Benchmark and improvement of fuel performance codes

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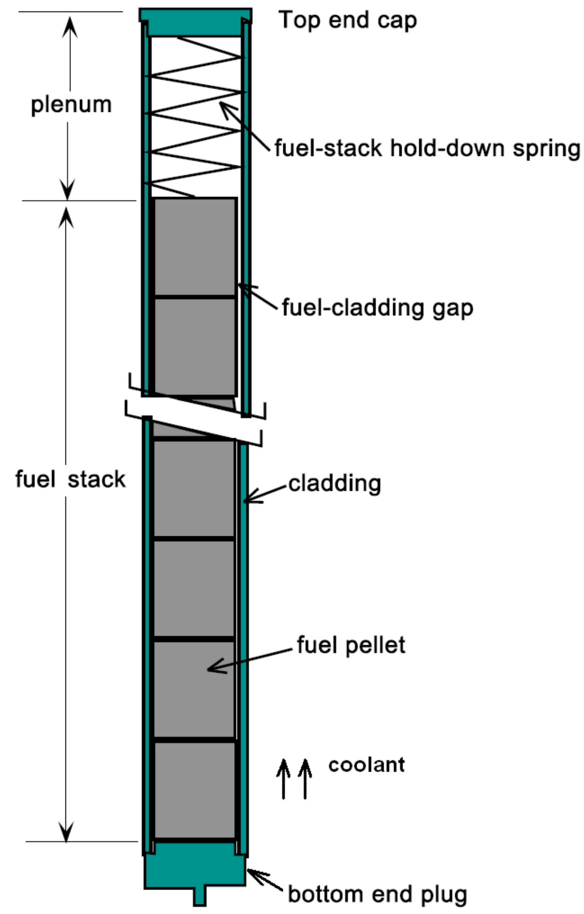
Fuel Performance Codes (i)

<u>Fuel Performance Codes</u> (FPCs) are able to calculate the **overall thermo-mechanical response…** (→ $\bar{\bar{\sigma}}, \bar{\bar{\epsilon}}, \bar{u}$, and T) of the fuel pin (fuel + cladding) to the imposed reactor power and boundary conditions, which are represented by the coolant pressure, core inlet temperature and mass flow rate, and the irradiation history (i.e., power and fast neutron flux evolution with time, axial peak factors).

→ **<u>Fuel pin for solid-fuelled nuclear reactors</u>**

- **thermo-mechanical behaviour** of fuel and cladding materials (e.g., heat transfer by conduction, convection and radiation, thermal expansion, creep, elasticity, plasticity, fatigue, phase changes and melting, stresses and deformations).
- **irradiation / neutron flux** effects (e.g., cladding hardening, embrittlement, axial growth and void swelling).
- **burnup and fission product** effects (e.g., non-uniform heat generation, generation and release of fission gas (Xe, Kr), helium, fuel densification and swelling).
- **microstructural changes** in the fuel (e.g., formation of high burnup structure, grain growth and restructuring, pellet cracking and fuel fragment relocation, oxygen migration and plutonium redistribution).
- **chemical phenomena** (e.g., fuel-clad bonding, stress-corrosion cracking and cladding oxidation, erosion and dissolution).



[Olander 2009]

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Fuel Performance Codes (ii)

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→ All this involves **modelling & simulation** of a large number **of inter-connected phenomena:**

- **thermo-mechanical behaviour** of fuel and cladding materials (e.g., heat transfer by conduction, convection and radiation, thermal expansion, creep, elasticity, plasticity, fatigue, phase changes and melting, stresses and deformations).
- **irradiation / neutron flux** effects (e.g., cladding hardening, embrittlement, axial growth and void swelling).
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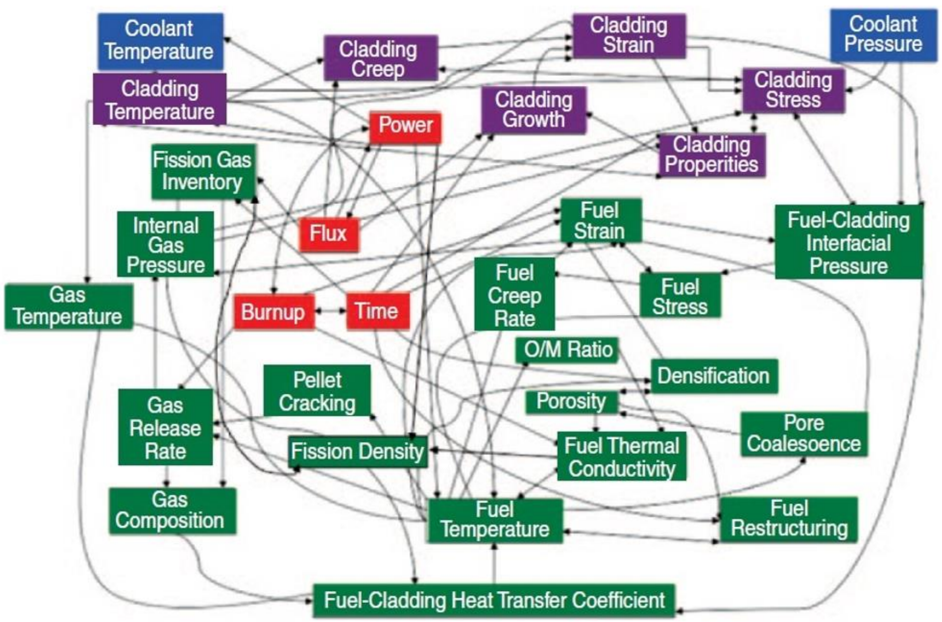
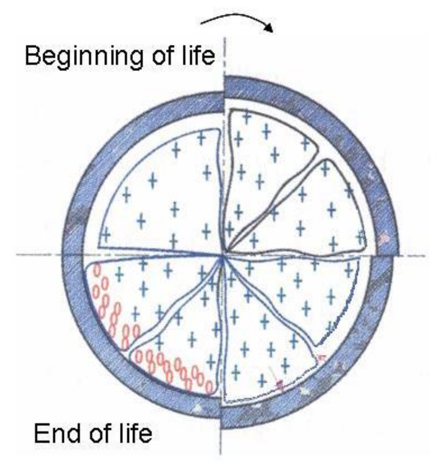


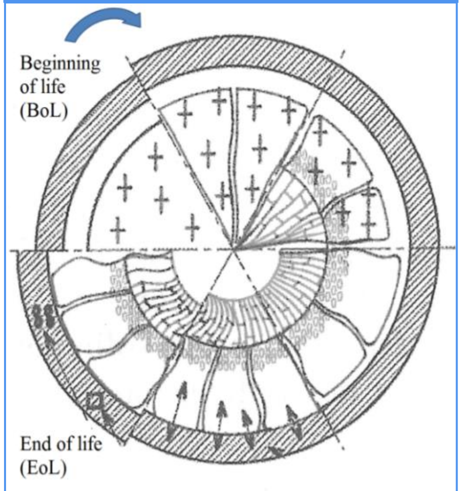
[Lassmann, NED 57 (1980) 17-39; Rashid et al., JOM 63 (2011) 81-88]

Complexity of fuel pin behaviour modelling

LWR → UO_2/Zy



FR → $(U,Pu)O_2$/SS



- Complex **multi-physics phenomena** featured by *different time* (22 oom: ps-y) and *space scales* (10 oom: atomic/nm-m) concerning both **fuel and cladding as a "coupled system"**, depending on reactor type, conditions and materials.

- **Numerous material and behavioural models** represent the engineering level multi-material/multi-domain complex interaction in the fuel pin:

  - they contribute to the **internal capability of a FPC** and are generally characterized as "point models"

    (i.e., they describe material behaviour over a representative small volume, and are therefore independent of the FPC numerical or computational structure in which they reside).

  - Various **code styles**: geometrical representation (1.5-D, 2-D, 3-D, "hybrid type") / numerical technique (finite difference, finite element) / type of analysis (steady-state, transient).

  - Analysis of **individual fuel pins** (conveniently selected: average + hot pin → conservative "limiting pin" approach).

- Need of simulation of steady-state and transient irradiation conditions, accidental scenarios (e.g., LOCA, RIA).

[Rossiter, Understanding and modelling fuel behaviour under irradiation. In: I. Crossland (Ed.), Nuclear fuel cycle science and engineering, Woodhead Publishing Limited, 2012]

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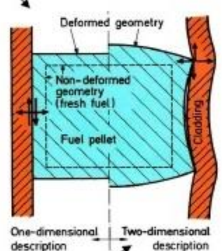
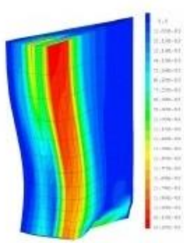
FPC variety (i)

- Employed by: **fuel designers and vendors** (Copernic), **research institutes** (Alcyone, Bison, Cosmos, Enigma, Falcon, Femaxi, Frapcon, Fraptran, Germinal, Transuranus), **safety authorities** (Frapcon, Fraptran), **utilities & industry** (Cyrano, Galileo, Pad, Rodex).
- **Thermal / fast reactor conditions** (e.g., ALCYONE / GERMINAL)**, or both** (e.g., TRANSURANUS).
- **1.5D / 2D / 3D**.
  - **1D, radial × slice number**
    - for 1 rod
    - for the whole core
  - **2D, rθ or rz × slice number**
  - **3D**
    - generally applied on a short section of the rod, even on a portion of one pellet





[Noirot, International School in Nuclear Engineering - Nuclear fuels for Light Water Reactors and Fast Reactors, CEA, 2016]

Country	Organization	Code name (precursor codes)
Argentina	CNEA	BACO, DIONISIO
Belgium	Belgonucleaire	COMETHE
	SCK-CEN	MACROS (ASFAD)
China	Xi'an Xiaotong Univeristy	FROBA
	CIAE	FTPAC
	NPIC	FUPAC
	CGNPC	JASMINE
Czech Republic	UJV	PIN-MICRO (GAPCON-THERMAL2)
France	CEA	ALCYONE (METEOR-TRANSURANUS)
	Framatome	COPERNIC (TRANSURANUS), GALILEO (COPERNIC/RODEX/CARO)
	EdF	CYRANO
	IRSN	SCANAIR
Germany	Siemens	CARO
	Framatome	GALILEO (COPERNIC/RODEX/CARO)
	GRS	TESPA-ROD (TESPA)
	JRC	TRANSURANUS (URANUS)
Hungary	MTA EK	FUROM (PIN-MICRO)
India	BARC	FAIR, PROFESS
	PNC	FUDA
Japan	CRIEPI	EIMUS (FEMAXI-III)
	JAEA	FEMAXI, RANNS
	SEPC	IRON (FEMAXI-III)
	NFD	TRUST
Korea	KAERI	COSMOS, INFRA
Russian Federation	VNIINM	START, RAPTA
	TRINITI	RTOP
	IBRAE	SFPR (MFPR)
Sweden	Westinghouse Sweden Electric	STAV
United Kingdom	NNL, EDF Energy	ENIGMA (MINIPAT, SLEUTH, HOTROD)
USA	USNRC	FRAPCON, FRAPTRAN (FRAP), FAST
	Siemens	RODEX
	EPRI	FALCON (FREY, ESCORE)
	INL	BISON
	Framatome	GALILEO (COPERNIC/RODEX/CARO)
	Westinghouse	PAD

[Van Uffelen et al., JNM 516 (2019) 373-412]

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FPC variety (ii)

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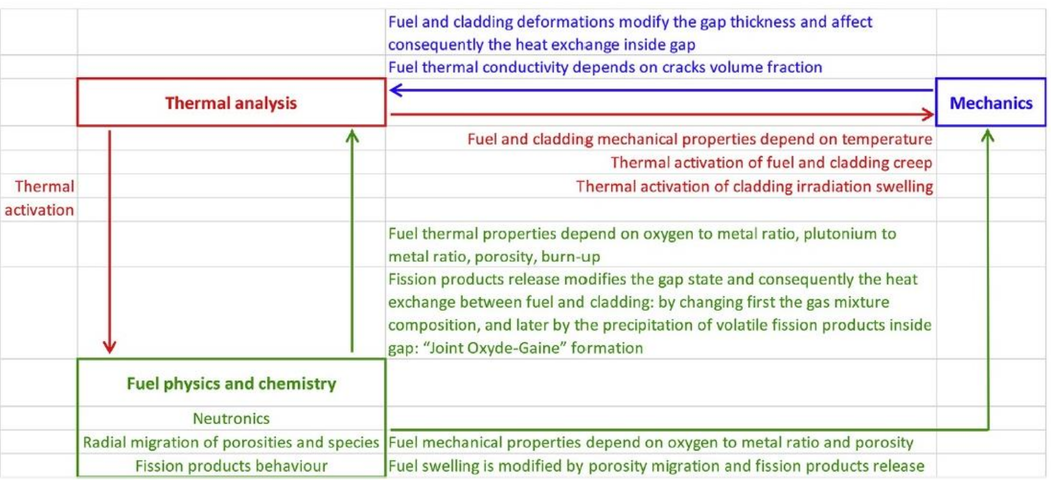
- **Thermal / fast reactor conditions** (e.g., ALCYONE / GERMINAL)**, or both** (e.g., TRANSURANUS).
- **1.5D / 2D / 3D**.
- **General coupling scheme**:



[Lainet et al., JNM 516 (2019) 30-59]

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Sweden	Westinghouse Sweden Electric	STAV
United Kingdom	NNL, EDF Energy	ENIGMA (MINIPAT, SLEUTH, HOTROD)
USA	USNRC	FRAPCON, FRAPTRAN (FRAP), FAST
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[Van Uffelen et al., JNM 516 (2019) 373-412]

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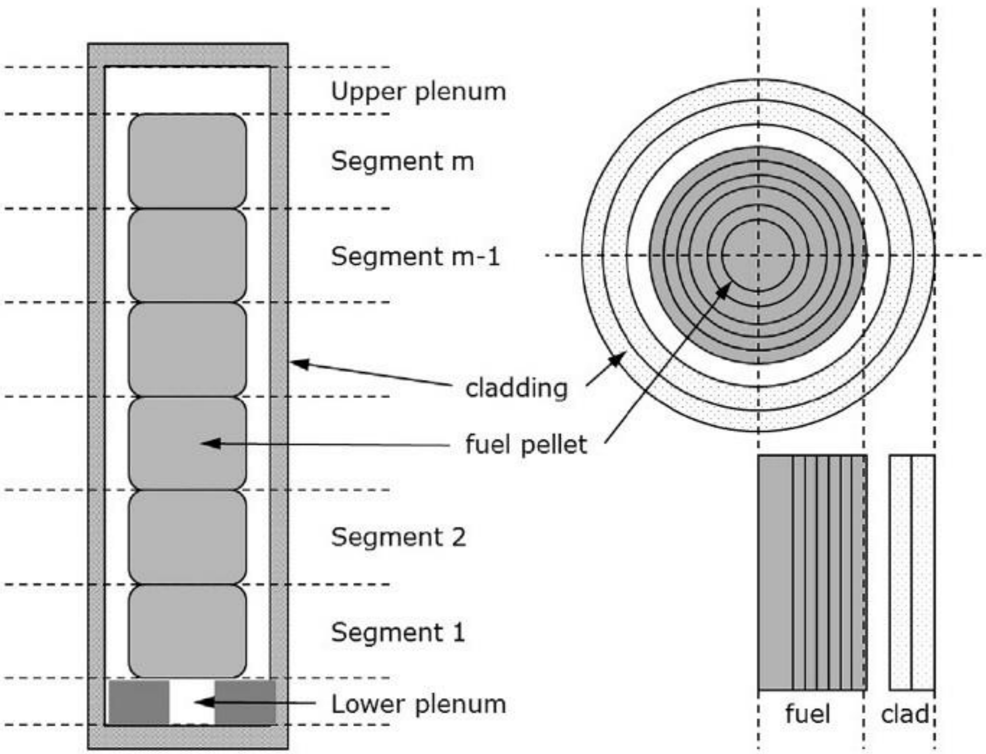
1.5D FPC analysis

- **1.5D FPC**: *GERMINAL, MACROS, TRANSURANUS, ...*
- 3D effects (caused by shear stresses, e.g., pellet hour-glassing, Missing Pellet Surface imperfection, pellet cracking evolution) cannot be simulated.



[Van Uffelen et al., JNM 516 (2019) 373-41]

- **Active length** of the fuel pin subdivided in a series of <u>axial slices</u> (coupled), and in each axial zone fuel and cladding are divided into <u>radial rings</u>.
- **Axial-symmetry + ortho-cylindricity** + **generalized plane strain** approximation.
- **Thermal** (energy conservation) **and mechanical equations** (force balance, stress-strain + strain-displacement relationships) are typically solved by a **finite difference scheme**.
- <u>Traditionally</u>, a series of **step-by-step calculations**: **temperatures** are calculated in the fuel pellets and the cladding **+ displacements**, **strains** and **stresses**, with both sets of calculations performed within an <u>iteration loop</u>.

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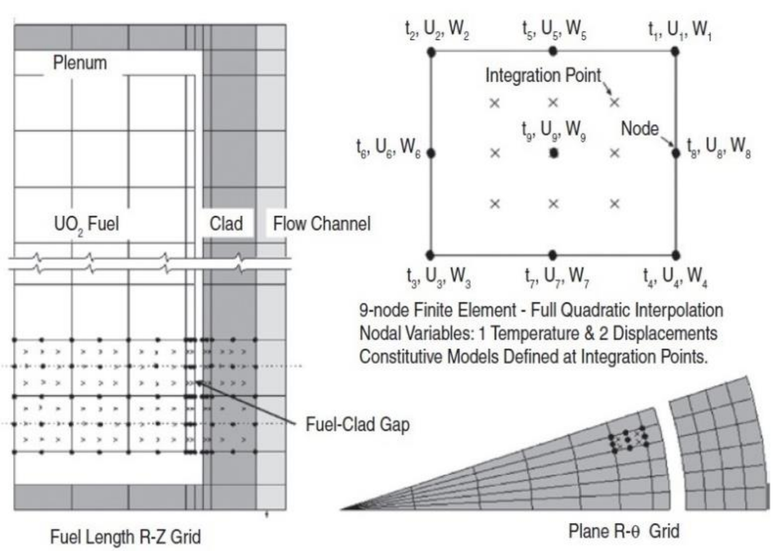
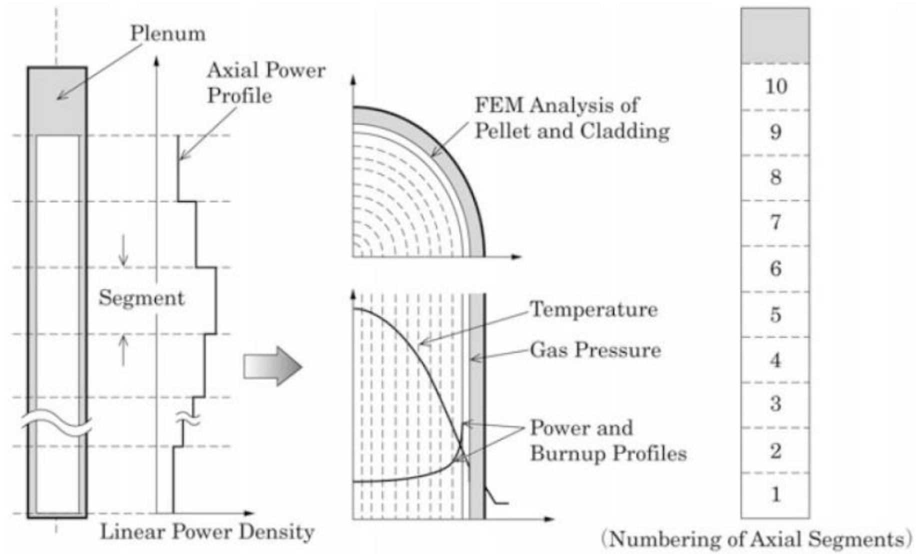
2D FPC analysis (i)

- **2D FPC**: *FALCON, FEMAXI, ...*



[FALCON, Rashid et al., JOM (2011) 63]



[FEMAXI-7, Suzuki et al., JAEA-Data/Code 2013-005, 2013]

- ➢ Fuel pin geometry representation (effectively only applicable to pelleted fuel) by means of either **axial-symmetric (r-z) or plane (r-θ) grids**.
- ➢ There is radial and axial modelling of a fuel pellet in each axial zone → **axial-symmetry** is still assumed.
- ➢ **Thermal and mechanical equations** are typically solved by a **finite element technique** (FEM).
- ➢ **Advantage over 1.5D codes**: 2D phenomena such as pellet hour-glassing, clad ridging, large-strain ballooning-type displacements (LOCA), MPS (missing pellet surface) induced failure pattern can be modelled somehow. **Disadvantage**: more complex, therefore slower running time.

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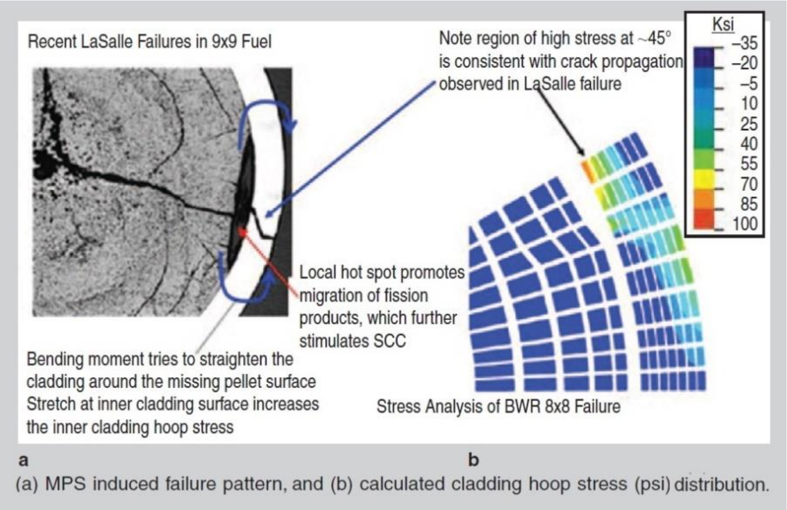
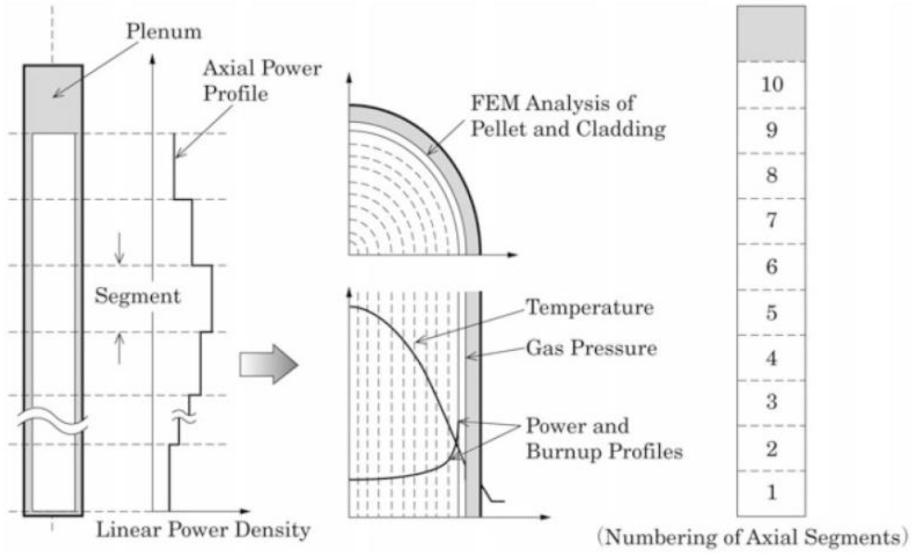
2D FPC analysis (ii)

- **2D FPC**: *FALCON, FEMAXI, ...*



(a) MPS induced failure pattern, and (b) calculated cladding hoop stress (psi) distribution.



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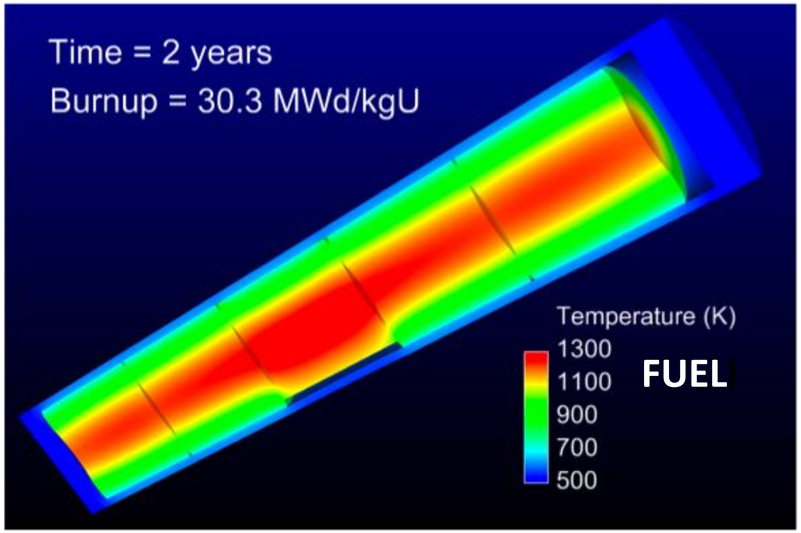
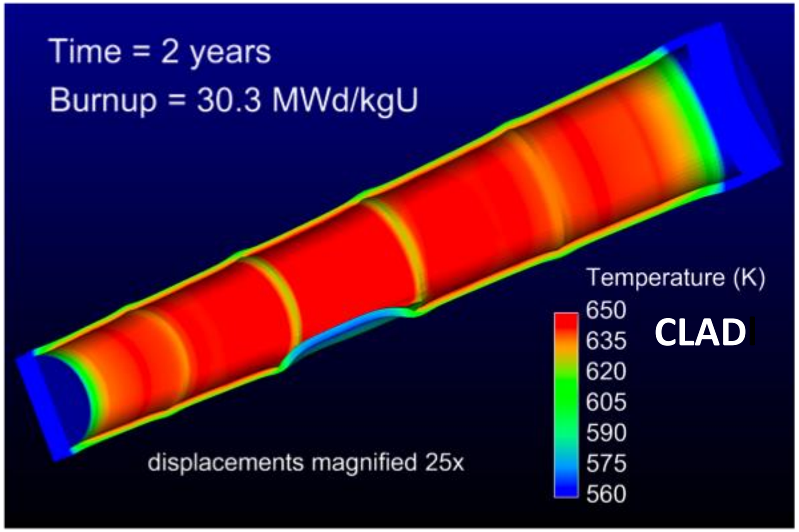
3D FPC analysis (i)

- **3D FPC**: *ALCYONE, BISON, ...*

[BISON, bison.inl.gov]



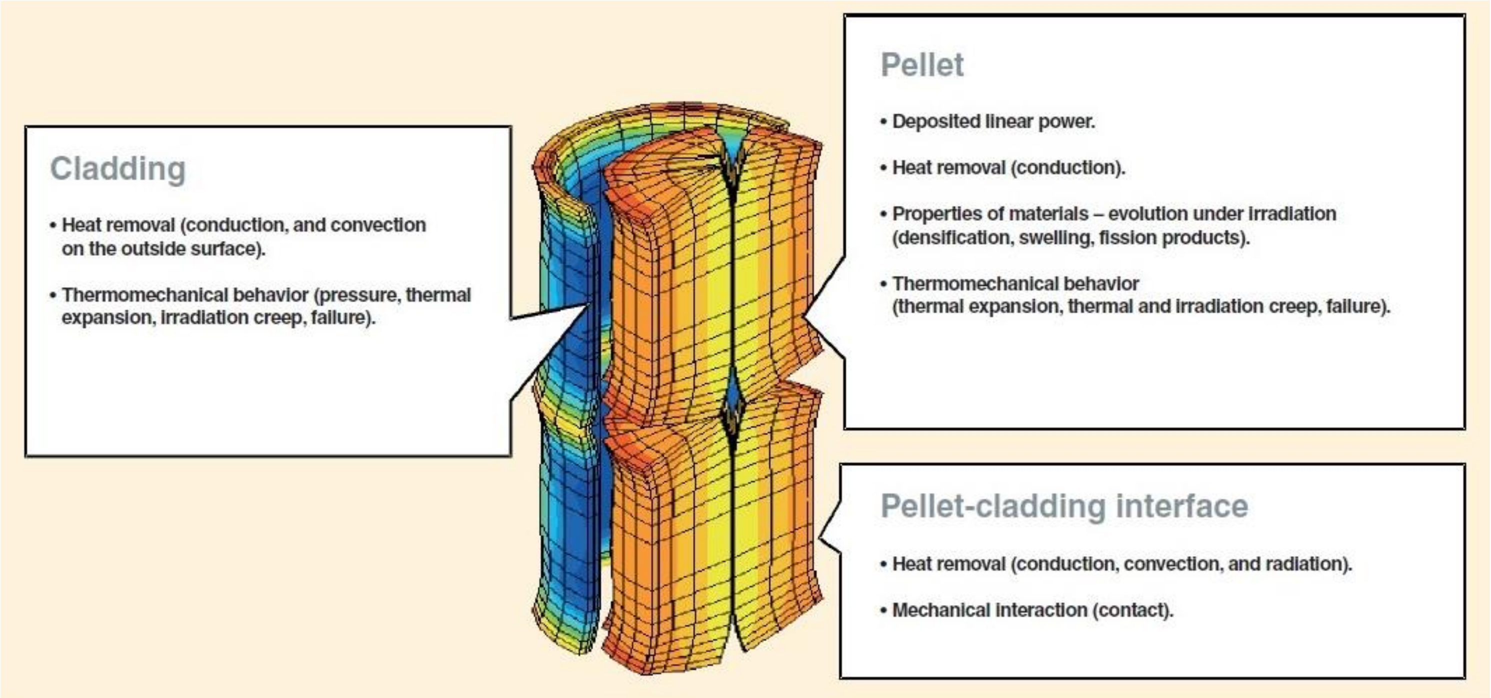


- **3D, fully thermal-mechanically coupled** analysis of fuel pellets and cladding: possible to explicitly consider **local effects** such as ridging, stress concentration due to "bambooing", detrimental effects of a **MPS imperfection** in defective fuel rods.
- As in the 2D representation, thermal and mechanical equations are typically solved by **a finite element technique** (FEM) **but** applied for the **analysis of limited regions only** (short section of the rod, a portion of one pellet). **Advanced numerical techniques** generally required in the solution scheme.
- **Advantage over 2D codes:** pellet-cladding eccentricity or PCI-related effects (which cannot be modelled when axial-symmetry / ortho-cylindricity is assumed) can be simulated. **Disadvantage:** increased complexity, more demanding for the computational time.

3D FPC analysis (ii)

- **3D FPC**: *ALCYONE, BISON, ...*

[CEA, 2009]



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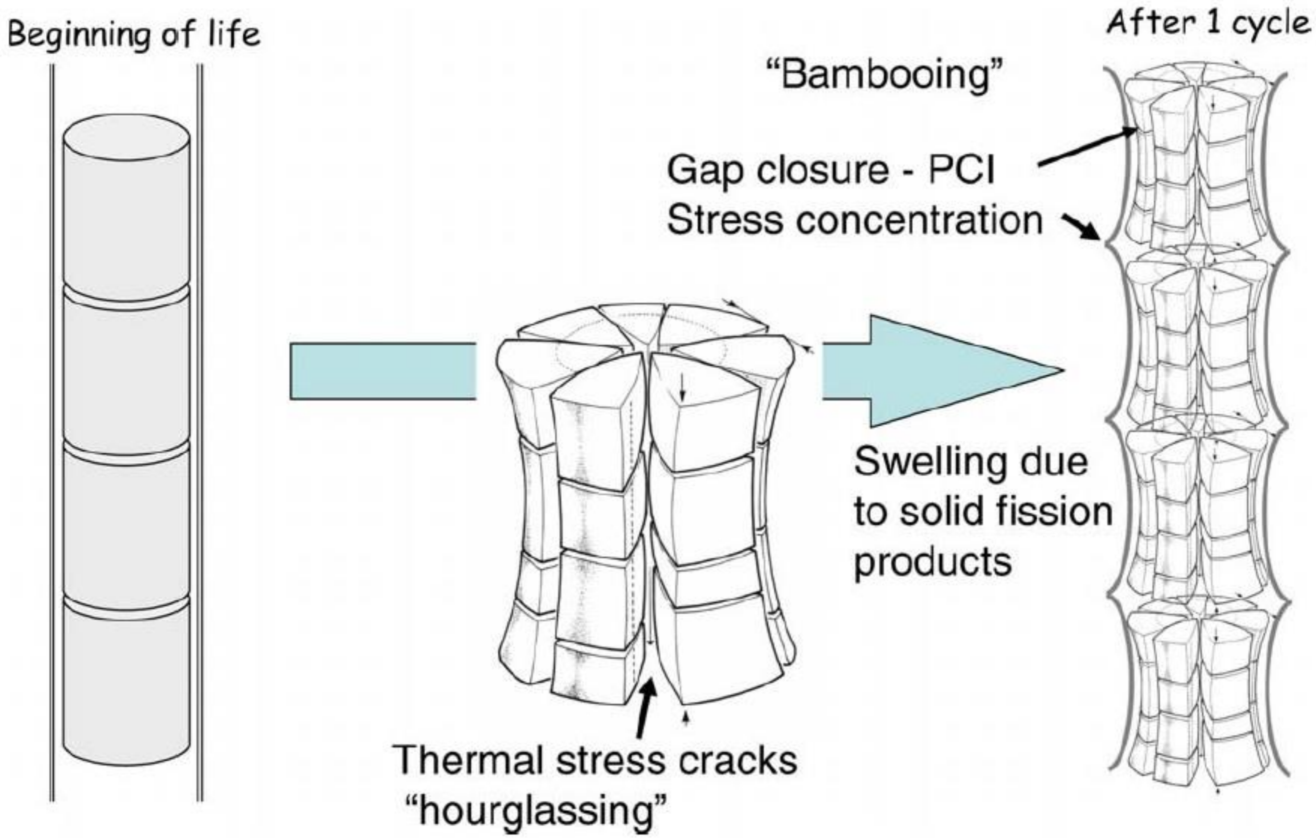

[Olander 2009]

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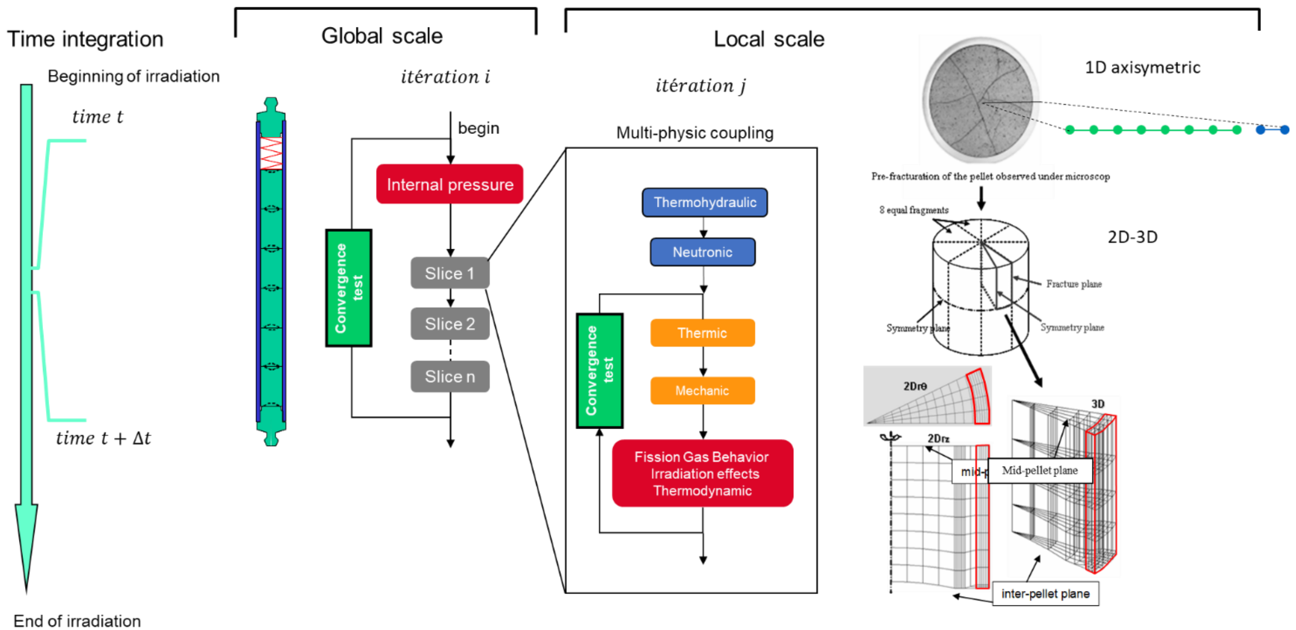
Current, near- and long-term **R&D trends in** high-fidelity **modelling & simulation** of fuel pin behaviour:

- **coupling of computer codes** (neutronics + system/core thermal-hydraulics + fuel pin performance), also through the implementation of more advanced modelling & simulation techniques → MOOSE, PLEIADES, SALOME, NURESIM multi-physics platforms.
- **multi-scale fuel performance modelling** → coupled with the need to move to 3D fuel pin modelling, the implementation in FPCs (engineering-scale) of atomistically-informed, more physically-grounded models should yield large advances in the simulation of fuel pin behaviour.



PLEIADES computational scheme for fuel rod type geometries.

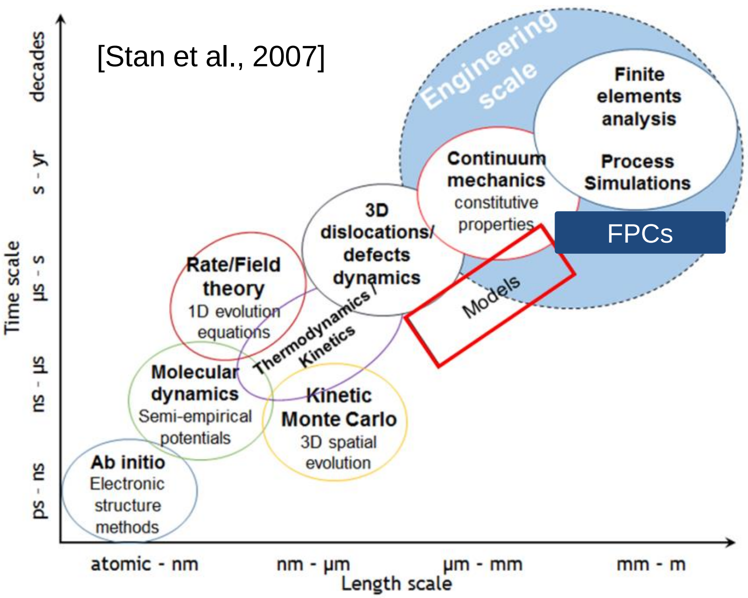
[Michel et al., in: Nuclear Power Plant Design and Analysis Codes - Development, Validation and Application, Chapter 9, 2021]

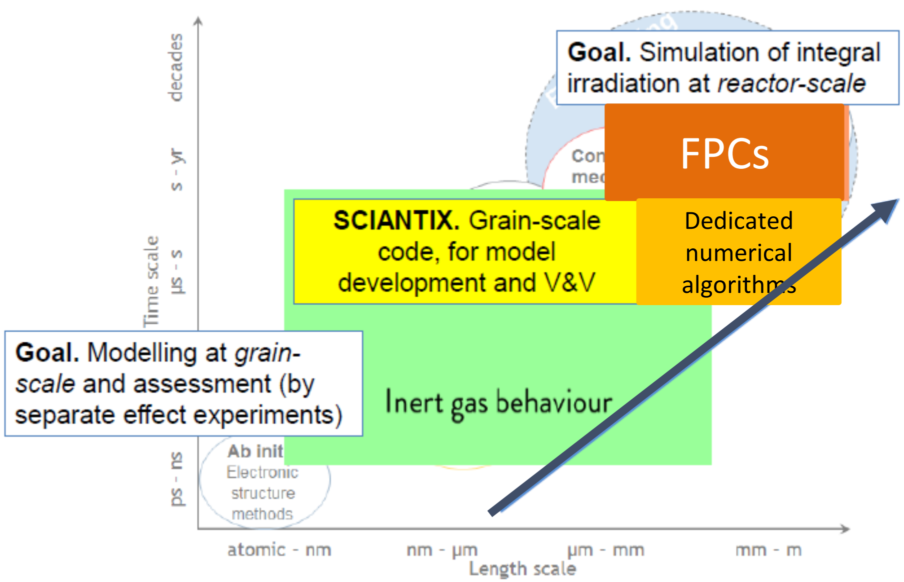
Multi-scale FPC analysis (ii)

Development path: **multi-scale fuel performance modelling**

Implementation in FPCs (or in modules/codes coupled with FPCs, e.g., SCIANTIX, MFPR-F) of **atomistically-informed ("mechanistic") engineering-scale models:**

- Bridge from lower-length scales to continuum mechanics' scale: atomistic information in engineering model parameters (e.g., trapping / re-solution rates of fission gas in / from gas bubbles).
  - large advances in the simulation of fuel behaviour and performance.
  - identify the most informative validation experiments.
- Overcome limitations of correlation-based approach (currently the most exploited): limited range of validity, limited physical meaning.
- Mechanistic: applicable to both steady-state and transient conditions.





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[Pizzocri et al., SCIANTIX: A new open source multi-scale code for fission gas behaviour modelling designed for nuclear fuel performance codes, JNM 532 (2020), 152042]

FPC improvement: IGB in transient conditions (i)

STATE OF THE ART

Modelling of **inert gas behaviour** (IGB) currently available in FPCs has **several limitations in transients** (and in DBAs: RIAs, LOCAs).

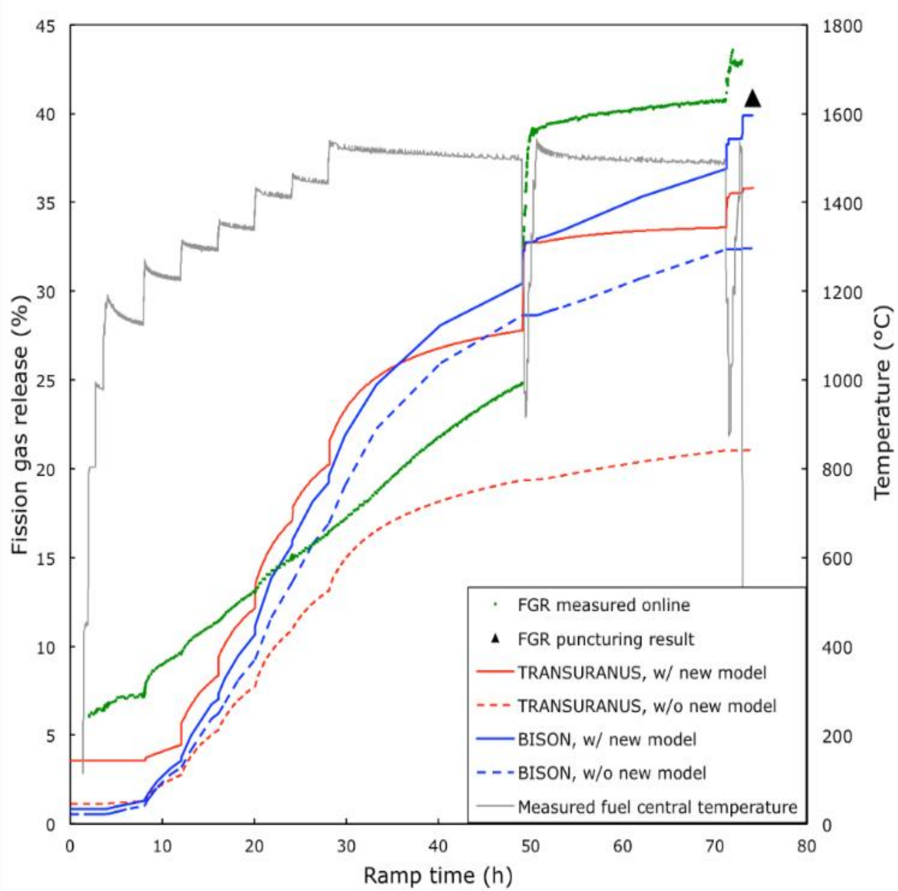
- Majority of current models are **correlation-based**
- Modelling of several phenomena is neglected:
  1. Intra-granular bubble coarsening and coalescence are neglected.
  2. Inter-granular fission gas behaviour is modelled based solely on the diffusion process, not considering grain-boundary micro-cracking (especially during RIAs).
  3. Present models for fission gas behaviour (FGB) in the High Burnup Structure (HBS) are oversimplified, usually assuming quasi-stationary conditions.
  4. Description of helium behaviour is over-simplified.
  5. Current algorithms (e.g., for intra-granular gas diffusion) can only handle simplified equations.

IMPROVEMENTS

1. FGB: bubble coarsening (absorbing vacancies) along dislocations + bubble coalescence (in BISON, SCIANTIX coupled with TRANSURANUS, GERMINAL).
2. Inter-granular micro-cracking: mechanistic model, leading to **burst release** and impacting on fission gas release (FGR), rod internal pressure, gap conductance (in BISON, TRANSURANUS). ⇨ **SEE SLIDE**
3. Mechanistic model for FGB in HBS: more generally valid, also in transient conditions (in BISON).
4. Inclusion of **helium behaviour** according to mechanistic FGB modelling approach. ⇨ **SEE SLIDE**
5. Dedicated advanced numerical schemes, able to solve time-dependent equations (e.g., PolyPole-1 and PolyPole-2, in BISON).

- Barani et al., *Modeling intra-granular fission gas bubble evolution and coarsening in uranium dioxide during in-pile transients*, JNM 538 (2020) 152195.
- Pizzocri, *Modelling and assessment of inert gas behaviour in UO_2 nuclear fuel for transient analysis,* PhD thesis, 2018.
- Luzzi et al., *Development / Assessment of models describing the inert gas behaviour in the fuel for application to the TRANSURANUS fuel pin thermo-mechanical code*, AdP MiSE-ENEA, PAR2017, Progetto B.3 - LP2, 2018.
- Pastore et al., *An effective numerical algorithm for intra-granular fission gas release during non-equilibrium trapping and resolution,* JNM 509 (2018), 687-699.

FPC improvement: IGB in transient conditions (ii)

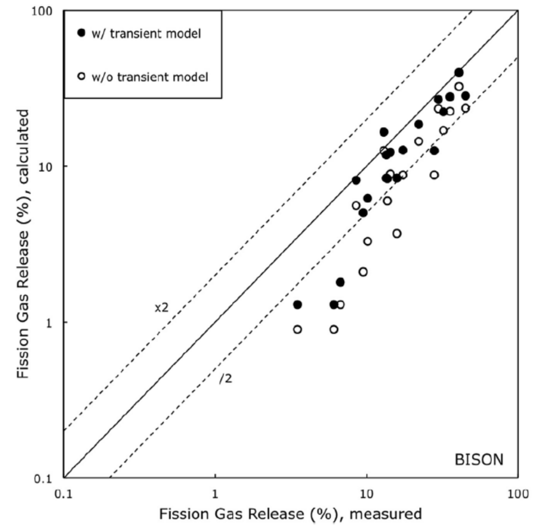


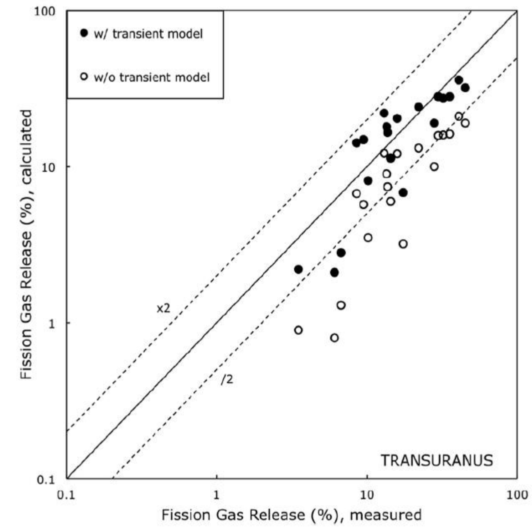
Outcomes of the **U.S.-EURATOM I-NERI Project**

NEW MODEL

for

BURST RELEASE





Quantitative improvement, and **better representation of FGR kinetics** (AN3 experiment, IFPE OECD/NEA Database), for **both BISON and TRANSURANUS**.

- Barani et al., *Analysis of transient fission gas behaviour in oxide fuel using BISON and TRANSURANUS*, JNM 491 (2017), 55–66.
- Pizzocri, *Modelling and assessment of inert gas behaviour in UO_2 nuclear fuel for transient analysis*, PhD thesis, 2018.

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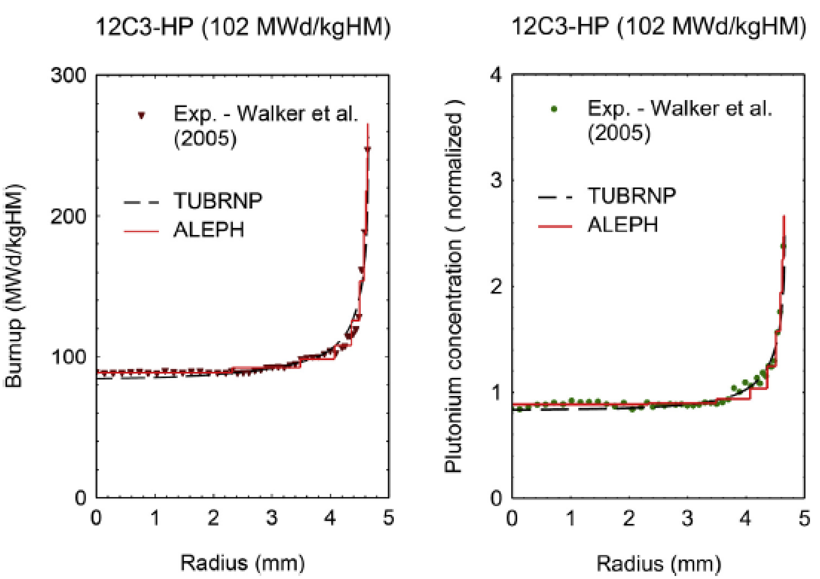
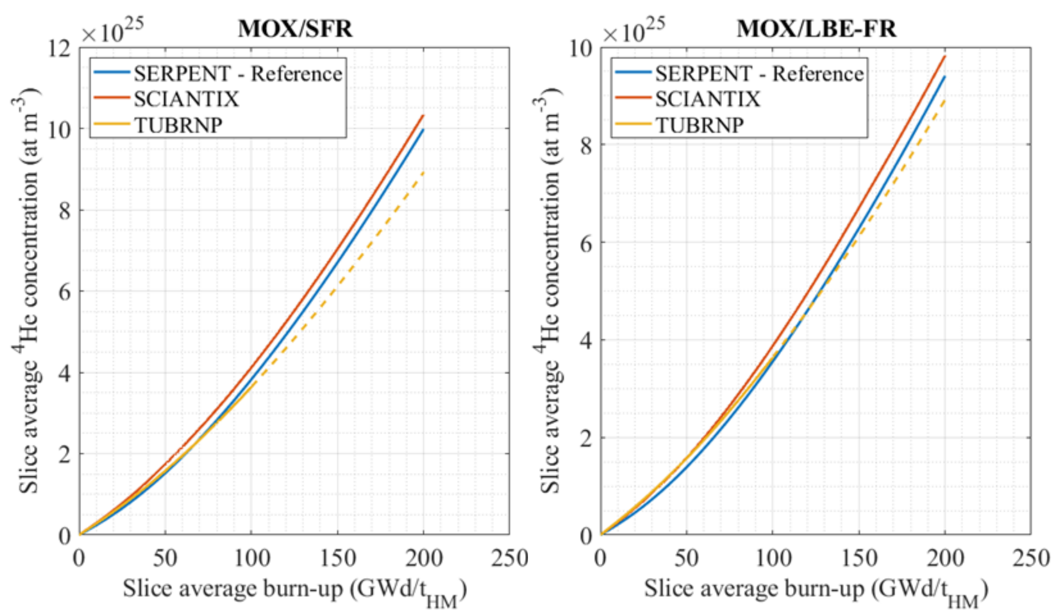
FPC improvement: helium production and behaviour

Equipping FPCs with capabilities to better predict **He production and evolution** (in both UO_2 and MOX fuels):

- Novel and more suitable **correlations for helium solubility and diffusivity**, accounting for He introduction technique (infusion, implantation, doping) and sample characteristics (single crystal, poly-crystal, powder)
  → Cognini et al., NED 340 (2018); Luzzi et al., NED 330 (2018).
- Development of a **new burnup module for FPC applications** (in SCIANTIX code), to calculate the **production of helium** from the evolution of alpha-decaying actinides:
  - ➢ Reaction cross-sections from SERPENT (offline) and implementation in SCIANTIX look-up tables (example in right figure)
  - ➢ Solution of Bateman equations in SCIANTIX and verification vs. SERPENT high-fidelity results and TUBRNP (TRANSURANUS burnup module: example in left figure).





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- Van Uffelen et al., *A review of fuel performance modelling*, JNM 516 (2019) 373-412.
- Cechet et al., *A new burn-up module for application in fuel performance calculations targeting the helium production rate in (U,Pu)O_2 for fast reactors*, NET (2021), in press.

FPC improvement: MOX thermal properties

STATE OF THE ART

Modelling of **MOX fuel thermal properties** (thermal conductivity k, melting temperature T_m) is currently limited in FPCs:

1. Correlations based on experimental data from LWR MOX fuel (typically stoichiometric, low Pu content, operated at lower temperatures).
2. Old correlations mostly based on data from unreliable, outdated measurement techniques (e.g., fuel melting in a W capsule).
3. Current correlations miss some important dependencies (e.g., Pu content in k correlations).
4. Neglect thermal recovery effect at high T, fission product contribution.

Fuel temperature affects all the other processes occurring during in-pile irradiation: its correct prediction is fundamental for the integral simulation of fuel pins. Importance of reliable and accurate thermal conductivity and melting temperature models…

IMPROVEMENTS (INSPYRE, to be continued in PUMMA, PATRICIA H2020)

1. New correlations from data fitting on FR-type MOX fuel: higher Pu content, hypo-stoichiometric (implemented in **TRANSURANUS** and **GERMINAL**) → integral validation in TRANSURANUS vs. HEDL P-19 FR irradiation (→ Magni et al., BEPU2021 Int. Conference) and in **INSPYRE H2020 Project**.
2. Fit of recent experimental data, up-to-date measurement techniques (e.g., **ESNII+ Project**).
3. Correlations inclusive of all the fundamental dependencies of k and T_m (e.g., temperature, O/M, Pu content, porosity, burnup), physically grounded.
4. Planned physics-based modelling to account for defects and FP (fission product) effects.

- Magni et al., *Report on the improved models of melting temperature and thermal conductivity for MOX fuels and JOG*, INSPYRE Deliverable D6.2, 2020.
- Magni et al., *Modelling and assessment of thermal conductivity and melting behaviour of MOX fuel for fast reactor applications,* JNM 541 (2020) 152410.

FPC improvement: thermo-chemistry capabilities

STATE OF THE ART

- **LWR conditions: ALCYONE FPC** (in the multi-physics scheme of PLEIADES) coupled with the OpenCalphad thermo-chemical solver, enabling the estimation of FPs inventory, their equilibrium chemical associations (based on thermodynamics database TAF-ID) and their migration/release in gaseous form from the fuel to the gap.
- **FR conditions:** new phase of volatile FPs (Cs, Mo, Te, I) and O, called **"Joint Oxyde Gaine" (JOG**), at the fuel-cladding interface → significant **impact on the heat transfer in the fuel-cladding gap**.
  - **GERMINAL FPC**: model for JOG thickness based on Cs release and considering an average molar volume representative of the elements entering the JOG composition (FPs, O). The real thickness of the JOG is estimated considering a coupling with fuel pin mechanical modelling (e.g., deformations).

ONGOING IMPROVEMENTS

To improve the JOG composition assessment, the CALPHAD solver is used to compute the thermodynamic equilibrium in the pellet and in the pellet-cladding gap. **Computational scheme**:

- Estimation of the quantities of fission products available in the fuel.
- Thermodynamic solver (relying on TAF-ID) to compute the inventory of the multi-phase and multi-component system as a function of the pellet radius and in the pellet-cladding gap.
- Simplified release into the fuel-cladding gap of gaseous chemical compounds available in the pellet.
- Estimation of the JOG thickness and composition based on the thermodynamic equilibrium in the pellet-cladding gap.

First results and comparison with experimental data → *Samuelsson et al., EPJ-N 6 (2020) 47*.

[Michel et al., in: Nuclear Power Plant Design and Analysis Codes - Development, Validation and Application, Chapter 9, 2021]

FPC validation strategy

To assess the fuel pin thermal and mechanical behaviour + compliance with functional requirements & design limits:

- **Separate-effects** (dedicated experiments) + **integral** (irradiation experiments) data.
- **Power ramps/cycles** for LWR (PWR, BWR, VVER) and FR (mainly SFR) fuel pins.
- **Code-to-code comparison and benchmarks**: EU H2020 Projects (e.g., **INSPYRE**), International Projects (e.g., **NEA WPFC-EGIF, IAEA FUMAC**).

In-pile dedicated tests

- temperature measurements
- pressure measurements
- diameter measurements
- sweeping gas analysis of the in-pile release
- post-test examinations

Out-of-pile annealing tests

- for gas models, without irradiation

Post-Irradiation Examinations (PIE)

- diameter measurements, 1D at mid-pellet, 3D including ridges
- axial gamma scanning
- rod length measurement
- fission gas release } pin pressure
- free volume } pin pressure
- density measurements
- porosity measurements
- EPMA and SIMS Xe measurements
- EPMA and SIMS FP creation measurements
- Zirconia thickness (non-destructive and ceramography)
- gap (ceramography measurement)
- intergranular gas measurements
- fuel thermal conductivity

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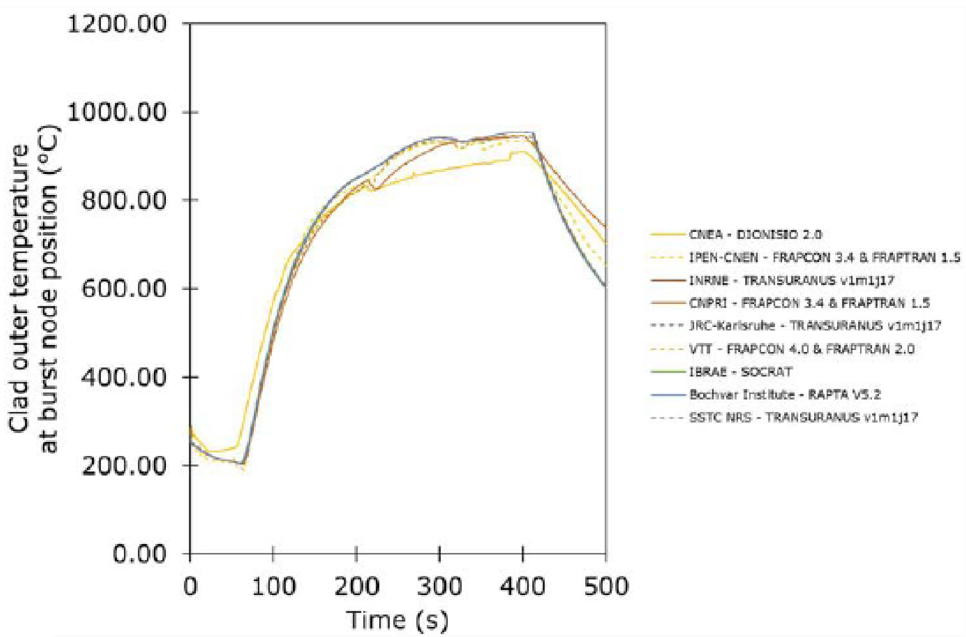
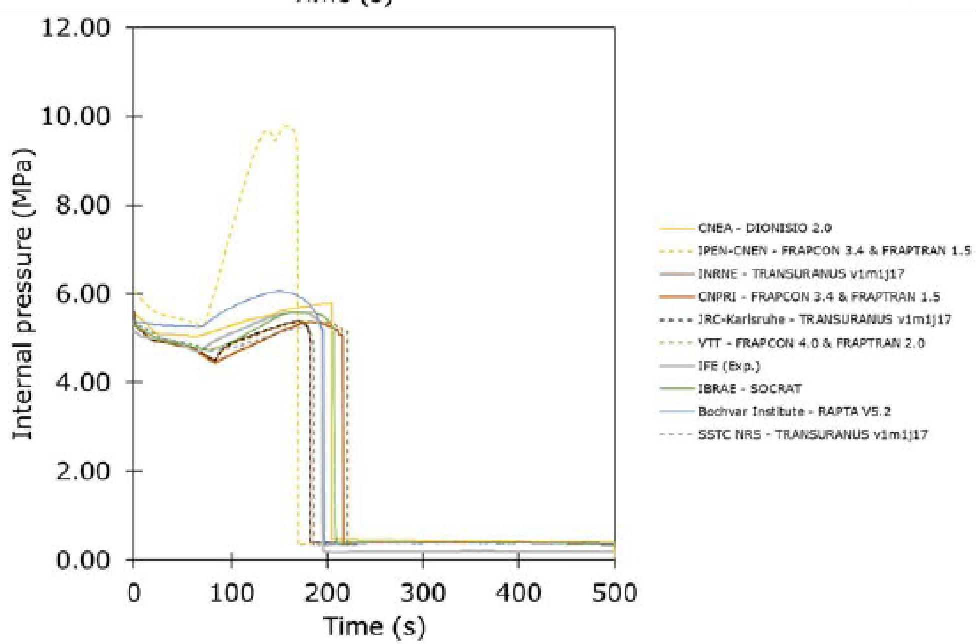
[Noirot, Int. School in Nuclear Engineering - Nuclear fuels for Light Water Reactors and Fast Reactors, CEA, 2016]

Example of FPC benchmark: FUMAC (LWR)





- **IAEA CRP on Fuel Modelling in Accident Conditions** (**FUMAC**, 2014 - 2018) focused on accident conditions.

Objectives:

- ➢ Analyse and better understand fuel behaviour in accident conditions, with a focus on LOCA (DBA);
- ➢ Quality results from accident simulation experiments;
- ➢ Application of physical models and computer codes, enhancing the predictive capabilities.

Codes involved (international benchmark):

fuel performance codes (DIONISIO, FRAPTRAN, FTPAC, RAPTA, SFPR, TRANSURANUS), system or severe accident codes (ATHLET-CD, MELCOR, SOCRAT), multi-dimensional fuel performance codes (ALCYONE, BISON).

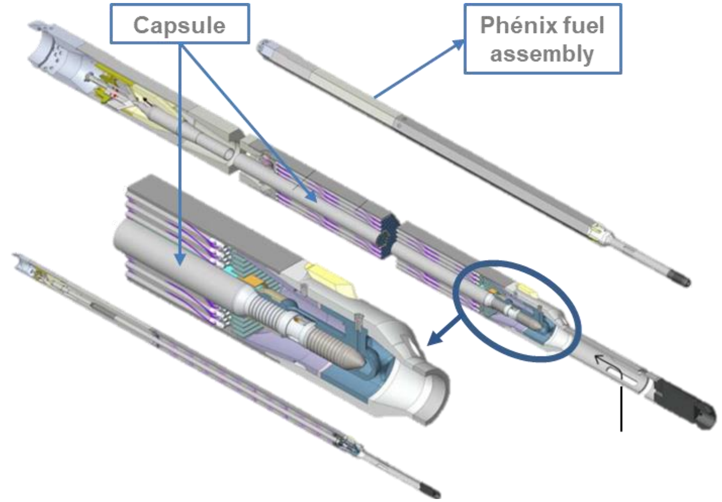
Examples of **benchmark results** on the IFA-650.11 (Halden LOCA tests)

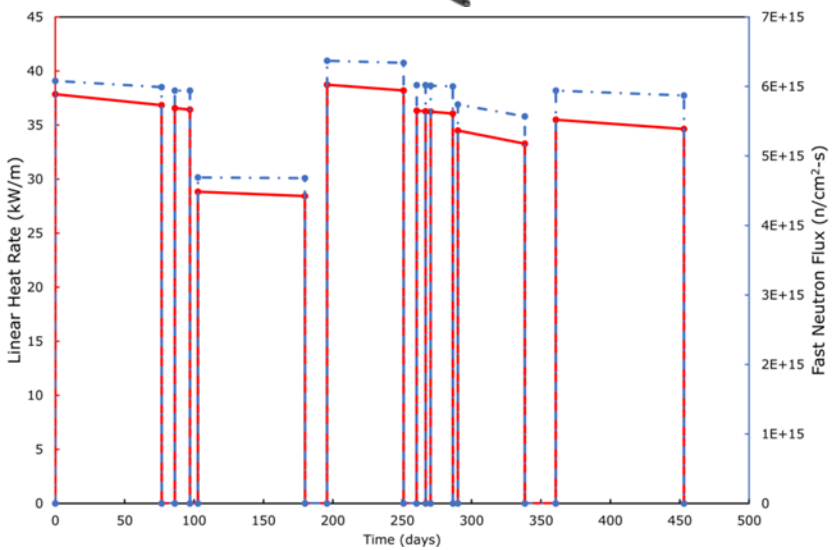
[IAEA, IAEA-TECDOC-1889, 2019]

Example of EU FPC benchmark: SUPERFACT-1 (FR)

- Irradiation of **MA-MOX** fuel in **Phénix sodium fast reactor** to demonstrate technical feasibility of transmutation of minor actinides (MA) through homogeneous (i.e., low content MA fuel) and heterogeneous concepts (i.e., high MA content).
- Irradiation experiment selected for **FPC benchmark** in **INSPYRE H2020 Project**, together with RAPSODIE-I and NESTOR-3 (MOX).
- SUPERFACT-1 pins selected: representative of **homogeneous** fuel strategy:
  - ✓ **SF7** and **SF13** bearing **2.0 wt.% of ^{237}Np**
  - ✓ **SF4** and **SF16** bearing **1.8 wt.% of ^{241}Am**

  Peak burnup at EOL was about **6.5 at.%** and peak cladding damage was about **52 dpa$_{NRT}$**.
- Simulated with current version of EU FPCs (**INSPYRE**):
  - ➢ GERMINAL (v2.2.3) – CEA
  - ➢ MACROS – SCK•CEN
  - ➢ TRANSURANUS (v1m1j20) – JRC-Karlsruhe, POLIMI, ENEA





- J.-F. Babelot, N. Chauvin, JRC-ITU-TN-99/03,1999.
- L. Luzzi et al., *Assessment of the current European Fuel Performance Codes against the Fast Reactor irradiation experiment SUPERFACT*, NuFuel-MMSNF 2019 Workshop, 2019.
- L. Luzzi et al., *Assessment of three European fuel performance codes against the SUPERFACT-1 fast reactor irradiation experiment*, submitted to NET.

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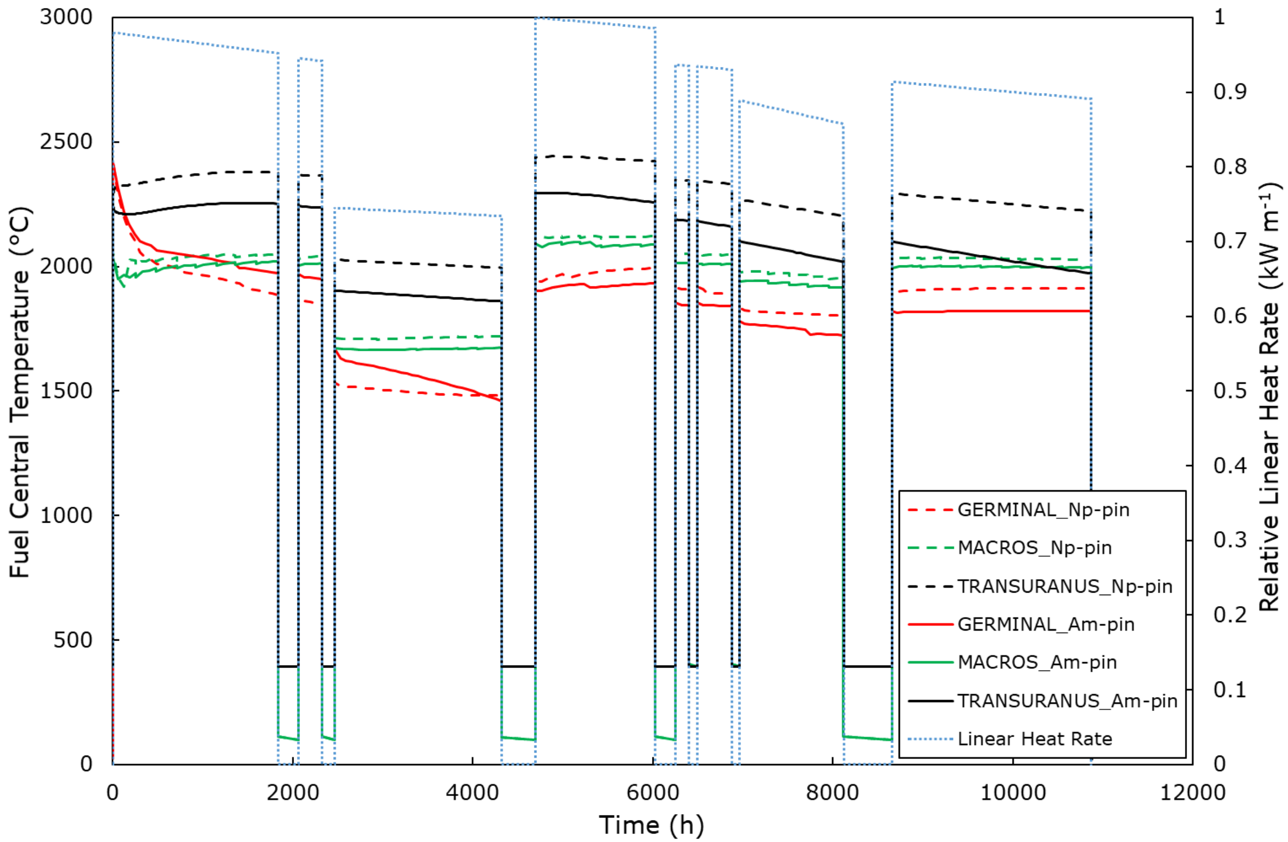
SUPERFACT-1 - Fuel central temperature (i)



Different temperature regimes and evolution, as a function of irradiation, predicted by the codes, especially in the first cycles. This can be ascribed both to the **different gap sizes**, thus to the different gap conductance and radial relocation models (subject to large uncertainties), and to the different fuel thermal conductivity correlations employed.

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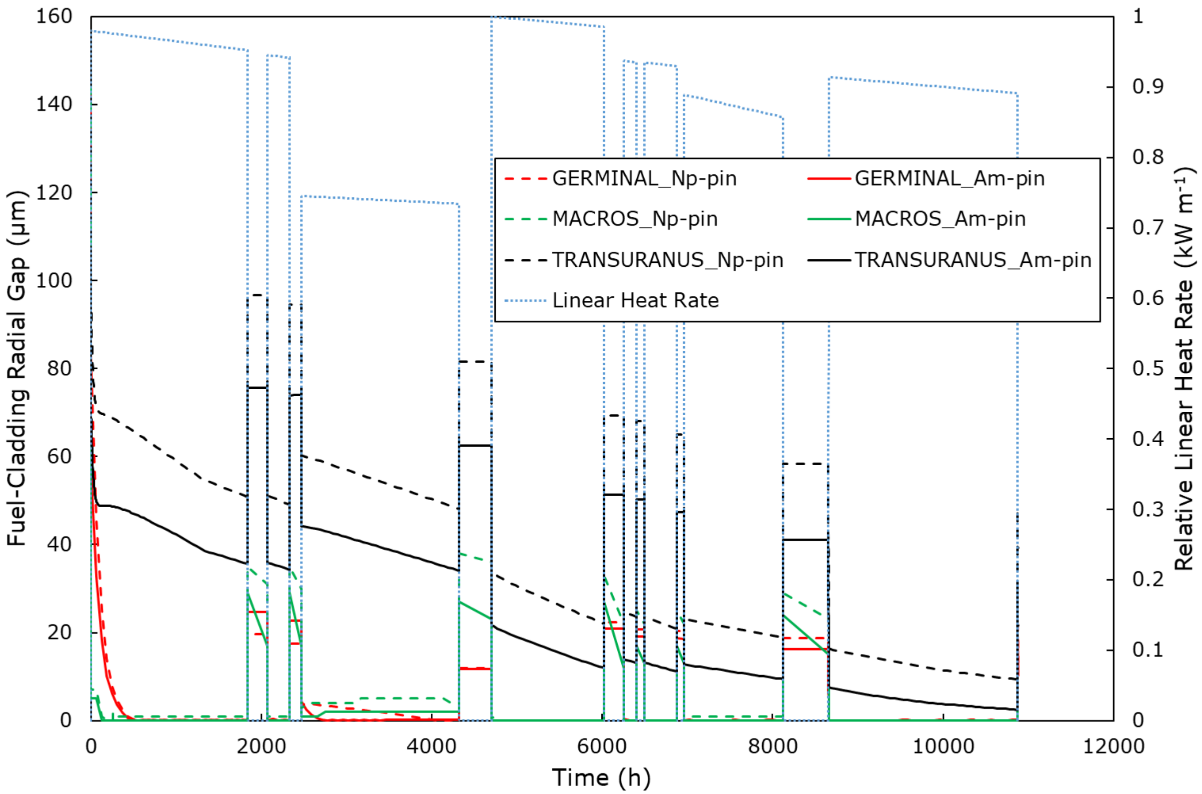
- L. Luzzi et al., *Assessment of three European fuel performance codes against the SUPERFACT-1 fast reactor irradiation experiment*, submitted to NET.
- B. Boer et al., *Report describing the results of the benchmark between improved codes and previous versions on selected experimental cases*, INSPYRE Deliverable D7.3, February 2021, under preparation.

SUPERFACT-1 - Fuel-cladding gap size (ii)



- Significant differences arise in the code calculations (predicted values and dynamics).
- **MACROS** and **GERMINAL**: fast closure of the gap (in both type of considered rods) at BOL, ascribed to fuel relocation and fuel creep.
- **TRANSURANUS**: slower closure of the fuel-cladding gap (never closes), leading to higher temperature regime predicted in the fuel pellets.

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- L. Luzzi et al., *Assessment of three European fuel performance codes against the SUPERFACT-1 fast reactor irradiation experiment*, submitted to NET.
- B. Boer et al., *Report describing the results of the benchmark between improved codes and previous versions on selected experimental cases*, INSPYRE Deliverable D7.3, February 2021, under preparation.

Conclusive remarks

- **State-of-the-Art** FPCs are able to deal with both steady-state and transient (power ramps/cycles, accidental scenarios also) irradiation conditions.
- **Developments** were performed specifically for **transient analyses** (e.g., transient FGB modelling) and for **high burnups** (e.g., modelling High Burnup Structure formation coupled to FGB).
- Recent **improvements for MOX fuel in FR conditions**: thermal property modelling (thermal conductivity, melting temperature, heat capacity: INSPYRE), thermo-chemical tools for FCCI and JOG simulation (CALPHAD solver coupled with GERMINAL FPC).
- FPC **assessment** is performed against both **separate-effect** (for single models / model parameters) and local and integral PIE data + recent **international code benchmarks** (to complement the lack of experimental data and to evaluate the range of results achievable with different FPCs, useful for design & licensing).
- **Examples** of recent code benchmarks in the framework of CRP FUMAC (**LWR, accident conditions**) and INSPYRE H2020 Project SUPERFACT-1 irradiation experiment (**MOX fuel** in sodium-cooled **FR conditions**):
  - **FUMAC**: improved models, material properties and numerical algorithms for the simulation of LWR nuclear fuel under DBA conditions, with consideration of uncertainties.
  - **INSPYRE**: European FPCs (**GERMINAL, MACROS, TRANSURANUS**) exhibit encouraging predictive capabilities, together with a substantial room for improvements. Important differences in fuel temperature profile predictions: strong impact on predicted gap size and overall thermal-mechanical performance of the pin.

(other: e.g., **IAEA CRP ACTOF** on Accident Tolerant Fuels)

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Current developments and future perspectives

IMPROVEMENTS

- Extension of **physics-based modelling** to various fuel thermal-mechanical properties (e.g., conductivity, specific heat).
- Need of **additional data** (experimental / calculated) on **new fuel / cladding materials** of interest (e.g., Enhanced-ATFs, ODS steels for the cladding), to support proper modelling in FPCs.
- Improved description of fission product (and their stable compounds) behaviour in nuclear fuel, their release in the fuel-cladding gap and chemical interaction with the cladding:
  - **Coupling FPC – thermo-chemistry codes** and databases is ongoing for GERMINAL FPC (and e.g., CEDAR FPC)
  - **Mechanistic modelling of FP behaviour** (grain-scale codes SCIANTIX, MFPR-F, coupled with FPCs including transport and axial effects): in the framework of **R2CA H2020 Project**.

COUPLING

- FPC coupling in a **multi-scale framework** (already started, e.g., in the **McSAFE H2020 Project**): with 3D codes (e.g., OFFBEAT) for local multi-dimensional analyses, with lower-length scale modules for chemistry and FP behaviour (e.g., SCIANTIX, MFPR-F).
- FPC coupling in a **multi-physics framewor**k: with neutronics (e.g., SERPENT), thermal-hydraulics and system (e.g., RELAP, ATHLET) codes.

VALIDATION

- Validation of FPCs for **design basis accidents** (e.g., **R2CA Project**, ongoing), to bring it at the same level as that achieved for normal operating conditions, and extended application to safety evaluations (e.g., ESSANUF Project).
- Better use of **uncertainty & sensitivity analyses**, which become available thanks to statistical tools, but challenging to be consistently and easily applied in the fuel performance field.

Thank you for your kind attention!

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