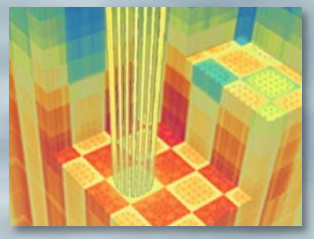
PCI Capability Development and Challenge Problem Progress

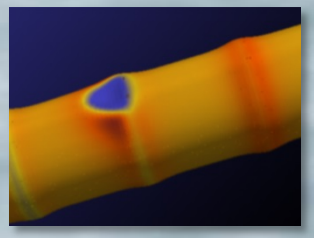
Joe Rashid[1], Brian D. Wirth[2], Rich Williamson[3]

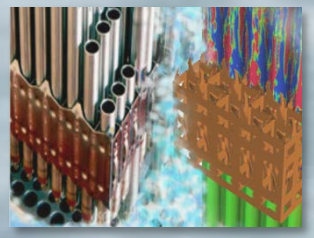
[1] *ANATECH Corp*

[2] *University of Tennessee*

[3] *Idaho National Laboratory*







The Consortium for Advanced Simulation of LWRs
A DOE Energy Innovation Hub

CASL-U-2016-1086-000

U.S. DEPARTMENT OF ENERGY

Outline

- State of the art of PCI & Fuel Performance Codes (FPCs)
- FPCs compatibility with Utilities needs – *what are the gaps? Can BISON close these gaps?*
- PCI Capability Development: BISON progress to-date
- BISON as a Phase-2 product – *will it fulfill its promise?*

State of the art of Fuel-Performance / Fuel-Behavior Codes

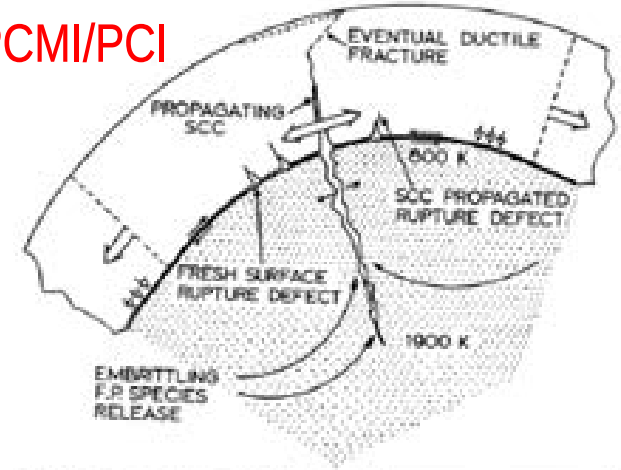
- **Group 1**: 1 ½ D Codes – Finite difference numerics, steady-state simulation
  - Licensing Codes developed by fuel suppliers
  - Codes developed by national/government research organizations
    - Long list – Best known: TRANSURANUS, ENIGMA, FRAPCON/FRAPTRAN
  - Emphasis on thermal behavior, simple mechanics, weak thermo-mechanical coupling
    - Inadequate simulation of PCMI/PCI

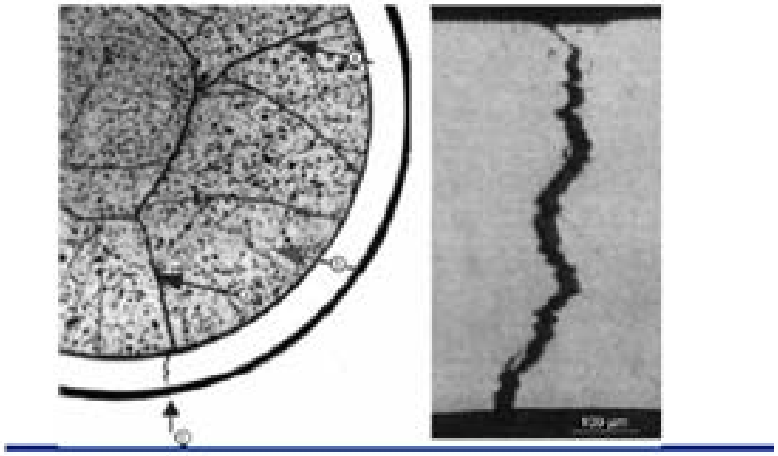
State of the art of Fuel-Performance / Fuel-Behavior Codes – *Cont.*

- **Group 2**: 2D & 3D codes – Finite Element numerics
  - EPRI: FALCON – 2D Full-length *r-z* & Plane *r-*θ
  - CASL: BISON – Full 3D & 2D *r-z* / *r-*θ simulation
  - Steady state and transient
    - Full power-burnup cycle, load follow, ATWS, RIA, LOCA, reactor tests, material property tests
  - Strong thermo-mechanical coupling
    - Essential capability for the PCI Challenge Problem - *see next slide*

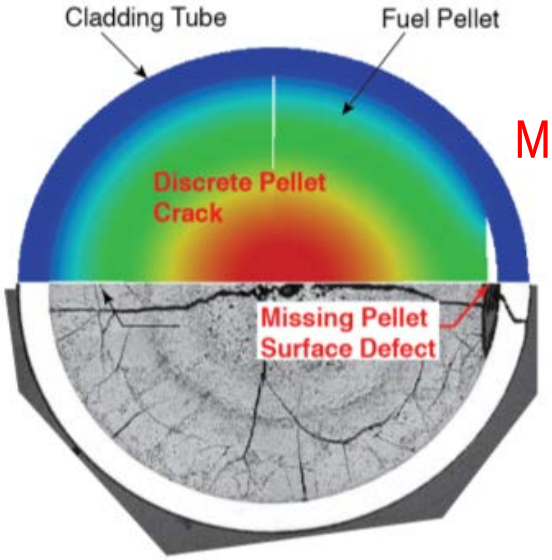
Elements of PCI Challenge Problem

PCMI/PCI



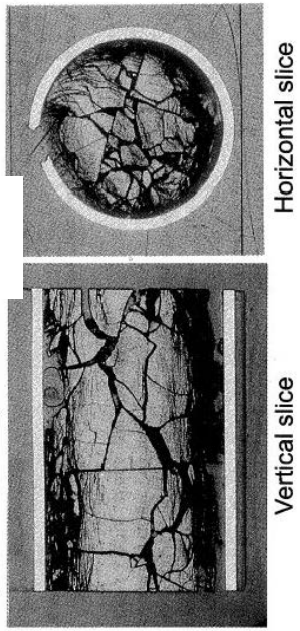


MPS

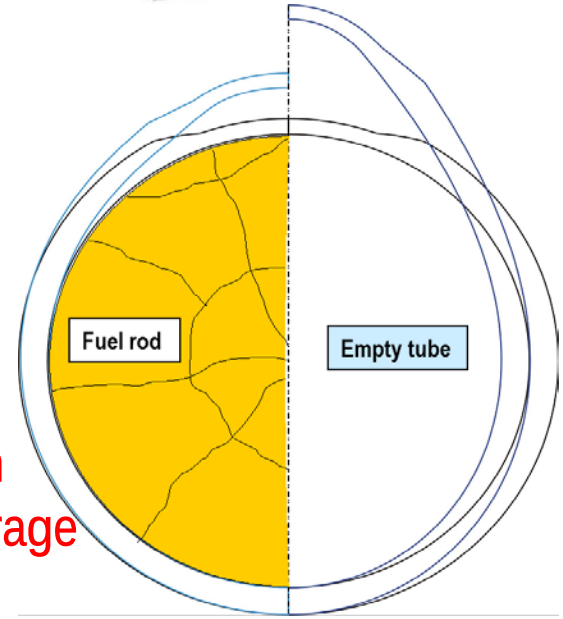


LOCA

RIA Test
220 cal/g



Creep in
Dry Storage



FPCs compatibility with Utilities needs – *what are the gaps?*

- Need # 1: Operate with no fuel failures
  - Sources of failure and how simulated in FPCs:
    - Pellet-Cladding Mechanical Interaction PCMI/PCI-SCC, MPS
      - No simulation in the 1½ D Licensing Codes – ***Gap #1***
    - Grid-to-rod-fretting (GTRF) & Crud induced localized corrosion (CILC)
      - No prospects for simulation in 11/2 D Codes – ***Gap #2***
  - Closing the Gaps – BISON's 3D and 2D simulations
    - Current: PCMI/PCI-SCC, MPS
    - Potential: GTRF & CILC Models under development for implementation in BISON

FPCs compatibility with Utilities needs– *what are the gaps? (Cont.)*

- Need # 2: Flexible Power Operations / Load Follow (FPO/LF) w/o risk of fuel failure
  - Nuclear plants in the US operate in base-loading mode
  - Currently, FPO/LF is done at the operator's risk – ***Gap #3***
  - Closing the Gap: BISON's modeling of fuel deconditioning that results from extended reduced power operation (ERPO)
    - Crack re-cohesion Model to simulate fuel loss of conditioning
    - Power ramp-rate optimization
      - Robust damage/failure model

FPCs compatibility with Utilities needs– *what are the gaps? (Cont.)*

- Need # 2: (FPO/LF) – *Cont.*
  - Not a fuel behavior issue alone
  - Potential impact on plant operations and flow regimes, plant safety analyses, violating operational set points, dealing with Xenon oscillations, axial offset anomalies, etc.
  - Requires coupled fuel-performance/physics methods, which are lacking – ***Gap #4***
  - Closing the gap: BISON-MPACT in VERA-CS

FPCs compatibility with Utilities needs– *what are the gaps? (Cont.)*

- Need # 3: Fuel cycle backend – Used fuel management
  - Hydride precipitation/re-orientation during dry storage
    - An issue for all cladding alloys – worse for burnup levels above 45 GWd/MTU
      - End of life rod internal pressure: Hydride re-orientation (HRO)
      - Fuel-clad bonding – a high-burnup issue with potential benefits
    - Ductile-brittle transition temperature (DBTT) – Fn. of HRO
      - A major regulatory issue for spent fuel transportation

FPCs compatibility with Utilities needs– *what are the gaps? (Cont.)*

- Need # 3: Fuel cycle backend – *Cont.*
- Issue is treated outside the domain of FPCs because of multi-disciplinary interaction: thermal, chemical, structural
  - This drives NRC to depend totally on DBTT data, no modeling
  - Regulatory Information Summary (RIS) report – latest NRC position
    - Ship the fuel hot, temperature above the DBTT ??, or
    - Demonstrate sub-criticality under regulatory accidents
  - No Industry position for dealing with NRC RIS report – ***Gap #5***
- BISON has the Potential to Close the Gap: Implement in BISON the following models:
  - Chemistry (hydride precipitation/reorientation) model, multi-phase damage model, (both currently exist), and mass/inertia
  - This transforms BISON into a "thermal-chemical-structural" code
  - This BISON's "soup to nuts" treatment of spent fuel issues should move NRC to accept data-supported modeling and simulation

FPCs compatibility with Utilities needs– *what are the gaps? (Cont.)*

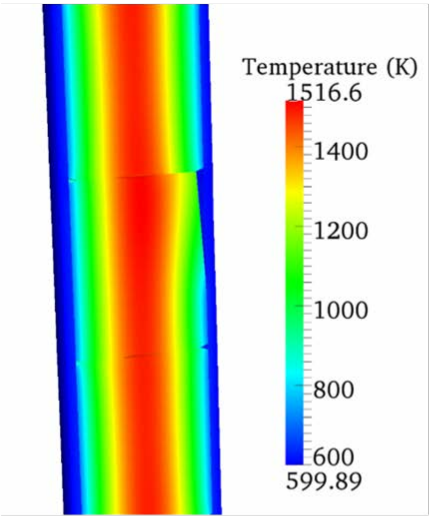
- BISON as a "thermal-chemical-structural" code coupled with Physics Codes (VERA-CS) could potentially provide the needed capability to address Un-resolved Issues:
  - LOCA for increased burnup
  - CIPS (CILC induced power shifts)
  - Fuel assembly distortions
  - BWR channel bow
  - Spent fuel transportation

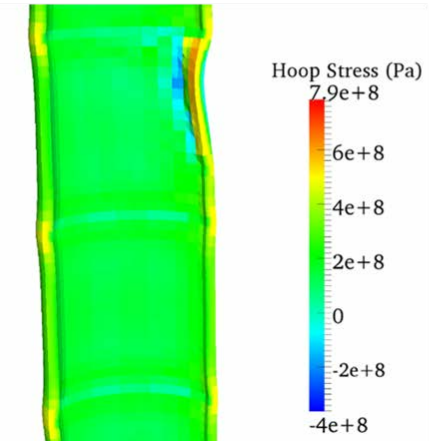
PCI Capability Development: BISON progress to-date

- Progress is compatible with pre-defined milestones
- Although the code is not yet fully ready for prime-time, it already shows favorable comparisons with much older international codes:
  - Comparable to TRANSURANUS and ENIGMA at a recent OECD PCMI Benchmark meeting
- In the interest of time, two problems are selected:
  - MPS analysis (*see next slide*), with video demonstration
  - Application to spent fuel, analysis of fuel-cladding bonding
    - *Four slides*

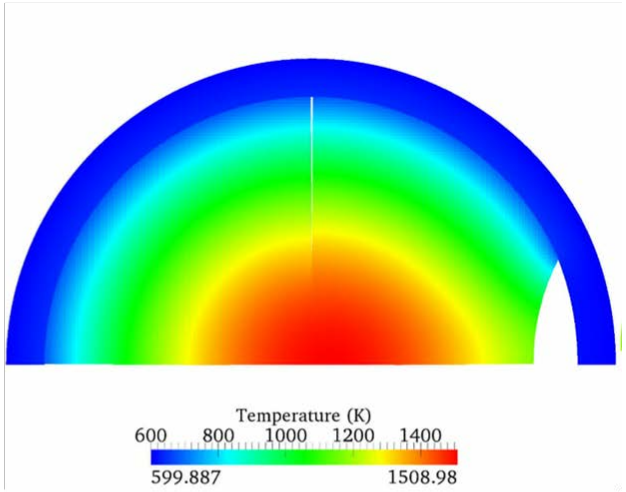
BISON progress to-date: Missing Pellet Surface (MPS) Analysis

3D Simulation





2D Simulation

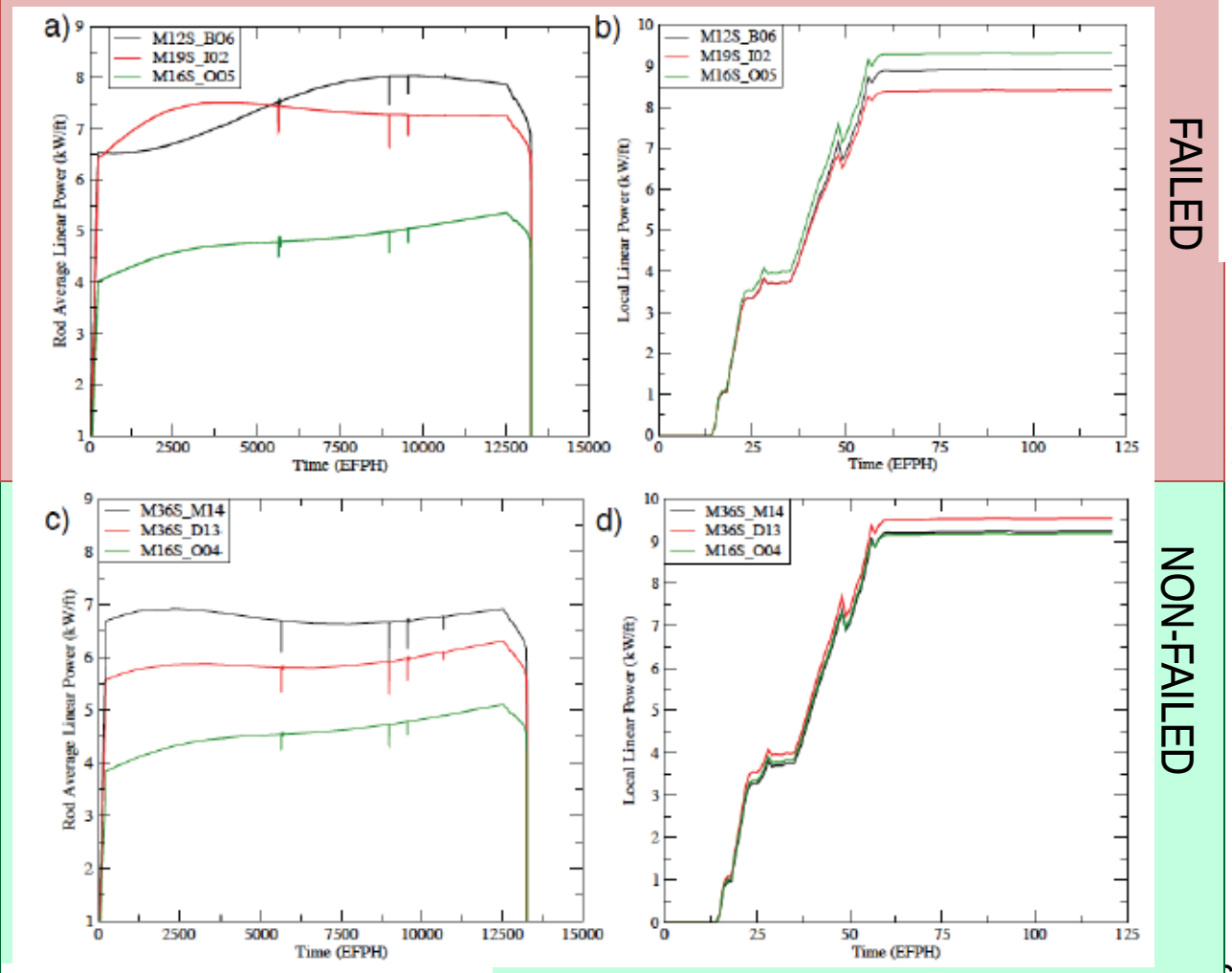


Movie

CASL-U-2016-1086-000

BISON progress to-date: Missing Pellet Surface (MPS) Analysis

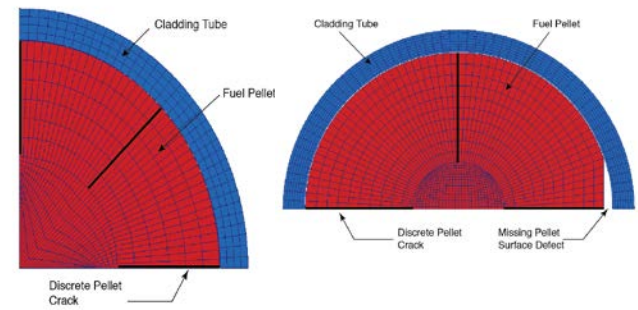
Cycle 10 | Cycle 11

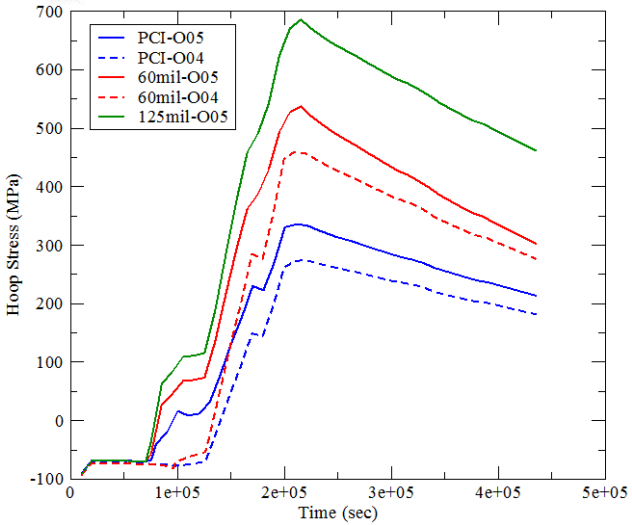


FAILED

NON-FAILED

PCI analysis | MPS analysis



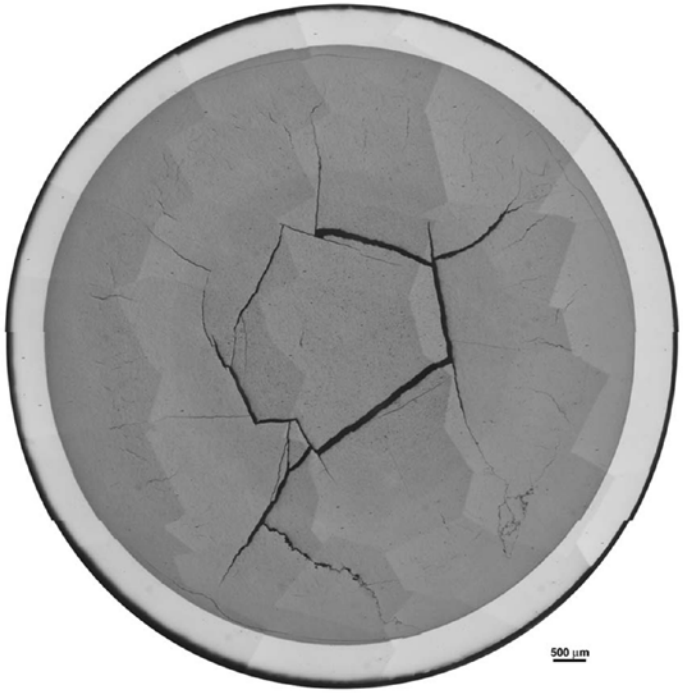


Conclusively shows MPS are cause of failed commercial rods for this PWR

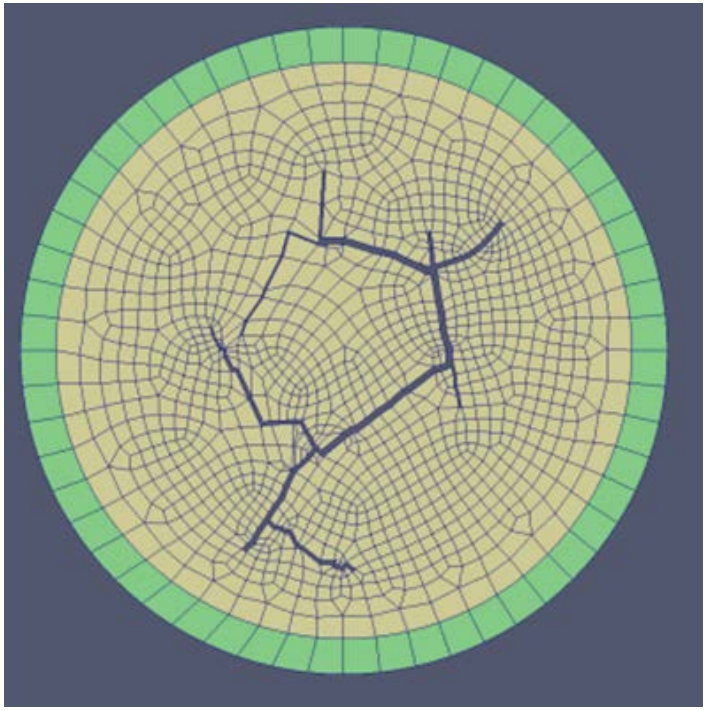
* CASL-I-2013-0165-000

BISON progress to-date: Application to Spent Fuel – Pellet-Cladding Bonding

High-burnup Fuel Rod at EOL

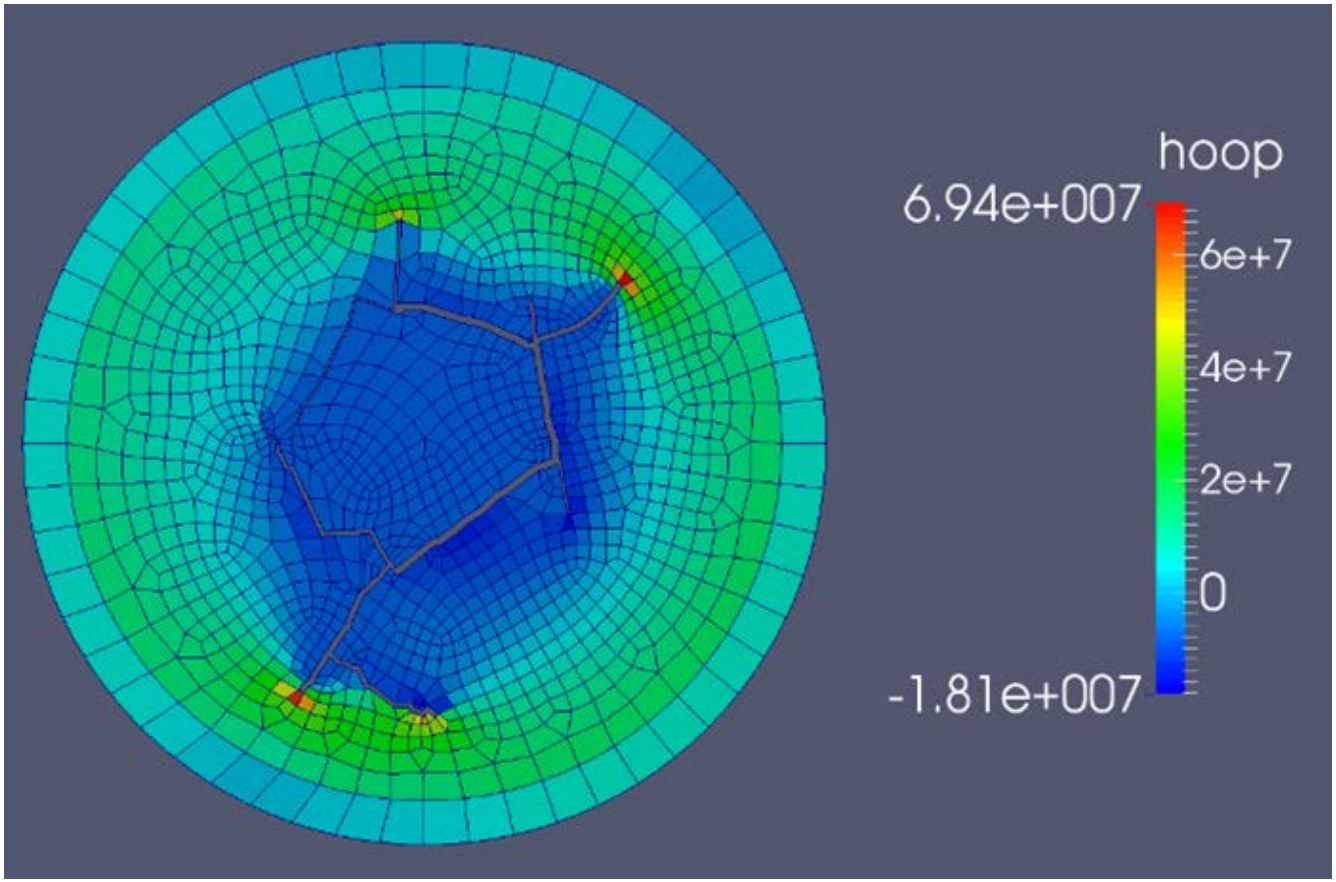


BISON Mesh



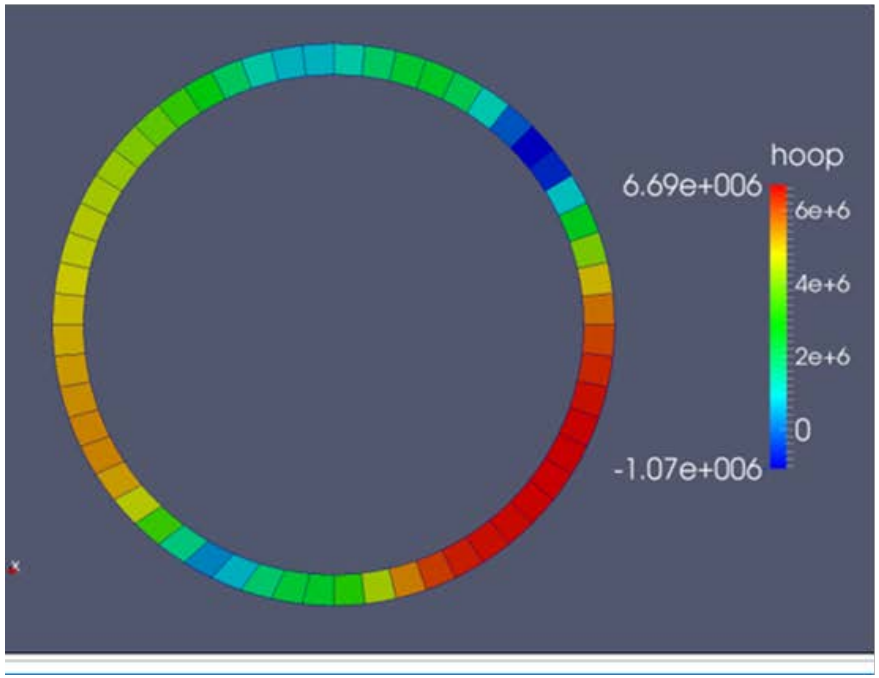
BISON progress to-date: Application to Spent Fuel – Pellet-Cladding Bonding

Hoop stress distribution at 400°C due to pressurized cracks
Note that cladding stress is below 10 MPa << HRO Threshold

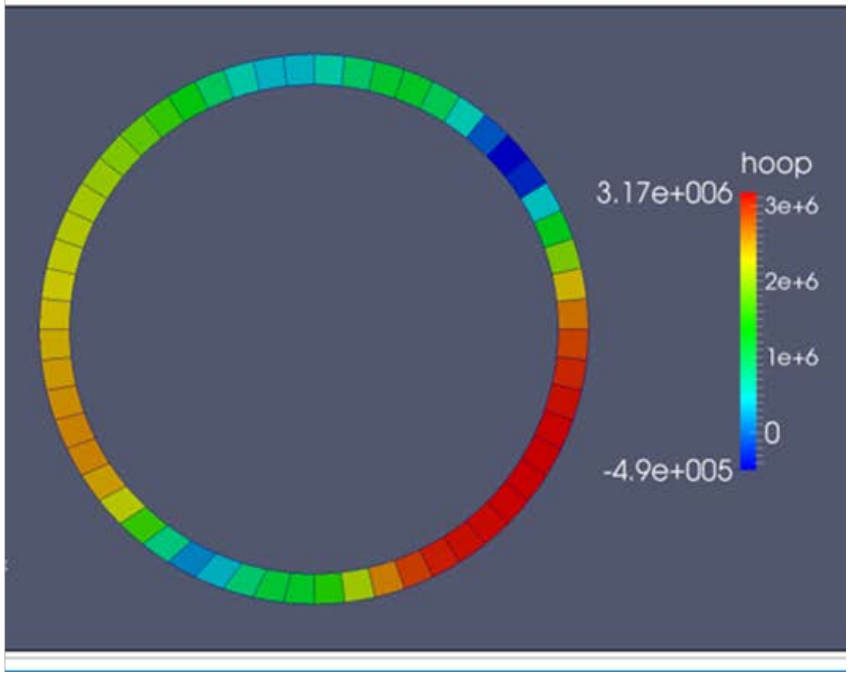


BISON progress to-date: Application to Spent Fuel – Pellet-Cladding Bonding

Cladding hoop stress at 400°C



Cladding hoop stress at 40°C



BISON as a Phase-2 product – *will it fulfil its promise ?*

It already has, for the completed capabilities

No known impediments to future progress

Definition of a Fuel Performance Expert

To have the ability to foretell, today, tomorrow, and next year, how to operate the reactor without PCI failures
and to have the ability afterwards
to explain why PCI failures happened

CASL

A DOE Energy Innovation Hub

www.casl.gov