# Evaluation of Radioactive Waste Streams and Management Options for Molten Salt Small Modular ReactoR

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**Abstract**

Small modular reactors as a strong candidate for the future of nuclear energy seem to be the prospective contributors to the spent fuel inventory of the world. There are more than 70 SMR concepts with various core designs and fuel cycle options including molten salt small modular reactors which will produce various amounts of spent fuel with different radiological and chemical properties during the operation. Therefore, the characteristics of spent fuel and radioactive waste generated from proposed small modular reactor designs should be evaluated and the implications on the back-end nuclear fuel cycle stages should be assessed. Since the molten salt reactor fuels are completely different in form and design from the conventional fuels used in the current reactor technologies, to develop the technologies needed for the back-end fuel cycle stages, the characterization of spent fuel from a molten salt small modular reactor is crucial for the deployment of this technology. This work focuses on the evaluation of spent fuel inventory and radioactive waste streams for a molten salt small modular reactor and the identification of steps to be applied for the management of wastes and spent fuel from discharge to disposal.

## INTRODUCTION

Up to date, approximately 390,000 tons of spent fuel have been generated from the operation of nuclear power plants worldwide. The amount of solid radioactive waste is 38 million m3 and %2 of the total amount is intermediate-level waste (ILW) and high-level waste (HLW) [1]. It is expected that the amount of spent fuel and radioactive waste originating from nuclear facilities will increase further with time due to operating and planned nuclear power plants. For this reason, safe and effective management of the present and prospective spent fuels and radioactive wastes is crucial to ensure the sustainable usage of nuclear energy.

As one of the new generation reactor designs, Small Modular Reactors (SMRs) are gaining significant interest for their reduced footprint and innovative features. Even though they offer enhanced safety features and reduced cost, just like conventional large-scale reactors, SMRs will generate spent fuel and radioactive waste during power production which needs to be managed safely. So, the safe management of spent fuel and radioactive wastes from SMRs can be considered one of the key issues in the successful deployment of these new reactor designs.

There are more than 70 SMR concepts with various core designs and fuel cycle options including molten salt small modular reactors which will produce various amounts of spent fuel and radioactive waste with different radiological and chemical properties during the operation. Molten salt reactors are considered to be one of the six Generation IV reactor designs and promise many advantages including enhanced safety, single-phase cooling system that eliminates the need for large reactor containment, high efficiency and flexible fuel cycle [2]. Departing from conventional reactors, molten salt reactors utilize fluid fuel in the form of molten salt. A broad range of molten salt reactor concepts have been proposed. The designs of the molten salt reactors vary in terms of used salt (fluoride-based and chloride-based), fissile and fertile fuel material (plutonium, enriched uranium, thorium, or actinide bearing), and the energy spectrum of the neutrons (fast and thermal). There are also compact molten salt reactor designs that are proposed as SMR technologies. The proposed designs include a range of molten salt SMR concepts in various stages of development. The most of the proposed molten salt SMR designs are conceptual, while designs of Integral MSR (Terrestrial Energy, Canada), Thorcon (Thorcon International, U.S. and Indonesia), and FUJI (International Thorium Molten-Salt Forum and Japan) are detailed.

Since the form of the fuel in the molten salt-fuelled SMR designs is liquid, the characteristics of spent fuel generated will be different from the spent fuel in the solid form which is generated from the current reactor technologies in operation. Therefore, the back-end fuel cycle stages such as storage, transport, reprocessing, and disposal to be applied for the spent molten-salt fuel will mainly be different from the technologies developed for the traditional spent oxide fuel from currently operating reactors. In the study, by considering the development stages of the proposed reactor concepts, Thorcon is selected as representative of molten salt-fuelled SMRs and the spent fuel and radioactive streams and the management stages to be applied for the generated waste streams are discussed.

## REFERENCE MOLTEN SALT REACTOR DESIGN

Thorcon reactor design is the scale-up of the Molten Salt Reactor Experiment conducted in 1960s by the U.S. Oak Ridge Laboratory. The design has two modular reactors in separate sealed cans. Each can contains the reactor (named Pot), a primary loop heat exchanger, and a primary loop pump. Graphite is used as moderator in the Thorcon design. Since the lifetime of the graphite moderator is 4 years, a can operates for four years, cools down for four years, and then is changed out. Only one of the modules produces power at a time while the other module is in cool-down mode. Each can has 250 MWe power output. The fuel of the reactor is molten fluoride salt with dissolved thorium and uranium fuel (NaF-BeF2-ThF4-UF4) with an enrichment of 19.7 w/o. Molten salt fuel serves as also the primary coolant. During the operation of the system, liquid fluoride fuel leaving the Pot at 704 °C passes through the heat exchanger at a mass flow rate of 3000 kg/s and is cooled to 564 °C by transferring heat to a secondary salt. Then, fluoride fuel flows over to the bottom of the Pot, and as it rises in the core by the fission of uranium heat is generated and a portion of the thorium in the fuel is converted to fissile uranium isotope U-233. This process results in an overall plant efficiency of about 45%, and a net electrical output per can of 250 MW [3].

## Radioactive Waste Streams GENERATED IN THE REFERENCE REACTOR

Similar to current nuclear power plants, molten salt SMRs will generate spent fuel and radioactive waste. Since this radioactive waste and spent fuels are in different forms and content than the wastes originating from currently operating reactors, the management strategies to be applied to waste streams will also be different. By considering the reference molten salt SMR concept, the potential radioactive waste streams generated during the operation of the system can be classified mainly as spent molten salt stream, radioactive off-gases, graphite waste stream and metallic waste stream.

### Spent molten salt

The fuel of the reference molten salt reactor is molten fluoride salt with dissolved thorium and uranium fuel (NaF-BeF2-ThF4-UF4) with an enrichment of 19.7 w/o. Since the reactor is designed as a thorium converter, during the operation of the reactor, thorium in the fuel is converted to U-233 fissile isotope which contributes to energy production. The average daily enriched uranium (19.7 w/o) and thorium requirement of the reactor is 5.3 kg and 9 kg, respectively [3]. This results in the annual uranium and thorium consumption of the system for an 8-year fuel cycle being 1.93 t and 3.28 t respectively, on average. Since uranium and thorium are dissolved in molten fluoride salt, these amounts correspond to a feed of 4.55 t UF4 and 4.35 t ThF4. The other constituents of the molten salt fuel mixture are NaF and BeF2 and the amount of these constituents are 5.54 t and 0.99 t respectively. Thus, the total amount of annual fresh fuel requirement and the spent molten salt fuel discharged from the core is 13.43 t.

The spent molten salt discharged from the core can follow two paths. It can be immobilized to a suitable waste form and sent to storage. However, the spent molten salt fuel still contains U-235 and U-233 fissile isotopes in considerable amounts. Therefore, it may not be feasible to store spent molten salt fuel and it can be reprocessed to recycle valuable fissile material in it and reduce the amount of radioactive waste to be handled. The proposed methods for the reprocessing of spent molten salt are based on pyrochemical processes such as fluoride volatility, molten salt-liquid metal extraction and electrochemical separation processes. The reprocessing of spent molten salt consists of fluorination, protactinium removal, actinide extraction and lanthanide extraction steps. For the reference molten salt SMR, it is estimated that if reprocessing is applied for the separation of the valuable material from the waste, the total amount of spent molten salt reduces to 11.0 t [3].

Hence, whichever path is followed, the resulting molten salt stream (spent or separated) needs to be immobilized to a stable waste form before transferring to storage or final disposal. Several waste forms and immobilization techniques are being developed both for fluoride and chloride-based molten salt waste streams. Glass, ceramic and the composites of glass-ceramic and metal-ceramic are the proposed waste forms for the immobilization of molten salt waste [4-8]

Even though a significant amount of study has been conducted on the proposed waste forms and pyrochemical spent molten salt reprocessing techniques, the estimation of the total volume of immobilized waste forms to be sent to storage or disposal is not possible at this stage. To evaluate the final molten salt waste amounts, it is necessary to investigate the proposed immobilization processes in detail and assess them together with the storage and disposal concept to be applied.

### Radioactive off-gases stream

Since the fuel is in the liquid form and differently from traditional fuels there is no cladding to retain gaseous fission products in it, during the operation of the molten salt reactor, fission gases can be released to the headspace of the core. The gaseous fission products need to be removed from the reactor to safe operation of the system, to increase the lifetime of the molten salt fuel and to improve the neutron economy. In the reference molten salt SMR, Thorcon, and some other molten salt designs helium is used as cover gas to remove gaseous fission products generated at the core such as Xe and Kr. The potential species in the off-gas stream leaving the reactor are aerosols, volatile species, tritium, short-lived fission gases and their daughters, (Xe-133, Xe-135, Xe-137, Xe-139, Kr-88, Kr-89 and Kr-90) and long-lived radionuclides (Kr-85, Cl-36 and I-129) [10]. The abundance of species in the off-gas stream depends on the type and composition of the molten salt fuel, the design of the reactor, the neutron spectrum and the method used to process molten salt fuel.

The radioactive gas stream is processed through the off-gas treatment system which consists of a series of treatment components such as cooling tanks, traps for halides and tritium, charcoal delay line to decay of short-lived radionuclides of Xe and Kr, cryogenic gas processing system to separate the Xe and Kr gasses and helium recycle unit [3].

### Graphite waste stream

The moderator of the reference molten salt SMR is made of graphite which is a carbon-based material. Neutron irradiation damage is a limiting factor for the lifetime of the graphite moderator blocks and it is predicted that they need to be replaced in certain periods. Therefore, it can be considered that the graphite waste stream will comprise a large fraction of the total radioactive waste streams to be generated during the operation of the reactor. The conversion of the removed graphite moderator to waste form suitable for disposal, decontamination and recycling are the possible paths to be followed for this waste stream [9].

### Metallic waste stream

The metallic structural components of the reference molten salt SMR will be subjected to high temperatures and intense neutron irradiation during the operation. Especially, the core components in direct contact with molten salt will be working in a highly corrosive environment. These metallic structural materials will need to be dismantled and handled as a waste stream at the end of the reactor lifetime. Since the removed components will be contaminated with salt residue, after decontamination and size reduction, they can be disposed of as ILW or LLW [3,9].

## Conclusion

In the study, potential radioactive waste streams and spent fuel inventory to be generated during the operation of an SMR design based on the molten salt technology were identified and the management strategies for each stream were discussed. Molten salt reactor fuels are completely different in form and design from the conventional fuels used in the current reactor technologies. Additionally, several large-scale or small modular molten salt reactor designs use molten salt mixtures with different fissile/fertile materials and fluoride or chloride salts. Even though several spent molten salt processing methods are under development and research on immobilization of the residual waste is ongoing, because of the lack of experience, management of spent molten salt stream is anticipated to be most challenging compared to other waste streams to be generated from the reactor. In planning and identification of the processing methods and immobilization materials, subsequent management stages such as transport, storage, and disposal to be applied for the spent molten salts and residuals need to be taken into account. Therefore, it is essential to identify and detail the back-end fuel cycle stages at the beginning of the design of the molten salt type SMR fuel cycle and consider them as an integrated system to be developed.

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