waste from Light water nuclear reactors (LWRs),
- cheaper than coal,
- inexhaustible energy supply,
- minimal waste,
- capable of producing both electricity and fuel,
- relatively inexpensive,
- no environmental impact – (no threat to birds as with wind turbines or the desert as with solar).
- modular (thus avoiding the gigantic gigawatt reactors).
- does not require long power lines as with wind and solar.
- very safe.
- resistant to earthquakes (i.e. Fukashima)
- resistant to meltdowns (i.e Chernobyl, Three Mile Idland)
- resitant to terrorism
- affordable to developing nations.

This sounds like an impossible mix of dream requirements. There is however, one energy source that meets all these criteria – the Thorium Based Nuclear Power or Liquid Fluoride Thorium Reactors (LFTRs) and its cousin Denatured Molten Salt Reactors (DMSRs) that burn thorium or spent fuel from CWRs. A more generic term is simply **Molten Salt Reactors (MSR)**.

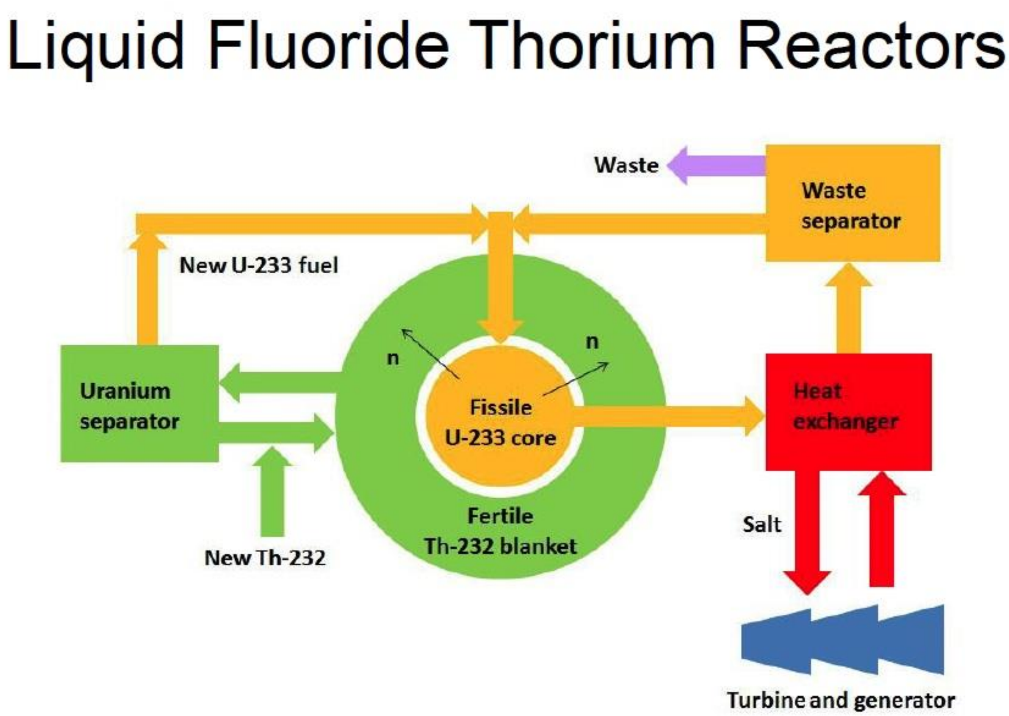
While many have stated that nuclear power is the ideal solution to renewable energy, given the experience with Chernobyl, Three Mile Island and Fukashima, many others are dead set against a nuclear solution to the problem. However, that negative mindset applies to the standard pressurized light water reactors (LWRs). There is a dramatically different form of nuclear power that eliminates virtually all of the disadvantages of current nuclear power plants including the large NIMBY (Not In My Back Yard) problem. That solution is LFTR type of MSR and MSRs in general.

What is a LFTR? [1-12]

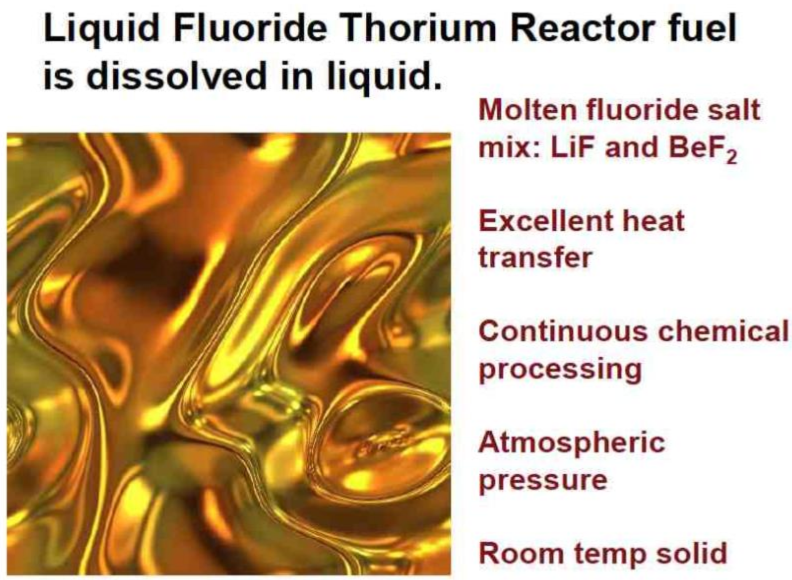
Fertile compounds are those that do not undergo fission themselves, but upon capturing neutrons are transformed to fissile compounds. Thorium is such a fertile compound. When exposed to a source of neutrons, thorium Th-232, decays to fissionable uranium U233. It is the fission of U-233 that provides the heat of a LFTR. Fissionable U-235 supplies the heat for LWRs. U-238, the major component of uranium ore, is also a fertile compound. When it is exposed to fissionable U-235 it decays to fissionable plutonium.



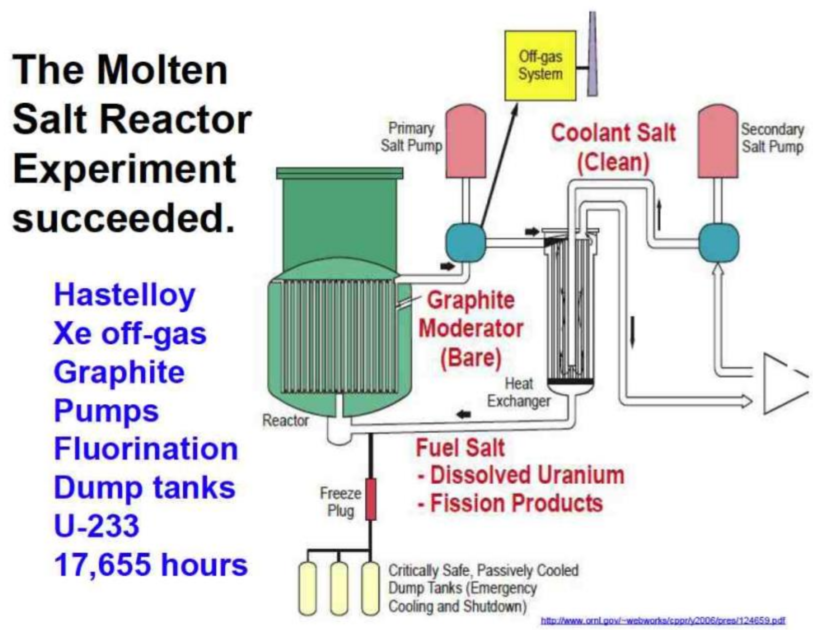
Thus the essence of a LFTR as shown below.



A blanket of fertile Th-232 as liquid ThF_4 and two fluoride salts, lithium fluoride (LiF) and beryllium fluoride (BeF_2) surrounds a liquid core of ThF4, LiF and BeF2 and some starter fissile U-233. The fission of U-233 produces the heat and neutrons for the further conversion of Th-232 to more U-233. The fusion products are chemically removed in the waste collector leaving uranium and transuranics in the molten salt fuel. The heat exchanger in red is a liquid salt of consisting of LiF and BeF_2 with no radioactive materials. Because of these features it is often called a Molten Salt Reactor.



The following is a more detailed diagram of a LFTR that was built and successfully operated in Oak Ridge National Laboratory in the 1960's.

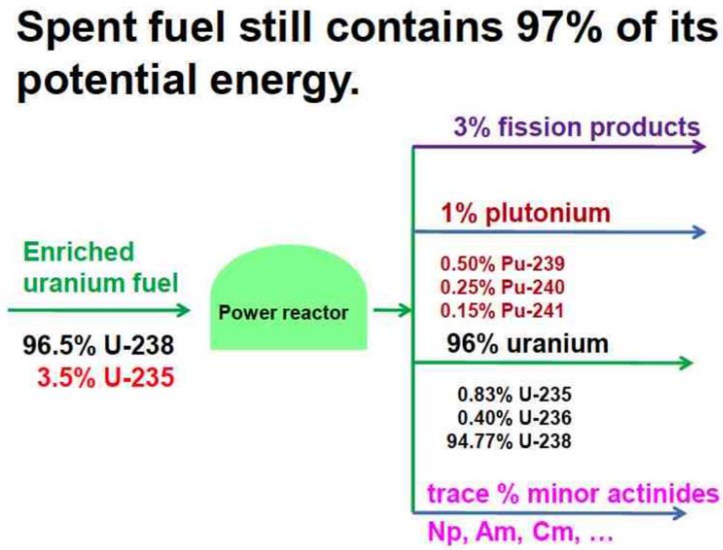


The **great safety feature** of the LFTR and MSRs in general is a **freeze plug** in a pipe from the main liquid container to safety collection vessels. A portion of the pipe is kept frozen by an electric freezing apparatus. As long as the electricity is on and this section is frozen none of the liquid passes into the safety collection vessels. However, if electricity fails, **even in the total absence of human intervention**, the plug unfreezes and the liquid thorium fluoride passively drains to the safety vessel where it solidifies, stopping the heating process. Working models built at Oak Ridge National Laboratory (ORN) in the 1950's and 1960's were turned off over the weekend by simply opening the freeze plug. To restart the reactor on Monday they turned on the heater and re-liquefied the LIF and BeF_2. Thus, it is as much a matter of resurrecting old technology as inventing new. The only reason this work was discontinued was because, at that time during the cold war, the *US was more interested in producing plutonium to make bombs than to produce cheap and safe renewable energy*. Thus, one of the features that make LFTRs so attractive now, resistance to conversion to making weapons, is the reason this work was discontinued in 1960's.

Advantages of LFTR over current nuclear power (CWRs and others).

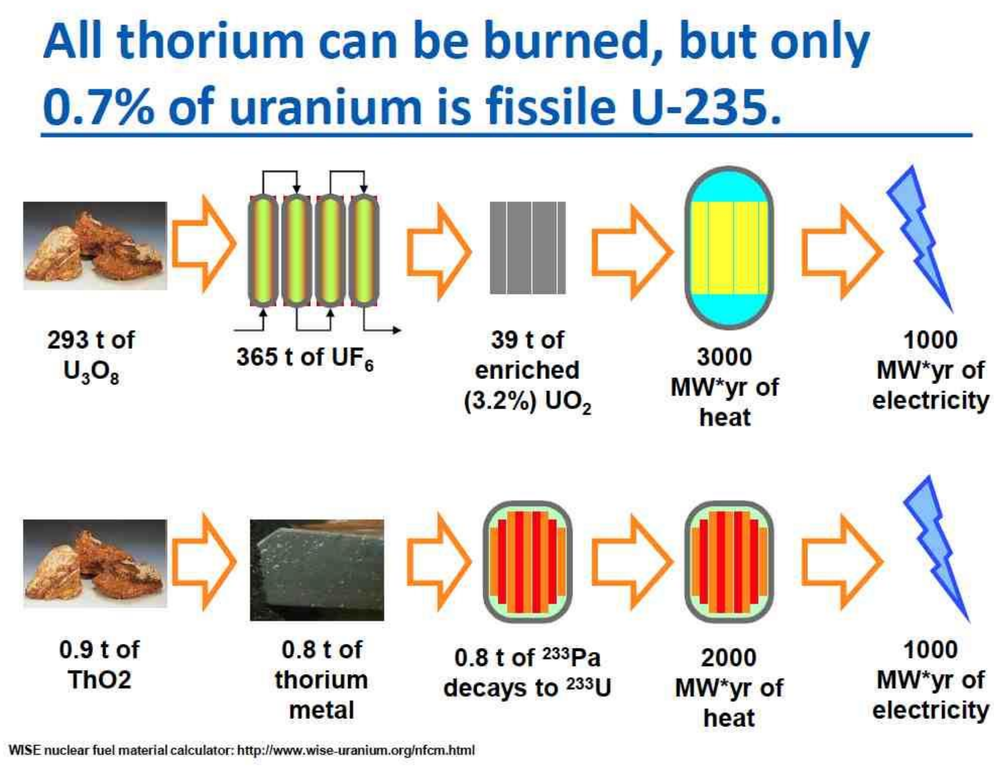
Inexhaustible fuel. Unlike uranium, which is relatively scarce supply and could get scarcer, thorium is common. In one area of Idaho there is enough thorium to supply the energy needs of the United States for one thousand years. Thorium is also present in many other sates and many other countries, making it easily available worldwide. In addition, as discussed below, the "spent" fuel from standard PWRs still contains 97 percent of its total available energy. MSRs (see Transatomics White Paper) can use the "spent fuel" and burn it down to 2%. The amount of "spent fuel" stored at reactors around the world is sufficient to fuel MSRs for hundreds of years while at the same time, eliminating this radioactive waste.

Much more efficient than uranium based nuclear power. Standard nuclear power plants use enriched U235 as the source of their fissionable material. Enriched fuel rods contain 3.5% fissionable U-235 and 96.5% U-238. After the reaction is complete only 3% of the fuel has been converted to fissionable products. The spent fuel still contains 97% of its potential energy.



By contrast, *LFTRs are close to 100% efficient*.

Another aspect of the efficiency of LFTRs is that all of thorium ore can be used but only 0.7% of the uranium ore can be used. Thus, *it only requires 0.9 tons of ThO_2 to produce 1000 MWyr while 293 tons of U_3O_8 are required to produce the same amount of electricity*.



Finally, based on the laws of thermodynamics and the efficiency of heat engines, because of the high heat of a LFTRs these reactors have a 45% efficiency for thermal to electricity conversion compared to the 33% efficiency of standard nuclear reactors.

Minimal nuclear waste. *After 300 years LFTRs produce 10,000 times less radioactive waste than today's nuclear plants*. The radioactive waste of current nuclear plants have a half-life of many thousands of years. In addition, the amount waste from a standard nuclear reactor is much greater than for LFTRs. LFTRs reduce the needed storage time of by products from millions of years for PWRs to hundreds of years for LFTRs.

The PWR waste can be used to fuel LFTRs. The waste from standard reactors can be used to fuel LFTRs thus providing a use for this waste and potentially removing it from the environment. LFTRs can also be started with plutonium thus helping to use up this nuclear reactor product that could be converted to building weapons.

No periodic replacement of parts. Solid fuel rods in standard nuclear power plants have to be replaced every few years because of cracks in the covering can release radioactive fission products. This is not a problem with the liquid fuel of LFTRs.

Safe. Although current nuclear plant safety has improved dramatically since Three Mile Island, the experience with the Japanese plants at Fukashima has shown that they can still be dangerous under extreme circumstances such as huge earthquakes and tsunamis. This concern has led Germany to decide to phase out its current nuclear power plants. By contrast, as shown below, the LFTRs are extremely safe. They can **never have a meltdown because they are already in a constant meltdown or liquid state.** In the case of an emergency, even if the electricity was permanently knocked out and the plant was unmanned because everyone in the area was dead, the liquid would automatically and passively drain to a collection vault and solidify into an inert mass.

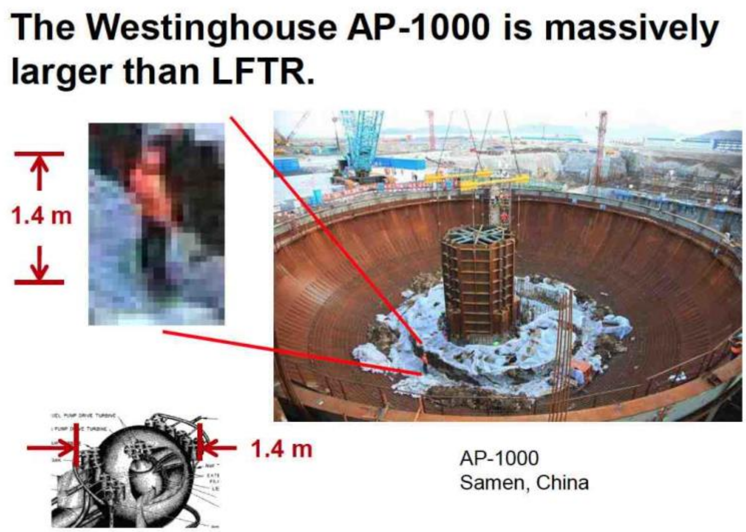
Less water use. A typical 1 GW nuclear or coal power plant heats 600,000 gallons/min of water or evaporates 20,000 gallons/min. The warm water run off from PWRs tend to pollute the environment. A high temperature LFTR cuts the heat loss in half and they can be air cooled, thus requiring no water. This is a great advantage in arid sites with little water supply.

Less of a threat from terrorists. There is much less of a problem with potential use by terrorists of the LFTRs products than with standard reactors. LFTRs produce only as much fissionable U-233 as they consume. The siphoning off U-233 for other uses would stop the reactor. In addition, for all practical purposes, U233 is worthless as a nuclear weapons material, and indeed no nation has weaponized U233 because of the many inherent difficulties of doing so. U233 is considered an unsuitable choice for nuclear weapons material because whenever U233 is generated, uranium-232 (U232) contamination inevitably occurs. U232 rapidly decays into other elements, including thallium-208, a hard-gamma-ray emitter whose signature is easily detectable. The hard gamma rays from thallium-208 cause ionization of other materials effectively destroying the explosives and electronics of a nuclear weapon and requiring heavy lead shielding to protect weapons personnel. A 5gm sphere with U232 radiates 4,200 mrem/hr of gamma radiation at distance of 1 meter, and quickly provides a lethal dose to any terrorists opening the reactor. Moreover, isotopic separation of the undesirable U-232 is even more difficult than the already daunting tasks of U-235 enrichment or plutonium breeding. As far as terrorists are concerned there are far more suitable potential sources of weapons grade uranium and plutonium from standard reactors than from LFTRs. Thus, LFTR technology is a proliferation-resistant source of electrical energy. The liquid form of the reactants and the constant removal of by-products minimizes the risk of gamma radiation in a working LFTR.

The Ashley report. In the December 6 issue of *Nature* 492:31-33, 2012, Stephen Ashley and colleagues point out that thorium is not totally free of use by terrorist. When irradiated by neutrons, thorium decays first to protactinium 233 (^{233}PA). This then spontaneously decays to fissionable ^{233}U. The Atomic Energy Agency (IAEA) considers 8 kilograms of ^{233}U to be enough to construct a nuclear weapon. They point out that exposure of 200 g of thorium to neutrons for one month in a research reactor, of which 500 exist around the world, or in a commercial nuclear reactor, could produce 1 g of ^{233}Pa or ^{233}U; 1.6 tons of thorium could produce 8 kg of ^{233}U. ^{233}Pa can be isolated from the irradiated thorium using one of two techniques: Acid-media or liquid bismuth separation.

It should be pointed out that this is not a risk of LFTR per se. Any country or group so interested could do this totally independent of any LFTR facilities. In fact, assuming all LFTRs would be under IAEA control monitoring, the risk is less for LFTRs than rogue processing of thorium independent of LFTRs.

Less expensive. One of the problems with current nuclear power is that the plants are very expensive, costing many billions of dollars per plant. To maximize efficiency, they are also built on a very large-scale producing Gigawatts of electricity. In addition to their large size the requirement for huge, thick-walled containment domes adds greatly to their expense. The following figure illustrates the dramatic difference is size of standard nuclear power plants versus LFTRs.



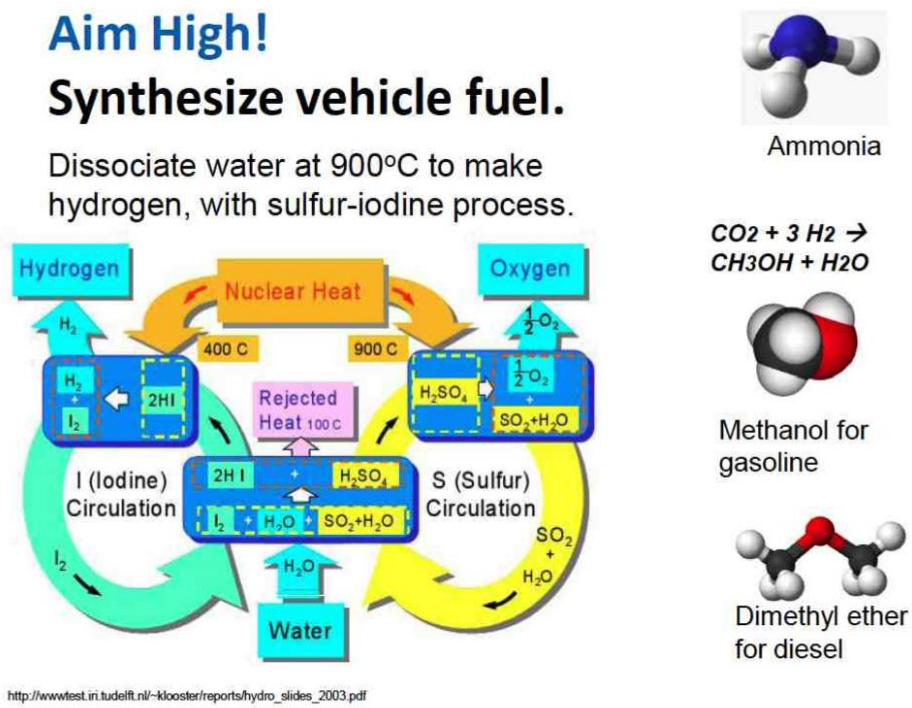
The figure on the right shows the construction of a Westinghouse AP-1000 nuclear plant in Japan. The tiny figure of a man at the base of the containment vessel is enlarged in the figure at the upper left. The lower left shows the size of a small modular LFTR reactor similar in dimensions to the human figure.

Because there is no risk of explosion and no high pressures, LFTRs require no containment domes. Because of the design and safety features of LFTRs they also require fewer operating personnel leading to further reductions in the cost of running the plants.

Other advantages

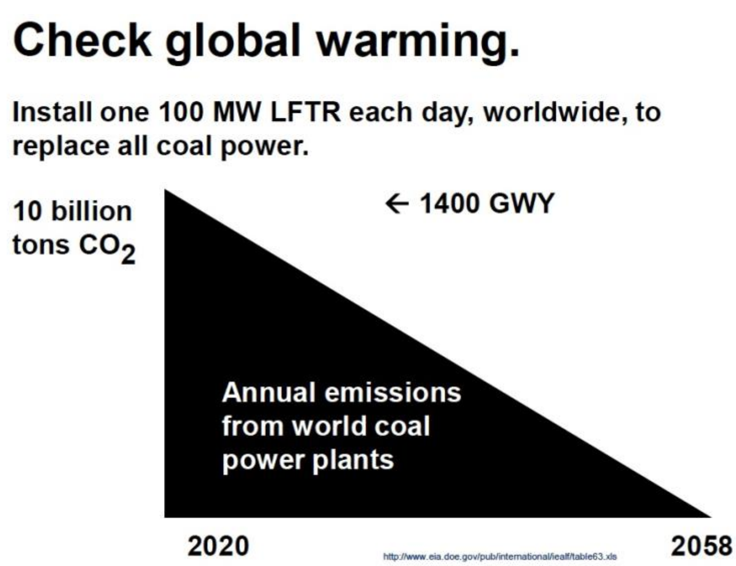
Cheaper than coal. [3] On a cost per kilowatt hour (kWhr) basis many forms of renewable energy, such as solar, have a hard time competing with coal generated electricity. At $40 per ton electricity from coal costs 2 cents per kWhr. By contrast, if modular LFTR units are built on an industrial scale, like airplanes, the cost per kWhr would be less than coal.

Can produce transportation fuel. The high temperatures of LFTRs allow them to easily decompose water into hydrogen gas H_2. In addition to the production of hydrogen for potential future use in hydrogen powered vehicles, LFTRs can also produce fuel from H_2, as shown below.



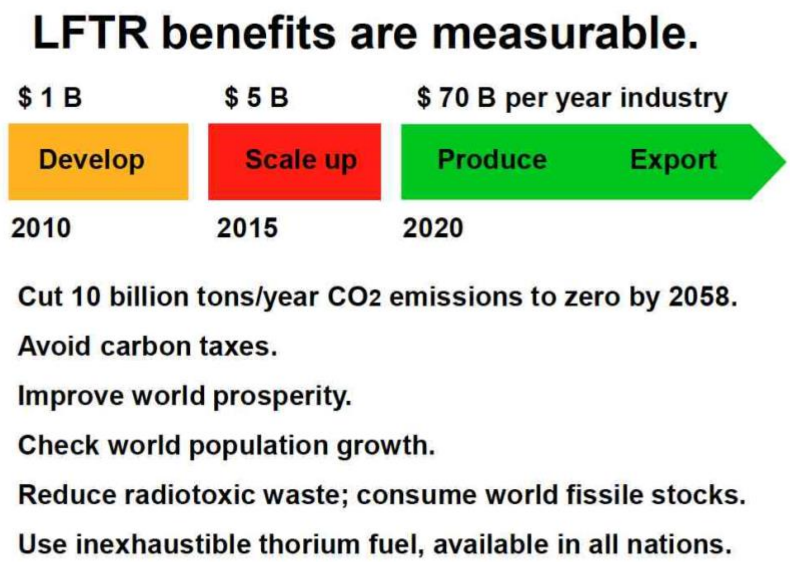
Such fuels would add no carbon to the atmosphere since it is derived from non-fossil sources.

Can replace coal plants dramatically reducing CO_2 emissions. Mass production of 100 MW LFTRs can result of each plant costing about $200 million dollars, less than a large commercial jet. The production of one such plant per day over a number of years could totally replace coal plants.



The relatively low cost of such 100 MW LFTRs could allow even developing countries with more limited finances to utilize this energy source. Providing such countries with affordable electric power can lead to an increased standard of living, a prime mover in lowering birth rates.

Summary of advantages. The following diagram summarizes many of the advantages of LFTRs.



As shown above, the development of this technology could lead to a $70 billion per year industry. Other nations, such as China, Canada, Russia, Japan, Netherlands and India, are currently exploring and developing this technology. In fact, in January, *China announced a 20-year plan to pursue and build a network of LFTRs to solve their energy and* CO_2 *emission problems* [12]. By contrast, the US is presently providing *no funding to develop this technology*. Given that LFTRs started in the US it would be tragic to let China become the world supplier of this technology, depriving the US of another multi-billion-dollar industry, and all the jobs that would entail. **We need to get started**.

Denatured Molten Salt Reactor

The only reactor specifically designed to be Proliferation resistant

There is a need to not only replace coal burning power plants with nuclear in the Unites States this will be necessary throughout the world. This means the nuclear plants need to be very proliferation resistant – impossible for terrorists or a rogue nations to subvert the use the reactor to produce a bomb.

There are many ways in which nuclear reactors can use thorium Th^{232} as fuel. The safest and most resistant to proliferation is the Denatured Molten Salt Reactor (DMSR). It is a single fluid reactor using fertile Th^{232} and fissile uranium U^{235}. The U^{235} is denatured by adding 80% U^{238}, thus making it unsuitable for weapons. Neutrons from fission either continue the chain reaction by interacting with uranium or absorbed by Th^{232} decaying to Pa^{233} and then to U^{233}, all happening in a molten salt. The some of the fission products, the noble gases and semi-noble metals, are removed by physical means. The remaining fission product elements become fluorides that remain dissolved in the molten salt for up to 30 years [22]. With some alterations the reactor could last for 300 years.

Molten salt reactors (MSRs) have been under study in the United States since about 1947. In late 1976 a study concluded that MSRs without denatured fuel would probably not be sufficiently proliferation resistant for unrestricted worldwide distribution. Thus, more extensive studies were undertaken at Oak Ridge National Laboratory (ORNL) to identify and characterize DMSR concepts for possible application in anti-proliferation situations [2]. The DMSR has the further advantage that it operated within a sealed containment from which no fissile material is added during the life of the plant. "This combination of properties suggests the possibility of a fuel cycle with a low overall cost and significant resistance to proliferation" [21].

In this 1980 report it was further concluded that, "although substantial technology development would be required, the denatured molten-salt reactor concept apparently could be made commercial in about 30 years…the cost for development is estimated to be $370 million (1978 dollars). The resulting system would be approximately economically competitive with current-technology light-water reactor systems." [21]

The isolation of protactinium (see above) would be avoided for proliferation reasons and chemical processing to remove fission products could be avoided without severe performance penalties. This system would have all the same safeguards against earthquakes, tsunamis, loss of electrical power, meltdowns, and even death of all the onsite operators, inherent in the LFTRs described above.

"MSR development has been carried out though the design and operation of a proof-of-principle test reactor, the MSRE, which was an 8-MWt reactor that operated at ORNL from 1965 to 1969 (see below). This reactor demonstrated the basic reliability of a molten-salt system, stability of the fuel salt, compatibility of fluoride salts with Hastalloy N and graphite, reliability of molten-salt pumps and heat exchangers, and maintenance of a radioactive fluid-fueled system be remote methods. The reactor was critical over 17,00 hours, circulated fuel salt for nearly 22,000 hours, and generated over 100,000 MWh of thermal energy. The MSRE has achieved all the objectives of the reactor test program when it was retired in 1969. After the successful operation of the MSRE, the reactor concept appeared ready for commercial development."[21]

For reasons other than technological, the government decided not to fund further development of MSRs. The program was canceled in 1973, restarted in 1974, and finally terminated in 1976. Alvin Weinberg, then director of the ORNL and prime mover in the MSR program, was fired in 1972, largely because of his voiced concerns about PWR reactor safety. **He was correct**. Issues with safety of PWRs have largely closed down the nuclear industry in recent years.

At the close of the MSRE operation, two major technical issues appeared unresolved. The first was the control of tritium, which is produced in fairly large quantities in a molten-salt system and which is how to diffuse through metal walls. Subsequent engineering-scale tests have demonstrated that tritium is oxidized in sodium fluroborate, the proposed secondary salt for the DMSR, and appears to be handled readily. However, this process is not yet well understood, and the effects of maintaining an adequate concentration of the oxidant on long-term compatibility of the salt with the structural alloy are unknown.

The second issue involved the compatibility of the Hastelloy-N with fuel salt. Operation of the MSRE showed that the general corrosion of the Hastelloy-N and graphite in an operating MSR was near zero, as expected. However, the metal surfaces exposed to the fuel salt containing fission products were unexpectedly found to exhibit grain boundary attack, which was subsequently shown to be caused by reaction with the fission product, tellurium. Further work has shown that tellurium attack could be controlled by either a modification of the Hastelloy-N alloy or by control of the oxidation potential of the fuel salt.

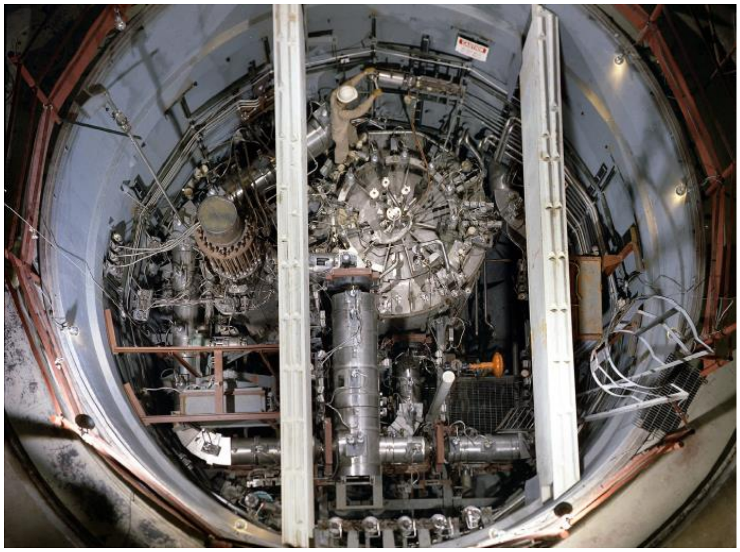
When Dr Cheu was interviewed by congress prior to his appointment as Secretary of the Department of Energy, he was asked about developing LFTR technology. He claimed there were problems with the metal alloy of the containment. He seems to have been unaware of these solutions.

The 1980 ORNL report on DMSR listed the items that needed work to progress to a commercial DMSR. All are doable. "There are no unresolved issues in the needed technology."[21]

Had the tragic and ill-conceived decision to discontinue MSR work not been made, the world could currently be having most of its electricity produced by this safe, inexpensive, carbon zero, and proliferation resistant approach, - going a long way toward avoiding global warming.

Past MSR Efforts in the United States

A Molten Salt Reactor (MSR) program was initiated in 1957, drawing upon the information developed in the Aircraft Nuclear Propulsion program to identify small modular nuclear power plants suitable for airplanes. By 1960 enough favorable experimental results were obtained to support authorization for design and construction of a 10-MW Molten Salt Reactor Experiment (MSRE). Design of the MSRE started in the summer of 1960, and construction started at the beginning of 1962. The reactor went critical in June 1965, and the MSRE initiated power operation in early 1966. The MSRE provided facilities for testing fuel salt, graphite, and alloys resistant to hot salts (Hastelloy N) under reactor operating conditions. *The basic reactor performance was outstanding* and indicated that the desirable features of the molten salt concept could be embodied in a practical reactor that can be constructed, operated, and maintained safely and reliably. A photograph of the MSRE from above the reactor vessel is shown below.



The MSRE experience was of major importance to the molten salt concept. Until the MSRE began to operate well, few people besides those actively involved in the development program considered molten salt reactors to be really practical. The major reason was that operation and maintenance of a system containing a highly radioactive fluid fuel that melted at over 425°C seemed extremely difficult. In 1966, however, the MSRE began to provide evidence to offset that view. When power operation began, the usual start-up problems were encountered, but sustained power operation provided a remarkable demonstration of operability. Starting in late 1966, an uninterrupted one-month run was made, then a three-month run, and finally a six-month run.

Next, using a small fluoride volatility plant connected to the reactor, the original partially enriched 235U fuel was removed from the salt and was replaced by 233U that had been made in a production reactor. The MSRE then operated *a final year* on the 233U, which made it the first reactor to ever have been operated on this fuel, and for a period plutonium was used as the makeup fuel. When shut down, the MSRE had circulated fuel salt at around 650°C *for a total of 2.5 years*. Perhaps the most important result from the MSRE was the conclusion that *it was quite a practical reactor*. In 1972 ORNL proposed a major development program that would culminate in the construction and operation of a demonstration reactor called the Molten Salt Breeder Experiment (MSBE). In January 1973, ORNL was directed to terminate MSR development work. The program was reinstated a year later, and in 1974 ORNL submitted a more elaborate proposal calling for about $720 million to be spent over an 11-year period. This last proposal was also rejected, and in 1976 ORNL was again ordered to shut down the MSR *program for budgetary and political reasons.*

The major political reason that the LFTR and other MSR designs were not pursued in the1950s and 1960s is that they did not produce high levels of fissionable weapons grade plutonium, and the development of weapons was the high priority during the cold war. With all the advantages of MSR designs and amid efforts to eliminate excess plutonium, *now is the time to reactivate these programs*.

In his confirmation hearing, when asked about LFTR development Dr. Chu, head of the U.S. Department of Energy, felt that more research was needed to develop materials able to resist the high salt concentrations and high temperatures even though past MSR reactors were working for 2.5 years.

The thorium fuel cycle offers exciting prospects for R&D needs, with investment and development required across the entire fuel cycle including fuel properties, performance and fabrication, reactor safety and reprocessing technology.

Current MSR Efforts in the United States and Canada

Unfortunately, there are currently very few programs in the US to develop LFTRs or other MSRs.

Transatomic Power **www.Transatomicpower.com**

This MIT based company is developing a MSR - "*Today, almost all nuclear reactors worldwide are one type: the light water reactor. We are challenging the status quo by bringing back and improving upon a different design from the earliest days of the nuclear industry: the molten salt reactor.*

All the technical details of their approach, which uses "spent" nuclear fuel, but can use thorium, is detailed in their White Paper available on their web site. They have solved many of the remaining technical problems of MRSs.

Teresterial Energy **www.Terestrialenergy.com**

Terrestrial Energy, a Canadian Company, was founded in early 2013. Its business objective is to develop its patent-pending Integral Molten Salt Reactor ("IMSR"), and be ready for commercial deployment by early next decade. The IMSR offers a completely new paradigm for civilian nuclear energy.

The Integral Molten Salt Reactor (IMSR) is a commercially viable MSR that is designed to meet today's market need – cost competitive, scalable and grid independent civilian heat and power, heat and power at source of demand and not supply. The IMSR is a completely new narrative for civilian nuclear energy: safe, low levels of manageable waste and exemplary proliferation resistance.

A unique feature of their approach is the reactor core is replaced every 7 years. See material on their web site for details. *This by passes many of the potential stumbling blocks toward approval by the nuclear regulatory commission making the Teresterial Energy reactor the closest to being ready for deployment now.*

Terapower **www.terrapower.com**

TerraPower® is a nuclear energy technology company based in Bellevue, Washington. At our core, we are working to raise living standards globally. The essential factor? Energy. In 2006, Bill Gates and a group of like-minded visionaries decided that the private sector needed to take action. They believed that business

interests could develop a scalable, sustainable, low-carbon and cost-competitive energy source that would allow all nations to quicken their pace of economic development and reduce poverty. TerraPower's goal is to provide the world with a more affordable, secure and environmentally friendly form of nuclear energy.
Since 2008, TerraPower has been bringing together the strengths and experiences of the world's public- and private-nuclear energy sectors. With deep technical knowledge and commercial experience, TerraPower set out to develop a new nuclear technology called the traveling wave reactor (TWR). TerraPower's traveling wave reactor (TWR) is a Generation IV, liquid sodium-cooled fast reactor (MSR)based on existing fast reactor technologies. Innovations in metallic fuel, cladding materials and engineering allow TWRs to utilize depleted uranium as their primary fuel. Mission-driven innovation has distinguished TerraPower from other nuclear energy endeavors. TerraPower's unique approach will greatly simplify the current nuclear energy supply chain and significantly mitigate many of the shortcomings of today's nuclear energy technologies. Learn more about our progress. Bill Gates has contributed a billion dollars to this company, helping to ensure its success.

Flibe Energy
The CEO of Flibe Energy (www.flibe-energy.com) is Kirk Sorensen. With the blessing of his former employer, Teledyne-Brown Engineering, where he was Chief Nuclear Technologist, his goal for Flibe Energy is to have a functional, pilot-design Lithium-Flouride-Thorium Reactor (LFTR) on line by 1 Jun 2015, the 50th anniversary of the first MSR achieving criticality at Oak Ridge. Flibe Energy plans to take the proven MSR theories and designs of 1965-1969 to commercial reality.

The key to plans of this company is the use of liquid-fluoride-salt technology—and a special combination of fluoride salts which gives Flibe Energy its name. Lithium fluoride (LiF) and beryllium fluoride (BeF_2) together form a solution often called "F-Li-Be", that is the ideal medium for nuclear chemical processing and reactor operation. It is chemically stable, nearly invisible to neutrons, and impervious to radiation damage, unlike almost every other nuclear fuel. These salts carry large amounts of heat at low pressures, leading to small, compact, and safe designs for nuclear reactors.

What can the Comings Foundation do? The Comings Foundation will help to financially support the above entities in an effort to accelerate the development of MSRs and IMSRs in the U.S. and Canada and eventually the rest of the world.

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For excellent and thorough reviews see:
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Integral Fast Reactors Wikipedia.org

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