Towards Modelling of Advanced-Technology Fuel with the TRANSURANUS Fuel Performance Code

A. Schubert, I.M. Paponetti, P. Aragón, D. Jaramillo Sierra, Zs. Soti, P. Van Uffelen

European Commission, Joint Research Centre, Karlsruhe, Germany

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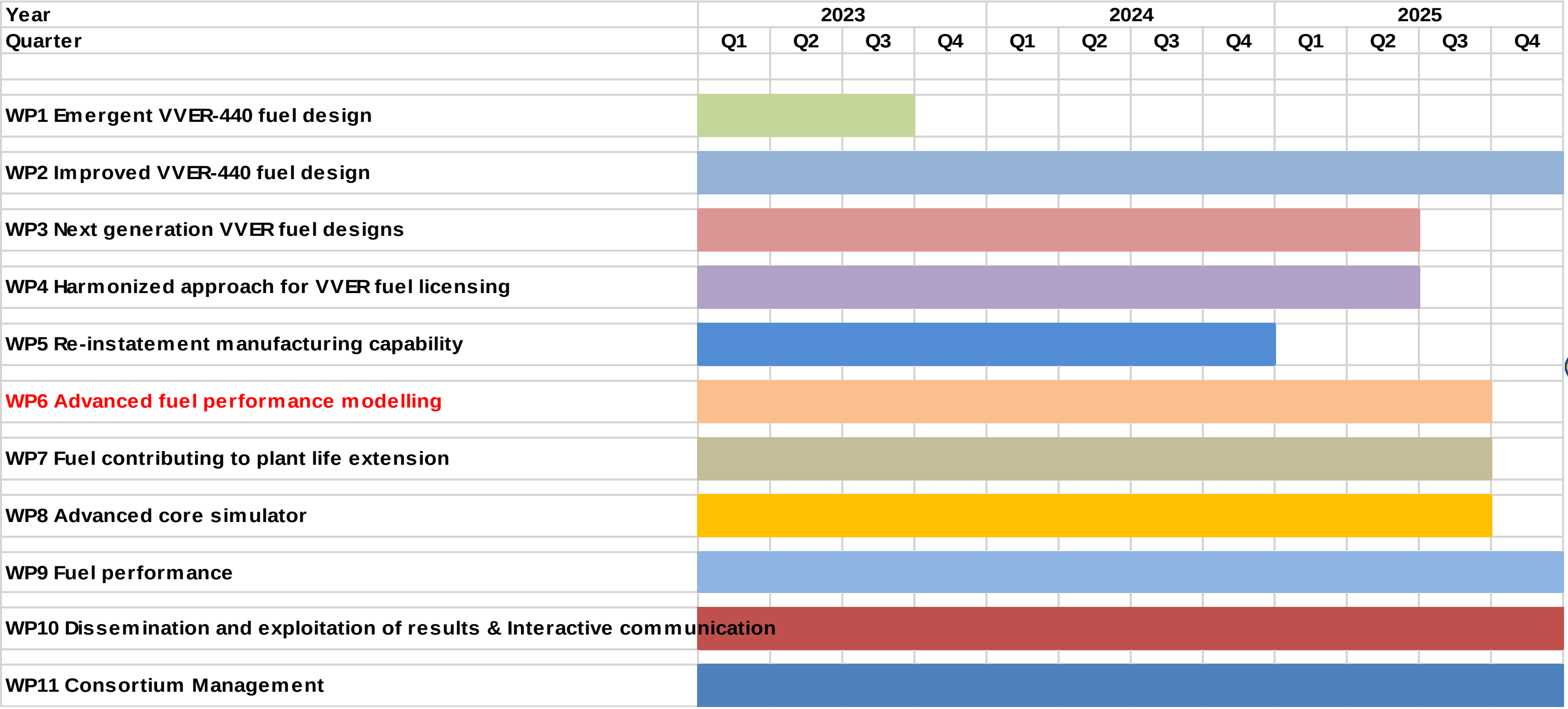
APIS – Accelerated Program for Implementation of secure WWER fuel Supply



WP6: Advanced Fuel Performance Modelling
Objectives

1. **Implement new ATF properties in latest version of TRANSURANUS**
2. Update coupling interfaces for upgraded TRANSURANUS code with DYN3D, ATHLET and RELAP for multi-physics analysis (e.g DBA or DEC-A)
3. Develop modern methodologies for model development and code calibration in the frame of BEPU analysis

APIS

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Contributions from Westinghouse

Implemented properties and models in TU-WSE code for ADOPT™ fuel

Fuel densification

Fuel creep

Contributions from JRC

Implemented models and correlations in TRANSURANUS code for Chromium-doped UO_2 fuel

Fission gas diffusion coefficient model
(Univ. Cambridge, Politecnico Milano, NFQ Spain)

Fuel cracking and densification models
(Univ. Cambridge)

Fuel creep model
(Univ. Cambridge)

Cr-coated Zircaloy cladding

in outermost radial zone
(CIEMAT)

FISA-EURADWASTE 11-16 May 2025, SNETP Forum 2025:
"Advanced technology fuels material property models implementation in the TRANSURANUS platform"

Test Cases - Background and History

Co-ordinated Research Project
Fumex-III
IAEA-TECDOC-1697

incl. application of fuel performance codes to ramp tests

analyzed: Kola3-MIR-RAMP
with irradiated WWER-UO_2 fuel

→ all datasets in International Fuel Performance Experiments (IFPE) database at OECD/NEA

Int. Seminar on WWER Fuel Performance, Modeling and Experimental Support, Varna, Bulgaria, Oct 2001
- A. Smirnov, B. Kanashov, V. Kuzmin et al.:
Results of Post Irradiation Examination to Validate WWER-440 and WWER-1000 Fuel Efficiency at High Burnups

IAEA Fumex-III – Base irradiations and ramp tests

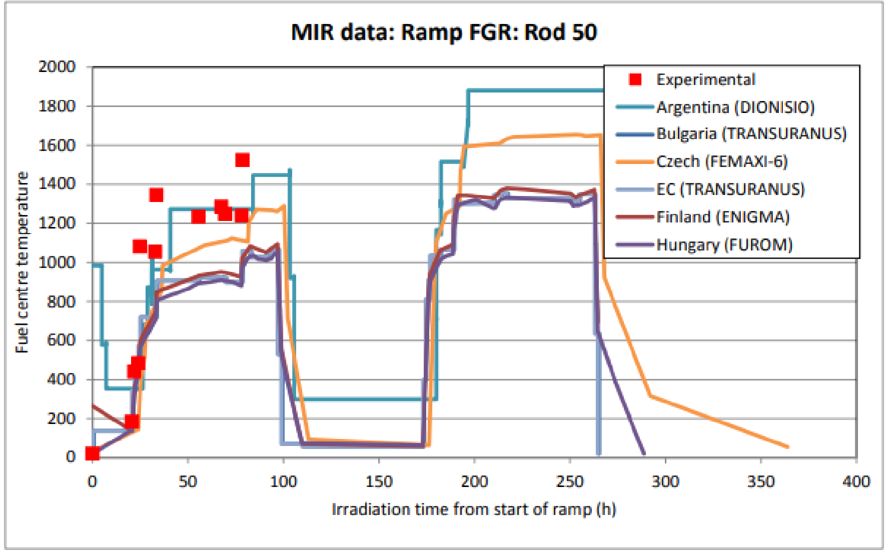

FIG. 57. Fuel centre temperature measurements and predictions for the ramp test of the MIR test rod 50.

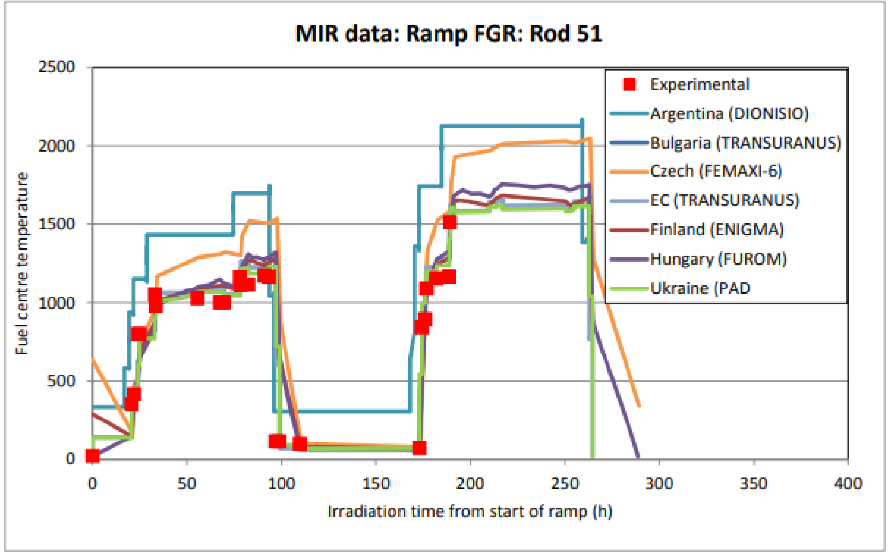

FIG. 59. Fuel centre temperature measurements and predictions for the ramp test of the MIR test rod 51.

IAEA-TECDOC-1697, and International WWER Fuel Conferences, Burgas, Bulgaria

- D. Elenkov et al., Analysis of the Kola3-MIR Transient Experiment with the TRANSURANUS Code (2009)
- S. Boneva et al., The priority cases of the FUMEX-III exercises simulated by means of the TRANSURANUS code (2011)

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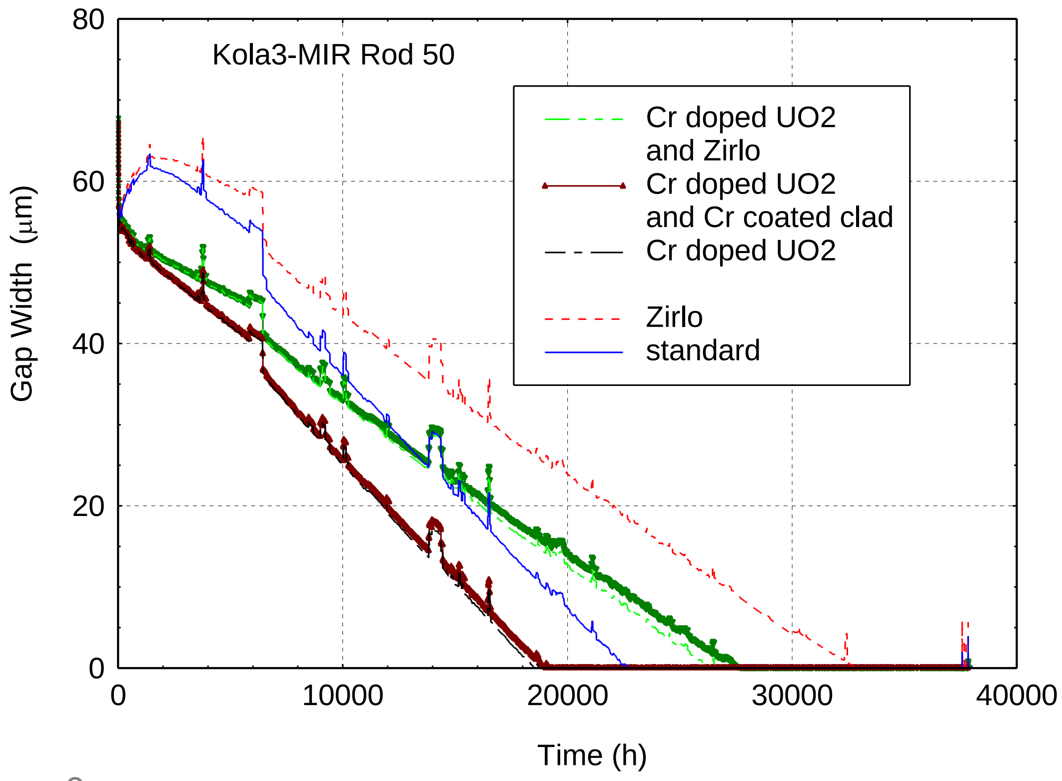
Impact of Cr-doped fuel, Zirlo clad and Cr coating (base irradiation)



Cr-doped fuel:
No densification -> shift

Zirlo clad:
clad creep -> smaller slope

Cr coating (markers): very small add. impact

Cr-doped fuel + Cr coated Zirlo cladding (combined)

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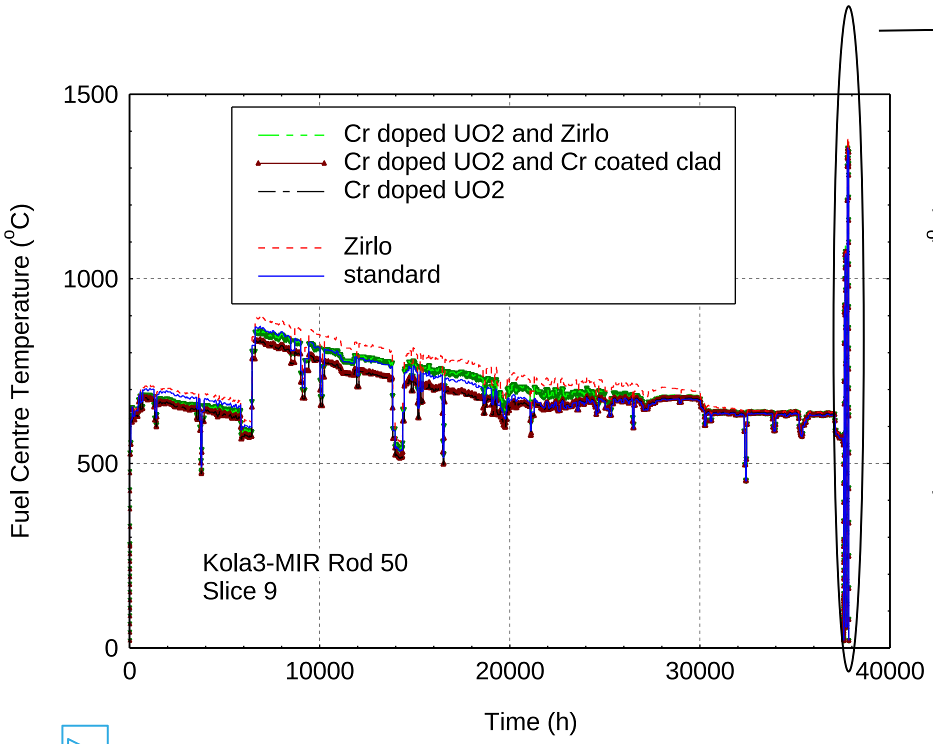
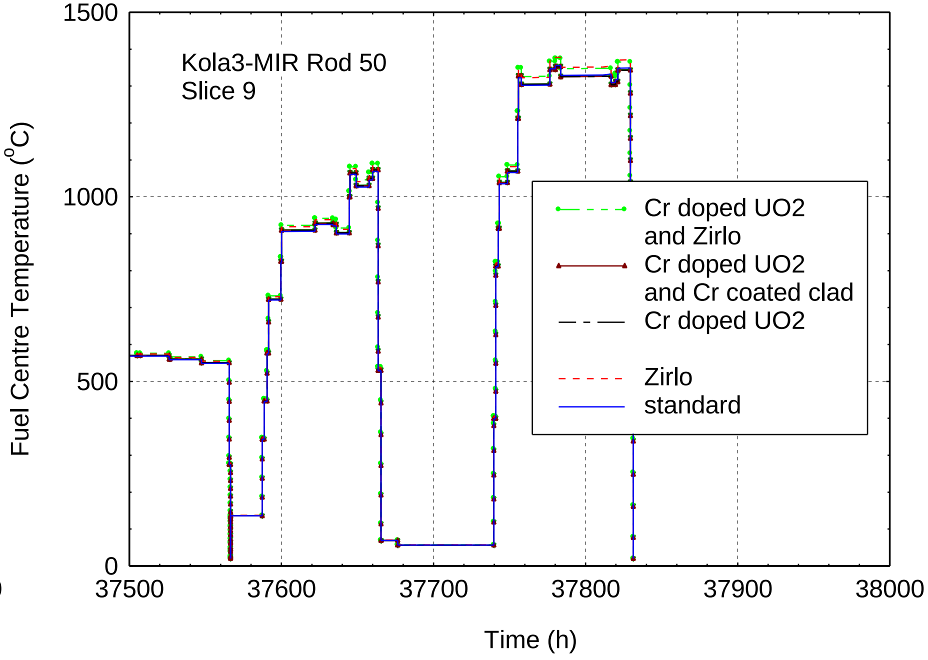
Impact of Cr-doped fuel, Zirlo clad and Cr coating

Ramp test





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Uncertainties considered

Assumptions applied earlier to simplified case in IAEA Fumex-II

Fuel material property	Uncertainty range
Thermal conductivity	±5%
Thermal expansion coefficient	±5%
Creep rate	0.5-10 (multiplication factor)
Density	±2%
Elastic modulus	±30%
Swelling	±20%
Heat capacity at constant pressure	±5%

Clad material property	Uncertainty range
Thermal conductivity	±20%
Thermal expansion coefficient	±30%
Creep rate	±50%
Poisson ratio	±10%
Elastic modulus	±5%
Heat capacity at constant pressure	±5%
Yield stress	±30%

in general three types (TUPython)

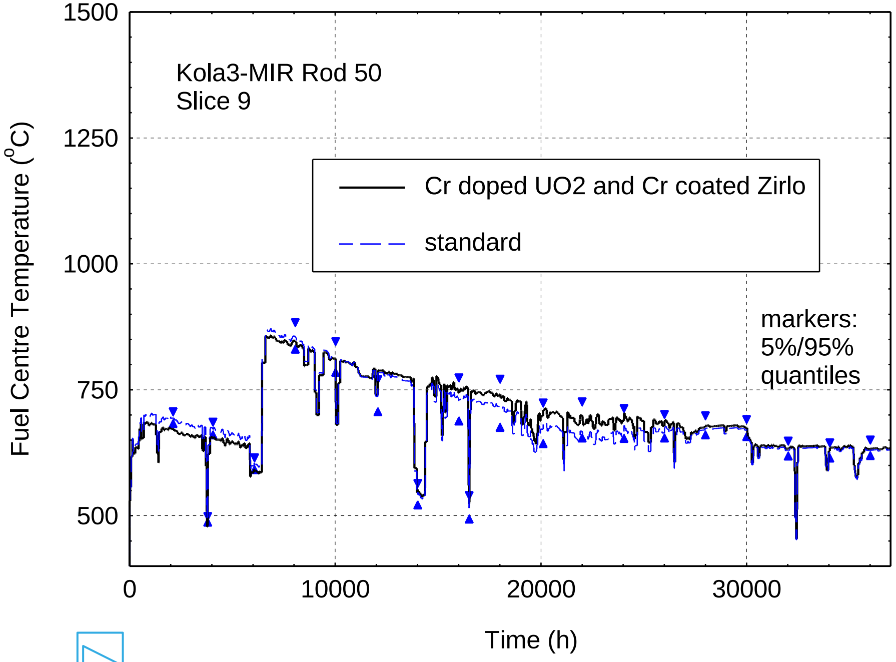
Material properties

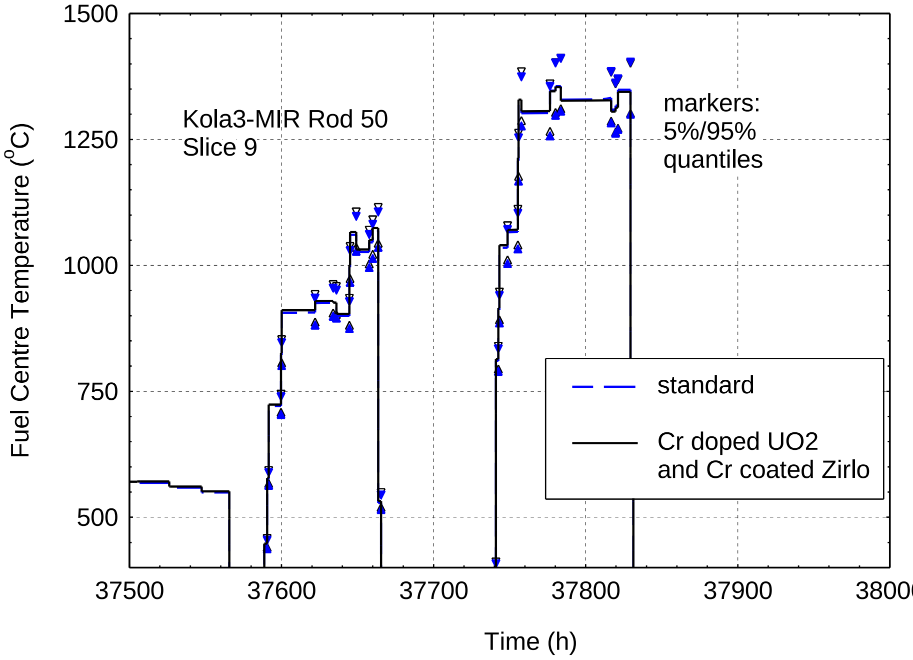
Fabrication parameters

Irradiation parameters

P. Van Uffelen et al., Assessing effects of some ATF materials and uncertainties under normal operation conditions
Pacific Basin Nucl. Conference, 2022

Impact of Cr-doped fuel + Cr coated Zirlo cladding
Uncertainty analysis





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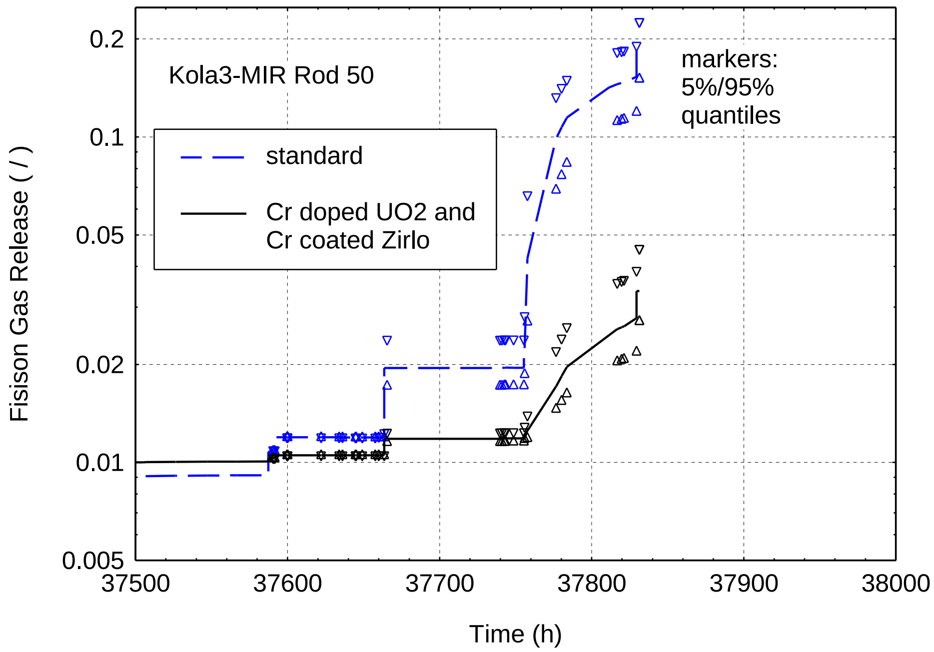
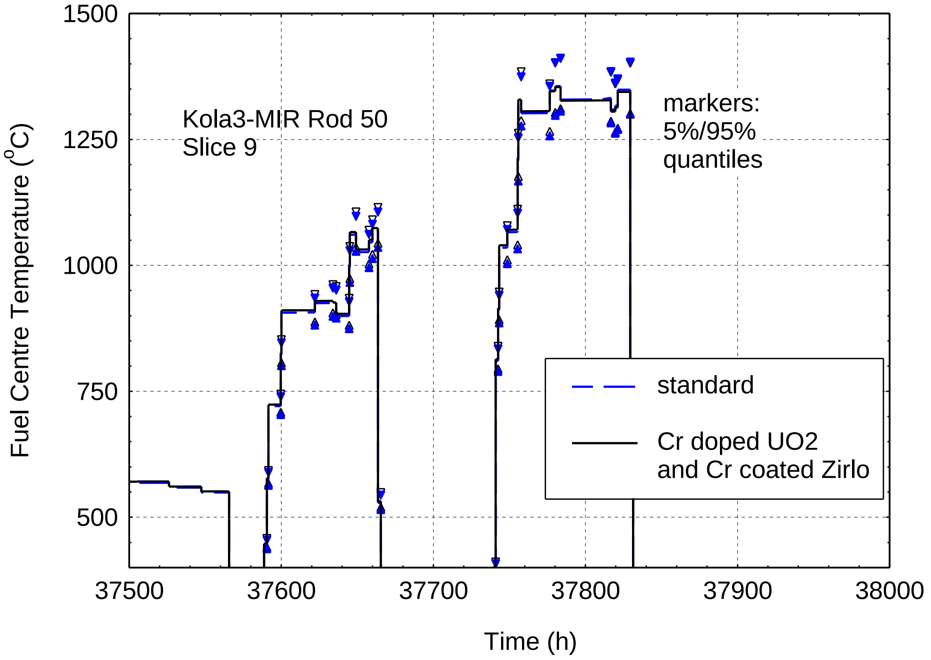
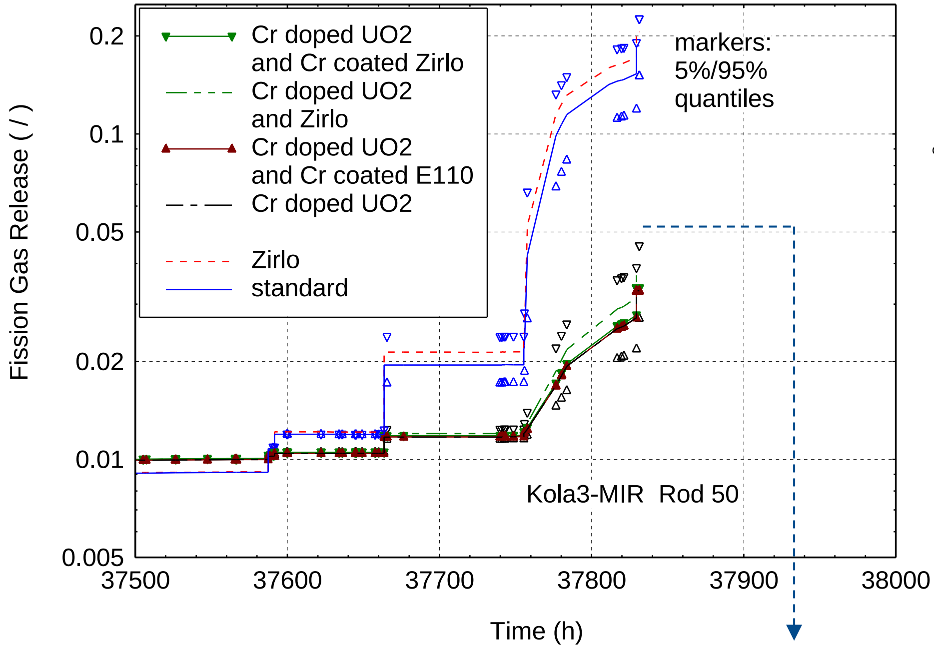
Ramps - fission gas release and fuel temperatures

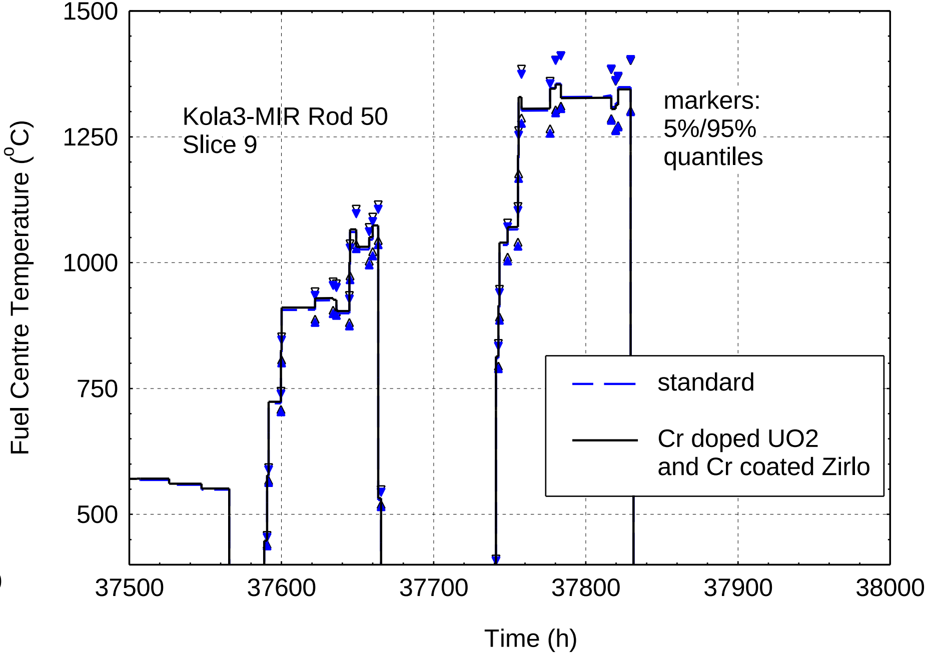
Uncertainty analysis





Ramps - fission gas release and fuel temperatures
Uncertainty analysis





Lower fgr: mainly due to larger grain size

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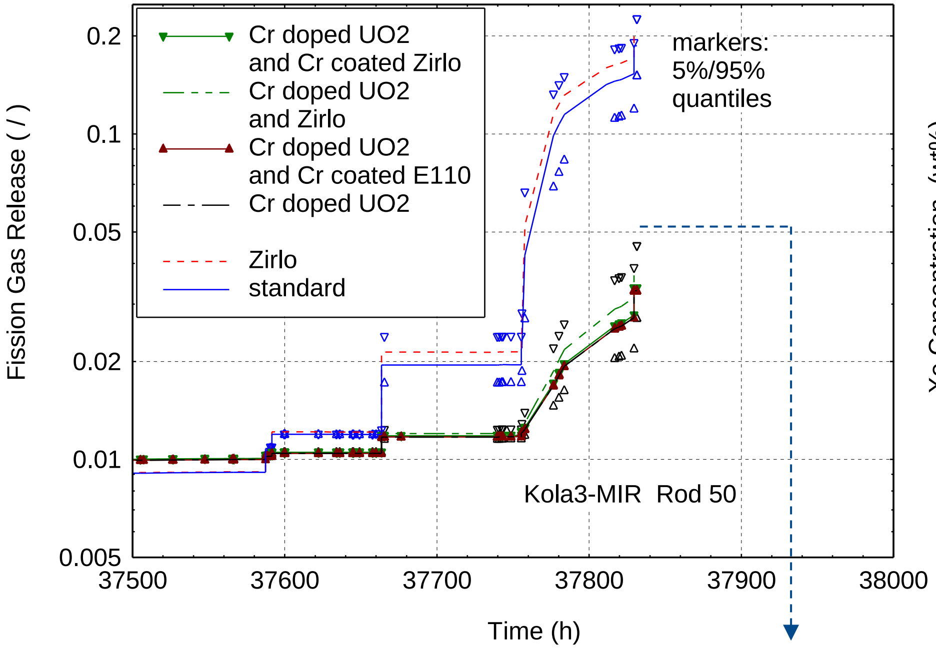
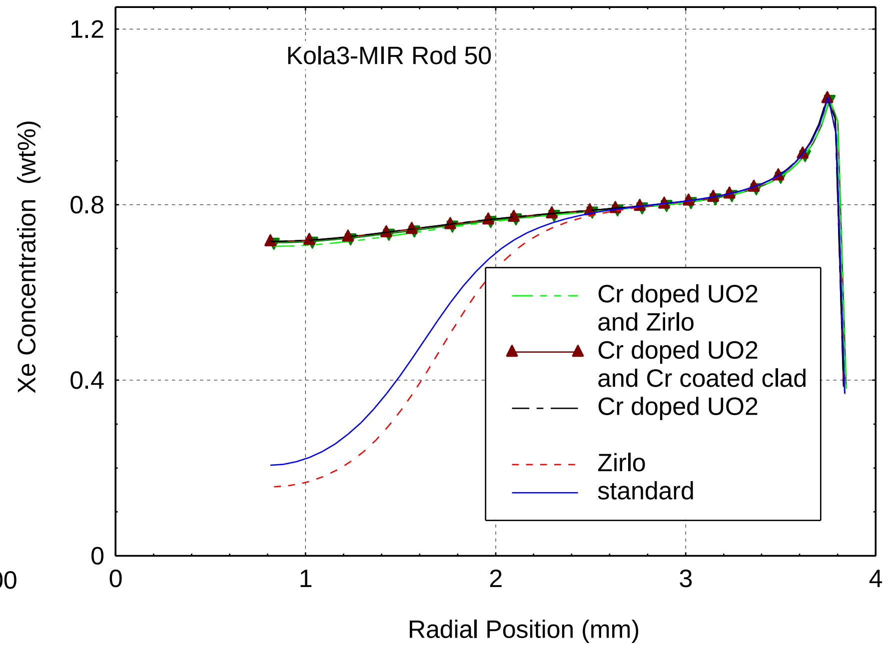
Impact on fission gas release





Lower fgr: mainly due to larger grain size

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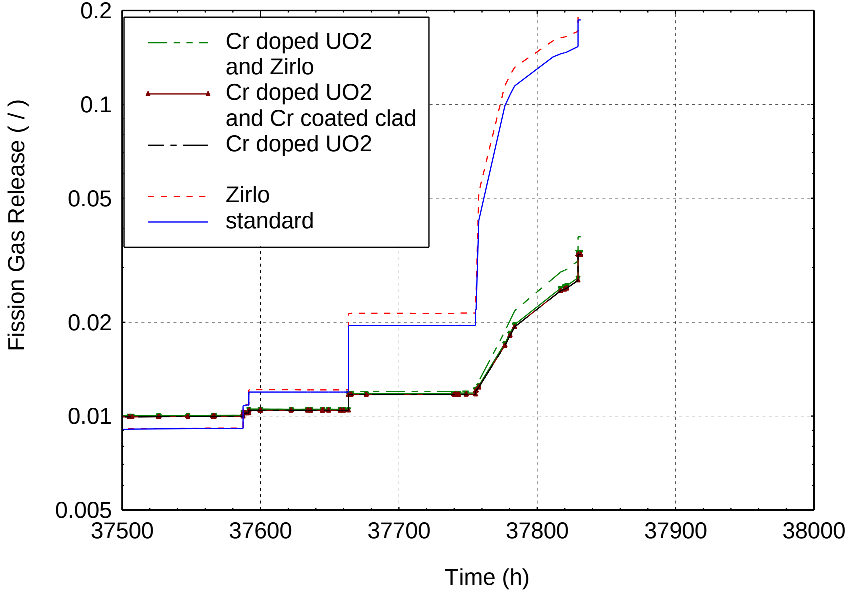
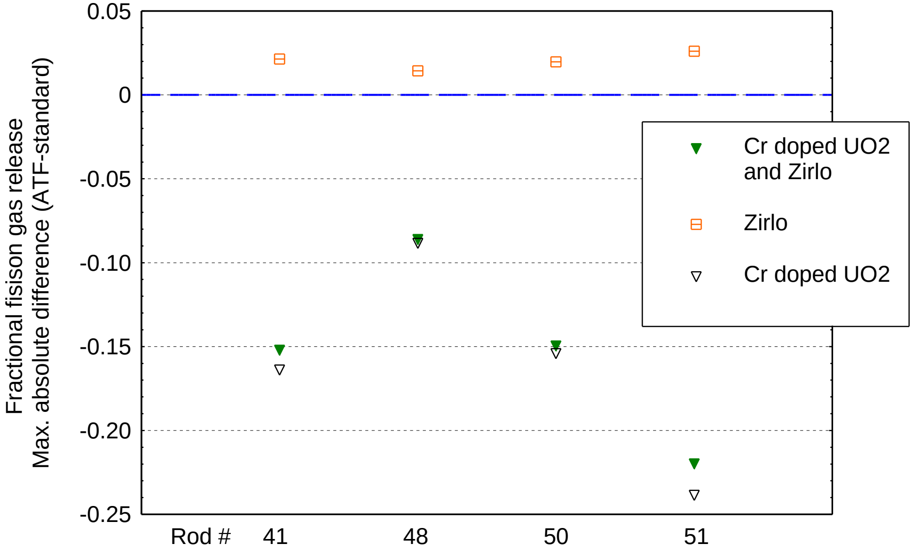
Impact on fission gas release – batch of simulations





New TUQuality tool: Impact of material properties on TRANSURANUS output for 4 ramp tests

I.M. Paponetti, PhD @ Univ. Bologna

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Summary and Outlook

BEPU analysis for ATF with TRANSURANUS

- As expected: lower fgr mainly due to larger grain size

Ongoing in APIS: Verify, validate and update

- *updated TU-WSE for fission gas release and gaseous swelling*
- *code coupling methodologies for fault analyses*

Under development: Transuranus pre- and postprocessing

- *incl. Uncertainty and Sensitivity analysis – TuPython*
- *Visualization tool – TuView*

APIS – ACCELERATED PROGRAM FOR IMPLEMENTATION OF SECURE VVER FUEL SUPPLY

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Euratom. Neither the European Union nor the granting authority can be

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- P. Aragón, F. Feria, L. E. Herranz, A. Schubert, P. Van Uffelen, Ann. of Nucl. Energy 211 (2025) 110950
- A. de Lara, X. Ha Nguyen, P. Van Uffelen, E. Shwageraus, Ann. of Nucl. Energy 218 (2025) 111355

- C. Strmensky, S. Bebjak, Int. Workshop "Towards nuclear fuel modelling in the various reactor types across Europe with TRANSURANUS, Torino, 11-12 June 2024
- P. Aragón: Extension of the predictive capabilities of nuclear fuel, PhD. Thesis, UP Madrid, 2024
- P. Van Uffelen et al.: 11th European Commission Conference on EURATOM Research and Training in Reactor Safety & Radioactive Waste Management (FISA-EURADWASTE), 12-16 May 2025, Warsaw, Poland

Reserve slides

ATF fuel and cladding properties considered

Creep anisotropy coefficients (Anisotrp)

Elasticity constant (ELOC)

Poisson's ratio (NUELOC)

Strain due to swelling (SWELOC)

Thermal strain (THSTRN)

Thermal conductivity (LAMBDA)

Creep strain (ETACR)

Yield stress (SIGSS)

Rupture strain (ETAPRR)

Burst stress (SigmaB, only for cladding)

Crystallographic Phase Transition (ZrBeta, only for cladding)

Fraction of heavy metals (ANSWME, only for fuels)

Specific heat at constant pressure (CP)

Density (RO)

Solidus–liquidus melt temperature (SOLIMT)

Heat of melting (FH)

Emissivity (EMISS)

P. Van Uffelen et al., Assessing effects of some ATF materials and uncertainties under normal operation conditions

Pacific Basin Nucl. Conference, 2022

TRANSURANUS - Assumptions for ATF

Cr-doped UO_2

Specific fuel creep - A. de Lara et al., Comparison of Advanced-Technology-Fuel options in soluble boron-free Small Modular Reactors, Ann. Nucl. Energy 218 (2025) 111355

Reduced initial porosity, Zero densification, Larger initial grain size

Zirlo cladding

Material properties - US-NRC MatLib 1.2.1 (PNNL-35702) implemented by FPoliSolutions, Pittsburgh,

Cr coating – in outermost radial zone of cladding

Material properties of Cr metal - P. Aragón et al. Fuel performance modelling of Cr-coated Zircaloy cladding under DBA/LOCA conditions, Ann. Nucl. Energy 211 (2025) 110959

No corrosion during base irradiation

Data Background and History

Kola3-MIR-RAMP → IFPE Dataset NEA-1766/02
with irradiated WWER-UO_2 fuel

Int. Seminar on WWER Fuel Performance, Modeling and Experimental Support, Sandanski, Bulgaria, Oct 1997
- A. Smirnov, V. Smirnov, A. Petuhov et al.:
The Peculiarities of the WWER-440 Fuel Behaviour at Higher Burnups

Int. Seminar on WWER Fuel Performance, Modeling and Experimental Support, Pamporovo, Bulgaria, Oct 1999
- Yu. Bibilashvili, A. Medvedev, G. Khvostov et al.:
Fission Gas Products Behaviour Modelling in the START-3 Code for the WWER Fuel at High Burnup and Transient Conditions
- A. Smirnov, B. Kanashov, G. Lyadov et al.:
Examination of Fission Gas Release and Fuel Structure of High Burnup WWER-440 Rods under Transient Conditions

Int. Seminar on WWER Fuel Performance, Modeling and Experimental Support, Varna, Bulgaria, Oct 2001
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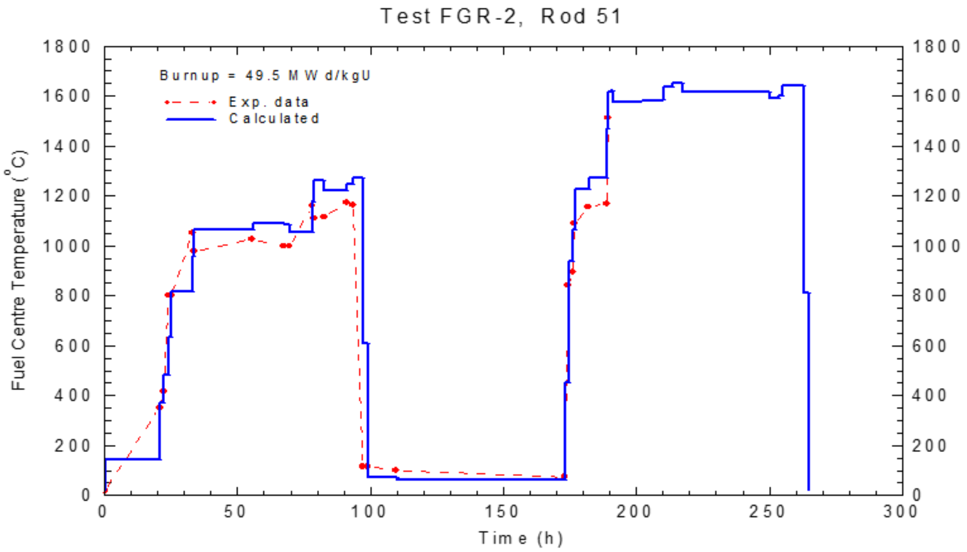
IAEA Fumex-III – Base irradiations and ramp tests simulated with TRANSURANUS



Int. WWER Fuel Conferences, Burgas, Bulgaria

- D. Elenkov et al., Analysis of the Kola3-MIR Transient Experiment with the TRANSURANUS Code (2009)
- S. Boneva et al., The priority cases of the FUMEX-III exercises simulated by means of the TRANSURANUS code (2011)
- see also IAEA-TECDOC-1697

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Transient simulations in IAEA CRP Fumex-III

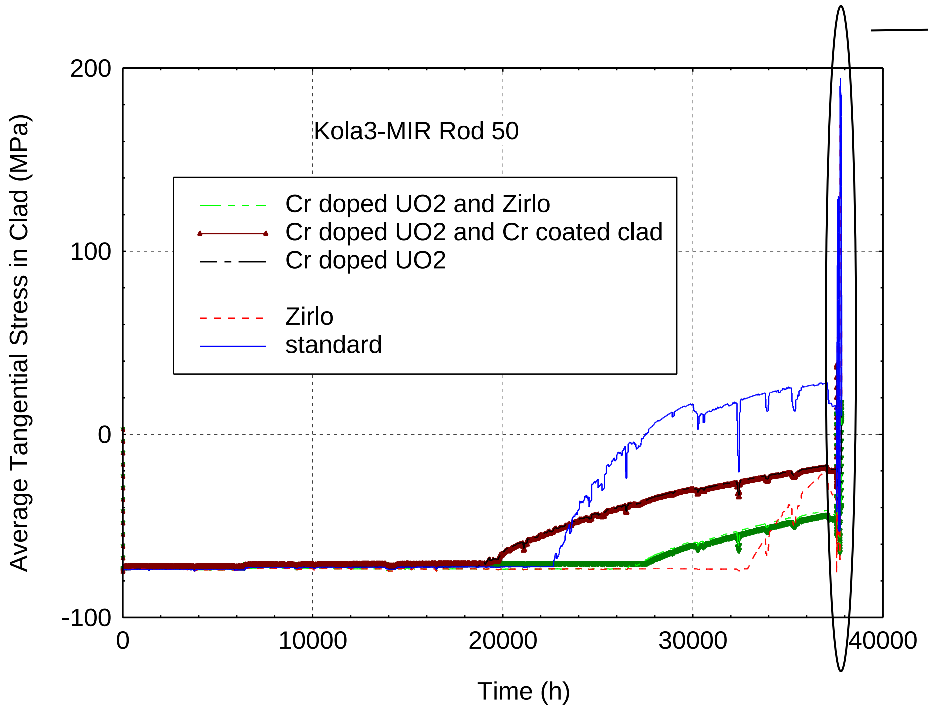
Refabr. fuel rod number	Calc. BU	Fuel centre temp., oC		Centre grain size, µm		Pellet-cladding gap (diam.), µm		Δd_{inn} Pellet hole diam.change, µm		FGR after test irradiation, [%]		FGR Punct. results
		v1m1j09	v1m2j11	v1m1j09	v1m2j11	v1m1j09	v1m2j11	v1m1j09	v1m2j11	v1m1j09	v1m2j11	
RAMP: rod33 (198)	47.6	1417	1418	7.53	9.66	10.10	10.69	-4	-4.8	2.44	*3.43*	31.3
rod37 (222)	57.8	1278	1277	6.69	7.02	5.64	6.12	-20	-20	1.98	*2.15*	16.9
rod38 (222)	58.0	1153	1153	6.60	6.60	4.26	5.04	-18	-18	1.55	*1.56*	19.6
FGR-1: rod41 (198)	48.2	1779	1784	28.89	43.4	35.42	38.08	-32	-34	19.77	*21.82*	47.5
rod32 (222)	58.8	1390	1391	11.58	11.58	18.06	18.48	-28	-28	7.92	*10.18*	46.6
rod48 (222)	59.7	1464	1465	10.48	15.37	17.02	16.26	-30	-30	8.22	*10.85*	50.0
FGR-2: rod51 (198)	48.6	1842	1846	31.28	47.35	36.58	37.5	-38	-37.5	30.68	*34.22*	-
rod50 (222)	57.5	1568	1572	13.73	20.75	20.0	20.6	-42	-42	14.58	*18.43*	-
rod52 (222)	57.4	1665	1669	18.74	28.4	26.12	27.3	-44	-44.6	21.74	*25.80*	48.4

Int. WWER Fuel Conference, Sept. 2011, Burgas, Bulgaria

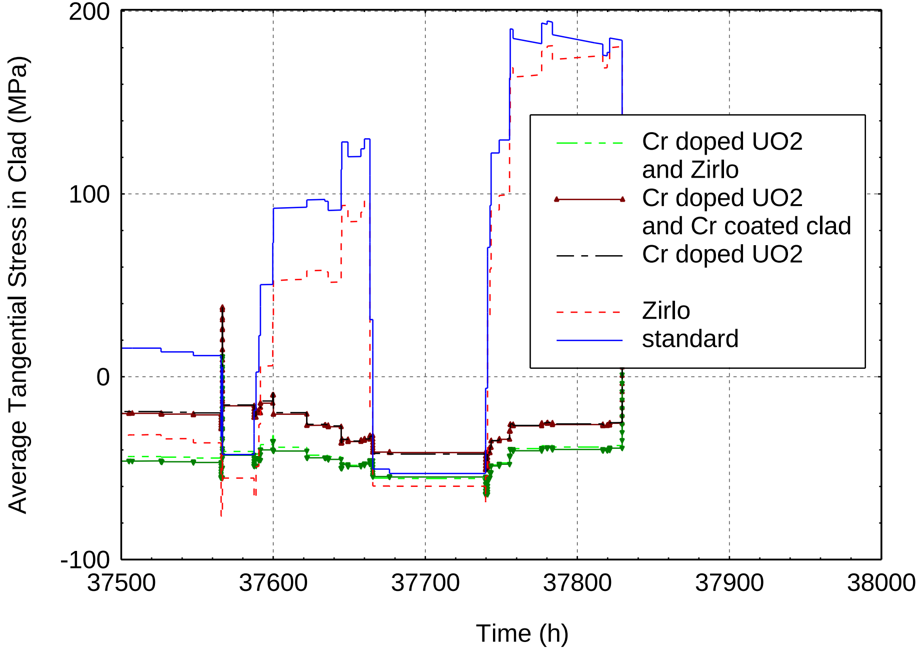
S. Boneva et al., The priority cases of the FUMEX-III exercises simulated by the means of TRANSURANUS code

see also IAEA-TECDOC-1697

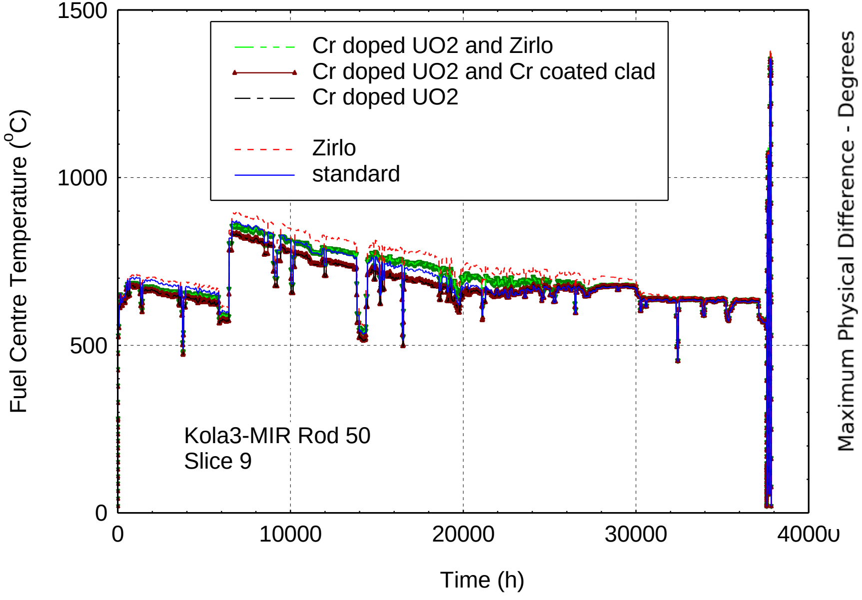
Impact of Cr-doped fuel, Zirlo clad and Cr coating

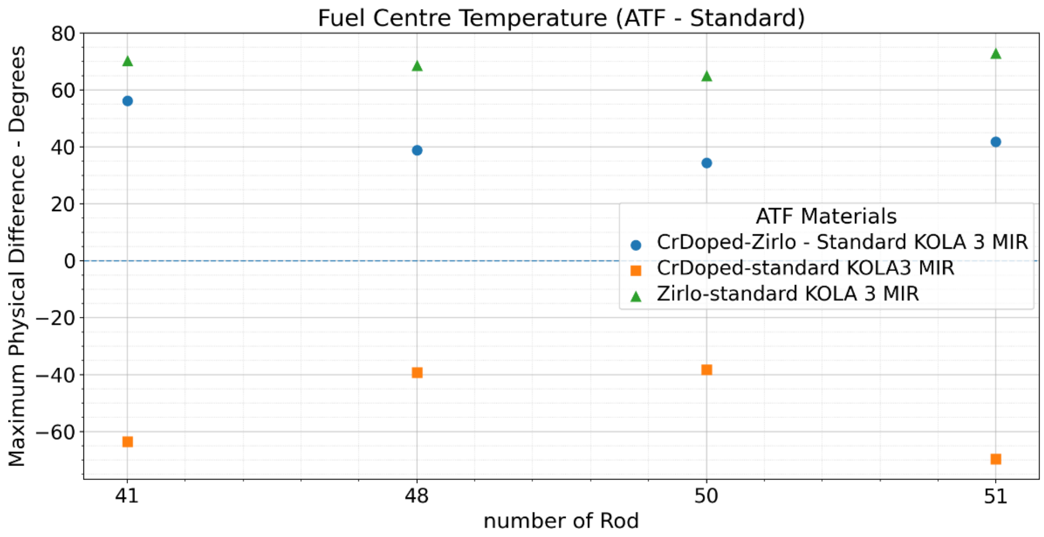


Ramp test



Impact on fuel temperatures – batch of simulations





New TUQuality tool: Impact of material properties on TRANSURANUS output for 4 ramp tests

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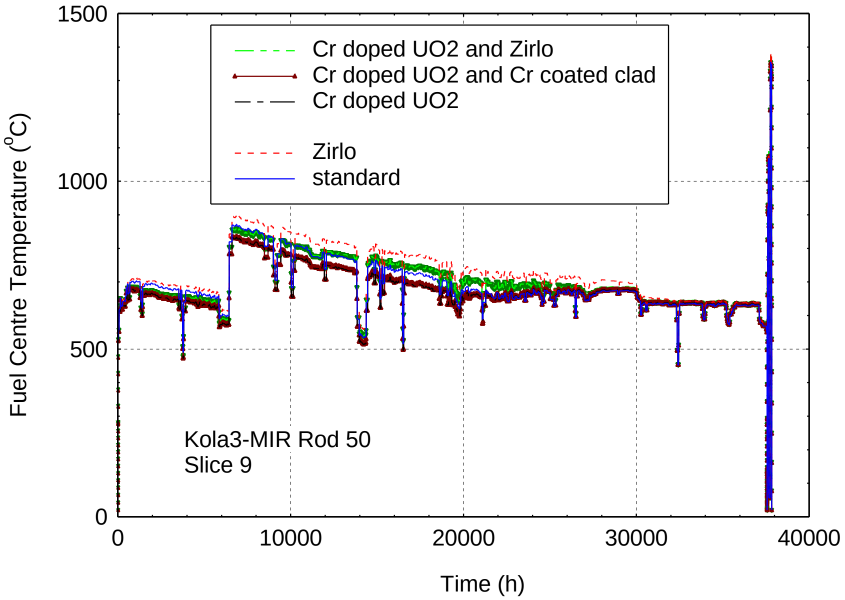

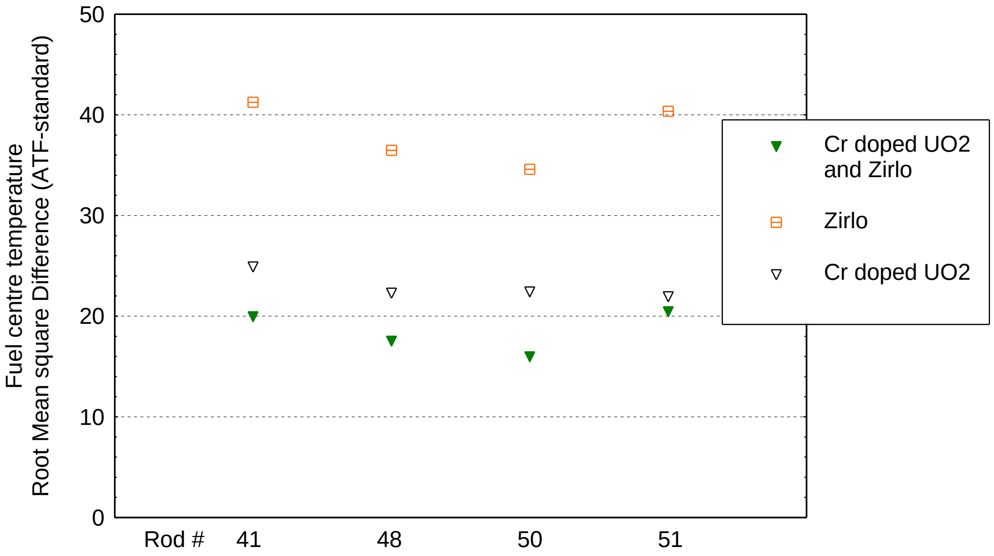

New TUQuality tool: Impact of material properties on TRANSURANUS output for set of simulations (e.g. 4 ramp tests)
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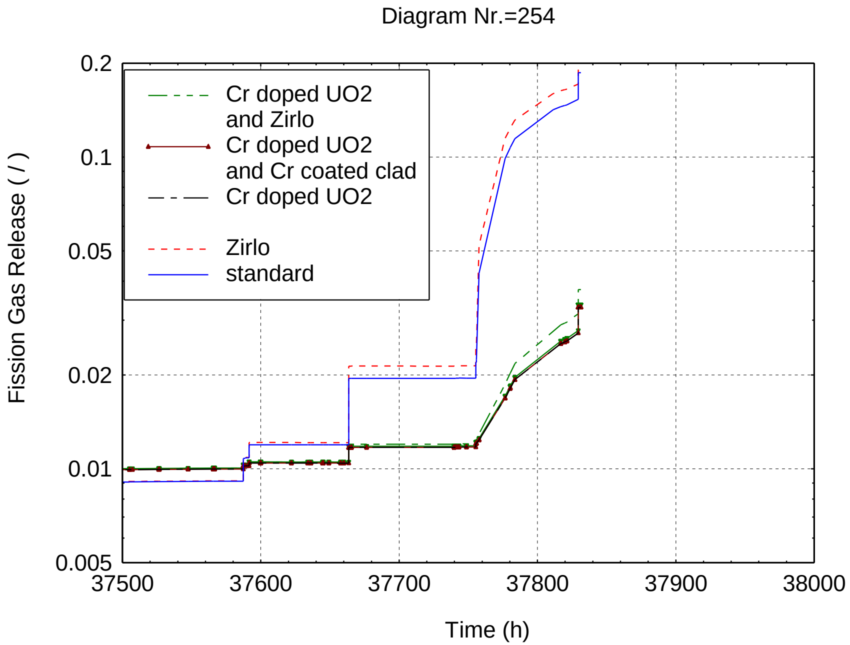
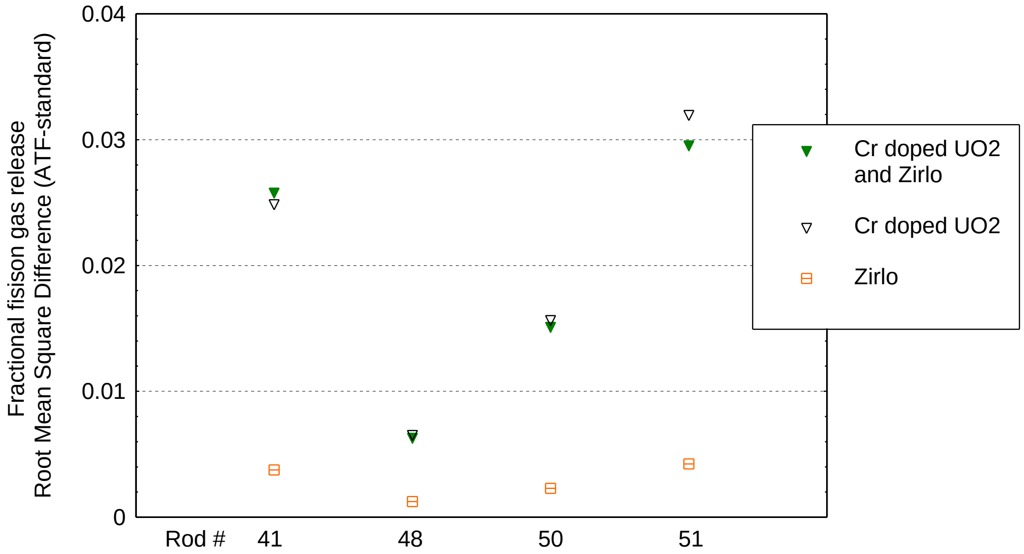
Impact on fission gas release – batch of simulations





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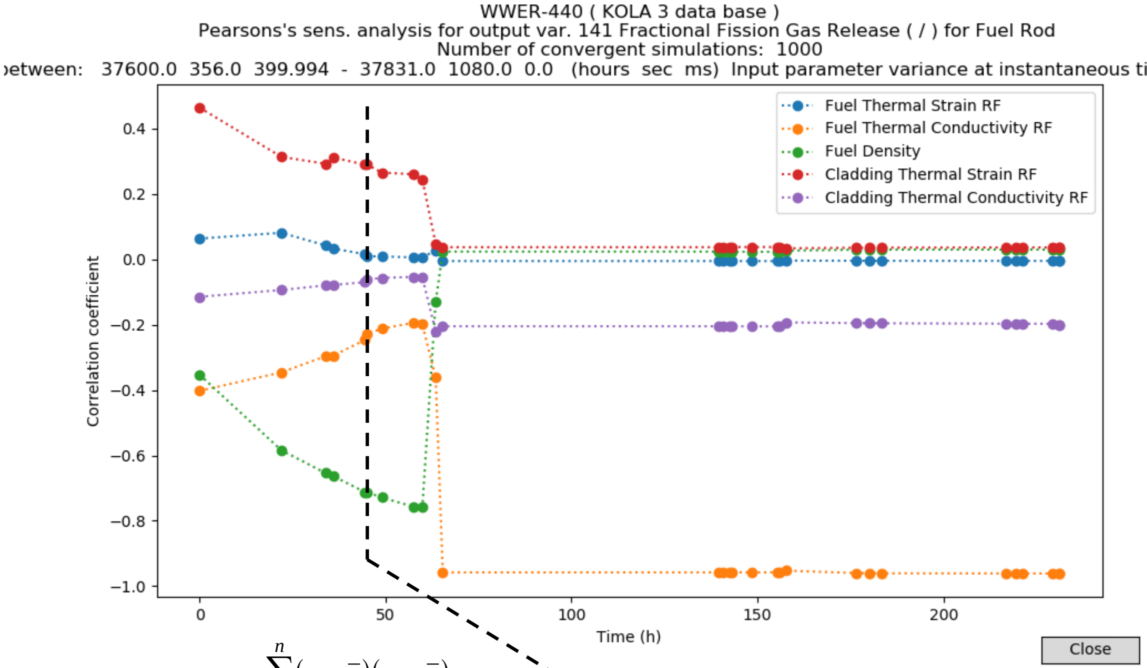
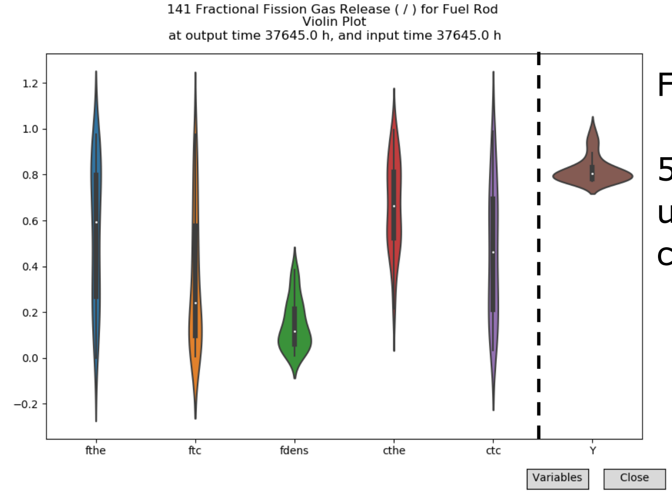
Impact on fission gas release - Uncertainty/Sensitivity Analysis



TUPython extended: ‚violin plots'
North Carolina State University
(NCSU, G. Delipei, K. Ivanov)



FGR

5% upper cases

$$SCC = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

‚violin plot' at 37645 h (1st ramp)

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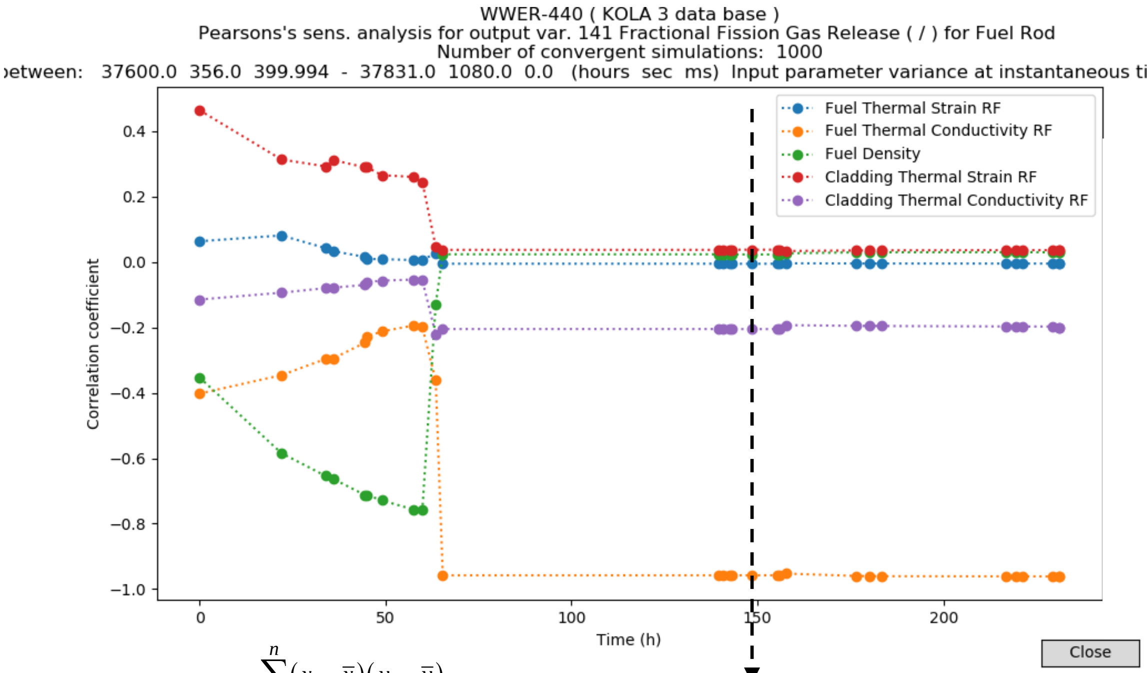
Impact on fission gas release - Uncertainty/Sensitivity Analysis



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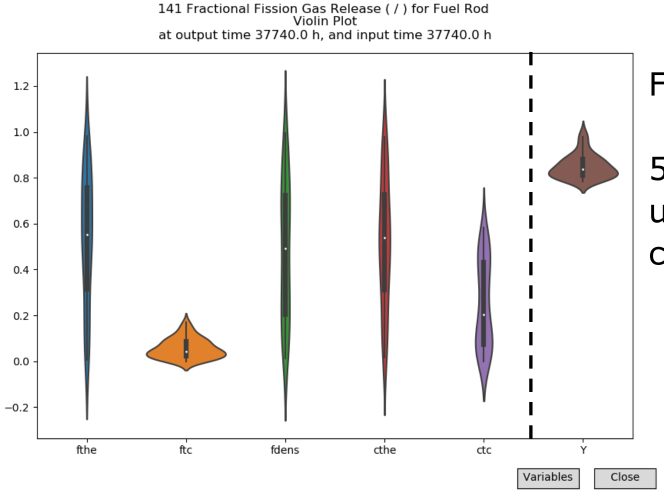

FGR

5% upper cases

$$SCC = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

‚violin plot' at 37740 h (2nd ramp)

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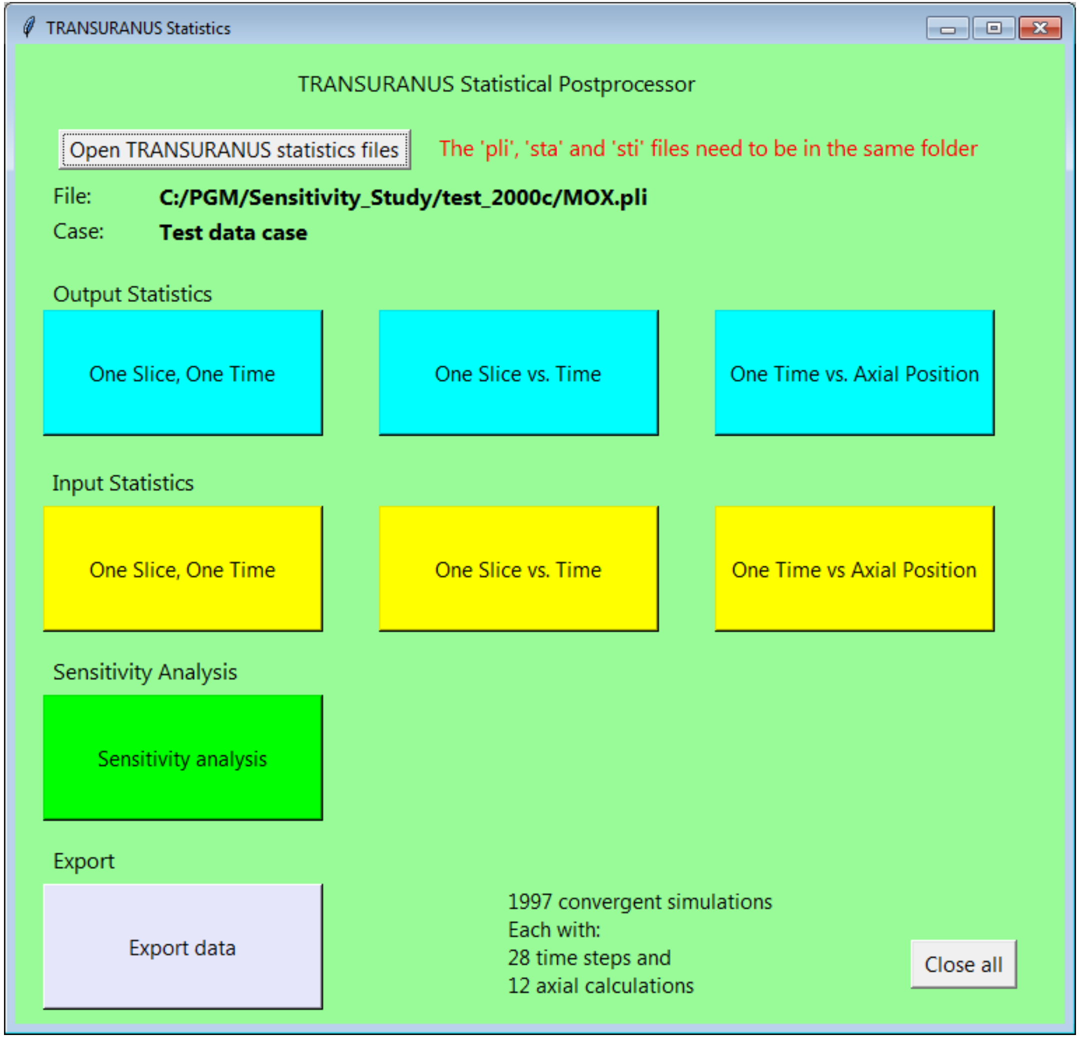
Pearson's or Simple Correlation Coefficient (SCC) vs. Spearman's or Ranking Correlation Coefficient (RCC)

$$SCC = \frac{\sum_{i=1}^{n} (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \overline{x})^2} \sqrt{\sum_{i=1}^{n} (y_i - \overline{y})^2}}$$

$$RCC = SCC$$

with replacing input and output values by respective ranks

TU Python GUI



Output UA

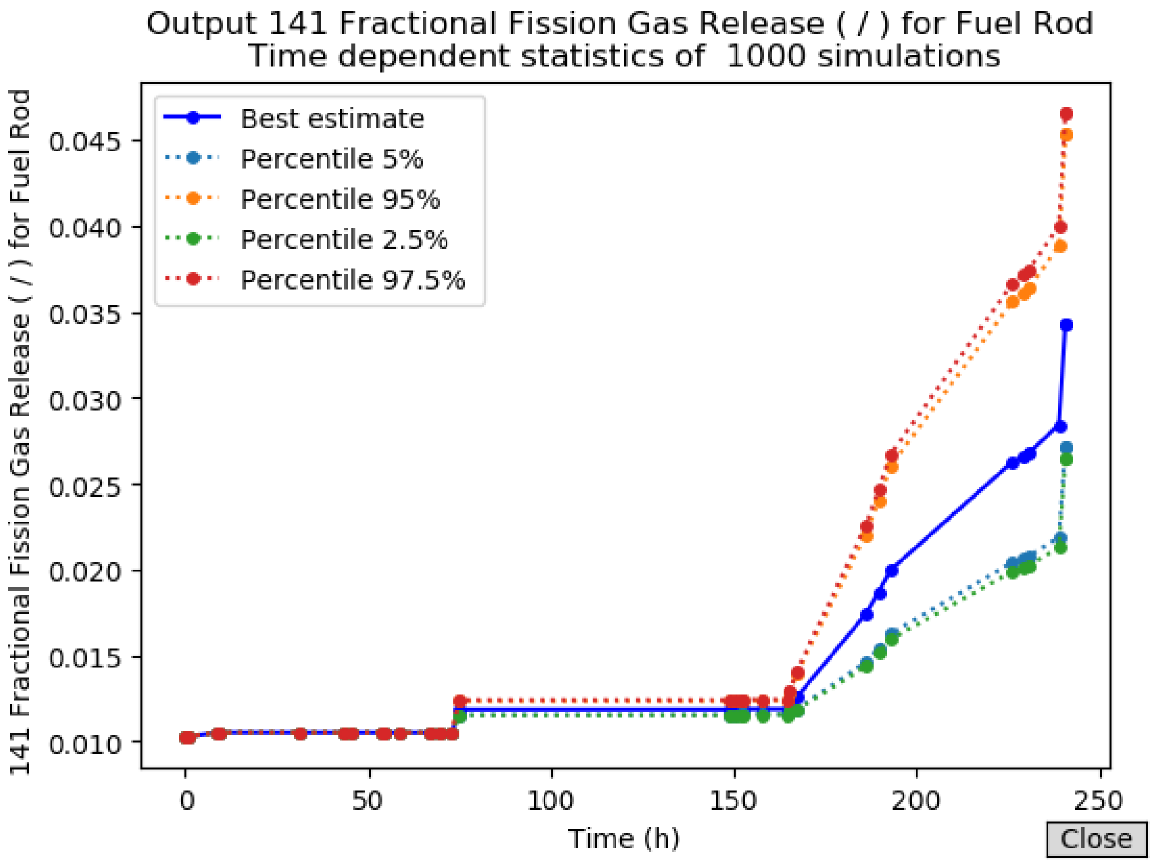
Input UA

SA

Data Export

TU Python GUI

Example:



Asymmetry in uncertainty