Analysis of fuel rod behavior during design basis accidents using the BISON code

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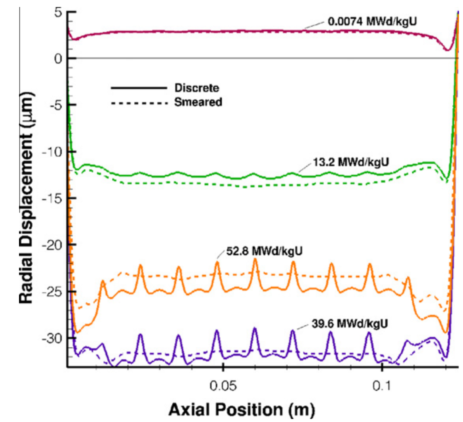
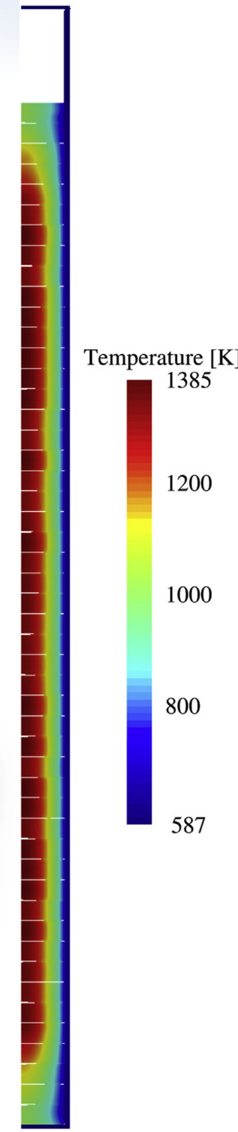
Outline

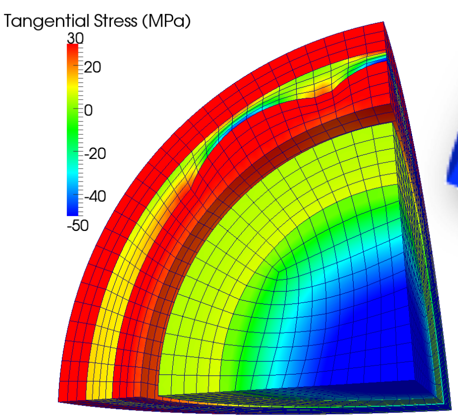
- BISON fuel performance code
- Examples of BISON LWR applications
- BISON models for design-basis accident analysis
  - Cladding high-temperature behavior
  - Fuel axial relocation, transient fission gas behavior
- LOCA simulations and comparisons to experiments
  - Cladding ballooning and burst tests
  - Halden integral fuel rod tests
- RIA simulations and comparisons to experiments
  - CABRI REP Na tests
- Summary
- Acknowledgments

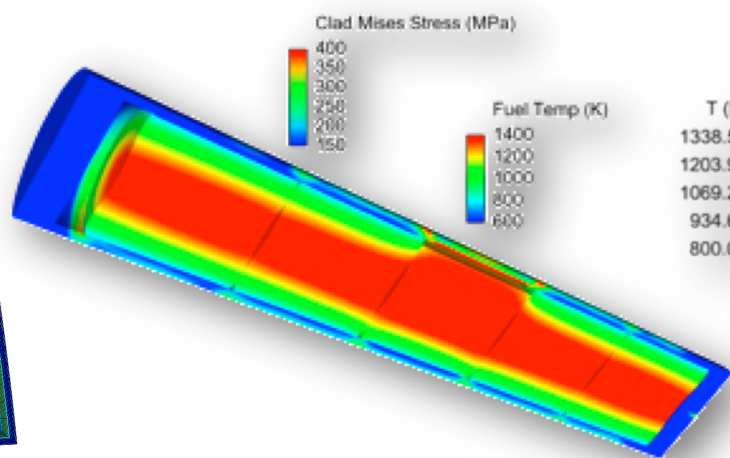
BISON fuel performance code

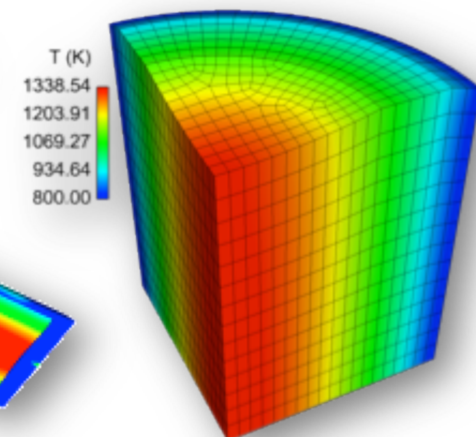
- Finite-element, engineering fuel performance code based on INL's open-source MOOSE framework
- Solution of fully-coupled thermo-mechanics equations in 1D, 2D axisymmetric or generalized plane-strain, or 3D
- Arbitrary geometry
- Used to analyze LWR, TRISO, and fast metal and oxide fuels
- Designed for efficient use on parallel computers







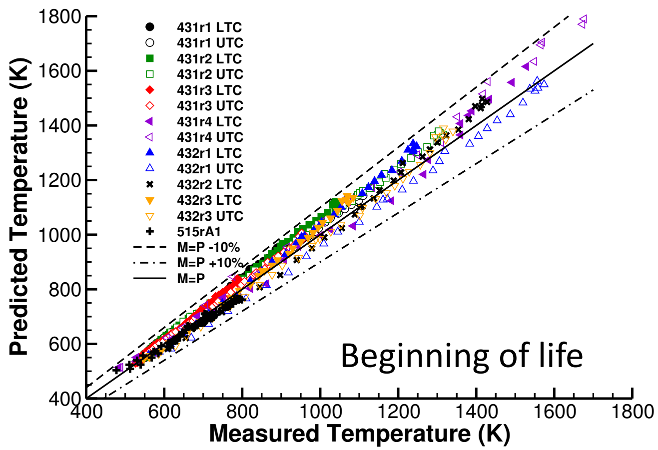


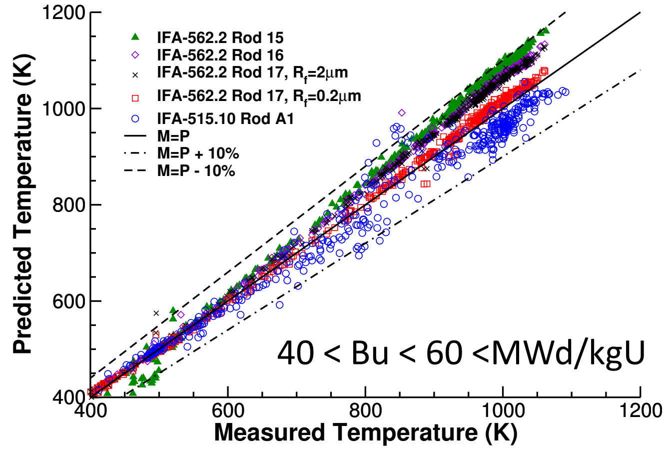


[1] R.L. Williamson et al., *Multidimensional multiphysics simulation of nuclear fuel behavior, J. Nucl. Mater. 423, 149, 2012*

[2] J.D. Hales et al., *Multidimensional multiphysics simulation of TRISO particle fuel, J. Nucl. Mater. 443, 531, 2013*

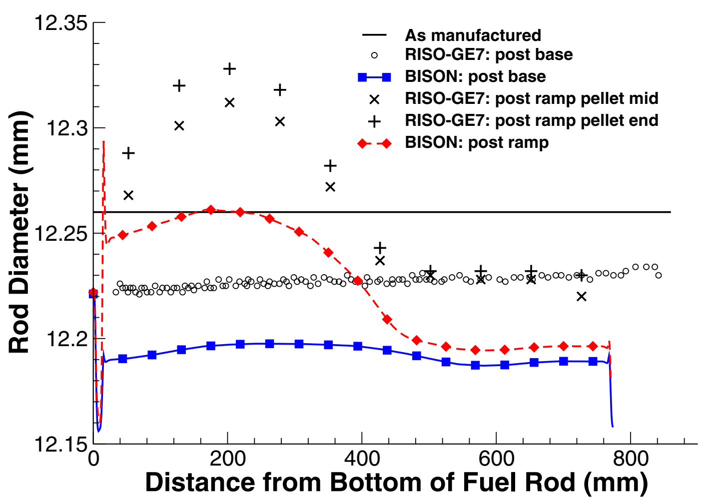
BISON LWR Validation





[3] R.L. Williamson et al., Validating the BISON fuel performance code to integral LWR experiments, Nucl. Eng. Des. 301, 232, 2016

BISON experimental comparisons of fuel centerline temperature for through-life rods for different burnup ranges[3]



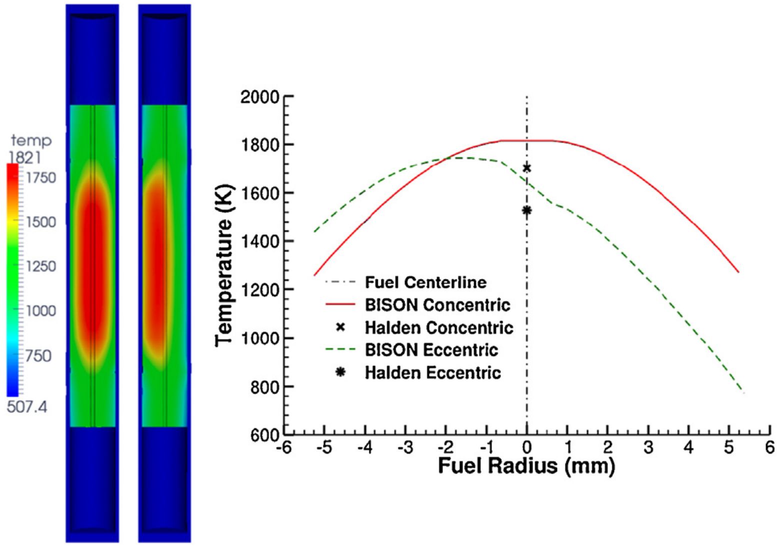
BISON experimental comparisons of cladding outer diameter for the Risø-3 GE7 test[3]

Experiment	Rod	Final Burnup (MWd/kgU)	FCT	FGR	Rod Dia	Refs.
IFA-431	1[a]	≈4	X			Hann et al. (1978)
IFA-431	2[a]	≈4	X			Hann et al. (1978)
IFA-431	3[a]	≈4	X			Hann et al. (1978)
IFA-431 (3D)	4[a]	≈4	X			Hann et al. (1978), Hales et al. (2013a)
IFA-432	1[a]	≈32	X			Hann et al. (1978), Sartori et al. (2010)
IFA-432	2[a]	≈32	X			Hann et al. (1978), Sartori et al. (2010)
IFA-432	3[a]	≈32	X			Hann et al. (1978), Sartori et al. (2010)
IFA-515.10	A1[b]	86.6	X			Tverberg and Amaya (2001)
IFA-534	18	59.0		X		Sartori et al. (2010)
IFA-534	19	59.0		X		Sartori et al. (2010)
IFA-535	809	54.4		X		Sartori et al. (2010)
IFA-535	810	54.4		X		Sartori et al. (2010)
IFA-562.2	15	56.7	X	X		Lösönen (1989)
IFA-562.2	16	56.2	X	X		Lösönen (1989)
IFA-562.2	17	56.2	X	X		Lösönen (1989)
IFA-597.3	8	68.1	X	X		Sartori et al. (2010)
Risø-2	GE-m	15.8		X	X	Sartori et al. (2010)
Risø-3	AN2	40.7		X	X	Sartori et al. (2010)
Risø-3	AN3	42.0	X	X		Sartori et al. (2010)
Risø-3	AN4	42.0	X	X		Sartori et al. (2010)
Risø-3	GE7	40.9		X	X	Sartori et al. (2010)
Risø-3	II3	17.6	X	X	X	Sartori et al. (2010)
Risø-3	II5	47.6	X	X	X	Sartori et al. (2010)
OSIRIS	H09	46.1		X	X	Sartori et al. (2010)
OSIRIS	J12	26.7		X	X	Sartori et al. (2010)
REGATE		47.0		X	X	Sartori et al. (2010)
USPWR 16x16	TSQ002	53.2		X	X	Sartori et al. (2010)
USPWR 16x16	TSQ022	58.1		X	X	Sartori et al. (2010)
R.E. Ginna	2	51.2		X	X	Sartori et al. (2010)
R.E. Ginna	4	57.0		X	X	Sartori et al. (2010)
HBEP	BK363	76.0		X		IAEA (2012)
HBEP	BK365	78.3		X		IAEA (2012)
Tribulation	BN1/3	50.7		X	X	Sartori et al. (2010)
Tribulation	BN1/4	50.6		X	X	Sartori et al. (2010)
Tribulation	BN3/15	51.1		X	X	Sartori et al. (2010)

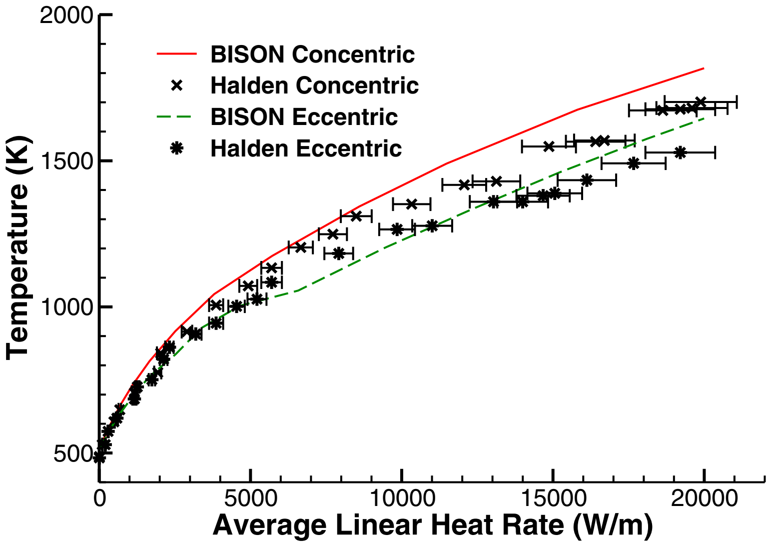
BISON validation database for normal operating conditions and power ramps[3]

BISON LWR Validation

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



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

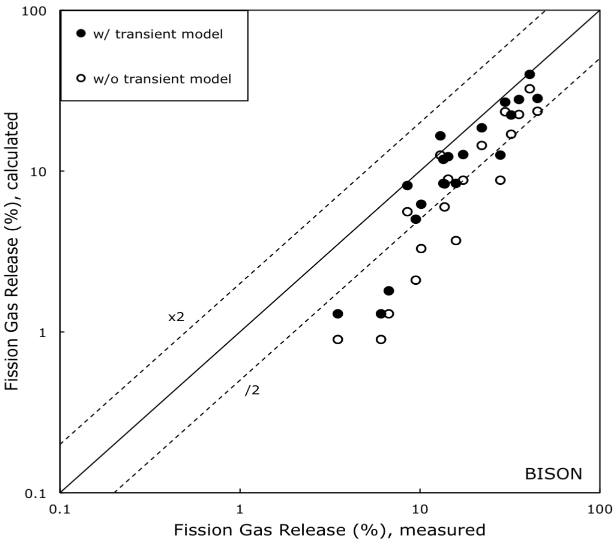


BISON fuel temperature results and experimental data for the concentric and eccentric pellets cases

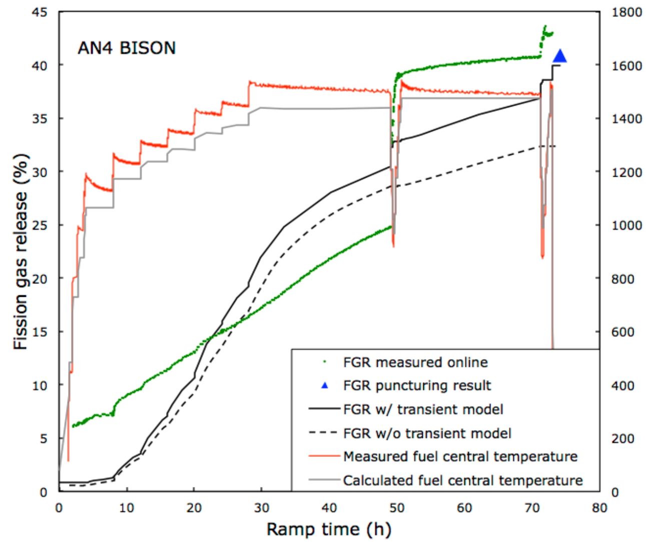
[3] *R.L. Williamson et al., Validating the BISON fuel performance code to integral LWR experiments, Nucl. Eng. Des. 301, 232, 2016*

BISON LWR Validation

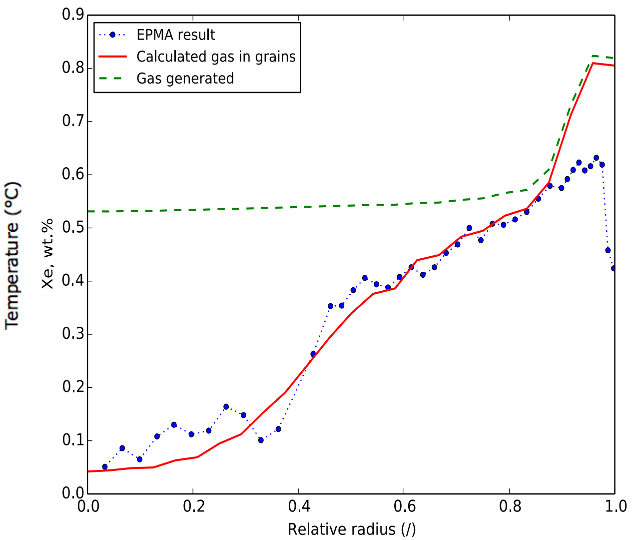
Physically based fission gas release and swelling model with diffusional mechanisms plus burst release during transients[4,5]



Integral FGR at EOL for 19 LWR fuel rod power ramp experiments



Integral FGR vs time during LWR fuel rod power ramp experiment Risø-3 AN4



Radial profile of Xe concentration at EOL for Risø-3 AN8 and PIE data

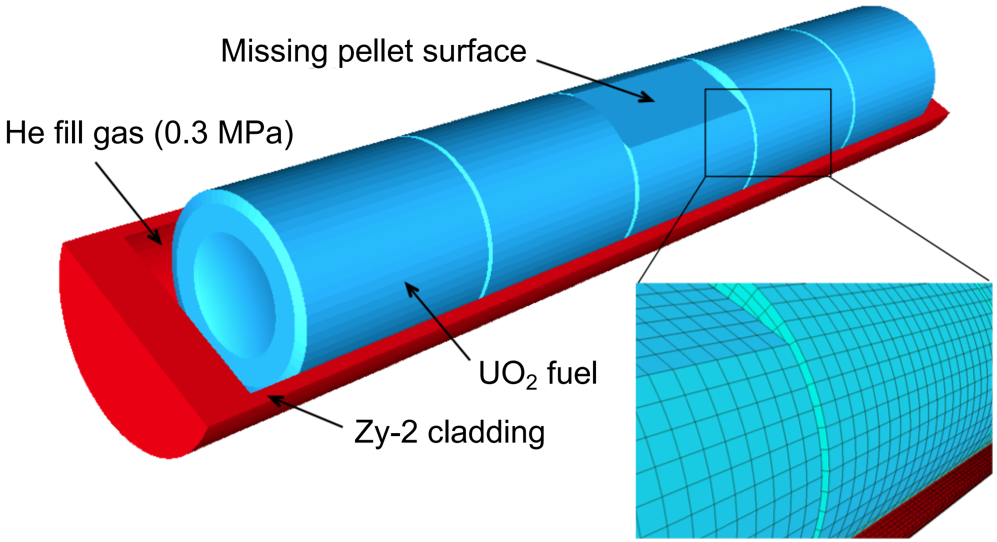
Collaboration with POLIMI and JRC Karlsruhe

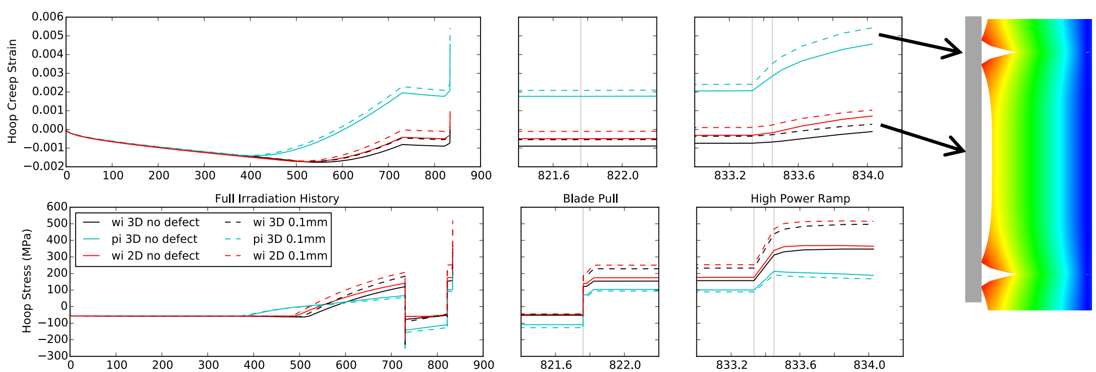
[4] *G. Pastore, L.P. Swiler, J.D. Hales, S.R. Novascone, D.M. Perez, B.W. Spencer, L. Luzzi, P. Van Uffelen, R.L. Williamson Uncertainty and sensitivity analysis of fission gas behavior in engineering-scale fuel modeling, J. Nucl. Mater. 456, 398, 2015*

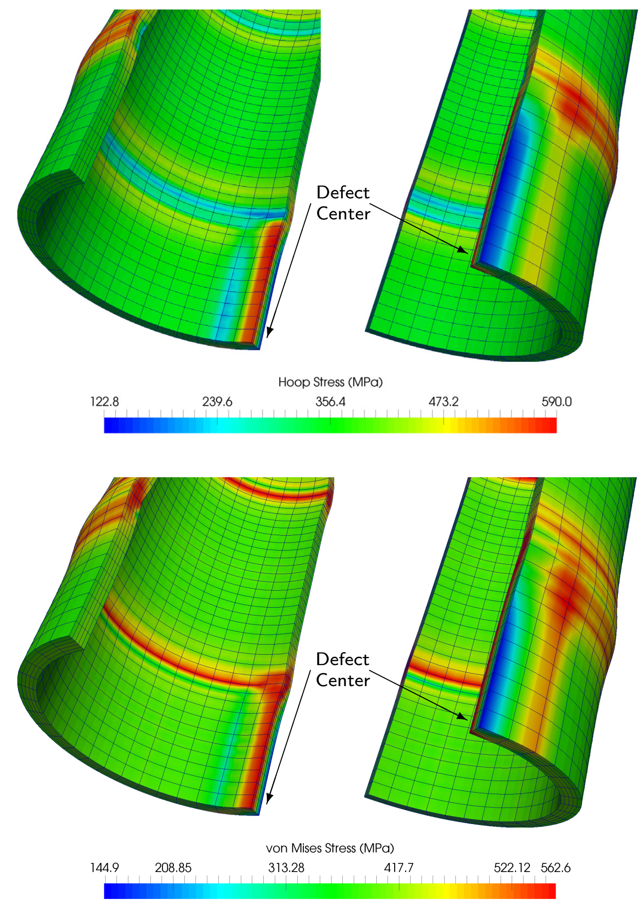
[5] *T. Barani, E. Bruschi, D. Pizzocri, G. Pastore, P. Van Uffelen, R.L. Williamson, L. Luzzi, Analysis of transient fission gas behaviour in oxide fuel using BISON and TRANSURANUS, J. Nucl. Mater. 486, 96, 2017*

Multidimensional analysis of MPS defects

- Analyzing the thermo-mechanical response of a BWR fuel rod subject to transient events in presence of a 0.1 mm deep missing pellet surface (MPS)[6]



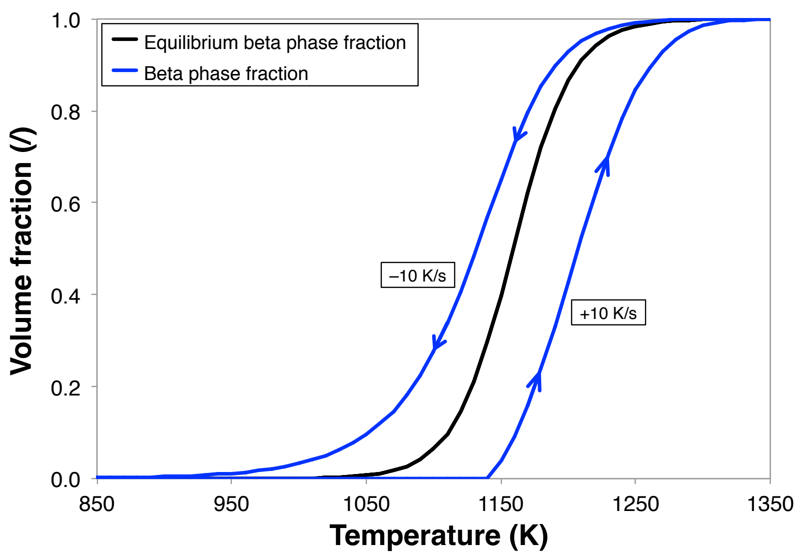


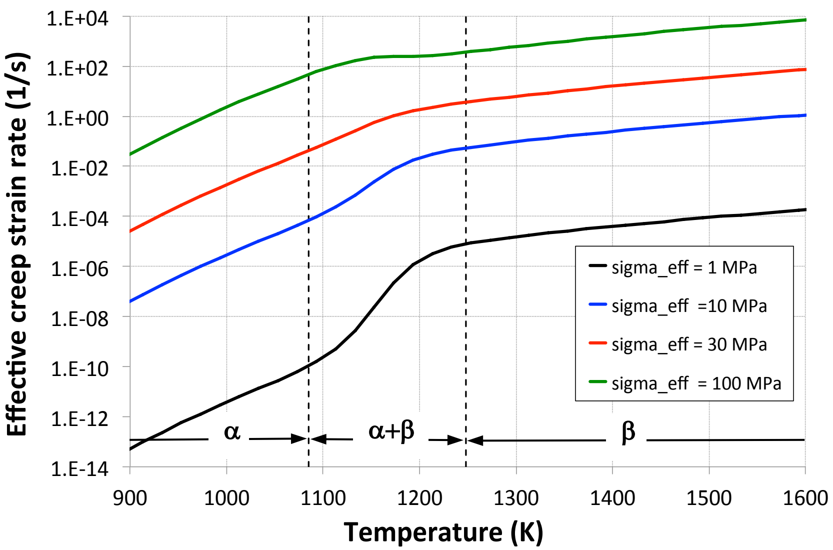


[6] *B.W. Spencer, R.L. Williamson, D.S. Stafford, S.R. Novascone, J.D. Hales, G. Pastore, Nucl. Eng. Des. 307, 155-171, 2016*

Cladding high-temperature models

- Zircaloy oxidation with Leistikov[7] (673K<T<1800K) and Prater-Courtright[8] (T>1900) correlations
- Crystallographic phase transition of Zircaloy[9]
- High-temperature creep of Zircaloy[10]
- Burst failure criteria including overstress[10], plastic instability and overstrain[11]



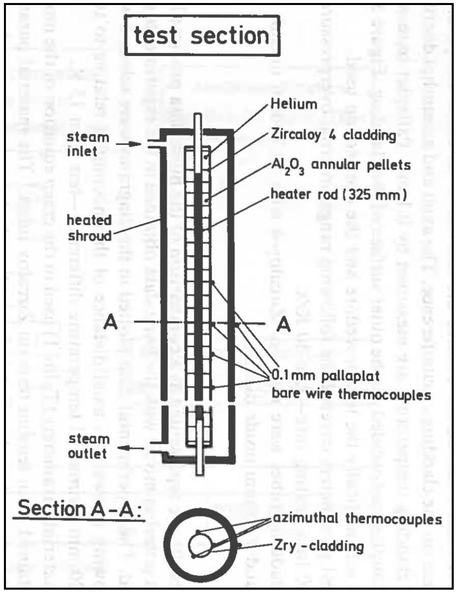


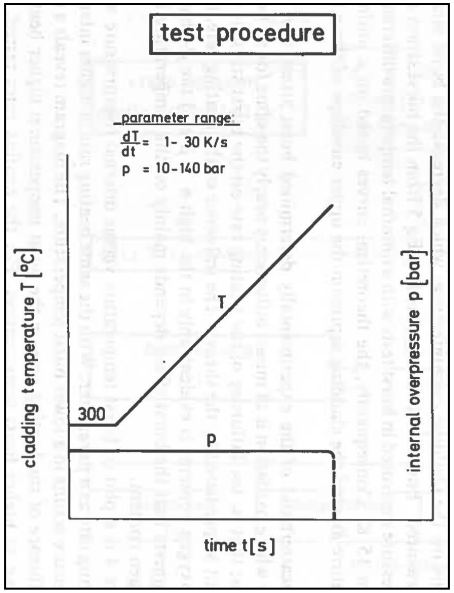
Calculated volume fraction of β phase (left) and effective creep rates (right) as a function of temperature

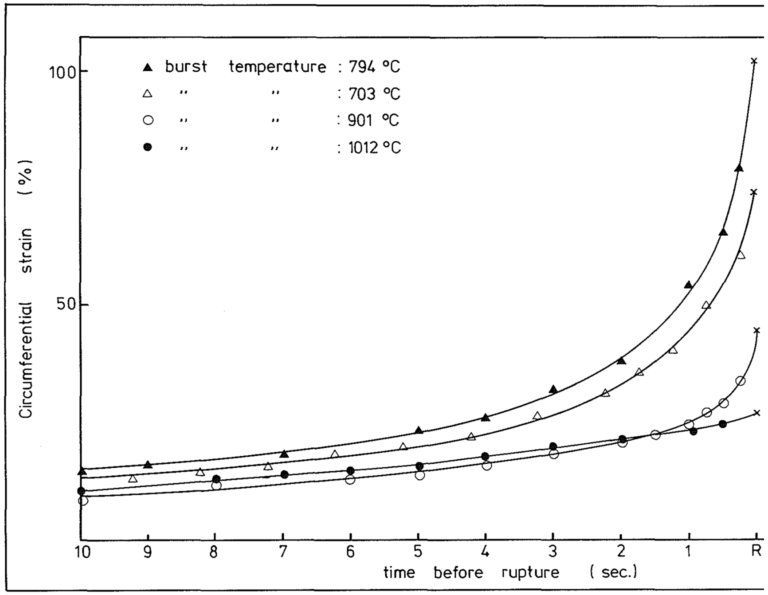
[7] *S. Leistikow et al., CSNI/IAEA specialists meeting on water reactor fuel safety and fission product release in off-normal and accident conditions, 1983*
[8] *J.T. Prater, E.L. Courtright, Zircaloy-4 oxidation at 1300 to 2400 C, NUREG/CR-4889, PNL-6166, Pacific Northwest National Laboratory, USA, 1987*
[9] *A.R. Massih, Transformation kinetics of zirconium alloys under non-isothermal conditions, J. Nucl. Mater. 384, 330, 2009*
[10] *F. Erbacher et al., Burst criterion of Zircaloy fuel claddings in a loss-of-coolant accident, Zirconium in the Nuclear Industry, 5th Conference, 1982*
[11] *V. Di Marcello, A. Schubert, J. van de Laar, P. Van Uffelen, The TRANSURANUS mechanical model for large strain analysis, Nucl. Eng. Des 276, 19, 2014*

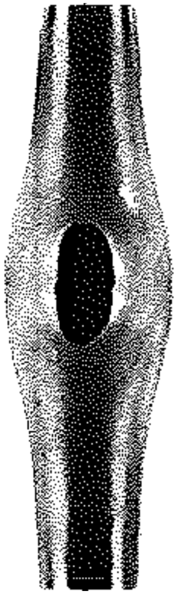
Ballooning and burst tests REBEKA

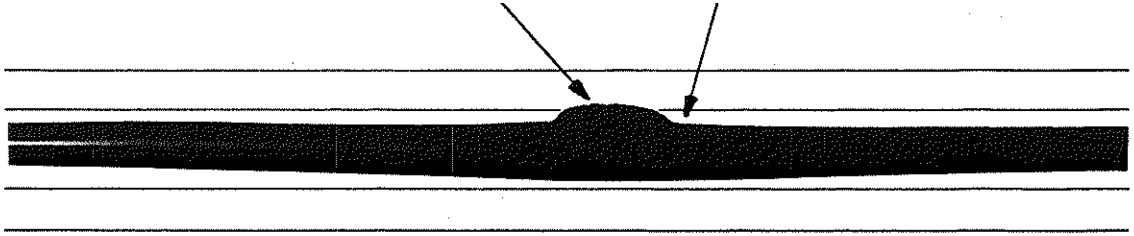
- Temperature transient tests in steam on PWR-size Zircaloy-4 tubes at various internal pressures[12,13]

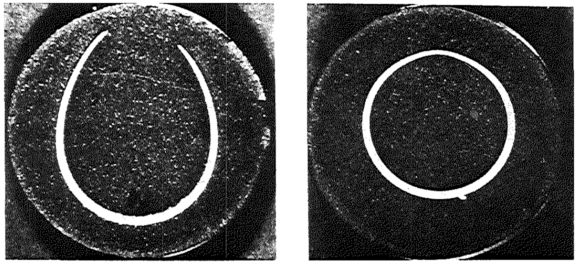










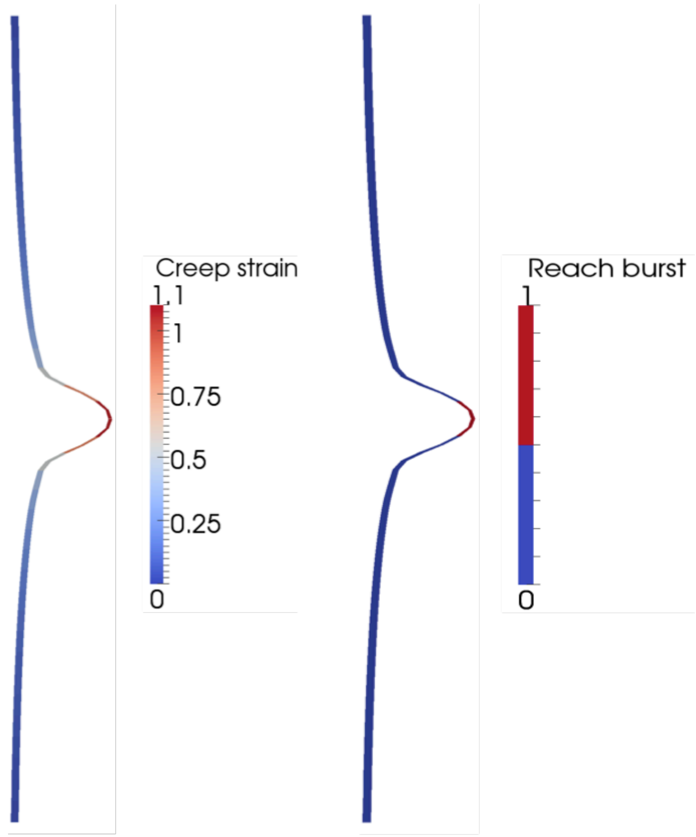


[12] *M.E. Markiewicz and F.J. Erbacher.,. Tech. Rep. KfK 4343, Kernforschungszentrum Karlsruhe, Germany, 1988*

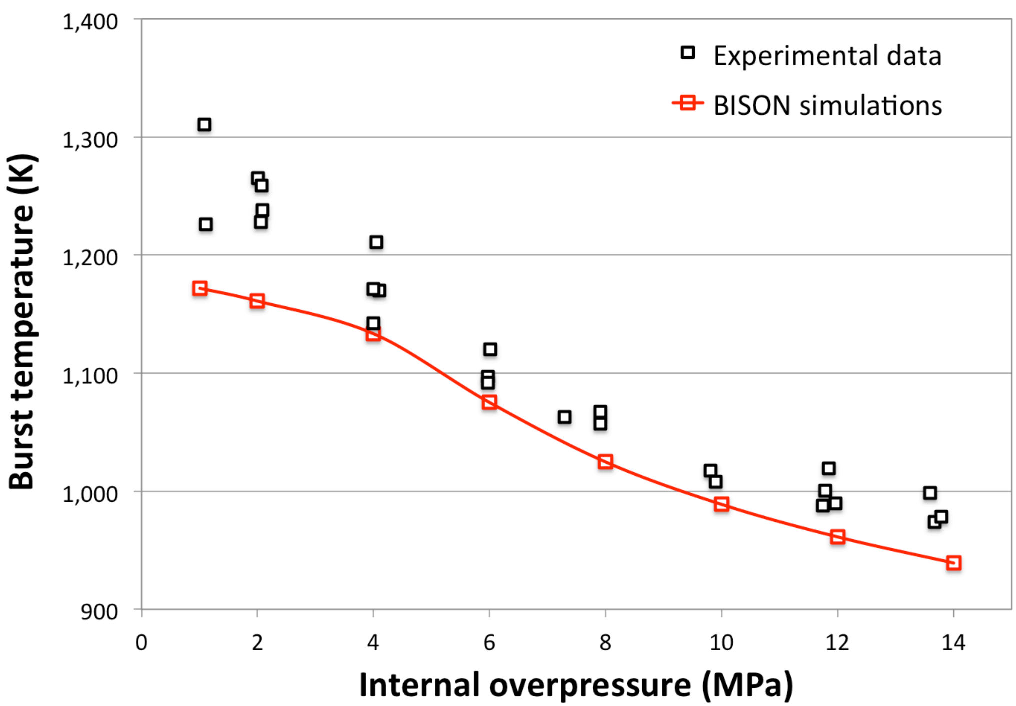
[13] *F. Erbacher, H. Neitzel, K. Wiehr, Tech. Rep. KfK 4781, Kernforschungszentrum Karlsruhe, Germany, 1990*

Ballooning and burst tests REBEKA

BISON 2D simulations of the REBEKA cases with 1 K/s heating rate



Scaled 4x in the radial direction for visualization

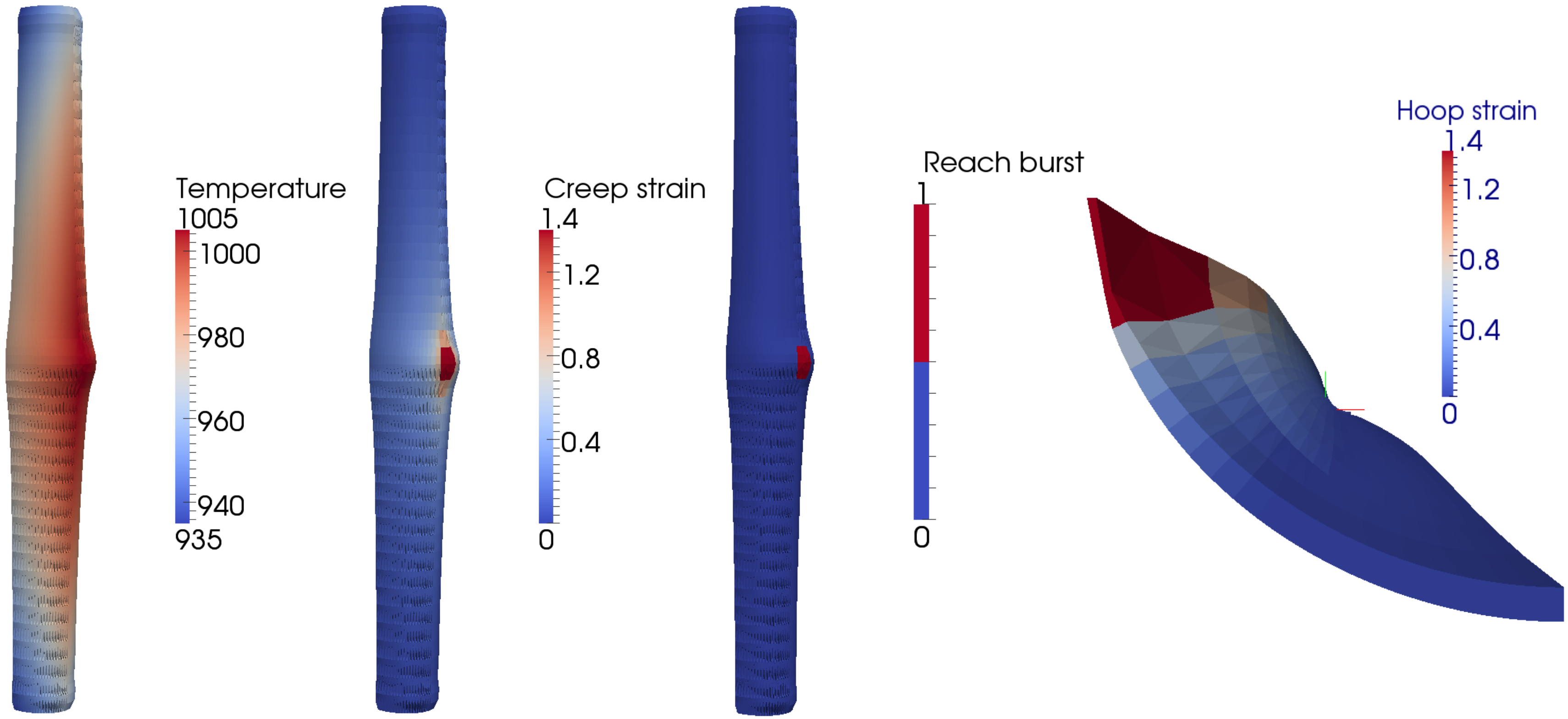


Comparisons of BISON predictions to experimental data of cladding burst temperature for the REBEKA tests

[14] *G. Pastore S.R. Novascone, R.L. Williamson, J.D. Hales, B.W. Spencer, D.S. Stafford, Modeling of Fuel Behavior during Loss-of-Coolant Accidents using the BISON Code, Proc. of Top Fuel, Zurich, Switzerland, September 13-17, 2015*

Ballooning and burst tests REBEKA

BISON 3D analysis demonstration with azimuthal temperature variation of 30 K [14]

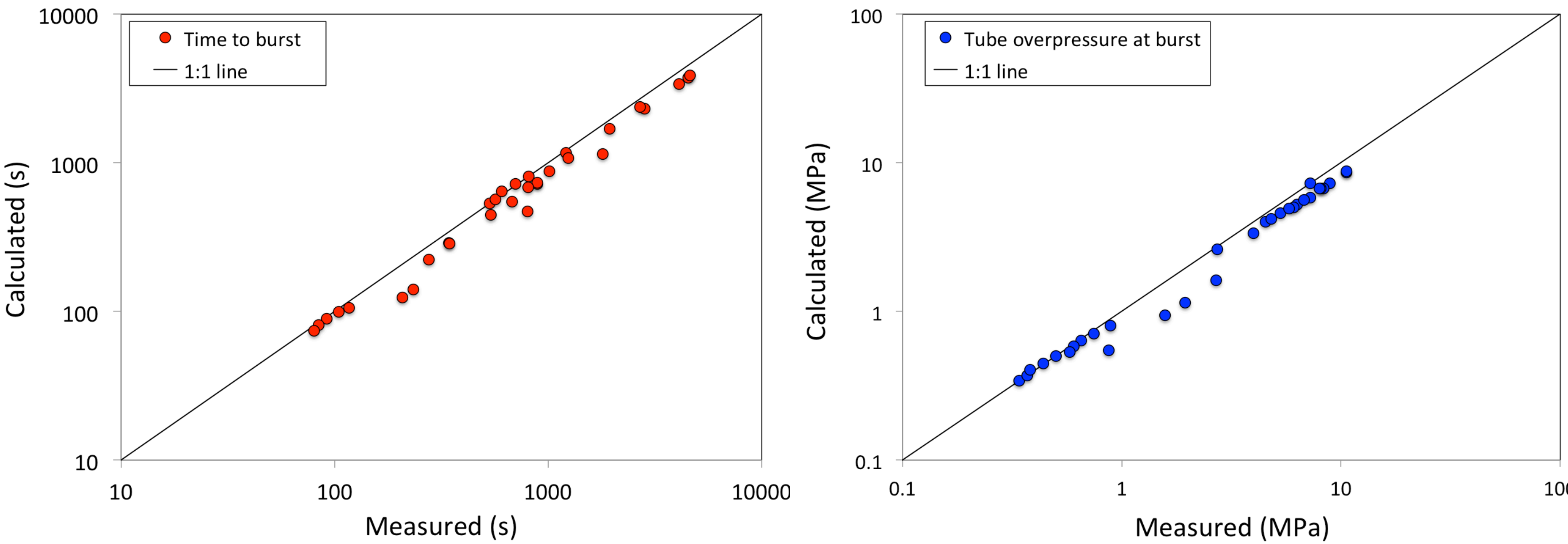


Scaled 3x in the radial direction for visualization

[14] *G. Pastore S.R. Novascone, R.L. Williamson, J.D. Hales, B.W. Spencer, D.S. Stafford, Modeling of Fuel Behavior during Loss-of-Coolant Accidents using the BISON Code, Proc. of Top Fuel, Zurich, Switzerland, September 13-17, 2015*

Ballooning and burst tests PUZRY

- Tests performed at MTA-EK[15] on Zircaloy-4 cladding tubes under isothermal conditions in the temperature range of 973-1473 K
- 2D BISON simulations were performed for all of the 31 PUZRY cladding tests

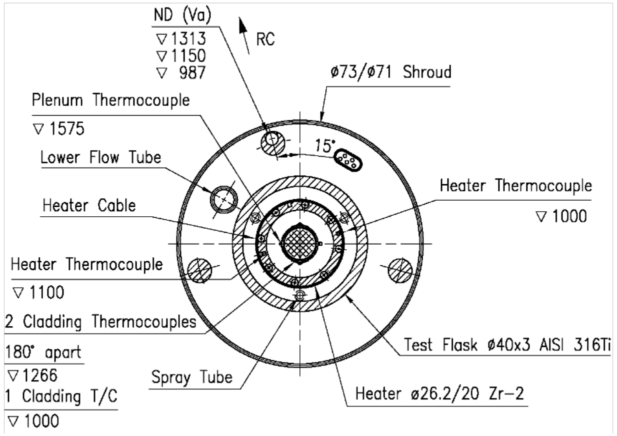


Comparisons of BISON predictions to experimental data for time to cladding burst (left) and burst pressure (right). Each symbol corresponds to a BISON simulation of one of the 31 PUZRY tests.

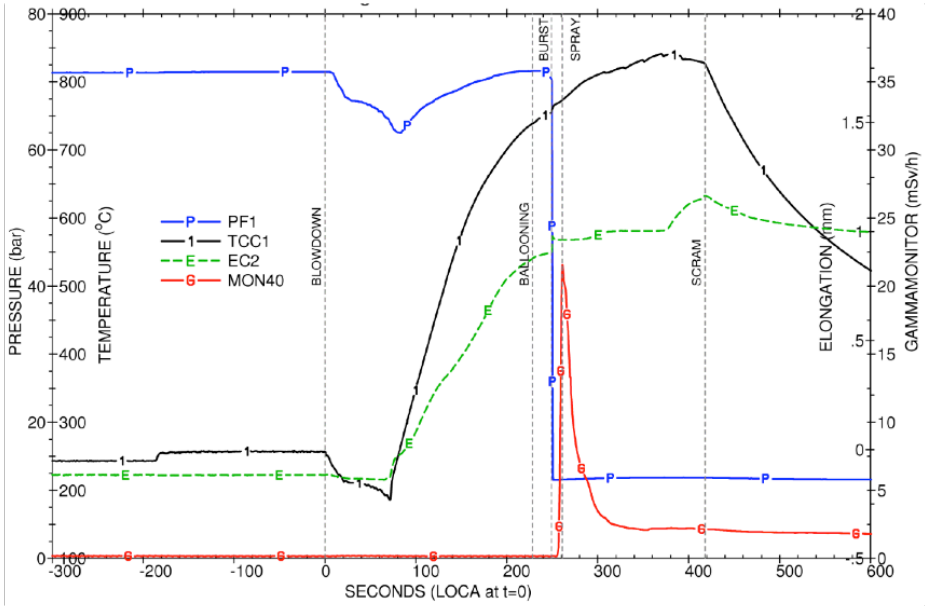
[15] E. Perez-Feró et al., Tech. Rep. EK-FRL-2012-255-01/02, Center for Energy Research, Hungarian Academy of Sciences, Budapest, Hungary, 2013

Halden integral LOCA test IFA-650.10

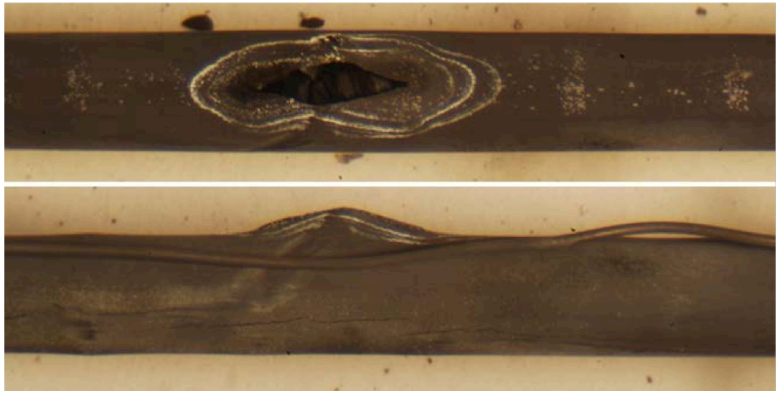
- Tenth Halden LOCA test[16]
- PWR fuel rod pre-irradiated to 61 MWd/kgU
- Modest ballooning, negligible fuel axial relocation
- 2D BISON simulation was performed



Cross sectional geometry of the IFA-650.10 test rig



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

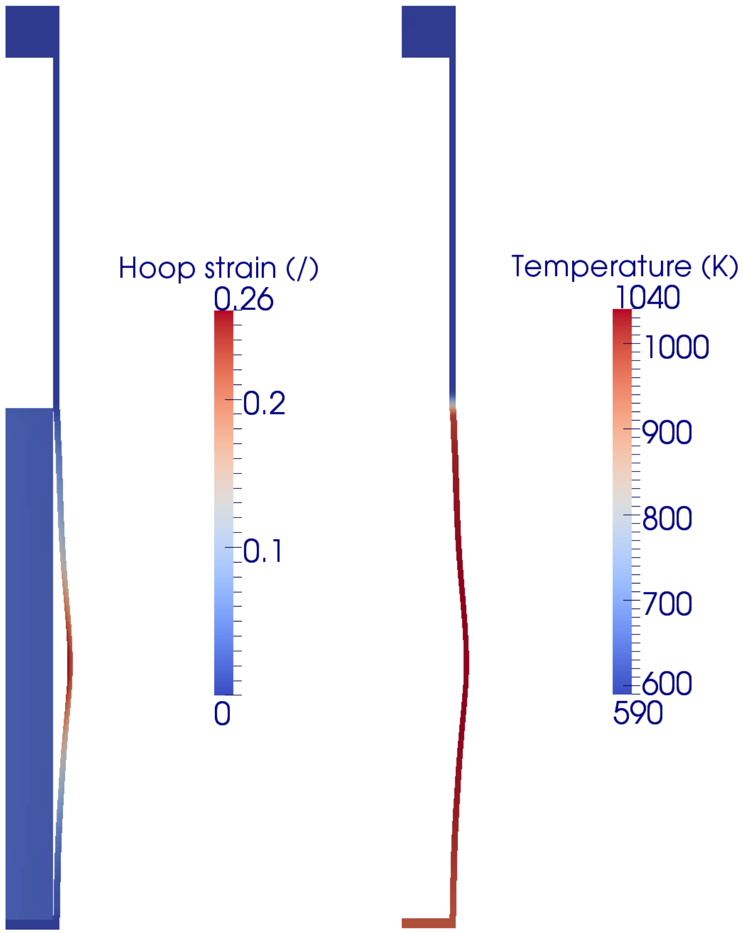


Post-test visual inspection for IFA-650.10 showing burst opening at two orthogonal orientations

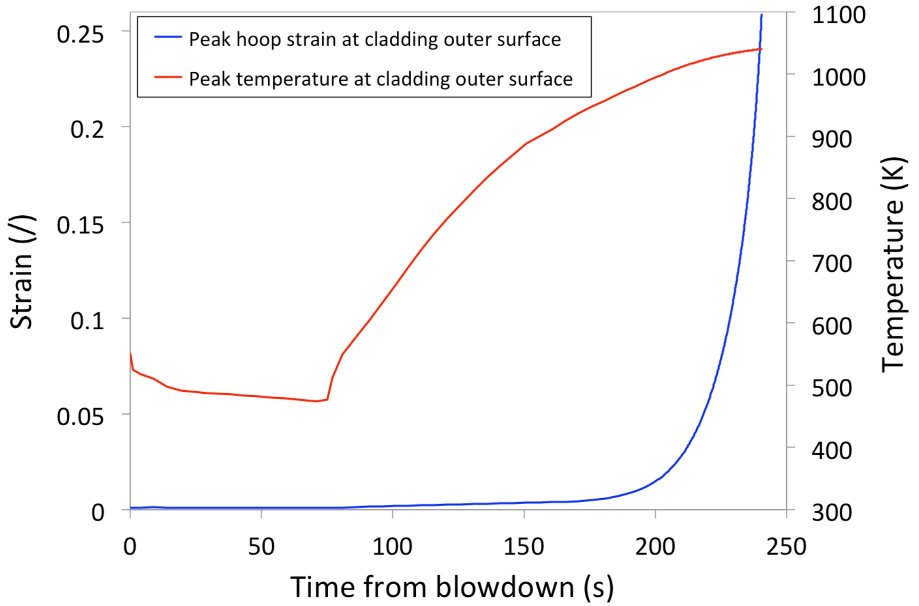
[16] *A. Lavoil, LOCA Testing at Halden; The Tenth Experiment IFA-650.10, Technical Report HWR-974, OECD Halden Reactor Project, 2010*

Halden integral LOCA test IFA-650.10

- Cladding ballooning due to high-temperature creep is reproduced



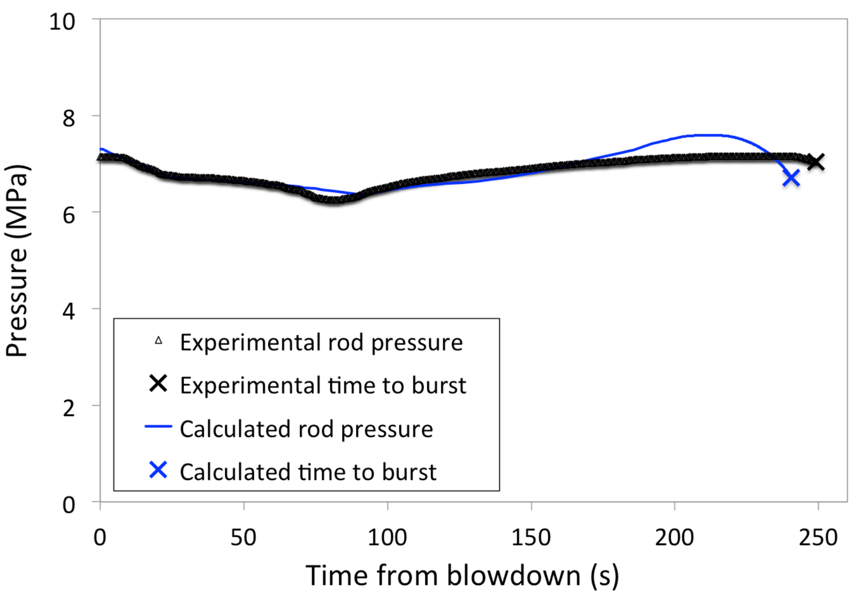
Contour plots for hoop strain (left) and cladding temperature (right) at the time of burst failure



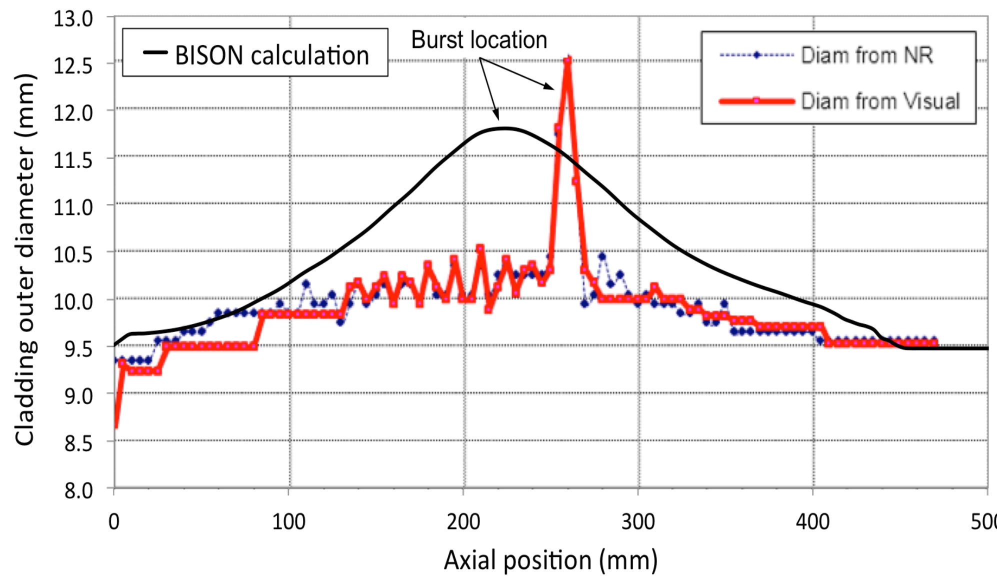
Hoop strain and cladding temperature at peak axial position during the post-blowdown period

Halden integral LOCA test IFA-650.10

- Predicted time to burst is ~240.5 s after blowdown (experimental ~249 s)
- Cladding diametral strain is overpredicted significantly



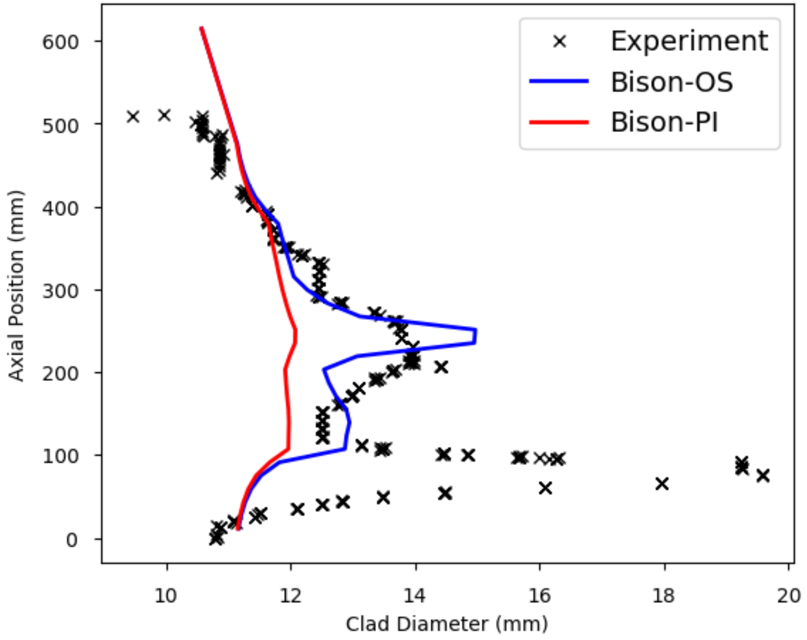
Calculated and measured rod inner pressure during the post-blowdown phase



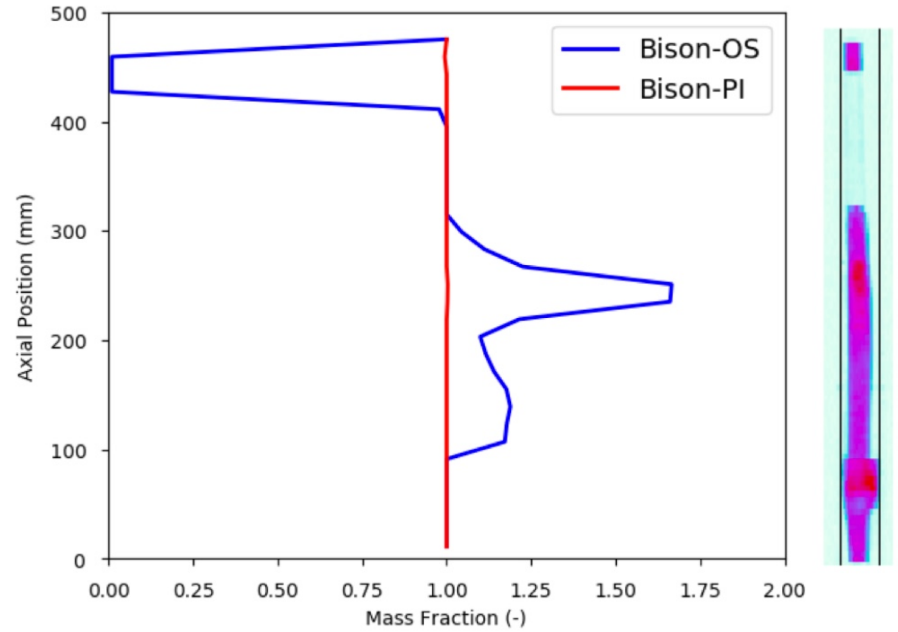
Calculated axial profile of cladding outer diameter at the end of the test and PIE data

Halden integral LOCA test IFA-650.9

- High burnup rod (89.9 MWd/kgU) with significant axial fuel relocation[11]
- The axial relocation model from Jernkvist and Massih[12] is used in BISON
- Early results, differing failure criteria of plastic instability (PI) and overstrain (OS)



Calculated cladding outer diameter profile at the end of the test and PIE data



Calculated fuel mass fraction as a function of axial position compared to a gamma scan of ^{137}Cs

[11] *L.O. Jernkvist and A.R. Massih, Technical Report SSM-2015:37, 2015*

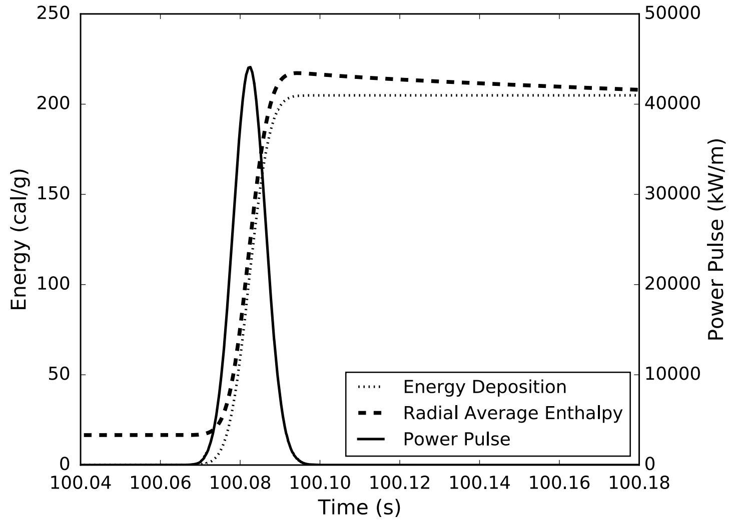
[12] *F. Bole du Chomont, LOCA testing at Halden, the ninth experiment IFA-650.9, HWR-917, OECD Halden Reactor Project, 2009*

RIA tests CABRI REP Na

- Tests at the CABRI reactor (France) on PWR rods at extended burnup[13,14]
- Transient tested in a sodium coolant loop with Gaussian-type power pulses
- 4 cases simulated with BISON
- Comparisons against reported data and prior FALCON simulations

Test (date)	REP Na-2 (6/94)	REP Na-3 (10/94)	REP Na-5 (5/95)	REP Na-10 (7/98)
Fuel Type	17x17 UO_2	17x17 UO_2	17x17 UO_2	17x17 UO_2
Cladding Type	Std Zy-4	Std Zy-4	Std Zy-4	Std Zy-4
Initial enrichment (^{235}U/U %)	6.85	4.5	4.5	4.5
Internal gas pressure (MPa, 20°C)	0.101	0.31	0.302	0.301
Active length (mm)	1004.9	440.8	563.5	559
Max. burnup (GWd/tU)	33	53.8	64	63
Corrosion thickness (μm)	10	35-60	15-25	60-100
Pulse width FWHM (ms)	9.6	9.5	8.8	31
Energy deposit (J/g) [cal/g]	865 [207]	511 [122.2]	435 [104]	453 [108.3]
Cladding OD (mm)	9.51	9.55	9.51	9.51
Cladding thickness (mm)	0.637	0.596	0.578	0.575
Pellet OD (mm)	8.05	8.19	8.19	8.19
Pellet height (mm)	11.99	13.69	13.74	14.25
Diametral fuel-cladding gap (μm)	186	164	164	164

Overview of the CABRI REP Na cases considered for BISON assessment for RIA analysis



Power pulse and computed (BISON) energy deposited and radially averaged fuel enthalpy at PPN for REP Na-2

[13] *F. Schmitz, J. Papin, Journal of Nuclear Materials, 270, 55–64, 1999.*

[14] *J. Papin et al., Synthesis of CABRI-RIA tests interpretation, Eurosafe Meeting, Paris, France, 2003*

RIA tests CABRI REP Na

CABRI REP Na-2

Property	BISON	FALCON	Experimental/ Reported Values	% Difference (FALCON)	% Difference (Experimental)
Energy Deposition (cal/g)	205	-	207	-	-1.0
Peak Fuel Enthalpy (cal/g)	217	200	199	8.7	9.2
Max Fuel Temperature (K)	3024	2948	-	2.6	-
Max Fuel Centerline Temp. (K)	2707	2775	-	-2.5	-
Clad Max Inside Temp. (K)	1036	1020	-	1.6	-
Max Hoop Strain (%)	1.36	2.60	3.5	-48	-61
Residual Hoop Strain (%)	0.46	2.20	-	-79	-
Max Clad Radial Disp. (μm)	64	135	-	-53	-
Clad Radial Disp. Residual (μm)	21	102	135	-79	-78
Fission Gas Released (%)	7.1	-	5.5	-	29
Corrosion thickness (μm)	5	-	4-10	-	-

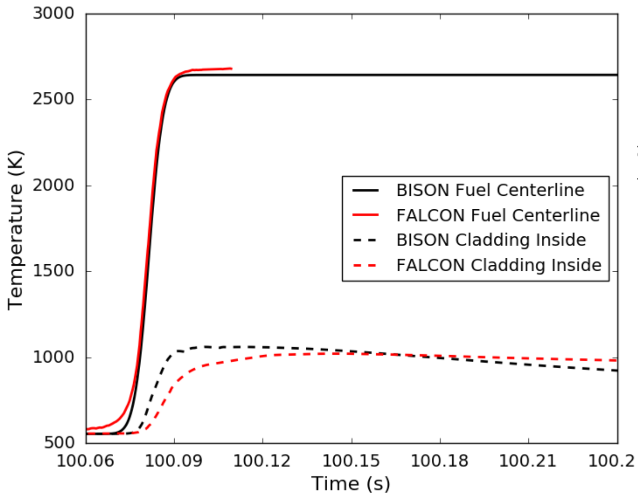
CABRI REP Na-3

Property	BISON	FALCON	Experimental/ Reported Values	% Difference (FALCON)	% Difference (Experimental)
Energy Deposition (cal/g)	122	-	122	-	0
Peak Fuel Enthalpy (cal/g)	136	118	124	15	10
Max Fuel Temperature (K)	2599	2480	-	4.8	-
Max Fuel Centerline Temp. (K)	1904	1960	-	-2.9	-
Clad Max Inside Temp. (K)	1002	935	-	7.1	-
Max Hoop Strain (%)	1.19	1.5	2.2	-21	-46
Residual Hoop Strain (%)	0.40	1.10	-	-64	-
Max Clad Radial Disp. (μm)	56	81	-	-31	-
Clad Radial Disp. Residual (μm)	18	51	55	-64	-67
Fission Gas Released (%)	9.8	-	13.7	-	-29
Corrosion thickness (μm)	51	-	35-60	-	-

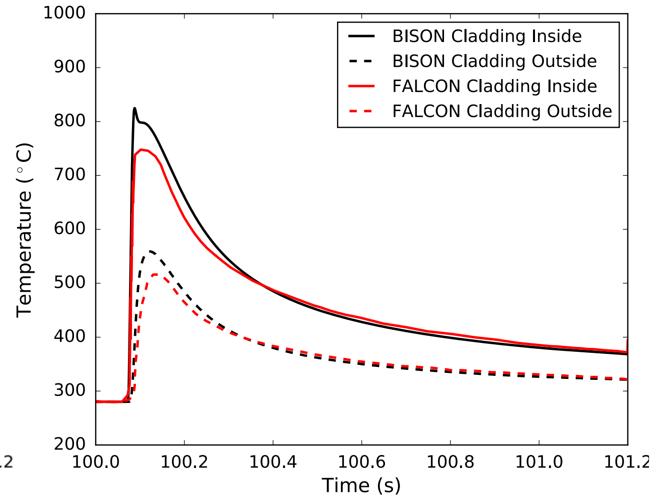
RIA thermal behavior comparisons

- Code-to-code comparisons with FALCON for fuel and cladding temperatures during the RIA transients

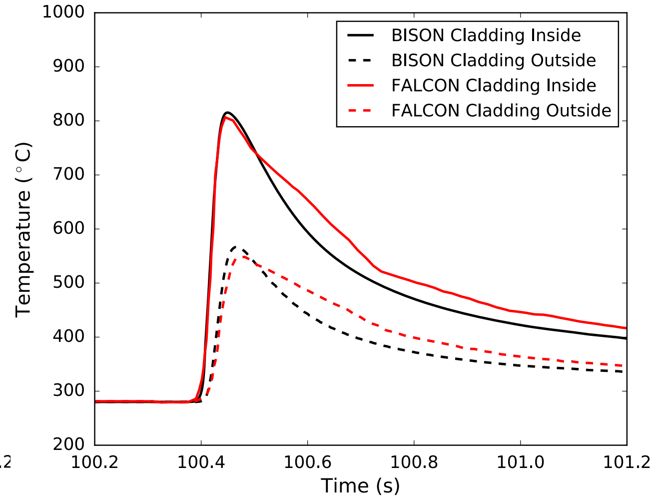
CABRI REP Na-2



CABRI REP Na-5



CABRI REP Na-10



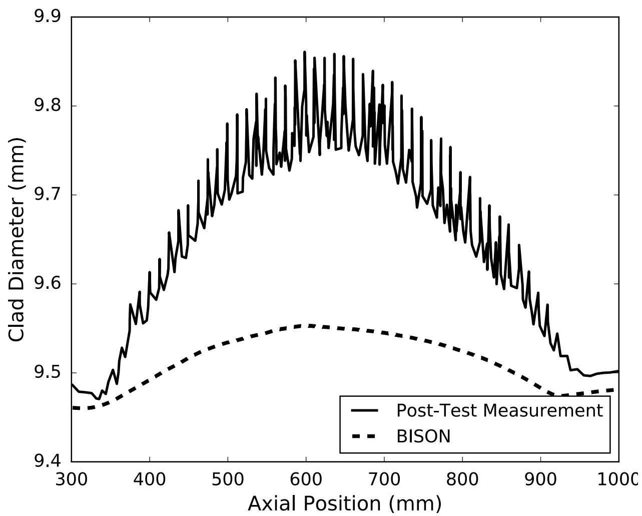
Fuel centerline and cladding inner surface temperatures at PPN, comparisons between BISON and FALCON for CABRI REP Na-2

Cladding inner and outer surface temperatures at PPN, comparisons between BISON and FALCON for CABRI REP Na-5 and Na-10

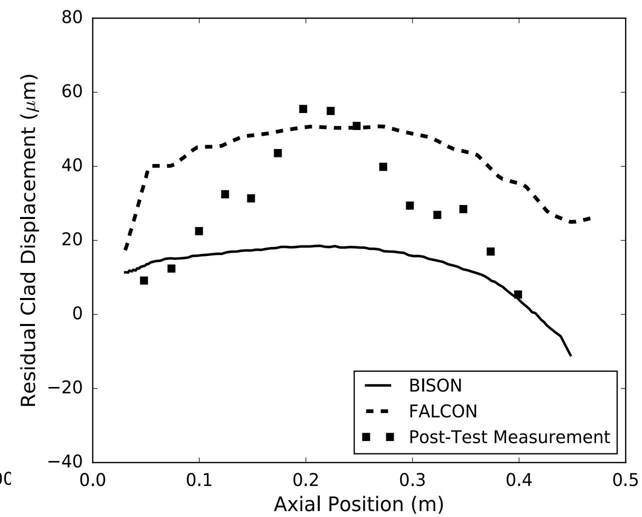
FALCON results from [15] *R.O. Montgomery, Y. R. Rashid. Evaluation of irradiated fuel during RIA simulation tests. Final report. EPRI-TR—106387, Electric Power Research Institute, Palo Alto, CA, USA; ANATECH Research Corp., San Diego, CA, USA, 1996.*

RIA mechanical behavior comparisons

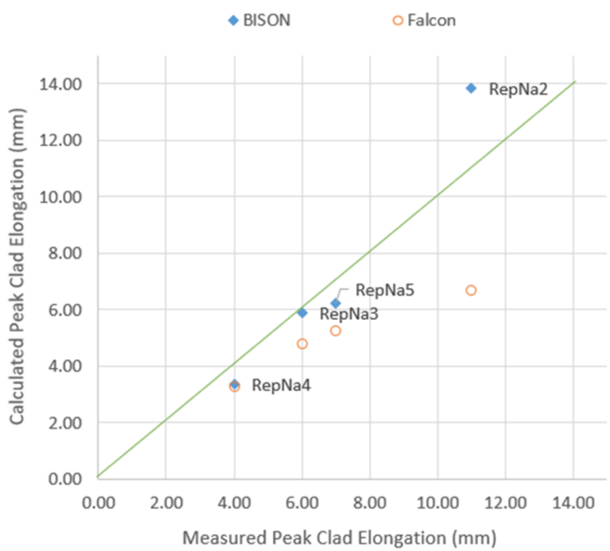
- Predictions of residual cladding diameter at the end of the test deviate significantly from the experimental data
- Cladding elongation comparisons show good agreement with the measured values



CABRI Rep Na-2 (33 MWd/kgU)[17]



CABRI Rep Na-3 (54 MWd/kgU)[17]

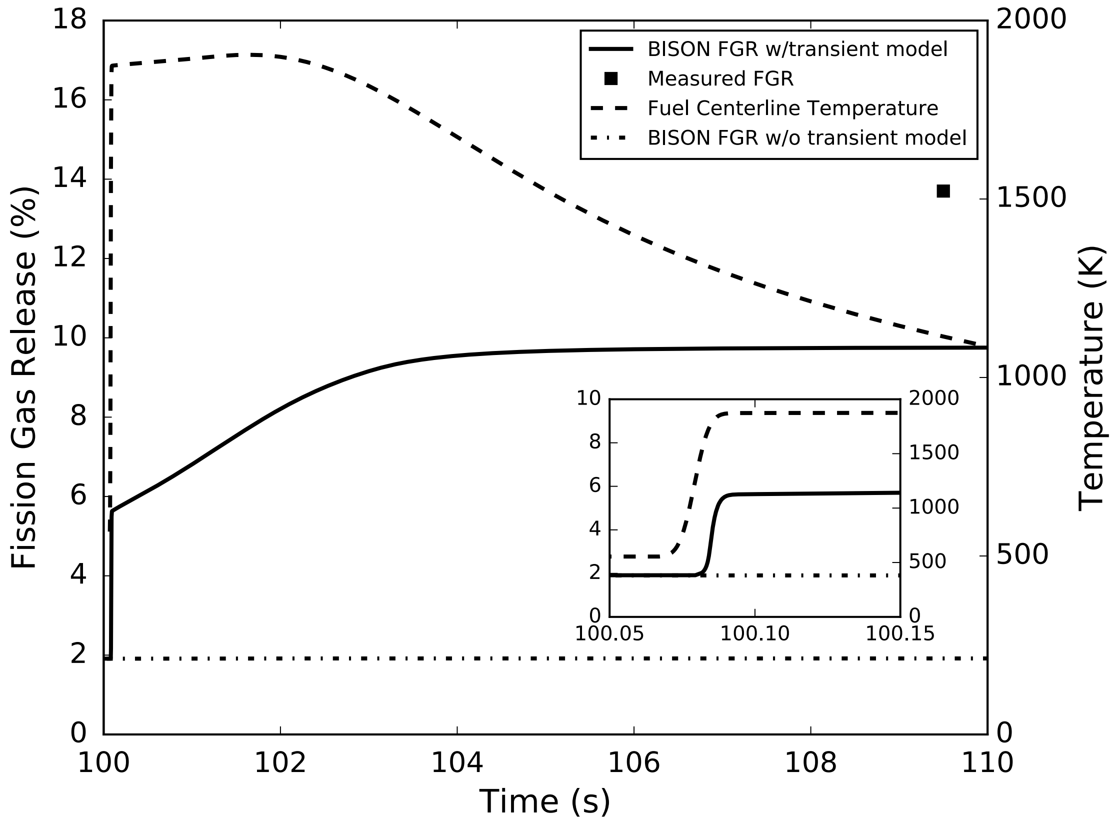


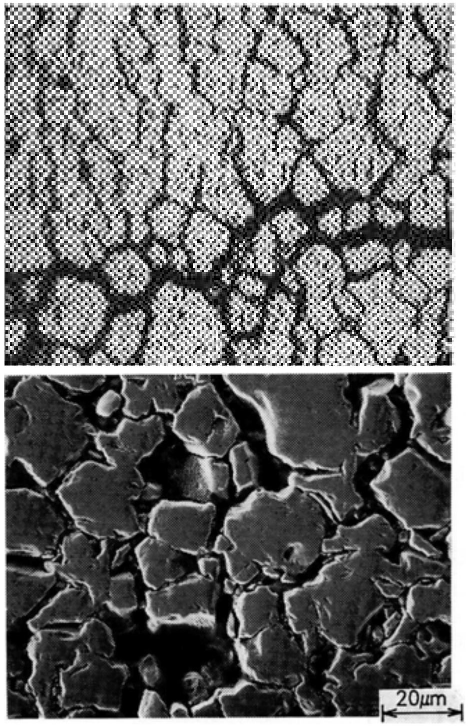
Cladding elongation comparisons[18]

[16] C.P. Folsom, R.L. Williamson, G. Pastore, W. Liu, Tech. Rep. CASL-U-2017-1403-000, Consortium for Advanced Simulation of Light Water Reactors, 2017

[17] W. Liu et. al., Bison Fuel Performance Modeling on RIA in a PWR, Tech. Rep. CASL-U-2018-1656-000, 2018

RIA fission gas release comparisons

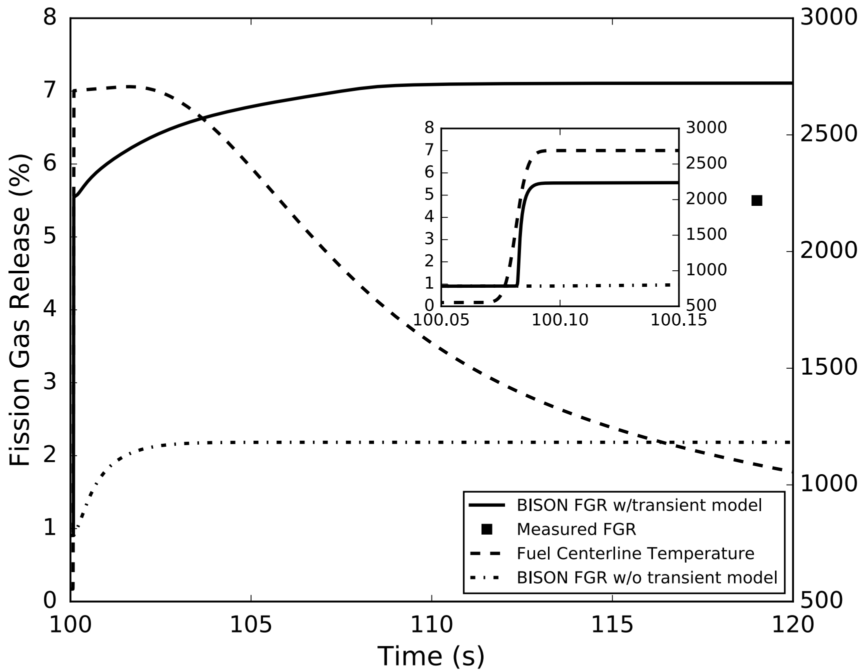


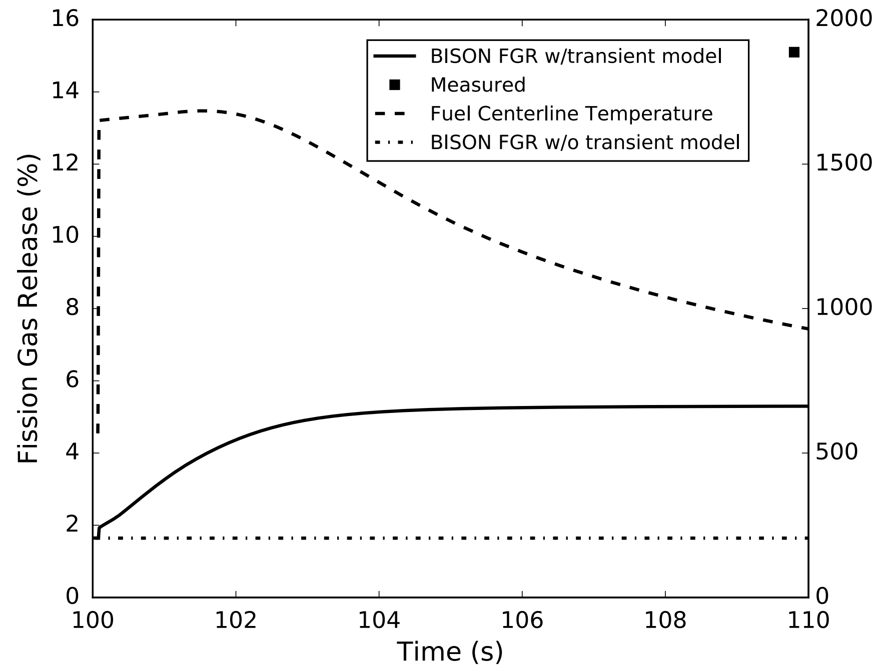


Left: BISON FGR results with fuel centerline temperature and measured post-test value for CABRI REP Na-3 RIA test. The inset shows a shorter time scale around the power pulse period

Right: Micrographs of from RIA tests showing fuel micro-cracking
(Top: REP-Na 5, Lemoine et al., 2000. Bottom: NSRR JM-4, Nakamura et al., 1996)

RIA fission gas release comparisons





BISON FGR results and measured post-test value for RIA tests CABRI REP Na-2 (left) and REP Na-5 (right)

[18] *G. Pastore, C.P. Folsom, R.L. Williamson, J.D. Hales, L. Luzzi, D. Pizzocri, T. Barani, Modelling Fission Gas Behaviour with the BISON Fuel Performance Code, Proc. of the Enlarged Halden Programme Group Meeting – EHPG 2017, Lillehammer, Norway, September 24-29, 2017.*

Summary

- Initial LWR applications of INL's fuel performance code BISON focused on normal operating conditions and power ramps. More recently, the analysis of design-basis accidents has been considered.
- Models are included in BISON for high-temperature behavior of Zircaloy cladding, fuel axial relocation and transient fission gas behavior.
- Simulations of cladding-only ballooning and burst tests indicate conservative predictions of cladding burst during LOCA.
- Simulations of integral Halden LOCA tests demonstrate encouraging predictions of rod pressure and time to burst, and fuel axial relocation. Predicting cladding strains accurately remains challenging (cf. FUMAC project).
- Simulations of RIA tests from CABRI REP Na were performed. Thermal results are in good agreement with FALCON. Cladding diametral strain predictions deviate significantly from experimental data; cladding elongation predictions are satisfactory.
- Applying the transient FGR model (developed in collaboration with POLIMI and JRC-Karlsruhe) in the analyzed RIA cases provides improved predictions.

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- US DOE Consortium for Advanced Simulation of Light Water Reactors (CASL)
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- Politecnico di Milano, Department of Energy, Nuclear Engineering Division
- European Commission, Joint Research Centre – Karlsruhe
- IAEA Coordinated Research Project FUMAC