Analysis of metallic sim-debris of the bundle degradation tests

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Collaborative Laboratories for Advanced Decommissioning Science

Introduction

Accident at Fukushima-1,
Photo of the Unit 3 taken on the 17th of March 2011 from a helicopter

Decommissioning preparation in Unit 2*:*
Pedestal debris inspection Feb. 2019

TEPCO decided to do a complete decommissioning of 1F damaged BWRs

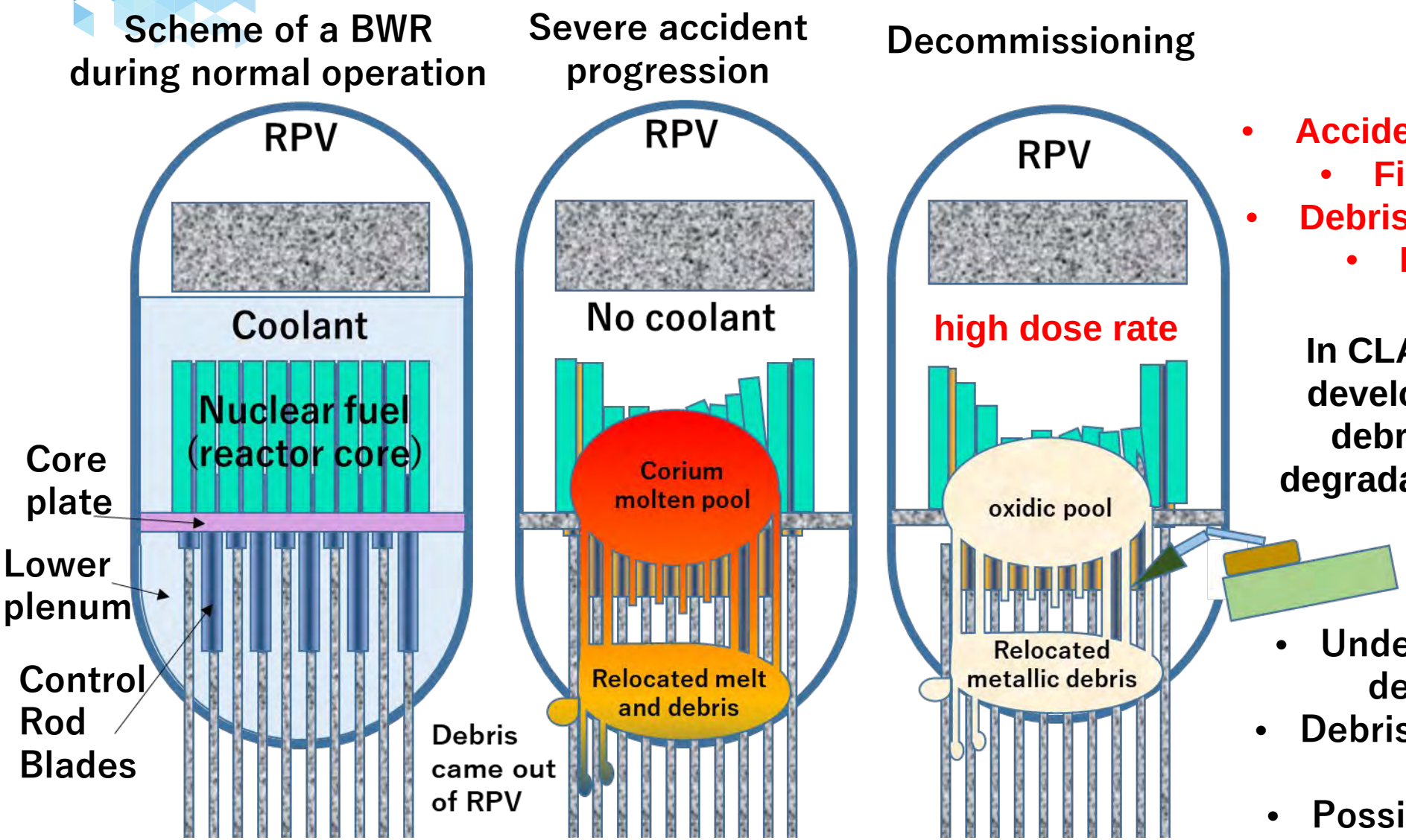
CLADS is performing R&D to find new solutions for the decommissioning challenges

Main challenges:

- **Development of the decommissioning technologies for the damaged reactors of the 1F**
- **Uncover the debris properties and distribution inside of the RPV and PCV of the 1F reactors**

#1 TOKYO ELECTRIC POWER COMPANY - Photos and Videos Library｜ Unit 3,Uniit4 of Fukushima Daiichi Nuclear Power Station (pictured from a helicopter) (tepco.co.jp)
#2 TOKYO ELECTRIC POWER COMPANY - Photos and Videos Library｜ Fukushima Daiichi Nuclear Power Station Unit 2 Primary Containment Vessel Investigation Results - Preliminary Report on February 13 - (tepco.co.jp)

General understanding of the accident progression



Uncertainties

- **Accident progression in BWR**
- **Final debris location**
- **Debris chemical composition**
- **Debris properties**

In CLADS a test approach is developed for studying sim-debris after control blade degradation tests to reduce the uncertainties

The goals

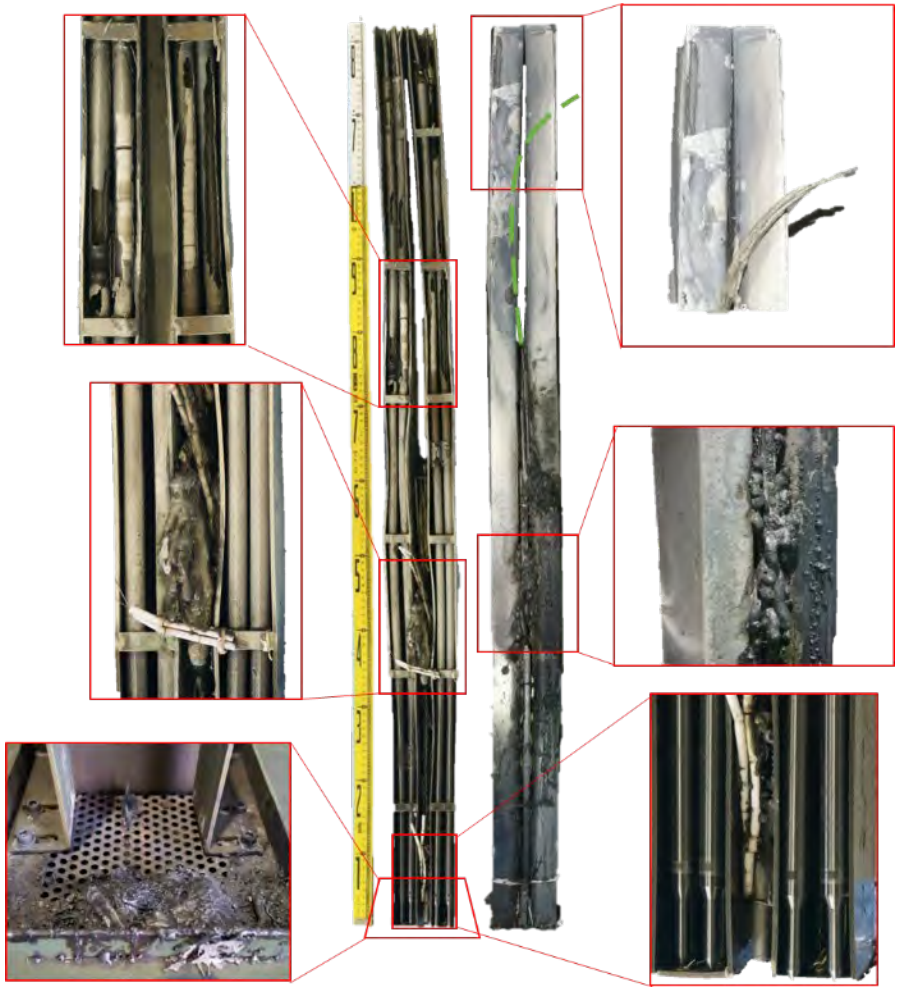
- **Understanding of BWR core degradation scenarios**
- **Debris formation mechanisms in BWRs**
- **Possible properties of debris under 1F-like conditions**

Research results on <u>debris distribution and properties would help</u> in choosing an effective decommissioning strategy and equipment

10 years of R&D for the problem of 1F Severe Accident

ID Date	Sample features	Gas	Initial rate, K/s	Maximum T, K
CRFCB-1 20 Feb 2014	1 Blade 2 Channel boxes	Ar	2	1688
CRFCB-2 20 Feb 2014	1 Blade 2 Channel boxes	-	-	Not tested
CRFCB-3 24 Feb 2014	1 Blade 2 Channel boxes	Ar	2	1807
CRFCB-4 26 Feb 2014	1 Blade 2 Channel boxes	Ar	2	1801
CR-1 3 Mar 2014	1 Blade	Ar	2	1713
CRFCBF-01 16 Dec 2014	1 Blade 2 Channel boxes 20 claddings	Ar	2	1936
CRFCBF-02 18 Dec 2014	1 Blade 2 Channel boxes 20 claddings	Ar	2	1818
CRFCBF-03 2 Mar 2016	1 Blade 2 Channel boxes 20 claddings	Ar Steam	2	1907
CRFCBF-04 7 Mar 2016	1 Blade 2 Channel boxes 20 claddings	Ar Steam	2	1910
CLADS-MADE-01 22 Mar 2018	1 Blade 2 Channel boxes 20 claddings	Ar Steam+ Starvation	0.4	1750
CLADS-MADE-02 18 Mar 2019	1 Blade 2 Channel boxes 16 claddings	Ar Steam	0.6	1880
CLADS-MADE-03 12 Mar 2020 (post-test investigation)	1 Blade 2 channel boxes 16 claddings	Ar Steam	1	1872
CLADS-MADE-04 15 Sep 2021	1 Blade 2 channel boxes 16 claddings	Ar Steam+ Starvation	0.6	1900

CLADS-MADE-01 test (2018)*

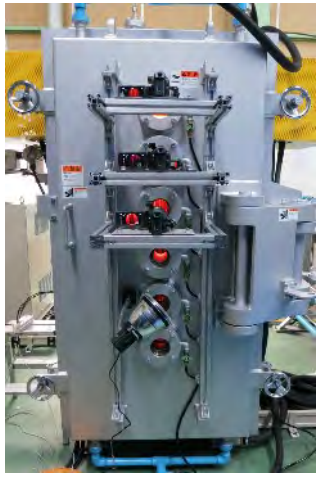


*A. Pshenichnikov, S. Yamazaki, D. Bottomley, Y. Nagae, M. Kurata *Features of a control blade degradation observed in situ during severe accidents in boiling water reactors*, Journal of Nuclear Science and Technology, Vol.56, No.5 (2019), P.440–453.

1F related severe accidents research using LEISAN facility

Large-scale Equipment for Investigation of Severe Accidents in Nuclear reactors

LEISAN outer appearance



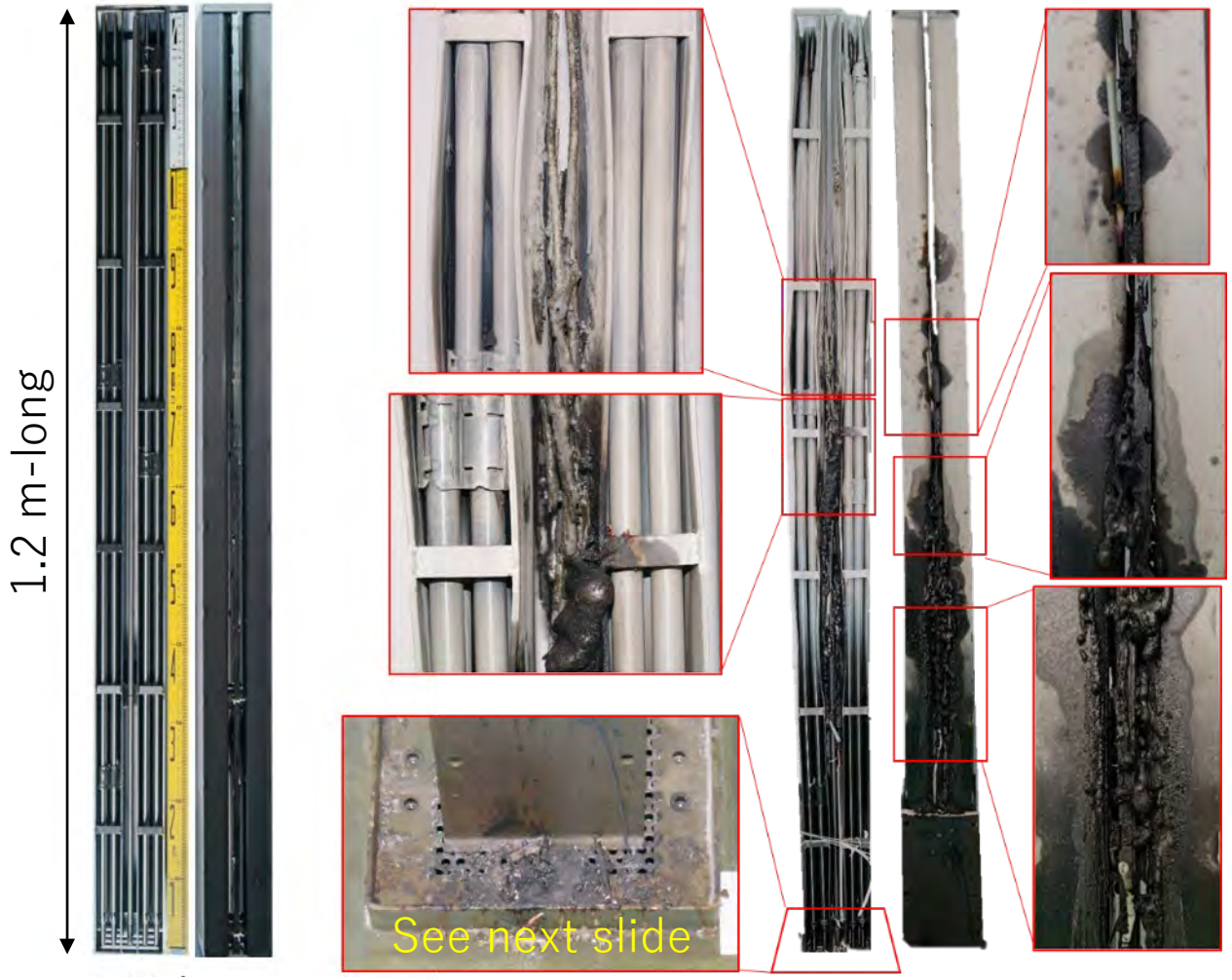
2014-2015

2016-present

Inside the furnace

2014-2015 2016-2019 2020-present

CLADS-MADE-02 steam-rich conditions for 1F Unit 3 (2019)*

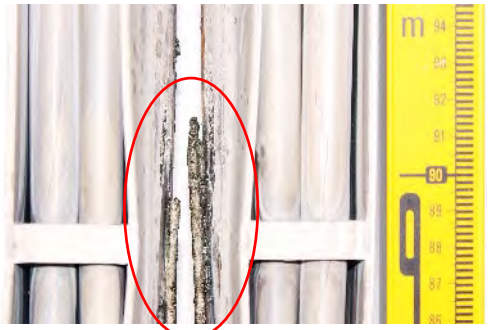


*A. Pshenichnikov, M. Kurata and Y. Nagae A BWR control blade degradation observed in situ during a CLADS-MADE-02 test under Fukushima Dai-Ichi Unit 3 postulated conditions, Journal of Nuclear Science and Technology, https://doi.org/10.1080/00223131.2021.1906777

Mock-up of BWR assembly after CLADS-MADE-02 test

before after

Only oxidized
T > 1500 °C



Remaining control rod
1400 < T < 1500 °C

Solidified melt in the
≈ 1200 < T < 1400 °C

Lower part Slight oxidation
T < 1174 °C

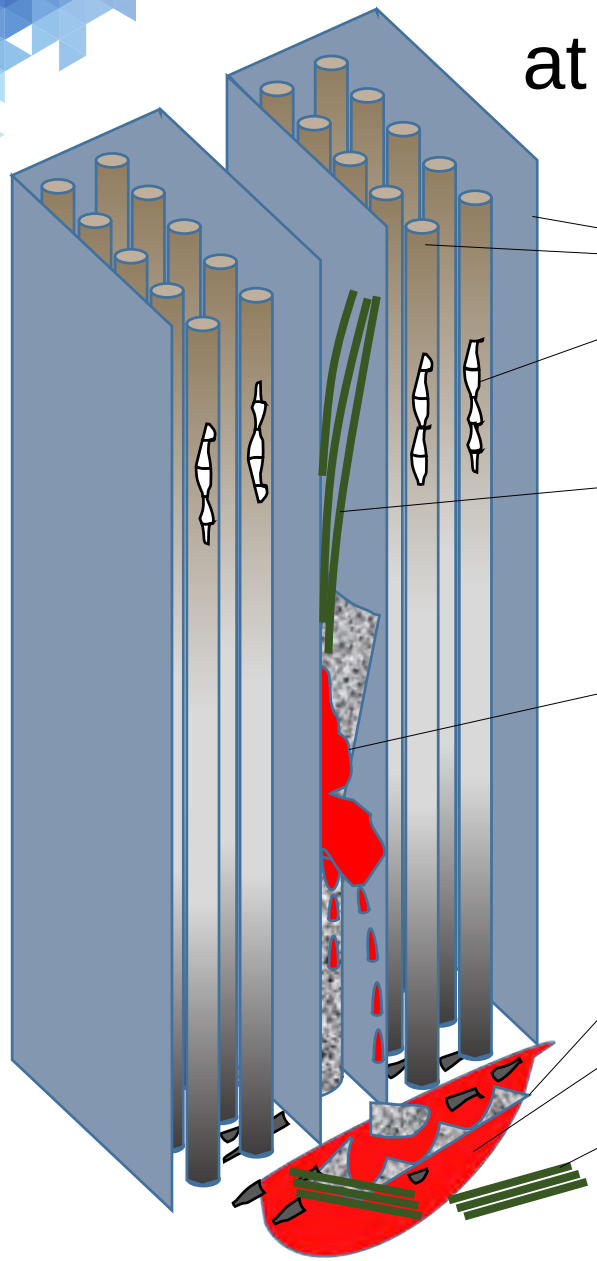
Sample Support
T < 1000 °C

Damaged control blade parts

A 10 mm-thick pile of the control blade melt

More details in Proceedings of the ICONE 28, 4-6 Aug 2021, **Paper No. ICONE28-65129**

Three types of debris at the beginning of an accident in BWRs



Post-test schematic 3D view

Type II Oxidic debris
(ZrO_2 or UO_2 or mixture of them + minor oxides + FPs)

Type III Degraded rests of a control blade or assembly parts
(may contain original chemical composition
but changed microstructure)

Type I Molten and solidified metallic debris blockage (chemical composition?)

Type II Relocated oxidised debris

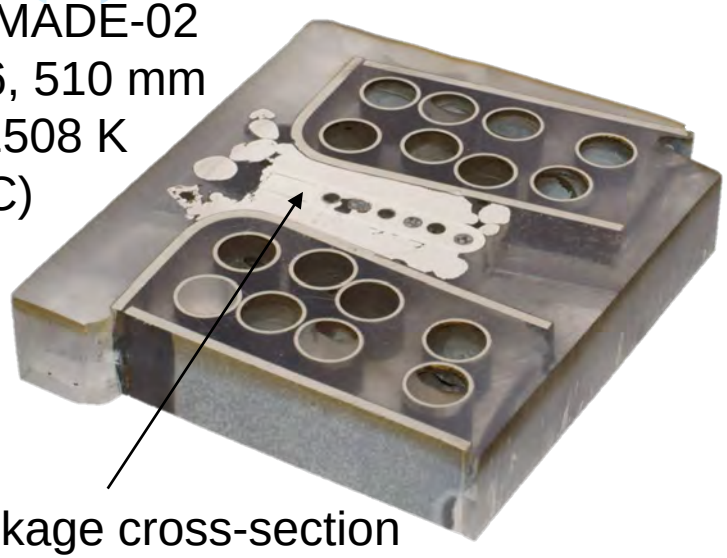
Type I Relocated and solidified metallic debris

Type III Relocated parts of a control blade

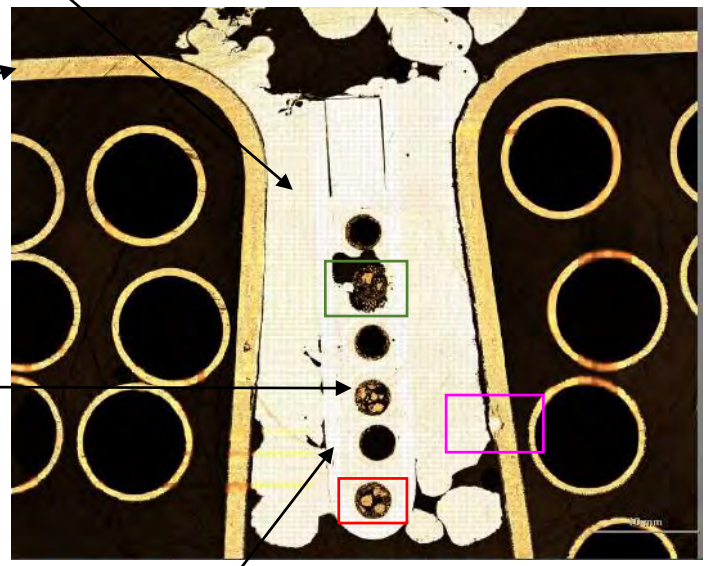
A. Pshenichnikov, Y. Nagae and M. Kurata, *On the degradation progression of a BWR control blade under high-temperature steam-starved conditions*, Mechanical Engineering Journal, Vol.7, No.3 (2020), P.1-10.

Post-test control blade debris characterization

CLADS-MADE-02
section 6, 510 mm
Tmax= 1508 K
(1235 °C)



Melt blockage cross-section

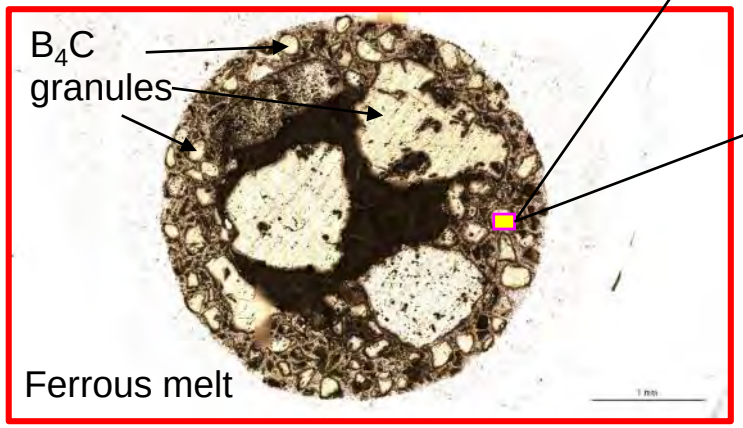


Channel box
(Zircaloy-4)

Ex-tubes
with B_4C
now melted

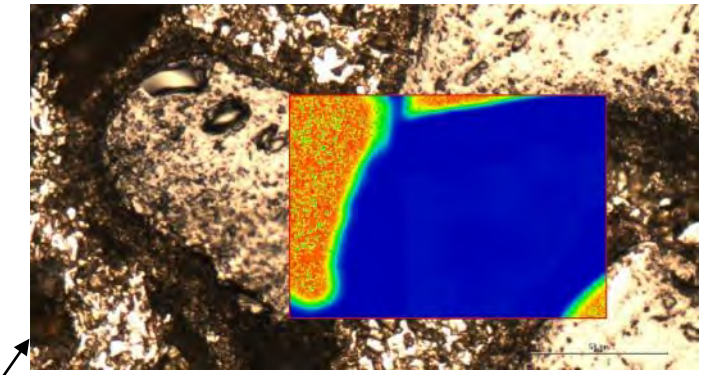
control blade covered by melt

Optical microscopy

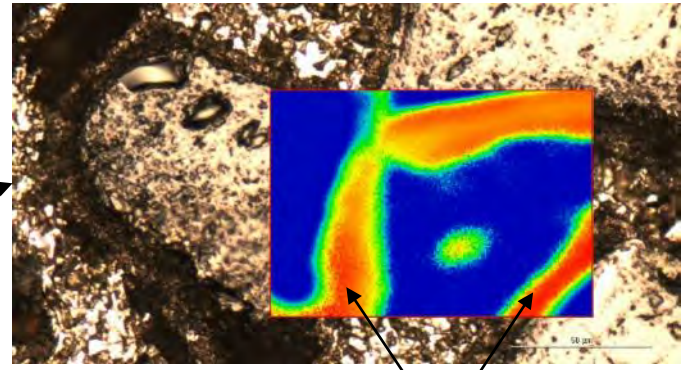


Raman spectroscopy

Remaining B_4C



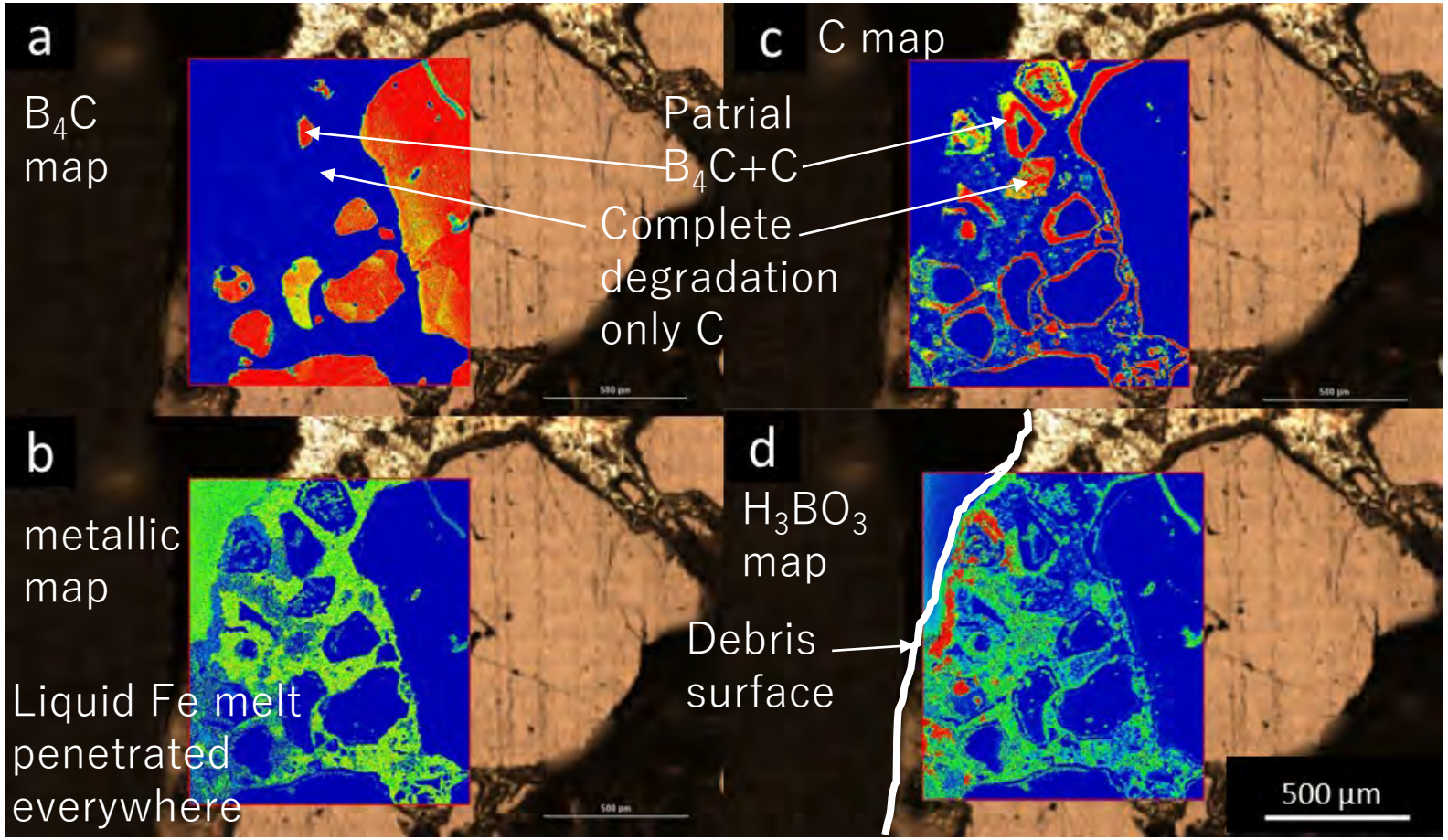
New-formed graphite



Area reacted with ferrous melt
B_4C turned into graphite

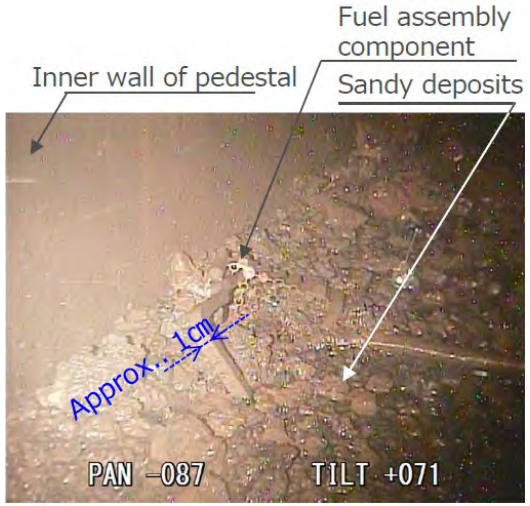
Control blade debris characterization by Raman spectroscopy*

762 mm, Tmax = 1663 K (1390 °C)

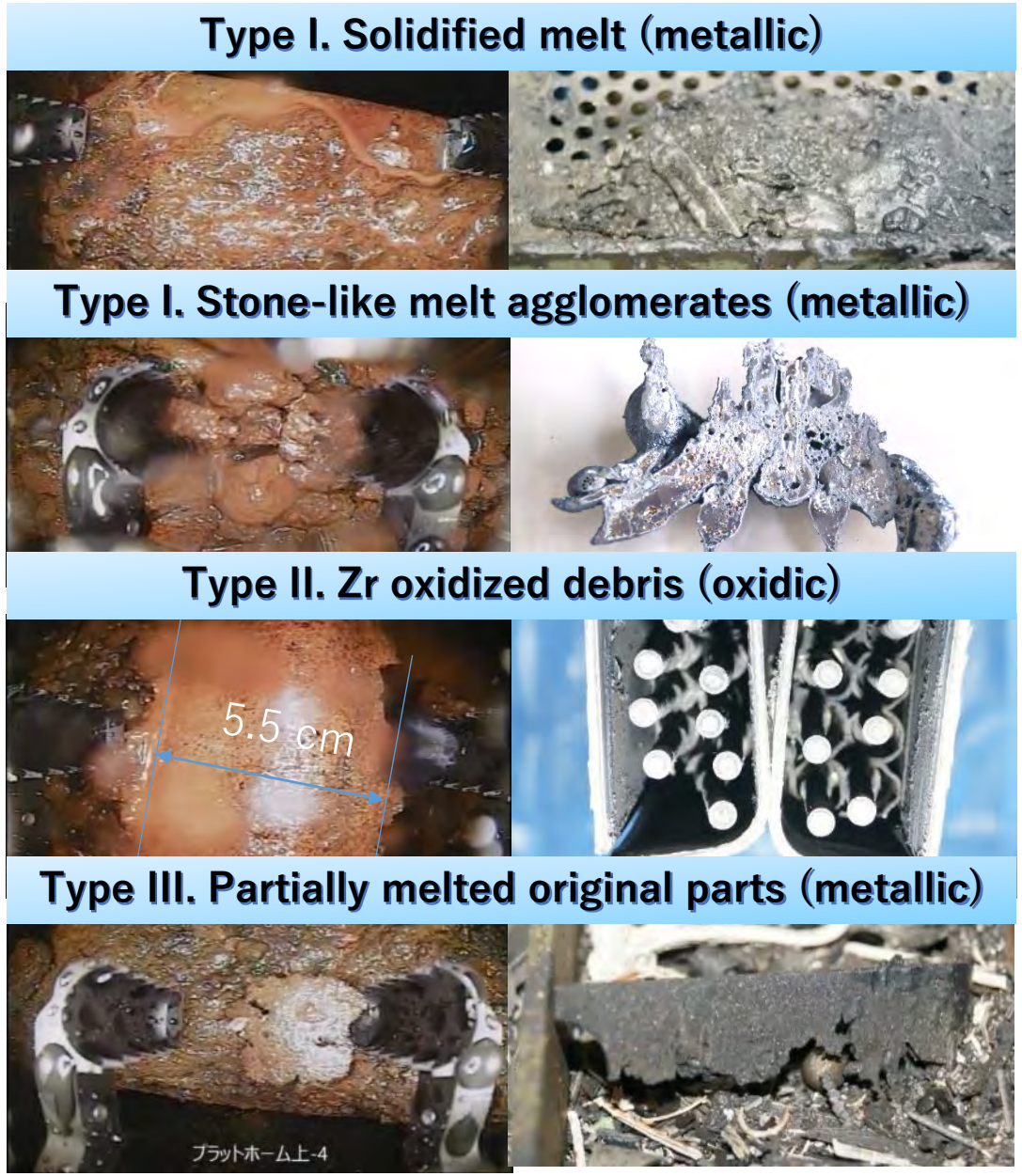


*In Proceedings of the TopFuel 2021, 24-28 Oct 2021 (online). Paper accepted. To be published.
Raman investigation of the CLADS-MADE-02 test debris to confirm the mechanism of the volatile and non-volatile boron compounds formation
Anton Pshenichnikov, Yuji Nagae, Masaki Kurata

Outcome: Comparison with the real debris



Tokyo Electric Power Company Holdings, Inc. *2019/02/14Fukushima Daiichi Nuclear Power Station Unit 2 Primary Containment Vessel Internal Investigation*
Available from: https://www.tepco.co.jp/en/news/library/archive-e.html?video_uuid=vy9uep38&catid=61785



- **LEISAN facility**
- **CLADS-MADE tests**

A. Pshenichnikov, Y. Nagae and M. Kurata, Comparison of Fukushima Dai-Ichi Unit 2 observed debris with simulated debris from CLADS-MADE-01 control blade degradation test, **Journal of Nuclear Science and Technology**, 58:4, P.416-425 (2021)

Conclusion

- Sim-tests look promising for grasping the mechanisms of initial core melting on a large scale, in particular, for understanding of a BWR control blade degradation
- Over the last 10 years much of new data and insights were accumulated on the features of the high-temperature degradation of a preoxidized BWR bundle with a control blade under steam-starved and steam-rich conditions
- Post-test investigations revealed mostly three types of sim-debris
- Post-test characterization suggested that sim-debris need to be further investigated regarding their properties because same kind of metallic debris with B is possible also in the damaged 1F units
- Comparison of the sim-debris and the TEPCO HD 1F Unit 2 PCV investigation data showed many similarities between the outer appearance of the sim and the real debris, which is promising for study of the real debris formation mechanisms by using sim-tests

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Thank you for your attention