Post-LOCA Ductility of Cr-coated cladding and its Implications on Accident Coping Time

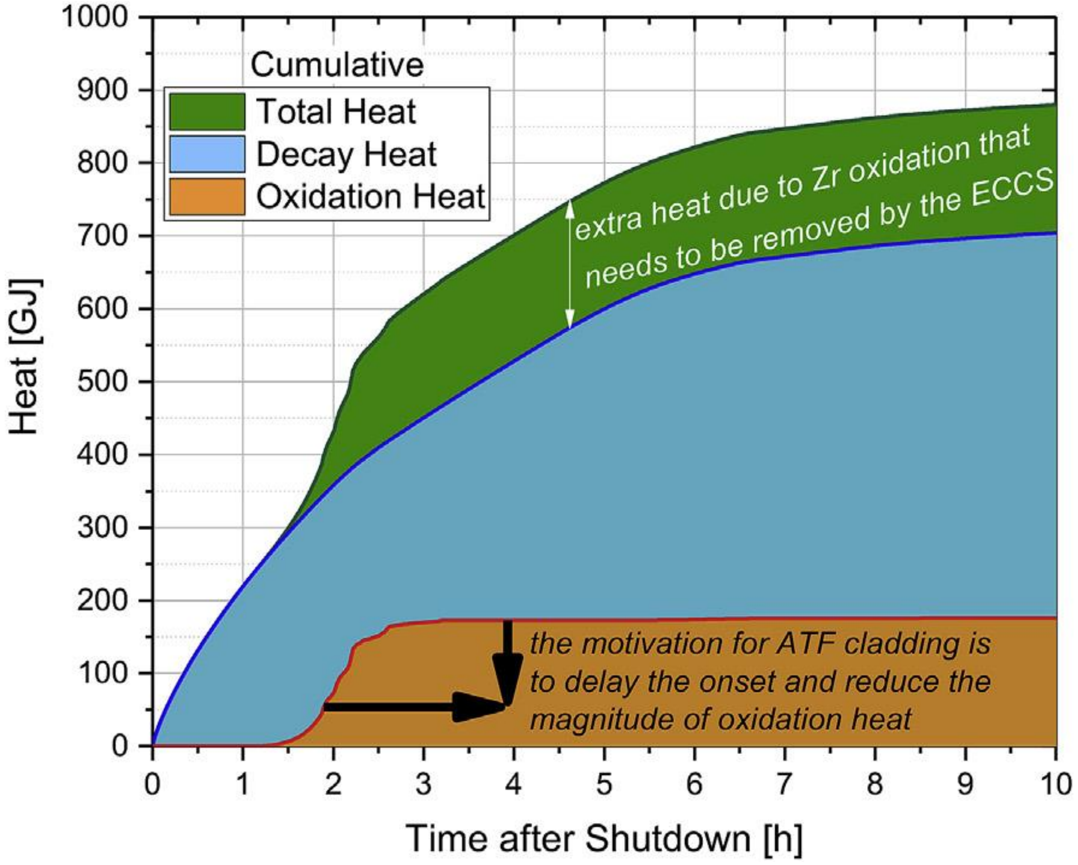
2021. 05. 14

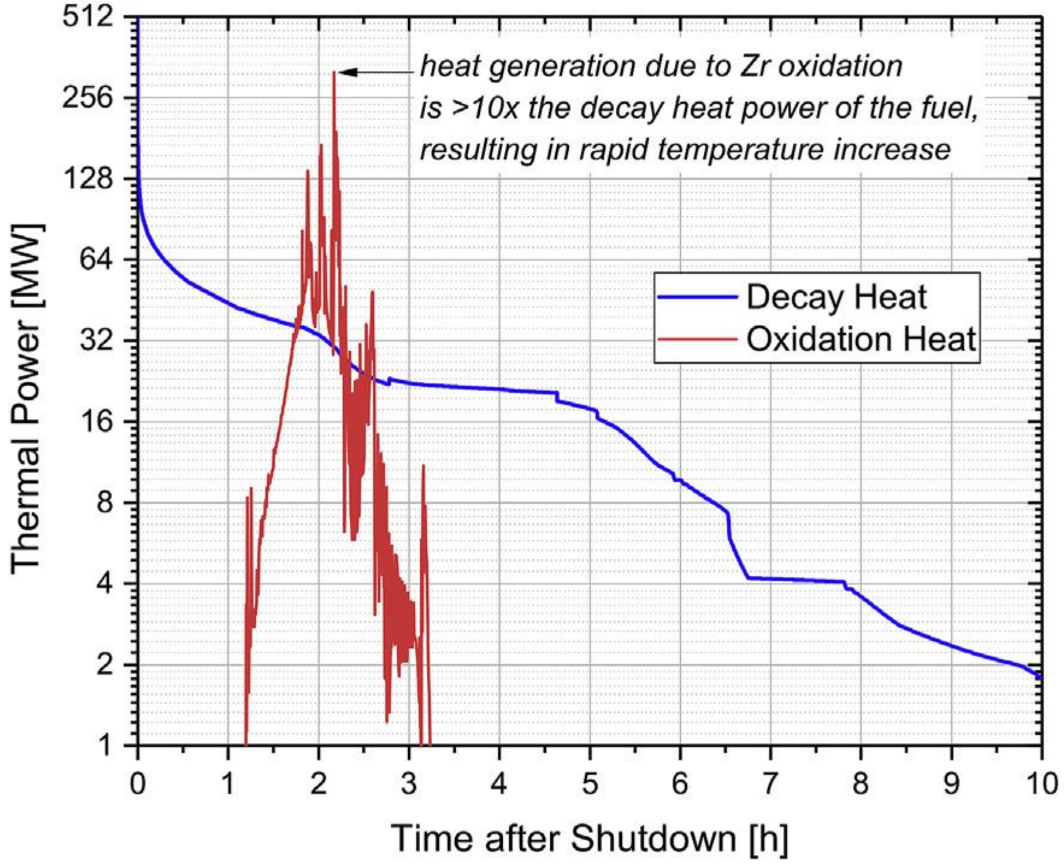
Hyunwoo Yook, Kyunghwan Keum, Dongju Kim, Prof. Youho Lee*

SNU Nuclear Fuel Materials & Safety Laboratory

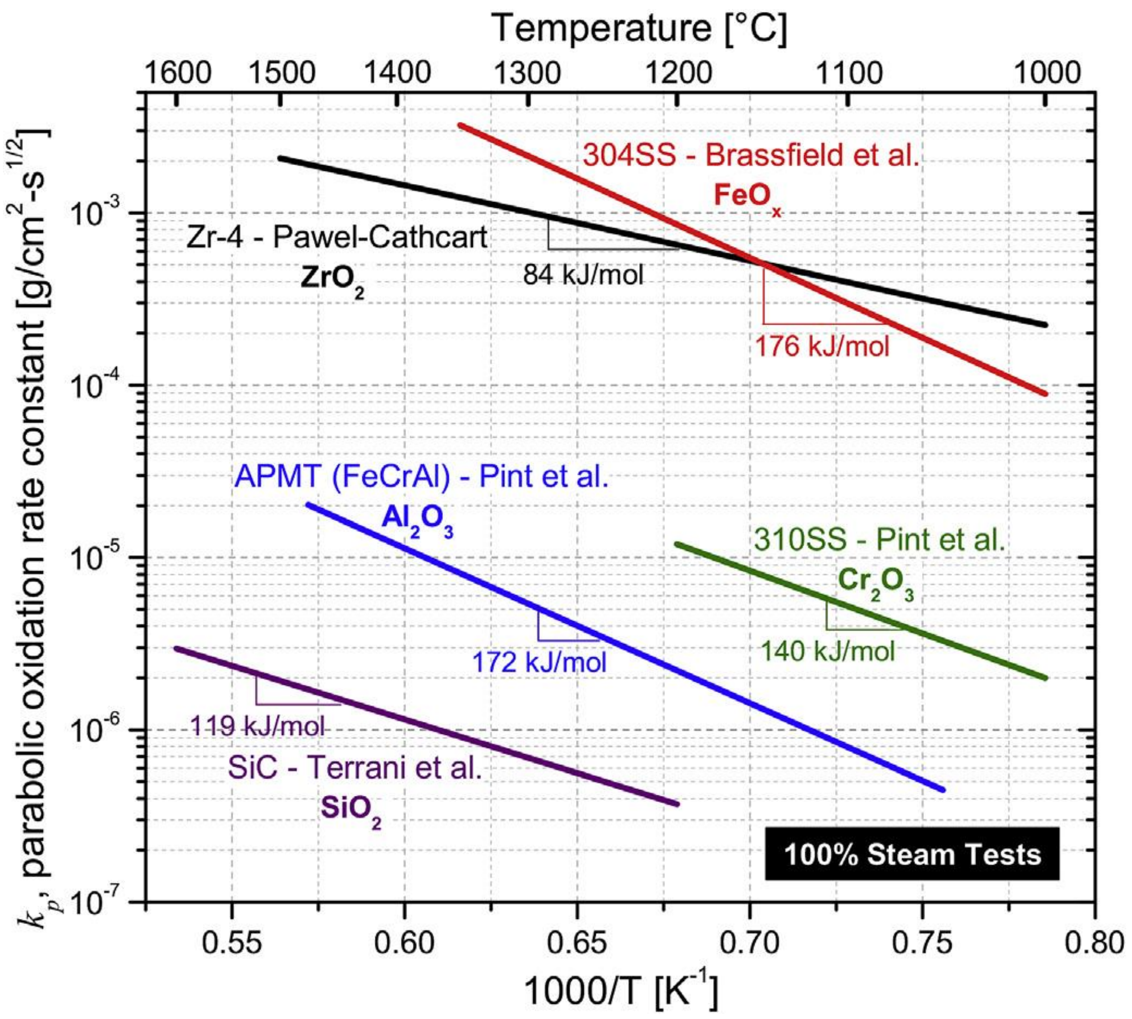
Contents

25~40 Tonnes of Zr metal in LWR core → **Huge Oxidation Heat**

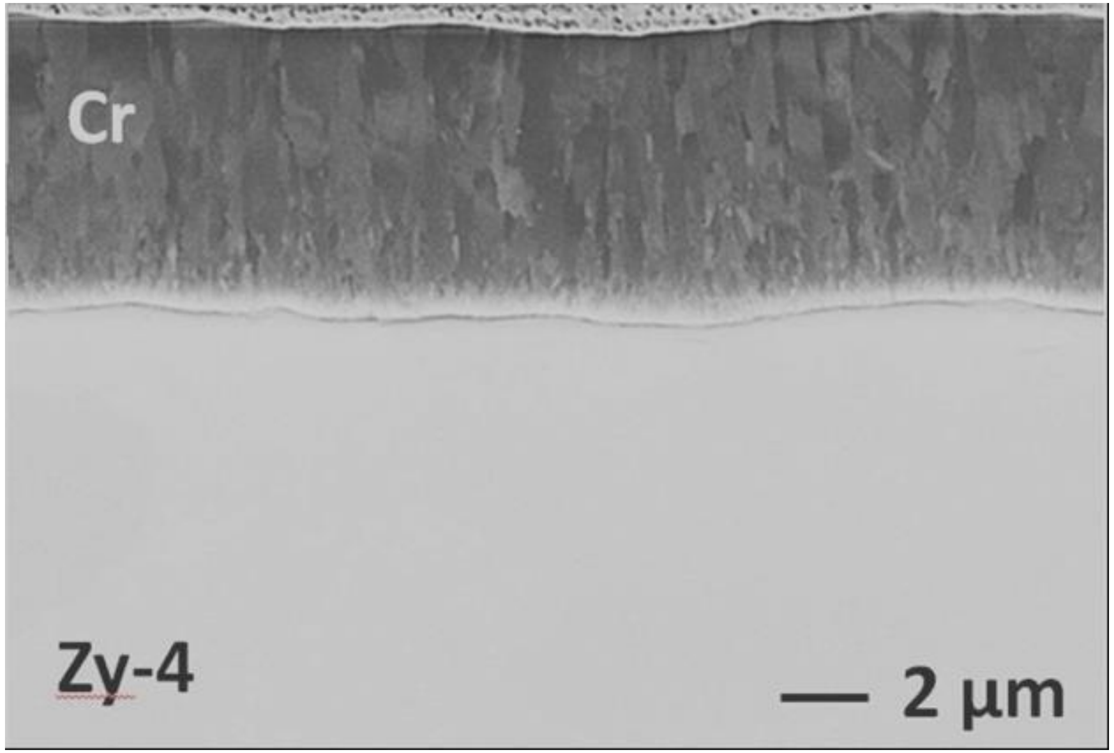




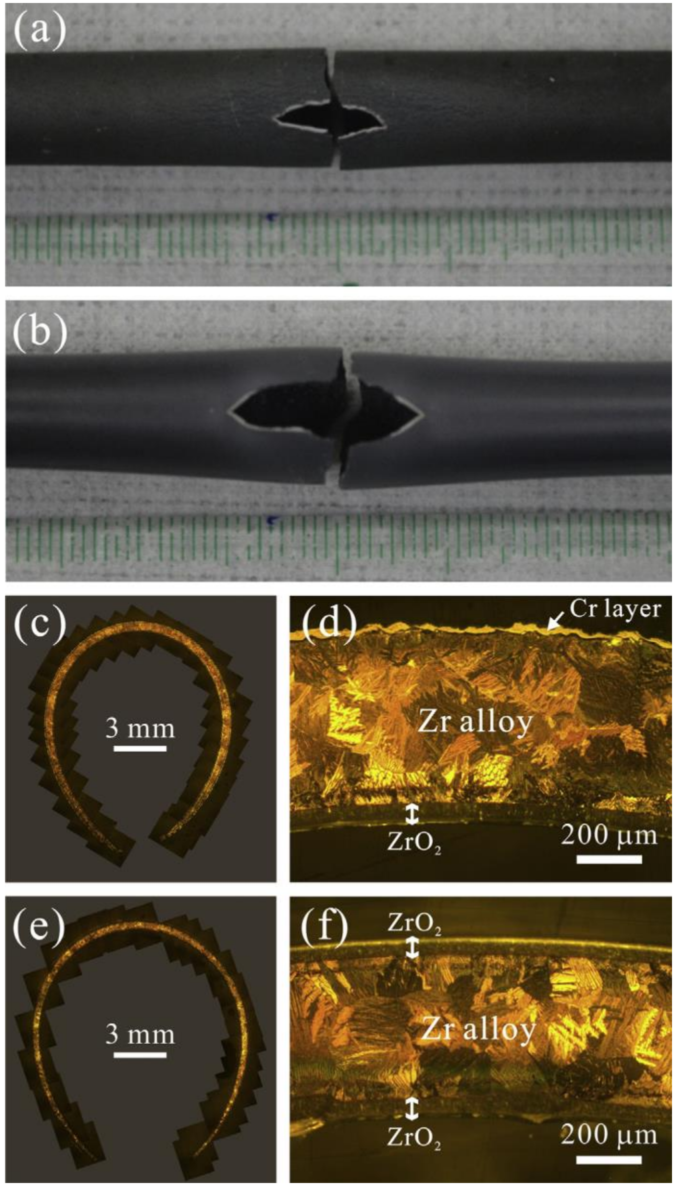
Thermal power and cumulative energy due to radionuclide decay heat and Zr-based cladding oxidation heat during a short-term station blackout [K.A.Terrani, 2018]



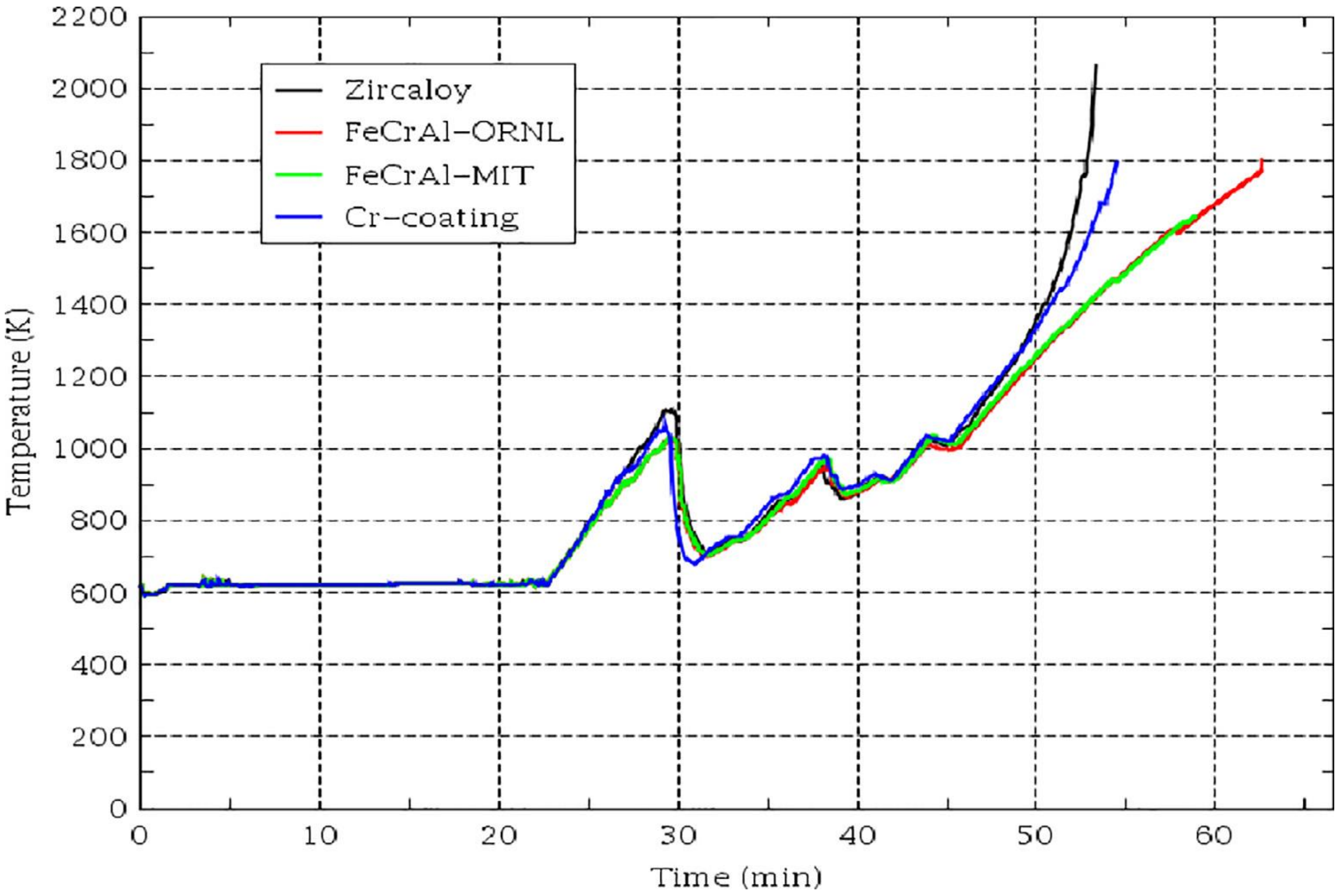
Parabolic **oxidation rate** as a function of temperature [K.A.Terrani, 2018]



Typical micrographs of **chromium coatings** [J.C.Brachet, 2014]



Ballooning of Cr-coated cladding[D.Park, 2016]



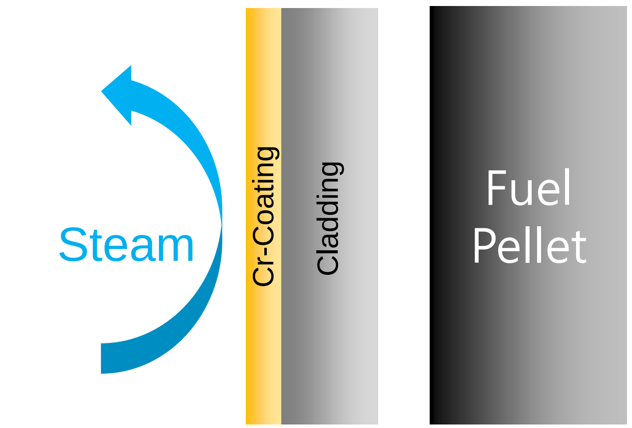
Temperature profile of cladding systems in short-term SBO considering ballooning [A.Gurgen,2018]

1. Introduction

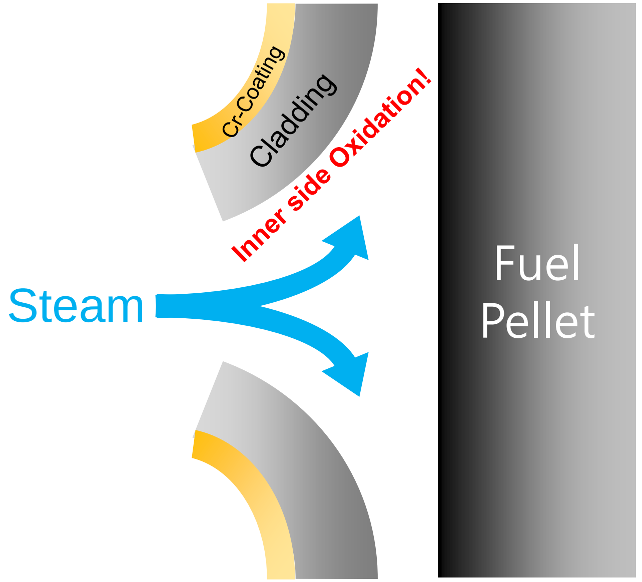
- **Ballooning & Burst occurs at 700~800℃ also for Cr-coated cladding**
- **Inner side of cladding is oxidized after ballooning**
- **Embrittlement of Cr-coated cladding with high temperature oxidation**
- **Rupture due to embrittlement may lead to leakage of nuclear fuel**

ECR limit and additional time for accident mitigation time of Cr-coated cladding were derived from post-LOCA experiments

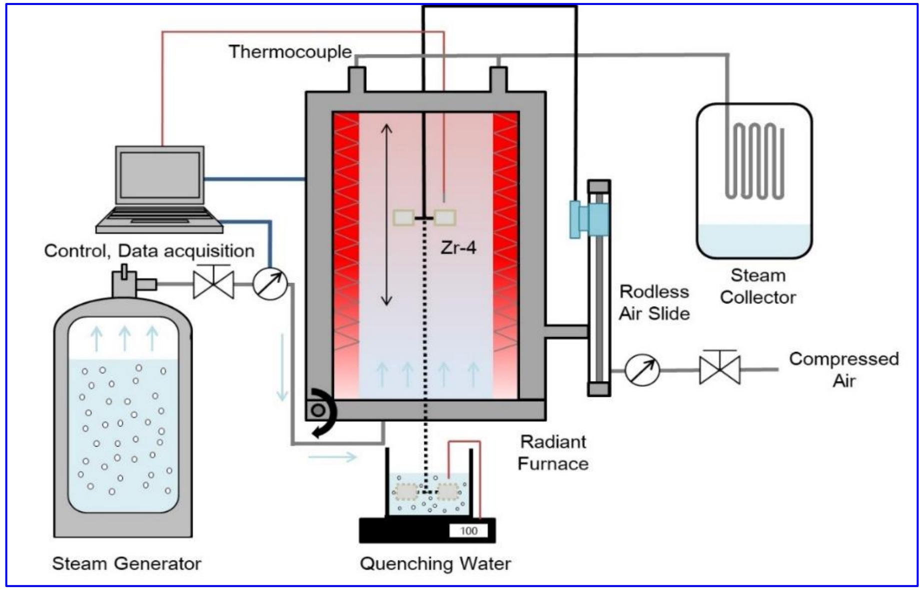
Before Ballooning & Burst

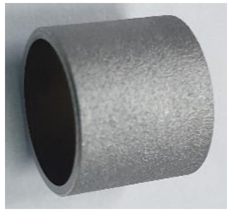


After Ballooning & Burst



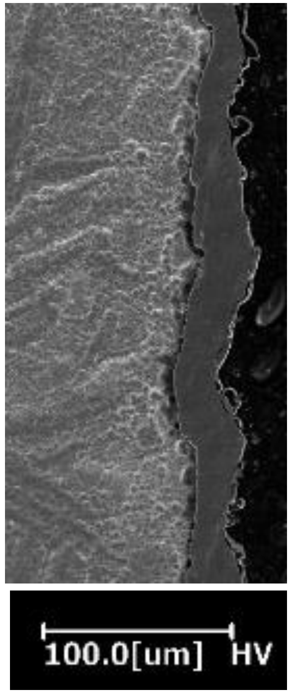
2. Experiments – Oxidation Facility & Materials

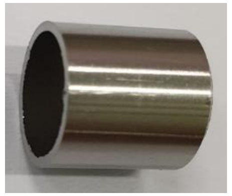




As-received
Cr-coated Zircaloy-4
(8mm)

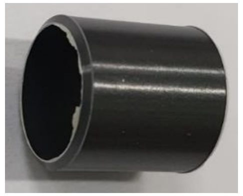
Cr coating : 30~50 μm





As-received
Reference Zircaloy-4
(8mm)

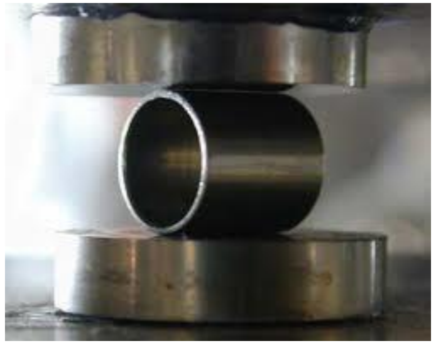
1200℃ Oxidation

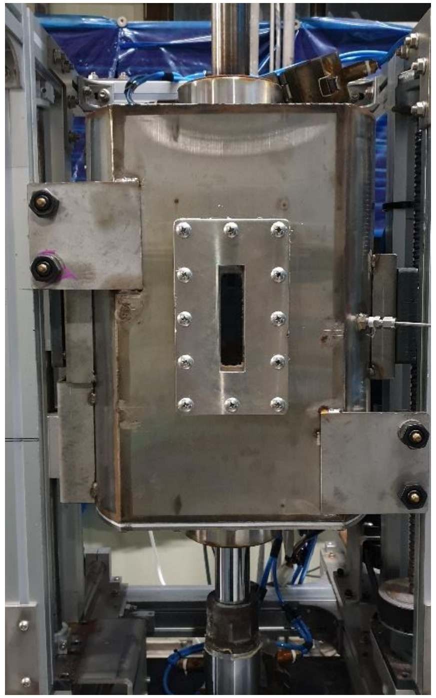


Oxidized Zircaloy-4

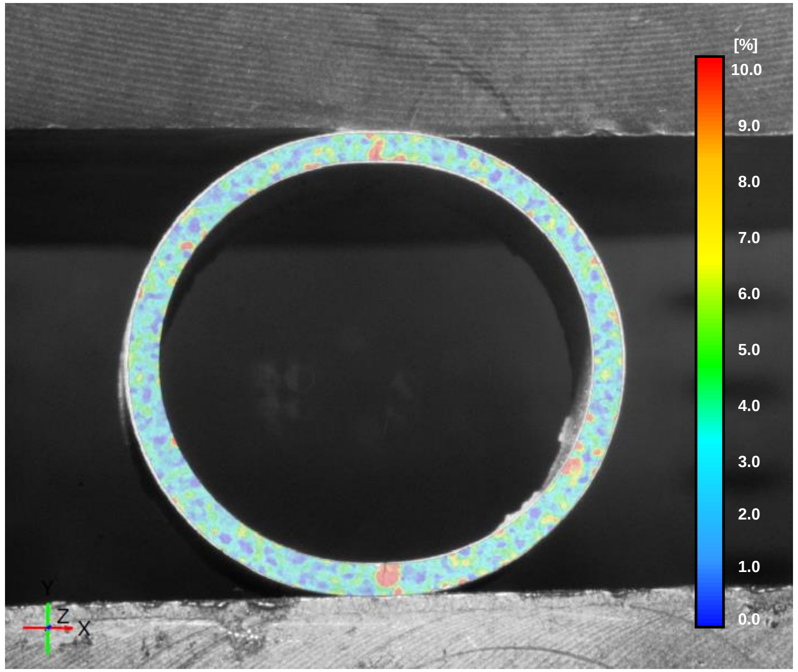
Specimen temperature measured with attached K-type thermocouple

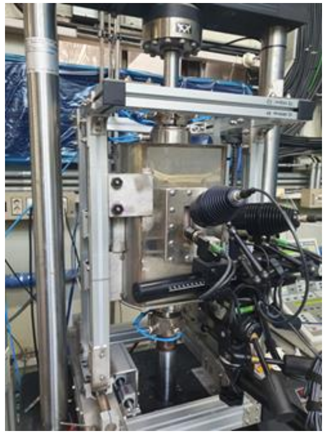
2. Experiments – Post-oxidation Analysis



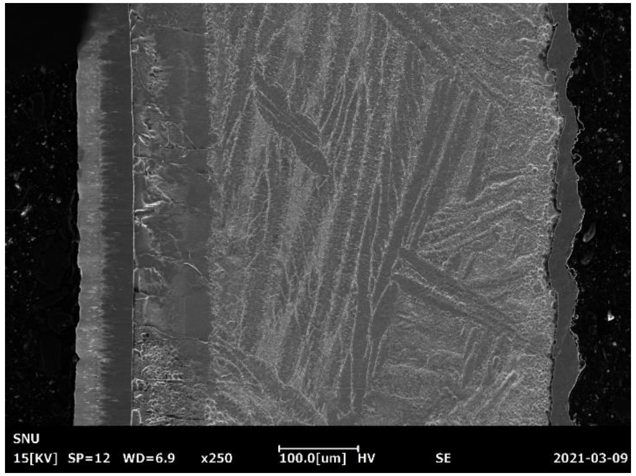


Ring Compression Test
at 135℃

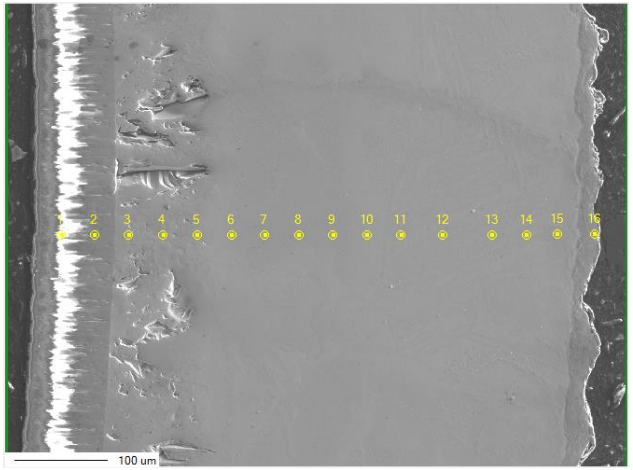




Digital Image Correlation

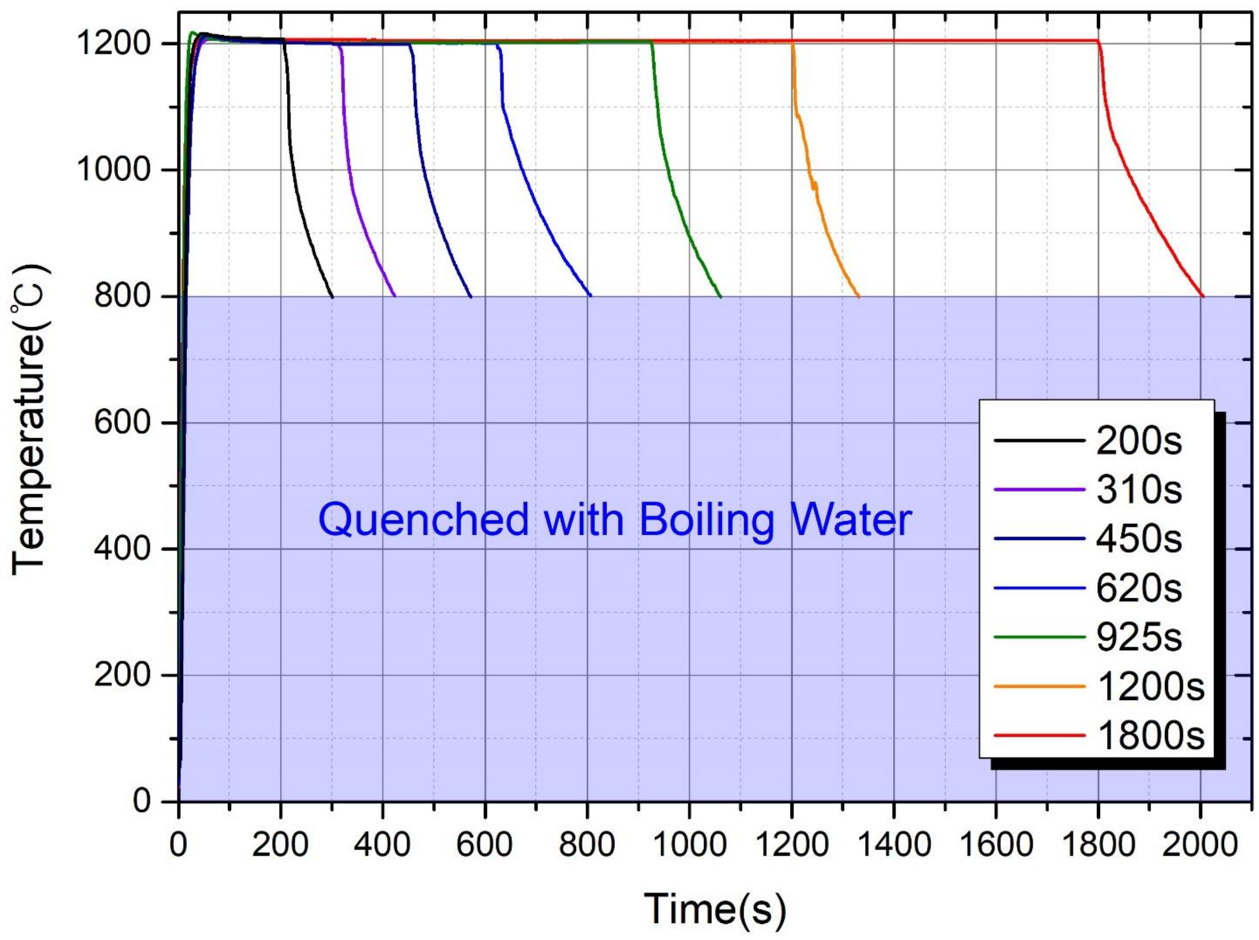


Scanning Electron Microscopy



Electron Probe X-ray Micro Analyer

2. Experiments - Oxidation



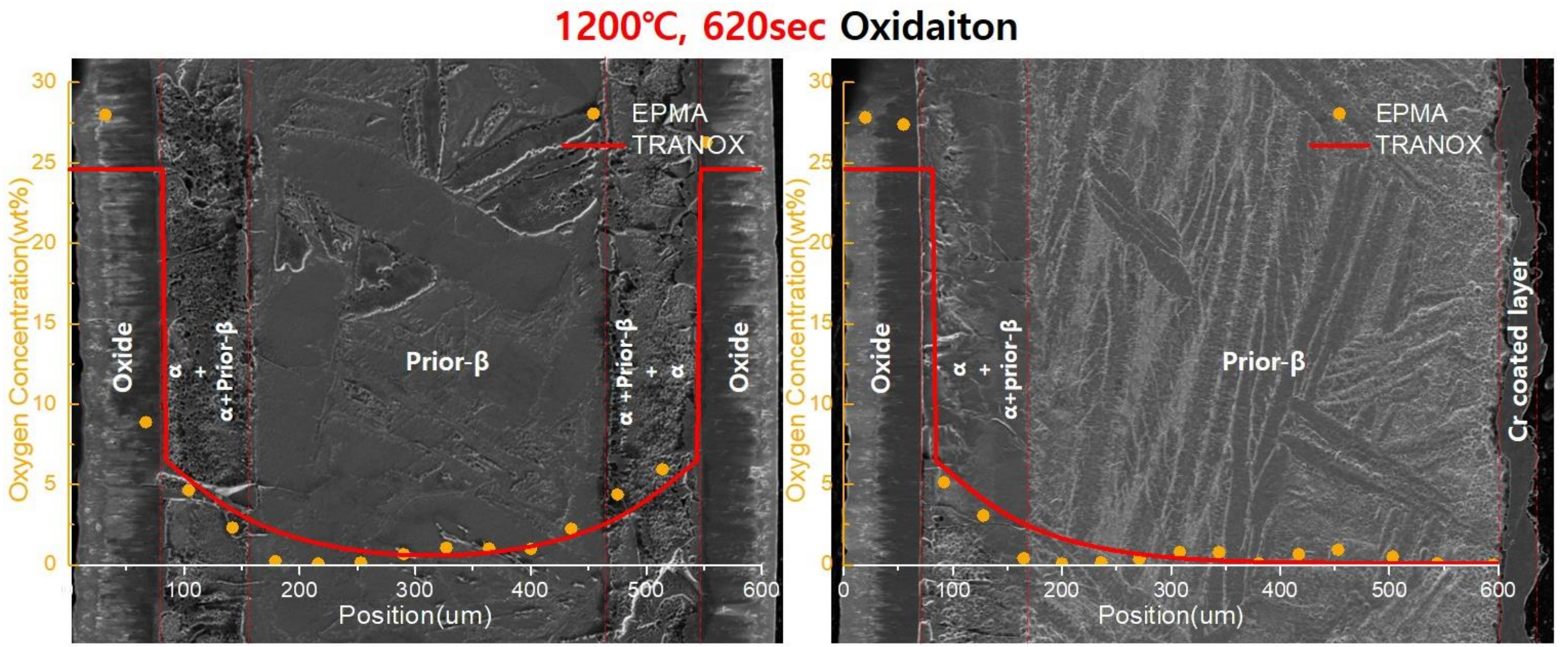
- Cr-coated specimens and reference uncoted specimens were oxidized for 200~1800s and quenched with boiling water

- ECR was obtained from weight gain measured before and after oxidation

- Cr-coated specimens were oxidized about half compared to the uncoated specimens oxidized for the same time

Oxidation Experiments		Oxidation time						
		200s	310s	450s	620s	925s	1200s	1800s
ECR(%)	Cr-coated Zr-4	6.75	8.24	9.50	11.66	13.83	15.53	19.49
	Reference Zr-4	13.23	16.55	18.95	22.72	27.38	31.09	38.76

2. Experiments - Oxidation

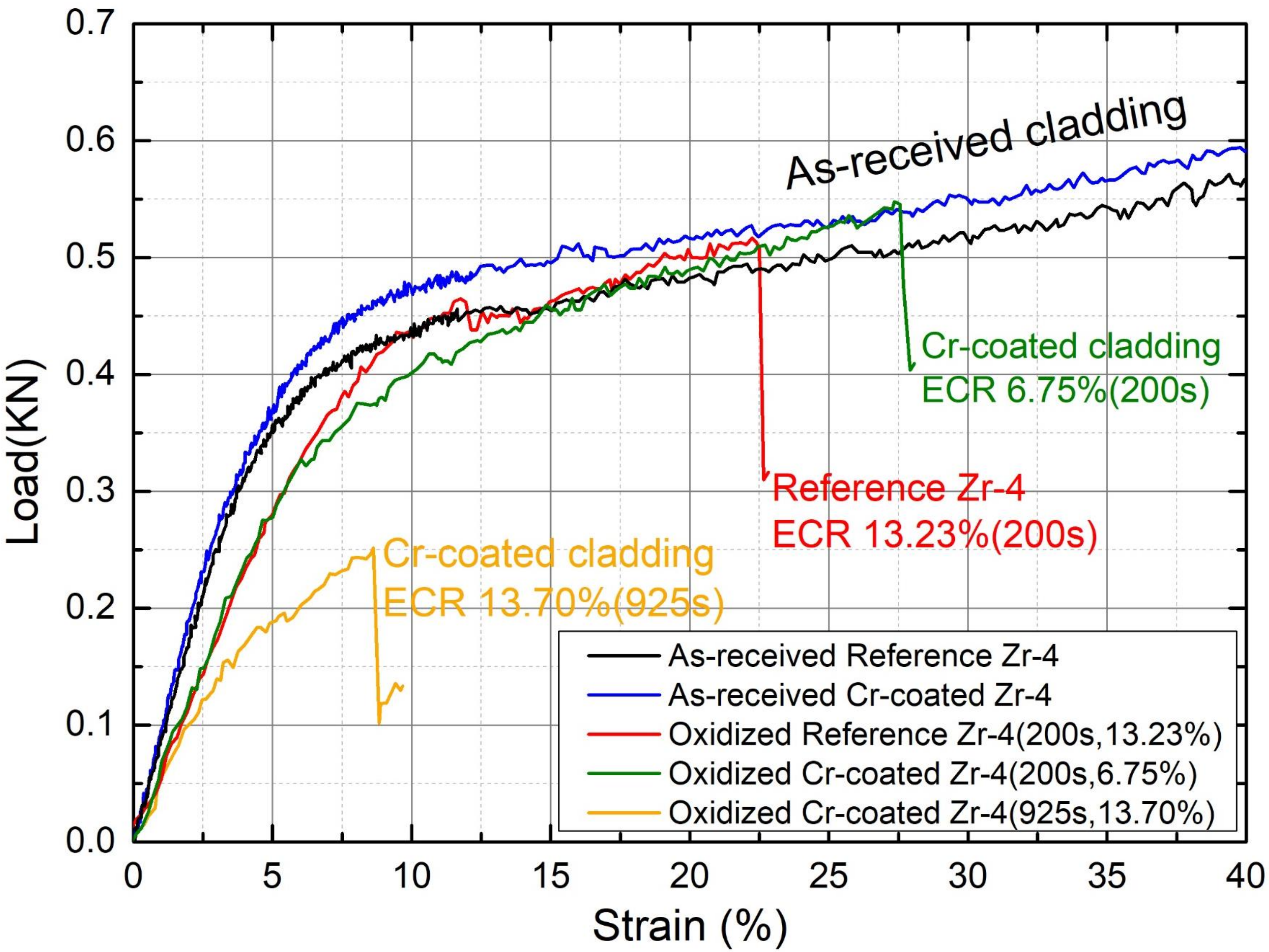


Reference Zircaloy-4(ECR 22.72%)　　Cr coated Zircaloy-4(ECR 11.66%)

- No oxygen penetration though Cr coating was observed
- Oxygen content distribution could be well predicted with TRANOX compared to EPMA results
- Hydrogen pickup by oxidation was negligible

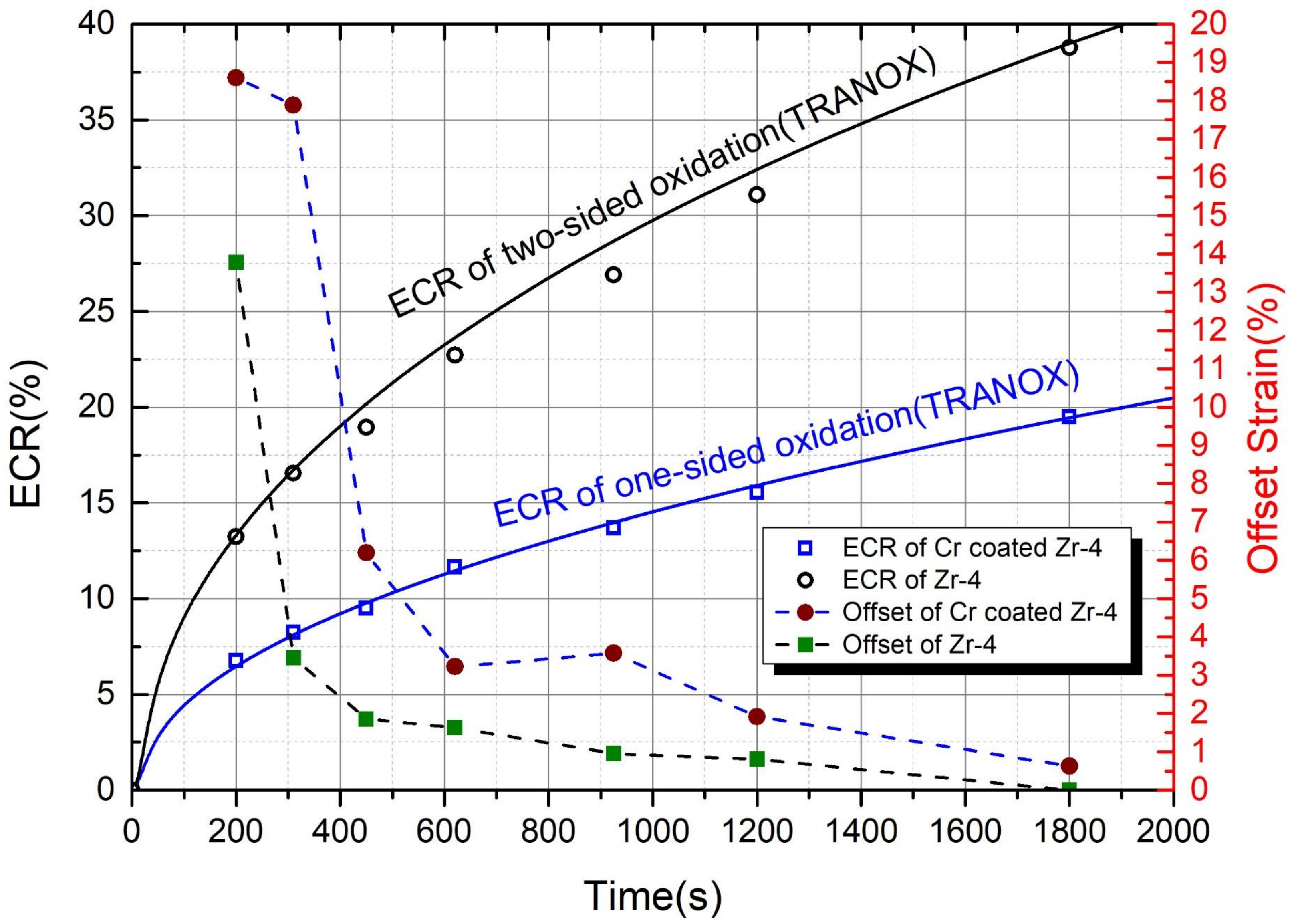
	Oxidation Time(s)	ECR(%)	H_{pickup}(wppm)
Cr coated specimens	200	6.75	15.7
	925	13.70	25.7
Reference specimens	200	13.23	11.6
	925	26.90	14.9

3. Results – Ring Compression Test



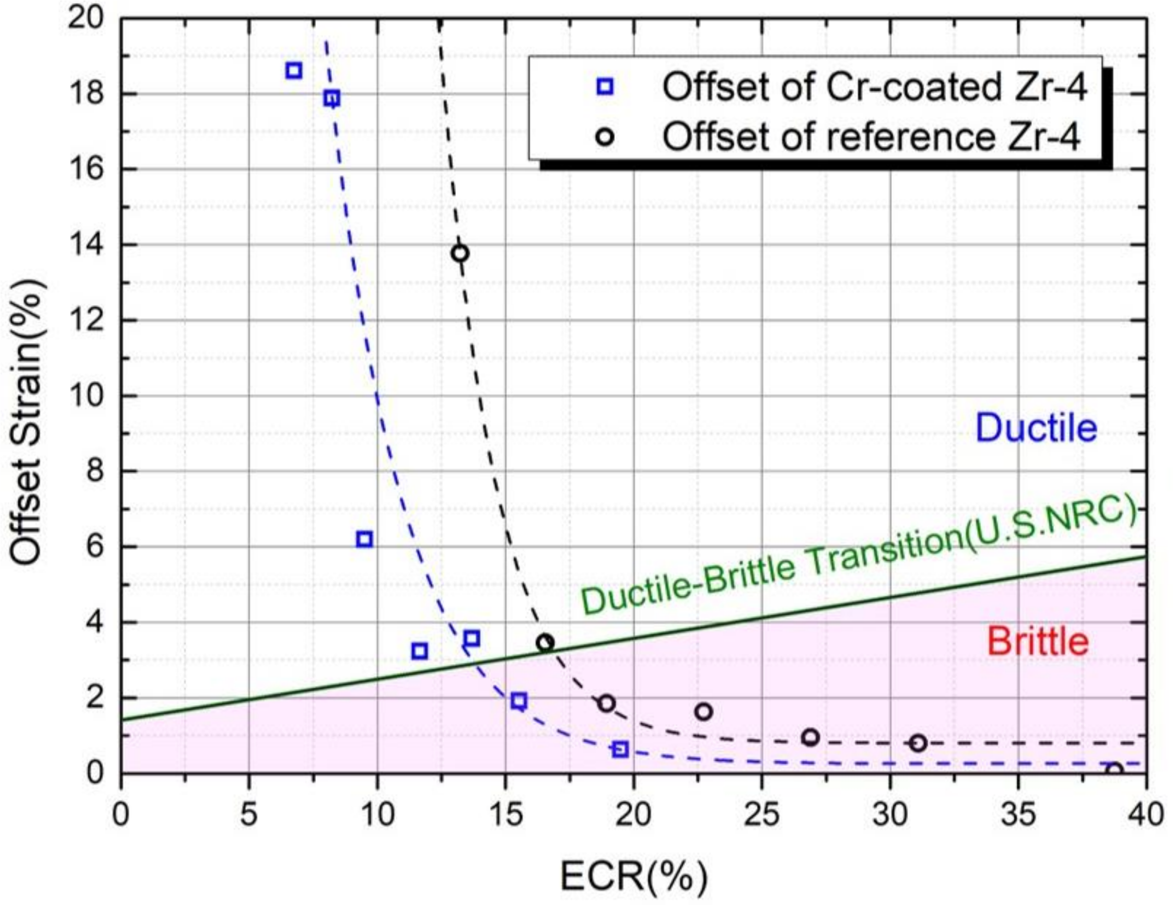
- **Cr coating enhanced as-received cladding strength**
- **Cr-coated cladding showed better fracture strain and load compared to uncoated cladding oxidized for the same time(200s)**
- **However when compared with similar ECR specimen, Cr-coated cladding showed lower fracture strain and load**

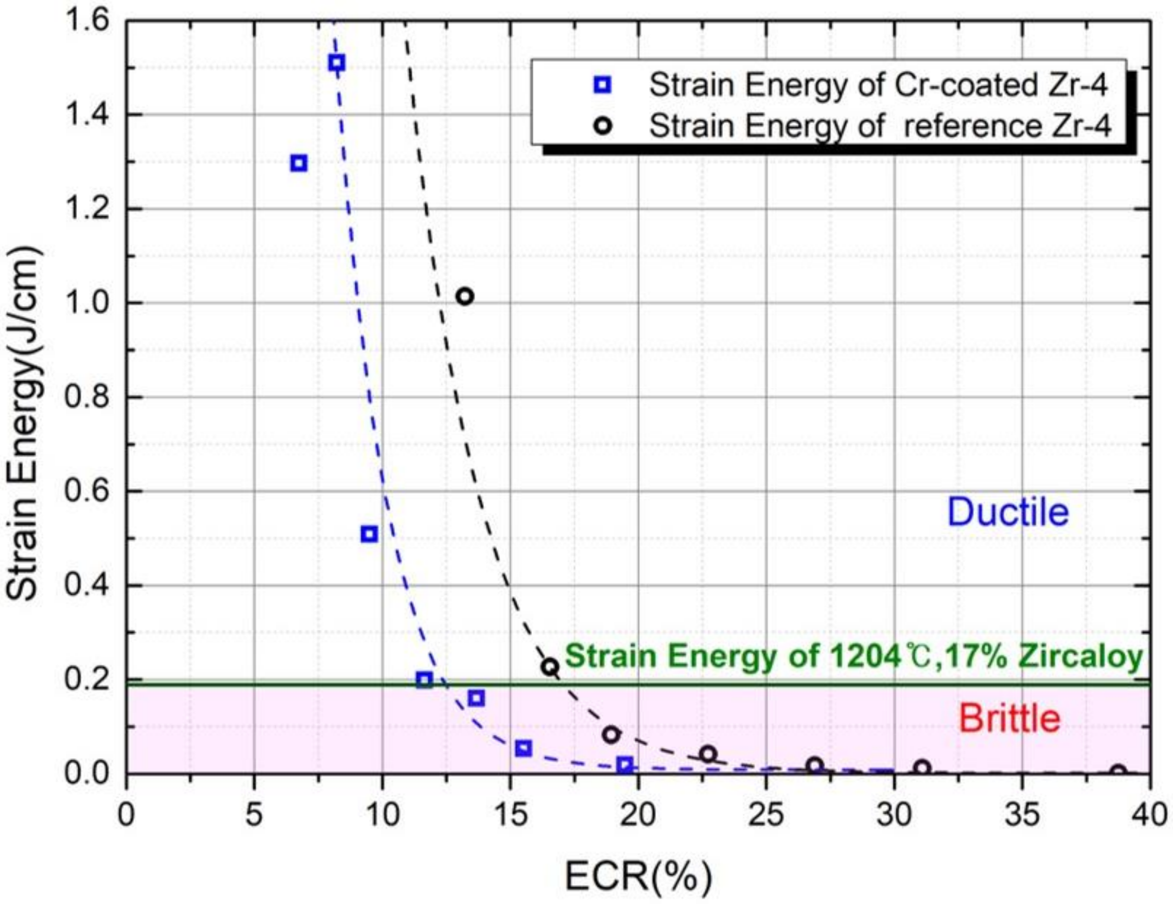
3. Results – Time vs Offset Strain



- ECR could be predicted quite accurately with TRANOX
- Cr coating prevented oxidation well as ECR of Cr-coated specimens suit one-sided oxidation
- Offset strain, one of the ductility criteria, decreased with oxidation
- Cr-coated cladding showed better offset strain compared to the uncoated cladding oxidized for the same time

3. Results – ECR vs Offset Strain



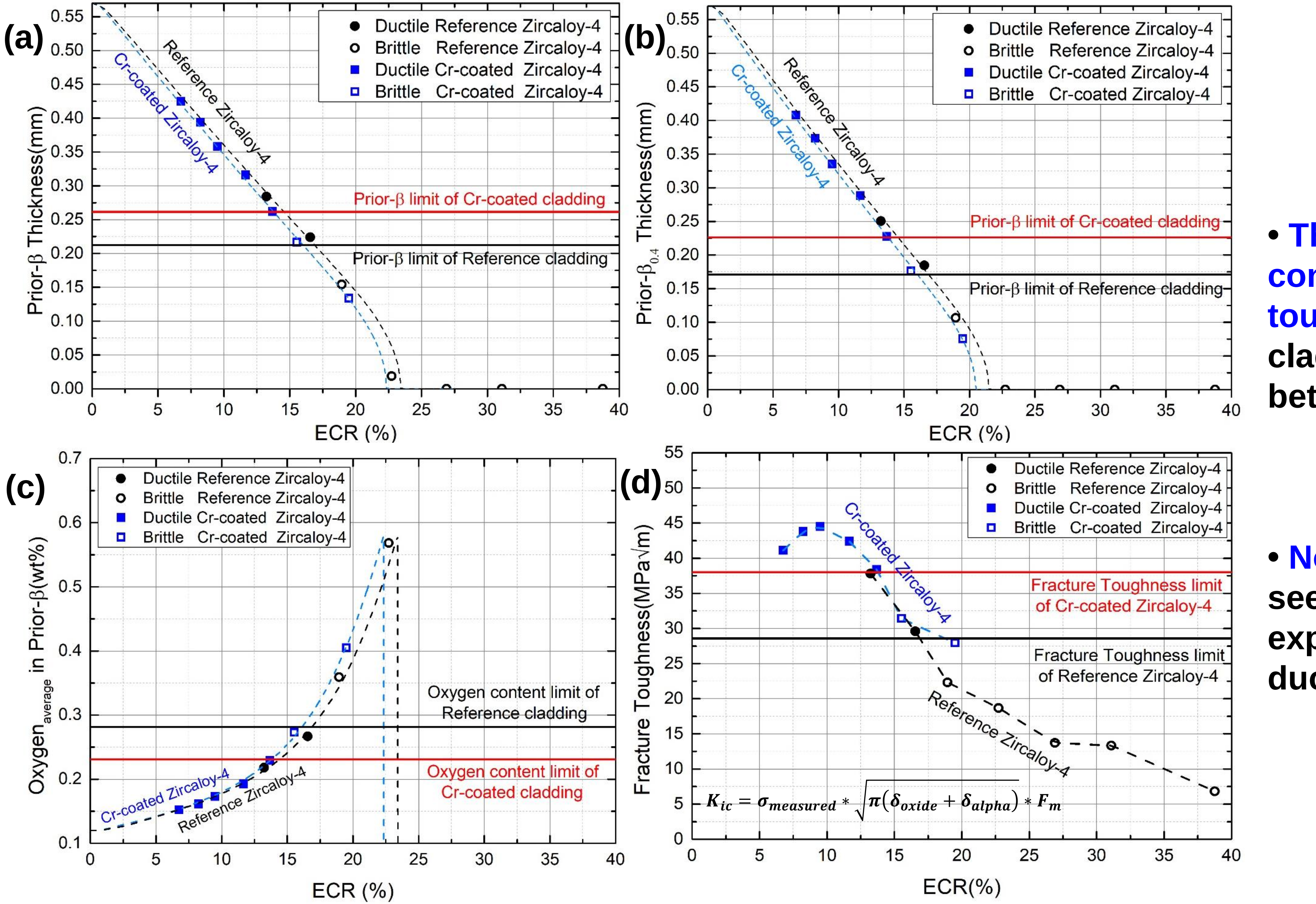


		Cr-coated Zr-4	Reference Zr-4
Offset Strain	ECR limit	13.79%	16.88%
	Critical time	900s	316s
Strain Energy	ECR limit	12.46%	17.05%
	Critical time	735s	323s

- **When compared with same ECR, Cr-coated cladding showed worse ductility**

- **ECR limit of Cr-coated cladding were also lower than them of uncoated cladding**

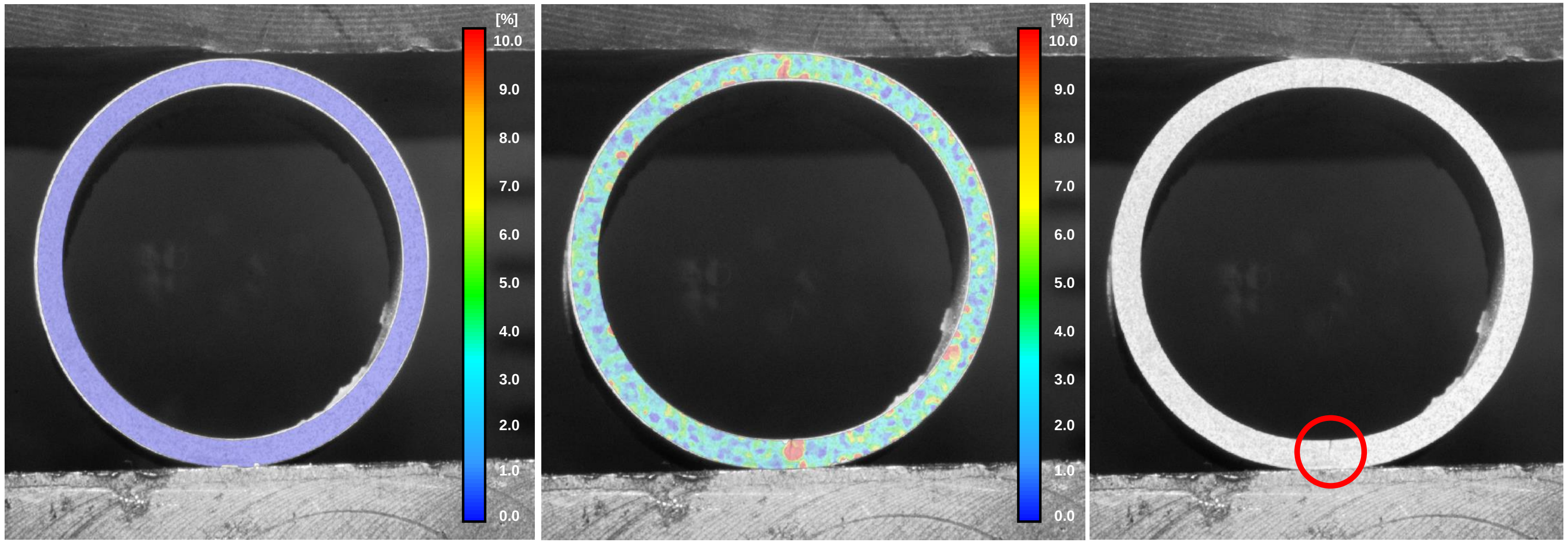
3. Results – ECR vs Brittle Transition Factors



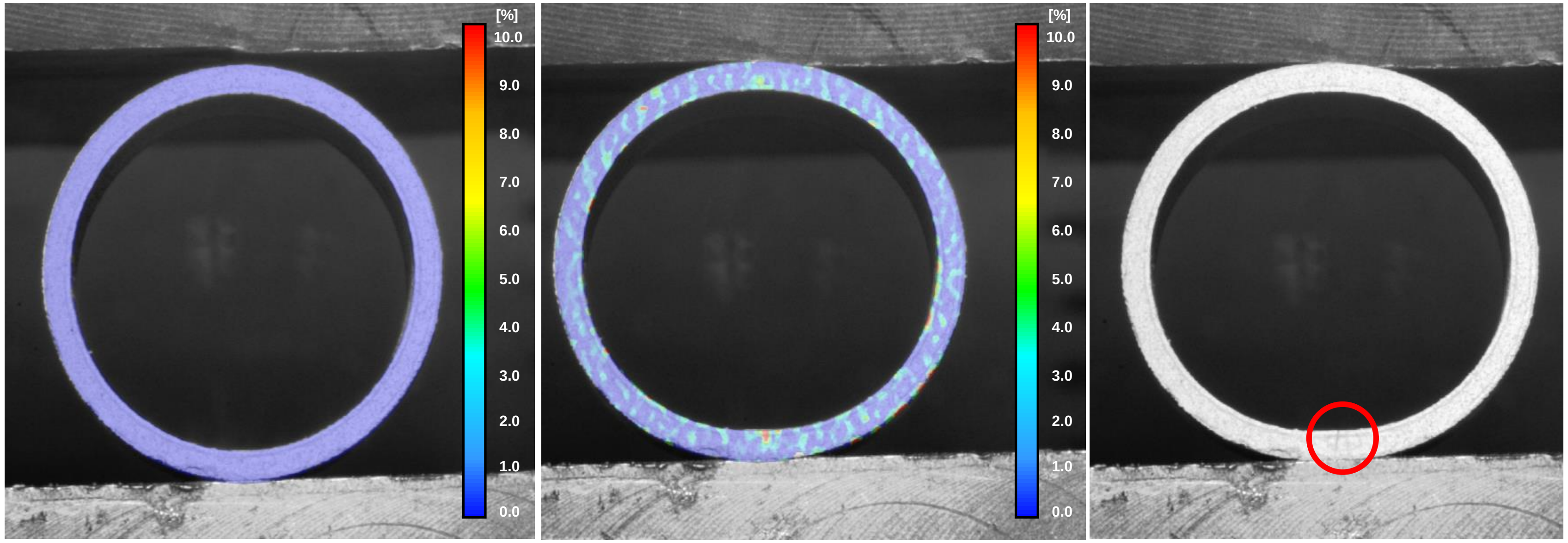
- **Thickness, oxygen content in prior-β, fracture toughness of oxidized cladding were compared between two claddings**

- **None of parameters seemed to be decisive as to explain the different ductility of two claddings**

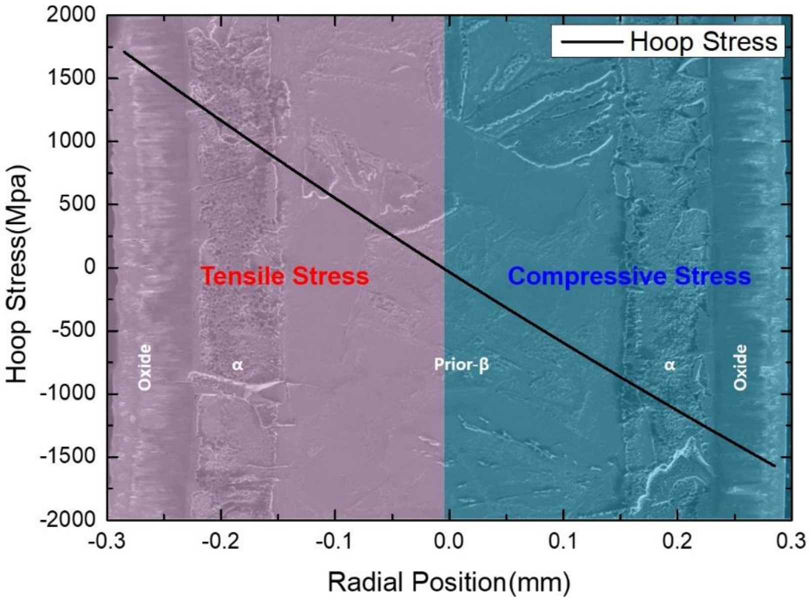
3. Results – Stress during Ring Compression Test



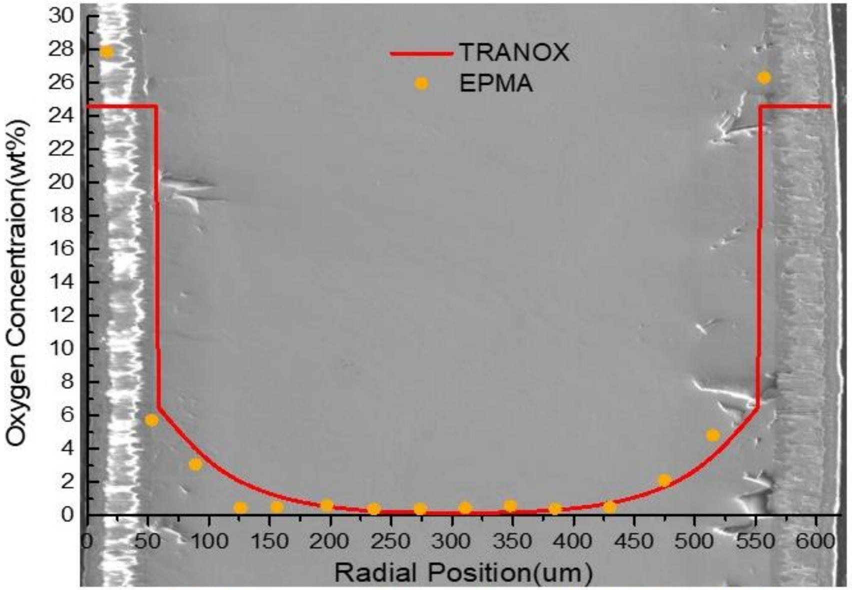
Reference Zircaloy-4 (925s, 27.38%)



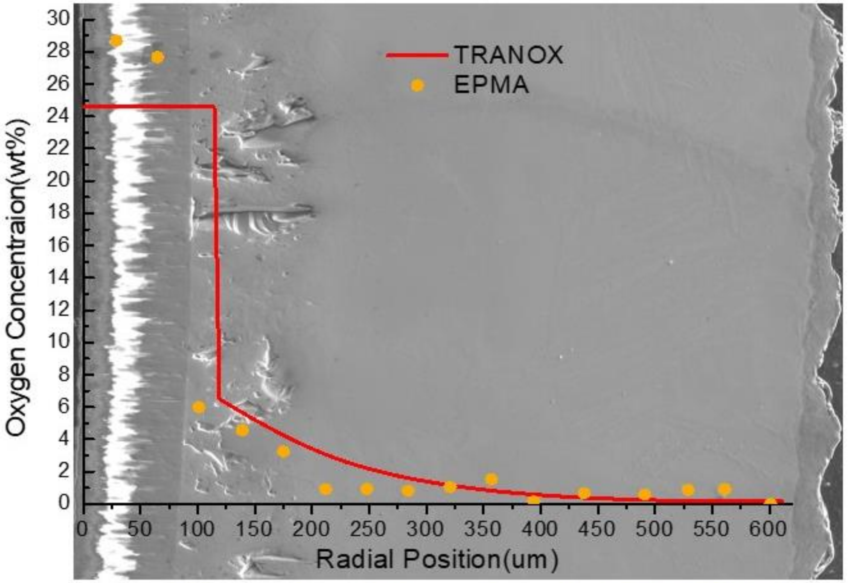
Cr-coated Zircaloy-4 (925s, 13.83%)



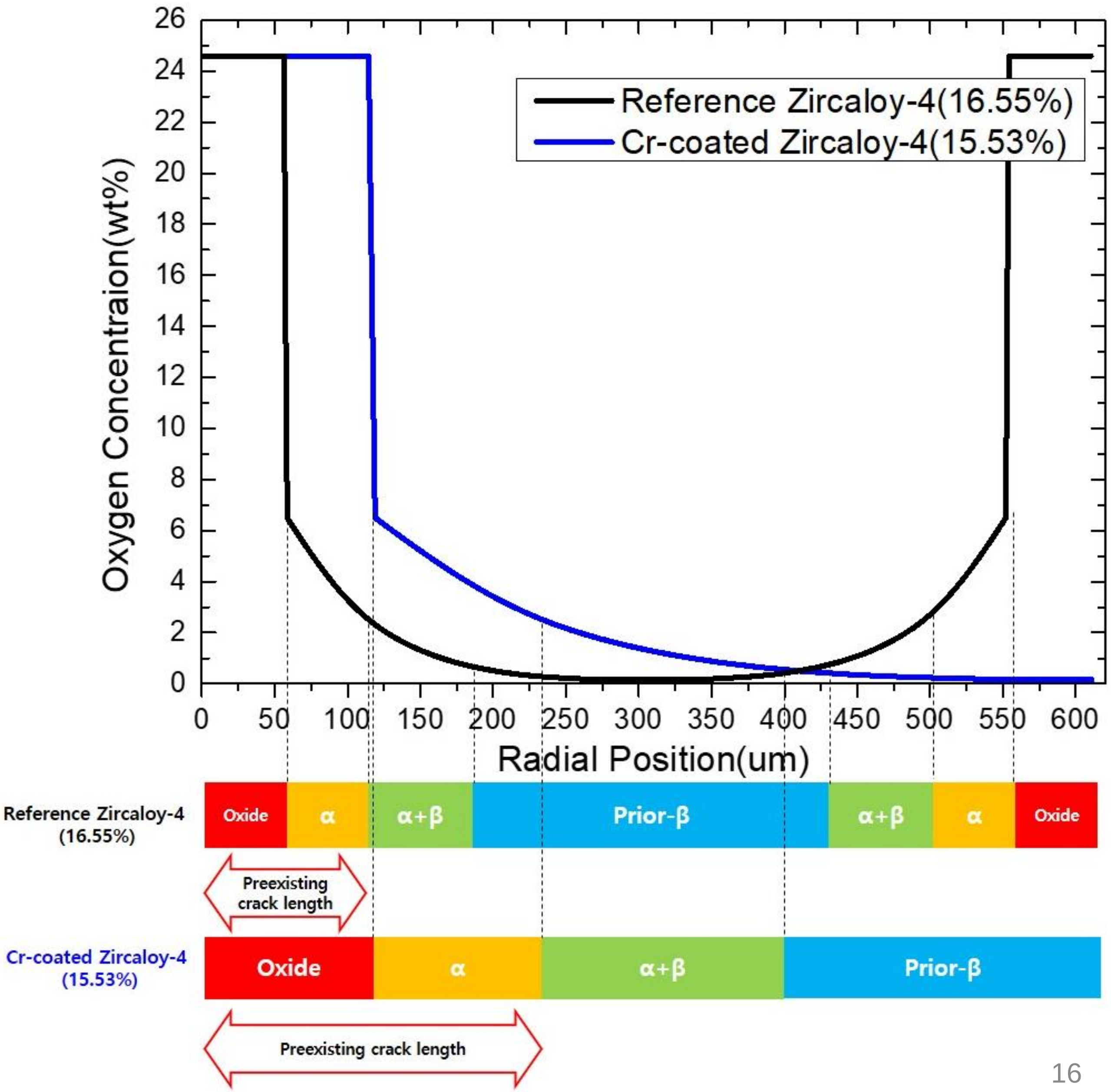
- The difference then should be found in the characteristic of RCT
- Hoop stress distribution of point where the load applied show the inner side of cladding is more dangerous
- Inner side preexisting crack was observed with DIC



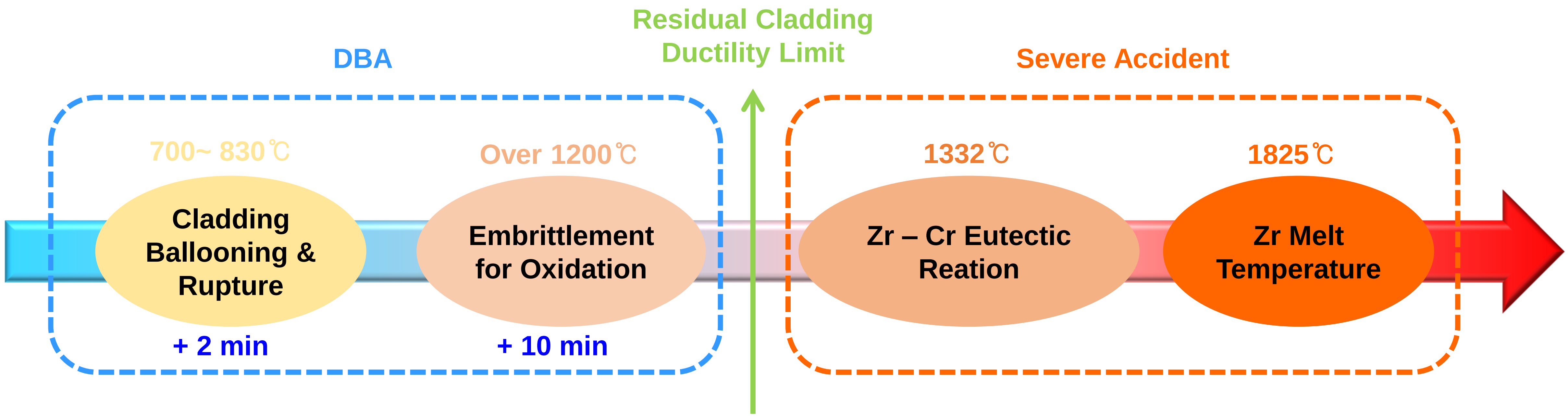
Reference Zircaloy-4 (16.55%)



Cr-coated Zircaloy-4 (15.53%)



3. Results – Accident Coping Time based on Cladding Ductility



- **Conservatively, the embrittlement limit could be applied as a signal for entering severe accident**

- **Total 12 min additional margin was secured with Cr coating in terms of DBA**

- **Two-sided Cr coating may be necessary to maximize the coating performance**

4. Conclusion

- ECR limit and additional time for accident mitigation time of Cr-coated cladding were derived from post-LOCA experiments

- Two-sided Cr-coated is an option for improvement to fully utilized the coating concept in terms of cladding embrittlement and core melting

- Accurate ductility assessment should be conducted and quantitative limit based on ductility should be set for the two-sided Cr-coated cladding, and the different brittle mechanism should be analyzed

5. Acknowledgement

- **This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety(KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission(NSSC) of the Republic of Korea. (No. 2101051)**

- **The Cr-coated cladding was supported by Koroush Shirvan and Bran Philips of Massashusetts Institute of Technology(MIT)**