framatome

GALILEE, Framatome fuel rod performance code for LWR

J. PLANCHER*, Y. WRTAL

Nessbar, Sept. 2025

Content

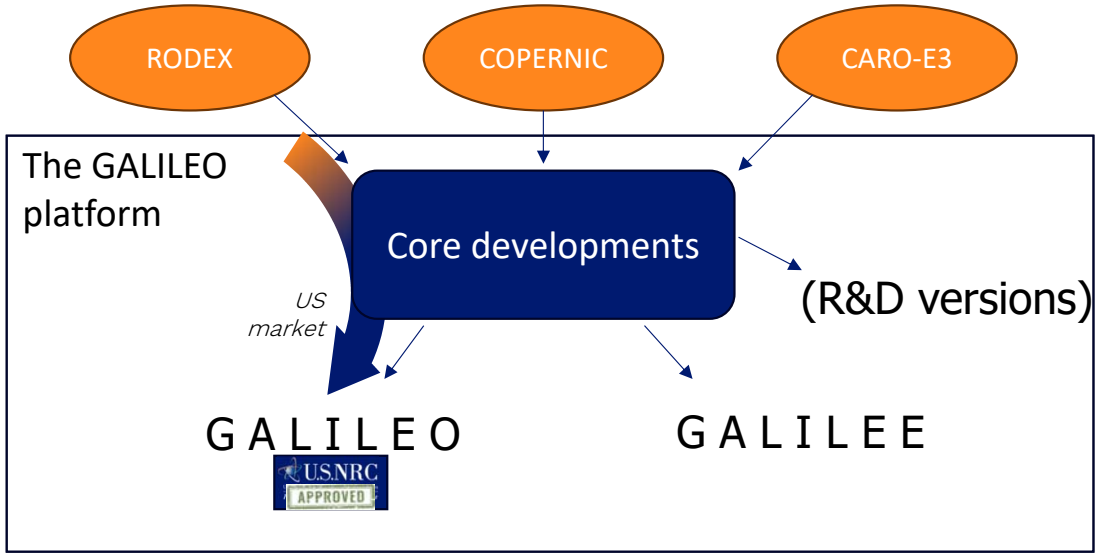
1. Presentation of GALILEE
2. Validation database
3. Main models validation
4. Perspectives

1

Presentation of GALILEE

GALILEE, a Framatome fuel rod performance code

- GALILEE is the Framatome latest 1.5D fuel rod performance code, developed with technical elements from the "GALILEO platform", which gathers and supplements the models from the Framatome legacy codes (RODEX, COPERNIC and CARO-E3).



- In parallel to GALILEO, the US certified fuel rod performance code, GALILEE is intended to be the reference fuel rod performance code to cover Framatome's current and future LWR fuel products in the European and export markets.

GALILEE technical scope

- GALILEE has been designed to meet industrial requirements and is intended to be used in normal and incidental conditions:
  - Either to justify that the fuel rod design criteria are met:
    Fuel central temperature, internal pressure, cladding hoop strain, corrosion thickness etc.
  - Or to participate in the plant safety analysis for fuel-related issues:
    Pellet-Cladding Interaction, fuel interface data for LOCA, RIA …

- The current version covers the following products:
  - Fuels: UO_2, UO_2-Gd_2O_3, MOX
  - Claddings: Zy-4, $M5_{Framatome}$
  - Reactor types: PWR, VVER, SMR

  The code is modular and other products can be easily added in the next versions

Continuous R&D around GALILEE

- GALILEE v1 gathers the best industrial models supported by recognized research centers. For example, the current version relies on the modelling from the CEA (French atomic research center) for the following models:
  - Continuous diffuse cracking model for the pellet mechanics
  - Helium production for MOX fuels
  - Helium incubation and release for MOX fuels

- The partnership with the CEA is still on-going to develop an industrial modelling for other phenomena such as:
  - Mechanistic modeling of the fission gas behavior (release, swelling) inside and between the fuel grains, in normal, incidental, and accidental conditions,
  - Accidental modelling in LOCA and RIA conditions

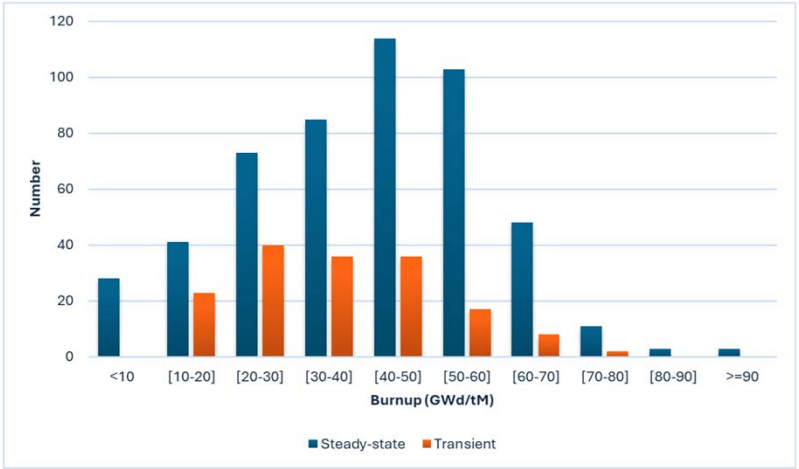
- In complement to this French partnership, GALILEE also relies on other European programs such as the OperaHPC project to boost the innovative features of the code and adapt the best state of the art modelling to the industrial usage of the code.

2

Validation database

Framatome's fuel rod database

- The Framatome fuel rod database benefits from the merging of the databases associated with COPERNIC, RODEX4 and CARO-E3 fuel performance codes.
- It results in a large variety of:
  - Fuel rod designs
  - Operating conditions
  - Burnup ranges
  - Power levels
  - Cladding types
- The measurement types are also very varied, and include:
  - Separate-effect tests to independently validate specific models on a standalone basis
  - PIE (Post-Irradiation Examination) measurements
  - Fuel ceramographies and cladding metallographies
  - Fuel EPMA (Electron-Probe Micro-Analyzer) profiles and SIMS (Secondary Ion Mass Spectrometry) examinations
  - Corrosion measurements on more than 30,000 rods
- Benchmarks on Halden and OECD/NEA data are also available to demonstrate that the code can also be used for VVER application



Partial description of the database (not including fuel surveillance programs)

		Fuels			Phenomena			
	Programs	UO2 (70% of the base)	Gd (7% of the base)	MOX (23% of the base)	FGR / He	Temperature	PCI	Rod Diameter Change
INTERNATIONAL PROGRAMS	DOE Extended Burnup High Burnup Ramp Program TRIBULATION, NFIR, RISO3	X			X			
	Halden	X	X	X	X	X		
	HBC	X	X		X	X		
	High Burnup Effect Program Over-Ramp, Super-Ramp	X	X				X	
	FIGARO			X		X		
	PRIMO			X	X			
	SCIP	X	X		X			X
	GAIN		X		X			X
BILATERAL PROGAMS	Transient database	X			X		X	X
	FGR / He database	X	X	X	X			
	Temperature database	X	X	X		X		

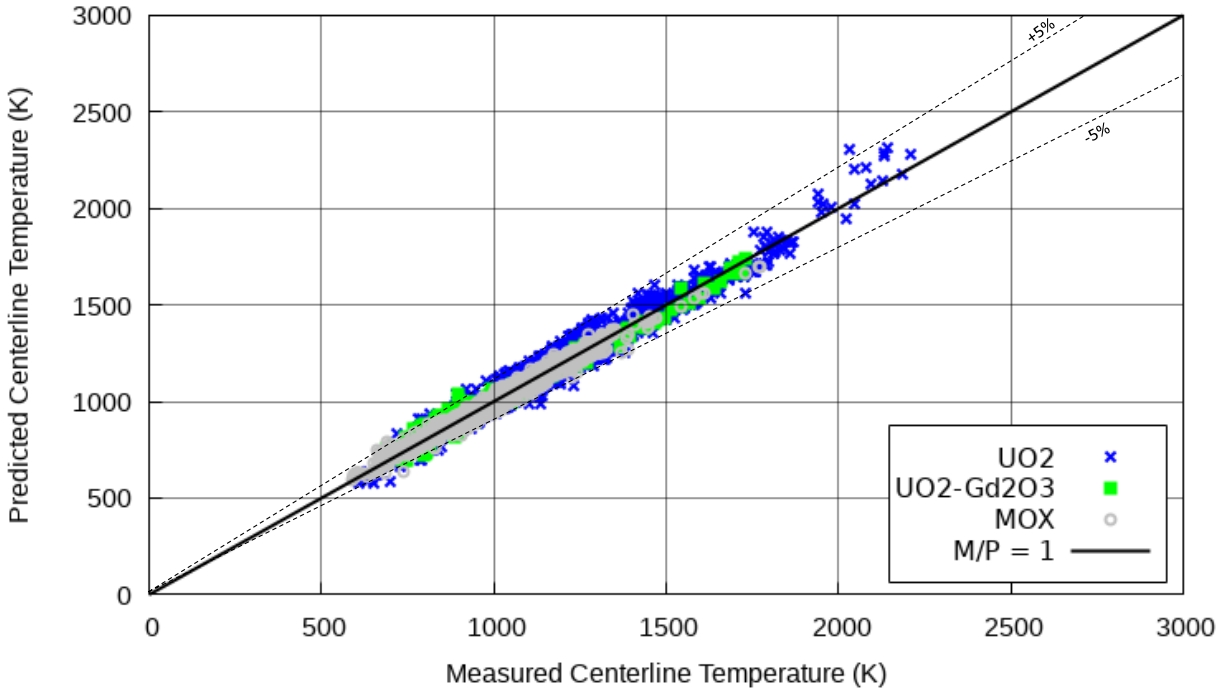
3

Main models validation

- Thermal models
- Fission Gas Release
- He production and balance
- Pellet mechanics

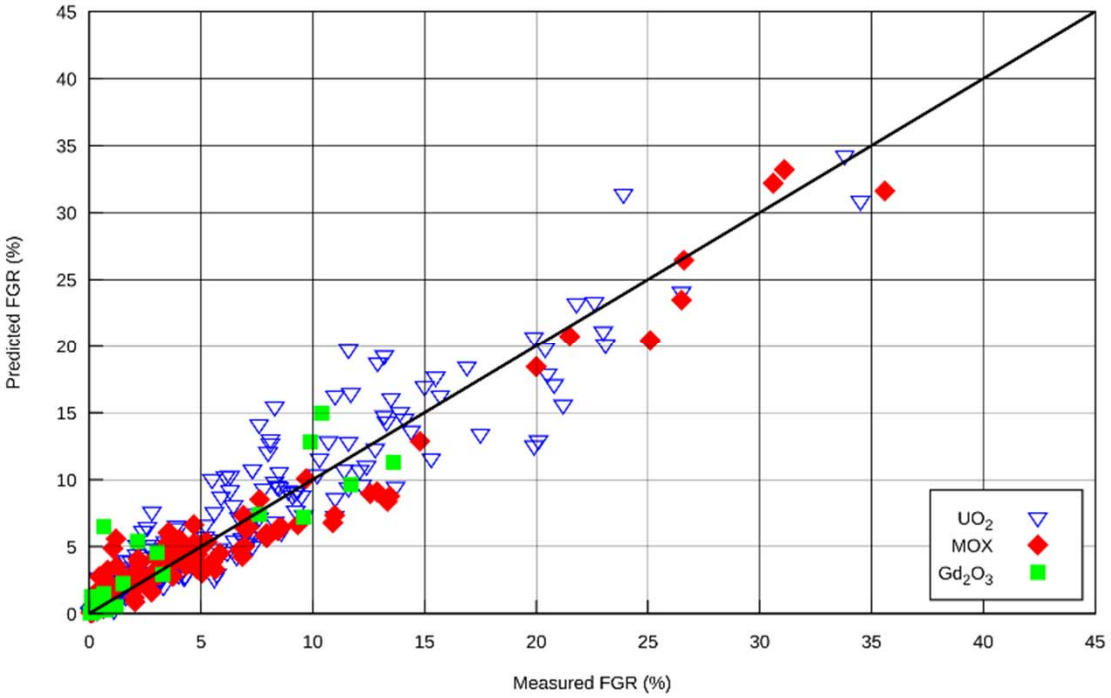
Thermal models

- As a complement to the unitary validation of the thermal conductivity, the integral validation of the whole thermal chain can be performed by using on-line central temperature measurements
- The examination of the Measured / Predicted ratio on these ~5000 points leads to a bias-free thermal performance
  - When plotted against several influent parameters (burnup, linear power…)
  - When distinguishing statistics by fuel type
- The thermal uncertainty is about 5% of the central temperature expressed in K



Fission Gas Release (FGR)

- The validation (and absence of bias) is performed on burnup ranges reaching at least 64 GWd/tM for each fuel type, including MOX fuel
- Thanks to the FGR burnup enhancement modelling features, the GALILEE predictions excellently match the measurements for both low rated 17x17 rods (around 20 kW/m) and high rated 15x15 rods (between 30 and 45 kW/m in the first cycles)
- Depending on the methodologies to be used to perform safety studies, Framatome can provide:
  - Either a bounding FGR model, which over predicts 95% of the points
  - Or statistical distributions of the FGR parameters to be sampled in Monte Carlo calculations

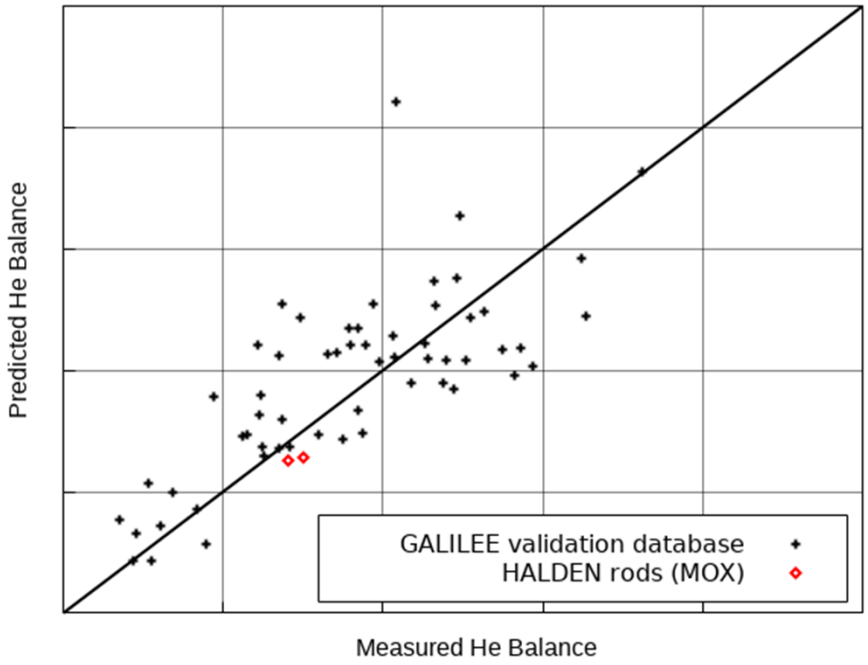


Helium balance

- GALILEE only addresses the Helium behaviour modelling for MOX fuels because only they can yield a significant amount of He

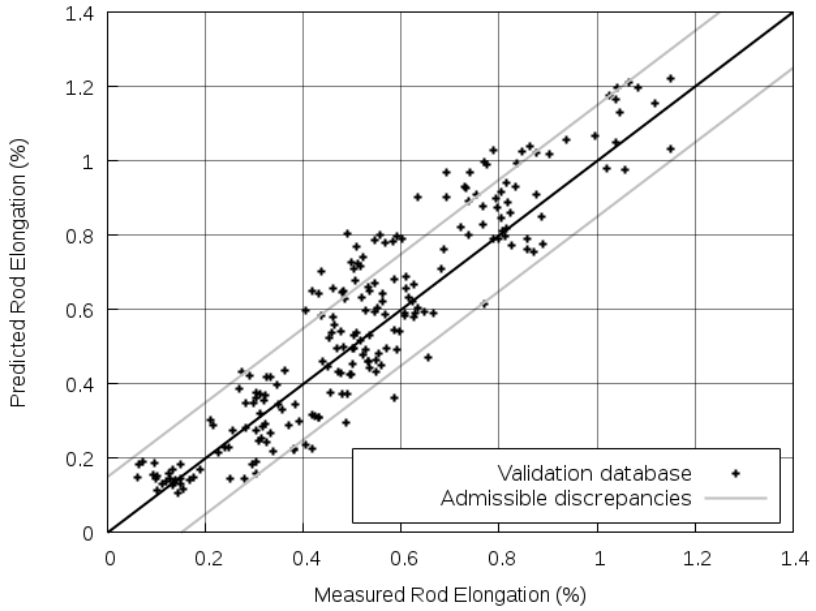
- The GALILEE steady-state He balance is validated using measurements acquired from several operators. Many of them are quite recent fuel rods manufactured in the ORANO MELOX facility

- These validation data cover:
  - MOX rods irradiated in several power reactors in Europe (mainly in France by EDF, but also other European MOX operators)
  - a burnup range up to 64 GWd/tM
  - Both steady-state and transient conditions

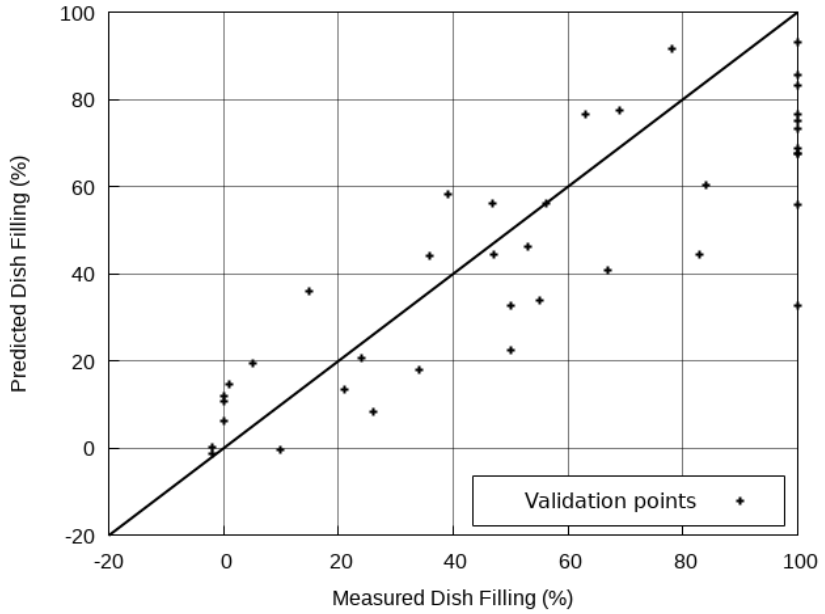


Pellet Mechanics

- Integral measurements can illustrate the ability of the code to compute properly the mechanical strain of the pellet. The integral mechanical chain performance also depends on the stress levels.
- In particular, the rod elongation is sensitive to the fuel creep



- The plot below represents the validation of the dish filling prediction capability of GALILEE, which depends mainly on the stress levels calculated by the code



5

Perspectives and conclusion

Conclusions

- GALILEE benefits from the development of fuel rod performance codes by Framatome since many years and aims to :
  - Use robust state of the art models
  - Cover the usual fuels including MOX
  - Justify operational margins with both deterministic or statistical methodologies
  - Meet the French safety authority requirements.

- The perspectives for the next versions of GALILEE are the following:
  - Short term: cover the E-ATF PROtect design with chromia-doped pellet and/or chromium coated cladding as well as Advanced Fuel Management (AFM) design with enrichments above 5%
  - Mid-term: cover the accidental conditions (RIA and LOCA)

framatome

Thank you