STABLE SALT REACTOR DESIGN CONCEPT

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ABSTRACT
The Stable Salt Reactor is a fast neutron static (unpumped) molten salt fueled reactor where the liquid fuel is incorporated into fuel tubes and assemblies very similar to those used in conventional solid fueled fast reactors. Construction materials are current, nuclear certified, steels with no need for relatively untested alloys such as Hastelloys. Fuel for the reactor is a low purity fraction readily isolated from spent nuclear fuel. The capital cost of the reactor promises to be radically lower than for current PWR reactors with a credible, independent cost estimate for UK construction of the nuclear island of £714 ($1080) per kW.

Keywords molten-salt nuclear static design safe

INTRODUCTION
It was recently discovered that reactors fueled with molten salts do not need to have those salts pumped rapidly through heat exchangers to efficiently extract the heat. The molten salts can instead be placed in simple tubes, similar to those used to clad conventional fuel rods, where natural convection permits adequate transfer of heat from the tube to a circulating coolant outside the tube.

That fundamental discovery allows reactor designers to eliminate the substantial complexity involved in actively circulating the intensely radioactive molten salt fuel. It opens up a large range of potential reactor designs. In order to identify critical aspects of such designs and to allow an initial order of magnitude cost estimate to be made, one reactor design was selected for more detailed investigation. This was a fast neutron spectrum, non-breeding, plutonium/higher actinide burning GW\textsubscript{e} scale reactor called the Stable Salt Reactor.

This paper describes the preliminary design of this reactor and presents the results of the capital cost estimation process.

CHOICE OF MOLTEN SALTS
Perhaps the most critical choice facing any designer of molten salt reactors is the salt to use. The choice affects the materials that must be used, the thermal hydraulics of the system and the neutronic behavior. Most designers opt to use fluoride salts because of their favorable neutronic properties but then have to utilize lithium or beryllium fluorides in order to avoid very high temperatures. This choice carries a large penalty because both lithium and beryllium generate tritium under neutron bombardment. Since tritium readily passes through metals it is necessary to design and construct tritium capture systems. These add yet more complexity to the reactor design.

The fuel salts chosen for the Stable Salt Reactor are chlorides. Natural chlorine cannot be used in thermal neutron reactors because the \textsuperscript{35}Cl isotope is a strong absorber of such neutrons. In a fast reactor however that is not a significant issue. The specific mixture used is 60mol\% NaCl mixed with 40mol\% of a mixture of actinide and lanthanide trichlorides. The phase diagram for the NaCl/UCl\textsubscript{3}/PuCl\textsubscript{3} system is known\cite{1} and shows a broad range of compositions melting around 450 to 520°C. The fuel salt would operate at a temperature range from just above the melting point
to 1200°C but the temperature of the fuel tube containing it would rise only a few tens of degrees above the temperature of the coolant salt.

The coolant salt chosen is a eutectic mixture of ZrF$_4$/NaF/KF (42/10/48) melting at 385°C[2]. The zirconium used is technical, not nuclear, grade since contaminating hafnium has relatively little neutron absorbance in the fast spectrum. It would operate across a temperature range from 450°C to 600°C.

**FUEL TUBES AND ASSEMBLIES**

Computation fluid dynamic calculations have shown that 10mm diameter fuel tubes are an optimal balance between thermal hydraulic and neutronic factors. These tubes are assembled into assemblies closely resembling those used for sodium cooled fast reactors. The assemblies are vented through diving bell valves so that fission gasses are released to the coolant. Valves such as this were in fact used in the early fuel assemblies of the Durey experimental fast reactor [3]. Figure 1 illustrates a single fuel tube and figure 2 illustrates a fuel assembly. The assembly is 200mm square and contains about 400 fuel tubes. The fuel tubes and assemblies are fabricated from Nimonic PE16 alloy, a well characterized and extensively used nuclear alloy with excellent resistance to neutron damage.

**REACTOR INTEGRAL AND POOL DESIGN**

The concepts of using a “pool” design to minimise the risk of a loss of coolant accident and of integral designs, with heat exchangers within the reactor vessel are now well established among the generation IV reactors. Both of these design principles were adopted for the Stable Salt Reactor whose design is illustrated in figures 3 and 4.

The main reactor structure is a tank containing a large pool of molten salt, the coolant salt. The tank contains a diagrid which has holes into which the spikes of the fuel assemblies locate and which guides coolant salt from the output of the secondary heat exchangers into the fuel assemblies. It is anticipated that the tank and all internal structures will be fabricated from standard stainless steels which are expected to be fully corrosion resistant.

The fuel assemblies have net negative buoyancy in the coolant salt and, when the coolant is not pumped, are held in the diagrid by gravity and maintained in a vertical orientation by the buoyancy of the gas plenums in the fuel tubes. When the coolant is being pumped the assemblies are held down against the thrust of the coolant by removable spring loaded assembly clamps located in the reactor lower lid. That lower lid is thermally insulated to reduce heat flow from the molten coolant salt which in normal operation will reach 600-650°C.

Secondary heat exchangers are located towards the edge of the tank with a minimum 1m of coolant salt between the heat exchanger and the fuel assemblies to ensure minimum neutron exposure of
the heat exchangers (1m of coolant provides a $10^4$ reduction in neutron flux, data not shown). At the tank periphery there is space for storage of spent fuel assemblies, with diaphragm type supports but no pumped coolant salt. Heat removal from these fuel assemblies is by convection of the coolant salt only.

![Figure 3 Side view of reactor](image)

The tank has an upper lid which is penetrated by the drive shafts for the coolant salt pumps and the control rod assemblies through gas tight seals. The space between the two lids, and the space above the coolant salt are argon filled. The argon is circulated through a chiller which operates at low capacity during normal reactor operation to maintain a temperature above the lower lid compatible with operation of the various sensor controllers located in this region. During fuel assembly changing, it operates at a higher capacity to manage the increased heat load passing through the open assembly clamp holes.

The tank sits inside a concrete pit below ground level, possibly lined with stainless steel. The gap between the tank and concrete pit is either air filled with a forced air flow or insulated – the purpose of both options being to prevent the concrete exceeding its long term temperature tolerance. In either case any void space is designed to be small enough that it can be completely filled with leaked coolant salt without lowering the coolant level enough to expose the fuel filled part of the fuel tubes.

![Figure 4 Top view of reactor](image)

Periodic inspection of the interior of the tank, if required, is by a remote operated heat resistant camera which is usable due to the transparency of the coolant salt.

Not shown are the heavy duty electrical heaters used initially to melt the coolant salt. They may be installed as permanent structures in the tank but since they will only be required at reactor start up, temporary heaters with dimensions similar to the fuel assemblies could be inserted in the spent fuel locations and removed when no longer required, that is when decay heat from the core will be sufficient to maintain the coolant salt in the molten state when the reactor is in a sub critical state.
Also not shown are neutron flux and temperature detectors. These are inserted into the reactor through the lower lid and located between the upper lattice sections of the fuel assemblies. Since this is a fast neutron reactor, it is expected that neutron monitoring around the periphery of the core will be adequate for reactor control without the need for detectors inside the core.

**FUEL MANAGEMENT AND REPLACEMENT**

Maintenance of uniformity of fission rate and replacement of spent fuel assemblies is achieved by moving fuel assemblies laterally within the array of fuel assemblies without fully withdrawing them from the core. This requires that the assemblies be square in section. Figure shows the process of moving the fuel assemblies. This takes place with the reactor in a shutdown state and when decay heat has fallen to a level allowing the pumps in the secondary heat exchanger to be idled, leaving convection alone slowly circulating the coolant. It is estimated that this would be less than 1 day after shutdown. Coolant salt temperature would be maintained at about 450°C during this process, as cool as possible while being safely above its freezing point of 385°C.

The key to the process is the migration of fuel assemblies, one step at a time, into an adjacent vacant space in the diagrid. The assembly is lifted a few cm, moved sideways and lowered into its new location. Repeating this process allows unlimited rearrangement of the fuel assemblies within the core.

Assemblies reaching the edge of the core can be moved laterally through slots in the lower lid and into the peripheral spent fuel storage region where they are lowered into diagrid type receivers.

The spent fuel assemblies are kept in this location with a slow flow of cooled salt from the heat exchangers. Additional heat loss through the tank wall lowers the coolant salt temperature to about 35° above its freezing point, ~420°C, which is below the freezing point of the fuel salt. The low thermal conductivity (~5Wm⁻¹K⁻¹) of frozen coolant salt ensures that any thin frozen layer of salt on the tank wall is self-limiting in thickness. When decay heat from the spent fuel assembly falls sufficiently, the fuel salt freezes.

After cooling for sufficient time (estimated 6 months) for gas convection alone to maintain them at a safe (frozen salt) temperature they are lifted out of the reactor tank through the larger access hatches in the reactor lids and transferred directly to air cooled dry flask storage.

Fresh fuel assemblies are lowered into the spent fuel storage region through the same access hatches, allowed to heat up to melt the fuel salt and then moved to the edge of the core in a reverse of the movement of the spent fuel assemblies. They are then shuffled step by step to their desired location.

This process involves many more movements of the fuel assemblies than would lifting them entirely out of the core. However, each movement is small and should require only a short time. The movements are also intrinsically safer since a dropped assembly would simply slot back into the diagrid quite gently. Indeed it would be desirable for the machine that lifts the assemblies to fail safe to releasing the assembly, thereby avoiding the risk of the machine failing with an assembly locked to its manipulator.

This process ensures that fuel assemblies are...
only handled outside of the coolant salt pool when the fuel salt is securely in the frozen state, thereby greatly mitigating the consequence of an assembly containing liquid fuel being accidentally dropped.

The assembly clamps need to be removed during the movement of the assemblies and then reinserted before the coolant pumps are restarted. At any one time only the pairs of assembly clamps on the fuel assemblies being shuffled should be removed, the remainder remaining in place to keep the fuel assemblies in their design positions in order to maintain the design spacing between the assemblies.

NEUTRONICS OF THE REACTOR CORE

The core neutronics were analysed using MCNP software. The specific core modelled differed slightly from that described above, specifically it used 20mm diameter fuel tubes fabricated from molybdenum rather than PE16 steel.

A fairly uniform core fission rate across the core could be achieved with a fissile isotope concentration in the fuel salt varying between 10-12 mole%. The temperature coefficient of reactivity of the fuel salt was strongly negative at -12.4 pcm/K. That of the coolant was slightly positive at +3pcm/K giving an overall strongly negative temperature coefficient for the entire core.

The void reactivity coefficient for the coolant salt was -0.6. This very strong negative coefficient is a major safety advantage, similar to that for light water cooled and moderated reactors and very different from the positive coefficient that has to be managed in sodium cooled fast reactors.

CAPITAL COST ESTIMATE

The ROM overnight capital cost estimate was prepared independently of Moltex Energy by Atkins Ltd. It covered only the manufacture, construction, installation and static commissioning costs for the:

- Nuclear Island comprising the Reactor building, which houses the reactor and its key support systems, including Fuel Assembly Shuffling Machine, Polar Crane, equipment maintenance areas, Off-gas Management equipment, electrical plant rooms, Heating, Ventilation and Air Conditioning (HVAC) plant rooms, Emergency Diesel Generator Buildings, Control Building, Interim Fuel Building and Interim Waste Building and the
- Conventional Island including the Turbine Hall with 1GW, steam turbine/generator

The cost estimate was only commenced after a sequential review of the design against the UK Nuclear Safety Assessment Principles and completion of a HAZOP 0 review which defined the structures, systems and components (SSC) required for safe construction, operation and decommissioning.

The “most likely” cost per kW was calculated as £1414 with a 90% probability of being less than £1756 per kW. Approximately half of this cost represented the Conventional Island cost. This compares very favorably with a “full plant” cost (ie including ancillary costs outside the nuclear and conventional islands) of £5000 per kW for a PWR reactor. It is in fact comparable to the overnight costs in the USA for a coal fired power station. With fuel costs far lower than for coal, such a reactor could plausibly generate electrical power at a lower cost than coal.

CONCLUSIONS

This project demonstrates the technical and economic feasibility of a fast reactor design built around the core concept of static molten salt nuclear fuel. While significantly more detailed design work is required, the major factors that could create significant obstacles to development and
deployment have been addressed and no “show stopper” issues have been identified. Many factors come together to make rapid development and deployment of this reactor feasible, including

- Very simple design with no high pressure systems
- All components fabricated from currently nuclear certified alloys and operating with wide margins below the temperature limits for those alloys
- Excellent intrinsic safety
- Low cost construction with clear potential for largely factory, modular, build
- Simple fuel cycle requiring only low purity uranium/plutonium salts with high levels of lanthanide contamination acceptable.

NOMENCLATURE

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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>MCNP</td>
<td>Monte-Carlo N Particle</td>
</tr>
<tr>
<td>ROM</td>
<td>Rough order of magnitude</td>
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<tr>
<td>SSC</td>
<td>Structures systems and component</td>
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REFERENCES