

EXPERIMENTAL INVESTIGATION OF VVER CLADDING IN HIGH TEMPERATURE ACCIDENT CONDITIONS

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BULGARIAN NUCLEAR SOCIETY
International Conference NUCLEAR ENERGY FOR THE PEOPLE
10- 13 September, 2018, Sveti Vlas, Bulgaria



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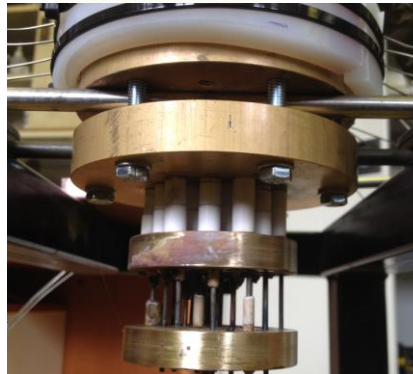
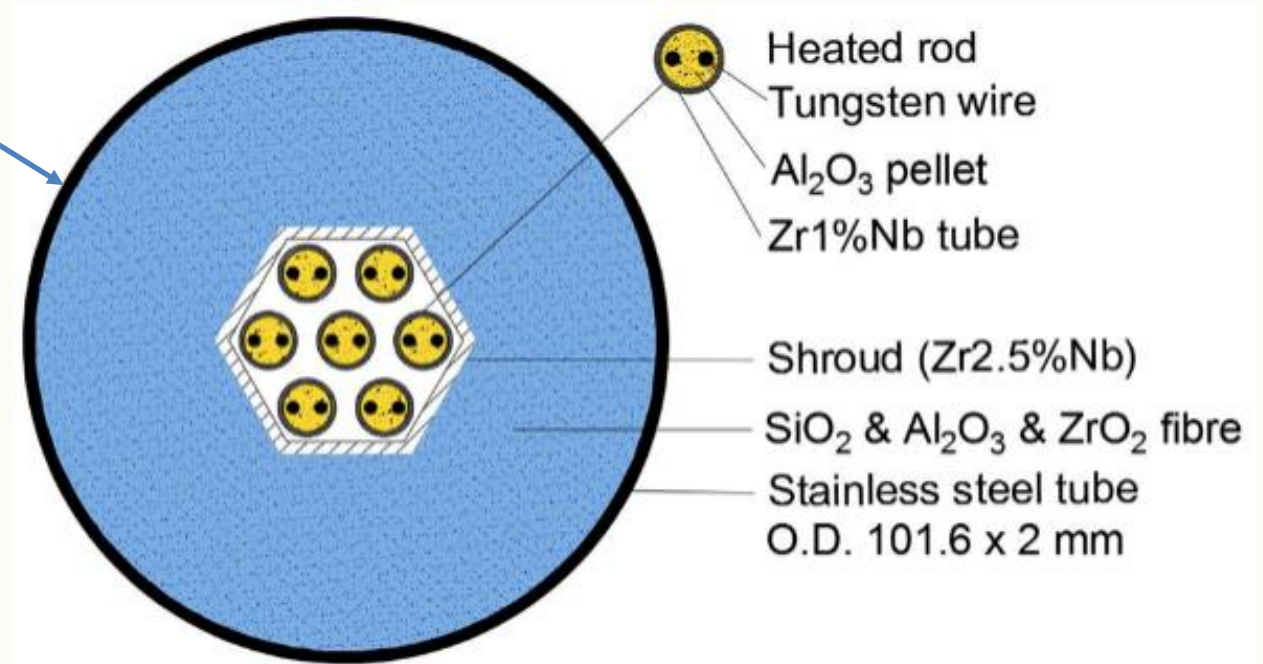
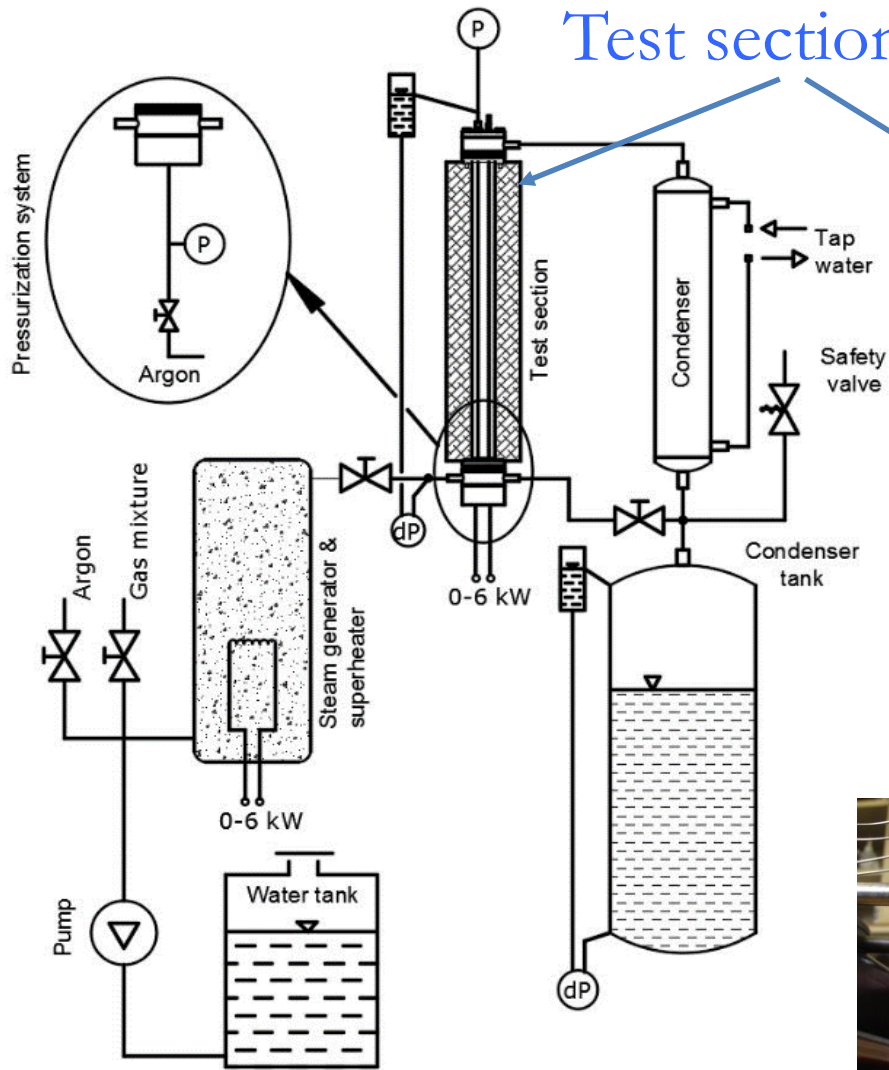
INTRODUCTION

- LOCA: high thermal and mechanical loads on fuel
 - Ballooning and bust
 - Oxidation
 - Embrittlement
- Scenarios: nominal power / shut-down reactor / spent fuel pool
 - Different temperature and pressure histories
- VVER reactors with E110 cladding
 - Traditional cladding: breakaway oxidation
 - Sponge based alloy: compact oxide scale
- CODEX-LOCA tests
 - Comparison of traditional and
 - sponge based E110 in integral tests



CODEX-LOCA TEST FACILITY

Test section with 7 rod bundle (3 E110 + 4 E110G)



SIMULATED LOCA SCENARIOS

- Temperature histories: the maximum reference temperatures were reached and the duration of the dry period covered the reference case.
- Fuel rod internal pressure: the maximum overpressure in the reference case (difference between fuel rod and coolant side pressures) was reached + different pressure values were set in the different fuel rods
- Main objectives:
 - Examination of cladding burst in scenarios close to design basis cases.
 - Investigation of cladding oxidation and hydrogen uptake in high temperature steam and their consequences on the embrittlement of Zr alloys.

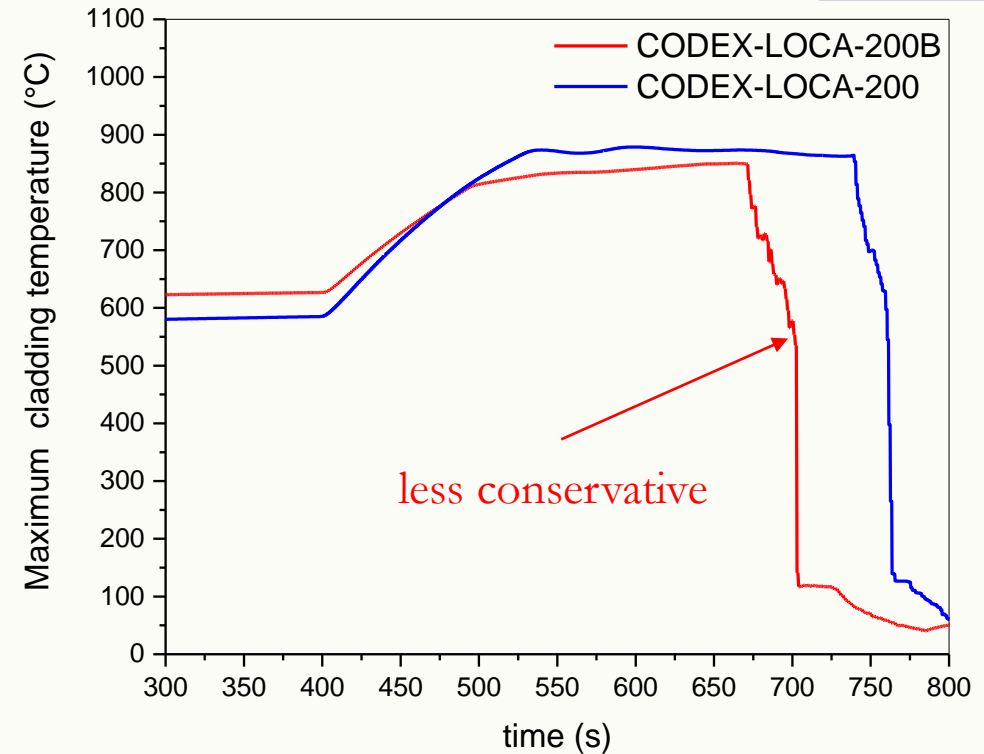
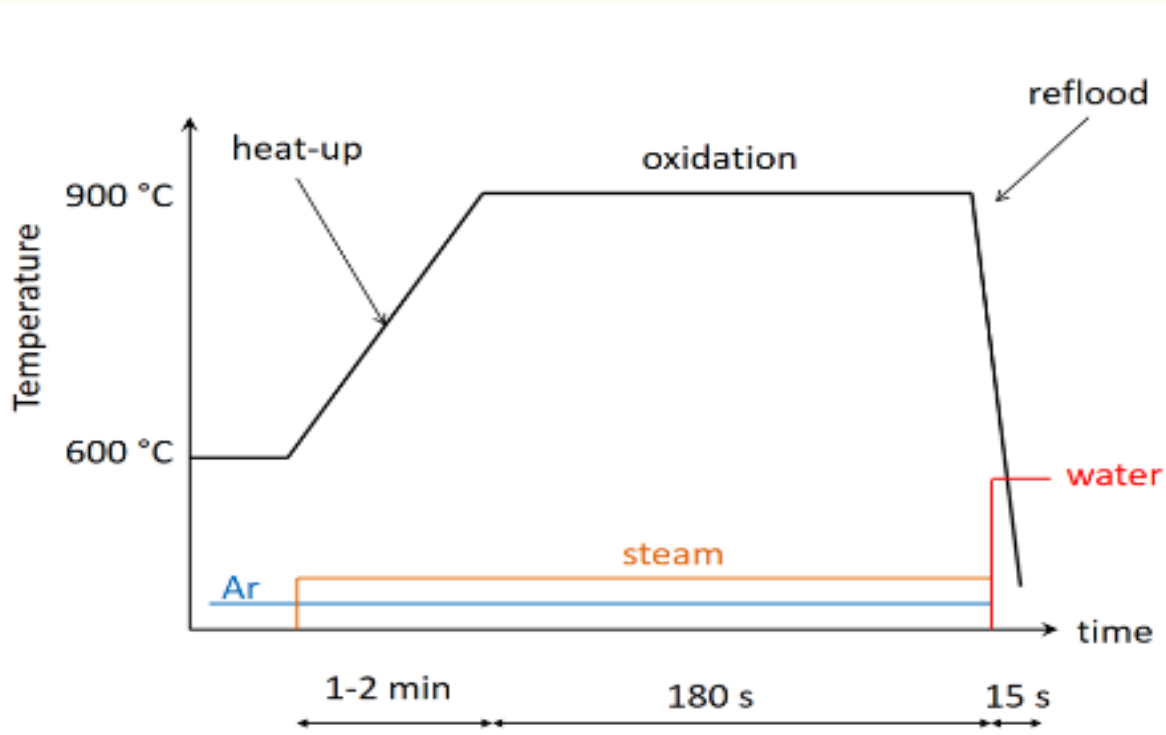
CODEX-LOCA TEST MATRIX

Test	Simulated conditions	Date
CODEX-LOCA-200	200% large break LOCA with conservative conditions	November 30, 2015
CODEX-LOCA-E4	Shutdown LOCA with limited availability of emergency cooling water	July 12, 2016
CODEX-LOCA-200B	200% large break LOCA	November 9, 2016
CODEX-LOCA-SFP1	Spent fuel pool LOCA with steam starvation and with limited availability of emergency cooling water	February 16, 2017
CODEX-LOCA-SFP2	Spent fuel pool LOCA with unlimited steam and with limited availability of emergency cooling water	July 3, 2017



SIMULATION OF 200% LARGE BREAK LOCA

Design basis
accident case



LOCA at nominal power reference case:

- 150 s dry period
- 900 °C in blowdown phase / 886 °C in oxidation phase
- 15.6 bar pressure difference hot rod (18 MWd/kgU)



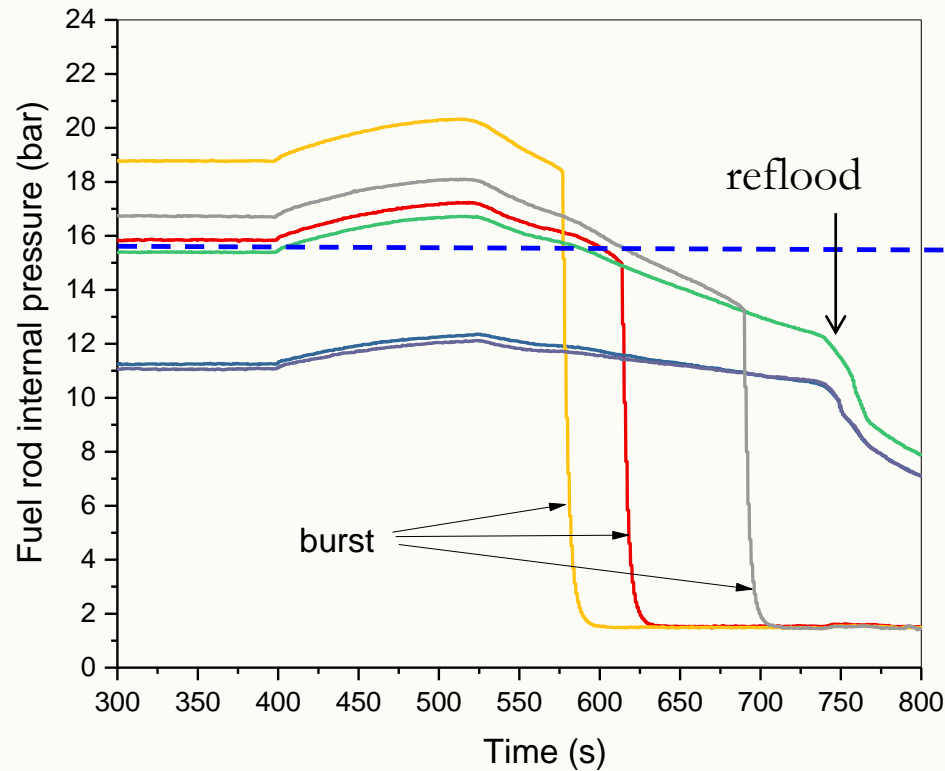
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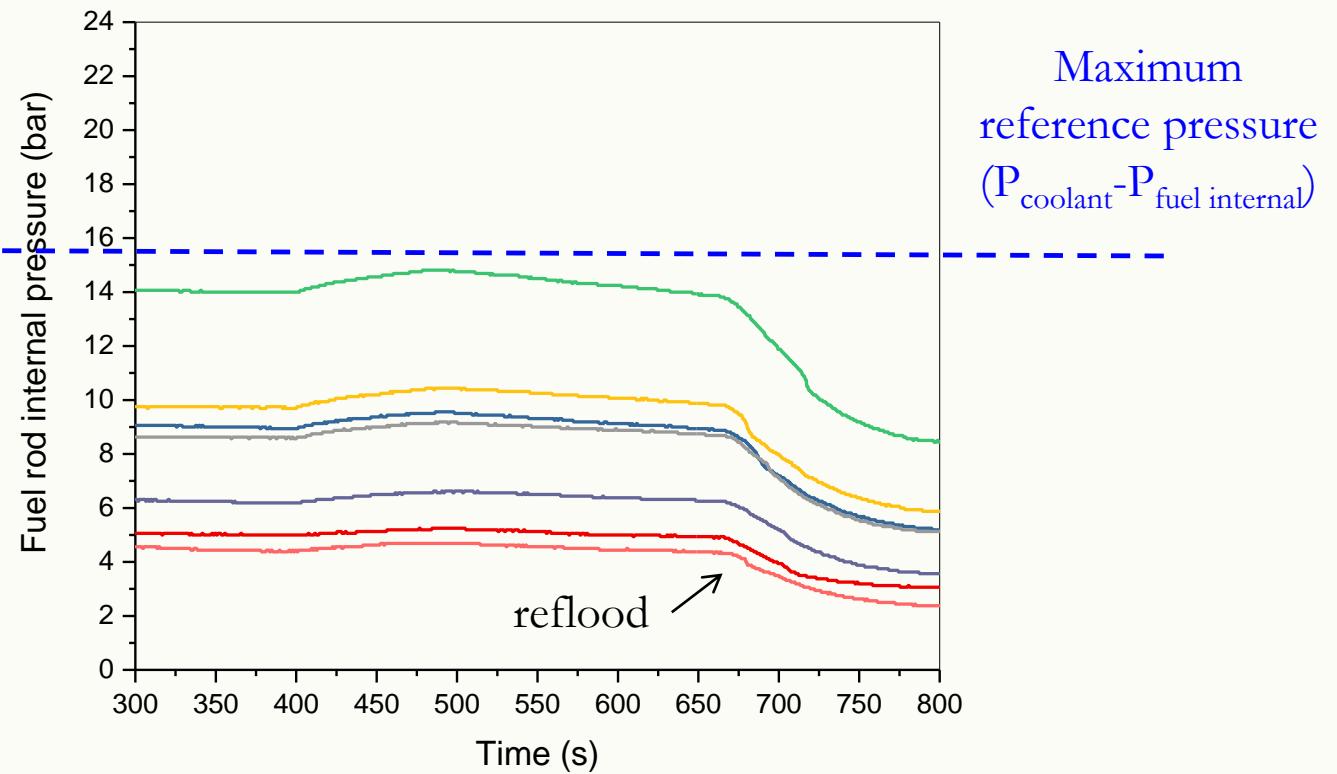
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SIMULATION OF 200% LARGE BREAK LOCA

CODEX-LOCA-200



CODEX-LOCA-200B



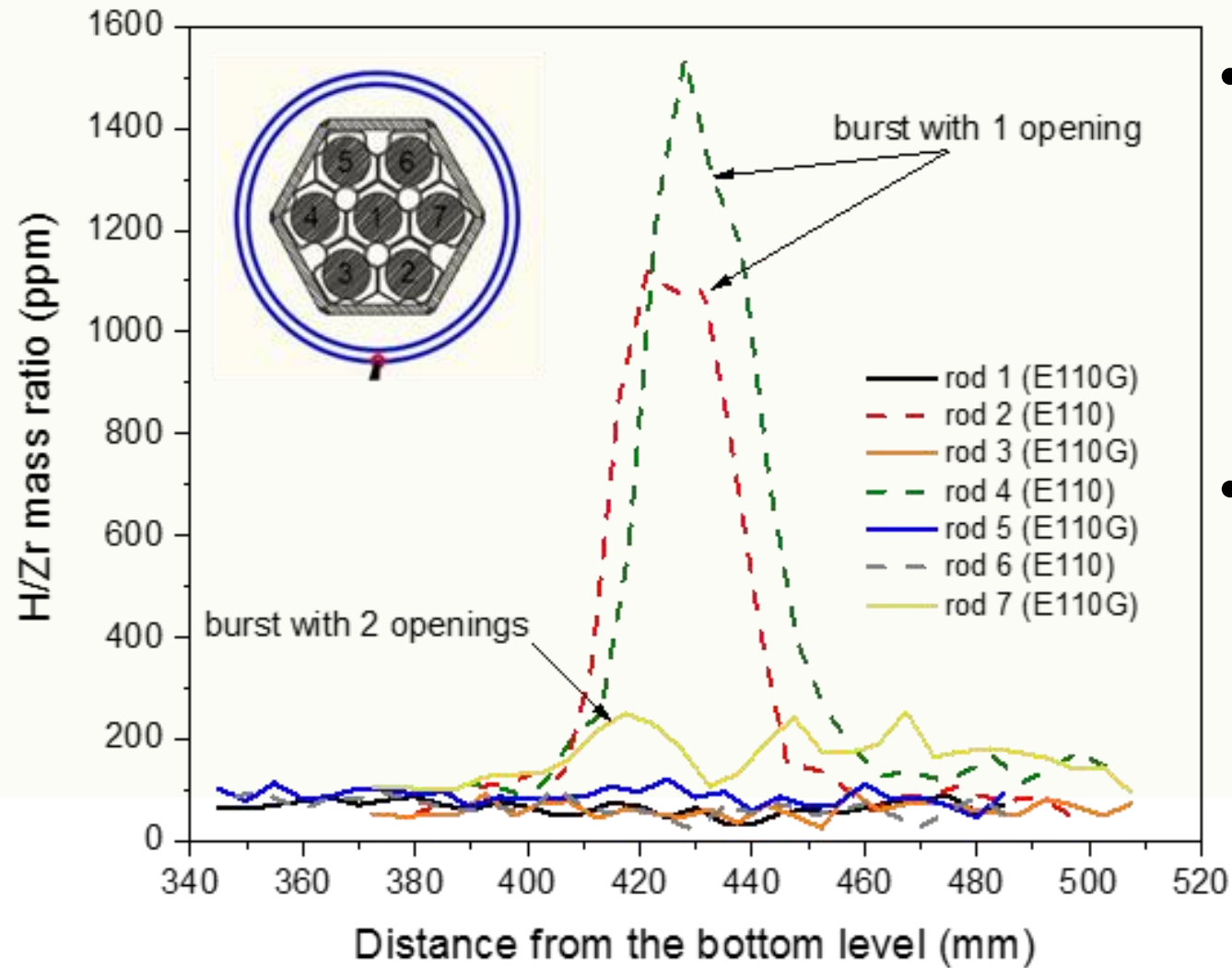
Slow pressurisation compared to reference case:
conservative approach since fast pressurisation leads
to higher burst pressure



- Large ballooning and minimal oxidation
- Similar behaviour of traditional and sponge based E110

LONGITUDINAL PROFILES OF THE H/ZR MASS RATIOS

CODEX-LOCA-200



- Position-sensitive prompt gamma-ray neutron activation imaging (PGAI) driven by neutron radiography (NR)
- High H content at burst locations (obviously due to steam penetration into the fuel rod)

LOCA TESTS WITH VVER FUEL

Facility	PARAMETER				MIR			Halden		CODEX	
Test	1.	2.	3.	4.	BT-2	BT-3	LOCA/72	IFA-650.6	IFA-650.11	LOCA-200	LOCA-200B
Bundle	19 rod	19 rod	19 rod	19 rod	19 rod (3 irradi.)	19 rod (3 irradi.)	1 rod (irradi.)	1 rod (irradi.)	1 rod (irradi.)	7 rod	7 rod
Max. temp. (°C)	1274	1100	1050	1180	950	820	1070	832	940	908	874
Burst pressure (bar)	31-38	30-37	28-37	32-34	58-77	65	66	65	57	13-18	-
Duration above 700 °C (s)	330	300	550	330	400	60	120	300	350	325	255



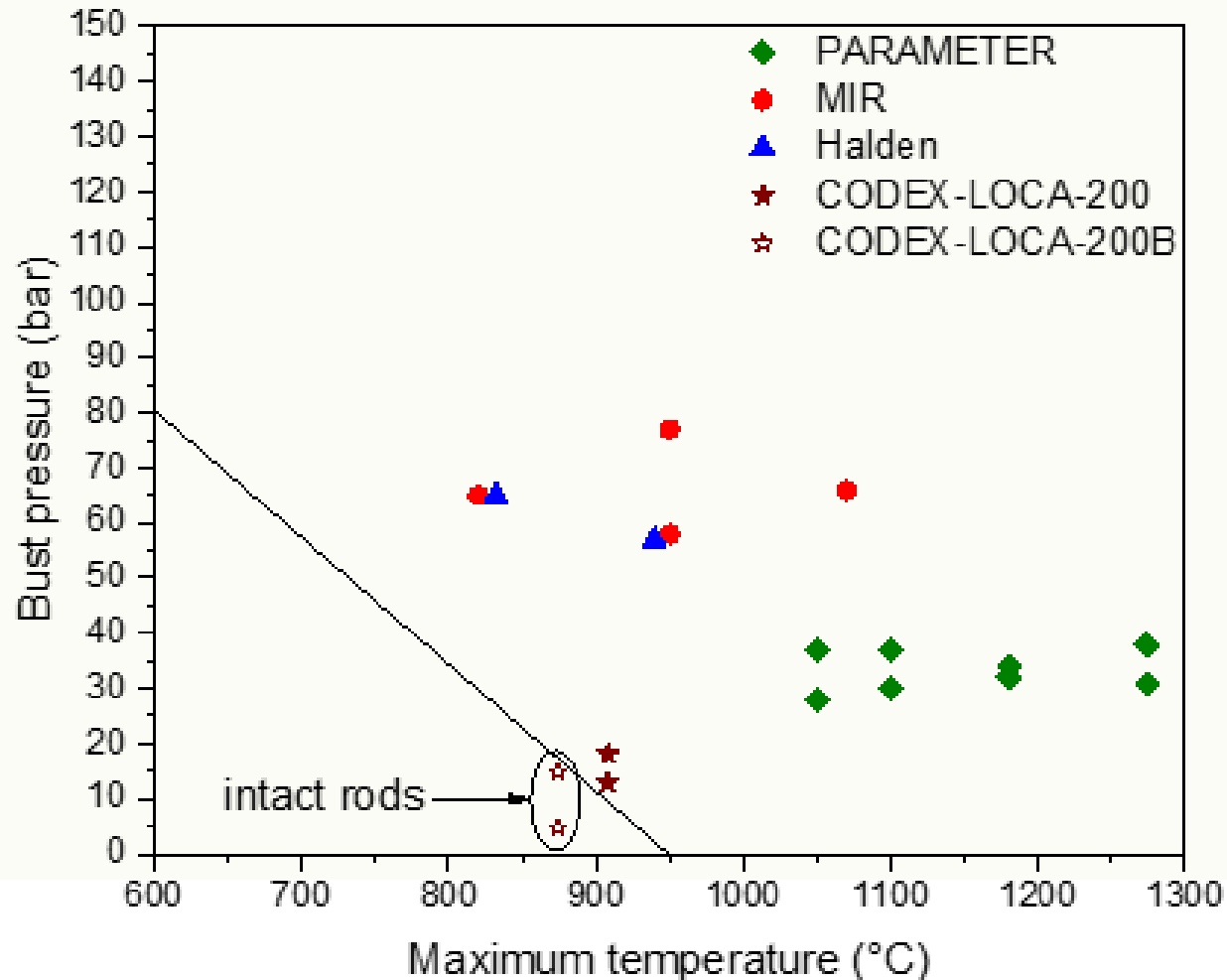
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LOCA TESTS WITH VVER FUEL

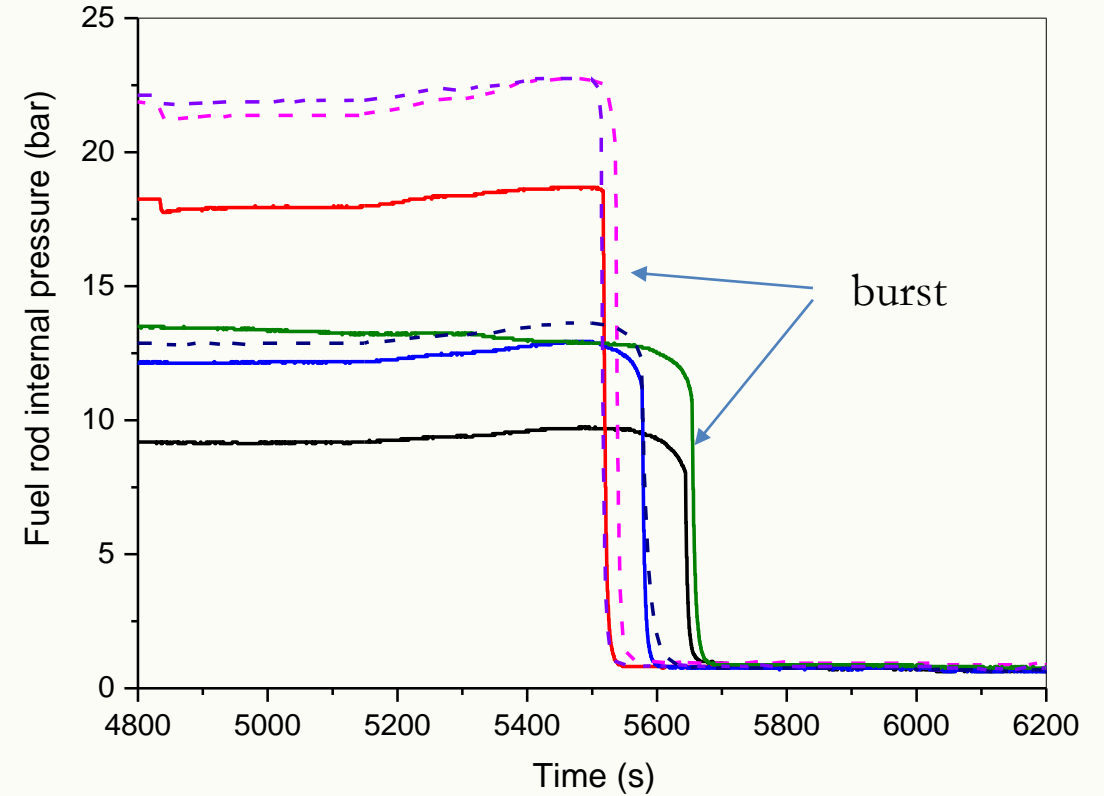
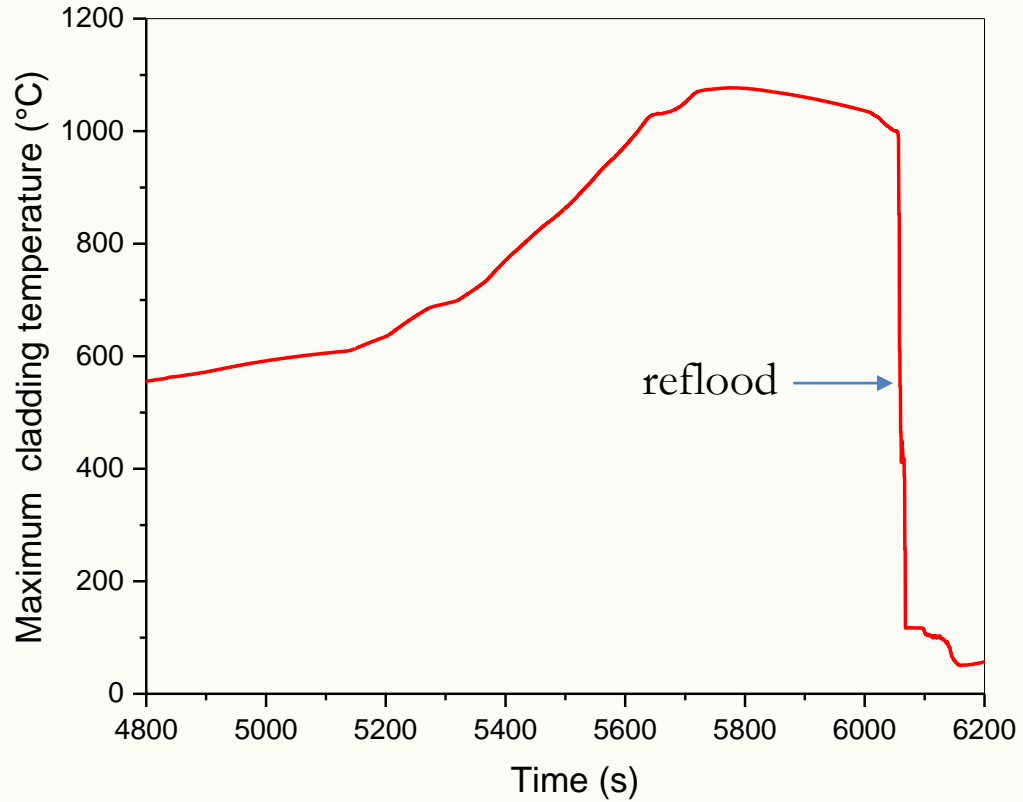


- Most of the VVER LOCA tests focused on the investigation of extreme conditions (in order to observe the significant phenomena)
- Cladding burst in design basis accident conditions will not take place for VVER-440 reactors

SIMULATION OF SHUT-DOWN LOCA

Beyond design basis accident case with limited emergency water supply

CODEX-LOCA-E4



- Long dry period (1/2 hour)
- Burst of all rod
- High maximum temperature (1089 °C)



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SIMULATION OF SHUT-DOWN LOCA

CODEX-LOCA-E4



- Spalling oxide layer on traditional E110
- Fracture of traditional E110
- Compact oxide scale on sponge based E110



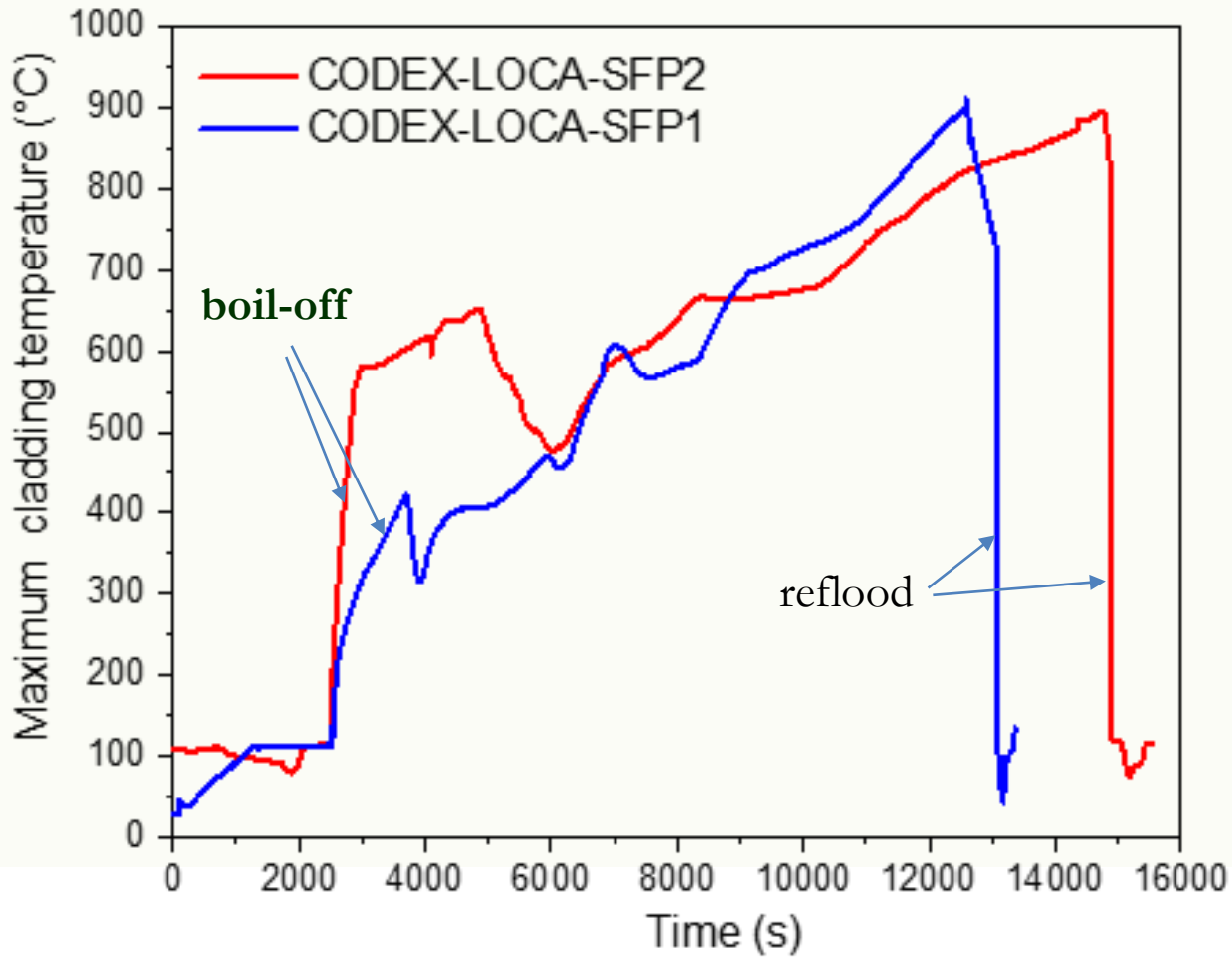
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SIMULATION OF SPENT FUEL POOL LOCA

Beyond design basis accident case with limited emergency water supply and with/without steam starvation



- Very long dry period (3 hours)
- Moderate maximum temperature (900 °C)

SIMULATION OF SPENT FUEL POOL LOCA

CODEX-LOCA-SFP1

180 mm



360 mm



390 mm



480 mm



Large deformations in steam starving conditions

No significant differences between traditional and sponge based E110



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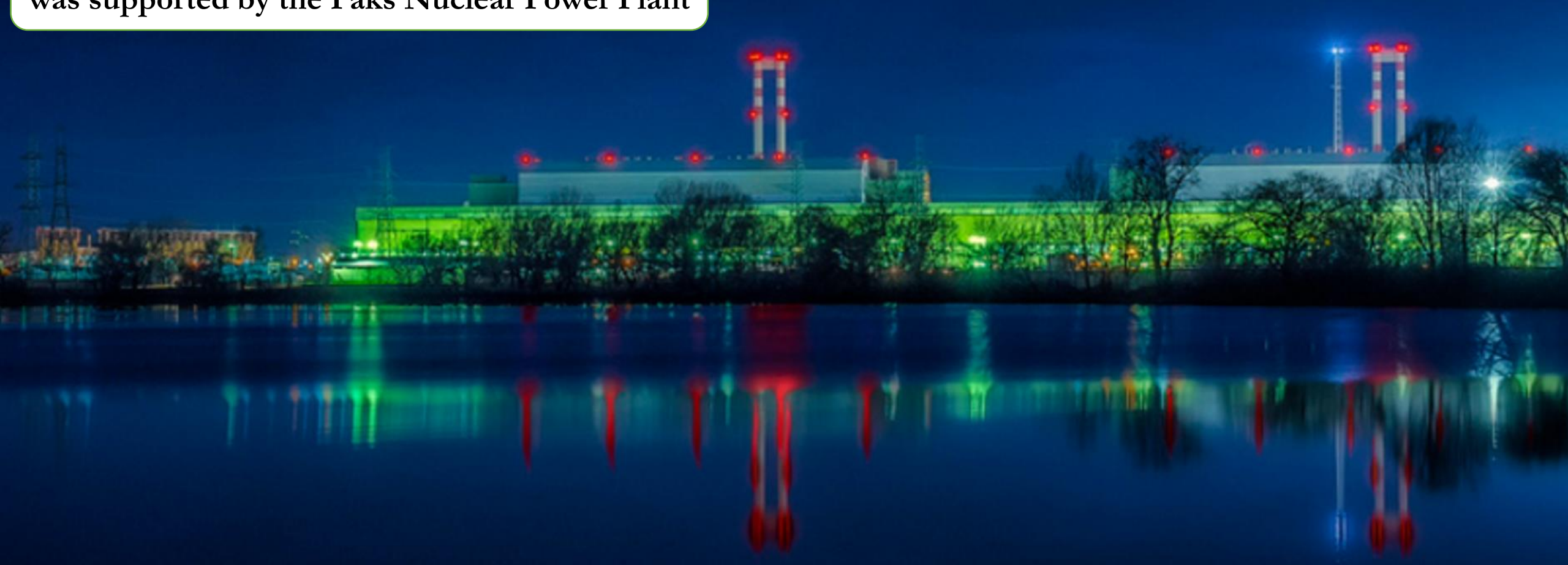
SUMMARY 1/2

- Integral LOCA experiments have been performed in the CODEX facility with electrically heated, non-irradiated VVER type fuel bundles.
- Two tests simulated the design basis LOCA accident scenario for a VVER-440 reactor. The results indicated that the representative pressure and temperature conditions would not result in cladding burst for this scenario.

SUMMARY 2/2

- Three tests simulated beyond design basis accident LOCA events in the shut-down reactor and in the spent fuel pool with limited availability of emergency cooling water injection.
- The long high temperature oxidation times resulted in the formation of oxide scale on the zirconium surfaces.
- The observed significant difference between the traditional and sponge based E110 alloys were in good agreement with the results from small scale separate effect tests

The CODEX-LOCA experimental programme was supported by the Paks Nuclear Power Plant



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CODEX

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