INL/MIS-19-56209-Revision-0

NRC Engagement and ATF Modeling

October 2019

Changing the World's Energy Future

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Idaho National Laboratory

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NRC Engagement and ATF Modeling

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October 16, 2019

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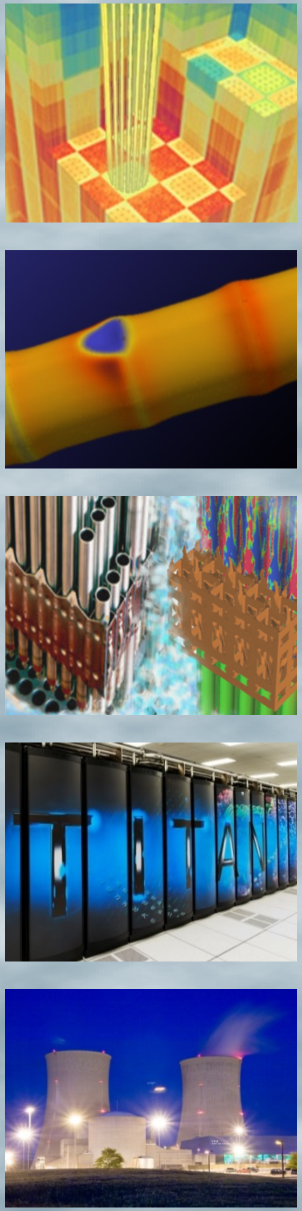

The Consortium for Advanced Simulation of LWRs
A DOE Energy Innovation Hub

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Acknowledgements

- **Kyle Gamble (INL)**
- Giovanni Pastore (INL)
- Michael Cooper (LANL)
- David Andersson (LANL)

NRC Engagement: Background

- 2018 Omnibus Spending Bill
  - $30M, a $5M increase over the $25M budget with additional scope
  - Includes collaboration with the Nuclear Regulatory Commission to evaluate the use of high-fidelity modeling and simulation tools in the regulatory environment
- 2019 approved budget of $27.585M
  - DOE direction to plan for last year of funding with sufficient carryover for FY20 close out
  - Significant NRC carryover funding for FY19
- Draft project plan developed
  - CASL centered this collaboration around the confirmatory analysis of accident-tolerant fuels (ATF).
  - The program plan defined the work that would be completed over the course of one year with funding from FY18 carryover

Multiscale ATF Modeling Timeline

NEAMS ATF HIP

NEAMS

CASL

NEAMS

FY17

FY18

FY19

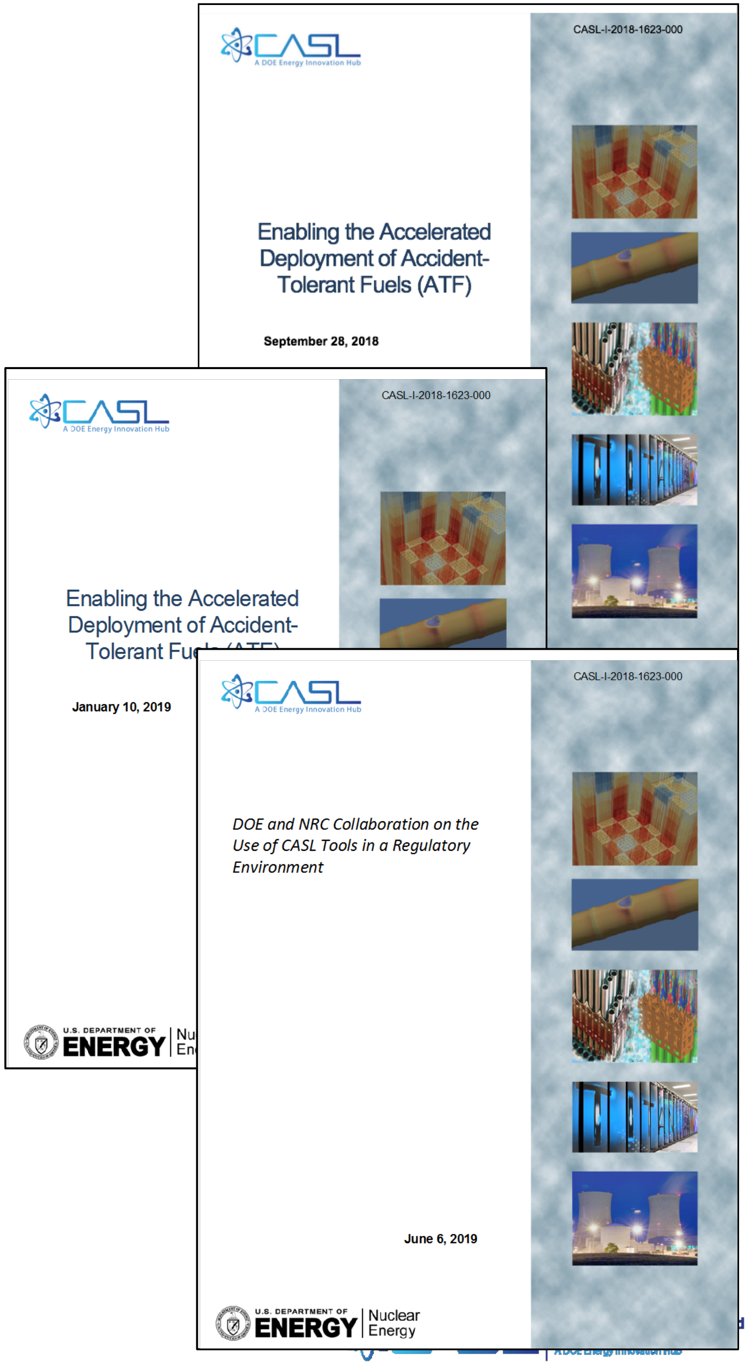
FY20

FY19 NRC engagement
funds from FY18 carryover

★ NEAMS/CASL/DOE meetings with NRC/ACRS regarding ATF/industry connectio

General NRC Feedback

- Nothing prohibits NRC from adopting DOE advanced modeling and simulation codes
- NRC needs:
  - Requirement for ‘deep knowledge’ of adopted codes (historically why NRC developed TRACE, FRACON and MELCOR codes)
  - Requirement for training and long term support
- It is likely industry will be adopting DOE codes for advanced reactors
- Collaboration needs to be aligned with “Project plan to prepare the US NRC for efficient and effective licensing of ATF” (Sep. 2018)



CASL-I-2018-1623-000

Enabling the Accelerated Deployment of Accident-Tolerant Fuels (ATF)

September 28, 2018

CASL-I-2018-1623-000

Enabling the Accelerated Deployment of Accident-Tolerant Fu

January 10, 2019

CASL-I-2018-1623-000

DOE and NRC Collaboration on the Use of CASL Tools in a Regulatory Environment

June 6, 2019

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FY19 NRC Collaboration Scope

Collaborate with the NRC on the use of advanced modeling and simulation tools in a licensing environment for ATF

2. Perform development, uncertainty quantification, and documentation of Bison models for ATF concepts

7. Develop collaboration regarding VERA-Shift calculations

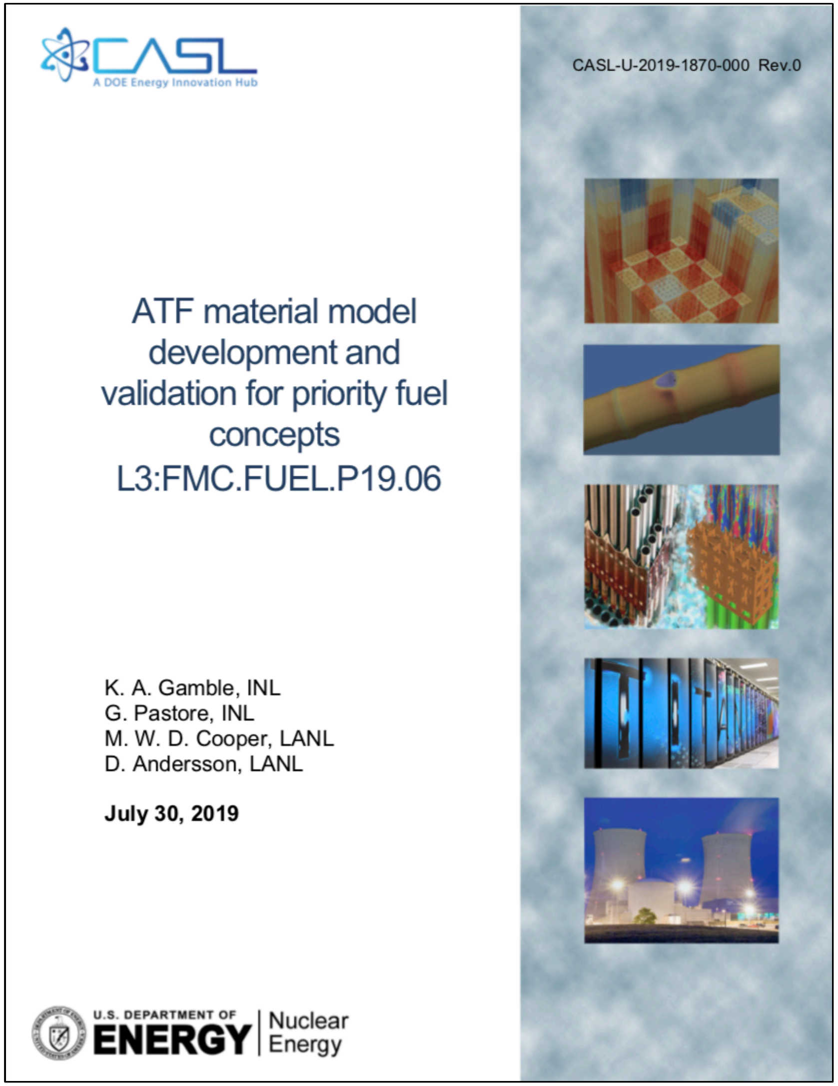
FY19 objective was enhanced NRC knowledge and expertise in the use of advanced modeling and simulation in a licensing environment

ATF Work: Introduction

- Priority ATF concepts were identified during early discussions with the NRC (late FY 18)
  - U_3Si_2 and Cr_2O_3-doped UO_2 fuel
  - Cr-coated Zircaloy and FeCrAl cladding
- Identify range of applicability and uncertainty in individual models
  - Propagate this uncertainty to fuel performance metrics of interest
- Construct reports in a form similar to NUREG/CR-7024
- Ensure all of the models for the priority concepts can easily be implemented into the NRC code FAST

This work was performed as part of the NRC collaboration effort but also benefits industry’s push for accelerated deployment of ATF.

ATF Material Model Reports



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CASL-U-2019-1870-000 Rev.0

ATF material model development and validation for priority fuel concepts
L3:FMC.FUEL.P19.06

K. A. Gamble, INL
G. Pastore, INL
M. W. D. Cooper, LANL
D. Andersson, LANL

July 30, 2019

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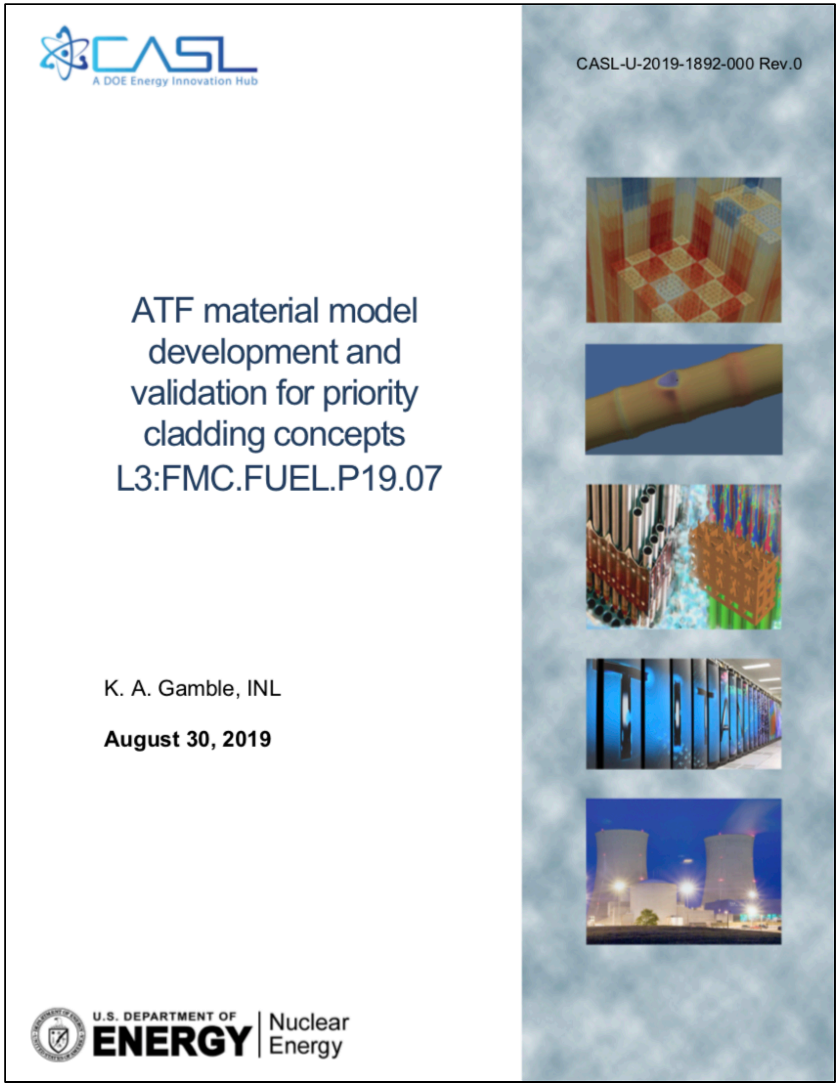

CASL
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CASL-U-2019-1892-000 Rev.0

ATF material model development and validation for priority cladding concepts
L3:FMC.FUEL.P19.07

K. A. Gamble, INL

August 30, 2019

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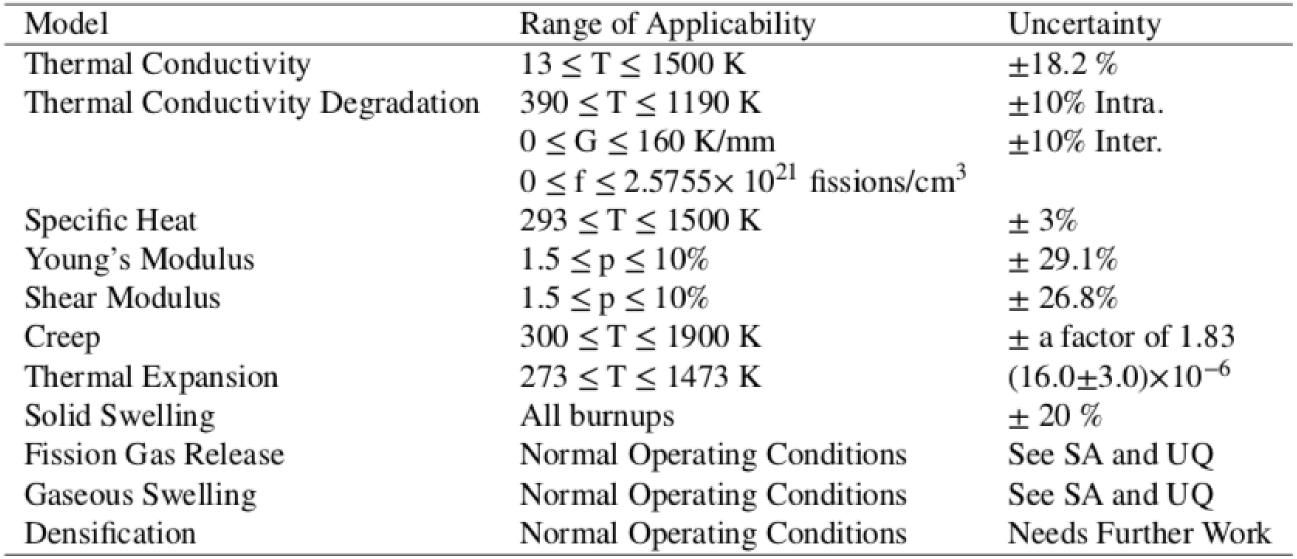
U_3Si_2: Material and Behavioral Models

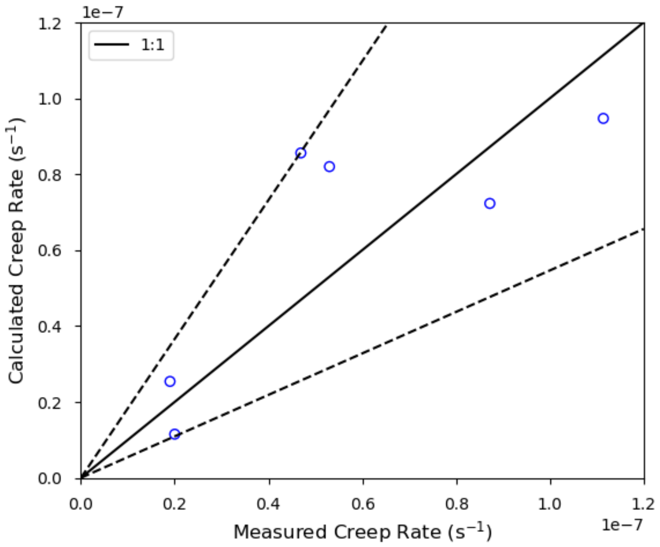
- Bison contains the following material and behavioral models for U_3Si_2:
  - Thermal Properties
    - Thermal Conductivity (4 options + degradation)
    - Specific Heat (3 options)
  - Elasticity
    - Porosity dependent Young’s and Shear moduli
  - Thermal and Irradiation Creep (2 options)
  - Thermal Expansion
  - Gaseous Swelling (3 options)
  - Solid Swelling
  - Densification
  - Fission Gas Release (lower length scale informed)
    - Stoichiometric and Si-rich

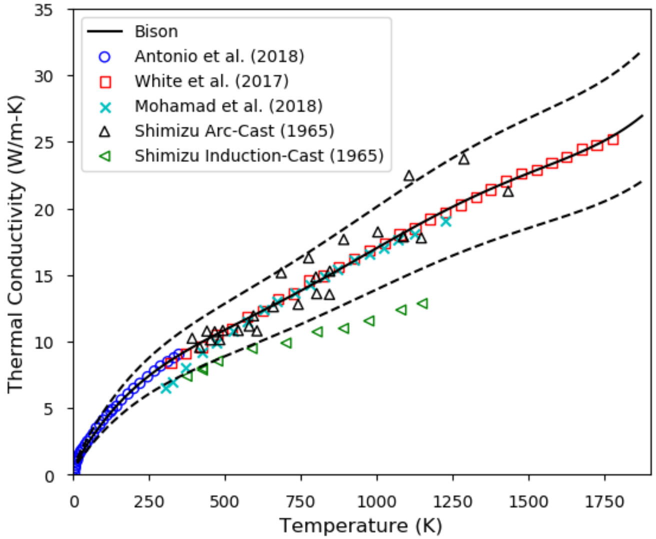


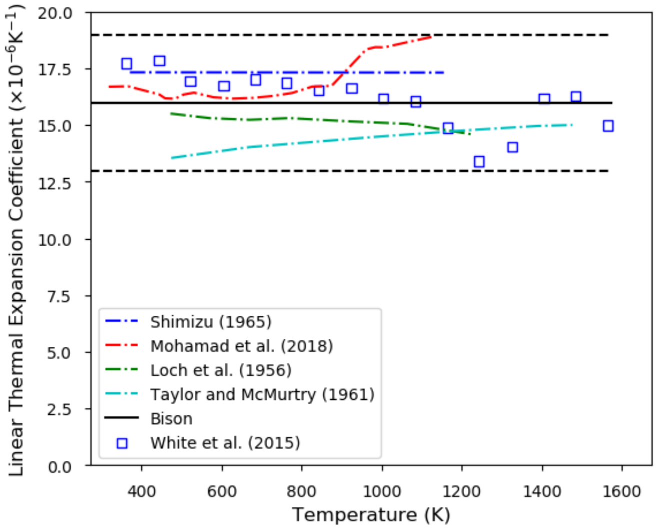
Model	Range of Applicability	Uncertainty
Thermal Conductivity	$13 \leq T \leq 1500$ K	±18.2 %
Thermal Conductivity Degradation	$390 \leq T \leq 1190$ K	±10% Intra.
	$0 \leq G \leq 160$ K/mm	±10% Inter.
	$0 \leq f \leq 2.5755\times 10^{21}$ fissions/cm^3	
Specific Heat	$293 \leq T \leq 1500$ K	± 3%
Young’s Modulus	$1.5 \leq p \leq 10\%$	± 29.1%
Shear Modulus	$1.5 \leq p \leq 10\%$	± 26.8%
Creep	$300 \leq T \leq 1900$ K	± a factor of 1.83
Thermal Expansion	$273 \leq T \leq 1473$ K	$(16.0 \pm 3.0)\times 10^{-6}$
Solid Swelling	All burnups	± 20 %
Fission Gas Release	Normal Operating Conditions	See SA and UQ
Gaseous Swelling	Normal Operating Conditions	See SA and UQ
Densification	Normal Operating Conditions	Needs Further Work

U_3Si_2: Material and Behavioral Models

- Uncertainty in empirical models is based upon the data used to develop the models.
- Uncertainty in lower length scale models is propagated to the engineering scale.
  - See SA and UQ section.

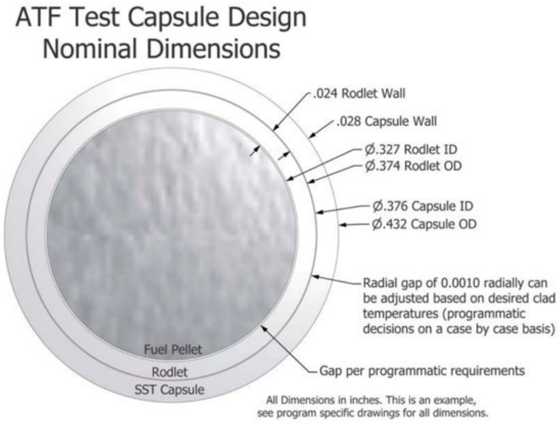




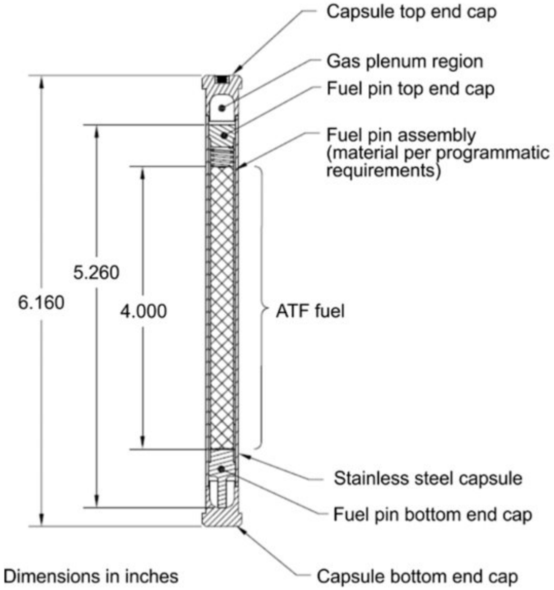


U_3Si_2: Validation

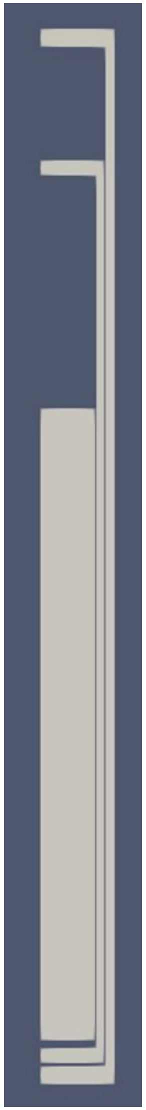
- Two U_3Si_2 fueled experiments with ZIRLO™
  - ATF-13 R4 filled with helium
  - ATF-15 R6 filled with helium/argon mixture
- Available data includes:
  - Fission Gas Release
  - Fuel axial elongation (inferred from neutron radiographs)
  - Clad profilometry


ATF Test Capsule Design
Nominal Dimensions

All Dimensions in inches. This is an example, see program specific drawings for all dimensions.

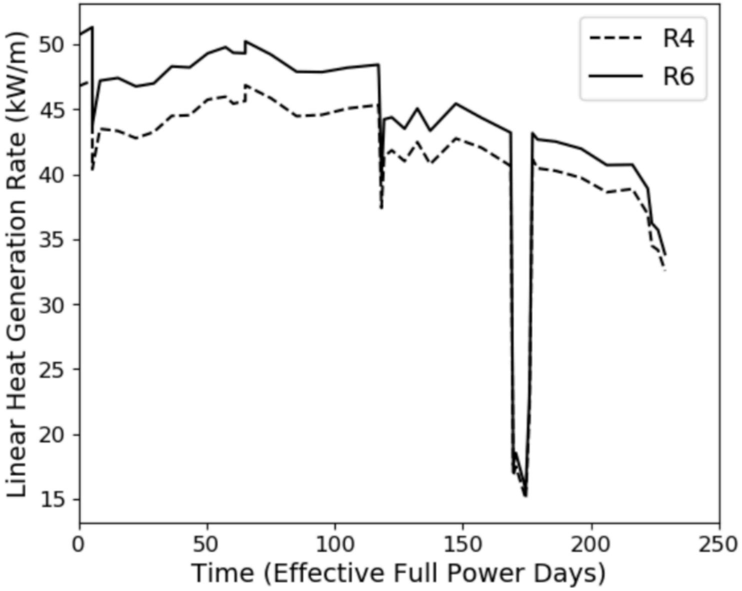


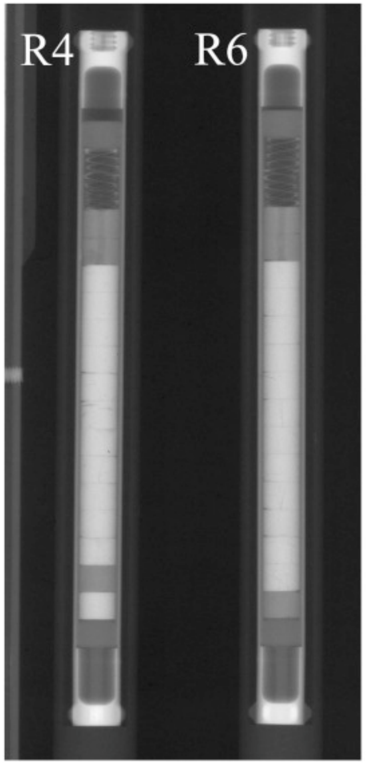
Dimensions in inches


Bison geometry used. Axial direction scaled by 0.5.

U_3Si_2: Validation

- Using the nominal models Bison underpredicts for R4 and overpredicts for R6.





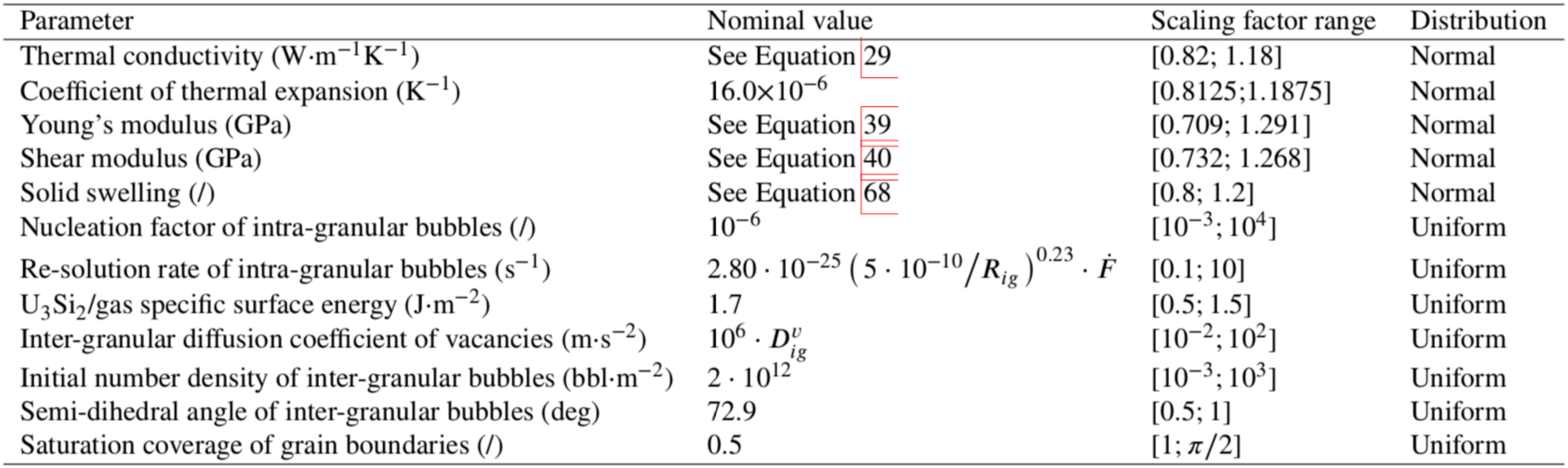
Bison comparisons to ATF-13 R4 and ATF-15 R6 PIE data

	Bison R4	Experiment R4	Bison R6	Experiment R6
Fuel Elongation (mm)	-0.0784	0.0	0.0128	0.0
Fission Gas Release (%)	0.0	0.06	0.19	0.06

U_3Si_2: SA and UQ

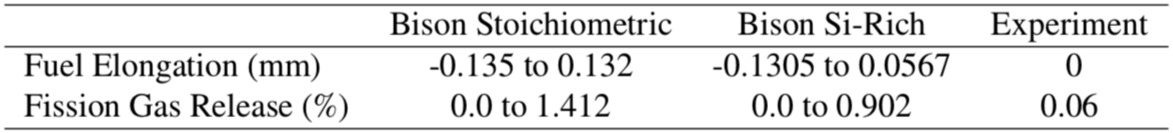
- Using the uncertainty defined in the individual material models, perform an SA and UQ analysis on the ATF-13 R4 case.

Parameters varied in the sensitivity analysis and uncertainty quantification



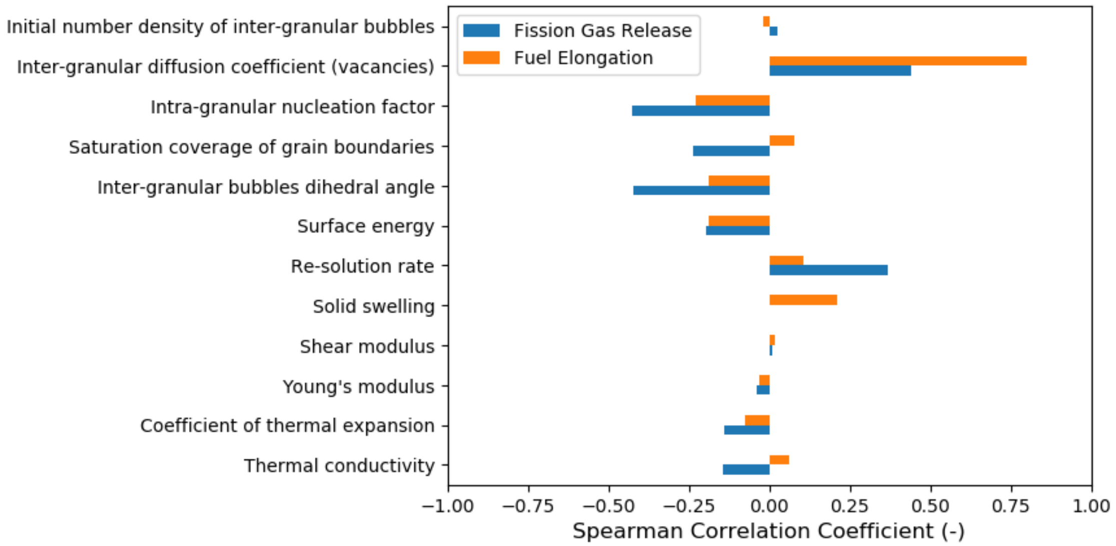
Parameter	Nominal value	Scaling factor range	Distribution
Thermal conductivity ($W{\cdot}m^{-1}K^{-1}$)	See Equation 29	[0.82; 1.18]	Normal
Coefficient of thermal expansion (K^{-1})	16.0×10^{-6}	[0.8125;1.1875]	Normal
Young's modulus (GPa)	See Equation 39	[0.709; 1.291]	Normal
Shear modulus (GPa)	See Equation 40	[0.732; 1.268]	Normal
Solid swelling (/)	See Equation 68	[0.8; 1.2]	Normal
Nucleation factor of intra-granular bubbles (/)	10^{-6}	$[10^{-3}; 10^{4}]$	Uniform
Re-solution rate of intra-granular bubbles (s^{-1})	$2.80 \cdot 10^{-25} \left(5 \cdot 10^{-10}/R_{ig}\right)^{0.23} \cdot \dot{F}$	[0.1; 10]	Uniform
U_3Si_2/gas specific surface energy ($J{\cdot}m^{-2}$)	1.7	[0.5; 1.5]	Uniform
Inter-granular diffusion coefficient of vacancies ($m{\cdot}s^{-2}$)	$10^{6} \cdot D^{v}_{ig}$	$[10^{-2}; 10^{2}]$	Uniform
Initial number density of inter-granular bubbles ($bbl{\cdot}m^{-2}$)	$2 \cdot 10^{12}$	$[10^{-3}; 10^{3}]$	Uniform
Semi-dihedral angle of inter-granular bubbles (deg)	72.9	[0.5; 1]	Uniform
Saturation coverage of grain boundaries (/)	0.5	$[1; \pi/2]$	Uniform

Bison comparisons to ATF-13 R4 PIE data including

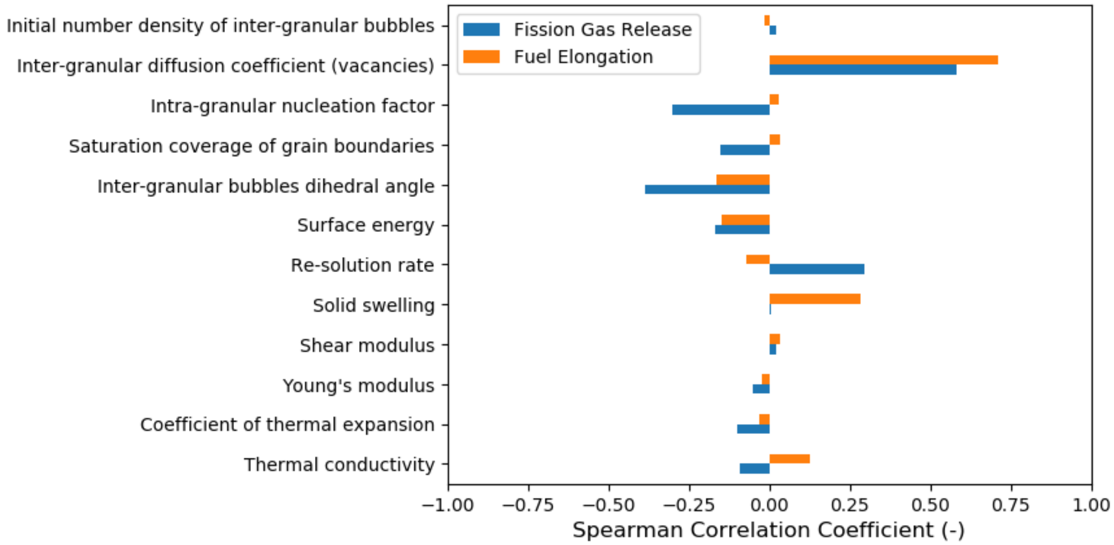


	Bison Stoichiometric	Bison Si-Rich	Experiment
Fuel Elongation (mm)	-0.135 to 0.132	-0.1305 to 0.0567	0
Fission Gas Release (%)	0.0 to 1.412	0.0 to 0.902	0.06

U_3Si_2: Sensitivity Analysis



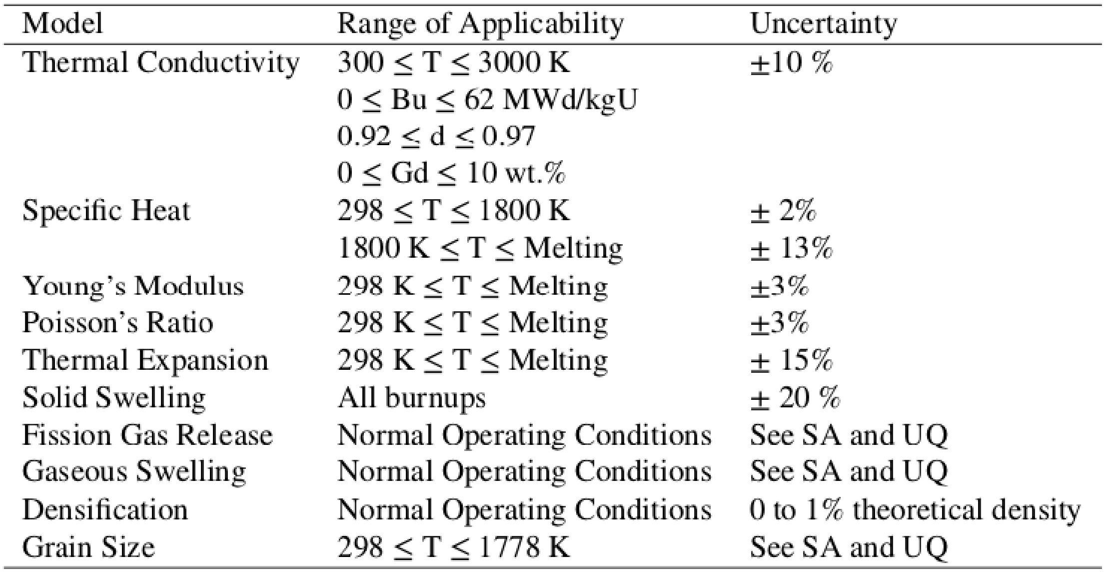
Stoichiometric



Si-Rich

Cr_2O_3-doped UO_2: Material and Behavioral Models

- Bison contains the following material and behavioral models for Cr_2O_3-doped UO_2:
  - Thermal Properties (temperatur dependent)*
    - Thermal Conductivity
    - Specific Heat
  - Elasticity and Cracking*
    - Temperature dependent You modulus and isotropic cracki
  - Thermal and Irradiation Creep*
  - Thermal Expansion*
  - Solid Swelling*
  - Densification*
  - Grain Size
  - Fission Gas Release (lower length scale informed)

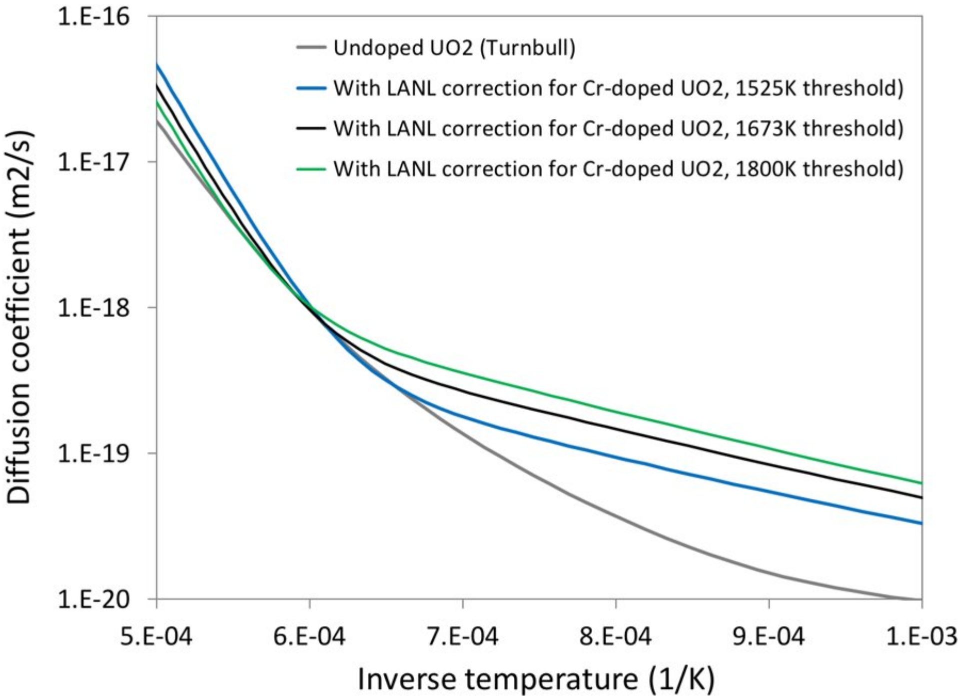


Model	Range of Applicability	Uncertainty
Thermal Conductivity	$300 \leq T \leq 3000$ K $0 \leq Bu \leq 62$ MWd/kgU $0.92 \leq d \leq 0.97$ $0 \leq Gd \leq 10$ wt.%	±10 %
Specific Heat	$298 \leq T \leq 1800$ K 1800 K $\leq T \leq$ Melting	± 2% ± 13%
Young's Modulus	298 K $\leq T \leq$ Melting	±3%
Poisson's Ratio	298 K $\leq T \leq$ Melting	±3%
Thermal Expansion	298 K $\leq T \leq$ Melting	± 15%
Solid Swelling	All burnups	± 20 %
Fission Gas Release	Normal Operating Conditions	See SA and UQ
Gaseous Swelling	Normal Operating Conditions	See SA and UQ
Densification	Normal Operating Conditions	0 to 1% theoretical density
Grain Size	$298 \leq T \leq 1778$ K	See SA and UQ

*Uses UO_2 model

Cr_2O_3-doped UO_2: Material and Behavioral Models

- Fission gas behavior (FGR and gaseous swelling) are computed using Bison's physics-based model for UO_2
- A specific FG diffusivity correction for Cr_2O_3-doped UO_2 developed at LANL using atomistic modeling was applied
- Various versions were implemented with different threshold temperatures
- Model can also naturally account for the larger grain size in doped UO_2 compared to standard UO_2



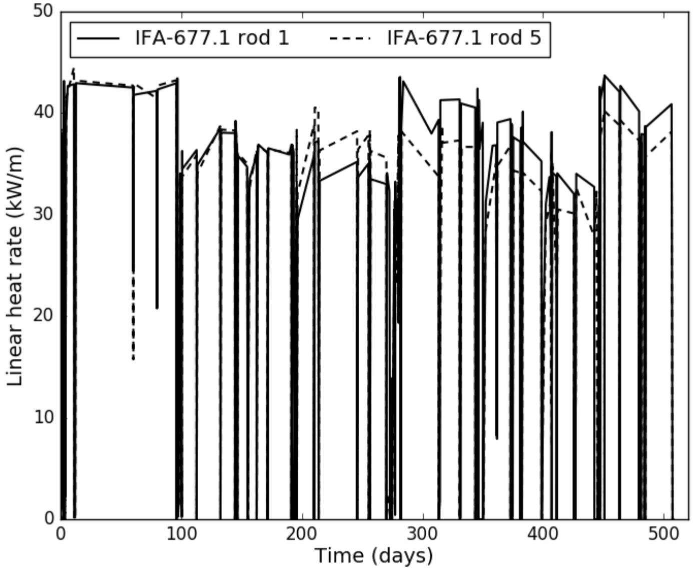
$$D^{doped} = \exp\left(-\frac{\Delta H_1}{k_B}\left[\frac{1}{T} - \frac{1}{T_1}\right]\right) D_1^{undoped} + \exp\left(-\frac{\Delta H_2}{k_B}\left[\frac{1}{T} - \frac{1}{T_2}\right]\right) D_2^{undoped} + D_3^{undoped}$$

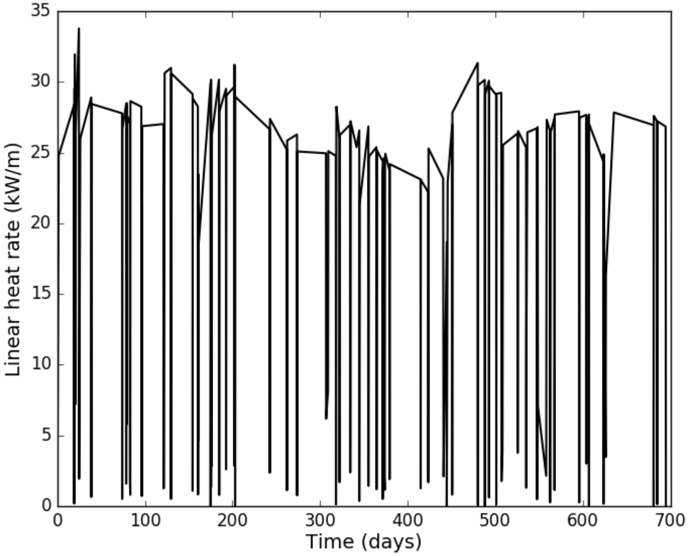
where $T_1 = T_2 = 1673$ K, $\Delta H_1 = 0.547$ eV, and $\Delta H_2 = -0.674$ eV.

Cr_2O_3-doped UO_2: Validation

- Three cases have been analyzed:
  - IFA-677.1 rod 1
  - IFA-677.1 rod 5
  - IFA-716.1 rod 1

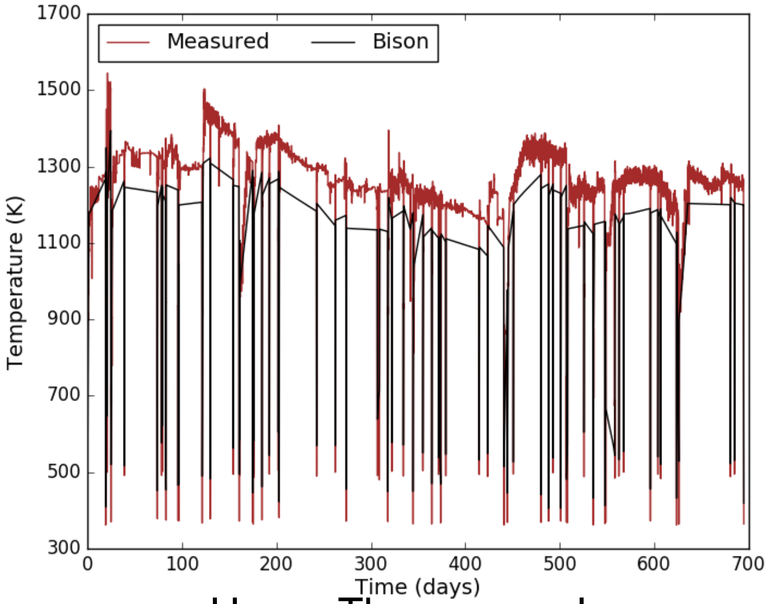
		IFA-677.1 rod 1	IFA-677.1 rod 5	IFA-716.1 rod 1
Cladding material		Zircaloy-4	Zircaloy-4	Zircaloy-4
Fuel material		UO_2 + additives	UO_2 + additives	UO_2 + additives
Fill gas		He	He	He
Total active fuel stack length	mm	398.6	403.5	399.5
Drilled active section length (top)	mm	109.2	111.0	115
Drilled active section length (bottom)	mm	109.7	111.1	-
Pellet inner diameter (drilled sections)	mm	1.8	1.8	1.8
Pellet outer diameter	mm	9.13	9.13	9.12
Diametral gap	μm	170	170	180
Cladding thickness	mm	0.725	0.725	725
Cladding outer diameter	mm	10.75	10.75	10.75
Free volume	cm^3	5.34	5.26	5.80
Fill gas pressure	MPa	1.35	1.35	1
Fuel Cr_2O_3 content	ppm	900	500	1580
Fuel Al_2O_3 content	ppm	200	200	-
Fuel U-235 enrichment	%	4.94	4.91	4.90
Initial fuel density	kg/m^3	10690	10700	10500
Fuel average grain radius	μm	28	22.5	35



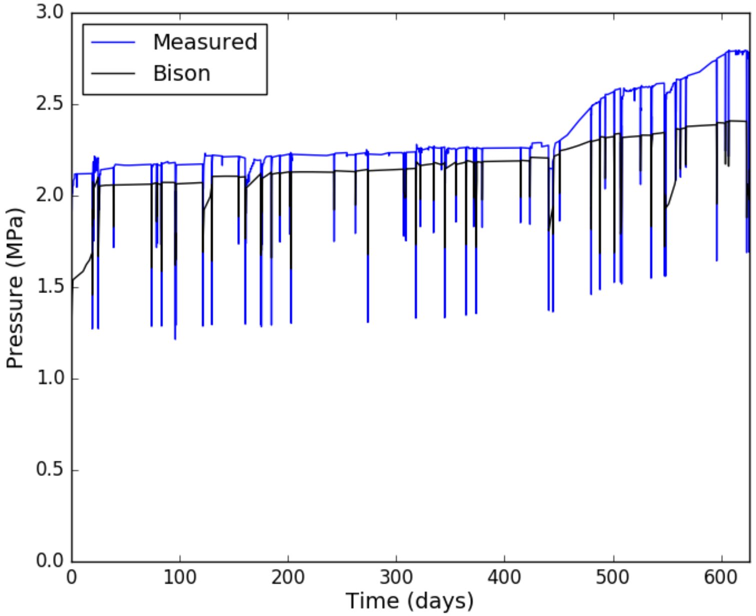


Cr_2O_3-doped UO_2: Validation (IFA-716.1 Rod 1)

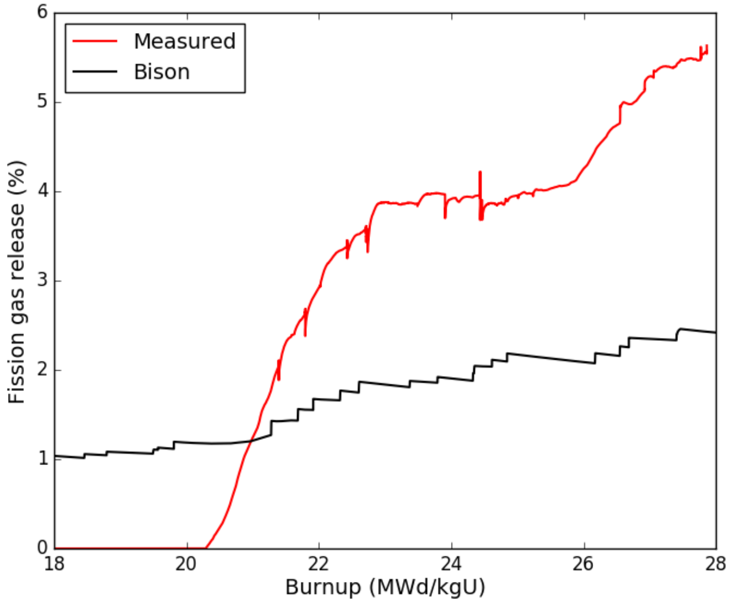
- Measurements include:
  - Temperature (upper thermocouple)
  - Rod internal pressure
  - Fission gas release



Upper Thermocouple



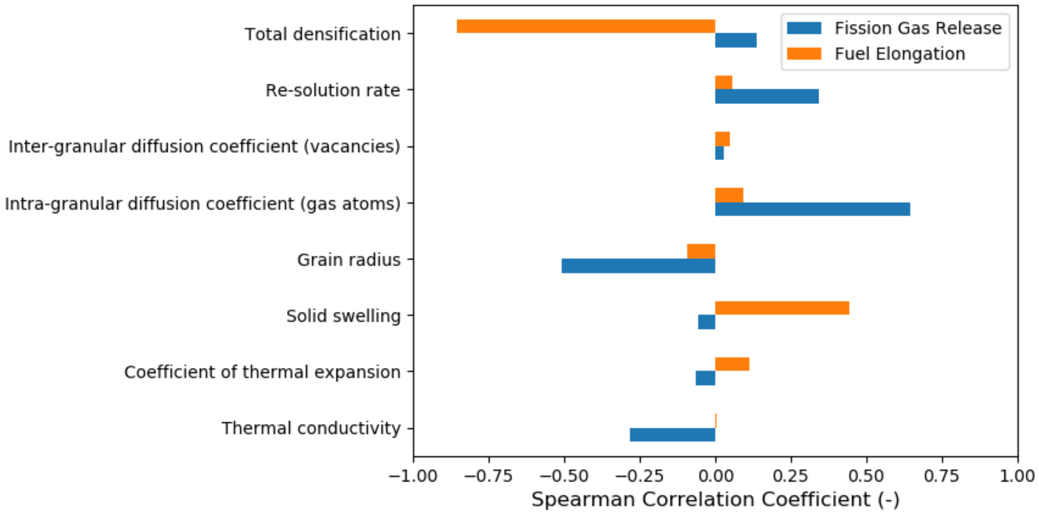
Rod Internal Pressure

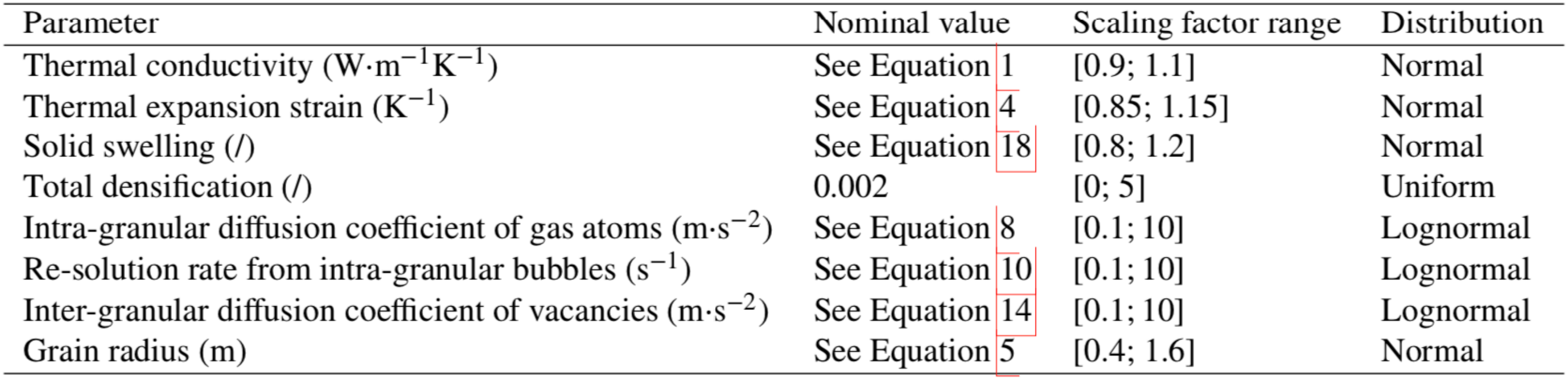


Fission Gas Release

Cr_2O_3-doped UO_2: SA and UQ

- Using the uncertainty defined in the individual material models, perform a SA and UQ analysis on the IFA-716.1 Rod 1 case.

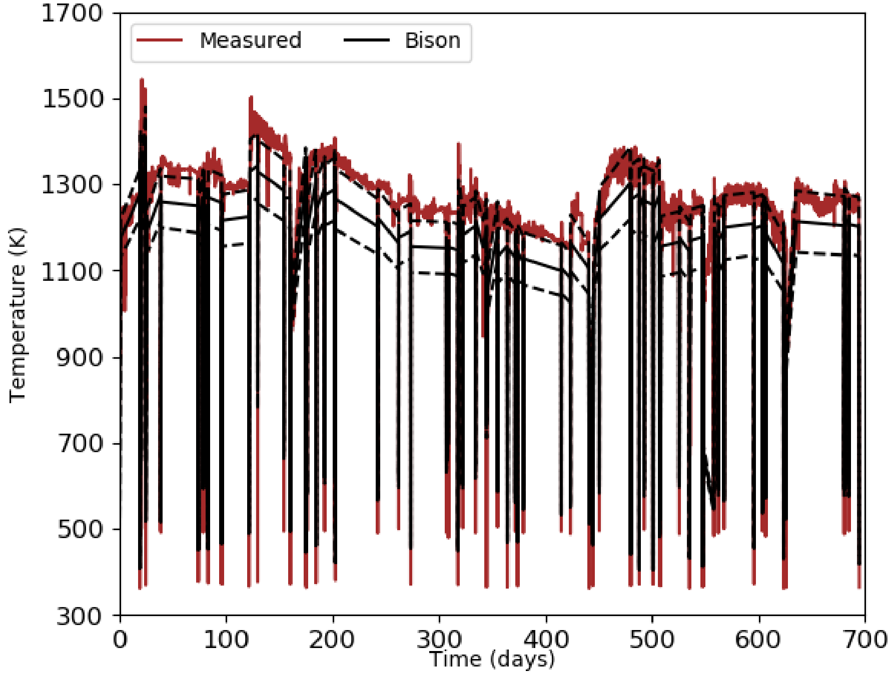




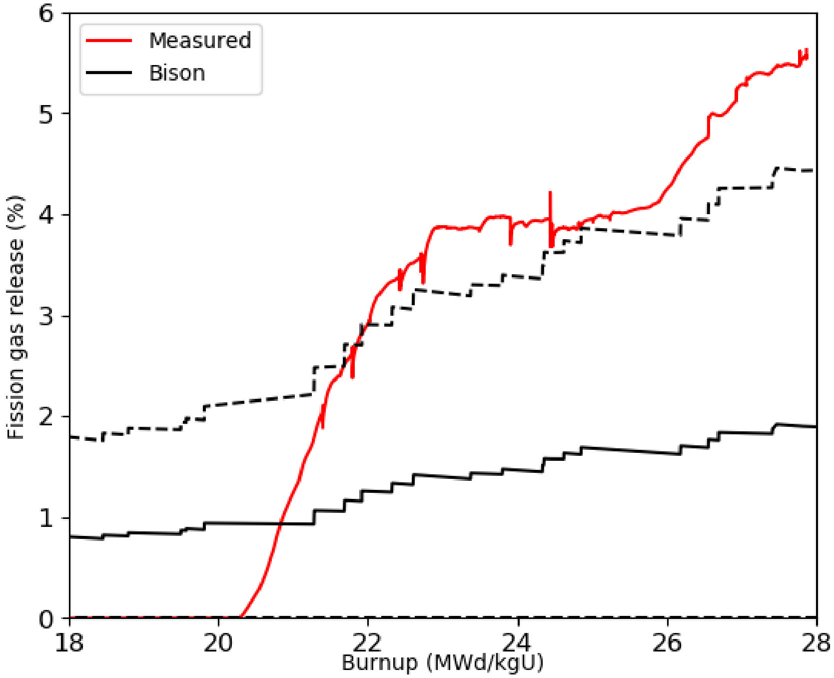
Parameter	Nominal value	Scaling factor range	Distribution
Thermal conductivity ($W \cdot m^{-1}K^{-1}$)	See Equation 1	[0.9; 1.1]	Normal
Thermal expansion strain (K^{-1})	See Equation 4	[0.85; 1.15]	Normal
Solid swelling (/)	See Equation 18	[0.8; 1.2]	Normal
Total densification (/)	0.002	[0; 5]	Uniform
Intra-granular diffusion coefficient of gas atoms ($m \cdot s^{-2}$)	See Equation 8	[0.1; 10]	Lognormal
Re-solution rate from intra-granular bubbles (s^{-1})	See Equation 10	[0.1; 10]	Lognormal
Inter-granular diffusion coefficient of vacancies ($m \cdot s^{-2}$)	See Equation 14	[0.1; 10]	Lognormal
Grain radius (m)	See Equation 5	[0.4; 1.6]	Normal

Cr_2O_3-doped UO_2: SA and UQ

- Bison comparisons to IFA-716.1 including
  - Solid line represents mean values, dashed lines represent the 2 band



Upper Thermocouple



Fission Gas Release

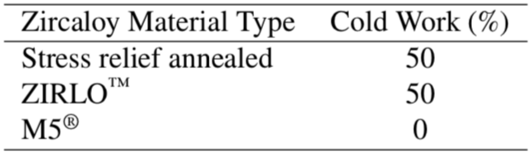
Cr-coated Cladding: Material Models

- Material properties were added to Bison for M5® and ZIRLO™ to permit analysis of the zirconium-based substrates of interest to industry.

- Primary differences between the substrates include the cold work, irradiation growth, and oxidation.
  - Oxidation kinetics of M5® and ZIRLO™ not added to Bison as information is not publicly available

- Uncertainty in zirconium-based clad models is taken from MATPRO and NUREG/CR-7204.

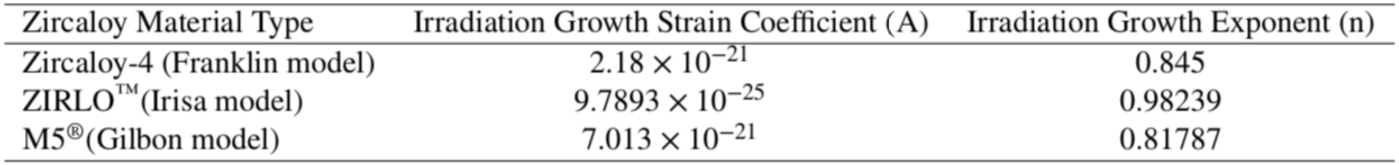
Cold work



Zircaloy Material Type	Cold Work (%)
Stress relief annealed	50
ZIRLO™	50
M5®	0

Coefficients in the irradiation growth model

$$\epsilon_{irr} = A\Phi^n$$

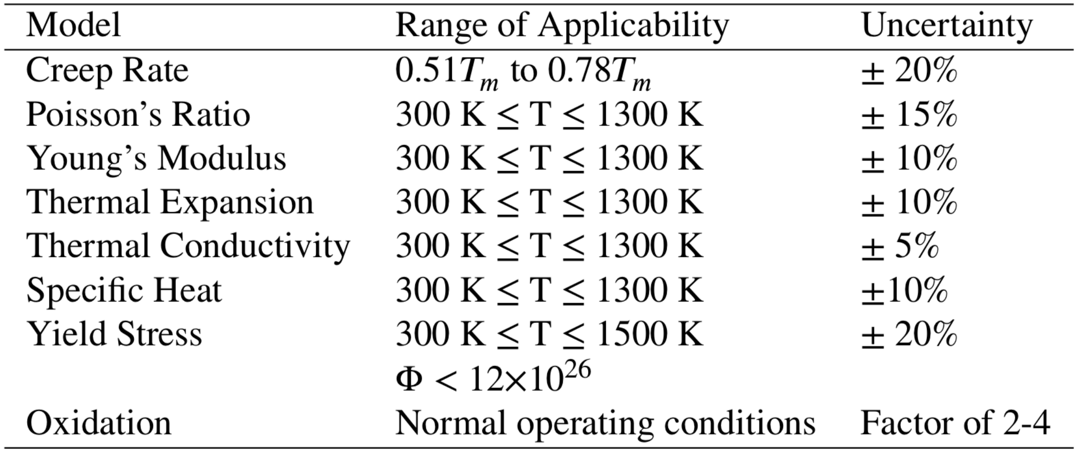


Zircaloy Material Type	Irradiation Growth Strain Coefficient (A)	Irradiation Growth Exponent (n)
Zircaloy-4 (Franklin model)	2.18×10^{-21}	0.845
ZIRLO™(Irisa model)	9.7893×10^{-25}	0.98239
M5®(Gilbon model)	7.013×10^{-21}	0.81787

Cr-coated Cladding: Material Models

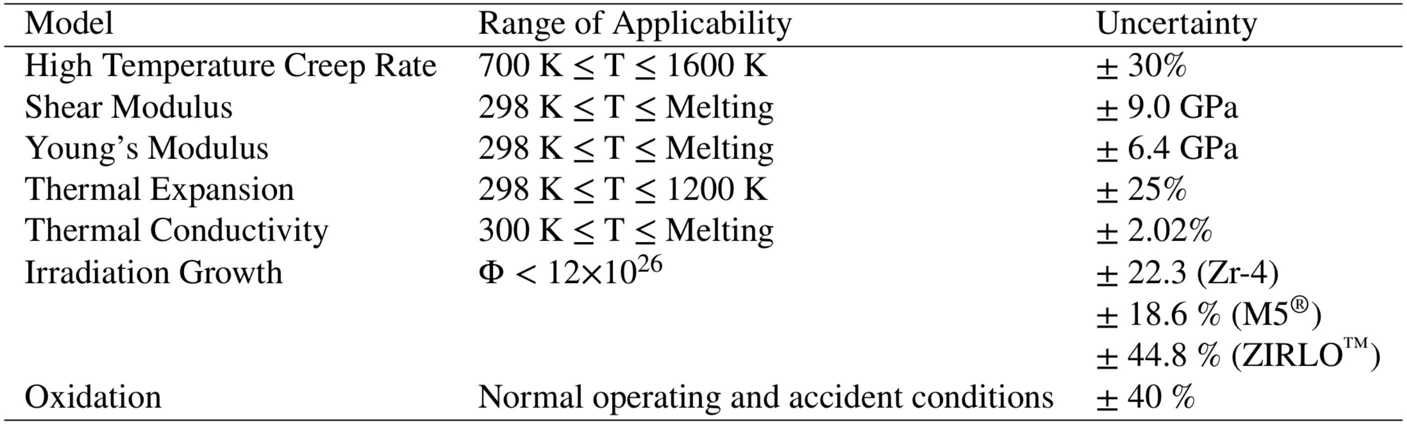
- Bison contains the following models for chromium:
  - Thermal Properties (temperature dependent)
  - Elasticity
    - Young’s Modulus (temperature dependent)
    - Poisson’s Ratio
  - Thermal Expansion
  - Thermal Creep
  - Instantaneous Plasticity
    - Irradiation Hardening
  - Oxidation

Chromium



Model	Range of Applicability	Uncertainty
Creep Rate	$0.51T_m$ to $0.78T_m$	± 20%
Poisson’s Ratio	$300\ K \leq T \leq 1300\ K$	± 15%
Young’s Modulus	$300\ K \leq T \leq 1300\ K$	± 10%
Thermal Expansion	$300\ K \leq T \leq 1300\ K$	± 10%
Thermal Conductivity	$300\ K \leq T \leq 1300\ K$	± 5%
Specific Heat	$300\ K \leq T \leq 1300\ K$	±10%
Yield Stress	$300\ K \leq T \leq 1500\ K$ $\Phi < 12\times10^{26}$	± 20%
Oxidation	Normal operating conditions	Factor of 2-4

Zirconium-based materials

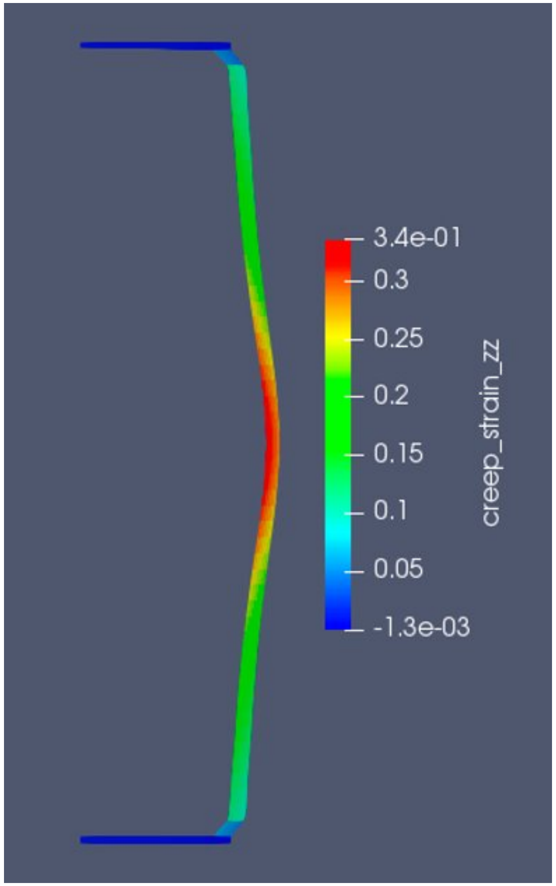


Model	Range of Applicability	Uncertainty
High Temperature Creep Rate	$700\ K \leq T \leq 1600\ K$	± 30%
Shear Modulus	$298\ K \leq T \leq$ Melting	± 9.0 GPa
Young’s Modulus	$298\ K \leq T \leq$ Melting	± 6.4 GPa
Thermal Expansion	$298\ K \leq T \leq 1200\ K$	± 25%
Thermal Conductivity	$300\ K \leq T \leq$ Melting	± 2.02%
Irradiation Growth	$\Phi < 12\times10^{26}$	± 22.3 (Zr-4) ± 18.6 % (M5®) ± 44.8 % (ZIRLO™)
Oxidation	Normal operating and accident conditions	± 40 %

Cr-coated Cladding: Assessment

- 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 than uncoated tubes.
  - 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
Fast Fluence (x10^{25} n/m^{2})	0, 2.5, 5

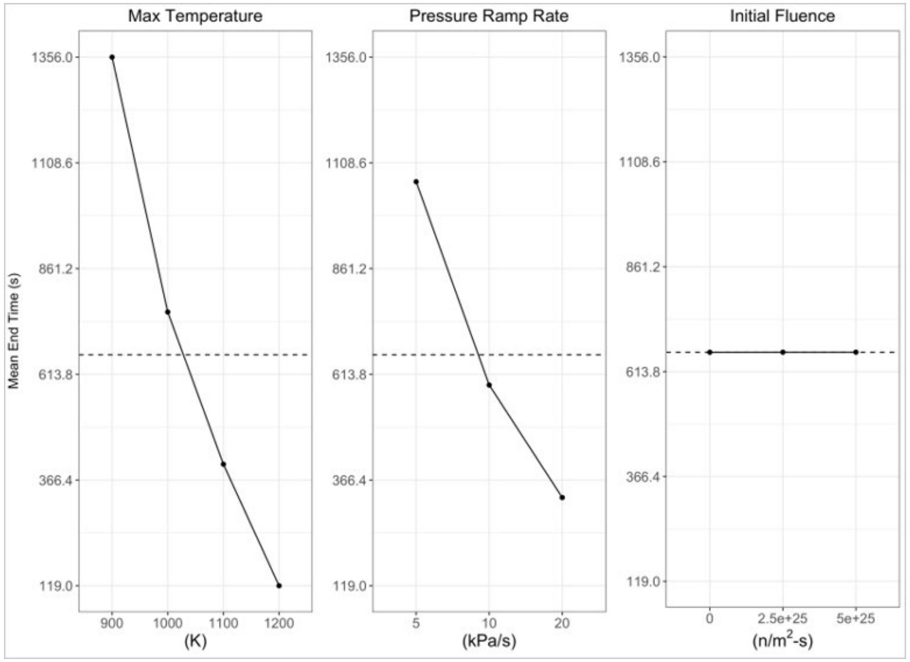


Creep strain at failure for one of the cases. Scaled axially by 0.1.

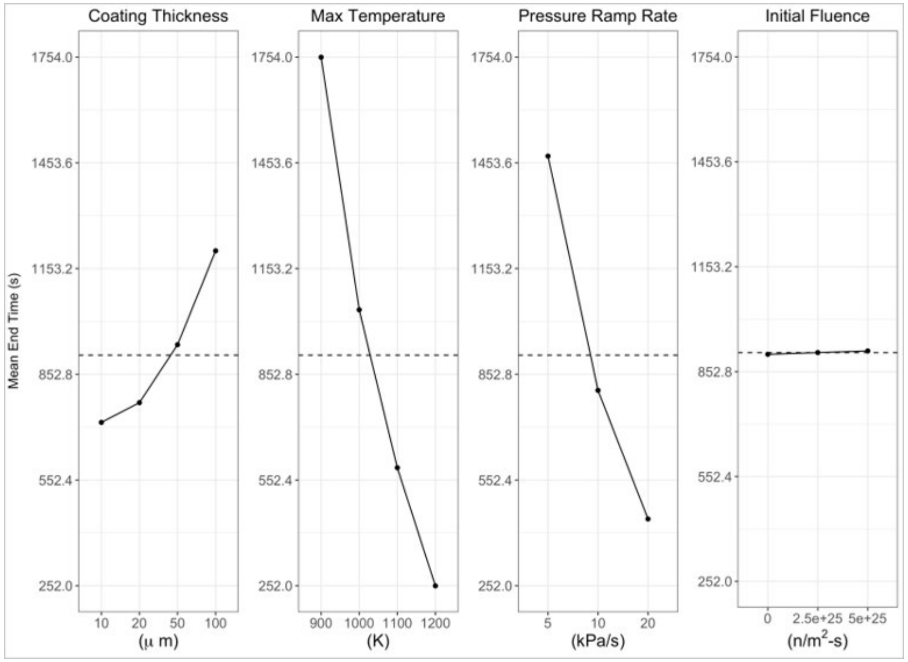
Cr-coated Cladding: Assessment

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

- Similar behavior observed for Zr-4 and M5® substrates.



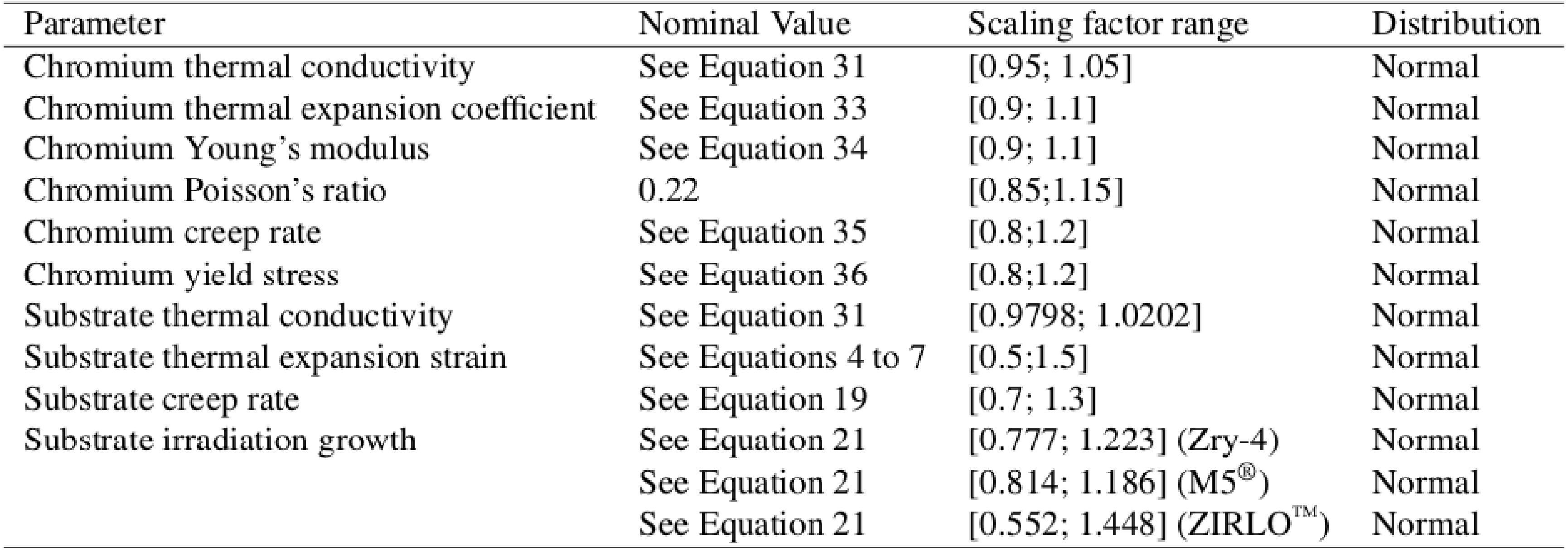
Uncoated Cases (36 total)



Coated Cases (144 total)

Cr-coated Cladding: SA and UQ

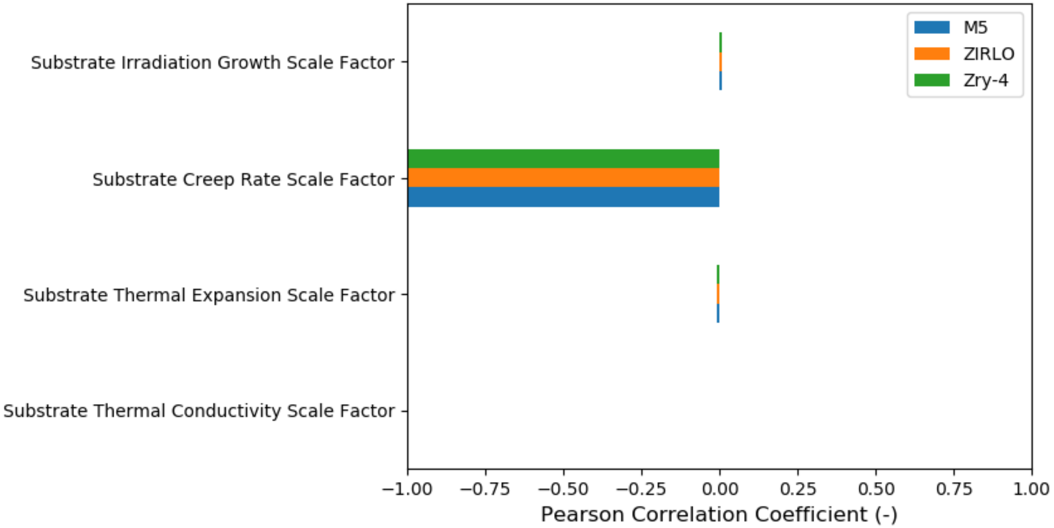
- Performed a sensitivity analysis and uncertainty quantification on one of the combinations from the parametric study:
  - Coating thickness: 20 m
  - Maximum clad temperature: 1000 K
  - Pressure ramping rate: 10 kPa/s
  - Initial fluence: 2.5e25 n/m^2

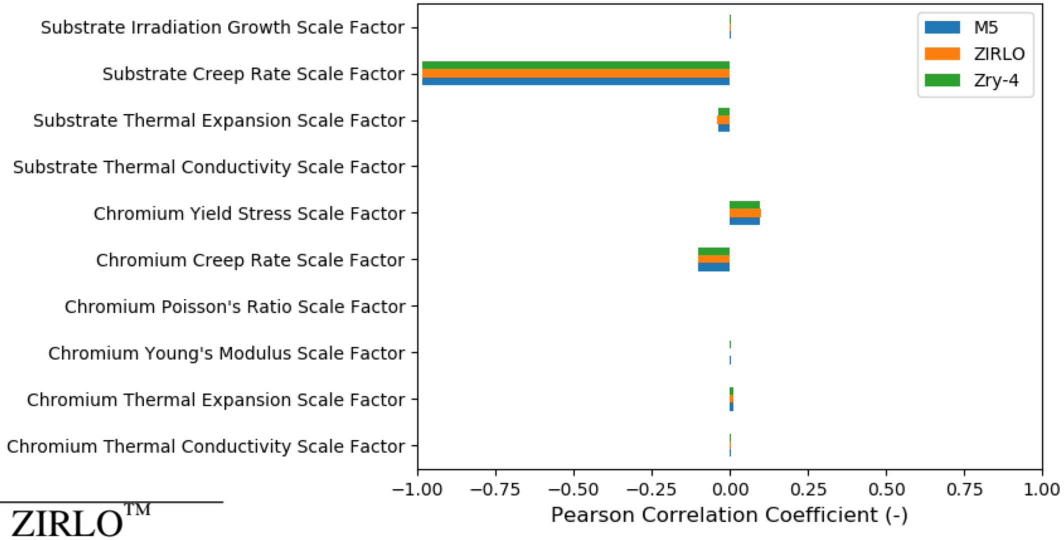


Parameter	Nominal Value	Scaling factor range	Distribution
Chromium thermal conductivity	See Equation 31	[0.95; 1.05]	Normal
Chromium thermal expansion coefficient	See Equation 33	[0.9; 1.1]	Normal
Chromium Young's modulus	See Equation 34	[0.9; 1.1]	Normal
Chromium Poisson's ratio	0.22	[0.85;1.15]	Normal
Chromium creep rate	See Equation 35	[0.8;1.2]	Normal
Chromium yield stress	See Equation 36	[0.8;1.2]	Normal
Substrate thermal conductivity	See Equation 31	[0.9798; 1.0202]	Normal
Substrate thermal expansion strain	See Equations 4 to 7	[0.5;1.5]	Normal
Substrate creep rate	See Equation 19	[0.7; 1.3]	Normal
Substrate irradiation growth	See Equation 21	[0.777; 1.223] (Zry-4)	Normal
	See Equation 21	[0.814; 1.186] (M5$^{®}$)	Normal
	See Equation 21	[0.552; 1.448] (ZIRLO^{TM})	Normal

Cr-coated Cladding: SA and UQ

- The creep rate of the substrate is the most important factor affecting time to failure.
- Minimal differences seen from one substrate to another.





Mean time to burst

	Zircaloy-4	M5®	ZIRLO™
Coated	790.12 ± 26.39	790.35 ± 26.40	789.96 ± 26.40
Uncoated	678.29 ± 26.65	678.55 ± 26.68	678.29 ± 26.65

FeCrAl: Material Models

- Bison contains the following models for FeCrAl (4 alloys*):
  - Thermal Properties
    - Thermal Conductivity
    - Specific Heat
  - Thermal Expansion
  - Elasticity
  - Thermal and Irradiation Creep (2 models)

- Thermal and Irradiation Creep (2 models)

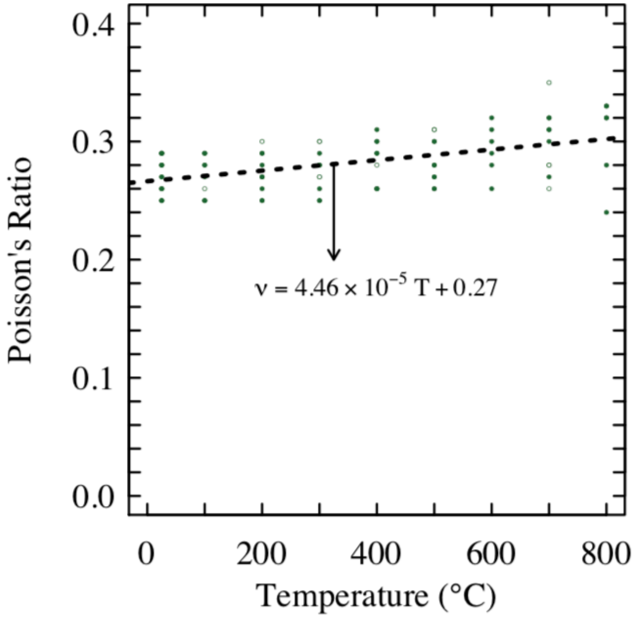
  - Irradiation Swelling
  - Instantaneous Plasticity
  - Failure
  - Tritium Permeability

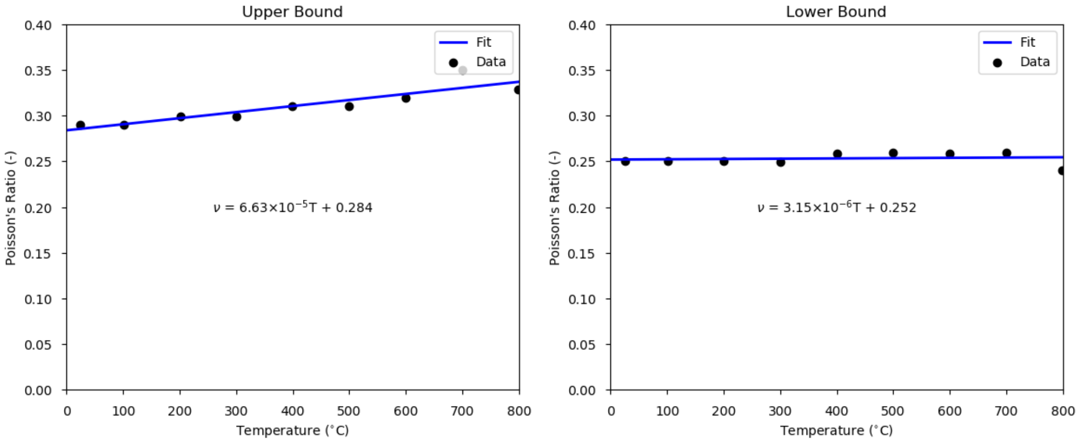
*APMT, C06M, C35M, C36M

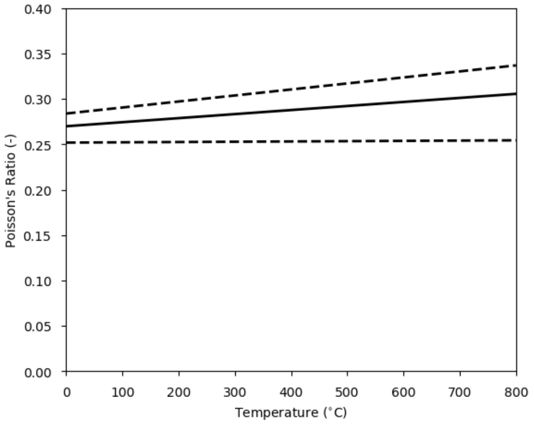
Model	Range of Applicability	Uncertainty
Failure (Burst Stress)	293 K ≤ T ≤ Melting	± 25%
Yield Stress	293 K ≤ T ≤ Melting	± 25%
Creep Rate	623 K ≤ T ≤ 1473 K	± 30%
Poisson's Ratio	298 K ≤ T ≤ 1123 K	± 20%
Young's Modulus	298 K ≤ T ≤ 1123 K	± 6%
Thermal Expansion	293 K ≤ T ≤ 1500 K	± 8%
Thermal Conductivity	300 K ≤ T ≤ 1400 K	± 7%
Specific Heat	298 K ≤ T ≤ 1400 K	± 10%
Irradiation Swelling	Normal operating conditions	0 to 0.05% per dpa
Tritium Permeability	623 K ≤ T ≤ 923 K	± 22.8% (Leading Coefficient) ± 8.1 % (Activation Energy)
Oxidation	Normal operating conditions	± 73 % (PWR) ± 77% (BWR)

FeCrAl: Material Models

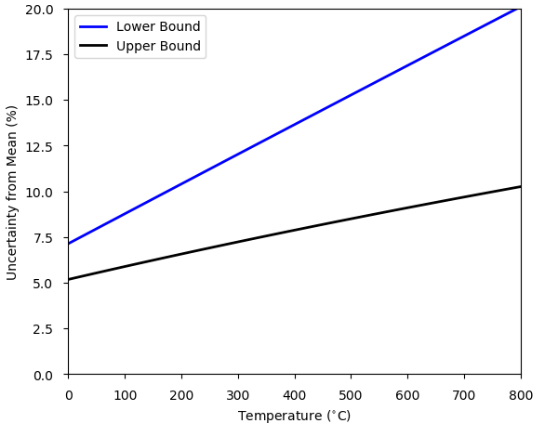
- Uncertainty in empirical models is based upon the data used to develop the models.







Uncertainty Bands



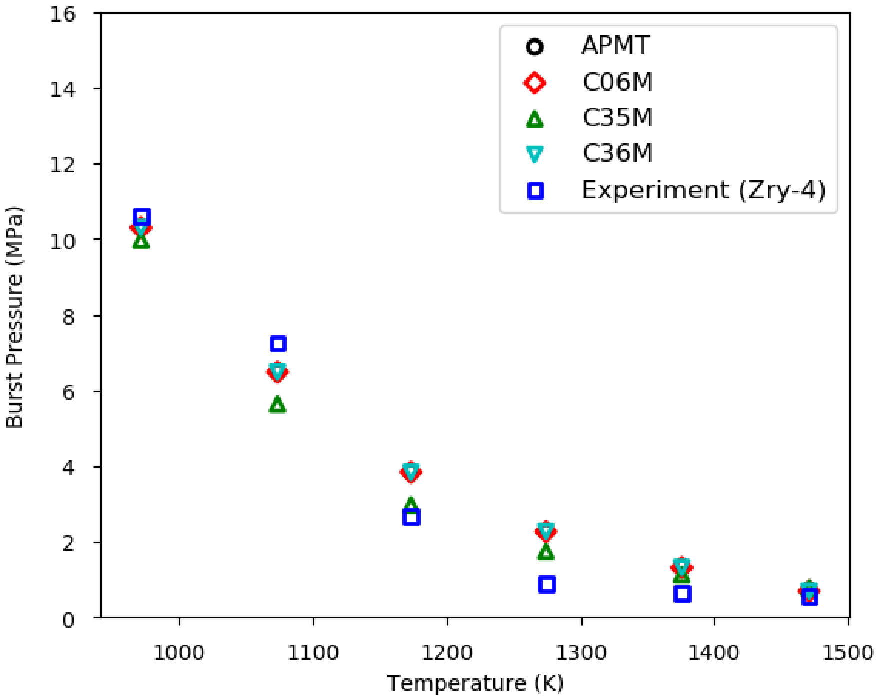
Percentage Uncertainty

FeCrAl: Assessment

- Revisited the PUZRY non-oxidizing burst experiments using the latest FeCrAl models for the alloys
- FeCrAl tube thickness assumed to be ~485 μm for this study.

Conditions of the selected PUZRY experiments

Rod Number	Temperature (K)	Pressure Ramp Rate (MPa/s)
8	1274.15	0.00763
10	1375.75	0.00710
12	1470.85	0.00723
18	1173.35	0.01151
26	971.55	0.01193
30	1073.55	0.02630



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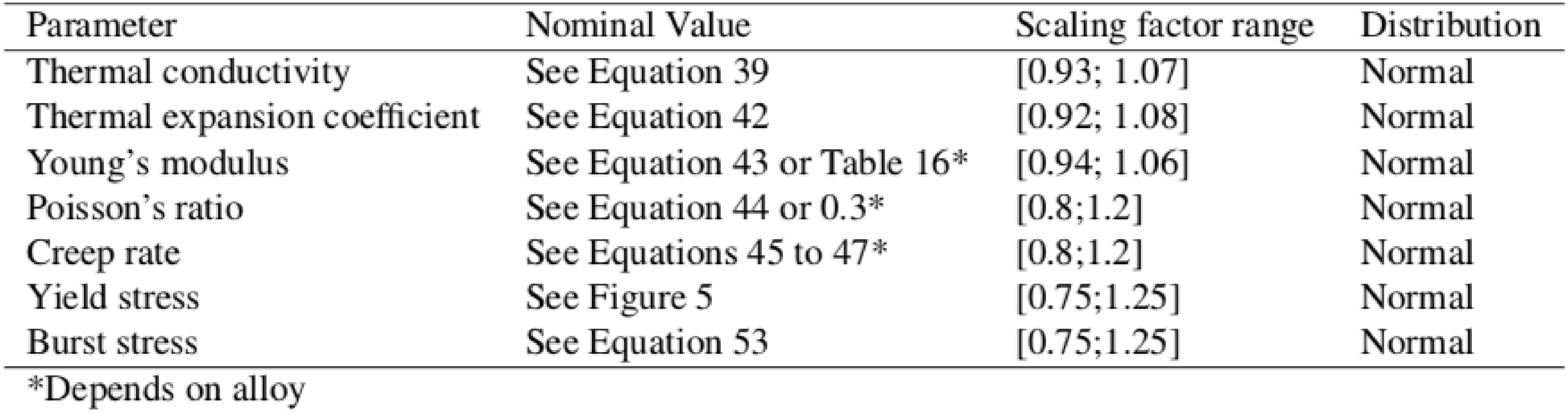
[1] Gamble et al., “An investigation of FeCrAl cladding behavior under normal operating and loss of coolant conditions,” JNM, 2017

FeCrAl: SA and UQ

- Performed a sensitivity analysis and uncertainty quantification on the PUZRY case 30 from the previous analysis.

- Two different studies completed
  - One with burst stress and one without

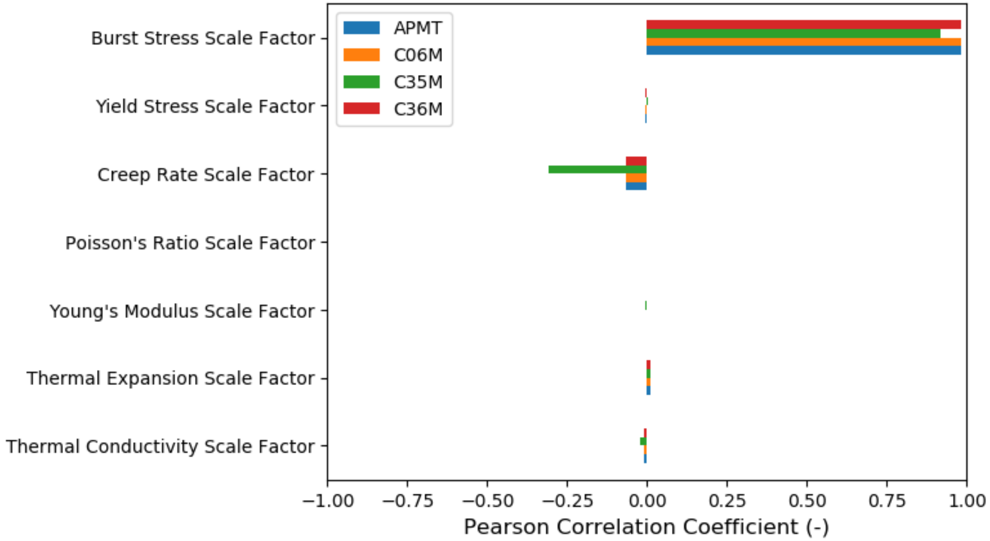


Parameter	Nominal Value	Scaling factor range	Distribution
Thermal conductivity	See Equation 39	[0.93; 1.07]	Normal
Thermal expansion coefficient	See Equation 42	[0.92; 1.08]	Normal
Young's modulus	See Equation 43 or Table 16*	[0.94; 1.06]	Normal
Poisson's ratio	See Equation 44 or 0.3*	[0.8;1.2]	Normal
Creep rate	See Equations 45 to 47*	[0.8;1.2]	Normal
Yield stress	See Figure 5	[0.75;1.25]	Normal
Burst stress	See Equation 53	[0.75;1.25]	Normal

*Depends on alloy

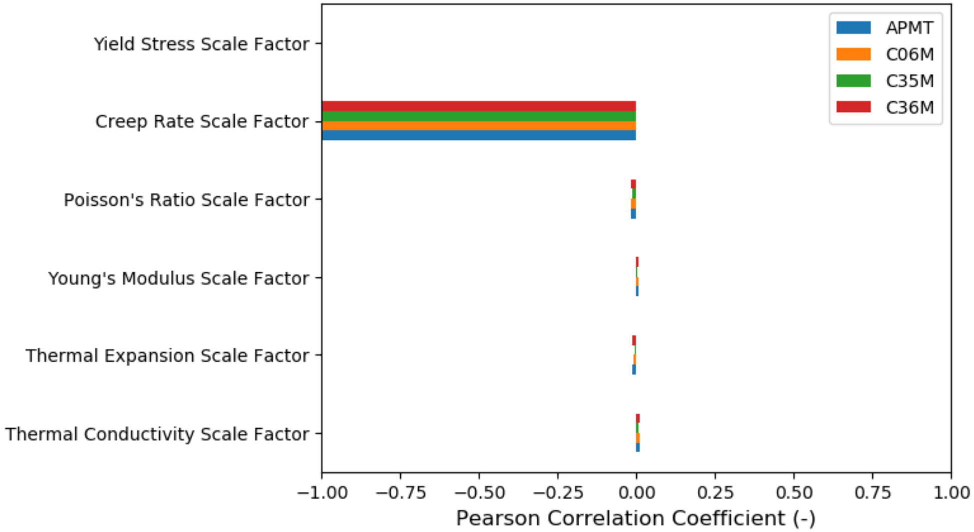
FeCrAl: SA and UQ

- The results indicate that the two most important parameters for FeCrAl cladding burst predictions is burst stress and the creep rate.



Burst stress case

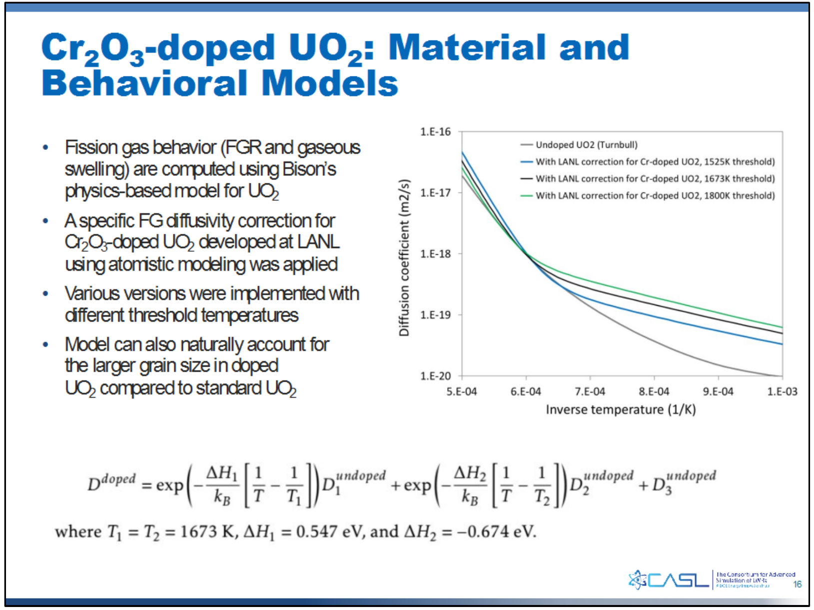
Alloy	Pressure at Burst (MPa)
APMT	6.412 ± 0.958
C06M	6.412 ± 0.958
C35M	5.601 ± 0.465
C36M	6.412 ± 0.958
Zircaloy-4 (Experiment)	7.251



No burst stress case

Alloy	Pressure at Burst (MPa)
APMT	6.492 ± 0.071
C06M	6.492 ± 0.071
C35M	5.646 ± 0.153
C36M	6.492 ± 0.071
Zircaloy-4 (Experiment)	7.251

Summary

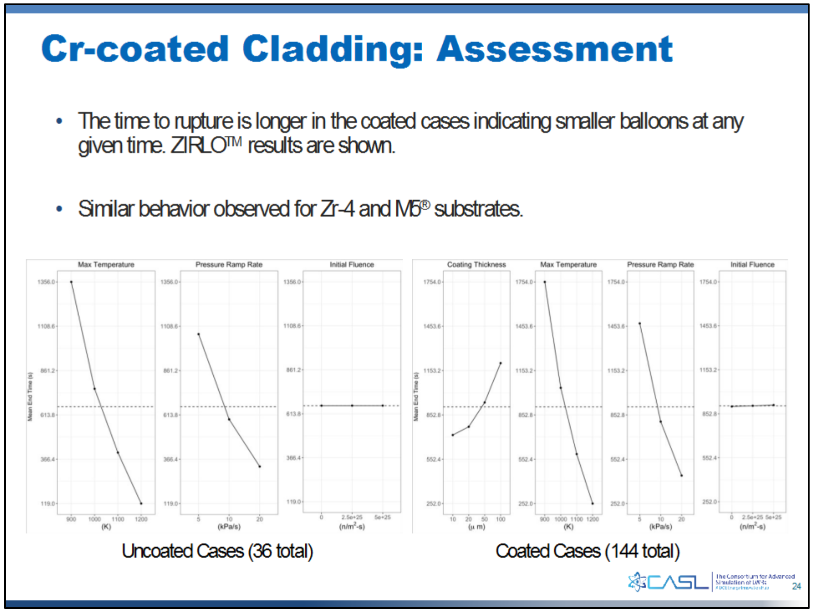


Cr_2O_3-doped UO_2: Material and Behavioral Models

- Fission gas behavior (FGR and gaseous swelling) are computed using Bison's physics-based model for UO_2
- A specific FG diffusivity correction for Cr_2O_3-doped UO_2 developed at LANL using atomistic modeling was applied
- Various versions were implemented with different threshold temperatures
- Model can also naturally account for the larger grain size in doped UO_2 compared to standard UO_2

$$D^{doped} = \exp\left(-\frac{\Delta H_1}{k_B}\left[\frac{1}{T}-\frac{1}{T_1}\right]\right)D_1^{undoped} + \exp\left(-\frac{\Delta H_2}{k_B}\left[\frac{1}{T}-\frac{1}{T_2}\right]\right)D_2^{undoped} + D_3^{undoped}$$

where $T_1 = T_2 = 1673$ K, $\Delta H_1 = 0.547$ eV, and $\Delta H_2 = -0.674$ eV.

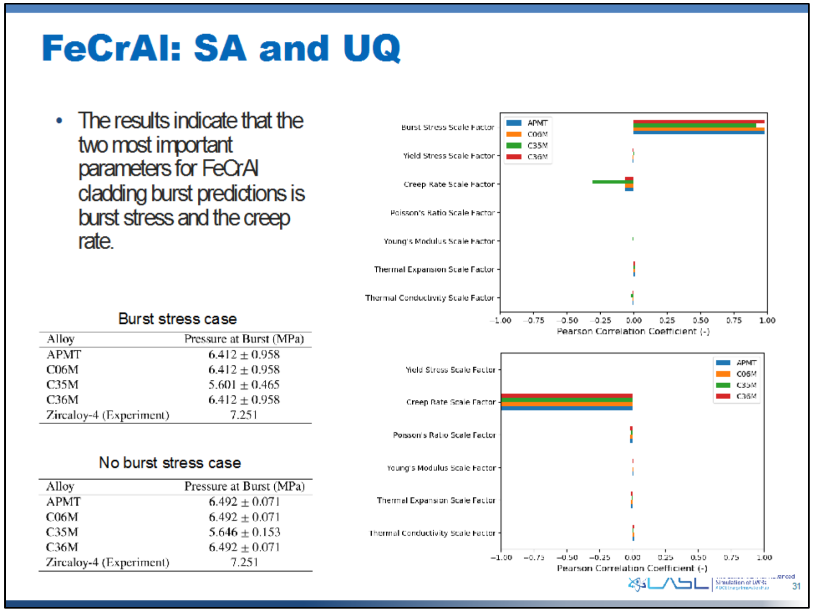


Cr-coated Cladding: Assessment

- The time to rupture is longer in the coated cases indicating smaller balloons at any given time. ZIRLO™ results are shown.
- Similar behavior observed for Zr-4 and M5® substrates.

Uncoated Cases (36 total)

Coated Cases (144 total)



FeCrAl: SA and UQ

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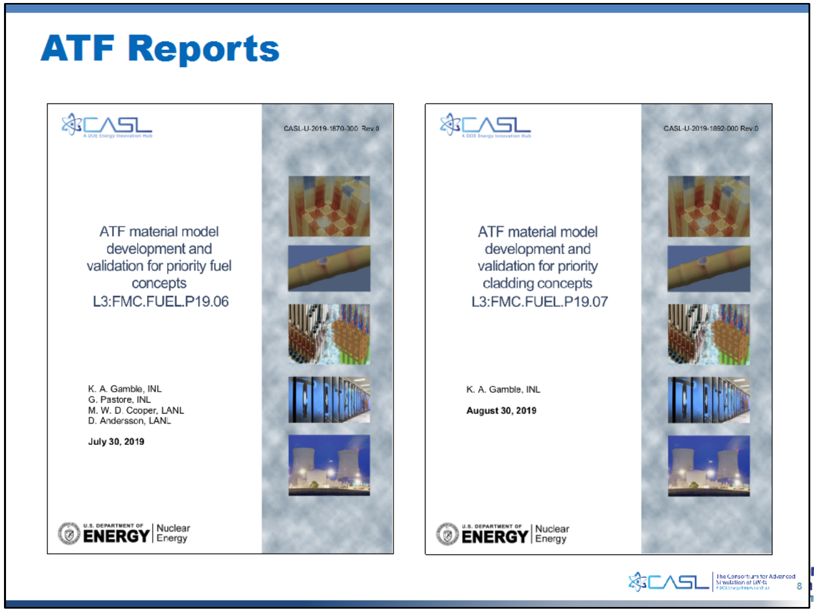

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K. A. Gamble, INL
G. Pastore, INL
M. W. D. Cooper, LANL
D. Andersson, LANL

July 30, 2019

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