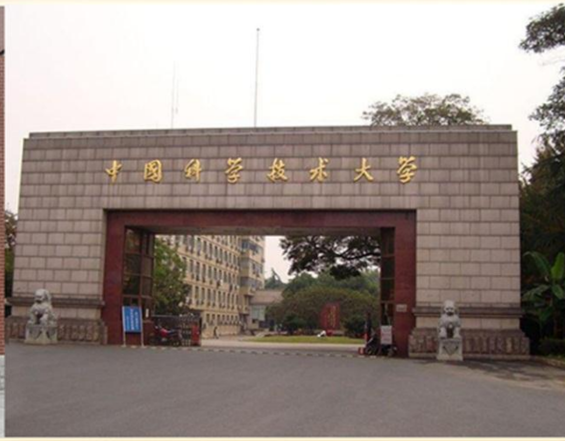
Institute of Nuclear Energy Safety Technology, CAS · FDS Team



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Corrosion Evaluation on Structural Materials for CLEAR in Oxygen Controlled Lead-Bismuth Eutectic at 500 ^{o}C

Presented By ZhiZhong Jiang

Contributed by FDS Team

Institute of Nuclear Energy Safety Technology (INEST)

Chinese Academy of Sciences

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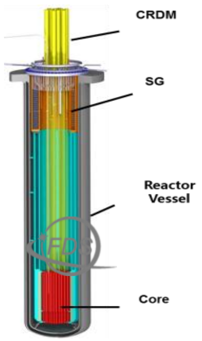
Outline

- ❖ Background
- ❖ Experimental Procedures
- ❖ Experimental Results
  - ■ Effect of Oxygen Concentrations
  - ■ Long-Term Corrosion Behaviours
  - ■ Anti-corrosion of Si-Contained Steels
- ❖ Summary

China LEAd-based Reactor (CLEAR)

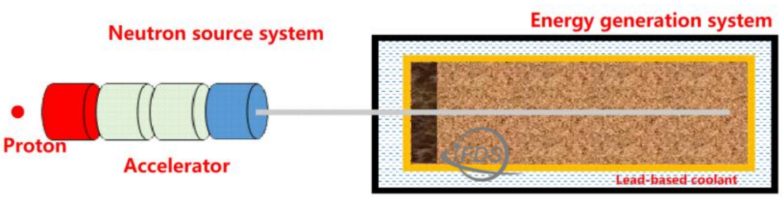
❖ CLEAR series was proposed by FDS Team

- **CLEAR-M** : China LEAd-based Mini-Reactor for independent power supply.
- **CLEAR-A** : Advanced external neutron source driven nuclear energy system for multi-purpose.
- **CLEAR-I**: China LEAd-based Research Reactor with subcritical and critical dual-mode operation capability for nuclear waste transmutation research.

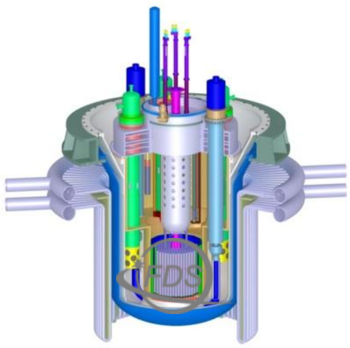


CLEAR-M10

Neutron source + Subcritical Operation+ Lead-based reactor



CLEAR-A



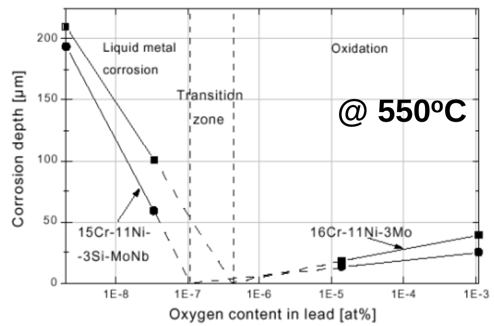
CLEAR-I

Lead-based reactor has many attractive features and may play an important role in the future energy supply

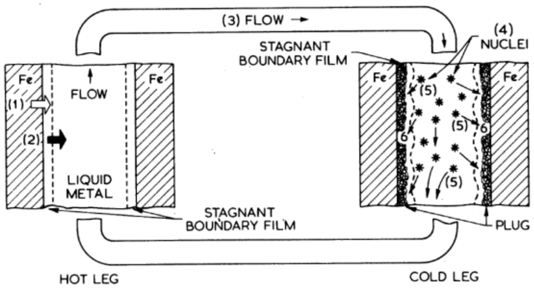
Key Issues of Material Compatibility in LBE

❖ **Liquid metal corrosion (LMC)**

- Corrosion thinning: Dissolution or oxidation
- Blocking flow paths: Corrosion products deposition



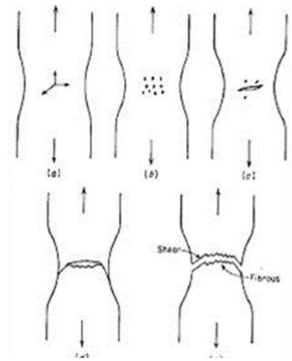
Corrosion of stainless steels



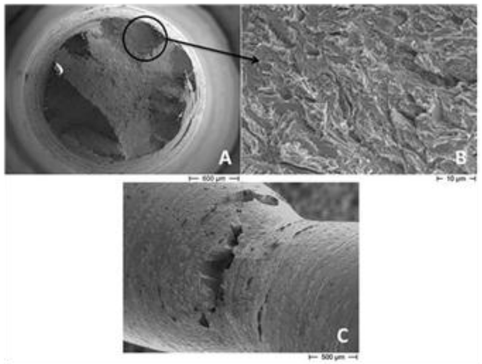
Mass transfer in Non-Isothermal system

❖ **Liquid metal embrittlement (LME)**

- Crack initiate both at the surface and interior of some materials :F/M steels are obvious
- Degradation of mechanical properties, such as tensile, creep, fatigue …



Conventional crack pattern



T91 in LBE

Material compatibility evaluation is important for supporting engineering design and safety analysis report

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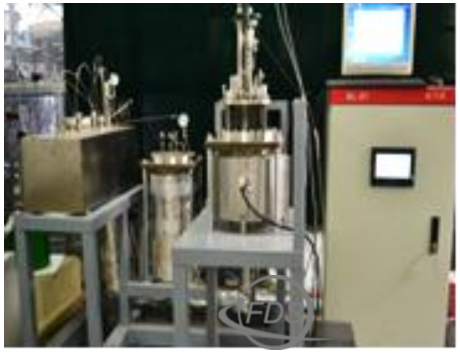
Corrosion Tests in Static LBE

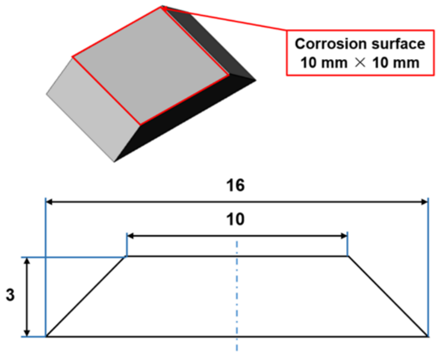
❖ Objectives

- Effect of oxygen concentrations on corrosion behaviours for F/M (T91)and austenitic steels (15-15Ti).
- Screening the new anti-corrosion materials.

❖ Test conditions



Corrosion Device
with Oxygen Control



Corrosion sample

Parameters	
Temperature（℃）	500 or 550
Flow rate（m/s）	static
Time（h）	2000
Oxygen content（wt%）	~10^{-6} /~10^{-7} /~10^{-8}

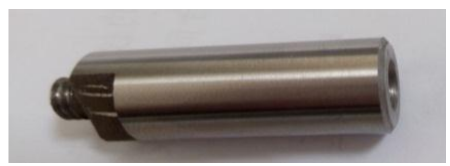
Long-term Corrosion Tests in Flowing LBE

❖ Objectives

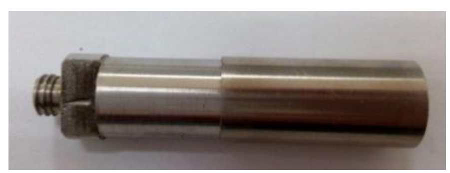
- Obtaining corrosion data of candidate structural materials for CLEAR-I.
- Assessment of corrosion properties for CLAM and other materials.

❖ Test conditions

KYLII-II-M loop



Rod



Tube

Corrosion sample

Parameters	
Temperature（℃）	500
Flow rate（m/s）	1
Time（h）	8000
Oxygen content（wt%）	~10^{-6}

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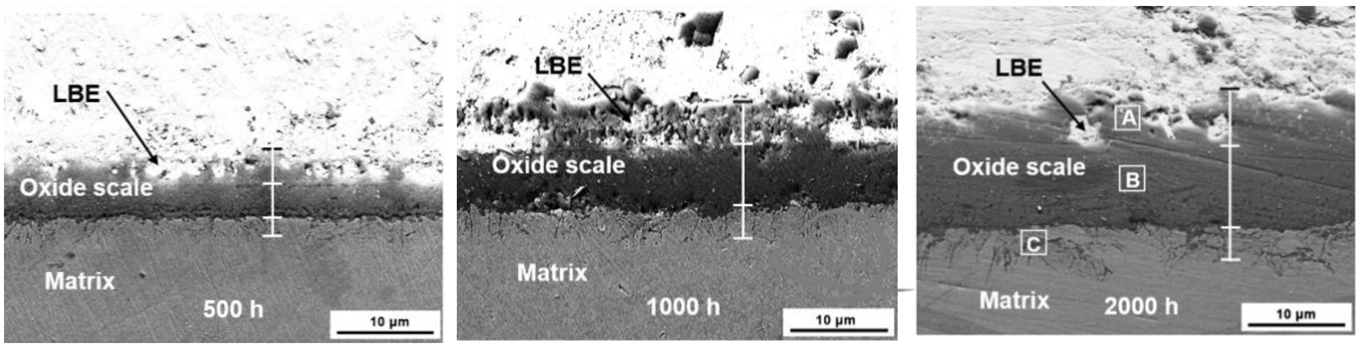
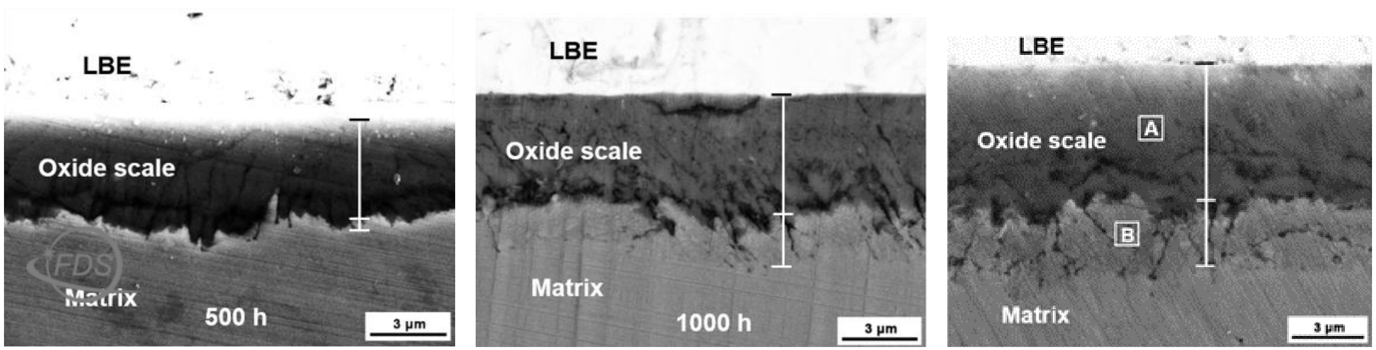
Corrosion Products of F/M Steels (T91)

10^{-6} wt%



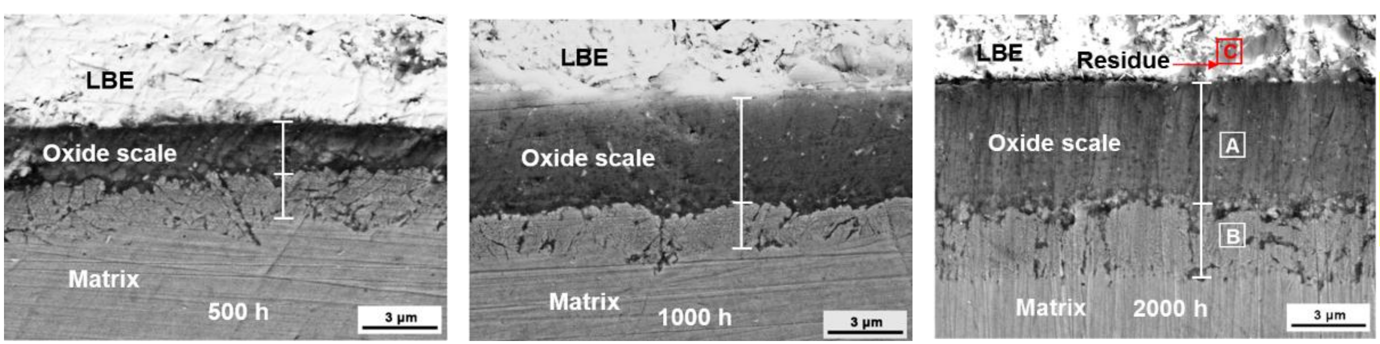
Fe_3O_4
+
$(Fe,Cr)_3O_4$
+
IOZ

10^{-7} wt%



$(Fe,Cr)_3O_4$
+
IOZ

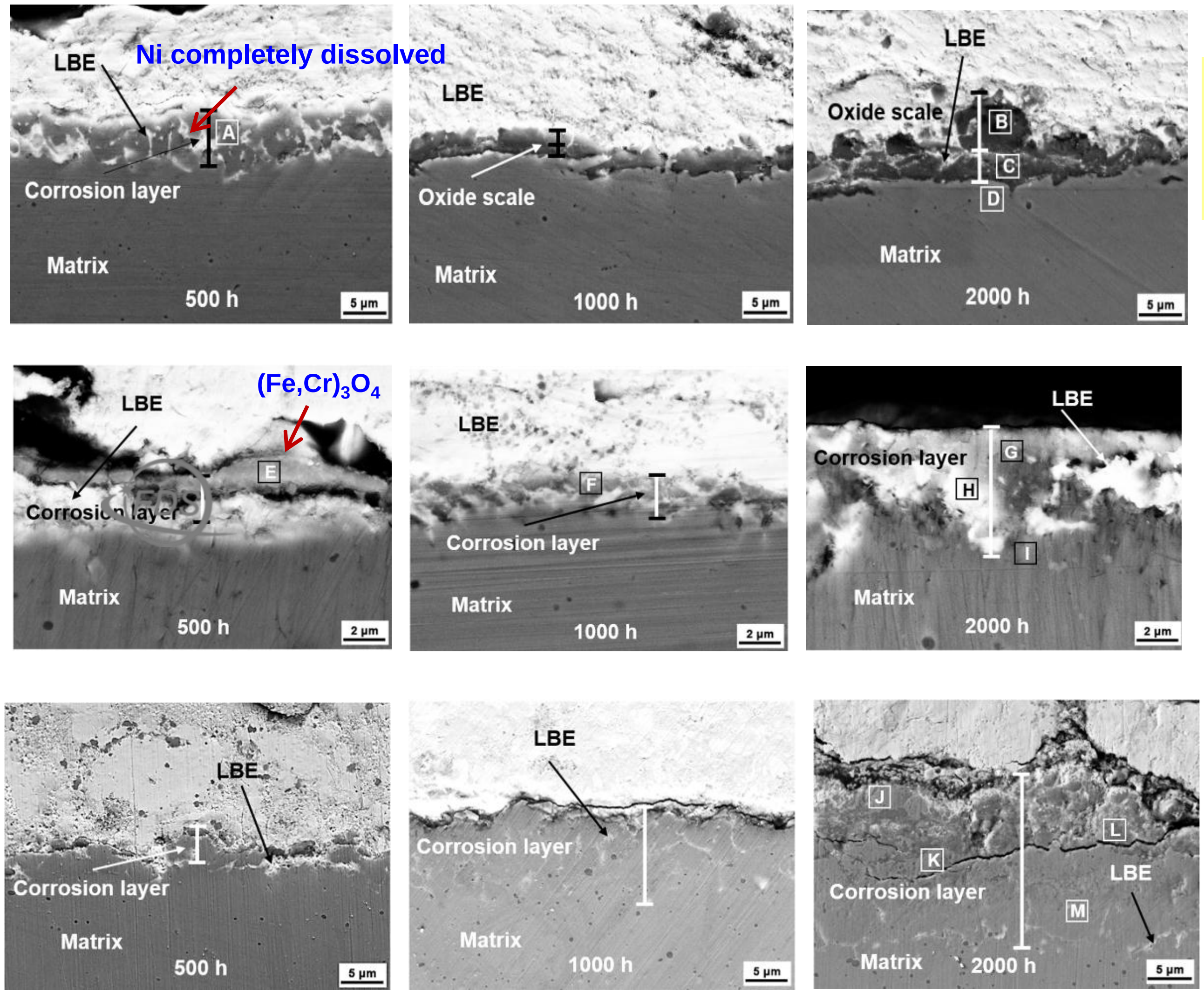
10^{-8} wt%



$(Fe,Cr)_3O_4$
+
IOZ

Shujian Tian. 2016. PhD Thesis, University of Science and Technology of China.

Corrosion Products of Austenitic Steels (15-15Ti)



Oxygen concentration	Corrosion products
10^{-6} wt%	Fe_3O_4 + $(Fe,Cr)_3O_4$
10^{-7} wt%	Little $(Fe,Cr)_3O_4$ + Little ferrite
10^{-8} wt%	Little $(Fe,Cr)_3O_4$ + Much ferrite/

Shujian Tian. 2016. PhD Thesis, University of Science and Technology of China.

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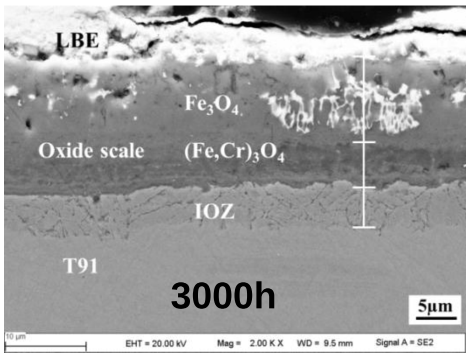
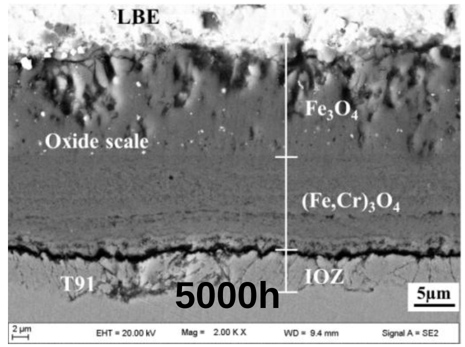
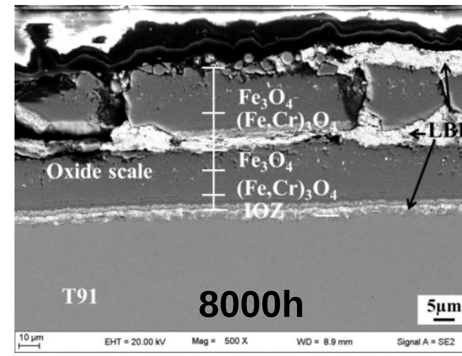
Cross-sectional Morphologies

F/M steels

❖ T91





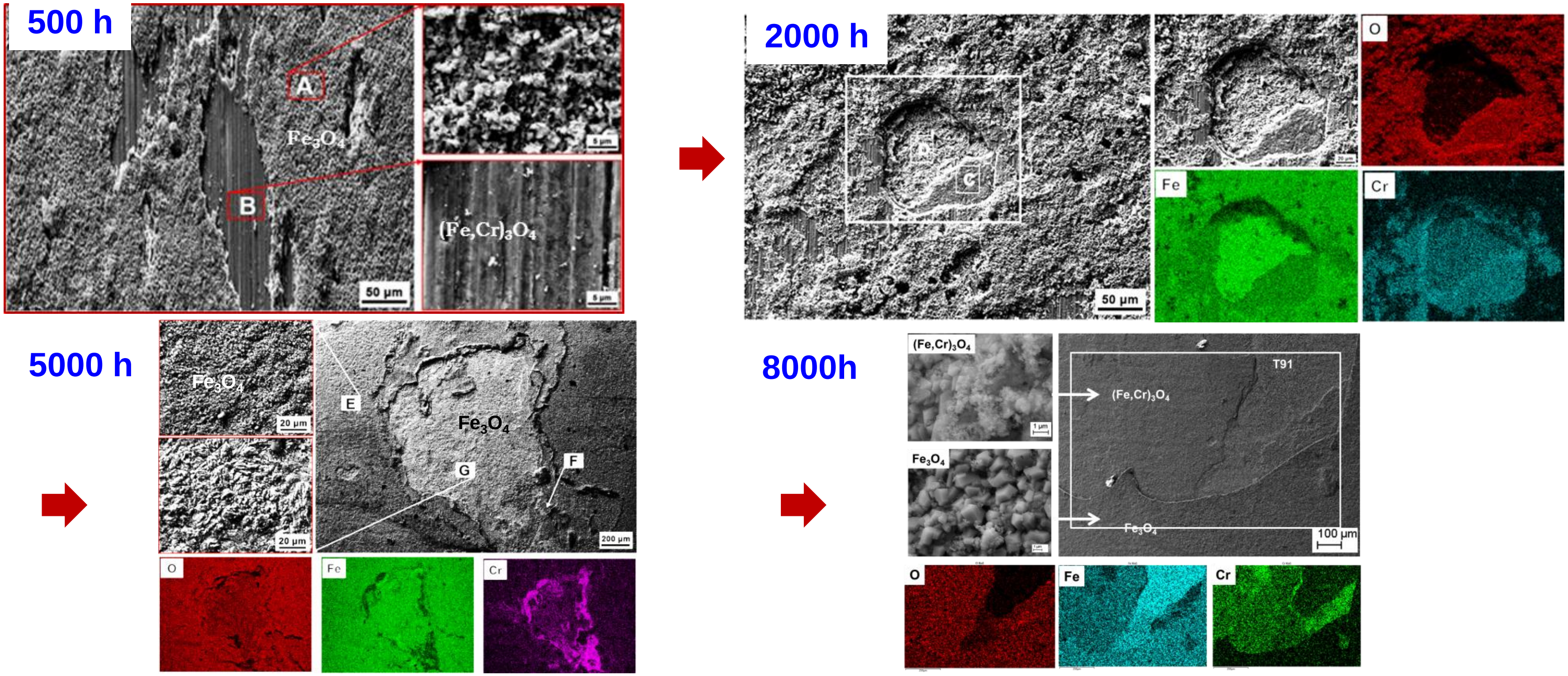


- **3000h, 5000h:**
  - Oxide Scale: **three sub-layer structure** , i.e., (Fe_3O_4/$(Fe,Cr)_3O_4$/IOZ).
  - A few LBE has penetration into Fe_3O_4 sub-layer.
- **8000h:**
  - Oxide Scale**: five sub-layer** structure , i.e., Fe_3O_4/$(Fe,Cr)_3O_4$/ Fe_3O_4/$(Fe,Cr)_3O_4$/IOZ, **may be associated with severe LBE penetration.**
  - LBE has infiltrated the T91 substrate near IOZ layer.

Tian, S. J., et al. (2016). Materials and Corrosion-Werkstoffe Und Korrosion 67(12): 1274-1285.

Exfoliation and Regeneration of Oxide Scale

F/M steel



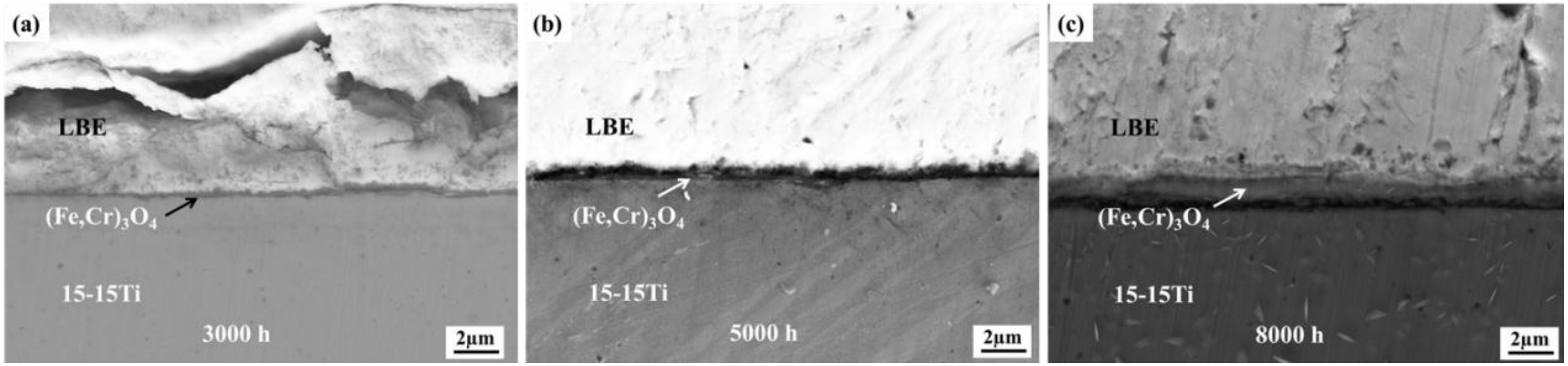
- At the initial stage of corrosion, Fe_3O_4 began to peel； Then, local exfoliation of Fe-Cr spinel and IOZ occurred.
- The exfoliation area of oxide increased with exposure time； The exfoliation area was oxidized again, and new oxide formed.

Tian, S. J., et al. (2016). Materials and Corrosion-Werkstoffe Und Korrosion 67(12): 1274-1285.

Cross-sectional Morphologies

Austenitic steels

❖ 15-15Ti

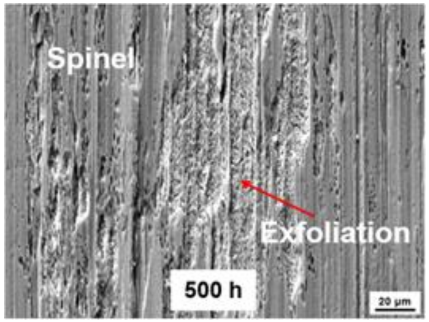


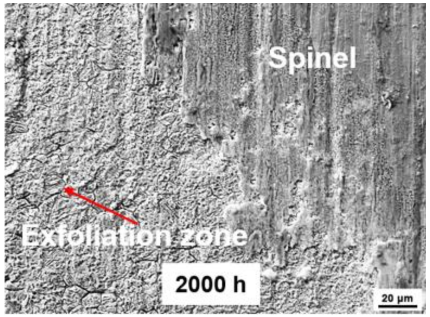
- **The morphologies are different from those of T91 steel:**
  - A thin and dense $(Fe,Cr)_3O_4$ is formed.
  - the corrosion morphologies for 3000 h, 5000 h and 8000 h are similar.
- **Single-layer oxide scale, which is different from that of static corrosion.**

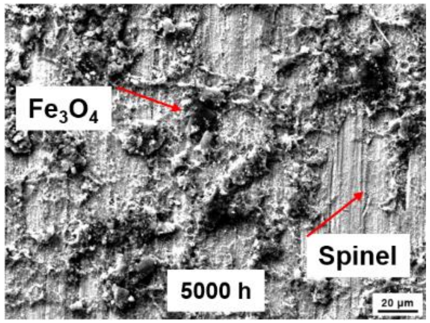
Tian, S. J., et al. (2016). Materials and Corrosion-Werkstoffe Und Korrosion 67(12): 1274-1285.

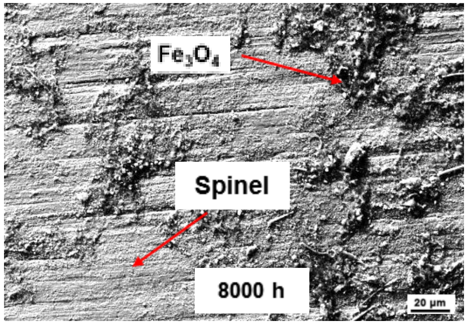
Exfoliation and Regeneration of Oxide Scale

Austenitic steel









- ❖ At the initial stage of corrosion, local exfoliation of oxide occurred as a result of LBE erosion. However, the corrosion pits could not be seen.
- ❖ The exfoliation area of oxide increase with exposure time.
- ❖ The exfoliation area was oxidized again, and new oxide Fe_3O_4 formed.

Tian, S. J., et al. (2016). Materials and Corrosion-Werkstoffe Und Korrosion 67(12): 1274-1285.

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Anti-corrosion of Si-Contained Steels

- Si-contained Austenitic Steel: CLED
- Si-contained ODS-CLAM Steel

China LEad-based reactor fuel claDding: CLED

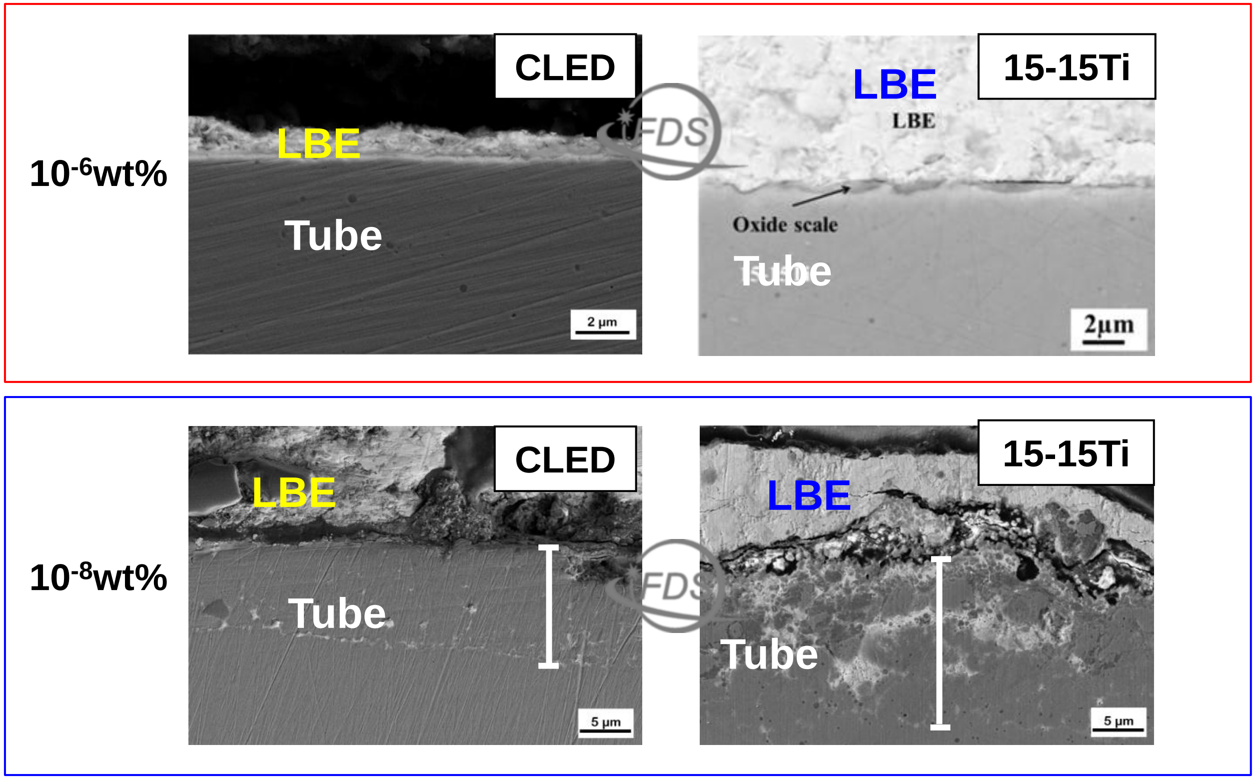
- High mechanical properties by increasing the Ti/C ratio.
- Good compatibility with LBE by increasing Si content.

Forging Bar

Cladding tube

Compatibility with LBE

- CLED (Si: 0.75wt%) compared with commercial 15-15Ti (Si: 0.40 wt%)



CLED shows better corrosion resistance than that of 15-15Ti steel.

Anti-corrosion of Si-Contained Steels

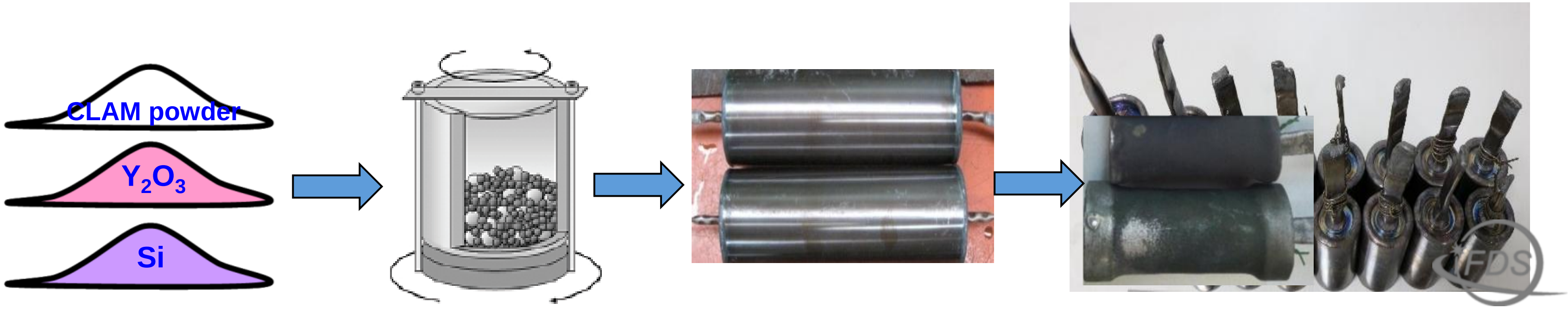
- Si-contained Austenitic Steel: CLED
- Si-contained ODS-CLAM Steel

Si-contained ODS-CLAM Steel

❖ Composition：9Cr-1.5W-0.2V-0.15Ta-0.3Y_2O_3-xSi

- Add Si into the CLAM matrix to improve corrosion resistance to LBE
- Add nano-sized oxide particles to Improve mechanical properties

❖ Preparation Process



Powders → **Mechanical alloying** (Ar/15:1/36h/350r/min) → **Vacuum packaging** (550℃/<10^{-3}Pa) → **Hot isostatic pressing** (1150℃/150MPa/3h)

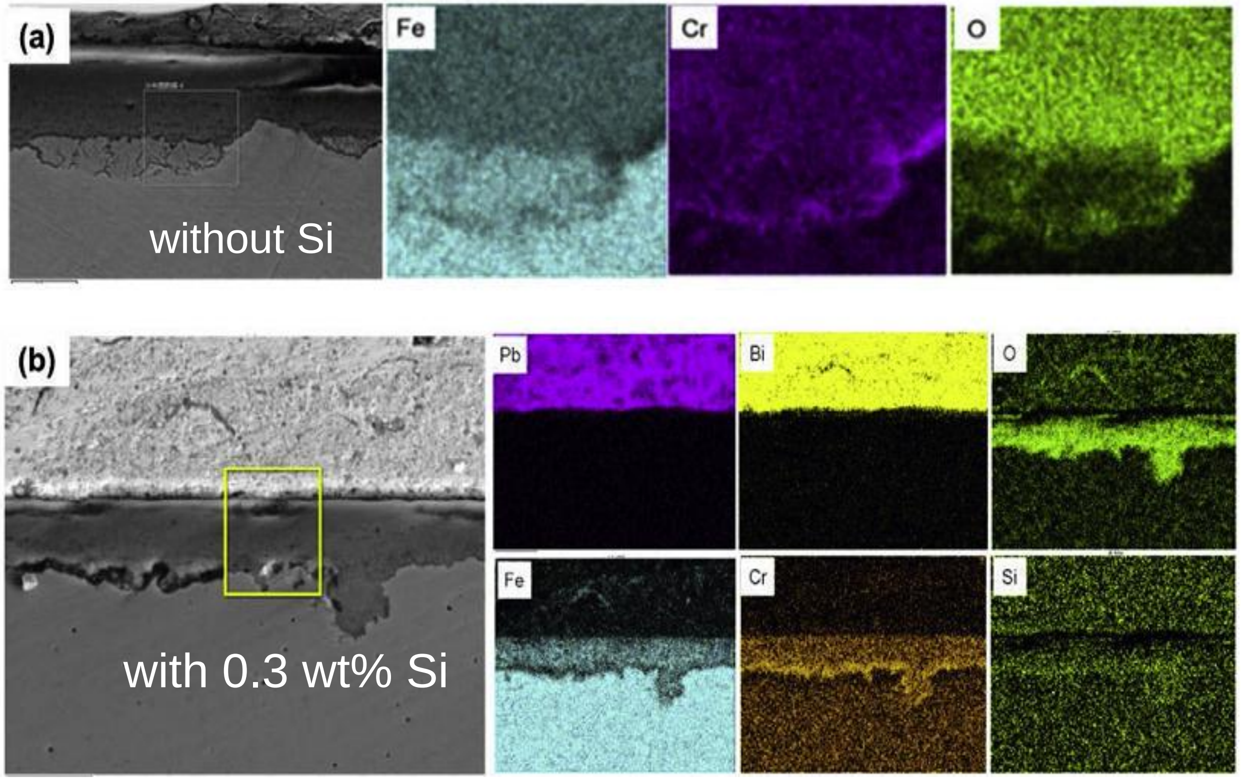
Elemental Distributions of Corrosion Interface

❖ ODS-CLAM without Si:

- A **less continuous** Cr-enriched oxide ribbon formed between interface of **IOZ**-matrix.

❖ ODS-CLAM with 0.3wt% Si:

- A **continuous** Cr-enriched oxide ribbon formed at the interface of **$(Fe,Cr)_3O_4$ layer**-matrix.



The addition of Si had great influence on the continuity of Cr-enriched oxide ribbon.

Liangliang Song. 2018. PhD Thesis, University of Science and Technology of China.

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Summary

- **A series of compatibility evaluations on structural materials for CLEAR has been carried out in oxygen controlled LBE.**
  - **The oxygen content in LBE is a key factor in determining the corrosion behaviors of ferritic/martensitic steel and austenitic steel, and also the dominant factor affecting the types and properties of corrosion interface products.**
  - **The growth kinetics curves of oxide layers for T91, 15-15Ti, CLAM and 316L steels follow a parabolic rule ($\Delta x^2 = K_p t$), and the rate constant for 15-15Ti steel is lowest.**
  - **Corrosion resistances of Si-containning stainless steel and ODS-CLAM steel has been developed. Compatibility evaluation revealed that the corrosion resistances of the above steels have attained considerable improvement.**

Thanks for Your Attention!

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