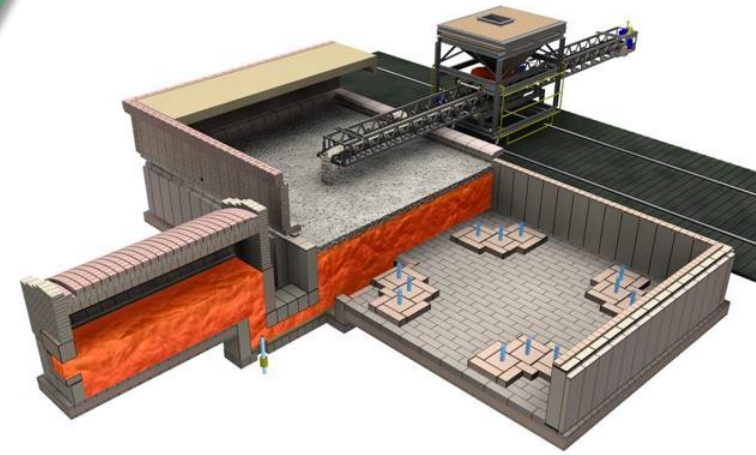


Amber Glass Foam Reduction – Lessons from Nuclear Waste

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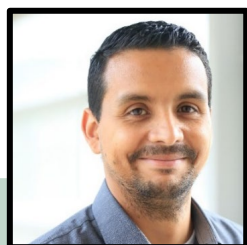
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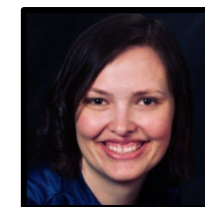
Stakeholders



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GMIC Industrial Steering Committee

- Darryl Shaffer (Gallo Glass)
- Aaron Huber (Johns Manville)
- Daniel Johnson (Libbey Glass)
- Bruno Purnode (Owens Corning)
- Jan Schep (O-I)
- Ufuk Senturk (Potters Industries)
- Roberto Cabrera (Vitro)



Commercial production of amber glass

Amber glasses make up 1/4 of container production¹

Amber chromophore is formed by reduction of sulfur compounds during melting

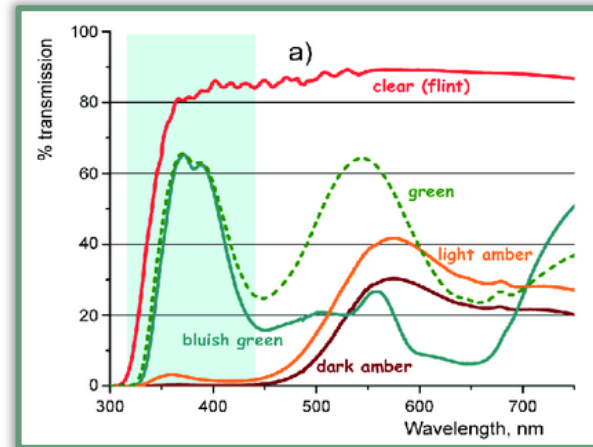
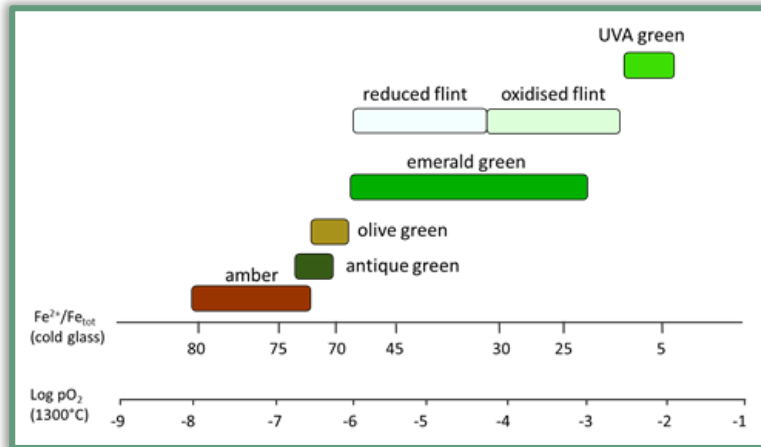
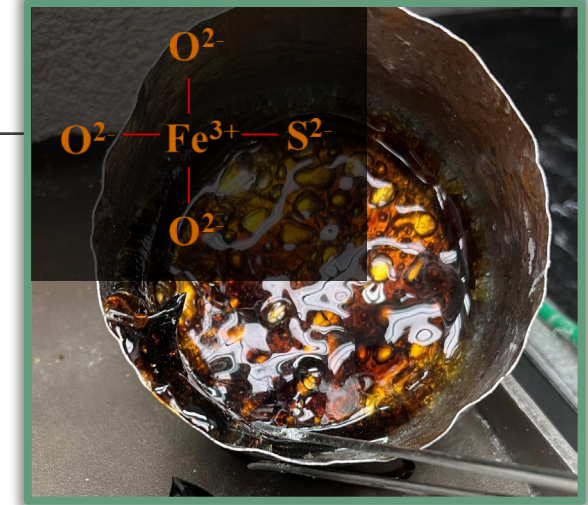
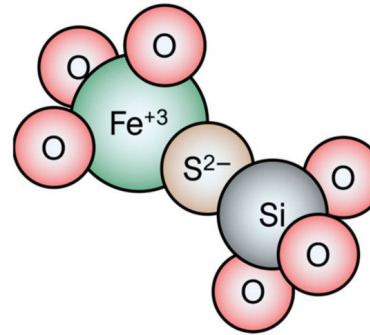
Amber chromophore absorbs 100% UV, protecting contents (beer, wine, etc.) aging and photodegradation



¹ NORTH AMERICA GLASS BOTTLES AND CONTAINERS MARKET SIZE & SHARE ANALYSIS - GROWTH TRENDS AND FORECAST (2026 – 2031) Source: <https://www.mordorintelligence.com/industry-reports/north-america-glass-bottles-containers-market>

Amber chromophore $S^{2-}Fe^{3+}$

Raw materials: Iron oxide + saltcake

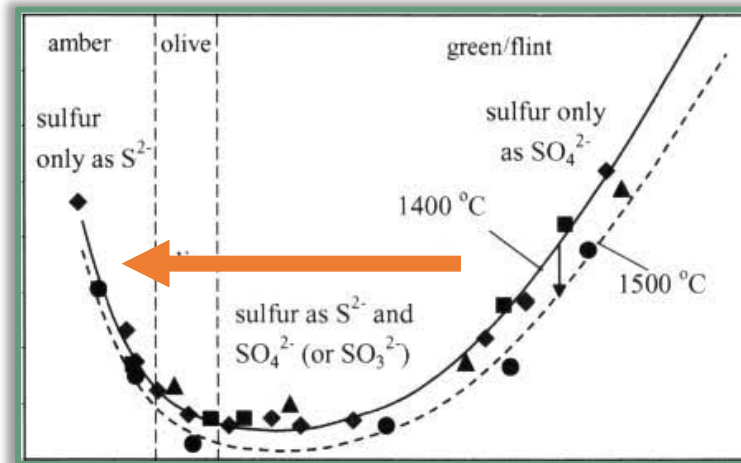
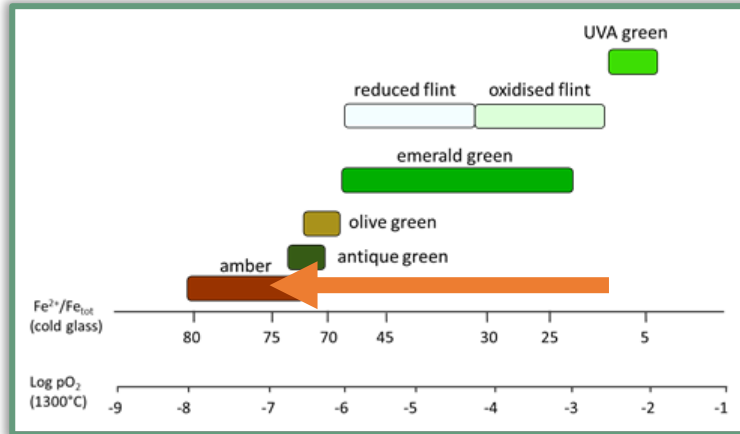


Typically, **carbon** is used as a reducing agent

² Lais, Galois, et al. (2025) Spectroscopic properties of amber chromophore in silicate glasses, Journal of the American Ceramic Society 109:e70316

³ <https://www.readox.com/product/glass-melt-redox-sensor/>

Foaming in amber glass production



SO₂ gas release

Foaming in the melt

“Cold cap” instability issues

Lower melt rate

Reduced production efficiency and potential downtime

⁴ Hubert, Faber, et al. (2017) Impact of Redox in Industrial Glass Melting and Importance of Redox Control. 77th Conference on Glass Problems: Ceramic Engineering and Science Proceedings (pp.115-129) Wiley Ed. S.K. Sundaram

⁵ Beerkens, (2009) Fining of glass melts: what we know about fining processes today. Ceramic Engineering and Science Proceedings. (pp. 13 – 28) Ed. Charles H. Drummond III.

Nuclear Waste Vitrification

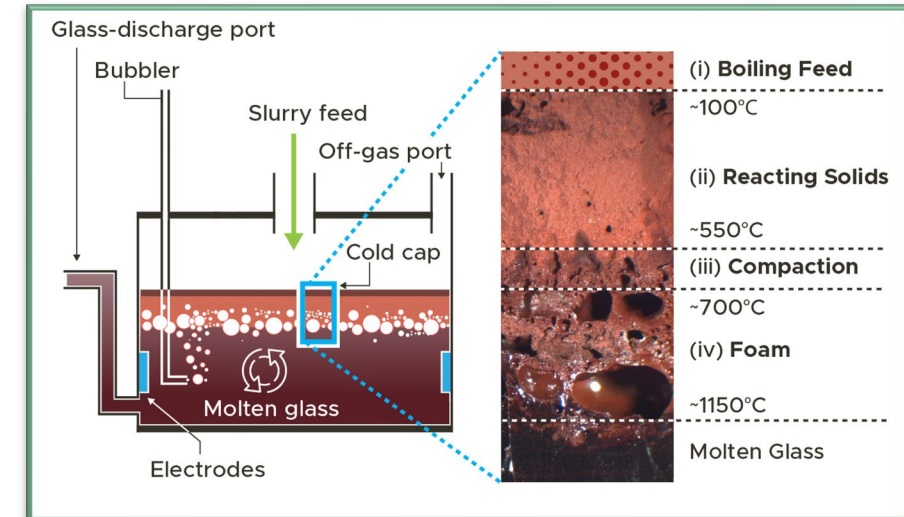
Radioactive isotopes are immobilized in glass waste forms at the Hanford site

Incoming wastes are high in sodium, sulphates, nitrates, aluminum, metal hydroxides, etc.

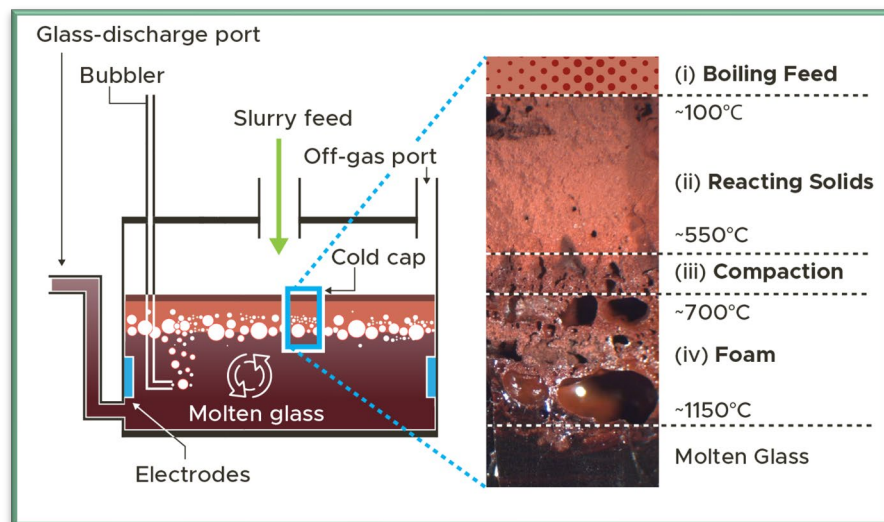
Silica, wollastonite (CaSiO_3), kyanite (Al_2SiO_5), boric acid, lithium carbonate, are added as glass formers

The combined melter feed is fed into the top of a Joule-Heated Ceramic Melter

Feed-to-glass reaction layer on the surface of the melt is called the cold cap



Redox Control in Nuclear Waste Glasses



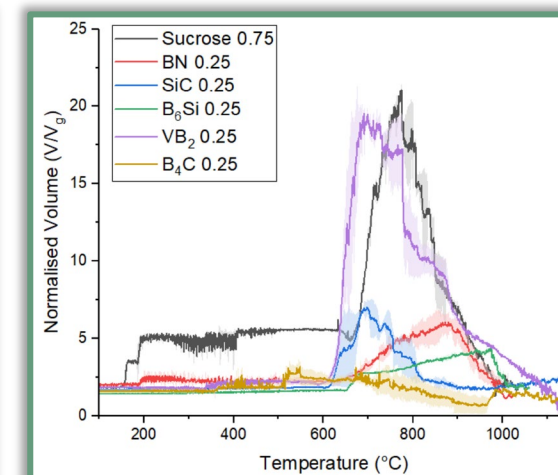
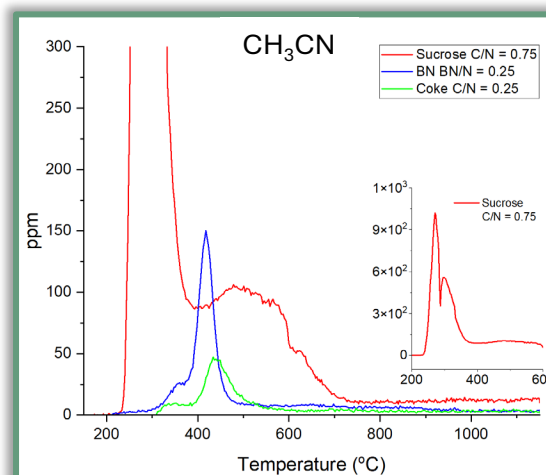
Sucrose is the baseline reductant at Hanford but it produces high quantities of Products of Incomplete Combustion (PICS) such as acetonitrile (CH_3CN)⁶

Alternative **carbon-based/organic** reducing agents explored

Oxalic, formic, glycolic, tartaric, malonic, glycolic, pyruvic, propionic, lactic, levulinic, butyric, citric and acetic acid¹, sucrose, graphite, coke, polyethylene, HEDTA⁷⁻⁹

Alternative **ceramic** reductants

BN^{10} , SiC , B_4C , B_6Si and VB_2^{11}



⁶ Matlack, K. & Pegg, I. (2019). (VSL-19S4573-1, Rev A) (ORP-67600-00/VSL-19S4573-1). VSL, CUA. Richland, WA. (United States).

⁷ Ryan, J. L. (1995). (No. PNL-10510). PNNL. Richland, WA (United States).

⁸ Seymour, R. G. (1995). (No. WHC-SD-WM-SP-008). Westinghouse Hanford Co., Richland, WA (United States).

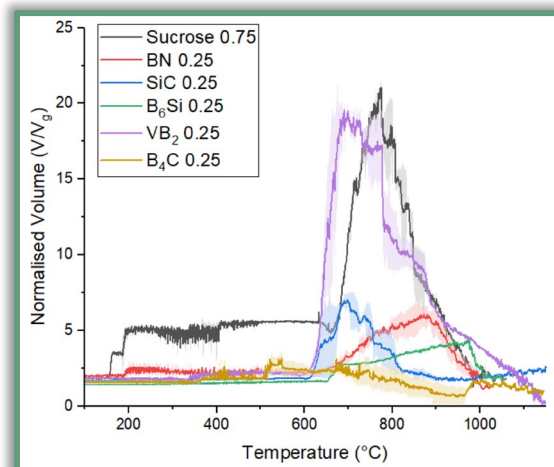
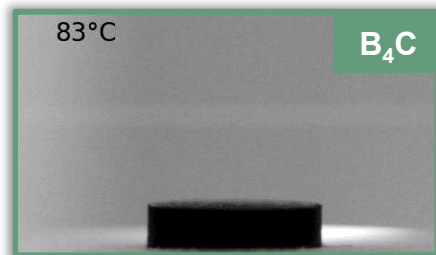
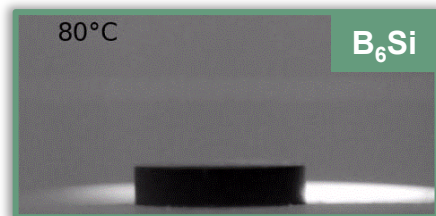
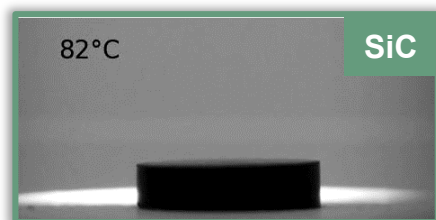
⁹ Seymour, R. G. (1995). (No. WHC-SD-WM-SP-009). Westinghouse Hanford Co., Richland, WA (United States).

¹⁰ Rigby, J. C., et al. (2024). Journal of the American Ceramic Society. 2025;108:e20192.

¹¹ Rigby, J. C., et al. (2025). International Journal of Applied Glass Science.

Alternative Reductants in Nuclear Waste Glasses

Foam control



Redox control

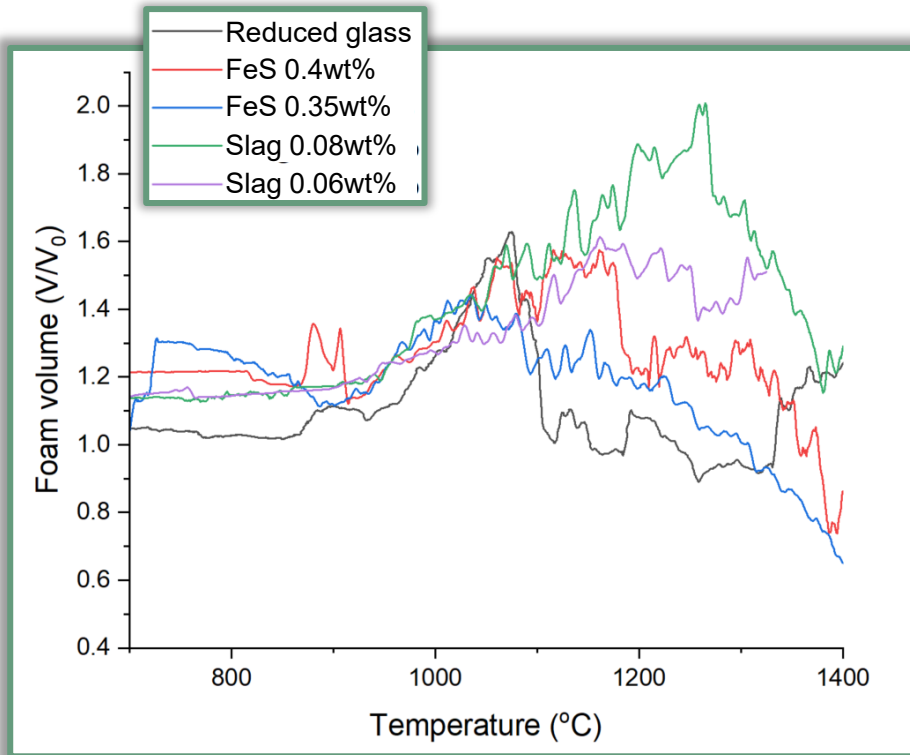
Reducing agent	Fe ²⁺ /Fe _T
Sucrose	< 0.1
BN	0.24
B ₄ C	0.49
B ₆ Si	0.28
SiC	0.47
VB ₂	< 0.10

¹¹ Rigby, J. C., et al. (2025). International Journal of Applied Glass Science.

Alternative reducing agents: slag and FeS

Slag increased overall foaming

FeS had similar peak foam to reduced glass



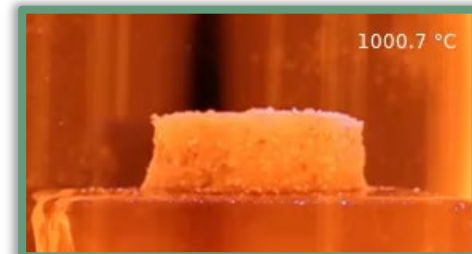
Reduced glass



Slag 0.08wt%

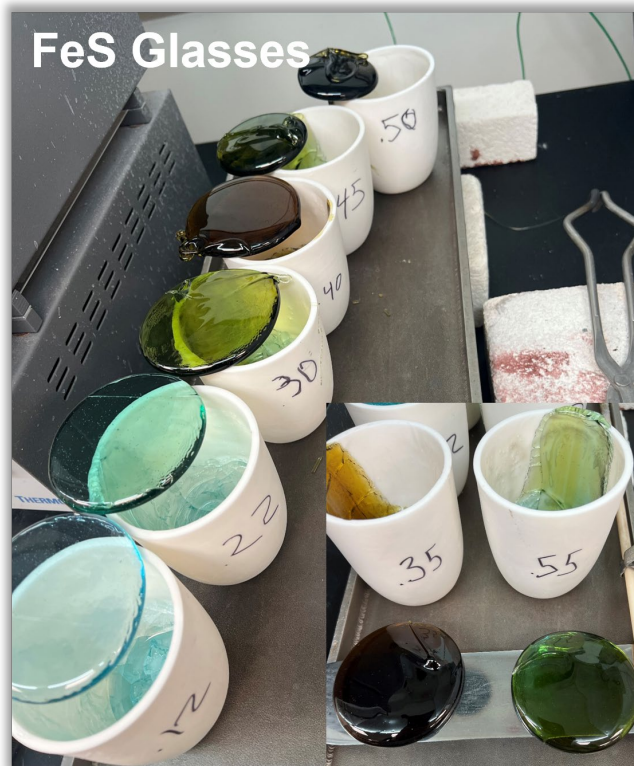


FeS 0.4wt%

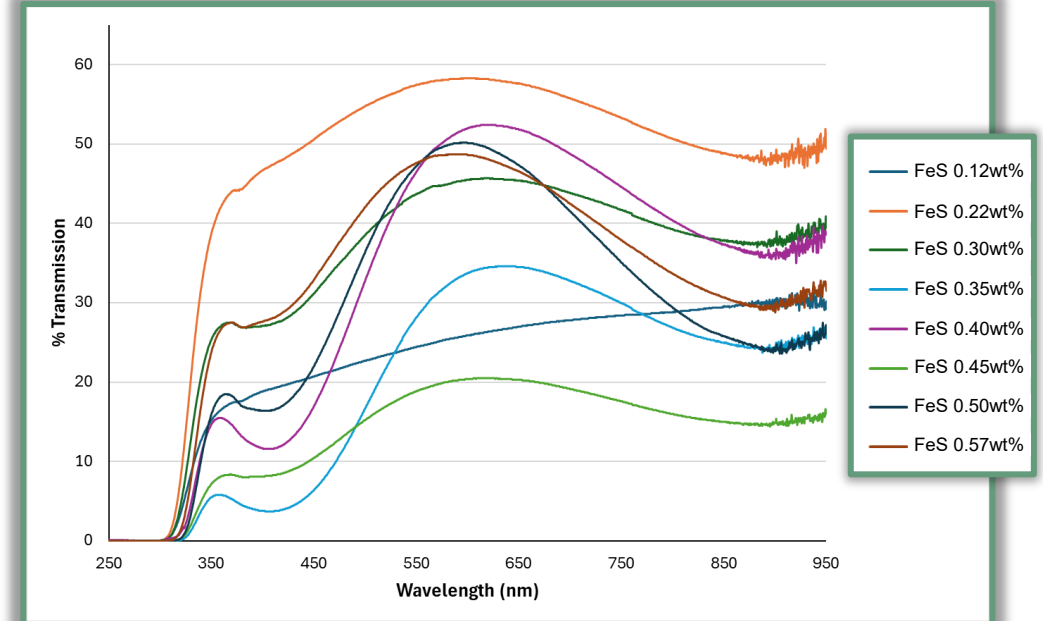


FeS Redox Control

FeS 0.35 – 0.4 maintained desired redox range and amber chromophore



Reducing agent	$\text{Fe}^{2+}/\text{Fe}_T$
FeS 0.4wt%	0.88
FeS 0.35wt%	0.86



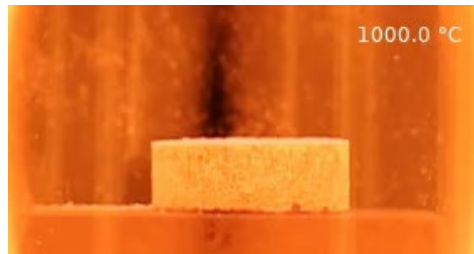
Removing CO₃

Replacing soda ash (NaCO₃) and limestone (CaCO₃) with Na-metasilicate and burnt lime reduced primary foam

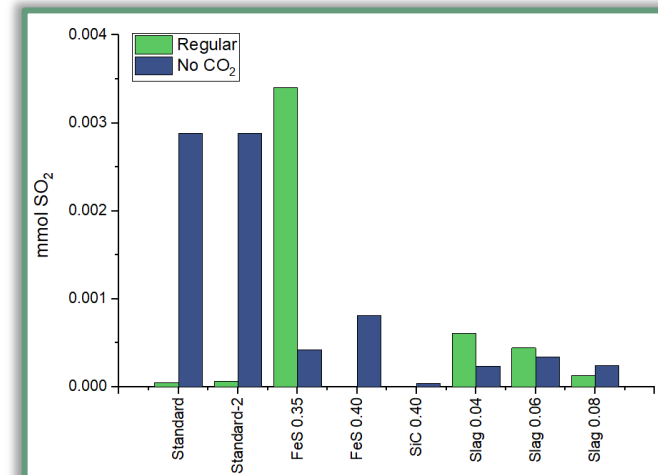
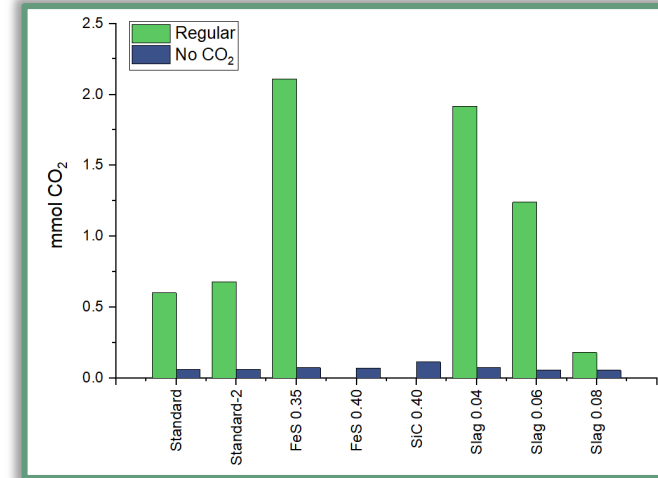
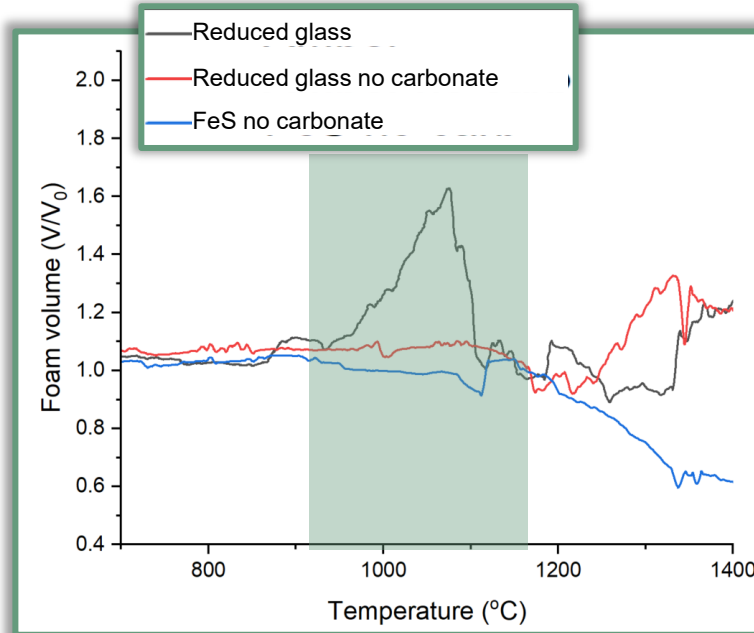
In standard reduced glass formulation removing CO₃ from the batch increased secondary foam and SO₂ evolution



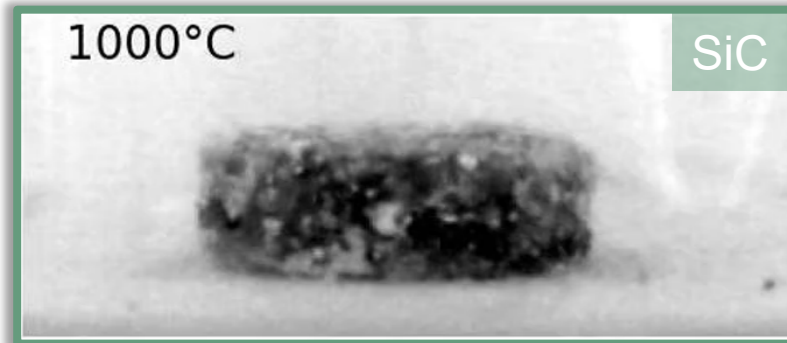
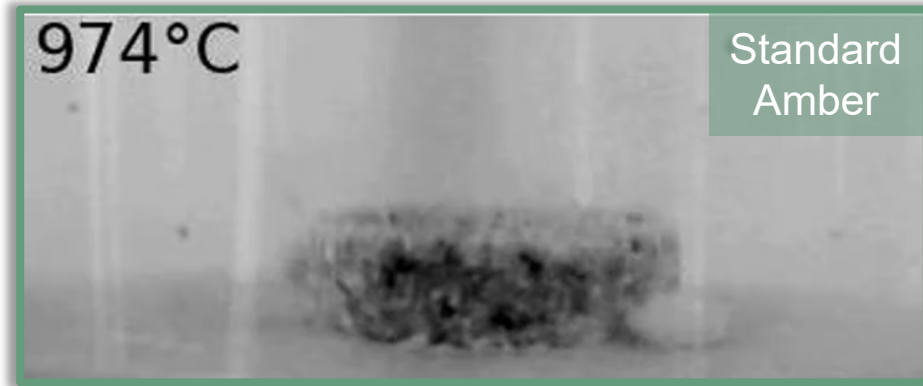
Reduced glass no CO₃



FeS no CO₃

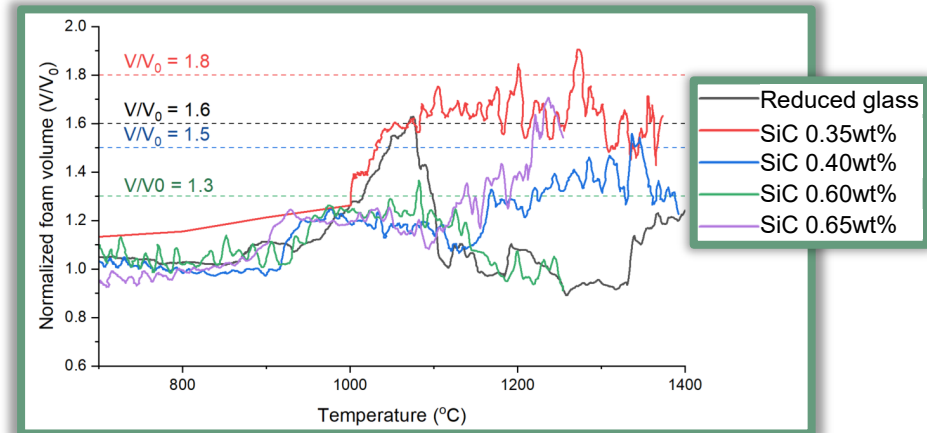


SiC in Amber Glass: Foam volume



SiC hard material with high decomposition temperature

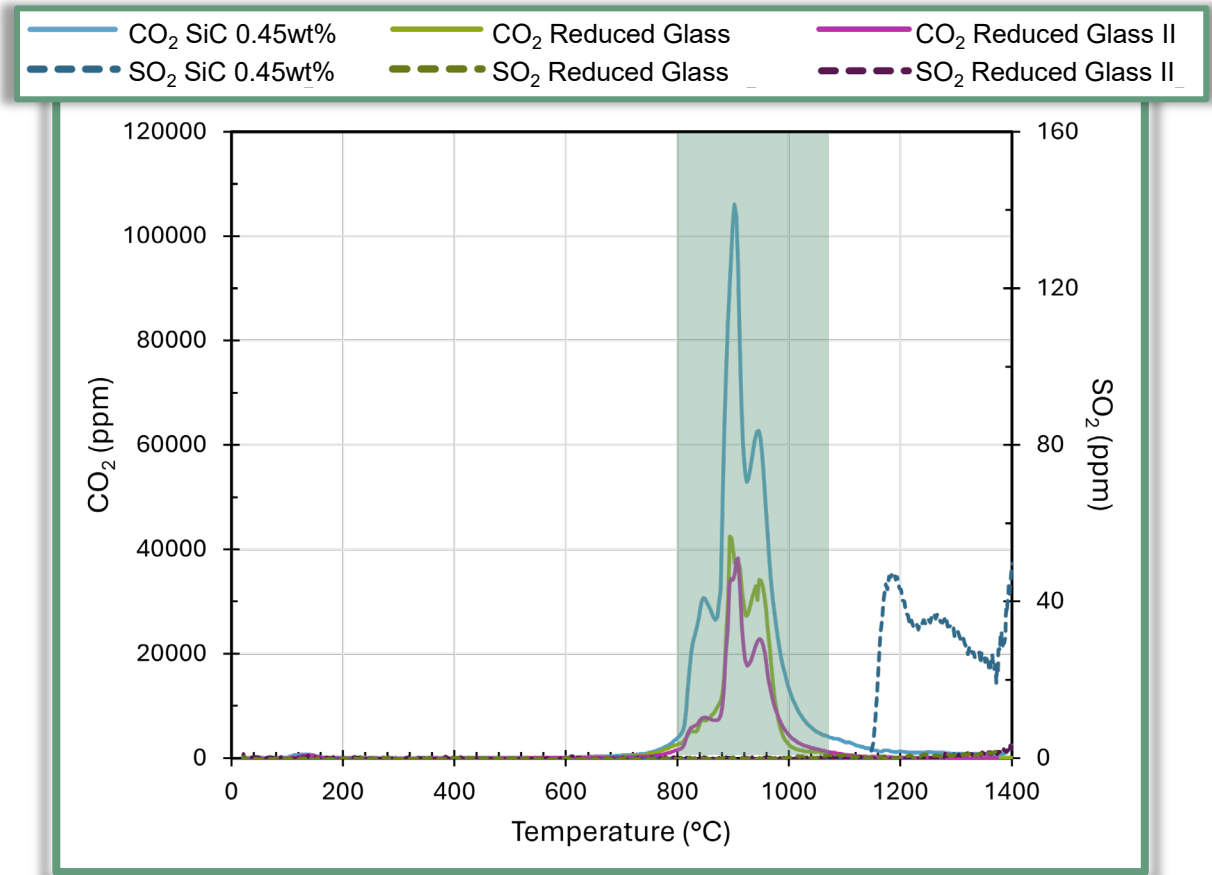
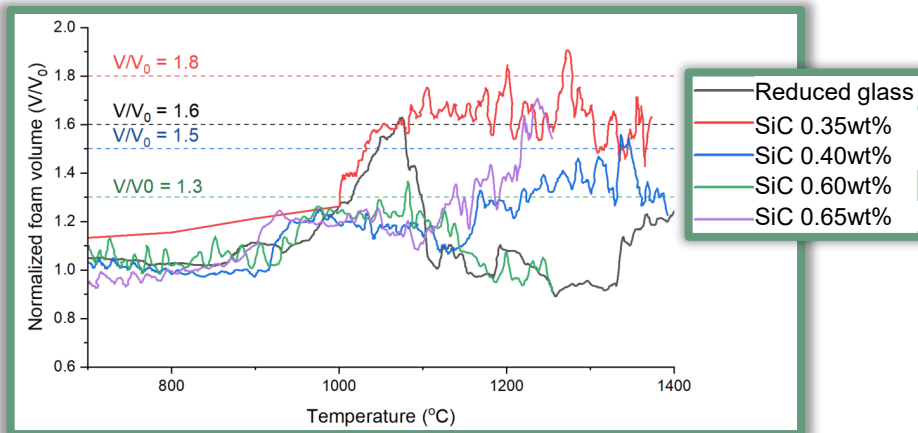
SiC replacing **carbon** and some silica as raw materials resulted in a normalized peak foam volume reduction of 43 %



Gas contribution to primary foam

SiC increased overall CO₂ evolution

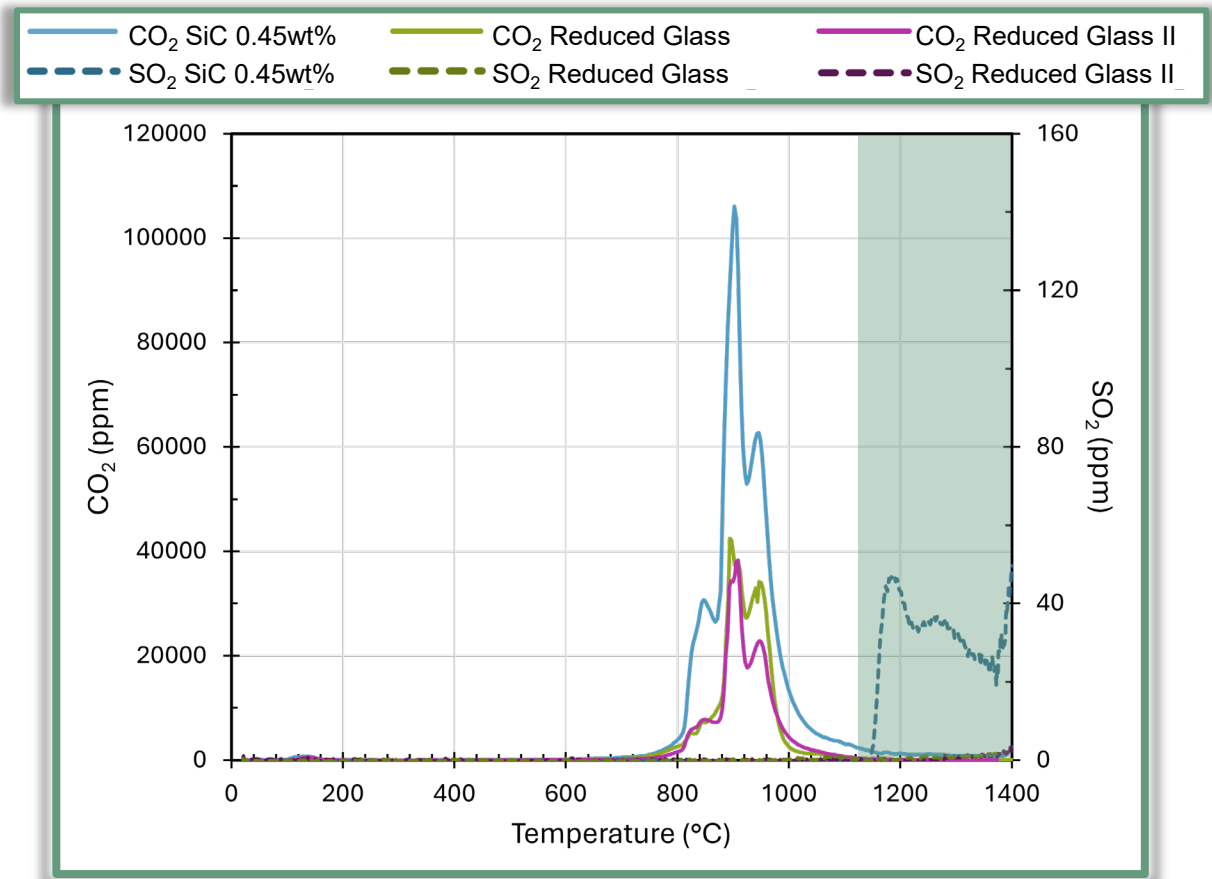
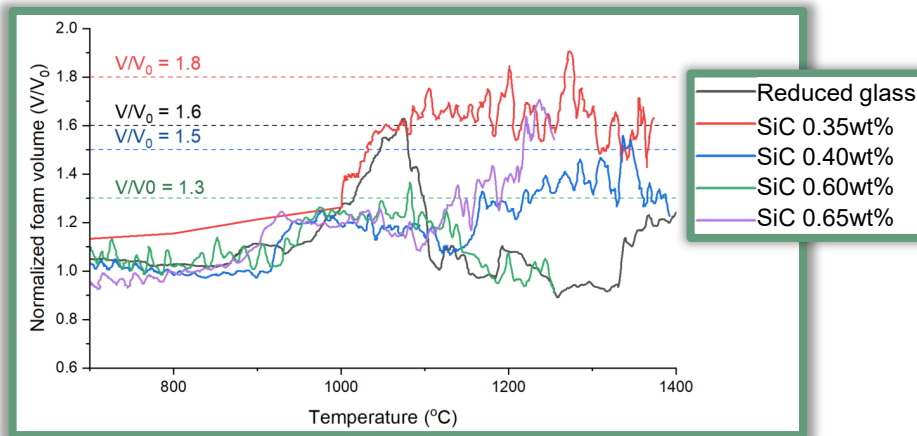
Foam reduction therefore comes from lower viscosity of glass-forming melt at gas-evolution temperature regions



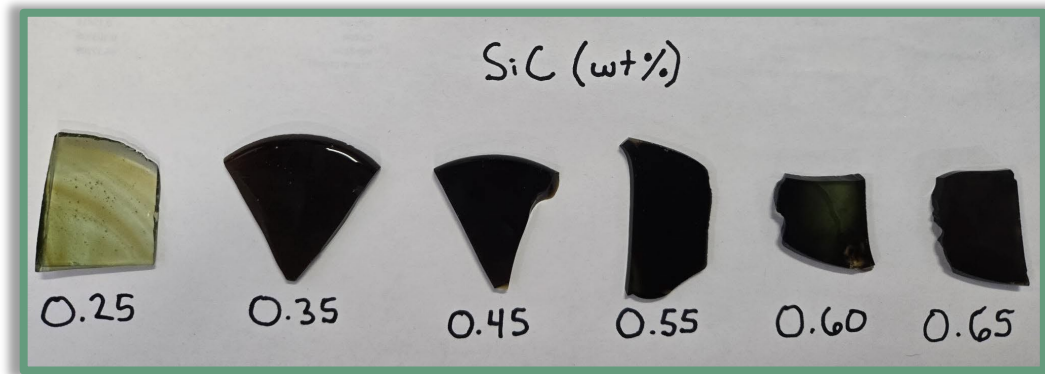
Gas contribution to secondary foam

SiC increased SO_2 evolution

More secondary foam



SiC in Amber Glass: Redox Control

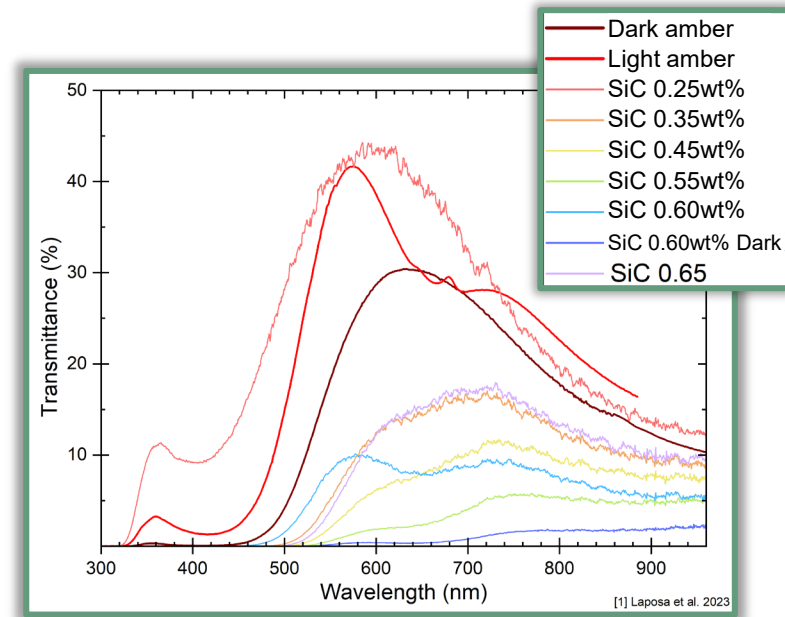


Amber chromophore not achieved

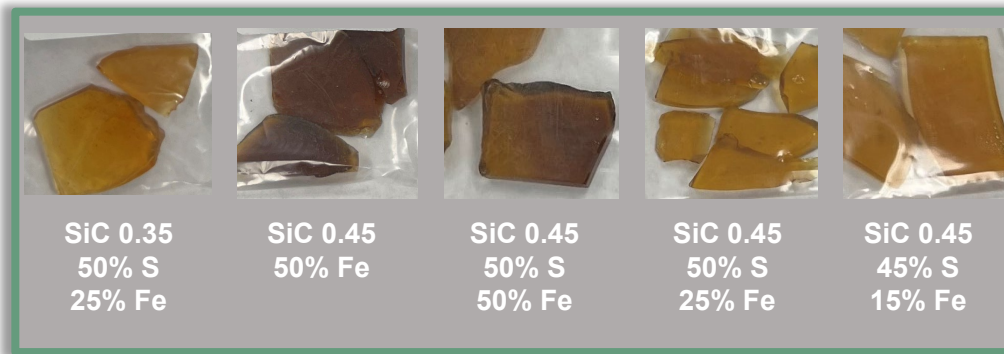
SiC 0.25 – too light

SiC 0.35 – too dark

Reducing agent	$\text{Fe}^{2+}/\text{Fe}_T$
Standard	0.87
SiC 0.45	0.90

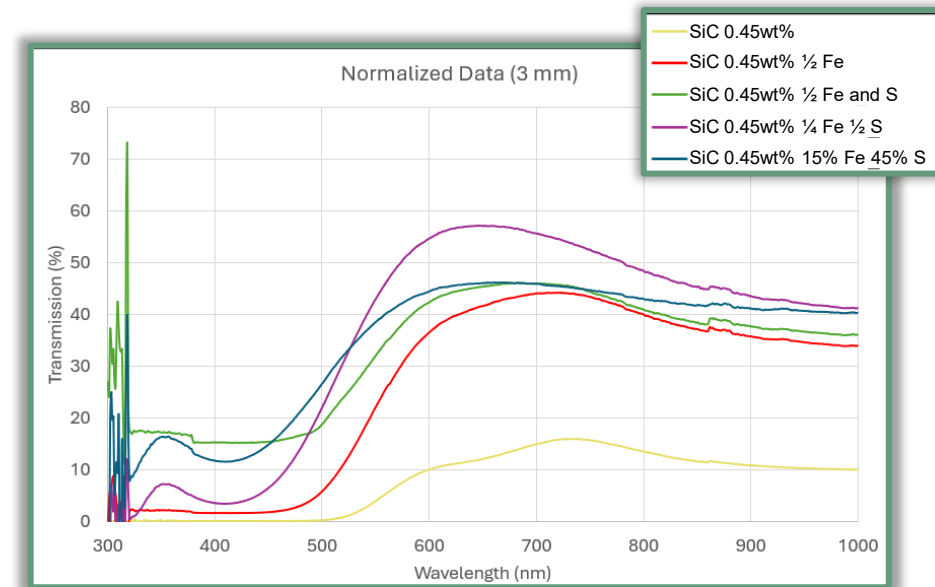


SiC in Amber Glass: Reduced Fe and S

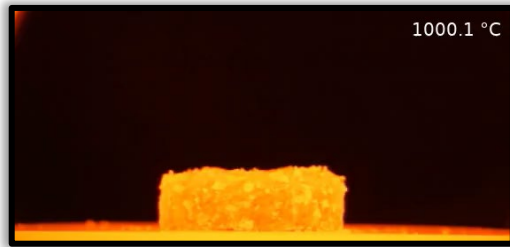


Dark amber chromophore achieved with SiC
0.45wt% at 45% S and 15% Fe

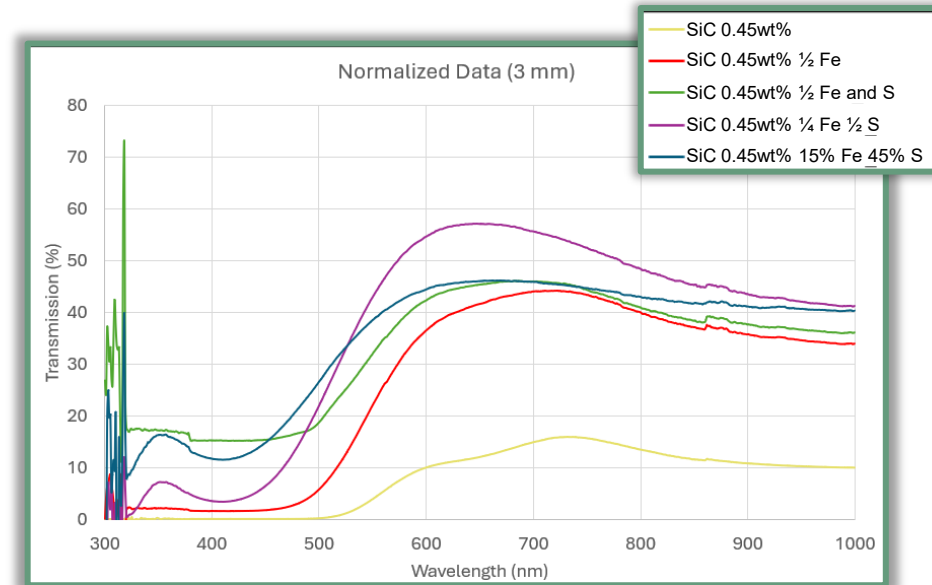
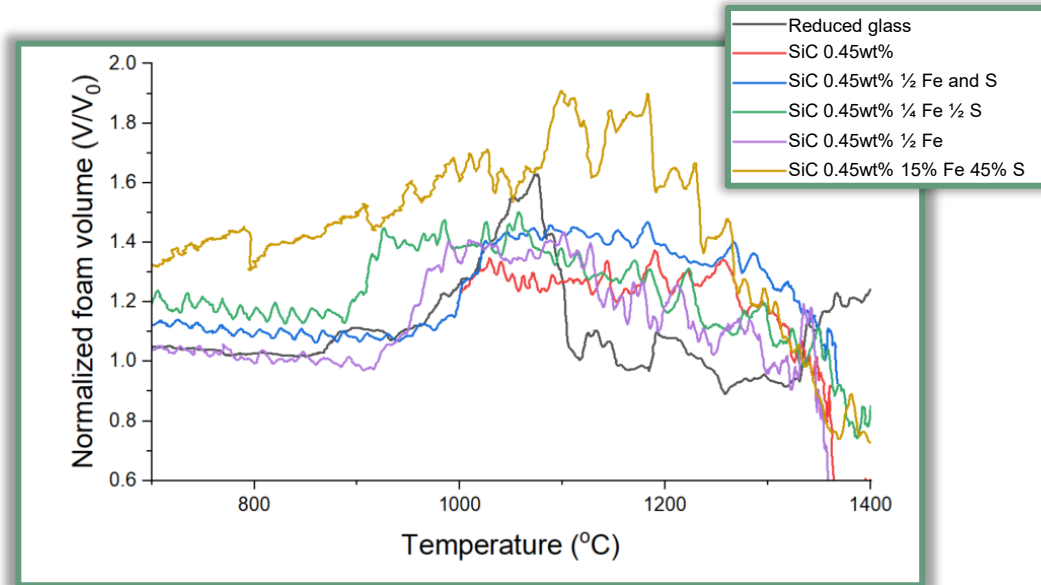
Reducing agent	Fe^{2+}/Fe_T
Standard	0.87
SiC 045	0.90
SiC 0.45 less Fe/S	0.86



SiC in Amber Glass: Reduced Fe and S



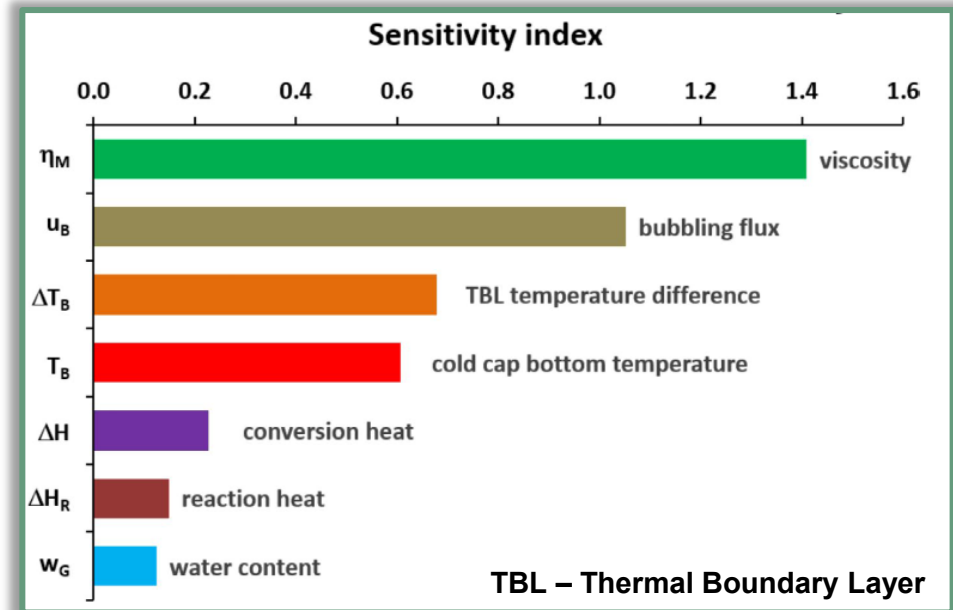
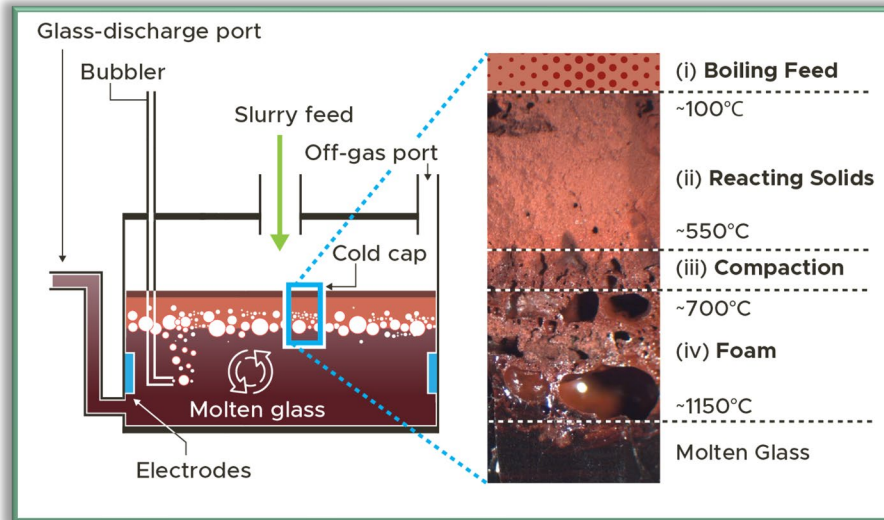
Reducing agent	$\text{Fe}^{2+}/\text{Fe}_T$
Standard	0.87
SiC 045	0.90
SiC 0.45 less Fe/S	0.86



Other lessons from nuclear waste vitrification

Bubbling¹²

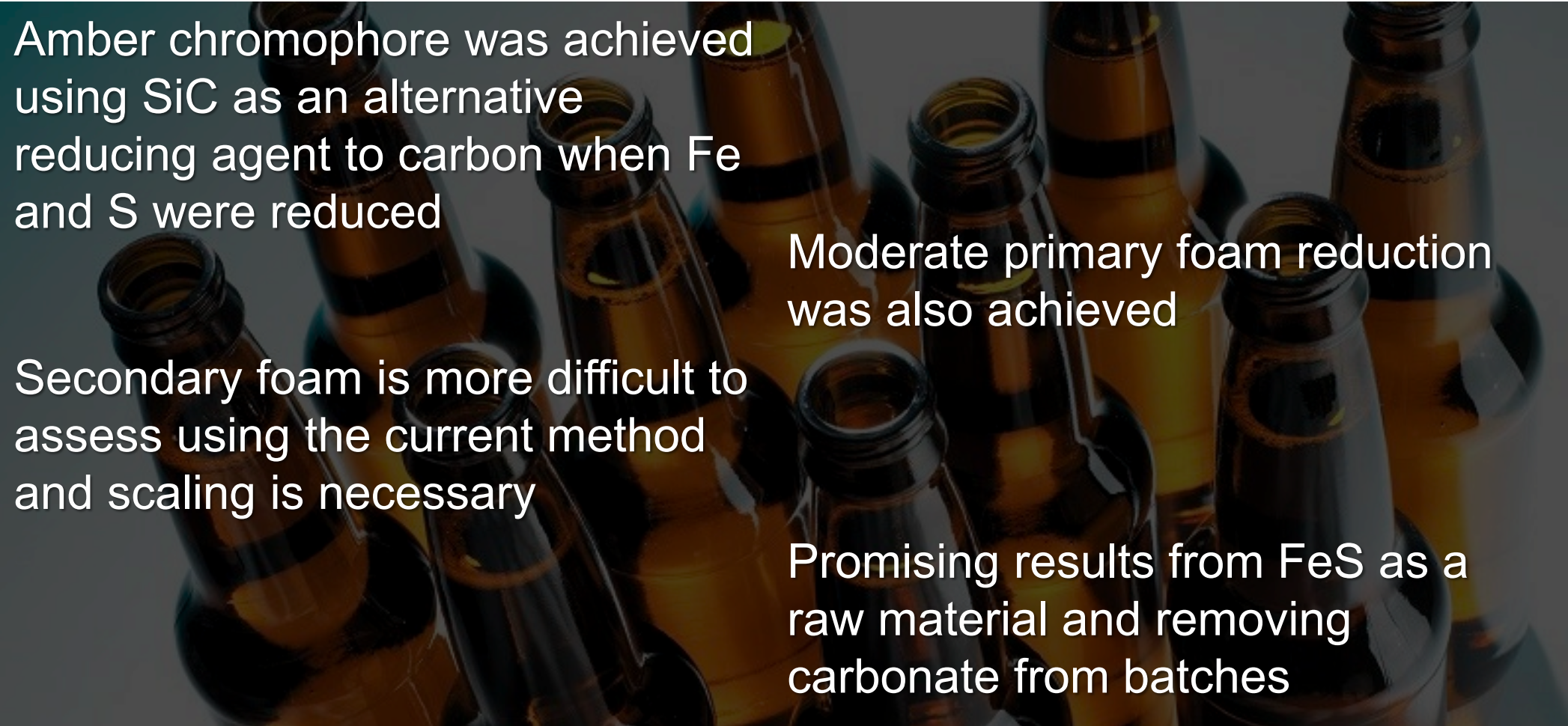
Radiative heat transfer¹³



¹² Lee, S. et al. (2019) Glass production rate in electric furnaces for radioactive waste vitrification. *Journal of the American Ceramic Society*. 102 pp 5828 – 5842.

¹³ Ferkl, et al. (2026) Heat Transfer in Nuclear Waste Glasses: Measurements and Modeling of Thermal Radiation Properties. *Journal of the American Ceramic Society*. 109e. 70647.

Summary



Amber chromophore was achieved using SiC as an alternative reducing agent to carbon when Fe and S were reduced

Secondary foam is more difficult to assess using the current method and scaling is necessary

Moderate primary foam reduction was also achieved

Promising results from FeS as a raw material and removing carbonate from batches