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The SSR – a new path for nuclear energy?

UK company Moltex Energy believes it has made a major breakthrough in Molten Salt Reactor technology, opening up a new avenue for an industry plagued by rising costs. The design of the Stable Salt Reactor does indeed look simple and cheap, but whether it can really deliver electricity at lower cost than coal is debateable. This would not be the first time the nuclear industry has made such claims. **Ross McCracken**

The cost of nuclear energy has risen because of the inherent complexity of solid fuel reactor designs and the increased safety requirements imposed on them as a result of serious accidents. According to a 2013 report by the UK Energy Research Centre, Presenting the Future: An assessment of future costs estimations methodologies in the electricity sector, “the ongoing changes and increasing complexity [of nuclear plants] compromised the learning effects that were expected over time,” (see Learning curves and cost projections, Energy Economist 388, February 2014).

Notably, in Asia and Eastern Europe, the cost of nuclear new build did fall between the 1990s and early 2000s. Shorter construction times were achieved in environments with less regulation. Greater standardization had a clear impact on cost. However, with a new generation of designs and post-Fukushima, plants have become ever more complex. This has put costs back on an upward trajectory, as demonstrated by the construction of the first European Pressurized Reactors in Finland and France.

Solid fuel reactors suffer from a number of features that make them expensive. They have to be able to control high levels of reactivity, which means multiple redundant failsafe systems. They also employ large volatile fission product inventories. This requires failsafe emergency cooling and multi-level expensive containment systems. High pressures within the reactor core also mean that plants need highly specialized forgings and safety control equipment.

Design complexity and the need for a rigorous regulatory environment suggest nuclear technology, as currently conceived, is intrinsically ill-suited to delivering technology cost reductions over time.

Revisiting the past

As a result, some scientists are advocating a return to an old concept – the Molten Salt Reactor. MSRs have a long, if interrupted, history. The idea was originally proposed in the 1940s and the first design was developed as a US aircraft reactor experiment, which was part of the US Aircraft Nuclear Propulsion Program from 1946-1961.

In November 1954, a 2.5(th) MSR operated for 100 MWh over nine days and, according to David Holcomb of the US Department of Energy, was considered successful, despite issues with leaking radioactive gas. A 60 MW(th) design was under construction when the program was terminated in 1961.

Although the military’s interest had ended, a civilian program had got underway and in the 1960s the Molten Salt Reactor Experiment operated intermittently for five years from 1965-1969 at the Oak Ridge National Laboratory in the United States. This established both a proof of principle and an operating record, although the experiment was not a complete demonstration plant.

The MSRE had generating capacity of 8 MW(th). Its key advantages were its compact configuration, passive safety, low pressure system, and long-term operation through online fueling.

Why then were MSRs not pursued? There are two versions. One is that the concept suffered materials problems relating to the corrosive nature of the molten salts. This in turn created serious safety issues and complex engineering problems.

The other is that while scientists at ORNL supported the technology, the Nixon government of the time had decided that solid fuel reactors were the way to go and people were put in place that supported this line of research. The pro-MSR director of ORNL, Alvin Weinberg, was fired in 1972, and no further MSRs were built.

However, there was a demonstration of long-lived thorium liquid fuel nuclear breeding that was completed in 1982, again in the US, and research funds for MSRs were renewed under the Clinton administration. In 2001, MSR became one of six technologies chosen by the US Department of Energy as representing the next generation of nuclear designs, but the technology failed to receive funding under the Bush administration.

In the meantime, other countries became interested in the technology and there are now research programs in France, Russia and Japan. According to the World Nuclear Organization, the Chinese Academy of Sciences launched an R&D program in 2011 known as the Thorium-Breeding Molten Salt Reactor. There is a 5 MW(e) prototype under construction at the Shanghai Institute of Applied Physics, which is targeted for operation this year. The Chinese government has charged its scientists with delivering a commercial MSR within ten years.

Breakthrough claim

However, UK company Moltex Energy says it has made a breakthrough that could now deliver a Molten Salt Reactor at a capital cost similar to that of a conventional coal-fired power station. Called the Stable Salt Reactor, Moltex has commissioned cost estimates from nuclear engineering company Atkins Ltd, which suggest that a 1 GW SSR could be built for £1,414/kW ($2,083/kW) – the cost range is put at £909-£2514/kW. This estimate is explicitly for an 'nth' of a kind plant – a first-of-a-kind plant would inevitably cost more.

If realized, even at the high end of the estimate, this would represent a massive reduction in nuclear costs, making the technology competitive against pretty much any other form of power generation.

The reason for Moltex's optimism is that previous MSRs pumped the intensely radioactive and corrosive molten salt fuel around pipes, valves and heat exchanges outside of the reactor core, which proved extremely hazardous. The SSR keeps the molten salt fuel locked up in closed tubes within the reactor core and the whole core assembly is immersed in a molten salt coolant bath.

The challenges then become primarily materials-based as fuel tubes are required that are resistant to the coolant salt and the molten salt fuel. Other components must also be resistant to the coolant salt, while the boiler tubes need to cope with both the coolant salt and high pressure water and steam. Moltex believes there is a high probability that the required components could all be fabricated from alloys already used and tested in nuclear applications.

According to the company, using the traditional MSR design would be unlikely to result in a capital cost less than a solid-fuel Pressurized Water Reactor. But the SSR's intrinsic safety would reduce the need for multiple, redundant failsafe systems. In addition, its engineering simplicity should allow the use of replaceable factory made components.

The company has had five detailed costings reports prepared by Atkins Ltd and says they have tried hard to be as realistic as possible, reflecting the fact that fabricating a component can cost five times as much for a nuclear application as it does for the same component in a non-nuclear application.

Moltex is sending out a summary of its technology to government and participants in the nuclear industry in March in the hope of finding an investor willing to take its SSR technology forward from the design stage.

In addition to the cost estimates, Atkins Ltd has conducted a review of the safety of the reactor against UK Safety Assessment Principles and conducted a HAZOP 0 process. The nuclear physics have been confirmed by Professor Tim Abram and Olga Negri at Manchester University. The heat flow dynamics have been assessed by engineering consultancy Wilde Analysis Ltd, and analyses have been carried out on the chemistry and materials. All these studies are available to interested parties under a confidentiality agreement.

MSR advantages

There are sound reasons why molten salt fuel should prove inherently safer than solid fuel, and the argument

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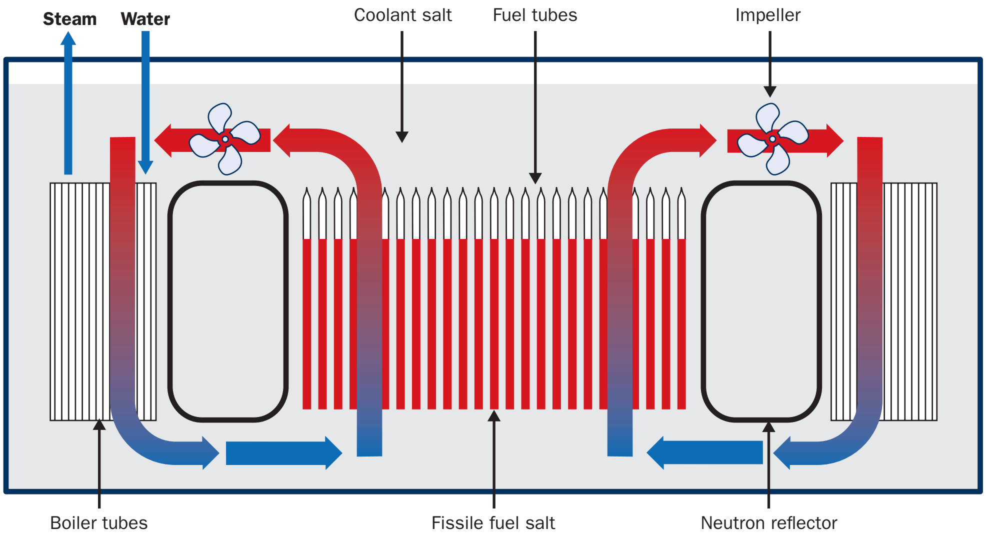
The Stable Salt Reactor



Source: Moltex Energy

Core reactions

Nuclear fission is the break-up of an atom into two or more smaller pieces. For sufficiently heavy atoms the combined mass of the resultant particles can be less that the mass of the original atom and the difference in mass is converted into energy according to Albert Einstein's equation showing the equivalence of mass and energy.

This reaction can be caused by a neutron and if more than one neutron is released in the fission process then a chain reaction can occur, leading to a series of fissions. The principle requirement is to have a sufficient mass of the fissionable material so that the neutrons which cause the chain reaction are not lost. This process occurs in conventional fission reactors.

Most designs use solid fuel made of pellets of uranium dioxide. These are held in tubes requiring high dimensional tolerance and are surrounded by a moderator to slow down the neutrons. The system can run away if it is not controlled by neutron absorbing rods. The design of the system and the safety criteria are very strict and this results in high cost.

The use of a fluid fuel consisting of uranium salts held in tubes simplifies the structure; typically uranium chloride can be used. About 12% plutonium salt is required to supply the initiating neutrons and obtain critical reactivity. The use of salts also makes heat transfer simpler. They can be operated at a temperature of 500-600°C and at normal pressure.

The moderator is also a salt at high temperature and this salt can be circulated to a heat exchanger. The system has no excess reactivity and a high negative coefficient of reactivity, meaning that as the temperature rises the reaction rate falls, providing an important safety feature. Most of the reaction products are contained in the liquid salts, and the gases, mostly helium, are released to atmosphere.

that a safer plant needs fewer expensive safety systems also holds water.

The radioactive fission products that are high pressure gases in other reactors are stable salts in MSRs. This means that even complete core destruction will not result in a massive release of radioactivity into the atmosphere. In addition, a core meltdown shouldn't be possible because the molten fuel can't get to the temperatures needed to melt steel and concrete. There is no water in the core of an MSR and no hydrogen, so catastrophic steam or hydrogen explosions shouldn't occur.

MSRs have other remarkable features. In a 1 GW, solid fuel reactor, 250 tons of natural uranium is required to produce 35 tons of enriched uranium and 215 tons of depleted uranium. The enriched uranium is used in the reactor as solid fuel and some plutonium is formed. This creates 35 tons of spent nuclear fuel which needs to be stored effectively in perpetuity. Despite nuclear energy having been around since the 1950s, no long-term storage sites for this dangerous material have been built.

MSRs use molten liquid salts for both fuel and coolants. As there are no solid fuel pellets to degrade, the MSR can use up to 30 times more of the nuclear fuel than a conventional Light Water Reactor, which means the production of more energy from less fuel and much less radioactive waste, again factors that reduce cost.

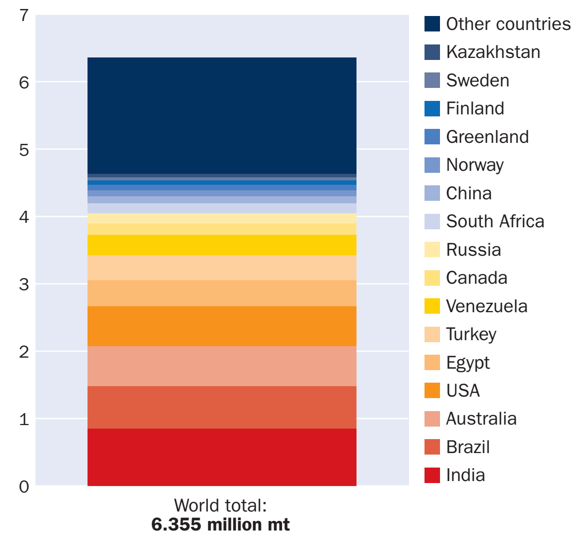
Thorium versus uranium

MSRs are well suited to the use of thorium, which is a fertile material that can be used to breed uranium-233. According to the World Nuclear Association, thorium is about three times as abundant as uranium. However, there is no international or standard classification for thorium resources and identified resources do not have the same meaning in terms of classification as identified uranium resources.

Uranium 2014: Resources, Production and Demand, a publication produced by the International Atomic Energy Agency and the OECD's Nuclear Energy Agency, gives a figure of 6,355 thousand tons for reasonably assured and inferred thorium resources recoverable at a cost of $80/kg. The IAEA-NEA provides a figure of 5,902 thousand tons for reasonably assured and inferred global uranium resources at a cost of up to $130/kg.

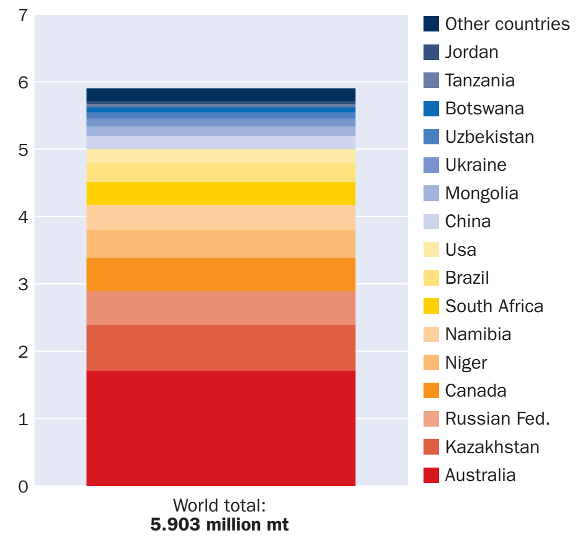
The distribution of thorium is different to that of uranium, which is one of the reasons why India has been pursuing a thorium-based fuel cycle for some time. India has the world's largest thorium resources but hardly any uranium.

Estimated thorium resource (million mt)



Source: OECD NEA & IAEA, Uranium 2014: Resources, Production and Demand ('Red Book'), using the lower figures of any range

Estimated uranium resource (million mt)



Source: OECD NEA & IAEA, Uranium 2014: Resources, Production and Demand ('Red Book'), using the lower figures of any range

With a thorium-fuelled MSR, one ton of natural thorium would be converted to uranium, producing one ton of fission products but no plutonium. As a result, 83% of the fission products become stable within 10 years and then have industrial and medical uses. The rest needs to be stored for about 300 years.

The MSR also works at atmospheric pressure, which eliminates the risk of high pressure blow outs. In addition, there is less risk associated with coolant leakages because the molten salt is inert and cools down and solidifies if it escapes from the reactor.

Time scales

Any new nuclear design must go through rigorous and lengthy regulatory processes in all of the jurisdictions in which it might be deployed. These processes can and do last years; it is not possible to predict accurately how long they might take.

Moltex's Ian Scott says that the regulatory process in the US would be lengthy because the US system is rules-based and designed around the approval of Light Water Reactors rather than novel concepts. In the UK and Canada the regulatory systems are principles-based and the vendor must provide a safety case that satisfies those principles.

Scott says this plays to the SSR's strengths because whole areas of these principles do not apply. For example, there are entire sections that address the reactor pressure system, but the SSR works at atmospheric pressure. The simplicity of the design should make winning regulatory approval easier, but regulators will have to set this against the novelty of the design.

Taking an optimistic scenario, Scott says a small-scale prototype could be fully designed and approved within a five-year period using the regulatory system that exists for research reactors. The Generic Design Assessment process used in the UK for utility-scale reactors can start before a prototype is built and operate partially in parallel, but the prototype would need two years of operational experience to generate the data that regulators would need for final approval of a utility-scale plant.

The GDA process itself has taken 5 years in the UK. A plant would only take around one to two years to build once approved, Scott estimates. On that basis, the SSR is about ten years from a commercial utility-scale plant, providing Moltex can find the right backer and provided that all goes well. In addition, any reactor needs a site and this can also prove problematic and cause time delays. The time scale could be compressed if approved and built in a highly supportive jurisdiction.

Silver bullet?

Almost everyone will remember the infamous misquote that nuclear energy would be "too cheap to meter." And the nuclear industry's cost estimates in the past have often as not proved pure fiction. As a result, Moltex's claim that its SSR could produce electricity cheaper than a conventional coal-fired plant is likely to meet with a great deal of skepticism, if not cynicism.

(The statement by US Navy officer Lewis Strauss made in 1954 was actually that "our children will enjoy in their homes electrical energy too cheap to meter." He was referring to the advances scientific knowledge in general, rather than nuclear energy specifically, could deliver to future generations.)

What Moltex have is a conceptual design. On the one hand, the case that molten salt as a fuel is intrinsically safer and cleaner than solid nuclear fuel looks very convincing. Moreover, this addresses fundamentally the reason why nuclear has been unable to deliver the cost reductions that might have been expected from what is, in its current form, a very mature technology. There was every reason to go back to the drawing board.

On the other hand, this is only a conceptual design, albeit one that recognizes that many challenges still need to be overcome in materials, the fuel cycle, certification and other areas. Complications are bound to arise in moving to a working plant, and the onus will very much be on the developer to prove that any new form of nuclear plant is not just intrinsically safer than existing ones but operationally so.

Moreover, the SSR will inherit a regulatory framework and culture that reflects the conventional nuclear industry. Given the history of nuclear accidents, regulators may prove unsympathetic to novel designs, and that would have a bearing on cost. Nonetheless, if the nuclear industry is to have a renaissance, it must address its cost basis, and the SSR appears, on paper at least, to do just that.