POWER & energy

TOO GOOD TO LEAVE ON THE SHELF

A reactor design mothballed 40 years ago doesn't seem like a technology with much potential. But molten salt reactors could actually deliver on nuclear power's long-heralded promise of cheap and limitless energy.

By David LeBlanc

▲ These technicians were at work on the graphite core of the Molten Salt Reactor Experiment, a 1960s test of an alternative reactor design.

The idea of nuclear-powered aircraft seems crazy with the benefit of hindsight. But for the U.S. Air Force generals of the late 1940s and 1950s, it was the answer to a Cold War dilemma: How can you have a round-the-clock nuclear deterrent when the planes carrying atomic bombs have to stop for fuel every few hours? The fear was that a sneak attack from Soviet bombers could destroy the capacity of the U.S. to retaliate, thus providing an incentive for a first strike.

An atomic-powered bomber would provide the ultimate deterrent, the Air Force Generals believed. With an ability to stay aloft for an extended period, the planes could circle in Arctic airspace waiting for the orders to attack. Crews would live on the bombers much the way that submariners do in nuclear subs, which were just coming online.

Test flights of the NB-36 Crusader carried a 3-megawatt water-cooled reactor in the rear bomb bay (and 12 tons of shielding around the crew compartment). The reactor aboard the NB-36 wasn't connected to the engines—the plane burned conventional fuel for power—but was simply in place to learn about operating a flying reactor.

One thing became obvious: a smaller, simpler reactor was needed. Much as the U.S. Navy had shepherded in the pressurized water reactor for its nuclear submarine fleet, an Air Force research program developed its own reactor design—an elegant piece of technology that could have become the foundation for a very different nuclear power industry.

Instead, the atomic plane program was canceled, its rationale eliminated with the advent of intercontinental ballistic missiles. And except for two experimental reactors mothballed over 40 years ago, the elegant solution discovered during research on flying reactors has never been fully tested.

▼ The NB-36 made a number of flights in the 1950s carrying an operating nuclear reactor. The crew worked from a lead-shielded cockpit.

U.S. AIR FORCE

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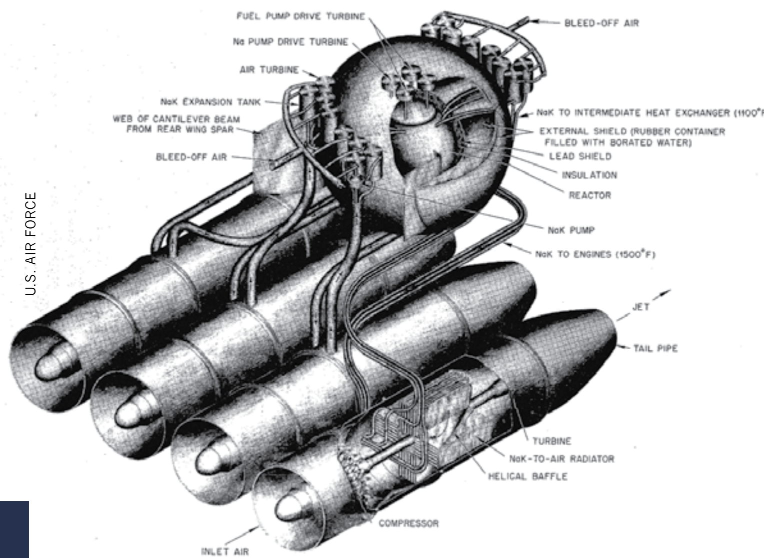
That's a shame, because the concept that was developed—the molten salt reactor—is one that has a number of decided advantages over conventional reactor designs. MSRs run at low pressures and so don't need the large pressure vessels common in today's reactors. They can run on a variety of fuels and can even burn transuranic waste produced at other reactors. More intriguingly, molten salt reactors can be designed to breed their own fuel without the need for off-site processing.



U.S. AIR FORCE

▲ Researchers designed a molten salt reactor for use on nuclear-powered bombers. Heat from the reactor would replace the combustion of fuel within the jet engines.

With resurgent interest in nuclear power—the so-called nuclear renaissance—now is a good time to ask whether we want to build more copies of the old reactor designs. Molten salt reactors may seem like a odd technology that's been on a strange trip in obscurity, but given a fair hearing, the MSR's day could be at hand.

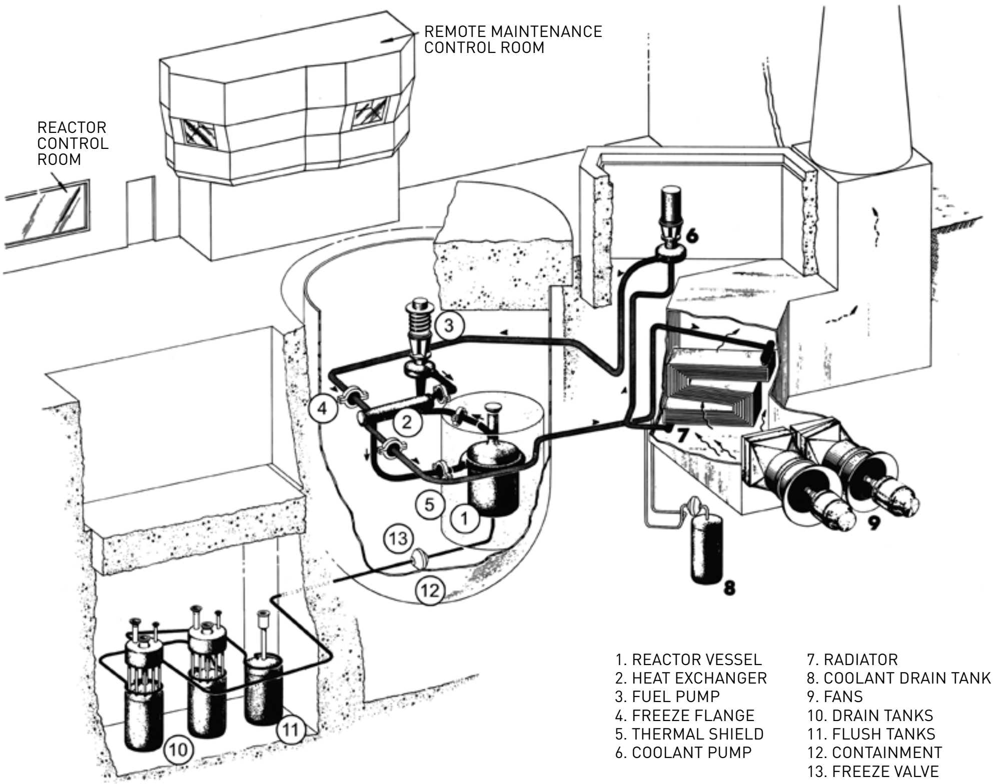
Molten salt reactors (sometimes referred to as liquid fluoride reactors) contain no fuel pellets. Instead, the fissile and fertile materials are dissolved in a fluid medium. The fluid can be one of various fluorides of uranium, thorium, or plutonium, which form low melting point eutectics when combined with certain carrier salts such as $2^{7}LiF\text{-}BeF_2$, which is known as flibe. When raised above the melting point (some 460 °C) this mixture becomes a very stable liquid that can flow continuously between a simple core (typically containing graphite moderator) and external heat exchangers. Heat from the radioactive primary salt is transferred to a clean intermediate salt that then transfers heat to either a steam or gas cycle.

There are multiple advantages to this design. To start with, molten fluoride salts are excellent coolants, with a 25 percent higher volumetric heat capacity than pressurized water—and nearly five times that of liquid sodium.

OAK RIDGE NATIONAL LABORATORY

MOLTEN SALT REACTOR EXPERIMENT

Although the design of the MSRE was radically different from anything that had been built before, researchers at Oak Ridge National Laboratory were able to operate the 8 MW reactor without incident for almost five years.



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That greater heat capacity results in more compact primary loop components like pumps and heat exchangers.

Molten salt reactors run at near-atmospheric pressure, so the thick-walled pressure vessels found in light-water reactors is unnecessary. Since there is no water or sodium in the reactor fluids, there is zero possibility of a steam explosion or hydrogen production within the containment. Indeed, molten salt reactors can be designed without a graphite moderator, so combustible material need not even be present.

MSR designs have very strong negative temperature and void coefficients, which act instantly, aiding safety and allowing automatic load following operation. Also, the fluid nature of the fuel means meltdown is an irrelevant term. In the case of emergency, the fuel salt is automatically drained to passively cooled, critically safe drain tanks. Any salt temperature above normal simply melts a frozen plug of salt like pulling the plug on a bathtub.

Fissile material concentrations within an MSR are easily adjusted on a continuous basis. Such adjustments eliminate excess reactivity and the need for burnable poisons, which is common in solid-fuel reactors.

Also, many fission products quickly form stable fluorides that will stay within the salt during any leak or accident. Others are volatile or insoluble and can be passively and continuously removed. Xenon gas, which represents almost half of all neutron absorptions to fission products in most solid-fuel reactors, will just bubble out of the fuel salt and can be stored outside the reactor loop.

Some of the fission products must remain isolated for several hundred years, but there is no need for Yucca Mountain-type repositories intended to last millennia. It is plutonium and the other transuranic elements of light water reactor spent fuel that are the real issue. MSRs produce them at much lower rates and recycle them, thus the long-lived radiotoxocity of MSR waste is one-ten-thousandth that of an LWR.

There are many design variations, which can be grouped into two main categories. Breeder reactors produce their own fissile fuel after startup. The typical plan for a breeder is to start with fertile thorium, which after capturing a neutron decays to fissile uranium-233. This cycle is capable of being a breeder in softer neutron spectrums where neutrons are slowed down, typically by graphite; the familiar breeding cycle that converts uranium to plutonium requires a harder or faster neutron spectrum.

The reactors don't have to be breeders, or be limited to a thorium cycle. Without fuel processing, MSRs can run as simple converters with excellent uranium utilization even on a once-through cycle. Converter designs, which require annual additions of fissile material, can run excellently off even low-enriched uranium. Converters and breeders each offer advantages, and the main point of difference between the two is whether fission products are actively processed out of the salt during operation.

Another point of design optimization is in fluid flow through the reactor. Some breeder designs, for instance, call for a single fluid containing both the fissile U-233 and the fertile thorium. Such a configuration tends to be the simplest core design, but processing out fission products is quite difficult because thorium is chemically almost identical to the rare earth fission products.

One way around the processing problem is to keep the fertile thorium separate from the fissile uranium. Essentially, then, there are two fluids: a fuel salt that runs through the reactor core and a blanket salt that contains the thorium. Because the thorium captures neutrons and produces U-233, uranium is periodically removed from the blanket salt and transferred to the fuel salt. Removing the uranium from the blanket salt is relatively straightforward: simply bubbling fluorine gas through the salt will convert UF_4 salt to gaseous UF_6. The uranium hexafluo-

▶ The radiator of the MSRE (top) dissipating heat from the molten salt coolant. ORNL director Alvin Weinberg (right) notes the 6,000th hour of full-power operation.

OAK RIDGE NATIONAL LABORATORY

ride can be converted back to a salt and added to the fuel. The two-fluid design has other advantages but can suffer from complexity in the reactor core.

There is also a hybrid molten salt reactor design, nicknamed the "one-and-a-half fluid" design. It sees a fuel salt containing uranium and thorium surrounded with a blanket salt intended only to catch neutrons leaking from the core. All three modes of operation have merit and continue to be studied worldwide.

The ill-fated Aircraft Reactor Program for the U.S. Air Force developed a large knowledge base and led to a successful test reactor. The Aircraft Reactor Experiment was built and tested at the Idaho National Laboratory. The ARE was a high-temperature reactor with a peak temperature of 860 °C employing a $NaF\text{-}ZrF_4$ carrier salt and fueled with highly enriched uranium-235. Clad blocks of beryllium oxide provided moderation.

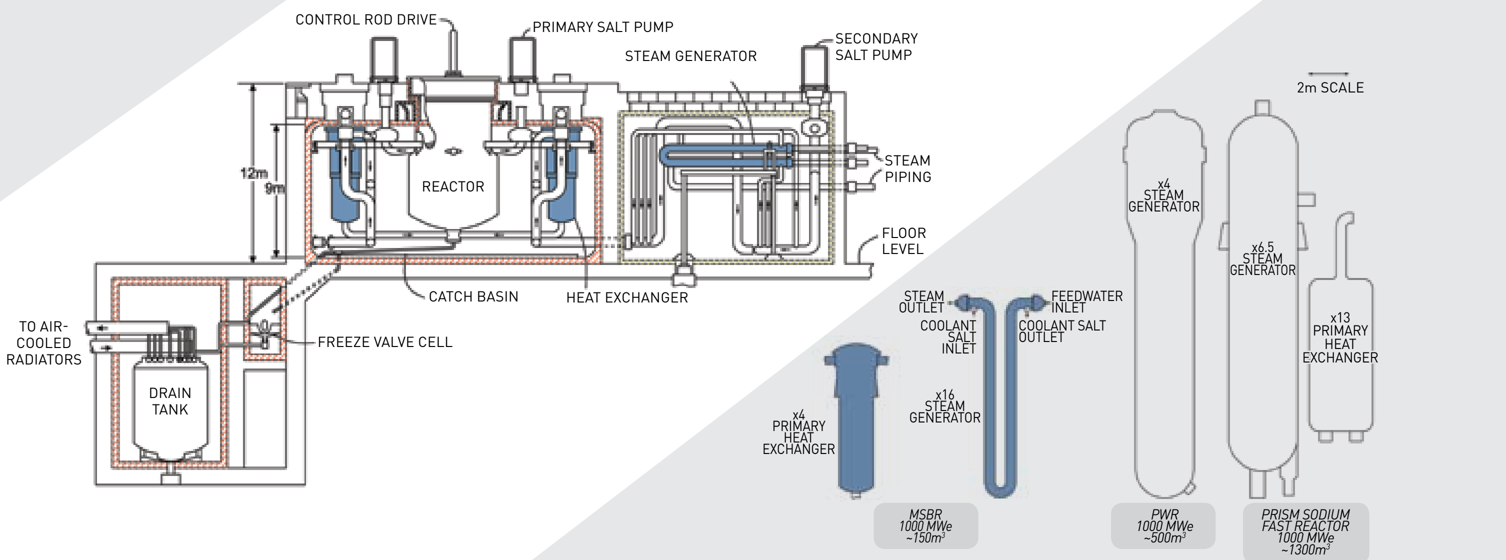
With the success of the first test reactor, researchers at Oak Ridge National Laboratory, led by Alvin Weinberg, began work on MSRs as power-producing reactors. The work went through three distinct eras. In the mid-1950s the focus was on a simple one-and-a-half fluid design of nested tanks of fuel and blanket salt. Once it was discovered that graphite worked well with the molten salts, Oak Ridge researchers developed two-fluid designs that featured complex plumbing to keep the two salts separate but interlaced within the core.

During this period in the early 1960s Oak Ridge also designed and built the eight-megawatt Molten Salt Reactor Experiment (MSRE). For simplicity it was designed as a simple single fluid without thorium, just a simple tank of graphite with flow channels. It operated at a temperature of 650 °C to allow long life out of the nickel alloy used as piping and heat exchangers, and had a highly successful run for almost five years between 1965 and 1969. The MSRE showed that maintenance and repair could be carried out smoothly and that reactor control was highly stable, as predicted.

Meanwhile, Oak Ridge continued to focus on the two-fluid design for a power reactor but the graphite

MOLTEN SALT BREEDER REACTOR

A more advanced design that was never built, the MSBR would have been capable of breeding its own fuel. Because of its simple, low-pressure design, many of the components of the MSBR would have been smaller and cheaper than those found in competing reactor technologies. A comparison of heat exchange units is shown at right.



plumbing proved too large a challenge (graphite first shrinks and then swells in operation). In 1968 they gave up and switched to the simpler single-fluid core with its harder fuel processing. This became the new standard for many years.

In 1973, however, the Atomic Energy Commission (a precursor to the U.S. Department of Energy) made a controversial decision to cut funding for molten salt reactor development. The main official rationale was corrosion discovered during MSRE operation, though Oak Ridge had already mostly addressed that issue.

Many other theories have been raised for why such a promising system was canceled. One theory is political: Oak Ridge was the only lab working on the MSR, while work on the sodium-cooled fast breeder, the competing technology, was being conducted with a much larger budget at several national labs. Another theory was that it was personal—Oak Ridge's director, Alvin Weinberg, had drawn the ire of the AEC by publicly raising safety concerns about pressurized water reactors. Finally, and more speculatively, is the theory that the MSR was killed because it didn't produce plutonium, which was a military objective.

Limited work continued at ORNL until about 1980 with an increased emphasis placed on maximizing proliferation resistance. This led to the discovery that the same basic single-fluid design could work remarkably well as a simple converter reactor using low enriched uranium and thorium. Regardless of past success, once funding was cut, it has been almost impossible within the U.S. and difficult elsewhere to get even modest funding for research since the system was viewed as being abandoned by its U.S. inventors.

After decades of the idea's being kept alive almost by word of mouth, there has been a recent resurgence of interest in molten salt reactors. There are now substantial programs in France, Russia, and the Czech Republic with smaller efforts in many other countries. Russian efforts have focused on a simple design to burn transuranic waste, and there are great advantages to molten salt reactors in this regard. Czech work is extensive with a strong chemistry program; in particular, the development of fluoride volatility processing of spent LWR solid fuel.

The largest new effort has been in France with the development of the thorium molten salt reactor. The French design has evolved to one with a graphite-free core salt of thorium and U-233 surrounded radially by a thorium blanket salt and axially by reflectors. It features an excellent breeding ratio, but drawbacks include a high fissile load and a materials challenge of the reflector and blanket zones.

Perhaps the biggest boost to the concept came when a version of the molten salt reactor was one of the six featured technologies of the Generation IV reactor program beginning in 2002. Suddenly, this almost forgotten technology was a hot research topic.

Many of the drawbacks to the molten salt reactor approach have been worked out. For example, I have contributed a surprisingly simple solution to the plumbing nightmare of interlaced fuel and blanket salts that caused Oak Ridge to abandon the otherwise promising two-fluid concept in 1968. The new architecture is a tube within a tube: a large blanket tube enveloping a long and narrow core. The hundreds of barriers in the 1960s ORNL design are thus reduced to just one.

While it can be argued that this approach has many

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advantages over other breeder designs, it's likely that at the least the first generation of new MSRs, should they be built, will be simple single-fluid converter reactors that require a minimum of additional research and development. Such reactors would be based on Oak Ridge's DMSR concept that the laboratory developed in the late 1970s. The "D" stands for "denatured"—the uranium in the reactor contains too much U-238 to be useful in weapons. The concept also dispenses with processing the salt to remove fission products; the same salt is used throughout the 30-year life of the reactor with small amounts of low enriched uranium added each year to keep the fissile material constant. The amount of uranium fuel needed—about 35 metric tons per GWe year—is only one-sixth of what is used by a pressurized water reactor. That means the price of uranium could rise an order of magnitude above its 2007 peak of $300 per kilogram before the fuel cost of a DMSR would reach even 1 cent per kWh.

The amount of fissile material needed to start new reactors is also very important, especially in terms of a rapid fleet expansion. The 1 GWe DMSR was designed for 3.5 metric tons of U-235 (in easy-to-obtain low-enriched uranium) which can be lowered if uranium costs go up. A new PWR, by contrast, needs about 5 metric tons, whereas a sodium-cooled fast breeder such as the PRISM design requires as much as 18 tons of either U-235 or spent fuel plutonium. Any liquid fluoride reactor can be started on plutonium as well, but this turns out to be an expensive option, since removing plutonium from spent fuel costs around $100,000 per kilogram.

The DMSR features a larger, lower power density graphite core than other MSR breeder concepts. So while the graphite would last a full 30 years, the DMSR would still be only a fraction of the size of gas-cooled graphite reactors and would not require a pressure vessel. In fact, the simple thin-walled DMSR containment vessel would be wider but much shorter than those of PWRs and BWRs. The construction of the reactor containment building offers savings as it does not need the huge volume and ability to deal with steam pressure buildup needed for LWRs or CANDU reactors.

The overall thermal efficiency of the plant would be quite high. With a salt outlet of 700 °C and using the latest ultra-supercritical steam cycles or gas Brayton cycles, efficiencies close to 50 percent would be possible.

While up-to-date cost estimates for a molten salt reactor are not available, it is quite simple to see the potential overall advantages. The DMSR needs no capital and O&M costs for fuel processing, and the superior nature of the salts as coolants results in far smaller heat exchangers and pumps. Building and fabrication costs should be lower than conventional nuclear plants, since the design doesn't put the same sort of stresses on the system.

It is not unreasonable, then, to assume that capital costs could be 25 to 50 percent less for a simple DMSR converter design than for modern light water reactors. Compared to fast breeders such as the integral fast reactor, which rarely try to claim low capital costs, the DMSR should be even better.

As with any reactor, satisfying regulators' concerns correlates to costs. Molten salt reactors might be seen to suffer in this respect, given how fundamentally different their operating principles are and thus how difficult to fit within existing regulations made for solid-fuel reactors. However, the robust, inherent and simple-to-understand safety of these reactors suggests that if given a rational overview by a regulatory body, they may in fact prove relatively simple to license.

Adopting a new reactor design would be a huge undertaking. And commercial utilities may be forgiven for wanting to stick with proven, if less than perfect, designs. Indeed, the obstacles to overcome are substantial, but not necessarily technical. For instance, the traditional vendors in the nuclear power industry all have much at stake with their solid-fuel designs, including lucrative fuel fabrication contracts. And in the United States, at least, government funding has been equally unhelpful.

But perhaps the renaissance currently under way in the space industry can provide a map of the way forward. The recent decision by the Obama administration to rely on private companies for launch services is a vote of confidence in nimble and numerous entrepreneurs over the large and lumbering institutions first developed more than half a century ago.

Traces of this sort of entrepreneurial spirit are becoming evident in the nuclear power industry. One example is the traveling wave reactor, which is a new kind of sodium fast reactor being developed by Terrapower LLC, a company with a large Microsoft connection. Terrapower has hired many top nuclear engineers in the U.S., and its design core is bigger than most traditional nuclear vendors.

Molten salt or liquid fluoride reactors will also take a large effort, but every indication points to a power reactor that will excel in cost, safety, long-term waste reduction, resource utilization, and proliferation resistance. As we move deeper into a century that portends financial instability, political uncertainty, environmental catastrophe, and resource depletion, this technology is too valuable to once again place back on the shelf. ■

To Learn More

>> A. Weinberg, *The First Nuclear Era* (New York: American Institute of Physics, 1997)

>> H.G. MacPherson, "The Molten Salt Adventure." *Nuclear Science and Engineering* 90, 374-380 (1985)

>> D. LeBlanc, "Molten Salt Reactors: A New Beginning for an Old Idea," *Nuclear Engineering and Design* (in press)

>> As well as numerous documents and discussions at energyfromthorium.com