



Degradation of Magnetic Materials for High-Temperature Active Magnetic Bearing Applications in CO₂-Based Environments

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DISCLAIMER

This study was prepared as an account of work sponsored by an agency of the United States Government. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Motivation

- ❑ sCO₂ Turbines with Active Magnetic Bearings (AMB)
 - High-efficiency, compact, high-speed power conversion
 - Oil-free operation enables clean, closed sCO₂ cycles
- ❑ Material Challenge
 - Limited magnetic material and coating research for sCO₂ environments
 - Uncertain transferability from air-based performance data
- ❑ This Study
 - Rapid evaluation of magnetic materials and coating behavior in CO₂
 - Identify magnetic material selection risks for AMB design in sCO₂ turbines

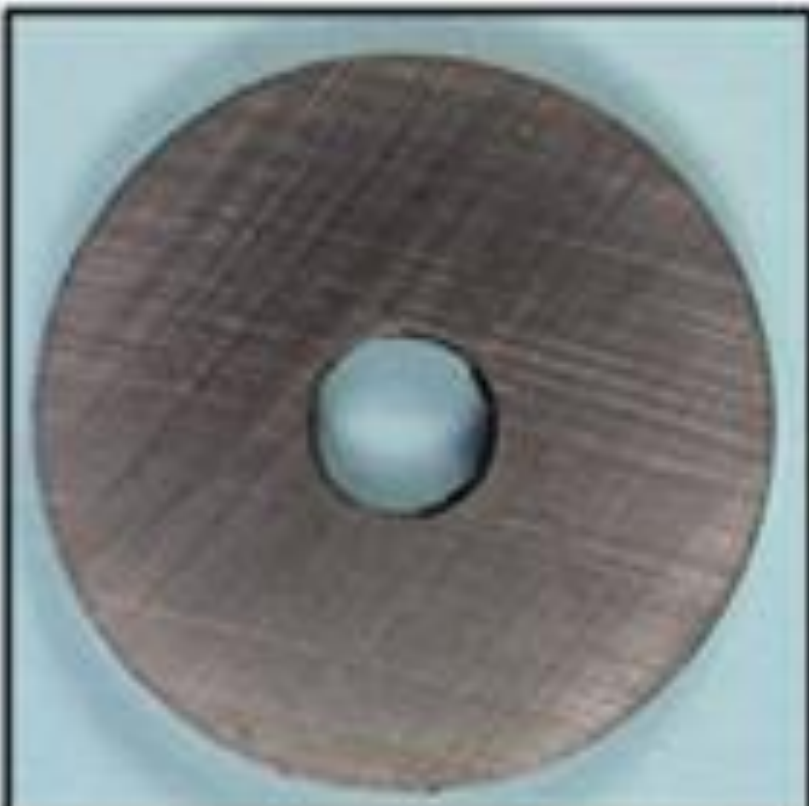
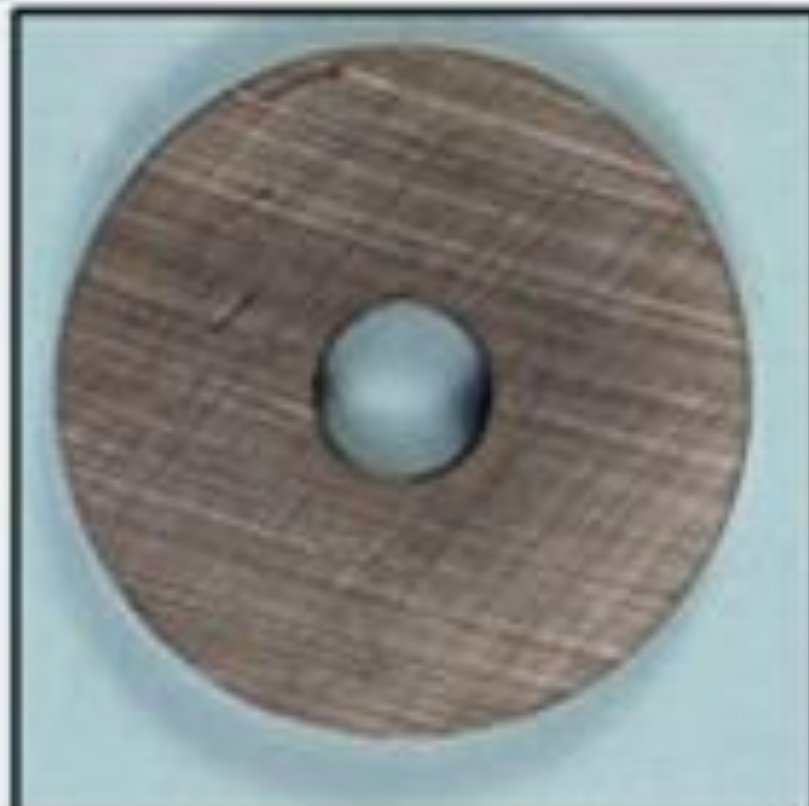

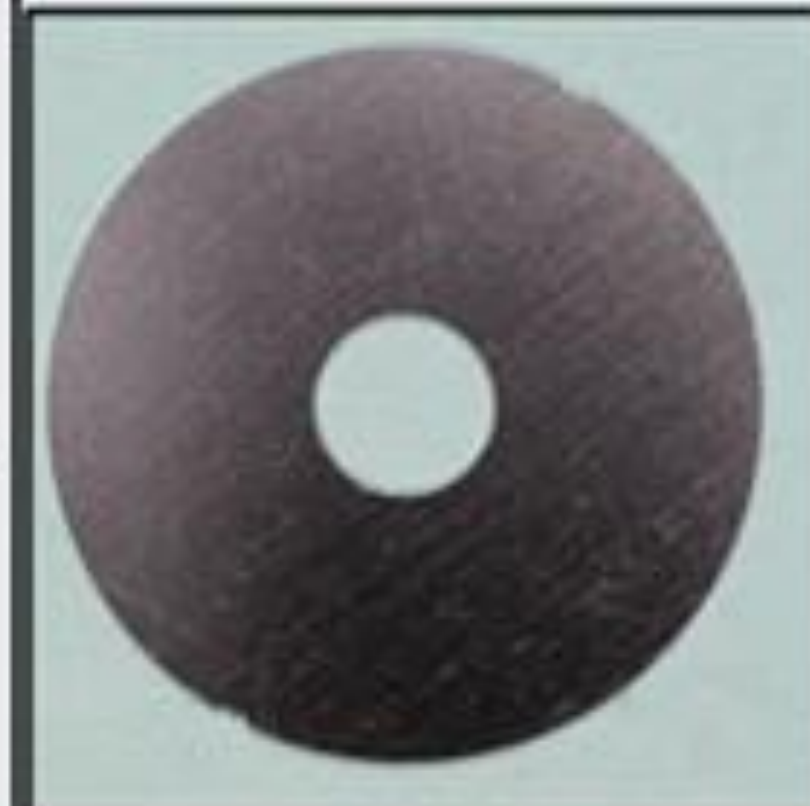
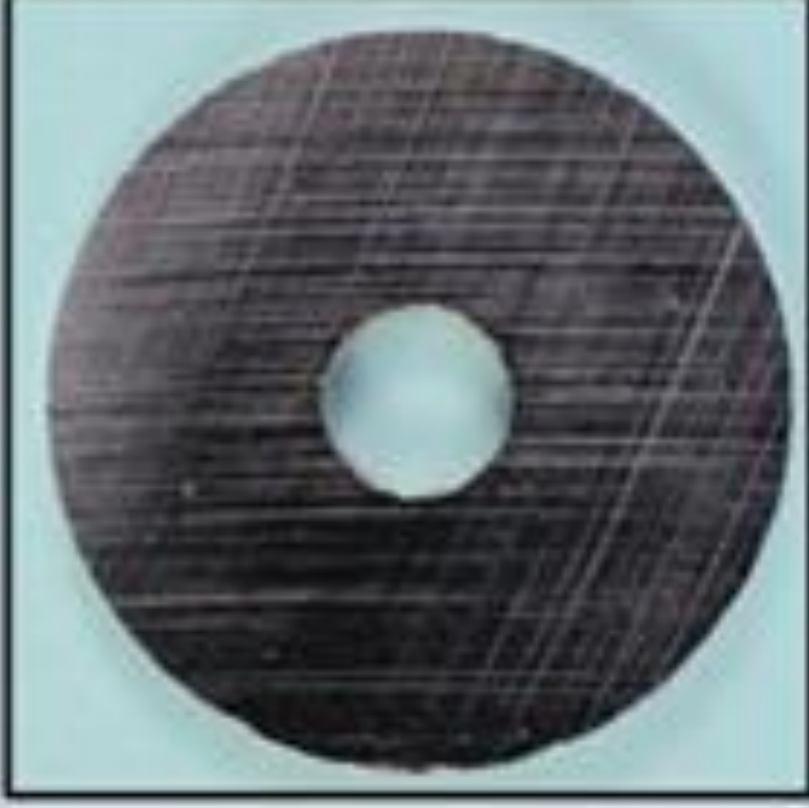
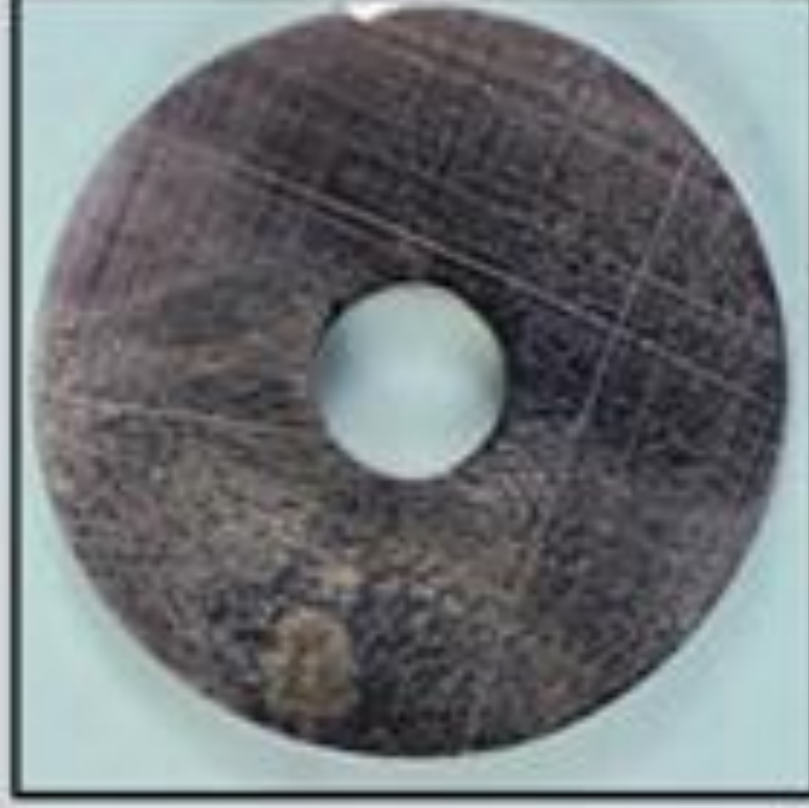




EXPERIMENTAL SETUP

Experimental Materials

No.	Material	Supplier	T _{max} (°C)	Br (T)	Hc (kOe)	(BH) _{max} (kJ/m ³)
PM1	18-T550 SmCo	Electron Energy Corp.	550	0.83	7.7	120
PM2	18-T550 SmCo + Ni plating ^a					
PM3	Alnico 5-7C	Adams Magnetic Products	550	1.35	0.74	60
PM4	Alnico 5-7C + Ni plating ^b					
PM5	Alnico 9C					
PM6	Alnico 9C + Ni plating ^b					
No.	Material	Supplier	μ_{max}		B _{sat} (T)	
SM1	Hiperco 50	Polaris Laser Laminations	19,200		2.4	
SM2	Hiperco 50 + C5 coating ^c					

a. 10 μm electroless nickel-boron plating; b. 10 μm Ni-Cu-Ni electroplating; c. 5-μm C5 coating

PERMANENT MAGNETS				SOFT MAGNETS			
OD-1" x ID-0.25" x T-0.125"							
OD-1" x ID-0.25" x T-0.014"							
PM1 AL9C		PM3 AL5-7C		PM5 SmCo 18-T550		SM1 Hiperco 50	
PM2 AL9C + Ni		PM4 AL5-7C + Ni		PM6 SmCo 18-T550 + Ni		SM2 Hiperco 50 + C5	

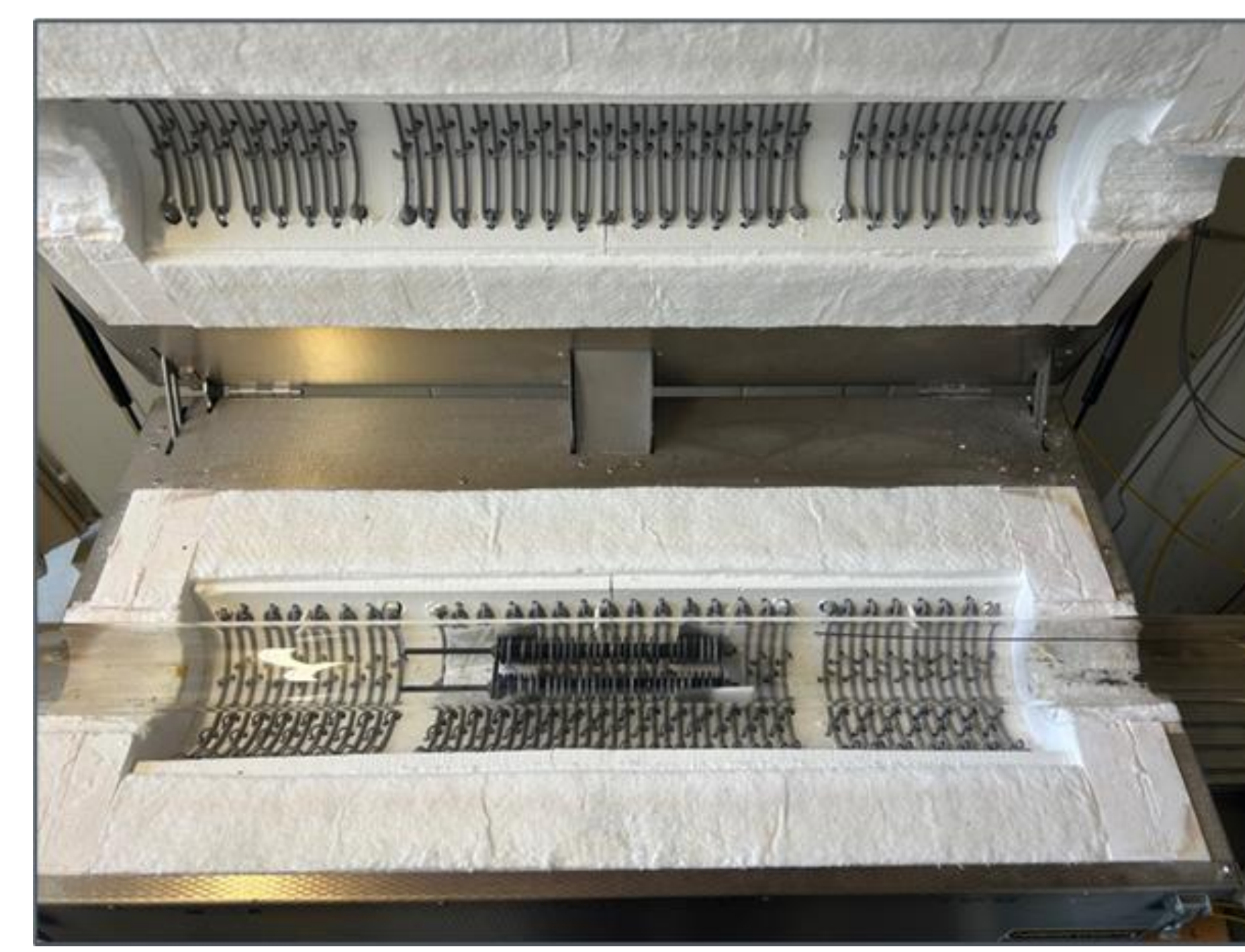
Exposure Conditions

- Vary chemistry (air / CO₂), Phase (gaseous/supercritical), and Temperature
- 3 exposures: 1000 hr., 2000 hr., 5000-6000 hr.
- 3 specimen duplications per each exposure condition and each material

Environment	Fluid	Pressure	Temperature
CO ₂ 1	Supercritical CO ₂	>80 bar	450°C
CO ₂ 2	Gaseous CO ₂	1 bar	550°C
Air 1	Air	1 bar	450°C
Air 2	Air	1 bar	550°C



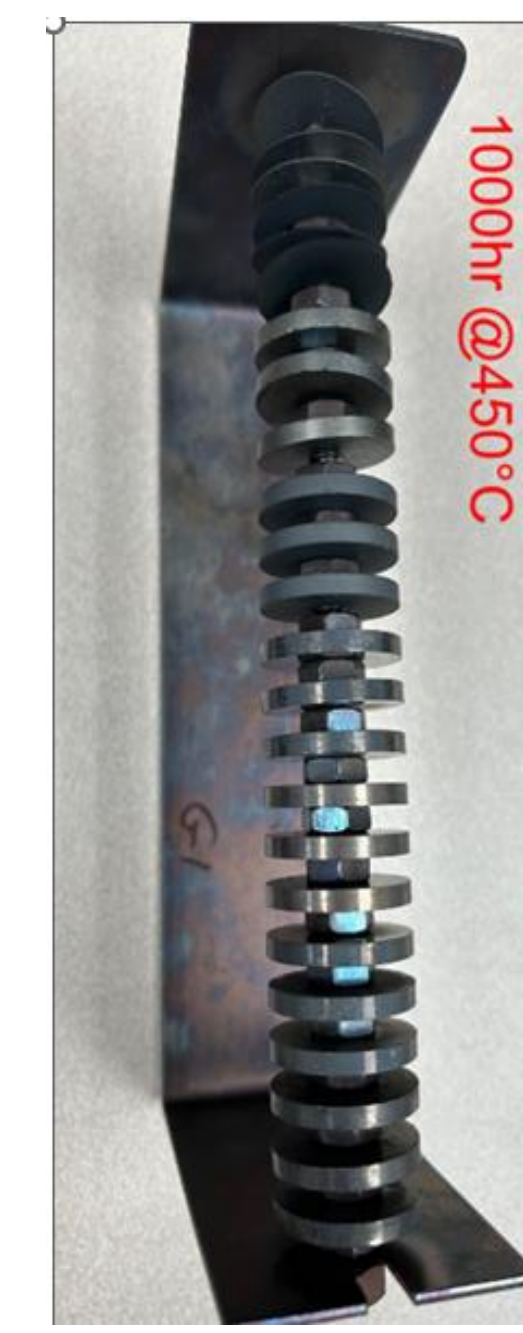
sCO₂ Autoclave



CO₂ Furnace



In CO₂



In Air



Air Furnace

Exposures and Characterization

CHARACTERIZATION

Time Zero:

- Mass – all
- Photo – all
- Br, Hc 25 °C – 2x PM
- Br, Hc 450 °C – 2x PM

End 1:

- Mass – 3x
- Photo – 3x

End 2:

- Mass – 3x
- Photo – 3x
- SEM – 1x PM

End 3:

- Mass – 3x
- Photo – 3x
- SEM – 1x PM
- Br, Hc 25 °C – 2x PM
- Br, Hc 450 °C – 2x PM

Load all samples

Remove 3x of each material

Remove 3x of each material

Remove 3x of each material

EXPOSURES

1000 hours

- sCO₂ 450 °C
- CO₂ 550 °C
- Air 550 °C
- Air 450 °C

1000 hours:

- sCO₂ 450 °C
- CO₂ 550 °C
- Air 550 °C
- Air 450 °C

4000 hours:

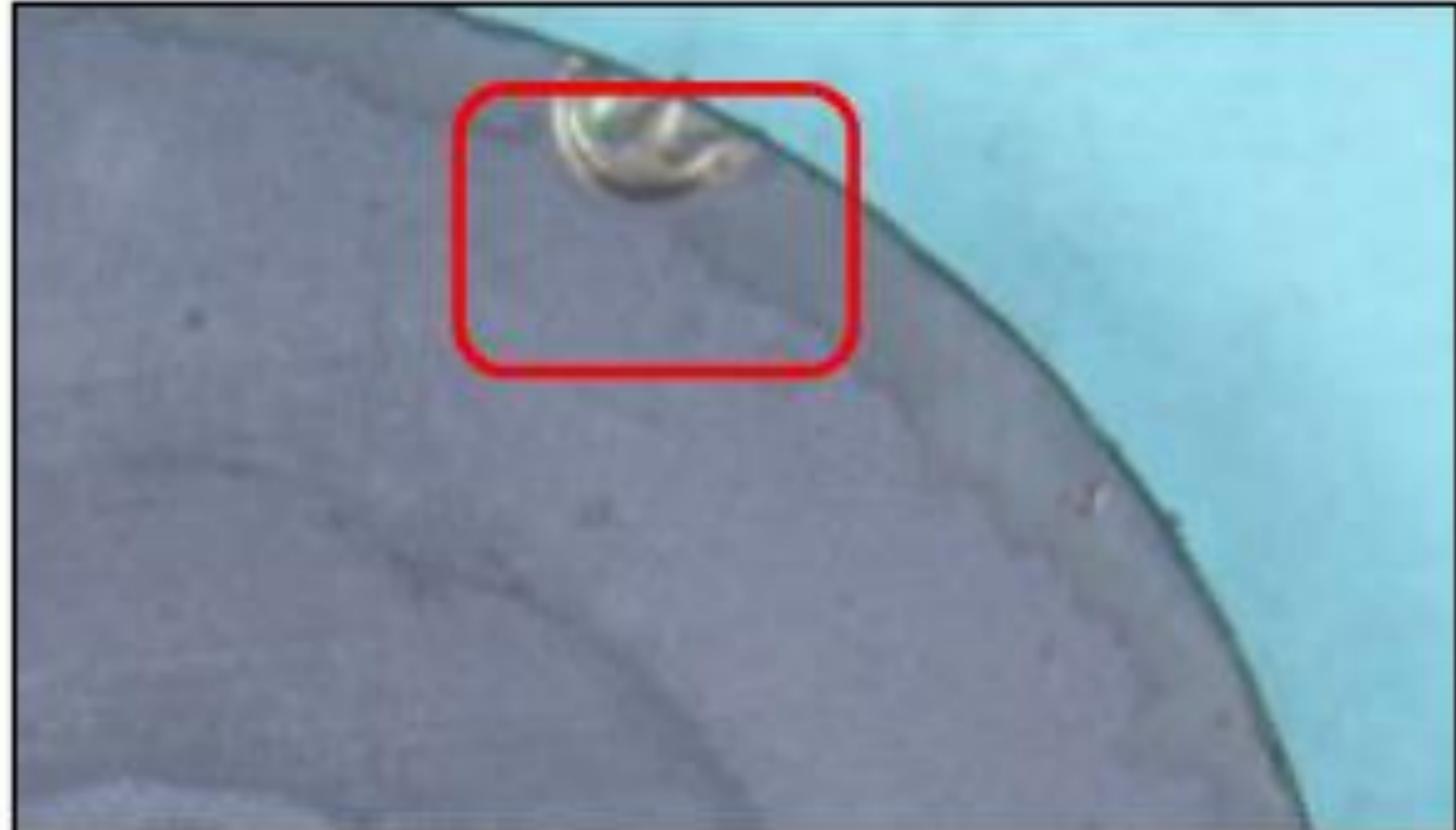
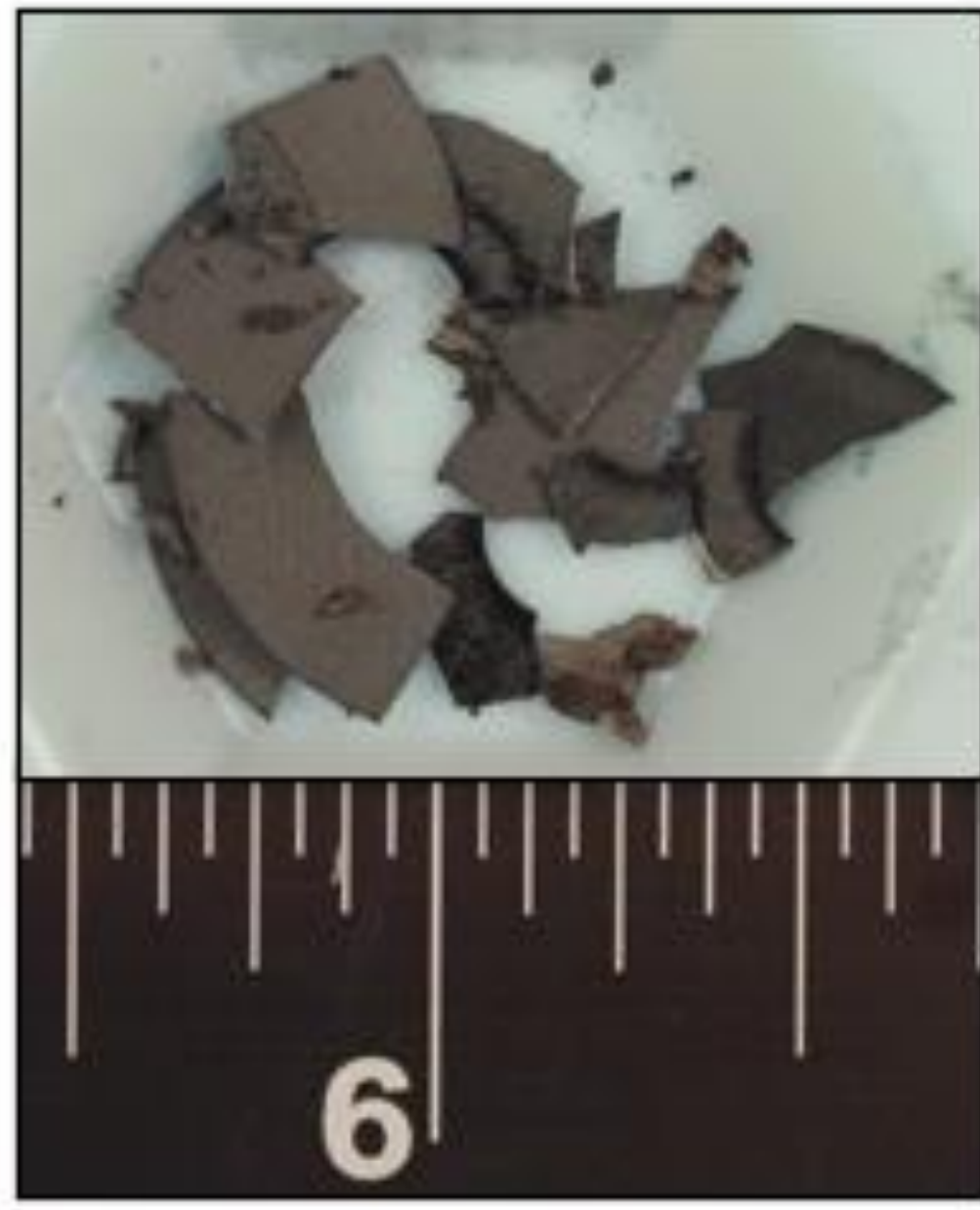

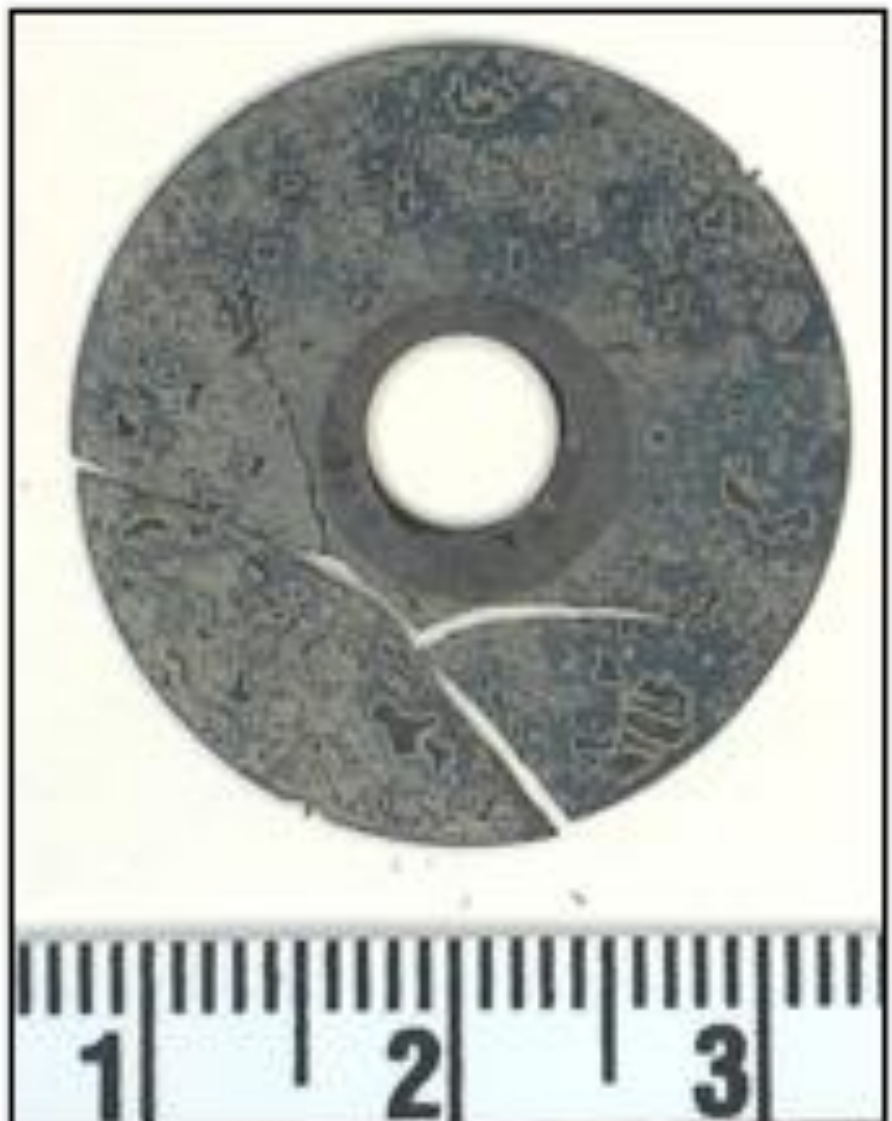


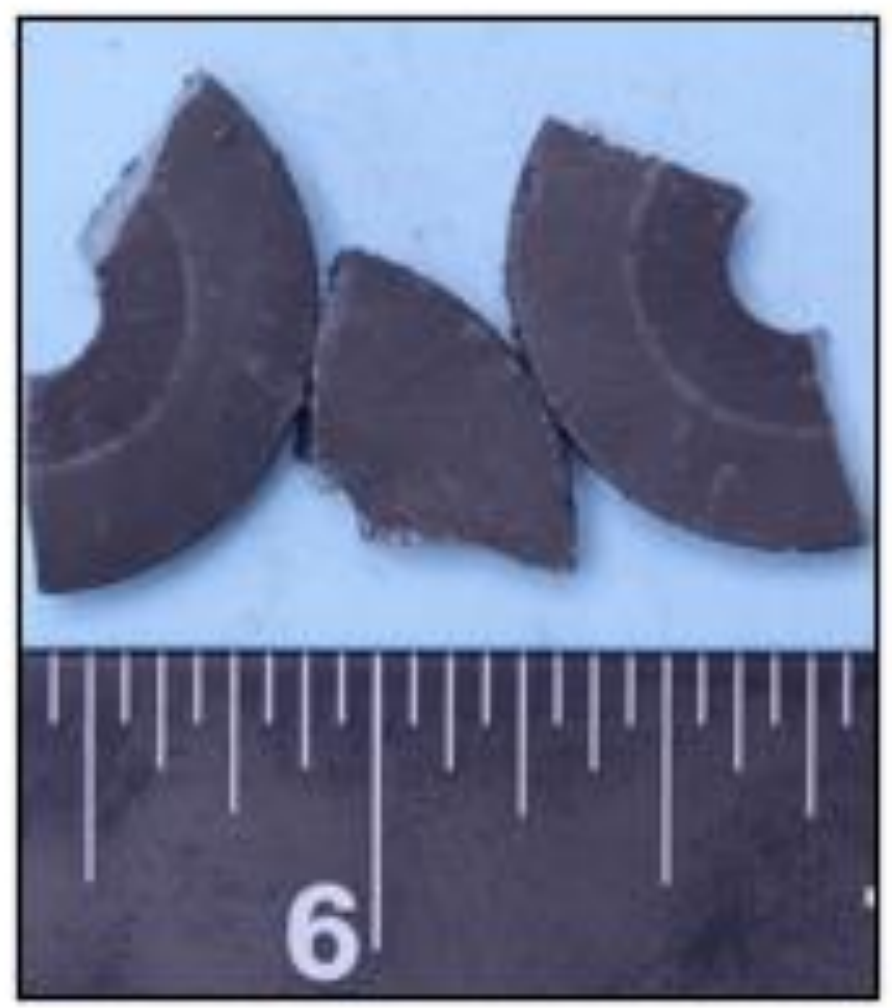

- sCO₂ 450 °C
- CO₂ 550 °C

3000 hours:

- Air 450/550 °C

RESULTS AND ANALYSIS

Results - Structural Integrity Failure

Hot CO ₂ , 550 °C at 1 bar	sCO ₂ , 450 °C at 103 bar		Air, 550 °C at 1 bar
 <p>Coated Alnico 9C, 6,000 hours</p>	 <p>Coated Hiperco, 6,000 hours</p>	 <p>SmCo 18-T550, 6,000 hours</p>	 <p>Coated Hiperco, 5,000 hours</p>
 <p>SmCo 18-T550, 6,000 hours</p>	 <p>Coated SmCo, 6,000 hours</p>	 <p>SmCo 18-T550, 1,000 hours</p>	 <p>SmCo 18-T550, 5,000 hours</p>

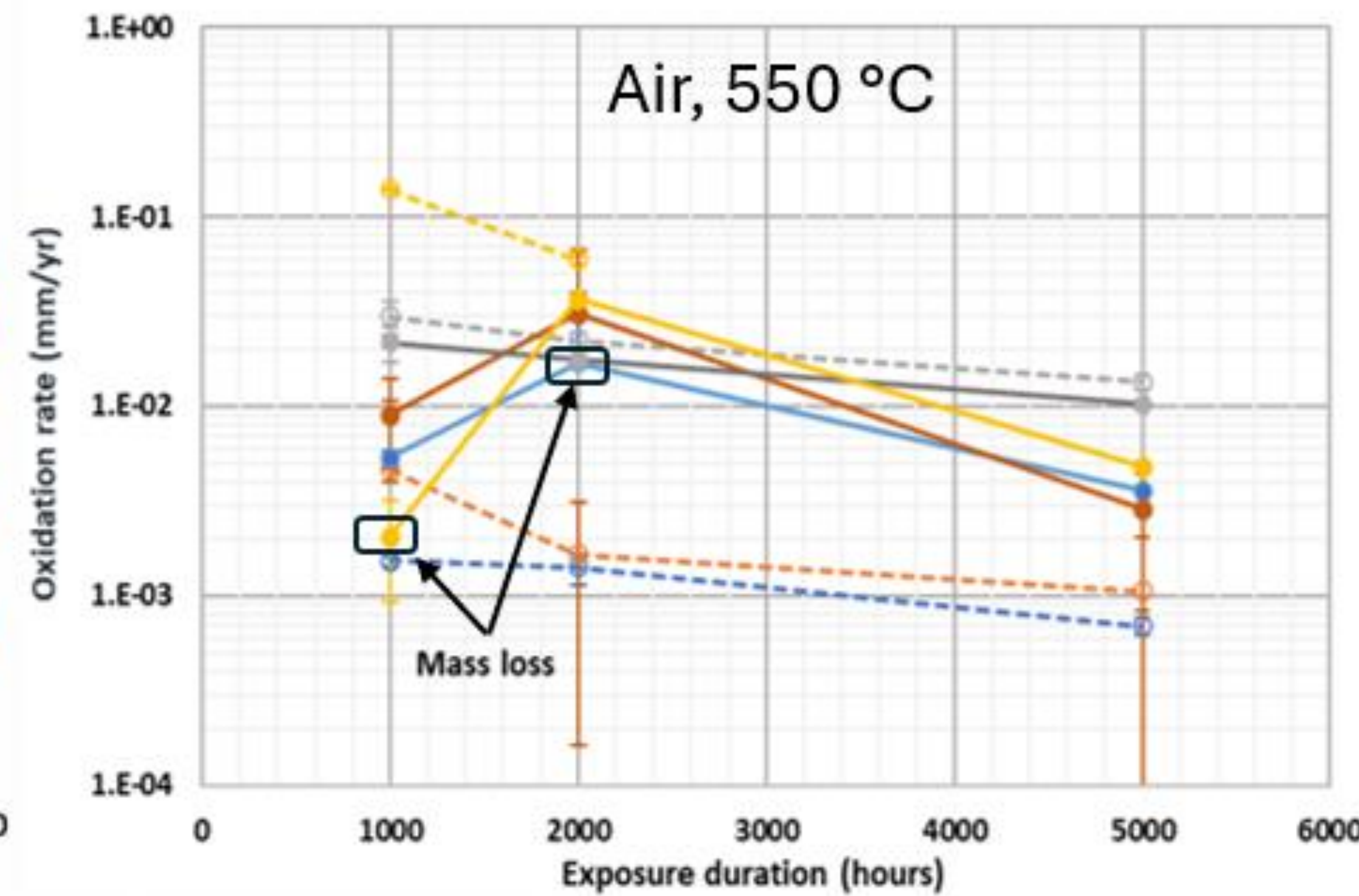
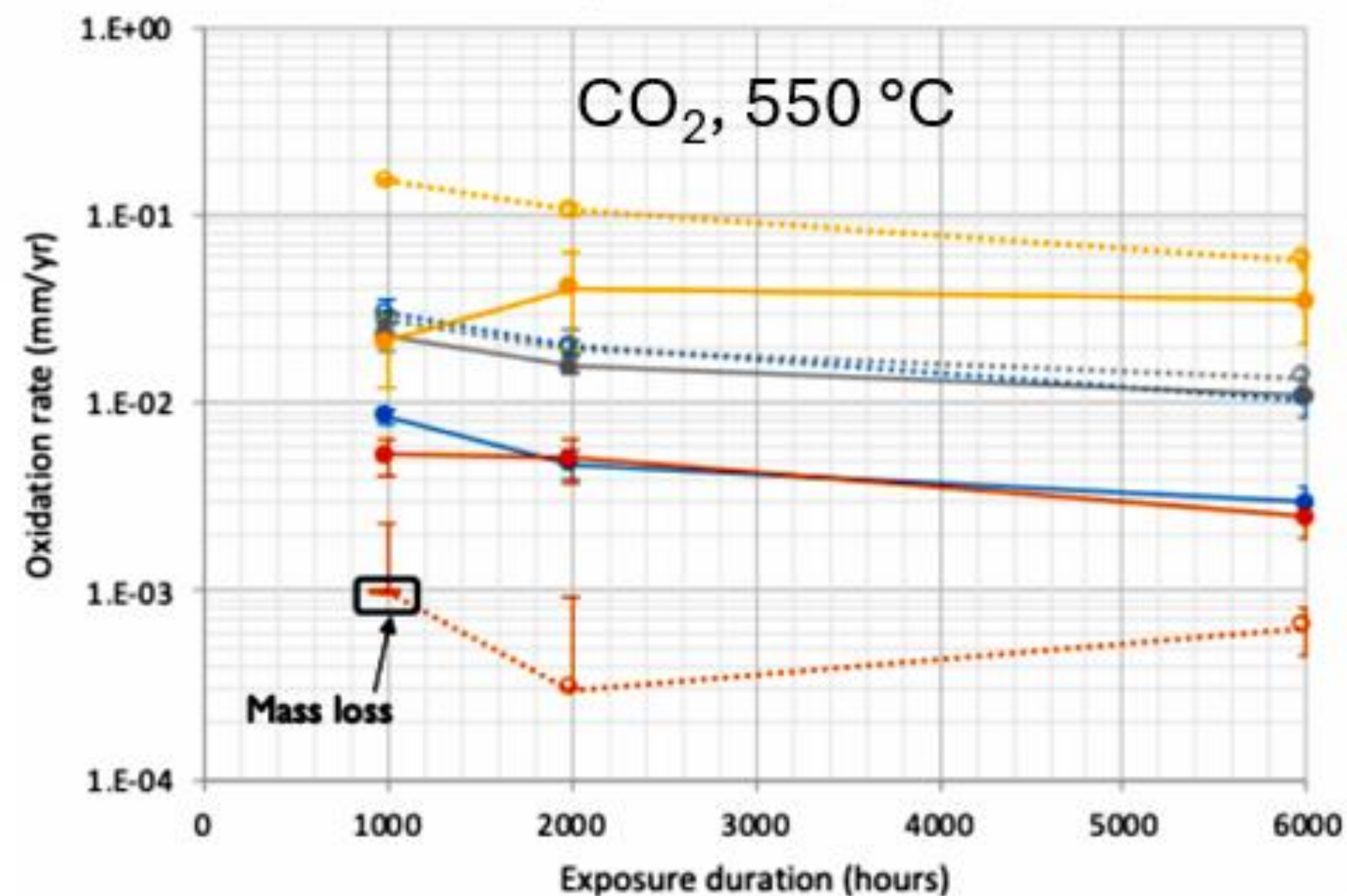
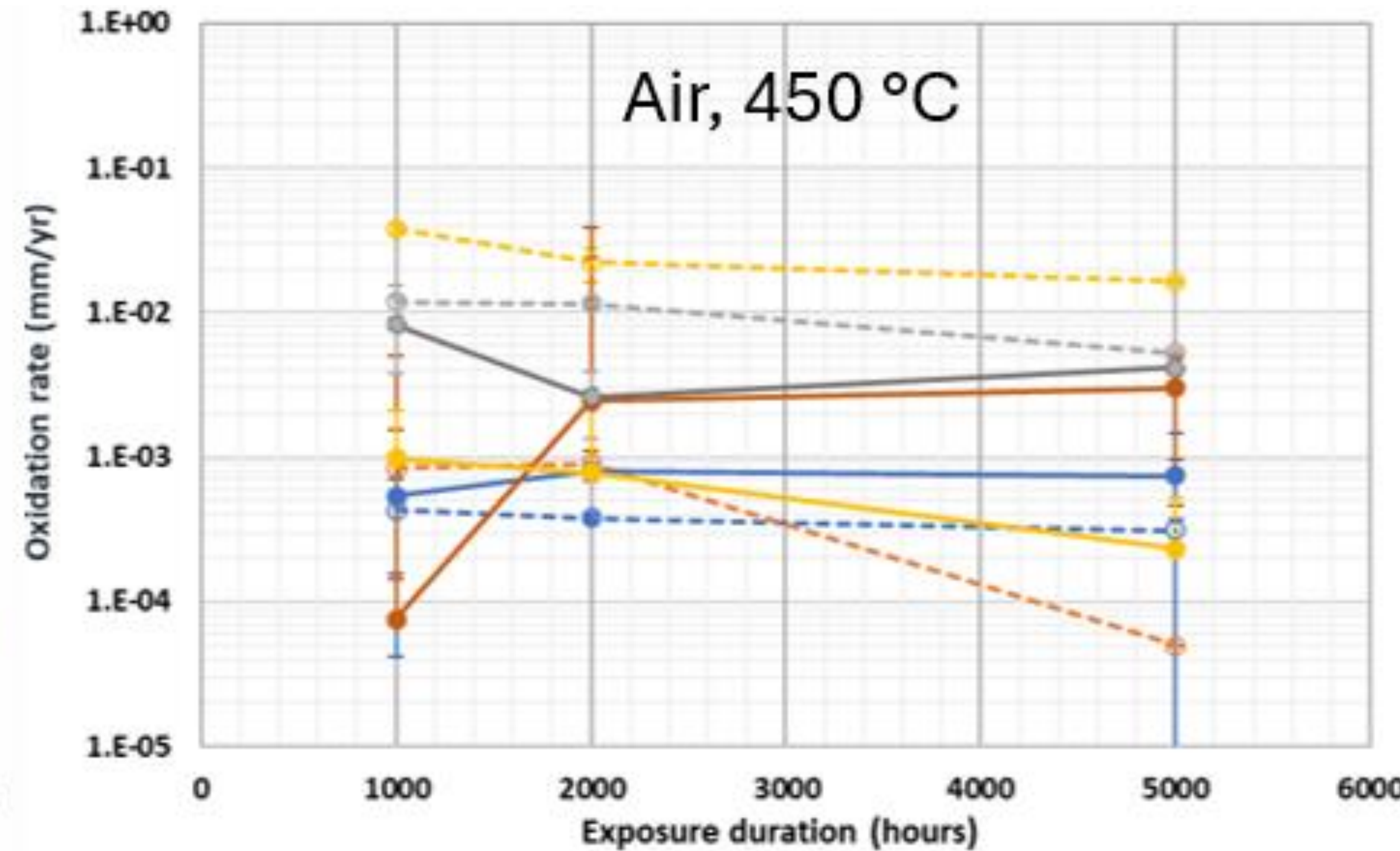
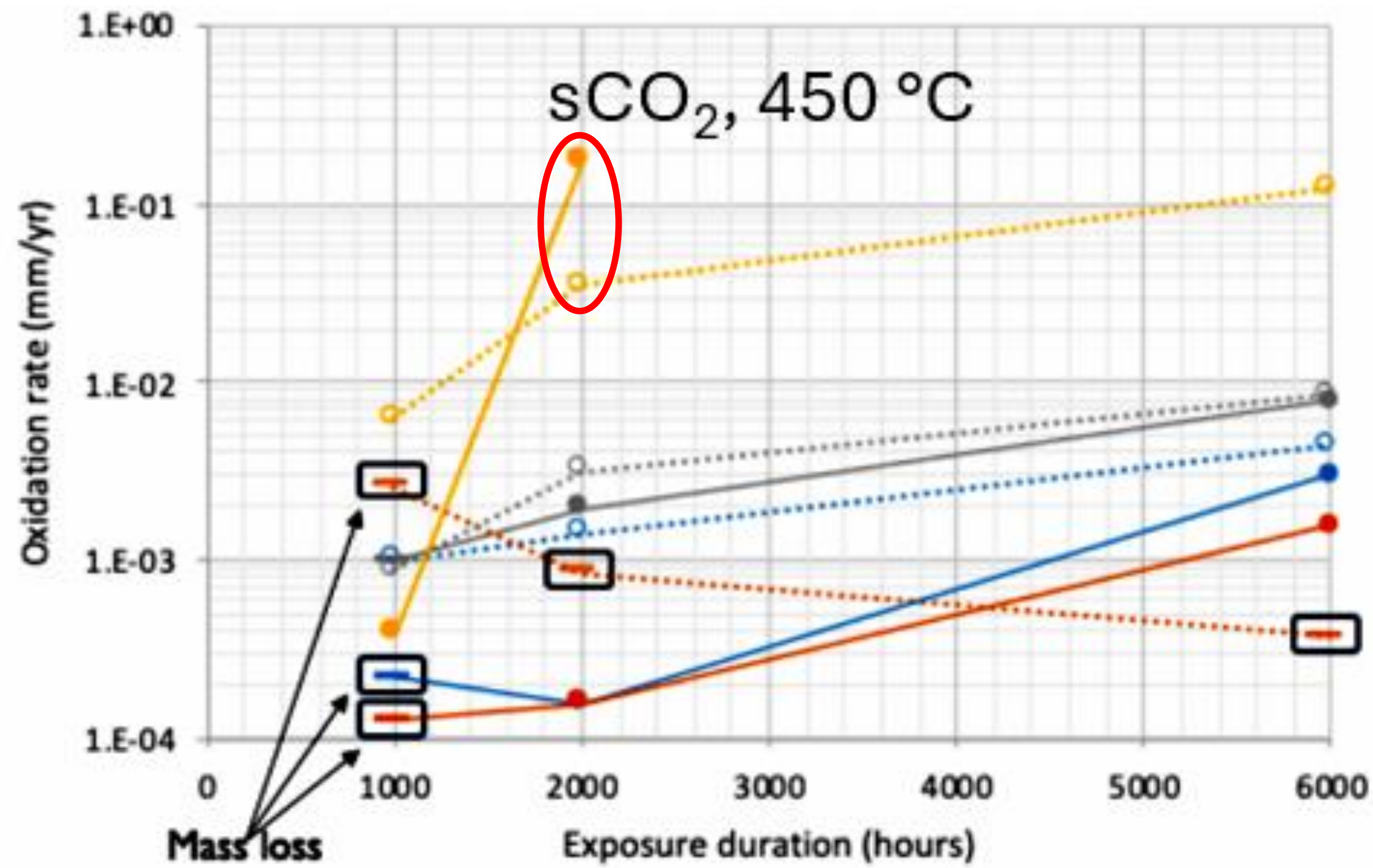
Alnico: Coating degradation on AL9C,
6000 hr., Air (550 °C) / hot CO₂

SmCo: {

- 1x bare, 1000 hr. sCO₂
- 1x coated, 1000 hr. sCO₂
- 3x coated, 6000 hr. sCO₂
- 3x bare, 6000 hr. sCO₂
- 1x bare, 6000 hr. CO₂
- 3x bare, 5000 hr. Air (550 °C)

Hiperco: 1x C5 coated, 6000 hr. sCO₂
1x C5 coated, 5000 hr. Air (550 °C)

• Results - Oxidation Rates



In sCO₂

- Accelerated oxidation
- Coating: beneficial to AL5-7C
- Coating: harmful to SmCo (2000 hr.)

In CO₂

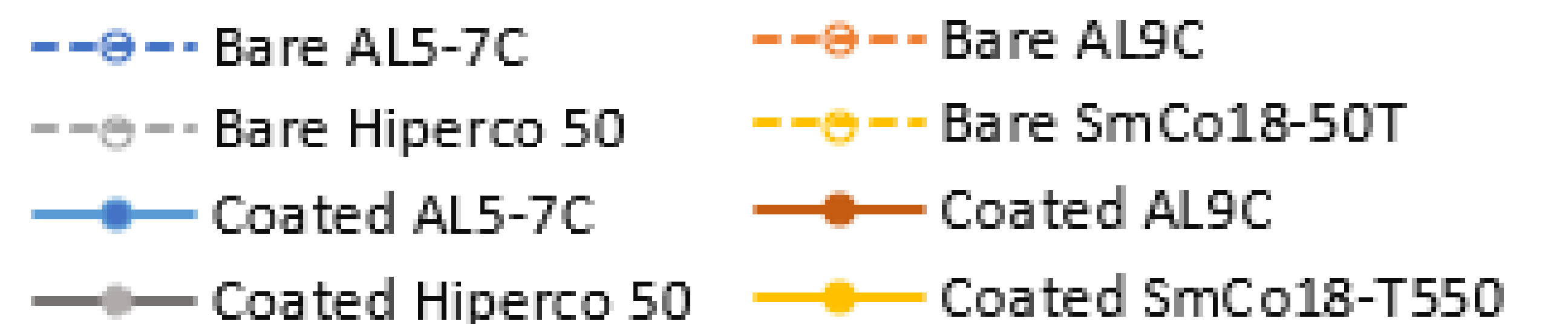
- Coating: beneficial to SmCo and AL5-7C

In Air

- Coating: beneficial to SmCo
- Coating: harmful to Alnicos

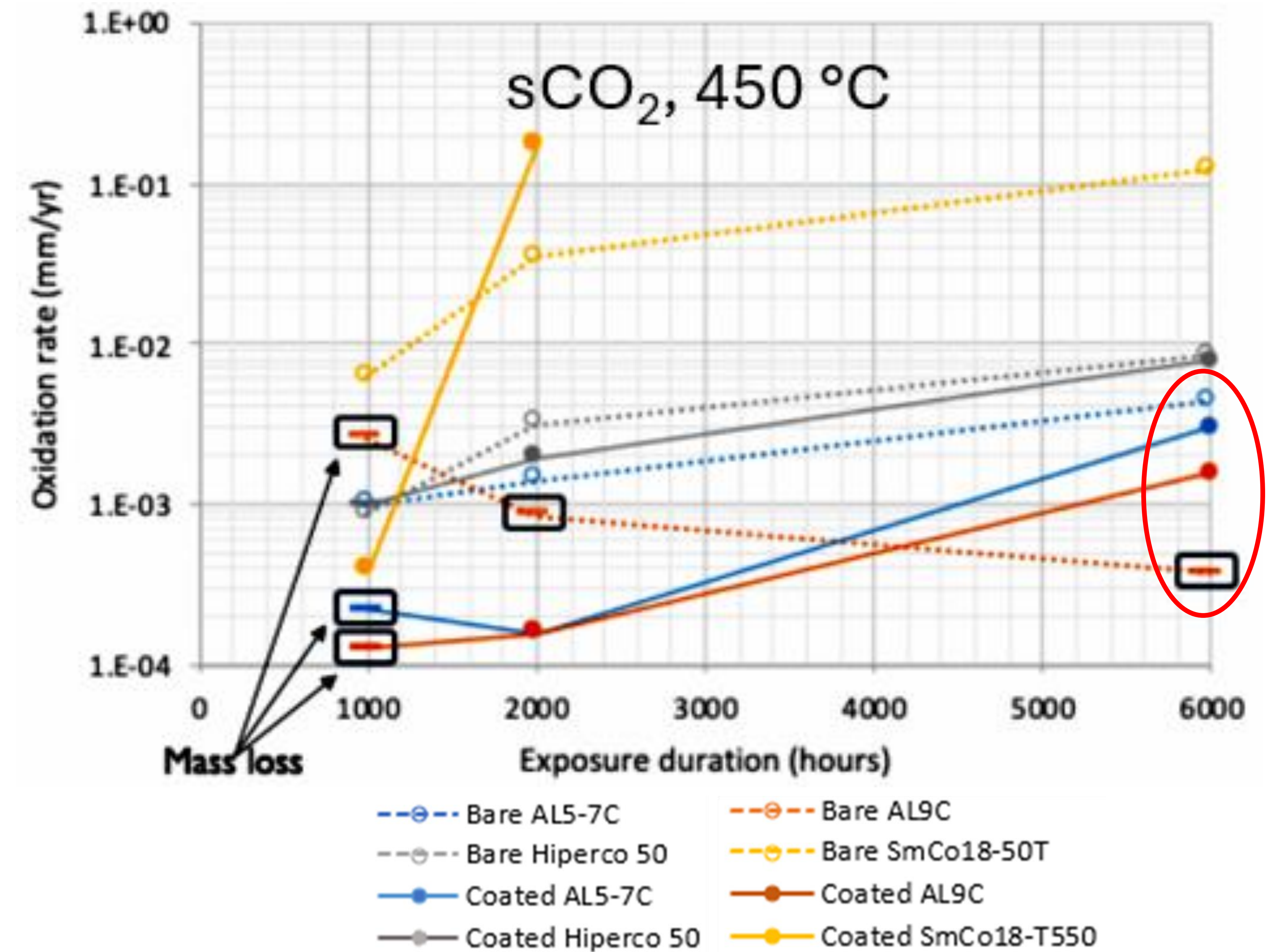
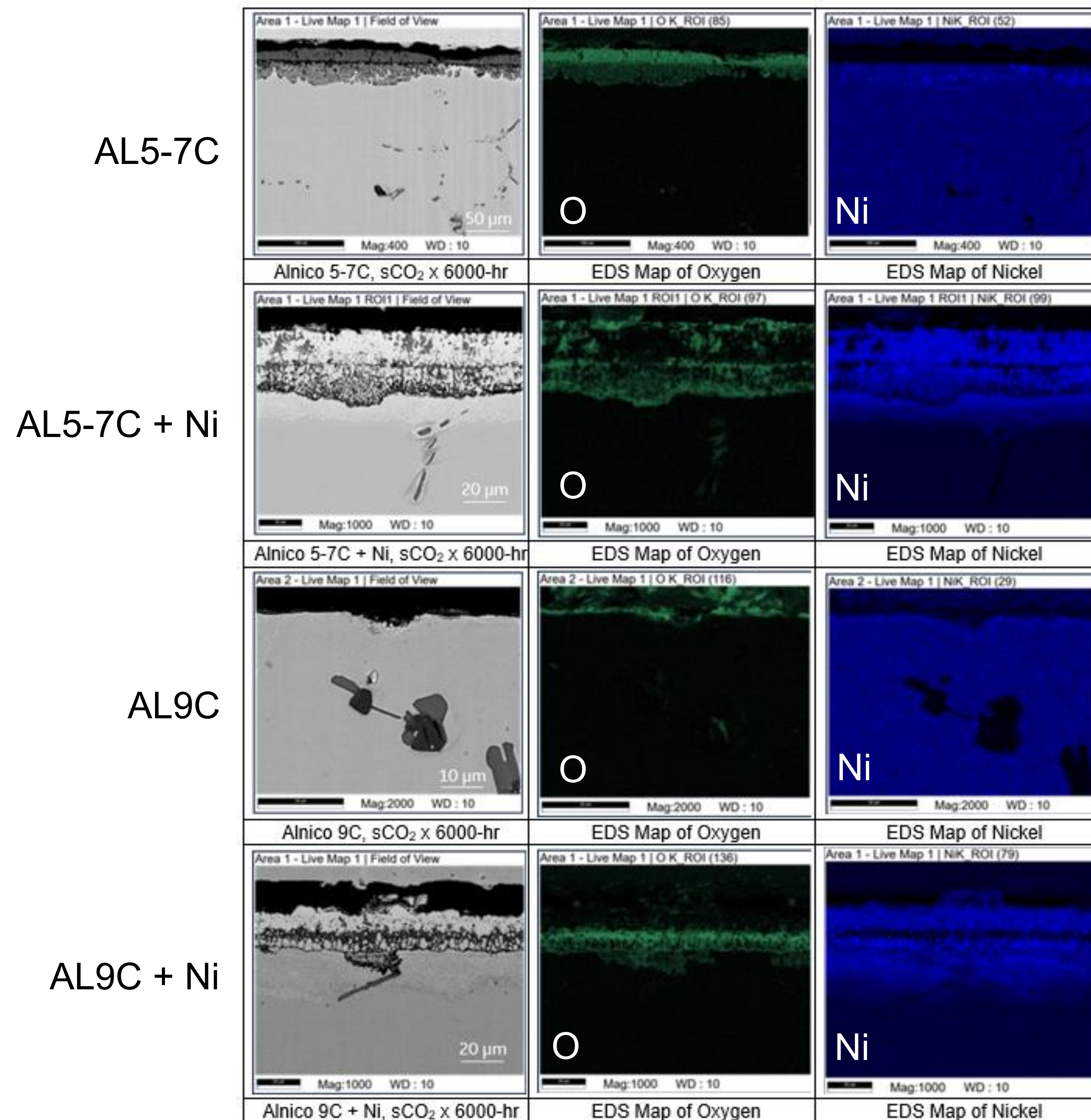
In All

- Coating: beneficial to Heperco
- Rates: SmCo > Heperco > Alnicos (bare versions)



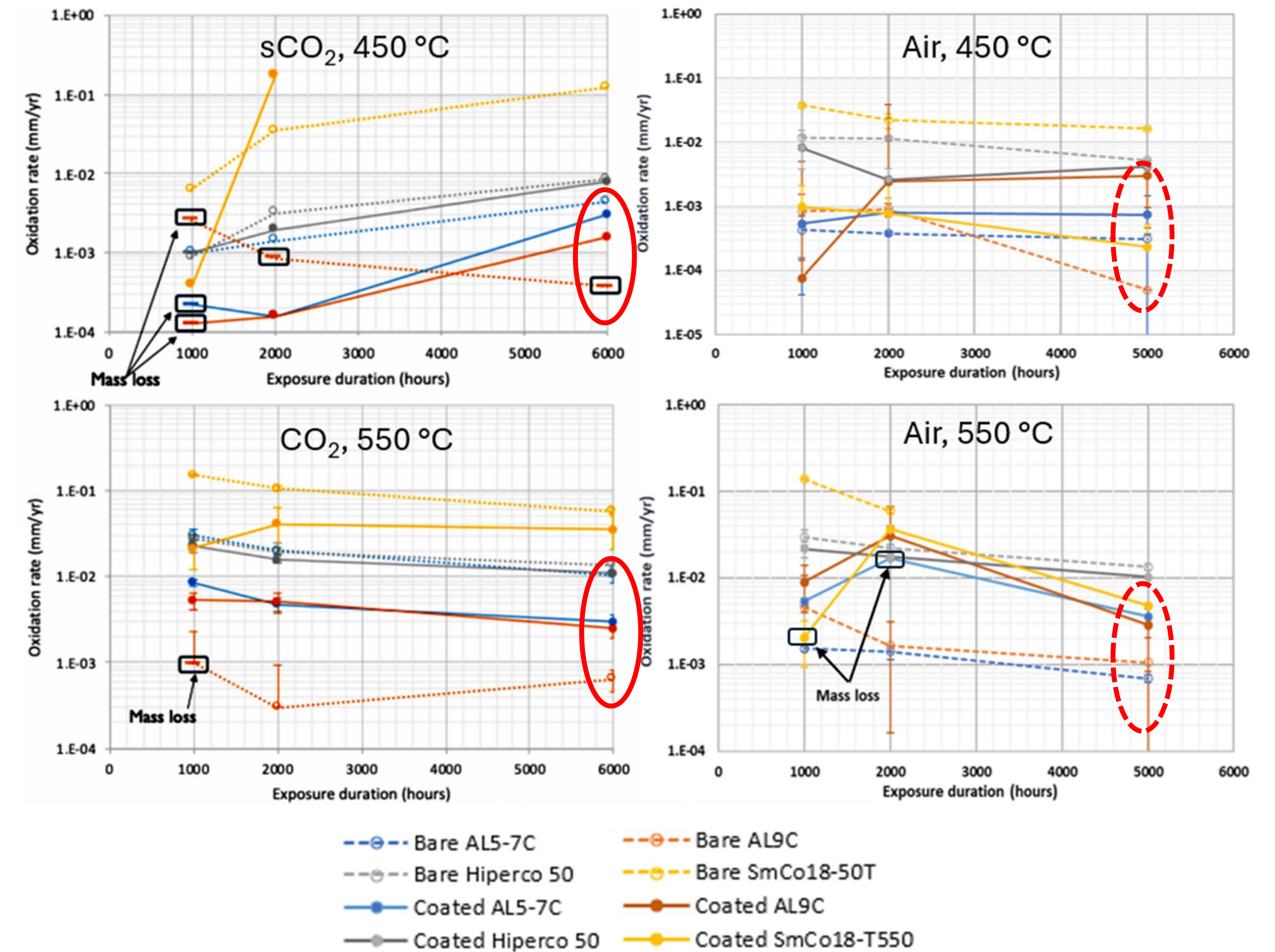
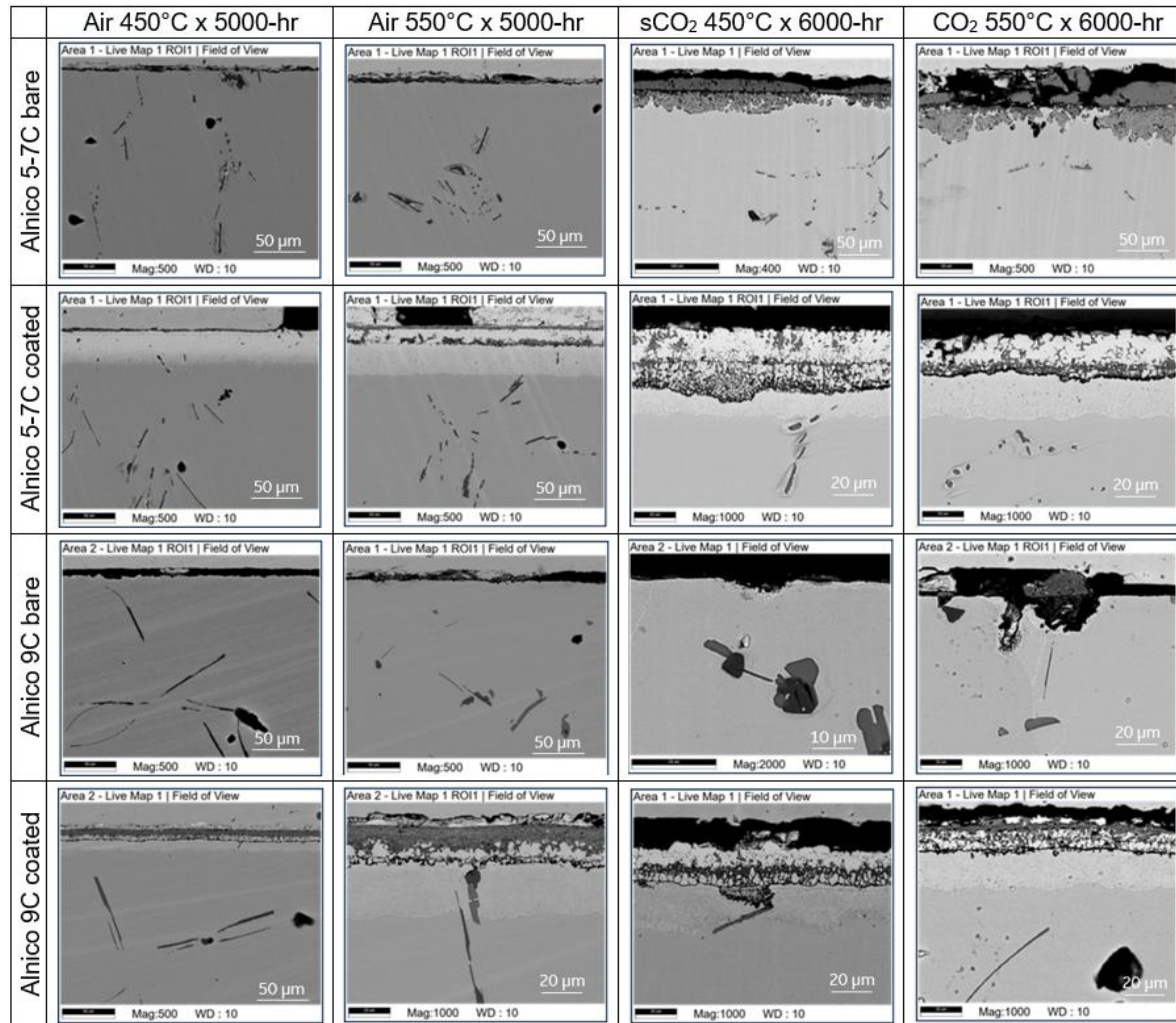
• Results – SEM Analysis of Alnicos

6000 hr. Exposure in sCO₂



- AL9C: Less oxidation than AL5-7C (bare version),
- Coating: **Harmful to AL9C.**

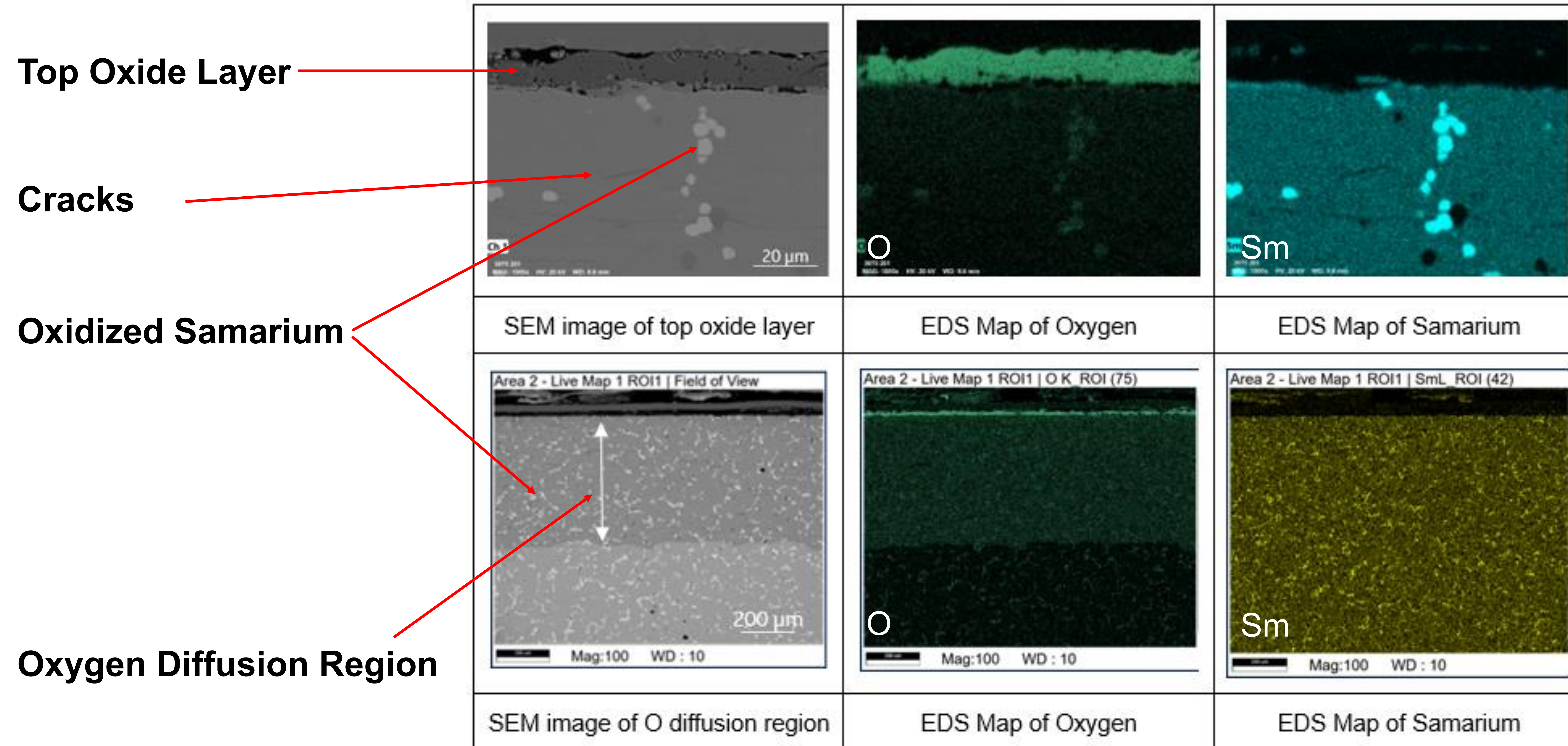
• Results – SEM Analysis of Alnicos



- Bare AL5-7C: More oxidation in sCO₂/CO₂.
- Coating: Harmful to Alnico in air and sCO₂/CO₂.
- Bare AL9C: Least oxidation in sCO₂/CO₂.

• Results – SEM Analysis of SmCo

Bare SmCo - 2000 hr. Exposure in CO₂ (550 °C)



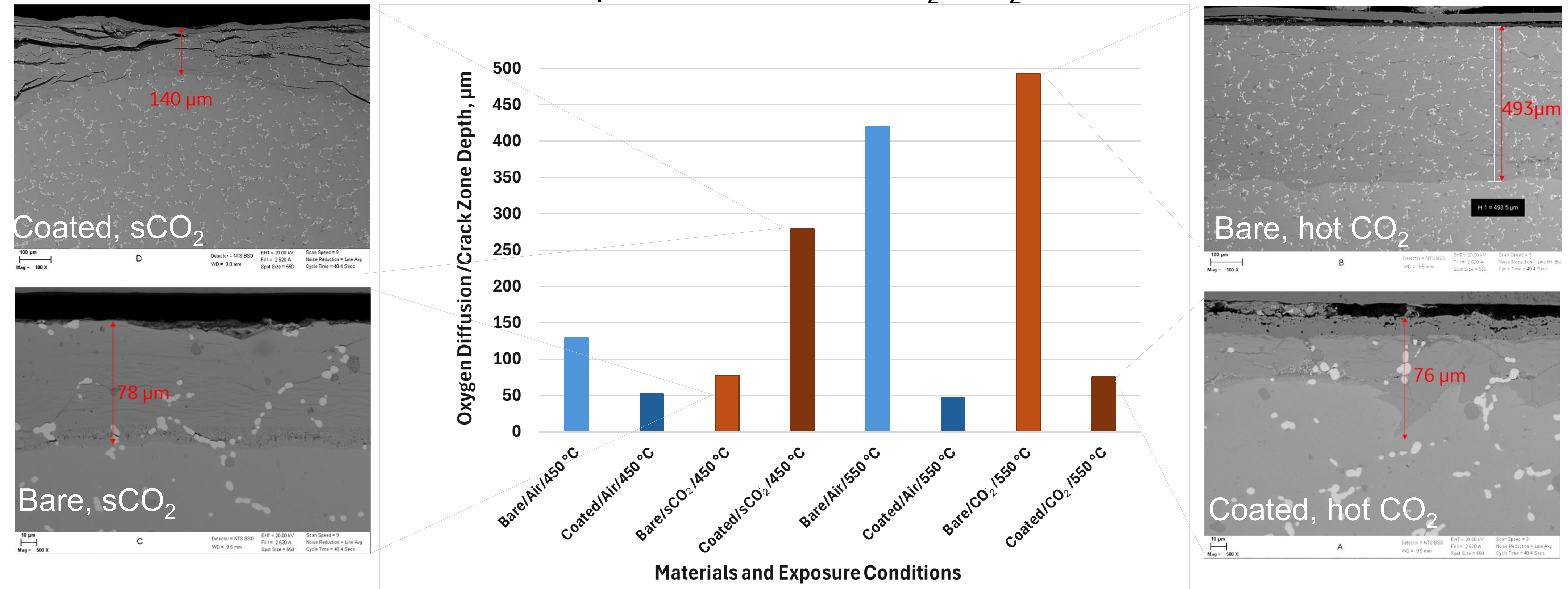
Factors in comparison:

- The depth of oxygen diffusion region
- Crack development in oxidized region

Oxidation of Sm → Coercivity Loss

• Results – SEM Analysis of SmCo

2000 hr. Exposure of SmCo in sCO₂ / CO₂ / Air



- Coating: **Induced large cracks extending into the bulk in sCO₂ exposure**
- Coating: Beneficial to SmCo except for sCO₂

• Results – Magnetic analysis

Effect of 6000-hour sCO₂ Exposure on Alnico Alloy Magnetic Properties

Material sample	Br _e /Br ₀ at RT	Hc _e /Hc ₀ at RT	Br _e /Br ₀ at 450 °C	Hc _e /Hc ₀ at 450 °C	α _e /α ₀ of Br
AL5-7C	1.00	1.07	1.10	1.00	0.62
Coated AL5-7C	1.00	1.11	1.10	1.05	0.61
AL9C	0.95	1.01	1.02	1.01	0.62
Coated AL9C	0.93	1.01	1.01	1.01	0.51

- Alnicos retained >93% of their initial Br and Hc, with some cases showing improvement;
- Exposure enhanced the thermal stability of Br in Alnico PMs;
- The coating effect was minimal.

• Results – Magnetic analysis

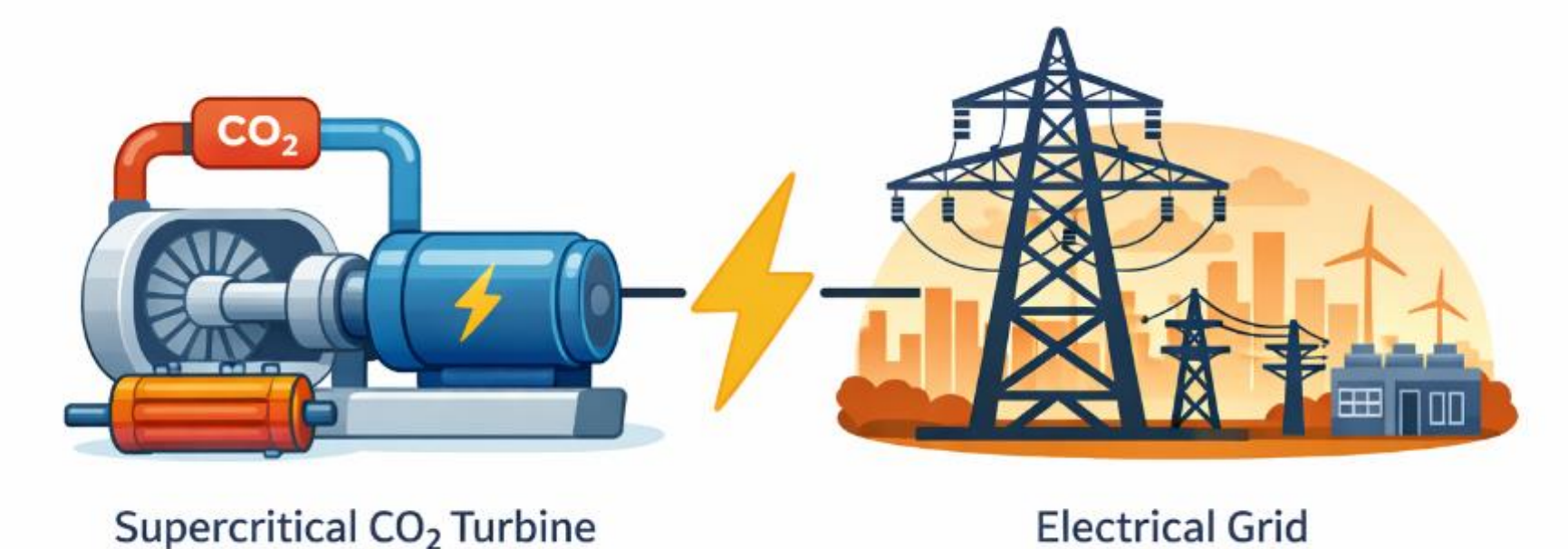
Effect of 6000-hour Hot CO₂ Exposure on Magnetic Properties

Material sample	Br _e /Br ₀ at RT	Hc _e /Hc ₀ at RT	Br _e /Br ₀ at 450 °C	Hc _e /Hc ₀ at 450 °C	α _e /α ₀ of Br
AL5-7C	0.98	0.92	1.08	0.87	0.60
Coated AL5-7C	0.98	0.84	1.09	0.80	0.59
AL9C	0.94	0.99	1.00	1.00	0.62
Coated AL9C	1.10	0.97	1.02	0.98	0.60
SmCo 18-T550	0.51	0.02	0.52	0.10	0.72
Coated SmCo 18-T550	0.82	0.02	0.80	0.27	1.46

- Alnicos: Significant reduction in Hc of AL5-7C.
- SmCo: Substantial loss of Hc and Br.
- Coating: Beneficial to SmCo on Br.

Conclusion

- Magnetic materials showed different corrosion behaviors in sCO₂, hot CO₂, and air,
- sCO₂ accelerated oxidation in most of magnetic materials,
- Ni coating degraded SmCo in sCO₂ though was beneficial in other environments
- Hot CO₂ caused major Hc and Br loss in SmCo,
- CO₂-optimized magnets and coatings are needed for reliable AMB designs.



QUESTIONS