# Ramp Test Rods Analysis using ROPER and ABAQUS

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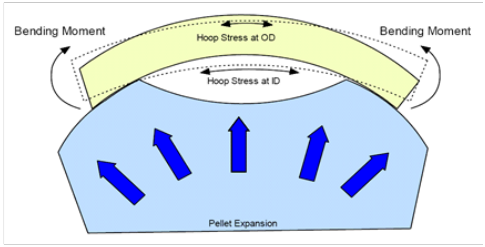
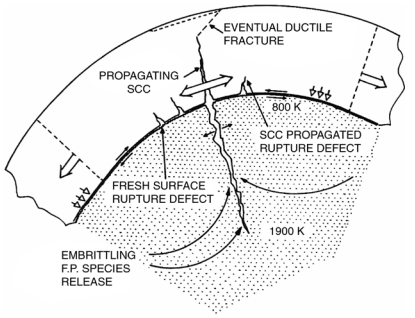
# Contents

# Introduction

- Pellet-Cladding Interaction (PCI)
  - **Damage mechanism** that leads to cladding failure associated with local power ramps during startup or maneuvering.
  - **PCI-SCC (stress corrosion cracking)** is initiated on **inside surface of cladding** due to tensile stress and the presence of a caustic agent such as I and Cs.
  - PCI with missing pellet surface (MPS)




Schematic of PCI failure mechanism[1]

- Purpose
  - Simulate and analyze for ramp test rods of various projects using ROPER[1)] and ABAQUS[2)]
  - **Propose a threshold** to limit PCI-induced fuel rod failure using **stress-based method**

1) ROPER: KEPCO NF's fuel rod performance analysis code
2) ABAQUS: commercial finite element analysis program

# Ramp test rods and analysis methods

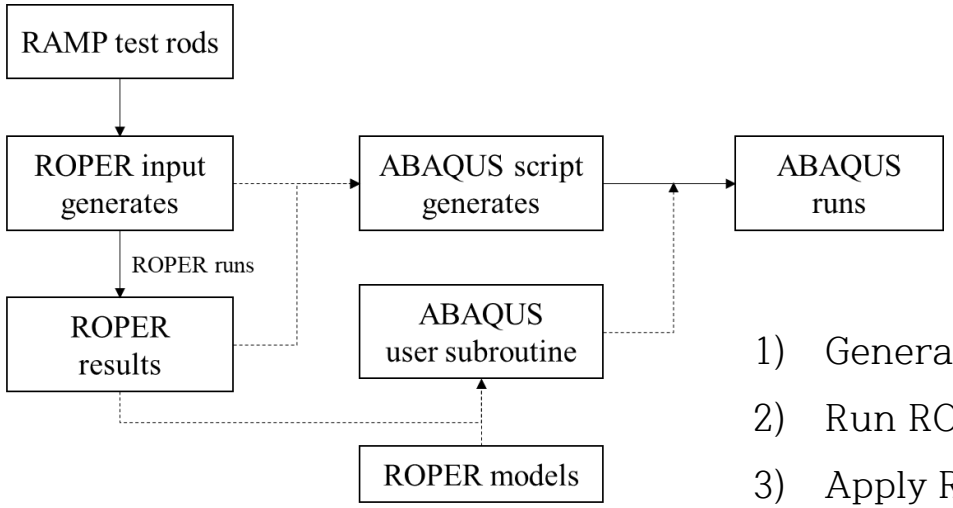
- Ramp test
  - Purpose: PCI mechanism research by simulating the potential power transition from a nuclear power plant in a research reactor.
  - Project
    - International Fuel Performance Experiment (IFPE)[4]: OSIRIS, over-ramp, super-ramp, trans-ramp
    - Studsvik Cladding Integrity Program (SCIP)
  - Ramp test rods for analysis
    - Use 44 rods among test rods of ramp test projects

| Project | Burnup (GWd/tU) | Total / Failed / non-Failed Rods | $P_{max}$ (kW/m) |
|---|---|---|---|
| OSIRIS | 26~27 | 2 / 0 / 2 | 39.5~45 |
| Over-ramp | 12~32 | 27 / 9 / 18 | 37~52.5 |
| Super-ramp | 35~45 | 6 / 0 / 6 | 40~49 |
| Trans-ramp | 23~30 | 7 / 6 / 1 | 42~50 |
| SCIP | 53~76 | 2/ 1 / 1 | 38~42 |

# Ramp test rods and analysis methods

## Analysis method

### Analysis flow for ROPER and ABAQUS

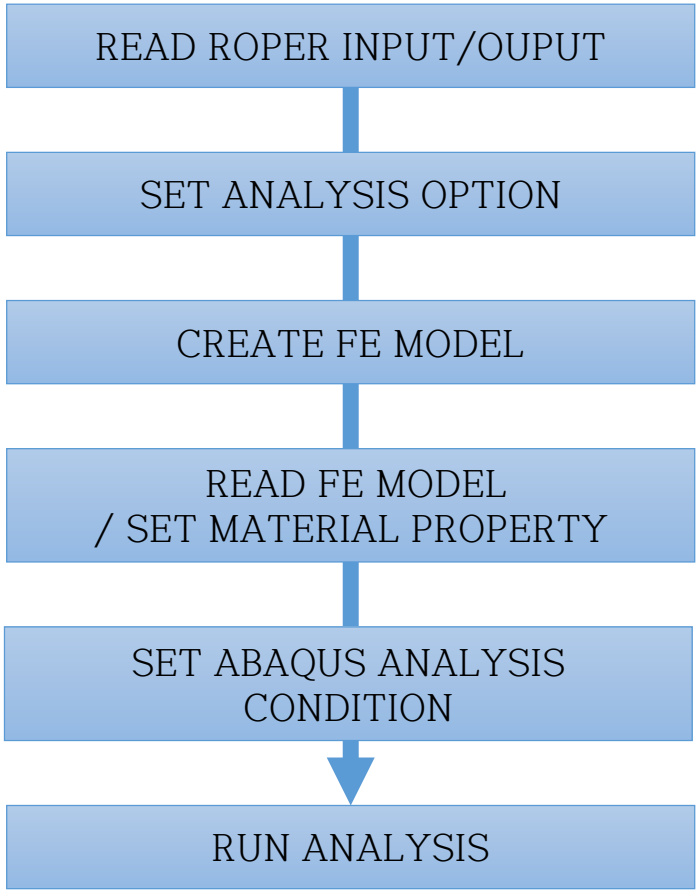



1) Generate ROPER input for each ramp test rod
2) Run ROPER
3) Apply ROPER input/output and ROPER models to ABAQUS python script and user subroutine
4) Run ABAQUS
5) Evaluate ABAQUS results

# Ramp test rods and analysis methods

## Analysis method

### Procedure of ABAQUS script

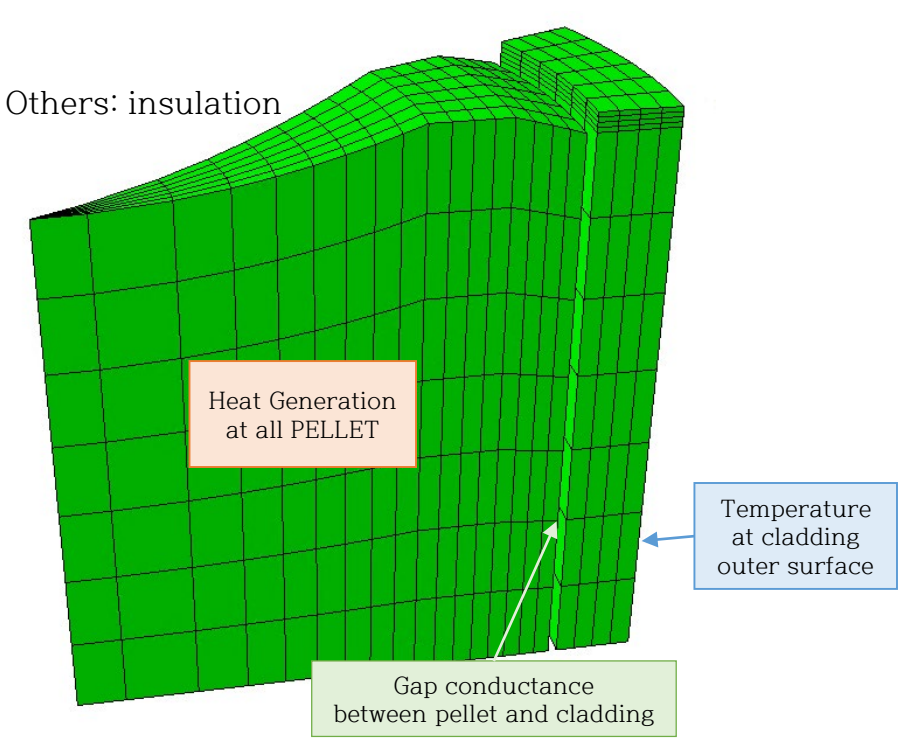



- Read input and output of ROPER for a test rod in ABAQUS script
- Set analysis option for ABAQUS analysis such as element size, boundary condition, contact condition, etc. except ROPER input
- Create models for pellet and cladding through generating node and element connectivity with a given ABAQUS keyword format
- Read FE model and set material properties for pellet and cladding in order to use user subroutine
- Set ABAQUS analysis condition: Analysis type (coupled temp-displacement analysis), boundary and load condition, contact condition, etc.
- Set job and run

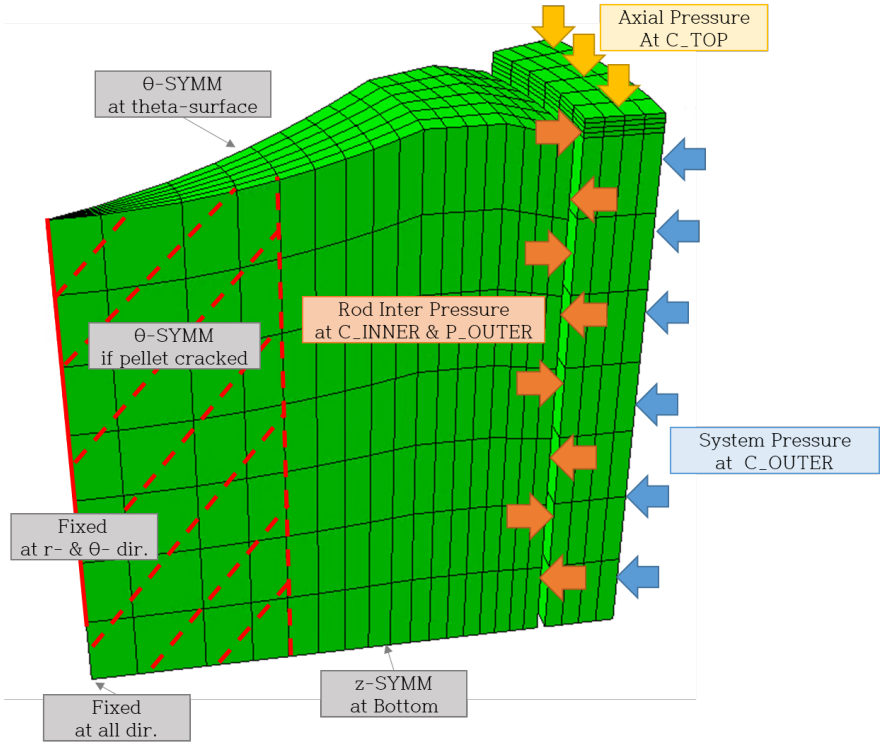
# Ramp test rods and analysis methods

## Analysis method

### Boundary condition



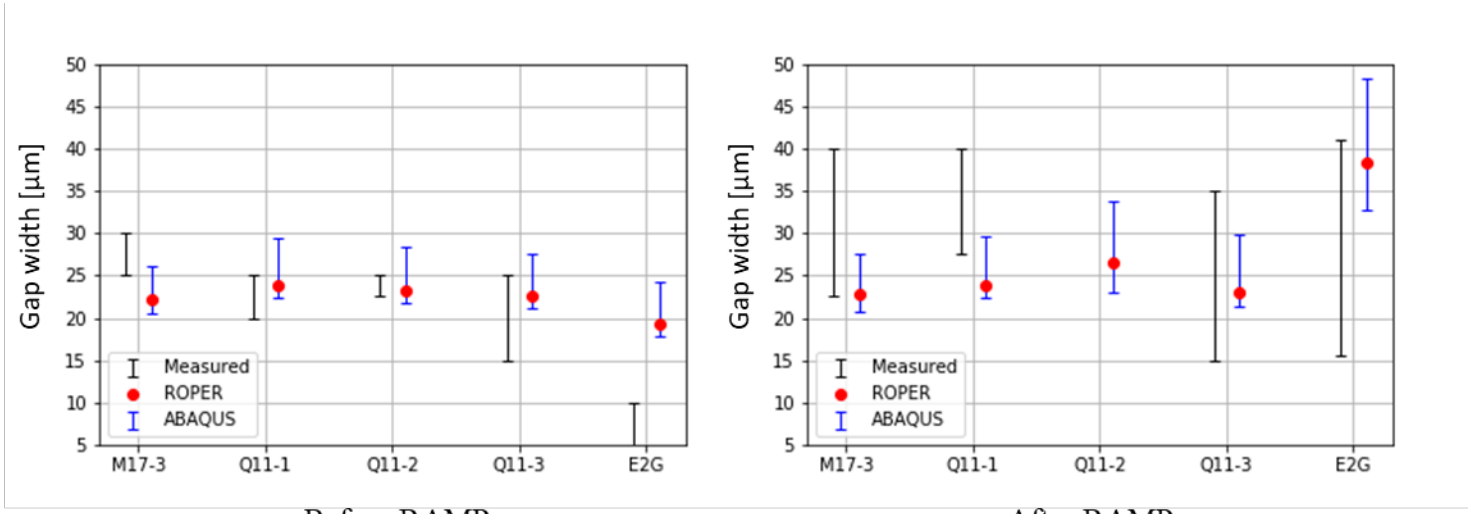

(a) THERMAL ANALYSIS




(b) MECHANICAL ANALYSIS

# Analysis results

- Comparison to PIE data
  - Purpose: to verify the accuracy analysis results
  - Gap between pellet cladding prior to ramp test
    - an indicator the accuracy of base-irradiation modeling
    - required to properly set the initial value to accurately reflect the test condition
    - Compressed gap measurement for some rods of trans-ramp project and E2G rod vs. ROPER/ABAQUS results

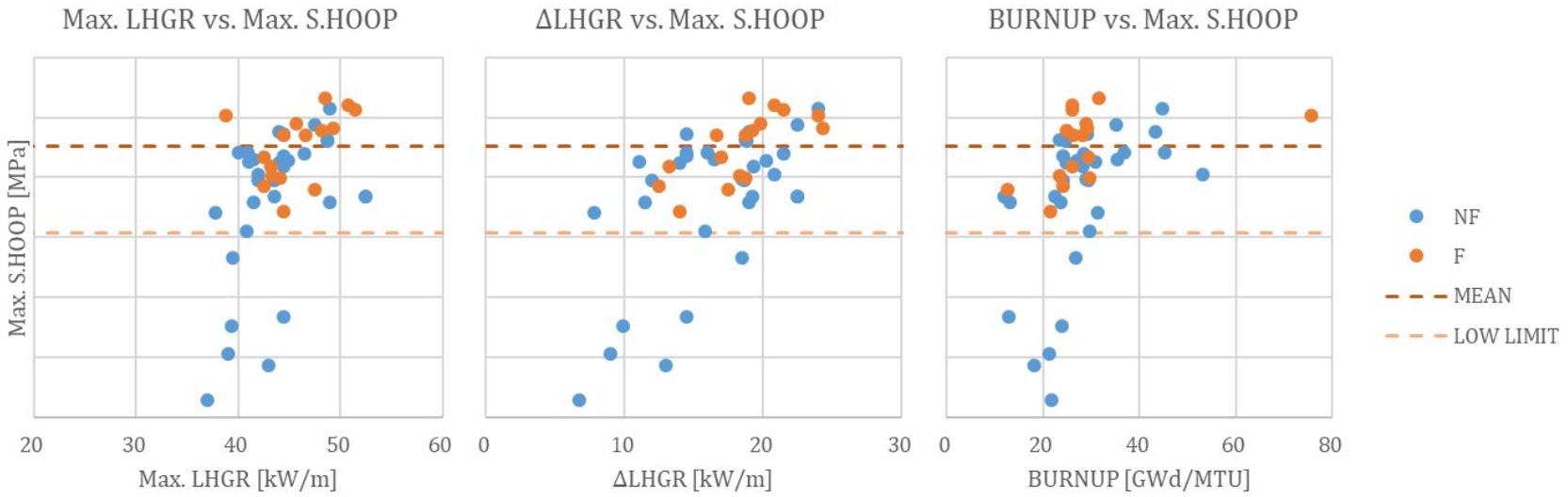



Before RAMP

After RAMP

# Analysis results

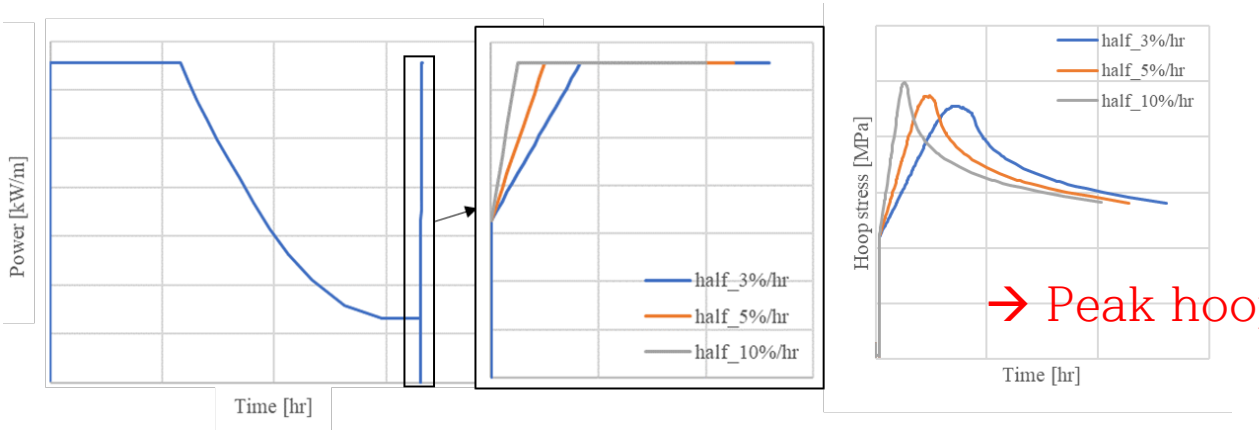
- Hoop stress-based failure threshold




- Failure rod and non-failure rod are **not distinguished** based on peak hoop stress.
- **Using only failure rods**, set threshold stress as lower one-side 95/95 tolerance limit.
  → about 400 MPa (similar to results of other paper and report)

# Analysis results

- Application to start-up condition
  - Preliminary analysis for PCI evaluation of fuel preconditioning guideline and flexible power operation
  - Condition
    - Set gap size which virtually burned to make smaller after 1st cycle
    - Cladding inner / outer diameter: decrease within tolerance to small gap size
      (pellet outer diameter: nominal value)
    - Start-up condition: increase to 50% immediately → increase to 100% at 3%/hr, 5%/hr, 10%/hr




→ Peak hoop stress < threshold

    - Later, it need to re-evaluate PCI analysis under specific condition for start-up, etc.

# Conclusion

- Using ROPER and ABAQUS, 3-D analysis for ramp test rods of over-ramp, super-ramp, trans-ramp, etc.
- It is not distinguished failure rods and non-failure rod by peak hoop stress as metric. Therefore the threshold value is proposed using failure rods.
- These results will be available as a reference for PCI evaluation in flexible power operation.
- In the future,
  we plan to evaluate in consideration of various scenarios for fuel preconditioning and missing pellet surface effects.

# References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2. Lyon W, Montgomery R, Rashid J, et al., “PCI analysis and fuel rod failure prediction using FALCON,” Proceedings of Top Fuel 2009, Paris, France September 2009.
3. Bessiron V, Jamet N, Gressier C, et al., “AREVA’s PCI methodologies for PWR enhanced plant maneuverability,” Proceedings of WRFPM 2014, Sendai, Japan, September 2014.
4. International Fuel Performance Experiments (IFPE) database, Nuclear Energy Agency, assessed March 5, https://www.oecd-nea.org/jcms/pl_36358/international-fuel-performance-experiments-ifpe-database.

# THANK YOU

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