The comeback of the molten salt reactor

A remarkable series of experiments in National Laboratories of the United States in the 50s and 60s did not deliver the nuclear airplane that the US Airforce wanted, but it did deliver a technology that has the potential to produce clean, carbon free energy for tens of thousands of years. This 'molten salt reactor' demonstrated the perspective of a nuclear energy system, unparalleled in safety, controllability, resource efficiency, without generating long term waste. Political agendas sidetracked the molten salt reactor, but in recent years it's making a remarkable comeback.

Ever since Kirk Sorensen put the extensive investigation reports of the MSR program of Oak Ridge National Laboratory online in 2006, the enthusiasm about this 'forgotten' technology has been spreading. From a multitude of possible designs, Sorensen picked one that has become his favorite: the Liquid Fluoride Thorium Reactor or LFTR in short (pronounced 'lifter').

On paper, the concept shows staggering numbers. As a molten salt reactor, it differs from today's light water reactors in virtually all respects. It is inherently safe, gives access to a supply of energy that easily lasts thousands, probably tens of thousands of years. It virtually solves the long lived nuclear waste problems and produces very small amounts of waste that only needs storage for about 300 years.

Alvin Weinberg, in the control room of the Molten Salt Reactor (1965, picture of ORNL)

These numbers however do not evenly apply to all thorium options nor to all types of molten salt reactors. In the media, there has been considerable confusion on this point. The trouble is that 'thorium' and 'molten salt reactors' are separate aspects of the proposed developments. Whether or not the two are combined makes a lot of difference. A simple way to summarize this would be to say that the molten salt technology adds safety and efficiency, while the thorium adds fuel abundance and virtual elimination of long-lived waste issues, provided that ‘thorium’ and ‘molten salt reactor’ are used in a single machine.

The advantage of the liquid fuel is easy to understand: liquids make it possible to remove unwanted waste products that appear during the process; you can keep the fuel in mint condition at all times. Thorium then paves the way for nuclear energy’s holy grail: a closed fuel cycle. Meaning the fuel is completely consumed, leaving behind only minimal amounts of short-lived waste products while producing abundant amounts of energy.

In the end, it all comes down to one single word: efficiency.

Clearing up some thorium confusion

Some confusion has arisen from the fact that both ‘thorium’ and ‘molten salt reactors’ can be used in very different ways.

For instance, thorium can be used in solid fuel reactors. In current solid fuel reactors, thorium could be introduced to decrease uranium demand somewhat. However, this is currently not pursued, as uranium prices remain too low in the foreseeable future, hence the benefits do not outweigh the costs of significantly changing current fuel designs.

On the other hand, molten salt reactors can be run on the kind of uranium that is presently used in existing nuclear power plants. Using this enriched natural uranium in molten salt reactors, allows for a higher ‘burnup’ of the uranium in comparison to traditional reactors. This is due to the fluid form that enables online purification and optimization of the fuel, enhancing efficiency and allowing the material to stay in the reactor much longer, until virtually completely used up. These simpler molten salt reactors hence offer substantial improvements of the waste profile in comparison to traditional nuclear power plants, when using the same fuel. The improved efficiency of MSR’s also offers the possibility of burning spent nuclear fuel that is present in existing stockpiles.

But the ‘ultimate’ molten salt reactor consumes thorium. In this reactor, the thorium is first transformed into a special type of uranium (U233), an isotope that is not found in nature and that has superior ‘burning’ properties. For reasons of simplicity, this two-step process is usually summarized as ‘a thorium MSR runs on thorium’. This process is made possible due to the MSR’s high and crucial ‘neutron efficiency’, allowing both transformation of thorium, and subsequent burning. This ultimate reactor has a waste profile that makes the thorium MSR a truly sustainable option.

One tonne of thorium could prevent the release of 12 million tons of carbon dioxide

So what could be the impact of thorium MSR’s? Let’s take a brief look at some numbers. For country-sized power plans, the Gigawatt year or GWey is a convenient unit. One GWey roughly equals the electrical energy that is needed to run a modern city of one million inhabitants for a year. To produce a GWey, the ultimate thorium MSR needs about a metric ton (1000kgs) of natural thorium. The thorium MSR uses all of its fuel. Hence it produces a waste stream of roughly 1000kgs of fission products per year, a quantity that would need storage for about 300 years — after which what is left is no more radiotoxic than regular thorium containing ore found in nature. [A bit of math. According to the Dutch Bureau of Statistics CBS, in 2013 the Netherlands used 119 billion kWh of electricity [http://www.cbs.nl/nl-NL/menu/themas/industrie-energie/publicaties/artikelen/archief/2015/elektriciteitsverbruik-16-keer-hoger-dan-in-1950.htm], 14GWey in rounded country-sized numbers. If produced in molten salt reactors, this would require 14 (metric) tons of fissionable material. A coal plant requires 3.3 million tons of coal to produce one GWey. If produced in coal plants, 14GWey would require 46 million tons of coal — about 8000 km of freight train cars, each train car filled with coal. The by-product would be 169 million tons of carbon dioxide. If thorium would replace the actual Dutch energy mix that produces this 14GWey (percentages: coal 24.4, natural gas 58, oil 1.2; biofuel and renewables: 16.4) CO2 reductions would be 98 million tons.*) Application of the recent proposal of the Dutch National Bank to tax carbon emissions with €30,- per ton CO2 puts this number in perspective. Replacing fossil fuel sources with msr's would then save the Dutch 2,9 billion euro per year.]

In live presentations, once the story has arrived at this point, people usually have two reactions and the two are closely interlinked.

The first is: 'wow, this is great!'.

The second is 'why aren't we doing this?'

*) source: EC Pocketbook Energy 2015.

The thorium vision — a carbon free supplement for wind, water and solar energy

Let's start with the first: 'wow, this is great!'

The vision of the thorium molten salt reactor is indeed impressive. Once it is realized, energy production becomes a whole new ballgame. This novel reactor type taps into a vast supply of carbon free energy. It promises to do so, by very efficiently using thorium, an abundant energy-dense resource, generating minimal amounts of nuclear waste that require safe storage for an overseeable period of 300 years. The energy production process of the molten salt reactor delivers safe and reliable energy at high temperatures. The heat can be used for highly efficient electricity production, but due to its high temperatures (up to 750 degrees Celsius) also as high quality industrial process heat. This allows for the production of bulk chemicals, including synthetic transport fuel for example.

Molten salt reactors can be designed in such a way that they can automatically 'load follow', making them ready for a future where energy is supplied by a multitude of intermittent sources like solar and wind.

Thorium is widely present on earth, and it is not a scarce resource. It is for example a byproduct from rare earth mining operations and currently stockpiled without being used. It is estimated that current mining operations each year excavate an amount of thorium that equals 40 years of worldwide energy production.

Thorium MSR's may also offer strategic energy independence for a country. Any nation that runs on thorium MSR's only needs very small amounts to produce its power, and a strategic supply of thorium could easily be bought. The Netherlands electricity demand would require a yearly supply of 14 tons of thorium — a quantity that easily fits in a truck. An Olympic swimming pool full of thorium, 2500 cubic meters, equals 2000 years of electric power for the Netherlands. At a price of 100 euro's per kg, this quantity could be acquired at 200 euro’s per inhabitant. So in short, every country with thorium MSR’s could simply buy a strategic supply of thorium.

The dark colour of the sands of Ameland comes from monazite, a thorium mineral

*) For instance in the Netherlands, the dark sand on the beaches of Ameland contain high amounts of thorium. But it’s easier to buy thorium from one of the many countries with abundant mine tailings that contain large amounts of unused thorium and leave the beaches of Ameland as beautiful as they are.

So where’s the catch?

This inevitably leads to the next question: ‘why aren’t we doing this?’

There are two sets of reasons for this, one set is historic and the other one is the present-day outcome of this history, a set of conditions that we need to face now if we want to see the vision of molten salt reactors realized. The easy answer to the above question is: 45 years ago, we took a wrong turn, and due to that, we are now 45 years lagging behind in research and development. But that is in hindsight, and this answer may be too easy.

Let’s look at some history first. In the 1950s and 1960s, the concept of the molten salt reactor emerged and was developed. These efforts resulted in the famous Molten Salt Reactor Experiment (MSRE), that had a molten salt reactor run flawlessly for more than four years, from 1965 to 1969. At first this reactor ran on uranium 235, the fissionable component of natural uranium that is also at the heart of conventional reactors. But in this reactor, the fuel was used in the form of a molten fluoride salt. Halfway through the experiment, this fuel was taken out of the core and replaced by a fluoride salt of uranium 233, the uranium isotope that can only be made from thorium. And although the conversion of thorium into uranium 233 did not take place inside this reactor — this in situ conversion was planned for later experiments that were cancelled by president Nixon — the MSRE was the world’s first reactor that did run on uranium 233. The experiments were considered as a huge success by the experimenters. After the experiments some materials issues were found, but these were essentially solved by the Oak Ridge scientists not long after they became known.

In his autobiography 'The First Nuclear Era' Alvin Weinberg gives two reasons for the discontinuation of the MSR-program (p.130). The competing fast breeder program arrived first and was therefore able to consolidate its position within the Atomic Energy Commission.

The other reason, as Weinberg states, is that the technology of the molten salt reactor was simply too different from the existing technology. And a technology too different has two hurdles to overcome: one is to demonstrate its feasibility. Another even greater one is to convince influential individuals and organizations who are intellectually and emotionally attached to a different technology.

Many have also interpreted the discontinuation of the MSR-program at the time as a perfectly logical decision. At the time, there was already considerable experience with light water reactors. At the same time, the liquid metal fast reactor was already far in its development – at least, that was the widely held perception at the time. The combination of the LWR and the LMFBR together would form a closed uranium cycle. The choice for the LMFBR at the time was a logical one.

Now, more than forty years later, even an expert like Jan Leen Kloosterman said he thinks we 'have taken a wrong turn, forty years ago'. What has happened in the meantime?

First, the program of the liquid metal fast breeder reactors, which politically outcompeted the molten salt reactor in the 1970s, in later decades turned out to be much more complex than originally thought. LMFBR's showed to be difficult to design and operate in line with safety requirements that were justifiably enhanced and tightened over the years. This led to some of the costliest failures in the history of nuclear development. Germany's Kalkar power plant, now famous as the theme park 'Kernwasserwunderland' (recommended!) is one of the more outstanding examples of politics betting on the wrong horse. And without fast reactors, light water reactors cannot create a 'closed nuclear fuel cycle'.

In his biography, Weinberg concludes his discussion with the observation: "Molten salt was a successful technology that was dropped because it was too different from the main lines of reactor development. But if weaknesses in other systems are eventually revealed, I hope that in a Second Nuclear Era, the molten-salt technology will be resurrected." (p.131)

We may extend this observation to three of our main energy technologies: fossil fuel uses the atmosphere as a waste dump, renewables are intermittent and light water reactors have a popularity problem. Now may be the perfect time to resurrect the molten-salt technology.

The present time: technical challenges, regulatory practices that do not fit, uncertainties for investors and uncertain development times

In essence, the molten salt reactor research needs to be picked up where it was left off in 1972. To an extent, the research of the MSRE experiments needs to be repeated as also experience needs to be rebuilt in line with current demands and standards, and present day regulators will not be satisfied with just references to the original Oak Ridge experiment reports, without the background of the people performing the tests.

Of course, there is no official list of technical challenges that are most relevant to the time frame that is needed to create the first working molten salt reactor in our age. Some scientists mention the challenge to find or develop materials that can withstand prolonged neutron flux at high temperatures. Others state that the chemical processes that need to take place within the demanding environment of a very hot reactor will need lots of research before they can be safely applied. Others claim that all of these challenges have long been solved — but within the context of other technologies. Some groups have recently come up with innovative ideas for processing aspects, like the Danish Waste Burner team, who came up with a novel idea to put existing laser sampling technology to work that allows for online screening for isotope mixtures — which may turn out to be a key ingredient in the challenge of adequate inventory tracking, a necessity for any future regulator that would be asked to license a molten salt reactor.

However, no one seriously contests that a lot of research work needs to be done. Especially because the combination of fuel and coolant creates a system in which chemistry, nuclear physics, material science and thermal-hydraulics can influence each other. As this cannot be predictively modelled in full detail, complex experiments to investigate material and salt behavior in its full complexity will be required to validate modelling and calculation tools that can reliably describe system behavior under all circumstances. This however does not mean that MSR complexity brings unsurmountable issues. So far, no show stoppers have been identified among the challenges of molten salt reactors. And the successful results of the four years of the MSRE stand firmly.

Which technical challenges will be the most relevant with regard to the development time frame, also depends on the choice of the type of reactor that is being pursued? The proposed trajectories differ widely.

Some of the contestants in the evolving molten salt reactor race

The most straightforward plan is to rebuild the Oak Ridge reactor that was successfully demonstrated. This plan, issued by Thorcon Power, avoids all difficult technical issues by proposing to simply replace the whole reactor core every four to five years. At the other end of the spectrum we find what may be called the 'ultimate thorium MSR' — a complete power plant that runs on thorium, employs inline chemical treatment of all components in the process, and features a 45% highly efficient Brayton power conversion system. This is the plan of Kirk Sorensen's Flibe Energy — and it is quite clear that Jan Leen Kloosterman of Delft Technical University has taken a keen interest in this version. In between we find reactor systems that are considered by its makers to be the most 'doable'. Terrestrial Energy's IMSR is a case in point — they are designing a modular system that does not breed its own fuel but runs on pretty standard low enriched uranium. The IMSR however makes better use of this fuel than could be done in a light water reactor. By employing the molten salt technology, the IMSR leads to better fuel use, a better waste profile and adds the inherent safety of the reactor. TE may also be the first to show a working MSR. The company recently announced their cooperation with the Canadian Nuclear Safety Commission, and their intention to build and operate the first commercial demonstration Integral Molten Salt Reactor plant in the 2020s.

The real challenge is to create an adequate regulatory framework, and generate the experimental data and experience to validate designs, MSR dedicated computational tools, and demonstrate MSR performance and safety

While every major technological innovation usually requires large upfront investments, innovative nuclear reactors have the extra challenge of proving their safety beforehand. With good reasons, of course: a critical nuclear system is not a toy and should not be start up before all operational and safety features are fully known, tested and demonstrated. And while part of this testing can be done by either modelling or with non-nuclear tests, an important part will be nuclear tests. And nuclear testing almost by definition is expensive and usually takes much preparation time, because each test has to be carefully designed, discussed, redesigned and permission needs to be acquired from the regulator.

In the case of molten salt reactors, it is essential to first do an appropriate amount of experimental work, build up experience and expertise, and generate the data that will be needed for design and licensing. Those who aim to develop molten salt reactors need to acknowledge that a regulator can never beforehand give any guarantee whether they will approve a design. Safety is a first priority of a regulator, there should be no commercial pressure on the regulator.

In a recent Meet&Greet' session with the Thorium MSR Foundation in Delft, a representative of the Dutch regulatory authority explained to the audience that the essence of her task was easy to understand. The applicant needs to prove that his reactor will, under all circumstances, remain its ability to contain, cool and control its nuclear content. That requirement is the easy part.

The difficult part is to prove that it will. This demands a deep understanding of all materials and processes proposed for the design, both in normal operation and in exceptional situations. Much of this information will be design-specific for a certain reactor. The knowledge of all the various aspects will have to be built up by both the developer and the regulatory authority – a regulator can only assess what he or she understands. While the research, including all the necessary validation tests for materials and processes, will have to be paid by the developer.

And nobody, she added, can expect a regulator to build up this knowledge before there is a request to license a molten salt reactor. Also, no guarantee can be given beforehand that the design will ultimately be given its license. This would be incompatible with the regulator's task to only license safe designs. This inevitably leads to high upfront cost for any designer of a novel reactor type.

Many see the large upfront investment and the long timeframe needed for development as an obstacle to attracting private investors in the early stage of development of MSR's. Waiting for the market to make it happen does not seem a viable strategy. Like many breakthrough technologies before – including GPS, the Internet and the microchip – MSR's will need a boost from government programs in order to materialize any time soon. Idealistic billionaires may offer an alternative option.

A challenge that can be met by political will

All of this is not to say that the challenges described cannot be met. They can be, the only requirement is the political will to meet them. There are signs that this political will is building up. The urgency of the climate change agenda has led prominent environmentalists and climate scientists to re-evaluate their previously held position on nuclear power. The vision of thorium in molten salt reactors has led others to release their previously held beliefs about the ban on all things nuclear. Along with those who already were in favor of nuclear power in the traditional form, these new pro-nuclear enthusiasts, including some that have the possibility and willingness to invest in its development, may just tip the scale. Once the political balance has shifted, molten salt reactors may be here much quicker than we now expect.