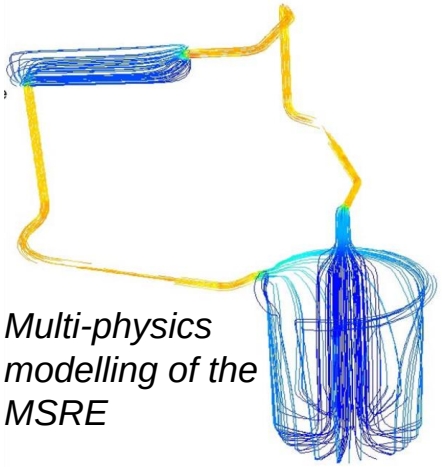
# The GeN-Foam multi-physics solver as a collaborative effort towards an open-source platform for reactor analysis: a historical perspective and lessons learnt

C. Fiorina

# GeN-Foam: Generalized Nuclear Field operation and manipulation

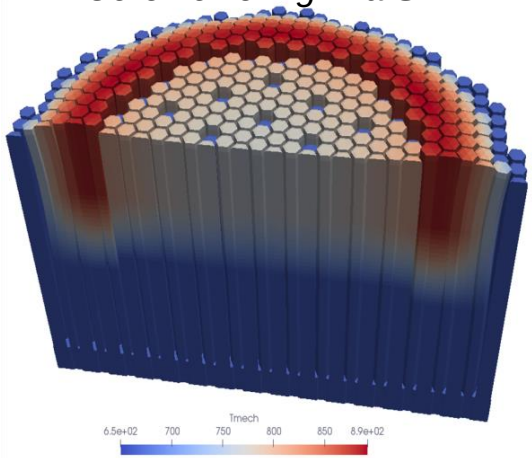
Carlo Fiorina

- **Since 2014, EPFL + PSI + contributions from various institutions**
- **Complement legacy codes** with more flexibility, mainly targeted **to advanced concepts**
- Distributed to 20+ institutions. Now freely available from GitLab and IAEA website
- Training via the IAEA (webinar, lecture, upcoming series of lectures), workshop at conferences

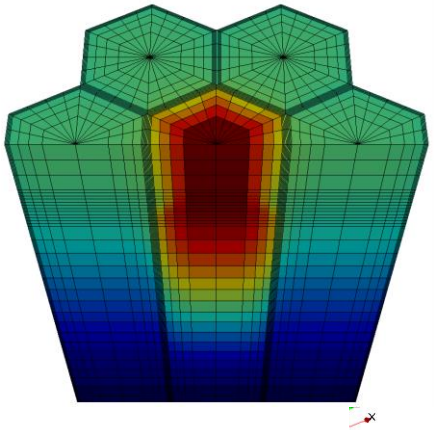


*Multi-physics modelling of the MSRE*

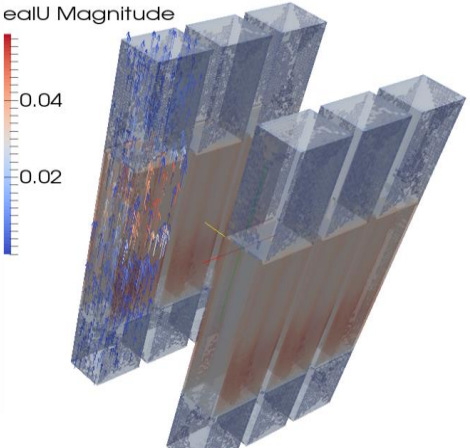
*Core flowering in a SFR*



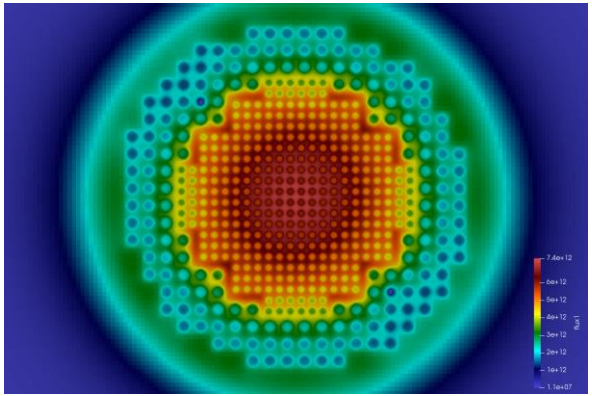

*Assembly windows in a SFR*

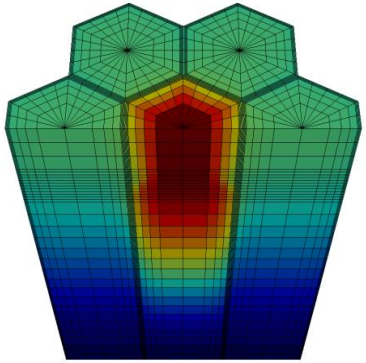


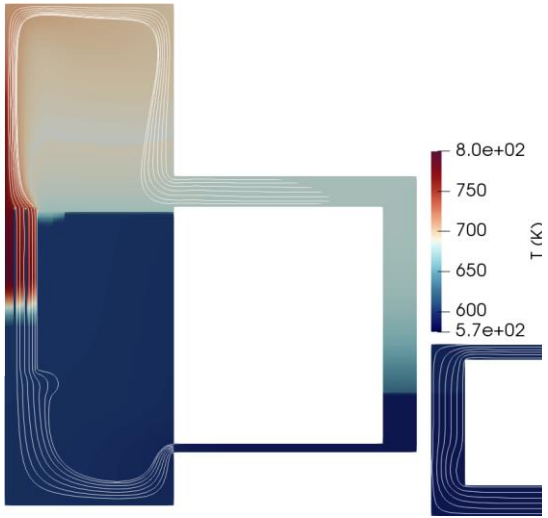
*The Argonaut reactor*



# GeN-Foam: which physics?



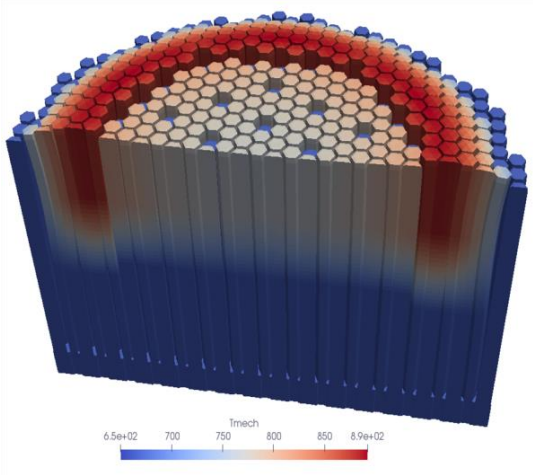





*Neutronics*

- *Diffusion*
- *SP3*
- *SN*
- *Point-kinetics*
- *Serpent*
- *OpenMC?*

*With precursor transport*




*Thermal-hydraulics:*

- *RANS CFD + porous-medium*
- *One and two phase*
- *Two phase models for sodium and water (not fully validated)*

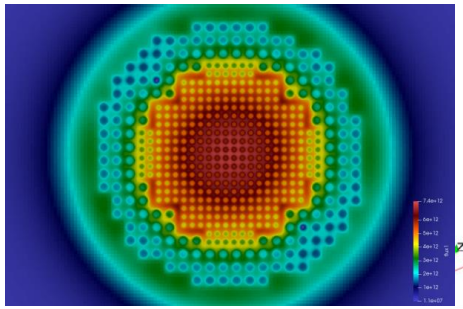
*Thermal-mechanics*

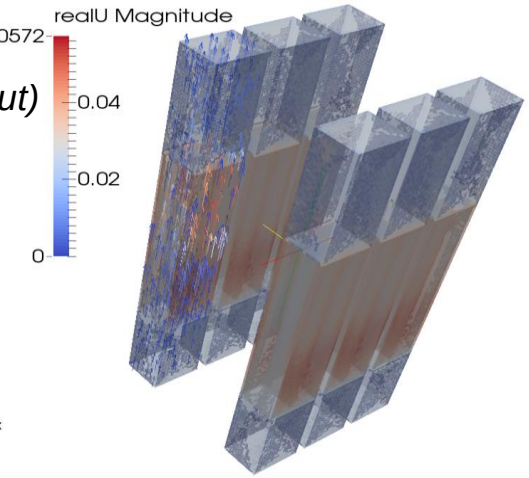
- *Linear elasticity*
- *BC for multi-material and contact*

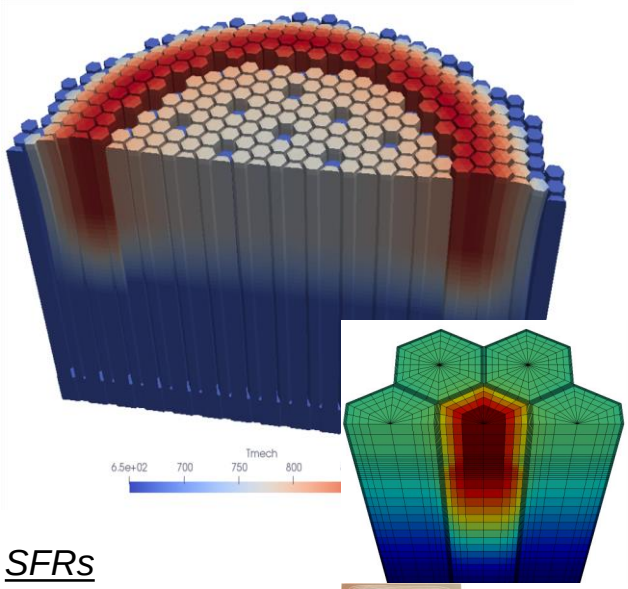
# GeN-Foam: examples of applications

*Experimental reactors (ex, CROCUS, Argounaut)*

- *Geometric flexibility*

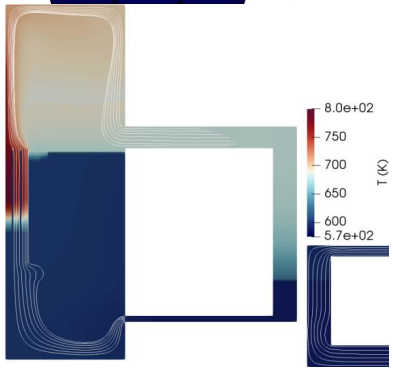


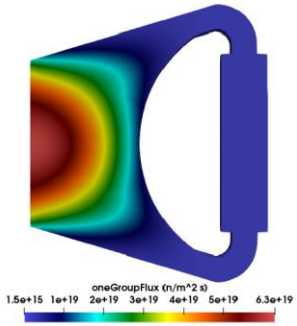


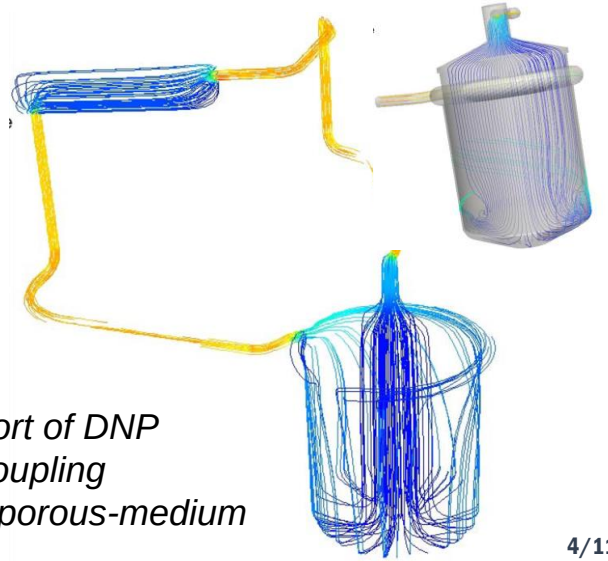




*SFRs*

- *Multi-D boiling*
- *Coupling of pools and core*
- *Direct simulation of deformations*



*MSRs*

- *Transport of DNP*
- *Tight coupling*
- *CFD + porous-medium*

# GeN-Foam: Usability



- Complex solver (multi-physics, general finite-volume methodologies on unstructured meshes, linux)
  - ✓ A background on CFD calculations has been observed to greatly reduce the initial barrier
  - ✓ Familiarity with OpenFOAM is necessary
  - ✓ Is quality assurance enough? Everything CFD like… Are we really going in the right direction?

- Still limited documentation
  - ✓ Users must be familiar with what they are modelling

+ Flexible solver
  - ✓ Unstructured meshes, several existing sub-solvers, possibility of tailoring

› Particularly suitable for PhD students and researchers that wish to experiment on methods, address particularly complex problems, or investigate non-traditional reactors

› An expanded documentation and set of tutorials have recently made it possible to use GeN-Foam in the frame of shorter projects such as Master Thesis, as well as a tool for education and training

# Open-source aspects: choice of the library – stand on the shoulders of giants!

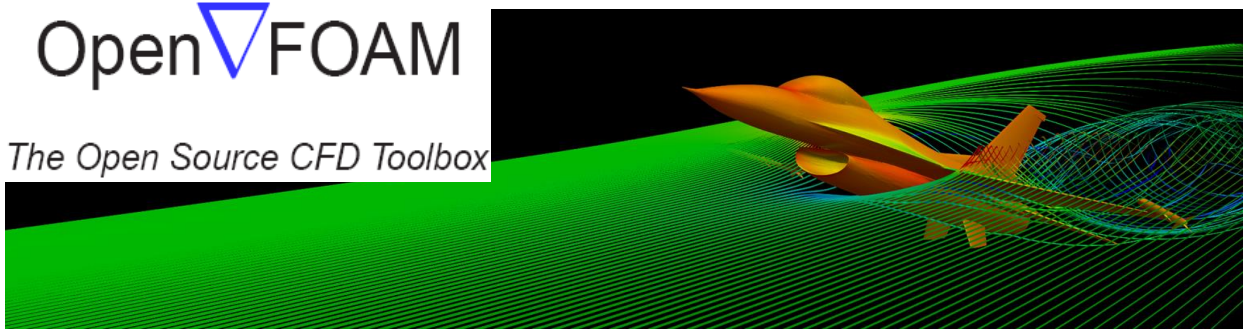


- CFD toolbox
  - Industrial level
- Library (90% of Gen-Foam and OFFBEAT)
  - ✓ C++
  - ✓ Impressively well-written
  - ✓ Object-oriented
  - ✓ Complete (not only discretization and solution)
  - ✓ Quality assured
- Community (20k)
  - ✓ Concurrent developments
  - ✓ Support

```
fvm::ddt(IV,flux_i])- fvm::laplacian(D,flux_i])= S
```

OpenFOAM

*The Open Source CFD Toolbox*



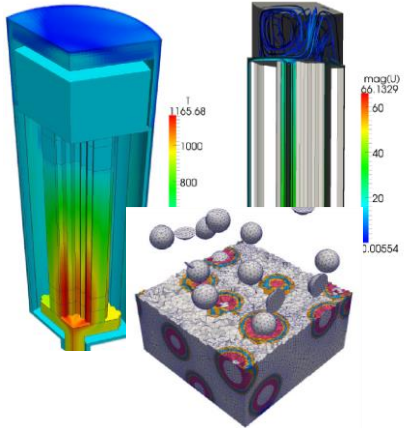
# Open-source aspects: building on available work



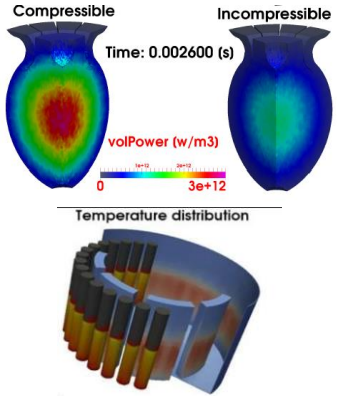
2000-2010
First activities

2010-2015
First widespread use

2015-2022
First coordinated and persistent developments



*PBMRs and HTRs*

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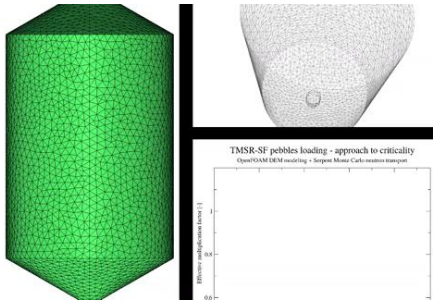
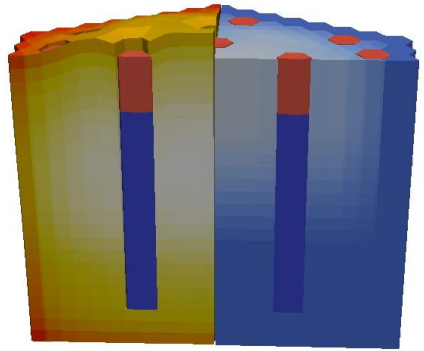
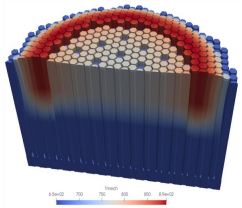


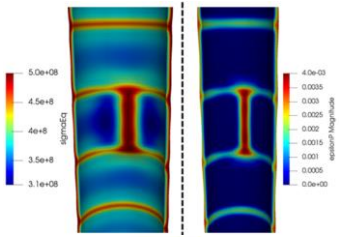

*FHR*



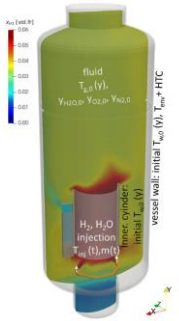
*SFRs*



*GeN-Foam*



*OFFBEAT*




*containmentFoam*

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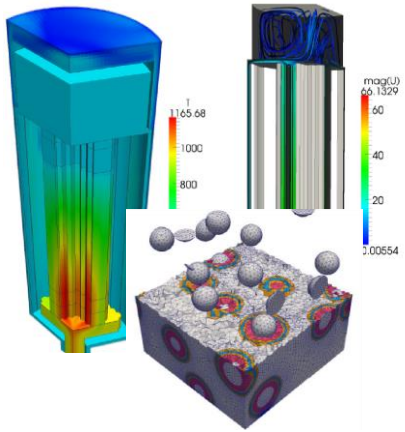
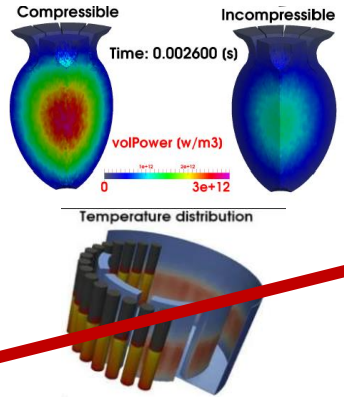



*PBMRs and HTRs*

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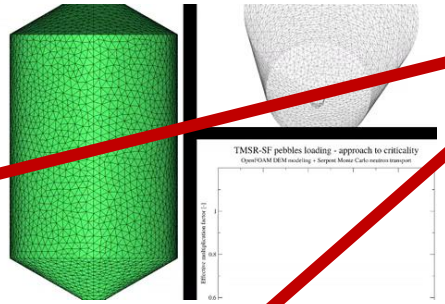


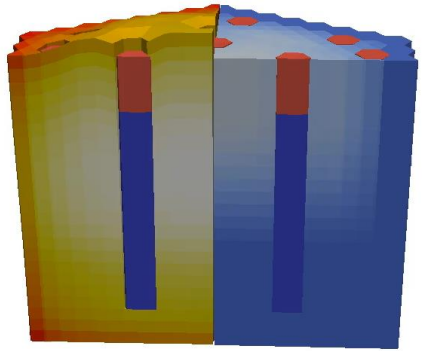

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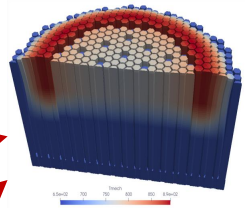
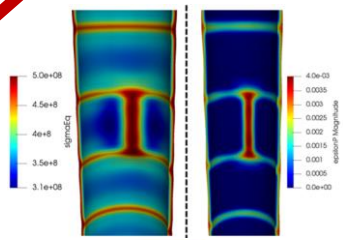
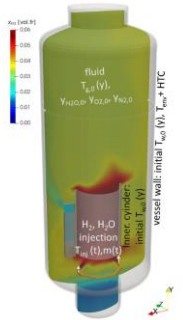


*GeN-Foam*




*OFFBEAT*




*containmentFoam*

# Open-source aspects: building on available work



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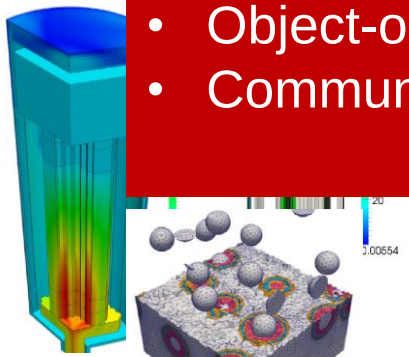
Ingredients:

- C++
- Object-oriented (well written)
- Community





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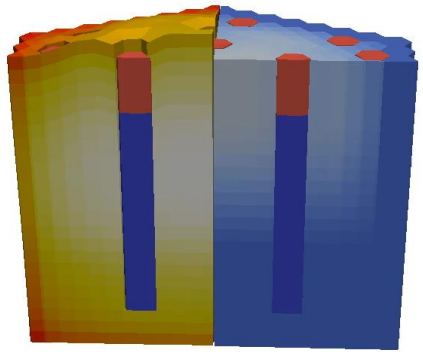
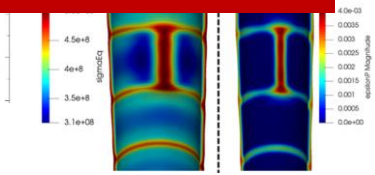


*SFRs*

*GeN-Foam*



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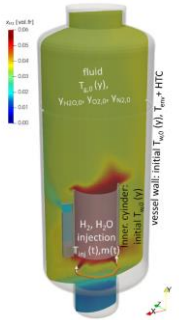


*containmentFoam*

# Open-source aspects: building on available work



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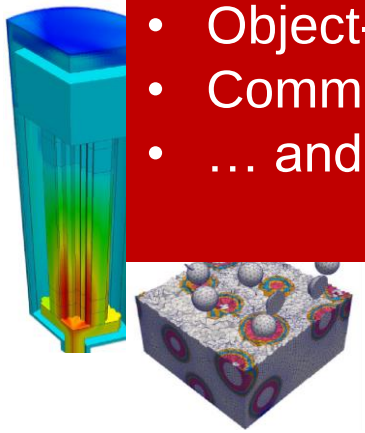
Ingredients:

- C++
- Object-oriented (well written)
- Community
- … and some luck



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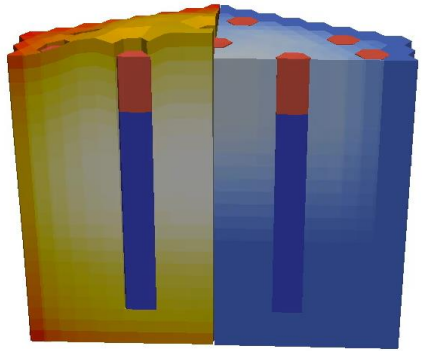

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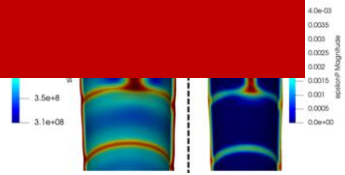

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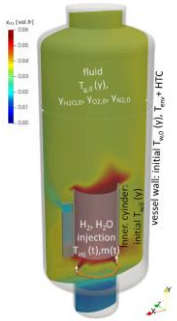


*containmentFoam*

# Open-source aspects: code integration and community contributions



- **Git with continuous integration and automatic testing**
- **Object-oriented programming** :
  - Encapsulated developments
  - Sharing of solvers / algorithms
- In GeN-Foam, **object-oriented logic extended to sub-solvers**
  - 3 main classes for thermal-hydraulics, neutronics, thermal-mechanics
    - ✓ Each class with derived classes for different models (e.g., diffusion, SP3, SN)
      - Run-time selection mechanism
      - Easy to implement new sub-solver starting from a copy-paste
    - ✓ Each class complemented by behavioral models. Each model is a class
      - Easy to implement new model starting from a copy-paste

# Open-source aspects: Quality Assurance



- **OpenFOAM is a quality-controlled** (ISO 9001) library
- **Git with continuous integration and automatic testing and automatic generation of (part of) the documentation**
  - ✓ Traceability
  - ✓ Reproducibility
  - ✓ Consistency over time
- Object oriented  high-level API -> reduced risks but behavioral models requires validation…
- Continuous poking from the community
- But again… difficult to guarantee the code is “well” used

# Open-source challenges: Documentation and resources



- Free downloaded from GitLab - https://gitlab.com/foam-for-nuclear/GeN-Foam/-/tree/master
- Online **Doxygen-generated documentation** with the addition of: Introduction to GeN-Foam; GeN-Foam Theory; Source code; Compiling GeN-Foam; Preprocessing; Running GeN-Foam; Postprocessing; Tutorials; Tips and tricks; and Important notes.
- Several **commented tutorials**. Entries to the various dictionaries are extensively commented in at least one tutorial ( indicated in the “Preprocessing” page of the online documentation).

- In addition
  - ✓ **High-level C++-**based object-oriented language of OpenFOAM
  - ✓ **Comments**, in particular in the header files
  - ✓ **Php Serpent-like forum** - https://foam-for-nuclear.org/phpBB/

- **Step-by-step guide and/or user manual seems still necessary, but…**


Thank you for your attention !

# GeN-Foam: V&V status



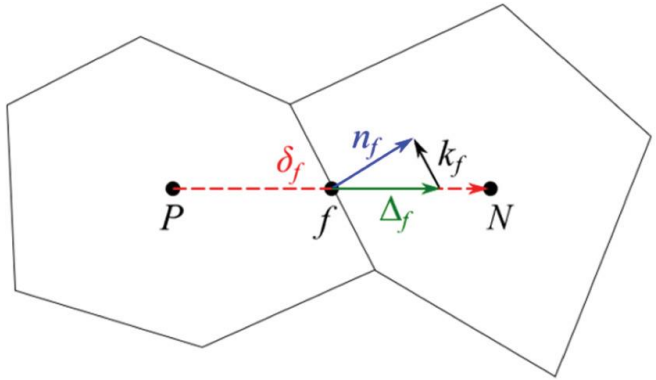
| Brief description | Neutronics | Thermal-hydraulics | Thermal-mechanics | Coupling |
|---|---|---|---|---|
| Comparison against PARCS for a PWR a mini-core [15] | x (SP3) | | | |
| Comparison against Serpent for the CROCUS reactor [15] | x (SP3) | | | |
| Comparison against Serpent for the ESFR [17] | x (Diffusion) | | | |
| Comparison against Serpent for a PWR mini-core [17] | x (Diffusion) | | | |
| Comparison against various codes for the ESFR-SMART design [21] | x (Diffusion) | | | |
| Verification against analytic solutions for a simplified MSR [22] | x (Diffusion) | x (1 phase) | | x |
| Verification against the CNRS MSR benchmark [23] | x (Diffusion) | x (1 phase) | | x |
| Comparison against TRACE for the ESFR core [3,18] | x (Diffusion) | x (1 phase) | x | x |
| Verification using the method of manufactured solutions [6] | | x (1-2 phases) | | |
| Validation against the Godiva IV experiment [16] | x (SN) | | | |
| Validation against the FFTF LOFWOS Test 13 [4] | x (pk) | x (1 phase) | | |
| Validation against the KNS-3-L22 experiment on sodium boiling [4] | | x (1-2 phases) | | |
| Validation against the ISPRA experiment on sodium boiling [4] | | x (1-2 phases) | | |
| Validation against the NEA PSBT benchmark on water boiling | | x (1-2 phases) | | |
| Validation against CROCUS measurements [19] | x (Diff, SP3, SN) | | | |

# Finite volumes



Conservation of quantities in each cell, with some wise interpolation at faces and techniques to deal with non-orthogonality and skewness

- Pros:
  - ✓ Flexible
  - ✓ Scalable
  - ✓ Conservative
  - ✓ CFD-friendly
  - ✓ Intuitive
- Cons:
  - ✓ Still require familiarity with concepts associated with PDEs (well-posed problems, initial and boundary conditions), geometry creation, meshing, discretization, linear solution, etc.
  - ✓ Require good quality meshes
  - ✓ Max second order in space



# GeN-Foam: which reactors?



- **LWRs**
  - ✓ TRACE boiling models implemented and tested
  - ✓ Under validation (PSBT)
- **HTRs and FHRs**
  - ✓ Only needs sub-scale model for temperature in pebbles
- **Micro reactors**
  - ✓ Mainly needs modelling skills
- **Heat pipes**
  - ✓ Under development
- …