FUTURE TECHNOLOGY

# Thinking nuclear? THINK THORIUM

Thorium-based reactors could be more efficient and create less waste than today's uranium-based generating plants.

**Thorium, a common mineral in the world, could supply relatively inexpensive and abundant power.**

From the early 1950s to the mid-1970s, an active R&D program at **Oak Ridge National Laboratory** in Tenn. came up with a promising way to use thorium for making large amounts of energy cleanly and safely. It was based on a revolutionary kind of nuclear reactor that uses liquid rather than solid fuel. Liquid fuel has significant theoretical advantages in operation, control, and processing over solid fuel, but a basic question had to be answered: "Will it work?"

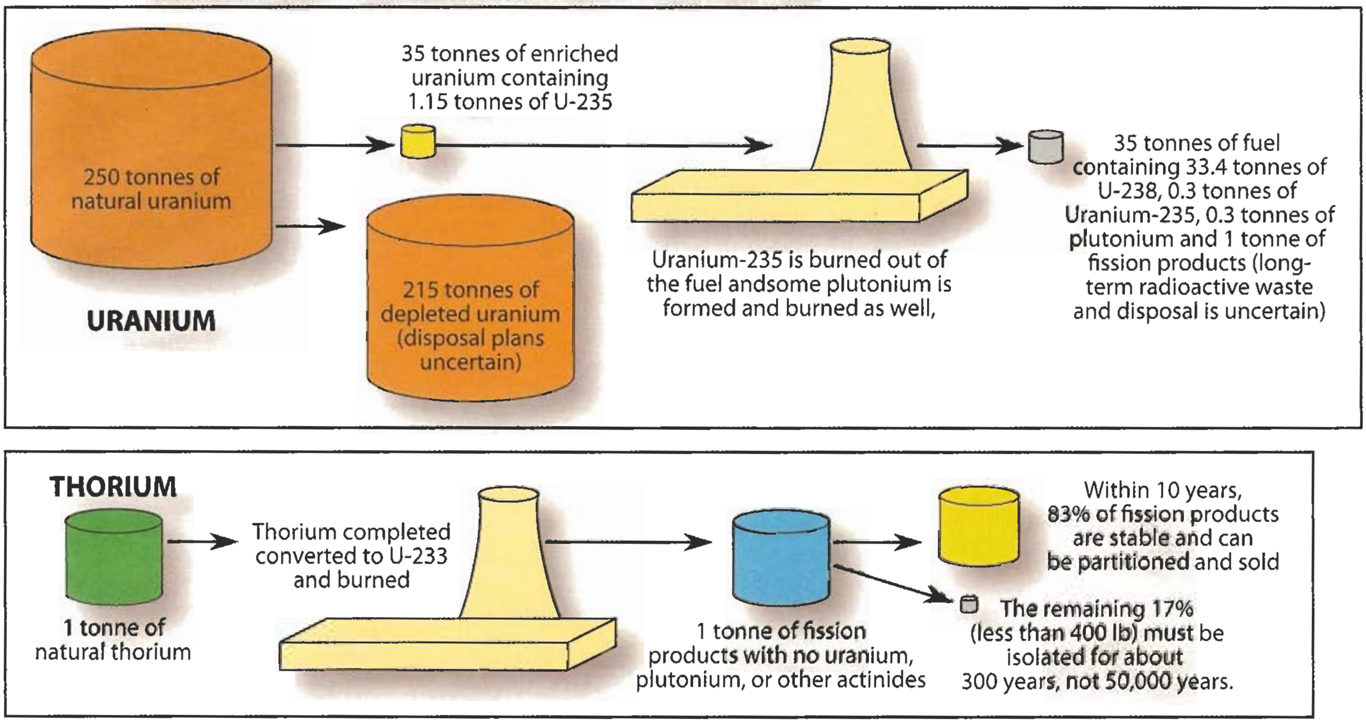
To that end, Oak Ridge engineers built four liquid-fueled reactors. Two used water-based liquids, and two were based on liquid fluoride salts. The water-based reactors had to operate at high pressures to generate the temperatures needed for economical power generation. They could also dissolve uranium compounds, but not those containing thorium, which made fuel reprocessing as complicated for the water-based rectors as it is for solid-fueled versions.

The fluoride reactors had neither of these drawbacks. They could operate at high temperature without pressurization. They could also dissolve both uranium and thorium in their fluoride-salt mixtures, and the mixtures were impervious to radiation damage due to their ionic bonds. Therefore, Oak Ridge engineers opted to concentrate on the technically superior liquid-fluoride-salt approach in future R&D.

In the late 1960s, however, the director of Oak Ridge National Lab, Alvin Weinberg, was fired by the U.S. Atomic Energy Commission for his advocacy for this type of reactor and his efforts to enhance the safety of conventional light-water reactors, a design he had patented. With Weinberg's departure, the AEC squashed research in liquid-fluoride reactors in favor of liquid-sodium-metal-cooled fast breeder reactors, which were based on converting conventional uranium to plutonium. Technical overlap between the two programs was almost nonexistent, so after can-

## Comparing thorium and uranium fuel cycles

**MISSION: MAKE 1,000 MW OF ELECTRICITY FOR ONE YEAR**



**Nuclear engineers can extract 100% of thorium's usable energy, compared to just 0.7% for uranium. So, as this illustration demonstrates, it takes much more raw material and leaves much more dangerous waste to generate 1,000 MW of electricity in a year using uranium than it does using thorium.**

cellation, research into liquid-thorium reactors faded away.

Interest in thorium reactors has undergone a significant resurgence in the last few years. Despite the lack of funding, individual efforts continue to advance the technology. This "open-source" effort has been greatly aided by the Internet and the vast amount of research done by government scientists and engineers.

### Thorium basics

Thorium is a naturally occurring, mildly radioactive element. To use it in reactors, thorium must absorb neutrons, a process that eventually converts it to an artificial isotope of uranium, uranium-233. U-233 is fissile, and when it absorbs a neutron it generally fissions, releasing two or three neutrons plus a million times more heat (energy) than burning an equivalent mass of fossil fuel. It takes two neutrons to release energy from thorium and U-233 can supply them, which means it is theoretically possible to sustain energy release from

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**Resources:**

**Energy from Thorium,** *www.energyfromthorium.com*

**Thorium Energy Alliance,** *www.thoriumenergyalliance.com*

## Another approach to thorium

Thorium as a nuclear fuel has been proposed for a variety of different nuclear reactors. One approach is to use solid thorium-oxide fuel rods in existing water-cooled nuclear reactors. This was demonstrated in the Shippingport nuclear reactor in the late 1970s and is currently advocated by a company called **Lightbridge,** McLean, Va. (*www.ltbridge.com*). Used in conventional reactors, thorium increases fuel performance by allowing longer fuel burn up, but the gains are nowhere near the improvement possible in LFTRs. That's because the thorium fuel would have to be reprocessed to extract more of its energy, and reprocessing thorium oxide fuel is substantially more difficult than reprocessing uranium oxide fuel, a procedure that is not currently cost effective.

## There's thorium in them thar hills

**Thorium is not rare. In fact, as shown here, the U.S. buried 3,200 tonnes of thorium in the Nevada desert when its interest in thorium withered. And a single Idaho mine could supply 4,500 tonnes of thorium per year. It's estimated there are already 1.2 million tonnes of known economically extractable thorium in the world, with the U.S. sitting on 160,000 tonnes of it, according to the U.S. Geological Survey.**

Thorium is more common in the Earth's crust than tin, tungsten, mercury, or silver, not to mention uranium. Out of a cubic meter of average crust, there is the equivalent of about 40 gm or four sugar cubes of thorium. This is enough thorium to provide enough electricity to fully support one person for about 10 to 15 years if completely fissioned to release its energy.

Our current regulatory environment requires that mined thorium be considered "waste" and disposed of at great expense. In fact, the U.S. has buried 3,200 metric tonnes of refined thorium nitrate in the Nevada desert due to the lack of demand.

It's estimated that there are 160,000 tons of thorium that could be dug out of the U.S. And it's easy to find the element on other planets such as Mars. In fact, our Moon has as much as the Earth. To make matters even simpler, the increased demand for rare-earth elements such as neodymium and samarium will lead to large amounts of available thorium in the near future because it is commonly found alongside these elements.

thorium indefinitely. This is the basis of a thorium reactor.

Recent efforts focuses on a concept called the Liquid-Fluoride Thorium Reactor (LFTR, pronounced "lifter"). In a LFTR, the reactor vessel contains two types of liquid-fluoride salts. One, the fuel salt, holds the fissile fuel (U-233) that sustains the nuclear reaction. The other, the blanket salt, has enough thorium to absorb about half of the neutrons from fission and produce more U-233.

The blanket salt also shields the reactor vessel from neutron damage and gamma-ray irradiation. As thorium in the blanket converts to U-233, it is physically transferred to the fuel salt, where it fissions, releasing neutrons and heat. Heat moves to a coolant salt outside the core, then to the working fluid of a closed-cycle gas-turbine engine to generate electricity. Waste heat can be rejected to either air or water, depending on the availability of cooling water. Waste heat could also be used to, for example, desalinate seawater, letting it profitably produce potable water.

### How it works

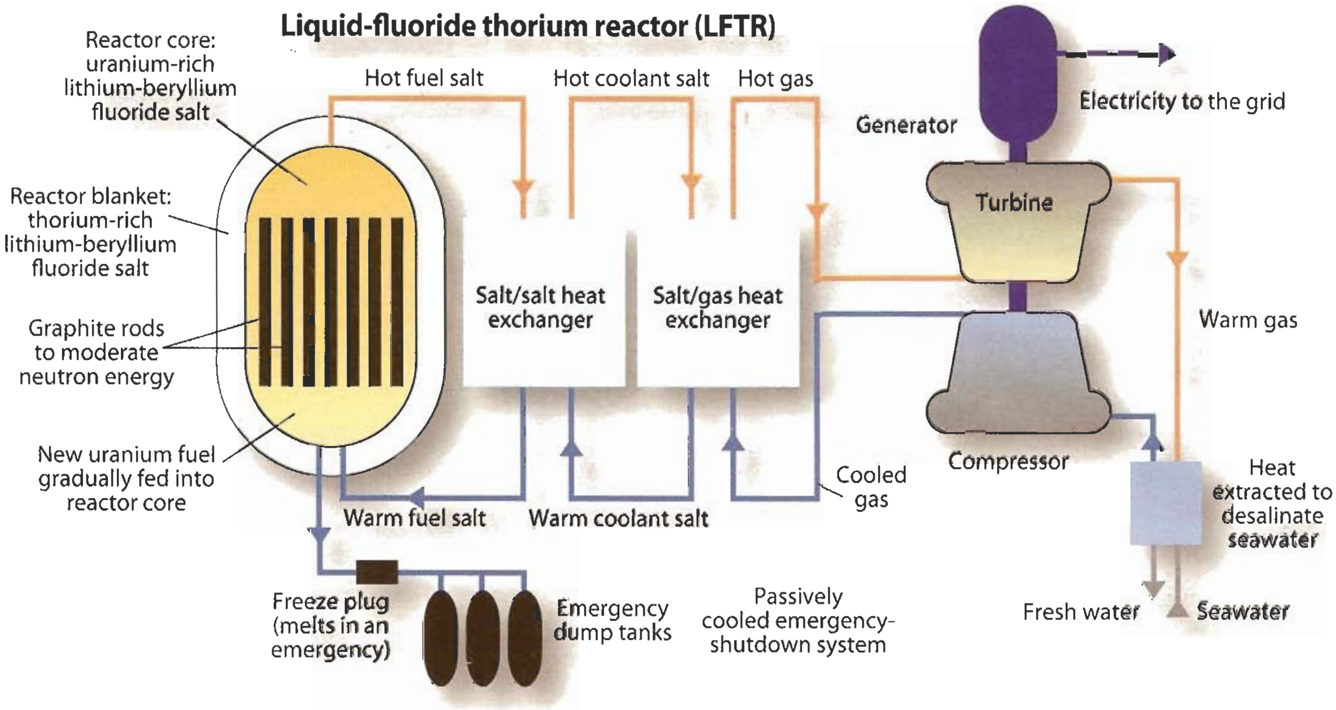
There are some key requirements for the fuel and blanket salts. They must:

- be chemically stable
- be impervious to radiation
- have little appetite for neutron absorption
- be able to dissolve significant amounts of uranium, thorium, and fission products
- have minimal melting temperatures
- have high heat capacities.

Fortunately, chemists long ago identified a mix of lithium and beryllium fluoride salts that fits the bill. One main ingredient is lithium fluoride (LiF), which is highly enriched in lithium-7. This isotope makes up 90% of natural lithium and has almost no propensity to absorb neutrons. The other ingredient is beryllium difluoride ($BeF_2$). It is toxic and must be used carefully, but is well understood by beryllium manufacturers. (This mix, lithium fluoride and beryllium fluoride ($LiF\text{-}BeF_2$) is sometimes called "FLiBe.")

Uranium tetrafluoride ($UF_4$) is dissolved in the FLiBe fuel salt, while thorium tetrafluoride ($ThF_4$) is dissolved in the blanket salt. Both mixtures have a volumetric heat capacity comparable to that of water (or four times that of liquid sodium and 2,000 times that of helium). This means reactors can be smaller than conventional ones with the same power output.

The coolant salt could be a variety of different mixtures, but the leading candidate is currently a mix of lithium fluoride, sodium fluoride, and potassium fluoride (LiF-NaF-KF),



**This schematic of a liquid-fluoride-thorium reactor shows the safety system. A plug of frozen material keeps salts in the reactor core. If power is lost, the plug thaws, draining the salts into passively cooled dump tanks where nuclear reactions would cease and prevent the spread of any radioactive material.**

sometimes called "FLiNaK". Coolant salt pumped through the primary heat exchanger pulls heat out of the fuel salt, then gives up that heat to a gaseous working fluid in the gas heaters.

The closed-cycle gas turbine could be based on a variety of different pure gases or gas mixtures. It differs from other gas turbines proposed for nuclear reactors because the gas in the turbine never directly cools the nuclear fuel itself. This is referred to as an indirect rather than a direct gas-turbine cycle, which has been proposed for pebble-bed and gas-cooled solid-fueled reactors.

Indirect gas turbines have several advantages over direct versions. For example, the gas never has to withstand the damaging neutronic environment of the reactor. Contamination concerns, which bedeviled nuclear-gas-turbine efforts such as pebble-bed reactors, are also nearly eliminated by keeping the gas away from the reactor fuel. Indirect turbines also let the core operate at ambient pressure even though the gas loop is at high pressure. The coolant salt that separates the gas and fuel salt prevents pressurization of the fuel salt in case of a gas leak into the coolant by blowing out check valves, thus preventing core pressurization.

The gas-turbine approach for LFTR could use nitrogen as a working fluid, which is essentially identical to air for design purposes. This would let engineers apply their vast knowledge of open-cycle, air-based gas turbines, saving time and money.

In the closed-cycle gas-turbine approach, the gas must be heated *and* cooled externally. Heating comes from the reactor's coolant salt. Cooling, on the other hand, will come from using either air or water as a heat sink. If air is used, the gas-to-gas heat exchangers will be large, but the reactor will not need local cooling water. This would let LFTRs be built in arid regions and other locations traditionally not able to handle nuclear plants because of scarce water supplies.

If water cools the gas in the turbine, the heat exchangers (and capital costs) will be much smaller. And using seawater as a coolant opens further possibilities. Currently, power plants using steam for power conversion must reject heat through the plant's condenser isothermally (at a constant temperature). So to improve efficiency at these plants, condensation is done at pressures far below atmospheric pressure and at extremely low densities. This leads to large equipment, large capital costs, and the need for lots of cooling water.

A LFTR's gas cooling, on the other hand, rejects heat from about 100°C down to about 30°. In properly built heat exchangers, the waste heat could be used to distill seawater into fresh water. Multiple-stage distillation at different pressures would even let this waste heat be "reused" several times to get even more fresh water. Thus LFTR plants in coastal regions could send both electricity and fresh water to local consumers.

## Burning it all up

The temperatures at which LFTRs operate (700 to 800°C) let their power-conversion system hit efficiency levels of nearly 50%, compared to only 35% for conventional nuclear plants. And the efficiency at which a LFTR converts thorium into heat lets utilities get 200 to 300 times more useful energy of out of a kilogram of thorium than they can from a kilogram of uranium.

Current uranium-fueled reactors can only extract a small amount of uranium's potential energy before it becomes too badly damaged from radiation and depleted of fissile content. Currently, technicians remove the spent and damaged uranium and it is stored until eventual disposal. The fuel could be reprocessed using conventional methods such as plutonium-uranium extraction (Purex) to remove fissile material and refabricate new fuel elements. But these techniques are expensive and only improve the energy payoff by a few more percent. To access all the energy in uranium fuel requires a fast breeder reactor, which costs significantly more than a conventional uranium reactor. Thus utilities have powerful incentives to use fresh uranium, extracting only a small amount of energy before throwing it away.

LFTRs, on the other hand, can profitably extract essentially all of thorium's energy without complicated reprocessing or excessive capital costs. This is because the fuel type and reactor configuration would be specifically chosen to simplify fuel processing. As uranium-233 fuel forms in the LFTR's blanket, it can be removed easily by sparging with fluorine gas in an external fluorination column. This converts the uranium tetrafluoride ($UF_4$) in solution into gaseous uranium hexafluoride ($UF_6$). $UF_6$ percolates out of the blanket and is directed to the fuel salt, where it is reduced back to $UF_4$ by hydrogen gas in a reduction column. The HF created during reduction is electrolytically split back into $H_2$ and $F_2$ to provide reactants for the process all over again.

Within the fuel salt, gaseous fission products such as xenon are released during fission that can "poison" the fission process and make changing power settings quite difficult. All high-power civilian reactors have to fight xenon poisoning during power level changes, and grid blackouts are especially troublesome. If a conventional nuclear reactor is shut down for more than a few hours because of a blackout, it has to remain shut down for about a day to let the xenon decay sufficiently before it can be restarted.

In LFTRs, xenon comes out of solution as the fuel salt is pumped, letting it be removed effortlessly and disposed of properly. This lets the reactor respond quickly and effectively to changes in power settings and changes in the power grid.

LFTRs also address the problem of fission products building up. The LiF-BeF2-UF4 fuel salt accumulates fission products which need to be removed every year or so. This could be done by removing the valuable uranium-233 from the salt by fluorination, as was mentioned previously, leaving a "bare" salt of FLiBe and fission products. Then in a high-temperature distillation still, the LiF and BeF2 are volatilized and separated from the remaining fission products. LiF, BeF2, and UF4 are then recombined to reform the fuel salt which is reintroduced into the reactor. The remaining fission products contain valuable stable minerals such as neodymium, lanthanum, and praseodymium which can be separated and used commercially.

And one of LFTR's major benefits is that because it completely "uses up" the thorium, there is relatively little nuclear waste.

The fuel choices, reactor configuration, and power conversion system of LFTR have all been chosen to make efficient energy from thorium a reality. It will take research, substantial development effort, and national will to achieve this goal, but the payoff will be immense. A world powered by thorium safely for many tens of thousands of years is the goal of those working to realize the potential of thorium. **MD**