Investigation of Degradation Mechanisms of Cr-coated Zirconium Alloy Cladding in Reactivity-Initiated Accident (RIA)

Dr. Woo Hyun Jung

Assistant Scientist, University of Wisconsin-Madison

Apr. 16, 2024

Project Team

- **University of Wisconsin, Madison (UW, Lead organization)**
  - Dr. WooHyun Jung (Lead PI)
  - Dr. Hwasung Yeom (Co-PI)
  - Dr. Kumar Sridharan (Co-PI)
  - Tyler Dabney (graduate student)
- **University of Illinois, Urbana-Champaign (UIUC)**
  - Dr. Brent Heuser
- **Nuclear Regulatory Commission (U.S. NRC)**
  - Ms. Michelle Bales
- **NSUF Technical Lead (INL)**
  - Dr. David Kamerman

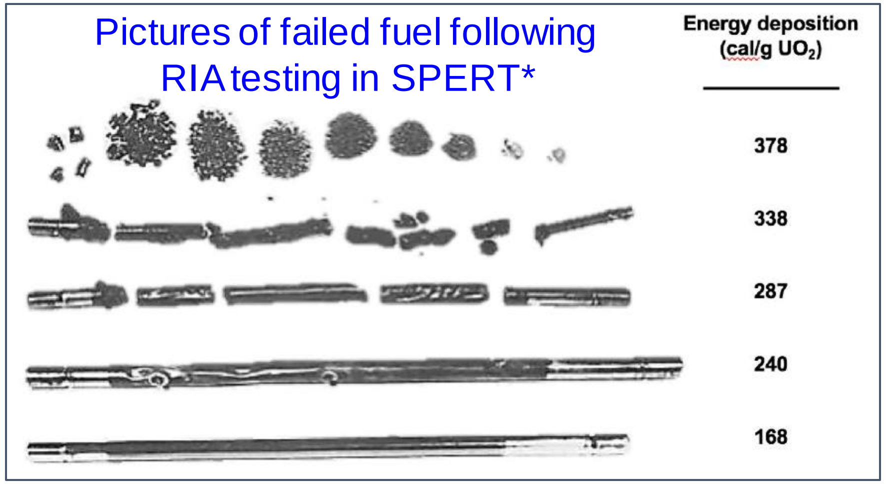
Background and Motivation

Data Gaps for Response of ATF Cr-coated Zr-alloy Cladding under Power Transient Conditions (RIA)

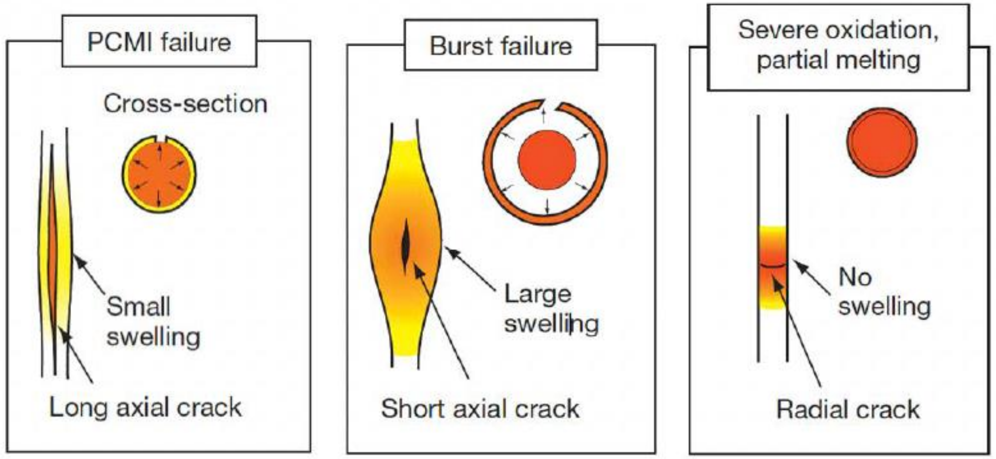
- **Reactivity-Initiated Accidents (RIA)**
  : Power transients in LWRs by sudden reactivity increase due to rapid control rod ejection

- **Data Gaps for ATF**
  : Many reports identify data gaps for licensing and severa l <u>performance criteria of Cr-coated cladding under RIA</u> including:
  - ✓ *Performance above Cr-Zr eutectic temperature (1332 °C)*
  - ✓ *Post-quench ductility*
  - ✓ *Coating integrity during swelling/rupture*
  - ✓ *Transient boiling phenomena*

Pictures of failed fuel following RIA testing in SPERT*



Three failure modes in RIA transients**



Project Objectives and Status

❖ Investigation of thermal, mechanical, and irradiation response of **Cr-coated Zr-alloy claddings** (Cold spray, PVD) under RIA conditions, **in comparison to uncoated Zr-alloy cladding** to demonstrate various cladding failure modes at the later phase transient (post-DNB)

Fabrication of Prototypical Cr-coated Zr-alloy Cladding Tubes
- Zircaloy-4 tube substrate
- Cold spray Cr coatings
- PVD Cr coatings

Test Train Design and Manufacturing
- Design and fabrication of INL's MARCH-SERTTA test capsule

Neutron Irradiation at TREAT
- Test variables: Nuclear energy deposition, rodlet internal pressure
- Test measurement: Cladding temperature, rod internal pressure, capsule pressure, cladding axial expansion, etc

1. Uncoated : Done
2. Cr-coated : Sep. 2024

PIE Experiment
- Non-destructive examination: Neutron radiography, visual inspection
- Microstructural analysis: OM/SEM-EDS, EPMA, SEM fractography
- Mechanical tests: Ring compression tests, three-point bend test

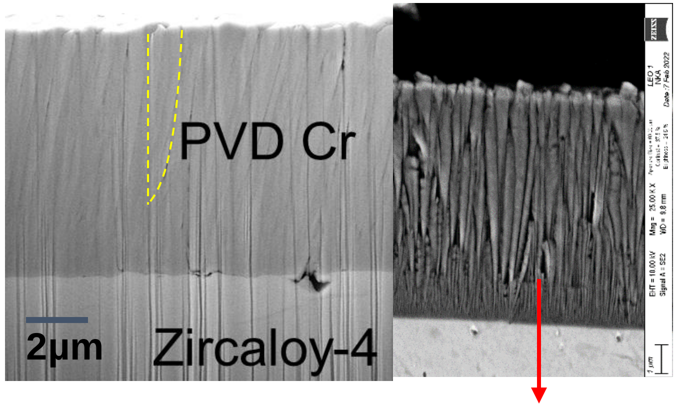
Mid 2025

Modeling of Failure Mechanism of Cr-coated Cladding
- Complete analysis and interpretation of the experimental data
- Mechanistic modelling on swelling and burst behavior of Cr-coated cladding under transient conditions

Rodlet & Irradiation Capsule Preparation

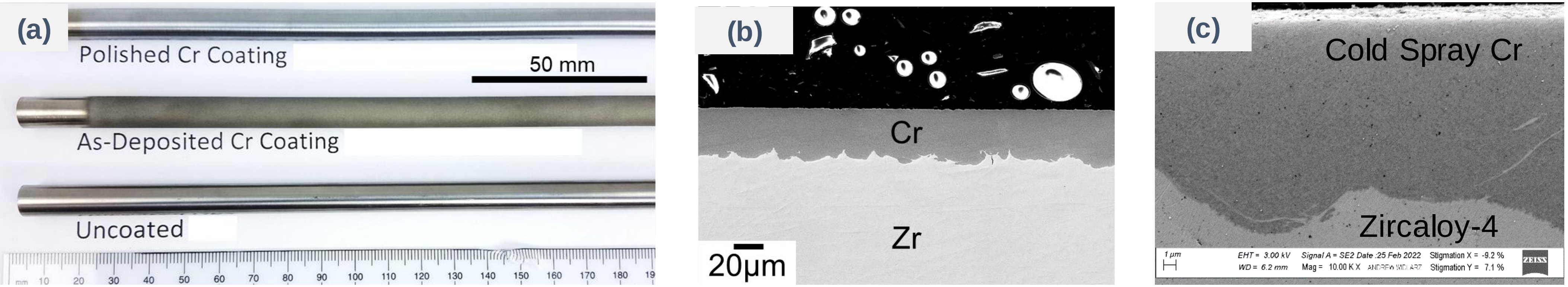
- **Framatome Zircaloy-4 tubes for substrate**
- **Two types of Cr coating have been developed**
  - **1. Cold spray technology at UW-M (~25 μm)**
    - **- Smooth homogeneous Cr-coating / Nanohardness: 5.34 GPa**
  - **2. Physical vapor deposition (PVD) at UIUC and external company (~8 μm)**
    - **- Columnar structure of Cr-coating / Nanohardness: 3.67 Gpa**
- **Tube dimensions**
  - - Total tube length: 5.5”
  - - Coated length: 4.25”

2. Cr-coated Zircaloy-4 tube by **PVD**
: Cross-sectional SEM images



Columnar structure of Cr-coating

1. Cr-coated Zircaloy-4 tube by **Cold Spray :** (a) visual images, (b) cross-sectional SEM image, and (c) High-magnification SEM image



Hypothesis of Cladding Failure MEchanisms

Hypothetical Response of Cr-coated Claddings in RIA Tests

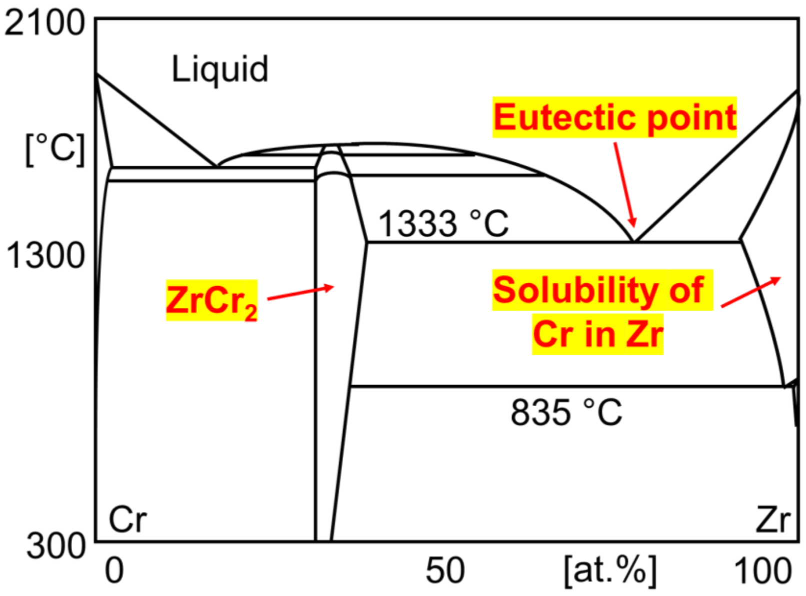
❖ In late phase transient, it is difficult to anticipate the failure modes due to the **multifactorial effects of Cr coating**

a) Cr coating mitigates **cladding-coolant interaction** (i.e., Oxidation of cladding outer surface)

b) **Adhesion strength** at coating/substrate interface would be changed by Cr-Zr intermetallic compound formation

c) **Mechanical properties** of the coated cladding would be altered by Cr-Zr interdiffusion and partial melting

d) **Rewetting behavior** of coated cladding are different from uncoated Zr-alloy due to evolution of surface characteristics



Cr-Zr binary phase diagram redrawn from published data [K. Zeng, 1993]

RIA Test Matrix

Total 5 RIA Tests Planned in 2023-2024

Test ID	Test Purpose	Sample ID	Target PCT (°C)	Target Energy Deposition (J/g)*	Rodlet Pressure (MPa)	Anticipated Failure Mechanism
NSUF-RIA-10 (CCZ-Zr-3)	**Reference test w/o severe oxidation**	**Zr-4**	**<1200**	**1000**	**2**	**Ballooning and Burst**
NSUF-RIA-11 (CCZ-Zr-2)	**Reference test w/ severe oxidation**	**Zr-4**	**>1332**	**1150**	**< 2 (leaked)**	**Severe oxidation + (Ballooning and Burst)**
NSUF-RIA-1 (CCZ-CS-1)	Quantifying eutectic melting, oxidation of CS Cr coating, DNB & film boiling	CS-Cr-Zr-1	>1332	1150	0.1	Partial melting due to Cr/Zr eutectic
NSUF-RIA-2 (CCZ-CS-2)	Effect of Cr-Zr interdiffusion on ballooning & burst **(Comparison w/ CCZ-Zr-3)**	CS-Cr-Zr-2	<1200	1000	2	Ballooning and Burst
NSUF-RIA-3 (CCZ-CS-3)	Effect of Cr/Zr eutectic melting on ballooning & burst **(Comparison w/ CCZ-Zr-2)**	CS-Cr-Zr-3	>1332	1150	2	Ballooning and Burst + Partial melting
~~NSUF-RIA-6* (CCZ-PVD-1)~~	~~Effect of Cr diffusion on ballooning & burst response in PVD coating **(Comparison w/ CCZ-CS-2)**~~	~~PVD-Cr-Zr-2~~	~~<1200~~	~~850~~	~~2~~	~~Ballooning and Burst~~

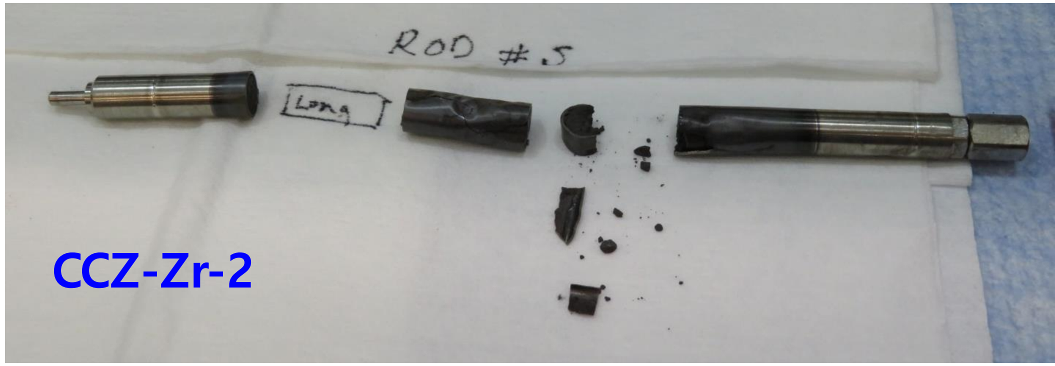
Done

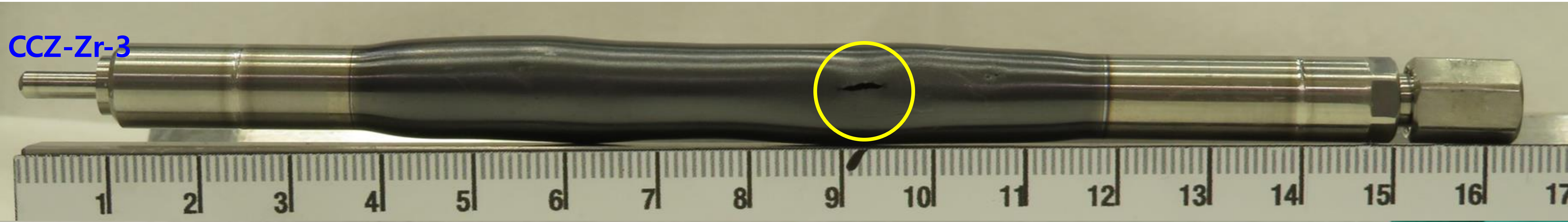
- RIA test for the PVD sample is canceled due to the budget limitation
- Target Energy Deposition is determined based on the analysis of the INL-TREAT team with past data
- In CCZ-Zr-2 test, there was a pressure leakage in the rodlet (< 2MPa)
- **RIA tests** for CS Cr-coated rodlets are planned in **September 2024**
- **PIE** is planned to be finished by **September 2025** (1-year NCE is approved)

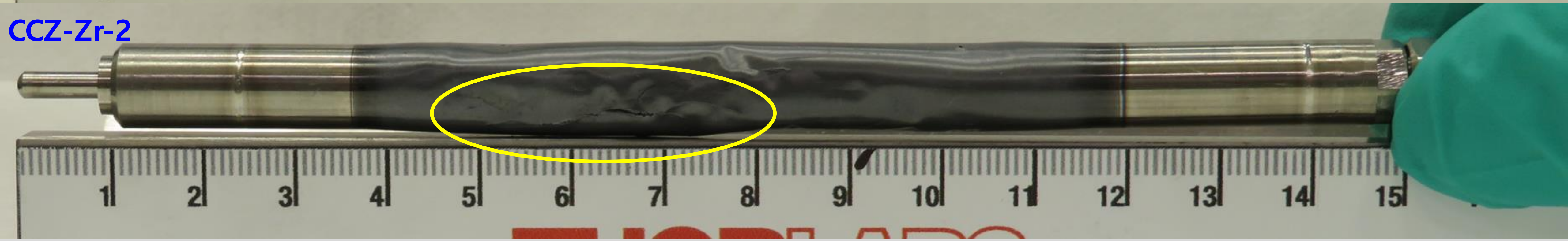
RIA Test Results

Visual observation for post-irradiation CCZ-Zr-3 & CCZ-Zr-2

- CCZ-Zr-3
  - Ballooning and burst was observed showing a burst opening
- CCZ-Zr-2
  - Severe oxidation was observed showing very brittle characteristic
  - Unclear if the ballooning and burst was occurred



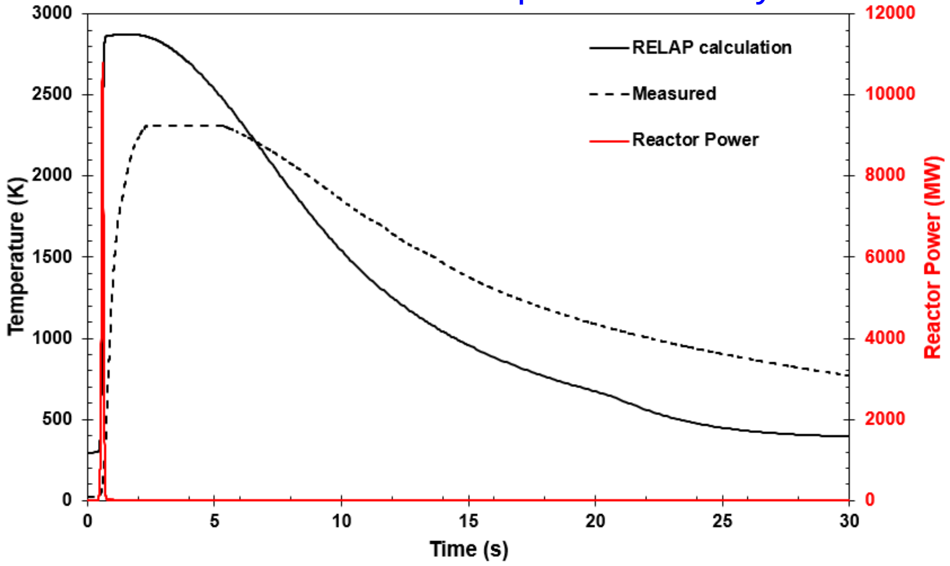




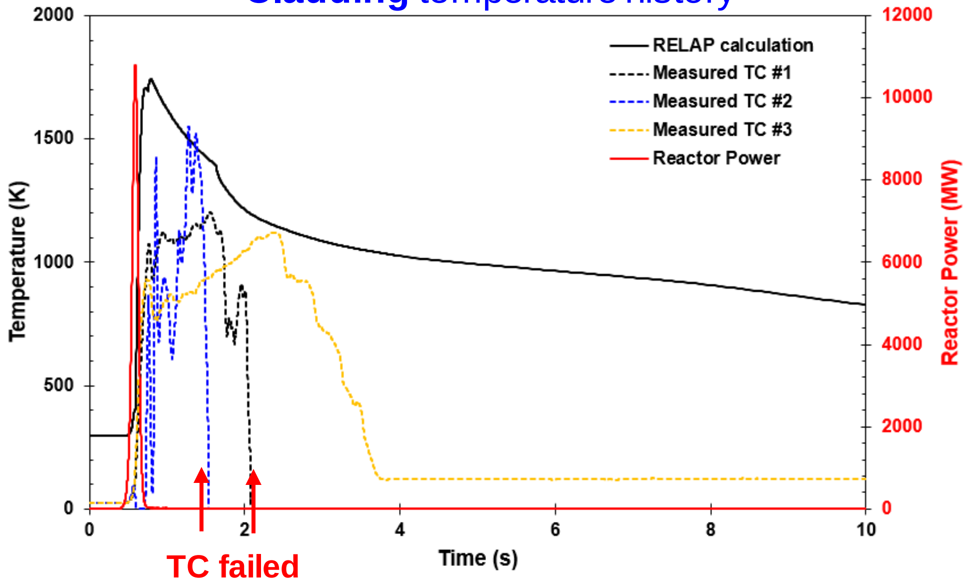
RIA Test Results

- **RELAP analysis**
- **CCZ-Zr-3 (1000J/g & 2 MPa)**
  - Centerline fuel temperature : Higher peak temperature than measured data due to TC's thermal response
  - Cladding temperature : RELAP results shows higher temperaturethan the Cr-Zr eutectic point with PCT of **1470 °C** (Higher than Cr-Zr eutectic point for **0.4 seconds**)
- **CCZ-Zr-2 (1150J/g & <2 MPa)**
  - PCT : 1645°C (Higher than Cr-Zr eutectic point for **0.65 seconds**)
- **PCT varies according to the multiplication factor in RELAP analysis**
  - With the conservative factor, PCT of CCZ-Zr-3 is **1725 °C** and of CCZ-Zr-2 is **1829 °C**

Fuel centerline temperature history



Cladding temperature history



RIA Test Plan and Future Works

RIA Test & PIE plan

Project Technical Task	2024				2025			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Sample preparation and Transient irradiation tests: Two uncoated rodlets								
Disassembly and basic inspections for two irradiated uncoated rodlets								
Transient irradiation tests: Three CS Cr-coated rodlets								
RELAP analysis for thermal behavior of rodlets								
PIE tests: Neutron radiography, visual inspections, mechanical tests, and microstructural analysis (SEM fractography, Cross-sectional SEM, EPMA)								
Data analysis and modeling								

- As overall RIA tests and PIE is delayed from our original plan, one-year NCE request is approved and the project end date is **Sep. 2025**

- **Our final goal is to investigate the failure mechanism of Cr-coated cladding under RIA**

Thanks for your attention

Questions?

WooHyun Jung

University of Wisconsin-Madison

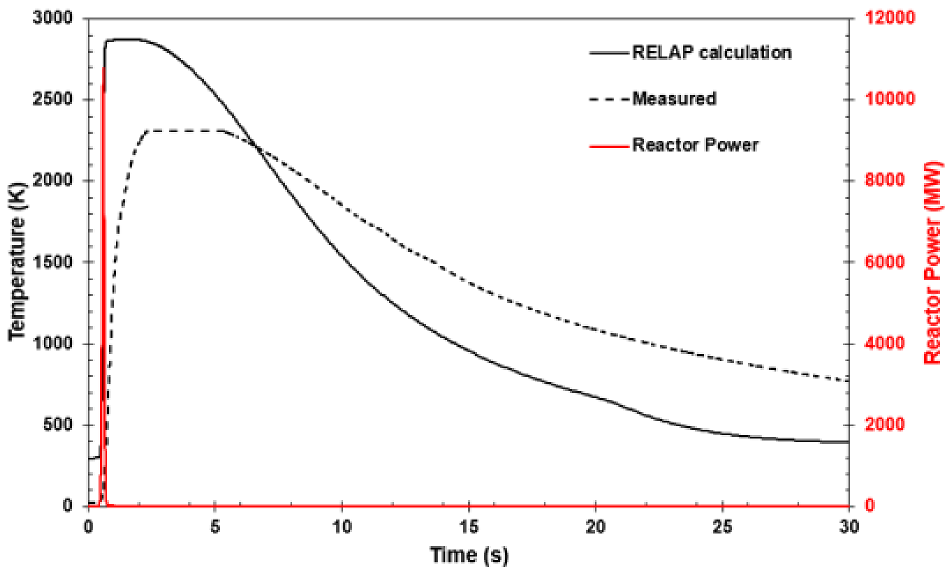
wjung37@wisc.edu

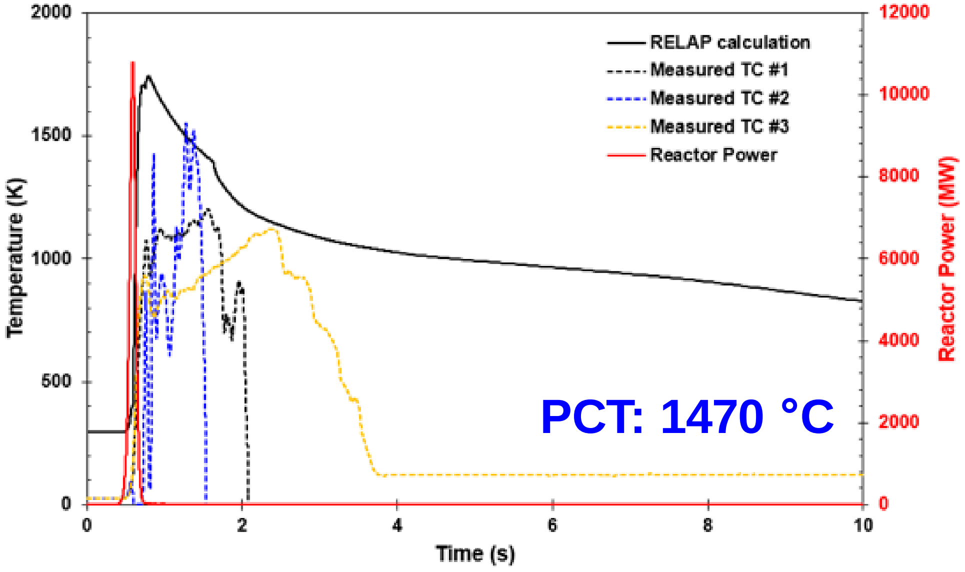
RIA Test Results

Fuel centerline temperature

Cladding temperature

<CCZ-Zr-3>





<CCZ-Zr-2>