PennState
College of Engineering

NucE 497: Reactor Fuel Performance

Lecture 17: Fuel performance codes

February 17, 2017

Michael R Tonks
Mechanical and Nuclear Engineering

Today we will finish talking about the coupling of temperature and stress and start numerical solutions

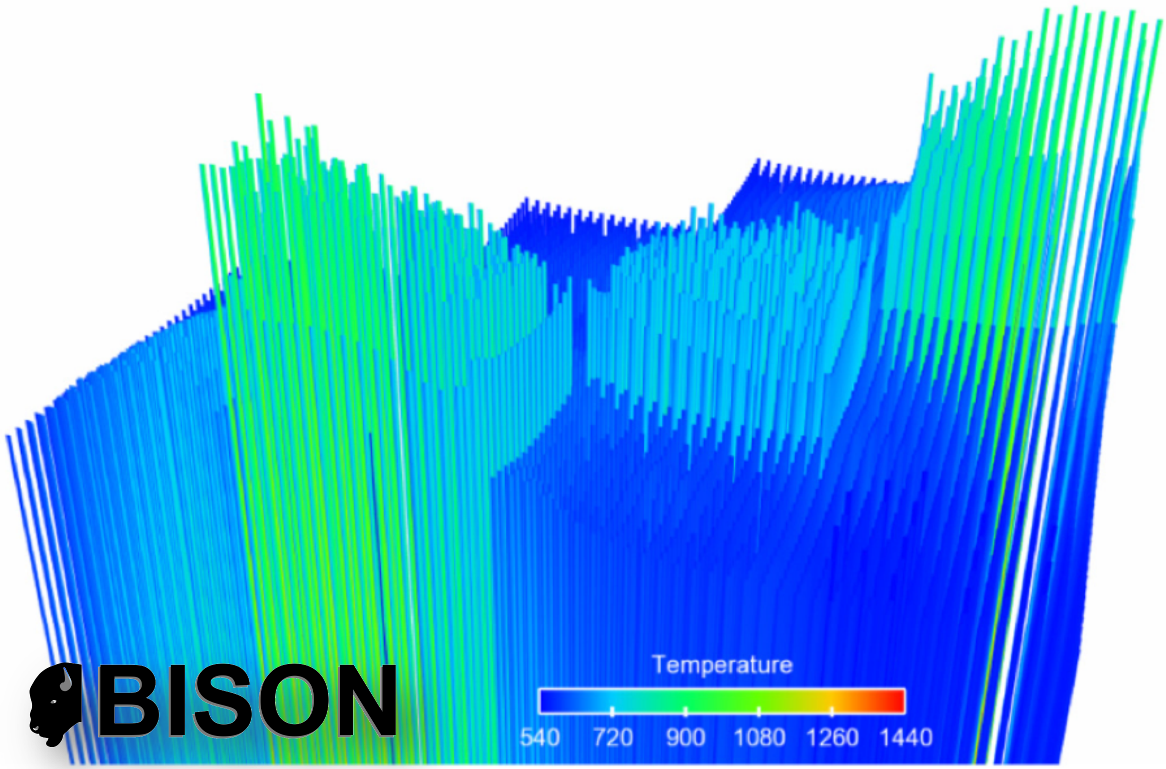
- Module 1: Fuel basics
- Module 2: Heat transport
- Module 3: Mechanical behavior
  - Introduction to solid mechanics
  - Analytical solutions of the mechanics equations
  - Thermomechanics, thermal expansion
  - Solving equations in 1D numerically
  - Solving in multiple dimensions with FEM
  - **Summary of fuel performance codes**
- Module 4: Materials issues in the fuel
- Module 5: Materials issues in the cladding
- Module 6: Accidents, used fuel, and fuel cycle

Here is some review from last time

- What is MOOSE?
  a) A tool for solving PDEs using FEM
  b) A tool for solving ODEs using FVM
  c) A next generation fuel performance code
  d) A tool for modeling heat conduction
- Why are fuel pellets dished and chamfered?
  a) To reduce stress concentrations
  b) To reduce interaction with other pellets and the cladding due to thermal expansion
  c) To simplify fabrication
  d) To make a more visually appealing design

The purpose of a fuel performance code is to simulate and evaluate fuel rod behavior

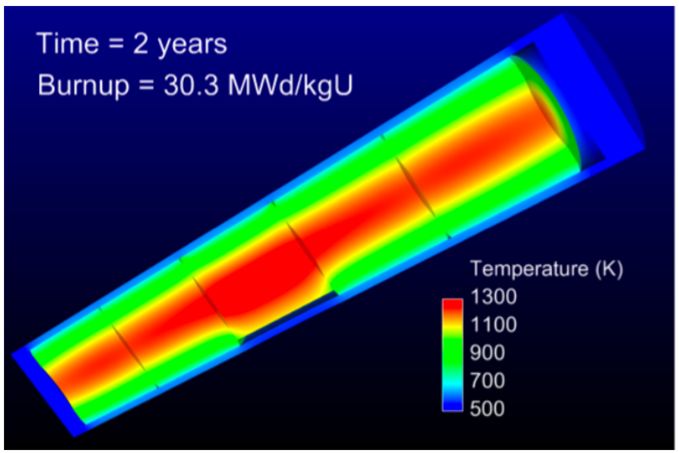
- The first fuel performance codes were developed in the mid seventies
- Advanced fuel performance codes are still under development today

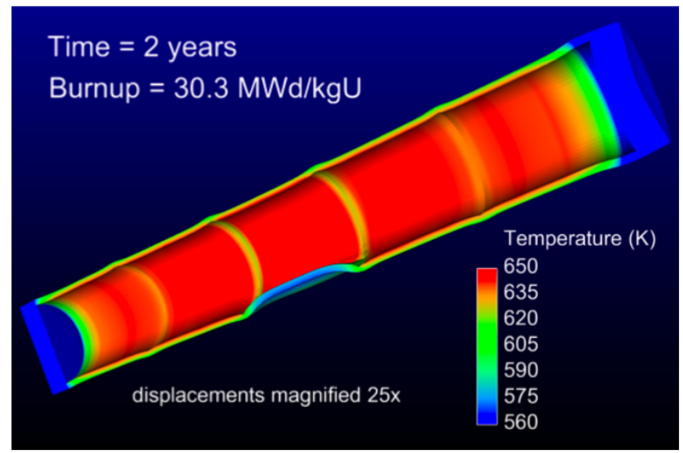


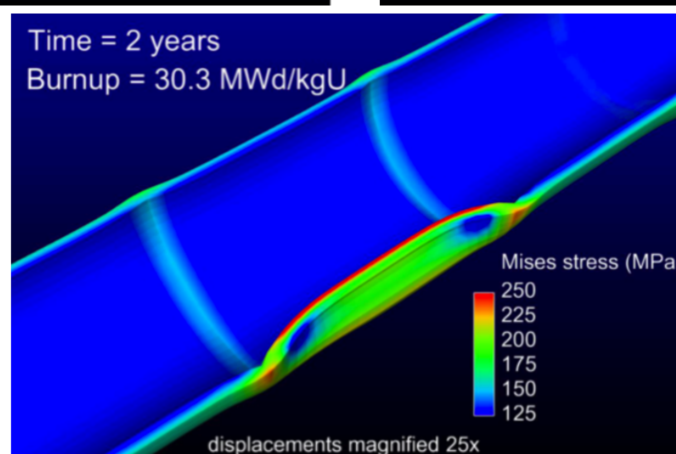
KAIST-3A benchmark results, showing displacement of 3432 rods, from Gaston et al. 2014

The primary goals are to predict the fuel centerline temperature and the stress in the cladding

- Fuel performance codes aren't focused on predicting power production, but rather to predict safety margins





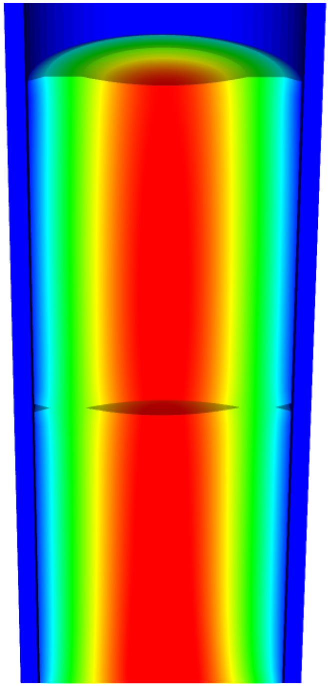


Fuel performance code capabilities vary, but they all have a bare minimum in common

- A fuel performance code must be able to predict

Fuel
- Temperature profile
- Volumetric change

Cladding
- Temperature profile
- Stress



Gap
- Gap heat transport
- Mechanical interaction between fuel and cladding
- Gap pressure

The primary focus is solving the thermomechanical problem

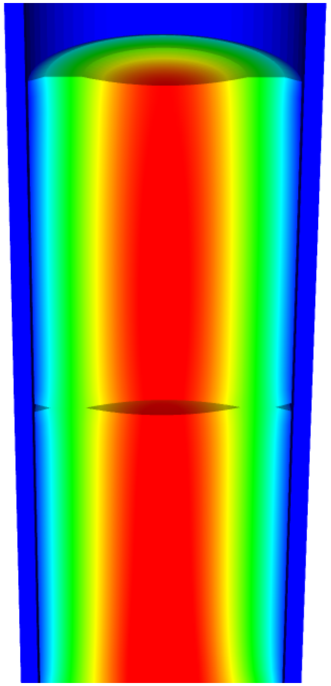
Fuel

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q$$

Solved Numerically

$$0 = \nabla \cdot \boldsymbol{\sigma}$$

Solved Numerically or analytically



Gap

- The handling of the gap changes the most between different codes

Cladding

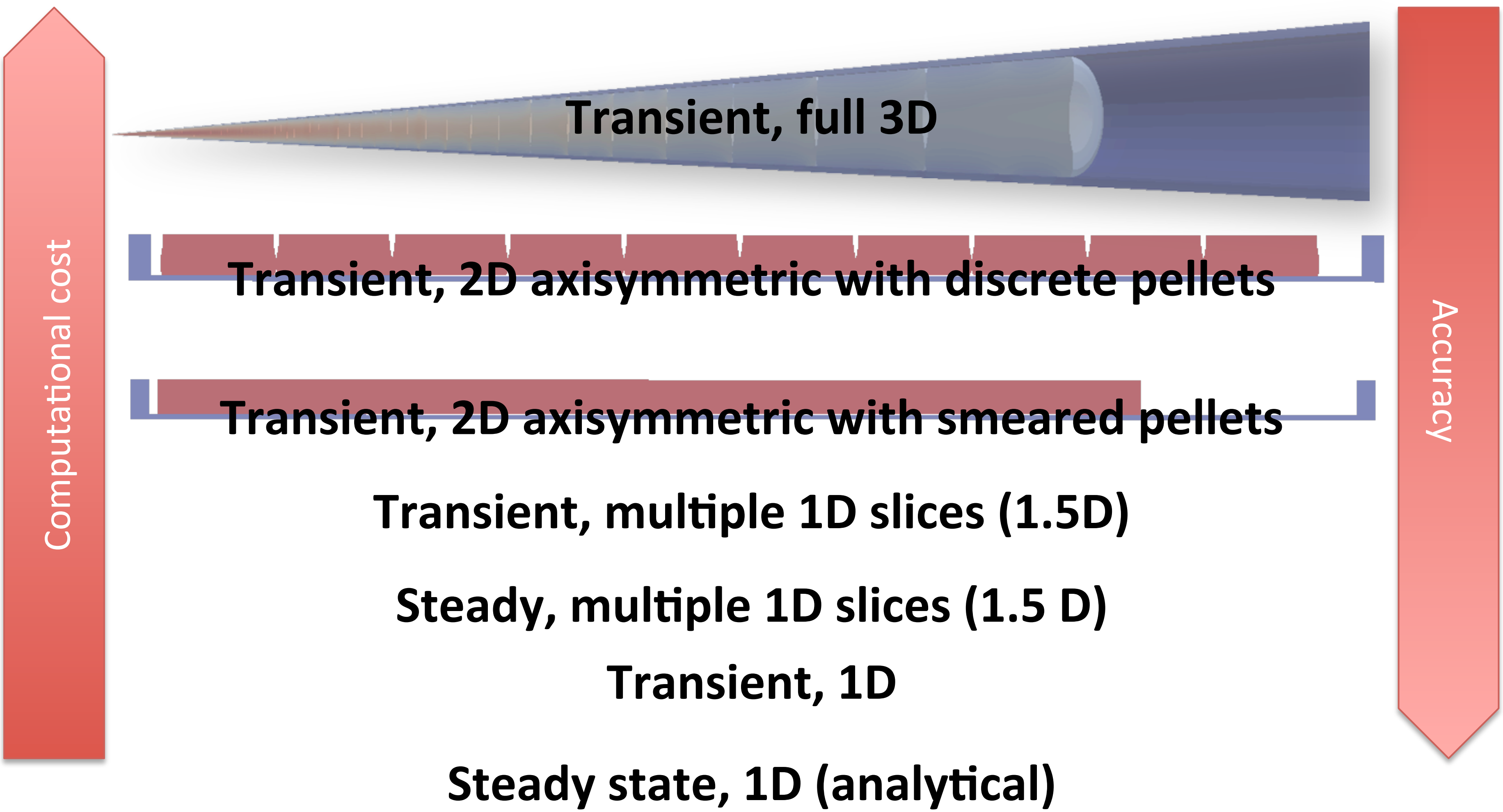
$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q$$

Solved Numerically or analytically

$$0 = \nabla \cdot \boldsymbol{\sigma}$$

Solved Numerically

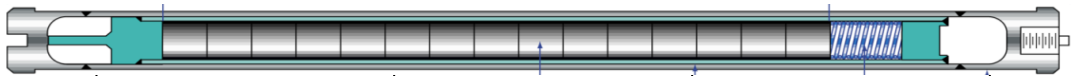
Remember the various approaches that are taken to model the fuel rod



Older fuel performance codes were made for either steady state or transient operation

- Steady state codes
  - Leave of the time derivative part of the heat equation $\nabla \cdot (k\nabla T) + Q = 0$
  - The material properties still evolve with time as a function of burnup
  - The volumetric changes in the fuel are also a function of burnup
  - Creep of fuel and cladding change with time
- Transient codes
  - Include the time derivative $\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k\nabla T) + Q$
  - Have similar burnup dependent models like steady state codes, but don't include creep
  - Have additional models for rapid transients

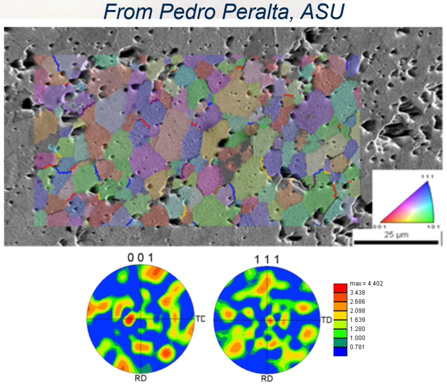
Property changes due to microstructure evolution during reactor operation must be considered in the codes



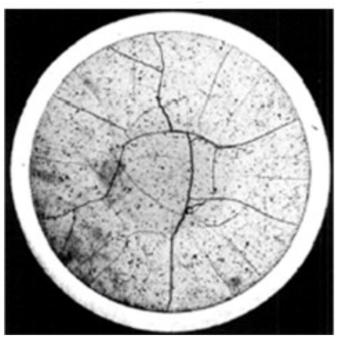
Insertion in reactor — **Removal from reactor**

Fuel Fabrication
- Sintered UO^2
- Height 2 cm
- Diameter 1 cm
- ~10 μm grain size
- Density > 95%

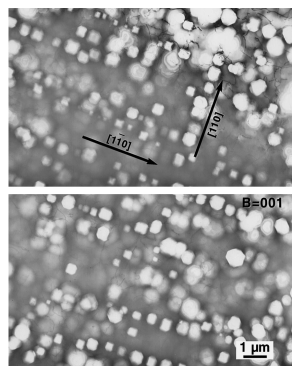
From Pedro Peralta, ASU



Early life
- Thermal expansion
- Fracture
- Point defect and fission gas generation
- Fuel Densification



Mid Life
- Point defect diffusion
- Point defect clustering
- Fission gas segregation to GB and voids
- Bubble nucleation

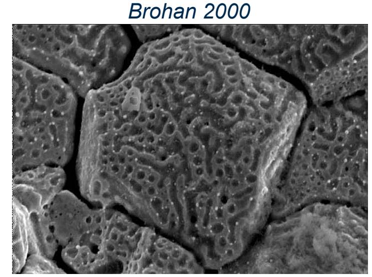


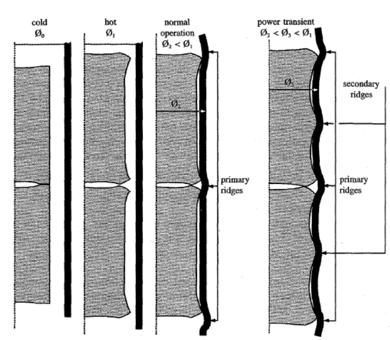
Zinkle and Singh 2000

Olander, p. 323 (1978)

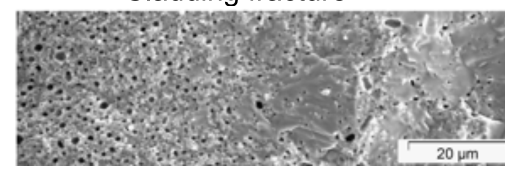
Late life
- Fission product swelling
- Bubble percolation and fission gas release
- Cladding creep
- Fuel creep

Brohan 2000

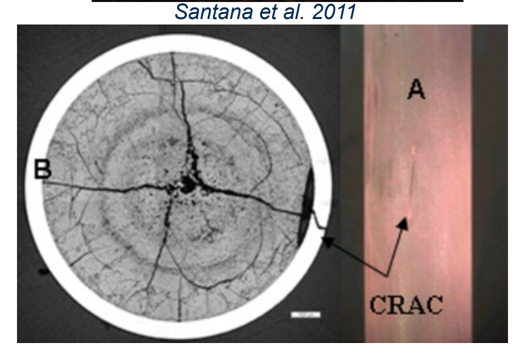




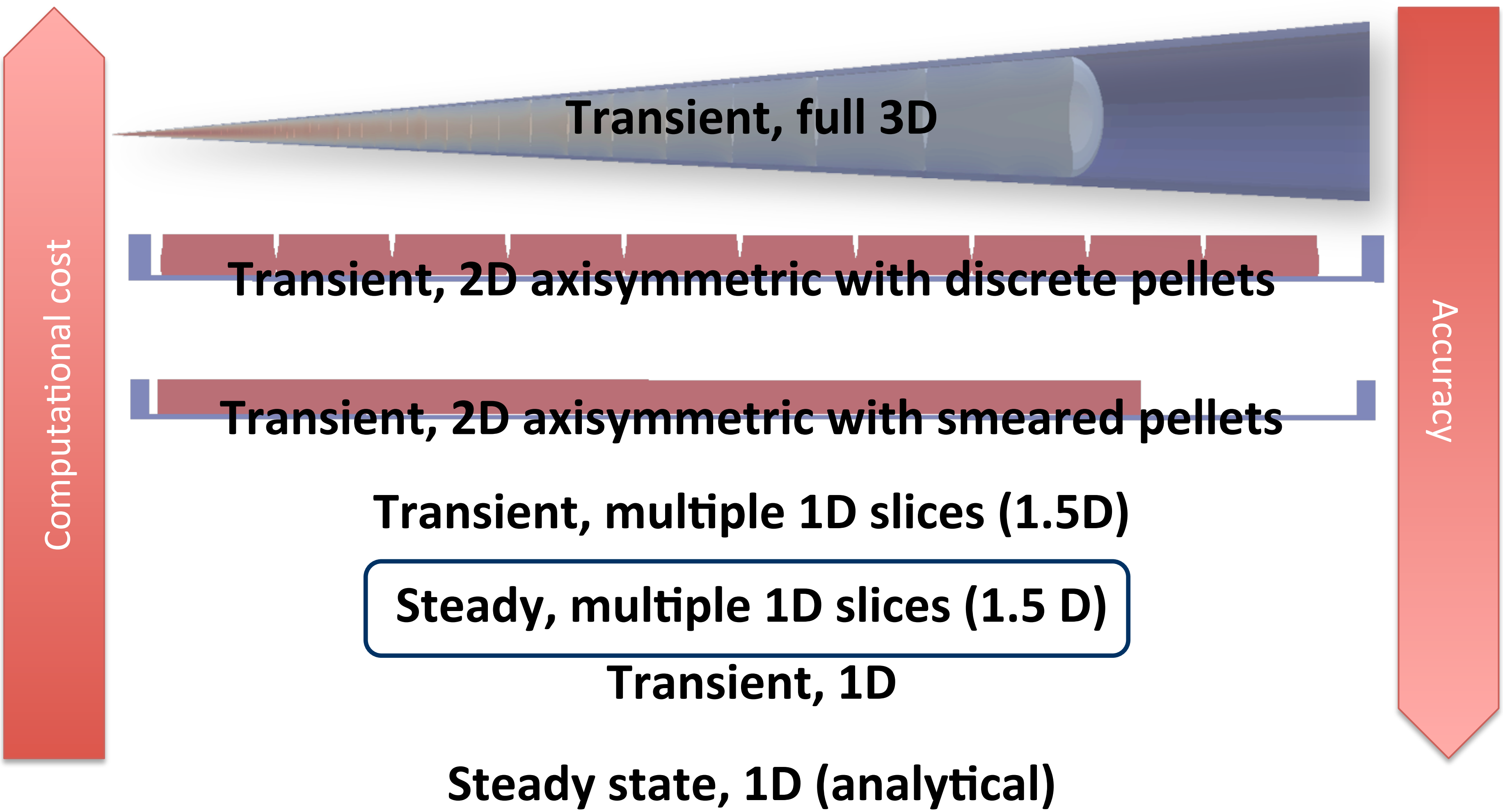
Fuel failure
- Pellet/cladding interaction
- Cladding corrosion
- Cladding fracture



Santana et al. 2011



The first code we will discuss is FRAPCON



FRAPCON is the oldest and most widely used fuel performance code in the US

- It is based on the FRAP-S codes that started in 1976
- The FRAPCON-1 code was created 1978
- It was developed at Idaho National Laboratory and Pacific Northwest National Laboratory
- The current version of the code is FRAPCON-4 and was released in 2015
- FRAPCON is the certified fuel performance code used by the NRC
- Anyone can get access to FRAPCON, but it costs
- http://frapcon.labworks.org/

FRAPCON is a 1.5D steady state code that solves the heat equation using finite difference

Fuel

$$\nabla \cdot (k \nabla T) + Q = 0$$

Solved with FD

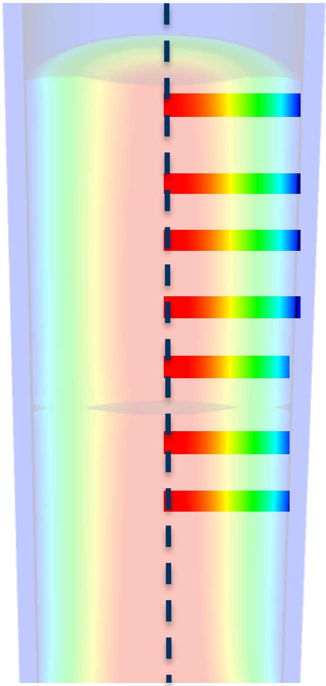
Volume change is solved analytically

Cladding

Temperature is calculated using analytical equation

$$0 = \nabla \cdot \boldsymbol{\sigma}$$

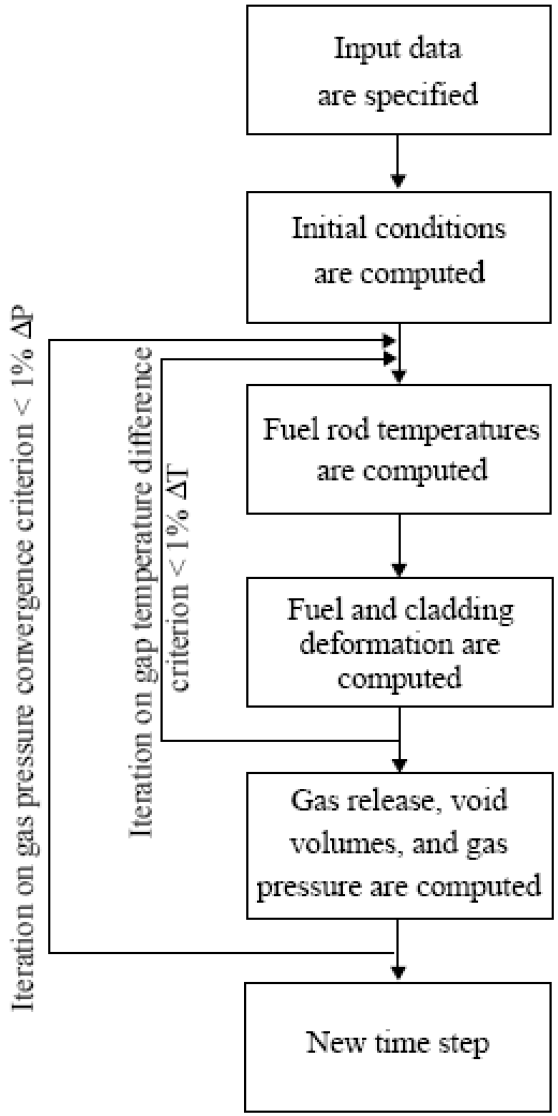
Solved Numerically



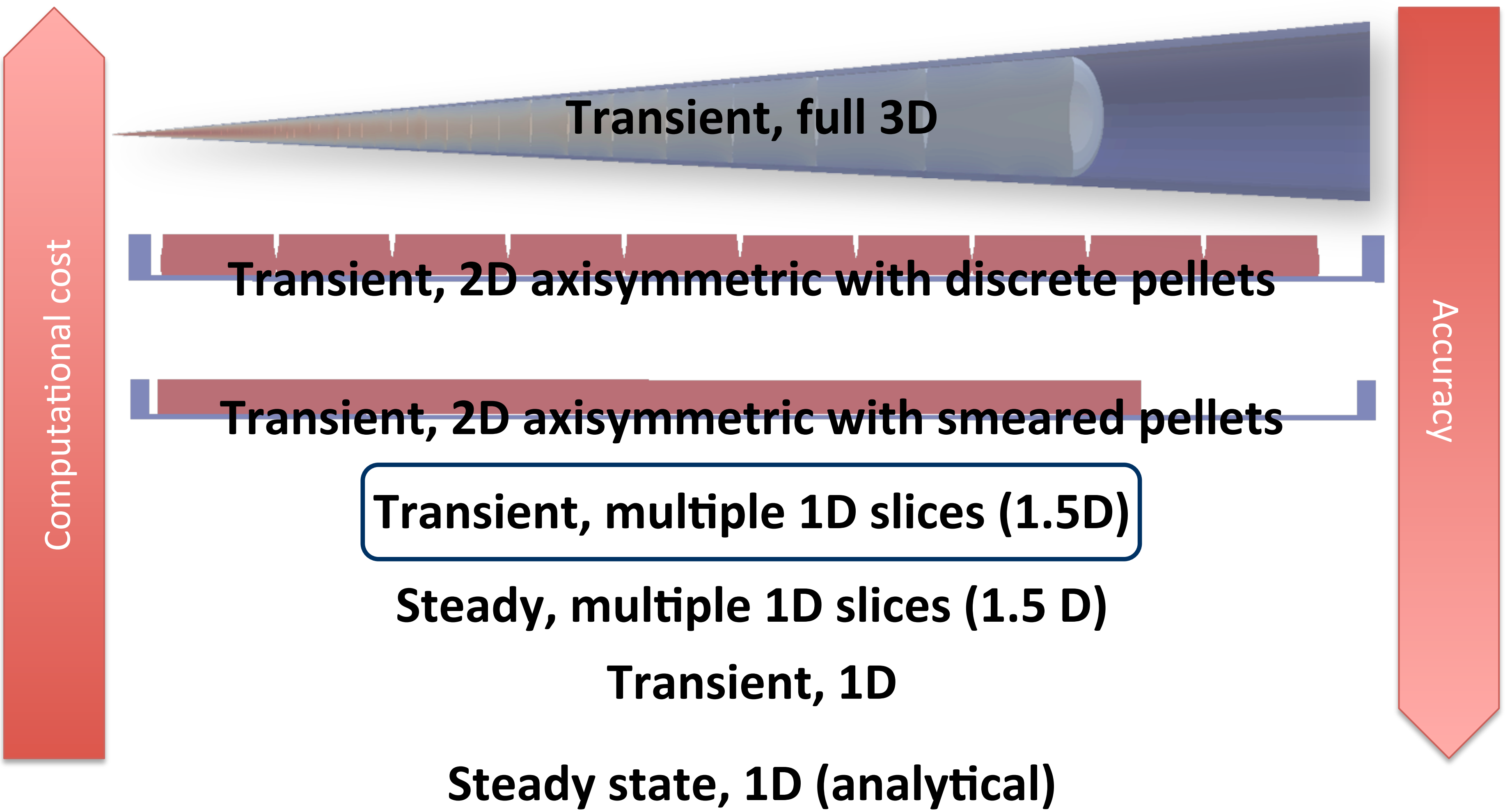
Gap

- Pressure is computed using ideal gas law
- Gap closure is computed across 1D slices
- Heat transport across gap is computed with analytical equation

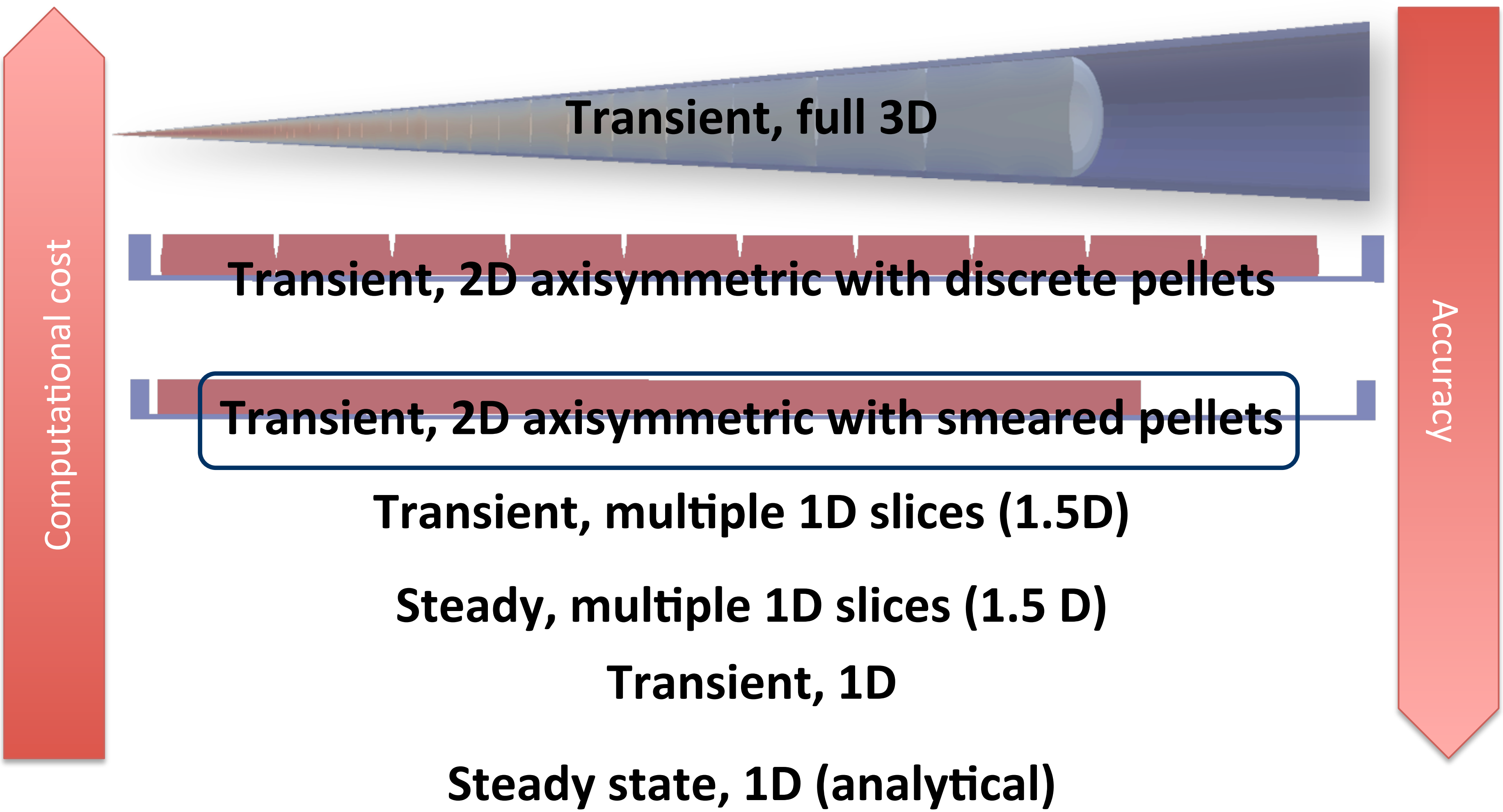
The computation process in FRAPCON is iterative



The transient code based on FRAPCON is called FRAPTRAN



Next we will discuss FALCON



FALCON is a 2D fuel performance code developed by EPRI

- Development of FALCON started in 1996
- The beta version was released in 2003
- It was developed by ANATECH for EPRI
- FALCON is proprietary, owned by EPRI
- It is no longer under active development in the US

FALCON is a 2D transient and steady state code

Fuel

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q$$

Solved with FEM

$$0 = \nabla \cdot \boldsymbol{\sigma}$$

Solved with FEM

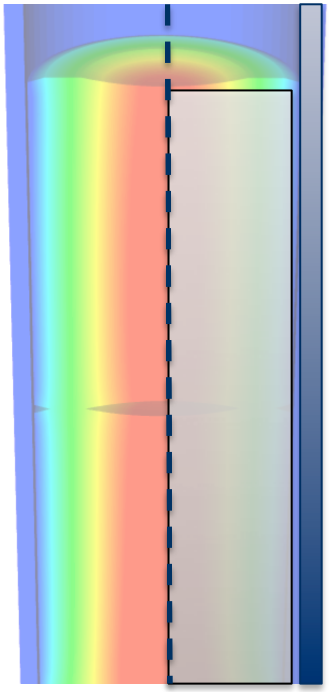
Cladding

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q$$

Solved with FEM

$$0 = \nabla \cdot \boldsymbol{\sigma}$$

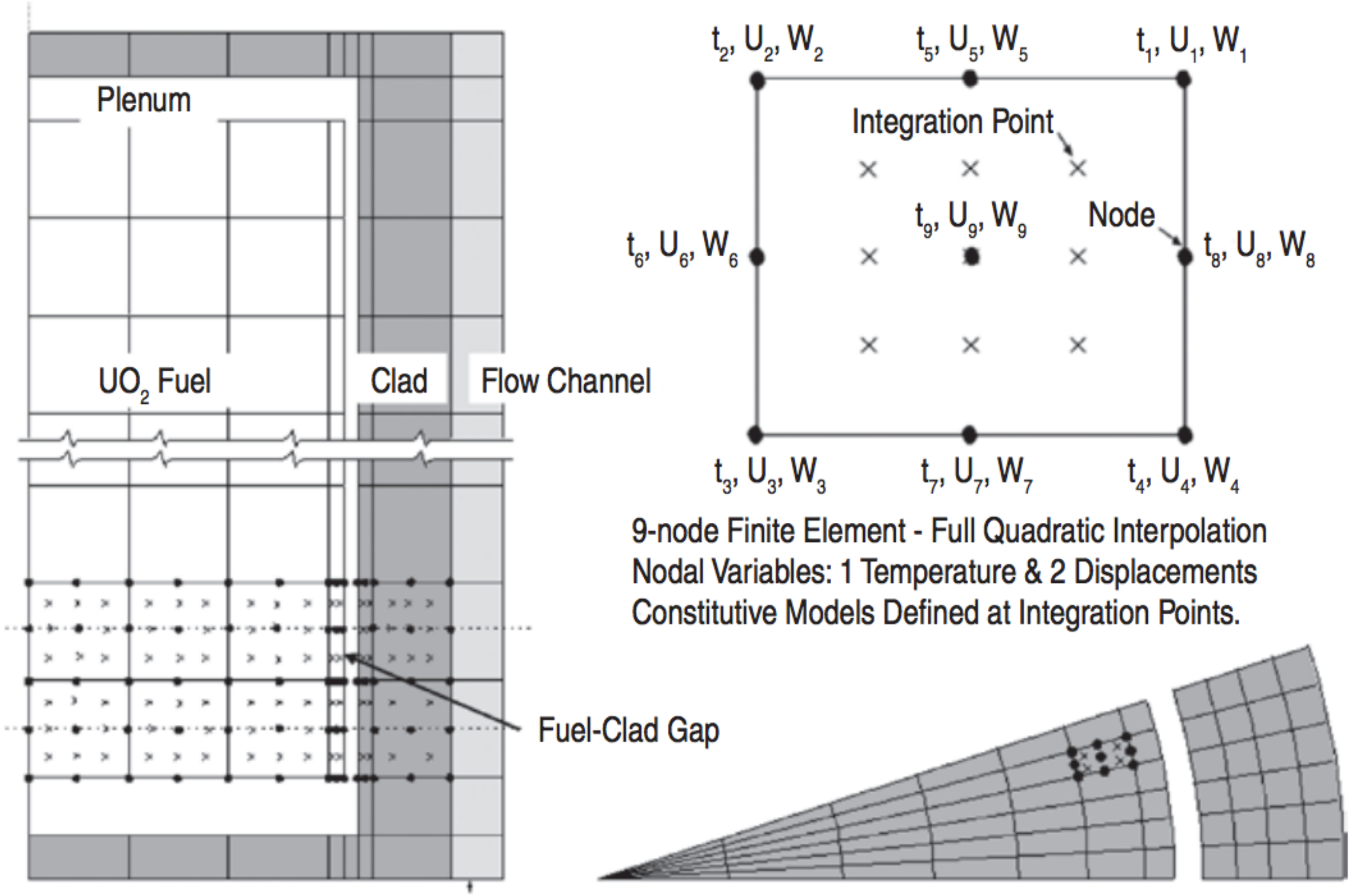
Solved with FEM



Gap

- Pressure is calculated using equation of state
- Simplified contact model is used for gap closure
- Gap heat transfer model is used

FALCON can predict the fuel performance in axisymmetric RZ space or in Rθ space

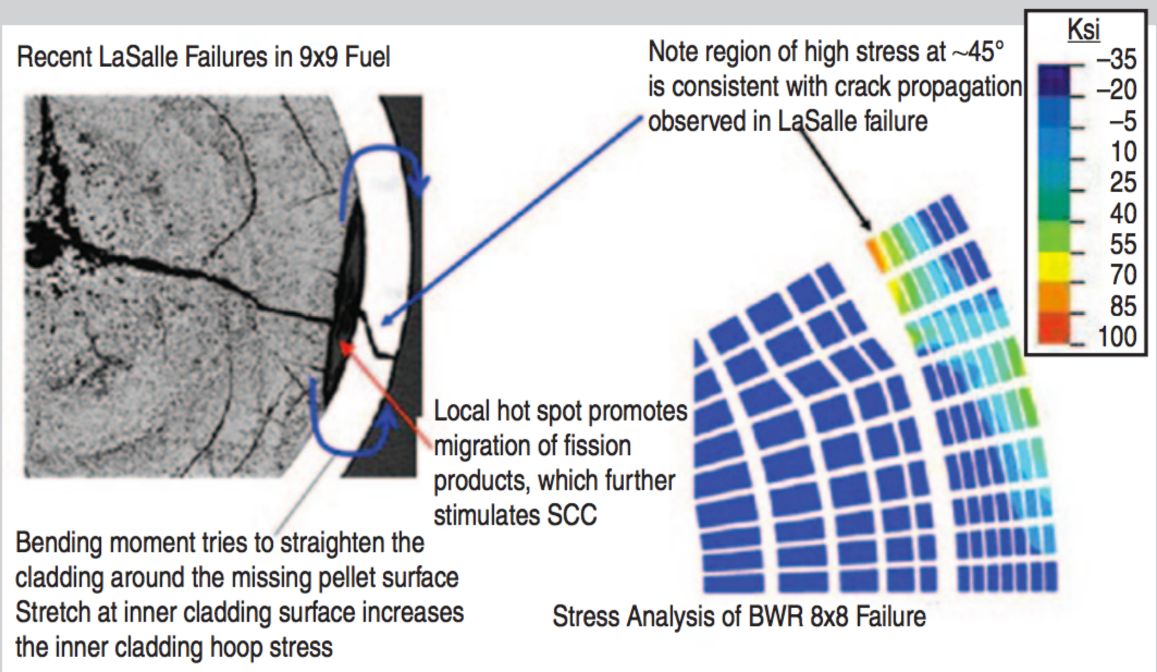


Fuel Length R-Z Grid

Plane R-θ Grid

Rashid, J. Y., Yagnik, S. K., & Montgomery, R. O. (2011). Light water reactor fuel performance modeling and multi-dimensional simulation. JOM, 63(8), 81.

FALCON has limited ability to look at the impact of defects on fuel performance



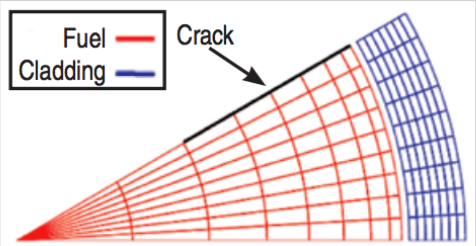


Figure 3. Standard PCI model.

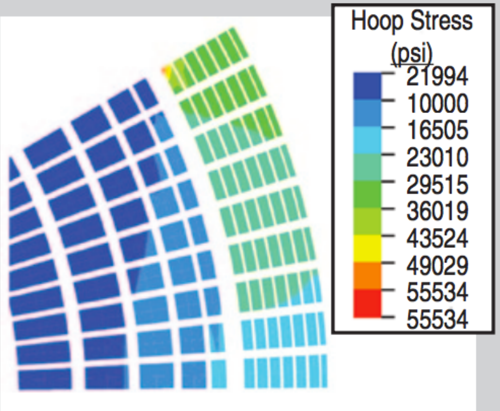


Figure 4. Calculated cladding hoop stress distribution (psi) using the standard PCI model.

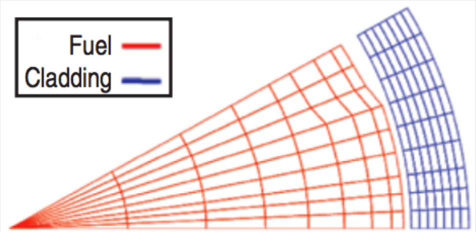
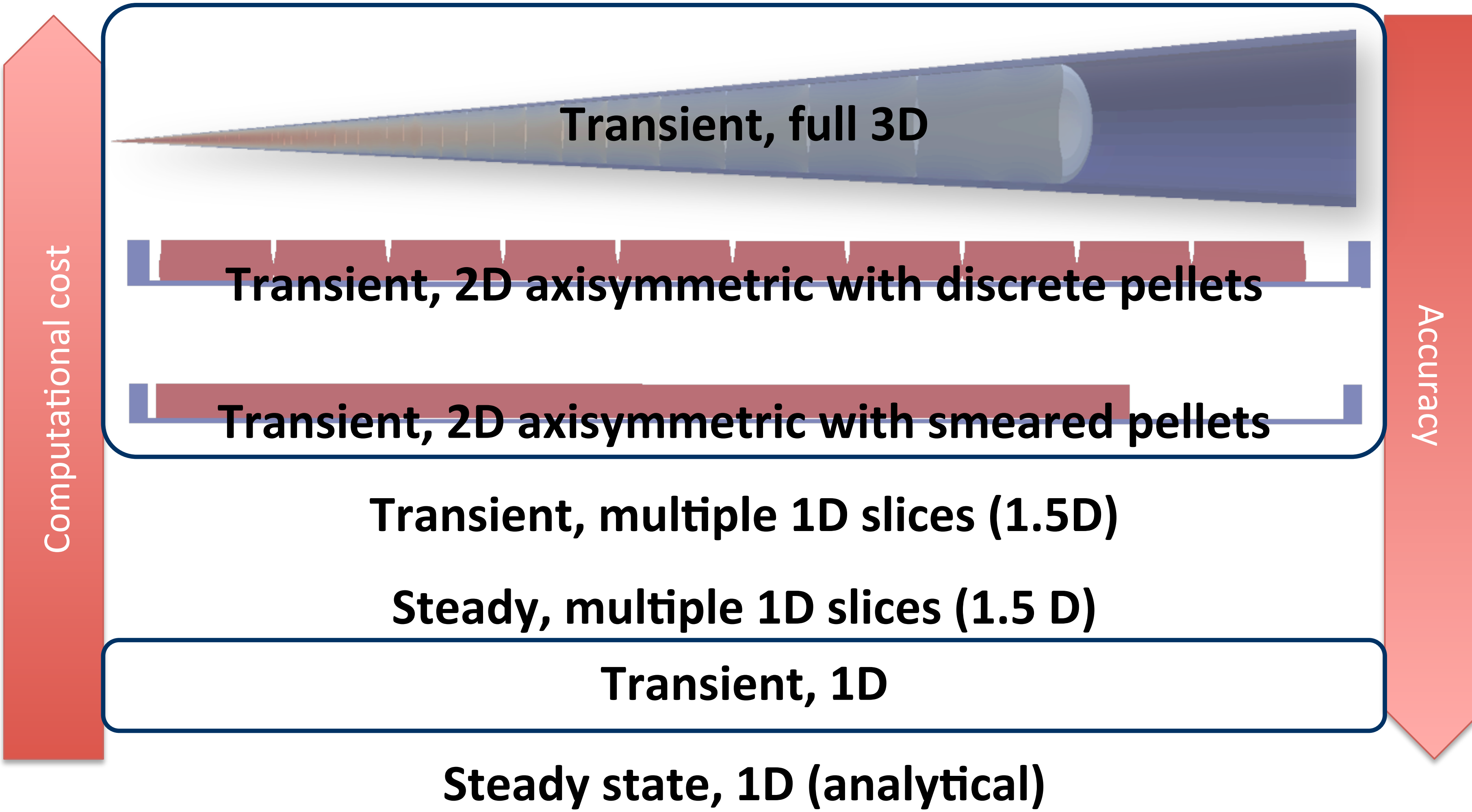


Figure 5. Missing pellet surface (MPS) PCI model.

Rashid, J. Y., Yagnik, S. K., & Montgomery, R. O. (2011). Light water reactor fuel performance modeling and multi-dimensional simulation. JOM, 63(8), 81.

The final US code we will discuss is BISON



BISON is the next generation fuel performance code under development in the US

- It uses the MOOSE framework
- Development was begun in 2008
- The first paper using BISON was published in 2009 and the paper summarizing its full capabilities was published in 2012
- It was developed at Idaho National Laboratory, with some support by ANATECH
- BISON is available for free, but it is export prohibited and requires a license agreement be signed
- https://bison.inl.gov/SitePages/Home.aspx

BISON models the fuel behavior ranging from 1D to full 3D and uses FEM

Fuel

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q$$

Solved with FEM

$$0 = \nabla \cdot \boldsymbol{\sigma}$$

Solved with FEM

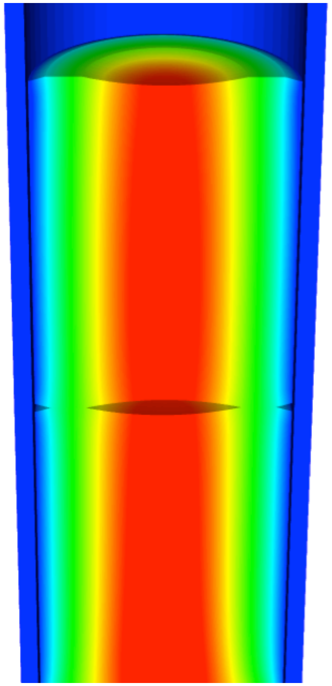
Cladding

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q$$

Solved with FEM

$$0 = \nabla \cdot \boldsymbol{\sigma}$$

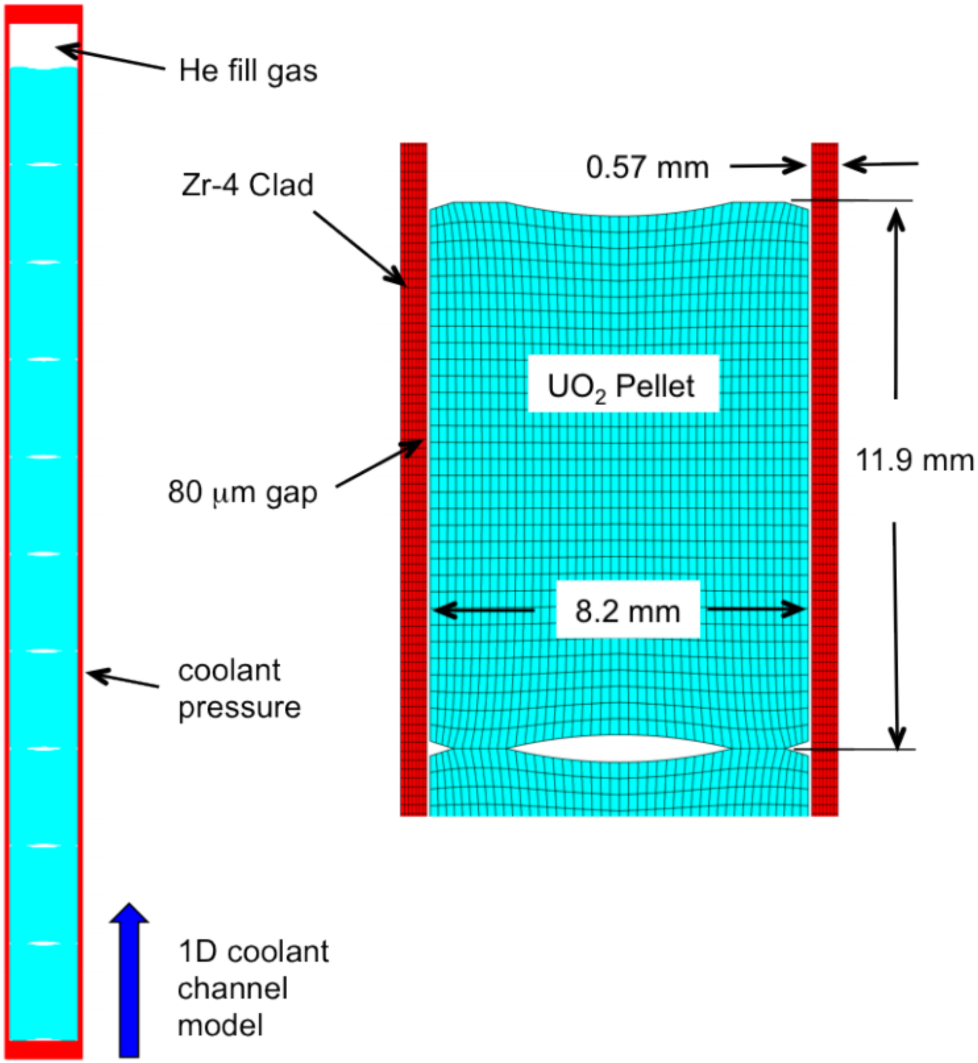
Solved with FEM

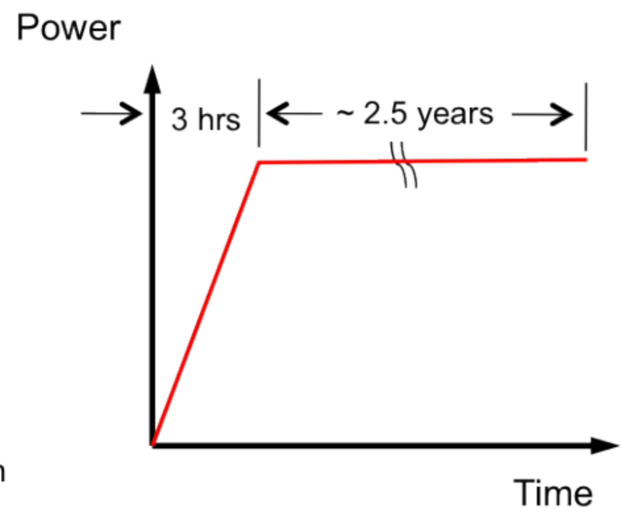


Gap

- Pressure is calculated using equation of state
- Fully implemented implicit contact algorithm
- Gap heat transfer model is used

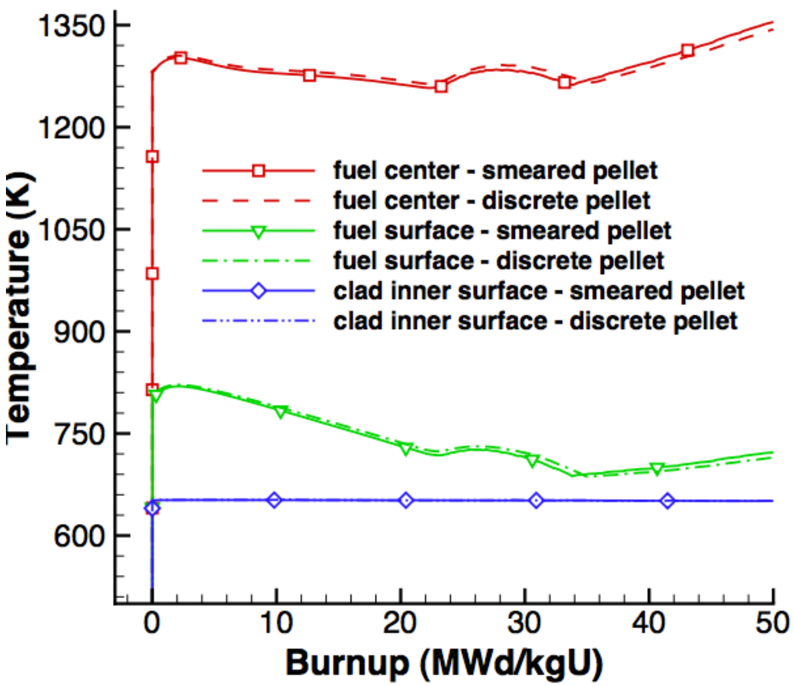
This is an example problem that the team provides to show off its capabilities

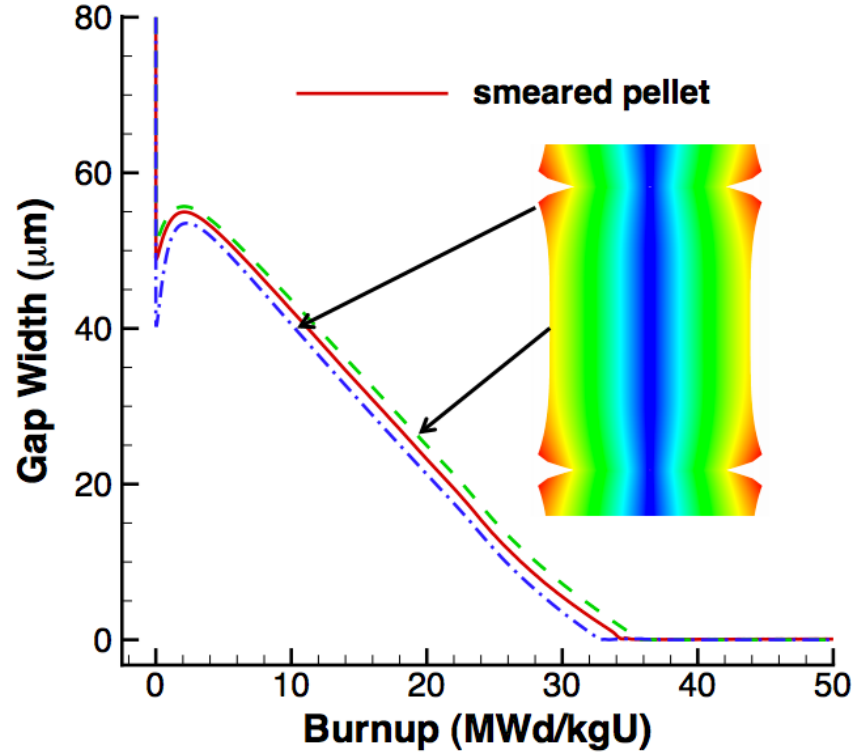




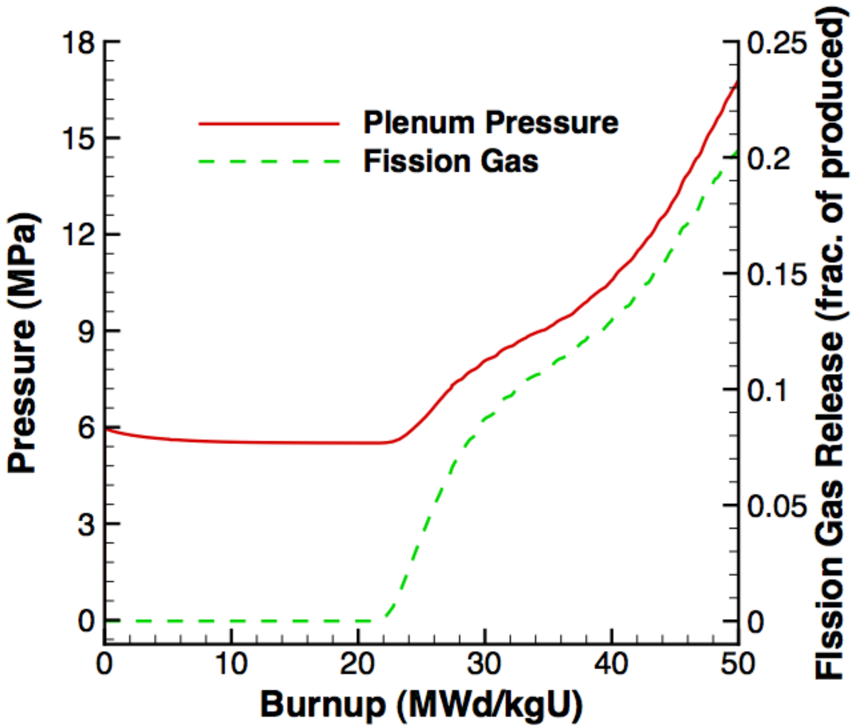
Linear average power	250 W/cm
Fast neutron flux	7.5×10^{17} n/m^{2}s
Coolant pressure	15.5 MPa
Coolant inlet temperature	580 K
Coolant inlet mass flux	3800 kg/m^2-s
Rod fill gas	helium
Fill gas initial pressure	2.0 MPa
Initial fuel density	95% theoretical
Fuel densification	1% theoretical
Burnup at full densification	5 MWd/kgU

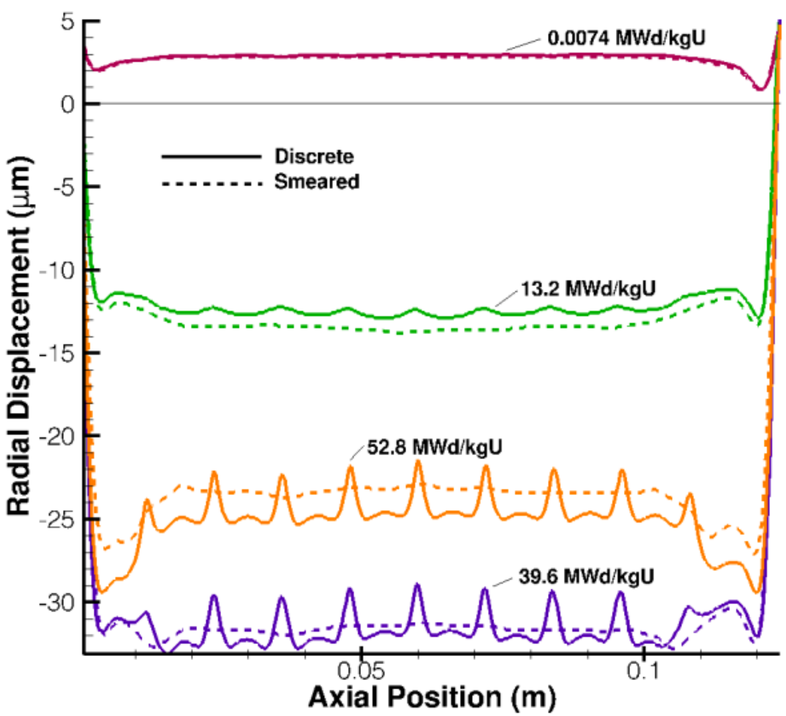
This is an example problem that the team provides to show off its capabilities



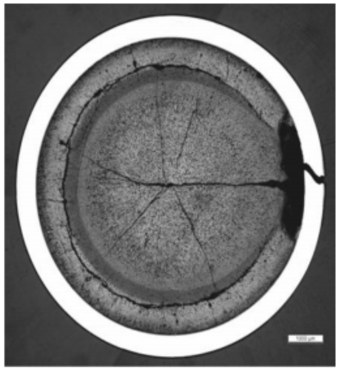


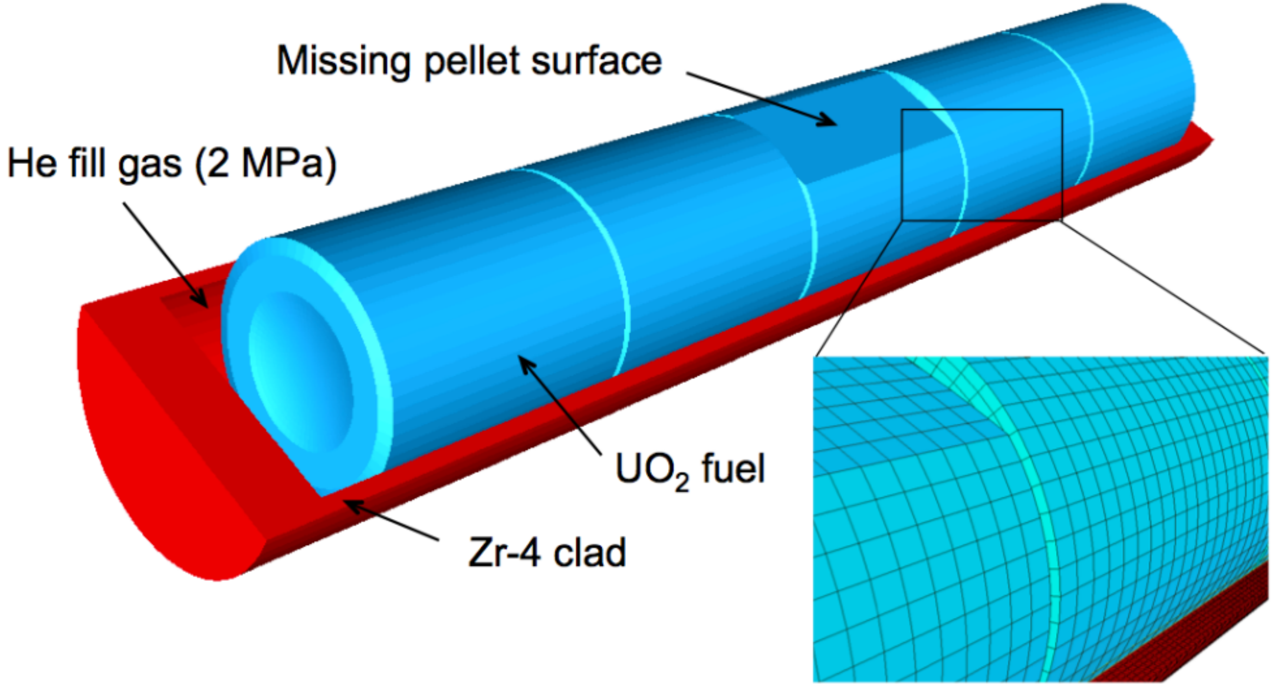
This is an example problem that the team provides to show off its capabilities





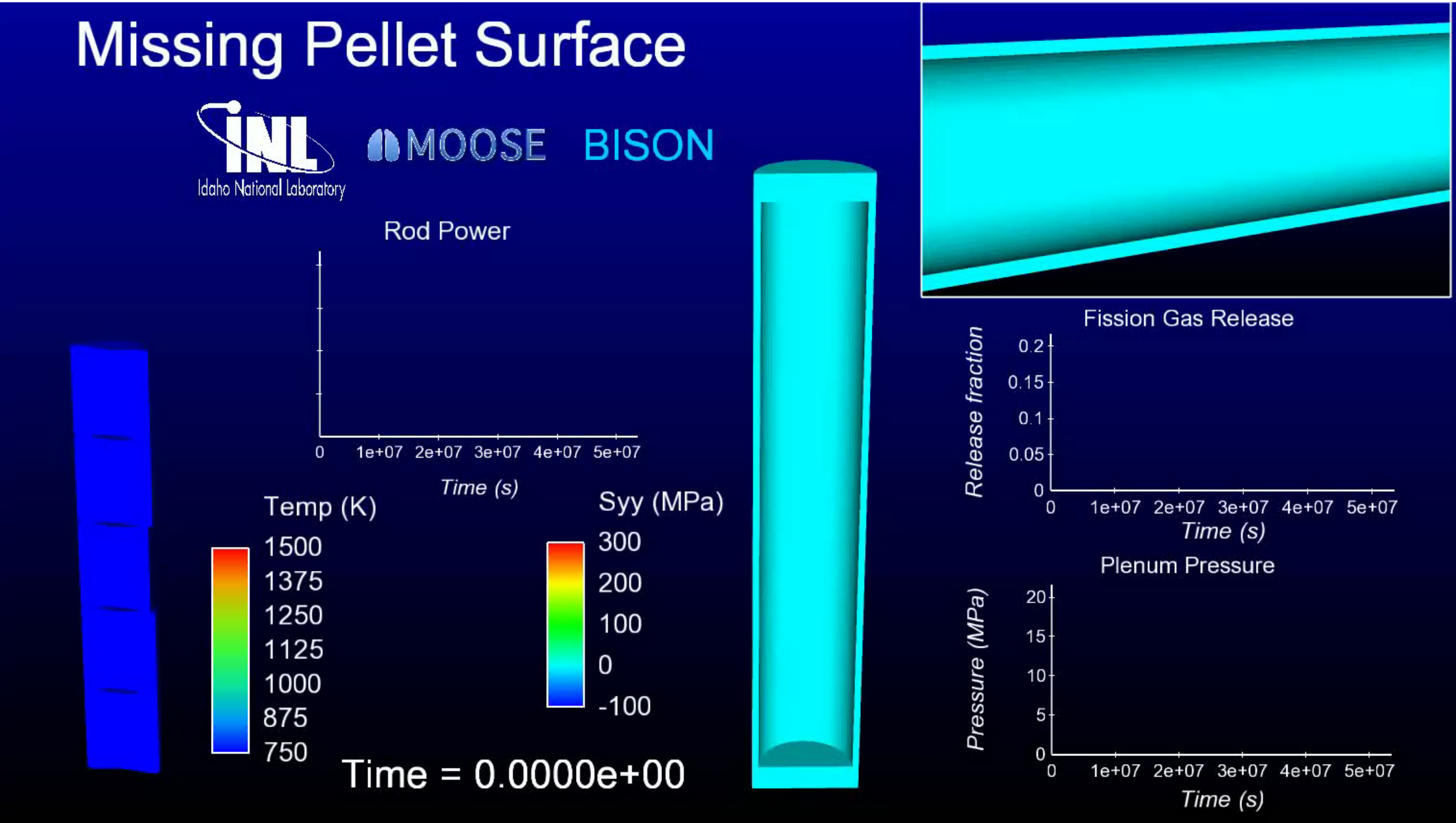
Because of its unique 3D capability, BISON can model truly 3D fuel performance problems





- High resolution 3D calculation (25,000 elements, $1.1x10^6$ dof) run on 120 processors
- Simulation from fresh fuel state with a typical power history, followed by a late-life power ramp

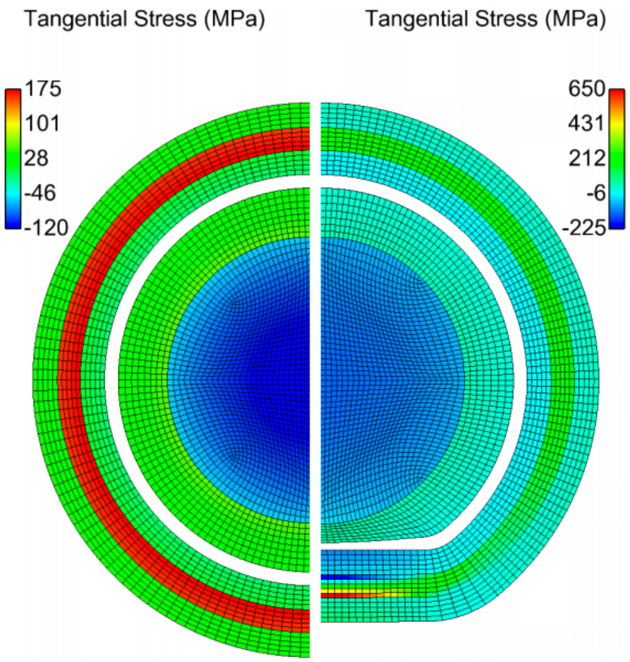
Because of its unique 3D capability, BISON can model truly 3D fuel performance problems



BISON can also model other fuel types besides LWR

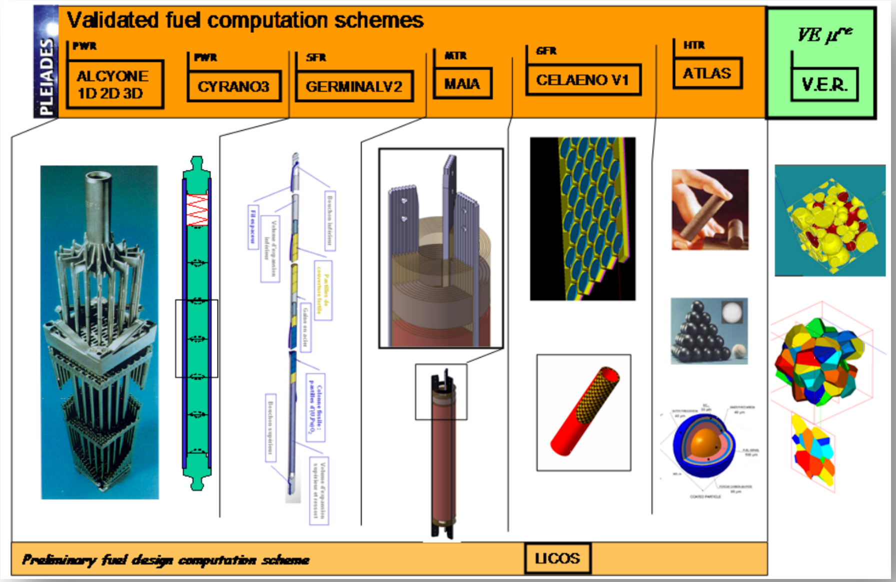
Metal fuel with an annular fuel pellet

TRISO fuel particle with ideal and more realistic shape



Other countries have other fuel performance codes

- TRANSURANUS: ITU (Germany)
- ALCYONE: CEA (France)
- ENIGMA: NNL (UK)
- FEMAXI-7: JAEA (Japan)
- SFPR: IBRAE (Russia)
- DIONISIO: (Argentina)

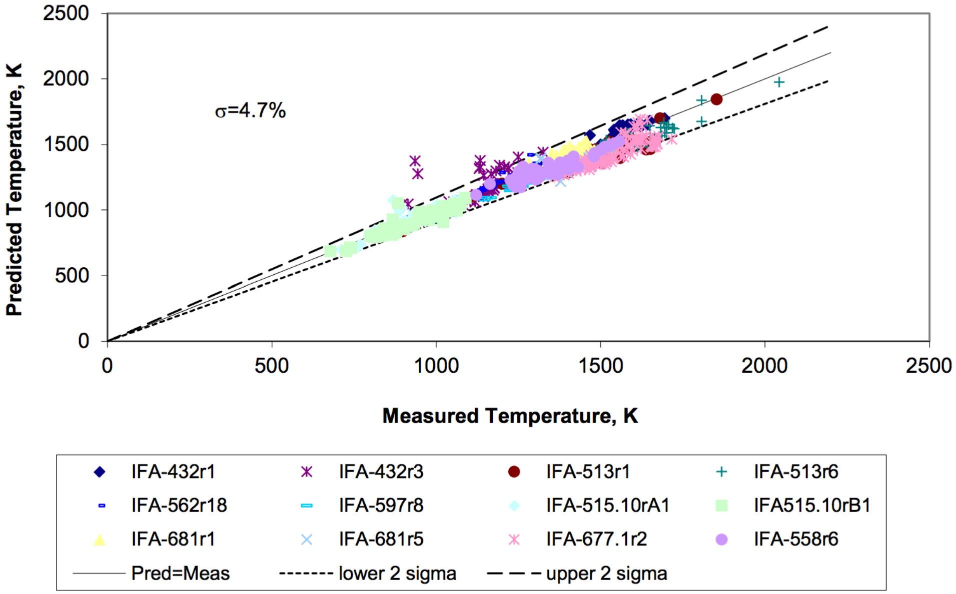


http://www.materials.cea.fr/en/PDF/PLEIADES-Platform.pdf

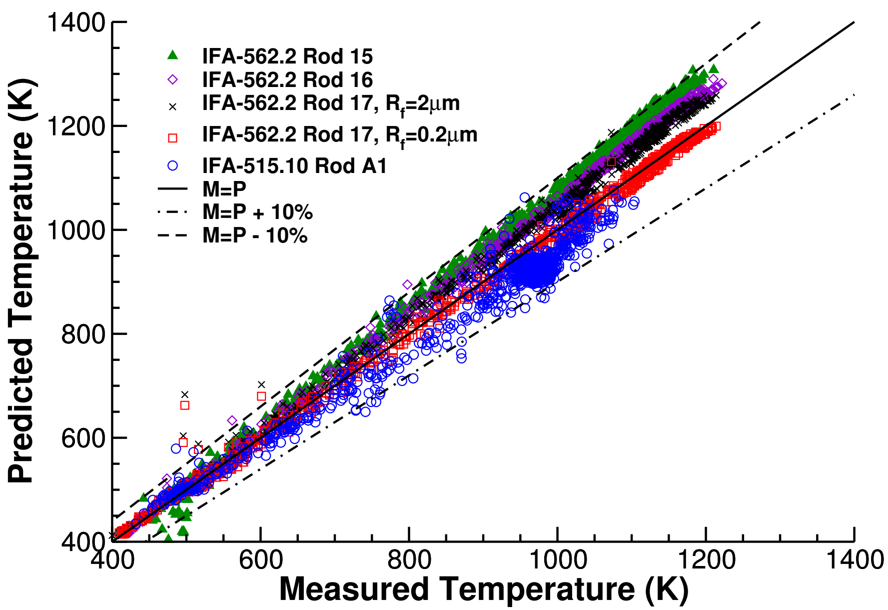
Fuel performance codes must undergo rigorous assessment to make sure they provide accurate results

- Over the years a large amount of data on instrumented fuel rods has been developed and is used to assess the accuracy of fuel performance models
- Typically, twice as much effort goes into assessing these codes as goes into developing them.

FRAPCON-4 Assessment example



BISON Assessment example



Summary

- Fuel performance codes are focused on predict the center temperature of the pellet and the stress in the cladding
- All fuel performance codes
  - Numerically model the temperature in the fuel
  - Numerically model the stress in the cladding
  - And consider gap pressure, closure, and heat transfer in some way
- The primary use codes are
  - FRAPCON – Steady state 1.5D, uses finite difference
  - FRAPTRAN – Transient 1.5D, uses finite difference
  - FALCON – Steady or transient 2D, uses finite element
  - BISON – Steady or transient, 1D – 3D, uses finite element