OPEn HPC theRmomechanical tools for the development of eAtf fuels

Deliverable D8.5 – OperaHPC: Minutes of the first End User Group meeting

Version [1] – 23/04/2024

Funded by the European Union

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Document type	Deliverable
Document number	D8.5 version [1]
Document title	OperaHPC: Minutes of the first End User Group meeting
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Release date	23/04/2024
Contributing partners	CEA
Dissemination level	PU

Version	Short description	Main author	PMO	WP leader	Coordinator
1	First Version	Bruno Michel (CEA) Date 19/03/2024	Silvia De Grandis (SINTEC) Date 10/04/2024	Silvia De Grandis (SINTEC) Date 15/04/2024	Bruno Michel (CEA) Date 23/04/2024

Abstract

This document presents the minutes of the first End User Group (EUG) meeting of the OperaHPC project. This meeting took place on January 8 on line, it was dedicated to a general information on the terms of reference and also to start the discussion process for the selection of the topics of interest between the project and the end users.

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1 Introduction

The objective of the End User Group (EUG) of the OperaHPC project is to help the project to enable approach and results to reach its end customers. The EUG is constituted of representatives of key customers and safety authorities in the domain of the Gen II-III reactor fuels. It is established for the duration of the OperaHPC project. The OperaHPC coordinator and WP leaders have permanent seats in the EUG, and act as point of contact between the EUG and the project. The EUG will appoint a chairperson, and if possible a vice-chairperson, from within its members as the main contact with the project.
Several meetings will be organised between selected OperaHPC participants and the EUG during the 54 months of the project from November 2022 to April 2027.
The first EUG meeting took place on January 8 on line, it was dedicated to a general information on the terms of reference and also to start the discussion process for the selection of the topics of interest for the exchanges between the project and the end users.
During the project, 2 or 3 meetings will be organized on focused topics to be determined, and a final EUG meeting will be organized at the end of the project. The EUG members will have the possibility to attend the plenary annual meetings of the project.

The EUG members list is given in Table 1.

Organisation	**Country**	**Representative**	email	**Position**
EDF	France	Antoine Ambard	antoine.ambard@edf.fr	Research engineer
EK-CER	Hungary	Zoltan Hozer	hozer.zoltan@ek-cer.hu	Head of Fuel and Reactor Materials Department,chair of OECD/NEA WGFS
Framatome GmbH	Germany	Wolfgang Schmid	wolfgang.schmid@framatome.com	Material designer
TVO	Finland	Arttu Knuutila	Arttu.Knuutila@tvo.fi	Team leader, fuel procurement
Vattenfall	Sweden	Pal Efsing	Pal.Efsing@vattenfall.com	Senior Specialist in Fracture and Materials Mechanics, professor at KTH
Westinghouse	Sweden	Paul Blair		Paul left Westinghouse, new correspondent in discussion with Magnus Limbäck limbacmn@westinghouse.com
IRSN	France	Alain Moal	alain.moal@irsn.fr	Senior Specialist fuel material safety

Table 1 : Members of the End User Group of the OperaHPC project

2 List of participants of the first EUG meeting

name	organisation	Observation
Antoine Ambard	EDF	EUG member
Wolfgang Schmid	Framatome GmbH	EUG member
Arttu Knuutila	TVO	EUG member
Pal Efsing	Vattenfall	EUG member
Magnus Limbäck	Westinghouse	EUG member
Alain Moal	IRSN	EUG member
Marjorie Bertolus	CEA	WP1 leader
Janne Heikinheimo	VTT	WP3 leader
Lelio.Luzzi	POLIMI	WP5 leader
Rosa Lo Frano	UNIPI	WP6 leader
Silvia De Grandis	SINTEC	WP8 leader
Davide Pizzocri	POLIMI	representing WP5
Clifford Ivor David	PSI	representing WP4
Bettina Hartmann	Framatome GmbH	representing WP7
Bruno Michel		Coordinator

3 Minutes of meeting

3.1 Introduction and presentation of the OperaHPC project:

The coordinator presented the objective of the End User Group and the main features of the OperaHPC project (see the slides in Appendix 1). The three strategic objectives of the project are:

- a basic research program on the mechanical behaviour of irradiated fuel and the development of improved mechanical laws for fuels and claddings,
- the development and the validation of open source fuel performance codes for simulating fuel rod behaviour in reactor,
- the application of these advanced tools for safety studies on enhanced Accident Tolerant Fuel elements (eATF).

Along the three OperaHPC strategic objectives, the project will develop a new experimental equipment for measuring the creep behaviour of irradiated fuel, and characterizing the physical-mechanical properties using a multiscale approach combining simulation and experiment.

Then, High Performance Computation tools will be developed and validated to simulate fuel behaviour at rod scale with the OFFBEAT code, and at microstructure scale with the MMM code.

Finally, the tools developed and improved will enable us to improve the models used in existing state of the art fuel performance codes and to perform fuel behaviour studies on eATF for VVER and PWR generation 2&3 reactors in Design Basis Accidents, such as Reactivity Insertion Accident or Loss Of Coolant Accident.

3.2 Planned output and status at month 15:

The coordinator and the Work Package leaders presented for each technical Work Package the planned output and the status at month 15 (see the slides in Appendix 2).

A. Ambard asked what type of safety studies was expected in WP7. B. Michel and R. Lo Frano indicated that the objectives of the studies are to analyse the individual fuel rod behaviour under various types of loading conditions. The analysis will be based mainly on the thermo-mechanical state and on the internal variables linked to the fission gas behaviour with some comparisons between various assumptions (standard versus EATF fuel, improved versus initial model,…)

3.3 Discussion topics of interest

The discussion, to defined the topics of interest with the EUG, started on the basis of the project planned output presented in the Appendix 2.

A. Ambard is interested to use the codes developed in the WP4 in order to test them. B. Michel indicated that a possibility will be to test the preliminary (beta) versions of MMM and OFFBEAT/SCIANTIX expected at the end of 2024 in the milestones MS-8 and MS-9 of the project. I. Clifford said that the current version of OFFBEAT can be already downloaded and tested from the open source site https://gitlab.com/foam-for-nuclear/offbeat. B. Michel proposed to discuss this in a dedicated meeting between the project and the EUG.

L. Luzzi proposed to plan a meeting with the EUG with a more detailed presentation of the tools developed including VVQU aspects. R. Lo Frano proposed also the same type of meeting with more details on actions related to WP6.

4 Questionnaire

After the meeting the OperaHPC team has defined a questionnaire in order to facilitate the definition of the topics of interest to discuss with the End User Group. This questionnaire was sent to the EUG members and the results will be used in the next meeting.

1) Would you be willing to present your needs linked to the expected results of the OperaHPC project (technical WPs and Education and training WP) during the next meeting?

☐ Yes ☐ No

If yes, what would be the topic(s)?

____

____

2) Based on the presentation “planned ouput” of the first meeting, do you already know which type of results correspond to your needs?

☐ Yes ☐ No

If you do, please indicate which type of results

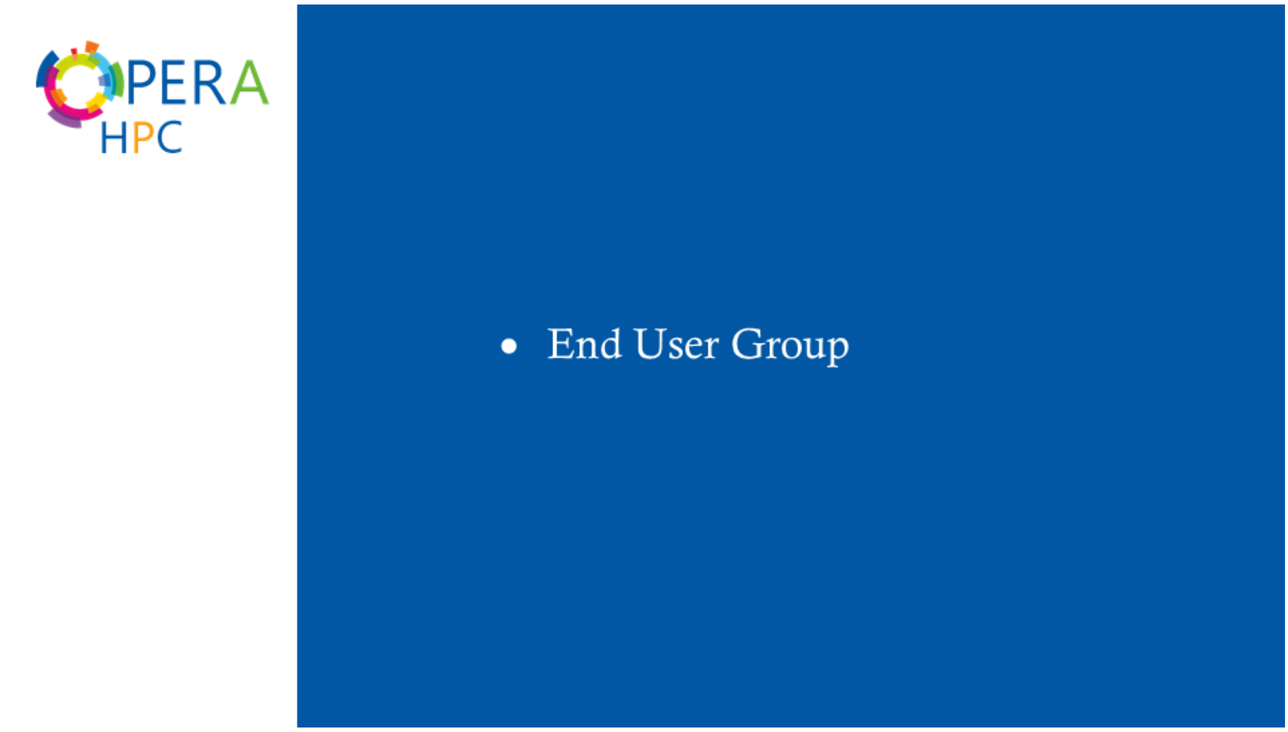
____

____

3) Please rank your interest for the topics below in the list of planned output of the project

Topic	1 high	2 med	3 low
1 **Physical data produced in WP1 on the mechanical behaviour of irradiated UO2 fuel**			
1.1 Creep	☐	☐	☐
1.2 Rupture	☐	☐	☐
1.3 Microstructural changes	☐	☐	☐
2 Mechanical laws developed for the cladding and the pellet in WP2			
2.1 Constitutive equations and material parameters	☐	☐	☐
2.2 Laws at the macroscopic scale	☐	☐	☐
2.3 Laws at the microscopic scale	☐	☐	☐
2.4 Numerical implementation using Mfront	☐	☐	☐
3 3D simulation tools deployed in WPs 3-4-5			
3.1 MMM	☐	☐	☐
3.2 OFFBEAT	☐	☐	☐
3.3 SPH	☐	☐	☐
3.4 Definition of HF boundary conditions and initial state for OFFBEAT	☐	☐	☐
3.5 Verification and Validation	☐	☐	☐
3.6 Quantification of uncertainties	☐	☐	☐
4 Improved industrial models developed in WP6			
4.1 Mechanisms to be included in the simplified models	☐	☐	☐
4.2 Approach used to build the reference or the learning database	☐	☐	☐
4.3 Computation time reduction methods (Reduced Order Model, Machine learning, Neural Networks, surrogate model…)	☐	☐	☐
5 Simulation of fuel element behaviour in operating and accidental transient conditions			
5.1 VVER irradiation conditions	☐	☐	☐
5.2 PWR irradiation conditions	☐	☐	☐
5.3 Assessment at the fuel rod scale	☐	☐	☐
5.4 Assessment at the microstructure scale	☐	☐	☐
5.5 Assessment of coated cladding	☐	☐	☐
5.6 Innovative fuel microstructure assessment	☐	☐	☐

5 Appendix 1 : Slides of the OperaHPC project presentation



End User Group : Terms of reference

Help the project to enable approach and results to reach its end customers. The UG is constituted of representatives of key customers and safety authorities in the domain of the Gen II-III reactor fuels. It is established for the duration of the OperaHPC project. The OperaHPC Coordinator and WP leaders have permanent seats in the User Group, and act as point of contact between the UG and the project. The UG shall appoint a chairperson and a vice-chairperson from within its members.

Several meetings will be organised between selected OperaHPC participants and the UG during the 54 months of the project (November 2022 to April 2027).

- First user group meeting : Information and exchanges to discuss topics of interest
- 2 or 3 meetings on focused topics to be determined during the first meeting
- Final user group meeting

EUG members will have the possibility to attend the plenary annual meetings of the project.

End User Group of the OperaHPC European project : information meeting 3

End User Group : Members

Organisation	Country	Representative		Position
EDF	France	Antoine Ambard	antoine.ambard@edf.fr	Research engineer
EK-CER	Hungary	Zoltan Hozer	hozer.zoltan@ek-cer.hu	Head of Fuel and Reactor Materials Department, chair of OECD/NEA WGFS
Framatome GmbH	Germany	Wolfgang Schmid	wolfgang.schmid@framatome.com	Material designer
TVO	Finland	Arttu Knuutila	Arttu.Knuutila@tvo.fi	Team leader, fuel procurement
Vattenfall	Sweden	Pal Efsing	Pal.Efsing@vattenfall.com	Senior Specialist in Fracture and Materials Mechanics, professor at KTH
Westinghouse	Sweden	Paul Blair		Paul left Westinghouse, new correspondent in discussion with Magnus Limbäck limbacmn@westinghouse.com
IRSN	France	Alain Moal	alain.moal@irsn.fr	Senior Specialist fuel material safety

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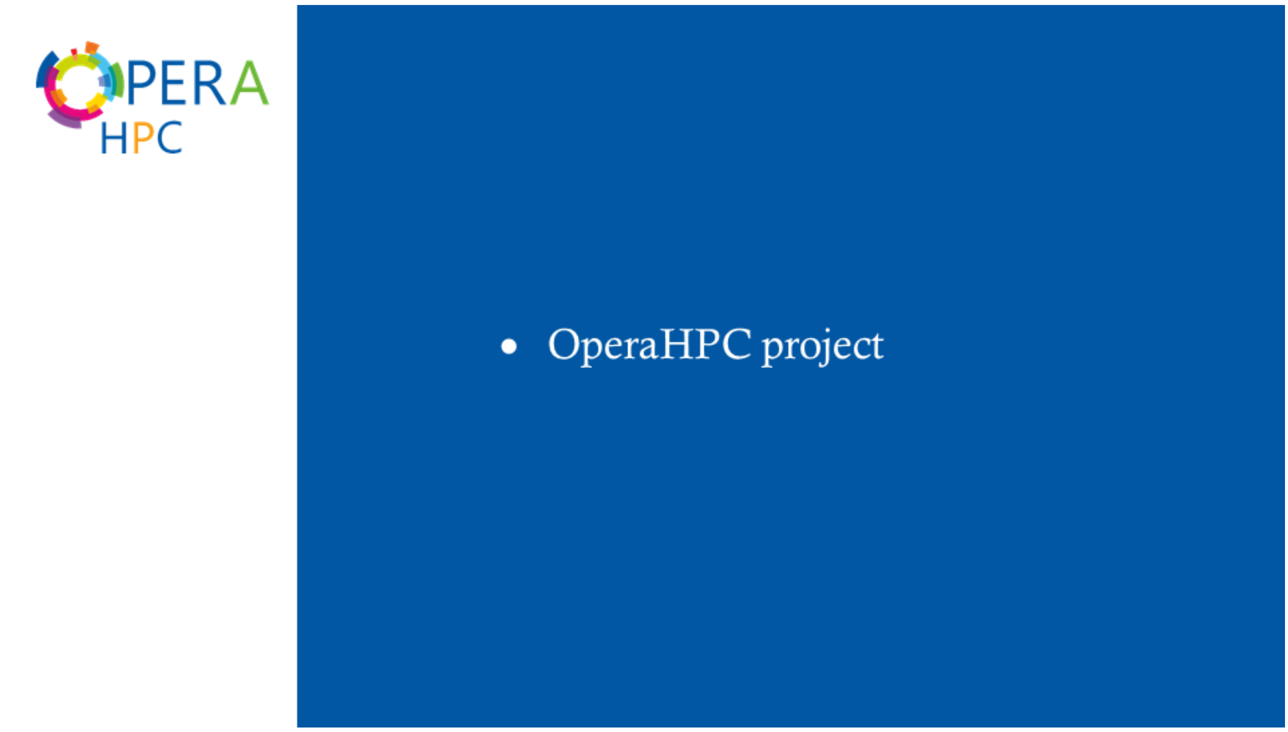
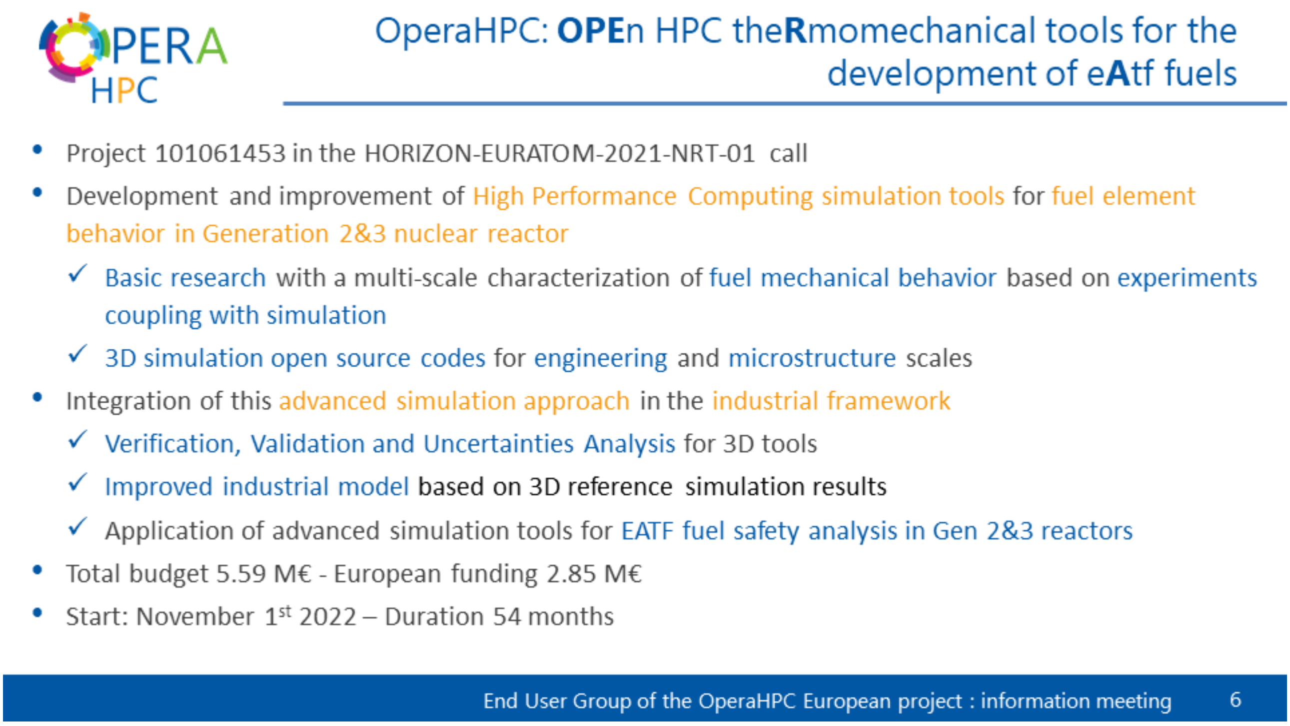

OPERA HPC
• OperaHPC project


OPERA HPC
OperaHPC: OPEn HPC theRmomechanical tools for the development of eAtf fuels
• Project 101061453 in the HORIZON-EURATOM-2021-NRT-01 call
• Development and improvement of High Performance Computing simulation tools for fuel element behavior in Generation 2&3 nuclear reactor
✓ Basic research with a multi-scale characterization of fuel mechanical behavior based on experiments coupling with simulation
✓ 3D simulation open source codes for engineering and microstructure scales
• Integration of this advanced simulation approach in the industrial framework
✓ Verification, Validation and Uncertainties Analysis for 3D tools
✓ Improved industrial model based on 3D reference simulation results
✓ Application of advanced simulation tools for EATF fuel safety analysis in Gen 2&3 reactors
• Total budget 5.59 M€ - European funding 2.85 M€
• Start: November 1st 2022 – Duration 54 months
End User Group of the OperaHPC European project : information meeting 6

- Context and Objectives

Needs and context

- Europe a climate-neutral continent by 2050 -> Electrification of the energy sector a key step
- Maintain/extend the production capacity of Gen 2&3 nuclear reactors in an evolving electricity mix
- Gen 2&3 reactor fuels have a large experimental feedback
  - ✓ Continuous evolution of fuel element design and materials while adapting new operating conditions
  - ✓ Accelerate this evolution in view of the expected changes in the energy sector
- Irradiation experimental programs and Fuel Performance Codes are the key stones for the fuel licensing
  - ✓ To meet use requirements, industrial FPCs need some simplification with partially empirical modelling
  - ✓ It takes time to adapt the FPC's qualification to new operating conditions or innovative designs
  - ✓ Existing 3D simulation tools can start to give some answers
- A large use of 3D simulation tools and results in an industrial context is still a challenging question
  - ✓ Improvements are needed to reduce the number of empirical parameters
  - ✓ Computation time and access to HPC tools are often limiting issues

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OPERA HPC

High Level Strategic Objectives

STO1) Advance the predictive capabilities of state-of-the-art fuel performance codes

- ✓ Improving significantly the understanding and description of the thermomechanical behaviour under irradiation of UO_2 based fuel elements
- ✓ Transferring the knowledge acquired from basic and applied research into operational tools.

STO2) Advance the numerical capabilities of open source 3D fuel performance codes

- ✓ Add the Microstructure description to the engineering simulation
- ✓ High Performance Computing (HPC) capabilities
- ✓ VVQU

STO3) Transfer the results and methods to end-users

- ✓ Allowing the use of advanced simulation tools for the licencing of new fuel concepts (eATF)
- ✓ Enhance the link between basic research, open source development and industrial applications
- ✓ Develop training for the next generation in the field of fuel performance codes

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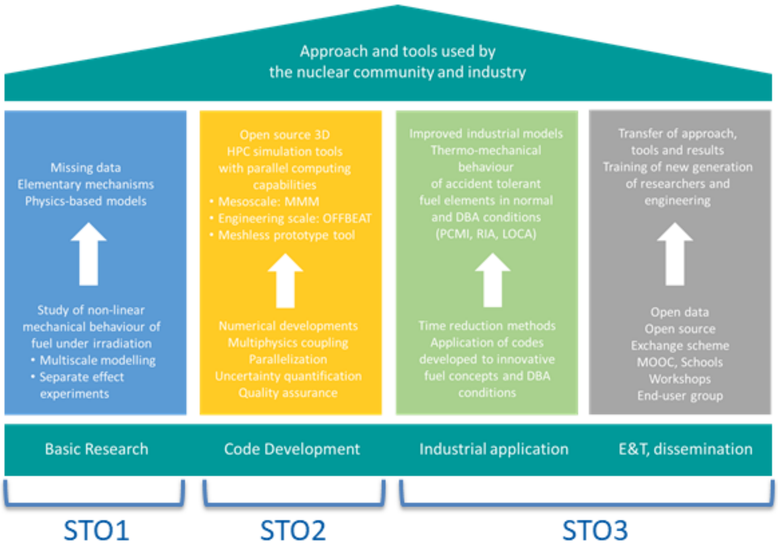
OPERA HPC

- Methodology, Impact

OperaHPC concept



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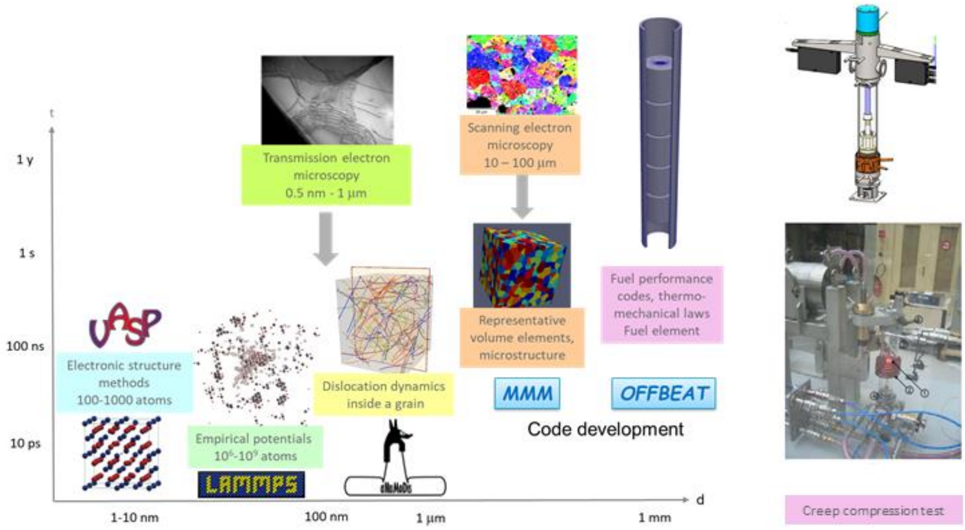
Techniques, methods and codes used in Opera HPC



ABAQUS
ALCYONE
BISON
CYRANO3/MFront
FALCON
FAST
FINIX
LAMMPS
MFEM
MFront
MMM
NUMODIS
OpenFOAM
SCIANTIX
SERPENT
SUBCHANFLOW
TRANSURANUS
VASP
Z-set

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OPERA HPC

Impact

- ✓ Basic research results with a multi-scale characterization of fuel mechanical behavior based on experiments coupling with simulation
- ✓ 3D simulation open source codes for the fuel element behavior at engineering and microstructure scales
- ✓ Qualification of 3D codes with Verification, Validation and Uncertainties Analysis
- ✓ Improved industrial model based on Machine Learning and AI methods
- ✓ Fuel safety analysis with advanced tools for Gen 2&3 reactors including enhanced Accident Tolerant Fuel concepts.
- ✓ Open publications, Workshops, Schools, MOOC dedicated to fuel performance codes

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OPERA HPC

Link with other initiatives

- SNETP/NUGENIA organization :
  - ✓ TA 7 Fuel Element : Objectives in link with priority topics agreed in the TA7
  - ✓ TA 1 Plant Safety and Risk Assessment : CAMIVVER for core scale analysis -> cross exchanges for boundary conditions and detailed fuel safety assessment
  - ✓ TA 3 Improved NPP Operation : new operating conditions to consider in the fuel safety analysis
  - ✓ TA 4 Integrity Assessment of Systems, Structure and Components : cross cutting topics on material (methods, open source codes,...), complementary results for eATF (Il Trovatore project)
  - ✓ TA6 Innovative LWR Designs and Technologies : tools for fuel safety assessment (SMR, ...)
- SNETP/ESNII and NC2I : cross cutting aspects on materials
- INCA OECD/NEA joint experimental program : In-pile Creep Studies of ATF Cladding
  - ✓ Experimental data available in the INCA JEEP for the development of an advanced mechanical model for eATF coated cladding
- ONCORE IAEA initiative : Open-source Nuclear Codes for Reactor Analysis

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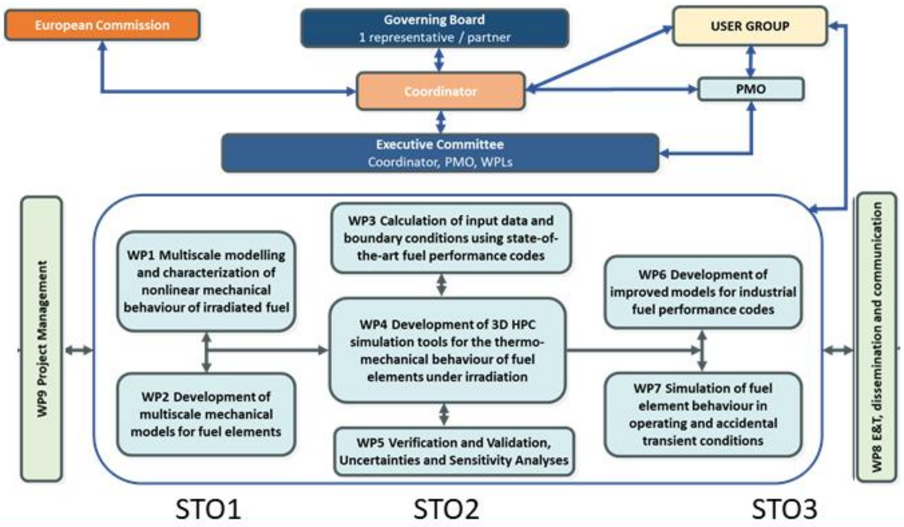
- Work plan

Overall structure of the OperaHPC project



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Technical WPs program

WP1
WP2

- Experimental device for creep tests on irradiated fuel samples,
- Physical data for fuel mechanical properties
- Improved physics-based mechanical laws for fuel and cladding

WP3
WP4
WP5

- Validated open source computational tools for fuel behaviour simulation :
  - ✓ MMM mesoscale (microstructure scale) code
  - ✓ OFFBEAT engineering scale simulation code (fuel element)
  - ✓ Prototype tool (meshless SPH method)

WP6
WP7

- Improved models for industrial Fuel Performance Codes
- Safety assessment for operating transients and DBA (state of the art fuel and eATF).

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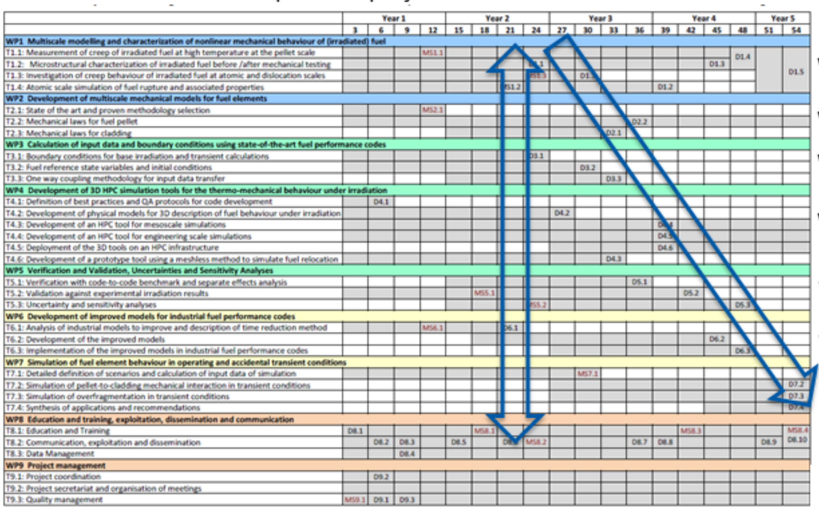
Timeline

- GANTT chart of the OperaHPC project



- WP1 – Basic research with input data for WP2
- WP2, WP3 – Input data for WP4
- WP4 – 3D simulations tools for WP5, WP6 and WP7
- WP5 – VVUQ for WP6 and WP7
- WP6 – Improved industrial model for WP7
- WP7 – Industrial application
- WP8 – Continuous transfer with technical WPs
- WP9

End User Group of the OperaHPC European project : information meeting 18

OPERA HPC

- Consortium

OPERA HPC

Partners

- 18 partners representing 9 countries including 14 beneficiaries and 4 associated partners from United Kingdom and Switzerland
- The large majority of the members of the NUGENIA/TA7.2 participate in OperaHPC and most of the partners have already worked together in previous European projects and other collaborative initiatives

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OPERA HPC

Domains of expertise

The multidisciplinary consortium constituted is composed of

- 9 public nuclear research organisations (50%)
- 5 universities (28%)
- 2 industrial partners (11%)
- 2 SME (11%)

Diverse consortium
Consistent continuum from research to industry

		Characterisation irradiated fuel	Atomic scale modelling	Mesoscale modelling	Engineering scale modelling	Multiphysics calculations	Development HPC applications	V & V & SA	Computation time reduction	Industrial study fuel behaviour	Education & Training	Dissemination & Communication	Project management
Nuclear research organizations	CEA	X	X	X	X	X	X	X	X	X	X	X	X
	CIEMAT				X	X		X	X				
	ENEA				X		X	X	X	X		X	
	JRC				X	X		X	X			X	
	LEI				X	X			X	X			
	NNL				X		X					X	
	PSI				X	X	X	X				X	
	UJV				X					X		X	
	VTT	X		X	X	X	X					X	
Ind-ustry	EdF			X					X	X			
	Fra				X					X			
SME	NINE					X		X		X			
	SINTEC										X	X	X
Academic partners	Bangor		X								X		
	EPFL				X						X		
	KTH		X								X		
	POLIMI				X	X	X	X	X		X		
	UNIPI							X	X		X		

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OPERA HPC

- Detailed Work Plan

OPERA HPC

Detailed Work Plan : Content

- Published since September 2023
- Introduction : Physical phenomena to address
  - ✓ General objectives structuring the work description
- Work Plan per Task
  - ✓ Objective/name of WP and Task leader
  - ✓ Detailed Work description including input and output (interaction with other WP&Tasks)
  - ✓ Task Schedule : Action/Who/When needed to reach Milestones and Deliverables
  - ✓ Experimental/calculation means + Risk/contingency plan
  - ✓ Milestones/Deliverables : Title/due date/contact person
  - ✓ Partners involved and individual contribution

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OPERA HPC

Detailed Work Plan : Physical phenomena to address

❑ Simulation of fuel element behavior **under transient irradiation conditions** is focused on:

- Cladding integrity in the event of **pellet-cladding mechanical interaction (PCMI)**
- Fuel integrity in the event of **fuel pellet over-fragmentation** (Fragment size in the range 50-500 μm)

❑ Pellet-cladding mechanical interaction

- Stress and strain in the cladding to assess the risk of failure during a power transient (power ramp or RIA)
- Topics of interest
  - ➢ Gap closure
  - ➢ Pellet swelling (thermal and gaseous),
  - ➢ Pellet viscoplastic mechanical behavior (accommodation of the volume expansion),
  - ➢ Stress and strain localization in the cladding (pellet fragmentation and hourglass shape).

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Detailed Work Plan : Physical phenomena to address

- Fuel over-fragmentation
  - Fission gas release and fuel relocation/dispersal associated to clad ballooning/rupture
  - Time of rupture and fuel fragment size under accidental conditions (RIA, LOCA)
  - Topics of interest
    - Small scale stress and strain induced by over pressurized bubble
    - Stress and strain heterogeneities (grain boundary, porosities,...)
    - Dynamic and/or hydro-dynamic loading induced by the depressurization in case of cladding rupture

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Thank you for your attention

OperaHPC is funded by the European Union. Views and opinions expressed, however, are those of the author(s) only and do not necessarily reflect those of the European Union or European Commission. Neither the European Union nor the granting authority can be held responsible for them.

6 Appendix 2 : Project outputs for End Users and progress

OPERA HPC

Project outputs for End Users and progress

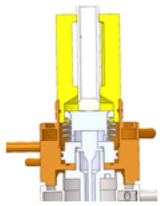
End User Group of the OperaHPC European project : information meeting: online 08-01-2024

Funded by the European Union

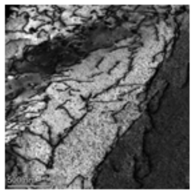
WP1 : Multiscale modelling and characterization of non-linear (creep and rupture) mechanical behaviour of irradiated fuel

- Planned output: Accurate data for the development and separate effect validation of mechanical models
  - ✓ Experimental and atomic to mesoscale modelling data on creep of irradiated fuel
  - ✓ Atomic scale data on rupture of irradiated fuel
- Status at Month 15
  - ✓ Detailed design of thermomechanical test device for irradiated fuel to be installed in CEA hot cell completed (MS2)
  - ✓ Preparation of 2 irradiated fuel samples for tests and SEM/TEM examinations before the tests
  - ✓ Modelling of dislocation movement and interaction with point defects at the atomic scale finalized ⇨ Mobility law for dislocation dynamics is being developed

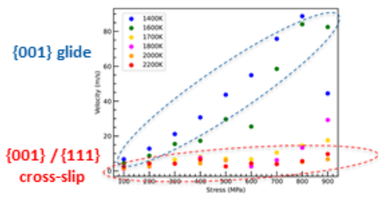
Detailed design of thermo-mechanical test device



Dislocation arrangements observed using TEM in irradiated UO_2



Average dislocation velocity in the average glide plane (MRSS in {001}) yielded by atomic scale modelling

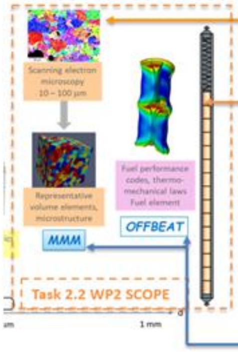


End User Group of the OperaHPC European project : information meeting 2

WP2 : Development of multiscale mechanical models for fuel elements

- Planned output: Open source mechanical laws for fuel and cladding
  - ✓ State of the art laws available in open literature
  - ✓ Improved physically based laws
  - ✓ Mfront implementation available for generalist mechanical solvers and Fuel Performance Codes

- Status at Month 15
  - ✓ Methodology and bibliographic experimental data selection : milestone MS-3 in Nov 23
  - ✓ Pellet and cladding physically based laws under development



- At the mesoscale => the objective is to describe single crystal viscoplasticity in UO_2 (standard and "EATF") porous polycrystalline microstructure
- At the engineering scale => homogenized mechanical laws or models will focus on the impact of heterogeneities induced by polycrystalline microstructure
- The rheological constitutive equations of these models or laws will describe :
  - Thermo-elastic and non-linear mechanical behavior including creep and rupture
- Experimental data:
  - From the international bibliography or WP1

Models or laws used in the mesoscale MMM tool and the engineering scale OFFBEAT tool of WP4

End User Group of the OperaHPC European project : information meeting 3

WP3-WP4-WP5 : Planned output

Ready to use* open source simulation tools for fuel element behavior in the reactor

* Input data and BC in WP3 – Solver in WP4 – VVQI in WP5

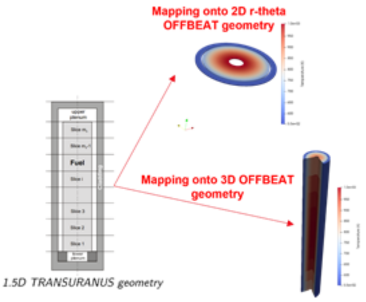
- OFFBEAT/SCIANTIX : 3D High-Fidelity simulation at fuel rod scale
  - ✓ Multi-dimensional and HPC approach with the OpenFOAM code (WP4)
  - ✓ Multi-physic computational scheme including thermo-mechanics and fission gas behavior with the SCIANTIX open source code (WP4)
  - ✓ HF boundary conditions and initial state with existing codes (fuel assembly/core scale and FPC) (WP3)
  - ✓ VVQI for the physics addressed in the the project (see Detailed Work Plan) (WP5)
- MMM : 3D high-fidelity simulation at microstructure scale
  - ✓ Multi-dimensional and HPC approach with the MFEM-MFront codes (WP4)
  - ✓ Stand alone use or one way coupling with OFFBEAT (WP4)
  - ✓ VV for the physics addressed in the the project (see Detailed Work Plan) (WP5)
- SPH : 3D prototype simulation tool using Smooth Particle Hydrodynamics approach
  - ✓ Simulation of fuel relocation or dispersal following the pellet over fragmentation (WP4)
  - ✓ V for some reference cases (WP5)

End User Group of the OperaHPC European project : information meeting 4

WP3 : Calculation of input data and boundary conditions using state-of-the-art fuel performance codes

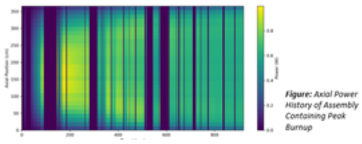
- Status at Month 15
  - ✓ Feasibility analysis of boundary condition computation for validation cases
  - ✓ First version of the restart interface for TRANSURANUS and OFFBEAT ready

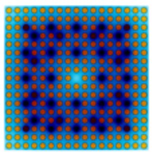
TRANSURANUS / OFFBEAT coupling



HF Boundary Conditions

- Core Follow Data for BEAVRS Benchmark
- LB-LOCA boundary conditions
- RIA boundary conditions



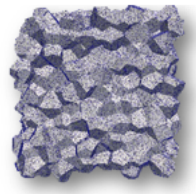


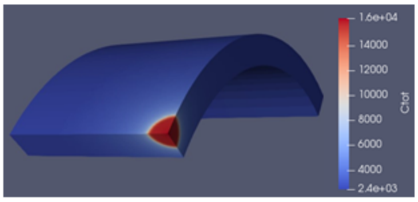
- Simplified RIA scenario
  Single 3D fuel assembly (reflective BC) and multi-physics approach.
  1) Base irradiation (with PSI core simulator BC)
  2) Transient
- Serpent/SUBCHANFLOW/SuperFINIX*

WP4 : Development of 3D HPC simulation tools for the thermo-mechanical behaviour under irradiation

- Status at Month 15
  - ✓ Published D4.1 “Best practices and QA protocols for code development”
  - ✓ Development of HBS formation and evolution model in SCIANTIX
  - ✓ Simulation of polycrystals under uniaxial traction with MMM
  - ✓ Preliminary simulations with prototype SPH tool for fuel fragmentation
  - ✓ Explicit modeling of oxide layer with OFFBEAT
  - ✓ Preliminary extension of OFFBEAT to RIA w/ hydrogen transport
  - ✓ Extension of OFFBEAT to large strain scenarios and LOCAs

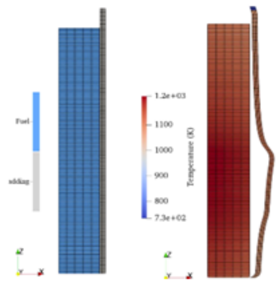
Polycristal mesh (1,4 MDOFs) for MMM





Simulation of hydride blister formation with OFFBEAT

Explicit oxide layer growth for cladding ring



IFA 650.2 LOCA test with OFFBEAT

OPERA HPC

WP5 : Verification and Validation, Uncertainty and Sensitivity Analyses

- Planned output:

  - ✓ Verification of OperaHPC tools: OFFBEAT, OFFBEAT+SCIANTIX, MMM, SPH
  - ✓ Benchmark among 3D codes (OFFBEAT, ALCYONE, BISON) with focus on 3D PCMI aspects (e.g., K11 OSIRIS case study)
  - ✓ Validation of OFFBEAT against selected IFPE integral experimental cases (PCMI, LOCA, RIA)
  - ✓ Validation of MMM against separate effect tests (fuel creep, fragmentation, HBS, dish filling)
  - ✓ Focus on cases where 3D models should bring the most progress for thermo-mechanical behaviour, linked with WP4 developments & target applications in WP6 and WP7
  - ✓ Uncertainty and sensitivity analyses to complement code simulations (uncertainty propagation / sampling methods)

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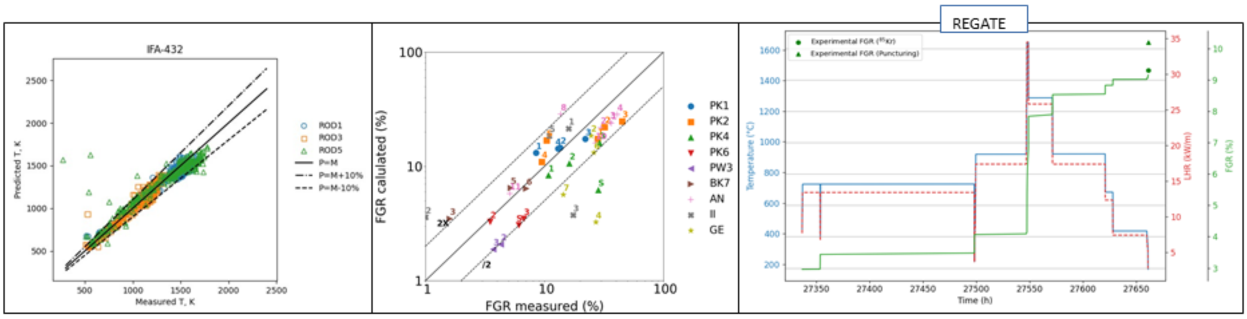
OPERA HPC

WP5 : Verification and Validation, Uncertainty and Sensitivity Analyses

- Status at Month 15:

  - ✓ Selection of case studies and bibliographic input data for V&V and UA&SA
    - PCMI: AN3, REGATE; LOCA: IFA-650.10, MT4, MT6A; RIA: IFPE/NSRR FK-1/2/3
  - ✓ Updating of OFFBEAT+SCIANTIX 2.0 and preliminary integral validation (IFPE database)



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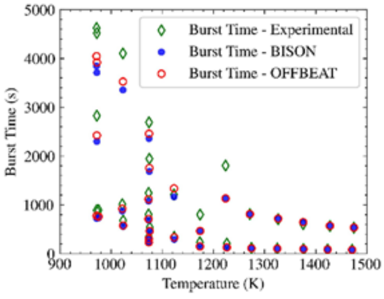
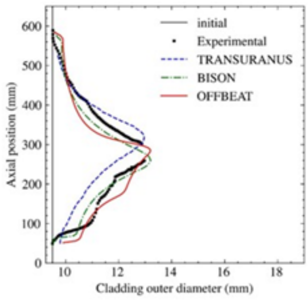
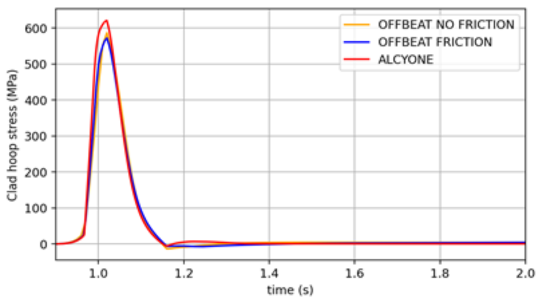
WP5 : Verification and Validation, Uncertainty and Sensitivity Analyses

- Status at Month 15:

  ✓ Extension of OFFBEAT to large strain and preliminary separate-effect validation (PUZRY burst test)
  ✓ Extension of OFFBEAT to RIA and comparison with ALCYONE







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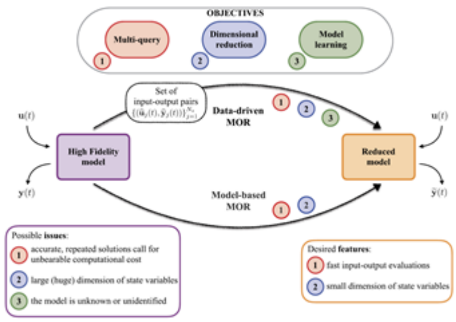
WP6 : Development of improved models for industrial fuel performance codes

- Planned output: Improved models for industrial fuel performance codes
  ✓ Reduced Order Models (ROM) for fuel over fragmentation : HBS and polycrystalline microstructures
  ✓ ROM/ML models for Pellet Cladding Mechanical interaction and Fission Gas Behaviour for standard and EATF fuel element

- Status at Month 15
  ✓ Detailed analysis of physical description to improve in industrial models: milestone MS-4 Nov 2023
  ✓ Starting review of Numerical and mathematical approaches for computation time reduction D6.1 July 2024



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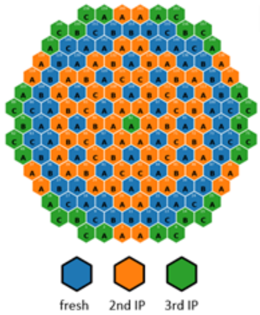
WP7 : Simulation of fuel element behavior in operating and accidental transient conditions

- Planned output: Fuel safety studies in operating and accidental transient conditions

Condition	Reactor	Fuel element	Code	Type of code	Partner (s)
Power transient in flexible operation	PWR	State of the art UO_2	FINIX	Improved 1.5D FPC	VTT
RIA	VVER	ATF with coated cladding	TRANSURANUS	Improved 1.5D FPC	LEI
RIA	VVER	ATF with coated cladding	OFFBEAT	3D HPC	EPFL, ENEA

Condition	Reactor	Fuel element	Code	Type of code	Partner
LOCA	VVER	State of the art UO_2	Standalone ROM	Improved 1.5D model	CEA
RIA	PWR	ATF with large grain UO_2	CYRANO3	Improved 1.5D FPC	EDF
Power transient	PWR	ATF with CERMET microcell UO_2	MMM	3D HPC	CEA



- Status at Month 15
  - ✓ Selection of irradiation conditions for fuel element safety in VVER and PWR
  - ✓ Starting VVER simulations at the core scale for the generation of input data of fuel element safety study

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Thank you for your attention

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