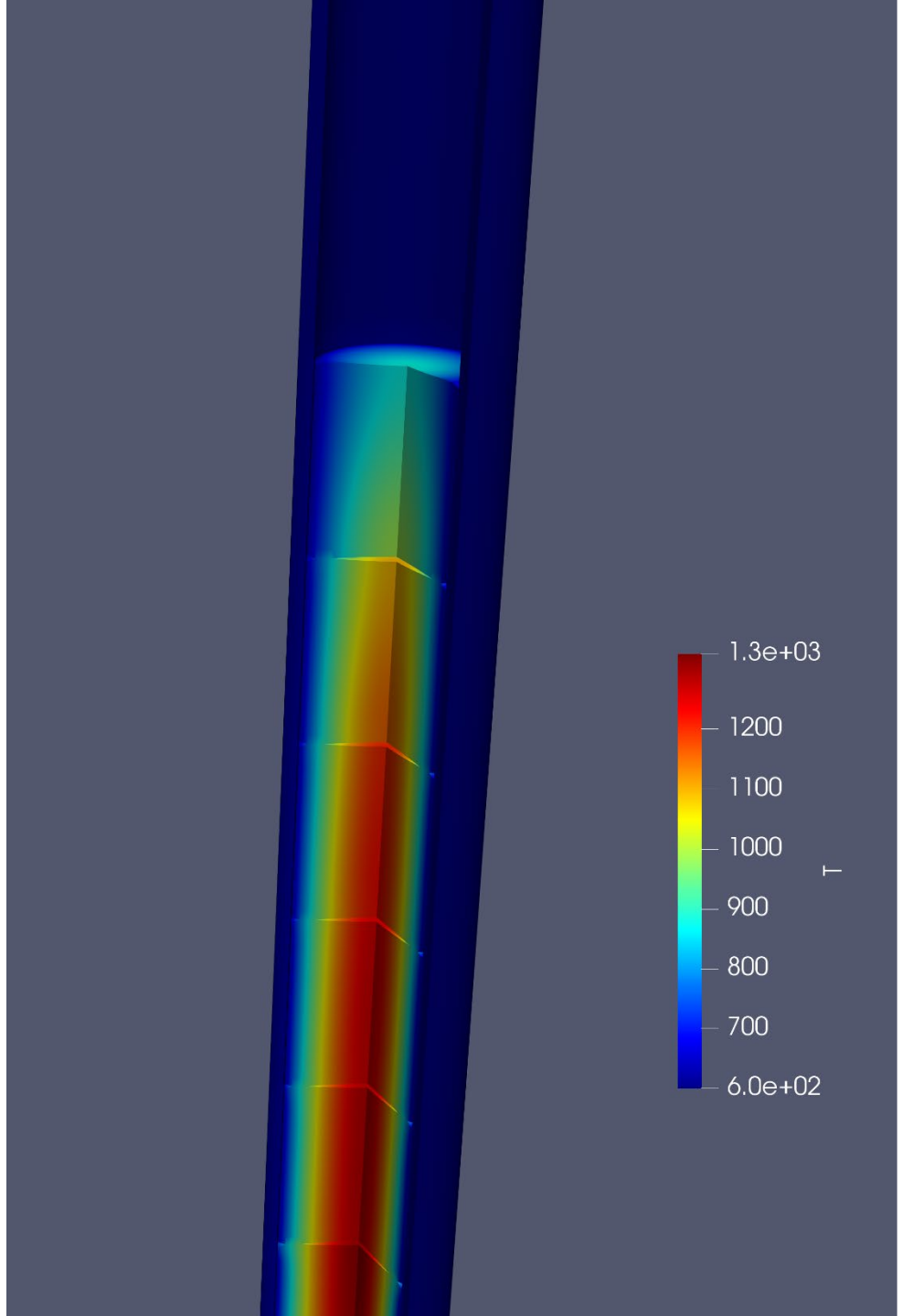
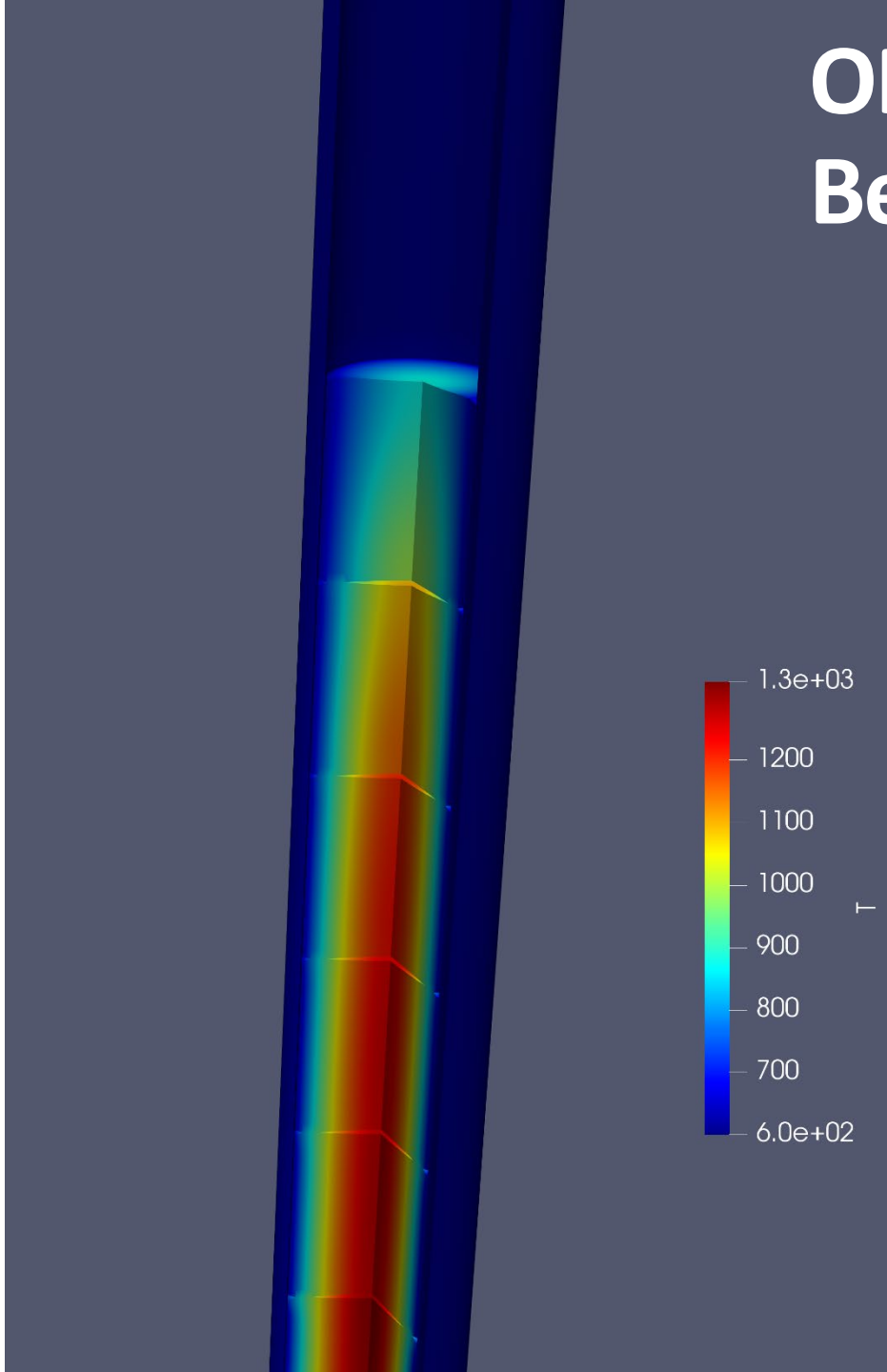


Development of the open-source multi-dimensional fuel performance code OFFBEAT

A. Scolaro - EPFL

OFFBEAT – OpenFOAM Fuel Behavior Analysis Tool



- Developed at EPFL in collaboration with PSI (Switzerland)
- Open-source
- Multi-dimensional (1-D, 2-D, 3-D)
- Part of ongoing international benchmarks (e.g. PUMMA, MPCMIV) and European proposals (e.g. operaHPC)

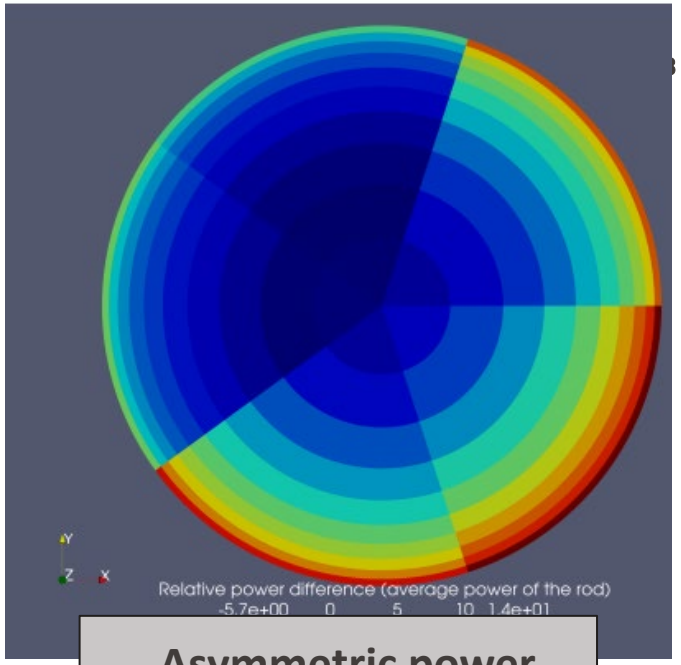
Main models

Main current applications is LWR fuel (UO_2 and Zircaloy):

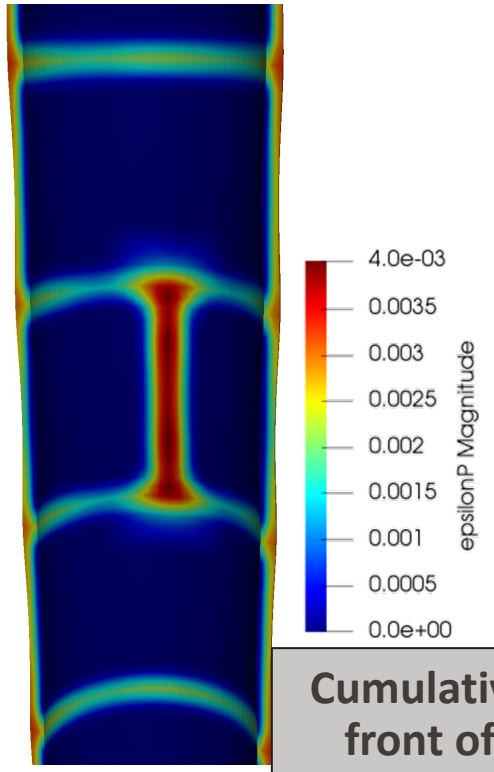
- Ongoing extension to MOX and fast reactors

Models for:

- Swelling, densification, relocation
- ***Creep*** and plasticity
- Neutronics and radial power profile ***(including coupling with Serpent)***
- Fission gas release ***– SCIANTIX from PoliMi***



Asymmetric power distribution – coupling with Serpent



Cumulative plastic strain in front of MPS (test case)

- Correlations and models only from open literature, proprietary information conflict with public release

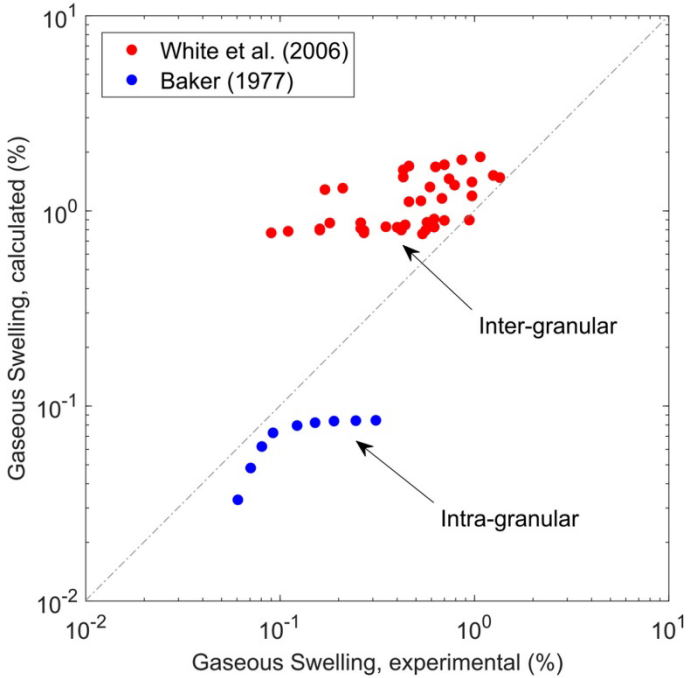
+ Introduction of new ones is very straightforward (can be tailored to specific fuel)

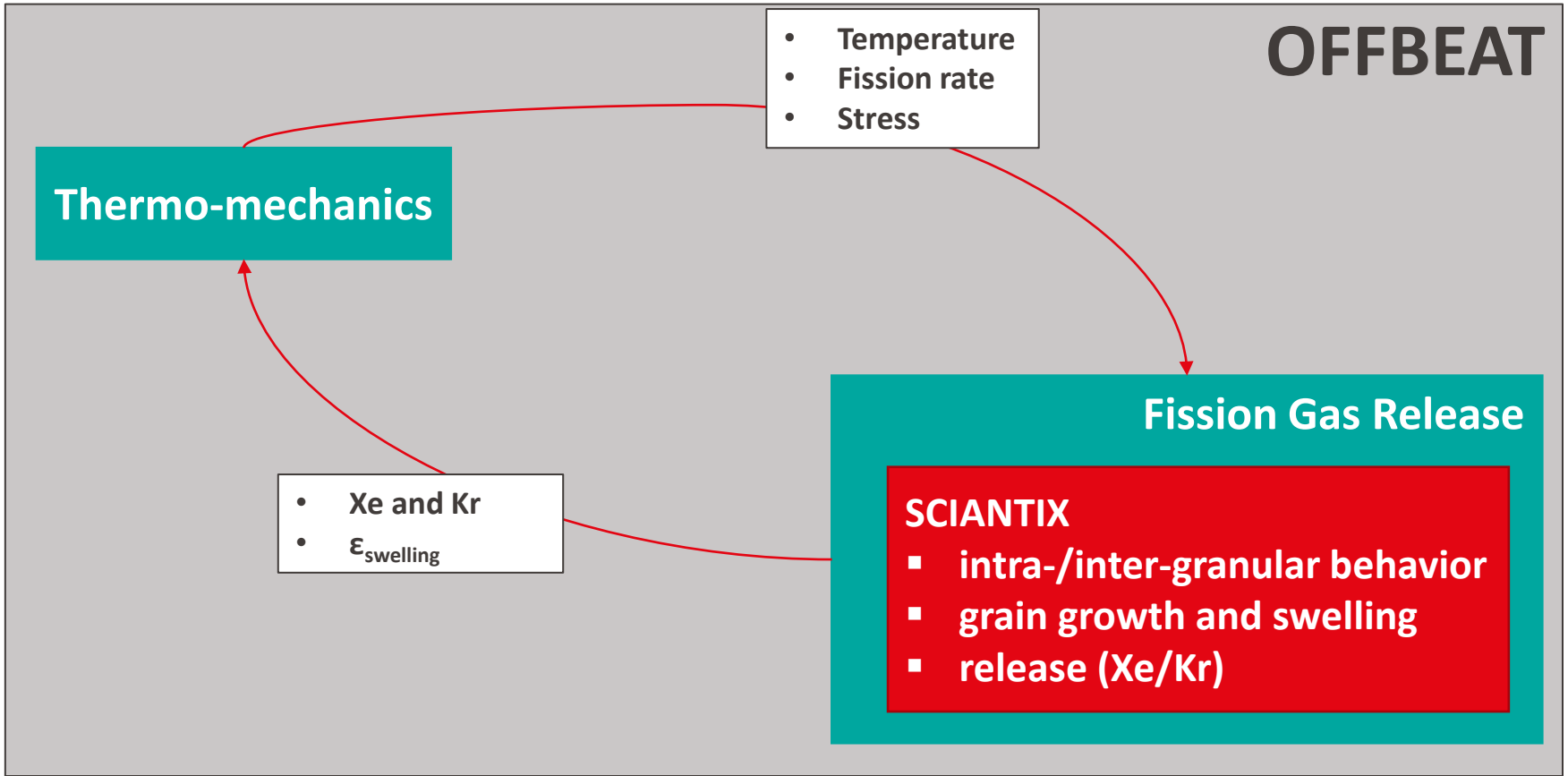
Fission gas release – example of straightforward coupling between open-source codes

- Coupling with ***SCIANTIX:*** open-source 0-D code from ***PoliMi***

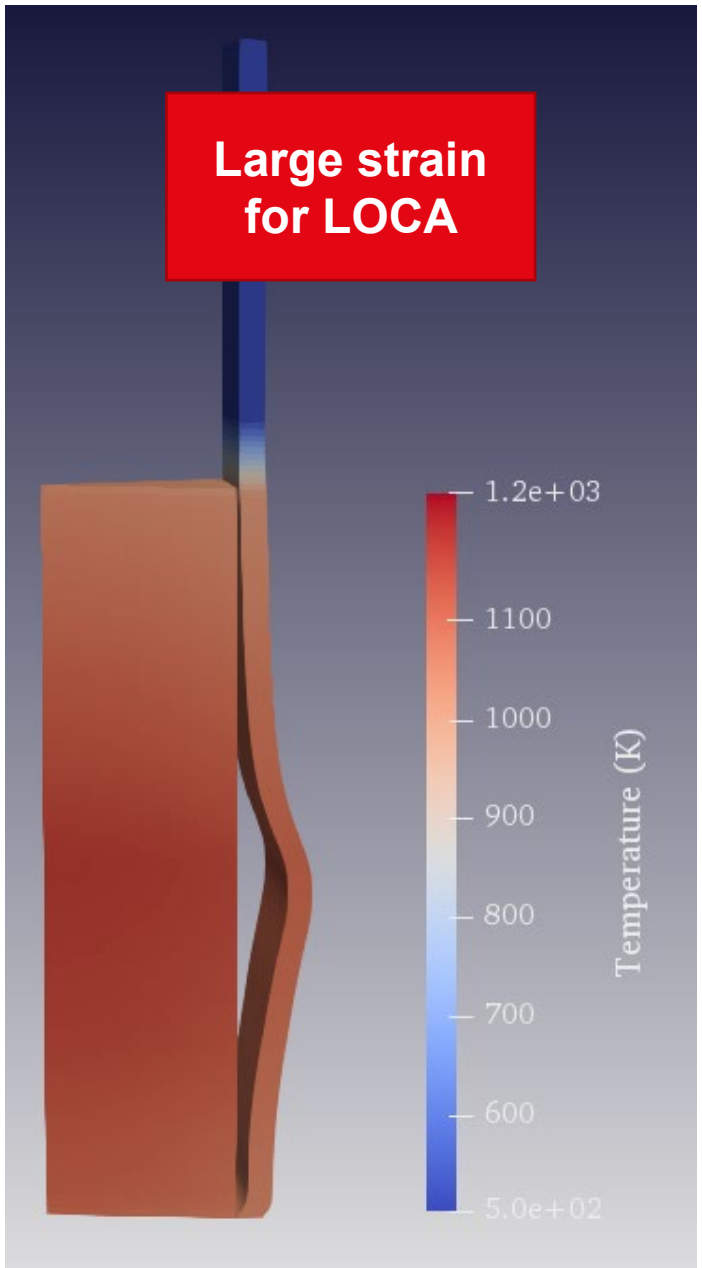
POLITECNICO MILANO 1863

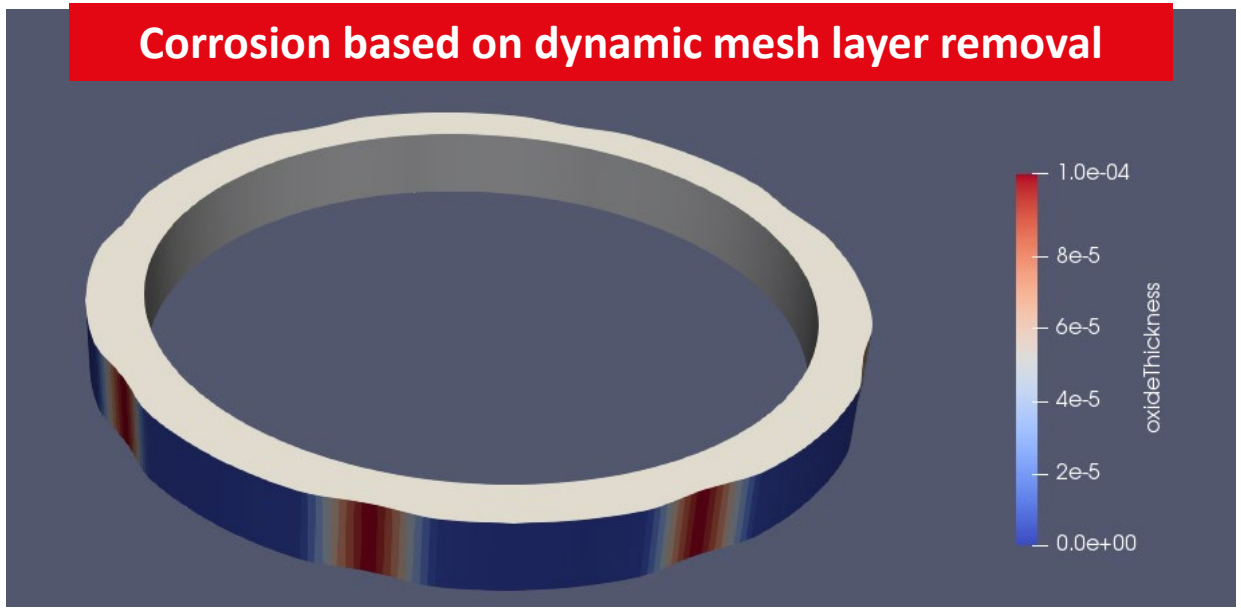
D.Pizzocri et al.,
Journal of Nuclear Materials, 2020





Ongoing developments





- Neutronics solvers based on diffusion/SP3/SN and coupling with Serpent

- Shift V&V to mechanics: testing frictional contact BC

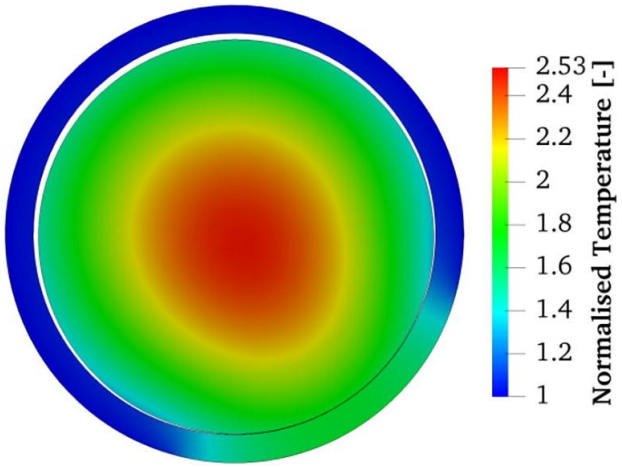
MPCMIV (with NCSU)

- MOX properties
- JOG and central hole formation for FR
- SCIANTIX extension to fast reactors

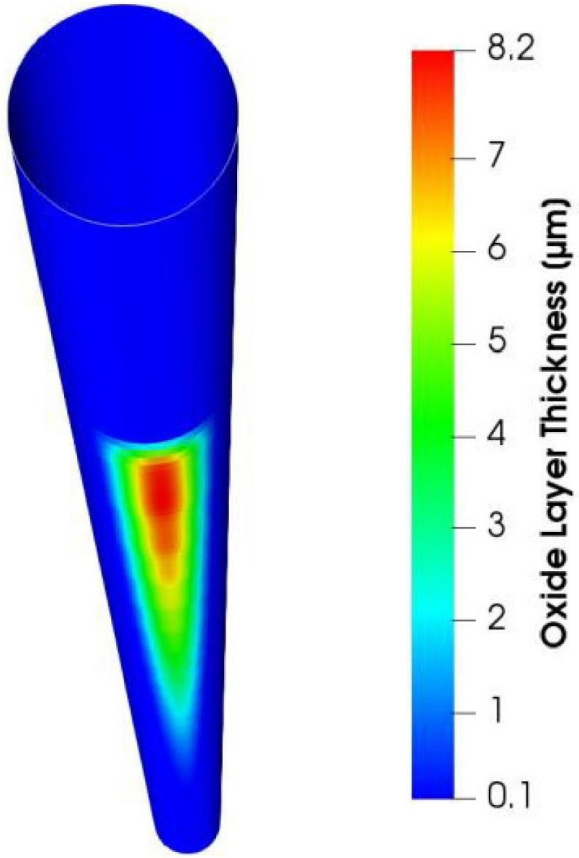
PUMMA project

Prompted in 2017 by fuel failure in Swiss NPP

- Lack of readily available multi-dimensional codes
- Complement to traditional codes:
  - Straightforward tailoring to specific needs
  - Open to coupling with other tools
  - Special focus on education and research



Temperature distribution for eccentric fuel under power peaking and partial dryout – **I. Clifford et al.**, *Ann. Nucl. En.*, 2019



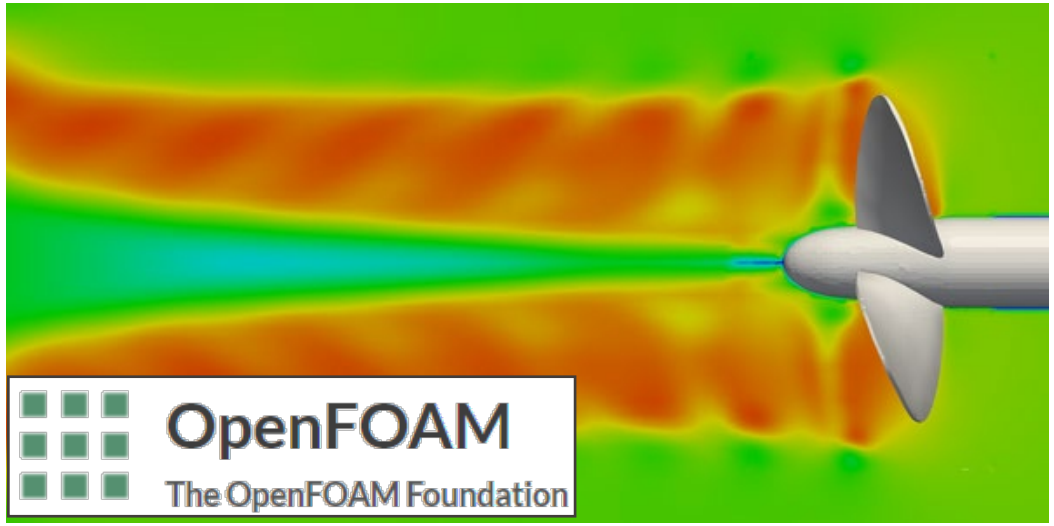
Cladding oxide layer thickness under partial dryout – **I. Clifford et al.**, *Ann. Nucl. En.*, 2019

OpenFOAM – a high-quality library for solving PDEs (not *just* industrial level CFD)

Simplified development thanks to:

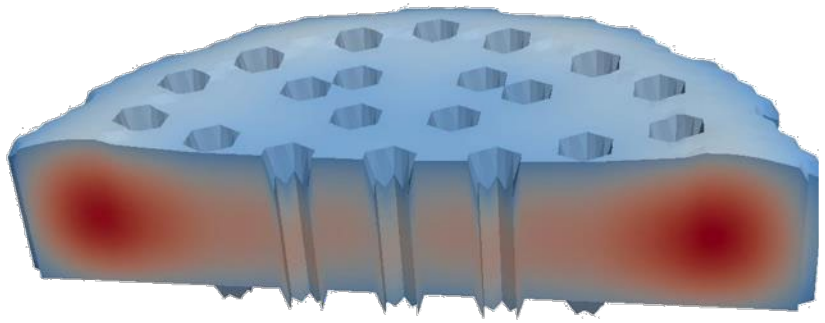
- Object oriented (C++) paradigm
- Complete package
- High-level API and intuitive formulation (FVM)

```
fvMatrix<scalar> Teqn
(
    fvm::ddt(rho*Cp, T)
    ==
    fvm::laplacian(k, T) + Q
);
```



OFFBEAT could build on:

- EPFL-PSI experience (e.g. Gen-Foam)
- OpenFOAM community contributions (~10k to 20k users)



Flux in the ESFR core - **C. Fiorina et al.**, *Nuc. Eng. Des.*, 2015.

OpenFOAM community contributions: extending the FVM to solid mechanics

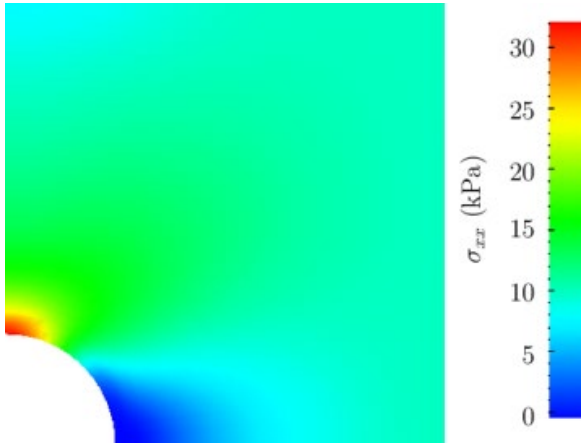
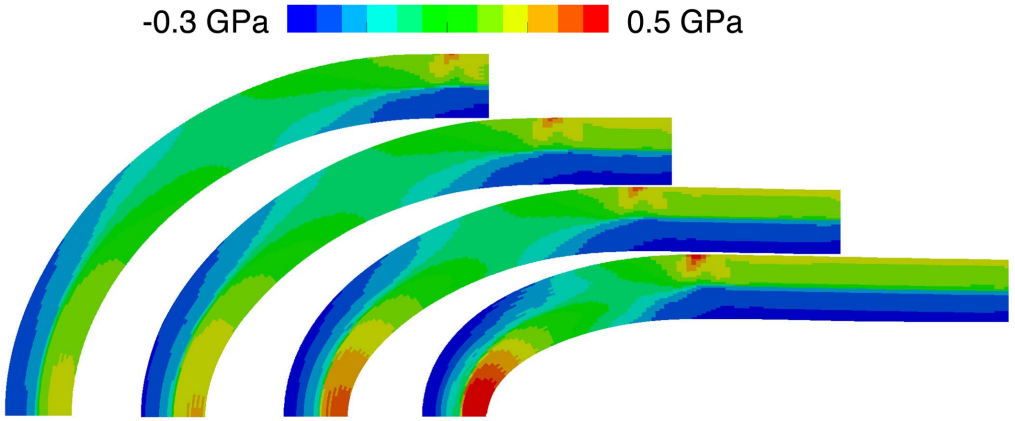
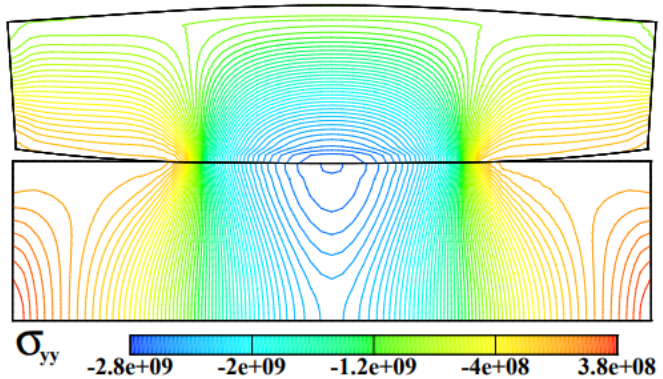


Plate with central hole –
Stress along the *x*-direction
H. Jasak, 2000

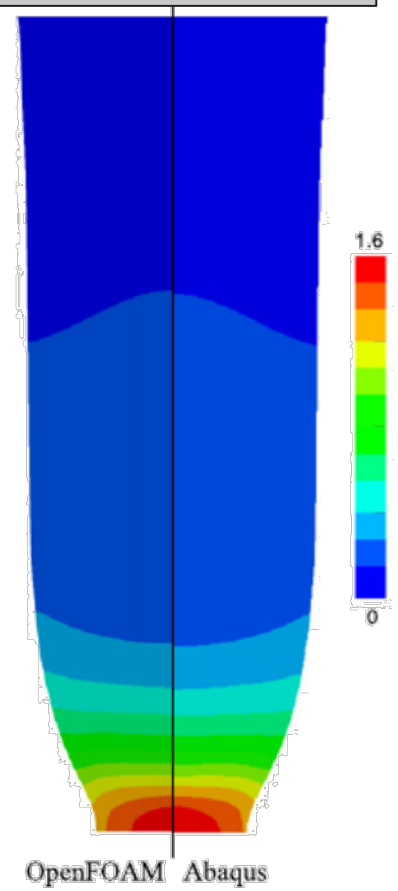


Hydrostatic stress –
Crushing of a pipe
P. Cardiff et al., 2017



Cylinder-plane contact –
Normal stress contour plot
H. Jasak et H.G. Weller, 2000

Plastic strain –
Bar necking
P. Cardiff et al., 2017



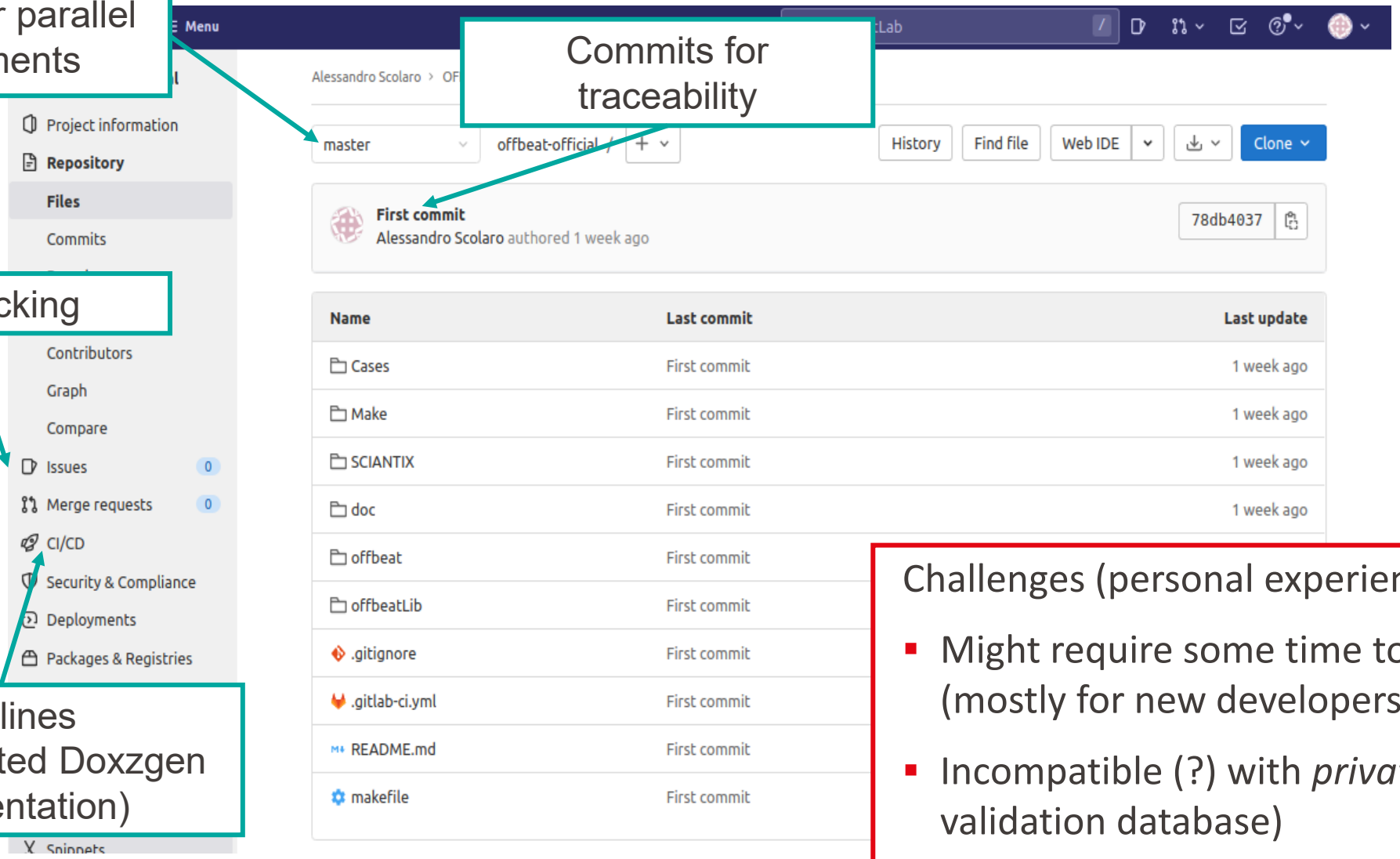
git and GitLab – simplified maintenance

Branches for parallel developments

Commits for traceability

Issue tracking

Pipelines
(e.g. integrated Doxzgen documentation)



Challenges (personal experience)

- Might require some time to get used to (mostly for new developers)
- Incompatible (?) with *private* data (e.g. validation database)

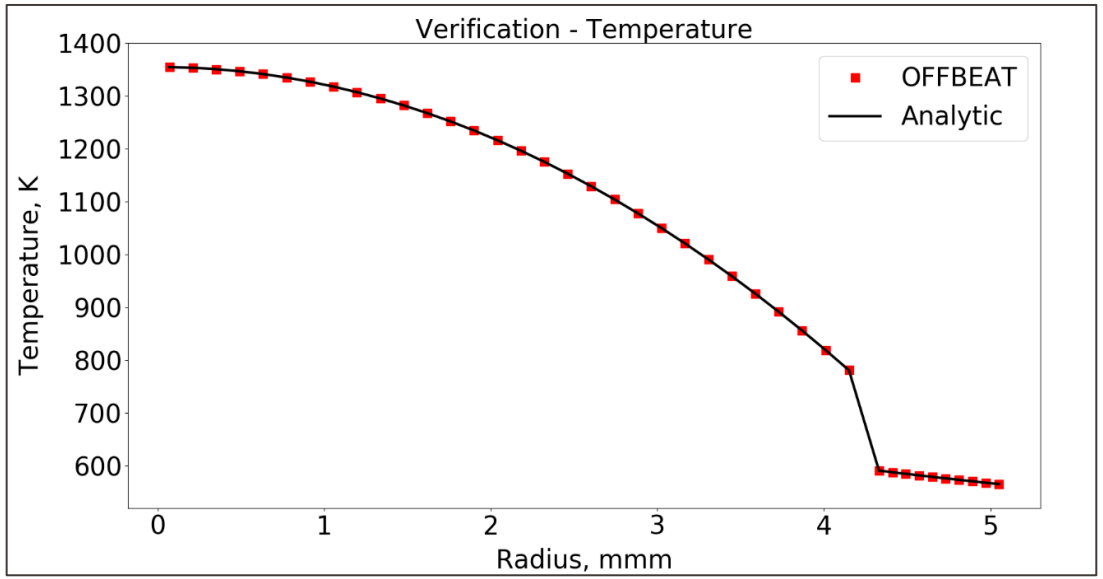
V&V database

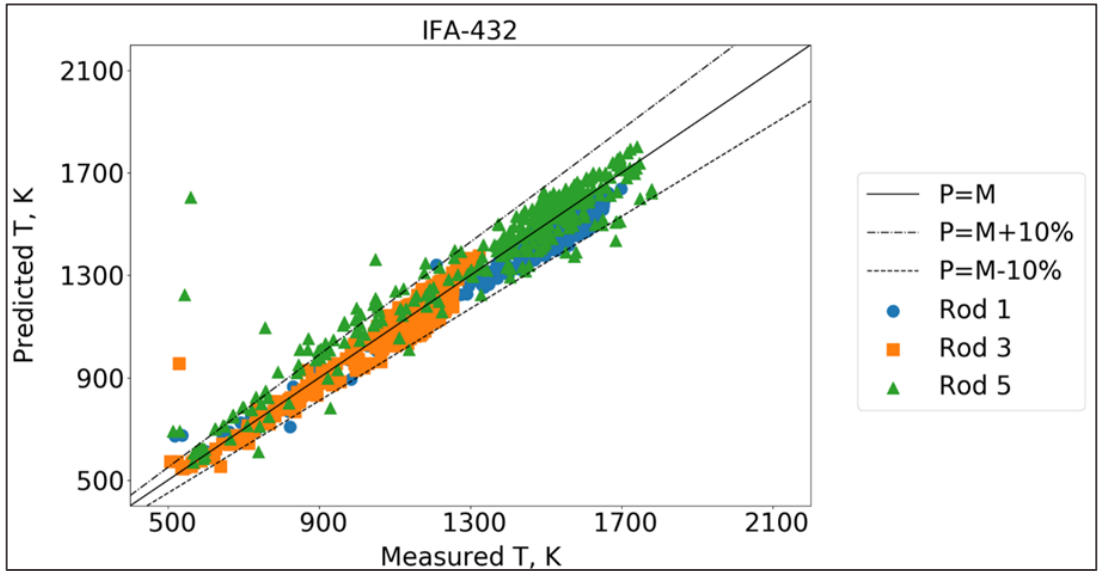
Verification
Simplified cases with focus on ***single aspects***

Validation (~50 rods)
Current focus on thermal analysis:

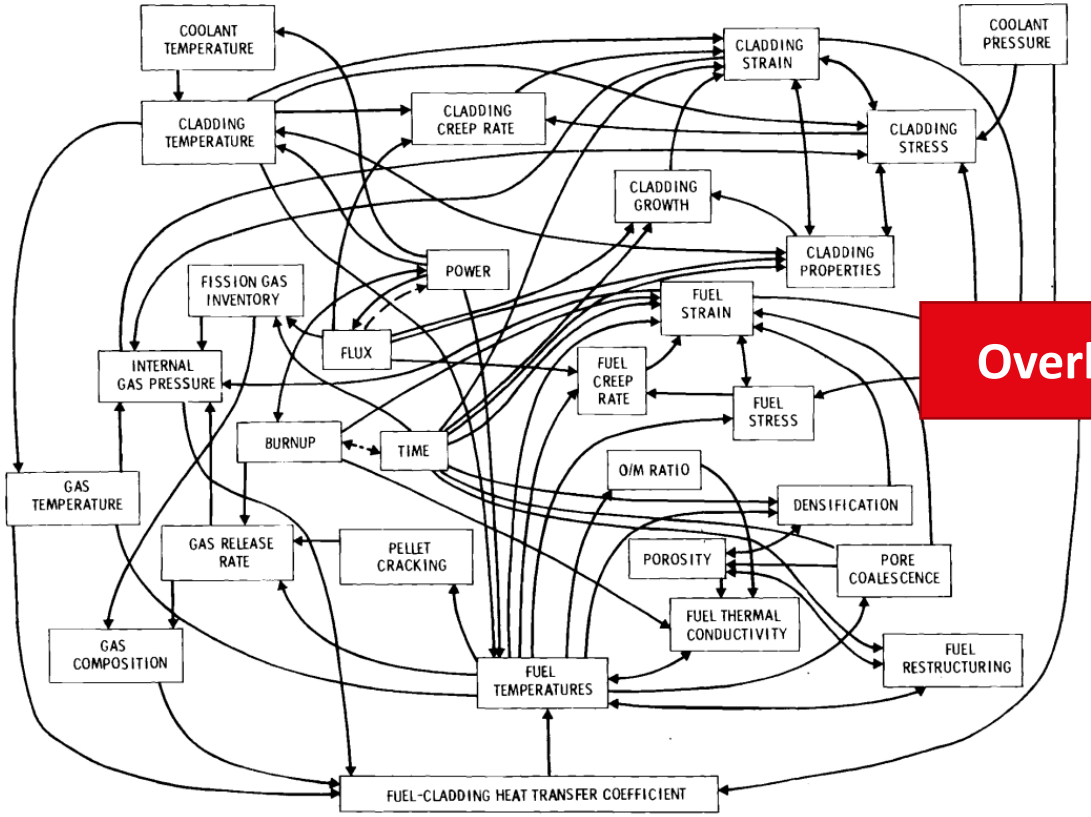
- Fuel Centerline Temperature (FCT)
- Fission Gas Release (FGR)

- **Tests currently performed semi-manually.**
- **Automatic regression test in the near future.**



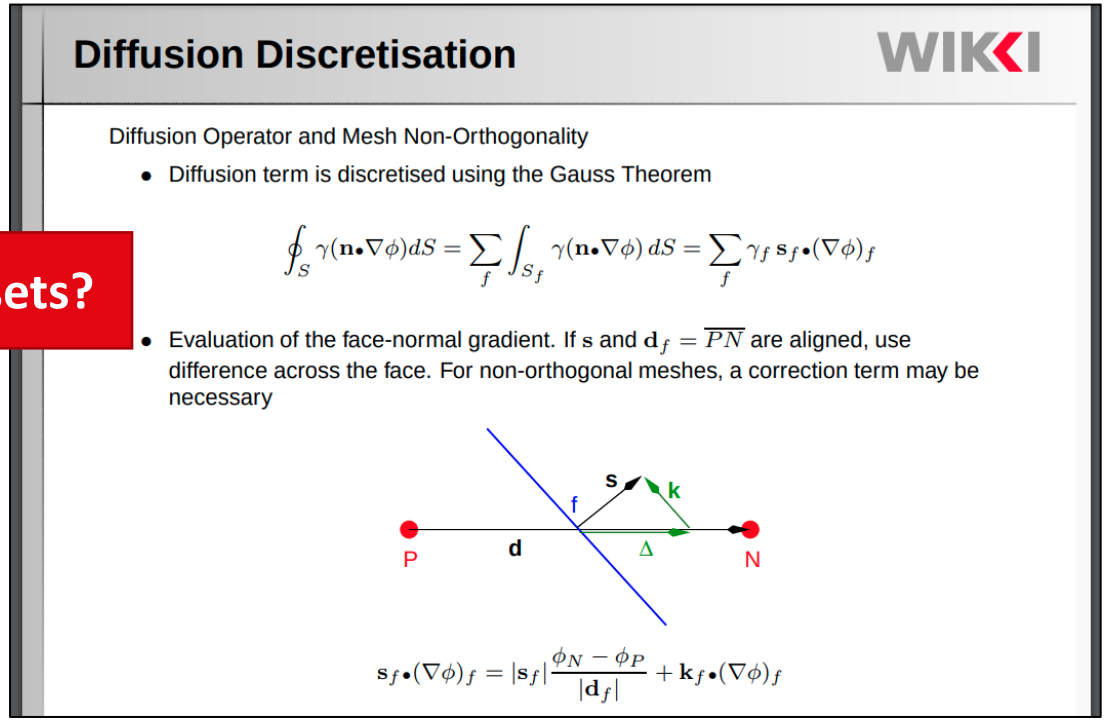


Main challenge: how to simplify the use of a complex multi-dimensional code



Fuel behavior phenomenology -
C. E. Beyer et al., 1975

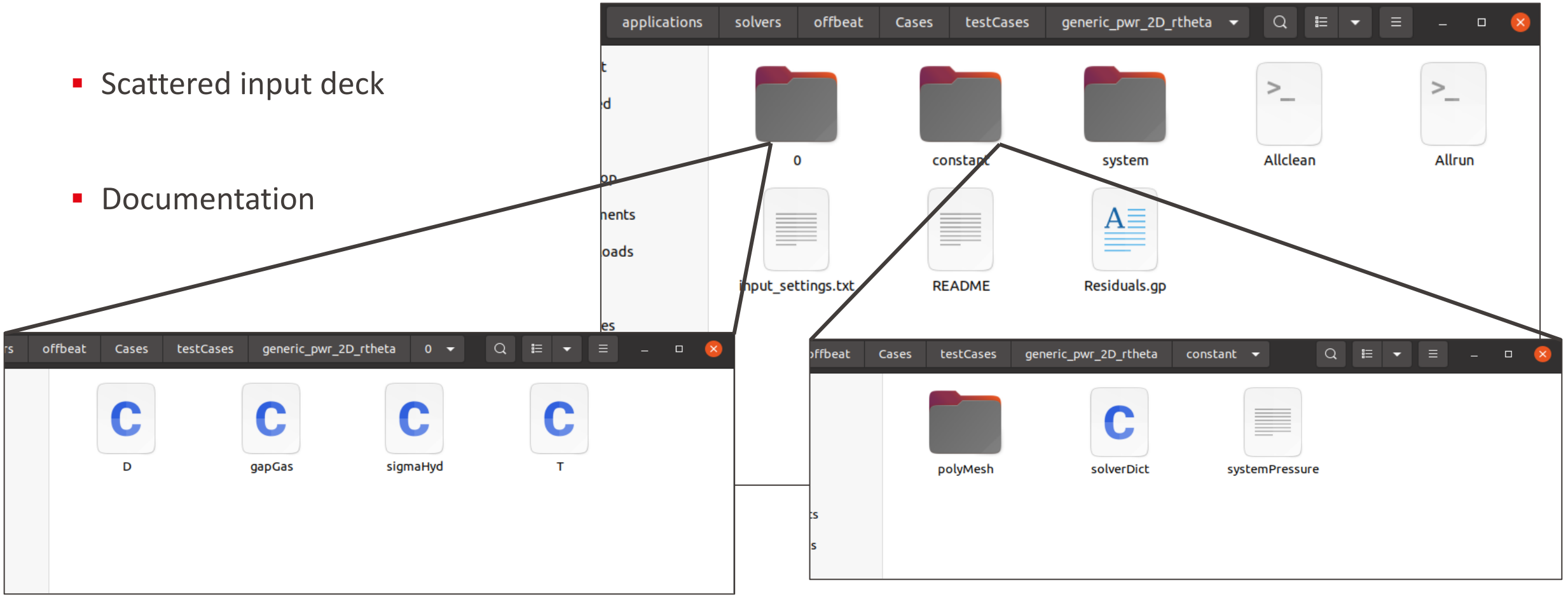
Overlapping skillsets?



Basics of numerical methods -
H. Jasak lecture on FV

A steep learning curve: the OpenFOAM way of doing things

- No native GUI
- Scattered input deck
- Documentation



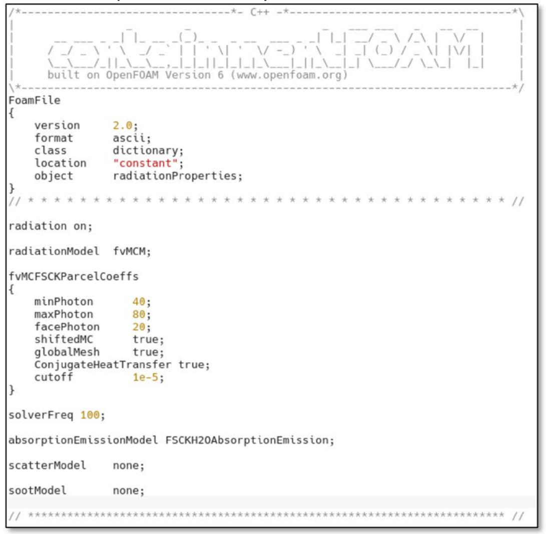
Available options

1. Streamlined and commented input

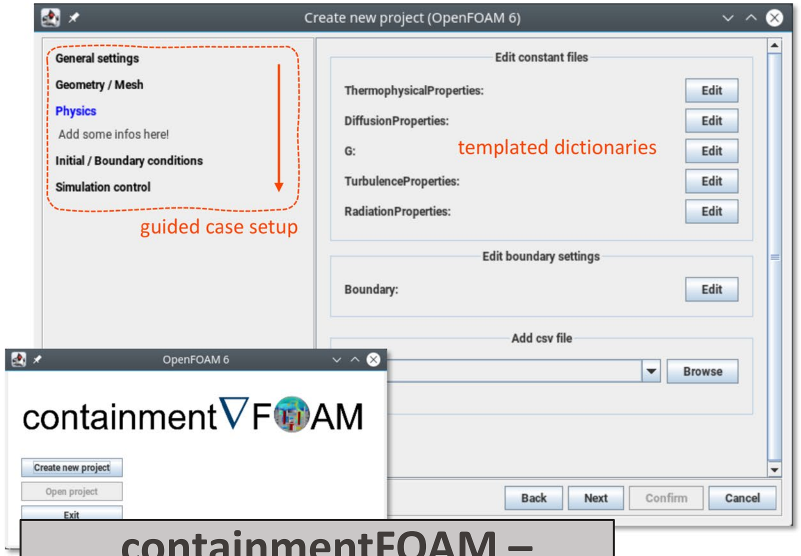
2. Input wizard or input generator (?)

3. **Documentation and tutorials**

radiationProperties dictionary:



```
/*---------------------------------*- C++ -*----------------------------------*\
  built on OpenFOAM Version 6 (www.openfoam.org)
\*---------------------------------------------------------------------------*/
FoamFile
{
    version     2.0;
    format      ascii;
    class       dictionary;
    location    "constant";
    object      radiationProperties;
}
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

radiation on;

radiationModel  fvMCM;

fvMCFSCKParcelCoeffs
{
    minPhoton       40;
    maxPhoton       80;
    facePhoton      20;
    shiftedMC       true;
    globalMesh      true;
    ConjugateHeatTransfer true;
    cutoff          1e-5;
}

solverFreq 100;

absorptionEmissionModel FSCKH2OAbsorptionEmission;

scatterModel    none;

sootModel       none;

// ************************************************************************* //
```



containmentFOAM – S. Kelm et al.

Documentation: Doxygen integrated .H files

Info on a specific class (e.g. `coolantPressureFvPatchVectorField`) using the search bar

OFFBEAT v20.01
OpenFOAM Fuel Behaviour Analysis Tool

C++ Source Code Guide

Main Page | Related Pages | Namespaces | Classes | Files | Search

OFFBEAT Documentation

OpenFOAM Fuel BEhavior Analysis Tool (OFFBEAT) is a three-dimensional finite-volume nuclear fuel performance code based on the OpenFOAM® C++ library. The first version of OFFBEAT is essentially the product of the founding research of Scolaro [5] [4]. Building on the works of Jasak, Weller, Tuković, Cardiff and Clifford [3] [6] [1] [2], OFFBEAT is developed according to a cell-centered finite-volume framework for total Lagrangian, small strain solid mechanics. This is combined with a framework for thermal analysis and with numerical developments concerning the treatment of the gap heat transfer and contact, based on a mapping algorithm that allows the use of independent non-conformal meshes for fuel and cladding. The code considers the temperature and burnup dependence of the material properties, and it can model fuel densification, relocation, swelling, growth, fission gas release, creep, plasticity, and other relevant fuel behavior phenomena. OFFBEAT is a joint development by the Laboratory of Reactor Safety (LRS) at École Polytechnique Fédérale de Lausanne (EPFL) and Laboratory for Reactor Physics and Thermal-Hydraulics (LRT) at the Paul Scherrer Institut (PSI).

This wiki provides the basic documentation for OFFBEAT, including the following:

- **Code Theory**
- **Code Installation**
- **User Manual**
- [Tutorials]
- [Miscellaneous]
- [Tips and tricks]
- [Project Roadmap]
- **References**

Documentation: Doxygen integrated .H files

Info on a specific class (e.g. `coolantPressureFvPatchVectorField`) using the search bar

Detailed Description

Coolant pressure patch-field of fixed-displacement type. It is designed for the top ca

A normal pressure is applied equal to fluid pressure. The shear stress is zero.

The fluid pressure can be provided as a fixed-value or as a time-dependent list.

Usage:

```
    cladOuter
    {
        type            coolantPressure;

        // coolantPressure 1e5;
        coolantPressureList
        {
            type                table;

            // Instead of "file", the user can insert "values"
            file                "$FOAM_CASE/constant/lists/topC

            // values
            // (
            //     (0.0 1e5)
```

- **More advanced feature (need to know what you are looking for)**

- **Very powerful for retrieving usage examples! Available for most (but not all) classes.**
- **Simple to maintain for developers**

Documentation: User Manual

OFFBEAT v20.01
OpenFOAM Fuel Behaviour Analysis Tool

C++ Source Code Guide

Main Page | Related Pages | Namespaces | Classes | Files

User Manual

The instructions contained in this guide assume that the user has a basic understanding of both fuel p

We recommend that new users work through the OpenFOAM v9 User Guide before attempting to use

Mechanics Solution

The momentum balance solution type is se and wi

- `fromLatestTime`, i.e. the displacem
- `smallStrain`, it solves the small str
- `largeStrainTotLag`, it solves for to
- `largeStrainUpdLag`, it solves for in

Additional entries might be required in the

Example of use in solverD

```
// Specify mechanicsSolver type:
// - fromLatestTime
// - smallStrain
// - largeStrainTotLag
// - largeStrainUpdLag
mechanicsSolver     smallStrain;

mechanicsSolverOptions
{
    // Print a summary of the bounda
    forceSummary          on;

    // Activate the calculation of cy
    cylindricalStress     on;

    // Apply RhieChowCorrection to st
    RhieChowCorrection    on;

    // //  Additional subDict for mul
    // multiMaterialCorrection
    // {
    //     type                    c
    //     interfaceWeights        0
    //     defaultWeights          0
    // }

    // Force linear strain tensor (read only when using a large strain solver; off by default)
    linearStrainTensor    on;
}
```

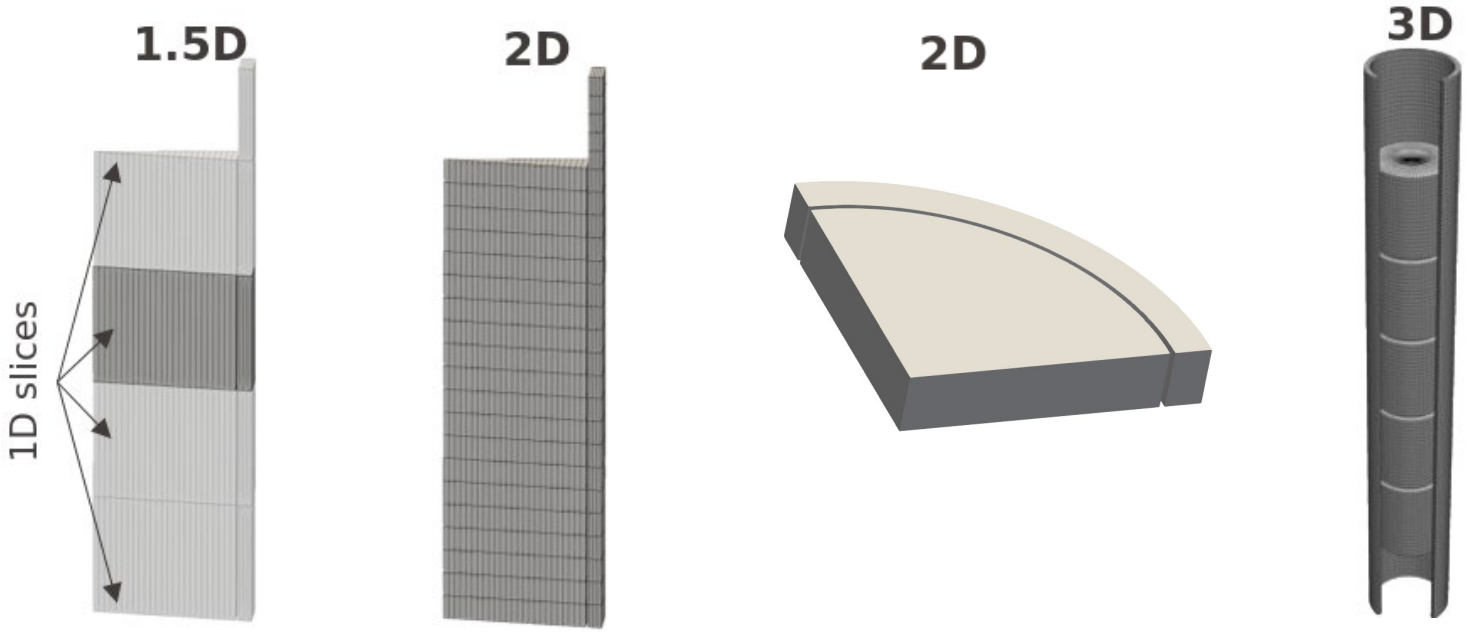
Return to Setting the `solverDict`

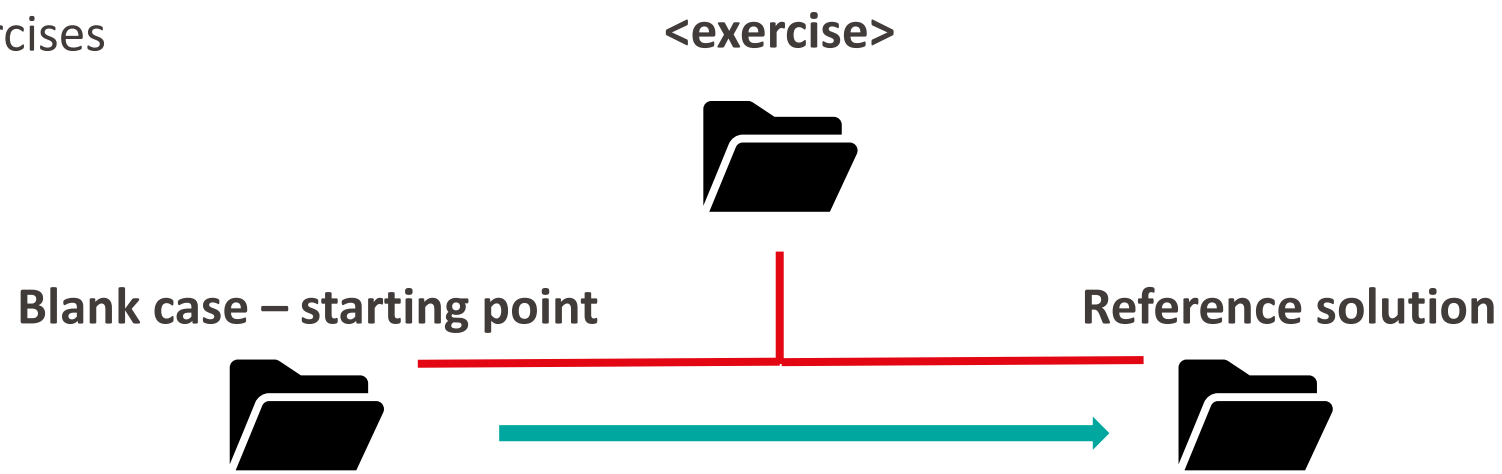
- **Risk of lagging behind the code**
- **Heavy on the developers (double work)**

- **Very useful for beginners**

OFFBEAT tutorials and training material

- Limited cases
- Verification tests could be used but are limited in scope
- Ongoing plans to create exercises






Thank you!
Questions?