Technical Letter Report

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Technical Assessment of Chloride Molten Salt Reactor Waste

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TECHNICAL ASSESSMENT OF CHLORIDE MOLTEN SALT REACTOR WASTE—
FINAL REPORT

Prepared for

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT DATA

DATA: There are no original CNWRA-generated data in this report. Sources of referenced data should be consulted to determine the level of quality of those data.

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ABBREVIATIONS

CNWRA	Center for Nuclear Waste Regulatory Analyses
INL	Idaho National Laboratory
MSR	Molten salt reactor
NRC	Nuclear Regulatory Commission

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EXECUTIVE SUMMARY

In anticipation of pre-licensing activities for chloride-based molten salt reactors (MSRs), the U.S. Nuclear Regulatory Commission (NRC) is evaluating storage and management strategies for chloride-based nuclear waste. The Center for Nuclear Waste Regulatory Analyses (CNWRA®) supported this effort by reviewing publicly available data, focusing on safety-relevant phenomena during interim storage. Sodium chloride (NaCl) was identified as the most likely carrier salt, being proposed for use in the Molten Chloride Reactor Experiment.

Of note in the application of chloride salts in fast reactors is the potential for generation of Cl-36, a long-lived gamma-emitting isotope produced via neutron activation of Cl-35. While separation technologies for Cl-36 are under exploration, they remain unproven at scale. Radiolysis of NaCl produces sodium nano-colloids and entrapped chlorine gas, with minimal free chlorine release, even under high radiation doses. However, a full understanding of interactions between colloids and fission products is evolving. Chloride volatilization requires high temperatures unlikely in storage conditions.

Corrosion is another important consideration, as chlorine is highly reactive. While dry NaCl environments are manageable in steel containers, the complex composition of spent salts may alter corrosion behavior. Studies show predictable corrosion in molten salt loops and stratification during cooling, potentially affecting thermal and radiological properties. Comparatively, chloride salts used in metal recycling and energy storage are not classified as hazardous and are typically landfilled, suggesting limited regulatory concern for non-radioactive chloride waste streams.

Further research into interactions with fission products, fuel, and water may reduce uncertainties associated with formation of radiation-induced colloids. Data on chlorine activation and solubility-driven segregation during cooling would help determine storage pathways. Further, if direct storage proves unsuitable, methods exist to convert salt waste into more stable forms for long-term management.

1 INTRODUCTION

In preparation for pre-licensing interactions and potential safety reviews for molten salt reactors (MSRs), the U.S. Nuclear Regulatory Commission (NRC) staff are assessing available information to understand technical considerations that may impact the safe storage and management of irradiated fuel waste generated from this reactor class. Of interest are the available technologies and information related to chloride-based salts in the nuclear industry and other enterprises that are relevant to the storage and management of spent chloride fuel salt.

Molten salt reactor technology that utilizes chloride fuel salt is gaining traction among developers in the nuclear energy industry. Key drivers of this technology include high thermal efficiency, enhanced fuel utilization, proposed inherent safety features, and the ability to incorporate alternative fuel cycles. The key characteristic of the MSR is the heat transfer mechanism, which utilizes a molten salt to conduct heat away from the fuel. The fuel can be a solid fuel, similar to a traditional reactor, or dissolved within a “carrier salt.” The selection of the carrier salt is a primary design decision that determines the fundamental nuclear characteristics of the reactor. The predominant salts under investigation are derived from the halogens, particularly fluorine and chlorine as they offer chemical compatibility with various fuel types envisioned (uranium, plutonium, and thorium) and have favorable neutronics.

Molten salt reactor fluorine salts typically consist of lithium fluoride and may include beryllium fluoride to reduce the melting temperature. These reactors are commonly intended to operate within the thermal to epithermal neutron energy regimes but are not limited to this range. The only MSRs that have operational history utilized fluoride salts; detailed summaries of their use and history are provided in previous CNWRA reports by Pensado et al. (2025) and Adams et al. (2023).

Chloride salts are under active investigation as these salts have advantages over their fluoride counterparts such as: lower melting temperature, higher solubility of actinides, and more favorable neutron utilization in the fast neutron spectrum, allowing for more efficient breeding of fuel from fertile sources and transmuting longer-lived radioactive isotopes.

Chapter 2 of this report identifies characteristics unique to chloride molten salts. The chapter addresses technical issues directly related to the use of chlorinated salts for MSRs and identifies various other industries and technologies that utilize or intend to utilize chloride derived salts. Chapter 3 provides an assessment of technical information and needs as applicable to chloride-based MSRs and waste management considerations, and conclusions.

2 INFORMATION AND EXPERIENCE PERTAINING TO STORAGE AND MANAGEMENT OF CHLORIDE SALTS

2.1 Nuclear Energy

2.1.1 Chloride Salt Compositions

A wide variety of chloride (Cl^-) carrier salts have been proposed for use in MSRs; however, the leading candidate is sodium chloride (NaCl). Binary and ternary carrier salts have been proposed, including the addition of magnesium chloride ($MgCl_2$) or potassium chloride (KCl).

The primary benefit of using a more complex mixture is utilizing the reduced melting temperature found at the eutectic composition, which is lower than the melting point of the individual components. However, investigation by Benes and Konings (2008) determined the addition of $MgCl_2$ to the fueled salt compositions of NaCl-UCl_3 (or $PuCl_3$) and in the NaCl-UCl_3-$PuCl_3$ had no measurable decrease in the melting temperature.

Various other binary and ternary chloride compositions have been proposed to include rubidium, lithium, and potassium chlorides. The addition of these compounds reduces the melting temperature. Williams (2006) compiled a list of candidate binary chloride salts and evaluated thermophysical properties relevant to their use as coolant salts in a salt coolant loop. In a recent study aimed at improving the understanding of chloride salt properties to support MSR design, Pixler et al. (2024) conducted a comprehensive survey of thermophysical and thermochemical properties relevant to binary chlorides for MSRs. This list of salts encompasses the alkali metals and alkali earth metals.

2.1.2 Effects of Irradiation

Natural chlorine is composed primarily of two stable isotopes—Cl-35 (74% abundance) and Cl-37 (24% abundance)—along with trace amounts of the long-lived radionuclide Cl-36, which has a half-life of 301,300-yrs. When natural chlorine is irradiated under a neutron fluence, Cl-35 has the potential to capture the neutron, generate high energy gamma rays, and convert to Cl-36. Segal (1959) investigated the resulting gamma excitation in the thermal neutron region and found the subsequent gammas were produced in the range of 0.5-MeV to 8.5-MeV. As the intention of Cl-MSRs is to operate in the fast spectrum, cross sectional data in these ranges tend to lack appropriate experimental validation and are instead based on models of the available data extrapolated to these higher neutron energies. Kuvin et al. (2020) investigated the neutron cross-section of Cl-35 from 0.6-MeV to 6-MeV and found that the newly acquired data were not accurately described by the models, and that resonances may appear in this region, which may contribute to a higher Cl-35 production than anticipated. To reduce Cl-36 generation separation of Cl-35 from natural chlorine could be conducted. Ongoing research has determined multiple pathways for Cl isotope separation; however, no method has progressed into a stage for commercial consideration (Degueldre and Bruno, 2024).

The effects of irradiation on NaCl salt have been investigated under ionizing radiation. In a recent study, Phillips et al. (2022) examined the effects of gamma irradiation on NaCl-UCl_3 at various temperatures. The samples in the study were irradiated for a total of 2,638-hours accumulating a dose of 31-MGy. No appreciable Cl_2 gas generation was observed. This may be explained by earlier investigations where Levy et al. (1984) determined that synthetic NaCl crystals and natural rock salt at elevated temperatures as low as 100°C would develop Na colloid clusters under 1 to 3-MeV gamma irradiation. A more recent study confirmed the formed colloids could entrap the liberated chlorine (Haynes, 2016). This work was further corroborated by Weerkamp et al. (1994) while investigating the colloid formations in irradiated NaCl single crystals between 20°C to 150°C, finding that the colloids are small and display quantum size effects similar to nanoparticles. Further, Weerkamp found that with the addition of impurities, sodium fluoride in this case, increased the rate of colloid formation, and this effect was pronounced at higher temperatures (Weerkamp, et al., 1994). Various other chloride species are mentioned as dopants by Weerkamp; however results were not reported. Sugonyako et al. (2005) while investigating melting properties of the irradiation-formed Na colloids, found that upward of 20% of the bulk material could be converted to the colloid centers.

2.1.3 Volatile Compounds

Volatility is a significant consideration for the safe storage and management of spent fuel salt. Radiolysis and radioactive decay can liberate the halogens forming volatile halogen or oxy-halogen compounds (if oxygen is present). Pensado et al. (2025) discusses this phenomenon in detail with respect to spent fluoride nuclear salts at Oak Ridge National Laboratory. Radiolysis, particularly of unprocessed salts, will produce headspace gases that could be highly corrosive (e.g., F_2(g), Cl_2(g), derivatives of F_2(g) or Cl_2(g)), depending on the redox conditions in the salt. However, overall, it appears that, unlike fluoride salts, chloride salts will not release any significant amounts of Cl_2(g) (Riley et al., 2018).

Very limited information is available on the topic of chloride volatility processes as it pertains to molten salts. Chloride compound volatility tends to be more complicated than corresponding fluorides and less understood. Little investigation has occurred, with most centered around uranium chlorides for use in separation streams. Riley et al. (2018) discusses chloride volatility and its limited use in more detail and presents thermochemical properties of interest. Table 2-1 shows the boiling point of select species of interest for safety and criticality of storage in chloride salts and their fluoride counterparts. This list is not exhaustive, additional species may produce similar concerns and are presented in detail by Riley et al. (2018).

Table 2-1: Boiling temperatures of select actinide species relevant to volatilization in molten salts. (X designates halogen component).

Species	T_b, X= Cl (°C)	T_b, X= F (°C)
UX_3[a]	—	—
UX_4	791[1]	1417[1]
UX_6	277[2]	56.5[1]
ThX_4	921[1]	1680[1]
PuX_4	Sublimate[3]	—
PuX_6	—	61.8[4]
NpX_4	847[1]	—
NpX_6	—	76.8[1]

[1] (Haynes, 2016)
[2] (Hariharan, et al., 1970)
[3] (Karlsson, et al., 2020)
[4] (Riley, et al., 2018)

With regard to the potential for gaseous uranium chloride species to form in spent fuel salt—analogous to the volatility issues associated with UF_6 in the MSRE salt waste (see Table 2-1)—there is no conclusive evidence that such behavior would occur in chloride-based systems. UCl_4 composition is stable at room temperature, while UCl_5 and UCl_6 are only stable under excess Cl_2 and decompose to UCl_4 and Cl_2 when cooled down (Haas, 1992; Fredrickson, 2018).] These studies indicate the potential of forming UCl_6 during MSR spent fuel processing but only given favorable experimental conditions such as high temperatures and the presence of chlorine agents in the system, particularly Cl_2 gas. However, such a reaction or the formation of UCl_6 has not been documented, probably due to the highly oxidized state of the compound and its

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[a] References not available. UCl_3 has a melting point of 842 ºC; UF_3 is expected to decompose before reaching boiling point [Katz and Rabinowitch, The Chemistry of Uranium, 1951].

instability at low temperatures. If a stable UCl_6 is formed, it will likely be in the gas phase due to its high vapor pressures at low temperatures (Hass, 1992).

For the volatility of additional transuranic chlorides that may be of interest: plutonium tetrachloride can be synthesized in a chlorinated environment, is gaseous upon formation, and will readily disassociate outside of the chlorine environment. Neptunium and plutonium pentachlorides have not been observed and are considered theoretical (Riley, et al., 2018).

2.1.4 Chlorine-Induced Corrosion

Chlorine is a highly reactive element known to be highly corrosive in reducing environments. Elemental Cl is a diatomic molecule (Cl_2) that is typically handled under pressure as a liquid. In this state under a dry environment Cl_2 can be safely stored in stainless steel or carbon steel vessels, as corrosion is mitigated (The Chlorine Institute, 2014). At elevated temperatures the chlorine will begin to react with the iron, possibly creating volatile species. Wet chlorine will readily form hydrochloric acid and will corrode carbon and stainless steels (The Chlorine Institute, 2014).

Sodium chloride in a solid state is not known to be corrosive; however, in its molten form, NaCl will convert alloying elements of the structural materials to salts and dissolve these compounds. According to Kelleher et al. (2022) the corrosion is predictable, based on the Gibbs free energy of formation of the alloying elements and the Gibbs free energy of the associate dissolvable salt. This same mechanism drives corrosion in the fluoride salts, although corrosion is even more favorable in the chloride system as the salt formation energy is closer to the alloy formation energy (Kelleher et al., 2022). Kelleher et al. (2022) investigated the corrosion of the alloying elements in a chloride-based forced circulation loop, determining that corrosion occurs in the hot leg (612 ± 20°C) and that the corrosion products would then deposit in the cold leg (498 ± 20°C) of the loop. This was attributed to the reduced solubility of the salts.

2.1.5 Solubility

Sodium chloride is well-known to be highly soluble in water. Pensado et al. (2025) conducted a preliminary investigation of various salts of interest for nuclear applications in geological disposal conditions and the subsequent intrusion of water and flow of the resulting solution away from the source. Results showed that NaCl would readily dissolve under specific geologic disposal conditions with complete dissolution in tens of years. While the Pensado investigation focused on geologic disposal, it highlights the concern of water intrusion, and the dissolution of NaCl; which is also a technical consideration for safe storage and management.

2.1.6 Processing and Potential Waste Forms

Chloride salts have historically been utilized in the nuclear industry as a mechanism for reprocessing of spent metallic fuel. Electrochemical processing was conducted on spent Experimental Breeder Reactor II fuel at Idaho National Laboratory (INL) to demonstrate a closed fuel cycle. Previous CNWRA reports by Pensado et al. (2025) and LaPlante et al. (2025) cover the process in detail. The culmination of this work at INL resulted in reprocessed metallic fuel, radioactive cladding hull waste, and NaCl salt with dissolved radioactive components (residual fuel and fission products). Immobilization and stabilization of the radioactive salt was covered in previous CNWRA reports (Pensado et al., 2025; LaPlante and Pan, 2025). Of these proposed waste forms, none have undergone long-term durability testing and qualification.

2.2 Alternative Energy

Alternative energy developers are actively engaged with investment into chloride salts, particularly thermal energy storage and solar power. Currently, these fields most commonly use a solar salt composed of sodium nitrate and potassium nitrate. This salt demonstrates a low melting temperature (131°C), favorable heat transfer properties, and low corrosion rates of the structural components. However, according to Cabeza et al. (2024), the chemical stability of the salt is up to 565°C, too low for many industrial applications. Investigation into life cycle management of solar salts identify expected prolonged use (i.e., >30-years) with the ability to process the salt for continued use if desired; however, other than a passing reference to landfill disposal, no details about ultimate disposal were provided (Gasa et al., 2021). Potassium and sodium nitrate salts may be disposed of in the United States as hazardous waste and can be treated for disposal to landfills. Therefore, concerns regarding storage and storage times beyond the expected operational use of the materials may be limited.

Investigation is proceeding to expand the applicability of solar power and energy storage to additional industries. This requires salts that are stable at higher temperatures. Cabeza et al. (2024) selected a range of ternary salt using NaCl, KCl, $ZnCl_2$, and $MgCl_2$ identifying that mixtures of the selected salts would enhance efficiency and increase operation temperatures. One concern the alternative energy industries have with NaCl salts is corrosion. Wei et al. (2024) determined that corrosion could be reduced by using a mixture of ternary NaCl salts and magnesium as a corrosion inhibitor. Ultimate disposal concepts or plans for NaCl salt were not identified for alternative energy applications. However, disposal of NaCl in the United States may be accomplished by direct landfill disposal as the salt is considered non-hazardous waste (Graziano et al., 1996).

2.3 Metal Processing

In metal recycling and purification, chloride salts serve as a flux. In this process, various salts such as NaCl, KCl, or calcium chloride may be utilized to remove heavy metal and oxygen impurities and lower melting temperatures of the molten source stream. As reported by Graziano et al. (1996) the resulting salt slag comprises between 30% and 60% of the metal produced. According to Graziano et al. (1996) the slag contains trace heavy metals, aluminum, and various metal oxides presently, the United States disposes of salt slag as non-hazardous waste and directly deposits it into landfills.

3 ASSESSMENT OF TECHNICAL CONSIDERATIONS AND INFORMATION NEEDS FOR STORAGE AND MANAGEMENT OF CHLORIDE WASTES FROM MOLTEN SALT REACTORS

The evaluation of spent nuclear chloride salt storage and management reveals several technical considerations to ensure safety and regulatory compliance. Chloride salts used in molten salt reactors (MSRs) are generally categorized into two types: carrier salts, primarily sodium chloride (NaCl), and coolant salts, which are typically binary or ternary mixtures designed to lower melting points. NaCl is currently the most likely candidate for carrier salt applications, while the specific compositions of coolant salts may vary depending on reactor design. Considerations of note are:

- Neutron activation of Cl-35, a naturally occurring isotope in chlorine, can transmute Cl-35 into Cl-36—a long-lived beta-emitting isotope with a half-life of over 300,000 years. This transformation introduces a persistent gamma source term that must be considered in shielding and criticality safety analyses. Although separation technologies for chlorine isotopes are under development, they remain at the laboratory scale and are not yet commercially viable. Assessment of safety and risk of transmuted products, such as Cl-36, would be beneficial in developing the safety case.

- Radiolysis behavior in NaCl appears to differ from that of fluoride salts. While fluoride salts can release volatile fluorine and form mobile uranium complexes, NaCl radiolysis results in the formation of nano-sodium colloids that entrap chlorine gas. This entrapment significantly limits chlorine mobility, reducing the risk of chlorine-induced corrosion or gas release. At elevated temperatures that may be present in storage environments the colloid formation rate may increase. However, the stability of these colloids in the presence of fission products or other fuel materials has not been characterized or reported.

- Corrosion in the presence of water or hydrogen. Although dry chlorine gas is not highly corrosive to stainless or carbon steel, the presence of water can lead to the formation of hydrochloric acid (HCl), which is highly corrosive. Although NaCl itself is non-corrosive and classified as non-hazardous, radioactive decay processes may generate hydrogen, potentially initiating corrosion in sealed environments.

- Water ingress poses a potentially serious risk. Water can dissolve NaCl and react with any free chlorine to form HCl, initiating corrosion. Additionally, sodium metal—if present in colloidal form—can react energetically with water, posing safety hazards. The interactions between water, sodium colloids, and radioactive components in spent salt are not fully understood.

- Volatility of chloride compounds is less of a concern compared to fluoride salts, as chlorides require significantly higher temperatures to volatilize—temperatures that are not expected under normal storage or management conditions. This reduces the likelihood of volatile radioactive species being released during storage.

- Stratification of radioactive components due to cooling-induced solubility changes. Experimental data from corrosion loops indicate that as salt cools, corrosion products may precipitate out, potentially leading to stratification of radioactive materials. This could affect criticality, dose, and thermal source terms used in safety evaluations.

Salt processing techniques have been developed to remove actinides such as uranium and plutonium from NaCl, if conditioning is required before storage. Several methods have also been proposed to convert spent salt into more stable waste forms. However, long-term data on the radiological stability and corrosion resistance of these waste forms is being developed through ongoing research.

In contrast to the nuclear industry, non-nuclear industries that use NaCl—such as metal processing and energy storage—can dispose of their waste salts in landfills, as the salts are not considered hazardous. However, in the nuclear context, complete removal of radioactive contaminants may not be feasible. Thus, spent nuclear salts may require longer-term storage solutions compared to their non-nuclear counterparts. Coolant salts, if they remain uncontaminated by fuel and experience minimal activation, may not need to be managed as radioactive waste. However, this depends on operational practices and the degree of cross-contamination with carrier salts.

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