INL/MIS-23-75030-Revision-0

EPRI TCF Project Overview

October 2023

Changing the World's Energy Future

Kyle A Gamble

Idaho National Laboratory

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Kyle A. Gamble

TCF Project Overview

Update on Coupling of BISON/RELAP for LOCA Analysis

Acknowledgments

- **INL BISON:** Jason Hales, Daniel van Wasshenova
- **INL RELAP5-3D:** George Mesina, Mauricio Tano Retamales, Brandon Cox
- **INL Computational Frameworks:** Cody Permann, Jan Vermaak
- **EPRI:** Ken Yueh, Mohammed Abdoelatef

Introduction

- **Aim:** Develop a computational tool able to evaluate high-burnup behavior under LOCA conditions.
  - Coupling thermal-hydraulics (RELAP5-3D) and fuel performance (BISON)

- The project officially began in May 2022 and has a duration of 2 years.

RELAP5-3D

BISON

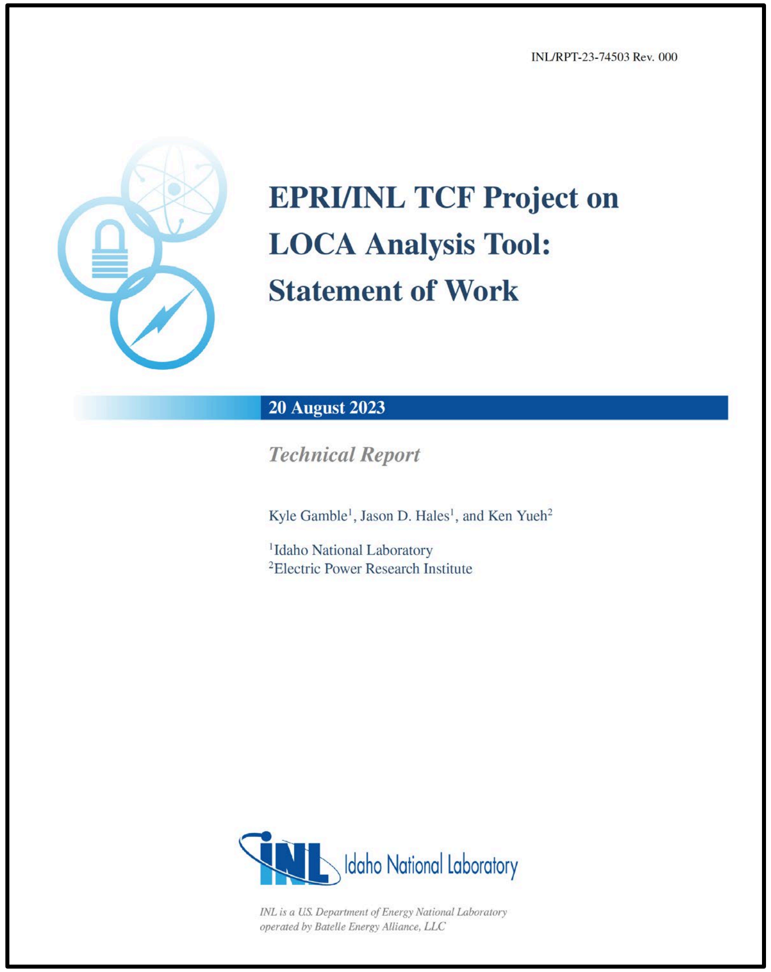
https://inl.gov/ncrc/code-descriptions/

Seven Major Tasks of the Project

1. Coordinate with the CRAFT Technical Expert Group (TEG) on planned activities, align activities with those recommended by the TEG, and revise plans based on feedback from the TEG.
2. Define areas where technical data is required to guide code development.
3. Develop and refine BISON models for higher burnup application.
4. Complete and document coupling of RELAP5-3D and BISON.
5. Verify and validate the coupled capability.
6. Develop and document best estimate plus uncertainty capability.
7. Issue final report demonstrating capability.

CRAFT Statement of Work Review and Input

- Initial interaction started with a kickoff meeting on May 11, 2023, held at INL.
- Goal of the meeting was to present existing capabilities of the codes to attendees and identify the path forward.
- Attendees included FFRD TEG members:
  - Ken Yueh
  - Dan Wachs
  - Stephen Novascone
- Current statement of work (SOW) is available for broader review (INL/RPT-23-74503)


INL/RPT-23-74503 Rev. 000

EPRI/INL TCF Project on LOCA Analysis Tool: Statement of Work

20 August 2023

Technical Report

Kyle Gamble[1], Jason D. Hales[1], and Ken Yueh[2]

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Idaho National Laboratory

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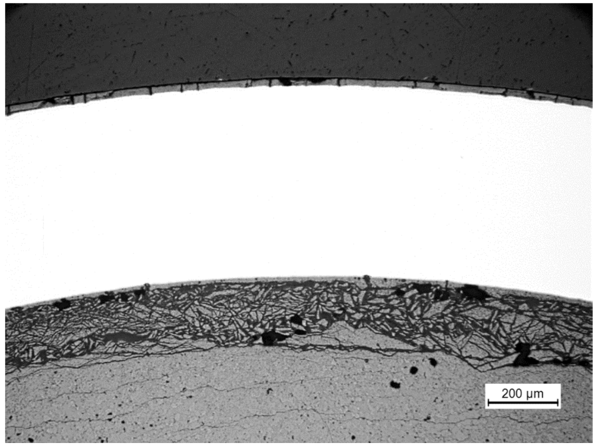
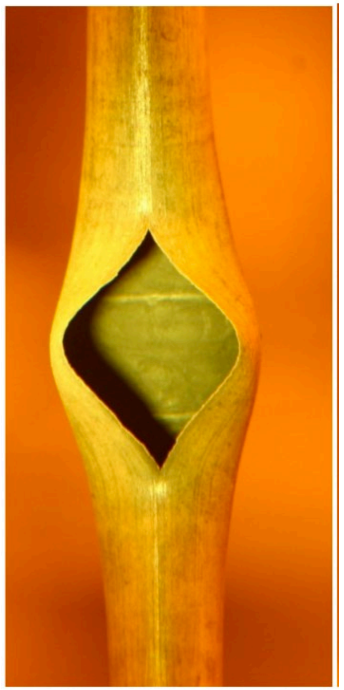
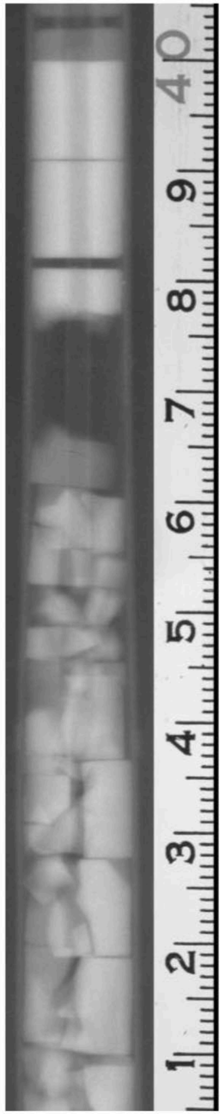
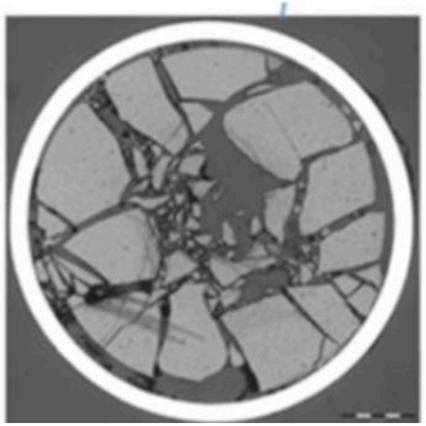
Define Areas where Technical Data is Required

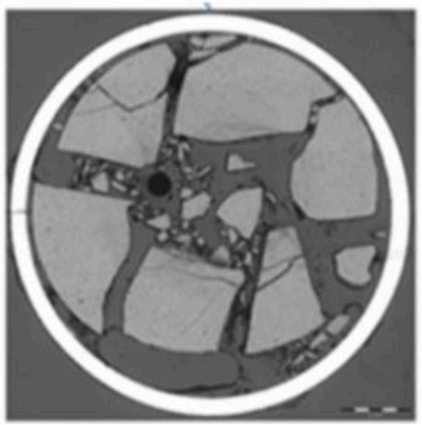
- Identifying available data and its applicability is important. Four areas have been identified:
  1. Data associated with high-burnup structure and fuel fragmentation.
  2. Database of experimental LOCA cases
  3. EPRI proprietary technical data
  4. Data available through coordination with CRAFT

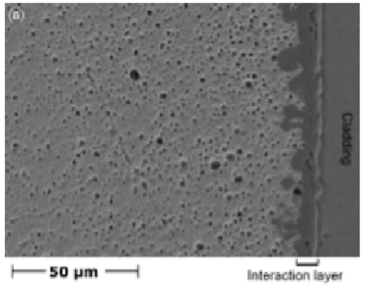


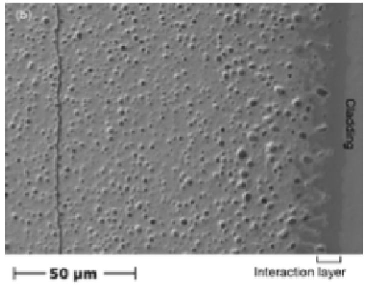


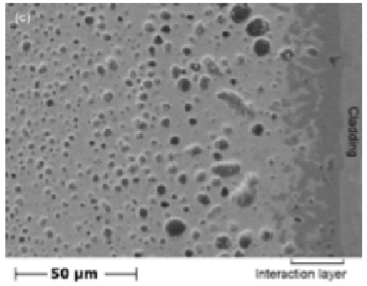








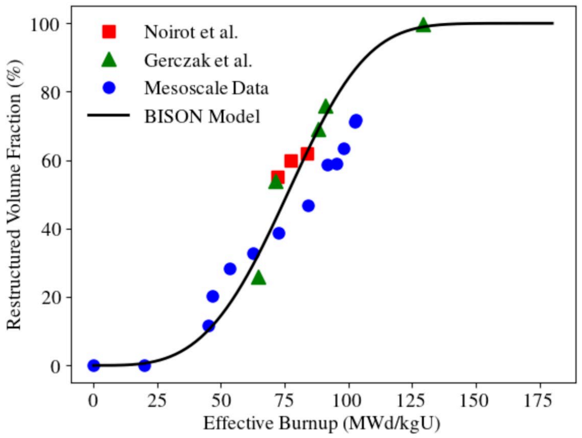


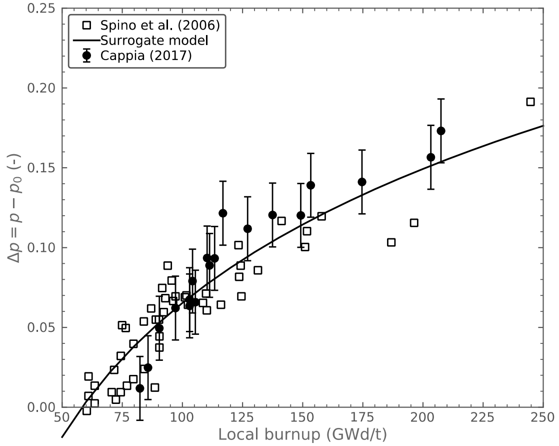


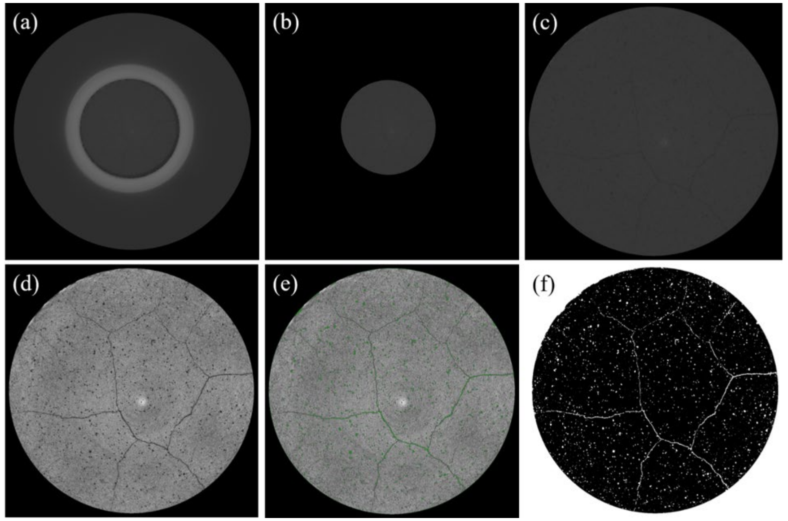
Develop and Refine BISON Models for High Burnup Application

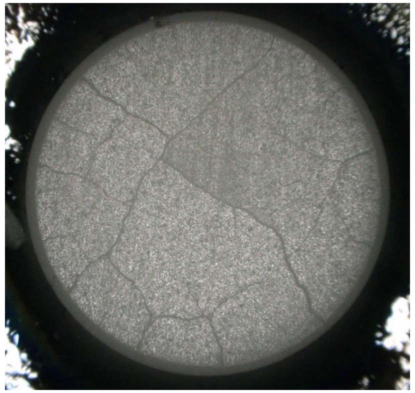
- Six areas have been identified in which developments or refinements are needed:
  - Formation of high burnup structure
  - Fuel fracture and pulverization
  - Transient fission gas release
  - Gas communication within the fuel rod
  - Cladding ballooning and burst
  - Axial fuel relocation

- Close coordination with the NEAMS program exists to ensure complimentary code improvements.



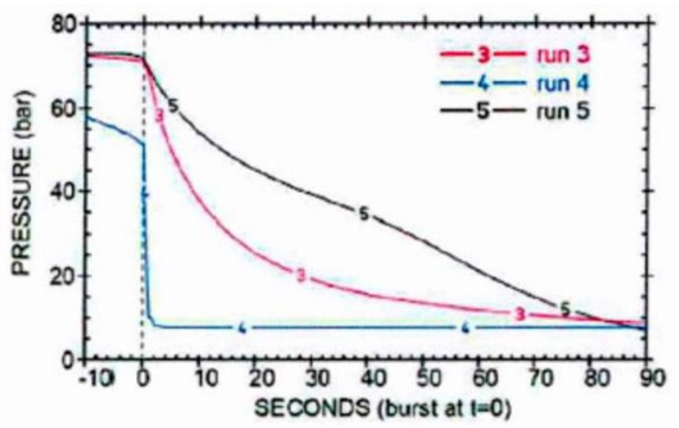


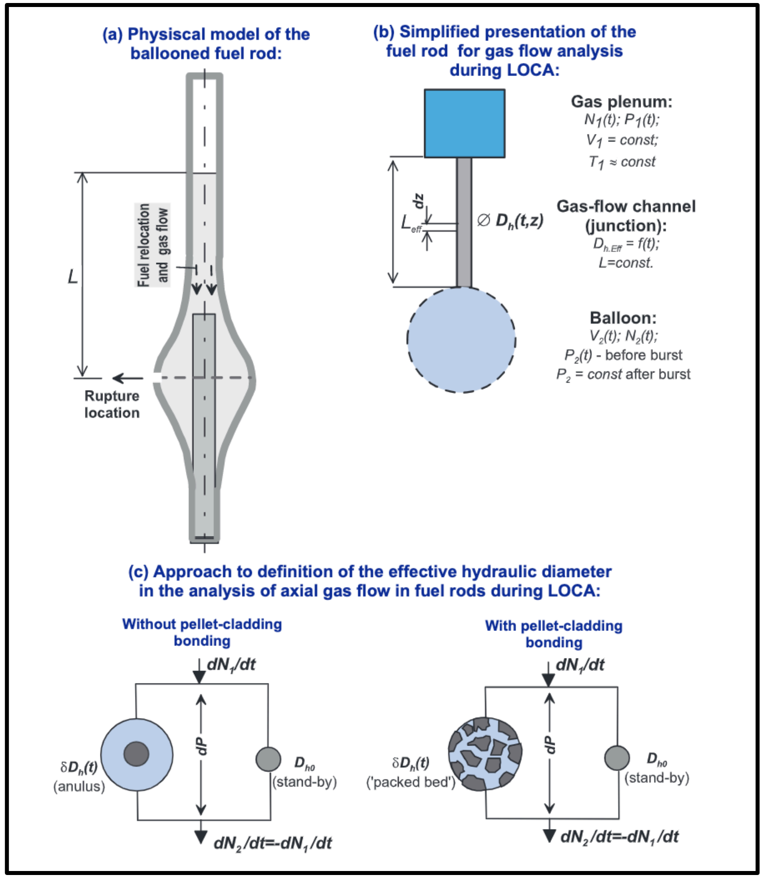




Gas Communication in the Fuel Rod

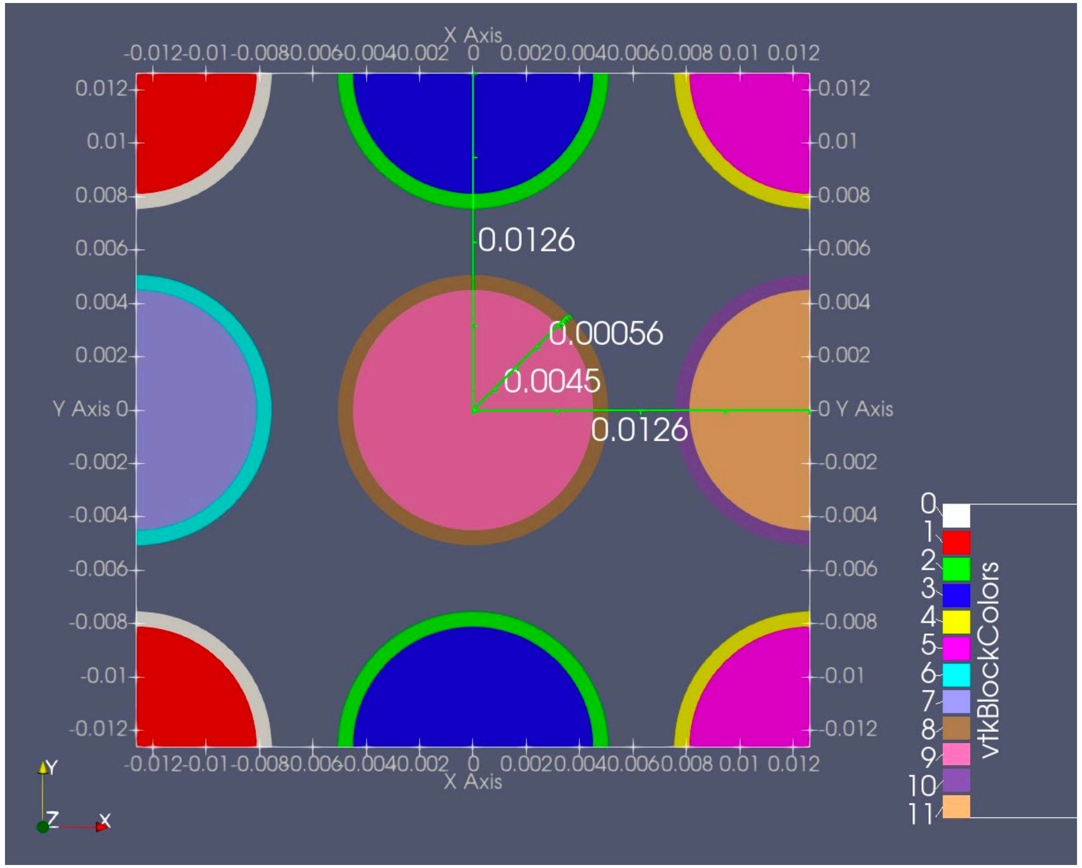
- Gas movement inside the fuel rod can influence how a rod balloons that may lead to burst.
- Integral tests using relatively short fuel segments have shown a large variation in depressurization of the plenum upon rod burst suggesting local fission gas pressure driving ballooning.
- Couple gas communication model to pulverization of the rim structure.
- Transient fission gas released locally will be combined with plenum gas for depressurization.





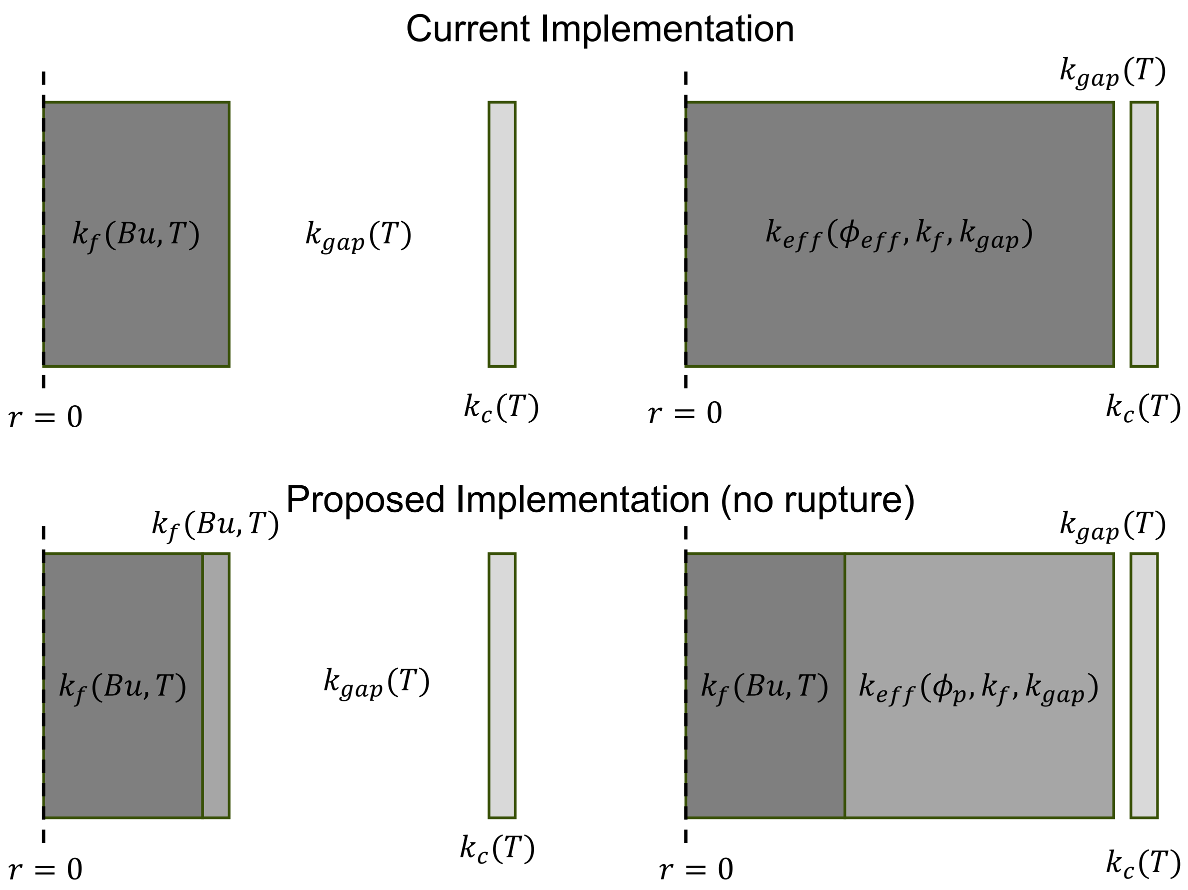
Cladding Ballooning and Burst

- Higher burnup fuels will result in increased fission gas release and potential plasticity induced failures (due to stored energy)
  - Include plasticity during LOCA analyses
- If rupture occurs due to plasticity, existing failure criteria do not apply as they are based solely on creep and ballooning failure.
- Majority of existing experiments occur on single isolated fuel rods attaining very high burst strains.
  - Develop the capability for multi-rod analysis.



Axial Fuel Relocation

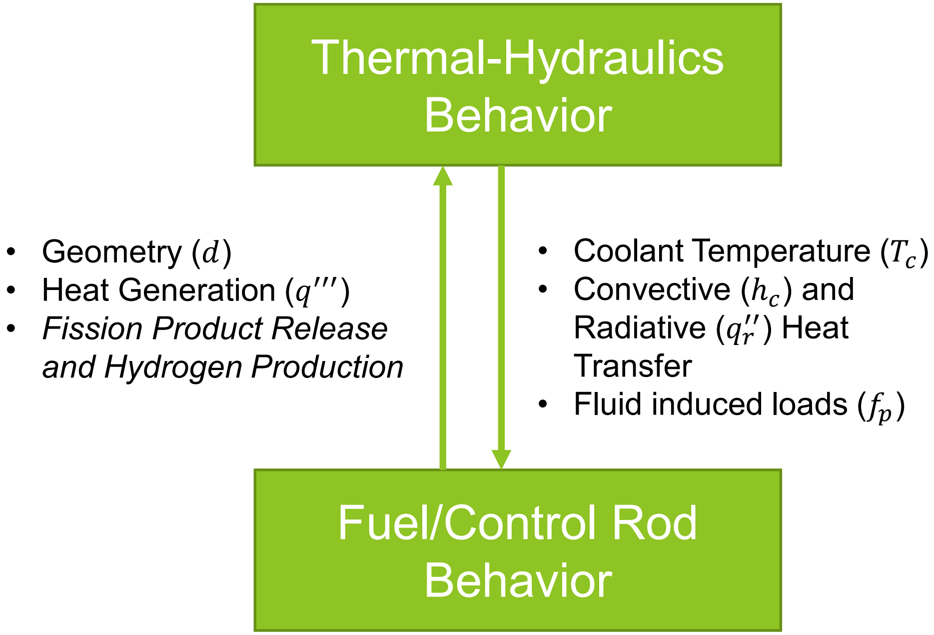
- Extend the existing axial fuel relocation model to no rupture conditions.
  - Only the pulverized region may relocate while the rod remains pressurized.
  - Relocation of the bulk of the fuel stack.
  - Appropriately account for the effective thermal conductivity of relocated fuel.
  - Simulate fuel relocation in multiple ballooning rods



k_f = fuel thermal conductivity
k_{gap} = gap thermal conductivity
k_{eff} = effective thermal conductivity
k_c= clad thermal conductivity
ϕ_{eff} = effective packing fraction
ϕ_p= pulver packing fraction

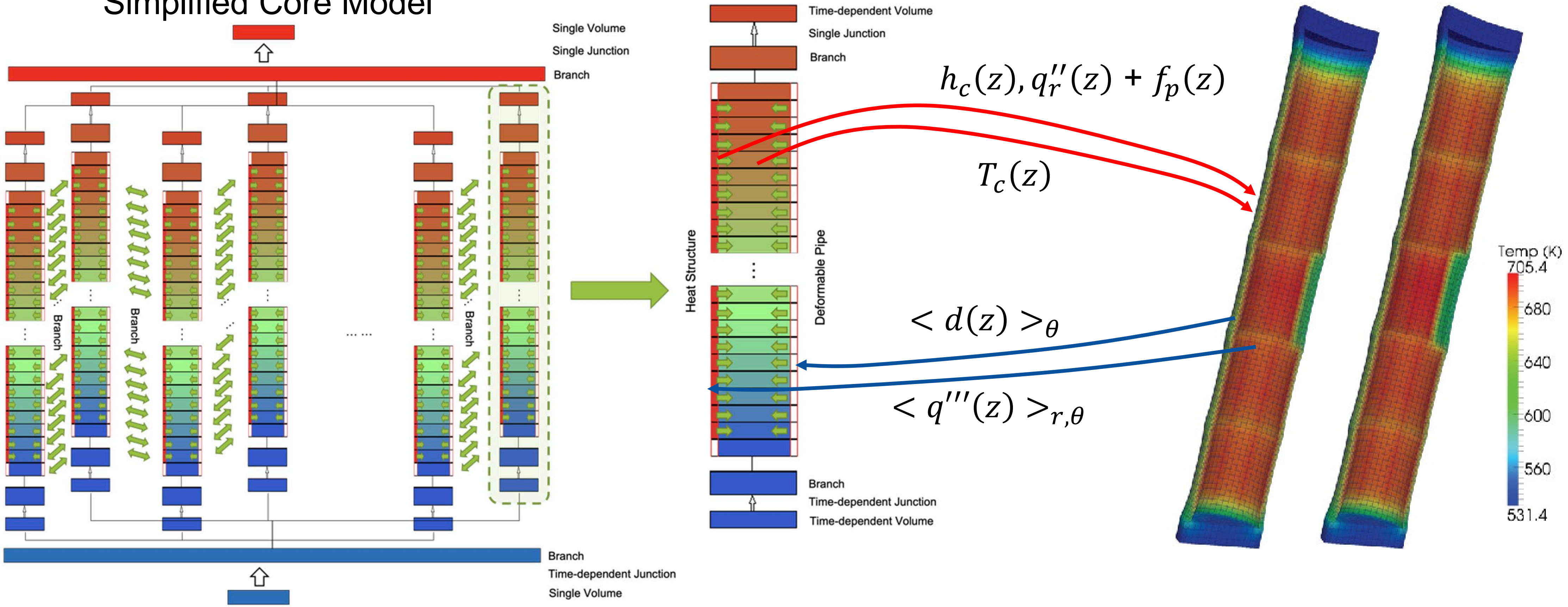
Thermal Hydraulics – Fuel Performance coupling

- Key models:
  - RELAP5-3D: two-phase flow thermal-hydraulics phenomena during LOCA phases
  - BISON: fuel performance during the LOCA transient
- Coupling principle – for one coupling iteration:
  1. RELAP5-3D performs one time step of the full RPS or experiment model and sends to BISON:
     - Axially-resolved coolant channel temperatures ($T_c(z)$)
     - Axially-resolved convective heat transfer coefficient ($h_c(z)$) and radiative heat flux ($q_r''(z)$)
     - Axially-resolved mechanical loads on the fuel rods ($f_p(z)$)
  2. With the provided boundary conditions, BISON performs the thermomechanical calculation to determine:
     - Axially-resolved rod deformation and displacements ($d(z)$) → are used to update the area and hydraulic diameters of the coolant channels over the channel height in RELAP5-3D
     - Axially-resolved heat generation ($q'''(z)$) → is used to update the heat source in the heat structure in RELAP5-3D representing the fuel rod



Coupling Schematics

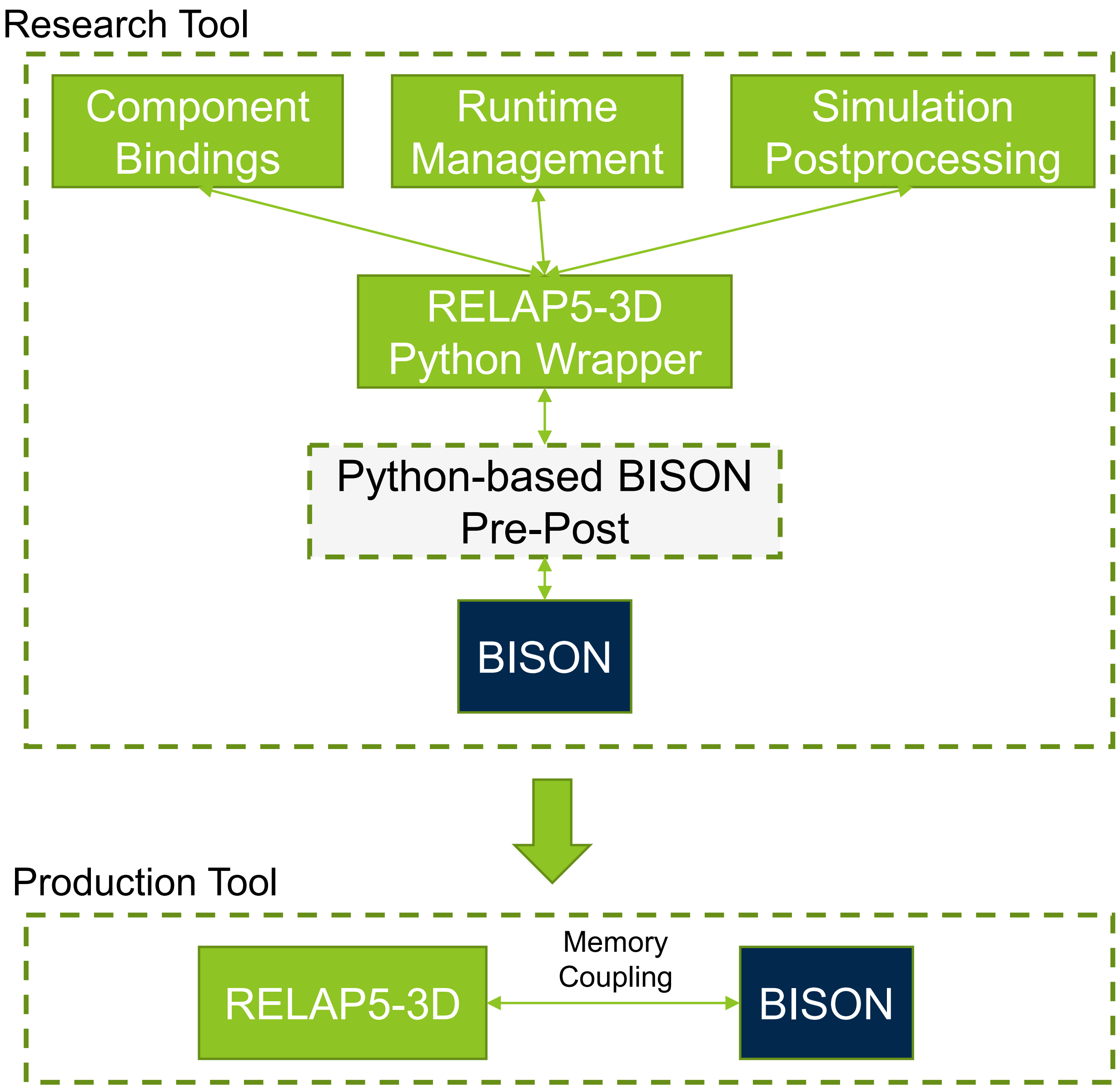
Simplified Core Model



- Key research points:
  - RZ vs 3D modeling
  - Time-stepping between RELAP5-3D and BISON

Proposed Workflow

- The **first part** of this work will extend RELAP5-3D Python's Wrapper with a shallow wrapper of BISON
- The key goal of this approach is to:
  - Streamline the coupling research tasks (coupling dimensionality, timestep matching needed, iteration acceleration, etc.)
  - More easily develop RELAP5-3D models for LOCA that compare well to experimental data
- In the **second part** of this work, RELAP5-3D and BISON will be coupled in memory (reutilizing RedCRAB work) and the coupled simulations will be verified against the work developed in the first part of this project.

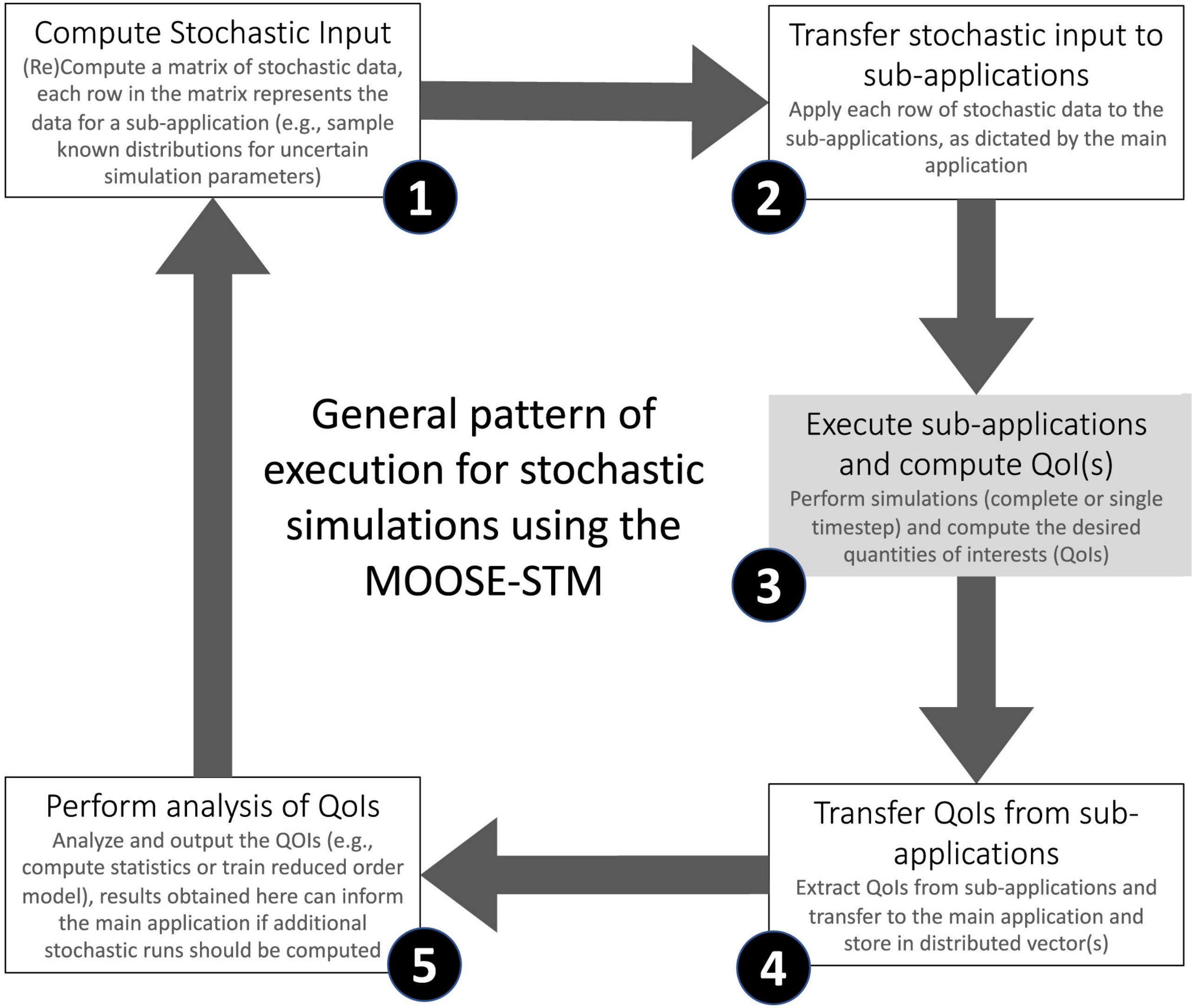


Verification and Validation

- Both solution and code verification will be completed as part of the development and refinement of the individual codes as well as the coupled tool.
- Validation to existing experiments.
- Comparisons to fuel vendor simulations results would be useful.

Develop Best Estimate Plus Uncertainty Capability

- After establishing in memory coupling and completing V&V on the coupled tool, incorporate uncertainties.
  - Enables the use of the MOOSE stochastic tools module.
- Extend capability to a wider range of accident conditions, advanced statistical measures, and core design optimization tools will be possible if time allows.



Andrew E. Slaughter, et al., “MOOSE Stochastic Tools: A module for performing parallel, memory-efficient in situ stochastic simulations,” SoftwareX, Volume 22, 2023, 101345, 10.1016/j.softx.2023.101345.

Deliverables

- Three reports will be generated:
  - BISON improvements
  - RELAP5-3D/BISON coupling
  - Final report
- The LOCA analysis tool
  - Documentation
  - Validation basis
  - Instructions for use

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