Milano Multiphysics

Smart solutions for complex problems

Developing modeling tools to improve new MSR designs

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Politecnico di Milano
Young MSR conference
June 6 2022

MMP is incubated at:

POLIHUB
INNOVATION DISTRICT & STARTUP ACCELERATOR
BY FONDAZIONE POLITECNICO DI MILANO

Milano Multiphysics

MMP is a startup founded in 2015.

From 2018 we are incubated at Startup Accelerator of POLIMI.

Ongoing research collaborations with the Energy Department.

Two main fields of activities:

- Development of multiphysics modeling tools, and performing design optimization for MSRs
- Probabilistic modeling for the energy sector
    - Also offering SaaS renewable generation and load forecasting services w/ spin-off company HelioSwitch.cloud

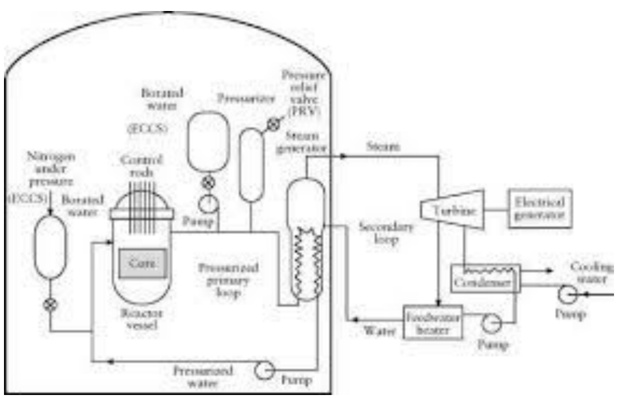
Overall 6 FT young engineer employees plus "youthful" founding partners

Developing innovative nuclear reactors...

In the past (50s-mid 80s)

Concept

Reactors as a mean to guarantee security of energy supply

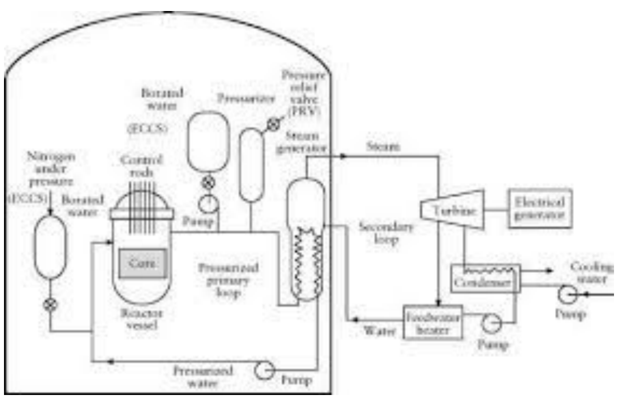


Developing innovative nuclear reactors…

In the past (50s-mid 80s)

Concept → **Design and deployment**

Reactors as a mean to guarantee security of energy supply

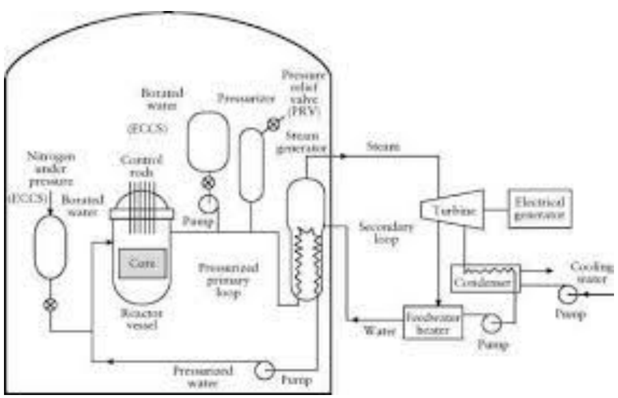


Design by experiment

Developing innovative nuclear reactors...

In the past (50s-mid 80s)

Concept	Design and deployment	Operating reactors
Reactors as a mean to guarantee security of energy supply	Design by experiment	Light Water Reactors



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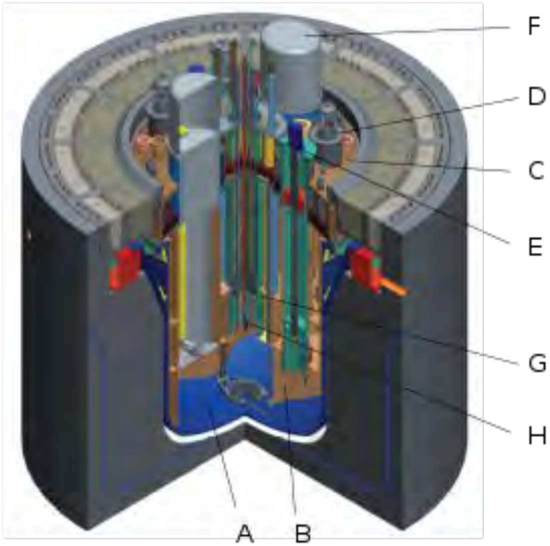
Developing innovative nuclear reactors...

Nowadays

Concept

Gen IV reactors:
Long-term sustainability
Nuclear waste burning
Improved fuel efficiency
Higher safety and reliability



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Developing innovative nuclear reactors...

Nowadays

Concept → Design and deployment

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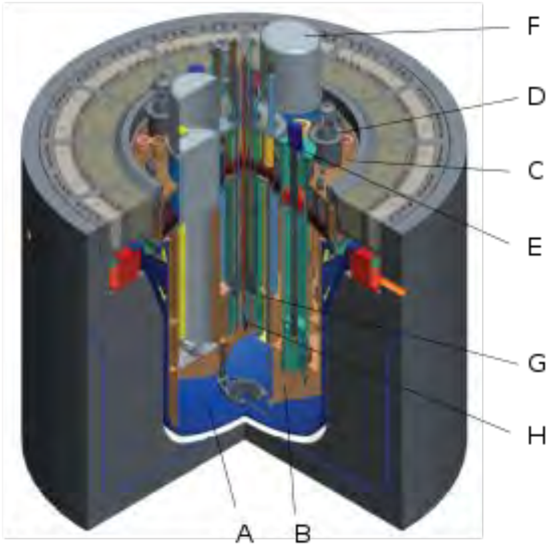

Numerical codes from the 80s based on experiments from the 60s and 70s

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Developing innovative nuclear reactors...

Nowadays

Concept | Design and deployment | Operating reactors

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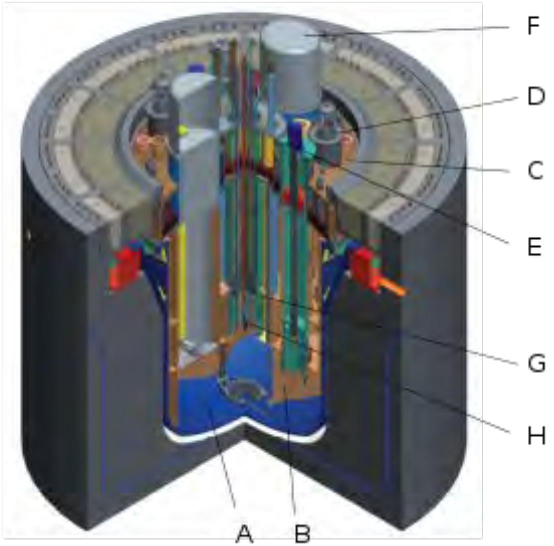

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Light Water Reactors

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Developing innovative nuclear reactors...

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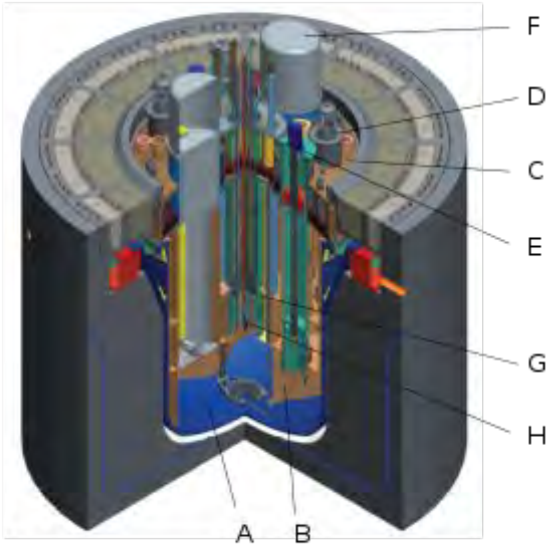

Numerical codes from the 80s based on experiments from the 60s and 70s

Light Water Reactors

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Developing innovative nuclear reactors...

Disruptive ideas stuck in a stale industry

Concept → Design and deployment → Operating reactors

Gen IV reactors:
Long-term sustainability
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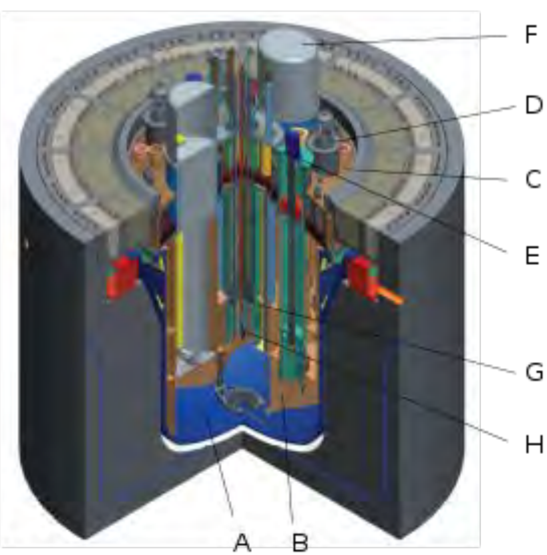

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Light Water Reactors

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Faster and reliable reactor development?

From design by experiments…

…to design by simulation!

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HPC-driven faster reactor development?

From **design by experiments** to **design by simulations** iterations.

We want faster and more reliable (and cheaper!) design iterations:

- Can we replace some of the expensive experiments in the early design phase with numerical simulations?
- Recent innovation in numerical methods and multiphysics modelling
- High performance and cloud computing are affordable for full-scale applications

Experiments will always be essentials for measuring fundamental material properties and validate modelling tools and final reactor designs.

HPC-driven faster reactor development?

A few examples to suggest an answer:

- Study of compressibility effects in fast-spectrum MSRs
- Pebble-by-pebble DEM and neutronics modeling of the TMSR-SF
- Draining and radiative heat transfer in the ThorCon drain tank

My first multiphysics model for MSRs (~2013)

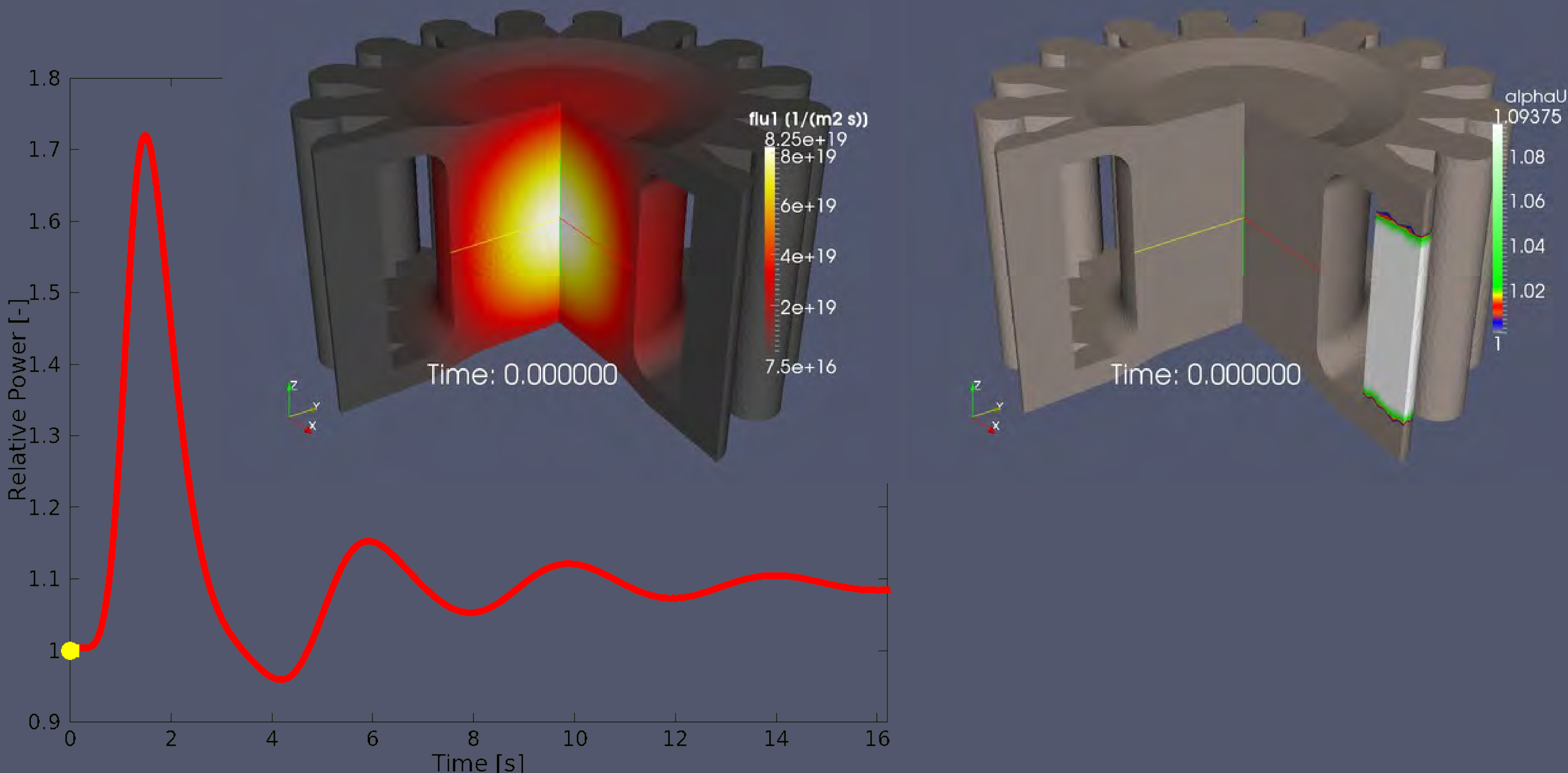
The developed model features the coupling among neutron diffusion, RANS equations for mass and momentum conservation, energy and delayed neutron precursor balances.

A simulation of a sudden insertion of fuel salt is shown in the next slides, reporting the power evolution and the uranium transport throughout the core.

M. Aufiero et al. "Development of an OpenFOAM model for the Molten Salt Fast Reactor transient analysis." Chemical Engineering Science 111

Accidental Uranium release

Accidental release of $\sim$ 15 kg of ^{233}U in one of the external loops



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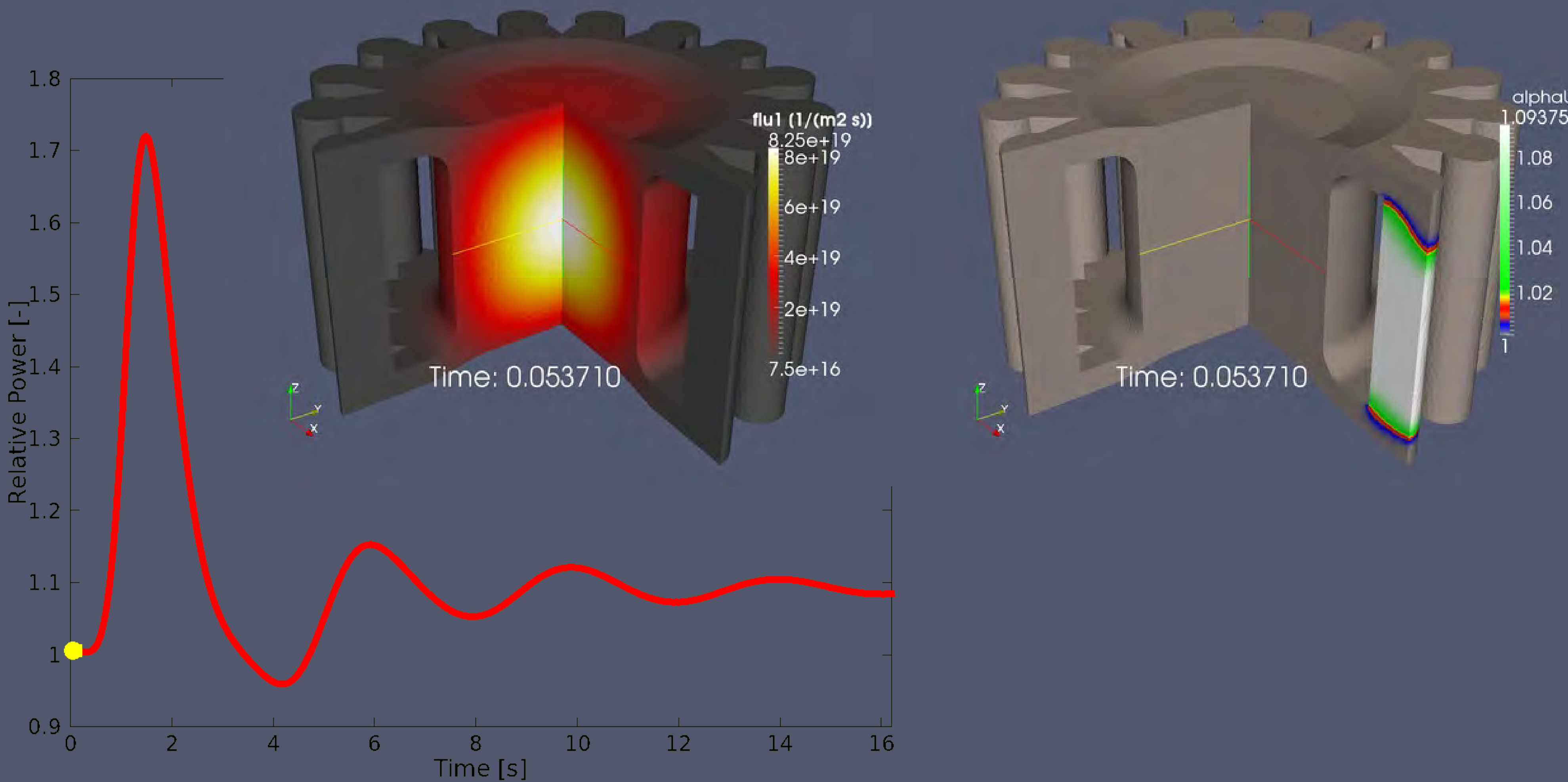

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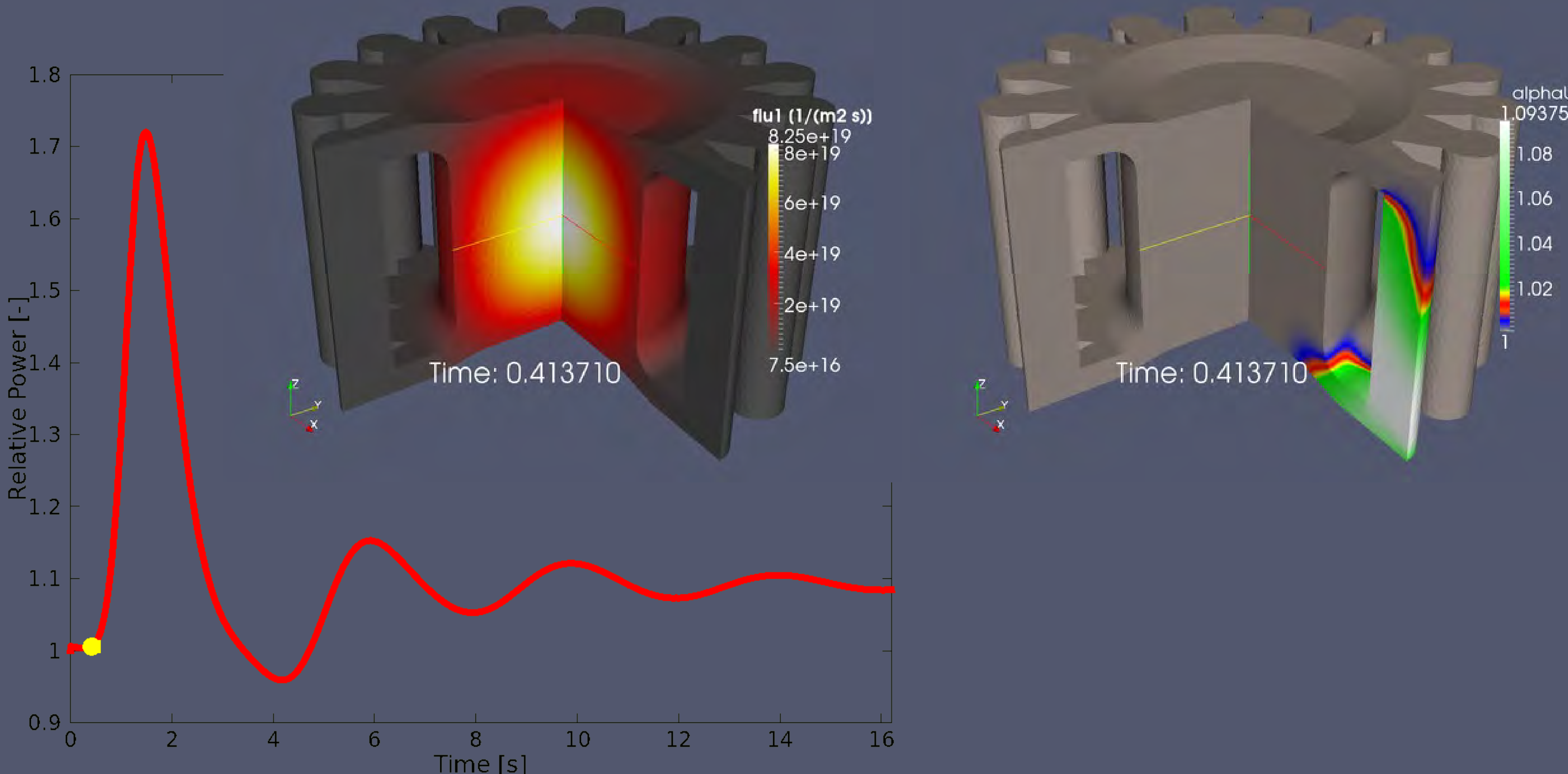

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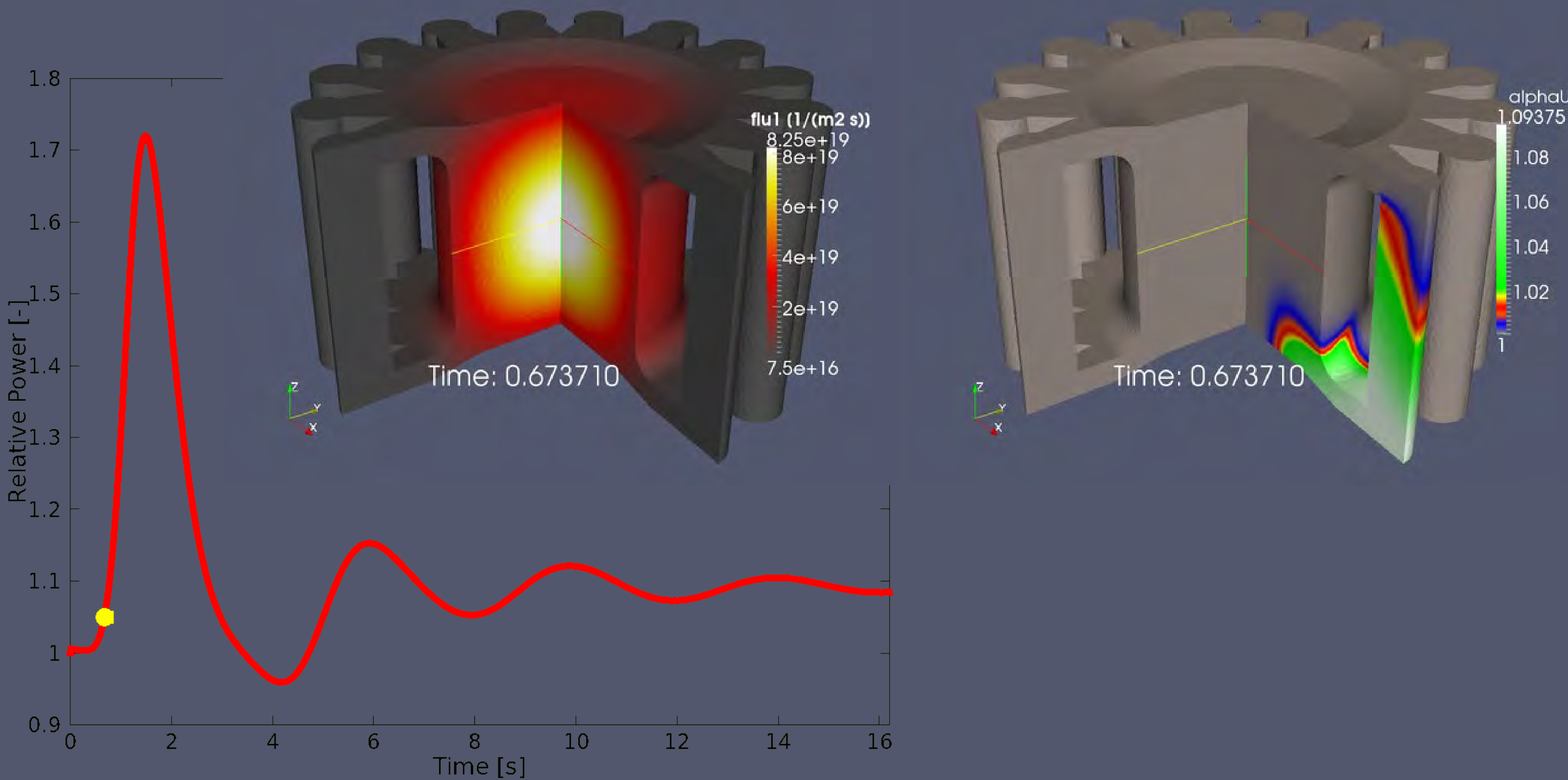

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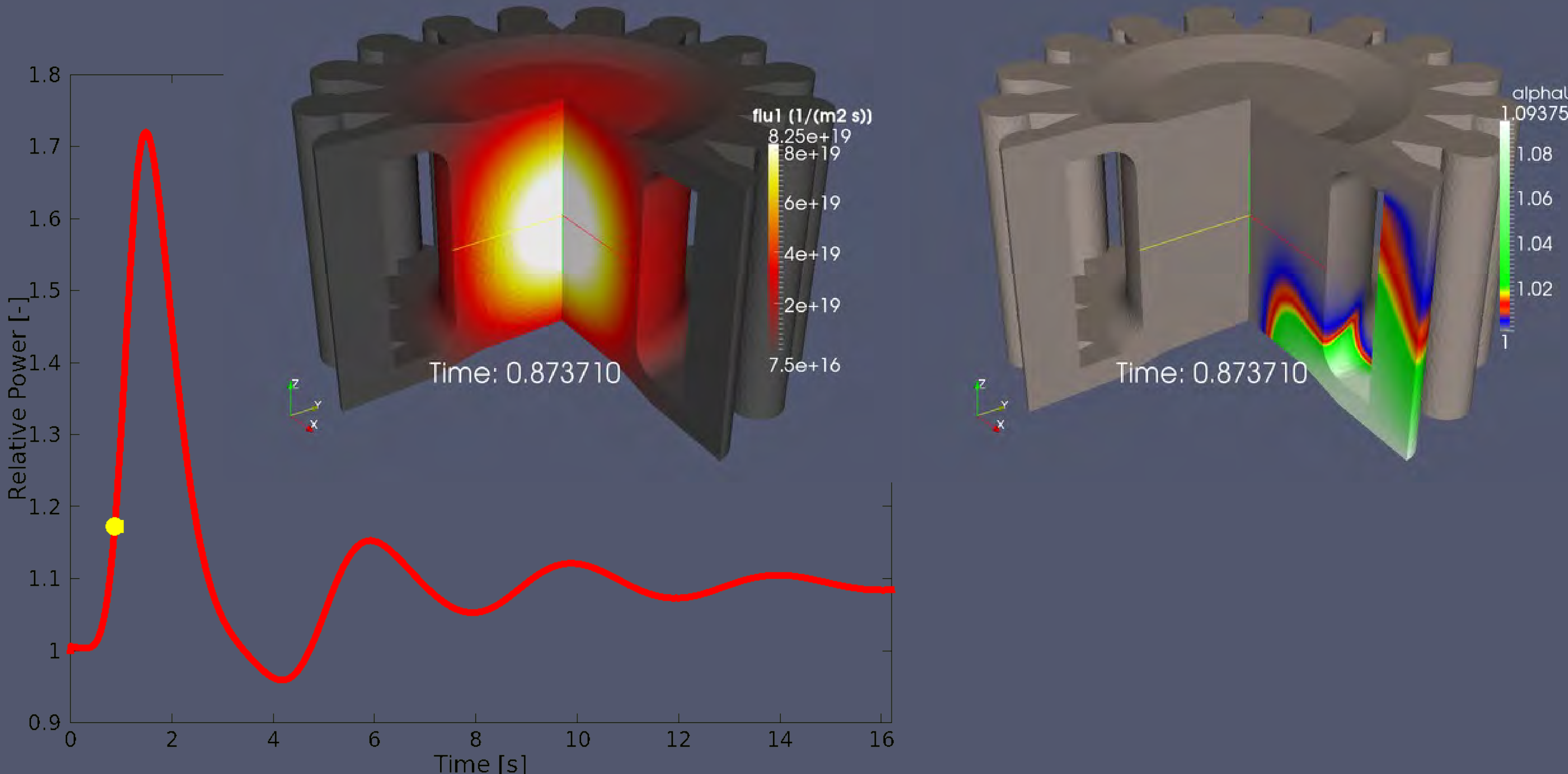

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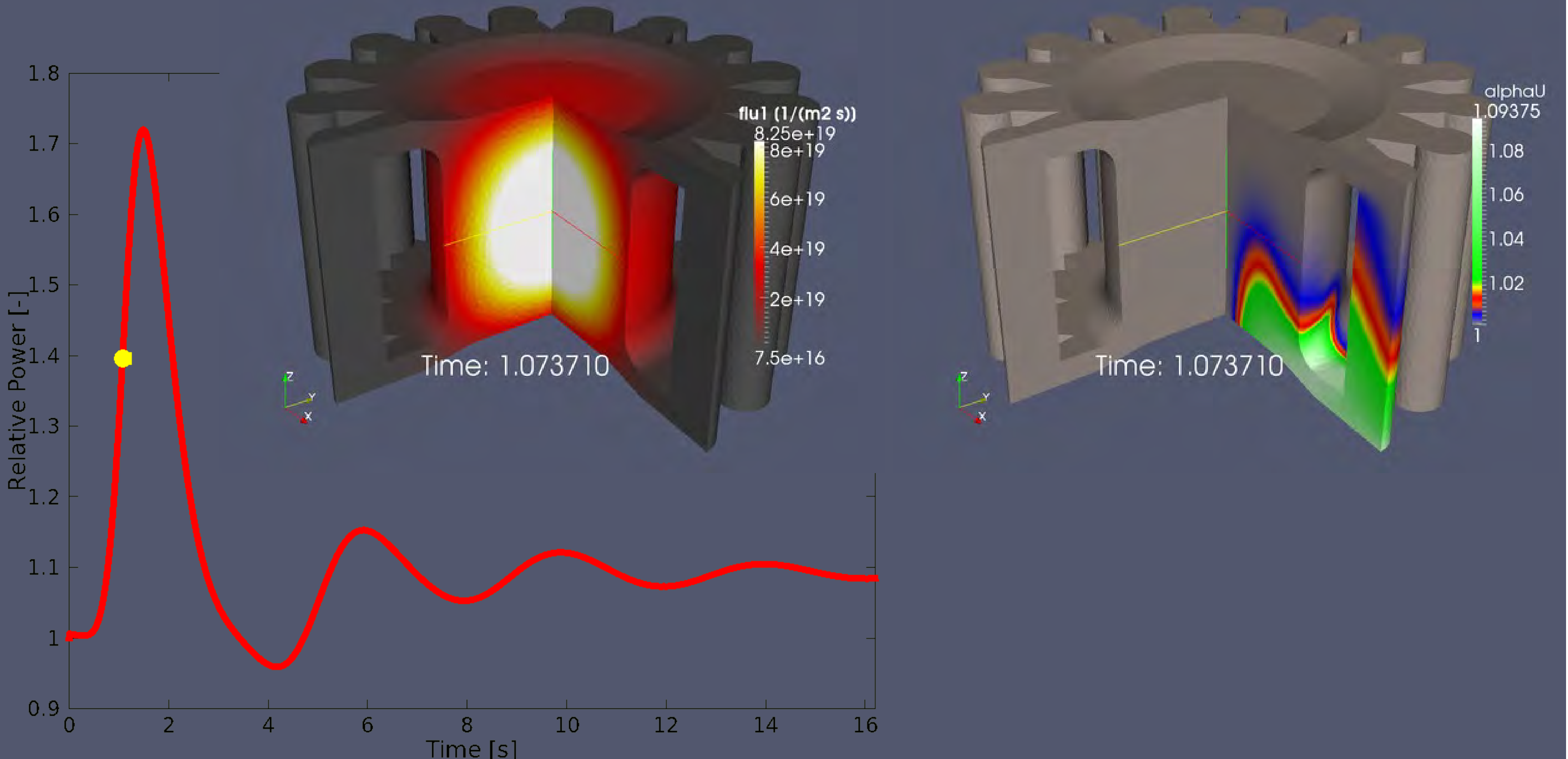

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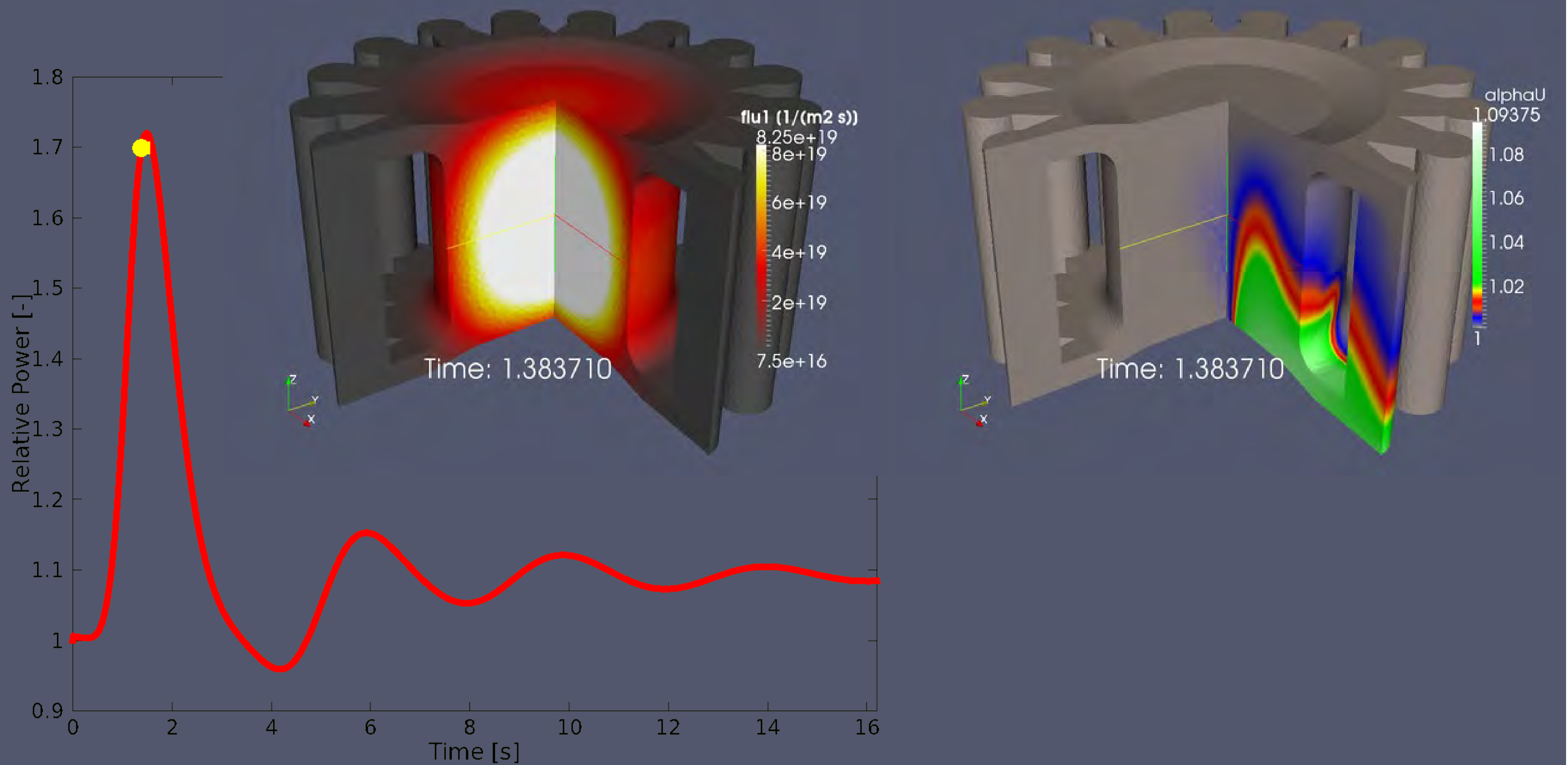

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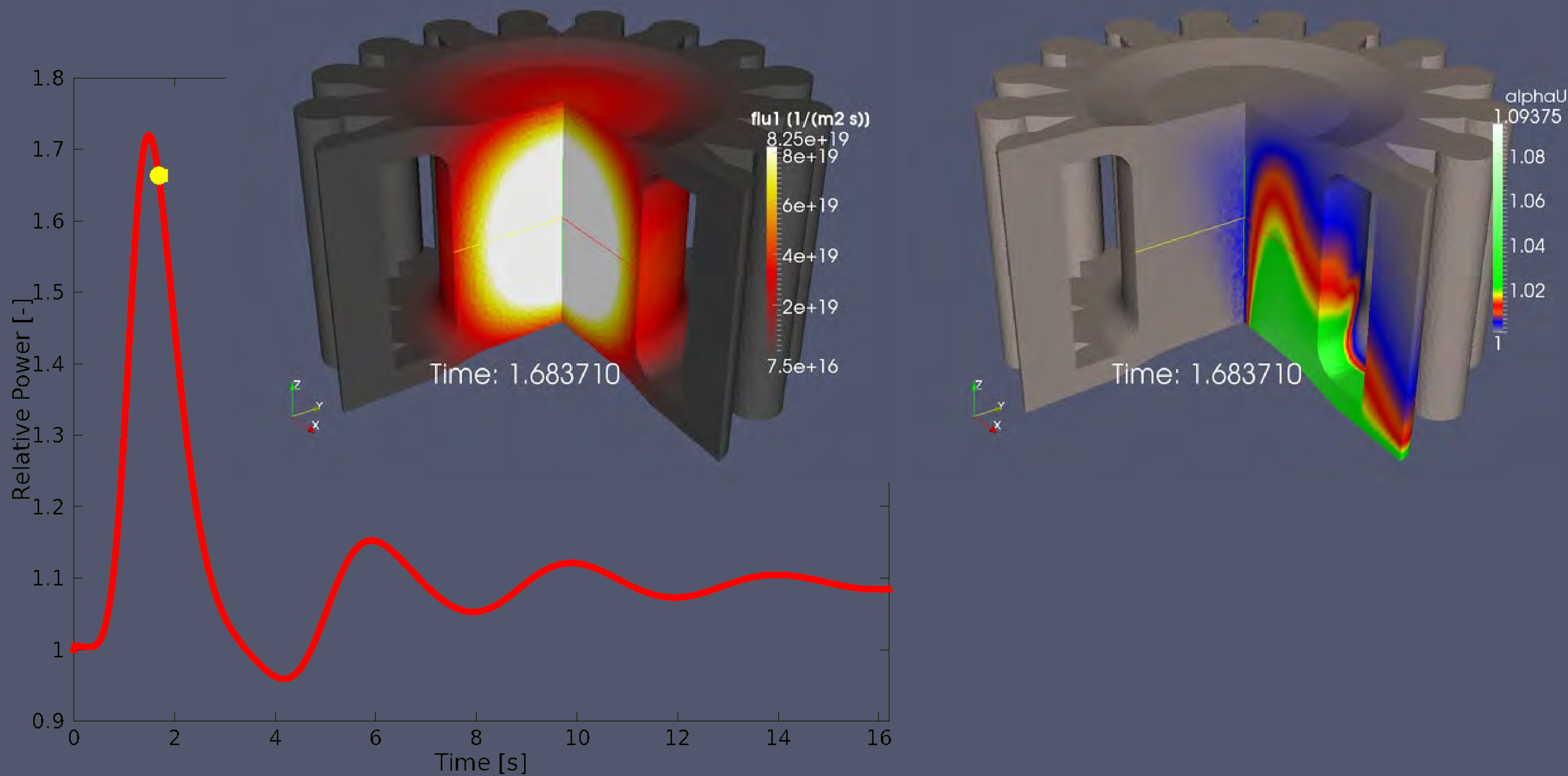

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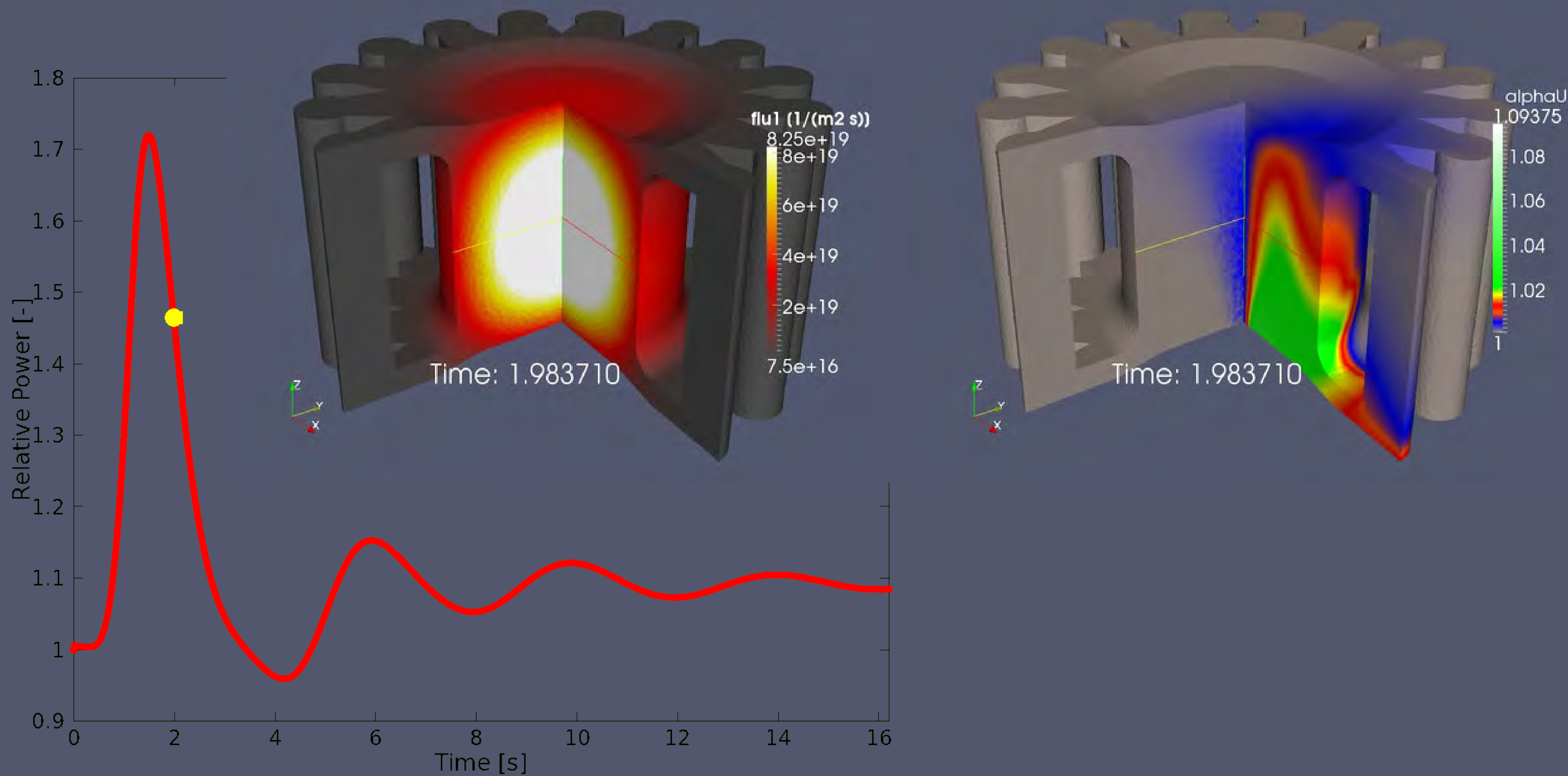

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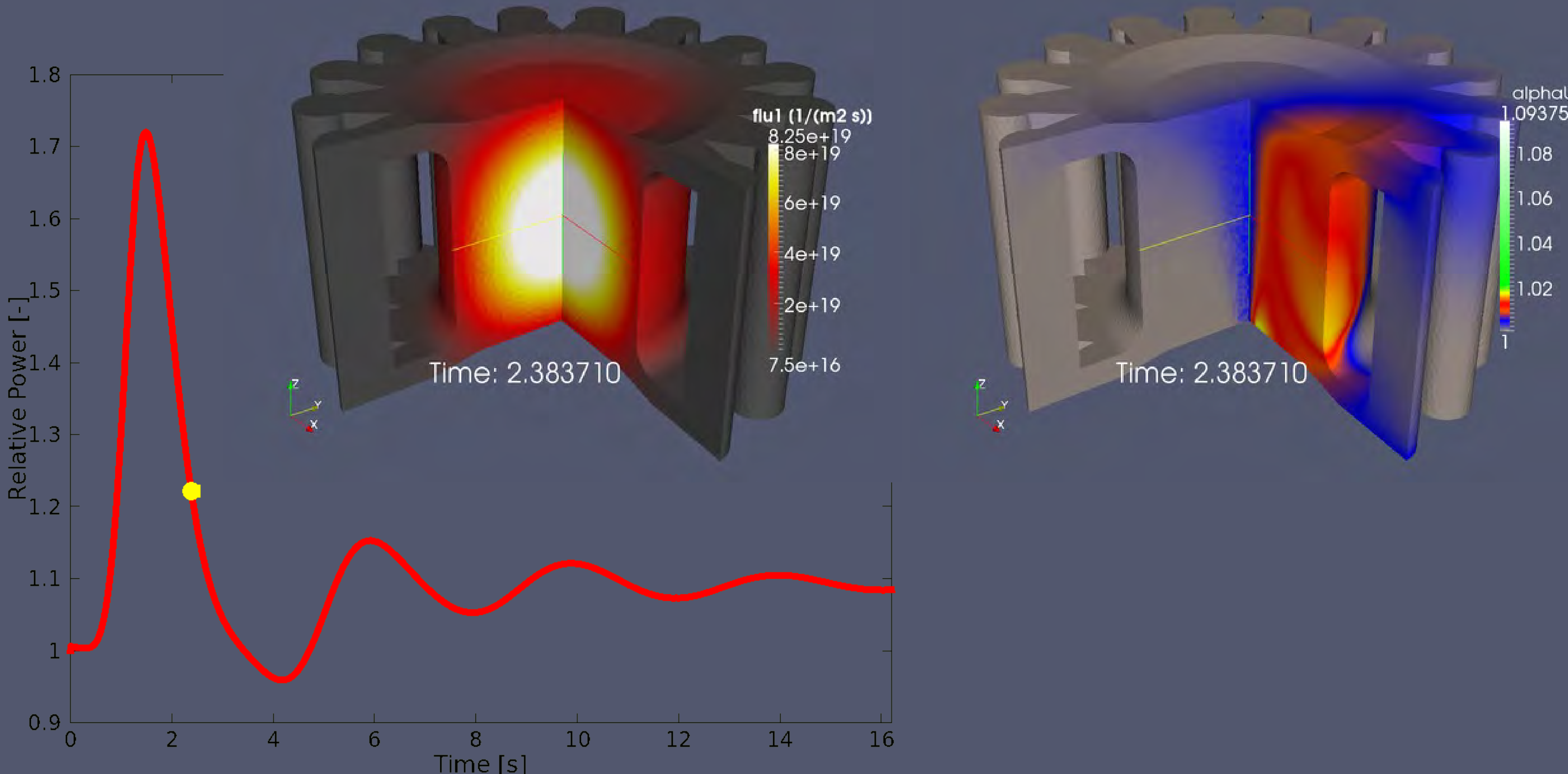

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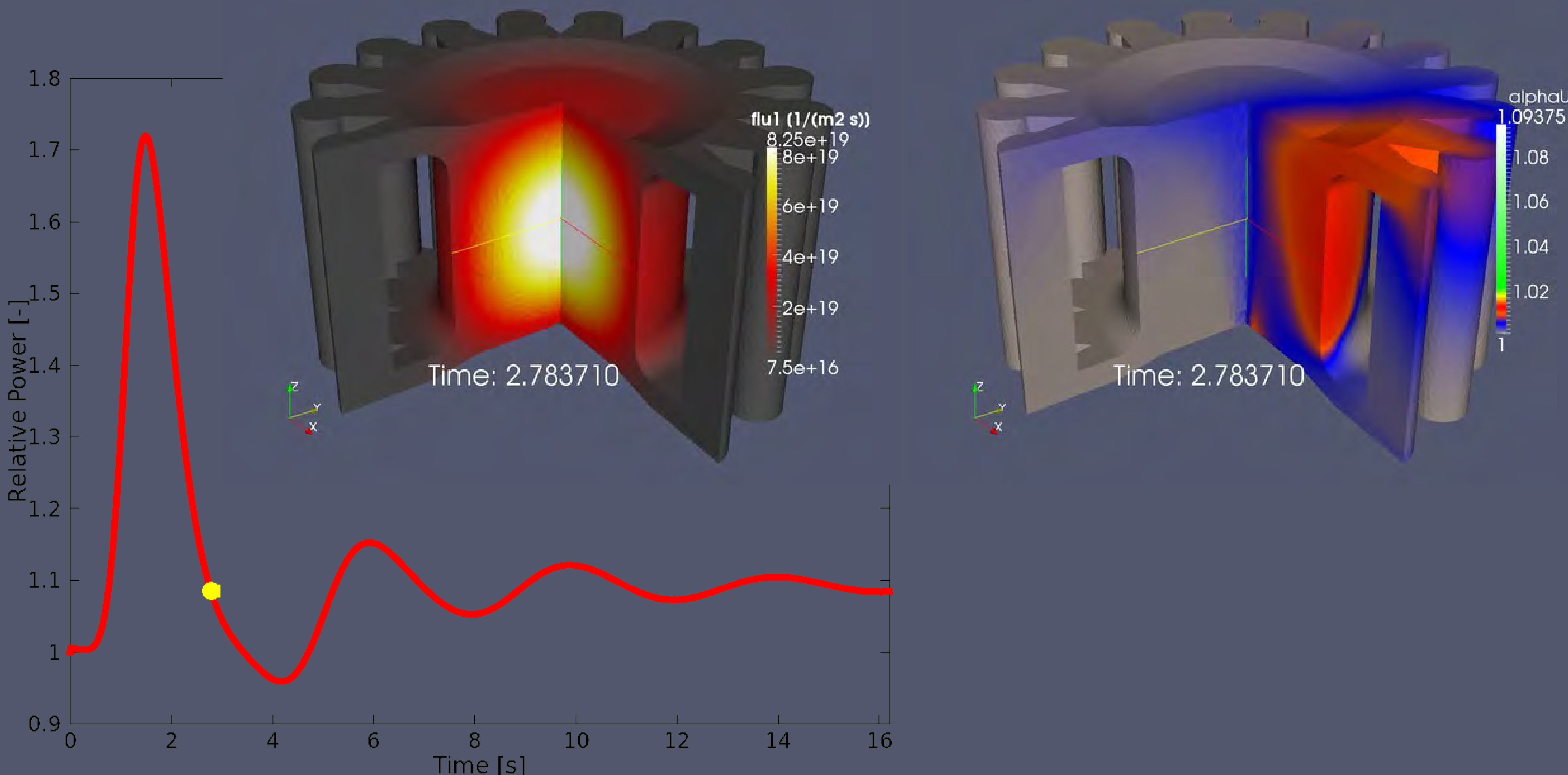

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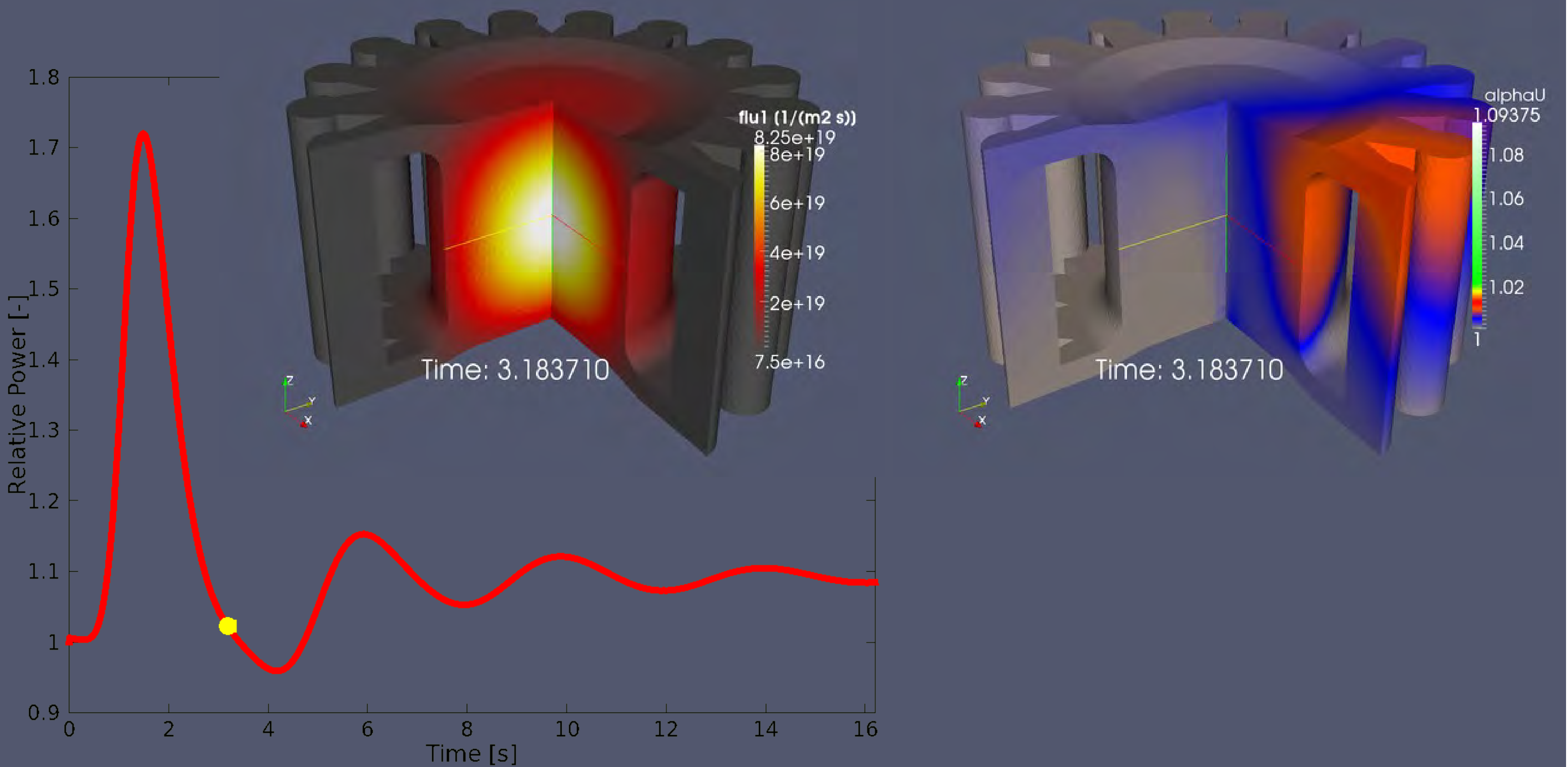

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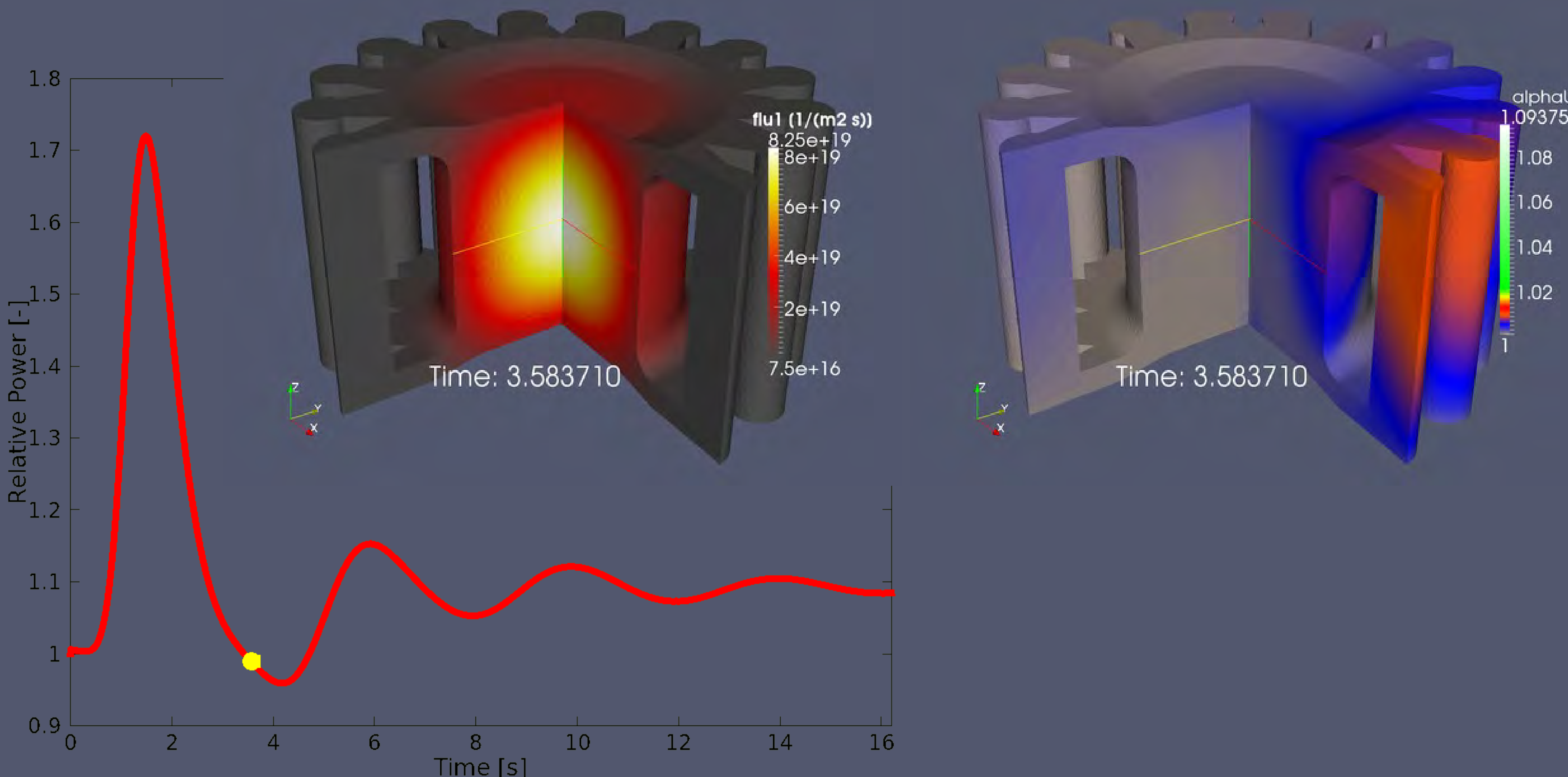

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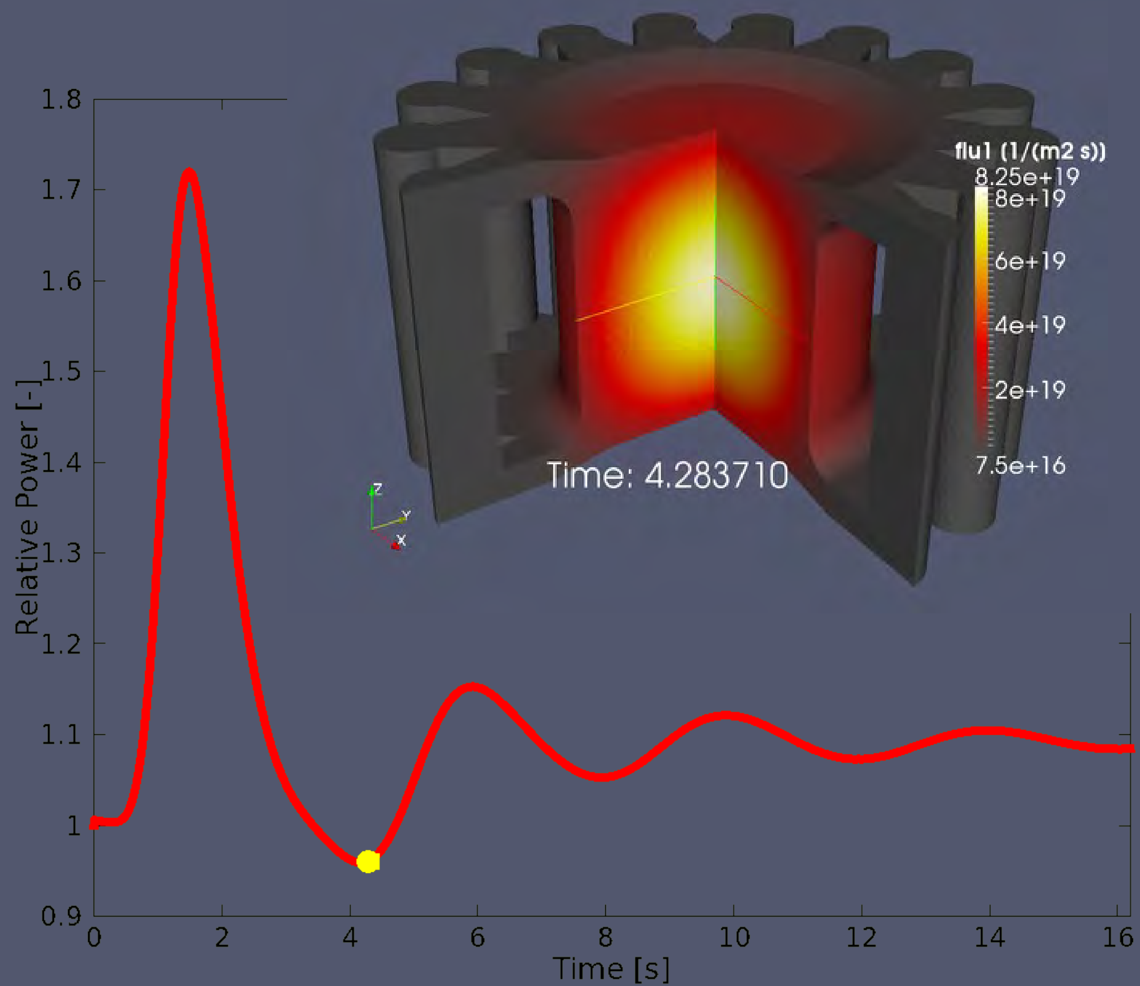

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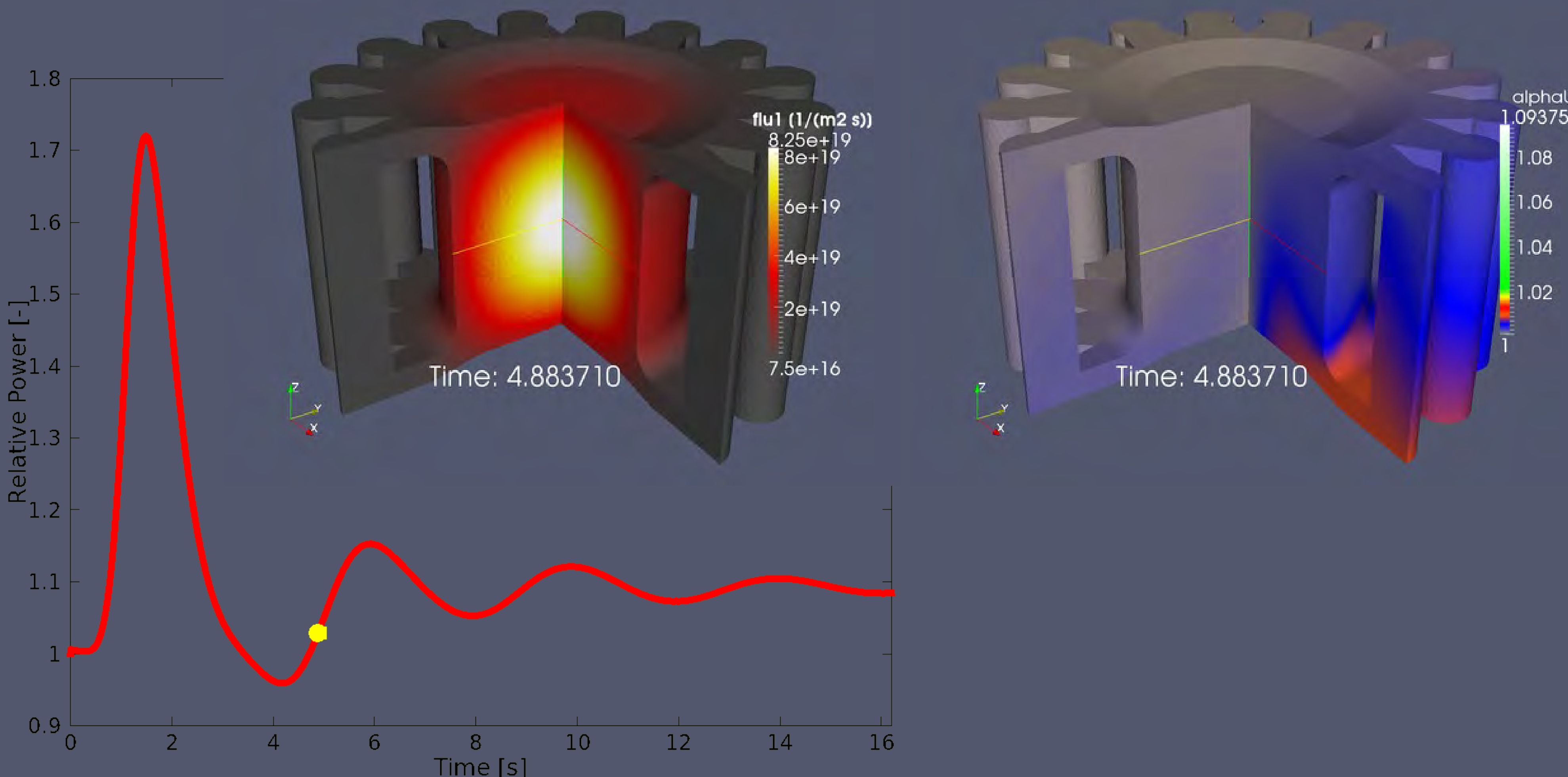

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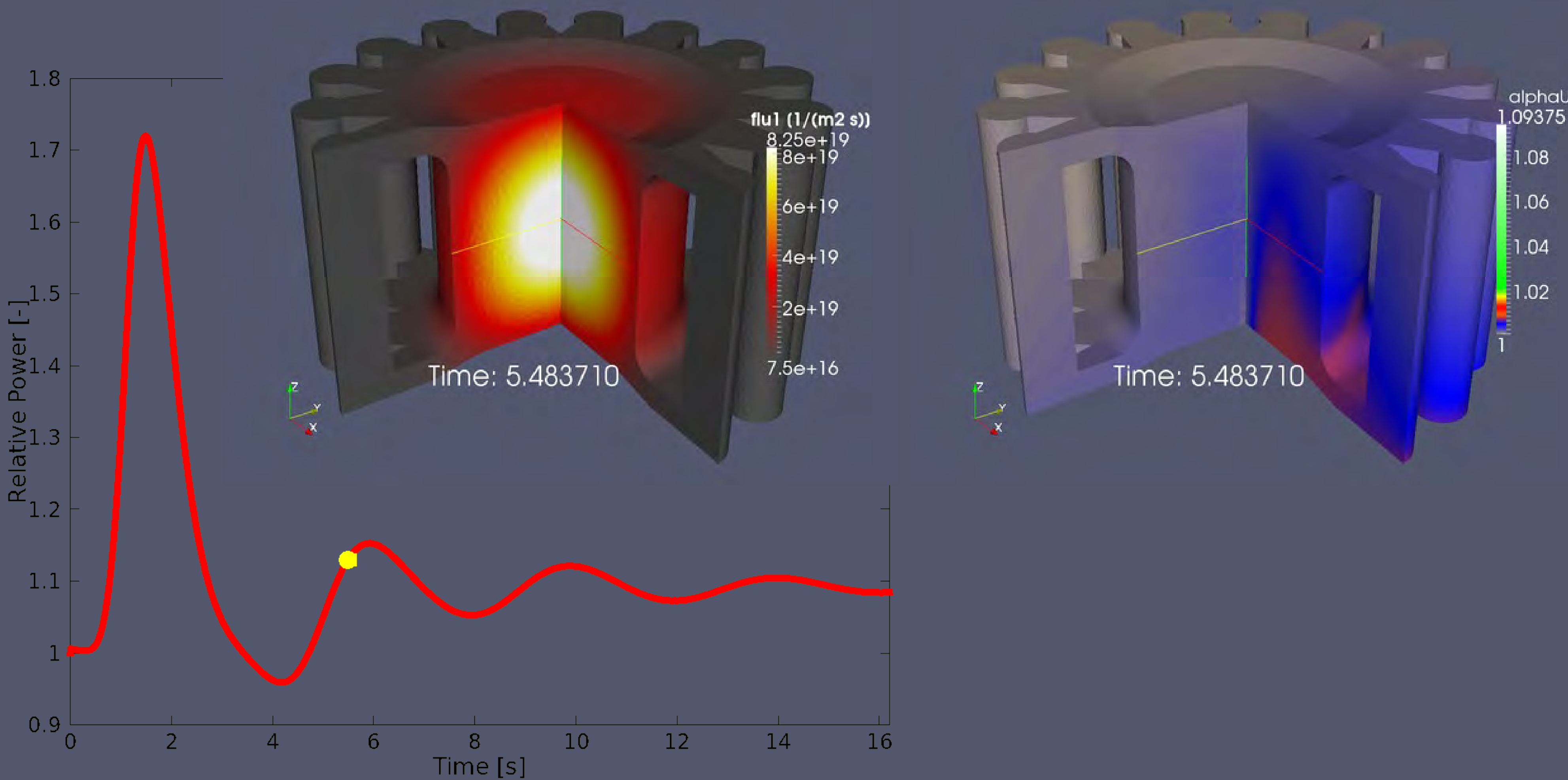

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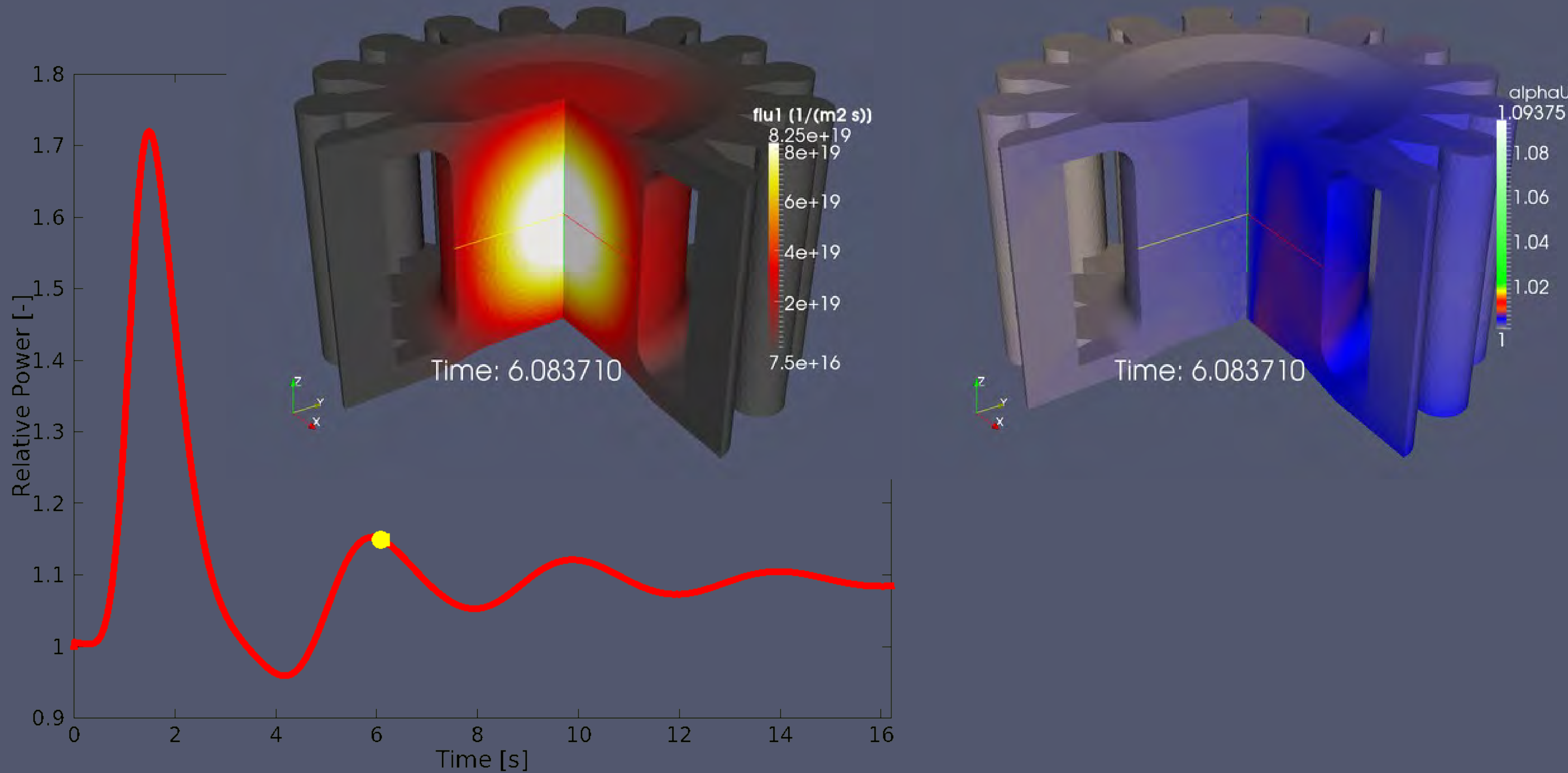

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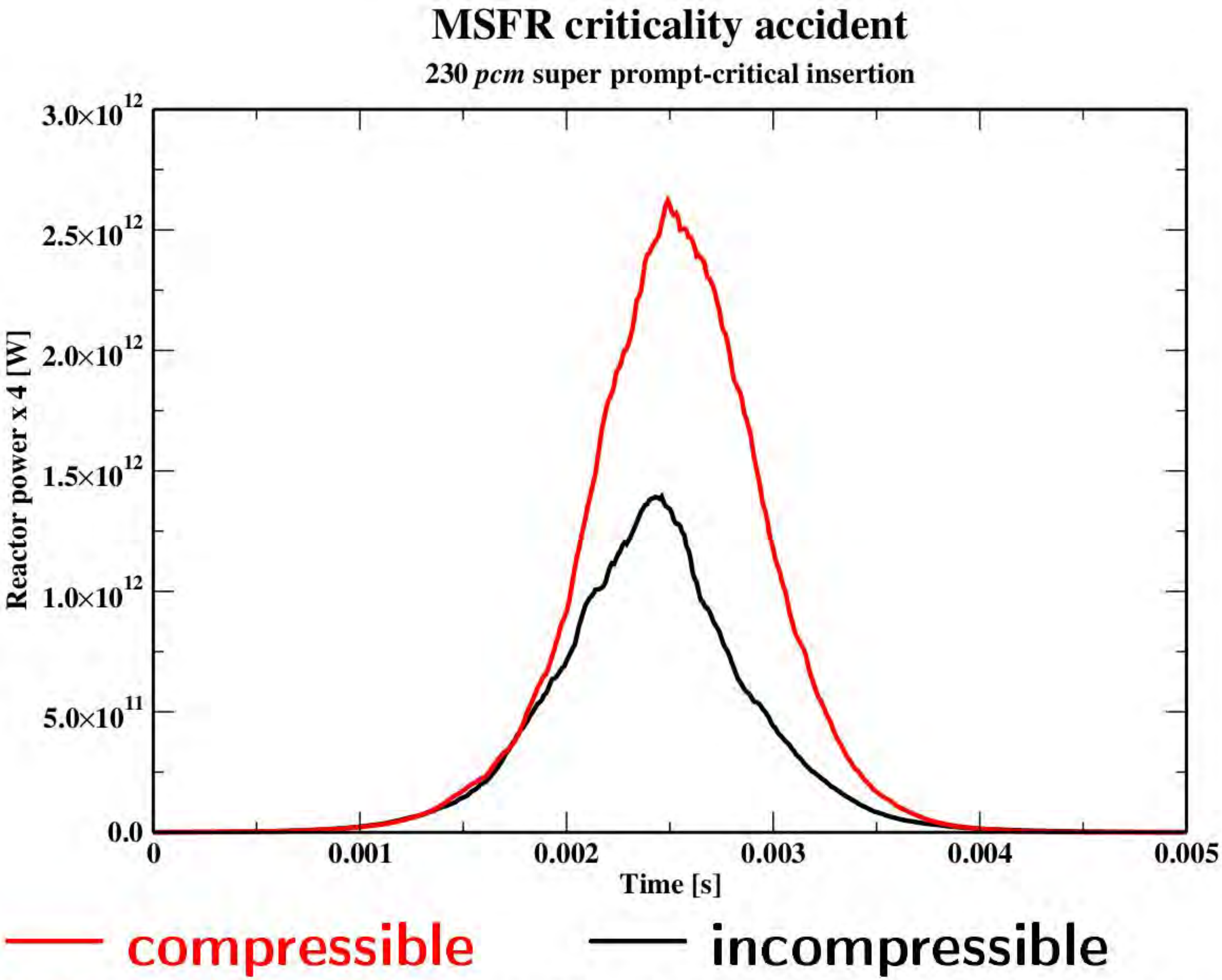
MSFR criticality accident



M. Aufiero, P. Rubiolo, M. Fratoni, "Monte Carlo/CFD Coupling for the modeling of delayed neutron precursors and compressibility effects in MSRs", ANS 2017.

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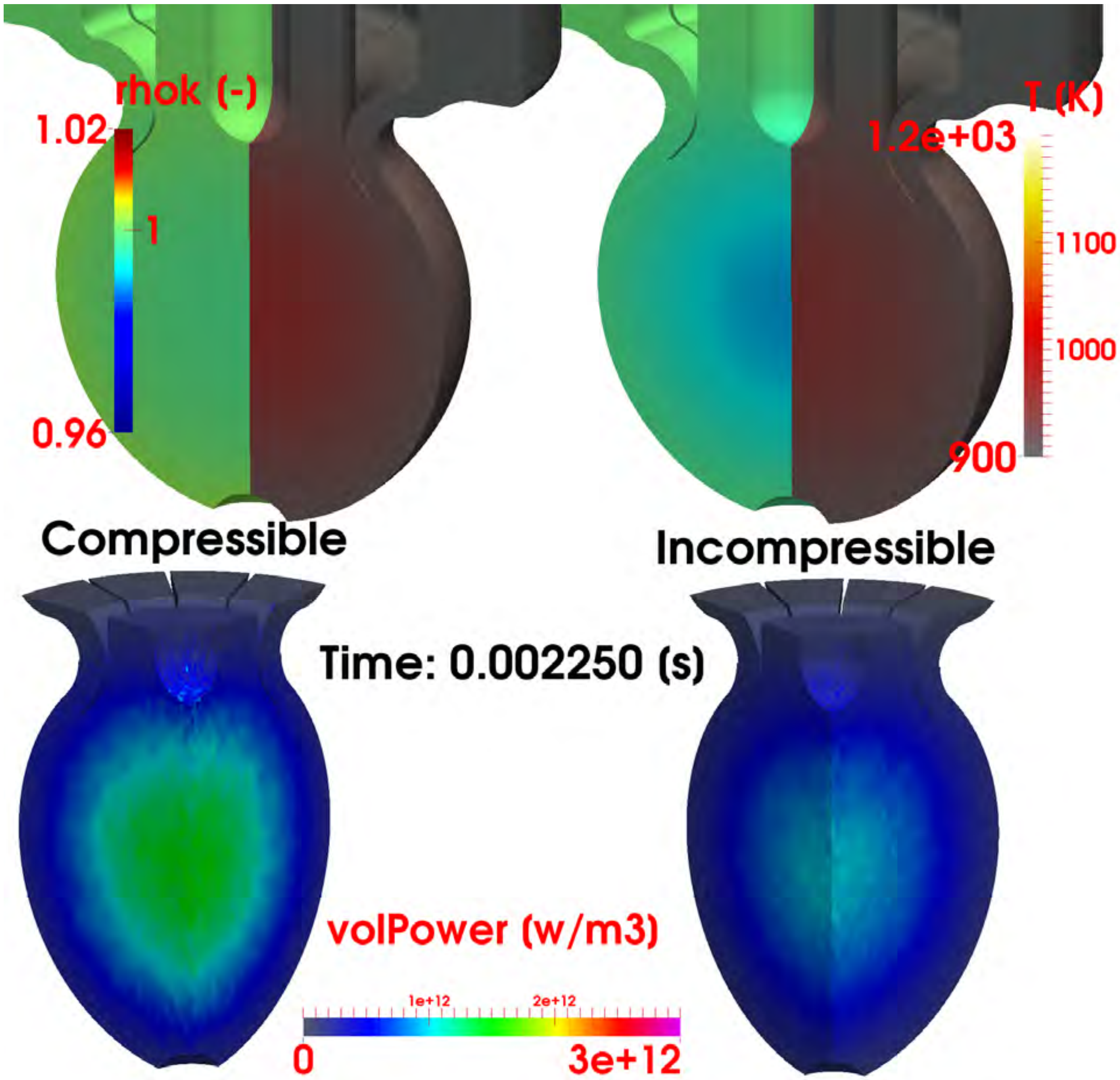
MSFR super prompt-critical burst
Effect of fluid compressibility



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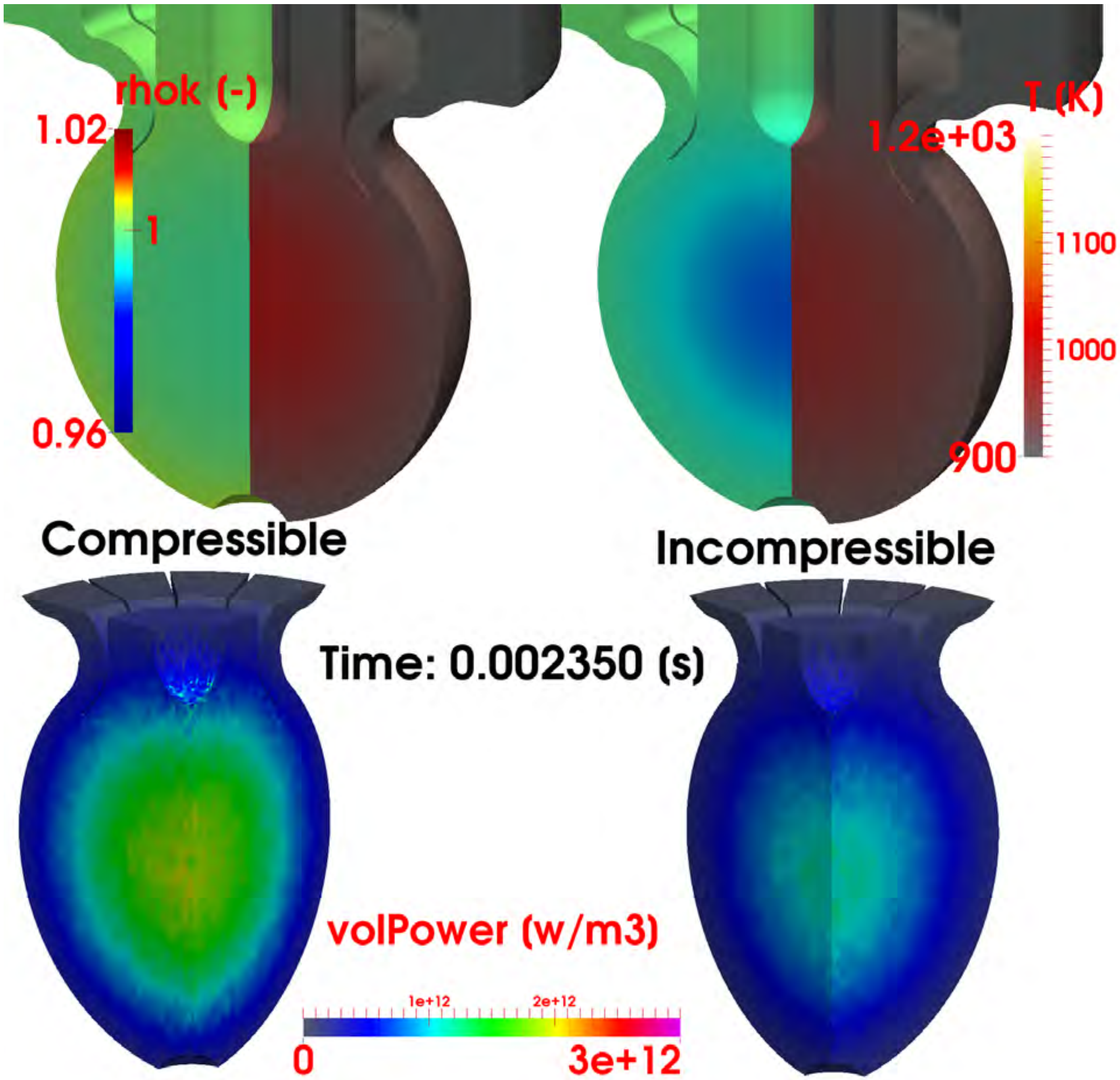

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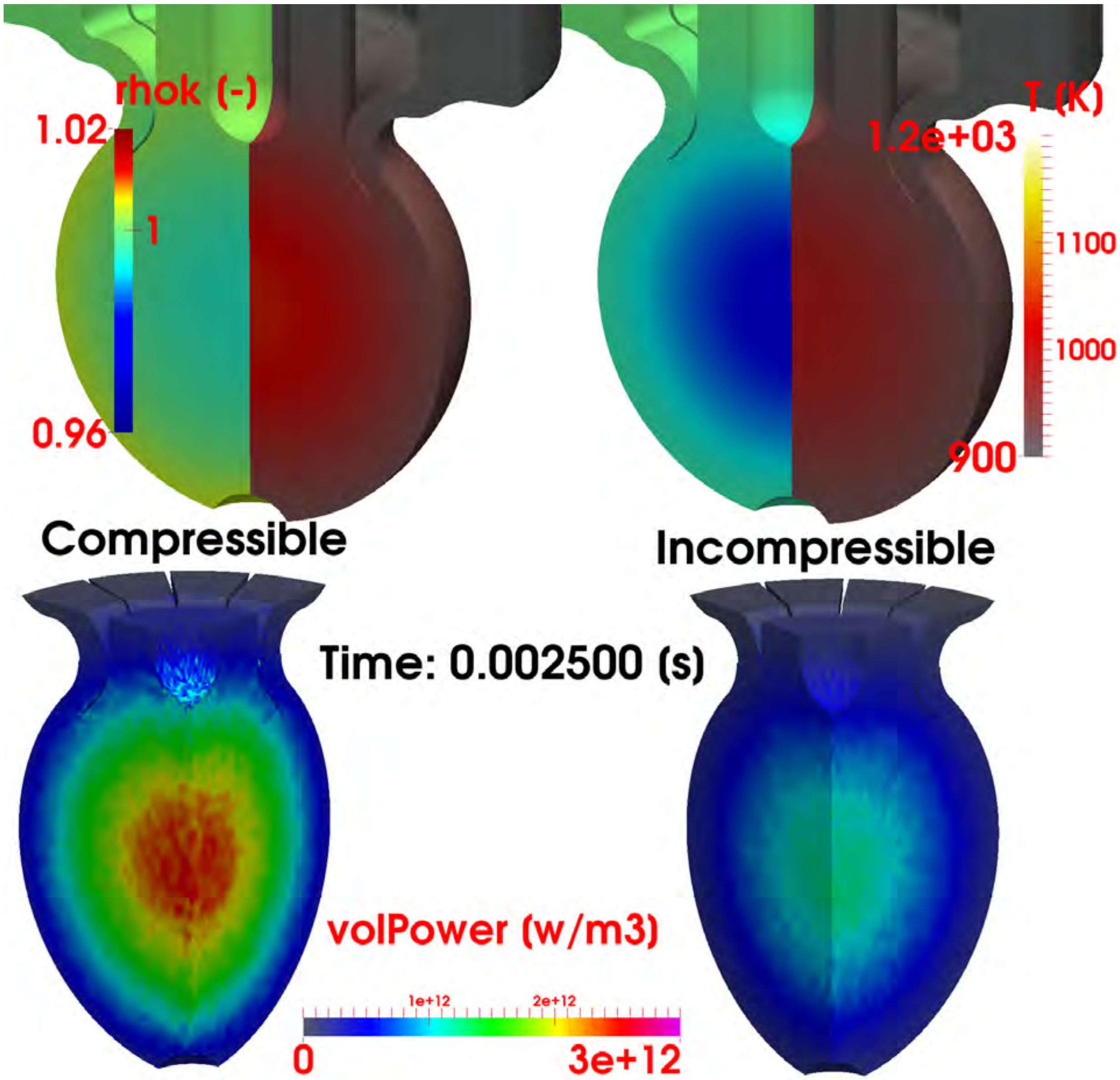

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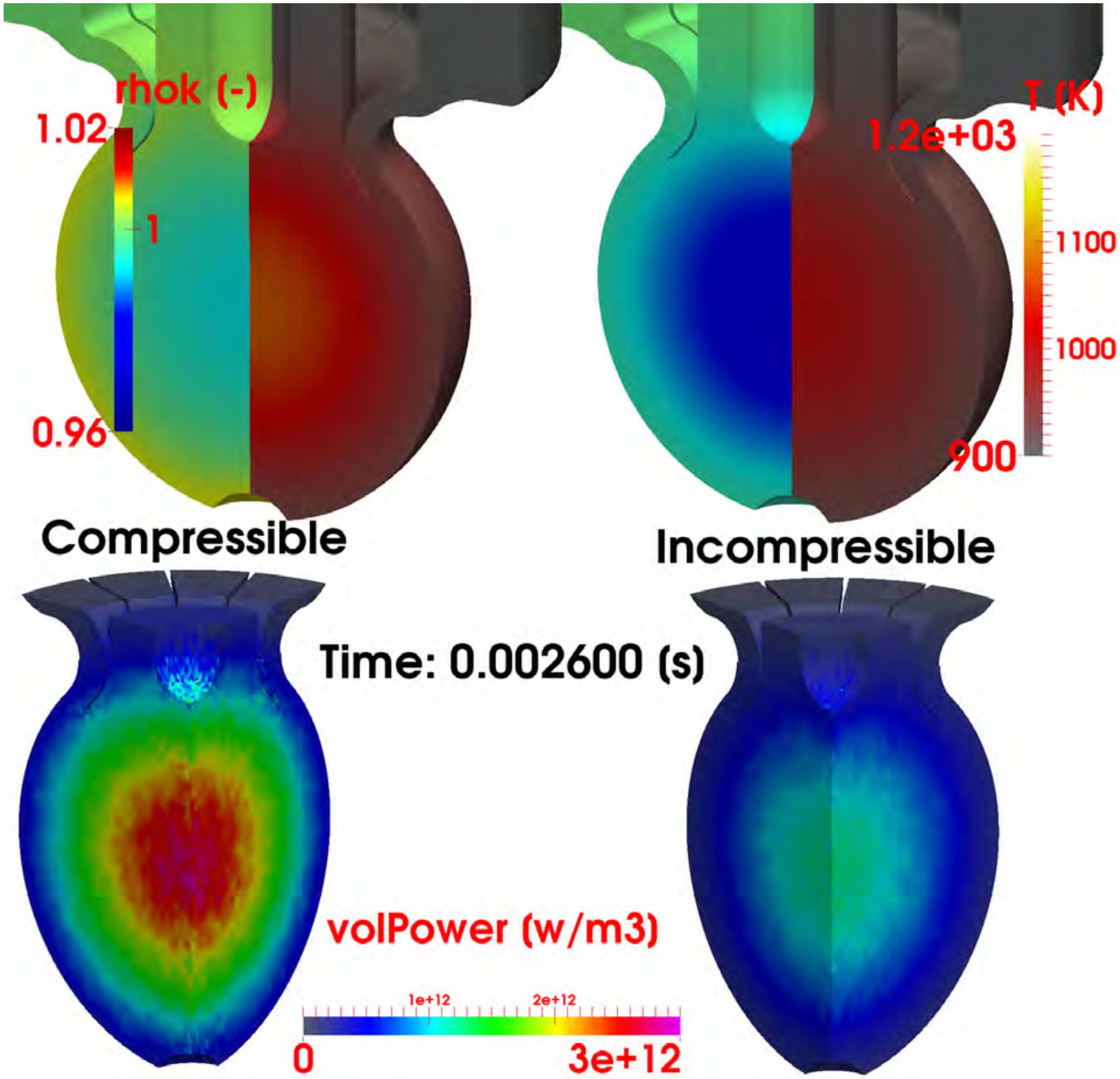

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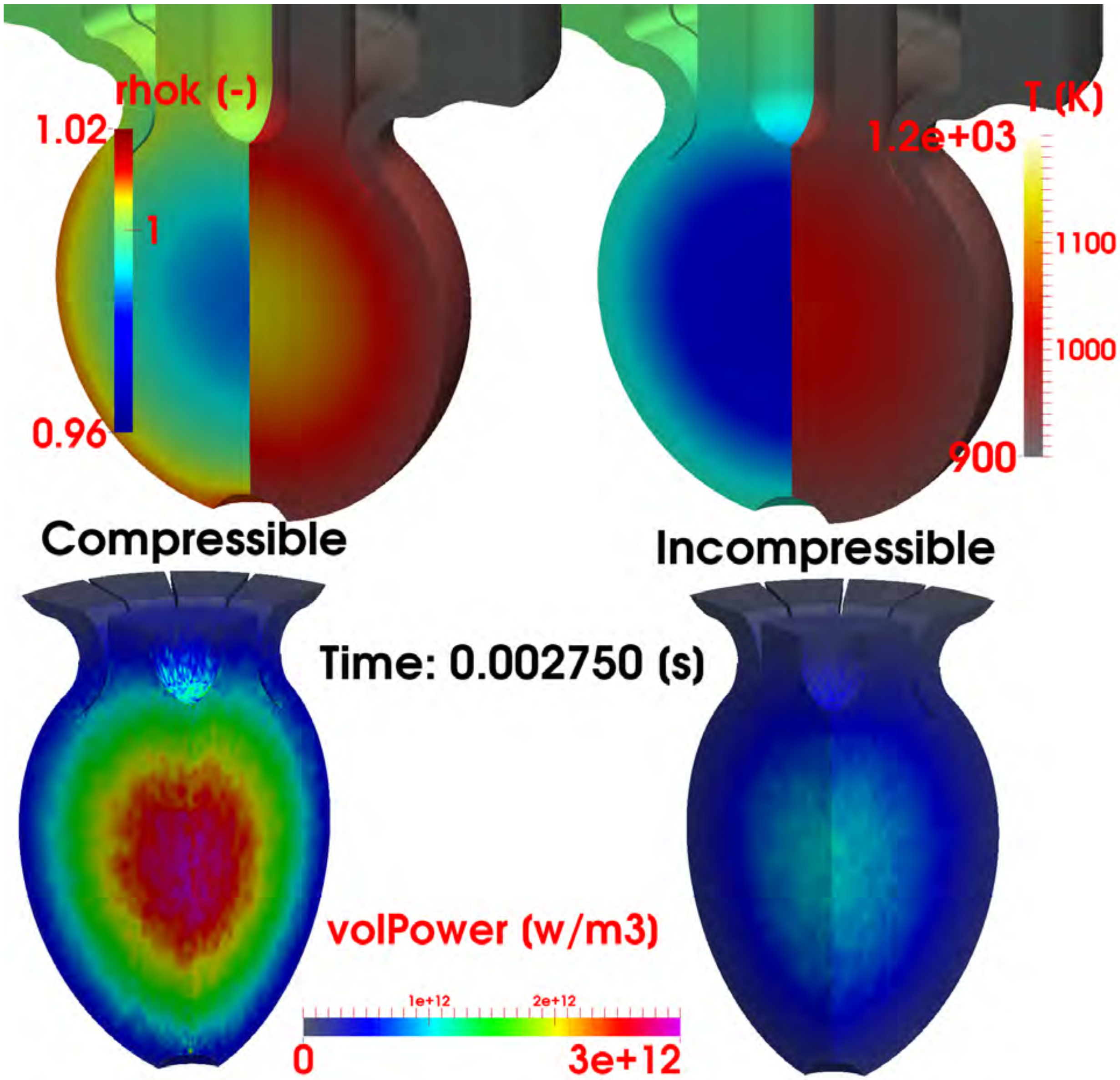

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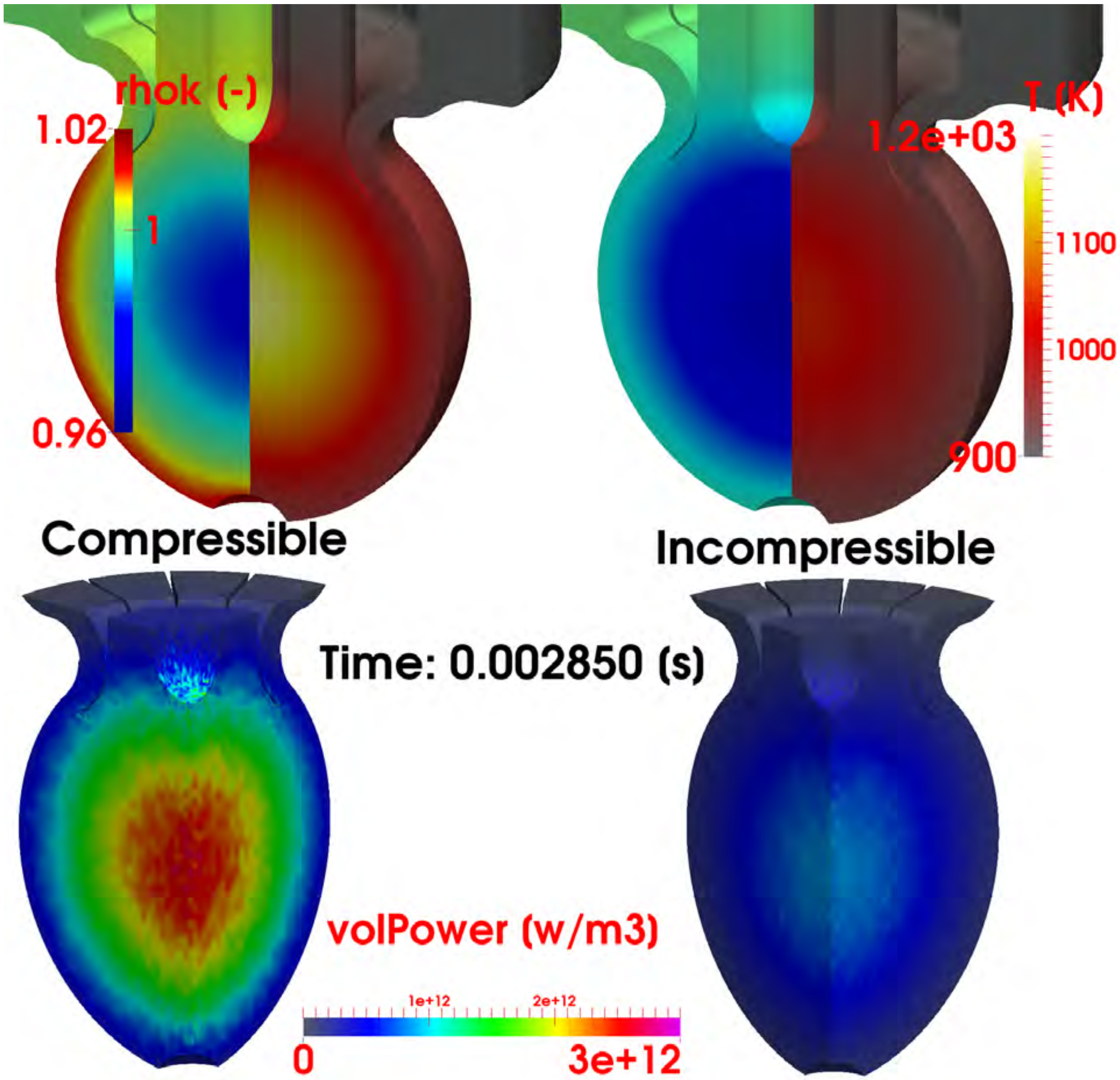

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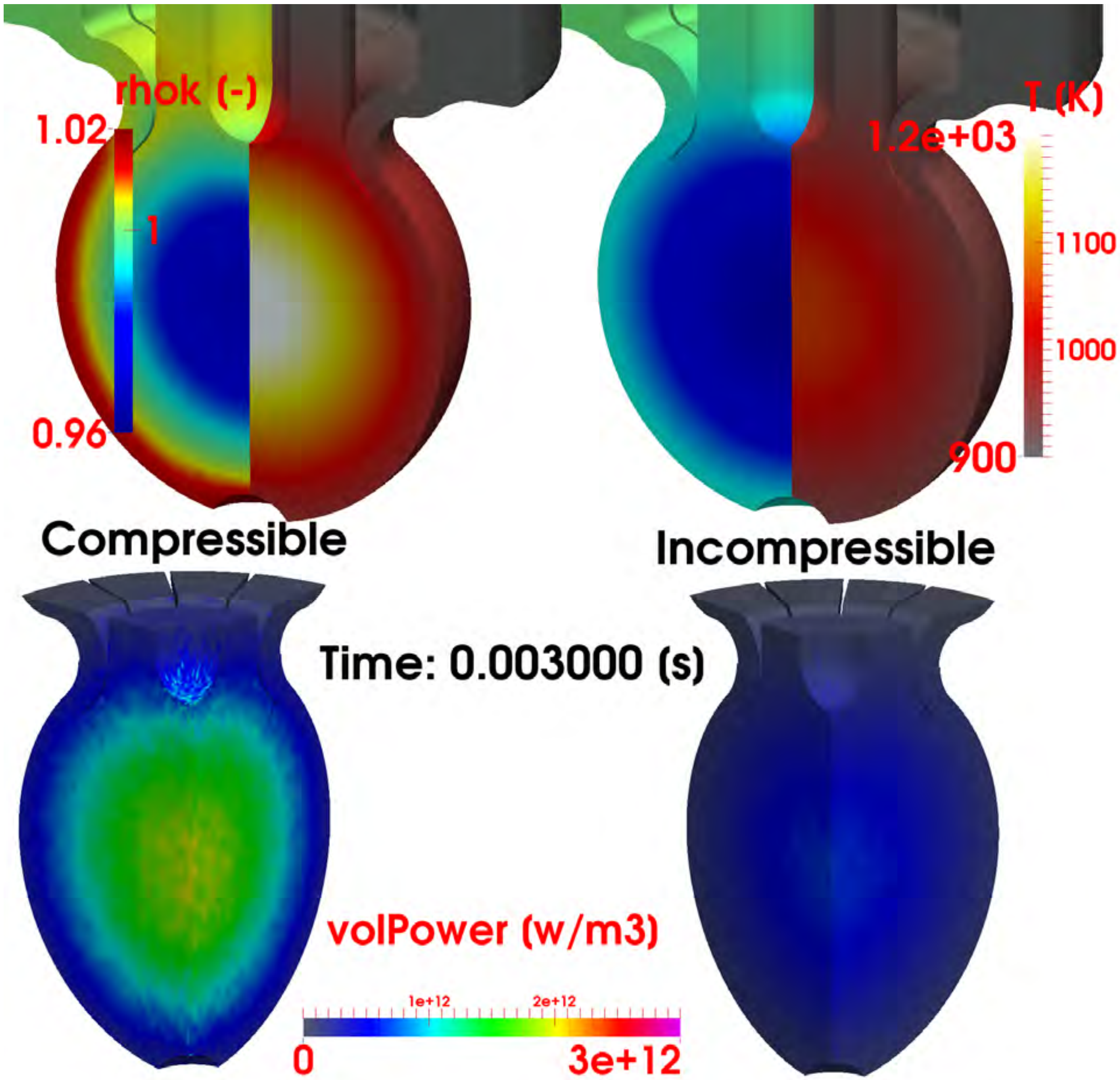

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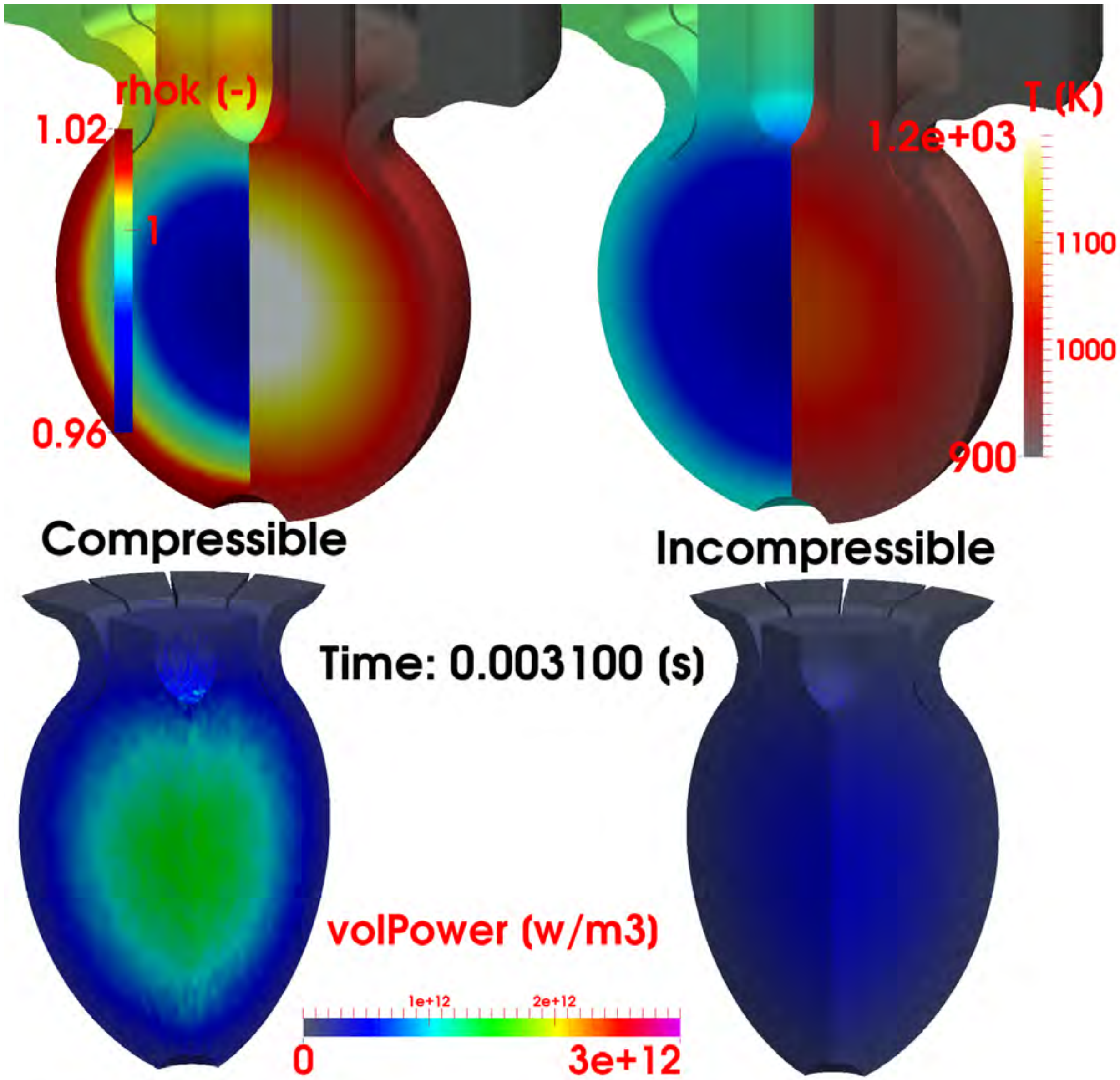

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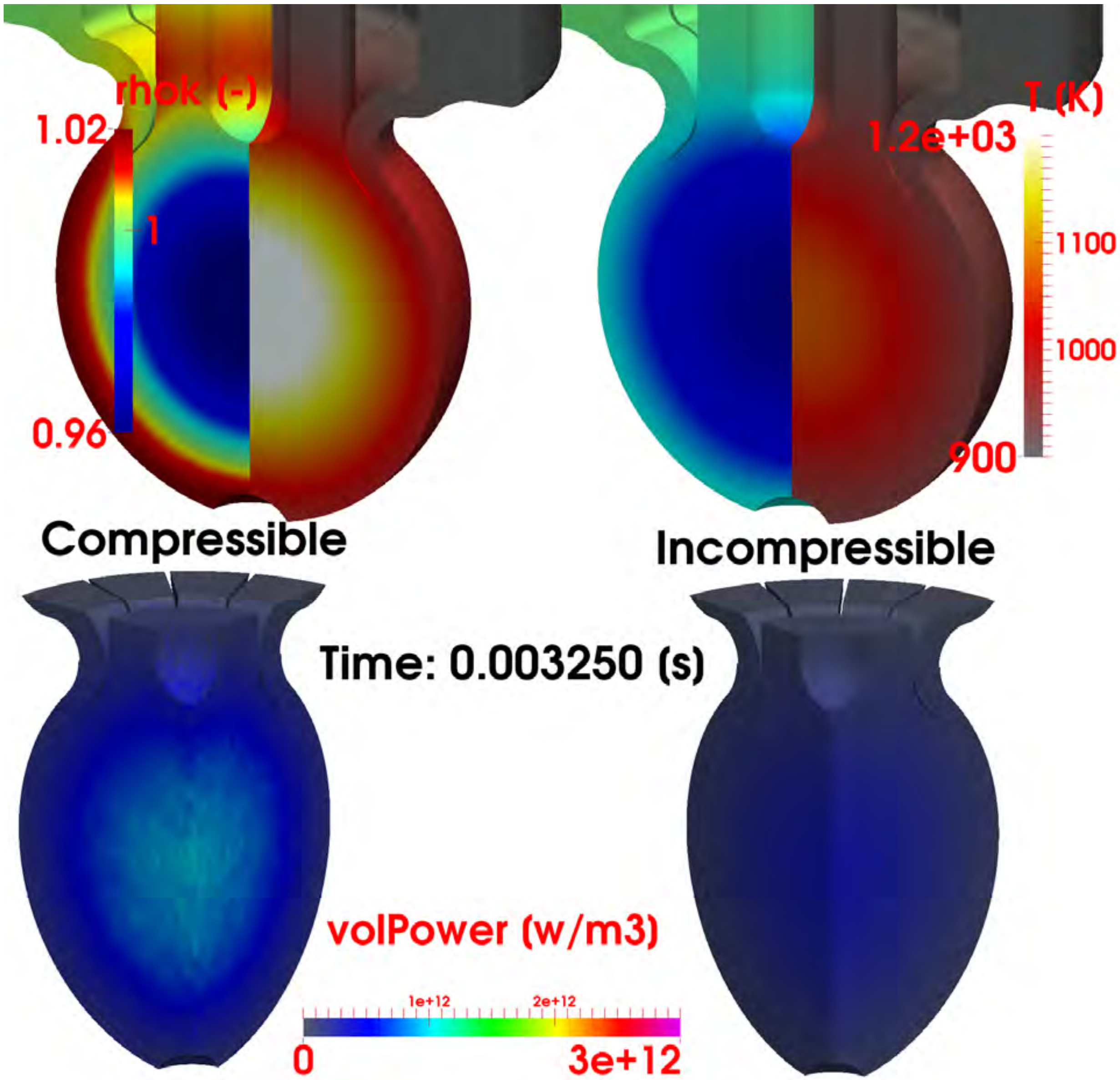

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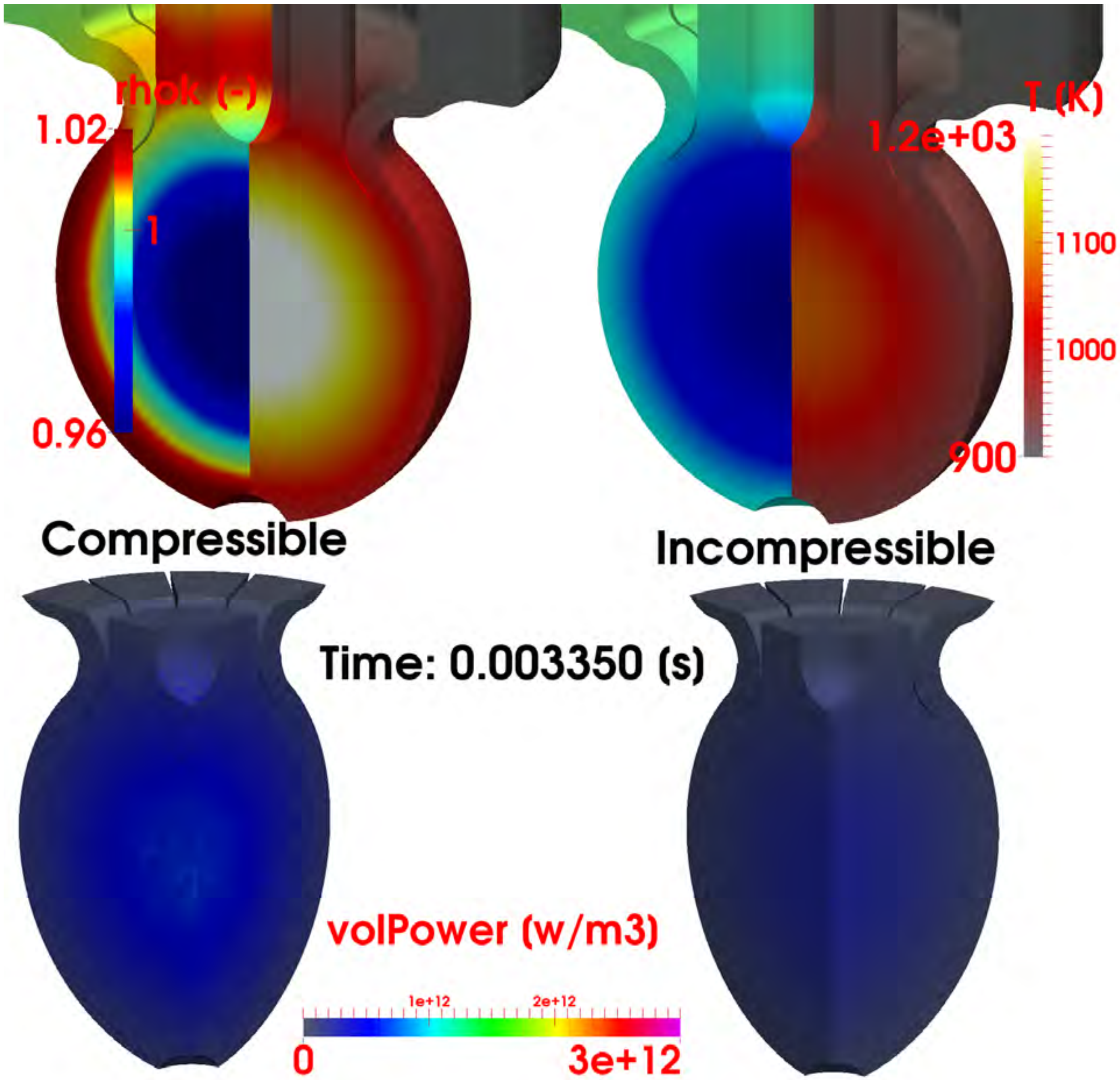

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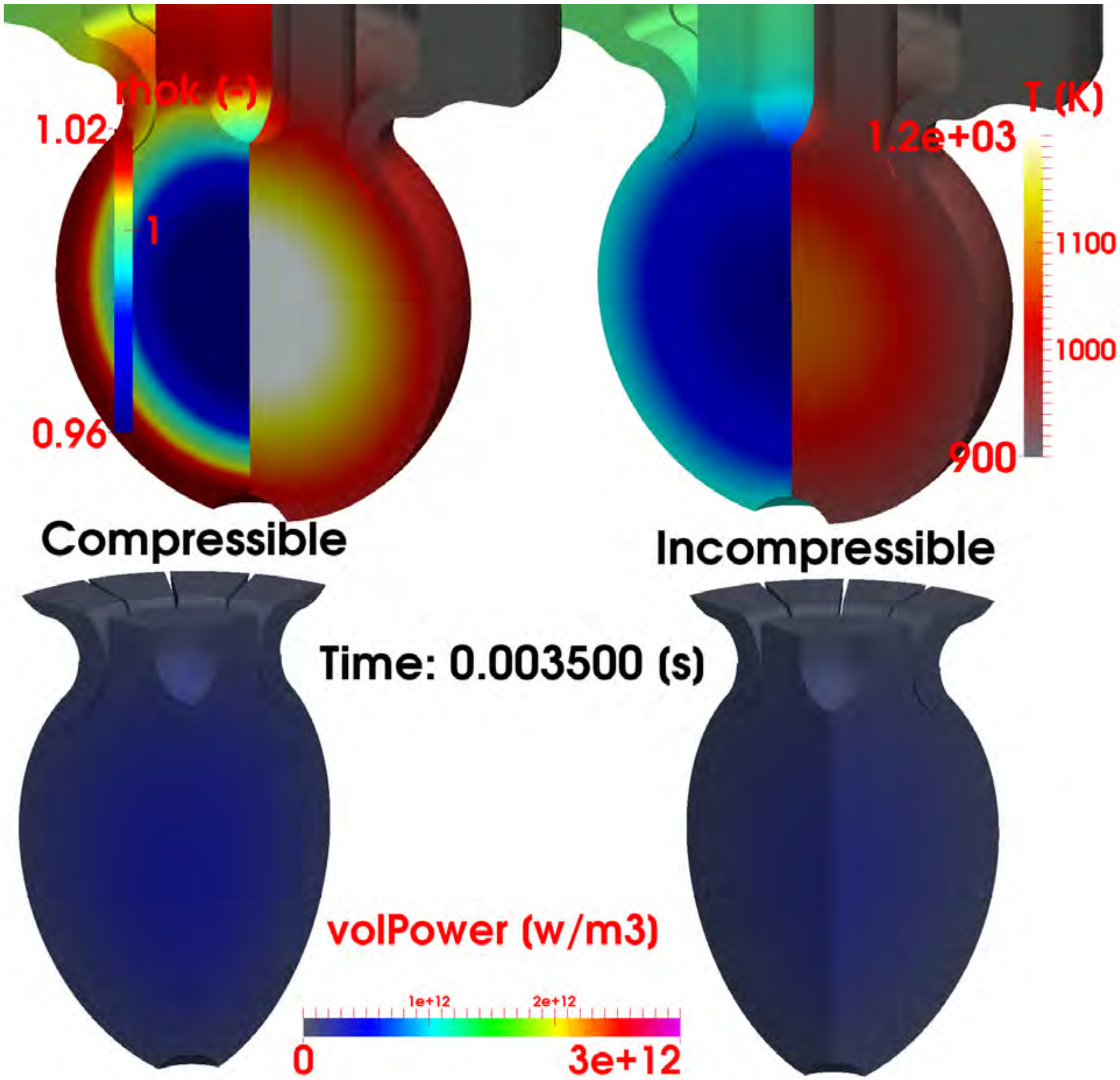

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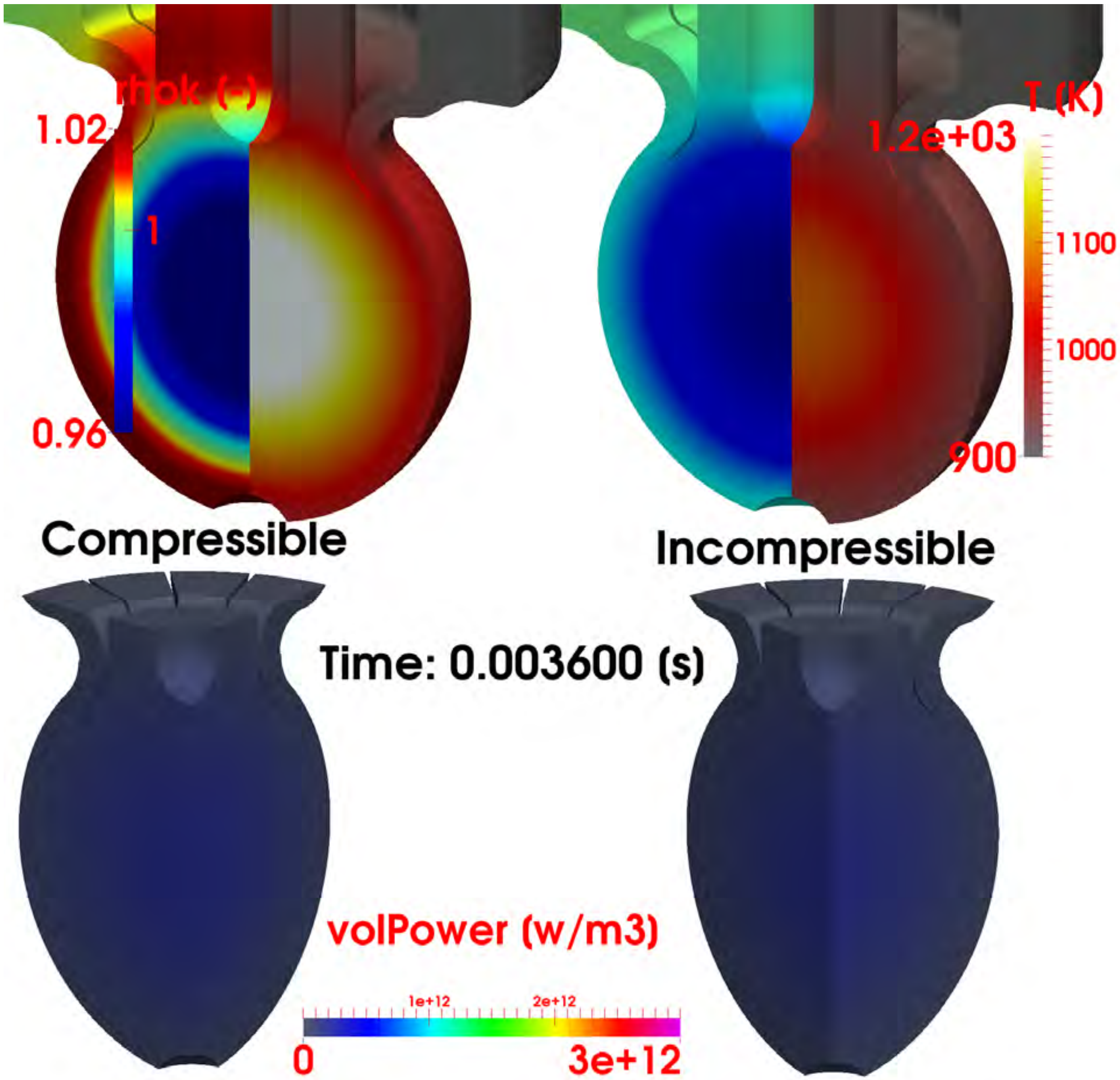

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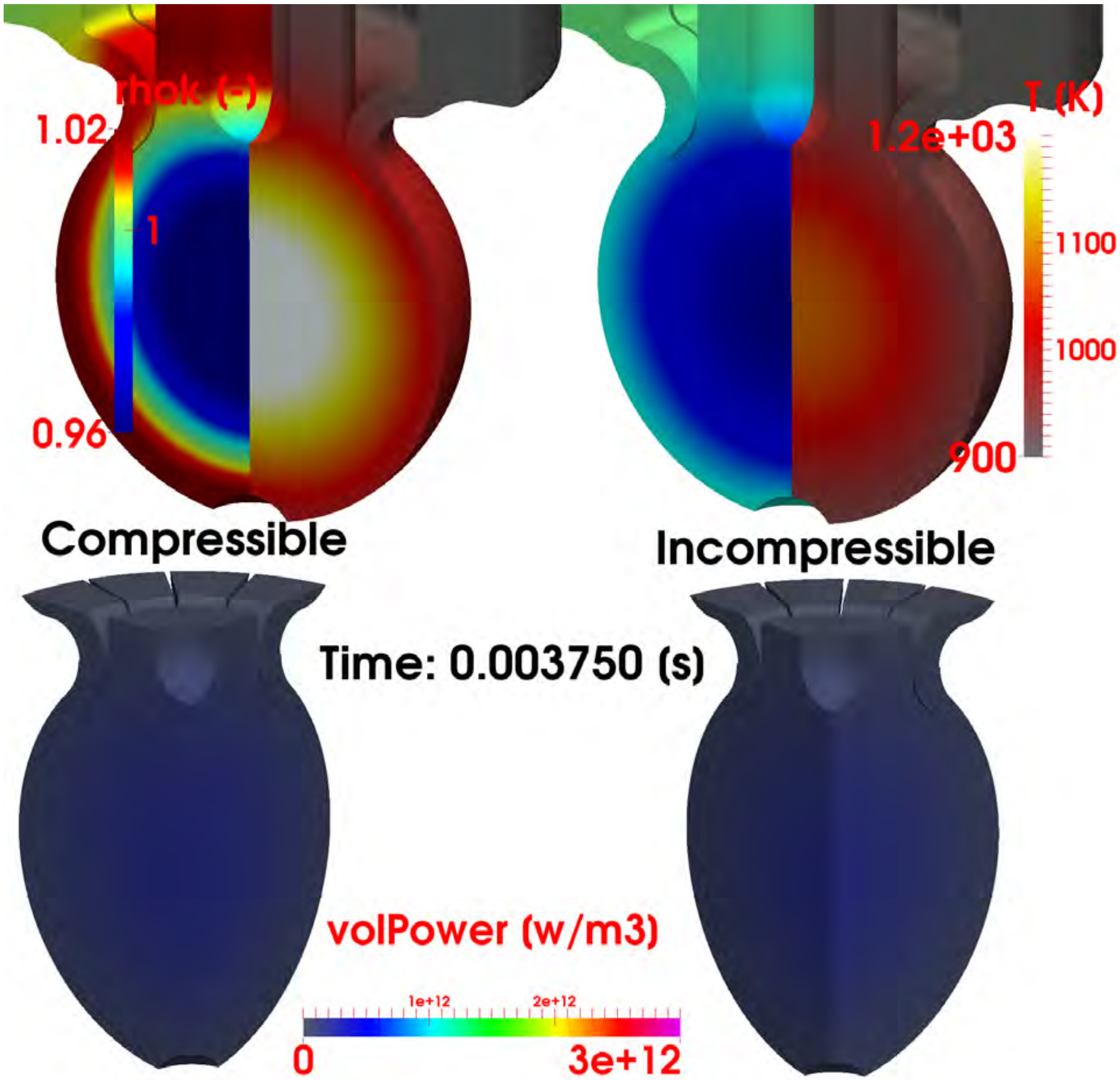

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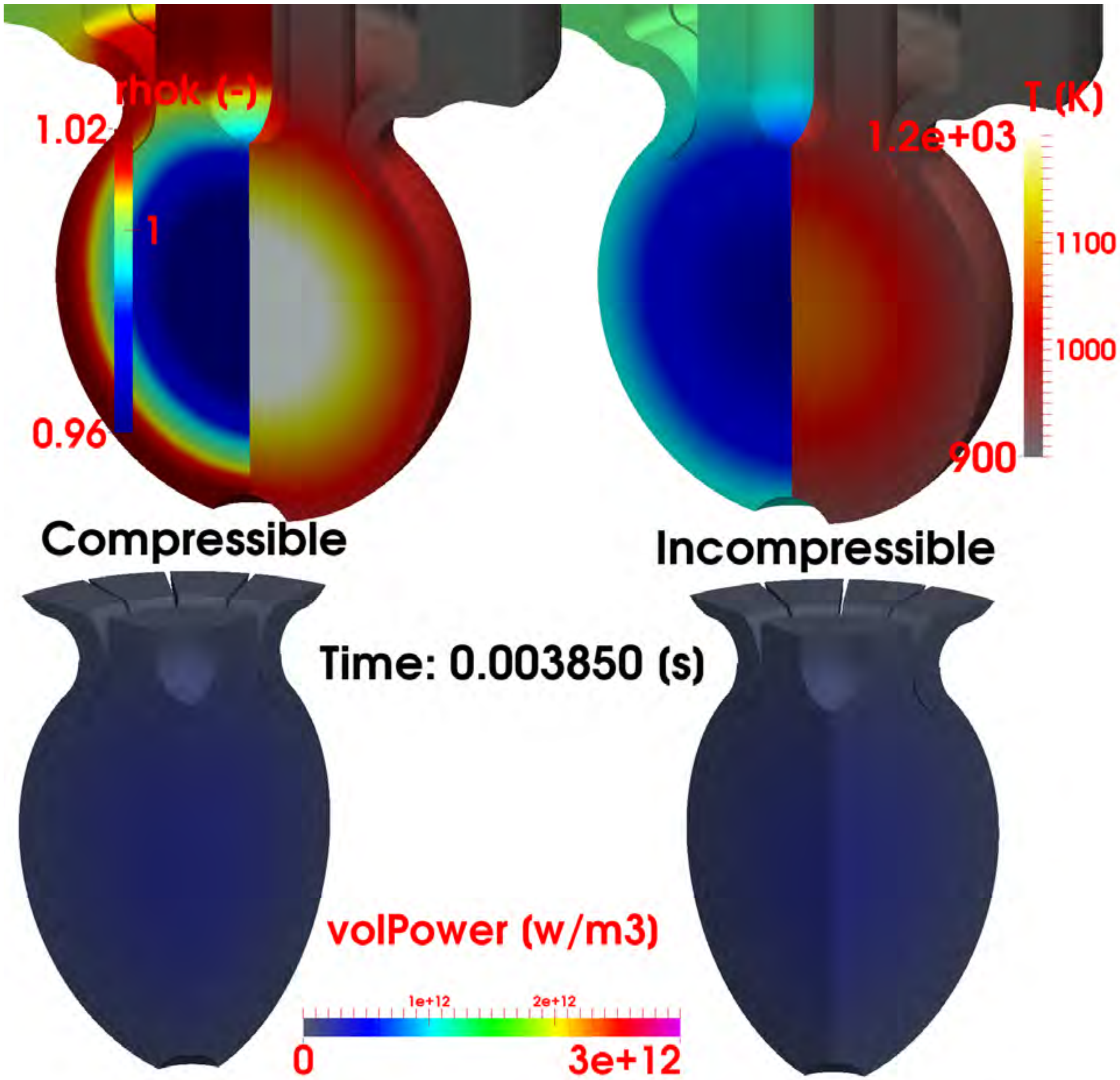
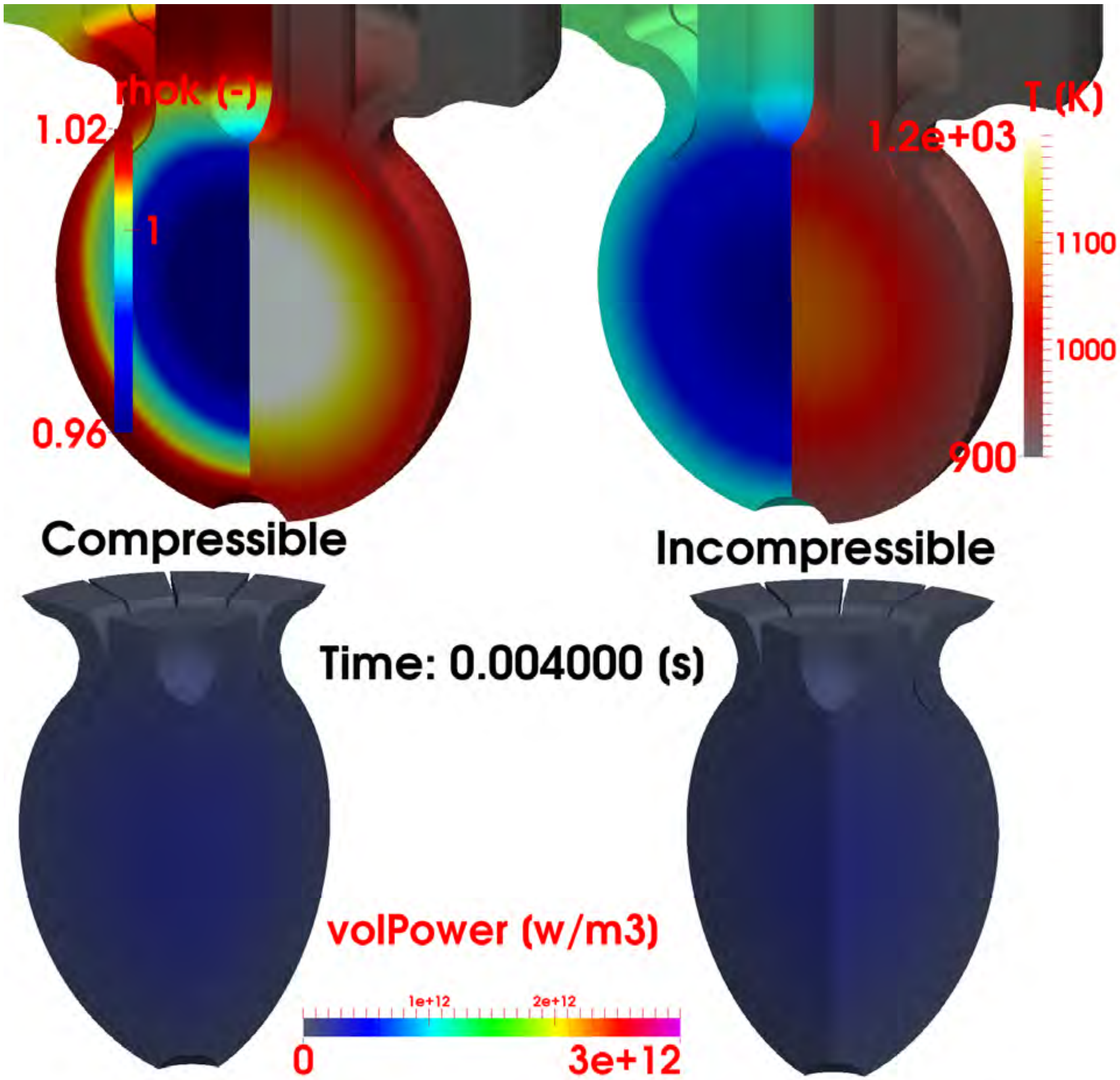
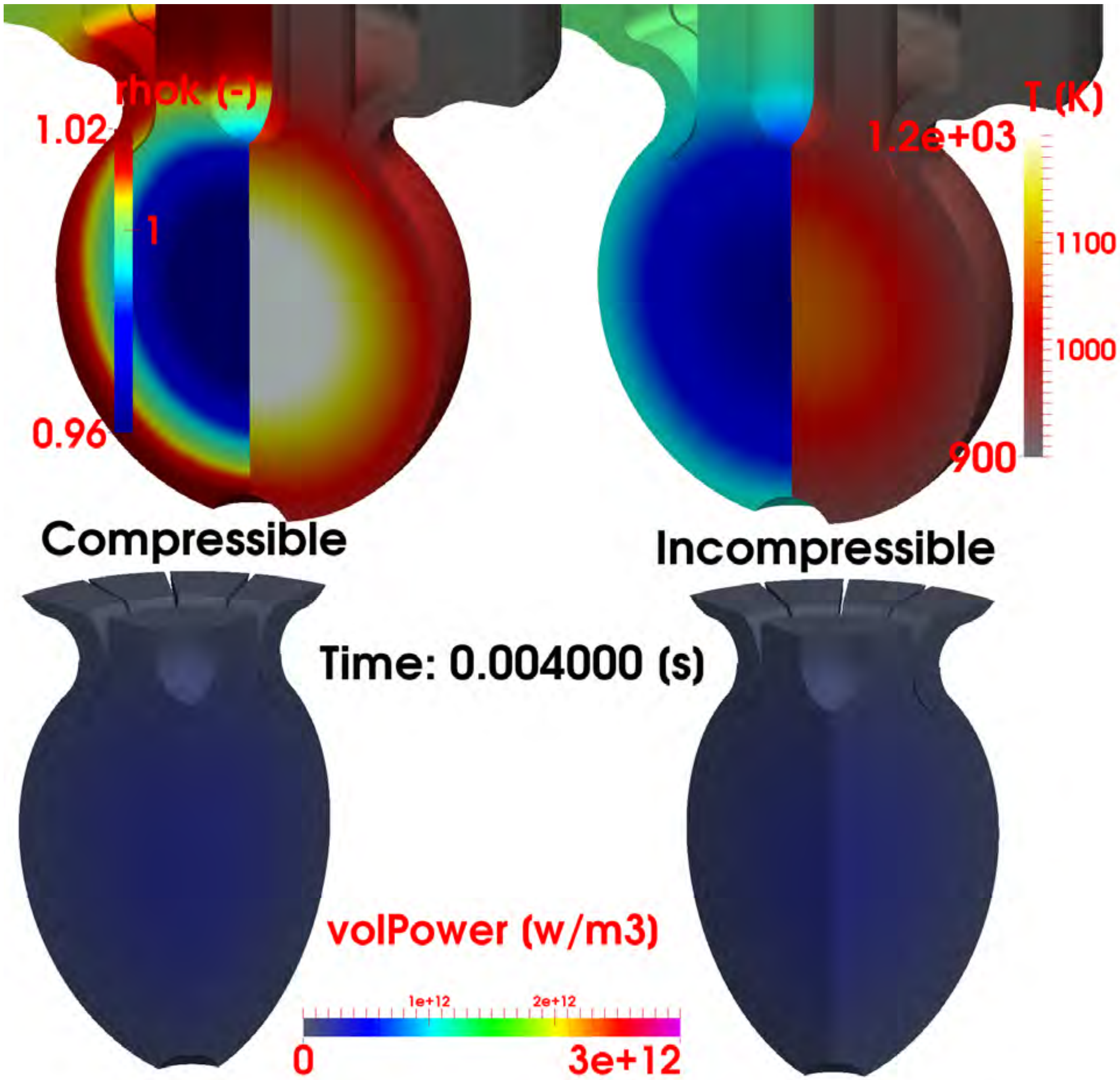




rhok (-)
1.02
1
0.96
T (K)
1.2e+03
1100
1000
900
Compressible
Incompressible
Time: 0.004000 (s)
volPower (w/m3)
1e+12
2e+12
0
3e+12

MSFR super prompt-critical burst
Effect of fluid compressibility



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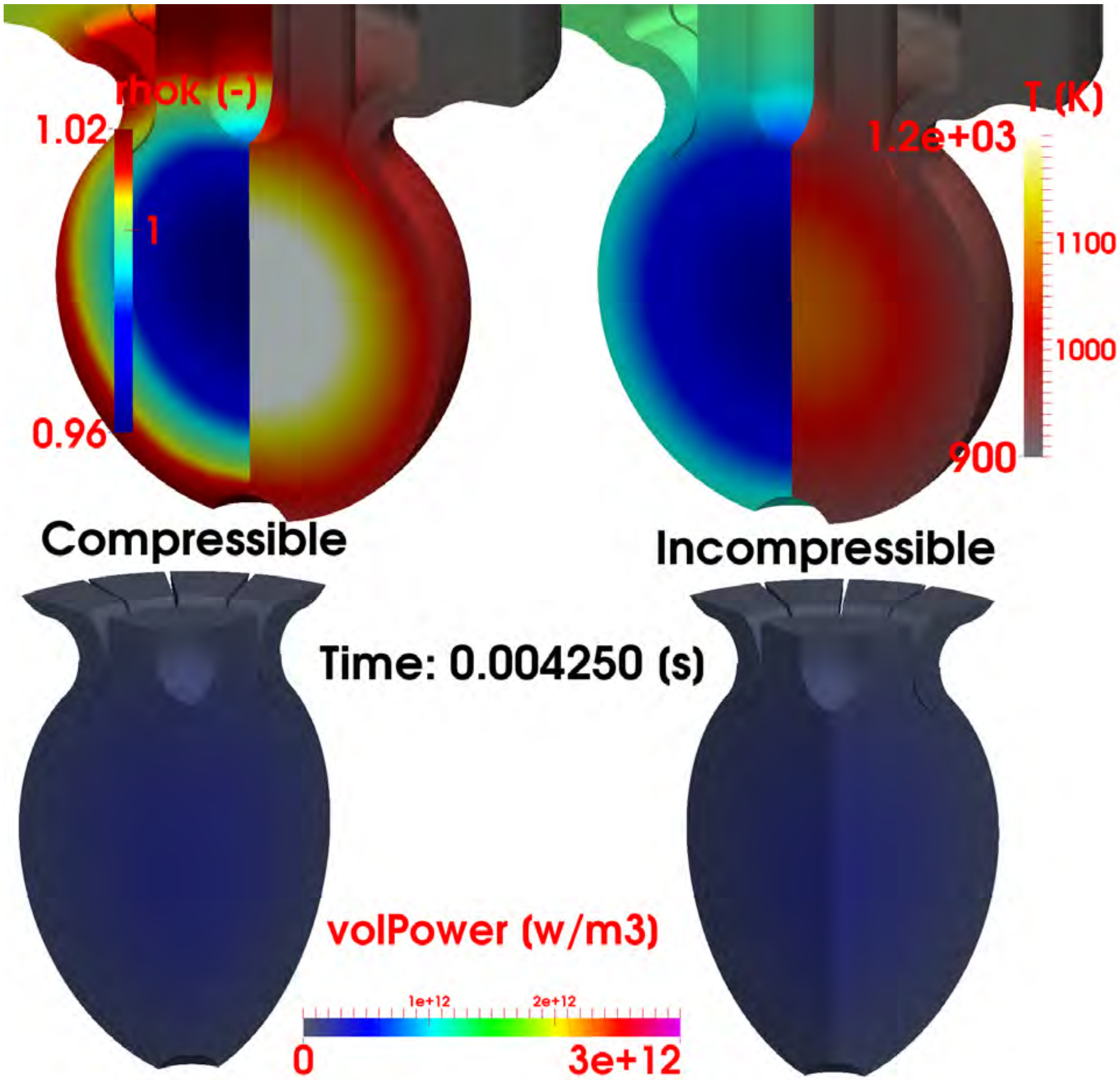

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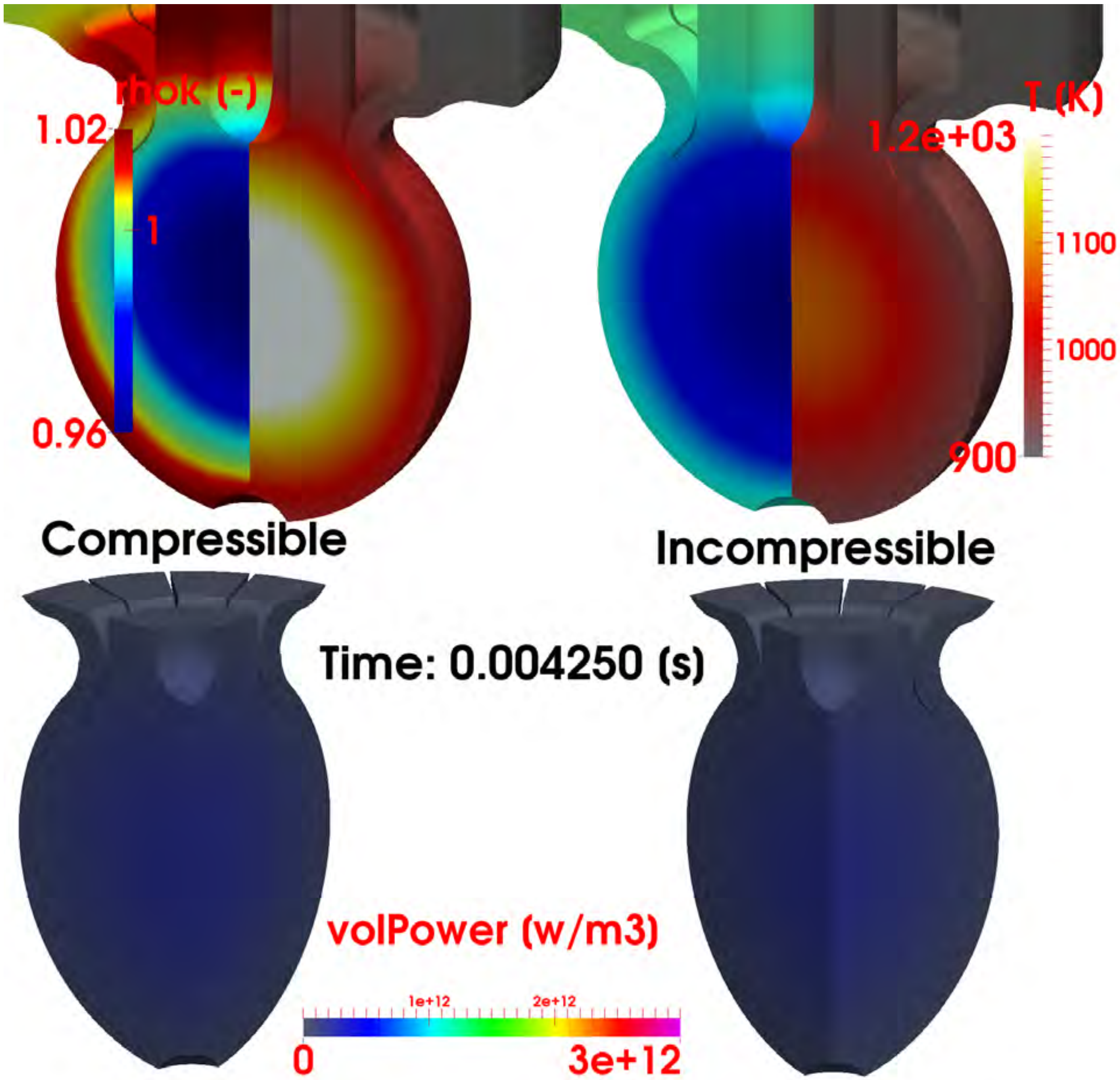

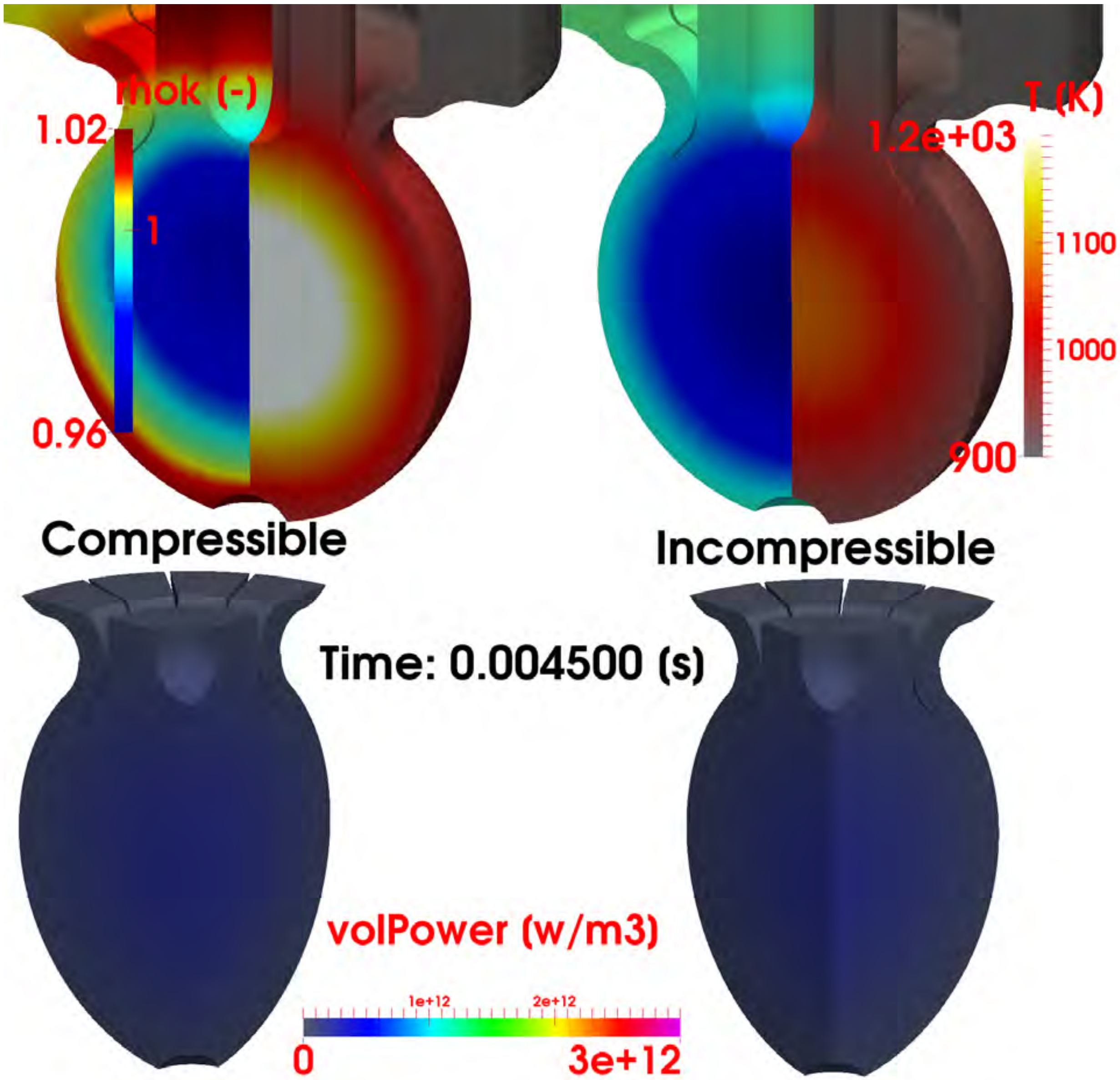

rhok (-)
1.02
1
0.96
T (K)
1.2e+03
1100
1000
900
Compressible
Incompressible
Time: 0.004500 (s)
volPower (w/m3)
1e+12
2e+12
0
3e+12

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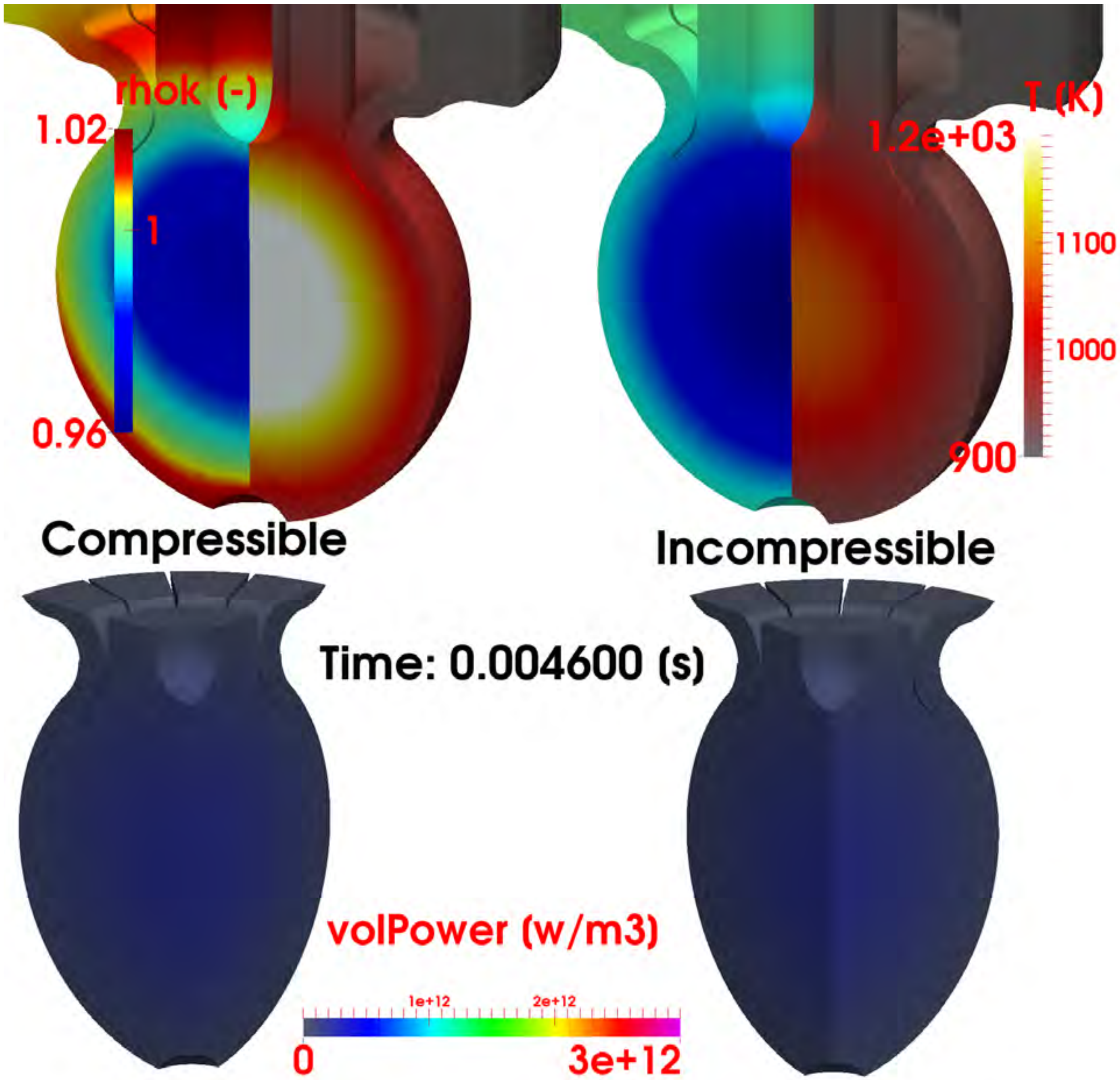
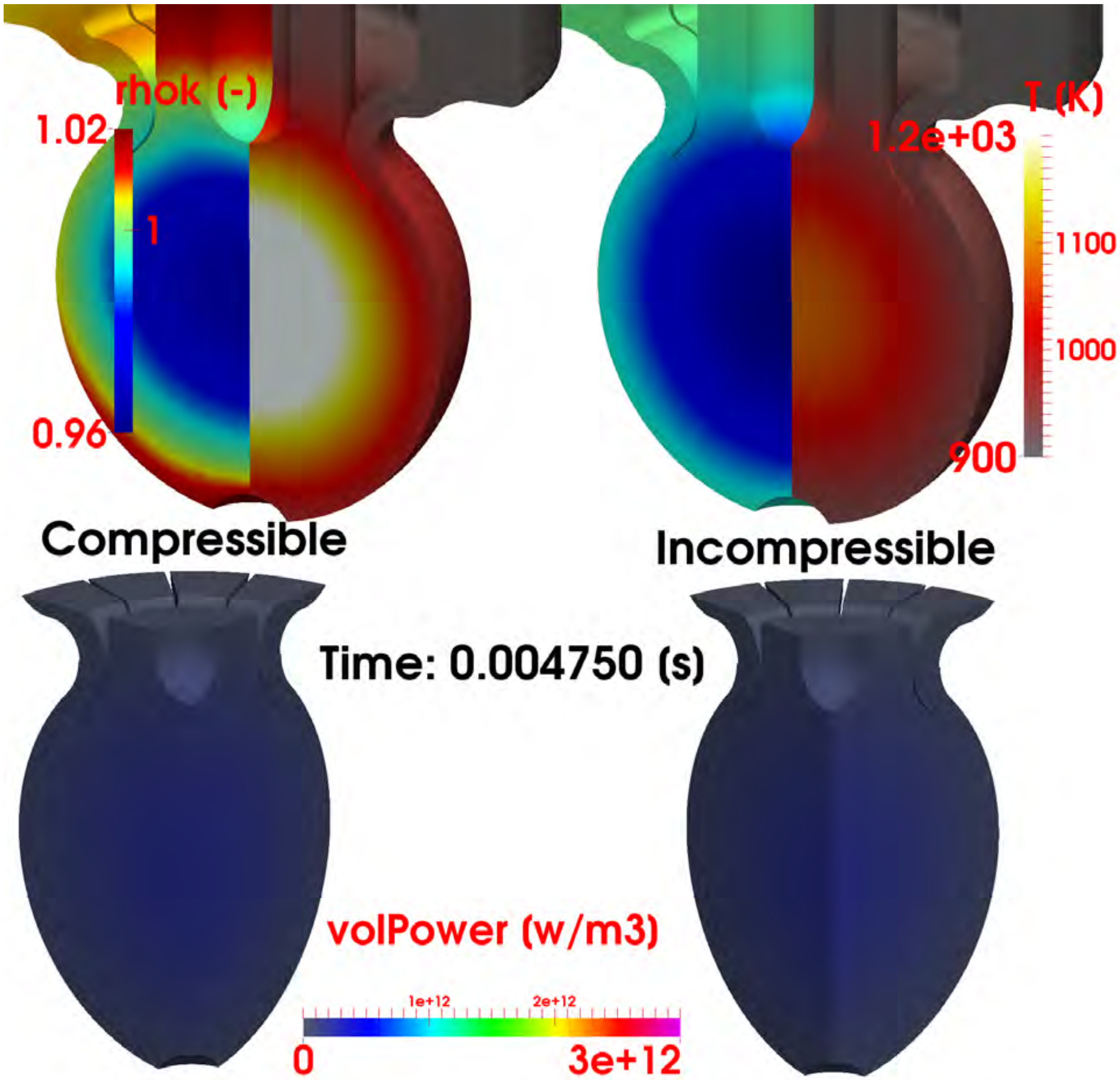
Effect of fluid compressibility





rhok (-)
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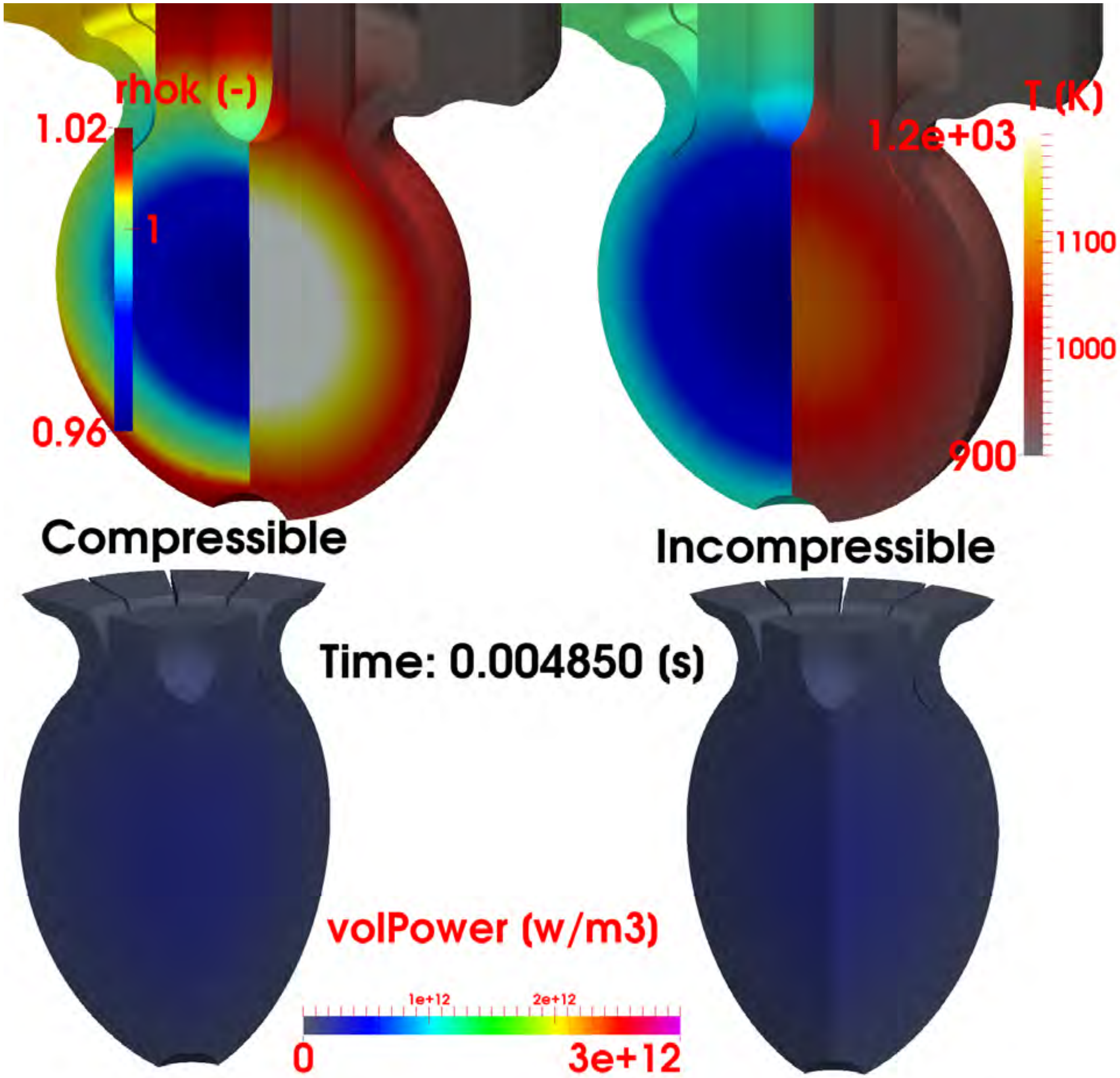
0.96
T (K)
1.2e+03
1100
1000
900
Compressible
Incompressible
Time: 0.004750 (s)
volPower (w/m3)
1e+12
2e+12
0
3e+12



rhok (-)
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1
0.96
T (K)
1.2e+03
1100
1000
900
Compressible
Incompressible
Time: 0.004850 (s)
volPower (w/m3)
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2e+12
0
3e+12

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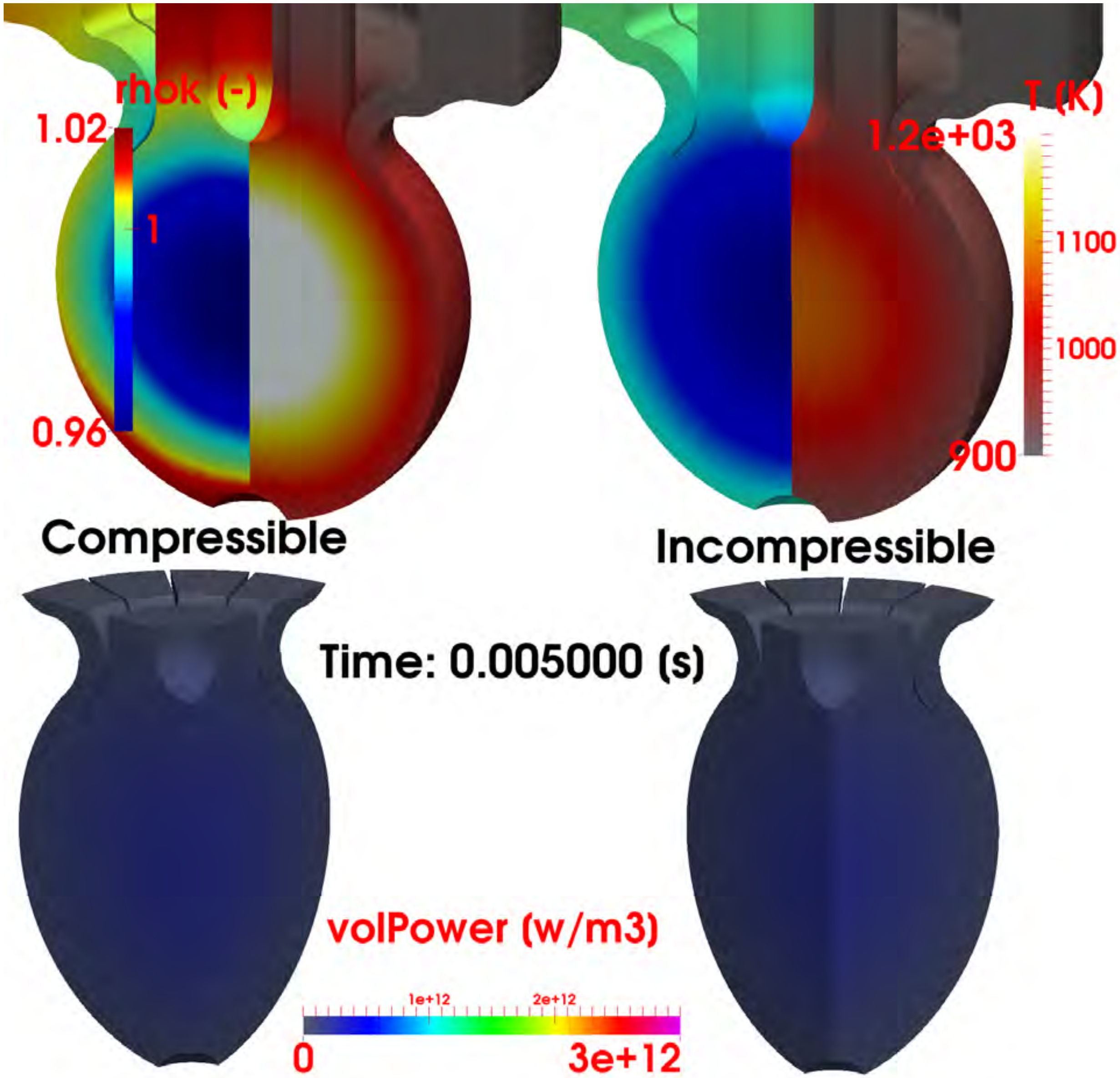
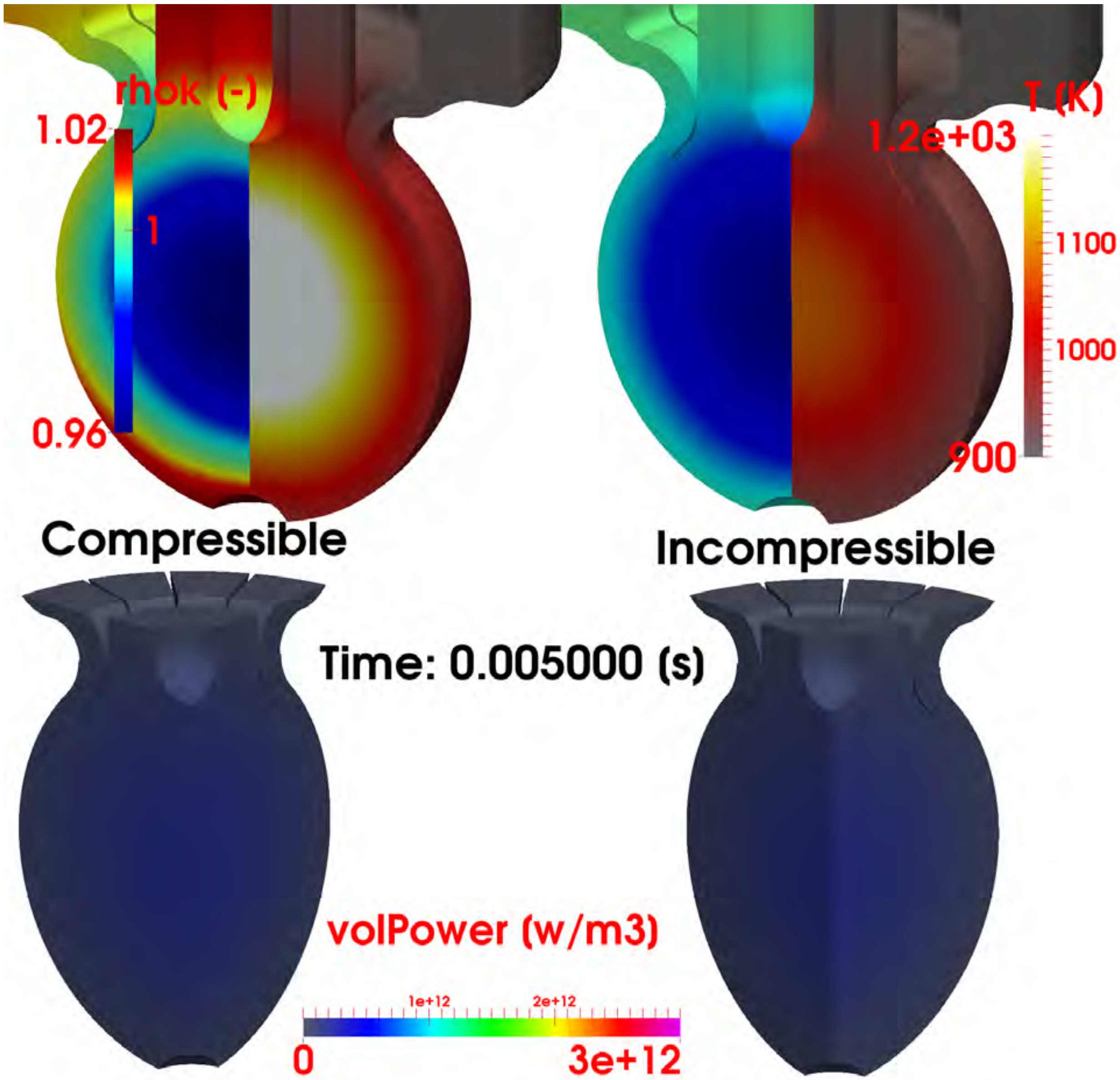
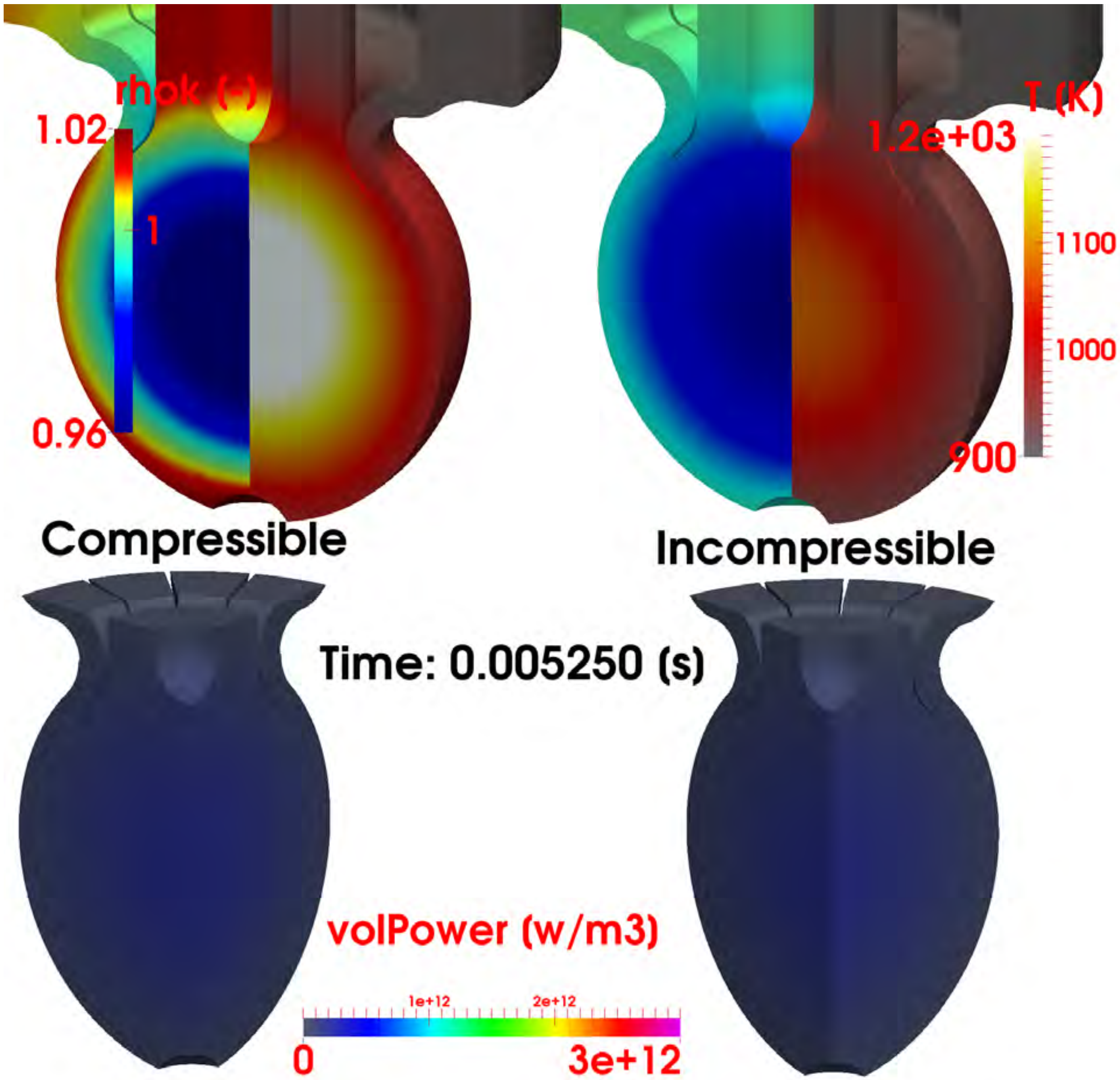


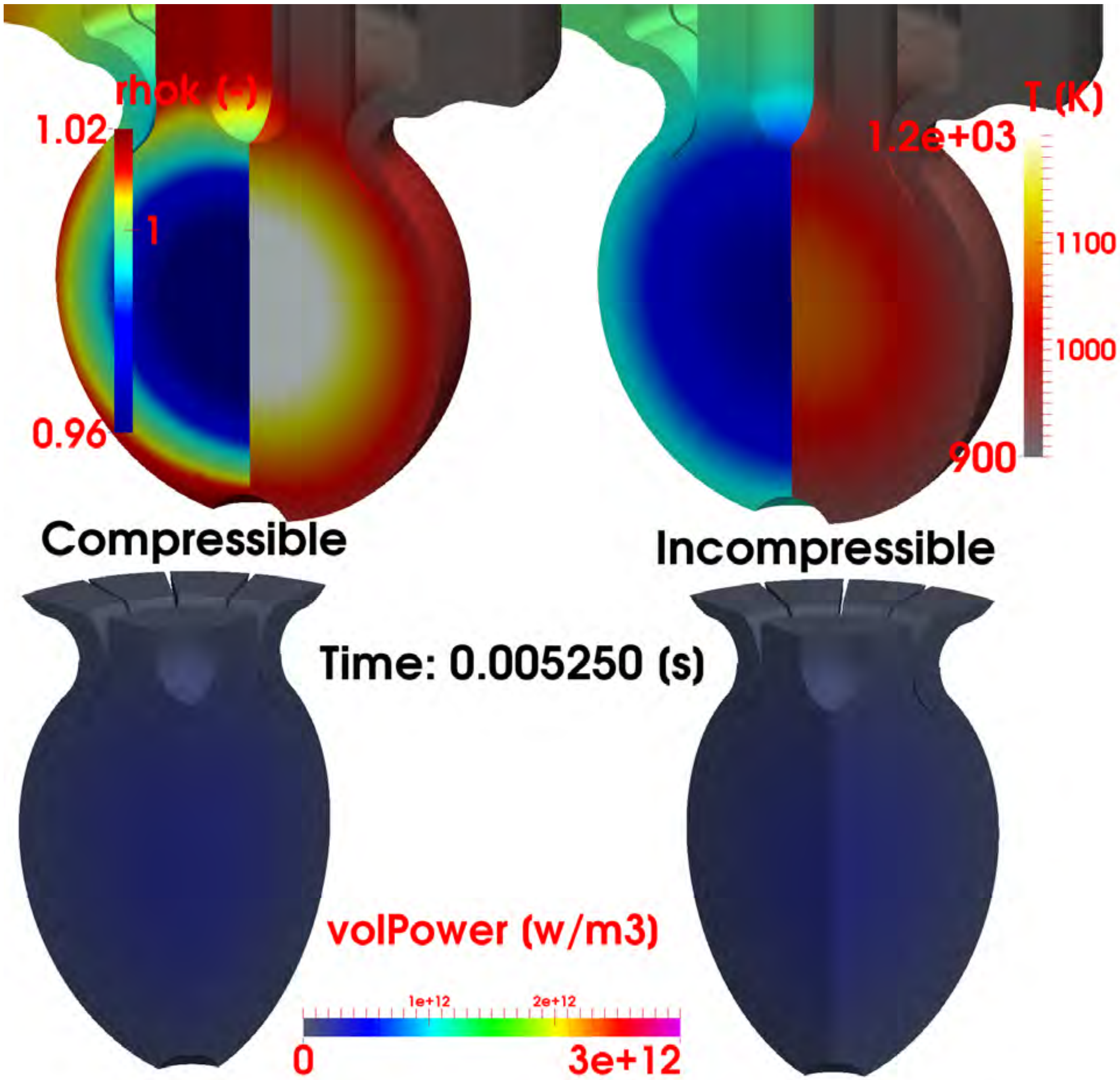

rhok (-)
1.02
1
0.96
T (K)
1.2e+03
1100
1000
900
Compressible
Incompressible
Time: 0.005000 (s)
volPower (w/m3)
1e+12
2e+12
0
3e+12

MSFR super prompt-critical burst

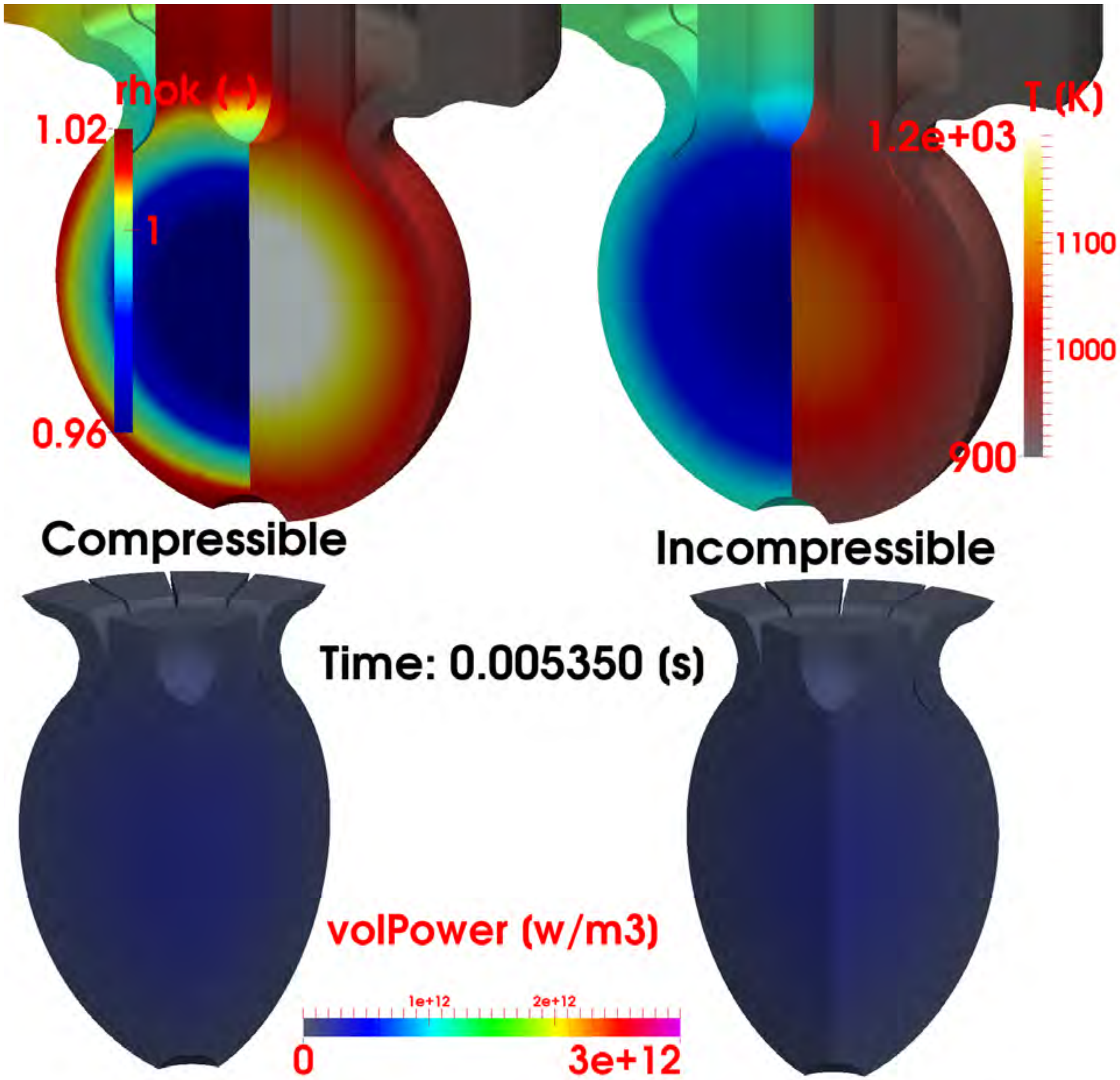
Effect of fluid compressibility



MSFR super prompt-critical burst
Effect of fluid compressibility

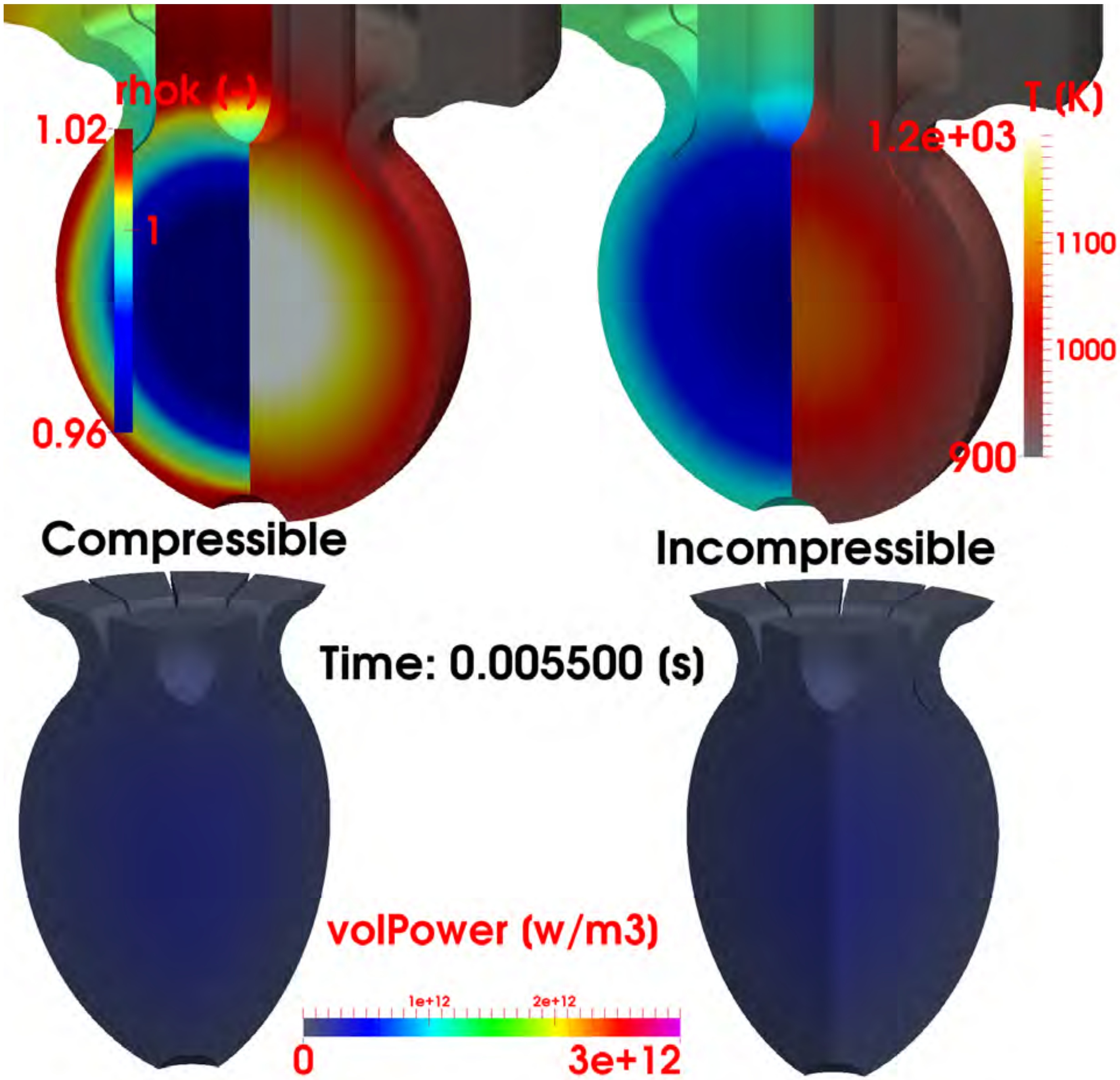


MSFR super prompt-critical burst
Effect of fluid compressibility



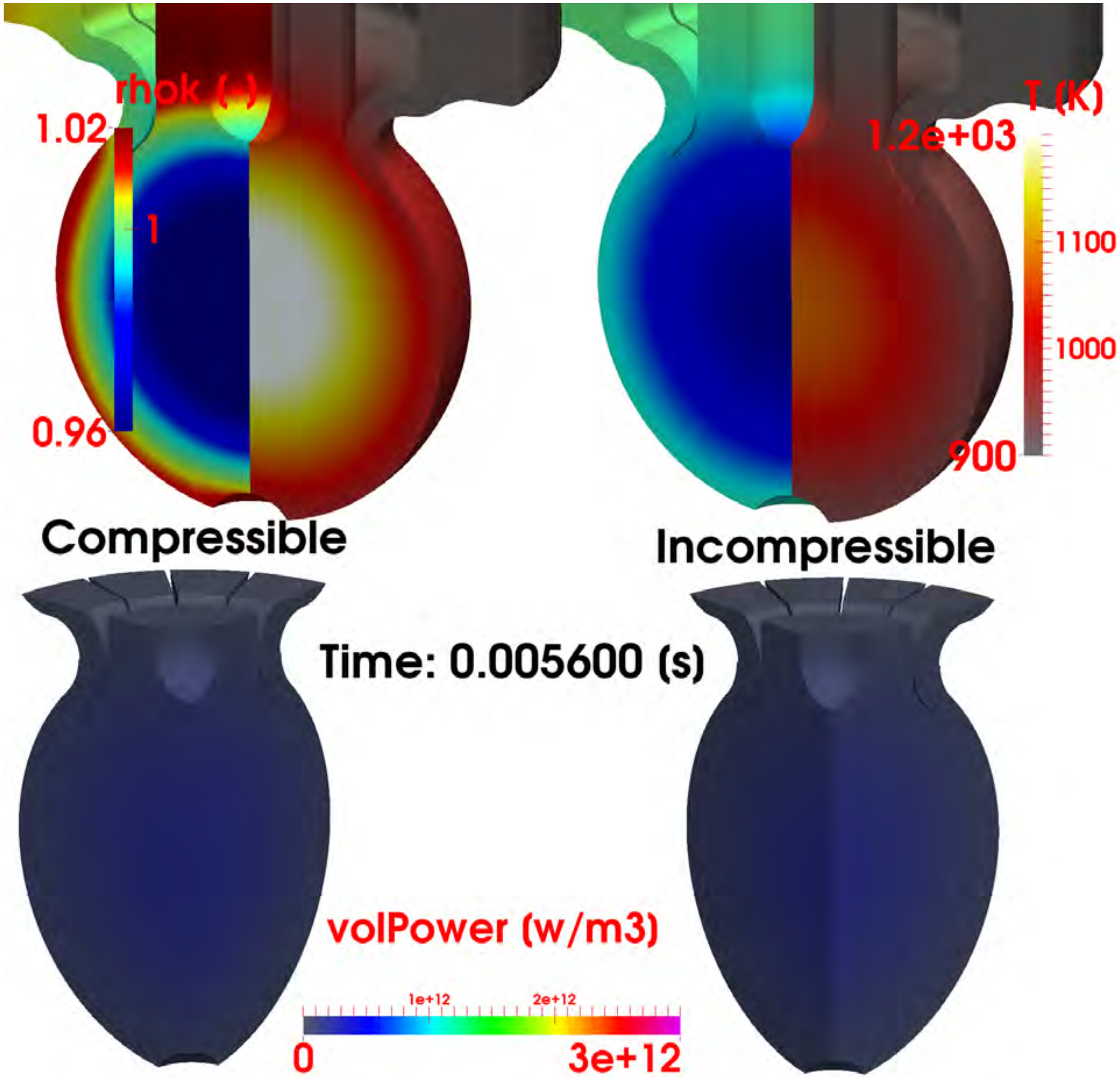
MSFR super prompt-critical burst

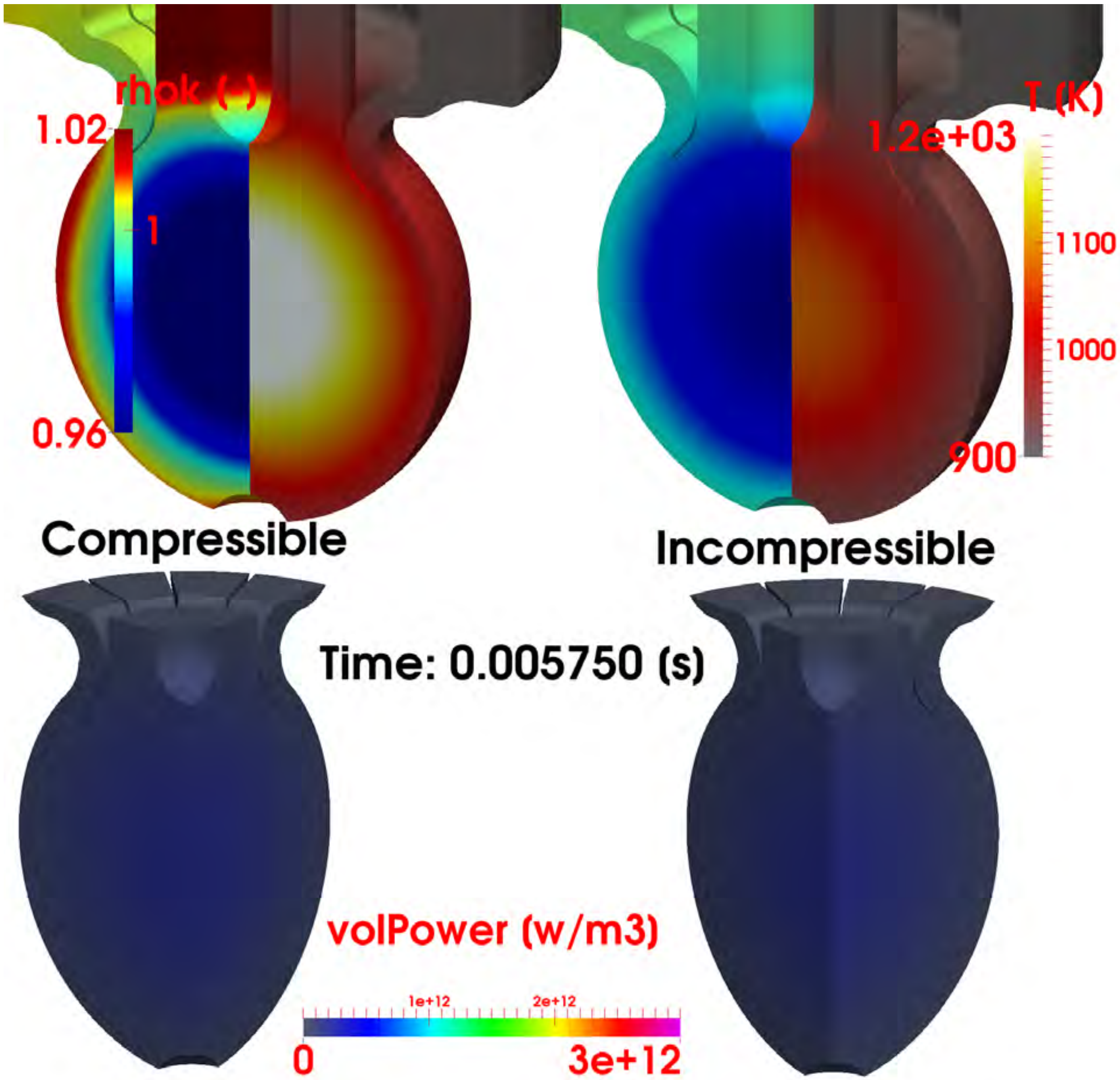
Effect of fluid compressibility



MSFR super prompt-critical burst

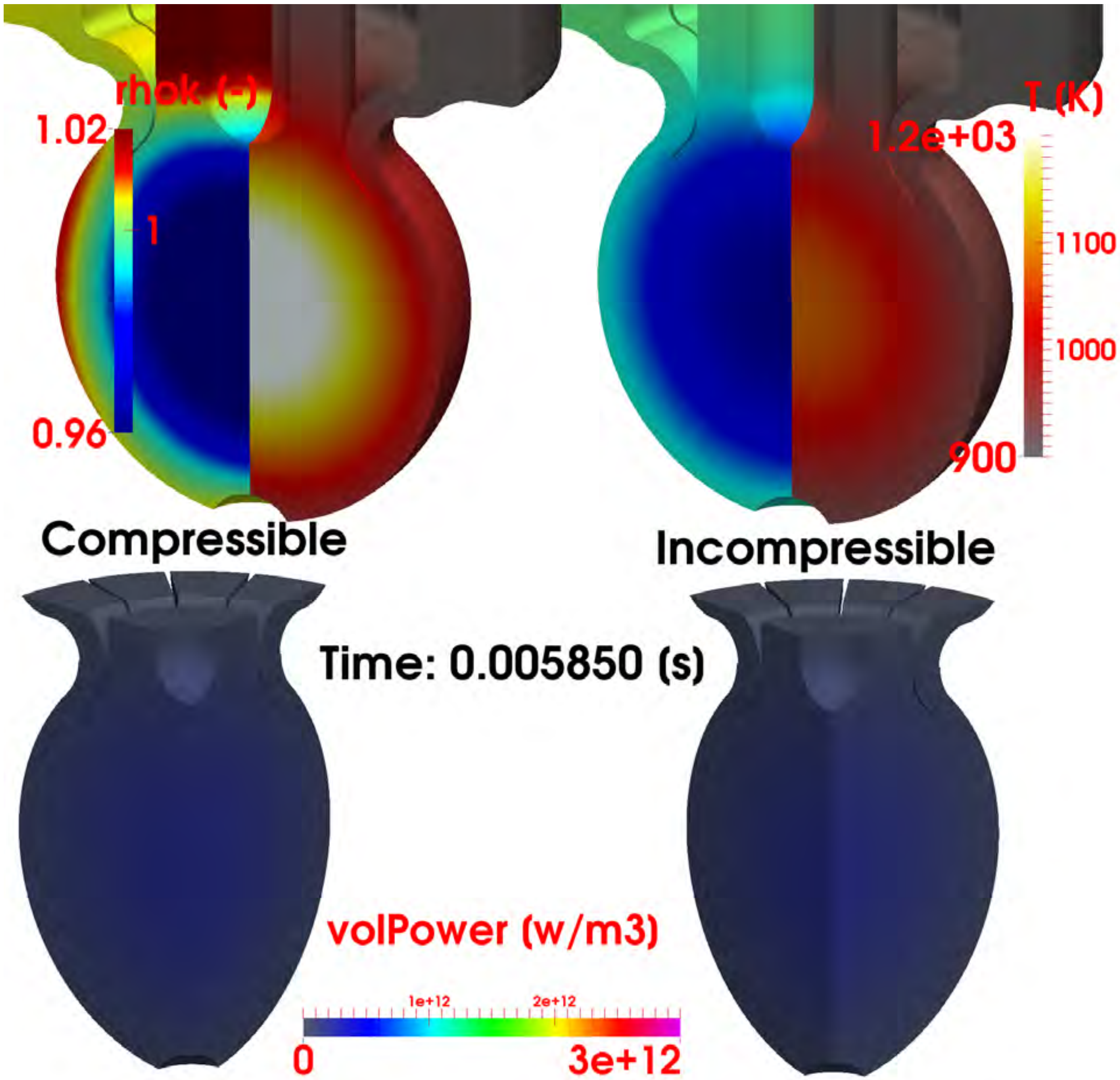
Effect of fluid compressibility





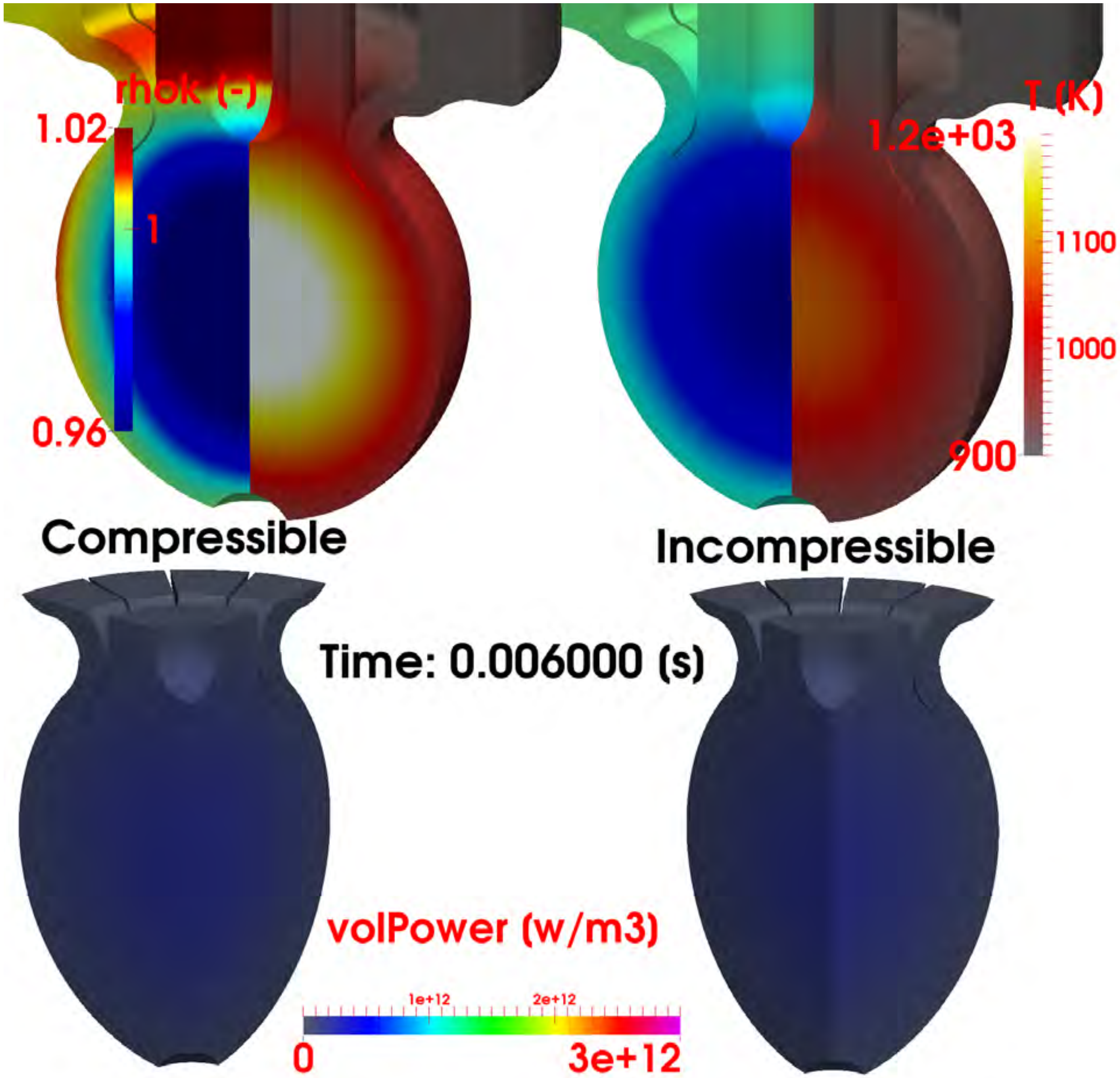
rhok (-)
1.02
1
0.96
T (K)
1.2e+03
1100
1000
900
Compressible
Incompressible
Time: 0.005750 (s)
volPower (w/m3)
1e+12
2e+12
0
3e+12

MSFR super prompt-critical burst
Effect of fluid compressibility



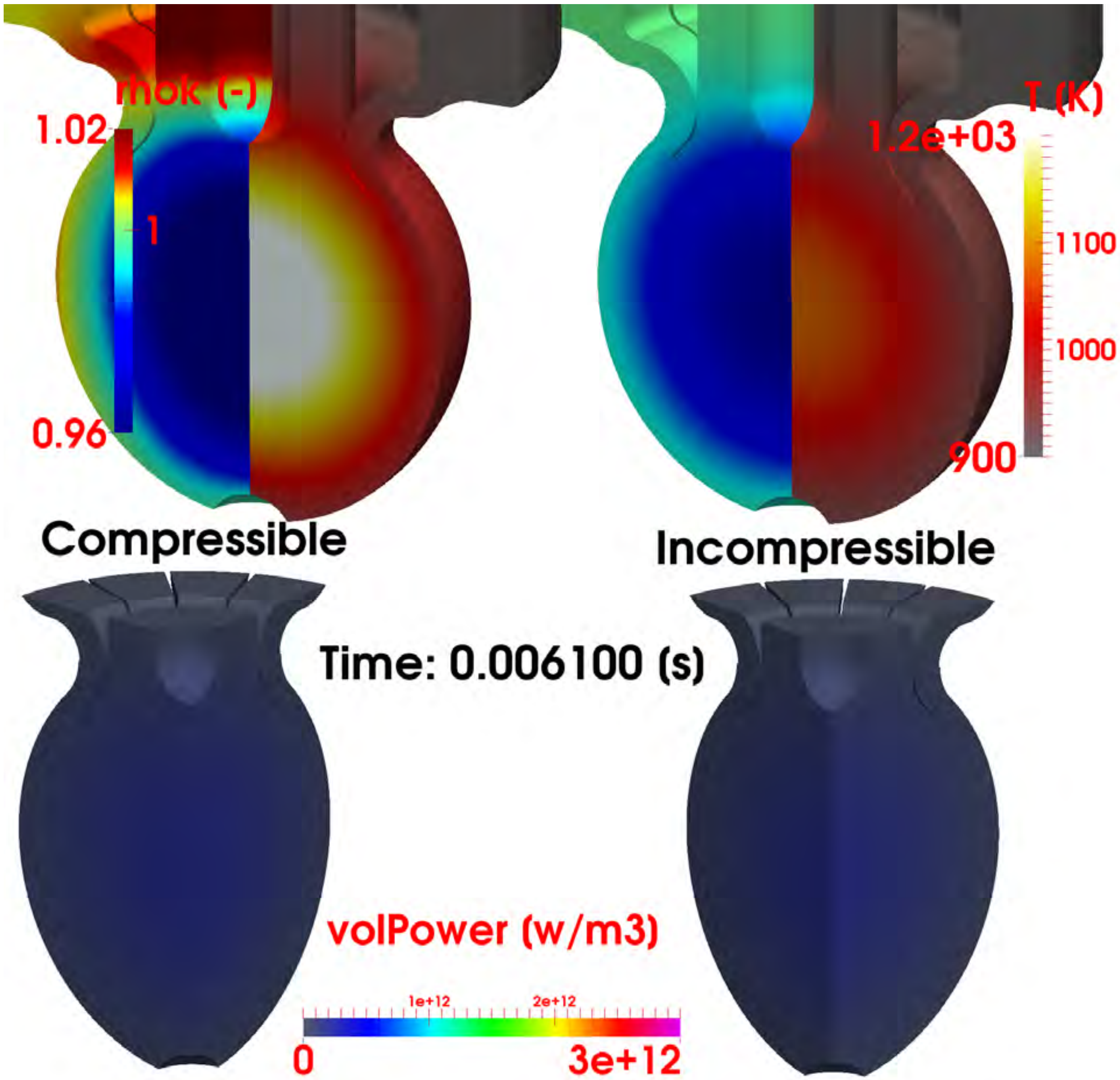
MSFR super prompt-critical burst

Effect of fluid compressibility

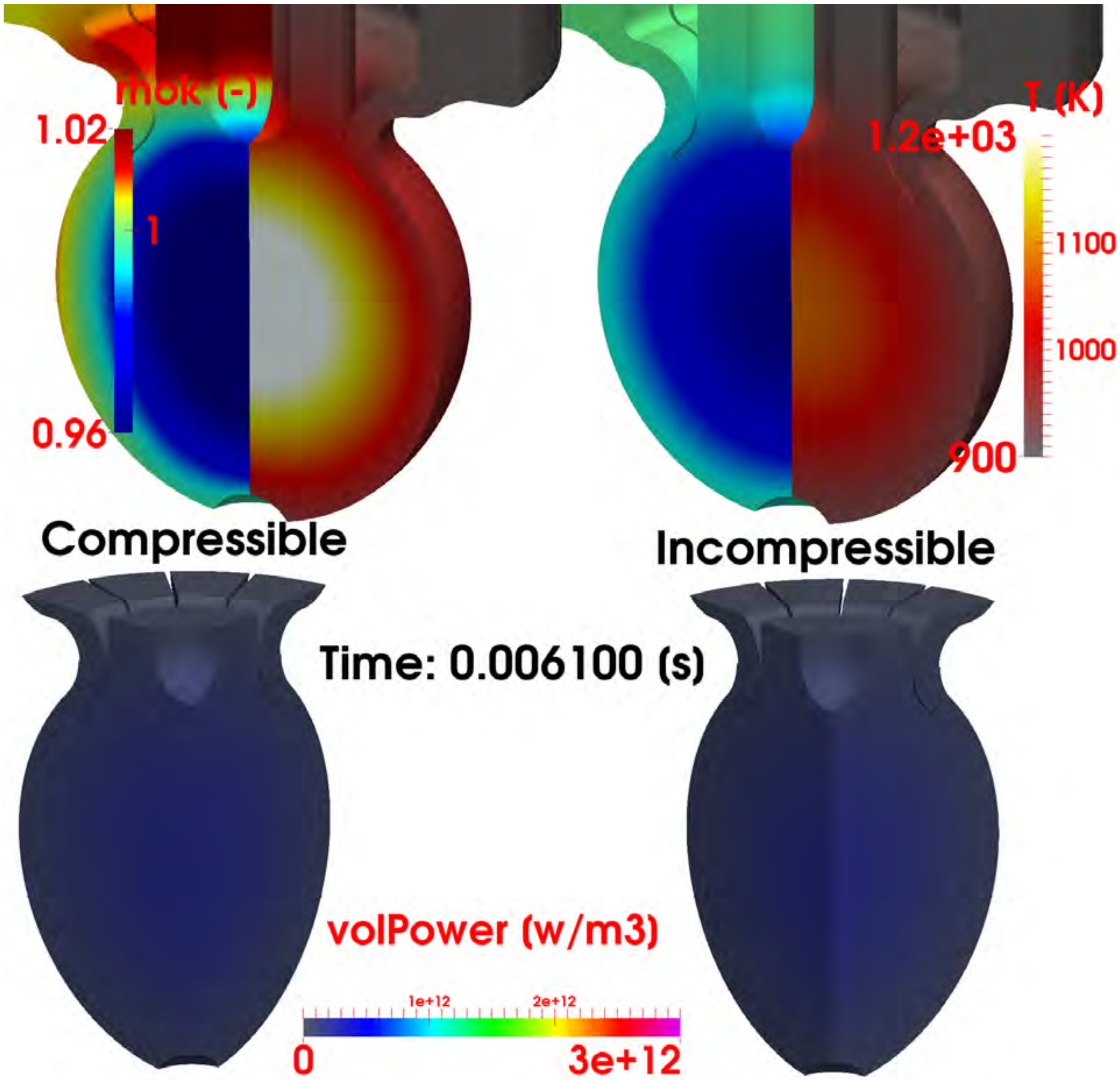


MSFR super prompt-critical burst

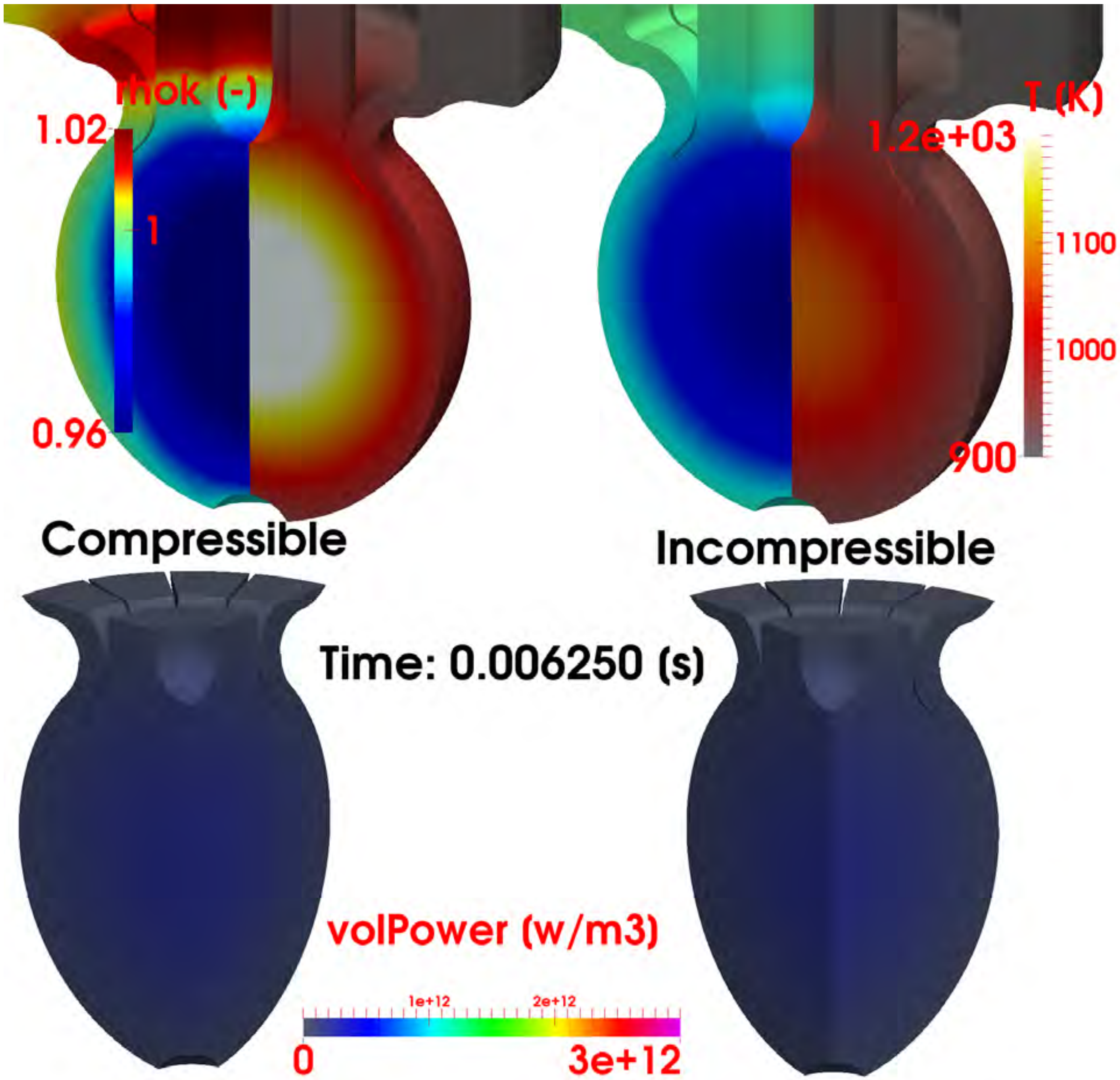
Effect of fluid compressibility

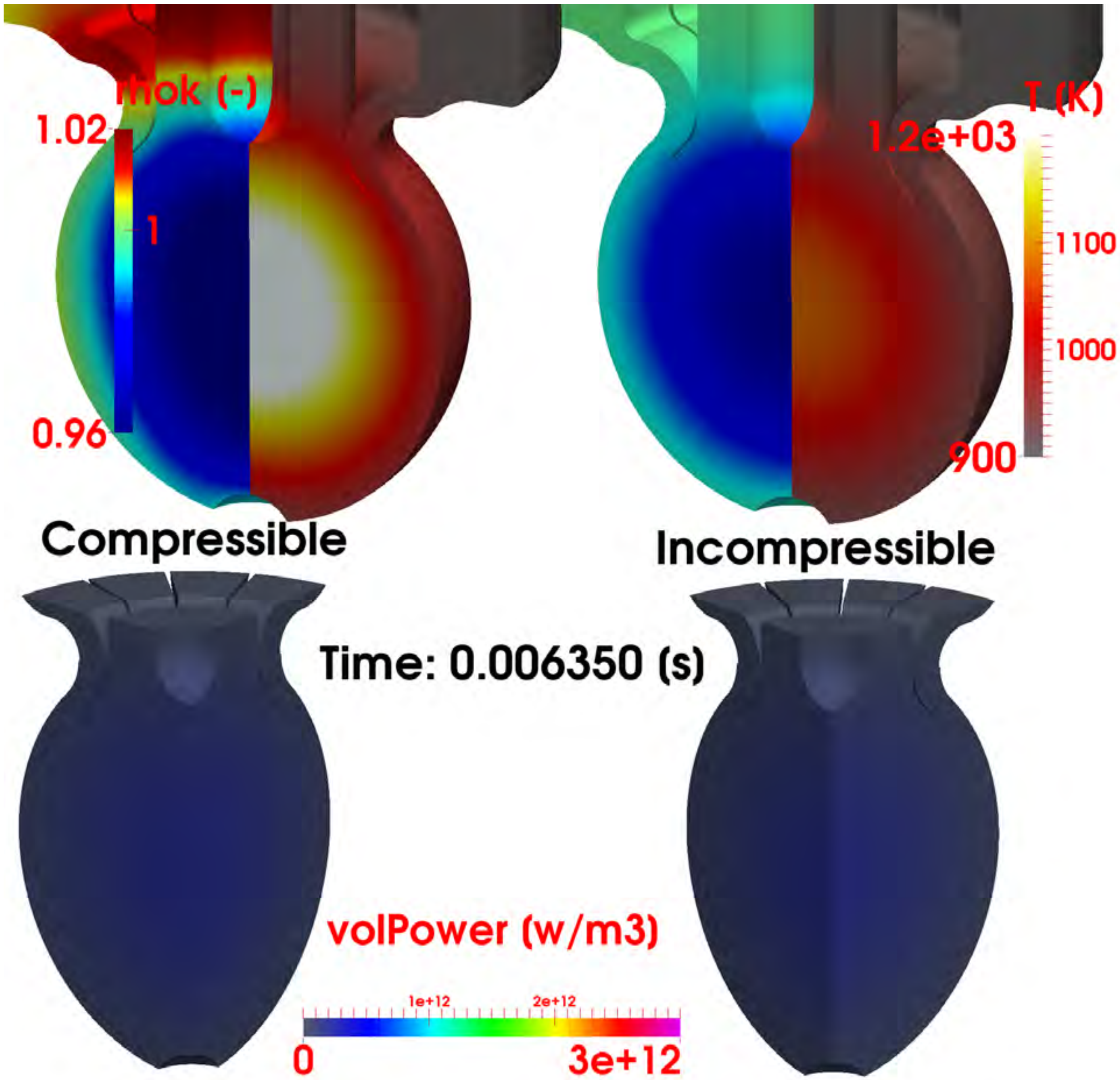


MSFR super prompt-critical burst
Effect of fluid compressibility



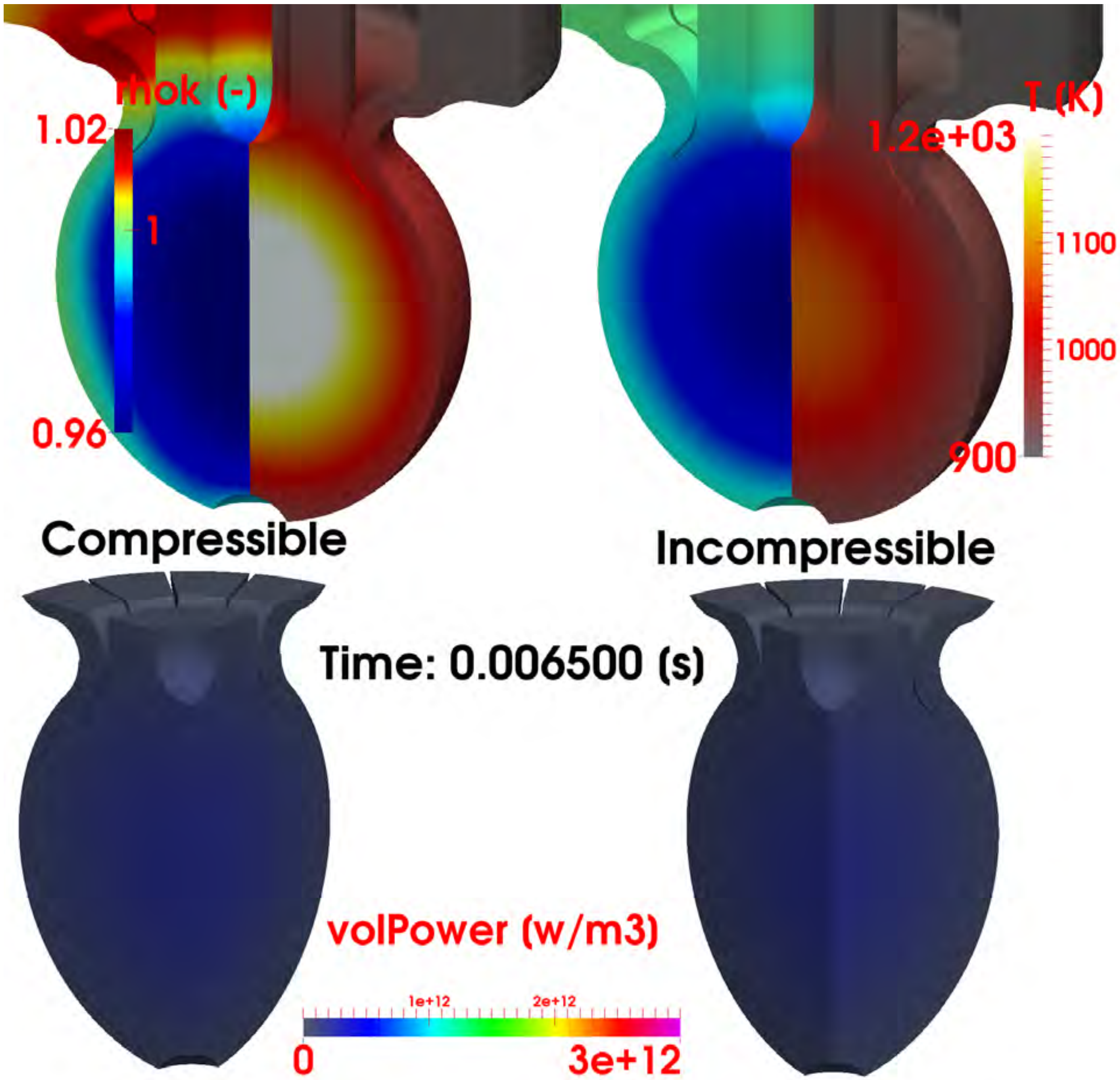
MSFR super prompt-critical burst
Effect of fluid compressibility





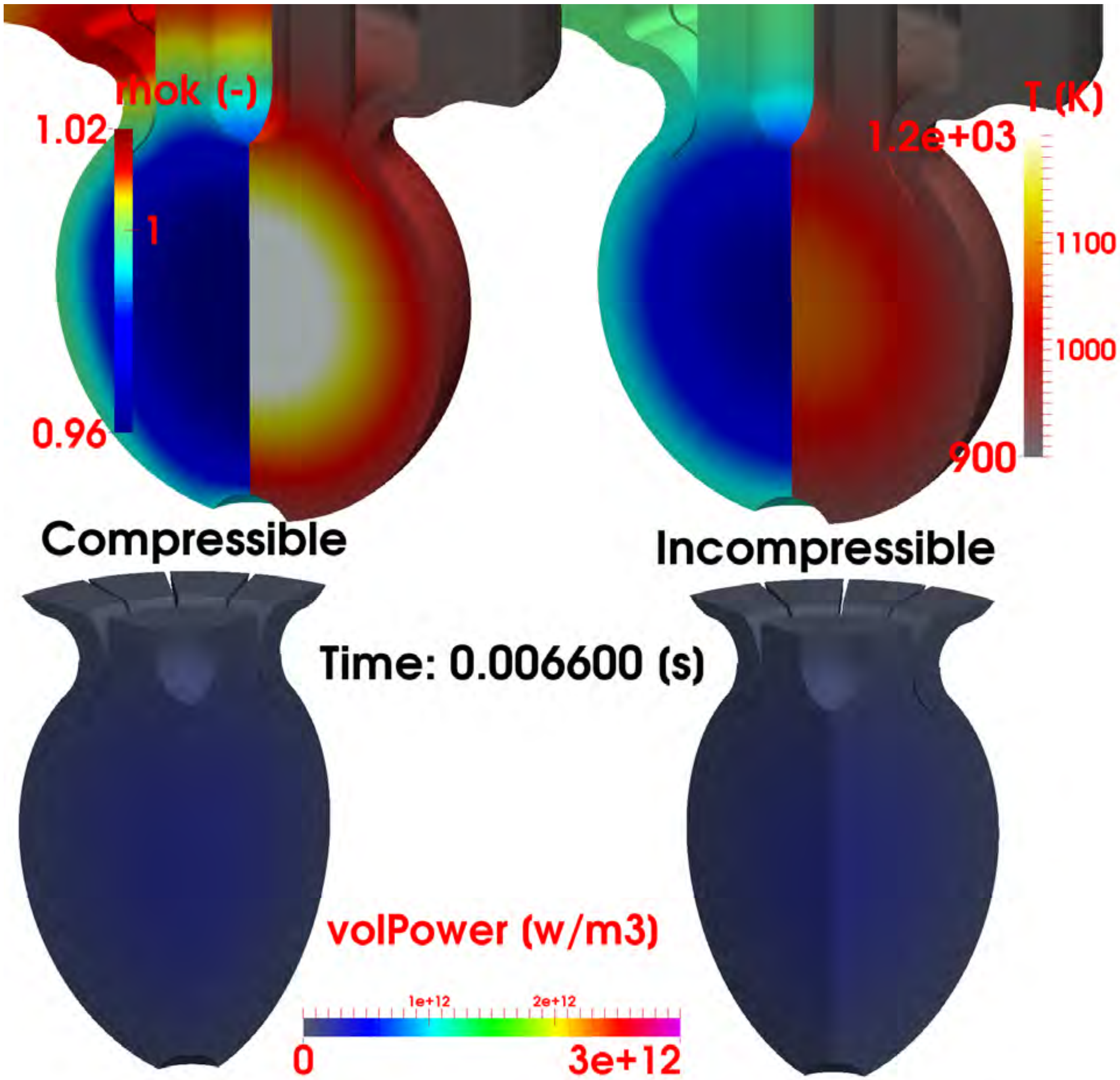
rhok (-)
1.02
1
0.96
T (K)
1.2e+03
1100
1000
900
Compressible
Incompressible
Time: 0.006350 (s)
volPower (w/m3)
1e+12
2e+12
0
3e+12

MSFR super prompt-critical burst
Effect of fluid compressibility



MSFR super prompt-critical burst

Effect of fluid compressibility



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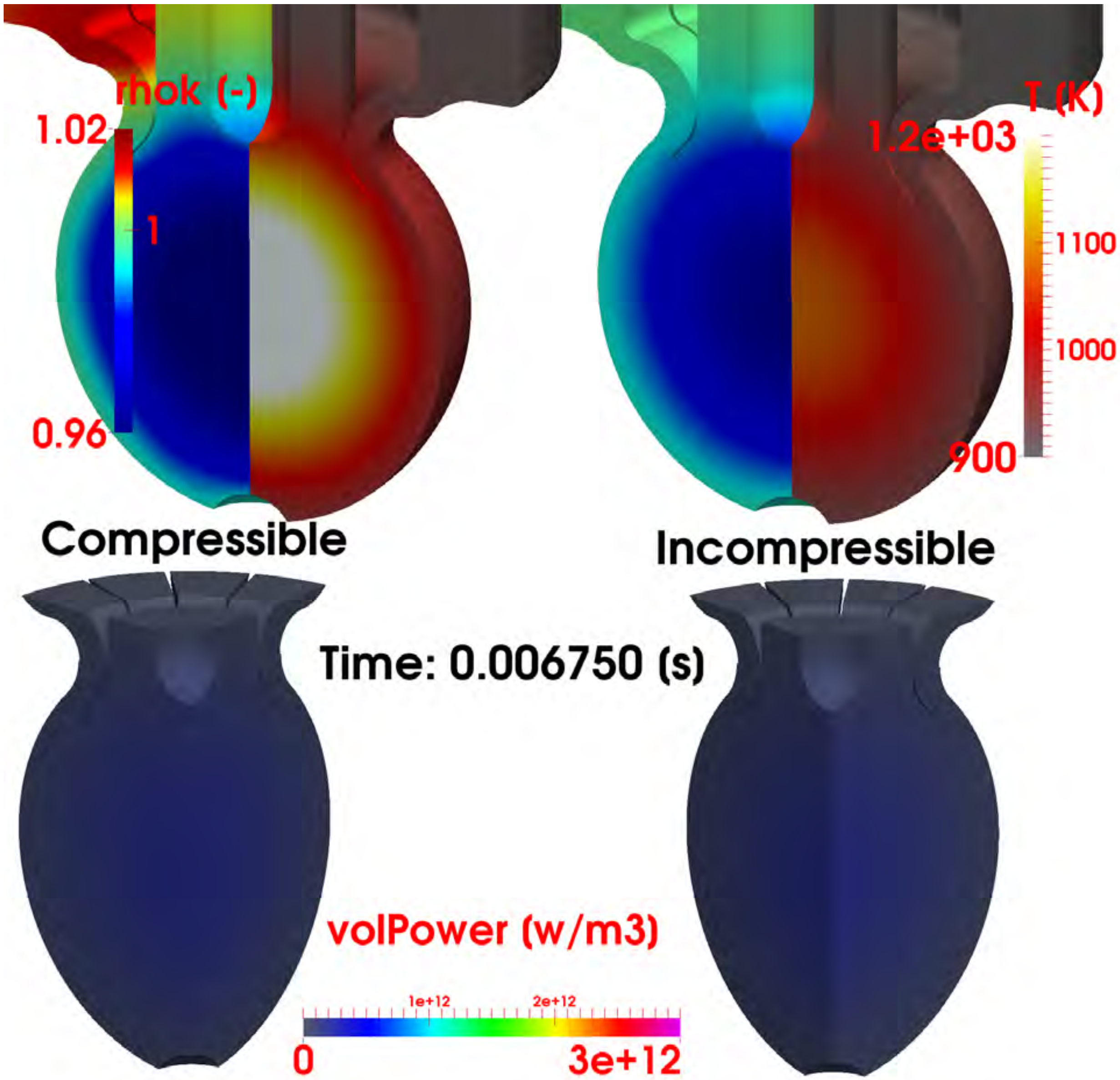
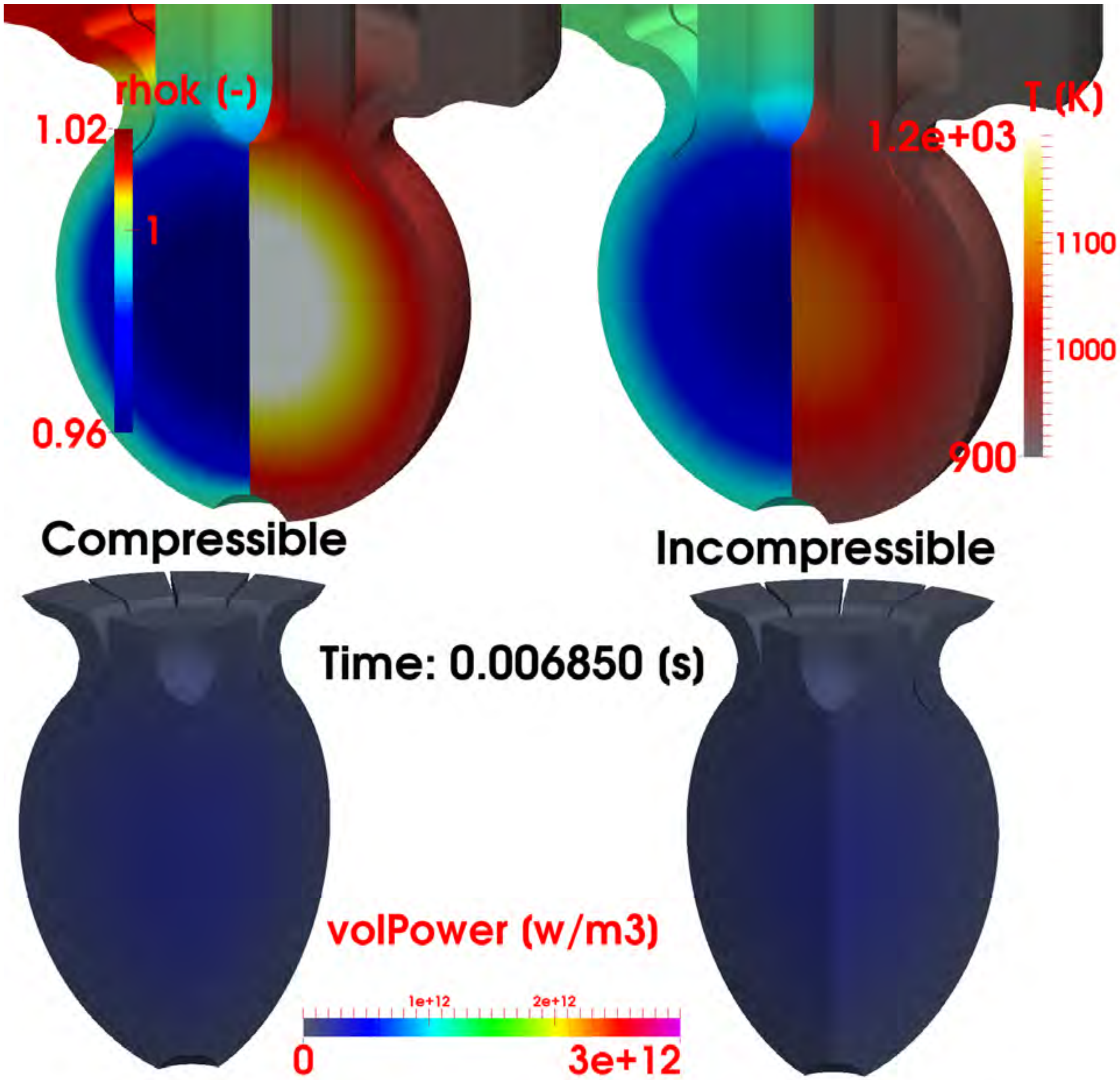
MSFR super prompt-critical burst
Effect of fluid compressibility



MSFR super prompt-critical burst

Effect of fluid compressibility



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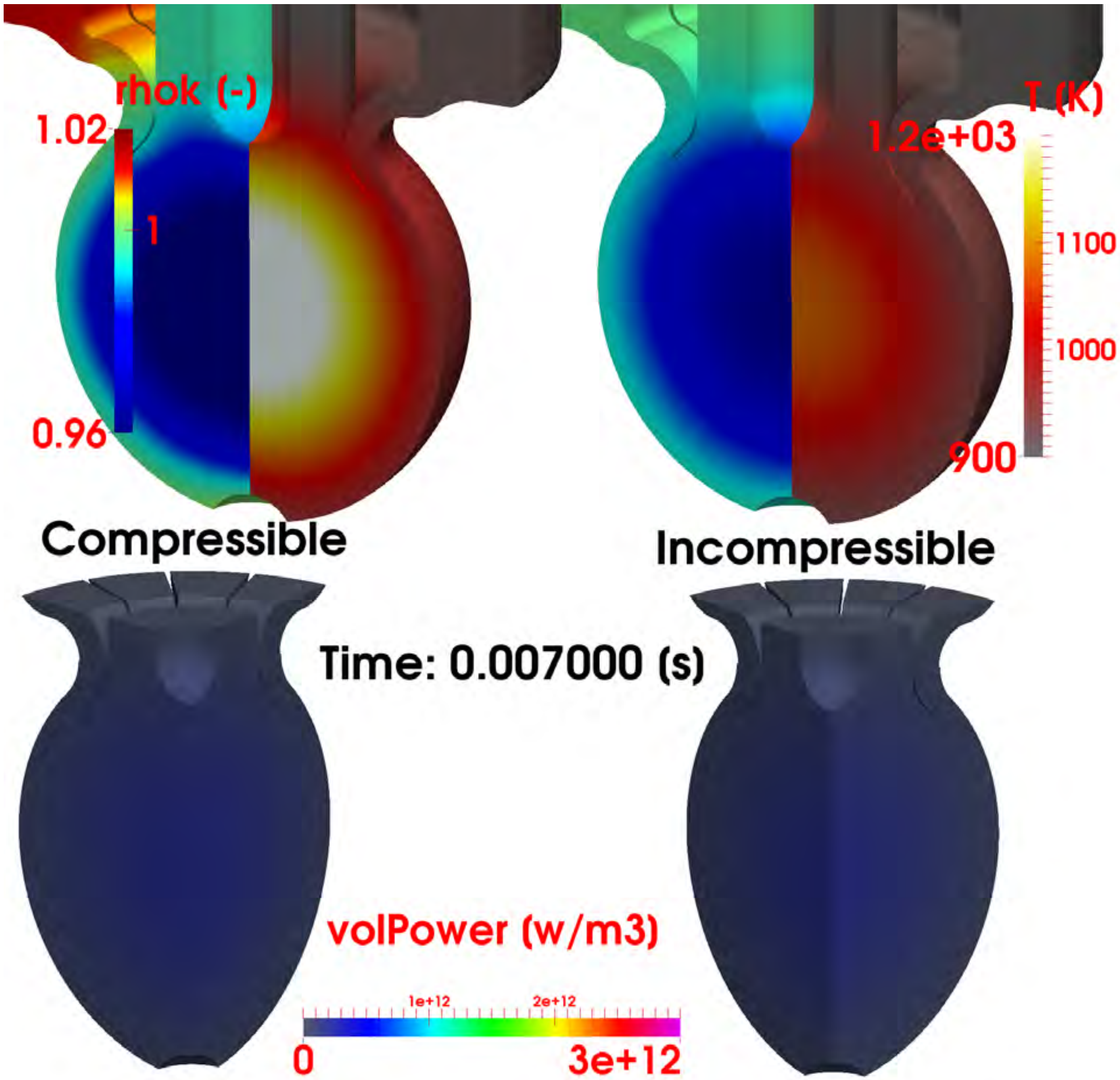
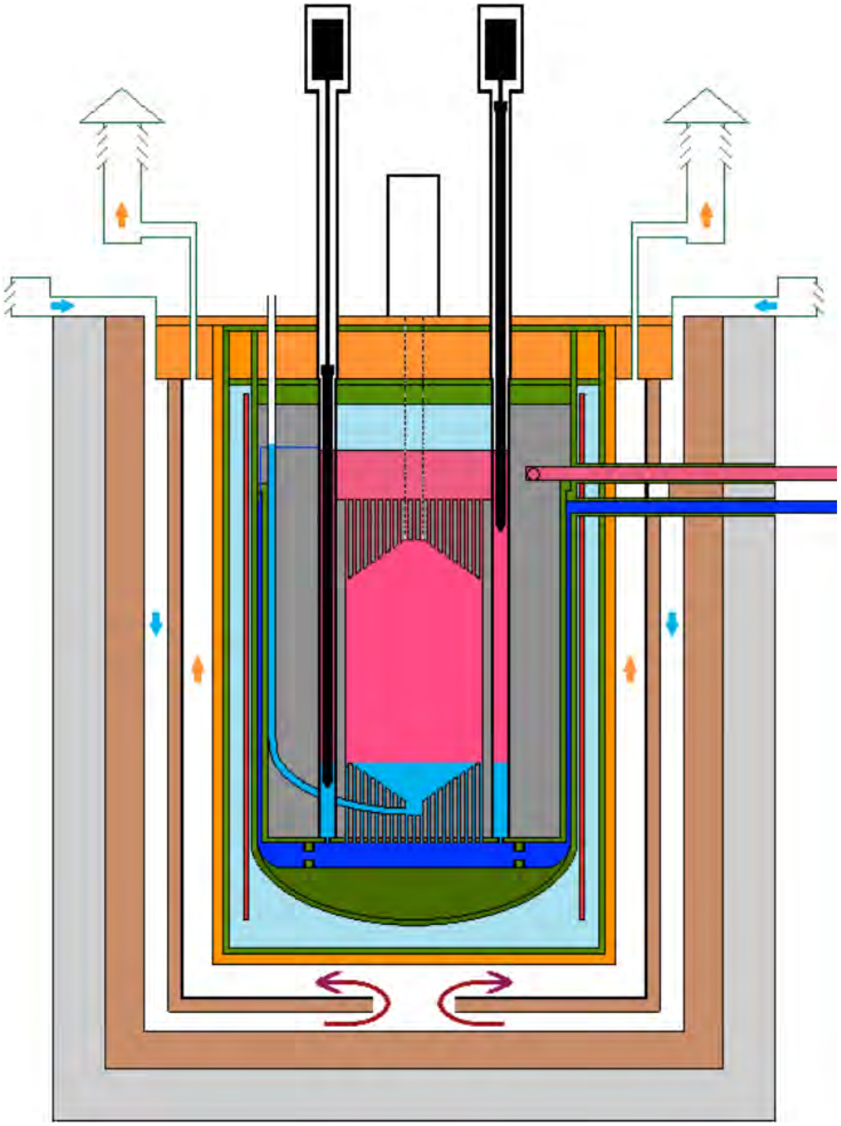
MSFR super prompt-critical burst
Effect of fluid compressibility

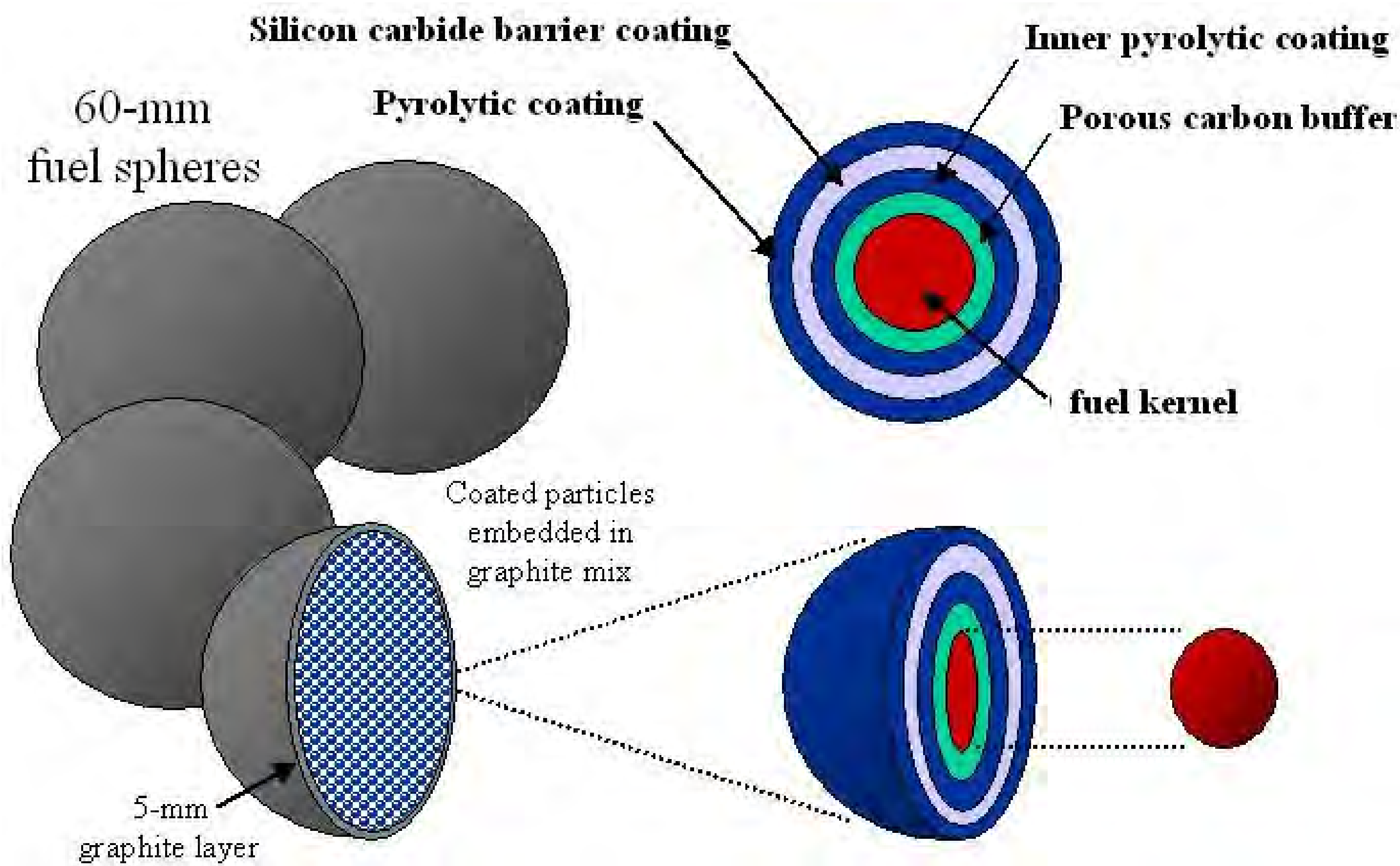


The TMSR-SF

10 MW demonstrator test reactor developed by the Shanghai Institute of Applied Physics and Chinese Academy of Sciences



The TMSR-SF



Silicon carbide barrier coating
Inner pyrolytic coating
60-mm
fuel spheres
Pyrolytic coating
Porous carbon buffer
fuel kernel
Coated particles
embedded in
graphite mix
5-mm
graphite layer

The TMSR-SF

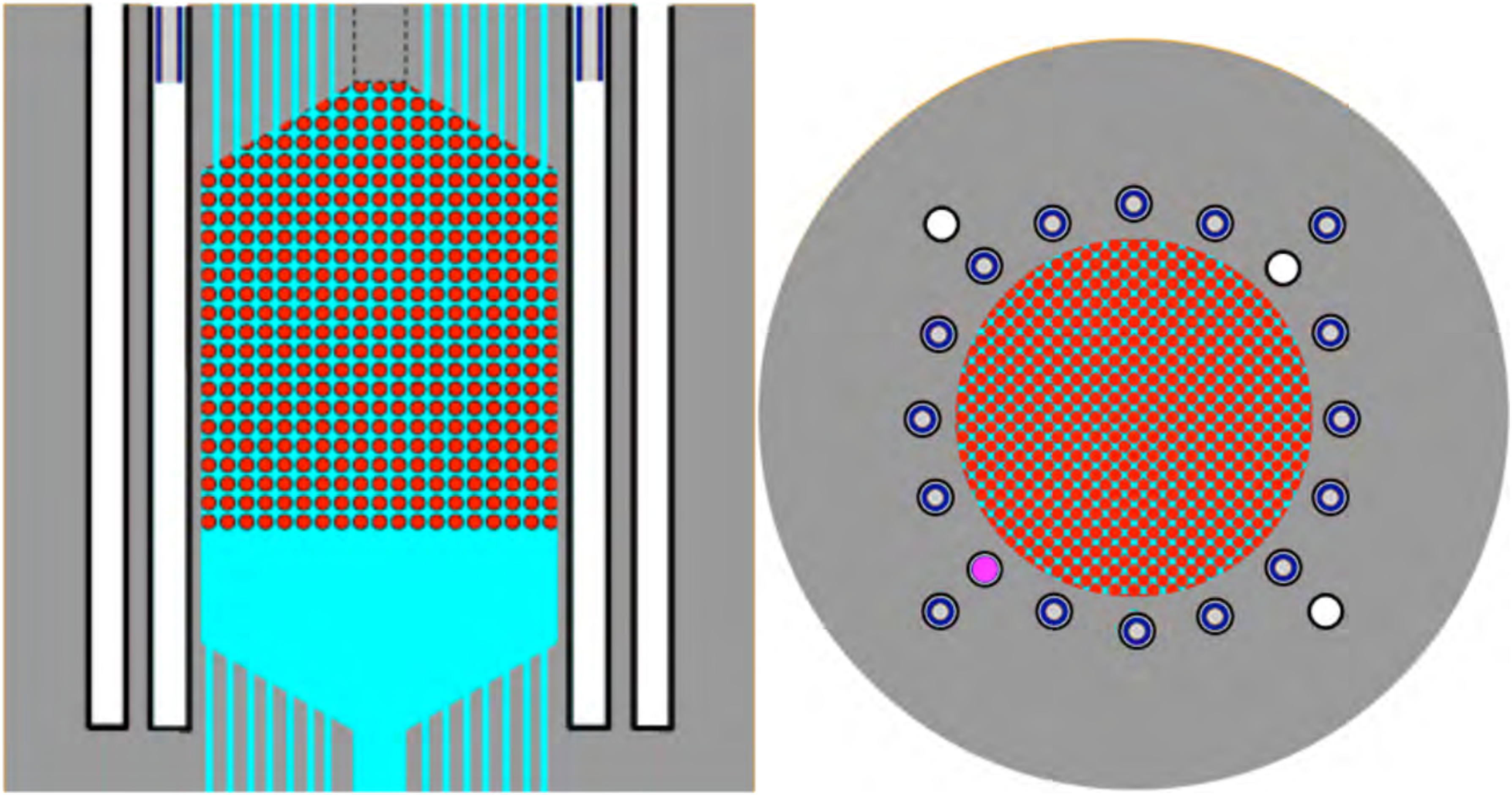


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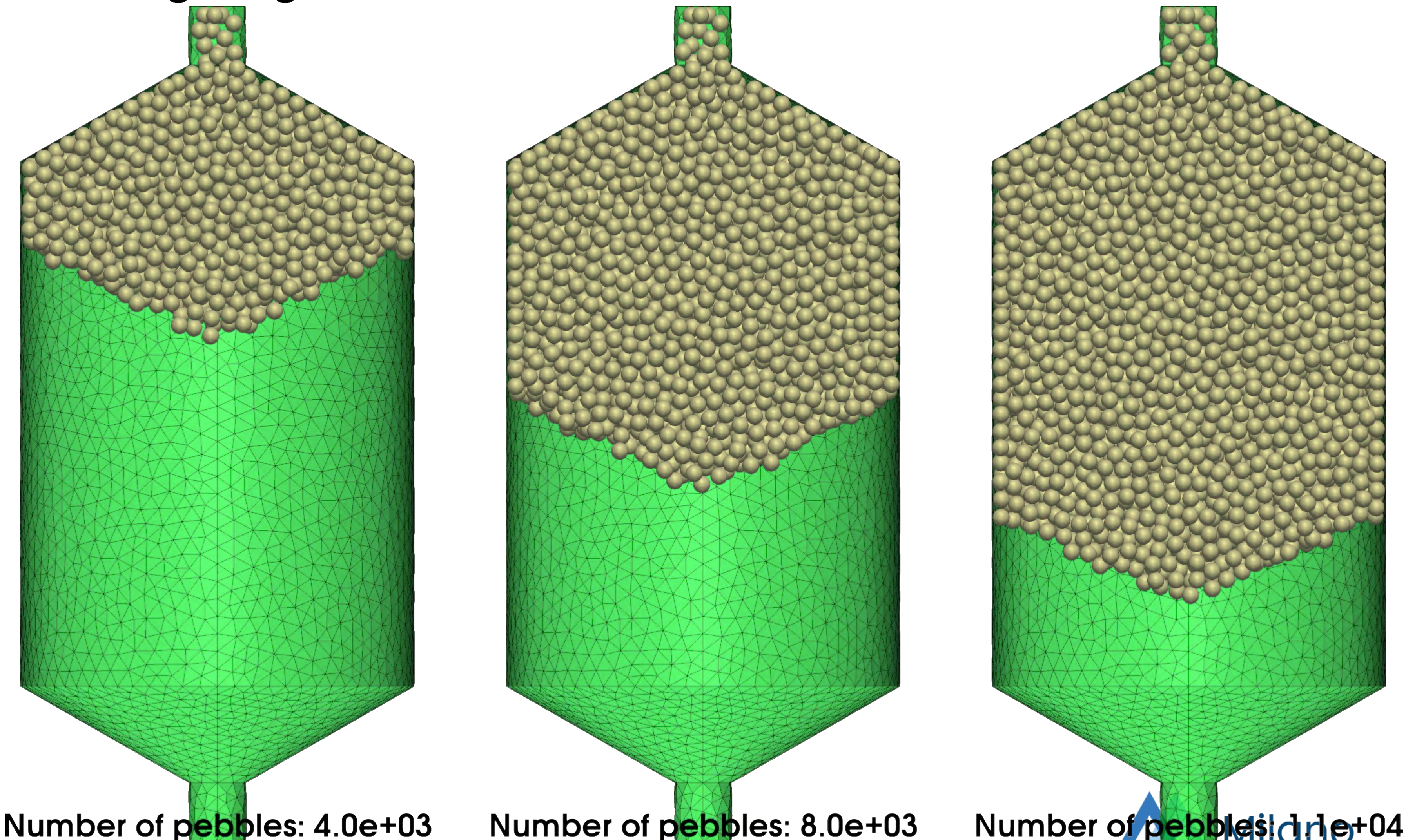
Table: Main parameters applied in the Serpent model of the TMSR-SF.

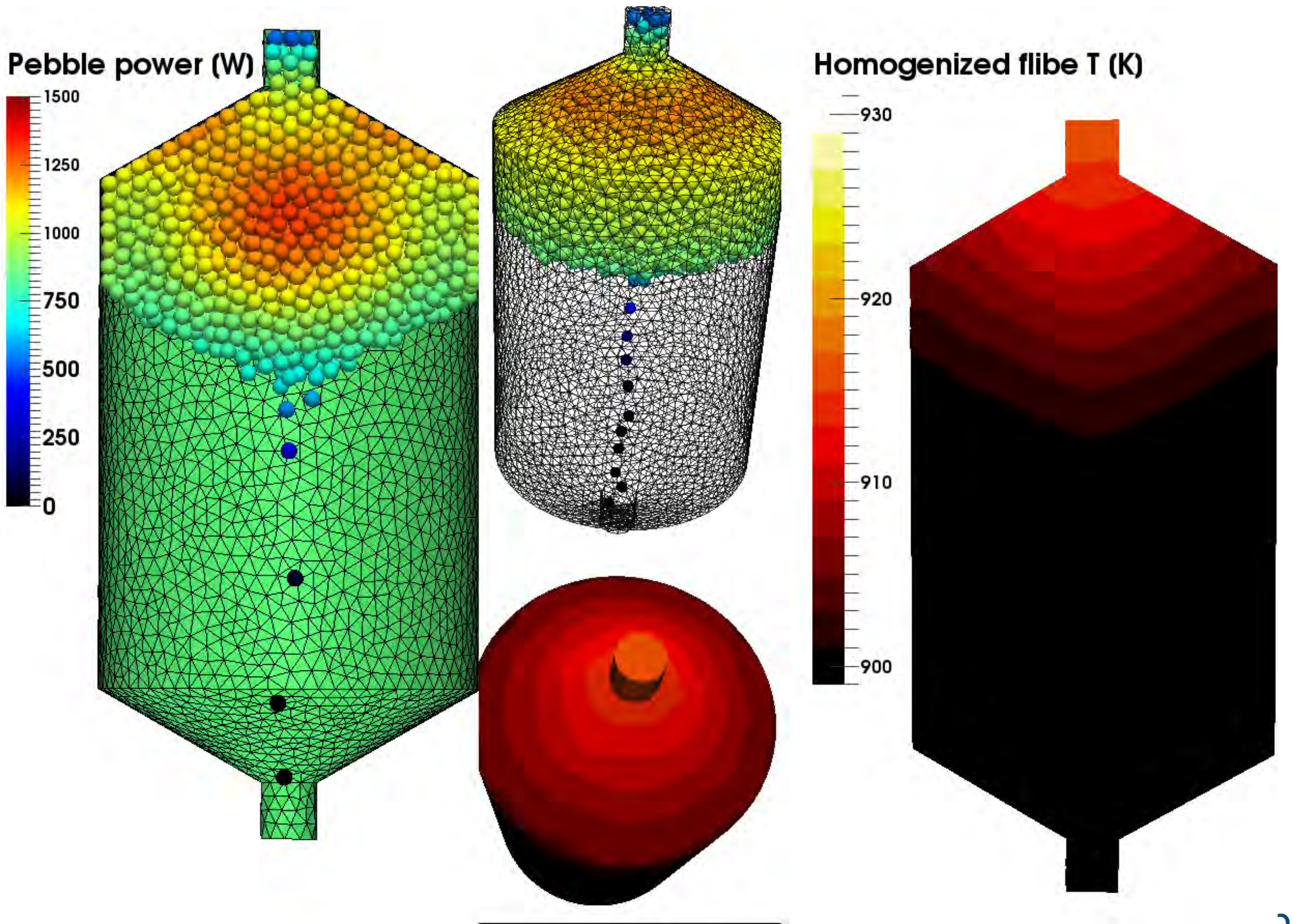
Parameter	Value
TRISO particles packing factor, %	7
Dispersion of TRISO particles inside pebbles	explicit random distribution
Number of fuel pebbles in the core	$\sim 11 \times 10^3$
Distribution of fuel pebbles in the core	OpenFOAM DEM model
Uranium enrichment, %	17
Uranium loading, g/pebble	~ 7
^{7}Li enrichment in flibe coolant, at.%	99.99
Coolant mass flow rate, $kg\,s^{-1}$	150
Reactor thermal power, MW	10

Discrete element modeling

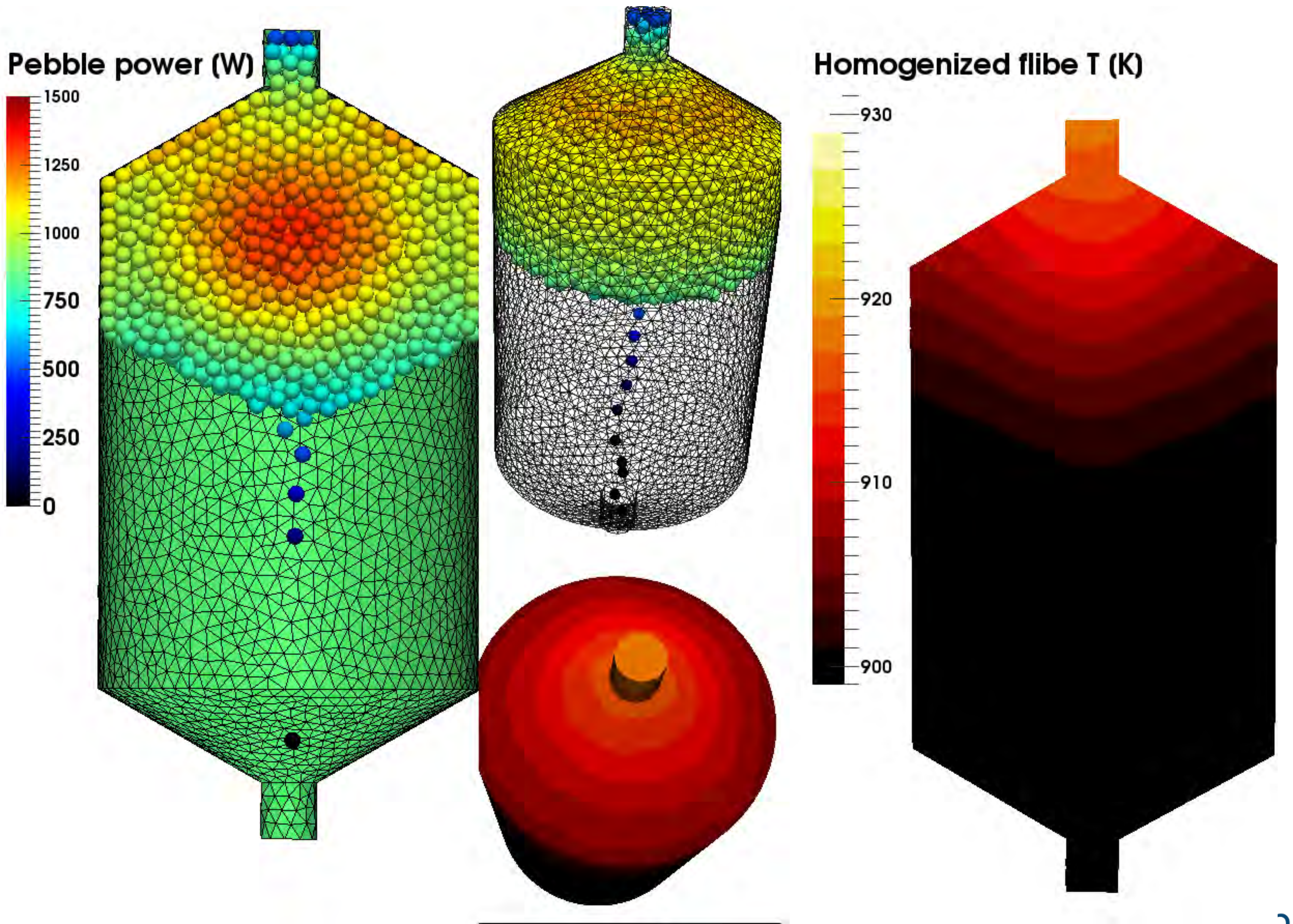
Solving the pebble-to-pebble and pebble-to-wall interactions
Including drag forces



Power and temperature distributions



Power and temperature distributions



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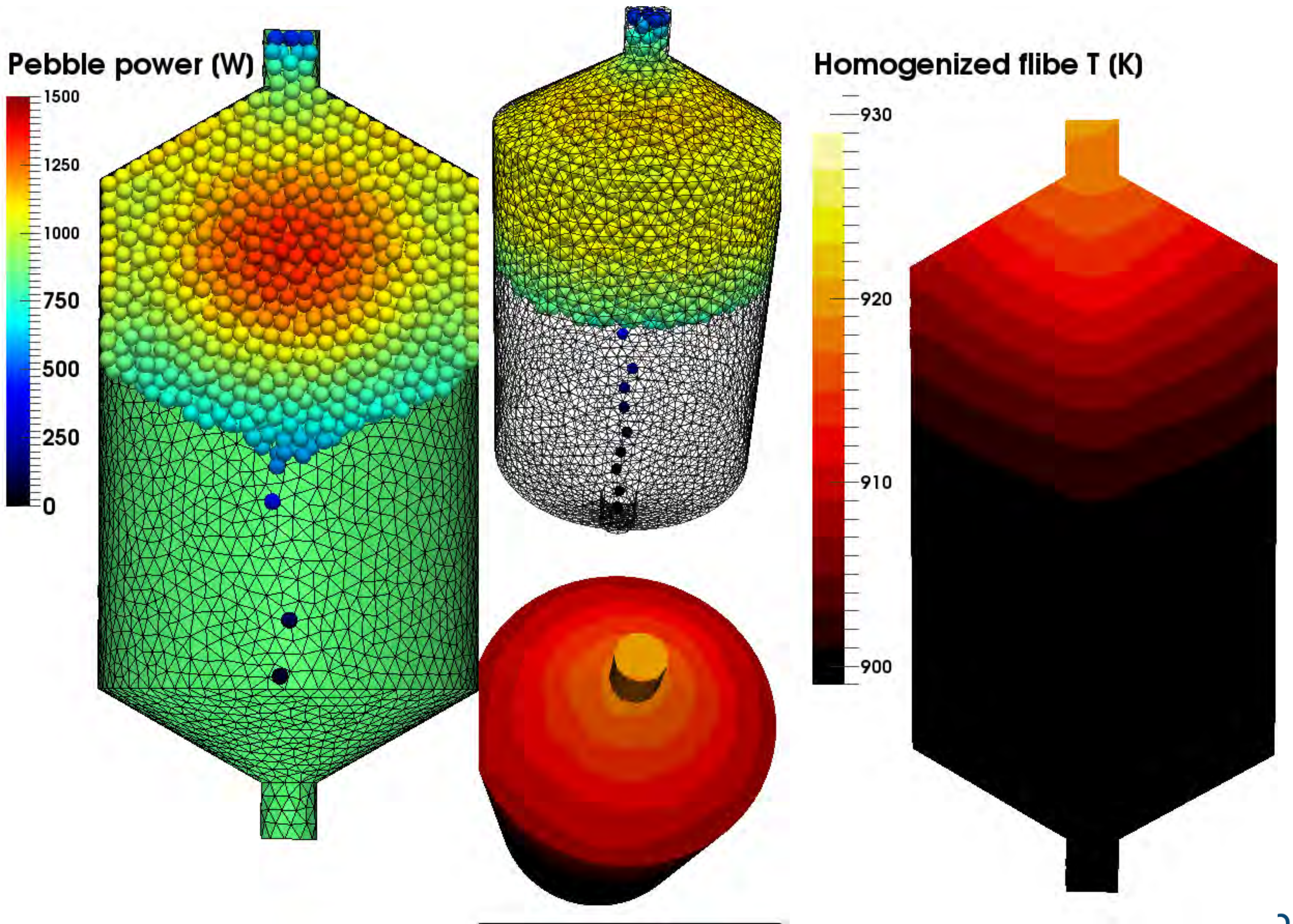
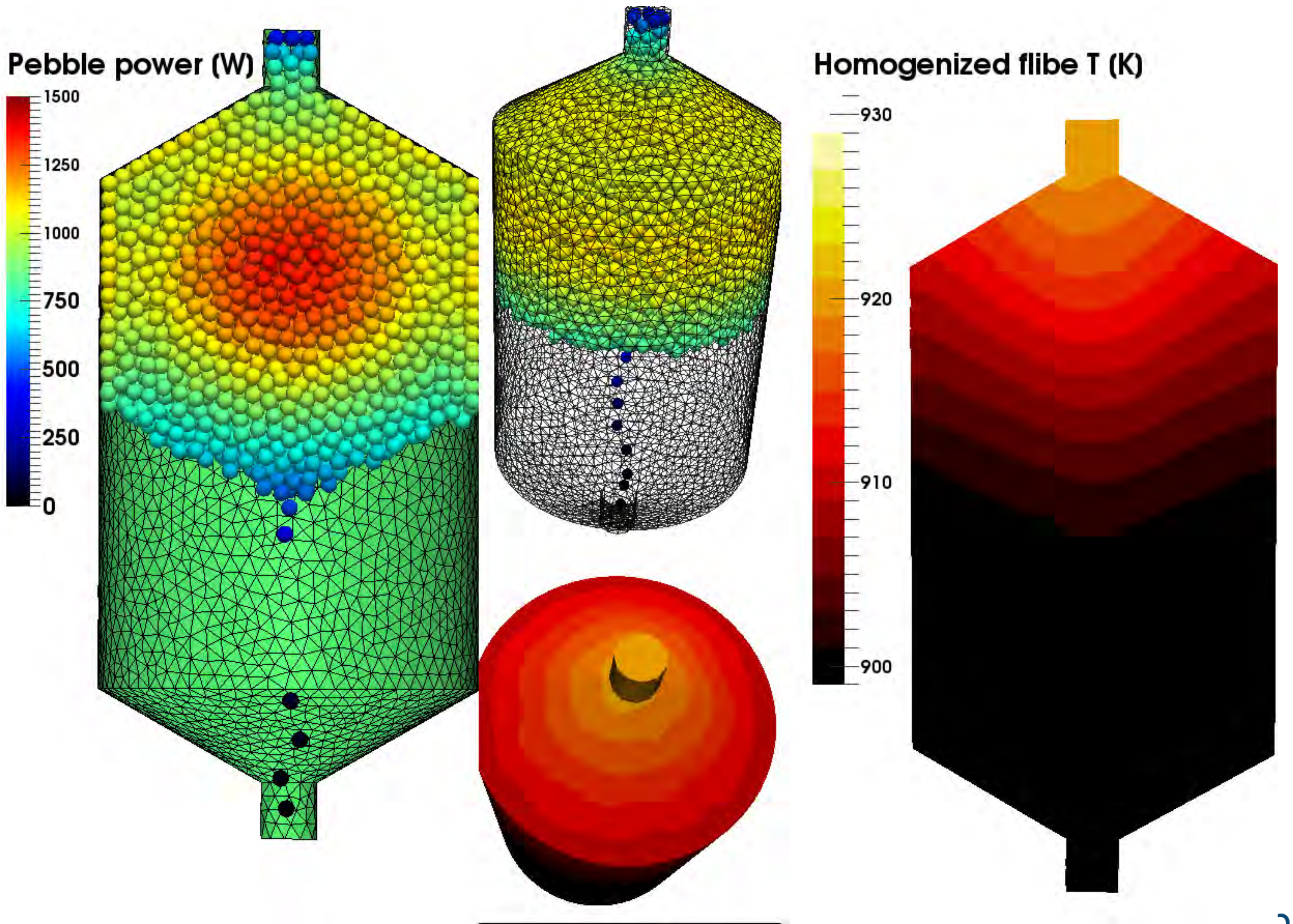
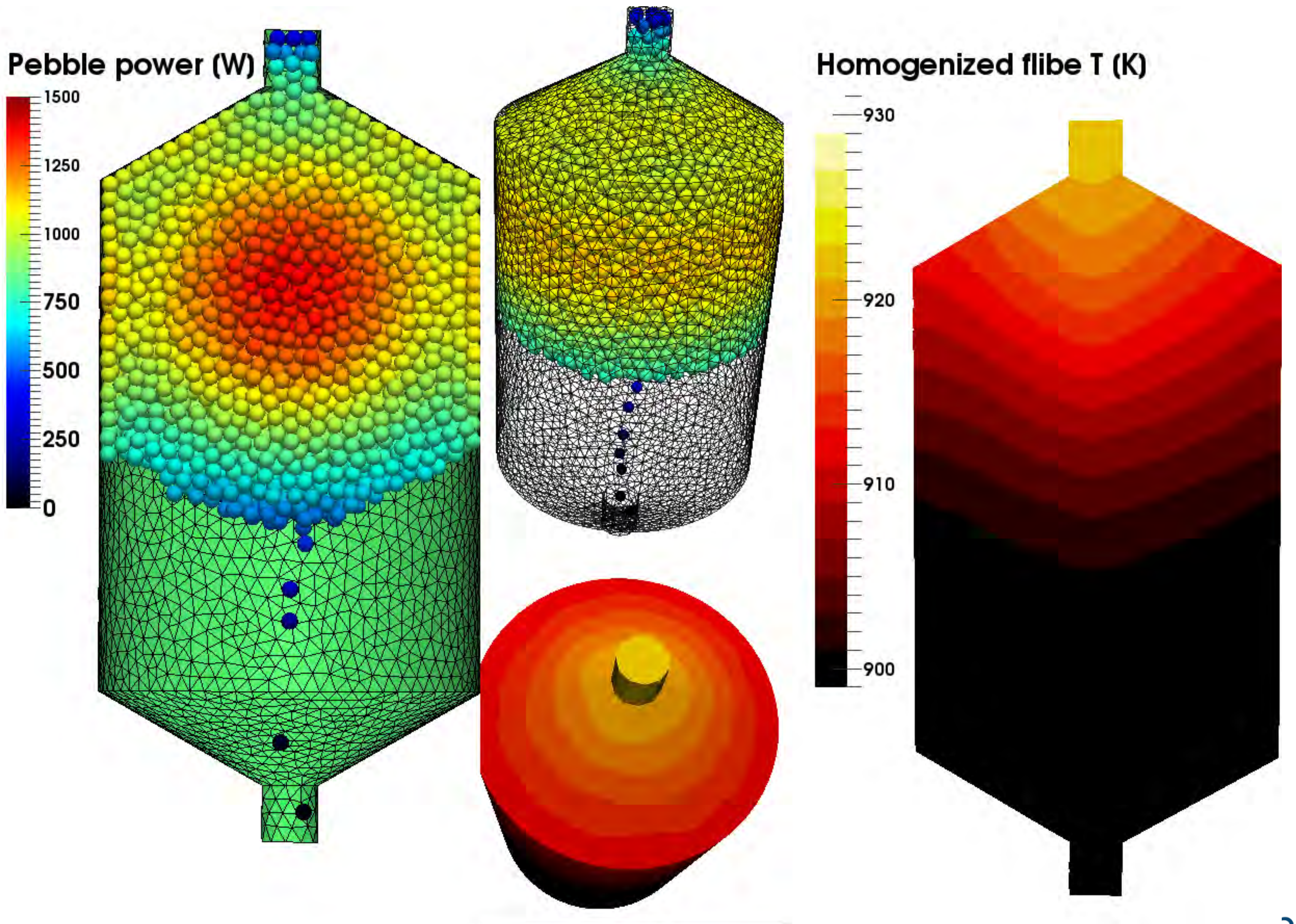
Power and temperature distributions



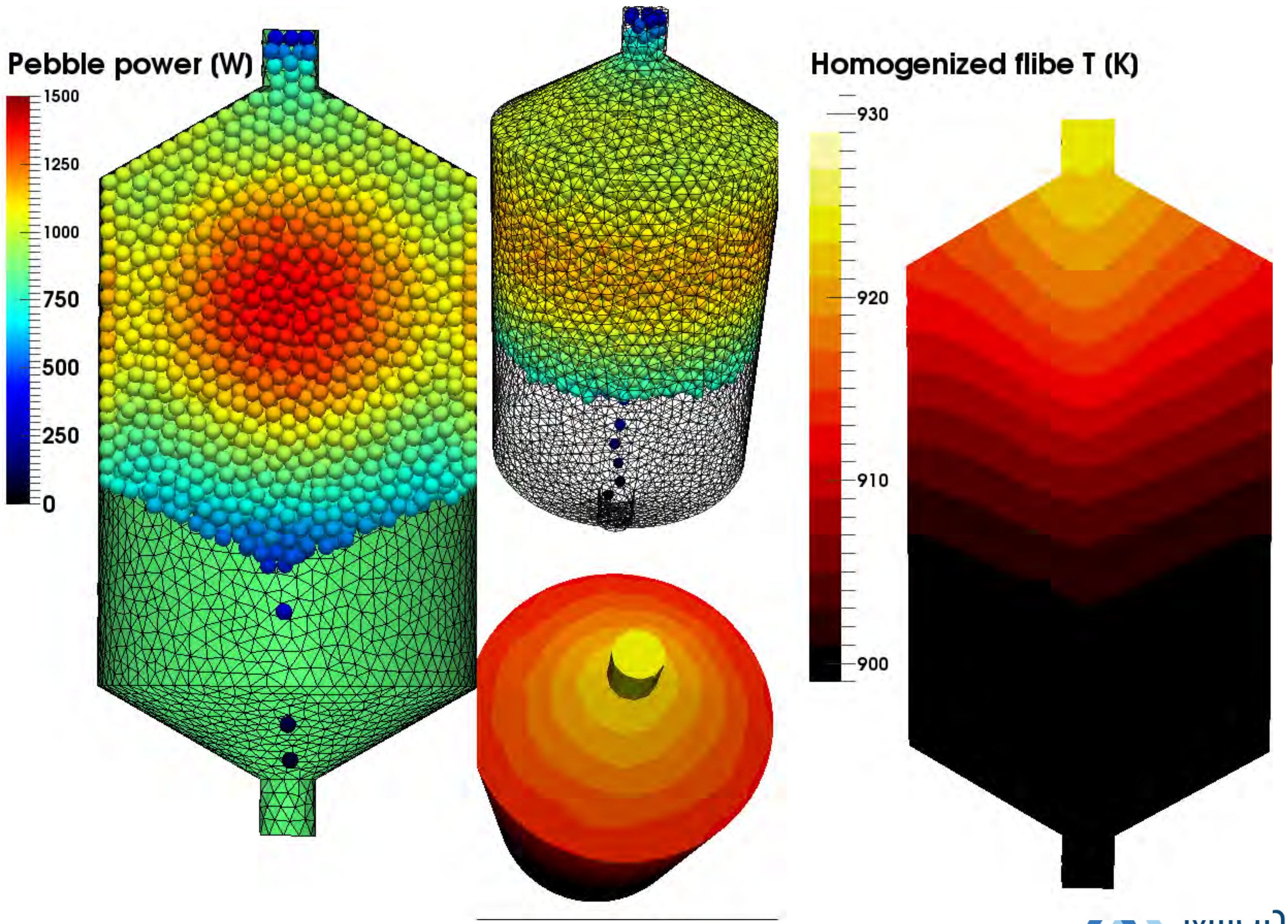
Power and temperature distributions



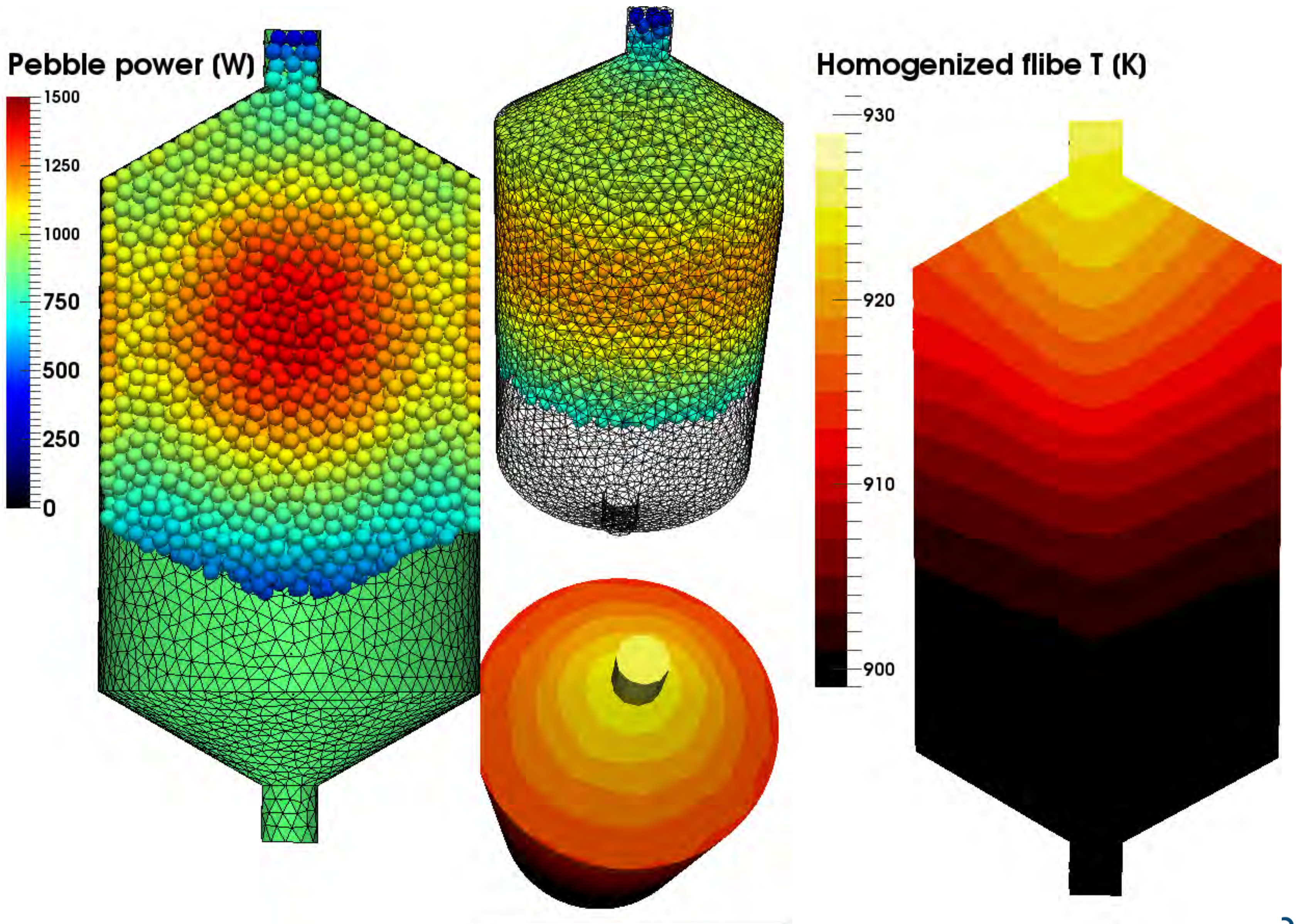
Power and temperature distributions



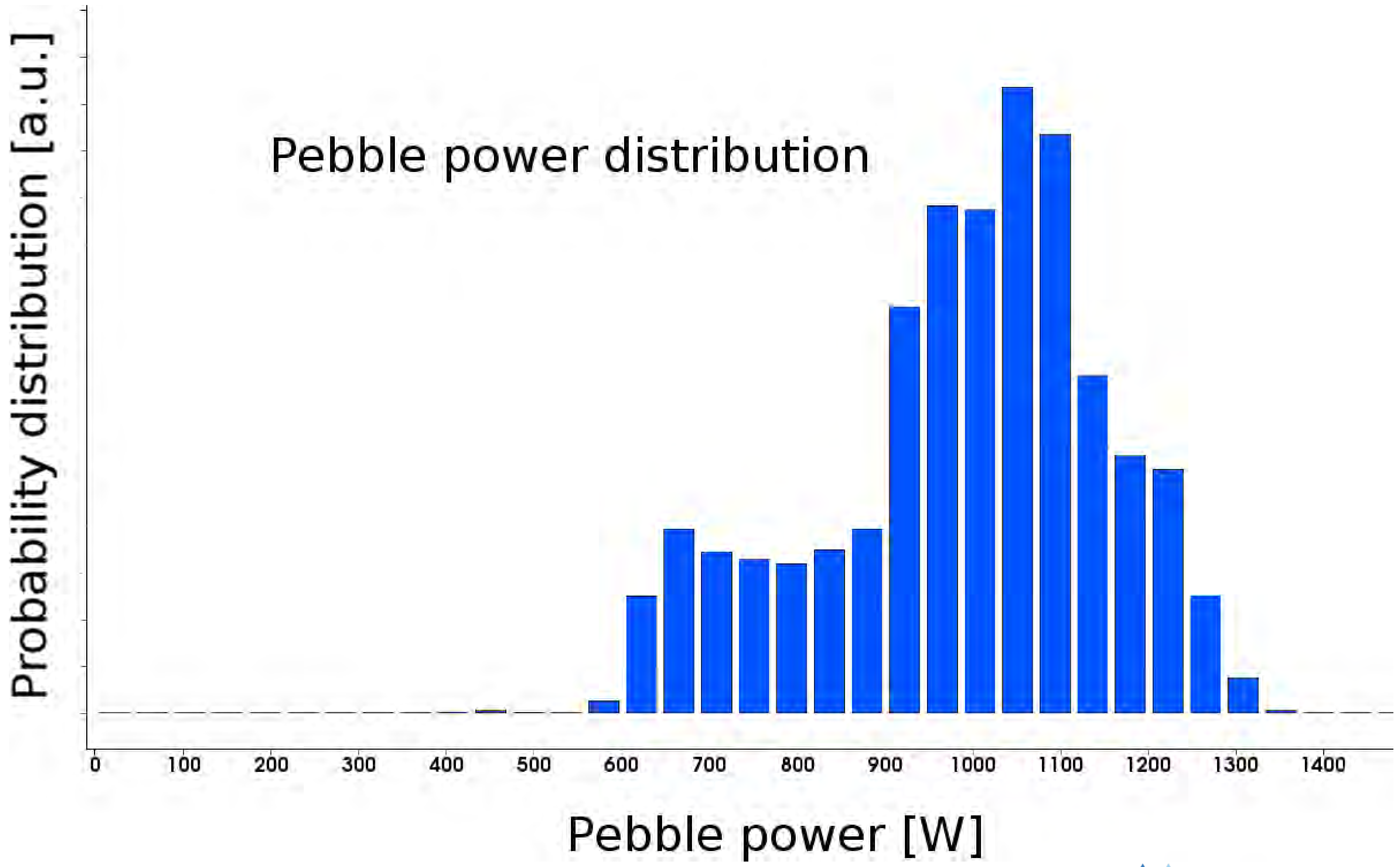
Power and temperature distributions



Power and temperature distributions

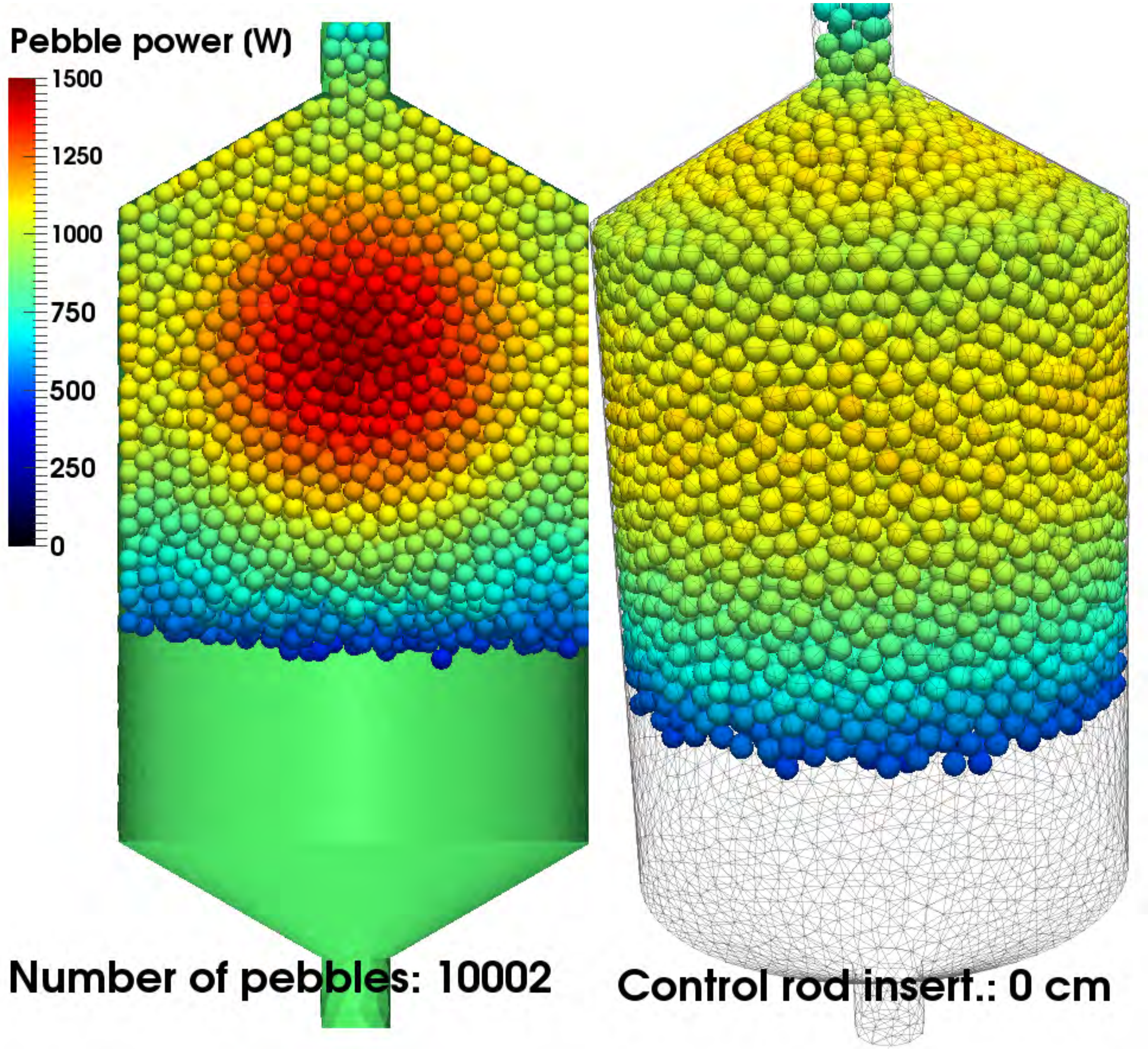


Power and temperature distributions

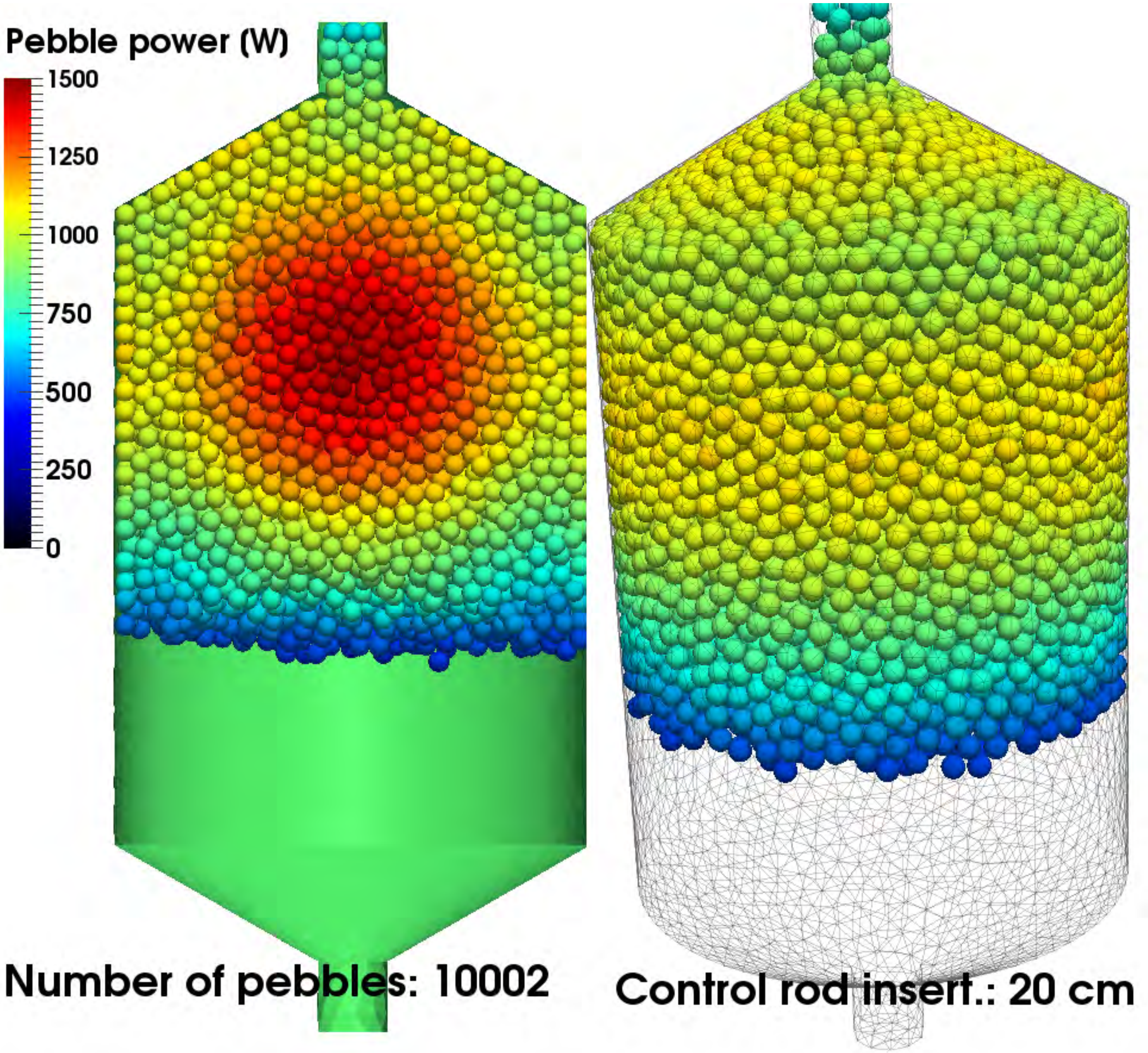


Effect of control rods insertion

Effect of control rods insertion



Effect of control rods insertion



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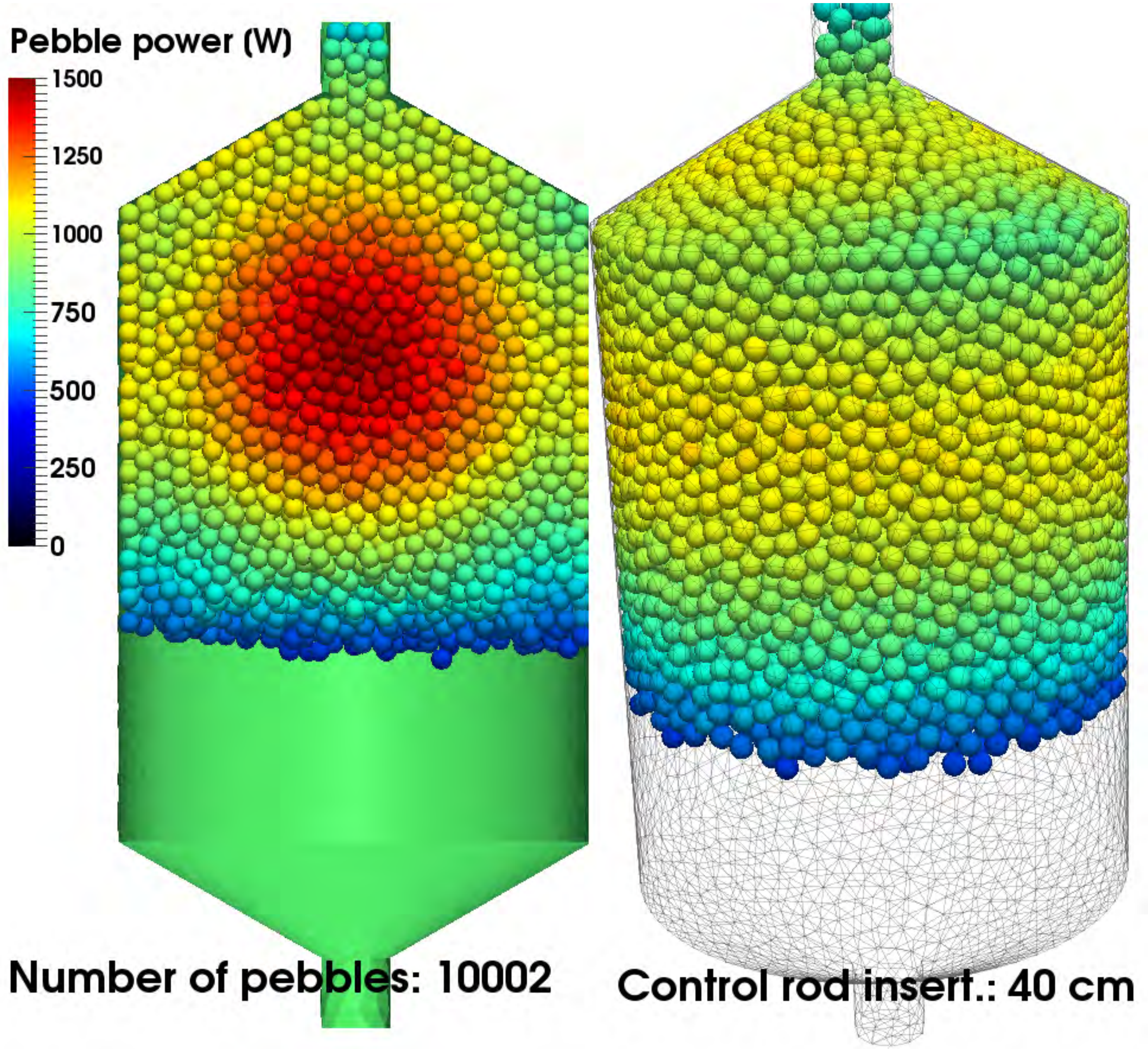
Effect of control rods insertion



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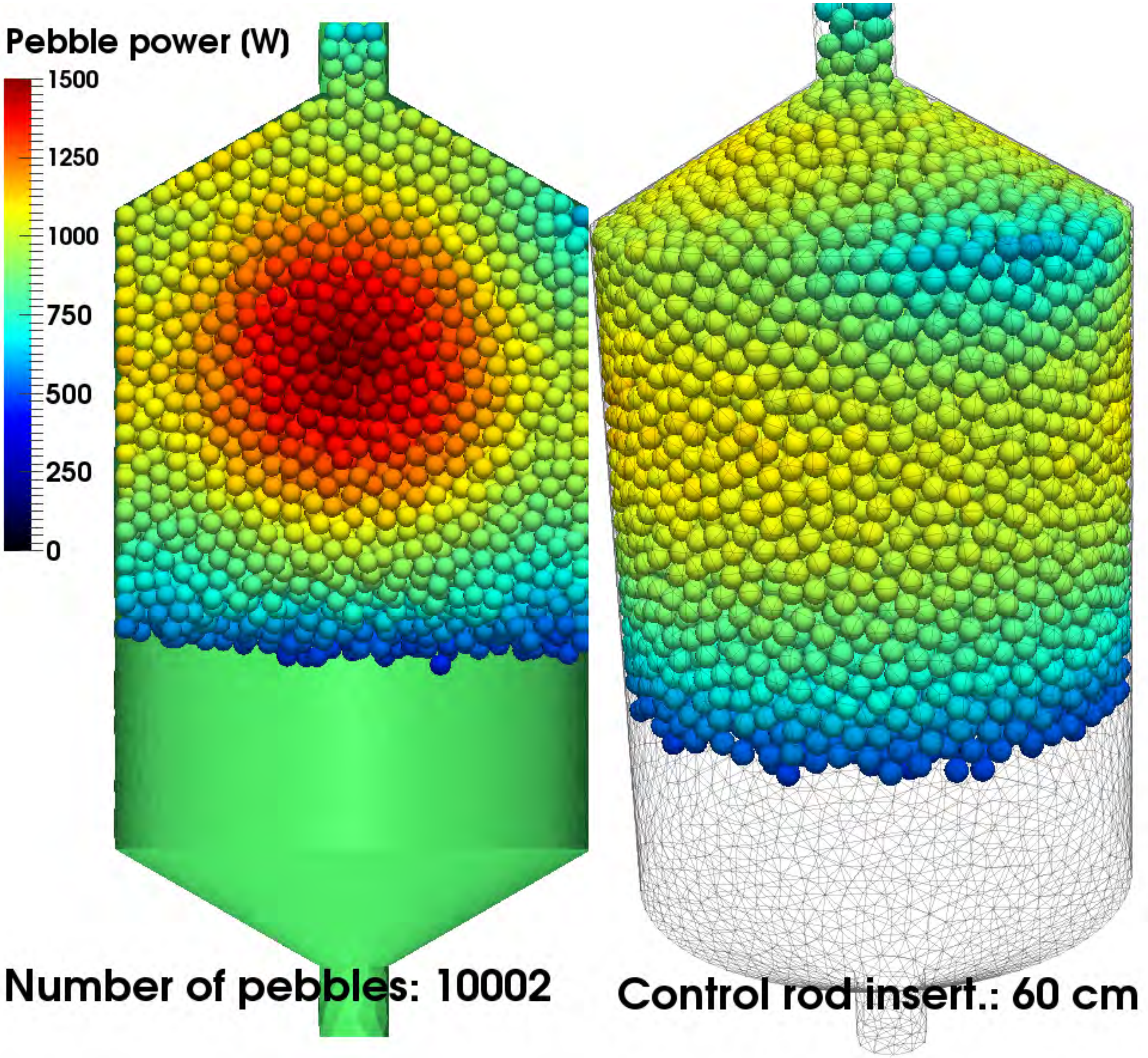

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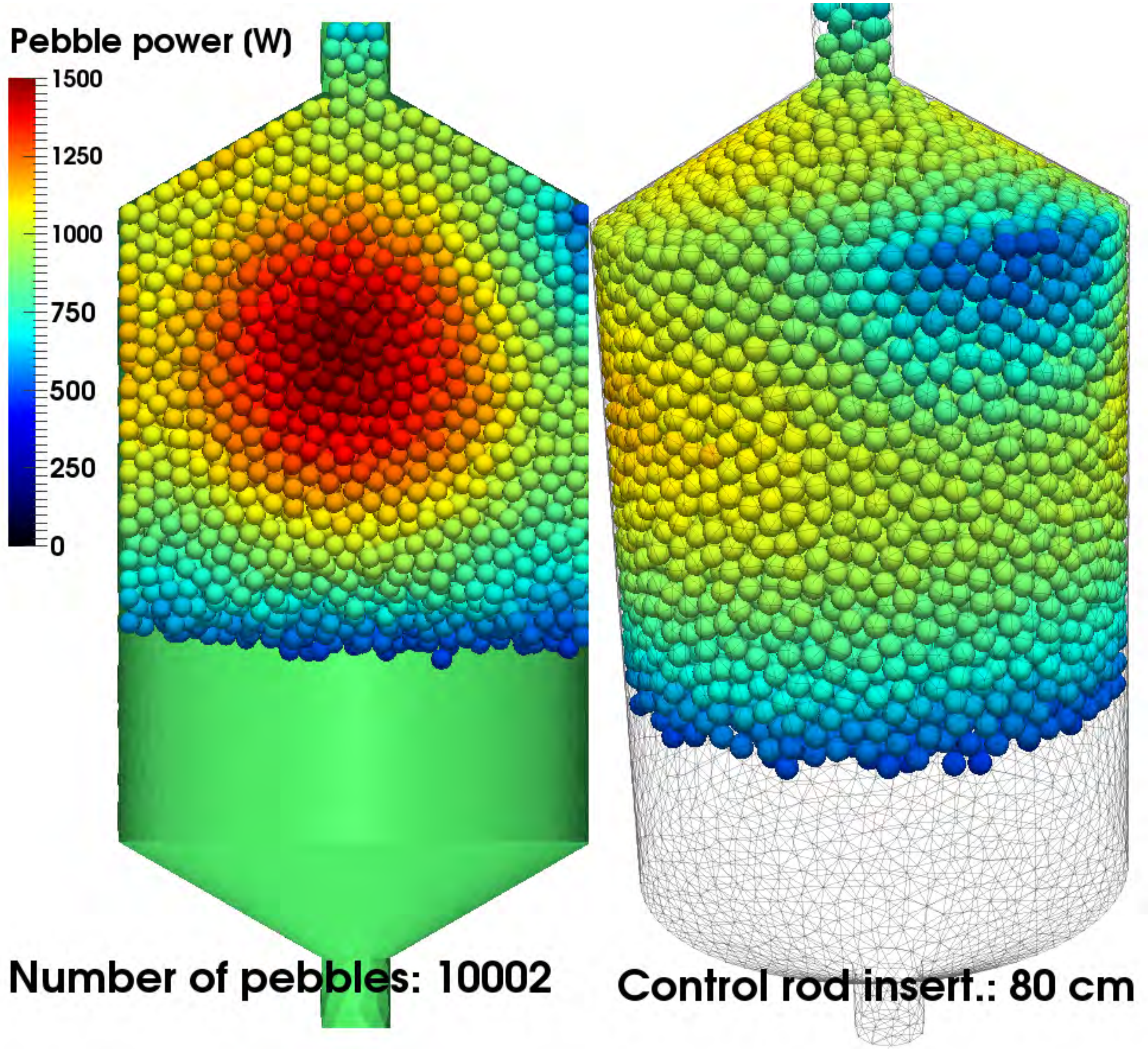
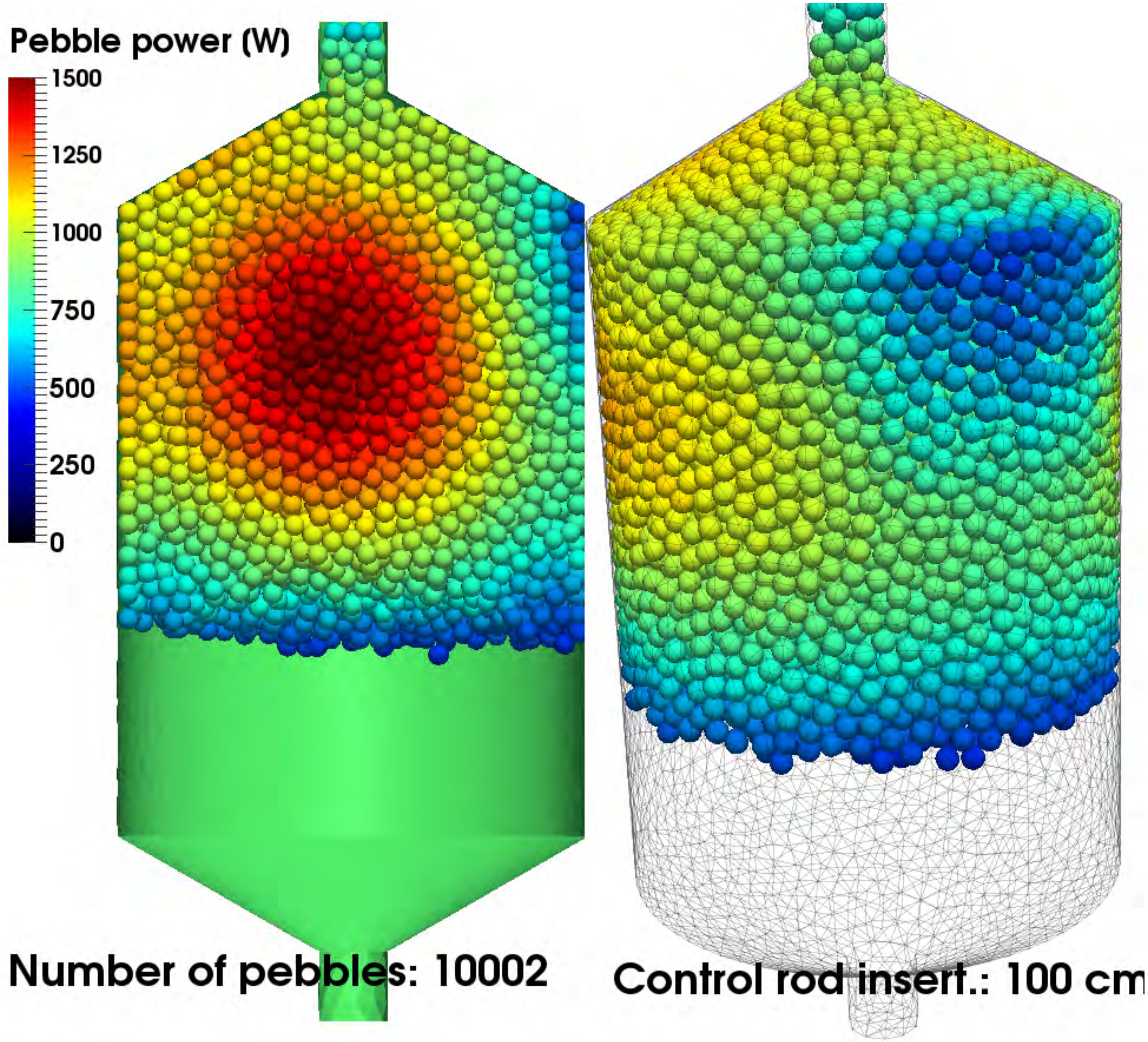
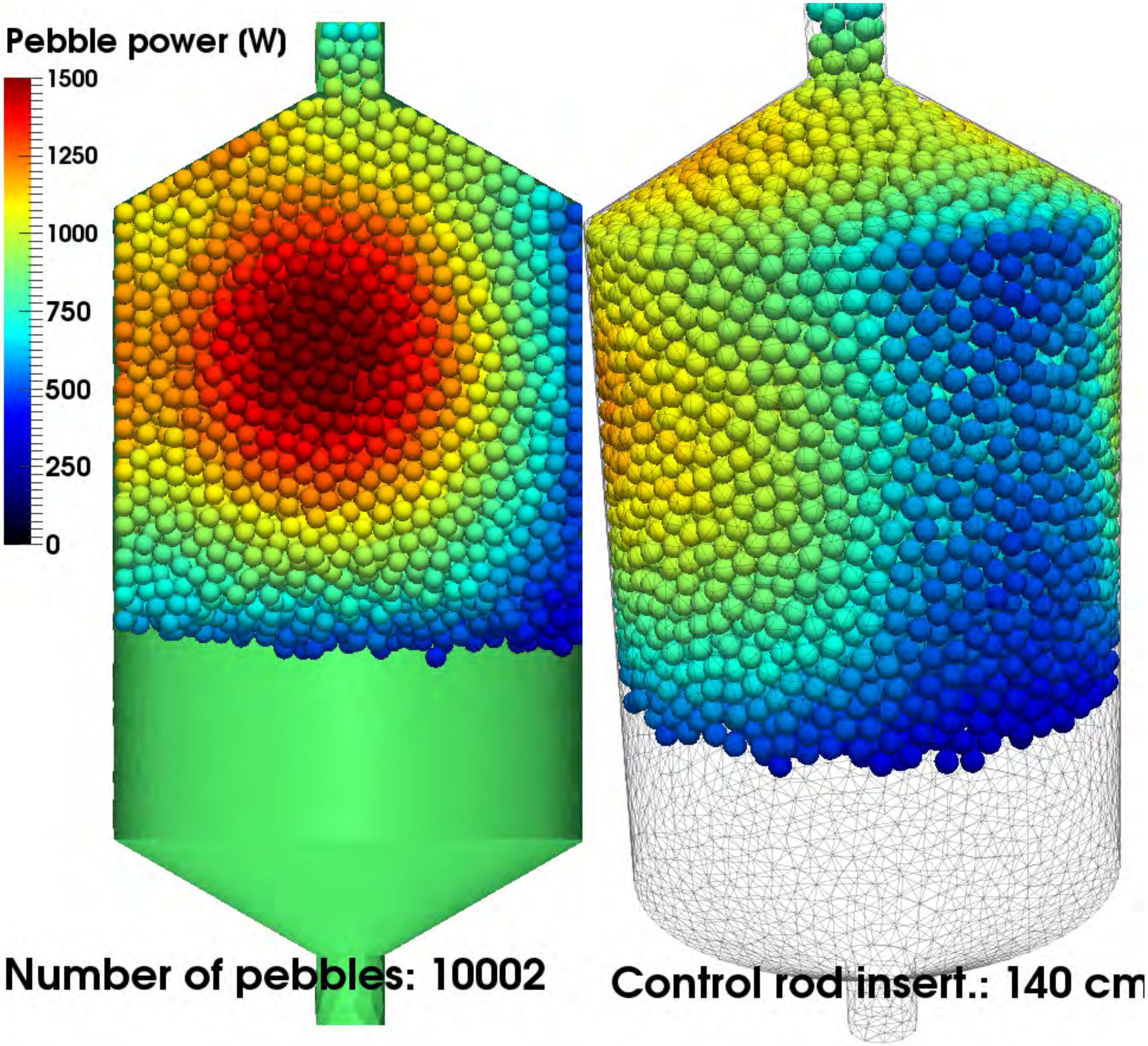
Effect of control rods insertion



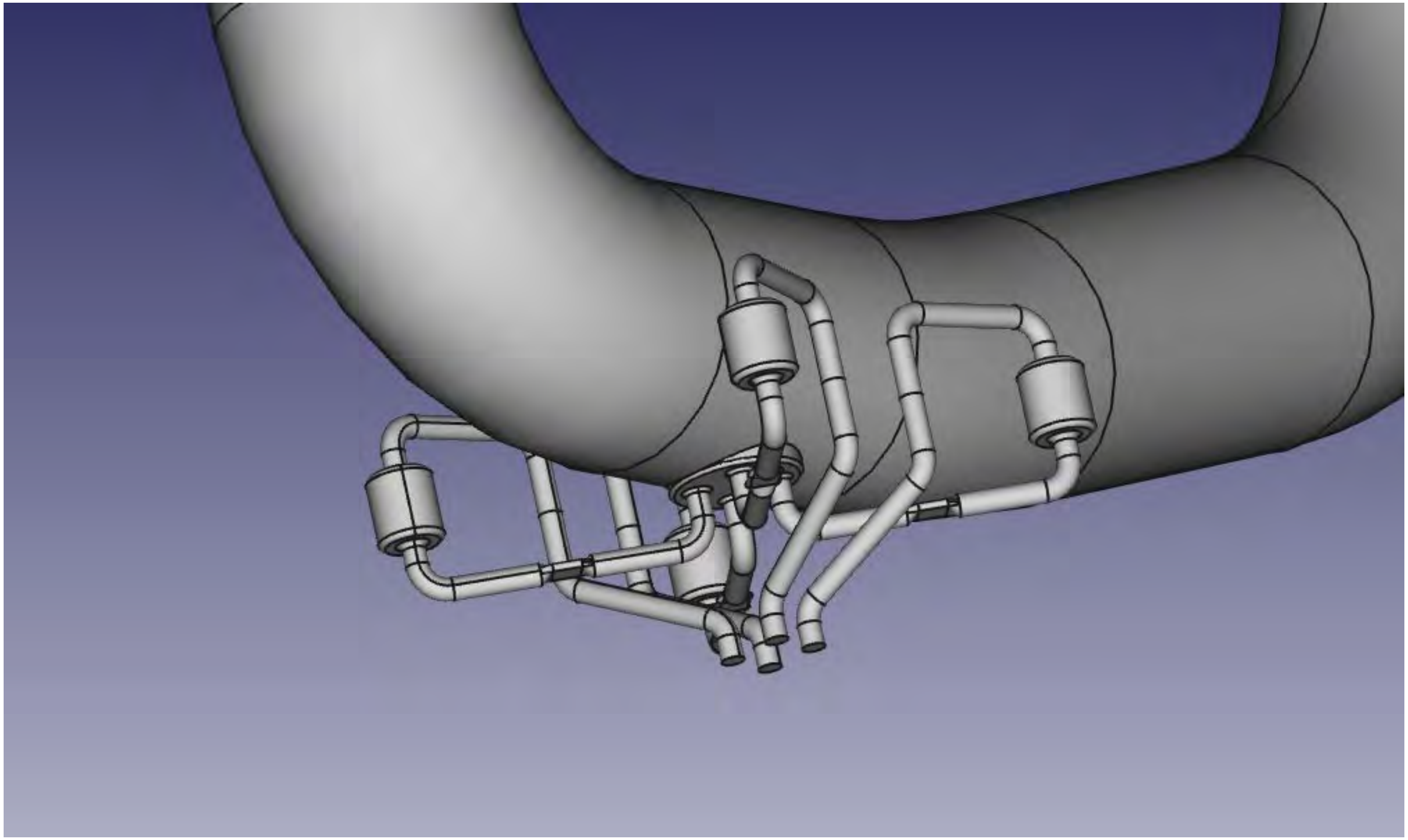
Effect of control rods insertion



Effect of control rods insertion

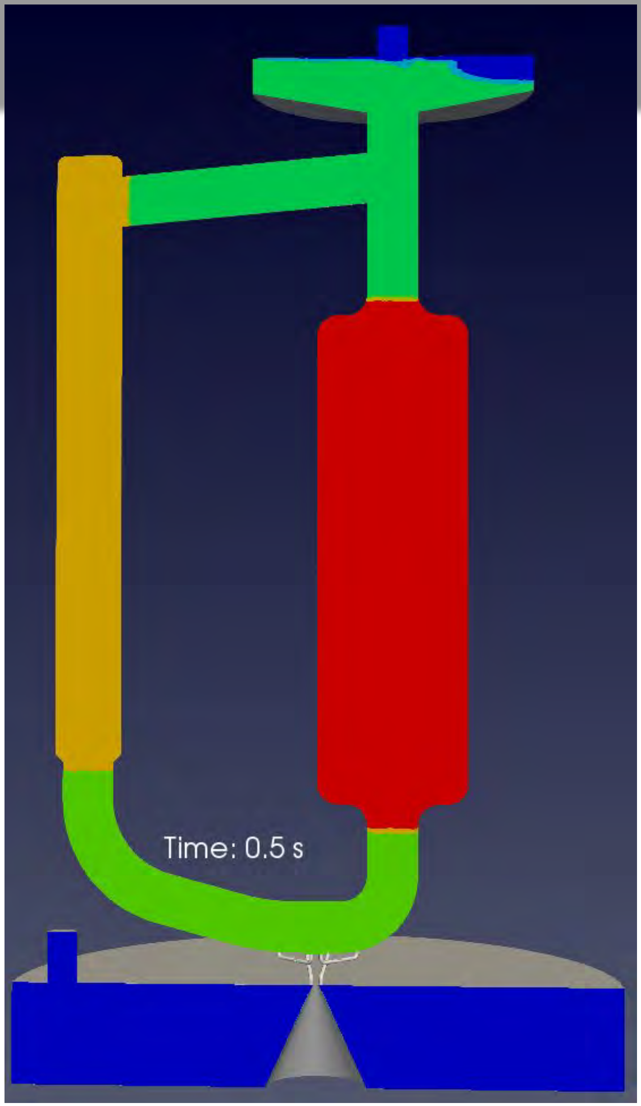


Draining simulation



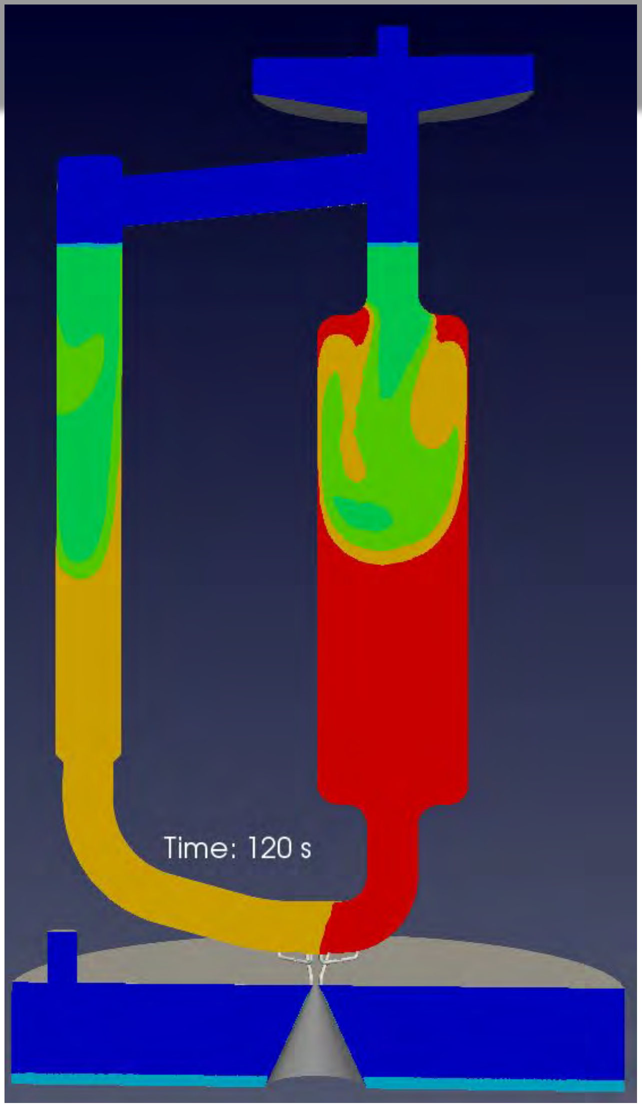
Draining simulation

Equivalent-area CFD simulation (VoF in OpenFOAM)



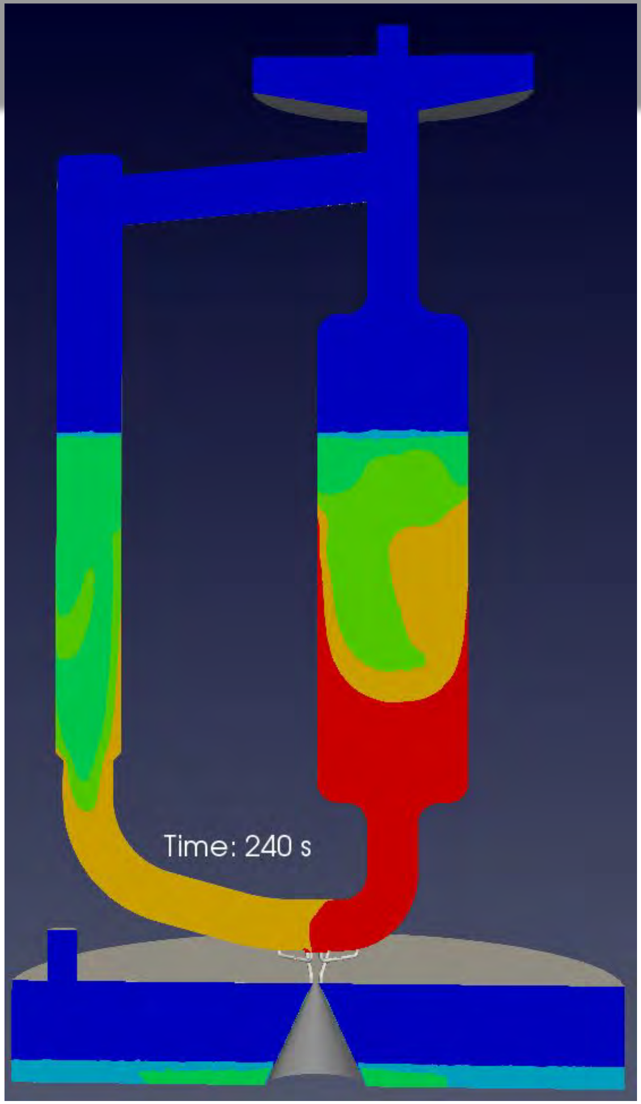
Draining simulation

Equivalent-area CFD simulation (VoF in OpenFOAM)



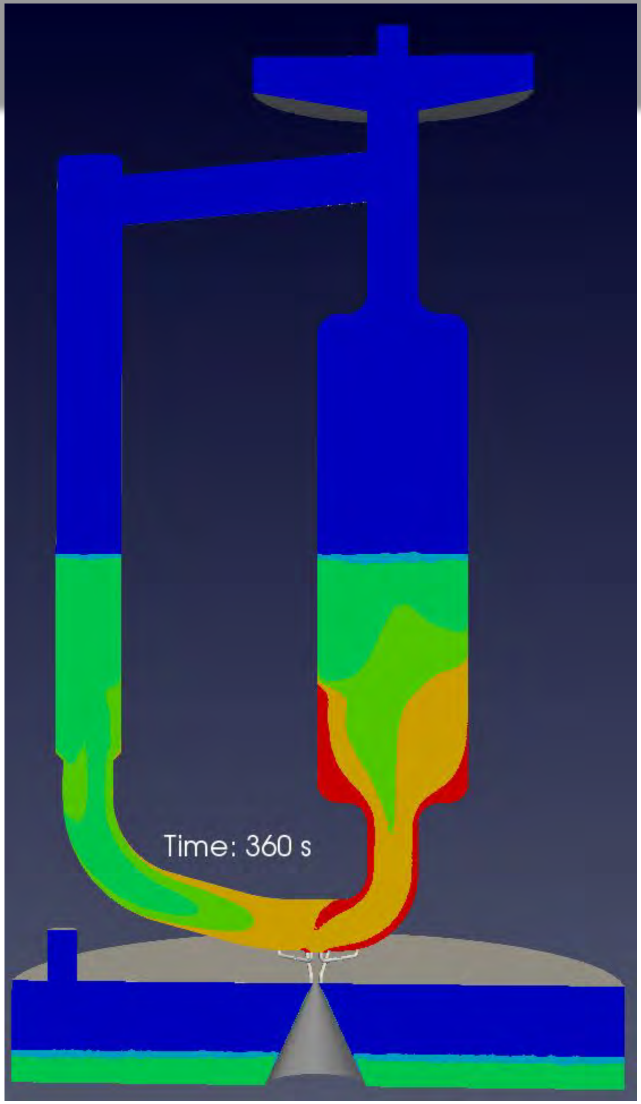
Draining simulation

Equivalent-area CFD simulation (VoF in OpenFOAM)



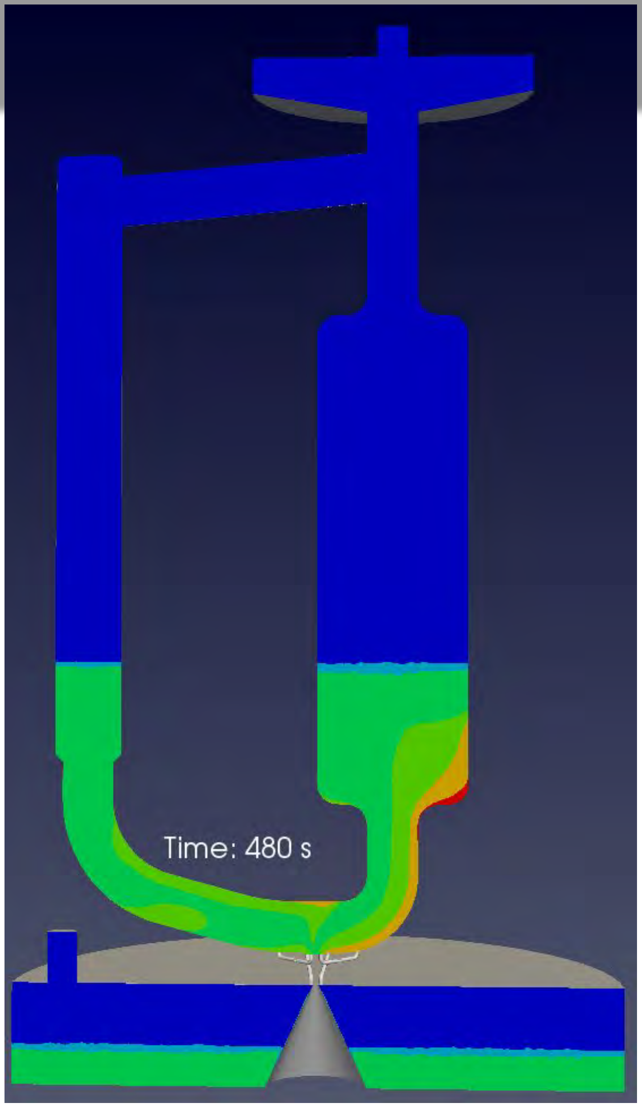
Draining simulation

Equivalent-area CFD simulation (VoF in OpenFOAM)



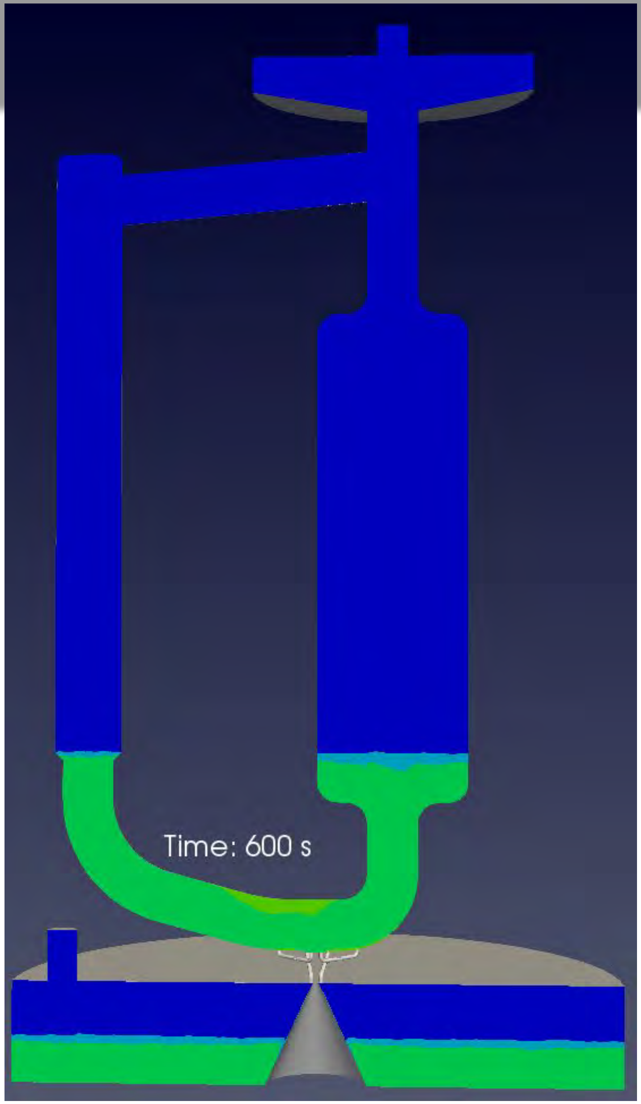
Draining simulation

Equivalent-area
CFD simulation
(VoF in OpenFOAM)



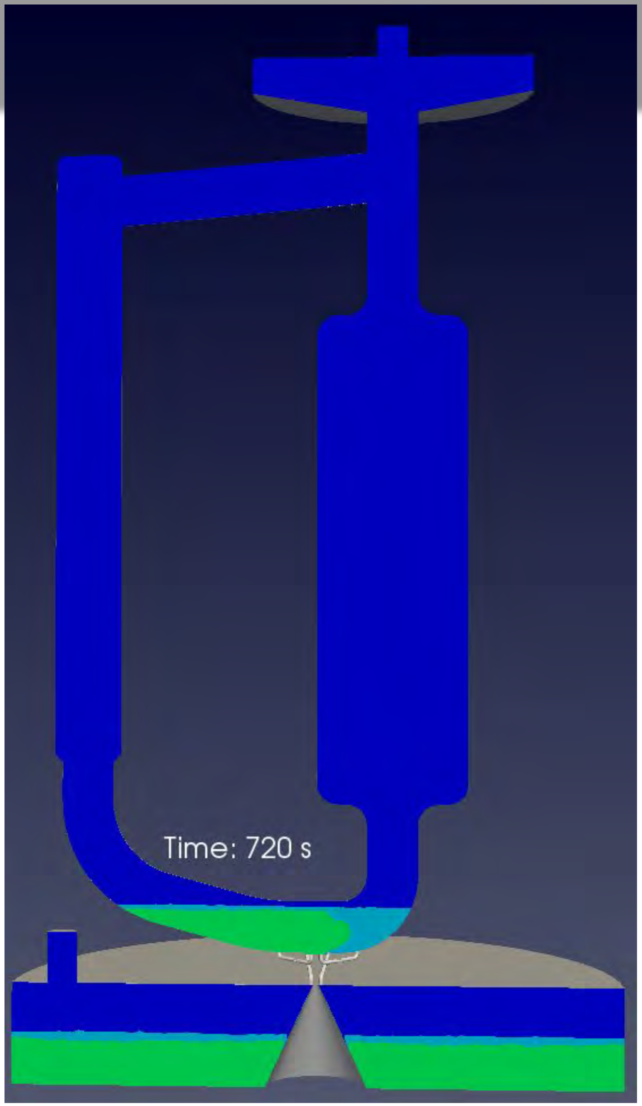
Draining simulation

Equivalent-area CFD simulation (VoF in OpenFOAM)



Draining simulation

Equivalent-area CFD simulation (VoF in OpenFOAM)

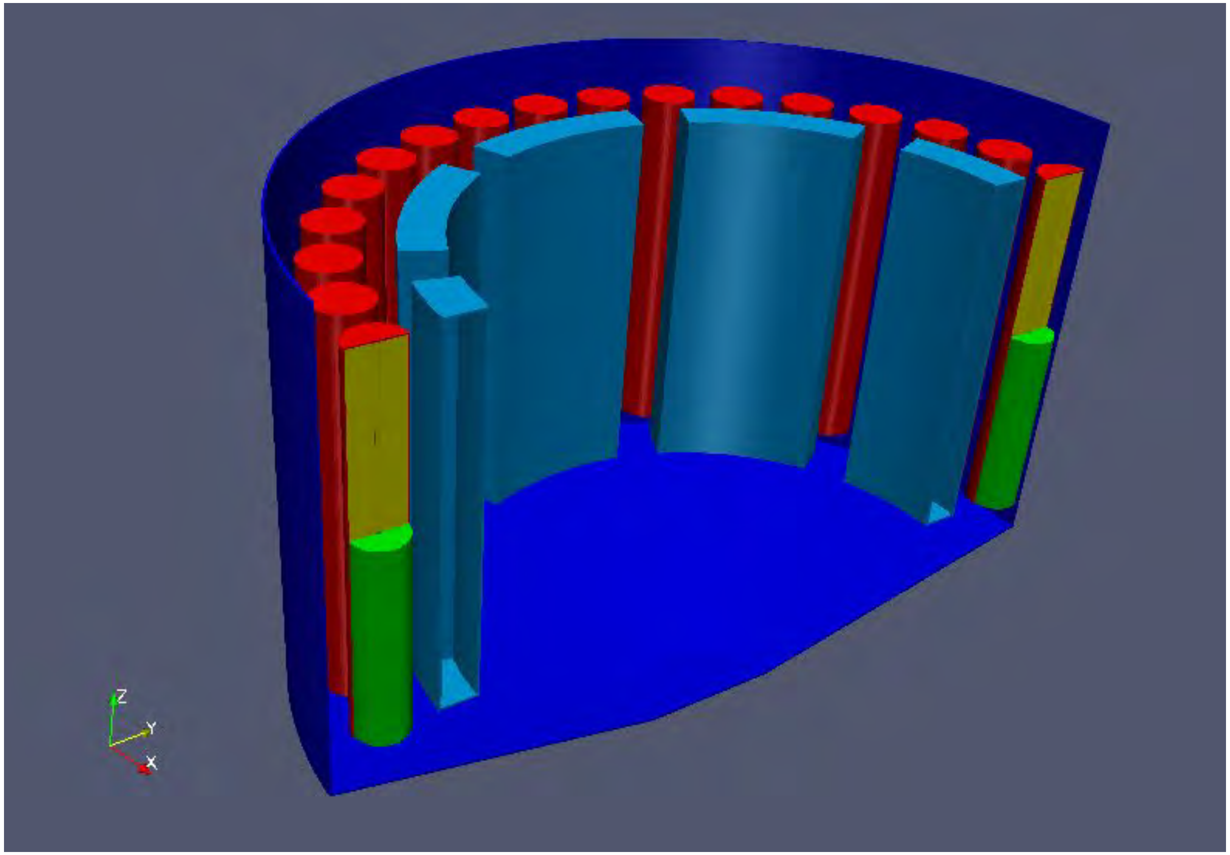


Draining simulation - CFD simulation

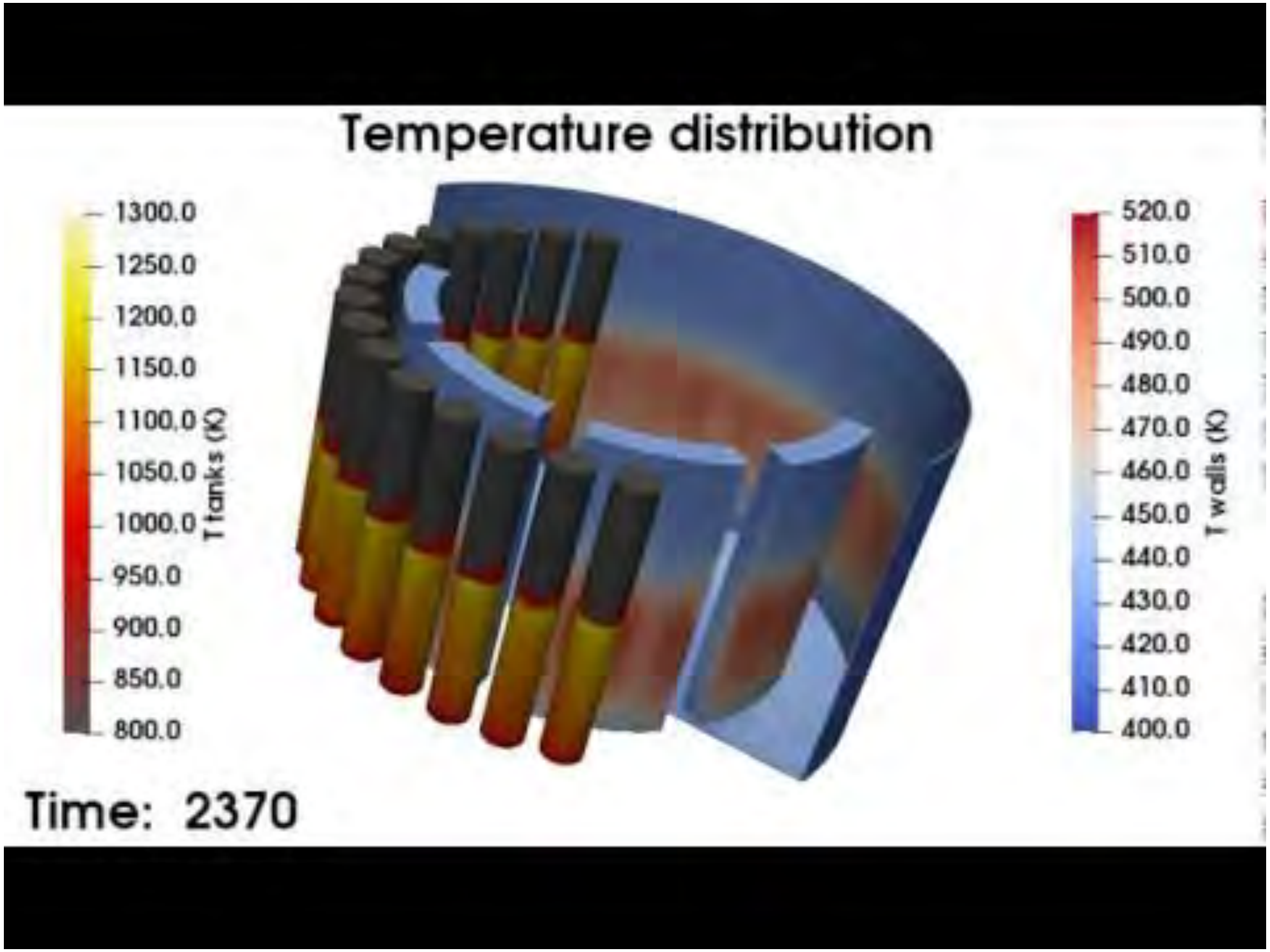
Draining simulation - CFD simulation

Geometry

Simplified drain tank geometry for CFD study



CFD - Radiative heat transfer + natural circul.



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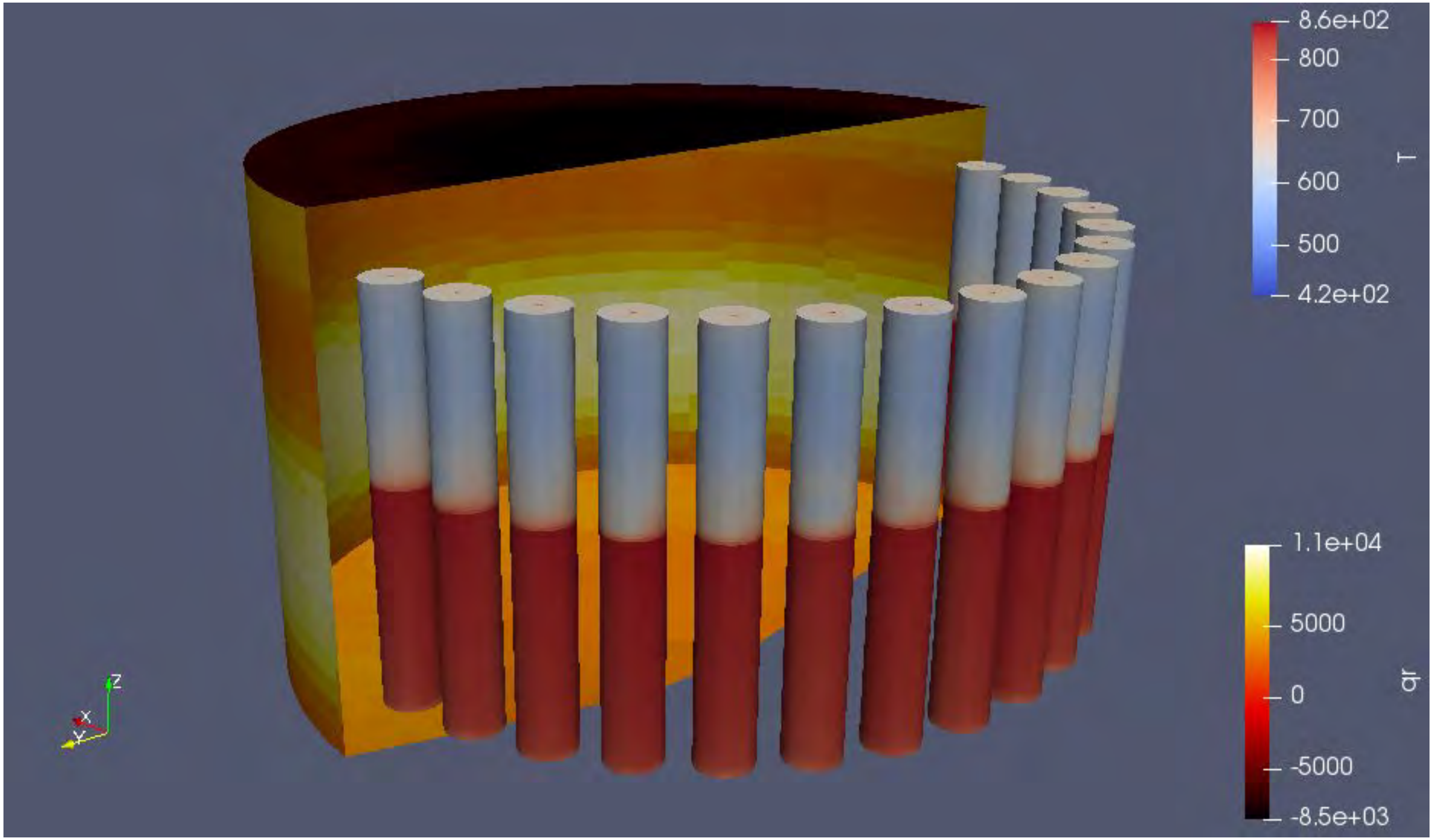
CFD - Radiative heat transfer + natural circul.



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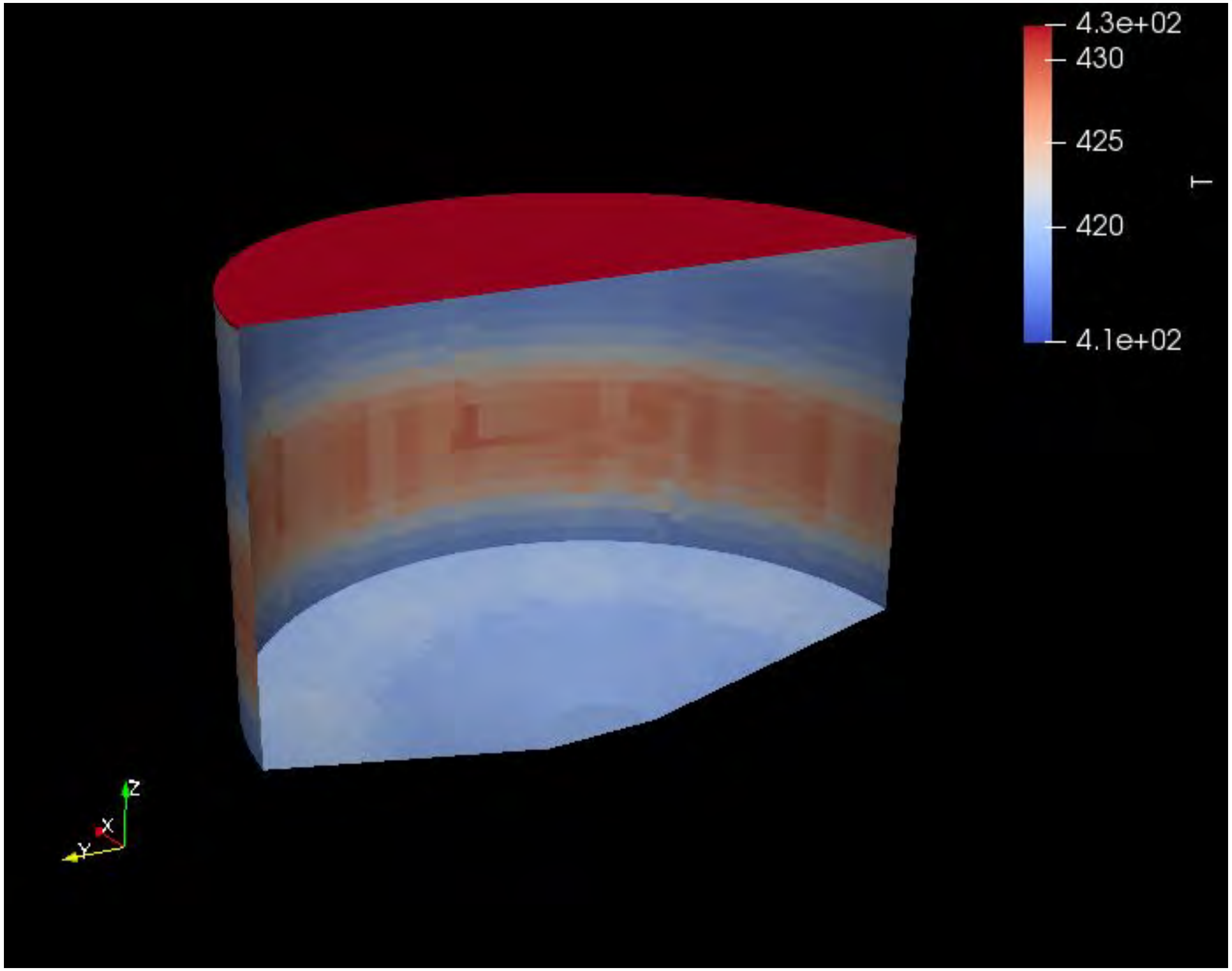
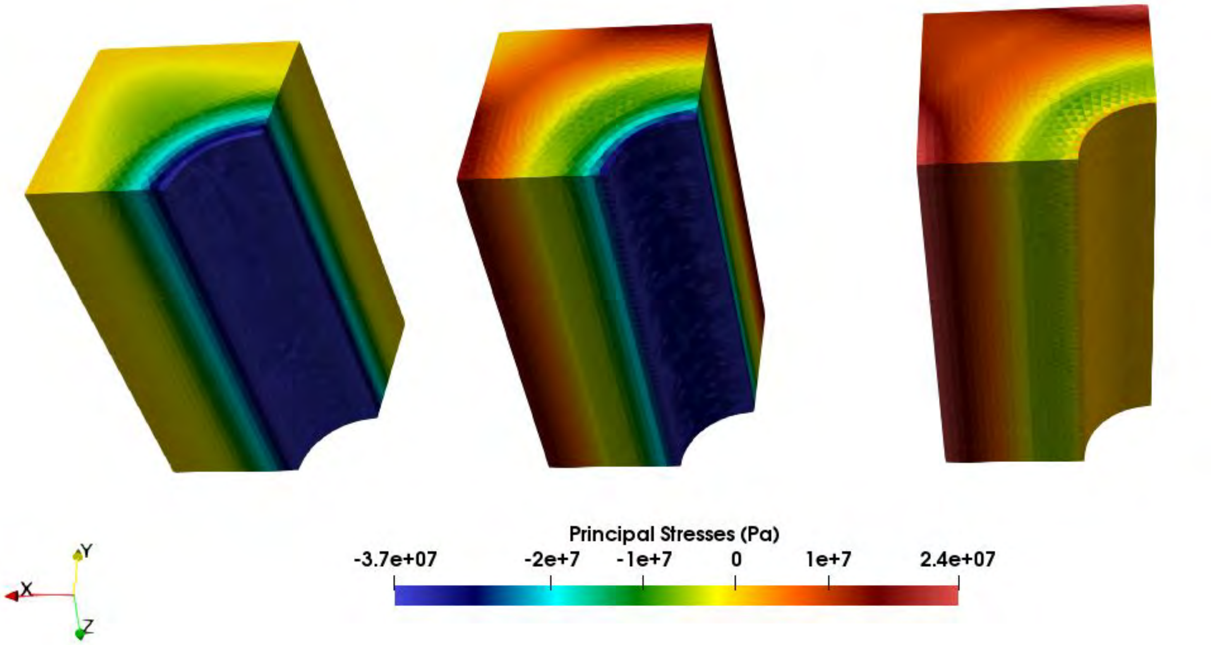
CFD - Radiative heat transfer + natural circul.



Fuel channel blockage accident

Blockage accidents happen when **a solid fragment obstructs a power channel** in a graphite-moderated MSR, stopping the flow.

A hot spot is generated inside the core, which can bring to **fuelsalt boiling** and/or **graphite brick rupturing**.



Will be presented on Wed. 11:20 am by Paolo Bianchini - stay tuned!

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HPC-driven faster reactor development?

From **design by experiments** to **design by simulations** iterations.

- Many physical phenomena were often neglected in legacy simulation tools due to the lack of modeling capabilities
- Nowadays, multiphysics modeling can contribute to faster and more reliable design iterations in innovative reactor design
- Experiments will always be essentials but advanced modelling tools makes design of testing campaigns easier and more representative of final reactor designs