The performance evaluation of tritium breeding materials under service conditions

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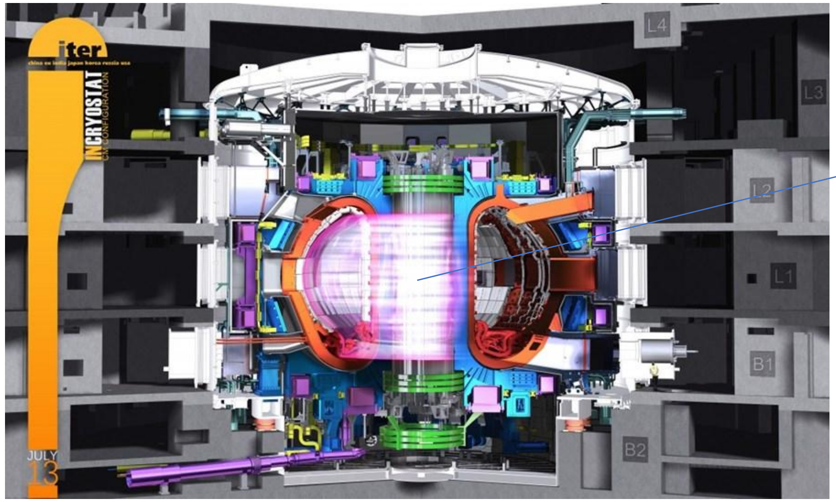
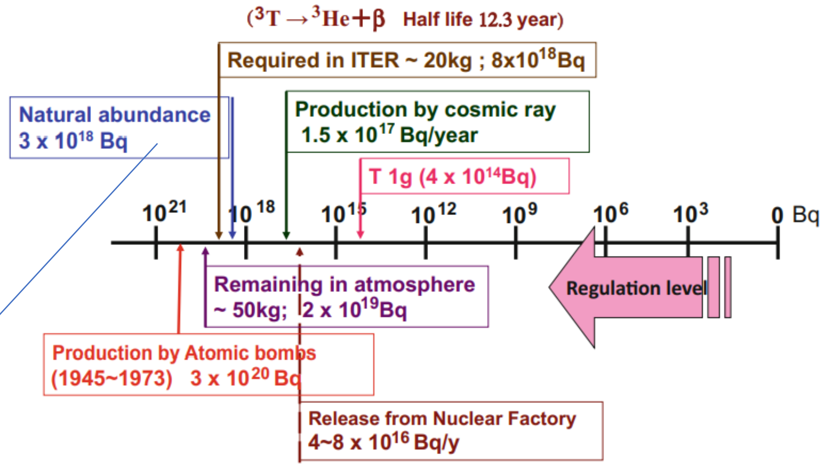
Background



Power output :1 GW;

Burn rate: 3%;

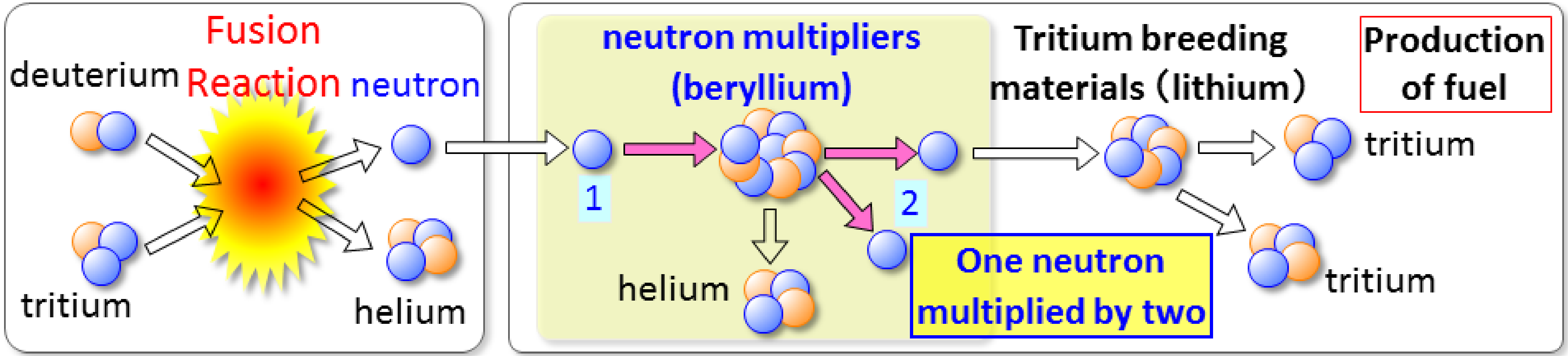
Burned tritium:~56 kg /year.



Natural abundance of tritium is nearly zero.

Fusion needs tritium

Tritium self-sufficiency is necessary



Background

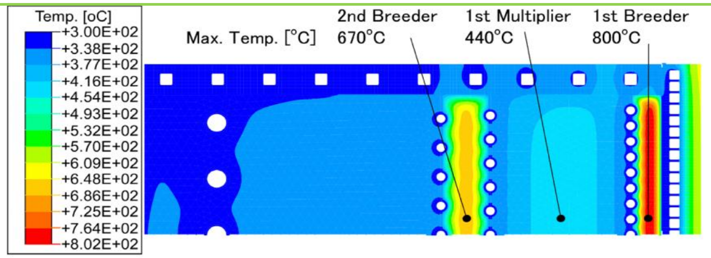
CLASS	Liquid breeding blanket	Solid breeding blanket
Breeder	Liquid metal (Li， Pb-16Li) or molten salt (FLiBe, FLiNaK)	Lithiated ceramic (Li_4SiO_4, Li_2TiO_3)
AD	High lithium density, High thermal conductivity, No irradiation damage Problems, Simple designs	Good material compatibility, Non-magnetohydrodynamics
DIS	Corrosion of structural materials, Magnetohydrodynamics	Need neutron multiplier, Limited thermal conductivity, Complex designs
Concepts	Helium cooled lithium lead (HCLL) Water cooled lithium lead (WCLL) Dual coolant lithium lead (DCLL)	Helium cooled ceramic breeder (HCCB) Water cooled ceramic breeder (WCCB)

Background

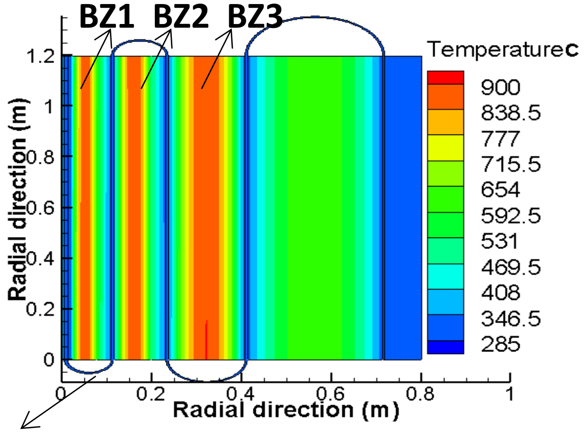
Service environment of solid tritium breeding blanket

$^{2}D+^{3}H\rightarrow^{4}He+n+17.58MeV$; $^{6}Li+n=^{3}H+^{4}He+4.8MeV$, $^{7}Li+n=^{3}H+^{4}He+n'-2.9MeV$.

High temperature

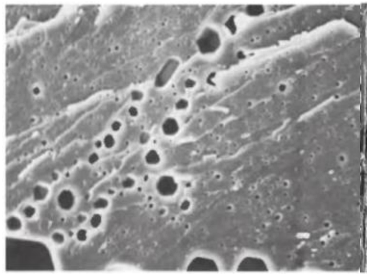


TBM simulation: the highest temperature over 800℃.

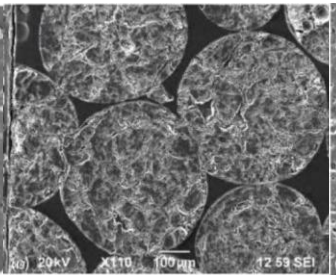


WCCB simulation: the highest temperature nearly 900℃.

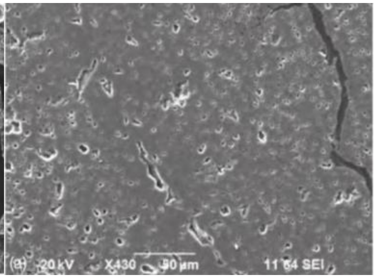
Irradiation



Neutron irradiated Li_2O



Neutron irradiated Li_4SiO_4



Neutron irradiated Li_2TiO_3

Blanket Conditions:

High temperature; High energy particles irradiation (Neutron, Tritium, Helium, self-ion); γ-ray; Gas sweeping, Squeezing……

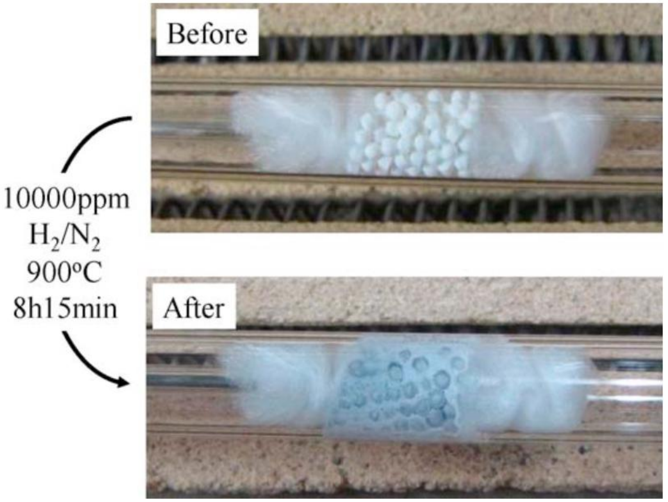
Problems:

Tritium release behavior? Mechanical performance at high temperature? Irradiation damage? Corrosiveness? Long-term operation……

Nuclear Fusion, 57(2017)092014; JNM, 329(2004)1313-1317.

Background

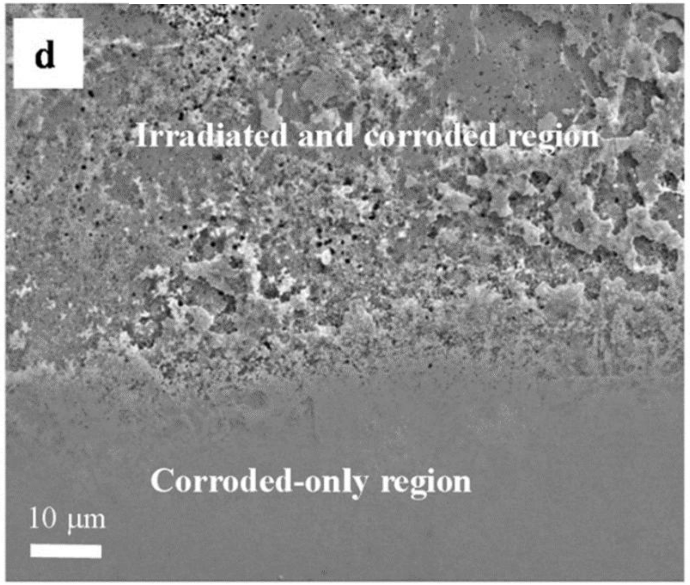
High-temperature



Li_2TiO_3 evaporation
K. Katayama (2012)

Shouxi Gu (2023)

Irradiation



J. Li, et al. (2020)

Key factors of corrosion:
- ◆ High-temperature
- ◆ Li-oxide evaporation
- ◆ Irradiation

Effects：
- ➢ Tritium permeation of structure material
- ➢ Thermal and mechanical performance
- ➢ Blocking the channel of sweep gas

Purpose of this work is to investigate the effects of tritium release and irradiation on corrosion of RAFM steel

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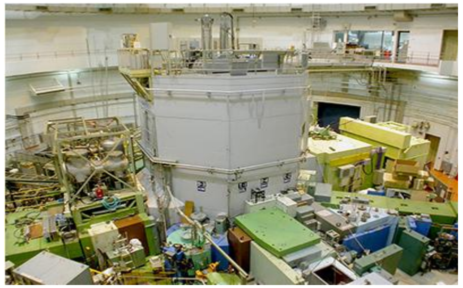
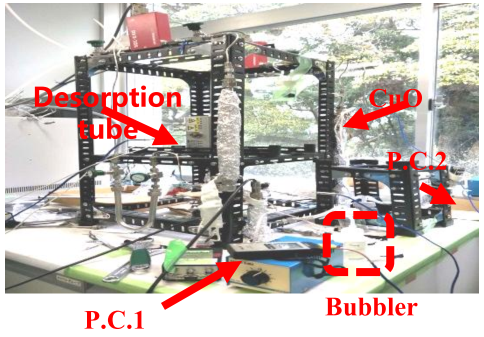
Experimental (Tritium Release)

KURRI, Japan



Shizuoka University, Japan



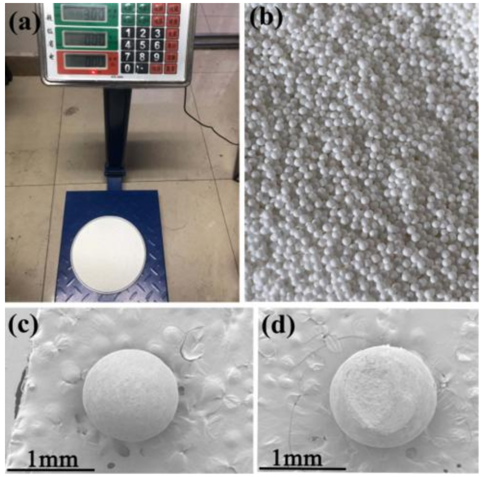
Neutron irradiation

↓

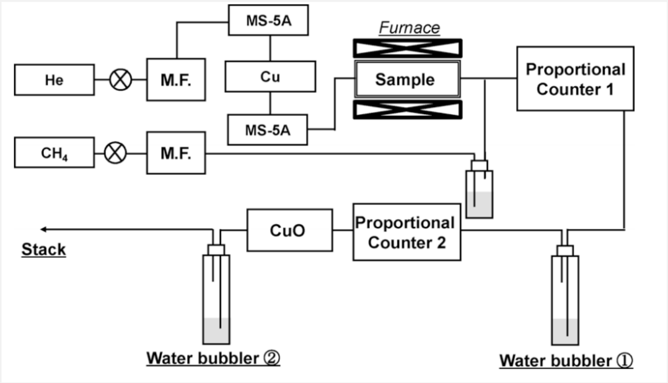
Tritium release (proportional counter)

↓

liquid scintillation (LSC) measurement

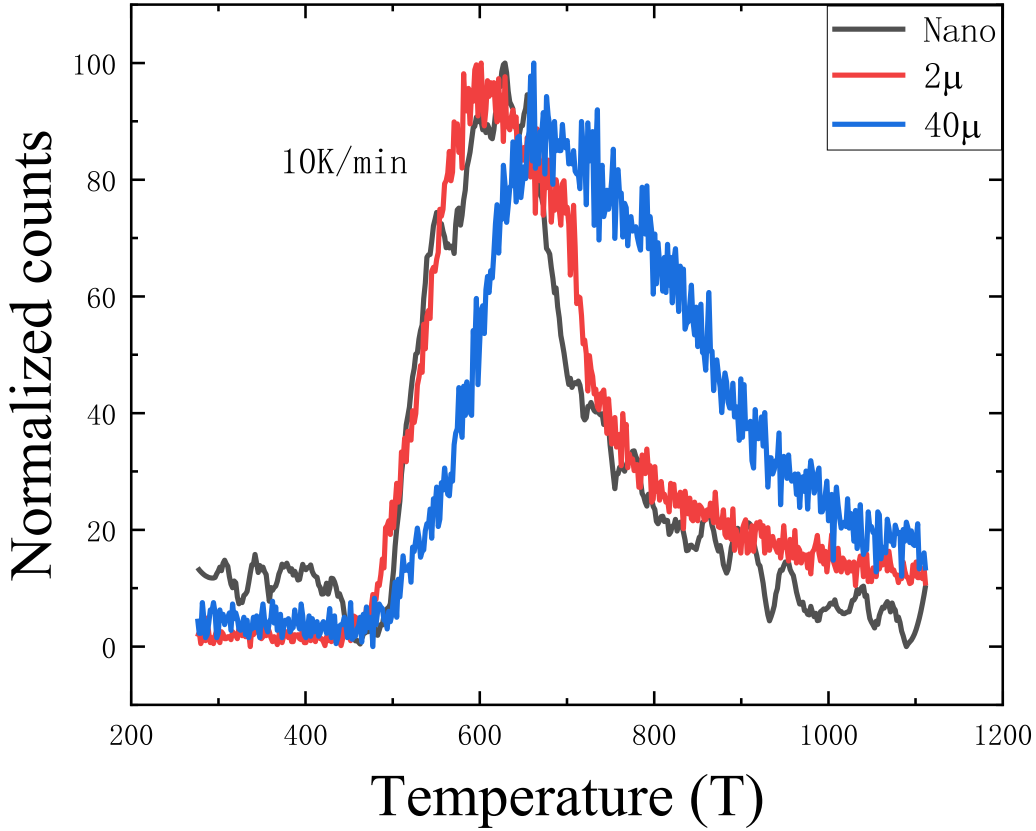


Power (MW)	Flux (n/cm² · s)	Fluence (n/cm²)	Temperature (K)
5	2.75×10^{13}	8.25×10^{15}	<370



Tritium release-Effect of grain size

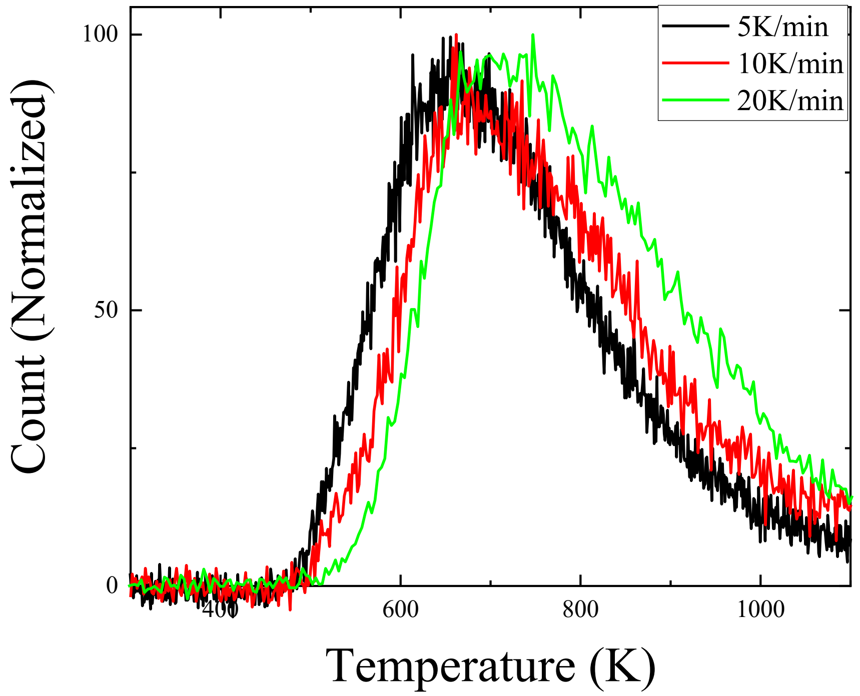
- The grain size significantly affects the tritium release behavior, and small grains are conducive to tritium release at lower temperature
- When the grain size is less than 2 micrometers, the effect on tritium release temperature is relatively small
- Considering the large-scale engineering applications and manufacturing difficulties, a grain size of a few micrometers is the optimal choice.

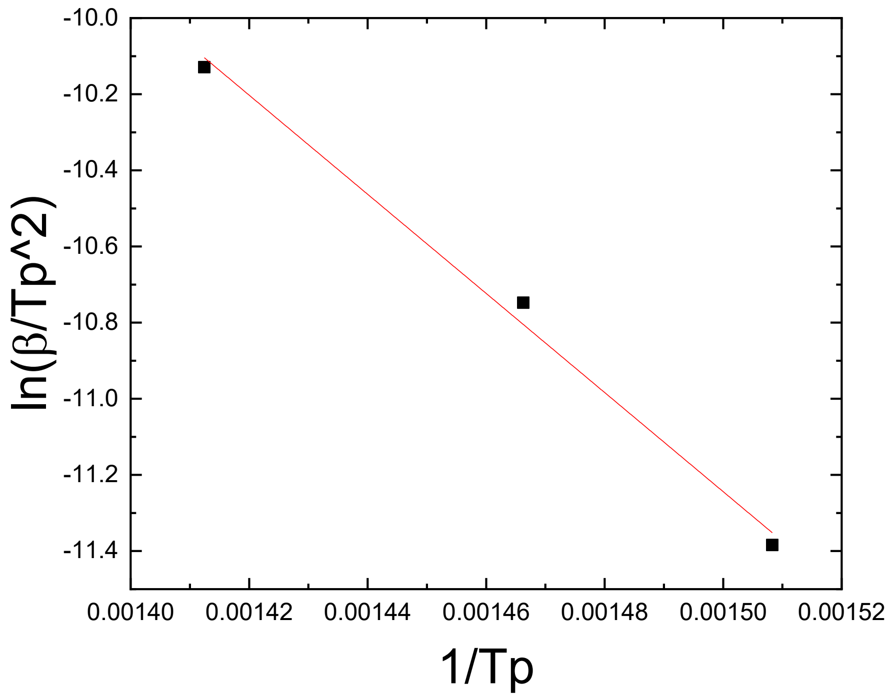


Tritium release-Effect of grain size

- One main tritium release peak indicating one main tritium trapping site.
- The activation energy for tritium release was obtained as 1.12 eV.
- Tritium amount was measured by liquid scintillation

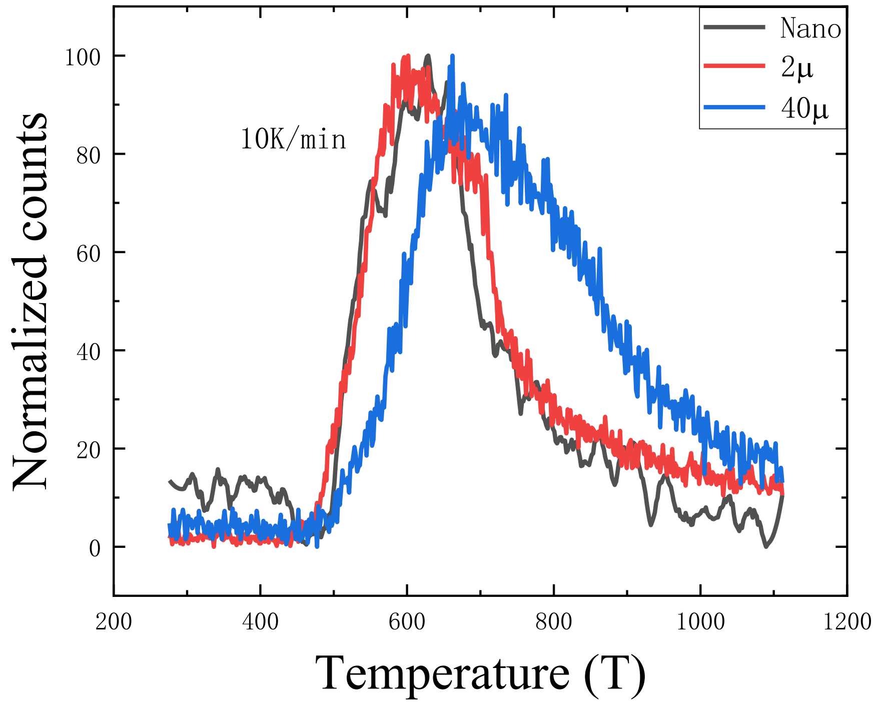
$$\frac{d\alpha}{dt} = kf(\alpha) = A\exp\left(\frac{-E_a}{RT}\right)f(\alpha) \Rightarrow \ln\left(\frac{\beta}{T_P^2}\right) = \ln\left(\frac{RA}{E_a g(\alpha)}\right) - \frac{E_a}{RT_P}$$





Tritium release-Effect of grain size

- The grain size affects the amount of tritium retained at low temperatures
- Due to the different amount of grain boundary, the effective diffusion barrier rises and the tritium release temperature goes up as grain size increase
- The amount of tritium released per unit mass is almost the same, though there are some differences, which originate from the variations in lithium density during the preparation process.

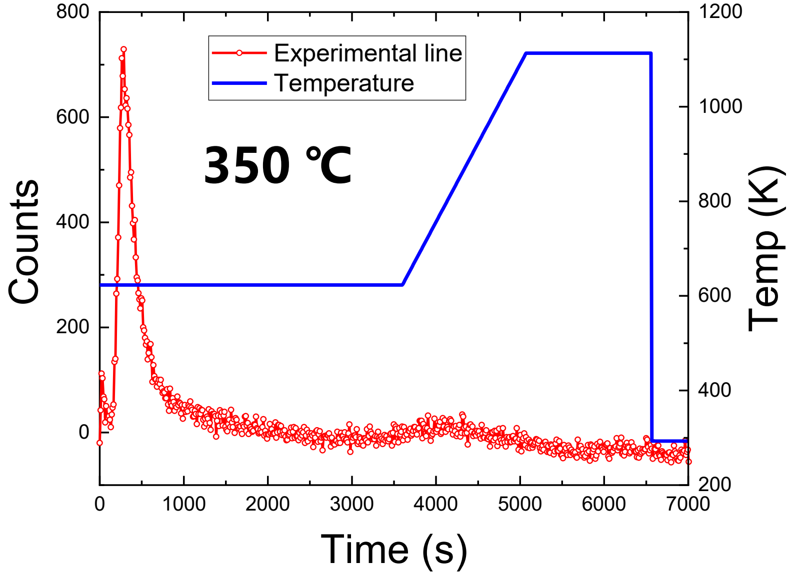


	Nano	2um	40um
Tritium Amount	2.7×10^6 Bq/g	5.2×10^6 Bq/g	4.3×10^6 Bq/g
Activation Energy	0.52eV	0.76eV	1.12eV

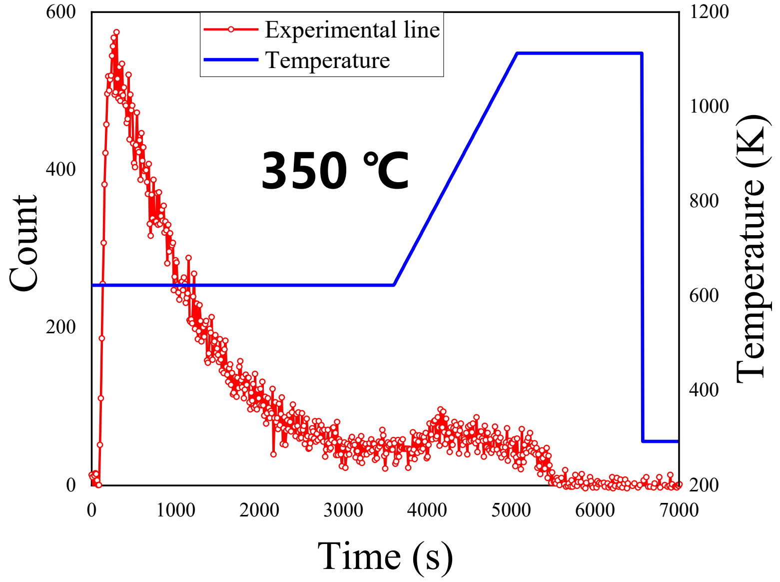
Tritium release-Effect of grain size

- Tritium retention enhances at a constant heating temperature as the grain size increases. It is indicated that grain size has a significant effect on tritium release

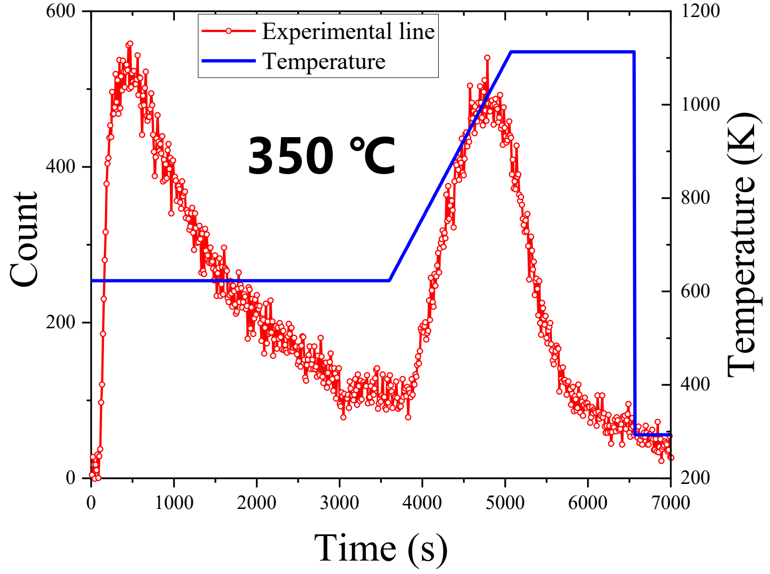
Nano



2μm

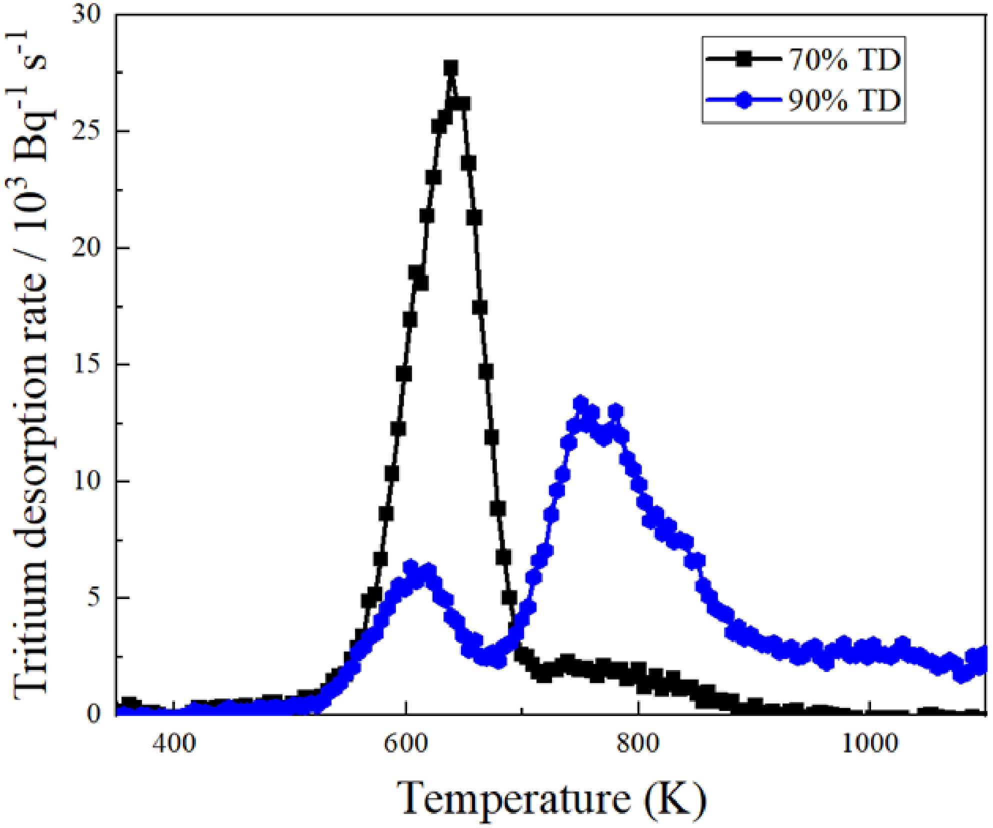


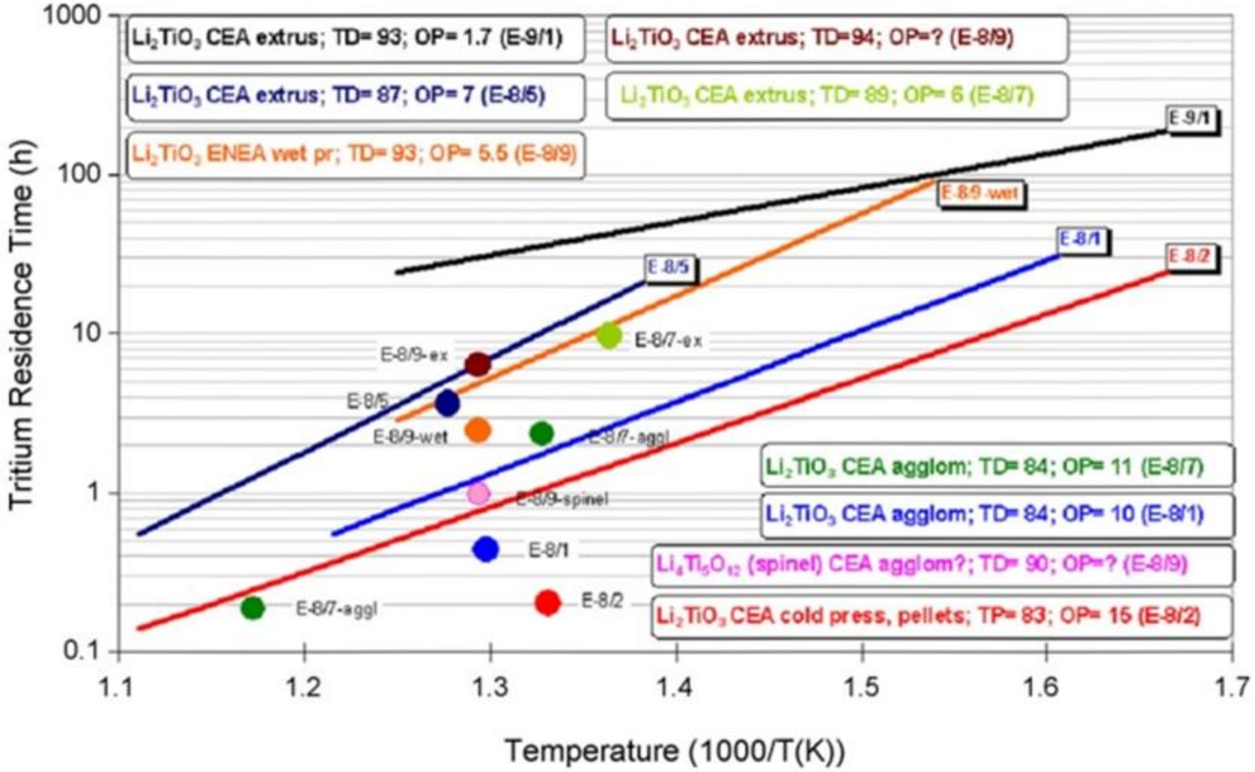
40μm



Tritium release-Effect of porosity

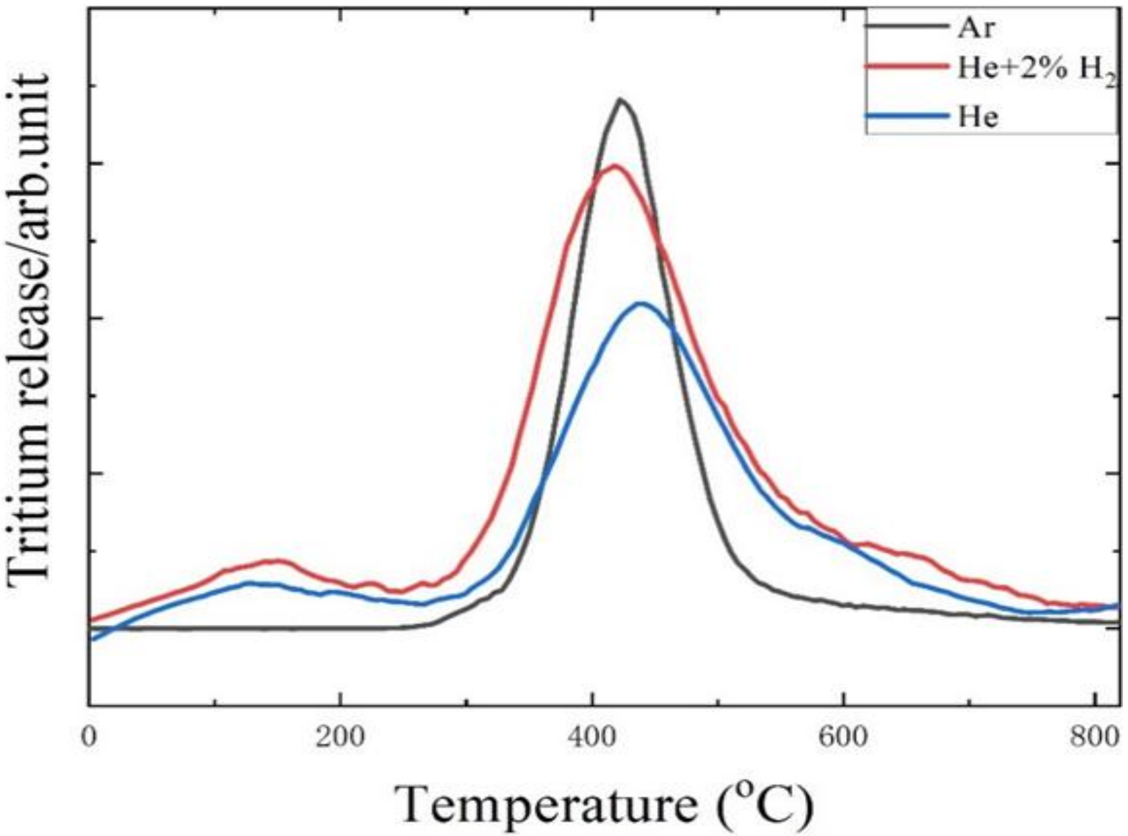
- The tritium release peak temperature of 70% TD porous Li_2TiO_3 is shifted to a lower temperature and there is no high-temperature peak. This indicates that the presence of pores promotes tritium release at low temperatures
- The result is consistent with the results observed in EXOTIC experiments
- However, lower porosity means lower lithium density, it should be considered comprehensively





Tritium release-Effect of sweep gas

- Due to the hydrogen isotope exchange effect, the addition of hydrogen to the sweep gas helium is conducive to the low-temperature release of tritium
- For the sweep gases argon and helium, the effect on the release peak temperature is relatively small

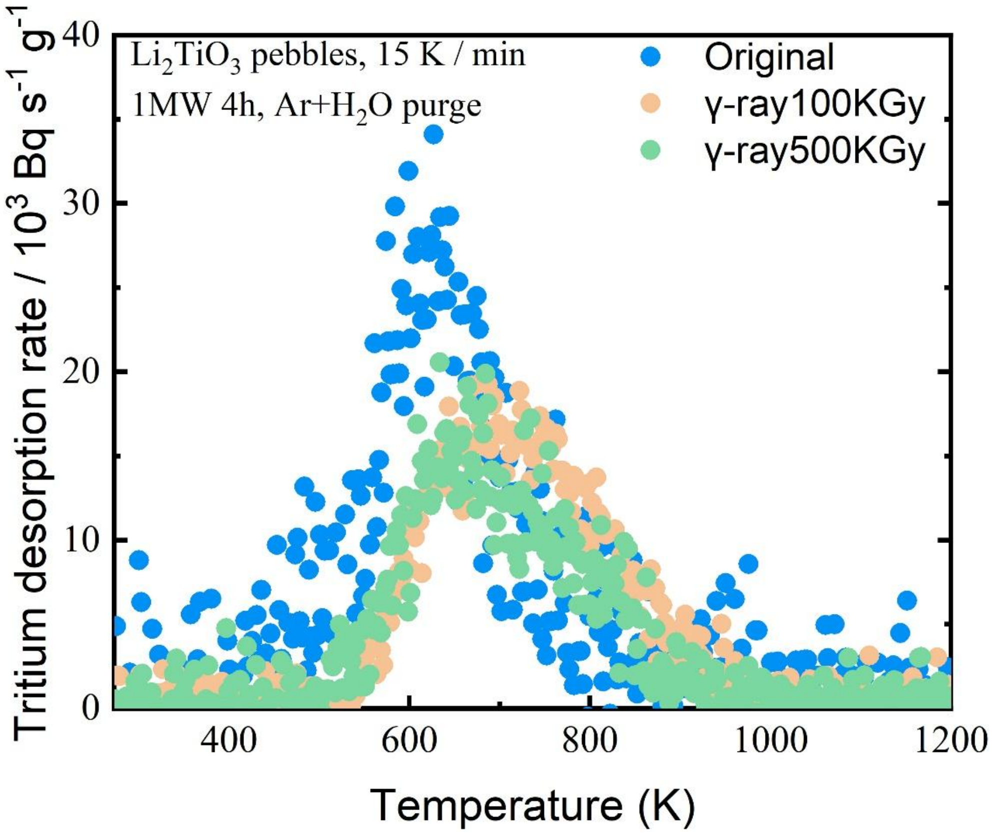


Tritium release-Effect of irradiation defects

- Due to the capture of tritium by irradiation-induced defects, the tritium release temperature shifts towards higher temperatures with increasing irradiation dose
- However, the change for the release peak is not significant due to the low amount of defects by gamma ray irradiation

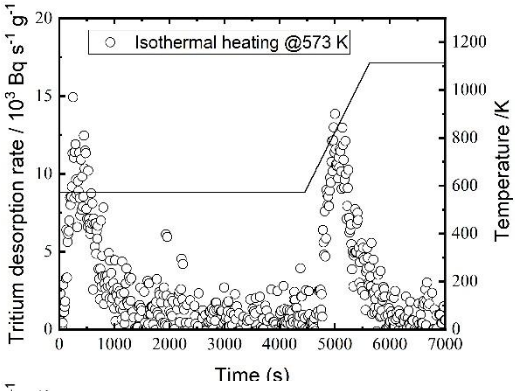
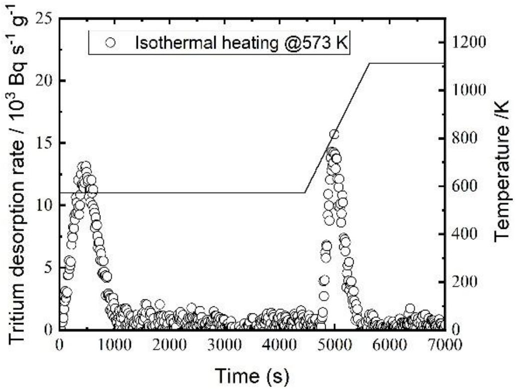
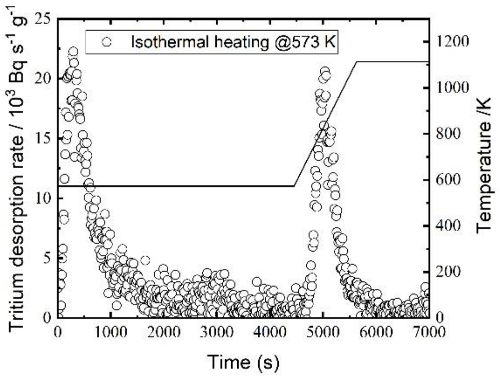
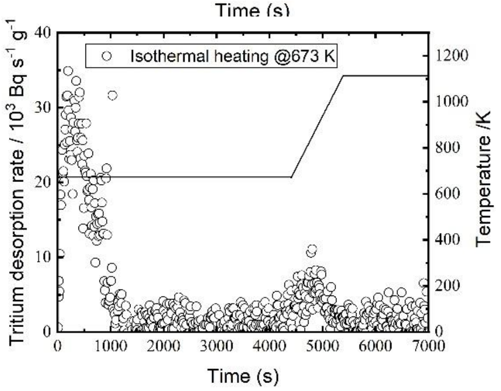
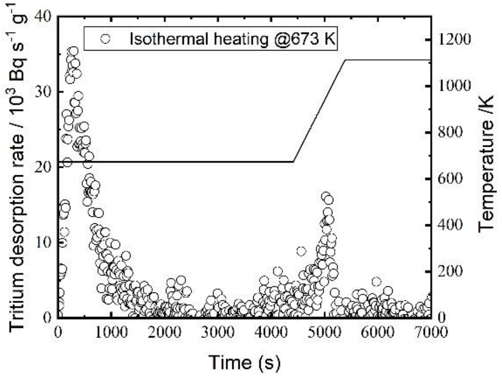
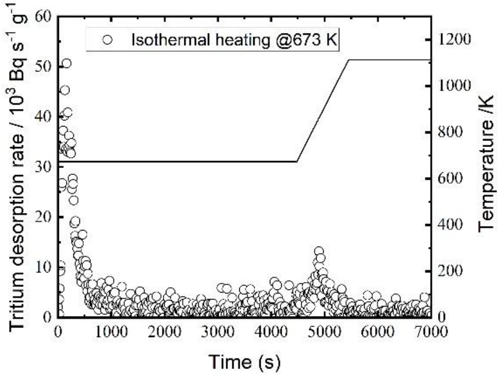
Deffects introduced by Irradiation	
Sample	Li_2TiO_3 Pebbles
Energy	^{60}Co gamma ray
Dose	Original，100kGy，500kGy

Neutron Irradiation			
Power (MW)	Flux (n/cm^2s)	Fluence (n/cm^2)	Temperature (K)
1	5.5×10^{12}	7.92×10^{15}	<373



Tritium release-Effect of irradiation defects

- Tritium retention decreases as the temperature increases
- There is little difference for tritium retention of different irradiated samples due to the low irradiation deffects
- The work for the effects of more irradiation defects on tritium release is under way

	Original sample	γ irradiation 100KGy	γ irradiation 500KGy
573K			
673K			

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Effects of irradiation on corrosion

Irradiation experiments

Ion： Helium

Samples： RAFM steel (CLF-1)

Ion energy： 100 keV

Fluence： 5×10^{16}, 1×10^{17}, 2×10^{17} ions/cm^2

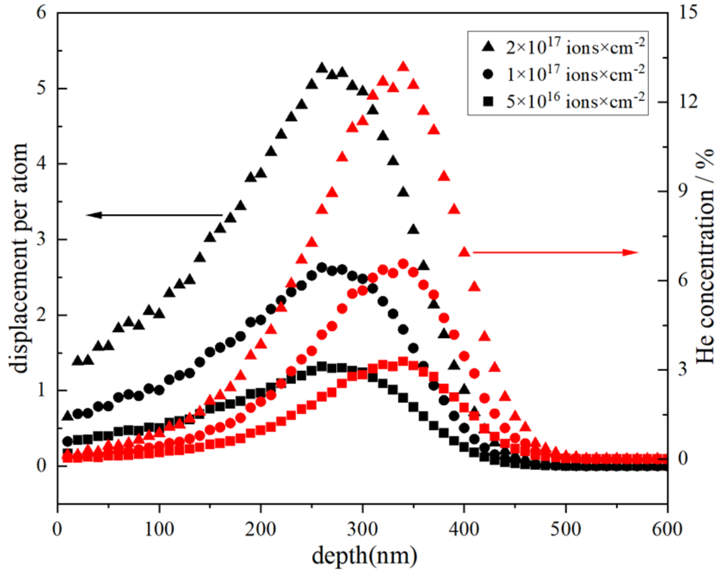
Corrosion experiments

Tritium breeder： Li_4SiO_4 powder

Corrosion time： 10 hours

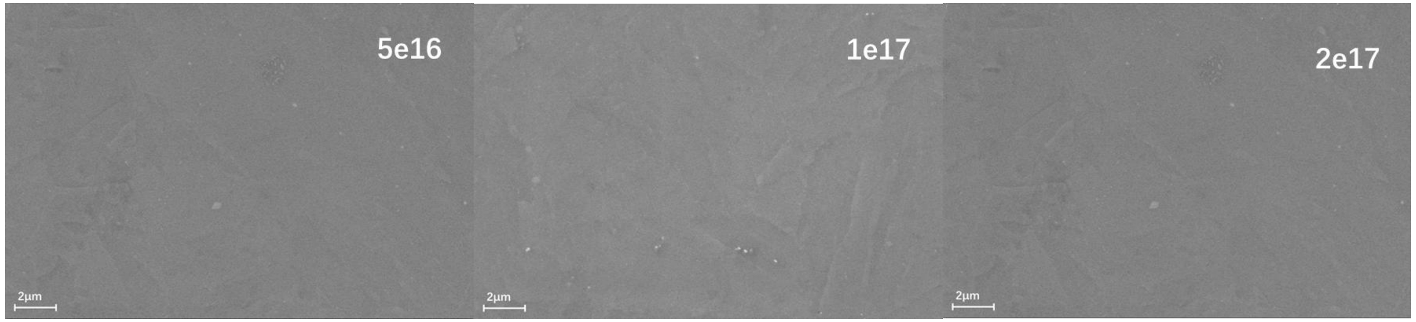
Temperature： 550℃

Atmosphere： He+0.1%H_2, 20mL/min



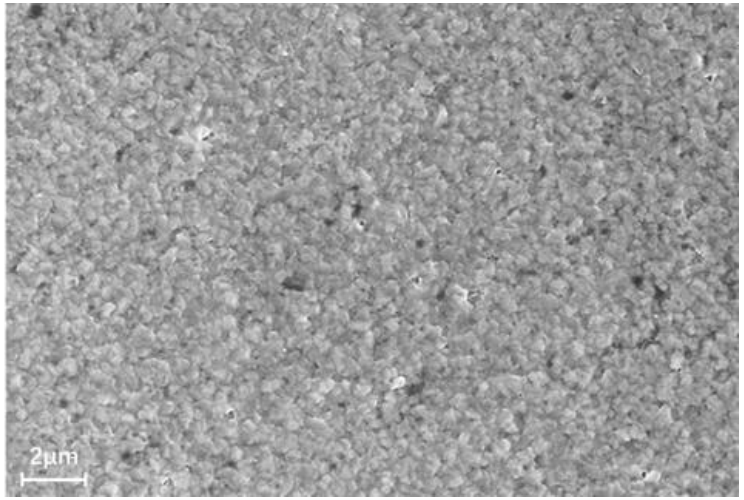
SRIM calculation of the dpa and distribution of He in CLF-1

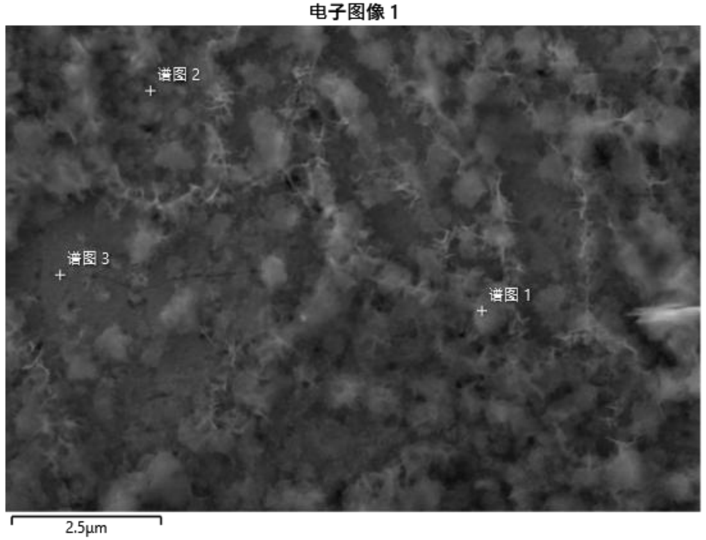
No significant changes

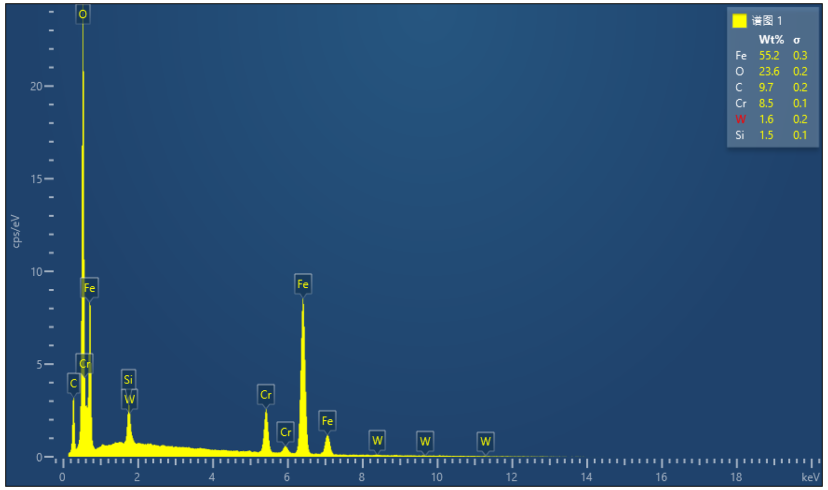


Irradiated samples annealed at 550°C for 10h without corrosion

Effects of irradiation on corrosion

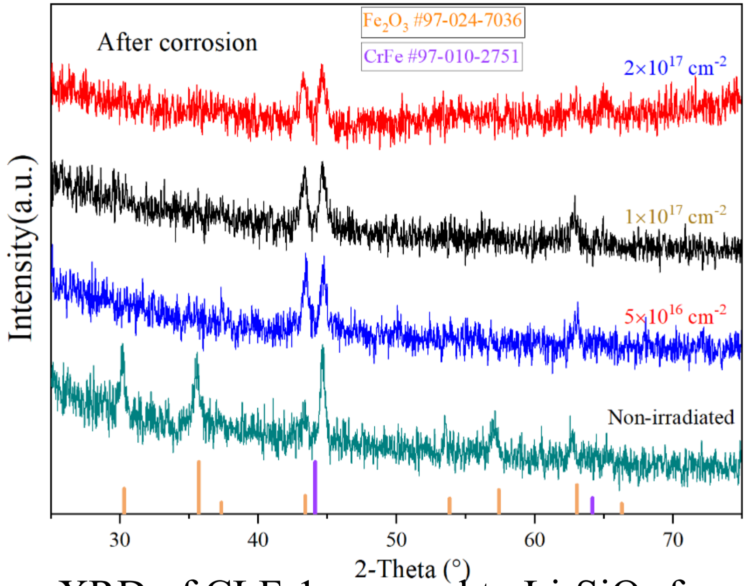






Surface morphology and EDS point analysis of un-irradiated CLF-1 exposed to Li_4SiO_4 for 10h

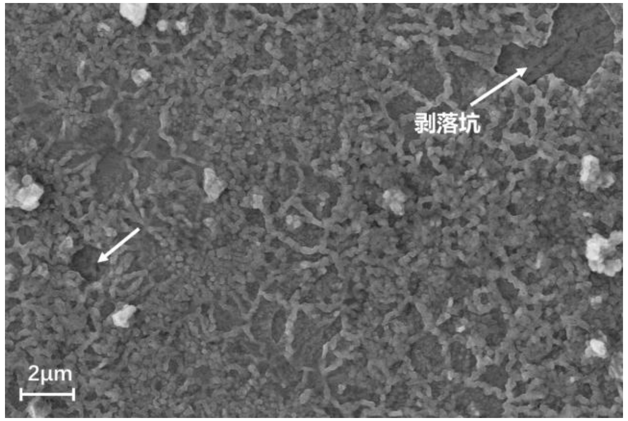
- EDS indicates that numerous particulate corrosion products on the surface consisted of Fe, O, Cr, and C, with only trace amounts of Si detected.
- XRD analysis of the surface corrosion layer identified the presence of CrFe and Fe_2O_3 phases.



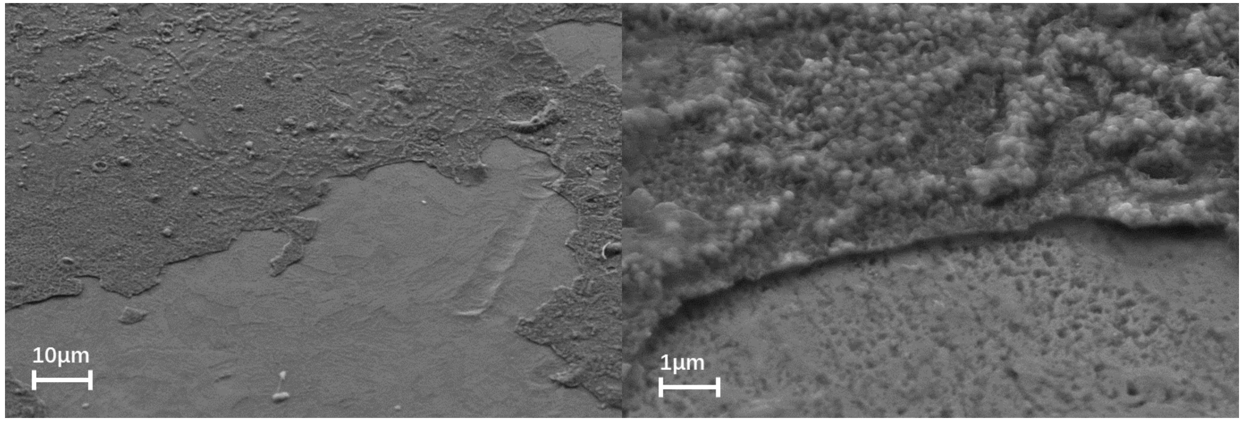
XRD of CLF-1 exposed to Li_4SiO_4 for 10h before and after irradiation

Effects of irradiation on corrosion

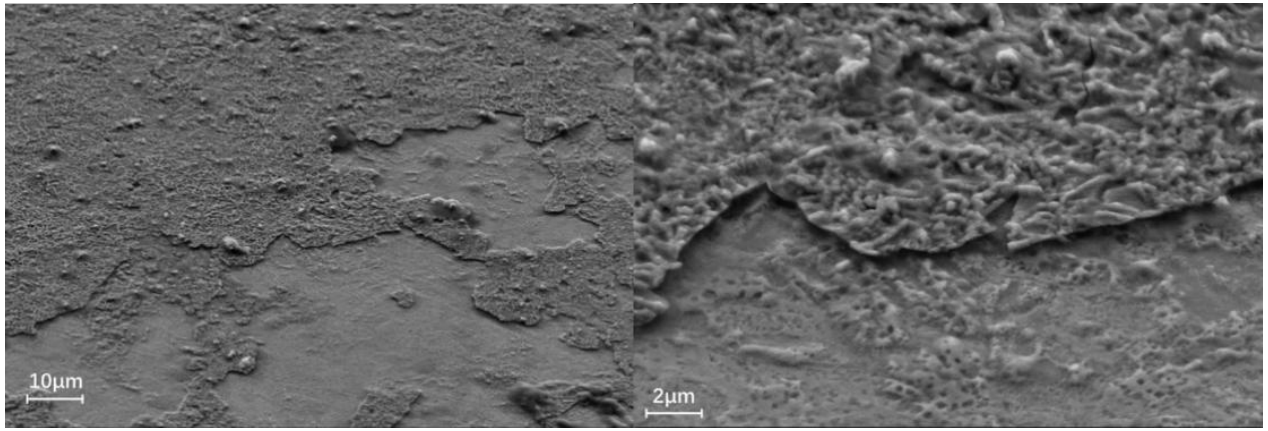
- Cracking and exfoliation of the corrosion layer appeared on the sample surface after irradiation.



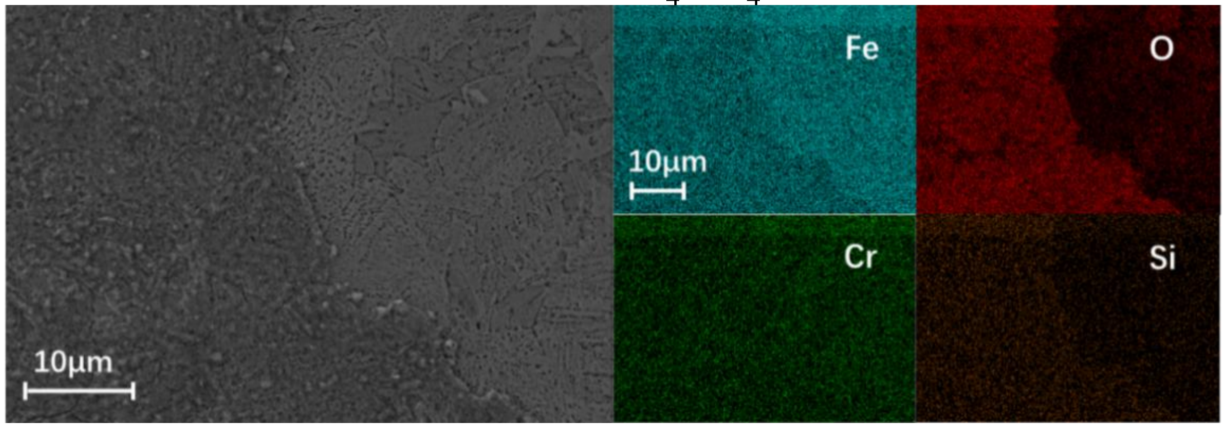
Surface of CLF-1 irradiated with 5×10^{16} ions/cm^2 after 10 h - corrosion with Li_4SiO_4



Surface of CLF-1 irradiated with 1×10^{17} ions/cm^2 after 10 h - corrosion with Li_4SiO_4



Surface of CLF-1 irradiated with 2×10^{17} ions/cm^2 after 10 h - corrosion with Li_4SiO_4

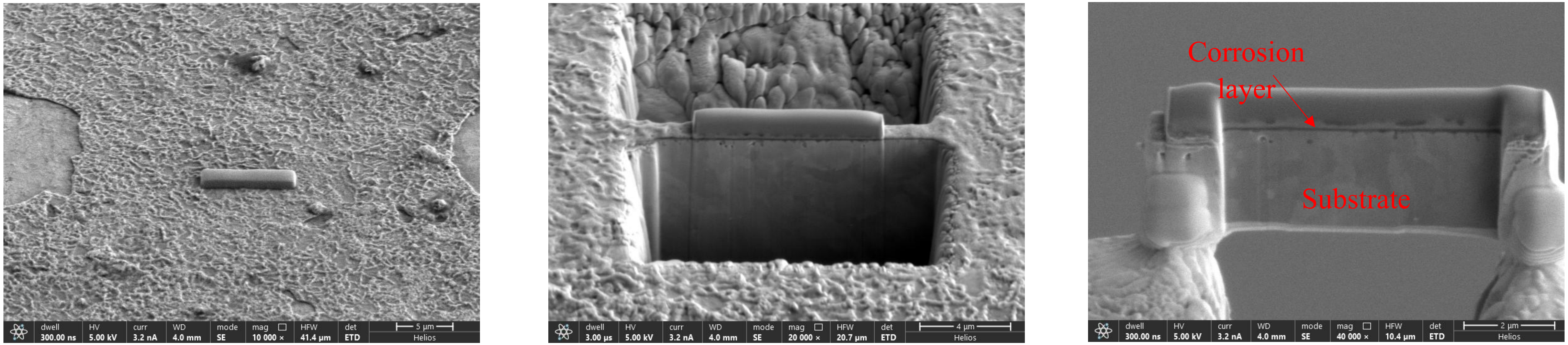


EDS mapping of the exfoliated region on the corroded surface

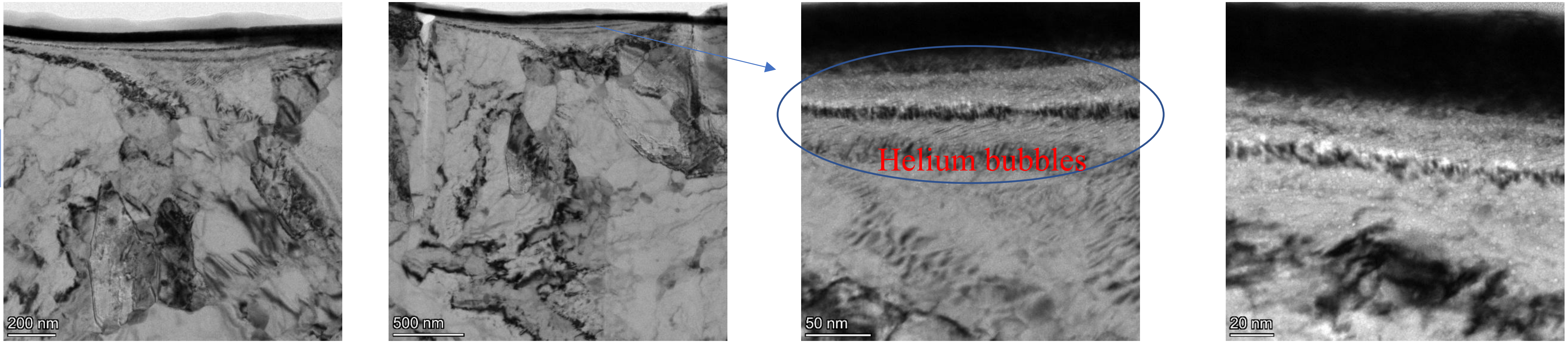
Effects of irradiation on corrosion

- Helium bubbles are observed accumulating in the steel substrate near the crack between the corrosion layer and the substrate.

FIB

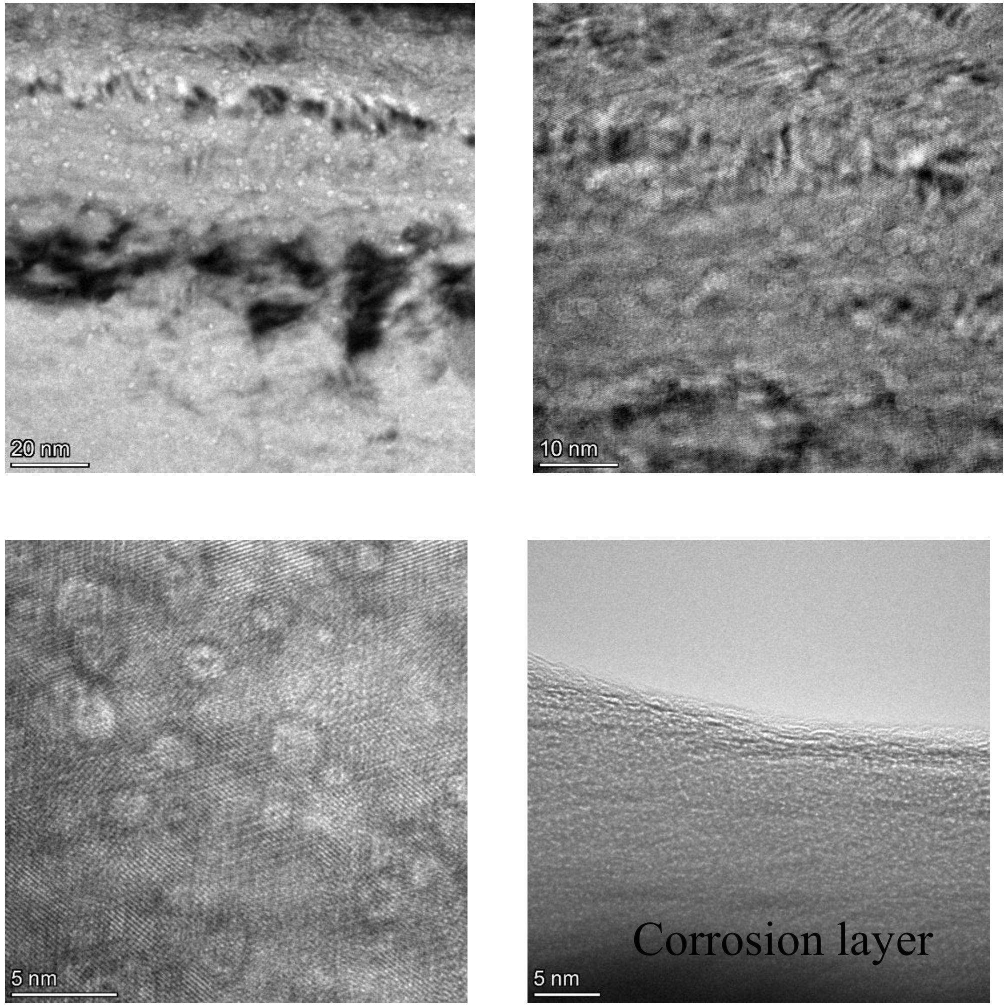


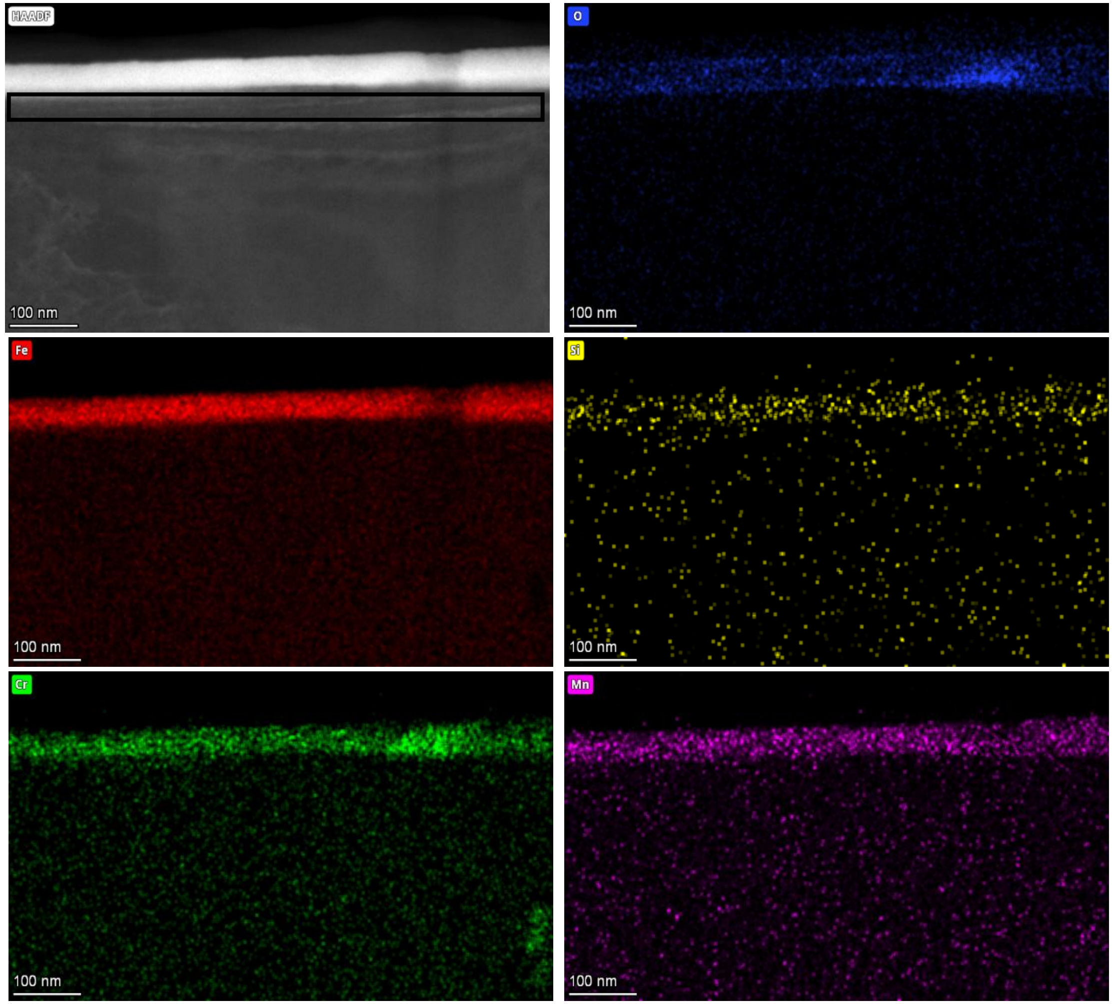
TEM



Effects of irradiation on corrosion

- The average bubble diameter increases from 0.77nm to 2.1nm.
- The thickness of the corrosion layer ranges from 50-120 nm.

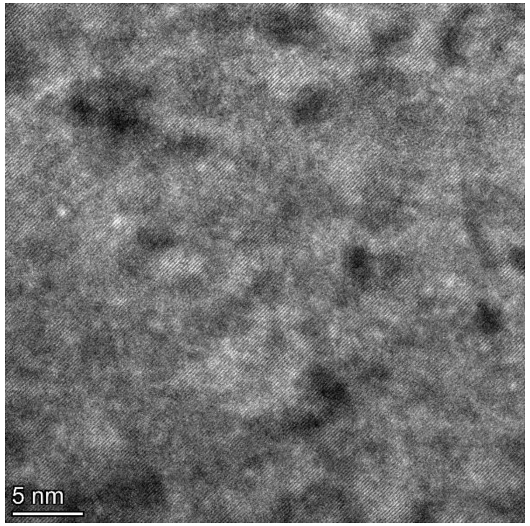


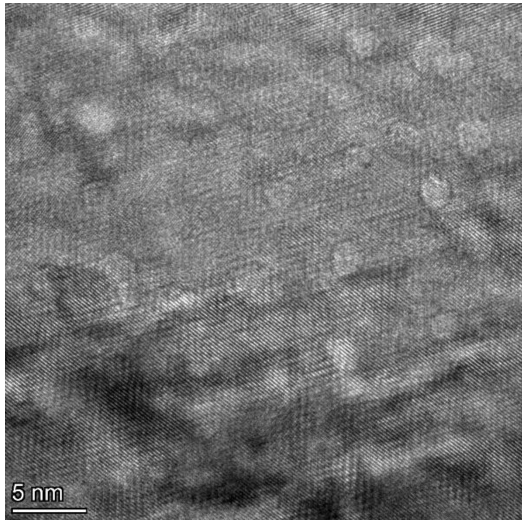


Effects of irradiation on corrosion

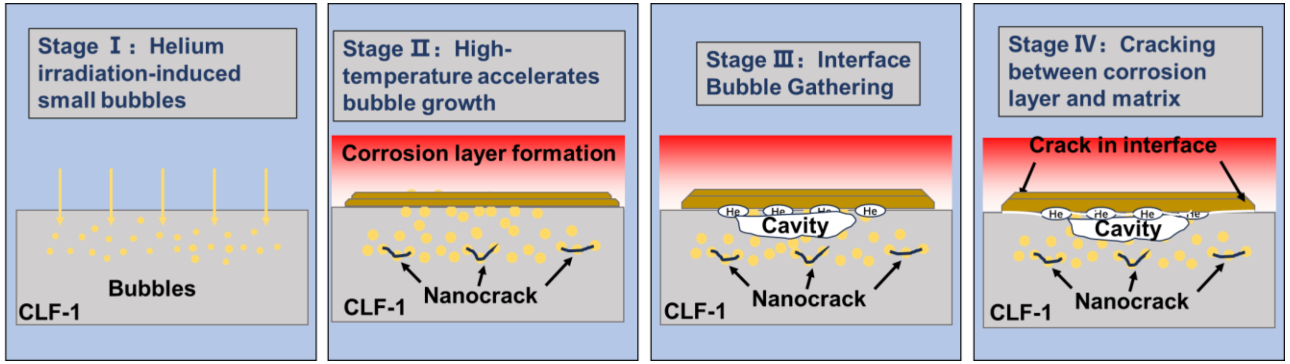
Mechanism of irradiation-corrosion cracking

He^+ irradiation | Exposed to Li_4SiO_4 at 550℃ 10h





Helium bubbles of CLF-1 irradiated with 2×10^{17} ions/cm^2 after 10 h - corrosion with Li_4SiO_4



① Clusters and small bubbles were induced by helium irradiation.
② Helium diffusion and bubble growth, formation of corrosion layer.
③ Diffusion of helium and bubble were inhibited, cavity formation.
④ High pressure cavities leading to the cracking of corrosion layer.

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Conclusions

- **Material design needs to take into account the effects of microstructure, porosity, grain size, irradiation damage, and other factors on tritium release**

- **Defects induced by helium ion irradiation accelerate the corrosion of CLF-1 steel, and the migration, growth, and coalescence of helium bubbles during high-temperature annealing readily lead to cracking and separation of the oxide corrosion layer from substrate**

Thank you for your attention！