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Fundamental discovery that Molten Salt could be used in conventional fuel tubes

The fundamental discovery that makes the entire family of Stable Salt Reactors possible is that molten salt fuel does not need to be pumped from a reaction chamber to a heat exchanger. It can simply be put into fuel tubes in fuel assemblies just like those in conventional solid fuelled reactors.

The advantages of this are enormous. All the complexity of pumps, valves, heat exchangers, drain systems, chemical treatment systems, filtration systems, degassing systems and so on, simply disappears. Molten salt reactors move from being one of the most technically challenging advanced reactor systems to perhaps the least challenging.

It may seem very strange to the reader that such an apparently obvious thing as simply replacing solid uranium oxide fuel pellets in nuclear reactor fuel assemblies had never been thought of in the 60 years since the potential for molten salts as an ultra-safe fuel was identified. In actual fact, the truth is even stranger. It was thought of – but rejected.

The very first molten salt fuelled reactor project was the Aircraft Reactor Program in the USA. It was an effort to produce a nuclear aircraft engine so that strategic bombers could remain in the air for months at a time. The first idea of those designers, in 1949, was to do exactly what Moltex Energy is now doing – put the ultra-safe fuel salt into tubes. But they ran into a problem. Molten salts are very poor conductors of heat, about 10 times worse than uranium oxide (which is not very good itself). Simple calculations showed that this was such a huge problem that fuel salt would boil if the tube containing it was more than 2mm in diameter. The idea was clearly impractical and was abandoned.

The Aircraft Reactor Program moved on to pumped salt systems, became in time the Molten Salt Reactor Experiment and that became the basis for every subsequent molten salt reactor design.

But the scientists on that program had done an apparently strange thing. When calculating the movement of heat out of the fuel salt, they only considered conduction of heat and ignored the contribution of convection. Any high school physics student knows that in liquids convection is far more important than conduction so why did they do this? They were clever people, they had a good reason. Convection is unreliable on an aircraft because it depends on gravity. Gravity can change in direction or even apparently go away as an aircraft banks and dives.

But by the time the idea of a nuclear powered aircraft had gone away and molten salt reactors had put their feet firmly on the ground, the momentum of the pumped molten salt project was so great that nobody went back and examined that original decision. The reports said that the tubes had to be less than 2mm in diameter and nobody questioned that. Such is the power of dogma.

It was not until 2013 that an outsider to the nuclear field challenged that dogma.

In the years since 1949 science had developed the tools (computational fluid dynamics) to predict how convection would work. This made it quite simple to test whether convection really would make a difference. It did, and this report summarises the key results of that analysis.

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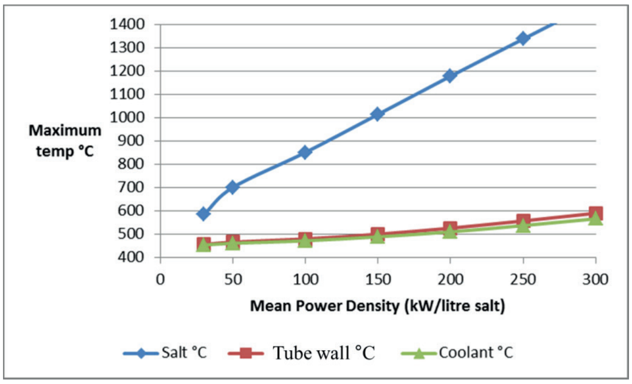
CFD analysis of heat transfer from a chloride based fuel salt

The table below shows the physical properties of the fuel salt that was used in these calculations. It is a chloride based, fast Stable Salt Reactor fuel. The calculations were carried out by a specialist engineering consultancy with specific expertise in using the CFD tools. Ansys Fluent was used as the software package.

Fuel salt composition	60 mol% NaCl, 20 mol% PuCl3, 20 mol% UCl3
Coolant salt composition	42 mol% ZrF4, 10 mol% NaF, 48 mol% KF
Fuel salt melting point/boiling point	730K / 1837K
Coolant salt melting point	658K
Fuel salt density	4.1690-9.014x10-4 x T (temp in K) kg/l
Coolant salt density	2.77 kg/l
Fuel salt viscosity	Log10 viscosity (cP) = -1.2675 + 1704/T
Coolant salt viscosity	0.17 x 10-6 m2/sec
Thermal conductivity fuel salt	0.5 W/m/K
Thermal conductivity coolant salt	0.7 W/m/K
Specific heat capacity fuel salt	510-700 J/kg/K over temp range 500-1500°C
Specific heat capacity coolant salt	1050 J/kg/K
Coolant flow velocity	4m/sec
Tube diameter	10mm diameter

The graph to the right shows the results of the calculations. It plots the maximum temperature reached by the fuel salt, the tube containing it and the coolant passing around it as level of fission energy in the fuel increases. Boiling point of the fuel salt is at about 1600°C so that represents the upper limit of what is possible.



It is clear that power densities as high as 250kW/l can be achieved while still leaving a good safety margin. What does that mean? Well a conventional PWR reactor operates at about 100kW/l while an Advanced Gas Cooled reactor operates at about 3kW/l. This means that the molten salt reactor can be very small indeed.

A second very important finding came out of these calculations. This was that the tube containing the hot fuel salt did not itself heat to a temperature much higher than the coolant flowing past it. This is because convection of the fuel salt is actually not all that effective. It is effective enough to get the heat out, but movement of the heat from the fuel salt to the tube wall represents a far higher barrier than movement of the heat through the tube and into the coolant. The tube wall therefore stays relatively cool.

This is hugely important because it means that standard steel alloys can be used to contain the fuel salt.

These two factor together show that using fuel tubes in fuel assemblies very similar to those used in today's reactors is possible with molten salt fuel. The discovery really is as simple as that!

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