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Enhancing Corrosion Resistance and Nuclear Fuel Salt Chemistry for Structural Integrity in Molten Chloride Salt Fast Reactors

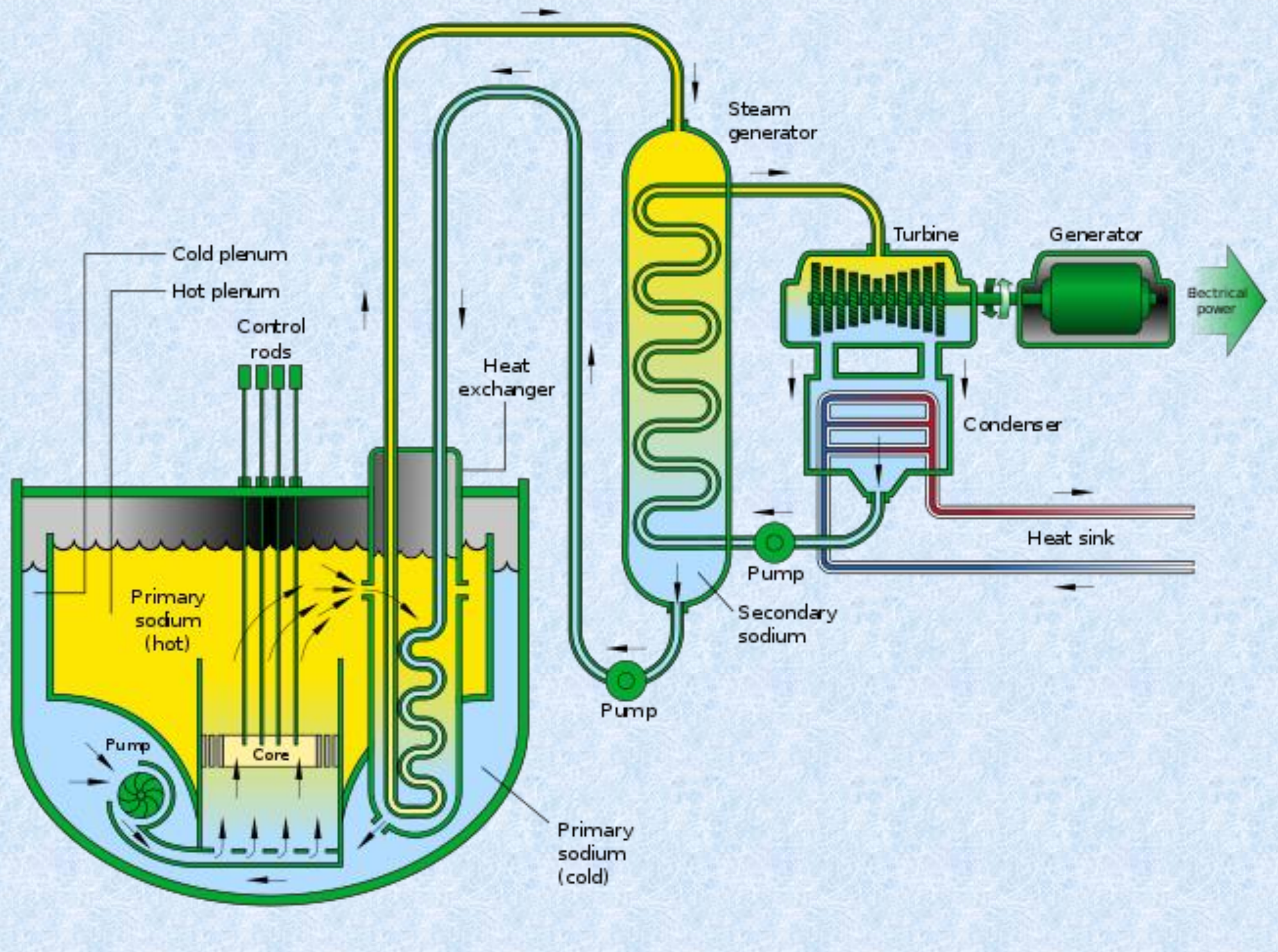
ABSTRACT

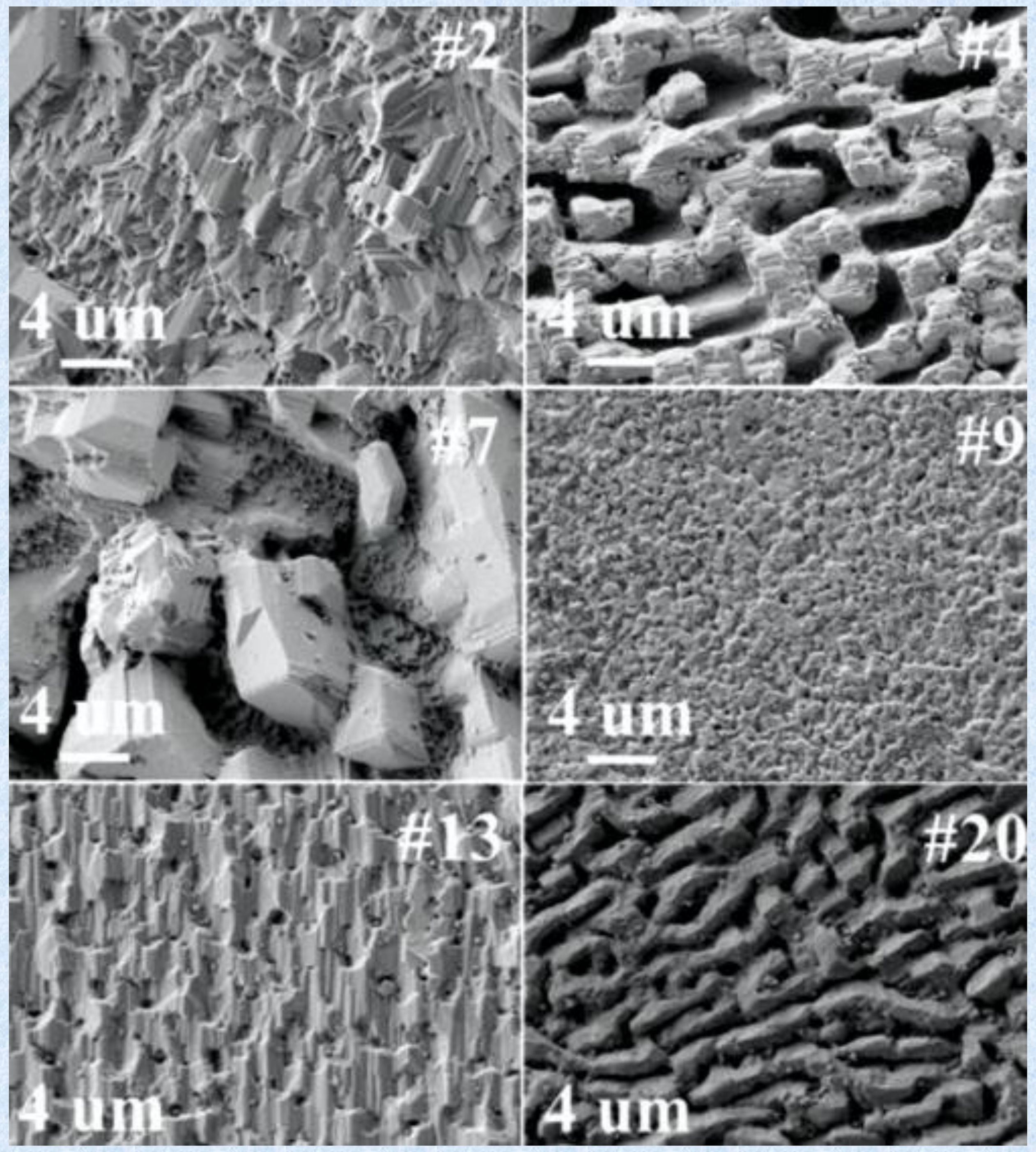
MCSFRs have the potential to revolutionize nuclear energy generation through their intrinsic safety and closed fuel cycles. The extreme corrosiveness of molten chloride salts at high temperature represents a major challenge that limits the operational lifetime and reliability of structural materials. Further fragmentation in the field includes disagreements regarding the best materials to use, how they perform over long-time scales in an irradiated environment, and what standardized testing methods to use, thus impeding the realization and utilization of innovative designs such as the MCSFR. This study includes a systematic review and a meta-analysis of 20 peer-reviewed articles (2014– 2025) analyzing corrosion rates, degradation mechanisms and material innovations for MCSFRs. Databases searched were Scopus, Web of Science, and INIS, utilizing keywords of 'molten chloride corrosion' and 'accident-tolerant fuels' . study prioritized inclusion of studies that reported quantitative measures of corrosion (>500h tests), and mechanistic evaluations.

INTRODUCTION

In the past few years, the increasing need for sustainable and safe energy solutions has led to a lot of interest in developing more advanced types of nuclear reactor systems. All of these systems are highly attractive, and among them Molten Chloride Salt Fast Reactors (MCSFR) have been identified as promising technology because of inherent safety features, high thermal efficiency and the potential for Closed Fuel Cycle (Forsberg et al., 2020). Improving Fuel Salt Chemistry and Developing Corrosion-Resistant Structural Materials to extend MCSFR Operation for longer time and improve Its Safety and Efficiency A key attribute that influences reactor lifetime, safety and performance is MCSFR fuel salt chemistry and the innovative development of structural materials that are corrosion resistant (Serp et al., 2014).

Whereas previous ATF design studies have focused on maintaining solid fuel rods' mechanical integrity during accident scenarios (Zinkle et al., 2014), MCSFRs have mechanisms that require consideration beyond material stability, including advanced fuel conversion. Originally, accident-tolerant fuels were proposed for the replacement of the traditional uranium dioxide (UO_2) with zirconium alloy cladding in light water reactors (LWRs), due to their susceptibility to high-temperature steam oxidation and subsequent hydrogen generation and fuel degradation during loss-of-coolant accidents (LOCAs) (Terrani, 2018). Summary: Silicon carbide (SiC) cladding, iron-chromium-aluminum (FeCrAl) alloys, and coated zirconium-based alloys are among ATF solutions that improve oxidation resistance (Ott et al., 2014).





SEM micrographs of the top surfaces of a few representative printed alloys after corrosion test: alloy #2, alloy #4, alloy #7, alloy #9, alloy #13, and alloy #20.

RESULTS

1. **Material Performance Hierarchy**
   - Ni-based alloys (e.g., Hastelloy-N) Ni-based alloys show strong resistance to materials in cl Salts resulting in a depletion rate of 5– 20 μm/year for Cr at 700– 800° C (Guo et al., 2018; Kim et al., 2024). Their performance is strongly linked to Cr content (15– 20 wt.%) in order to create passive oxide layers.
   - Fe-based alloys (SS304/316L) exhibit 2– 5× higher corrosion rates (30–100μm/year) due to aggressive Cr leaching (Pillai et al., 2023).
   - Co-Mo-Cr-Si alloys (e.g., Tribaloy T-400) show catastrophic failure (>150 μm/year) in F^- salts, emphasizing their incompatibility with MSR conditions (Wu et al., 2020).
2. **Impact of Salt Chemistry**
   - Cl^- salts (e.g., LiCl-KCl) induce 2– 3× faster corrosion than F^- salts (FLiNaK) due to higher ionic mobility and redox activity (Kim & Couet, 2024).
   - Contaminants (e.g., O_2 , H_2O) accelerate degradation. Studies controlling impurities report 40– 60% lower corrosion rates (Choi et al., 2024).
3. **Operational Factors**
   - Flow dynamics: Corrosion rates increase by 2– 3× under flowing vs. static salt conditions (Kim et al., 2024).
4. **Temperature**
   - Every 100° C increase raises corrosion rates by 1.5X to 2X with Cr depletion following Arrhenius kinetics (Arkoub et al., 2025)

CONCLUSION

These systematic reviews and meta-analysis indicate that Ni-based alloys, predominantly containing 15– 20 wt% Cr, seem to be the most promising structural materials for MCSFRs and hence appear to perform better than their competitors in molten chloride salts corrosion environments. Their performance, however, is dependent on strict impurity (10,000h) data and performance under prototypical flow conditions, (2) limited understanding of radiation-corrosion synergies and (3) unexplored opportunities of cer1amics and composites. Short-term, static experiments dominate current literature, highlighting the need for standardized testing protocols that mimic quasi-reactor environments sustained thermal gradients, flow velocities of >1 m/s and neutron fluxes. Computational modeling and irradiation facilities are a great combination to fill these gaps predicting the 60 year material performance. It is suggested that Ni-Cr alloys with conservative safety factors (≥3) should be utilized for short-term applications, with state-of-the-art coatings (e.g., SiC-SiC) applied to areas with high-radiation.

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