

Finite Element Simulations of Zr and Mo Based Metallic Fuels: Thermo-mechanical Model Validations

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Abstract

Fuel performance modeling is a topic of importance to assessment of nuclear reactors performance. Various fuel performance codes that rely on such model development have been established for metallic fuel applications. An example is the LIFE-METAL code developed at Argonne National Laboratory (ANL). This code was developed specifically for Zr based metallic fuels, which have long been identified as a promising fuel form for the sodium fast reactors (SFR). Advanced thermo-mechanical models for metallic fuels (both Zr based and Mo based) have been developed using the finite element multi-physics simulation software COMSOL (version 4.3a). The Zr based metallic fuel model is verified utilizing the finite element package ABAQUS and compared to LIFE-METAL calculations. The computational models, utilizing heat transfer and the structure mechanics modules, were used to evaluate the performance of the metallic alloy fuels in terms of fission induced fuel swelling and fuel and cladding creep. The mathematics module suite was used extensively for the purpose of implementing fission-gas-induced swelling and gas release correlations and the thermally- and irradiation-induced creep models. The computational setup consists of 2-dimensional (2-D) axisymmetric geometry representation of both cylindrical and annular nuclear fuel element. The time-dependent fission-gas/fission-products swelling and release correlations are essentially semi-empirical and have been widely applied in prior works. In order to assess the performance of the model, simulated cladding diametral strain was compared to existing post irradiation examination (PIE) data from Experimental Breeder Reactor II (EBR-II) and French data of annular U-Mo fuels. Simulation predicted cladding diametral strains are found to be in fair agreements with both experimental measurements and LIFE-METAL predictions for the U-Pu-Zr fuel from EBR-II experiment. Simulations on annular U-Mo fuels and comparison with experimental data have led to improved understandings of the swelling and creep behaviors.

Objectives

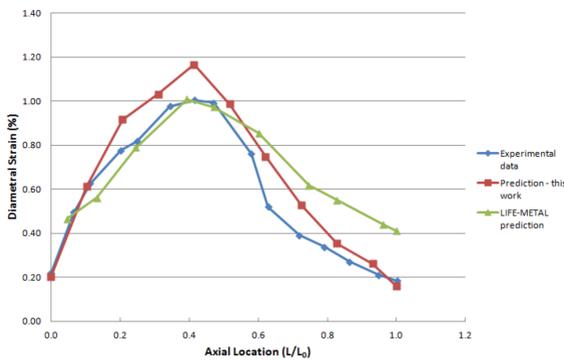
- Develop a comprehensive model for 3-dimensional (3D) behaviors of nuclear fuel elements using currently available multi-physics simulation platforms in order to improve fast reactors fuel design and assessment.
- Coupling physics models, such as fission gas release models, with thermo-mechanical advanced models.

Applications

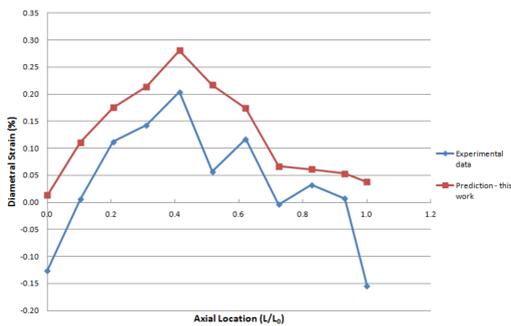
- Current applications are related to metallic fuel including ternary U-Pu-Zr and binary U-Zr and U-Mo alloys.
- COMSOL is coupled to swelling and fission gas release models and is used to model annular fuel.

Modeling of Pin T470 of X-425 Experiment

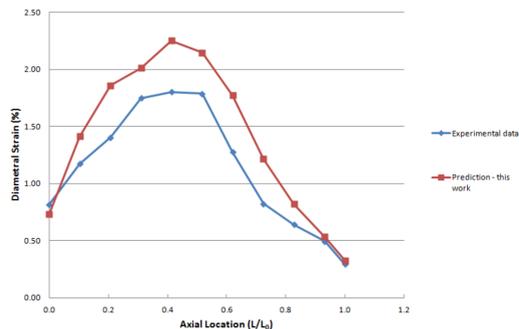
- U-Pu-Zr fuel simulation
 - Comparison between cladding diametral strain at multiple burnups showed reasonable agreement with experiment and LIFE-METAL



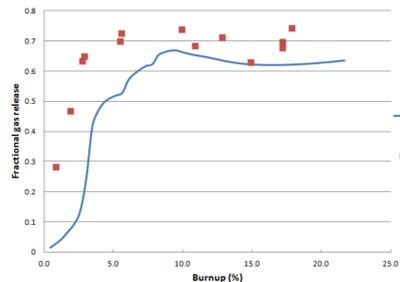
Comparison of simulated and PIE measured cladding diametral strain for pin T470 at peak burnup of 16.55 at. %



Comparison of simulated and PIE measured cladding diametral strain for pin T470 at peak burnup of 11.1 at. %



Comparison of simulated and PIE measured cladding diametral strain for pin T470 at peak burnup of 19.9 at. %

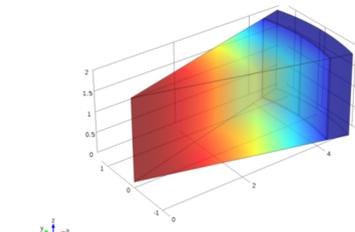


Comparison of simulated and PIE measured fission gas release for U-Pu-Zr fuel

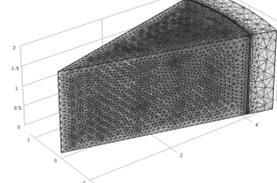
Simulation Platforms

- COMSOL (4.3a) commercial FE multi-physics platform developed by COMSOL, Inc.

- COMSOL Platform
 - 3D FE simulation
 - User defined physics by the mathematics module
 - User friendly GUI
 - Large deformations
 - Default meshing, user defined meshing and imported mesh
 - Parallel



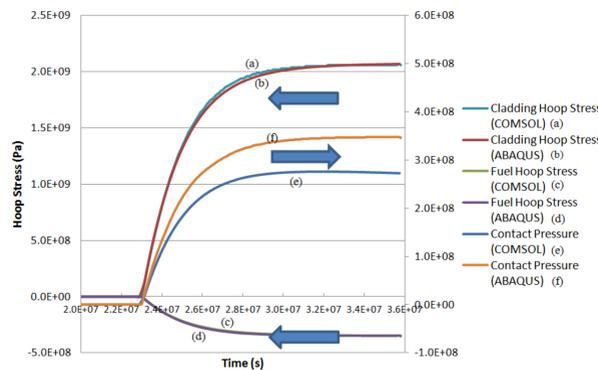
Geometry representation of a segment of nuclear fuel rod (including cladding and gap)



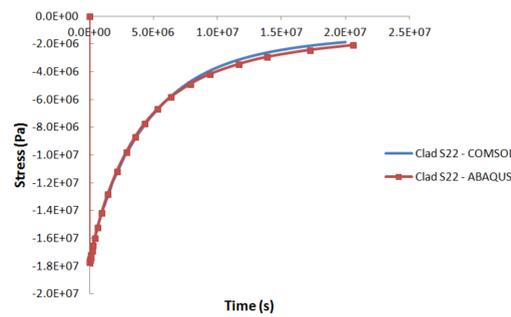
User defined mesh for a segment of nuclear fuel rod

- Objective
 - Simulate fuel swelling and cladding deformation for different types and geometries of metallic fuel

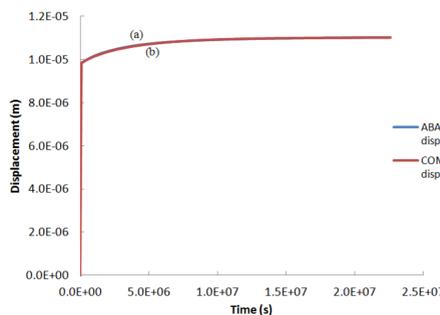
Verification by ABAQUS



Comparison between cladding and fuel hoop stress and contact pressure between COMSOL and ABAQUS simulations (Fuel Hoop Stress results from two simulations overlap with each other completely)

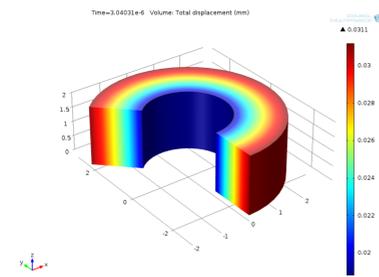


Comparison between cladding hoop stress by COMSOL and ABAQUS simulations (at the beginning of life, before contact)



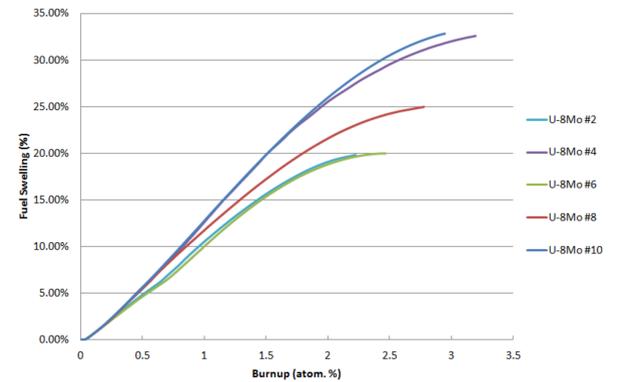
Comparison between fuel and cladding displacement by COMSOL and ABAQUS simulations (at the beginning of life, before contact, ABAQUS and COMSOL results are essentially un-distinguishable as they completely overlap)

Modeling of Annular U-Mo Alloy Fuel

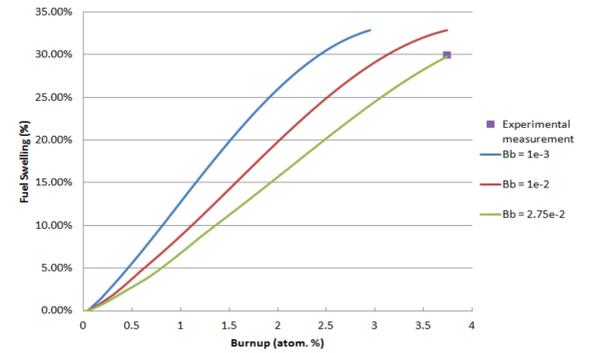


- U-Mo annular fuel simulation
 - Temperature and stress distribution in fuel
 - Hydrostatic stress impact on swelling rate and fission gas release and relation to experiment
 - Parameters derived by benchmark studies
 - Stress effects for co-extruded fuel and cladding

Fuel specimen	Central void to fuel volume ratio	Final burnup (MWd/t)	Linear Power (W/cm)	Cladding surface temperature (°C)
U-8Mo #2	1/5 (20%)	28100	305	507
U-8Mo #4	1/3 (33%)	30600	270	497
U-8Mo #6	1/5 (20%)	33400	305	507
U-8Mo #8	1/4 (25%)	34000	290	503
U-8Mo #10	1/3 (33%)	35300	270	497



COMSOL predicted fuel swelling for five U-8Mo samples



Comparison of predicted and PIE measured fuel swelling for annular metallic fuel sample #10

Summary

- COMSOL finite element platform was used to model thermo-mechanical performance of solid and annular metallic fuels
- Simulated cladding diametral strain for an EBR-II experimental pin showed reasonable agreements
- ABAQUS was utilized to provide verifications for COMSOL results with a simple fuel swelling model; the only difference seems to lie in the contact pressure which may be a reflection of different contact models
- Simulations of annular U-8Mo fuels provided useful insights to the parameterization of fuel swelling correlation for U-Mo metallic fuels

Future activities

- Improve implementation of fission gas models into multi-dimensional metallic fuels simulations
- Coupling with other models such as constituent distribution models, FCCL, ...
- Validate the simulations against more experimental data for both solid and annular fuels