RECENT ADVANCEMENTS OF METALLIC MATERIALS FOR INTEGRAL MOLTEN SALT REACTORS

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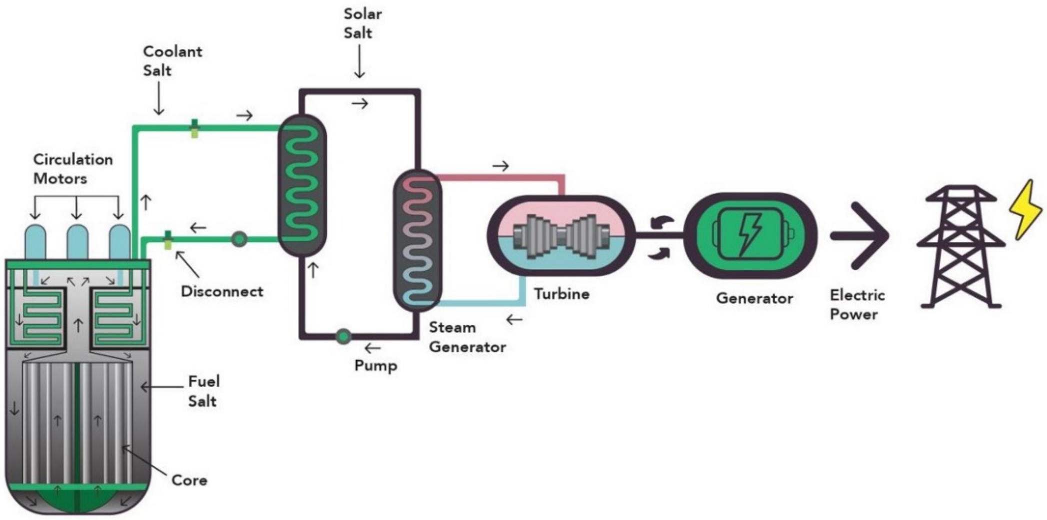
Abstract

The Integral Molten Salt Reactor (IMSR) is a design for a type of advanced nuclear reactor that utilizes molten salt as both the coolant and the fuel solvent, targeted at developing a commercial product for the small modular reactor (SMR) market. This innovative approach to nuclear reactor design offers several advantages over traditional solidfueled reactors, including enhanced safety features, improved fuel efficiency, and greater operational flexibility. The status of metallic structural materials for IMSR is an area of active research and development, driven by the unique demands that the molten salt environment places on reactor components. One of the primary concerns with metallic materials in IMSRs is their resistance to corrosion by molten salts. Furthermore, materials used in these reactors must maintain their mechanical integrity, resist creep, and avoid embrittlement under these conditions. High-temperature materials such as nickel-based superalloys and advanced stainless steels are under investigation for their suitability in MSR applications. The materials used in MSRs must also withstand the effects of neutron irradiation, including displacement damage and transmutation. Radiation can alter material properties, leading to swelling, hardening, and embrittlement. In this paper, recent advancements of metallic materials for IMSRs including advanced stainless steels and nickel super alloys are thoroughly presented and reviewed in terms of corrosion resistance, high-temperature performance and radiation resistance.

1. INTRODUCTION

Molten salt reactor (MSR) is one of the six Gen-IV reactor concepts, which distinguish themselves from conventional water-based reactors by utilizing melted fuel combined with a transference of heat material, where the molten salt, flows through a reactor core. Graphite as moderator can regulate the core, but whether it does or not depends on whether an epithermal or thermal neutron mechanism is needed [1,2]. Afterwards, the salt is transported via an exchange of heat, where thermal energy is converted to a salt that does not contain any radioactive elements. Subsequently, we channel the heated salt into a secondary system, where water is transformed into steam, which generates power using the traditional method. MSRs typically operate within a temperature range spanning from 400 to 900°C. MSRs offer a secure, effective, and prospective nuclear energy alternative via unique features like online fuel processing. Unlike conventional reactors, MSRs operate without high pressure or water cooling, thus eliminating steam explosion risks. If damaged, MSR fuel will safely transfer to sub-critical storing container. Integral Molten Salt Reactor (IMSR) is an SMR powered by molten salt, which comprises a closed reactor container equipped with heat exchangers, incorporated pumps and control rods. The complete container, referred to core of the IMSR, is exchanged as a one unit after about 7-year of service. IMSR method promotes superior manufacturing standards and cost-effectiveness, while avoiding the necessity for on-site opening and maintenance of the reactor vessel. Fig.1 displays (IMSR400) designed by ORNL.

Figure.1 conceptual diagram of the IMSR main components [3].



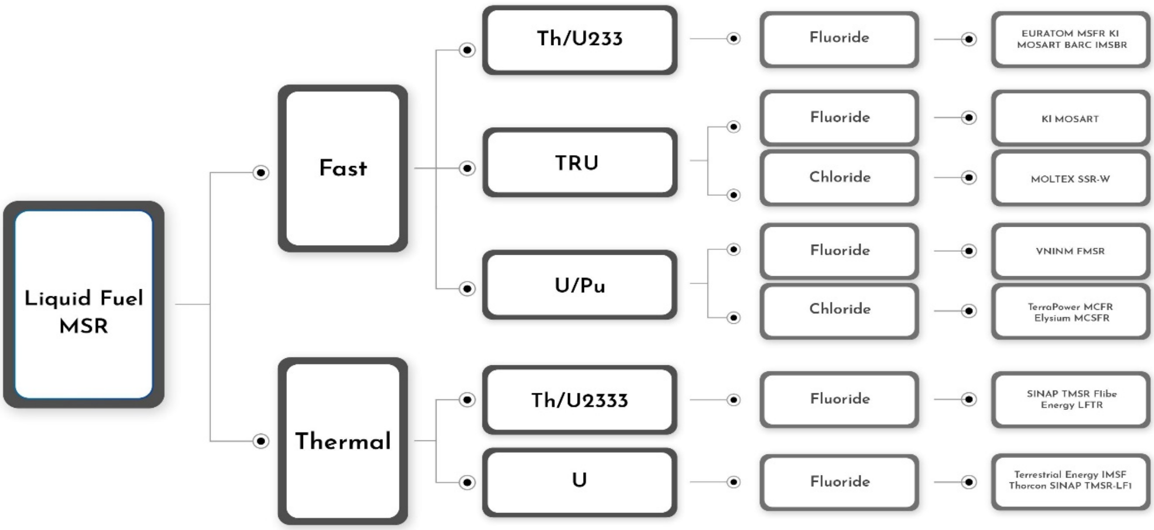


Figure.2: classification of Liquid Fuel MSR [3].

2. MATERIALS CHALLENGES IN MSR

The materials used in Molten Salt Reactors (MSRs) are a focus of research due to the demanding operational conditions which necessitate high corrosion resistance, good ductility following irradiation, resistance to fatigue, mechanical stability at elevated temperatures, and low activation for waste disposal [2-6]. While many of these requirements are common to all nuclear applications, the primary challenge for MSRs is managing corrosion caused by the reactor's environment and maintaining strength at high temperatures. [4].

Corrosion issues manifest the main challenge in structural metals for MSR [8]. The fuel and coolant combinations for Liquid Fuel Molten Salt Reactors (MSRs) can be categorized into Fast and Thermal neutron spectrum reactors. Figure 2 shows how different fuel compositions can be paired with various coolant salts (fluoride or chloride) and the specific reactors or reactor concepts being developed globally. Each combination of fuel and coolant leads to different reactor technologies with varying operational characteristics and potential uses.

In principle, there are two strategies to mitigate corrosion in Molten Salt Reactors (MSRs): altering the alloy or modifying the molten salt. For the alloys, one approach is to reduce the chromium or other reactive metals content to decelerate corrosion. The second approach involves changing the alloy's properties to slow the diffusion of chromium atoms [4]. Additionally, reducing the corrosive potential of the molten salts is another effective method [6]. In addition, neutron irradiation leads to the build-up of helium within materials. This process results in an increase in the ultimate tensile stress, a phenomenon known as radiation hardening, which unfortunately causes a decrease in the material's ductility. To counteract these adverse effects, one can modify the carbon content in the material or shield the vessel wall, potentially using a thorium blanket for effective protection.

2.1. Candidate structural materials for MSR:

For the structural materials for MSR there is several candidate materials are under research and investigation and as per the table 1 [2-5, 9, 10] the Main selections (M) represent materials having a logical database exhibit, Secondary selections (S) regard to hopeful materials that require wide study and expansion.

The stainless steel 316, Hastelloy N and nickel-based alloy are being evaluated as structural materials for molten salt reactor (MSR) construction because of their demonstrated corrosion resistance, outstanding mechanical characteristics, and stability in high-temperature environments [10]. The commercialization of molten salt reactors (MSRs) poses challenges due to the limited availability of structural materials that can withstand their corrosive internal environment. The suitability of structural materials for MSRs was determined essentially for their mechanical specification, resistance to molten salt corrosion, and swelling behaviour. This indicates the possibility of the advancement of the structural materials resistant that can withstand both irradiation and corrosion in high temperature Molten Salt Reactors (MSRs). The investigation examined the static corrosion effects on Hastelloy N and SS 316 when exposed to molten FLiBe salt at 700℃ were studied [10]. The molten FLiBe Corrosion primarily involves the extraction of chromium from the alloy into the salt, with faster erosion observed along grain boundaries compared to within the grains. When Hastelloy N was studied within Ni capsules, there was evidence of a tinny, permeable layer forming near the surface, as well as the presence of numerous Mo-rich precipitates at grain boundaries. In contrast, trials conducted using graphite capsules led to the formation of carbide phases near the surface, along with the depletion of Cr and the creation of a Ni3Fe phase layer around 1.4 µm deep in the nearby area. Stainless steel 316 is being evaluated for potential use as a structural material in MSRs, where corrosive molten fluoride salts are commonly employed as coolants. This type of steel is valued for its outstanding mechanical properties and durability at high temperatures. Therefore, there are many alloys that put in research as a candidate structural material for MSR Table.1 shows the summary of positives and negative of the candidate structural alloys for MSR [8].

Table 1. Summary of characteristic (advantage and disadvantage) and possible limiting factors for MSR recommended alloy [2, 4, 5, 8-10]

Reactor system	Advantages	Disadvantages	Limiting Factors	Comments
Grade 316 SS	• ASME Code Section III, Division 5 compliant • partial helium embrittlement	• Limited to temperatures around 700°C and requires effective redox control	• Corrosion-resistant at elevated temperatures. • Low permitted stresses for long-time operation	-

Hastelloy N	• Shown in the Molten Salt Reactor Experiment (MSRE). • Has marketable experience in manufacturing. • Extensive information of rupture characteristic.	• Strength Limited to temperatures around 700°C • Susceptibility to the embrittlement • Poor oxidation resistance	• Susceptible to helium embrittlement. • Susceptible to tellurium embrittlement if redox reactions are not managed correctly.	• Haynes offers some of these product forms on the market. • Produces a lot of heat. • Currently being evaluated in China.
Modified Hastelloy N Composition	• Modifying with titanium reduces helium embrittlement compared to nitrogen. • Adding niobium decreases embrittlement caused by tellurium.	• Restricted knowledge with making and scaling up. • Few rupture results present. • Strength is only slightly improved than nitrogen at raised temperatures..	• Some variants are prone to helium embrittlement. • Low strength at high temperatures.	• Large batches have been produced, and welding has been successfully demonstrated.
ORNL Advanced Alloys 20-23	• Different types of alloys can be used at temperatures until 850°C. • Each version is planned to be corrosion resistance compering to Hastelloy N, but with improved resistance to creep. • Some types outperform Hastelloy N in terms of strength. • Based on experience with Modified Hastelloy N, some variants are expected to resist helium and tellurium embrittlement well.	• There's limited experience with manufacturing and scaling up. • Only a small amount of rupture data is available from lab-scale batches.	• The best alloy with the right mix of characteristics needs to be found for each use. • One solution might not meet all needs. • Solid solution strengthened alloys should be used where long-term stability is required.	-
Haynes242 and244 24,25	• Precipitation strengthened alloys might reduce helium embrittlement. • Alloy 242 is commercially available, while Alloy 244 is still being developed. • These alloys are created by a vendor with extensive experience in melting and processing.	• There's slight or no experimental proof for corrosion resistance. • Limited data available on creep and rupture.	• Possible for tellurium embrittlement if redox chemistry isn't well managed needs to be assessed. • Alloy 244 is restricted to a maximum operating temperature of 760°C. • The stability of precipitates over time for MSR applications is not well understood.	• Ongoing corrosion testing with capsules is being carried out at ORNL.
HN80M Variants	• A series of alloys derived from Hastelloy N. • Some types are highly resistant to	• The mechanical properties have little to no data available. • The expected outcome is a level of oxidation	• Prone to helium embrittlement. • Predicted to have a high-temperature strength that closely resembles that of Hastelloy N.	• Developing resistance to tellurium-induced cracking is a

	tellurium embrittlement.	resistance same to that of Hastelloy N.		key focus for these alloys.
MONICR	• Czech variant of Hastelloy N.	• The maximum temperature is restricted to around 700°C due to strength limitations. • Prone to tellurium embrittlement. • Has poor resistance to oxidation.	• Helium and tellurium embrittlement can occur if redox chemistry is not properly managed.	• The primary area of interest in the investigation of this alloy has predominantly been on thermomechanical processing.
EM-721	• Adding tungsten aims to enhance creep resistance. • Resistant to tellurium embrittlement if redox chemistry is properly managed.	• Not much property data has been reported. • Has limited ductility.	• Helium and tellurium embrittlement can occur if redox chemistry isn't properly managed	• Reports on material properties are very limited.
Alumina formers	• Possible alternative approach to corrosion resistance might allow chromium content similar to that in commercial nickel alloys.	• Limited evidence of concept exists.	-	• If proven, this concept could enable the use of a variety of commercial alloys in MSR construction.
ODS Alloys	• Other approach to enhance creep and rupture resistance. • Possible to reduce helium embrittlement.	• Limited evidence of concept exists.	-	• This type of materials has historically been expensive.

3. FINAL REMARKS

Despite their potential benefits, the widespread adoption of molten salt reactors faces challenges, particularly in materials science. The corrosive environment of MSRs poses significant material challenges, necessitating the development of advanced alloys capable of withstanding high temperatures and irradiation. Research into materials such as Ni-based alloys strengthened with nanoparticles shows promise in addressing these challenges. Ongoing studies on corrosion mechanisms and the performance of materials provide valuable insights into the behaviour of structural materials in molten salt environments. Key materials include Grade 316 SS, Hastelloy N, Modified Hastelloy N, and other advanced alloys, with considerations such as resistance to embrittlement, corrosion, and strength at high temperatures. Each material has specific trade-offs related to manufacturing challenges, operational limitations, and susceptibility to issues like helium or tellurium embrittlement.

In addition, code qualification and regulatory considerations pose significant challenges in the development and deployment of materials for Molten Salt Reactors (MSRs). One key challenge is the lack of standardized codes and regulations specifically tailored to the unique operating conditions of MSRs, including high temperatures, corrosive salt environments, and neutron irradiation. Current regulatory frameworks are primarily based on traditional water-cooled reactors, necessitating adaptation to accommodate the distinct characteristics of MSRs. Additionally, the qualification of materials for MSR applications requires rigorous testing and validation to ensure compliance with safety standards and regulatory requirements. This process involves evaluating material performance under simulated reactor conditions, including exposure to molten salts and neutron flux, to assess corrosion resistance, mechanical stability, and irradiation effects. Furthermore, the dynamic nature of molten salt chemistry presents complexities in code qualification and regulatory oversight. The composition of molten salts can vary over time due to factors such as reactor operation, fuel processing, and impurity accumulation, leading to changes in corrosion rates and material degradation mechanisms. Ensuring the long-term integrity of structural materials in such environments requires comprehensive understanding of salt chemistry and its interactions with reactor components. Regulatory bodies must develop guidelines for monitoring and managing salt chemistry within acceptable limits to maintain reactor safety and performance. In summary, achieving the goal of expanding nuclear power capacity requires a concerted effort in research, development, and deployment of both traditional and innovative reactor designs. Addressing materials challenges is essential to realizing the full potential of nuclear energy in mitigating climate change and ensuring a sustainable energy future.

ACKNOWLEDGEMENTS

The authors are grateful to King Abdulaziz City for Science and Technology (KACST) in Saudi Arabia for their support.

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