# Liquid-Fluoride Thorium Reactor Development Strategy

Kirk Sorensen

**Abstract**

Flibe Energy has worked to advance the technology for liquid-fluoride thorium reactors (LFTRs) since its incorporation in April 2011. Its objectives for modular reactor design and its plans for manufacturing and deployment of these reactors will be described. Flibe Energy has also undertaken a feasibility study of LFTR technology along with its partner Teledyne Brown Engineering. This study will be conducted under the auspices of the Electric Power Research Institute (EPRI) and Southern Company Services (SCS). The outcome of the study will be an estimate of the levelized cost-of-electricity (LCOE) from a 250-MWe modular LFTR built in the 2030 timeframe.

One of the great challenges for electrical utilities in the United States is the accelerated retirement of coal-fired powerplants. These retirements are taking place predominantly in the eastern United States, and particularly along the Ohio River Valley, Virginia, and the Carolinas. Coal plant retirement is being driven in large part by ever-tougher emissions requirements from the US Environmental Protection Agency. Coal and nuclear are two baseload electrical energy sources in the United States. "Renewable" energy options are not going to be able to meet the electrical demand in the regions where coal and nuclear plant retirements are going to be most significant. An intermittent and unreliable energy source such as wind or solar cannot replace a stable, reliable baseload energy source like coal and nuclear.

Several new light water reactors (LWR) are under construction in the United States, most notably the Vogtle 3 and 4 reactors being built in Georgia by Georgia Power, a division of Southern Company. They are AP1000 reactors and many of their components are built in a factory and shipped to the site, but they are still very large reactors and extensive site work is necessary.

The great challenge that looms for the US nuclear industry is that, even with license extensions, the time is coming when large numbers of nuclear reactors will be retired. This is sometimes called "the retirement cliff". The Fukushima incident and the onset of inexpensive shale gas, as well as market distortions surrounding solar/wind incentives, have accelerated the retirement of existing nuclear plants and exacerbated this challenge.

In order to preserve nuclear power's role in US electrical power generation it will be necessary to produce large numbers of new nuclear power plants starting in the late 2020s and continuing for several decades, and the rate at which they must be deployed means that there will need to be a very different approach to siting and construction.

The emphasis on private industrial leadership in new nuclear developments is something that is different in the United States compared with many other countries. For decades after World War 2, development of nuclear technology was the exclusive responsibility of the US Atomic Energy Commission (AEC). Private companies had to be invited to work with the AEC or be excluded entirely from any sort of nuclear enterprise. This approach has been slowly changing over the intervening decades, but it has only been in the last 10 or 20 years that the notion of nuclear "entrepreneurialism" could even be considered. Now, according to the Department of Energy's own outlook for the future of nuclear power, they expect that private industry will lead the way into new technologies. They see their own role as a supporter of research and development, and this is a significant change. It means that private businesses will have to develop business plans that can attract industrial investment

K. Sorensen (✉)
Flibe Energy, Huntsville, AL, USA



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and show the potential for profit. The DOE will help as they see fit but will not drive any particular technology direction.

Recognizing that it must be private industry that drives new nuclear technology forward in the United States, Flibe Energy was founded in 2011 with the ambition to provide the world with affordable and sustainable energy, water, and fuel. We believe that the way to achieve this goal is to use liquid-fluoride thorium reactor (LFTR) technology, which is an evolution of work done at the Oak Ridge National Laboratory (ORNL) on the Molten Salt Reactor Program (MSRP), which ran from 1957 to 1976.

Flibe Energy is located in Huntsville, Alabama, sometimes called the “Rocket City”. Huntsville is a high-tech community and its metro area has the highest per capita concentration of engineers in the US. It’s a place that has literally shot for the Moon and achieved it, as this is where Wernher von Braun and his rocket team developed the Saturn V moon rocket. It’s also the home of a large military facility, Redstone Arsenal, and NASA’s Marshall Space Flight Center facility, where I spent the first 10 years of my career. We consider it a good place to undertake the ambition of solving the world’s energy needs.

Huntsville is also geographically blessed for manufacturing and shipping activities. From its position on the Tennessee River, one can conveniently access the Gulf of Mexico, but it is far enough inland that the danger of severe storms is mitigated. An extensive rail network connects the country, and Huntsville International Airport is small in terms of passenger traffic but large in terms of air freight. Heavy manufactured components can be moved anywhere in the world from this location.

Huntsville is also not far from Oak Ridge National Laboratory in Tennessee, which is where some of the earliest discoveries about thorium were made. Thorium carbonate was first irradiated on a large scale to produce uranium-233 in ORNL’s Graphite Reactor in 1943, and from these samples it was discovered that uranium-233 had superlative nuclear properties, which permitted the development of a thermal breeder reactor. Later, in the 1950s, Oak Ridge also built the first molten salt reactor, the Aircraft Reactor Experiment, and showed it was stable and self-controlling. In the 1960s, the thorium fuel cycle and molten salt reactor technology was united when the Molten Salt Reactor Experiment was built and operated successfully on uranium-233 as a fuel, which comes only from thorium. Although its molten salt reactor research days ended long ago, proximity to ORNL is still an advantage. Many of the retirees still live in the local community and are willing to share their knowledge of molten salt reactors. There are also a great number of design and operations documents that reside in the Oak Ridge archives. So the proximity between Huntsville and Oak Ridge is advantageous.

To understand how we arrived at our decision to pursue a liquid-fluoride reactor based on the thorium fuel cycle, let us simplify a nuclear power system to its essential components. There is the reactor itself, where thermal energy is generated from over a million trillion fission reactions each second. This thermal energy is carried away by a coolant fluid to a heat exchanger, where that thermal energy is transferred to another fluid that will pass through the power conversion system. The power conversion system has a turbine, which turns a shaft connected to a generator, making electricity. About two thirds of the thermal energy produced is rejected as a waste product to the environment. In a pressurized water reactor (PWR), the primary coolant is pressurized water and the working fluid is also pressurized water raised into steam, with a steam turbine as the power conversion system. But there are other possible ways to build a reactor if different coolants are considered.

The temperature at which thermal energy is delivered from a reactor to its power conversion system is important because it determines how efficiently that thermal energy can be converted into useful work, most often electricity. The higher the temperature at which thermal energy can be transferred, the more of that thermal energy can be converted to work and, thus, less must be rejected as waste heat. So achieving higher and higher operating temperatures have always been a goal of nuclear operations. Achieving higher temperatures has depended greatly on the choice of coolant used in the reactor.

Nuclear reactors have generally been divided into four different families of coolants, and one could consider them in a two-by-two matrix, with operating pressure across the top axis and operating temperature along the side axis. Gas coolants operate at high temperature and high pressure. Fluoride salt coolants operate at high temperature and low pressure. Liquid metal coolants operate at medium temperatures and low pressures, and water operates at relatively low temperatures and high pressures. Ideally, the most desirable kind of coolant would be one that reaches the highest temperatures at the lowest pressures, and this can be achieved by considering the use of liquid fluoride salts as a coolant. Pressurized water, by contrast, must operate at very high pressures to achieve modest temperatures, which limits the efficiency at which it can be used to produce electricity.

There is another important attribute that should be considered very early in reactor design, and that is the volumetric heat capacity of the coolant, in other words, how much thermal energy a unit volume of the coolant can hold. Volumetric heat capacity is the product of the specific heat of the material and its density. In this category water is an exemplary choice, but its performance is exceeded by a fluoride salt composed of lithium and beryllium fluorides. The volumetric heat capacity of liquid sodium is marginal and gases have very low performance on this metric. Volumetric heat capacity is very important because it is the basic yardstick that sizes the reactor vessel, the piping, and the primary heat exchanger. The higher the volumetric heat capacity, the more compact the reactor can be. Gas-cooled reactors are particularly disadvantaged in terms of the volumetric heat capacity of their coolant because of its very low density.

As a class of materials, fluoride salts embody many advantages. They are the most chemically stable of all materials, which gives them a tremendous liquid temperature range of roughly a thousand degrees Celsius. This is far in excess of the few hundred degrees Celsius of liquid range that can be achieved with water under great pressure. Their ionic bonding structure also makes them entirely impervious to radiation damage from neutrons or gamma rays. This is again contrasted with water, which is continuously broken apart by radiation into hydrogen and oxygen, and must be recombined.

With the goal of reducing construction costs, it is highly desirable to use materials in the reactor to perform multiple functions. The pressurized water reactor is a good example of this, in that it uses water to both cool the fuel rods and to slow down, or moderate, the high-energy neutrons from fission. Liquid fluoride salts can also be more than just a coolant. The mixture of lithium fluoride and beryllium fluoride, sometimes called "flibe", can be used as a solvent to carry nuclear fuels such as uranium, plutonium, and thorium. When fluoride salts carry salts of nuclear fuels in them, they can fulfill the goal of having a material that serves multiple purposes in the reactor, and this has the potential to simplify the reactor and reduce costs.

In a liquid-fluoride reactor, fuel salt containing fissile material passes through metallic piping into the reactor vessel, where internal graphite structures slow down (moderate) neutrons, increasing the probability that these neutrons will cause fission reactions in the fissile material. Fission reactions deposit thermal energy in the fuel salt, which increases its temperature. As the heated fuel salt passes out of the reactor vessel into the piping system, fission reactions are no longer possible because the fuel salt has been separated from the graphite. In an external heat exchanger, the fuel salt heats a coolant salt and returns to the reactor vessel. The coolant salt passes out of the reactor containment region and heats the gaseous working fluid of a gas-turbine power conversion system, analogous to the gas turbines used in today's jet engines. The hot, high-pressure gas expands in a turbine, generating shaft work that turns a generator and produces electricity while also turning a compressor. The turbine gas exhaust, now at low pressure, is cooled either by external air or water. This cooling process can serve as the thermal input for a seawater desalination process if the reactor is located near salt water. The cold, low-pressure gas is then compressed in the compressor using shaft work from the turbine and is ready to be heated again to generate work and power.

A liquid fuel enables a remarkable passive safety feature to be implemented, which can solve perhaps the most vexing problem in reactor safety. For many years, there has been great concern about how to cool the solid fuel of a reactor in the event of a loss-of-coolant accident (LOCA) in order to prevent a meltdown of the fuel and the release of radionuclides. Various approaches have been proposed, including some newer and more innovative ideas involving large thermal sinks. But the use of liquid fluoride fuel enables a simple and remarkable solution, based on the melting temperature of the fuel, which is about 400 °C. The reactor is fitted with a drain line that is kept plugged by a frozen slug of salt. This plug is kept frozen by an active flow of coolant over the outside of the drain line. In the event of a complete loss of power, the salt plug melts, and the fuel salt in the reactor drains through the line into a dedicated tank called a drain tank. This tank is configured to maximize the passive rejection of decay heat to the environment. This enables the reactor to dispense with a multitude of emergency core-cooling systems that are required in solid-fueled reactors, particularly those that operate at high pressure. Because the frozen salt plug requires active cooling, in the event of complete power loss, that cooling will be interrupted and the plug will melt, causing the fuel to drain and the reactor to completely shut down. This remarkable safety attribute of the reactor is a compelling argument for consideration of the liquid fuel approach.

These numerous advantages of liquid-fluoride reactors would only be theoretical if it were not for the successful demonstration of this technology at Oak Ridge National Lab in the late 1960s. There, they designed and operated a molten salt reactor experiment, which used graphite to slow down or moderate the neutrons. Liquid fluoride salt, loaded with dissolved enriched uranium tetrafluoride fuel, flowed through channels milled in the faces of the graphite moderator elements. This structure was loaded in a reactor vessel made from a nickel superalloy called Hastelloy-N, which had been specially developed to be compatible with fluoride salts. As the salt flowed through the graphite lattice in the reactor vessel, it was heated by fission reactions.

The salt then passed into the primary heat exchanger where it was cooled by another salt, called the coolant salt, which carried the thermal energy outside of the reactor cell. The coolant salt was itself directly cooled by air as it flowed through a radiator structure. The reactor vessel, its pump, and primary heat exchanger were quite compact owing to the high volumetric heat capacity of the fluoride salts used, and the operation of the reactor was shown to be highly stable and self-controlling. Those who operated the reactor took the greatest pride in the fact that they had demonstrated that they could maintain the reactor over 20,000 h of successful operation from 1965 to 1969. The reactor ran on all three different kinds of fissile fuels during its operation, becoming the first and only reactor to achieve this feat.

The engineers, scientists, and technicians were very proud of their accomplishments and wanted to take the next step—a larger reactor that would demonstrate the complete thorium fuel cycle. However, the new Nixon Administration was cutting budgets across the board and insisted that the US Atomic Energy Commission consolidate all of their breeder reactor efforts into a single line of research. The liquid-fluoride reactor, demonstrating the thorium fuel cycle, was cancelled in 1972.

Breeder reactors were the goal of the entire US advanced nuclear enterprise at the time, and they could efficiently use either abundant thorium or uranium-238 as their basic fuels. However, breeder reactors were considerably more ambitious than reactors that just burned the very small fraction of natural uranium that is already fissile. They had to carefully manage their neutron supply and had to incorporate features to allow fuel that had been generated in the periphery of the reactor to be transferred to the central areas of the reactor.

For solid-fueled reactors this was quite a challenge, as it meant that periodically all of the fuel assemblies would have be removed and chemically dissolved. Then, various elements would be separated one from another and new fuel elements would have to be fabricated, which would be a substantial challenge. Molten salt reactors had a tremendous advantage in this respect as their fuel could be processed and refined in the same chemical state in which it was used in the reactor. Complicated steps of fuel removal, disassembly, decladding, dissolution, and later fuel refabrication were all eliminated in this concept.

As Flibe Energy has considered this technology, we plan to take advantage of several technological improvements since the 1970s. The first is that the technology for compact, reliable gas-turbine engines has also advanced considerably since the 1960s. Today's gas turbines, which use air as the working fluid and burn hydrocarbons to generate thermal energy, have excellent power density and are very responsive. However, other types of gas-turbine engines are possible, which would be heated by nuclear energy rather than combustion. They are based on a closed-cycle and have the potential to use fluids other than air, and which have superior properties.

One of the important advantages of a liquid-fluoride reactor is that it can supply thermal energy at temperatures suitable for a gas turbine power conversion system. This can lead not only to improvements in electrical generation efficiency, but also reductions in size and capital costs. The waste heat from a gas turbine is still of sufficiently high temperature to potentially drive a desalination system, which would be of tremendous value and importance in regions where water is just as important as electricity.

There has also been a far greater interest in small modular reactors, with the goal of building reactor components in a factory environment and reducing site preparation time. The researchers at Oak Ridge were proposing small modular reactors based on liquid-fluoride technology as far back as 1968. Creating modular reactors with liquid-fluoride technology is much easier because the reactors do not operate at high pressure and can be shipped and returned unfueled.

Today's approach to generating nuclear energy begins with mining uranium oxide ore out of the ground and chemically converting it to a fluoride salt—first uranium tetrafluoride and then uranium hexafluoride. This chemical conversion, from oxide to fluoride, is undertaken so that the uranium can be enriched. But at the end of the enrichment process, the uranium fluoride salt must be converted back to an oxide form and this is chemically unfavorable. Then, the oxide powder is sintered into pellets, which are loaded into rods that are formed into assemblies. It is these assemblies that are loaded into the reactor, irradiated to produce electricity, and then removed and disposed.

A liquid-fluoride reactor has the potential to dramatically simplify several of the steps in the nuclear fuel chain. Because the reactor uses fuel in the fluoride form, there is no need to convert uranium hexafluoride back to oxide and to form it into pellets, rods, and assemblies. The uranium hexafluoride can be reduced to uranium tetrafluoride as it is loaded into the reactor and used in that form to produce electrical energy. By using the nuclear fuel in fluoride form, the fuel cycle is not only simplified but fuel recycling is far more straightforward.

The long-term viability of nuclear energy will come about when nuclear fuels can be used with far greater efficiency than is done today. Only a small fraction of natural uranium is fissile; most uranium and all thorium is fertile, meaning that it can be converted into fissile fuel inside a nuclear reactor. Both thorium and uranium-238 require two neutrons to release their energies. One neutron converts them into a fissile form and the other neutron actually causes the fission. Thorium absorbs a neutron and becomes uranium-233, which will fission when struck by another neutron. Uranium-238 absorbs a neutron and becomes plutonium-239, which will also fission. However, there is an important difference between these two options. The fission of uranium-233, when one accounts for non-fission absorptions, will produce 2.3 neutrons. This is enough to continue the conversion of more thorium to uranium-233 fuel, even when accounting for various losses. But the fission of plutonium-239 will produce less than two neutrons. It is not sustainable in today's thermal-spectrum reactors.

The only way to sustainably use uranium-238 and plutonium is to design fast-spectrum reactors, which intentionally attempt to keep neutrons at as high a velocity as possible. In these reactors, non-productive neutron absorption in plutonium is suppressed and plutonium fission will produce more than two neutrons, enabling sustained consumption of uranium. The fundamental disadvantage of fast reactors is that the probability of neutron reactions, typically represented by a cross-sectional area, is much lower when the reactions are caused by fast neutrons than by slowed-down, thermal neutrons. Plutonium-239 will absorb thermal neutrons roughly one out of three times. The cross sections of plutonium-239 for fast neutrons are much, much smaller than for thermal neutrons; so much so that it requires hundreds of plutonium atoms to achieve the same probability of fission as a single plutonium atom to a thermal neutron. The implication of this difference is that fast reactors require much larger inventories of fissile fuel for a given power rating.

When the performance of uranium-233, which comes from thorium, is compared and contrasted with plutonium-239, which comes from uranium, it can be seen that uranium-233 has a much greater probability of fission and less probability of non-productive absorption. This is the reason why only the thorium fuel cycle is sustainable in thermal-spectrum reactors. Indeed, the central advantage of thorium as a nuclear fuel is its unique ability to be sustainably consumed in a thermal-spectrum reactor.

Thus, nature presents three nuclear options for nuclear energy. The first and most obvious is to use the tiny sliver of fissile uranium that occurs naturally, or to use uranium (and plutonium) in fast spectrum reactors with large fissile inventories, or to use thorium (and uranium-233) in thermal-spectrum reactors that have low fissile inventories.

In the thorium fuel cycle, thorium-232 is struck by a neutron, forming thorium-233. Thorium-233 has a short half-life of about 20 min and decays to protactinium-233, which is chemically distinct from thorium. Protactinium-233 decays with a half-life of about a month into uranium-233, which is fissile. If uranium-233 is struck by a neutron it will fission nine times out of ten, releasing 2.5 neutrons and continuing the process of releasing the energy of thorium.

Using the thorium fuel cycle nearly eliminates the production of transuranic waste, which is a major concern in the disposal of nuclear fuel. Because the thorium fuel cycle begins roughly six mass units before the uranium approach, it requires more neutron absorptions before it reaches its first transuranic nuclide, in this case neptunium-237. Because there are two opportunities for fission along this path, in the form of uranium-233 and uranium-235, the theoretical maximum production of transuranics is only 1.5 % and plutonium generation has the potential to be completely eliminated. By contrast, most of uranium fuel is only a single neutron absorption away from plutonium production.

The efficiency at which thorium could potentially be used as an energy source could cause us to rethink some of our opinions about energy resources. Imagine a single cubic meter of material—average continental crust—taken from anywhere in the world. That cubic meter contains, on average, about two cubic centimeters of thorium and half a cubic centimeter of uranium, if each was in its metallic form. If that thorium were converted to energy in a liquid-fluoride reactor, it would be equivalent to the energy in thirty cubic meters of the finest crude oil in the world. Truly, the efficient use of thorium is a transformational technology that can change the energy balance of the world.

Thorium would be used in a liquid-fluoride reactor by generating a thorium tetrafluoride salt similar to the uranium tetrafluoride salt discussed earlier. Thorium tetrafluoride would be dissolved in flibe salt and then introduced into a "blanket" region of the reactor, where it would absorb neutrons and convert to uranium-233. This uranium would be chemically removed from the blanket and introduced into the central fuel salt, where it would be fissioned, releasing energy and generating the neutrons needed to continue fission and produce more fuel. Both the blanket and the fuel could be continuously chemically processed to remove the fission products that built up.

We see a tremendous opportunity for liquid-fluoride reactors to generate energy at high temperatures, low pressures, and low costs. They simplify the fuel cycle and allow the use of any fissile material. They are particularly well-suited to implement the thorium fuel cycle, which can achieve far greater fuel efficiencies that our present use of rare uranium-235.

Alvin Weinberg was the inventor of the pressurized water reactor and the strongest champion of the liquid-fluoride thorium reactor. Dr. Weinberg died in 2006, but in his 1991 autobiography he said: "During my life I have witnessed extraordinary feats of human ingenuity. I believe that this struggling ingenuity will be equal to the task of creating the Second Nuclear Era. My only regret is that I will not be here to witness its success." I hope that we may realize his dreams.