FUEL SAFETY EVALUATION METHODOLOGY FOR ATFS UNDER LOSS-OF-COOLANT ACCIDENTS

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Introduction

IAEA Coordinated Research Project (CRP) on Testing and Simulations for Accident Tolerant and Advanced Technology Fuels (ATF-TS)

- Initiated in 2020, completed in 2021-2024, with 29 organizations from 22 Member States
- To support Member States to understand and model the behaviors of ATFs, and to increase technology readiness for candidate ATF materials

The ATF-TS CRP comprises four key Work Tasks (WTs):

- WT1. experimental testing of ATF claddings and fuels with higher technology readiness levels under normal operating and accident conditions,
- WT2. benchmarking of computer codes against selected separate effect and bundle tests,
- WT3. development of a best estimate plus uncertainty (BEPU) methodology for Loss-of-Coolant Accident (LOCA) fuel performance assessment, and
- WT4. establishment of an open-source ATF database.

→ This presentation focuses on WT3

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Introduction

- WT3 consists in two phases
  - WT3.1: Validation of fuel rod codes through BEPU simulation of the Halden LOCA tests IFA-650.9 and IFA-650.10
    - To verify the capability of the fuel rod codes for simulation of selected integral LOCA tests.
    - To quantify the uncertainty bands of the predicted key output parameters (cladding temperature, plenum gas pressure, cladding diameter) to check if they well bound the measured data during the tests.
    - To identify the important input uncertainty parameters through the partial rank correlation coefficients obtained by the global sensitivity analysis.
    - To predict the expected behaviours of ATFs for the selected Halden LOCA tests.
  - WT3.2: Development of a BEPU LOCA hot rod fuel safety evaluation methodology (FSEM) for LOCA scenarios of a typical nuclear power plant (NPP).
    - To reproduce the upper bound values of the key output parameters (cladding temperature, plenum gas pressure, cladding oxidation) for the reference rod, based on the the fuel rod codes and thermal hydraulic boundary conditions (THBCs) for a typical NPP LOCA, using the BEPU approach.
    - To predict the expected behaviors of ATFs for the selected NPP LOCA scenarios.

→To develop and apply an efficient LOCA fuel safety evaluation methodology to quantify the ATF benefit

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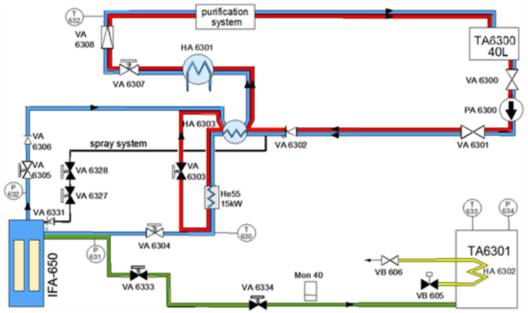
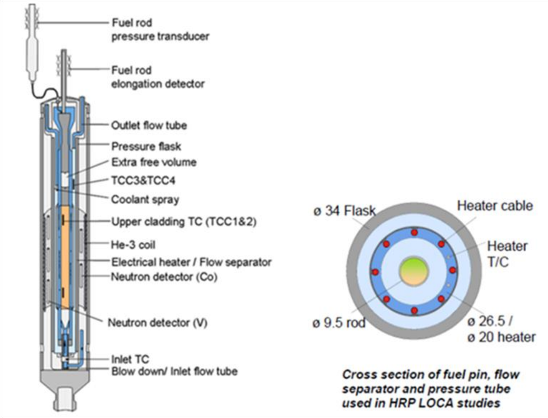
Selected Cases

Halden LOCA tests IFA650.9 and IFA650.10

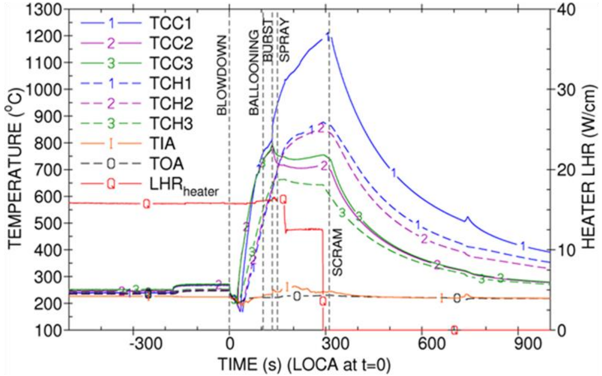
- IFA-650.9
  - PWR fuel rod with a very high burnup of 89.9 MWd/kgU
  - Considerable ballooning, fuel fragmentation and relocation.
- IFA-650.10
  - PWR fuel rod with a high burnup of 61 MWd/kgU
  - Moderate ballooning, fuel fragmentation and dispersal.

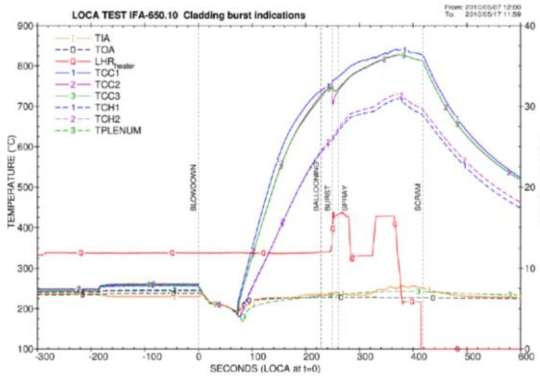
→ Taken from the previous CRP FUMAC, with SOCRAT calculated THBCs





Cross section of fuel pin, flow separator and pressure tube used in HRP LOCA studies



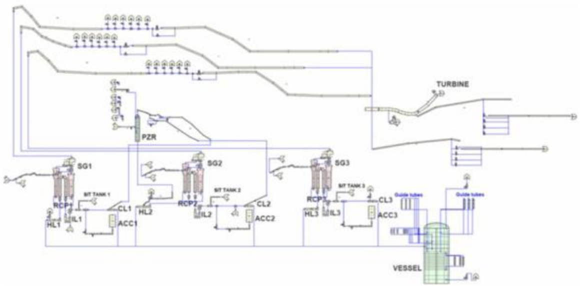


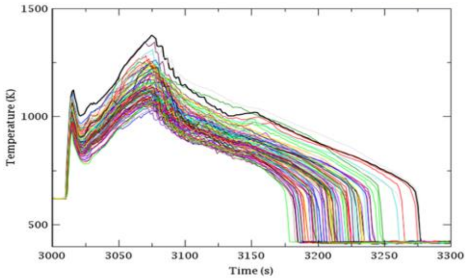
Selected Cases

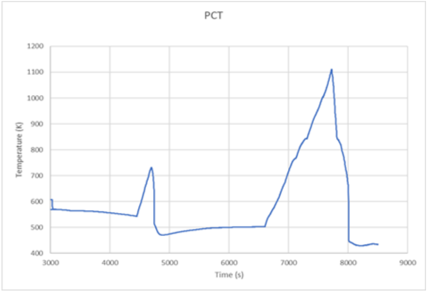
NPP LOCA scenarios

- PWR LOCA
  - A full plant LOCA safety analysis has been performed by UPM for a typical Westinghouse 3-loops PWR with reference fuel rod (UO2 fuel with Optimized Zirlo cladding):
    - DBA Large-break LOCA: double-ended break at one of the cold legs,
    - DEC Small-Break LOCA: a 3” break at one of the cold legs with failure of HPSI pumps.
  - Using system TH code TRACE V5, with core neutronic data from SIMULATE calculations and fuel rod initial states from FALCON calculations.
  - Using the BEPU approach for LBLOCA, with the second order of 100 cases to determine the limiting cases for maximum PCT and ECR, and the best estimate approach for DEC SBLOCA

→ The THBCs for hot assembly and hot rod were provided in the Excel files for the most limiting case.







Participants

Used Codes, ATF Concepts and Selected Cases

Organization	Country	Fuel Rod Code	UA/SA Code	ATF concept	WT3.1. Code validation		WT3.2. LOCA FSEM for NPP	
					IFA-650.9	IFA-650.10	LBLOCA	DEC SBLOCA
CNEA	Argentina	DIONISIO	DAKOTA	FeCrAl, Doped pellet		X		
TRACTEBEL	Belgium	FRAPCON/ FRAPTRAN-TE-1.5	DAKOTA	Coated Zr cladding, Micro-cell pellet	X	X	X	
IPEN/USP	Brazil	TRANSURANUS	SUNSET	FeCrAl	X	X	X	X
CNPE	China	FRAPCON/ FRAPTRAN-2.0P1	DAKOTA	FeCrAl	X	X	X	
CEA	France	ALCYONE	URANIE	Doped pellet		X		
AEOI	Iran	PARS/PART	SUAP	Coated Zr cladding, Doped pellet	X	X		
NINE	Italy	TRANSURANUS	MC built-in	FeCrAl		X		
KAERI	Korea	MERCURY	OpenTURNS	ATF1: Coated Zr cladding, doped pellet; ATF2: Coated Zr cladding, micro-cell pellet	X	X	X	X
UPM/Nfq	Spain	TRACE TRANSURANUS	DAKOTA	FeCrAl		X X	X	
CIEMAT	Spain	FRAPCON/ FRAPTRAN-2.0P1	DAKOTA	FeCrAl	X	X	X	X
NNL	UK	ENIGMA	CASINO	Coated Zr cladding		X		

Specifications

- Simulation of the reference fuel rod/ATF behaviours
    - The used fuel rod codes should be capable of simulating at least the following key LOCA fuel behaviours for the simulated reference fuel/ATFs:
        - Cladding corrosion and hydrogen pickup (steady state before the transient);
        - Cladding temperatures (based on the provided thermal hydraulic boundary conditions, using coupled or built-in thermal hydraulic models);
        - Cladding high temperature oxidation (and optionally hydriding);
        - Cladding creep and deformation: ballooning and elongation;
        - Cladding burst: burst criteria based on stress or strain;
        - Rod internal pressure: plenum temperature and fission gas release (FGR) model;
        - Axial fuel relocation (if available, needed for Halden LOCA test IFA-650.9).
    - Some specific physical models for ATFs may need to be implemented and validated with the separate effect tests (SETs) in WT1.1, or from other sources (FeCrAl, doped pellet, micro-cell pellet).

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Specifications

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- Simulation of the reference fuel rod LOCA behaviours
  - The initial conditions of the hot rod (Burnup, Tfuel, RIP, Corrosion) should be modelled by a steady state simulation of the base in-reactor irradiations.

→ The calculated reference fuel rod initial states should match the measured data within uncertainties

Halden LOCA Test IFA650.9

Fuel rodlet initial state	
Fuel average burnup (MWd/kgU)	89.9
Oxide thinkness (µm)	7-8
Hydrogen concentration (wppm)	30
Fill gas pressure at 295 K (MPa)	4.0

Halden LOCA Test IFA650.10

Fuel rodlet initial state	
Fuel average burnup (Mwd/kgU)	61
Oxide thinkness (µm)	20-30
Hydrogen concentration (wppm)	150-220
Fill gas pressure at 295 K (MPa)	4.0

NPP LOCA

Fuel average burnup (MWd/kgU)	11.6 (LBLOCA) 26.4 (DEC)	±5%
Max fuel average temperature (K)	1227.50 (LBLOCA) 1019.73 (DEC)	±10
Max cladding oxide thickness (µm)	4.521 (LBLOCA) 18.707 (DEC)	±20%
Rod internal pressure (MPa)	10.606 (LBLOCA) 9.94 (DEC)	±0.2

- Except for the assumed fuel rod initial states and activation of these specific models for the simulated ATFs, the same THBCs and assumptions as in the simulation of the Halden LOCA tests or NPP scenarios for the reference fuel should be used for ATFs.

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Specifications

- Simulation of the reference fuel rod/ATF LOCA behaviours
  - For the transient simulation, it is recommended to impose the provided time history of hot rod power (LHGR), effective coolant temperature (Tcool) and HTC for each thermal hydraulic node as the boundary conditions for the fuel rod thermal mechanical calculation, with cladding temperature (Tcl) being calculated by the used fuel rod codes.
  - Alternatively, the participant may choose to calculate the local thermal hydraulic conditions (Tcool, HTC, Tcl) using the provided hot channel inlet/outlet T/H conditions or simply use the cladding temperature (Tcl) as the boundary conditions for the fuel rod thermal mechanical calculation.

→ The calculated effective Tcool and HTC should match the measured or provided total heat flux, using a simple lumping method, e.g.:

$$Tcool = (1\text{-}void)*Tl + void*Tv$$

$$HTC = qtot / (Tcl – Tcool).$$

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Specifications

- Uncertainty and sensitivity analysis (Halden LOCA tests)
  - Uncertainty ranges and distributions: Follows the specifications or user defined

Input uncertainty parameter	Uncertainty Range and Distribution				
	Mean or Nominal	Standard Deviation or Range	Type	Lower bound	Upper bound
Cladding outside diameter (mm)	10.75/9.50	0.01	Normal	10.73/ 9.48	10.77/ 9.52
Cladding inside diameter (mm)	9.3/8.36	0.01	Normal	9.28/ 8.34	9.32/ 8.38
Pellet outside diameter	9.13/8.19	0.01	Normal	9.11/ 8.18	9.15/8.2 2
Fuel density (kg/m3 at 20 °C)	10457	50	Normal	10357	10557
U235 enrichment (%)	3.50/4.487	0.05	Normal	3.4/4.38 7	3.6/4.58 7
Filling gas pressure (MPa)	4.0	0.05	Normal	3.9	4.1
Relative power during base irradiation	1	0.01	Normal	0.98	1.02
Relative power during test	1	0.025	Normal	0.95	1.05
Test rod power profile	1	0.01	Normal	0.98	1.02
Code calculated coolant temperature (°C)	-	±20	Uniform	T-20	T+20
Code calculated clad-to-coolant heat transfer coefficient (W/m^2.°C)	-	±30%	Uniform	0.70	1.3
Fuel thermal conductivity model	1.00 (1.5 for micro-cell pellet)	±10%	Uniform	0.90 (1.35 for micro-cell pellet)	1.10 (1.65 for micro-cell pellet)
Clad thermal conductivity model	1.00	±10%	Uniform	0.90	1.10
Fuel thermal expansion model	1.00	±10%	Uniform	0.90	1.10
Clad thermal expansion model	1.00	±10%	Uniform	0.90	1.10
Fuel densification model	1.00	±10%	Uniform	0.90	1.10
Fuel swelling model	1.00	±10%	Uniform	0.90	1.10
Clad Yield stress	1.05	±0.1	Uniform	0.95	1.15
Fuel heat capacity	1.00	±3%	Uniform	0.97	1.03
Cladding elastic modulus	1.00	±10%	Uniform	0.90	1.10
Cladding corrosion model during steady-state operation	1.00 (0.1 for Cr-coated cladding)	±25%	Uniform	0.75 (0.075 for Cr-coated cladding)	1.25 (0.125 for Cr-coated cladding)
Cladding hydrogen pickup fraction during steady-state operation	1.00 (0.5 for Cr-coated cladding)	±30%	Uniform	0.7 (0.35 for Cr-coated cladding)	1.30 (0.65 for Cr-coated cladding)
Cladding oxidation model at high temperature	1.00 (0.5 for Cr-coated cladding)	±30%	Uniform	0.7 (0.35 for Cr-coated cladding)	1.30 (0.65 for Cr-coated cladding
Thermal conductivity of the oxide layer	1.00	±20%	Uniform	0.80	1.20
Fission gas release (or gas diffusion coefficient)	1.00	±50%	Uniform	0.50	1.50
Gap gas conductivity	1.00	±25%	Uniform	0.75	1.25
Fuel fragment packing fraction (if applicable)	0.72	±20%	Uniform	0.58	0.86
Cladding strain threshold for fuel mobility (if applicable)	1.00	±20%	Uniform	0.80	1.20
Cladding annealing	0.15	±0.1	Uniform	0.05	0.25
Cladding high temperature creep model (Cr-coated cladding)	1.00	±60%	Uniform	0.40	1.60
Cladding burst stress criteria	1.00	±20%	Uniform	0.80	1.20
Cladding burst strain criteria	1.00	±20%	Uniform	0.80	1.20
Plenum gas temperature [°C]	-	±20	Uniform	T-20	T+20

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Specifications

- Uncertainty and sensitivity analysis (NPP LOCA scenarios)
  - Uncertainty ranges and distributions: Follows the specifications for Halden or user defined
    - Uncertainties in the calculated T/H boundary conditions can take the following examples:
      - LHGR (e.g., ±2%);
      - Local coolant temperature (e.g., ±20 °C);
      - Local clad to coolant heat transfer coefficient (e.g. ±30%).
    - Uncertainties on the following important model input parameters should be quantified and considered:
      - Fuel density (e.g., ±5%);
      - Fuel thermal conductivity (e.g., ±10%);
      - Clad thermal conductivity (e.g., ±10%);
      - High temperature oxidation and water-Zr reaction rate (e.g., ±30%);
      - Gas diffusion coefficient or FGR (e.g., ±50%)
      - Gap heat transfer coefficient (e.g., ±25%);
      - Burst stress (e.g., ±20%);
      - Burst strain (e.g., ±20%);
      - Creep model (e.g., ±60%).

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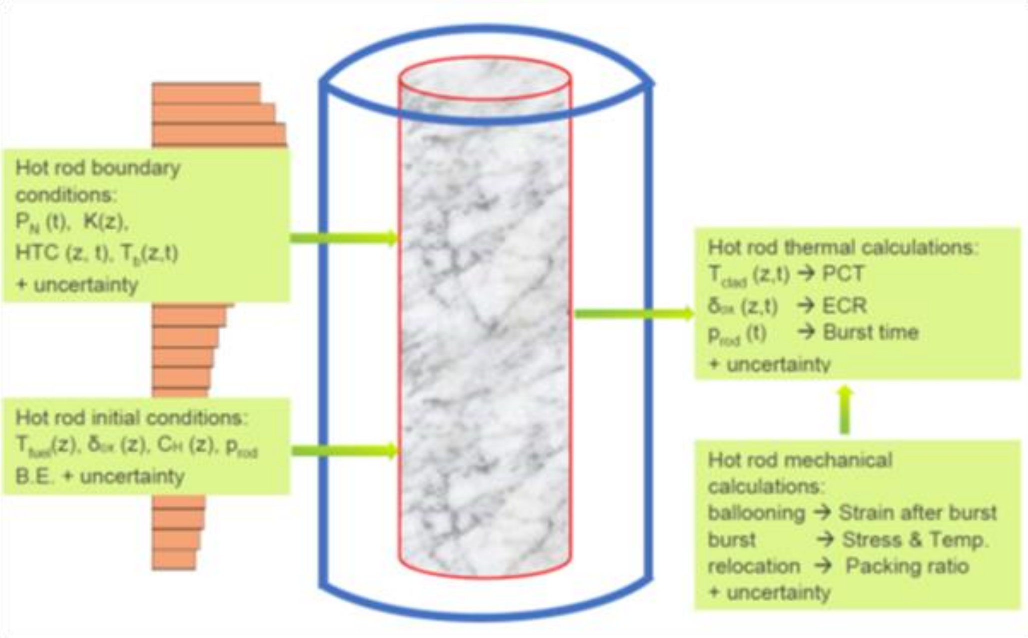
Specifications

- Uncertainty and sensitivity analysis
  - Code: Any UA/SA code (DAKOTA, URANIE, MC, CASINO, SUAP, …)
  - UA method: Forward uncertainty propagation based on Monte Carlo random sampling
    - Sample size: N = 200, 100 or 59 cases
    - Sampling the input uncertainties to generate the N input decks
    - Performing the N fuel rod code calculations
    - Order statistics of the responses (double-sided or single-sided) → uncertainty bands.
  - SA method: Global sensitivity analysis
    - The partial rank correlation coefficients (PRCC) is chosen as qualitative and relative index for screening the important input parameters.
    - Arbitrary significance thresholds of 0.25 and 0.5 are chosen to identify the importance:
      - Low (PRCC < 0.25),
      - Medium (0.25 ≤ PRCC < 0.5),
      - High (PRCC ≥ 0.5)

Specifications

- Simplified hot rod LOCA fuel safety evaluation methodology
  - Using validated fuel rod codes
  - Based on hot rod Thermal Hydraulic Boundary Conditions (THBCs)
  - Using Best Estimate Plus Uncertainty (BEPU) approach

→ Allows efficient assessment of the ATF performance



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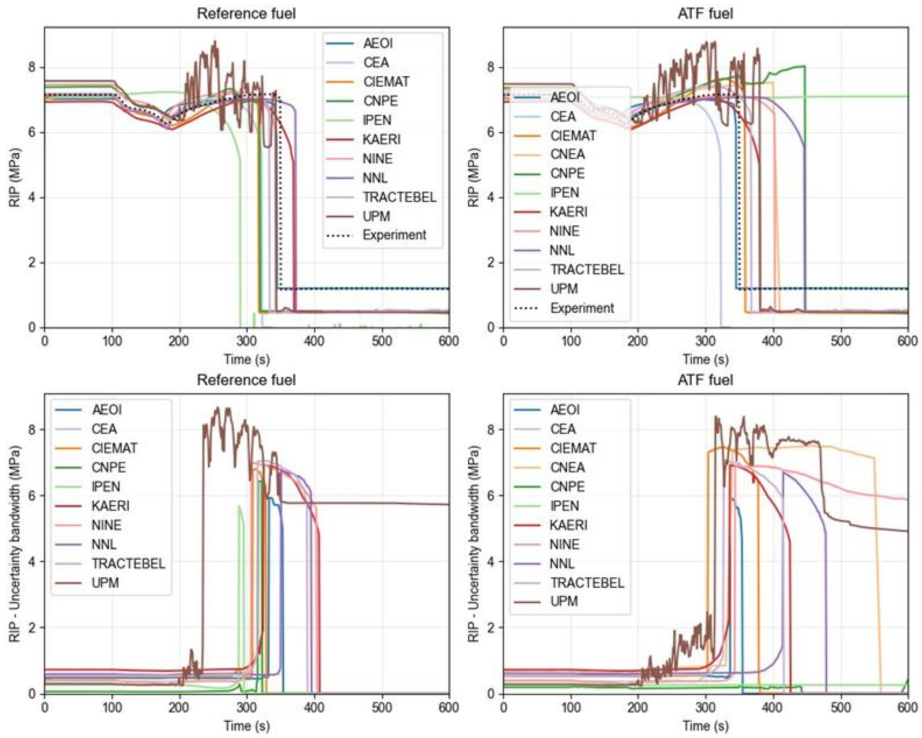
Results and Discussions

Halden LOCA test IFA650.10

- Results received from 11 participants
- Rod internal pressure and burst time
  - Reference fuel:
    - Reasonable agreement on the nominal calculation, with some dispersions on the burst time,
    - Large uncertainty bands, mostly cover the measurement
  - ATF: slightly delayed burst, but with wider uncertainty bands
    - IPEN predicts a quite different behaviour for ATF, probably due to the different assumption on the plenum temperature and the thickness of the FeCrAl cladding.
    - UPM predicts an oscillation of the RIP with TRACE during the reflood phase.



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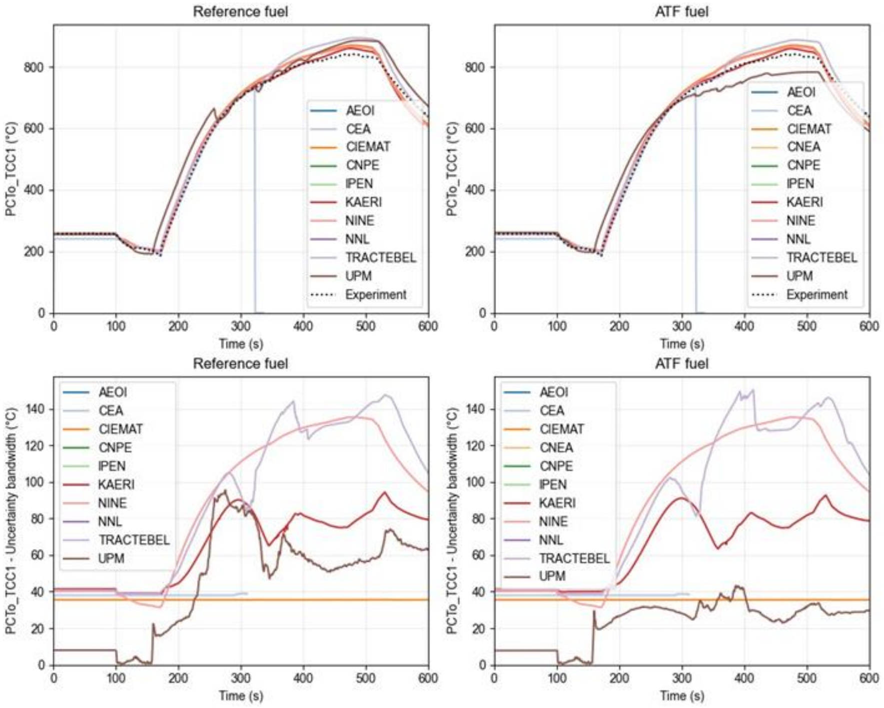
Results and Discussions

Halden LOCA test IFA650.10

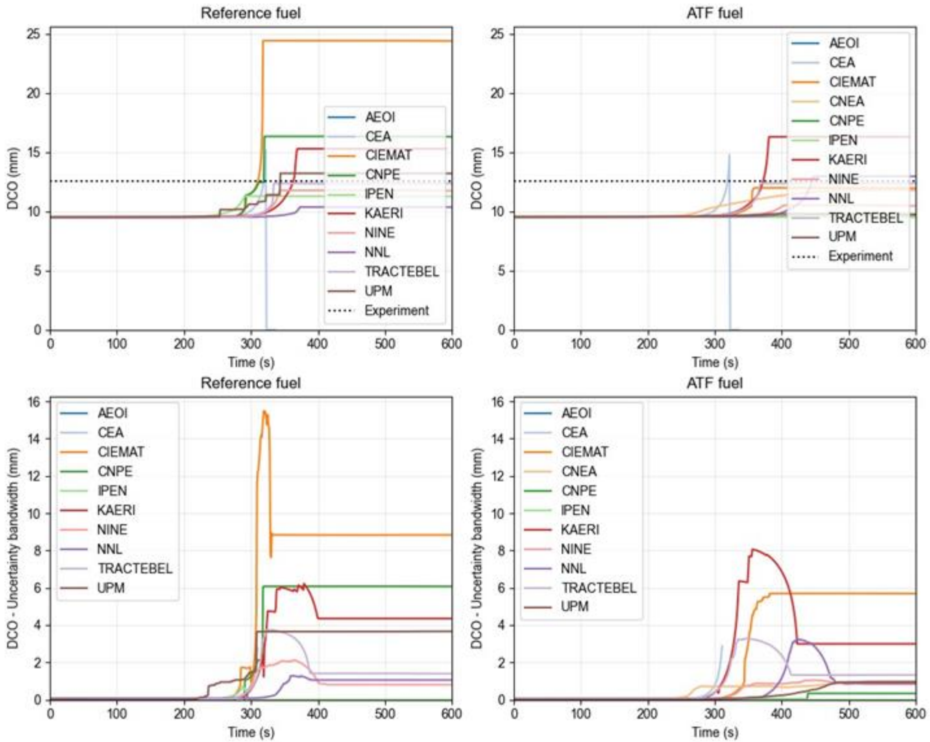
- Cladding outer temperature
  - The predicted PCTo are quite close to the measured value, since most of the participants used the provided THBCs by SOCRAT (UPM underpredicted the cladding temperature by the TRACE code).
  - The uncertainty bands depend on the assumed boundary conditions.
  - There are no significant differences between the reference and ATF fuel rods.



Results and Discussions

Halden LOCA test IFA650.10

- Cladding outer diameter
  - Reference fuel rod: large dispersions on the predicted DCO, with a significant uncertainty bands. → mechanical deformation models to be improved
  - ATF rod: Smaller DCO and uncertainty bands as expected due to the slower creep rates.



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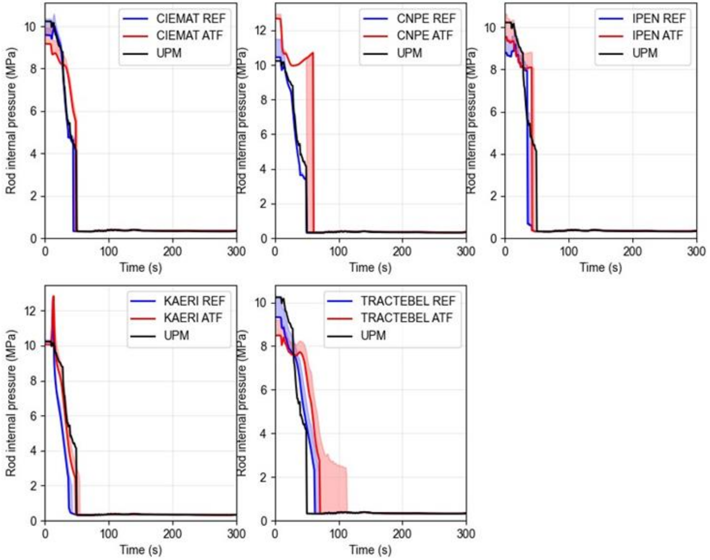
Results and Discussions

NPP LBLOCA

- Results received from 5 participants
- Rod internal pressure and burst time
  - Reference fuel: reasonable agreement with the UPM upper bound value.
    - KAERI predicted a sharp RIP overshoot and hence an early burst, due to probably an incorrect modelling of the THBCs and uncertainties for the upper bound case provided by UPM.
    - The uncertainty bands of most participants do not cover the upper bound value of the reference simulation, due to the mismatch in the hot rod initial states and the inappropriate consideration of the input uncertainties.
  - ATF:
    - The Cr-coated Optimized Zirlo cladding tends to lead to a slightly delayed burst,
    - The FeCrAl cladding is less subject to plastic deformation but does not seem to improve the time to burst.



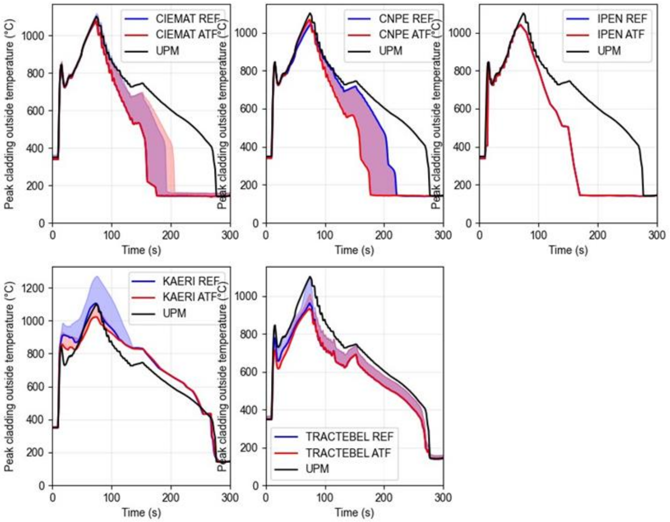
Results and Discussions

NPP LBLOCA

- Cladding outer temperature
  - Different application of the THBCs:
    - CIEMAT, CNPE and IPEN simulations used the UPM upper bound PCT values

      → The significant differences after the maximum peak cladding temperature around 80 s for CIEMAT, CNPE and IPEN are due to the change of the PCT location in the UPM calculation
    - KAREI and TRACTEBEL used the UPM upper bound values of the effective coolant temperature and heat transfer coefficient to calculate the PCT.

      → KAERI's overpredicted results are probably due to the consideration of different uncertainties in the thermal hydraulic boundary conditions, initial fuel states and models.
  - The ATF fuel concepts tend to show slightly lower maximum cladding temperature for the upper bound value while the nominal value are approximately unchanged.



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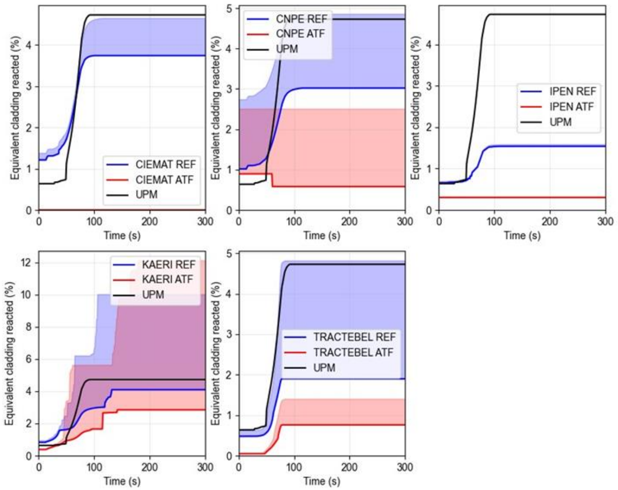
Results and Discussions

NPP LBLOCA

- Equivalent cladding reacted (ECR)
  - Reference fuel:
    - The UPM upper bound maximum ECR during the transient was well predicted by CIEMAT, CNPE and TRACTEBEL.
    - The high oxidation predicted by KAERI is the direct consequence of the higher cladding temperature due to incorrect consideration of the thermal hydraulic boundary conditions and model uncertainties.
  - ATF:
    - All participants except for KAERI predicted a much lower oxidation with ATFs, as expected.



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Conclusions

- Halden LOCA tests
  - Reasonable agreement on the rod internal pressure and burst time, with large uncertainty bands.
  - Large dispersion in the cladding outer diameter, indicating that mechanical deformation models still need to be improved.
- NPP LOCA cases
  - Need better simulating the initial states of the hot rod and correctly using the thermal hydraulic boundary conditions,
  - Need better consideration of the input uncertainties consistent with the UPM BEPU calculations.
- Preliminary results for ATF concepts
  - Cr-coated cladding: slightly delayed burst time (within uncertainty ranges), nearly no impact on deformation, and PCT and ECR.
  - FeCrAl cladding: no significant impact on burst time, but reduced deformation, reduced PCT and ECR.
  - Doped pellet: no significant impact
  - Micro-cell pellet: reduced fuel temperature and hence delayed burst, reduced PCT and ECR.

Perspectives

- The hot rod LOCA fuel safety evaluation methodology need to be improved
  - Providing more detailed information on the hot rod THBCs (initial and boundary conditions) for both the nominal and the upper bound values, including the uncertainties considered in the reference LOCA analyses;
  - Generating the THBCs without activation of the specific cladding ballooning and burst models to reduce their impacts on the THBCs;
  - Verifying the applicability of the THBCs and the matching of the hot rod initial states and improving the uncertainty analysis method;
  - Improving the modelling of cladding ballooning, burst and oxidation, as well as fuel fragmentation, relocation and dispersal (FFRD) phenomena for ATFs at higher burnups.
- The improved fuel safety evaluation methodology can be used to assess the benefit of ATFs within the framework of future IAEA activities.
  - To be continued in a possible future CRP on the ATF testing and simulation for improving the economics of nuclear energy production, including SMRs, in 2026

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Thank you for your attention! Any questions?

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