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# Oxide characterization of Fe-Cr-Si alloys formed in high-temperature water

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## Introduction

- **Problem:** Zirconium cladding causes hydrogen explosions under high-temperature steam accidents, requiring safer accident-tolerant fuel (ATF) alternatives.
- **Gap:** Promising Fe-Cr-Si candidates lack sufficient long-term corrosion research in PWR environments compared to FeCrAl and SiC/SiC.
- **Objective:** This study tests Fe16Cr2Si and Fe20Cr2Si against Si-free Fe20Cr to determine the impact of silicon addition in simulated PWR primary water.

## Methods

- **Specimen Preparation:** Fe20Cr, Fe16Cr2Si, and Fe20Cr2Si coupons were polished to 0.06 µm, ultrasonically cleaned, dried, and weighed.
- **Corrosion Testing:** Tests ran in a static autoclave at 360 °C and 19 MPa (simulated PWR water: 1200 ppm B, 2 ppm Li) for up to 2000 h.
- **Characterization:** Oxide layers were evaluated after exposure intervals using SEM (morphology), XRD (phase identification), and XPS (chemical composition).

## Results and Discussion

### Comparison of mass change

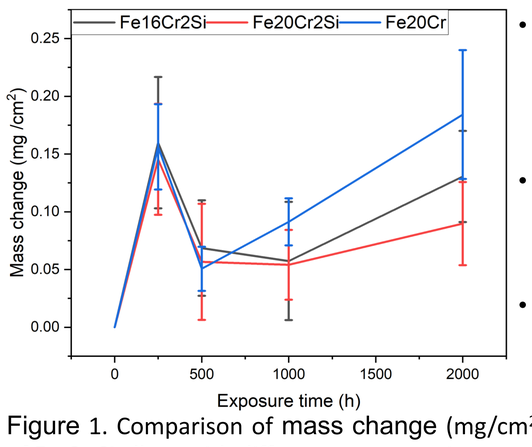



Figure 1. Comparison of mass change (mg/cm²) of Fe-Cr-Si alloys with different exposure times.

- All alloys peaked in mass at 250 h and dropped sharply at 500 h due to oxide dissolution driven by regular solution replacement.
- Behavior diverged after 1000 h, with Fe20Cr2Si having the lowest mass gain and Fe20Cr the highest at 2000 h.
- Combining high Cr and Si content delivers the best long-term corrosion resistance in deaerated PWR water.

### Surface oxide characterization

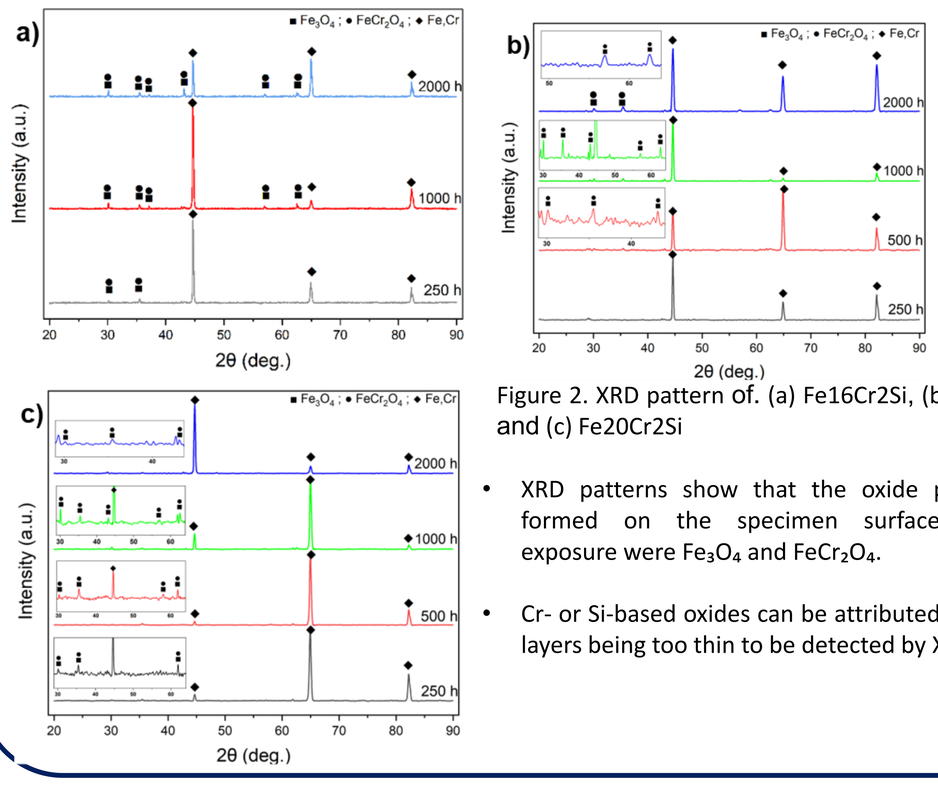



Figure 2. XRD pattern of. (a) Fe16Cr2Si, (b) Fe20Cr, and (c) Fe20Cr2Si

- XRD patterns show that the oxide products formed on the specimen surfaces after exposure were $Fe_3O_4$ and $FeCr_2O_4$.
- Cr- or Si-based oxides can be attributed to their layers being too thin to be detected by XRD

### Oxide morphology

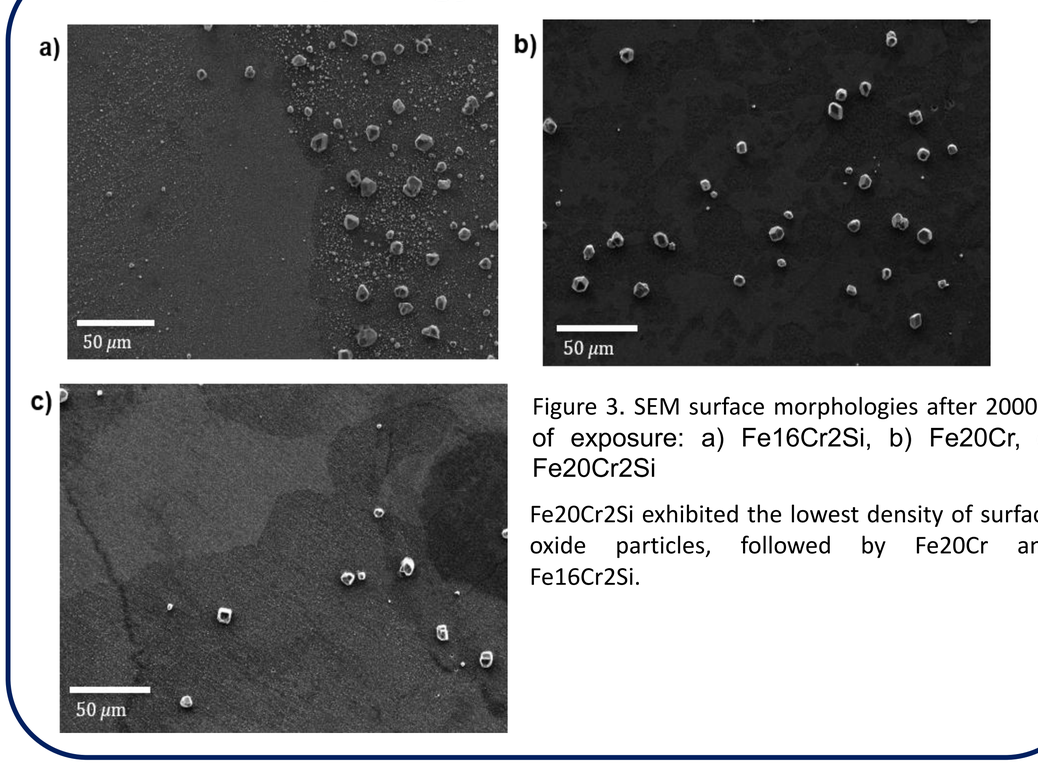



Figure 3. SEM surface morphologies after 2000 h of exposure: a) Fe16Cr2Si, b) Fe20Cr, c) Fe20Cr2Si

Fe20Cr2Si exhibited the lowest density of surface oxide particles, followed by Fe20Cr and Fe16Cr2Si.

### Oxide layer

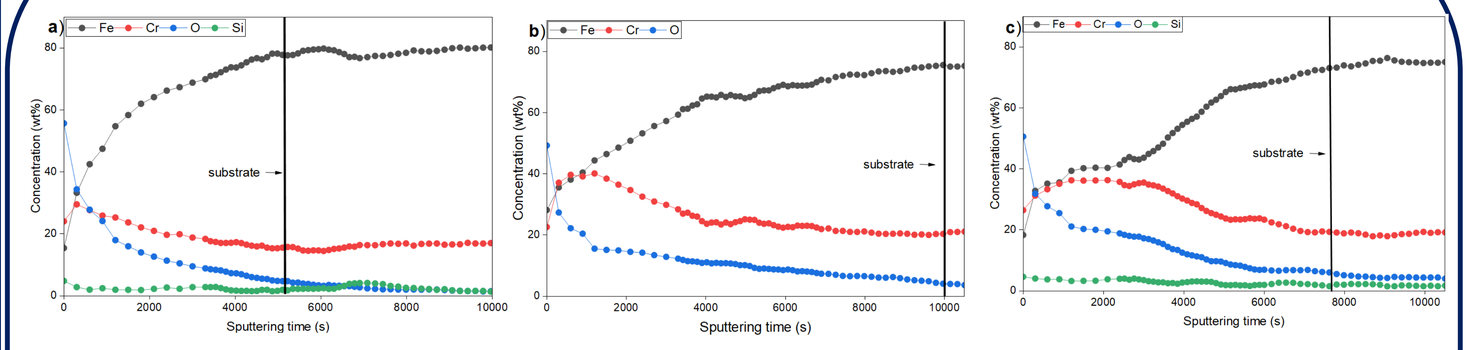



Figure 4. XPS depth profiles of (a) Fe16Cr2Si, (b) Fe20Cr, and (c) Fe20Cr2Si after 2000 h of exposure.

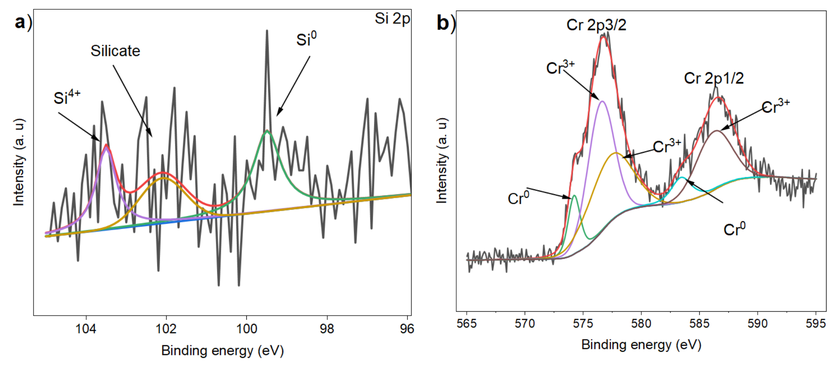
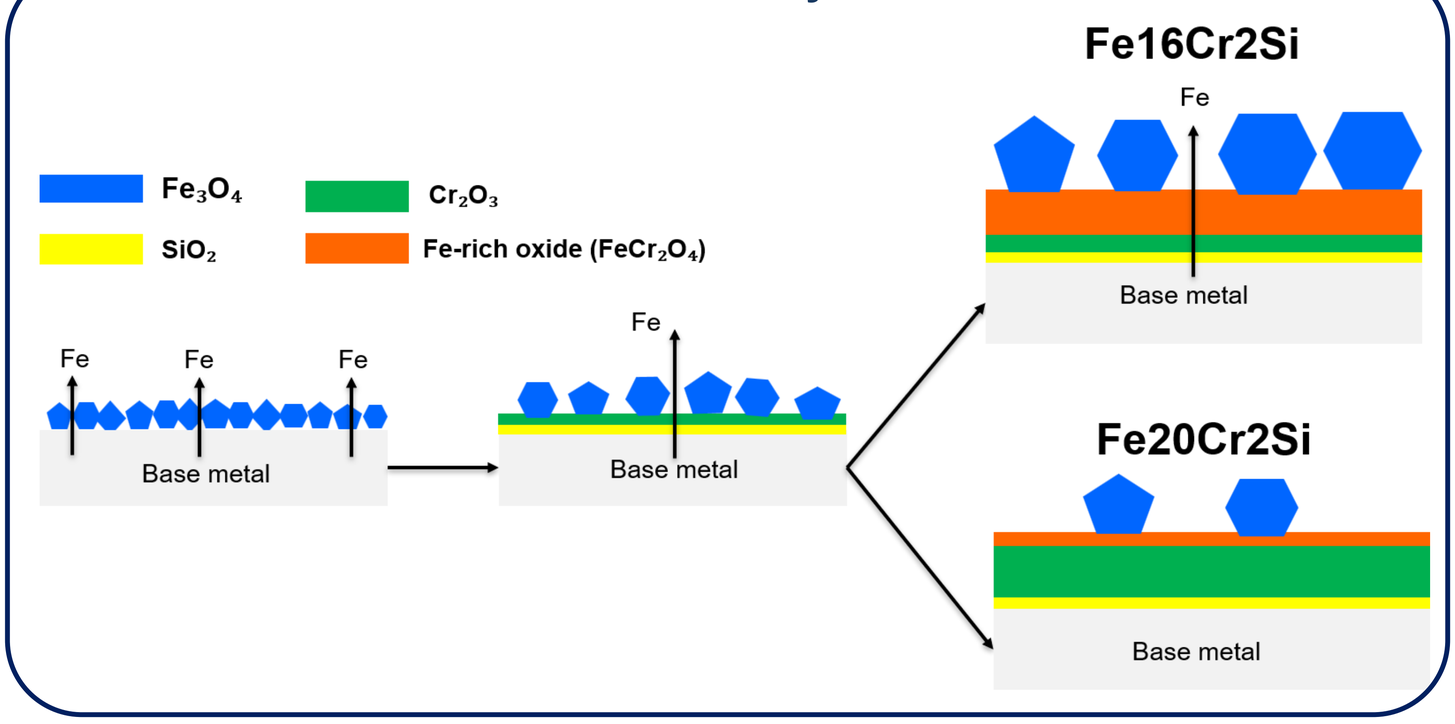



Figure 5. (a) Si 2p and (b) Cr 2p spectra acquired near the oxide/metal interface of Fe20Cr2Si after 2000 h of exposure in simulated PWR primary water.

- Sputtering time (oxide thickness) increased as Fe16Cr2Si < Fe20Cr2Si < Fe20Cr, proving both Si-added alloys formed thinner oxide layers than the Si-free alloy.
- Fe20Cr2Si developed a pronounced inner protective layer of $Cr_2O_3$ and $SiO_2$ whereas Fe16Cr2Si showed only surface Cr enrichment that decreased monotonically with depth.
- Despite having a slightly thicker oxide than Fe16Cr2Si, Fe20Cr2Si achieved the lowest mass gain, demonstrating that corrosion protection relies on an inner $Cr_2O_3$/$SiO_2$barrier rather than layer thickness alone.
- Fe20Cr exhibited the thickest oxide and highest mass gain, proving that 20 wt% Cr alone is insufficient and requires silicon addition to ensure effective corrosion resistance.

### Corrosion mechanism of Fe-Cr-Si alloys




## Conclusions

- Adding Si significantly reduces mass gain and oxide thickness compared to Si-free Fe20Cr in PWR water.
- Fe20Cr2Si performs best due to a protective inner layer of $Cr_2O_3$ and $SiO_2$, proving oxide composition matters more than thickness.
- Fe20Cr2Si demonstrates strong potential as an accident-tolerant fuel (ATF) cladding material under normal operations.

## References

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