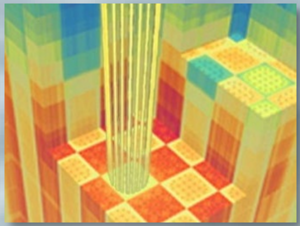
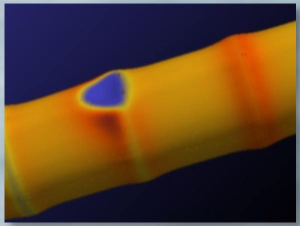
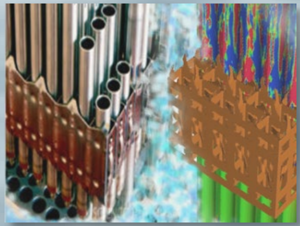
Bison Overview

Russell Gardner
Idaho National Laboratory

February 11, 2019

VERA Workshop

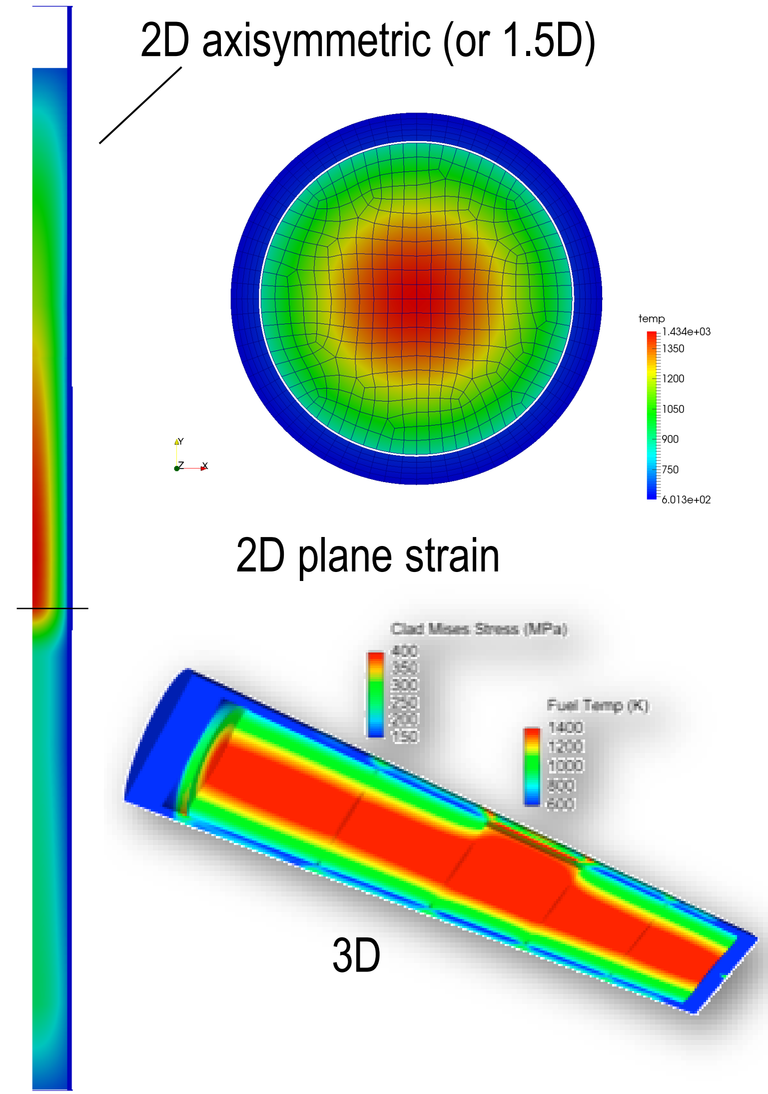




Outline

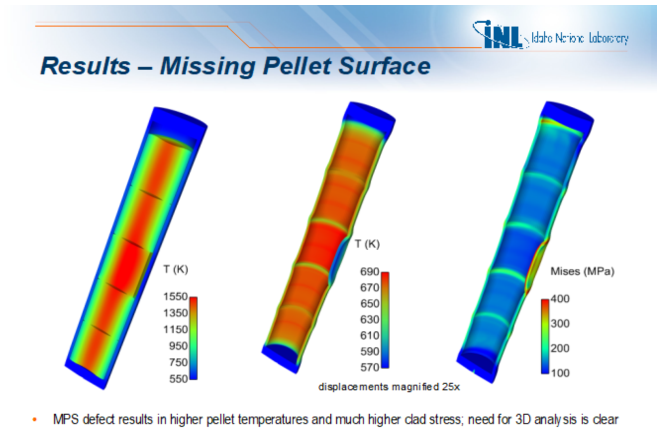
- Bison Background
  - What is Bison?
  - Code Verification
  - Documentation
- LWR Fuel
  - Capabilities
  - Base Validation
  - Accident Validation
  - Development/Validation Plan
- Bison in VERA
- Accident Tolerant Fuel
  - Cr-doped UO_2
  - Cr-coated cladding
  - FeCrAl cladding
  - U_3Si_2 fuel

What is Bison?

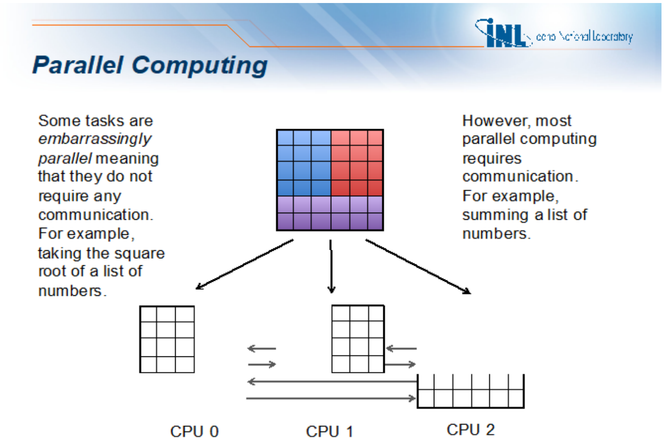
- Finite element-based engineering scale fuel performance code based on INL's open-source MOOSE computational framework
- Solves the fully-coupled thermomechanics and species diffusion equations in 1D, 2D axisymmetric or plane-strain, or full 3D
- Applicable to both steady and transient operation
- Used for LWR, TRISO, and metal fuels
- Readily coupled to lower length scale material models
- Designed for efficient use on parallel computers
- Includes LOCA and RIA accident capability



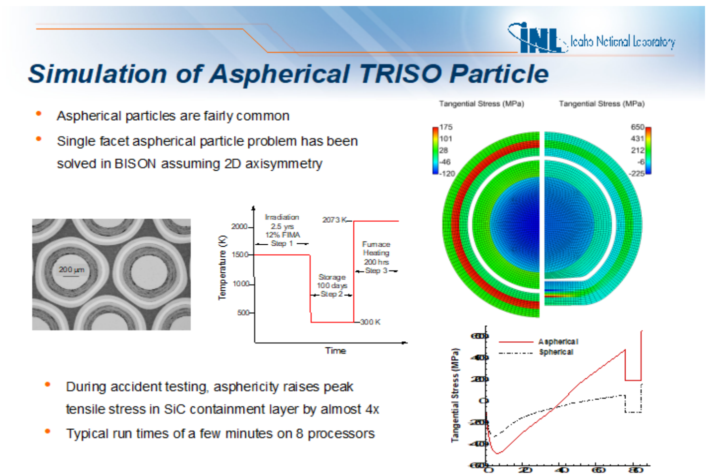
What is Bison?



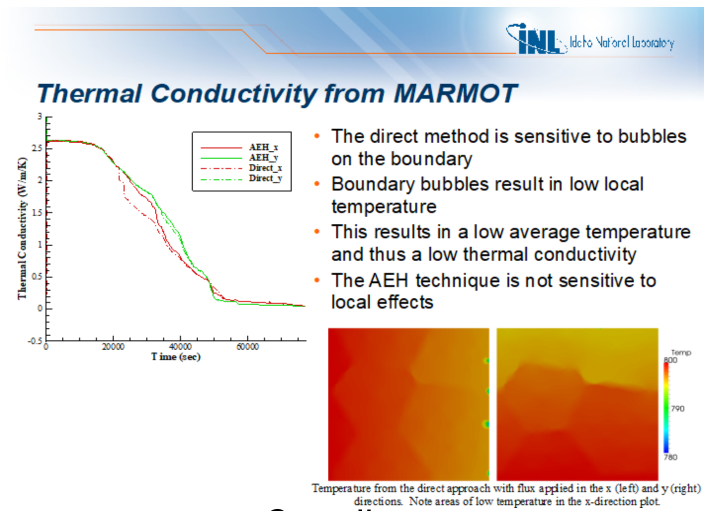
3D/Arbitrary Geometry



Parallel Computing



Fuel Types



Coupling

Bison Code Verification

- MOOSE/BISON is supported by >2000 unit and regression tests
- All new code must be supported by verification testing; all tests must pass prior to code merge
- Current BISON test coverage: 88%
- Documentation:
  - All tests distributed with source code
  - Code verification process described in journal article

LCOV - code coverage report

Current view: top level
Test: BISON Test Coverage
Date: 2019-01-31 21:20:43
Legend: Rating: low: < 75 % medium: >= 75 % high: >= 90 %

	Hit	Total	Coverage
Lines:	21440	24478	87.6 %
Functions:	1668	1809	92.2 %

Directory	Line Coverage		Functions	
src	91.7 %	11 / 12	100.0 %	3 / 3
src/actions	89.1 %	1179 / 1323	97.1 %	66 / 68
src/auxkernels	83.1 %	1049 / 1262	91.4 %	96 / 105
src/auxkernels/tensor_mechanics	87.8 %	43 / 49	100.0 %	5 / 5
src/base	76.9 %	30 / 39	69.2 %	9 / 13
src/bcs	80.8 %	539 / 667	84.4 %	54 / 64
src/bcs/coolant	85.8 %	596 / 695	86.8 %	46 / 53
src/functions	92.0 %	833 / 905	98.2 %	55 / 56
src/ics	96.2 %	153 / 159	100.0 %	5 / 5
src/kernels	83.3 %	733 / 880	84.7 %	100 / 118
src/materials	86.6 %	9223 / 10654	92.5 %	566 / 612
src/materials/tensor_mechanics	92.1 %	3696 / 4015	96.0 %	358 / 373
src/mesh	86.5 %	656 / 758	71.1 %	27 / 38
src/meshgenerators	96.6 %	480 / 497	100.0 %	23 / 23
src/parser	100.0 %	34 / 34	100.0 %	3 / 3
src/postprocessors	90.7 %	723 / 797	92.3 %	108 / 117
src/userobject	83.1 %	1302 / 1567	93.4 %	128 / 137
src/utils	100.0 %	19 / 19	100.0 %	4 / 4
src/vectorpostprocessors	96.6 %	141 / 146	100.0 %	12 / 12

Generated by: LCOV version 1.11

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ELSEVIER

Verification of the BISON fuel performance code

CrossMark

J.D. Hales *, S.R. Novascone, B.W. Spencer, R.L. Williamson, G. Pastore, D.M. Perez

Fuel Modeling and Simulation, Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415-3840, United States

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ABSTRACT

Complex multiphysics simulations such as those used in nuclear fuel performance analysis are composed of many submodels used to describe specific phenomena. These phenomena include, for example, mechanical material constitutive behavior, heat transfer across a gas gap, and mechanical contact. These submodels work in concert to simulate real-world events, like the behavior of a fuel rod in a reactor. If a simulation tool is able to represent real-world behavior, the tool is said to be validated. While much

LWR Validation Overview

- Current status
  - ~**75** integral, normal operation and ramp fuel rod experiments
  - 47 LOCA cases (43 burst tests, 4 integral rods)
  - 19 RIA cases
- Documentation:
  - Assessment report updated annually and distributed with code
  - Williamson et al., Validation of the BISON fuel performance code to integral LWR experiments, *Nuc Eng Des*, **301**, 232 (2016)

INL/MIS-13-30314 Rev. 5

September 2018

Assessment of Bison:
A Nuclear Fuel Performance Analysis Code
BISON Release 1.5

Idaho National Laboratory
Fuel Modeling and Simulation Department
Idaho Falls, Idaho 83415

Idaho National Laboratory

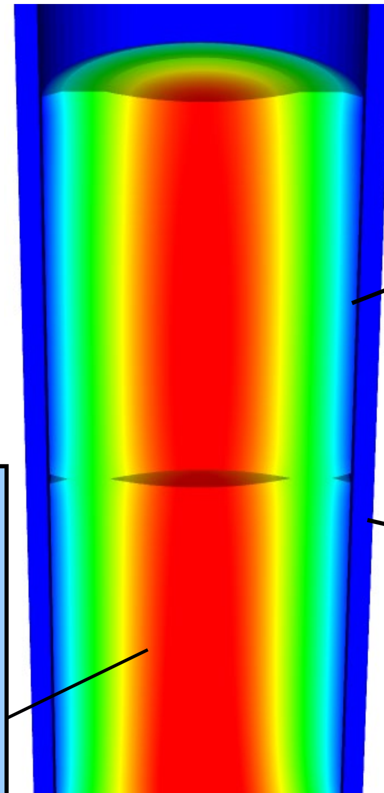
Bison LWR Capabilities

General Capabilities

- Finite element 1.5D, 2D-RZ axisymmetric and Cartesian and 3D fully-coupled thermo-mechanics with species diffusion
- Linear or quadratic elements with large deformation mechanics
- Steady and transient operation
- Parallel computation
- Meso-scale informed material models

Oxide Fuel Behavior

- Temperature/burnup dependent conductivity
- Heat generation with radial and axial profiles
- Thermal expansion
- Solid and gaseous fission product swelling
- Densification
- Thermal and irradiation creep
- Fracture via relocation or smeared cracking
- Fission gas release (two stage physics)
  - transient (ramp) release
  - grain growth and grain boundary sweeping
  - athermal release



Temperature

Gap/Plenum Behavior

- Gap heat transfer with $k_g = f(T, n)$
- Mechanical contact (master/slave)
- Plenum pressure as a function of:
  - evolving gas volume (from mechanics)
  - gas mixture (from FGR model)
  - gas temperature approximation

Cladding Behavior

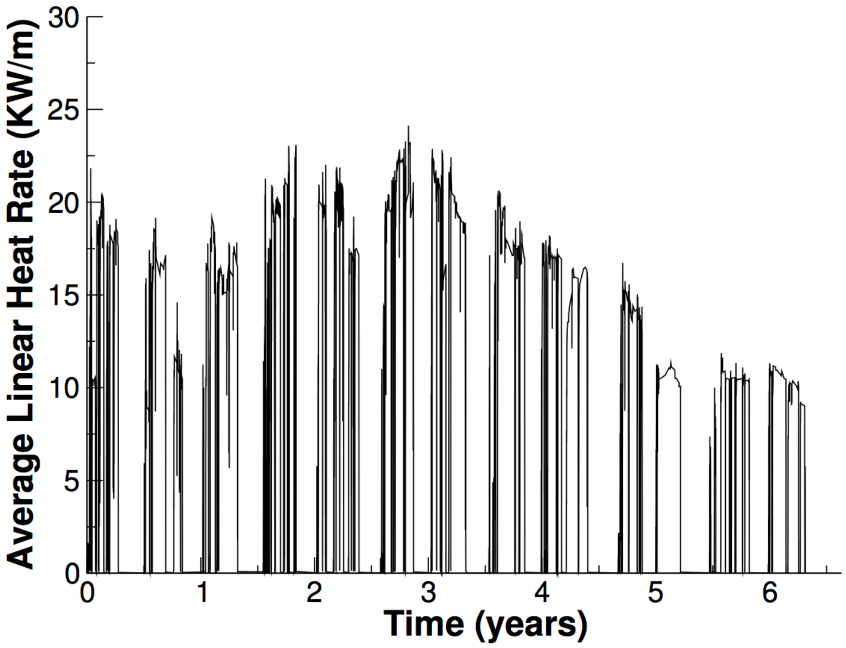
- Thermal expansion
- Thermal and irradiation creep
- Irradiation growth
- Gamma heating
- Combined creep and plasticity
- Hydrogen diffusion and precipitation

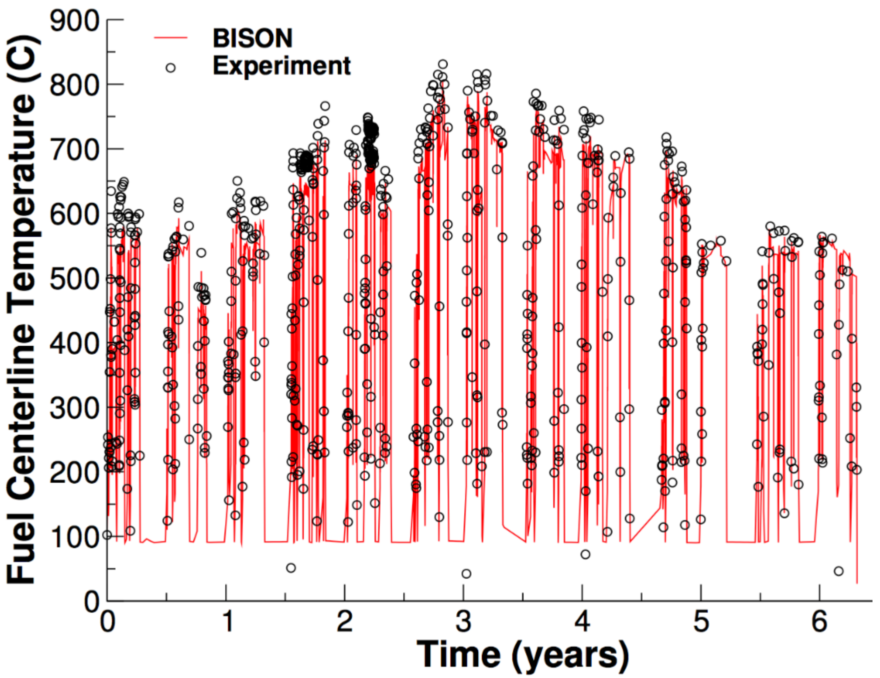
Coolant Channel

- Closed channel thermal hydraulics with heat transfer coefficients

LWR Validation Overview

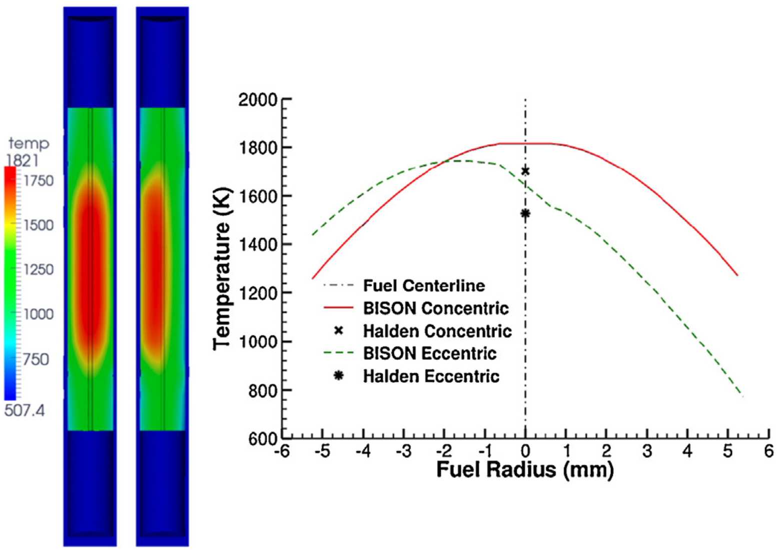
- Halden IFA 515.10 Rod A1
  - Complex power history
  - higher burnup rod



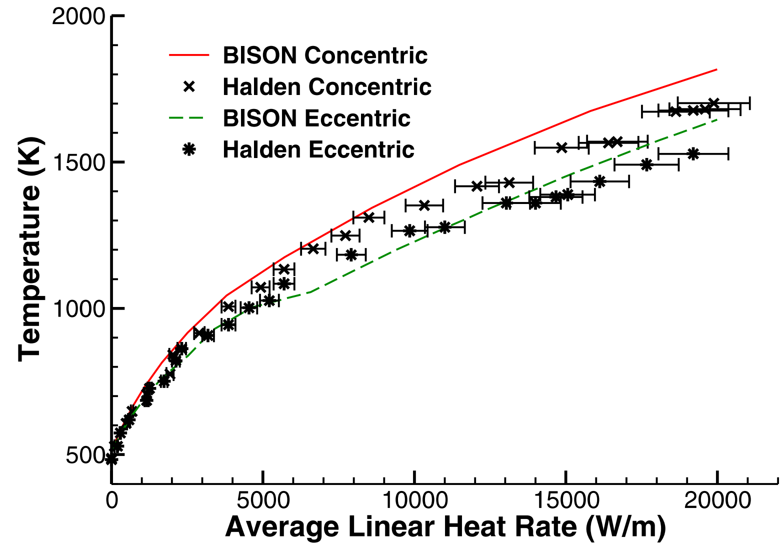


LWR Validation
Pellet Eccentricity

3D analysis of Halden IFA-431 rod 4
(effects of fuel pellet eccentricity)

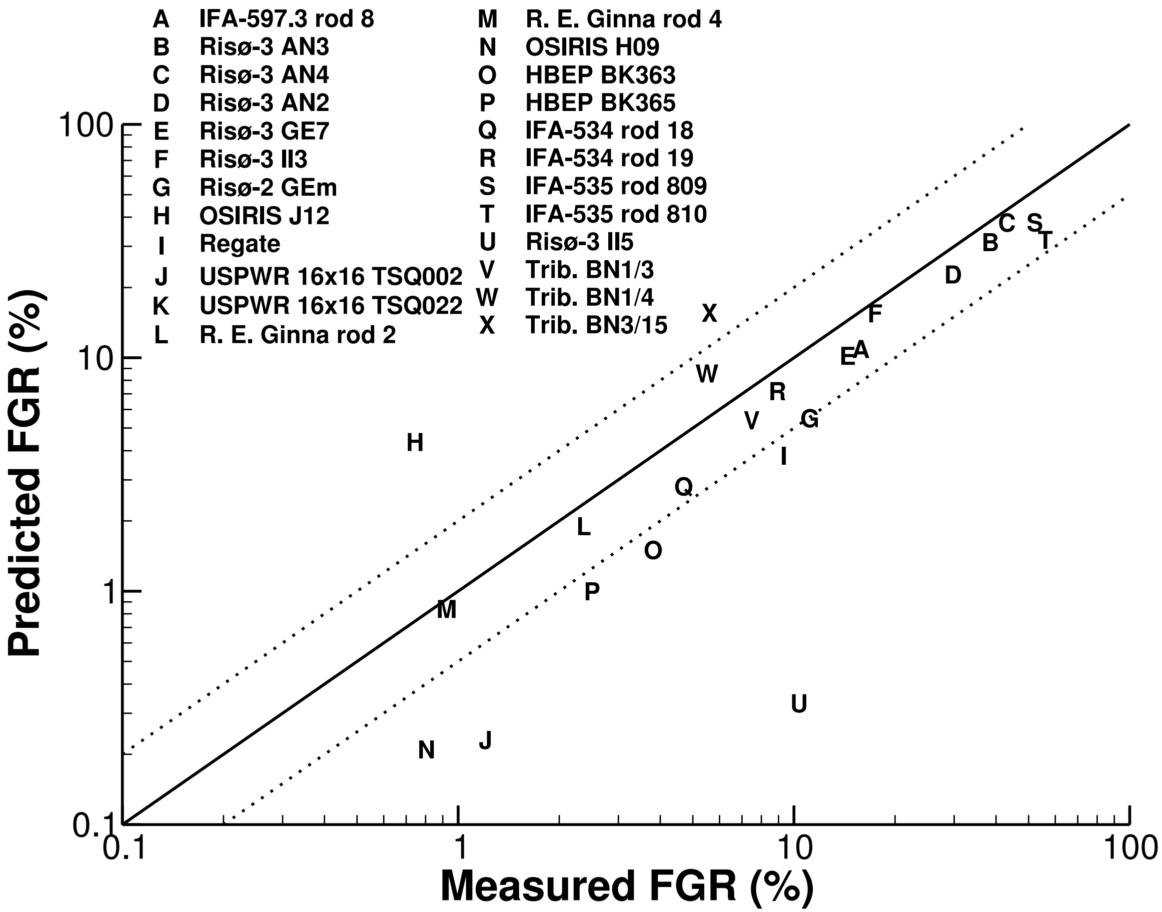


Temperature contour plots of the concentric (left) and eccentric (right) pellets and the fuel temperature profile across the diameter of the pellets at the fuel axial mid-plane

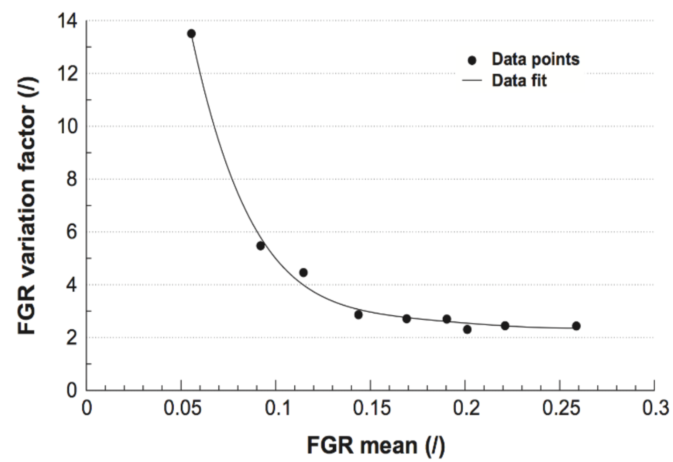


BISON temperature results and experimental data for the concentric and eccentric test pellets

LWR Validation
Fission Gas Release



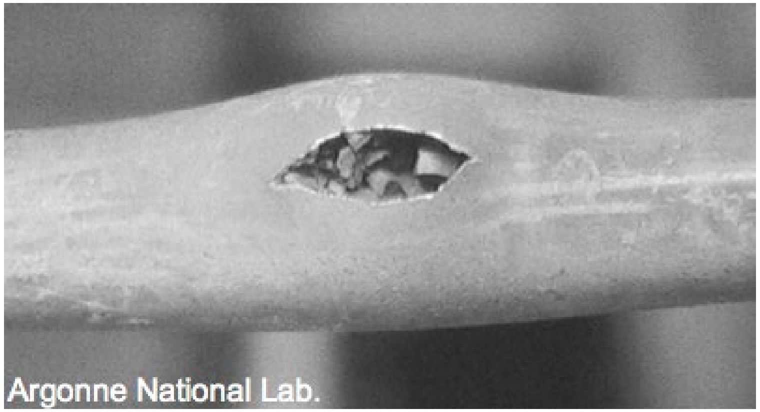
- Accuracy in predicting FGR is consistent with state-of-the-art modeling and with the involved uncertainties.



Pastore et al, *J Nuc Mat*, **456**, 398 (2014)

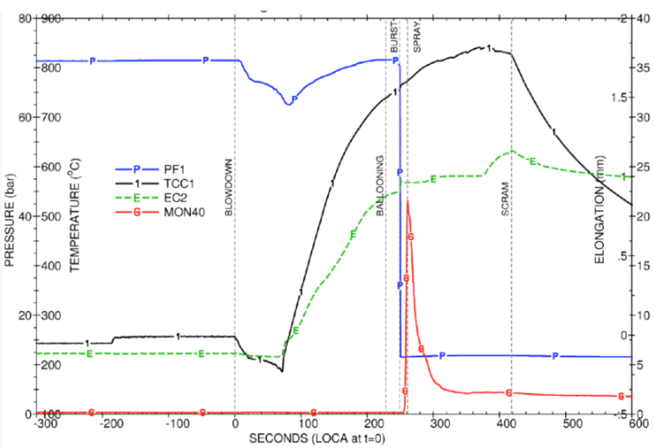
Capability for Accident Analysis (LOCA and RIA)

- Inherent
  - Steady and transient
  - Large strain (ballooning)
- Zircaloy cladding
  - High temperature oxidation
  - Energy deposition from oxidation
  - Microstructural phase transition
  - High temperature thermal creep
  - Temperature, strain and irradiation dependent plasticity
  - Burst failure model
  - Hydrogen/hydride behavior
- UO_2
  - Transient fission gas burst release
  - Axial relocation (during ballooning)
- Thermal hydraulics (TH)
  - Full coupling to TH code
    - CTF (via VERA)

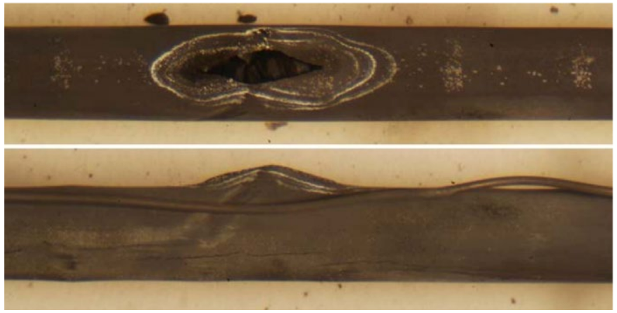


LOCA Integral Rod Experiment

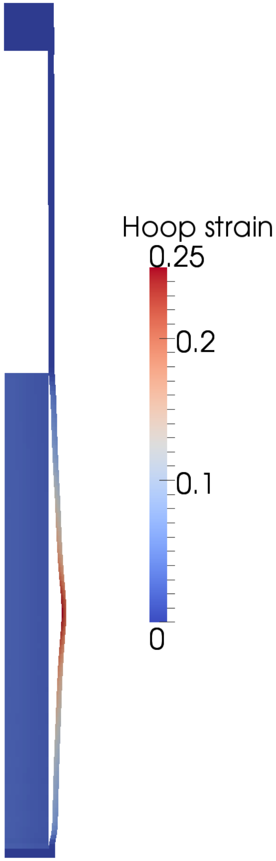
BISON analysis of integral fuel rod LOCA test Halden IFA-650.10



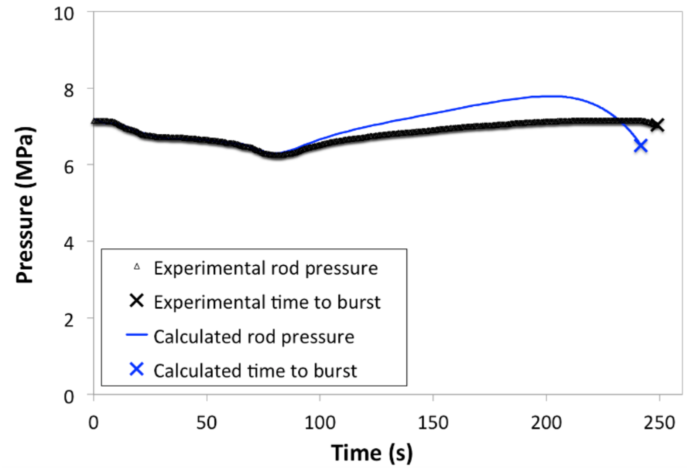
Signals for measured rod inner pressure (PF1), clad temperature (TCC), elongation (EC2) and gamma monitor response (MON40)



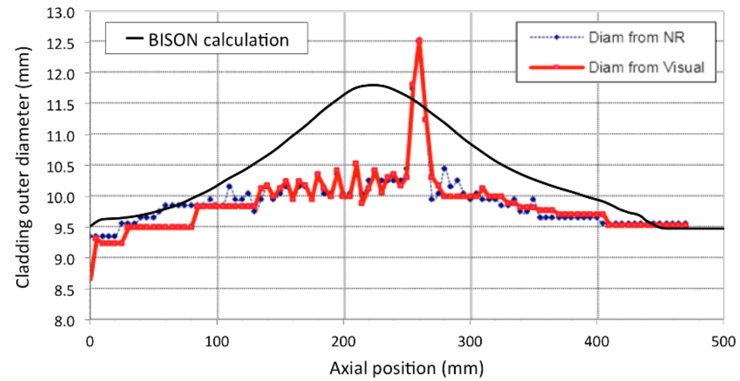
Post-test visual inspection for IFA-650.10 showing burst opening at two orthogonal orientations



BISON contour plot of hoop strain at the time of burst failure (magnified 10x along r)

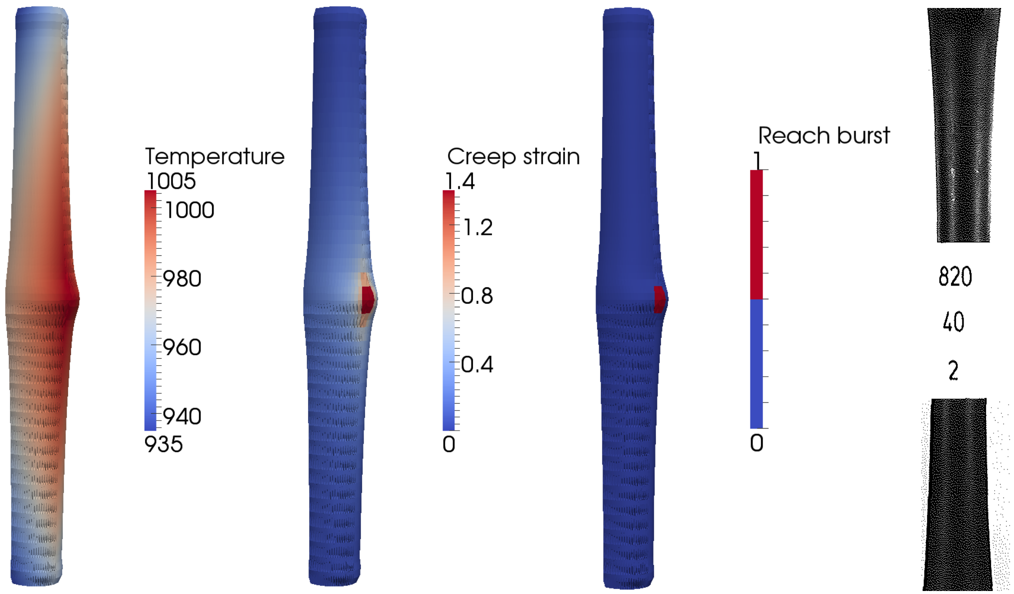


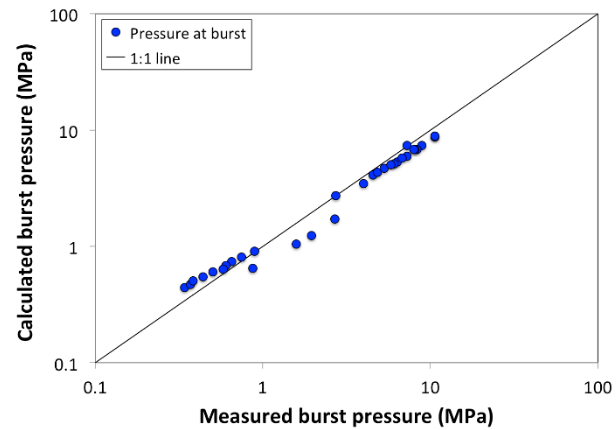
BISON calculated rod inner pressure evolution during the post-blowdown period and time to cladding burst

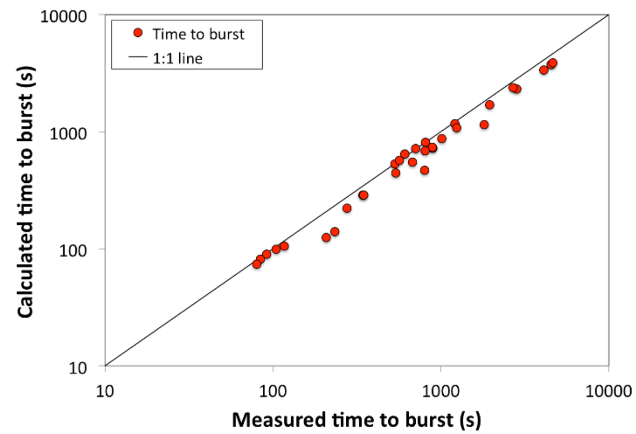


Calculated cladding outer diameter profile for IFA-650.10 at the end of the simulation compared to PIE experimental data

LOCA Cladding Burst Tests







Left: 3D LOCA cladding ballooning/burst simulations (REBEKA)

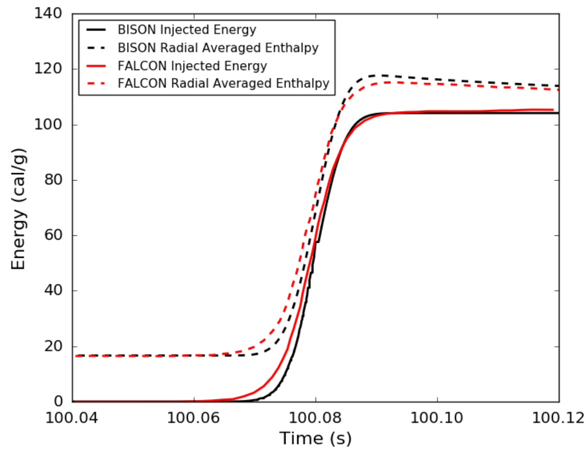
Right: BISON validation against 31 cladding burst experiments (PUZRY, IAEA FUMAC project)

REBEKA tests: Erbacher et al., Zirconium in the Nuclear Industry, 5th Conference, ASTM STP 754, 1982.

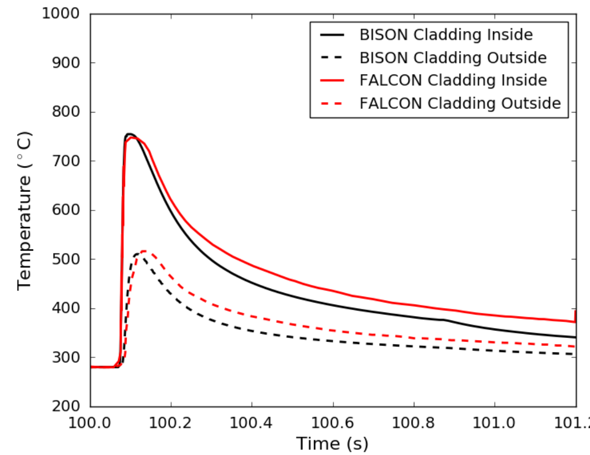
PUZRY tests: Perez-Feró et al., Technical Report EK-FRL-2012-255-01/02, Center for Energy Research, Hungarian Academy of Sciences, Budapest, Hungary, 2013.

RIA Validation
CABRI Sodium Tests

- Full experimental data not available thus comparisons were made to prior predictions (FALCON)

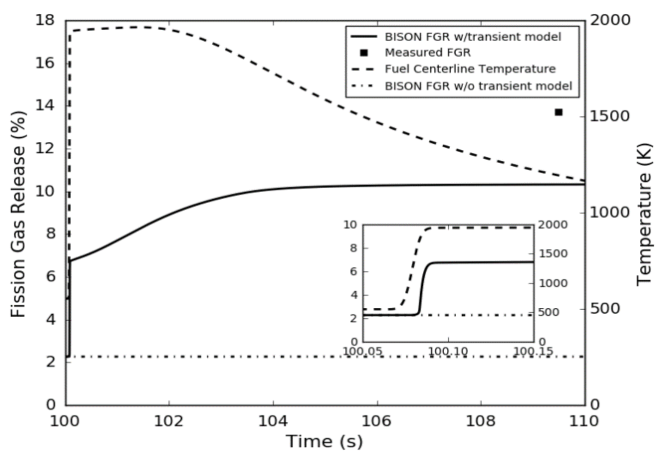


REP Na-5: Radial averaged enthalpy

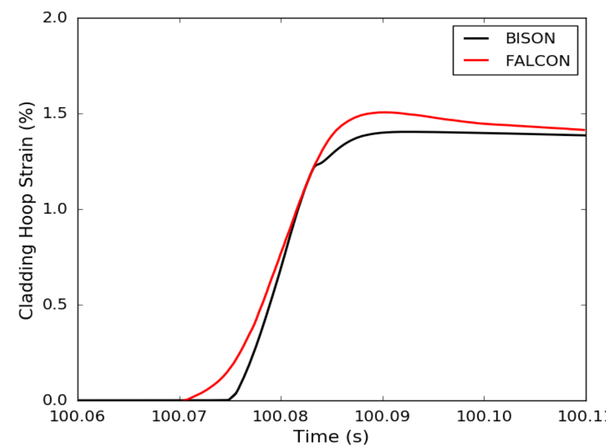


REP Na-5: Cladding temperature

- Fission gas release compares well to PIE measurements. A model for burst release is important.



REP Na-3: Fission gas release

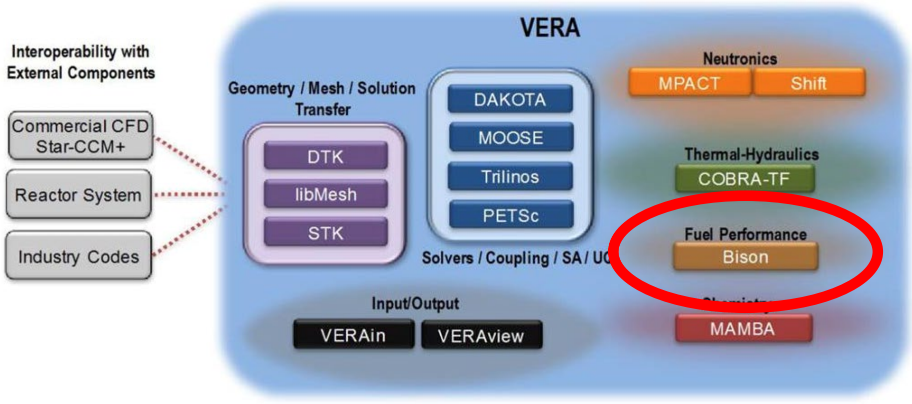


REP Na-3: Clad hoop strain

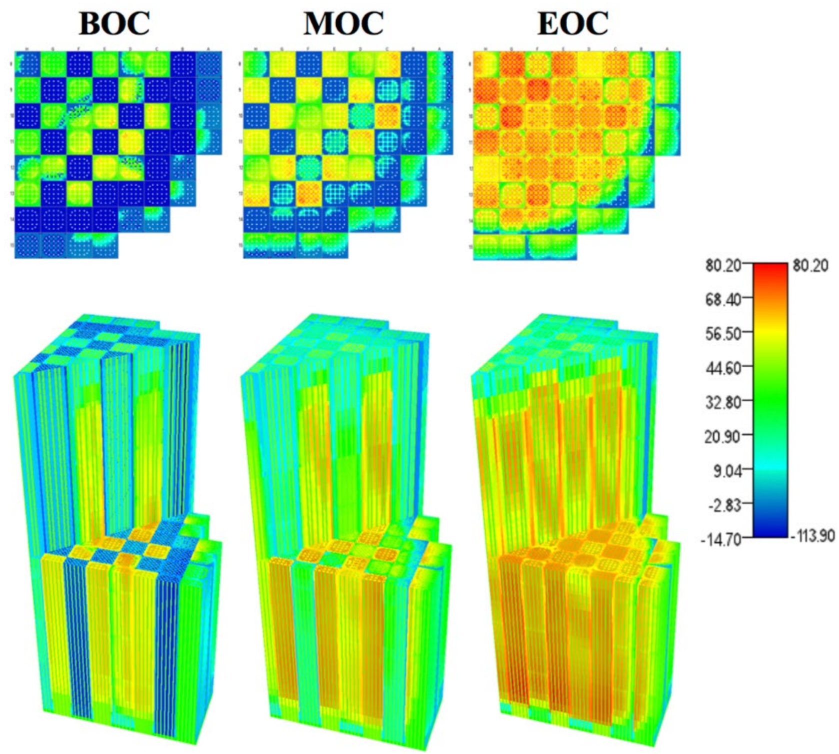
Current and Future Development

- Development
  - ATF material models
  - Improved code robustness and performance
  - 2.5D capability
  - Explicit material interface tracking via XFEM (e.g., rapid oxide layer growth during LOCA)
  - Fuel-cladding bonding (RIA)
  - Fuel crack healing (load following)
  - Documentation system
- Validation
  - Develop ATF cases as data becomes available
  - Include additional physics in PCMI cases:
    - Smeared cracking
    - Fuel creep
    - Relocation recovery
    - Discrete pellet geometry
  - Additional full-length rod cases
  - Additional LOCA cases
  - Additional RIA cases
  - System to provide validation metrics
  - Improve documentation

Bison in VERA



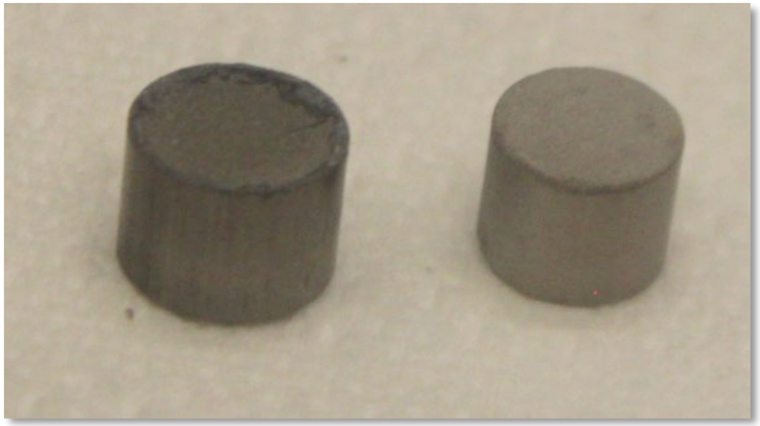
Nuclear Engineering and Design 2018 pp 172-186 April 25, 2018



Axial maximum hoop stress (top) and 3D nodal maximum hoop stress (bottom) from cycle 3 of normal operations as calculated with the Consortium for Advanced Simulation of Light Water Reactors (CASL) tool Virtual Environment for Reactor Applications (VERA)

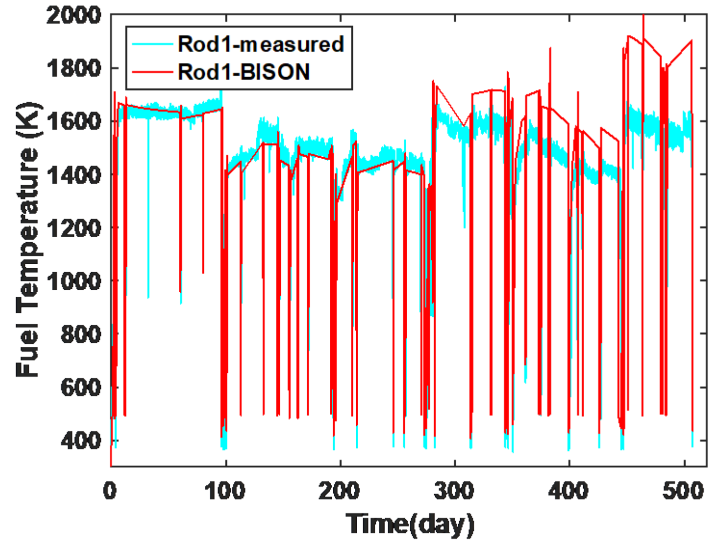
Accident Tolerant Concepts Under Development

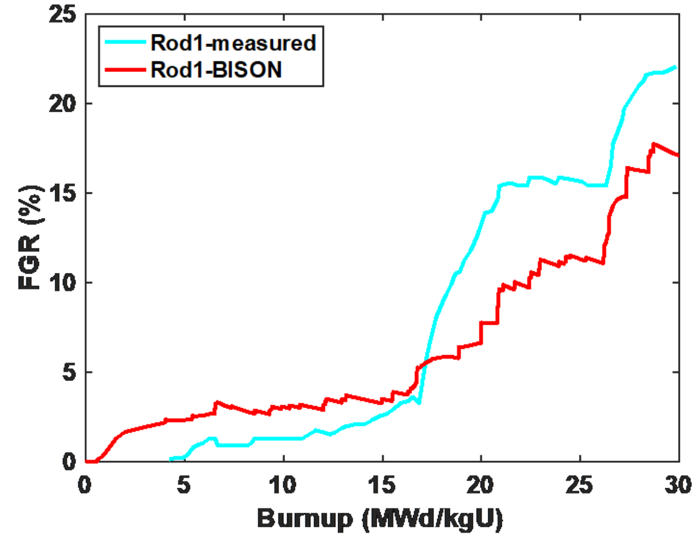
- Active development
  - Cr-doped fuel
  - Cr coated cladding
  - FeCrAl cladding
  - U_3Si_2 fuel



Cr-doped Fuel

- Cr-doped UO_2 is being considered as a replacement of UO_2 due to its higher thermal conductivity and larger grain sizes (expected to reduce fission gas release).
- Current capabilities
  - Diffusion coefficients of fission gases
  - Densification
- Validation against Halden IFA-667.1 (Right)



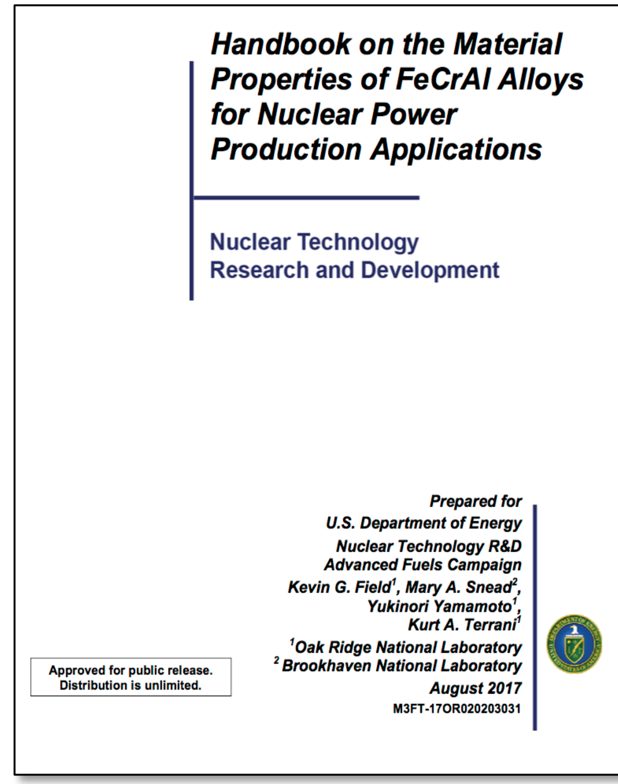


Cr-coated Cladding Capabilities

- Coating zirconium-based claddings with a thin (~15-20 μm) layer of Cr is expected to provide enhanced oxidation resistance
- Cr coatings are also reported to improve ballooning and wear resistance.
- Current capabilities
  - Temperature dependent thermo-mechanical properties
  - Isotropic plasticity and irradiation hardening
  - Thermal creep
  - Oxidation
  - Creep and plasticity

FeCrAl Cladding

- FeCrAl is of interest because of its higher strength and oxidation resistance. However, it has a lower melting point and high neutron absorption cross-section.
- Current capabilities (primary focus on C35M alloy):
  - Temperature dependent thermo-mechanical properties
  - Isotropic plasticity
  - Thermal and irradiation creep
  - Oxidation
  - Burst Criterion (failure)



Handbook on the Material Properties of FeCrAl Alloys for Nuclear Power Production Applications

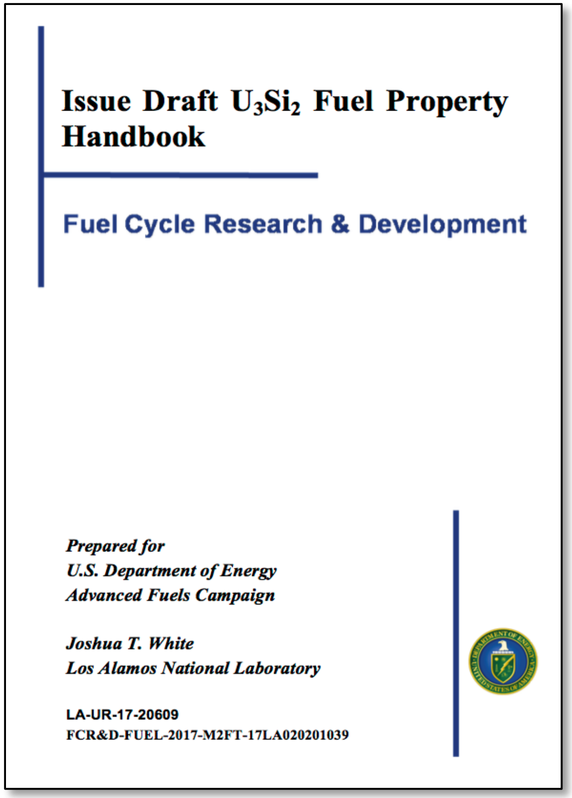
Nuclear Technology Research and Development

Prepared for
U.S. Department of Energy
Nuclear Technology R&D
Advanced Fuels Campaign
Kevin G. Field[1], Mary A. Snead[2], Yukinori Yamamoto[1], Kurt A. Terrani[1]
[1]Oak Ridge National Laboratory
[2]Brookhaven National Laboratory
August 2017
M3FT-17OR020203031

Approved for public release.
Distribution is unlimited.

U_3Si_2 Fuel

- U_3Si_2 is of interest because of its considerably higher thermal conductivity and uranium density compared to UO_2. However, it has uncertain gaseous swelling behavior, reacts with water and has a lower melting temperature.
- Current capabilities
  - Temperature dependent thermo-mechanical properties
  - Thermal Creep
  - Fission gas release
  - Three gaseous swelling models (empirical, rate theory, coupled)


Issue Draft U_3Si_2 Fuel Property Handbook

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Advanced Fuels Campaign

Joshua T. White
Los Alamos National Laboratory

LA-UR-17-20609
FCR&D-FUEL-2017-M2FT-17LA020201039

Thank you for your time.

Steve Novascone	stephen.novascone@inl.gov
Ben Spencer	benjamin.spencer@inl.gov
Jason Hales	jason.hales@inl.gov
Al Casagranda	albert.casagranda@inl.gov
Kyle Gamble	kyle.gamble@inl.gov
Russell Gardner	russell.gardner@inl.gov
Wen Jiang	wen.jiang@inl.gov
Giovanni Pastore	giovanni.pastore@inl.gov
Rich Williamson	richard.williamson@inl.gov