Static Corrosion Testing of Steel Alloys in Lead-Bismuth Eutectic

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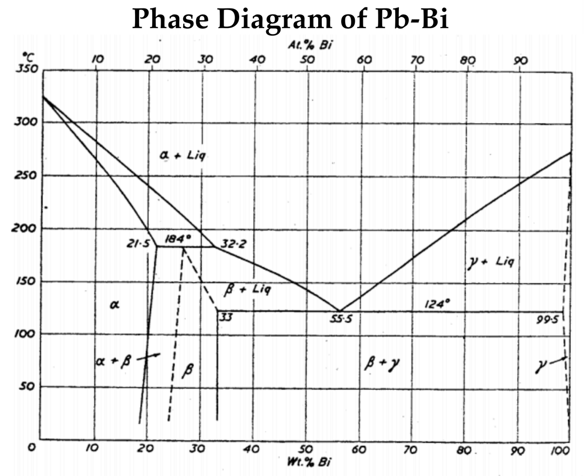
Abstract

Liquid metals have shown promise as a high temperature coolant for nuclear applications. Having a reactor operate at higher temperature would allow more efficient thermodynamic cycles to be used, increasing the efficiency of the plant. One of the candidate liquid metals is Lead-Bismuth Eutectic (LBE). Corrosion of steel, a primary structural material, in LBE is one of the main limiting factors for deploying this technology widely. It was shown that the corrosion of steels can be mitigated and reduced by creating an oxide layer at high temperatures. This work investigates the corrosion of different steel alloys at high temperatures with precise oxygen content in LBE. It's the goal of this research to examine whether a protective oxide layer can form on selected steels at high temperatures.

Advantages and Limitations of LBE

Phase Diagram of Pb-Bi

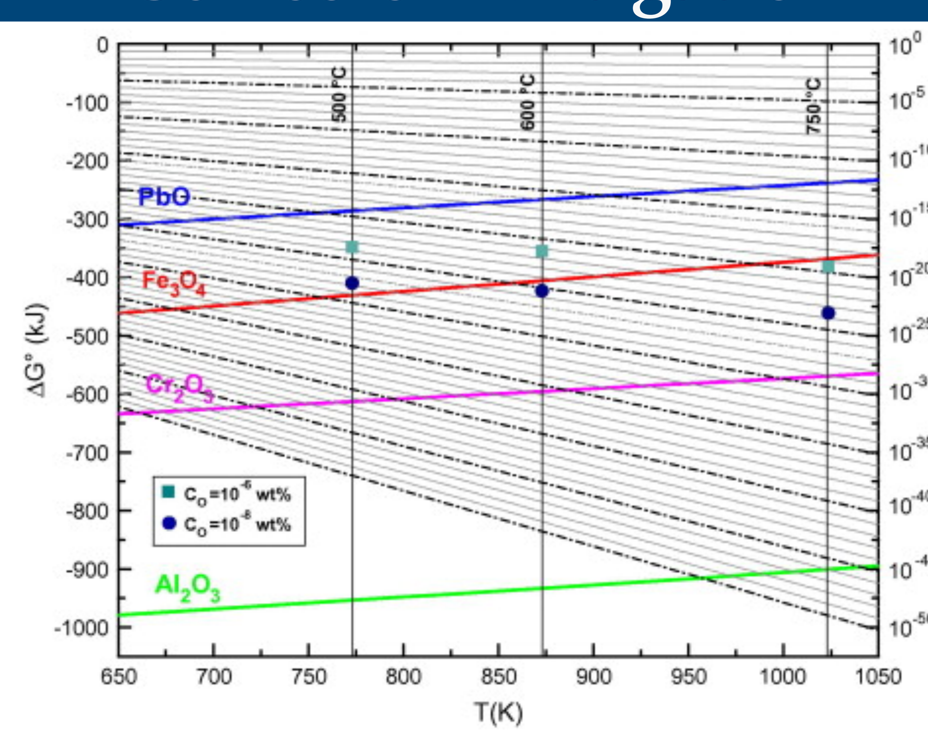


Advantages:

- High boiling point (1670°C), ➔ ➔ system doesn't have to be pressurized.
- Relatively low melting point (123.5°C) ➔ easier to refuel and service a reactor.
- A very strong potential against gamma rays; at the same time, virtually transparent to neutrons.
- Low reactivity with water or air ➔ non explosive

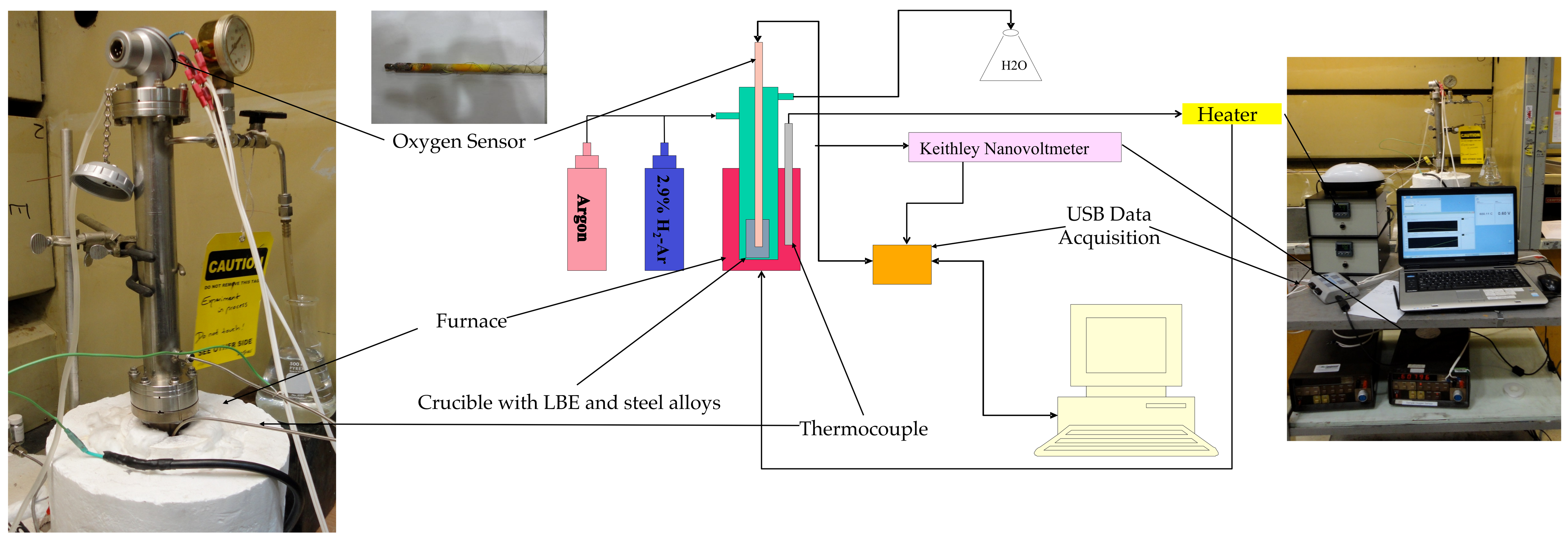
The main limiting factor: the corrosion of cladding and structural materials at high temperatures (>500°C). Therefore, LBE can be implemented as a coolant only after corrosion issues are resolved.

Oxygen Control is The Key For Corrosion Mitigation

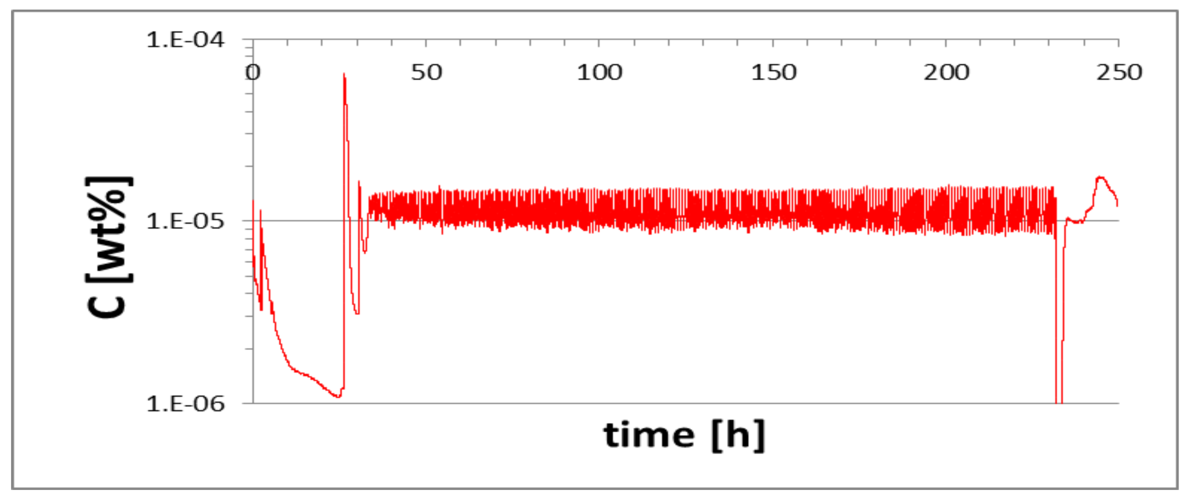


Ellingham diagram shows the Gibbs free energy of different oxides that could from in the liquid metal system. The formation of Fe_3O_4, Cr_2O_3, and Al_2O_3 is more favorable than formation of PbO. Precise control of the oxygen content of LBE allows growing **a protective oxide layer** on the steels surface that inhibits further corrosion. Oxygen concentration in the LBE should be high enough so that oxides of the steel constituents can form on the steel surface at all temperatures under consideration, but lower than the threshold for the precipitation of PbO and BiO oxides.

Experimental Design



The oxygen concentration in LBE in the setup is adjusted by adding reducing or oxidizing cover gas. Outside air and pure argon were introduced to increase the oxygen concentration in the in the liquid metal, while a 2.9% H2-balanced Ar gas mixture was introduced to create a reducing environment for the oxygen Automated oxygen control system was implemented after 8^{th} week.



Oxygen Content vs. Time diagram for the corrosion test conducted at 700°C for 250 hours with 10^{-5}wt% oxygen. Oxygen content is adjusted by automated oxygen control system ➔ steady oxygen content

Composition of Selected Samples

In this work the Fe-Cr-Al alloys (Kanthal ALK and Kanthal APM) and 316L steel alloy were chosen for corrosion testing.

Sample	Cr	Al	Fe	Ni
316L	16-18%	-	Balance	10-14%
ALK	14-16%	3.4%	Balance	-
APM	20-23%	5.8%	Balance	-

Atomic percentage of relevant components of steel alloys

Post Corrosion Testing Examination

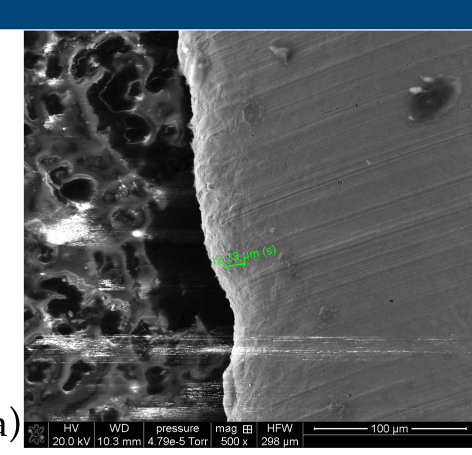
1. Tested samples were cut in cross-section, mounted and polished with Silicon Carbide papers up to 1200 grit (4.5-6.5 microns) and with Alumina up to 0.3 microns for subsequent cross section examination
2. Optical Microscopy (OM)
3. Scanning Electron Microscopy (SEM)
4. Energy Dispersive Spectroscopy (EDS) Analysis

Samples after corrosion test

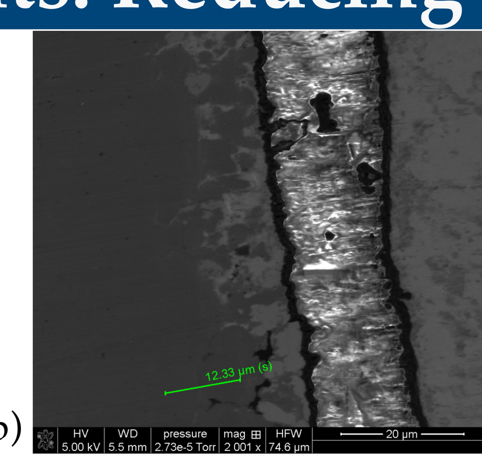
Mounted samples

Results: Reducing Environment

(a)



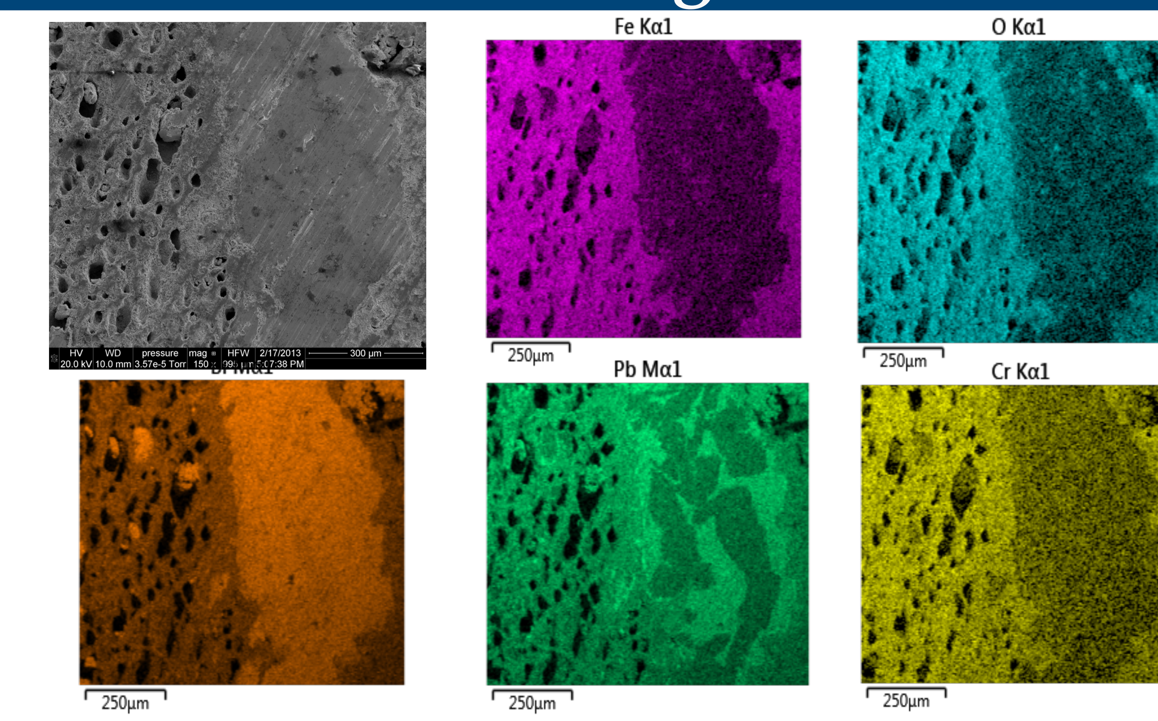
(b)



Post Corrosion SEM images of 316L (a) and Kanthal APM alloy (b) (Reducing environment, 70 hours, 600°C)

As SEM images show, a protective oxide layer was not formed on 316L alloy nor on Kanthal APM alloy. 316L steel alloy was partially dissolved into the LBE, which can be indicated by its rounded edges on the image. Kantal APM alloy was subjected to severe LBE penetration.

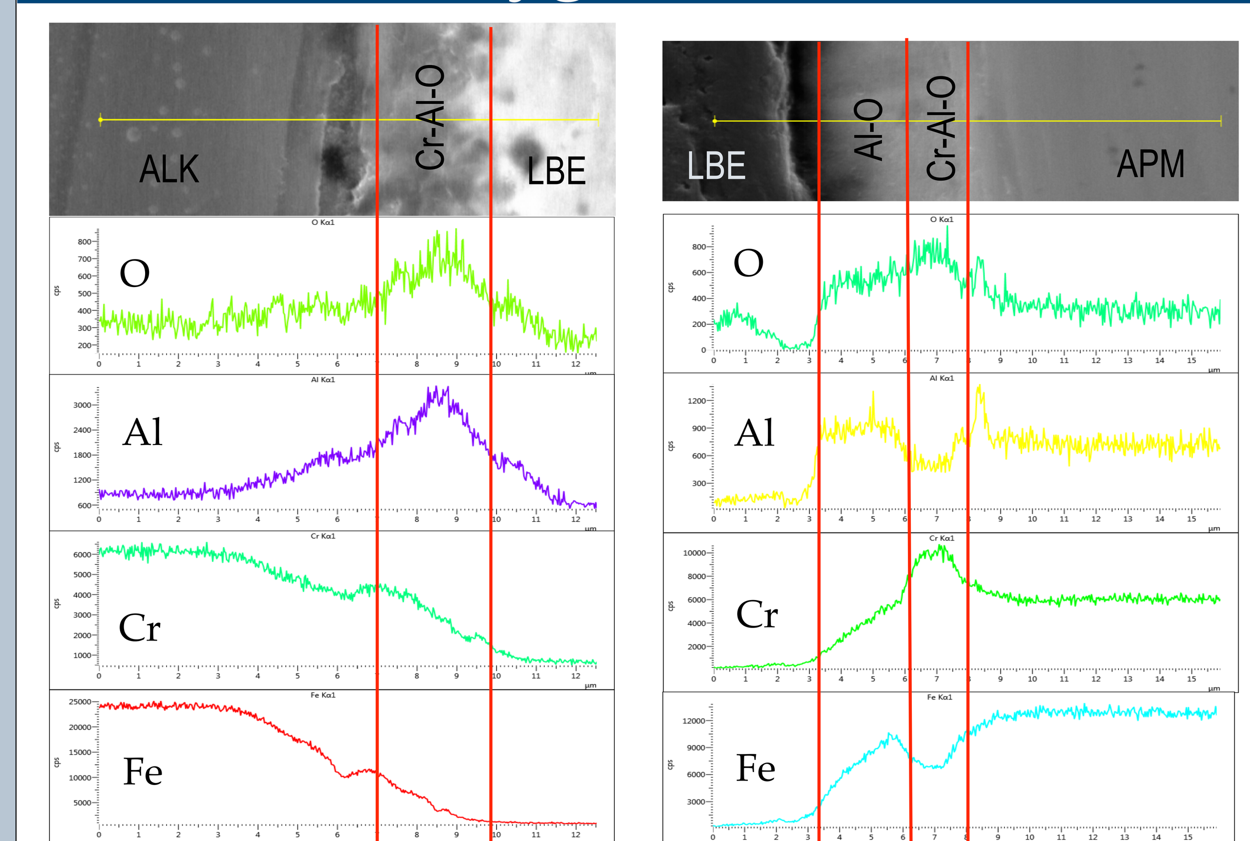
Results: Oxidazing Environment



SEM and EDS mapping of Kanthal APM sample exposed to LBE at 800°C for 90 hours at oxidizing environment

As it can be seen from the EDS images, the sample was severely oxidized after the corrosion test. Fe-Cr oxide with large pores formed.

Medium Oxygen Concentrations



EDS analysis of the ALK and APM samples from 500 hours long corrosion test, conducted at 700°C and 10^{-5} wt% oxygen.

It can be seen that the ALK and APM steels form thin and quite protective oxide layers. As EDS analysis shows, these oxide layers are Al-rich, and it is known that Al based oxides are among the most protective oxides.

This work has shown that **a continuous protective Al-rich oxide layer can be grown on Fe-Cr-Al steel alloys at temperatures above 600°C if the oxygen composition is precisely controlled.** Thickness of an oxide layer depends on temperature, oxygen content and testing time. More tests will be conducted to assess oxide formation at higher temperatures (~800°C) and different oxygen concentrations.

Acknowledgements

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