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Accident Tolerant Fuel Modeling in Bison

March 2019

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Idaho National Laboratory

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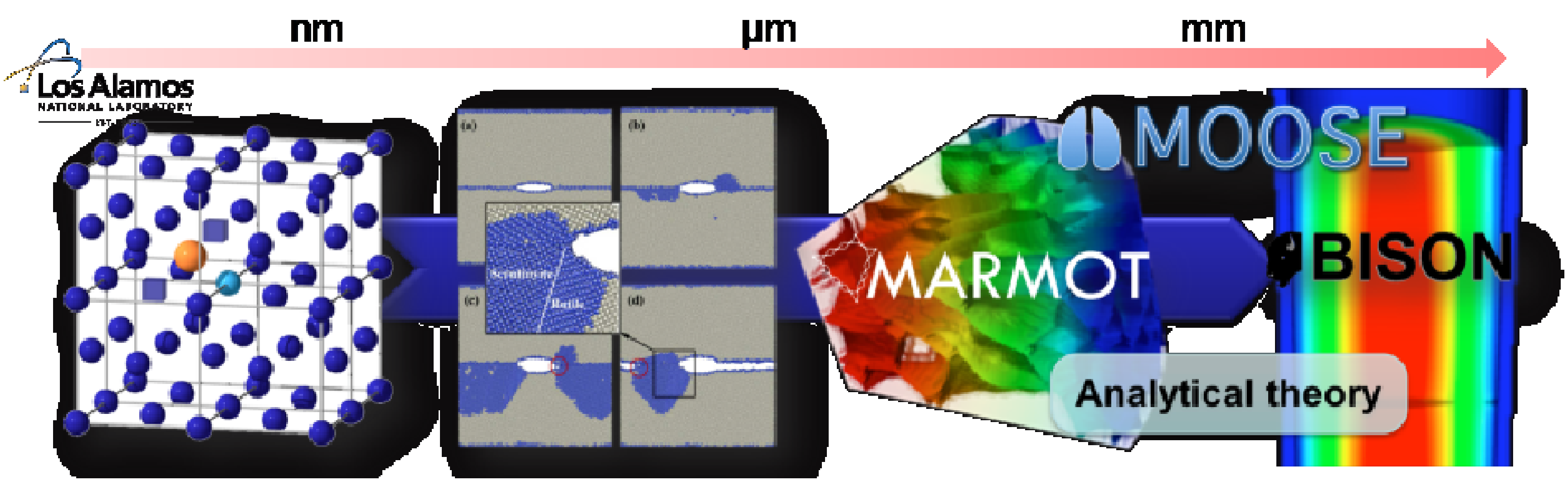
March 27-28, 2019
University of Cambridge
United Kingdom

Overview

- Introduction
- Chromium-Coated Cladding
- Silicon-Carbide Cladding
- Chromium-doped UO_2 Fuel
- U_3Si_2 Fuel
- Conclusions

Approach to Developing ATF Performance Code

1) Introduce basic ATF properties/models in **Bison** to establish simulation capability
2) Introduce mechanistic models into **Bison** from lower length-scale (LLS) activities as they become available
3) Use sensitivity analyses on ATF material properties/behavior models to prioritize LLS mechanistic modeling activities
4) On-going assessment/validation



nanometers
First Principles
- Determine unknown properties
- Create empirical potentials for U-Si

100's of nanometers
Molecular Dynamics
- Identify interfacial mechanisms
- Determine interfacial properties

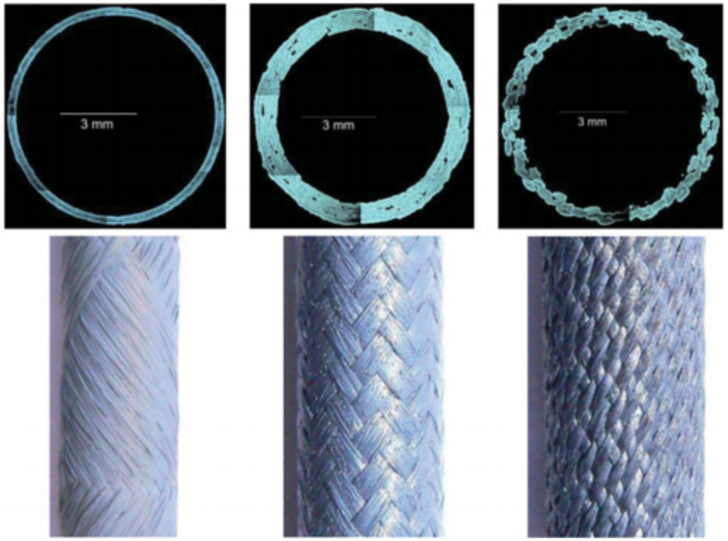
microns
Mesoscale
- Predict microstructure evolution
- Determine impact on properties

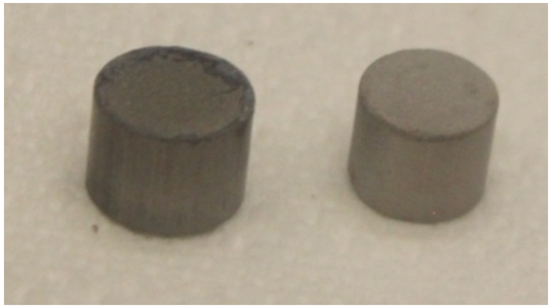
millimeters and up
Engineering scale
- Use analytical theory
- Predict fuel performance

Overview of ATF Concepts in Bison

- Bison has material and behavior models for the following ATF concepts:
  - FeCrAl Clad
  - Chromium-coated Clad
  - Silicon Carbide Clad
  - Cr_2O_3-doped UO_2 Fuel
  - U_3Si_2 Fuel

- Reports are currently being developed that summarize all of the models, their ranges of applicability and their uncertainties for priority fuel and cladding concepts.





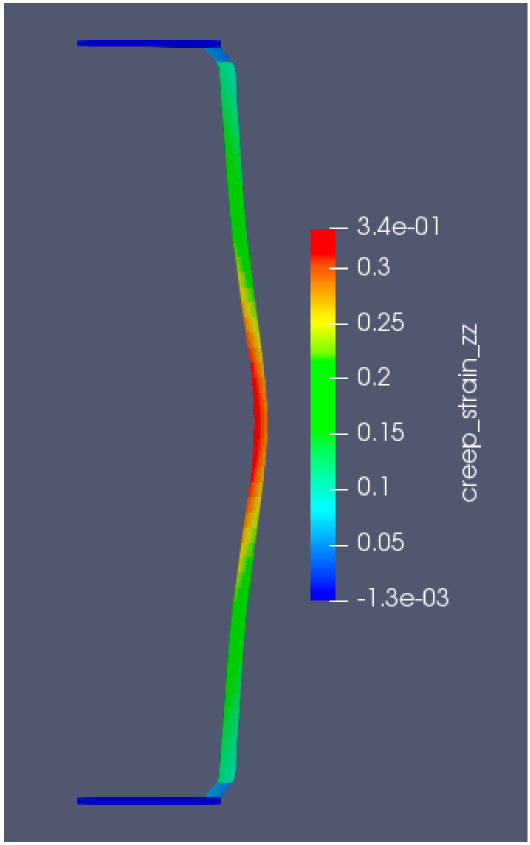
Chromium Coated Cladding: Model Summary

	Model in Bison	Experimental Data	LLS-informed	Documented	Tested
Basic thermal properties	Yes	Yes	No	Yes	Yes
Basic mechanical properties	Yes	Yes	No	Yes	Yes
Creep	Yes	Yes	No	Yes	Yes
Oxidation	Yes	Yes	No	Yes	Yes
Plasticity	Yes	Yes	No	Yes	Yes

Chromium Coated Cladding: Case Description

- Parametric study on cladding-only tubes under LOCA-like conditions until failure (overstrain criteria used).
  - Used to investigate the reported observation that coated tubes balloon less.
  - 0.25 m long, 8.36 mm ID, 0.57 mm thick tubes were used.
  - Temperature ramped from 300 K to a sinusoid centered about tube midplane with a 20 K variation with peak occurring at midplane over 10,000 s.
  - Pressure ramp begins at 10,000 s.

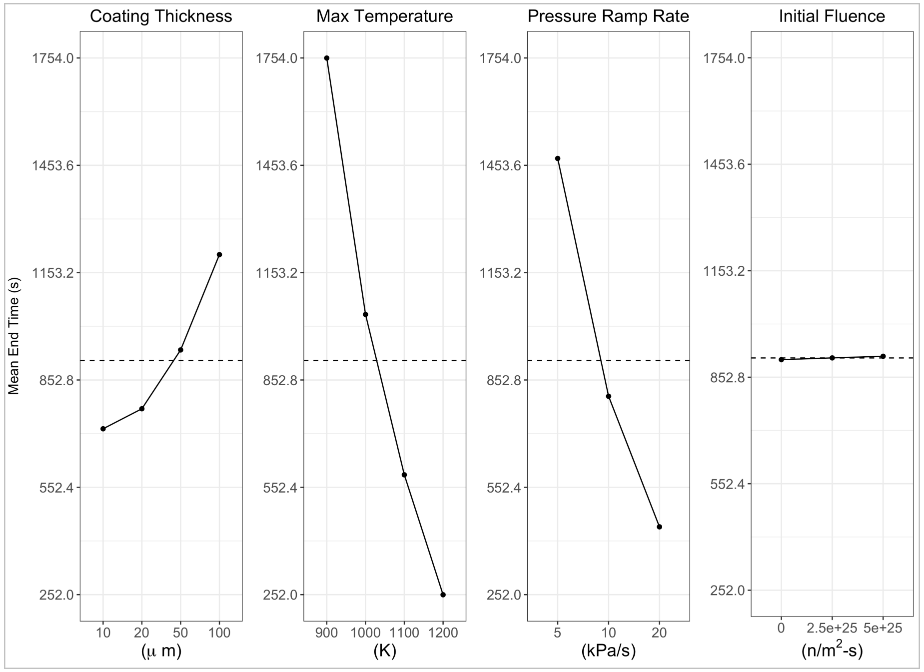
Model Parameter	Values
Coating thickness (m)	0, 10, 20, 50, 100
Clad material	M5, Zirlo, Zr-4
Pressure Ramp Rate (kPa/s)	5, 10, 20
Peak Clad Temperature (K)	900, 1000, 1100, 1200



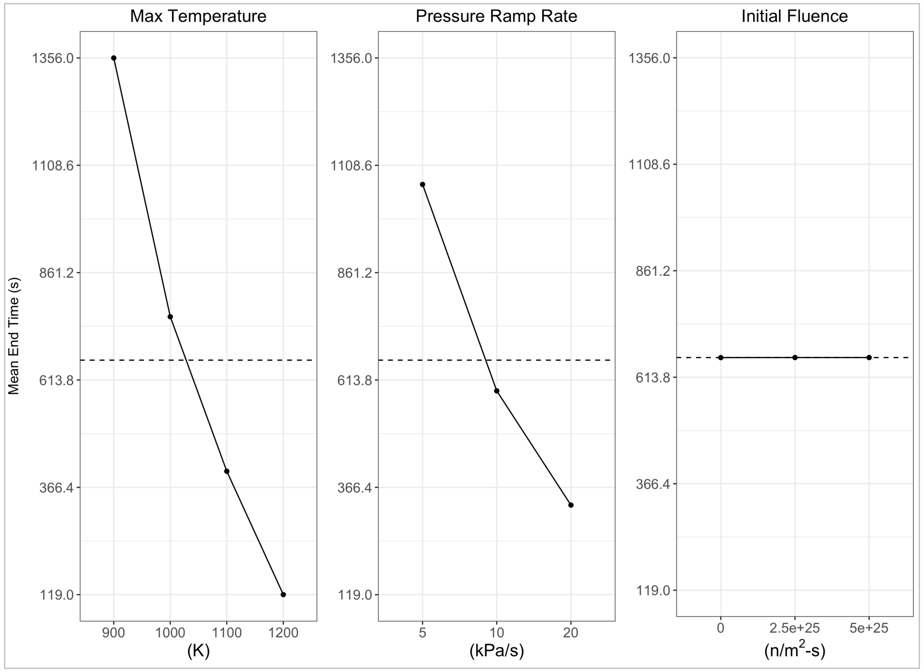
Creep strain at failure for one of the cases. Scaled axially by 0.1

Chromium Coated Cladding: Results

- The time to rupture is longer in the coated cases indicating smaller balloons at any given time. Zirlo results shown.



Coated Cases (144 total)



Uncoated Cases (36 total)

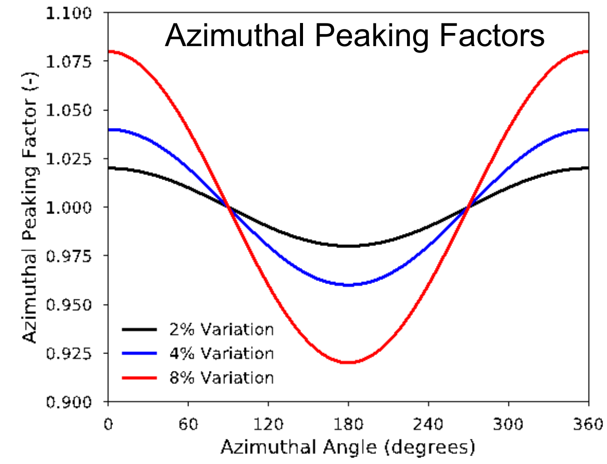
Silicon Carbide Cladding: Model Summary

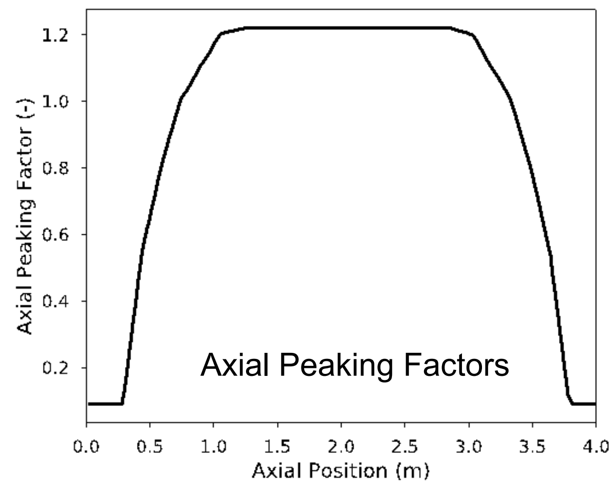
	Model in Bison	Experimental Data	LLS-informed	Documented	Tested
Basic thermal properties	Yes	Yes	No	Yes	Yes
Thermal conductivity degradation	Yes	Yes	No	Yes	Yes
Basic mechanical properties	Yes	Yes	No	Yes	Yes
Creep	Yes	Yes	No	Yes	Yes
Irradiation Swelling	Yes	Yes	No	Yes	Yes

Models exist for both monolithic and woven (composite) SiC.

Silicon Carbide Cladding: Case Description

- Singh et al.[1] investigated lateral deformation in 4 m long pure composite tubes under azimuthally and axially varying power distributions.
- A similar study is completed here on a tube containing a woven layer (0.75 mm) with an outer monolithic layer (0.25 mm).
- Internal pressure is linearly increased from 1 to 7 MPa over 2 years.
- Fast neutron fluence is linearly increased from 0 to 6 dpa over 2 years.
- Coolant bulk temperature linearly increases from 580 K to 620 K along the axial length.

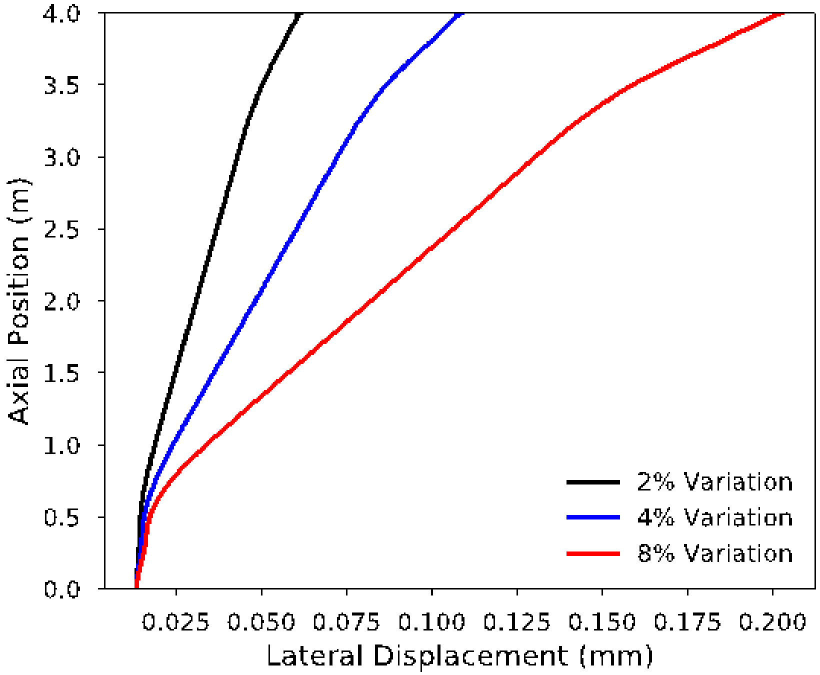




[1] G. Singh, R. Sweet, N.R. Brown, B.D. Wirth, Y. Katoh, K. Terrani, "Parameter Evaluation of SiC/SiC composite Cladding with UO_2 Fuel for LWR Applications: Fuel Rod Interaction and Impact of Nonuniform Power Profile in Fuel Rod," JNM, 499, p. 155-167, 2018.

Silicon Carbide Cladding: Results

- Displacements of the various SiC cladding tube concepts as a function of axial position indicate potentially large lateral displacements at the top of the rod such that coolant subchannels may be blocked.
- Unable to reproduce the bowing patterns and magnitude of bow observed by Singh et al.
- Appears that the monolithic layer suppresses the lateral deformation.

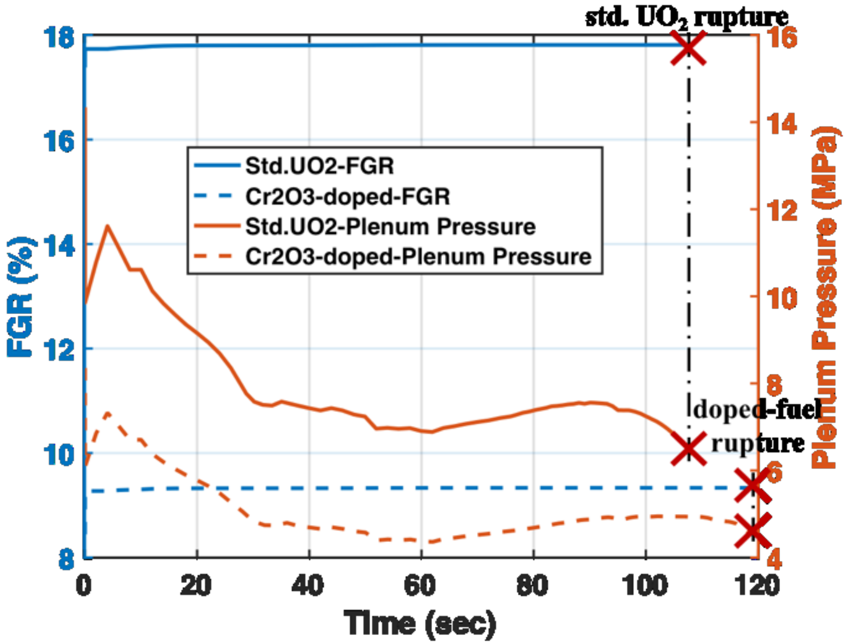


Cr_2O_3-doped UO_2 Fuel: Model Summary

	Model in Bison	Experimental Data	LLS-informed	Documented	Tested
Basic thermal properties	Yes (UO_2)	Yes	No	Yes	Yes
Thermal conductivity degradation	Yes (UO_2)	No	Yes	Yes	Yes
Basic mechanical properties	Yes (UO_2)	Yes	No	Yes	Yes
Creep	Yes	Yes	No	Yes	Yes
Swelling	Yes	Yes	Yes	Yes	Yes
Fission gas release	Yes	Yes	Yes	Yes	Yes

Cr_2O_3-doped UO_2 Fuel: LBLOCA Simulation

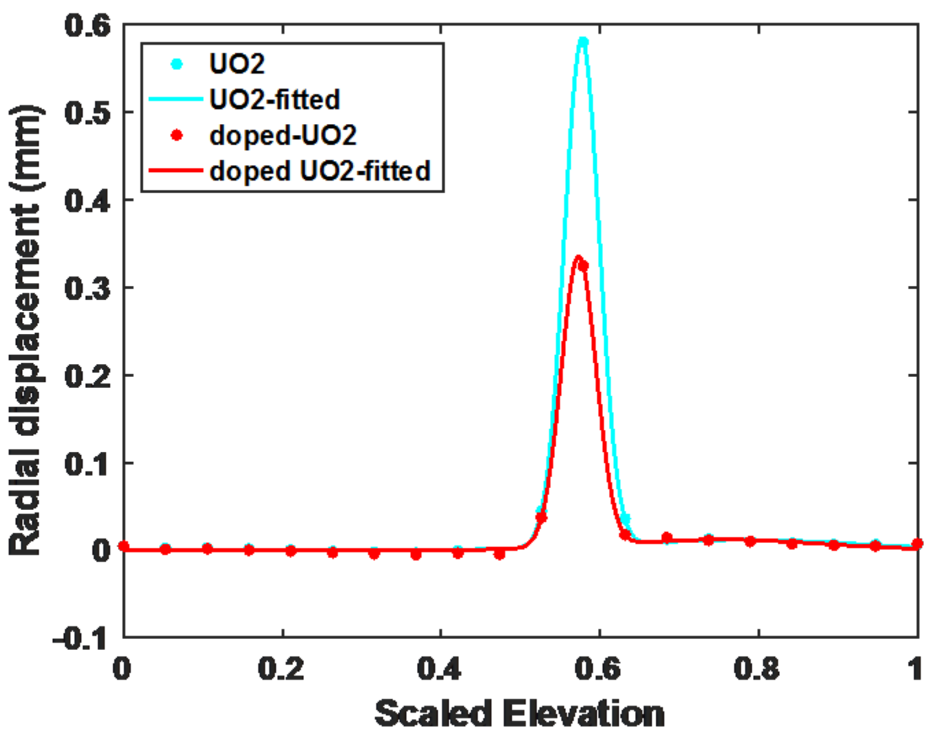
- Seabrook NPP (PWR) large-break LOCA scenario.
- Base irradiation to ~38 MWd/kgU, followed by LOCA.
- LOCA boundary conditions generated with the system code RELAP5.
- Grain diameter is 15.6 microns for undoped UO_2 and 56 microns for doped UO_2.
- Bison simulations indicate that a slightly longer coping time is associated with doped fuel.



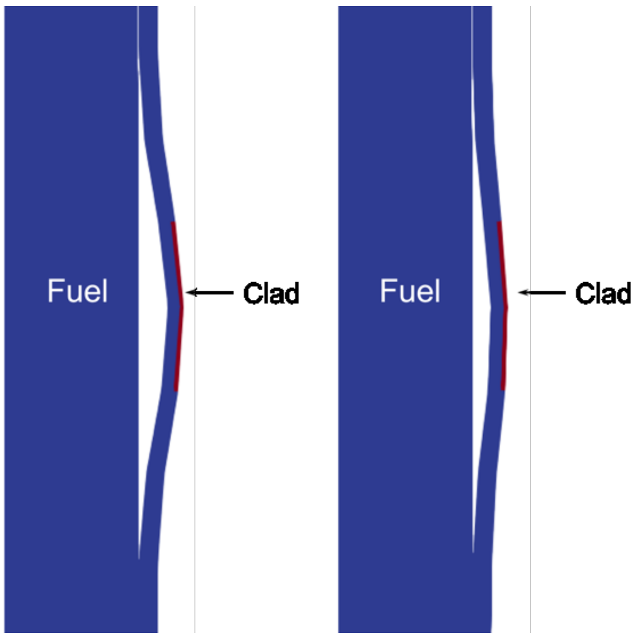
FGR and plenum pressure

Cr_2O_3-doped UO_2 Fuel: LBLOCA Simulation

- Ballooning is lower in the doped fuel calculation



Radial displacement in the cladding at failure



Std. UO_2 Cr_2O_3-doped UO_2

U_3Si_2 Fuel: Model Summary

	Model in Bison	Experimental Data	LLS-informed	Documented	Tested
Basic thermal properties	Yes	Yes	No	Yes	Yes
Thermal conductivity degradation	Yes	No	Yes	Yes	Yes
Basic mechanical properties	Yes	Yes	No	Yes	Yes
Creep	Yes	Yes	No	Yes	Yes
Swelling	Yes	Yes	Yes	Yes	Yes
Fission gas release	Yes	Yes	Yes	Yes	Yes

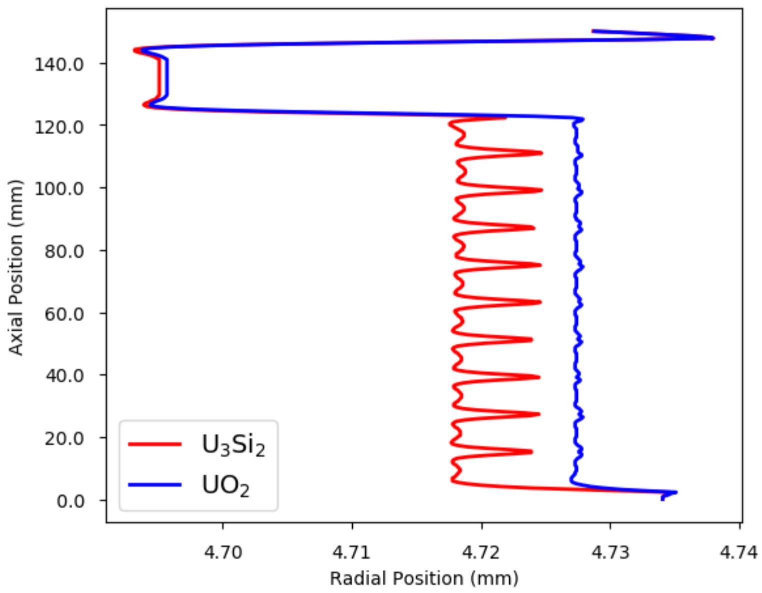
U_3Si_2 Fuel: Case Description

- A 10-pellet discrete fuel rodlet under normal operating (20 kW/m for 1e8 s) conditions using the newly developed coupled fission gas and gaseous swelling model.
- Comparisons to a UO_2 fueled rodlet under with the same dimensions to assess potential swelling issues of U_3Si_2.
- Comparison to the PIE data from the recent ATF-1 U_3Si_2 fueled rodlets is ongoing.

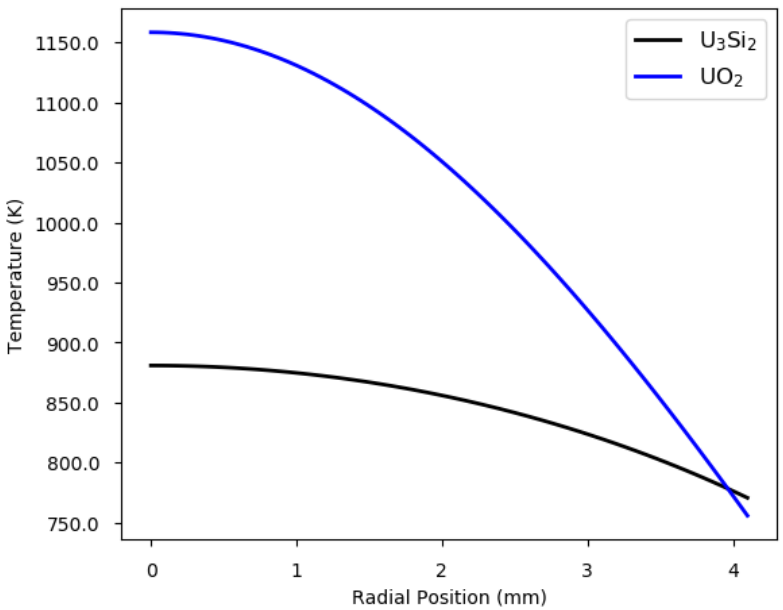
Number of pellets	10
Pellet length (mm)	11.86
Pellet outer diameter (mm)	8.19
Pellet dish depth (mm)	0.3
Pellet chamfer width (mm)	0.5
Pellet chamfer height (mm)	0.16
Radial gap width (μm)	80
Clad thickness (mm)	0.575
Rodlet length (mm)	150
Rodlet diameter (mm)	9.5
Initial fill pressure (MPa)	2.0
Initial fill gas	Helium
Plenum height (mm)	26
Initial fuel grain radius (μm)	10 for UO_2 fueled rodlet 25 for U_3Si_2 fueled rodlet
Coolant inlet mass flux (kg/m^2-s)	3800
Coolant inlet temperature (K)	580
Coolant pressure (MPa)	15.5

U_3Si_2 Fuel: Results

- Outer clad profilometry at the end of life indicates less radial displacement occurs in the U_3Si_2 rod.
- Radial temperature profile indicates a much more gradual decrease in temperature in U_3Si_2 due to the higher thermal conductivity.



Clad profilometry



Radial temperature profile after rise to power

Conclusions

- Bison has the capability to simulate a wide variety of ATF concepts under both normal operating and transient conditions.
- Example cases have been presented for the four concepts of interest to Westinghouse (Cr-coated and SiC/SiC clad, U_3Si_2 and Cr_2O_3 fuel)
- Validation of the models continues as additional data becomes available.
- Reports will be published at the end of the fiscal year that present all available models, their ranges of applicability, and their associated uncertainties.

Acknowledgements

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