SMALL MODULAR REACTORS: STABLE MOLTEN SALT REACTORS

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INTRODUCTION

The Molten Salts Reactor (MSR) technology is one of the categories identified by IAEA for Small Modular Reactors (SMR). As SMR the basic features are: (i) Power up to 300 MWe, (ii) Modularization, in the sense of modular constructed and/or multi-module power plants, (iii) Flexible application allowing its operation in remote locations and low powered grids, (iv) Smaller footprints and consequently reduced emergency planning zones, (v) Potential participation in hybrid energy systems. Specifically, MSRs use molten salts as nuclear fuel and primary coolant, mixed in many designs, to produce and transport heat to secondary loops or directly to steam generators for electricity production. There are several SMR Gen-IV MSR designs like: (i) Terrestrial Energy Inc. (Canada) IMSR is a 195 MWe MSR, (ii) Kairos Power LLC (US) KP-FHR is a 140 MWe modular pebble bed high temperature salt cooled reactor, (iii) Elysium Industries (US/Canada) MCSFR is a 50 MWe molten salt cooled reactor, (iv) FUJI (Japan) ITMSF is a 200 MWe molten salt cooled reactor (v) ThorCon (US) is a 250 MWe thermal molten salt reactor (vi) Moltex SSR is 300 MWe molten salt fuelled and cooled reactor.

Figure 1. SSR-W nuclear facility.

This article describes the characteristics of this type of nuclear reactors taking the developed one by Moltex as reference. The main mission of this design is to supply electricity at lower costs than fossil fuel sources and to do it at a global scale.

Moltex is designing a Generation IV nuclear Small Modular Reactor based on Molten Salts improving old designs including modern technological approaches: Stable Salts Reactor Waste-burner (SSR-W) and Waste to Stable Salts reprocessing facility (WATSS). The combination of both facilities allows the reprocessing of current spent fuel stockpiles coming from nuclear power plants in operation (CANDU, PWR, BWR, VVER,…), transforming them in new low enrichment fresh fuel with high level of impurities, capable to be used in the molten salts reactor.

Moltex is advancing with the plan to build FOAK 300 MWe (750MWth) SSR-W, WATSS facility, and GridReserve®, together with New Brunswick Power (NBP) who operates the CANDU-6 reactor at the site of Point Lepreau (New Brunswick, Canada).

TECHNOLOGY SSR

The Stable Salt Reactor (SSR) is a technology platform that can be deployed in three variants. These are (i) a fast spectrum reactor (SSR-W) with high neutron flux inside the core providing the opportunity to burn highly impure plutonium consuming the long lived radioactive waste from current reactors, (ii) a graphite moderated thermal spectrum reactor (SSR-U) that uses conventional low enriched uranium fuel and (iii) a thorium breeder reactor (SSR-Th) which breeds its own fuel from abundant thorium while operating. At the moment the focus of development is on SSR-W technology, while SSR-U and SSR-Th are expected to follow in the near future.

The SSR-W is an improved version of Molten Salt Reactor (MSR) firstly designed and operated in Oak Ridge National Laboratory in the 1960´s (MSR Experiment, MSRE). Instead of using conventional solid fuel pellets like in Light Water Reactors (LWR) or fuel salt mixed with coolant molten salt loop like other Gen-IV MSR, Moltex technology employs as nuclear fuel, a mixture of conventional potassium chloride and actinide trichlorides (UCl3, PuCl3, etc.) which is encapsulated into steel-lined fuel pins array, conforming core fuel assemblies. The use of encapsulated fuel provides a first containment barrier for nuclear material avoiding the hazards of contamination spread due to circulation of fuel salt mixed with coolant salt, even reducing the volume of high irradiation level zones inside nuclear facility layout. This makes the SSR the only Molten Salt fuelled reactor compliant with current IAEA non-proliferation procedures. The use of molten salt as fuel, primary coolant and also as heat transport vector, makes possible a very compact overall facility design as the heat density level achievable using molten salts is higher than pressurized water or even steam.

The nuclear core is placed inside a non pressurized stainless steel cylindrical tank, 6meters diameter by 4meters high, which incorporates the necessary internals to guide the coolant flow driven by main pumps through the core and to the primary heat exchangers (PHEX). The tank will provide the second confinement barrier for nuclear materials. The PHEXs will be placed outside primary containment. The reactor vessel will be installed inside the so-called Reactor Room, a steel liner structure containing the reactor tank, reactor crane and pipework, which can be accessed through an airlock with a trolley carrying the fresh fuel assemblies for the on-line refuelling. The Reactor Room atmosphere is filled with inert Argon gas and it is kept at 100ºC by means of the performance of the Ar Treatment System. The Reactor Room jointly with the reactor tank are placed in the reactor pit that is a concrete superstructure isolated with refractory materials, conforming the third containment barrier.

The SSR-W is provided with several inherent safety features:

- **Reactivity control** - The SSR is self-controlling and no mechanical control is required. This is made possible by the combination of a high negative temperature coefficient of reactivity and the ability to continually extract heat from the fuel pins. As heat is taken out of the system the temperature drops, causing the reactivity to go up. When the reactor heats up the reactivity goes down. Such large negative reactivity feedback allows the reactor to always be in a shutdown (subcritical) state when at temperatures exceeding 800°C. This provides safety against all overpower scenarios, such as a reactivity insertion accident.
- **Non-volatile radioactive material** - Use of molten salt fuel with the appropriate chemistry eliminates the hazardous volatile Iodine and Caesium, making multi-layered containment unnecessary in preventing airborne radioactive plumes in severe accident scenarios. The noble gasses Xenon and Krypton would leave the reactor core in normal operation, but are trapped until their radioactive isotopes decay, so there would be very little that could be released in an accident.
- **No high pressures** - High pressures within a reactor provide a driving force for dispersion of radioactive materials like in water-cooled reactor. Molten salt fuels and coolants have boiling points far above the SSR's operating temperature (650ºC<1200ºC), so no accident or operational

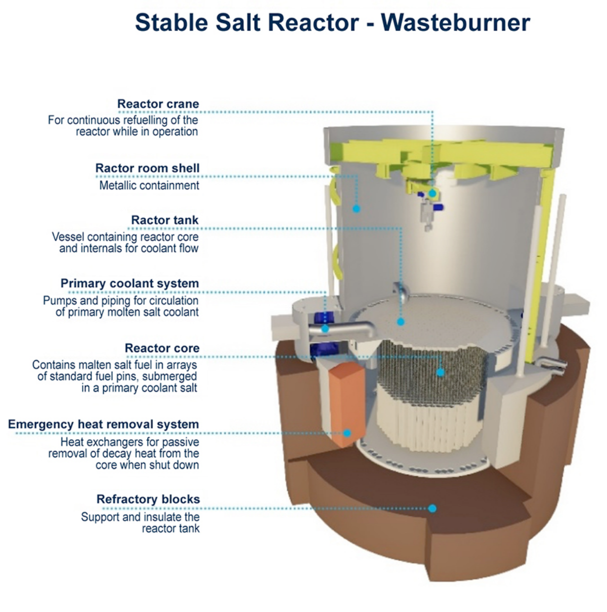

Figure 2. SSR-W reactor overview.

state can happen resulting in Reactor Room pressurization. Physical separation of the steam generating system from the radioactive core by means of a secondary coolant loop eliminates that driving force from the reactor. High pressures within fuel tubes are avoided by venting off fission gases into the surrounding coolant salt.

- **Decay heat removal** - The SSR operates at much higher temperatures than current nuclear reactors (650ºC) so this heat can be rapidly transferred away from the core. In the event of a reactor shutdown and failure of all active heat-removal systems in the SSR, decay heat from the core dissipates through passive heat removal system around the perimeter of the tank that operates continually. In case of stop of primary pumps, the primary coolant initiates a flow mode on reverse to normal operation driven by nuclear heat produced by the core.

DESCRIPTION OF THE WATSS PROCESS

Moltex's WATSS system is an environmentally and socially responsible way of dispensing with the existing finite stockpile of spent fuel from conventional nuclear reactors. The SSR-W is designed to operate on impure plutonium, which means the numerous and complex steps required for conventional used fuel reprocessing to produce pure plutonium are eliminated. That is because the fuel salt mixture within Moltex's reactor can contain almost as many chemical / element fission products (beginning with lanthanum) as plutonium. The importance of the lanthanides is that they are the most challenging element to separate from plutonium in reprocessing but are unacceptable in either oxide or metallic fuel because they degrade the physical properties dramatically. However, as trichlorides, lanthanides have similar melting points as the actinide trichlorides and are therefore expected to form stable eutectic mixtures in chloride-based molten salt fuels. Lanthanide contamination is thus entirely acceptable and even desirable (for non-proliferation reasons) in SSR-W fuel.

The process separates the large mass and volume of the CANDU spent fuel into a low radioactivity, non-heat generating uranium alloy containing ~99% of the mass of the CANDU fuel, a high radioactivity/high heat-generating fission product waste of ~1% of the volume of the CANDU fuel and a plutonium rich molten salt of ~1% of the volume of the CANDU fuel which is readily stored for future use in the SSR-W.

The technology is being developed with the initial focus of dealing with used fuel from CANDU reactors in order to close the nuclear fuel cycle for that technology, but same approach can be designed with spent fuel from PWR, BWR and VVER reactors with light modifications.

WATSS is a complete system that produces SSR-W fuel salt by means of pyroprocessing technologies to recover viable nuclear materials. The system has a compact footprint compared to other reprocessing facilities.

WATSS processes used CANDU fuel bundles in five-steps as outlined below:

- **Chlorine decladding** – the Zirconium cladding is removed from the fuel bundle. The Zirconium is fluorinated and reused as SSR-W primary coolant (zirconium tetraflouride).
- **Electroreduction** – the decladded fuel pellets are melted in a molten electrolyte salt while an electric current is passed through the mixture. During the process, the anode causes all higher actinides and most lanthanides along with the noble metal fission products are reduced to produce a molten uranium alloy, while the major radioactive fission products, such as Caesium, Strontium, and Iodine, remain in the electrolyte salt.
- **Alloy-salt exchange** – the Uranium alloy is placed in a clean sodium chloride / iron chloride salt to produce fuel salt for the SSR-W. The iron chloride is exchanged for plutonium and higher actinides and lanthanides contained in the uranium alloy. The process yields a residual alloy that is sufficiently free of long-lived actinides such that it can be disposed of as intermediate-level long-lived waste.

The 3 steps described above are the basics for first SSR-W manufacturing from CANDU spent fuel. But the reprocess-

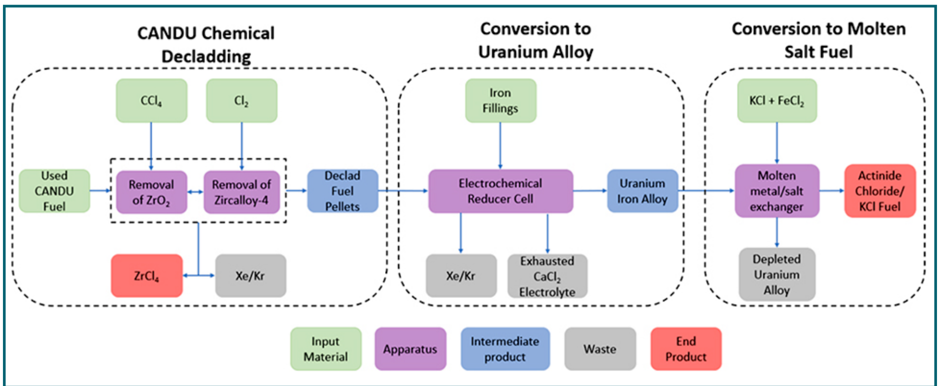

Figure 3. WATSS reprocessing steps for first core manufacturing.

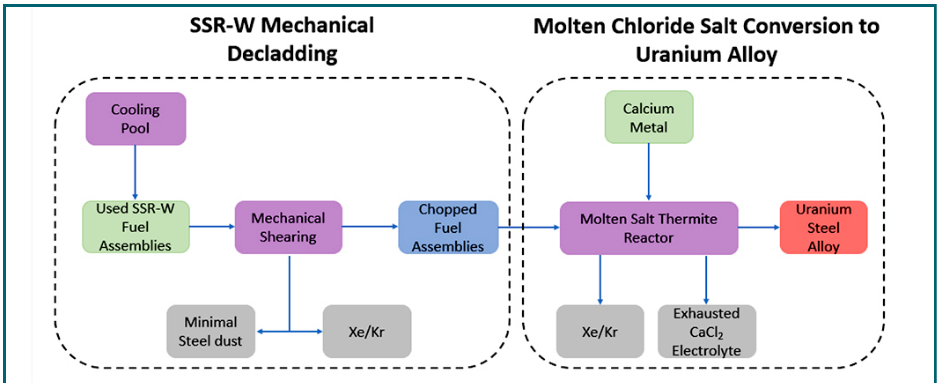

Figure 4. WATSS reprocessing steps for SSR-W spent fuel.

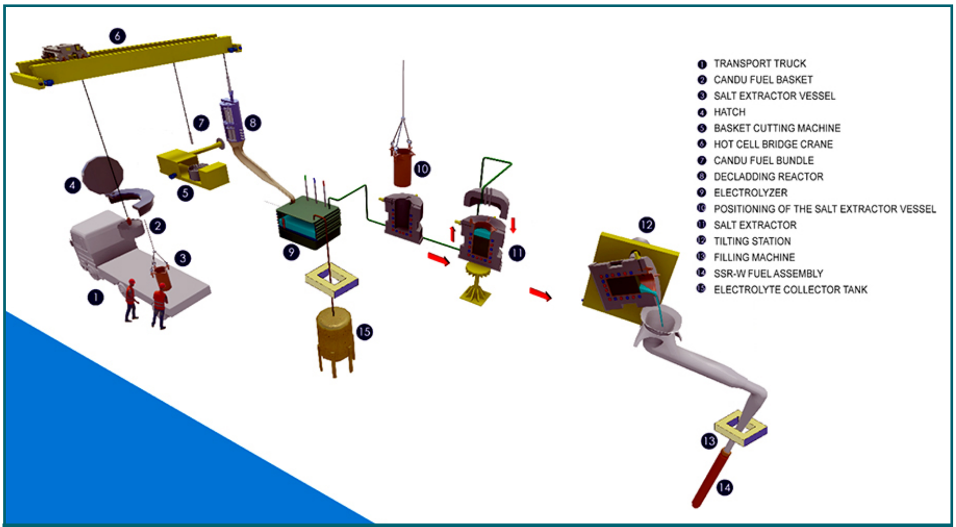

Figure 5. WATSS reprocessing process conceptual design.

ing capabilities of WATSS facility goes further, including the below steps aimed to reprocess the spent fuel coming from SSR-W operation and generate new fresh fuel.

- **Mechanical shearing** – this step shears the SSR-W fuel pins (with HT-9 stainless steel cladding). The shearing can be done mechanically or using a laser. The technology is mature, and no feasibility study is required.
- **Metallothermic reduction reaction** – fission products and alloy (noble metals, actinides, lanthanides, and cladding steel) are separated so that they can be reused for new SSR-W fuel.

This CANDU waste recycling process effectively reduces the hazardous lifetime of the radioactive waste by three orders of magnitude. This means that electrolyte salt only has to be contained for about 300 years instead of 300,000 years.

R&D - ONWARD PROJECT

Even knowing WATSS process steps have been successfully carried out in the different laboratories around the world separately, Moltex is leading with the support of Canadian Nuclear Laboratories (CNL), the so-called Oxide Nuclear WAste Reduction Demonstration (ONWARD). ONWARD is a key critical step in developing the WATSS technology, demonstrating its practicality and producing information necessary for the design and licensing of a full-scale plant. The University of New Brunswick (UNB) and University of Manchester will provide support in the early days of the program by undertaking work in designing, procuring and testing the inactive kit.

ONWARD focuses on research into the electro-reduction and liquid-liquid extraction processes and includes work necessary to assess the practicality and economics of chemical decladding. The electroreduction research starts with the use of a fabricated "simfuel" based on natural Uranium contaminated with impurities. The objective of using simulated spent fuel in UNB testing laboratories is to get key operational parameters related with electroreducer and salt extractor operation. Afterwards, and considering the data obtained from UNB tests, CNL will design and operate a small-scale complete facility and will use spent fuel to validate the complete process.

GRIDRESERVE®

GridReserve® system is the Moltex proposal to make possible a full load running operation of the nuclear reactor in a renewable powered electrical grid.

Energy storage is not possible at the low operating temperatures (~ 300°C) of current pressurized water reactors, making difficult their integration within low demand grids or with high variable demand/generation profiles. Moltex's SSR-W, in addition to partial load-following, can store thermal energy from the reactor and convert it to electrical energy for delivery to the grid during peak demand periods by adding their patented GridReserve® technology. The stored thermal energy can also be used to complement the intermittent, unpredictable and inflexible operational nature of renewables. For example, stored thermal energy could be used during night-time hours when solar farms are not generating electricity or during periods of light winds when wind turbines are not turning.

Moltex's GridReserve® energy storage system is a group of insulated molten salt storage tanks that are capable of storing thermal energy. The molten salt mixture used to store the thermal energy is similar to that used at a concentrated (mirror-focused) solar power plant. The molten mixture, which is highly thermally stable, is comprised of sodium and potassium nitrates. Heat generated from the SSR-W300 can be retained in the storage system for about 8 to 10 hours at the temperatures of about 550°C. Each tank, which will be manufactured from carbon and stainless steel and will contain internal heaters in order to maintain the mixture at a minimum temperature to keep the salt from solidifying.

A GridReserve® system for a 300 MWe turbine would occupy an area of about 2 ha. The idea is to locate the GridReserve® system outside the nuclear island, near turbine island, so no interaction with nuclear side is expected.

CURRENT STATUS

By the end of 2019 Moltex completed submissions of all 19 focus areas for Vendor Design Review Phase 1 (VDR1) for SSR-W 300. The VDR review is a 3 main steps (3rd is optional) service the Canadian regulator, CNSC, provides when a SMR vendor requests it. It is a high-level review of the proposed reactor technology's design information against Canadian regulatory requirements and guidance trying to avoid future licensee barriers (Prepare Site, Construct & Operate). The mentioned focus areas covered all design features a novel nuclear technology shall cover with enough detail depending on the VDR step:

FA.1. Assess general NPP description, defence in depth, safety goals and objectives, dose acceptance criteria.

FA.2. Classification of SSCs.
FA.3. Assess reactor core nuclear design.
FA.4. Assess fuel design and qualification.
FA.5. Instrumentation & Control.
FA.6. Assess means of reactor shutdown.
FA.7. Emergency core cooling and emergency heat removal systems.
FA.8. Assess containment and safety important civil structures.
FA.9. Mitigation of design extension conditions.
FA.10. Assess safety analysis (Deterministic & Probabilistic) and internal and external hazards.
FA.11. Assess pressure boundary design.
FA.12. Fire protection.
FA.13. Radiation protection.
FA.14. Out of core criticality.
FA.15. Robustness, Security and Cybersecurity, Safeguards.
FA.16. Assess vendor research and development program.
FA.17. Assess management system of design process and quality assurance in design and safety analysis.
FA.18. Assess human factors.
FA.19. Assess incorporation of decommissioning in design considerations.

Current design of the SSR-W 300 is at the transition from conceptual to preliminary engineering phase and nearly to start the second stage of CNSC VDR (VDR2).

Apart from the involvement with Canadian regulator, Moltex is collaborating with Oak Ridge and Argonne US national laboratories and with Purdue University, through ARPA-E program by US Department of Energy.

IDOM

In 2019 IDOM Consulting, Engineering, Architecture SAU (IDOM) recognized the potential of Moltex technologies and decided to invest in the project. The multi-million-dollar (USD) investment allowed Moltex to expand its New Brunswick office and to accelerate its design development and pre-licensing progress through VDR.

The work performed, among other activities, include the following:

- Licensing support, including elaboration of VDR1 FA5, FA7, FA8, FA11, FA13 & FA19.
- SSR-W Conceptual Design engineering support for thermo-hydraulics, fluid-dynamics, mechanical, electrical, I&C, neutronics, etc.
- WATSS Conceptual design engineering support for process design, mechanical, neutronics, etc.

CONCLUSIONS

The current planning notices that the SSR-W FOAK is possible to be built by late 2020s and a fleet deployment could be possible by mid 2030s. Most of the Western current nuclear power plants will be ready for shut off by this date with high liabilities compromised with spent fuel management, so Moltex technology can be the solution to keep the power generation capability at the same time to reduce the hazard and economic costs for spent fuel stockpiles. The reduced footprint of the nuclear island makes possible, in the current atomic sites, to carry out the decommissioning of old power plants at the same time new nuclear is built, taking advantage for other installations like Turbine Island or Electrical Switchyard that can be updated through easy refurbishment processes. ■