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Development of a RIA Experimental Benchmark for BISON L3:FMC.FUEL.P15.09

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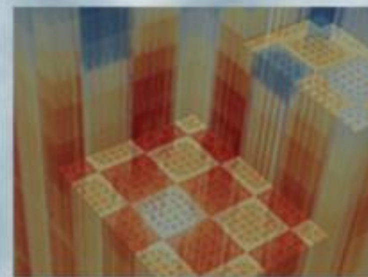
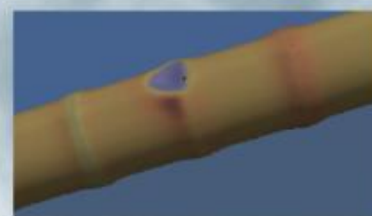
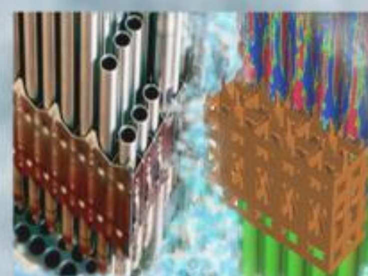
August 15, 2017







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Development of a RIA Experimental Benchmark for BISON
CASL FY17 Milestone Report

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Introduction

This milestone report documents FY-17 efforts for the Reactivity Initiated Accident (RIA) Challenge Problem to demonstrate PWR RIA Fuel Performance capability. The challenge problem implementation plan identified a series of experimental comparisons to validate RIA capability in BISON [1]. The specific cases chosen for FY-17 are CABRI REP Na-2, 3, 5, and 10. Work was also performed on the Nuclear Safety Research Reactor (NSRR) FK-1, 2, 3, 4, 5, 6, 7, 8, and 9 cases.

Many features have been implemented to improve RIA simulation capability in BISON. In FY-16 a few key features/-models were added for accident modeling that are particularly relevant for RIA scenarios. A Zircaloy cladding plasticity model that is applicable for irradiated fuel at high temperatures and strain rates was implemented, as well as a new time step control algorithm to help improve the numerical solution in the presence of non-linear material behavior (plasticity, creep) during accident situations [2]. More recently, improvements have been made to the fission gas release (FGR) model that captures rapid FGR (burst release) during transients due to fuel micro-cracking [3, 4]. One of the primary regulatory acceptance criteria for RIA is the fuel radial average enthalpy. Recently a postprocessor was added to BISON to calculate radial average enthalpy (RAE) of the fuel at each timestep.

This report will briefly discuss the state of RIA testing, the selected experimental cases validated against, the results from the validation efforts, and a discussion of the results and recommended future work. For this validation study a majority of the comparisons are against results from the FALCON fuel performance code [5] (performed by the Electric Power Research Institute (EPRI)) as access to the experimental data is limited to members of the CABRI International Program (CIP).

1 RIA Tests Overview

To date, more than a thousand pulse irradiation tests prototypic of RIA events have been carried out on previously unirradiated (fresh) fuel. About 140 tests have been done on pre-irradiated samples, but data is sparse beyond burnup levels of 40 GWd/tU and is based on older fuel rod designs. Only a few tests have been performed on rods at extended burnup and these have been performed at the CABRI facility in France and the NSRR facility in Japan. The purpose of these programs was to provide data for high burnup fuels that can be used to develop safety criteria at extended burnup levels and to provide data to validate fuel performance codes.

The RIA tests at the CABRI reactor facility began in 1992 by the "Institut de Protection et de Sûreté Nucléaire" (IPSN which is now IRSN) in collaboration with Electricité de France (EDF), Framatome, CEA, and with participation of the US NRC. A total of twelve tests were performed within the CABRI REP sodium loop using preirradiated fuel rods having burnups ranging between 33 and 65 GWd/tU. Of the twelve, eight contained UO_2 fuel and four were MOX. The cladding for all tests was Zircaloy 4 except test 11 which was M5.

The CABRI test reactor is a pool-type Light Water Reactor (LWR) designed with a central area that can accept the insertion of a test device. The central area was originally designed to study fast reactor transients and contains a sodium coolant loop. During the experiment, the test rod is placed inside a test capsule which contains the in-pile instrumentation. Due to the sodium coolant loop, the test capsule temperature and pressure are different from LWR conditions, but the tests are considered appropriate to study the response of the rodlet up to the departure from nucleate boiling point. Under these conditions the effects of pellet cladding mechanical interaction (PCMI) can be tested.

The tests chosen for evaluation in this study were identified as priority cases in the CASL RIA Challenge Problem Implementation Plan [1] and include the CABRI REP Na-2, 3, 5, and 10 cases with UO_2 fuel. Details of each case, including modeling options and comparisons to experimental data and other code predictions, are available in the BISON Assessment document. The most current version of that document is available as part of the source code distribution.

NSRR is a modified TRIGA (Training, Research, Isotopes, General Atomics) ACPR (Annular Core Pulse Reactor) with a dry space located in the center of the core. In a simulated RIA test for an irradiated fuel, a single instrumented fuel rod in a water-filled capsule is placed in the center of the core, and is pulse irradiated.

A large number of experiments on simulated RIA have been performed at the test facility of NSRR to evaluate fuel rod behavior and failures at different energy deposition, burnup, fuel design, and coolant condition. Since 1989, tests on medium and high burnup fuels in NSRR have been started and continued; recent experiments have moved towards testing on high burnup fuel with advanced corrosion resistant cladding alloys such as MDA and Zirlo^{TM} [6]. Pulse irradiation tests were normally performed in stagnant coolant water at room temperature (~20°C) and atmospheric pressure (~0.1 MPa) under a narrow power pulse with Full Width at Half Maximum (FWHM) of approximately 5 ms. Recent tests were performed at high coolant temperature (280°C) and high pressure (up to 6.4 MPa) to provide measurements on fuel failures at conditions close to Hot Zero Power (HZP) condition.

A number of tests on BWR type fuels with burnup from 41 to 61 GWd/tU (three and four cycles) have been selected for validation of BISON based on published information from JAEA (formerly known as JAERI) [7, 8]. These initially include cases FK-1 through FK-9 which include four tests (FK-3, FK-6, FK-8, FK-10) identified as priority cases in the CASL RIA Challenge Problem Implementation Plan [1]. Note that the NSRR validation cases are being prepared by Structural Integrity Associates (Anatech) under subcontract from NEAMS, but are included here for completeness. Note further that the NSRR cases are still preliminary, with this work scheduled to be completed and documented later in 2017.

2 Test Description

2.1 CABRI Sodium Cases

An overview of the four REP Na tests chosen for the BISON simulations are shown in Table 1 [9, 10, 11], including as-manufactured cladding and pellet geometry. All the test rods in the CABRI REP Na tests were short segments refabricated from 17x17 PWR-type fuel rods irradiated under nominal PWR conditions, except the Na 2 test. REP Na-2 was a 1 m long rod base irradiated to 33 GWd/tU in the BR3 reactor.

Details on the case geometry and base irradiation conditions were taken from the FRAPTRAN-1.5 Integral Assessment [12]. During all the REP Na tests the sodium coolant is heated to 280°C at the test capsule inlet and pressurized to 0.5 MPa. The sodium flows at a velocity of 4 m/s.

Proper initial conditions prior to the RIA transient are very important to being able to accurately predict and analyze the results from the transient correctly. A base irradiation of the fuel was performed in BISON according to the reactor

Table 1: Overview of REP Na cases

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

operating conditions specified in FRAPCON example input files [12]. The RIA simulations used the base irradiation simulation as the initial conditions by changing the necessary material models (especially the thermal-hydraulic model from water properties to sodium) and performing a recover option in BISON to continue the RIA simulation where the base irradiation ended. This method allowed all displacements, any non-linear strains, radial power factors due to burnup, cladding oxidation, and especially fission gas inventory in the fuel, to be used in the RIA simulation.

2.2 NSRR Water Cases

An overview of NSRR FK cases selected for BISON assessment is shown in Table 2. All nine test rods selected from the FK series are short rodlets with an active fuel stack length of 102 mm (10 pellets) or 128 mm (12 pellets). Fuel rod segments for Tests FK-1, FK-2, and FK-3 were irradiated in Fukushima Daiichi Unit 3 for three cycles to a burnup level of 41 to 45 GWd/tU, and FK-4 – FK-9 were irradiated in Fukushima Daini Unit 2 to a burnup level of 56 to 61 GWd/tU [7, 8]. The short fuel segment for each rod has a flat axial burnup profile from base irradiation, and a uniform axial power profile in the RIA transient. All the fuel types are UO_2 fuel enriched to 4.5% with zirconium-lined recrystallized Zircaloy-2 cladding. Those rodlets were tested in the NSRR reactor at room temperature (~20°C) and atmospheric pressure (~0.1 MPa) condition.

Table 2: Overview of NSRR FK cases

Test	FK1	FK2	FK3	FK4	FK5	FK6	FK7	FK8	FK9
Clad thickness (mm)	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
Fuel density (%TD)	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
U235 enrichment (%)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Burnup (GWd/tU)	45	45	41	56	56	61	61	61	61
Pre-test fill gas pressure (MPa)	0.3	0.3	0.3	0.5	0.5	0.1	1.5	1.5	1.5
Peak linear heat rate (W/cm)	228	228	209	350	350	350	350	350	350
Energy deposit (cal/g)	167	95	186	180	100	168	166	90	119
Peak fuel enthalpy (cal/g)	129.52	69.8	144.5	139.5	69.8	130.5	128.6	64.8	89.8
Power Pulse width (ms)	4.5	7	4.5	4.3	7.3	4.3	4.3	7.3	5.7
Failure enthalpy (cal/g)	-	-	-	-	-	70	62		86

3 Results

Without membership in the CABRI International Program there is limited access to the CABRI REP experimental data. So to the extent possible, BISON results are compared against those CABRI REP experimental data reported in the open literature [9, 10, 11]. To provide more detailed comparisons, BISON results are also compared against FALCON calculations for the same cases, as extracted from two EPRI reports [13, 14].

3.1 CABRI Sodium Cases

As stated previously, one of the primary safety criteria for a RIA is the fuel radial average enthalpy (RAE). The Gaussian shaped power pulse, energy deposited into the fuel and calculated fuel RAE along with comparisons to FALCON are shown in Figure 1 for case REP Na-5. The BISON, FALCON, and reported values for peak fuel radial average enthalpy are summarized in Table 3 for all four cases. The energy and RAE comparison with FALCON and the experimental/reported values show excellent agreement for this case with the resulting max increase in radial averaged enthalpy calculated in BISON was 116.8 cal/g compared to 115 cal/g from FALCON and 108 cal/g reported from IRSN. For the REP Na-2 case the calculated maximum change in radial averaged fuel enthalpy from 20°C is 217 cal/g compared to 200 cal/g calculated by FALCON and 199 cal/g reported by IRSN which agree within 10%. Regarding REP Na-3, the maximum change in fuel radial averaged enthalpy in BISON was 136 cal/g compared to 118 cal/g calculated in FALCON and 124 cal/g reported by IRSN. BISON over estimates the radial averaged enthalpy by 10-15% in this case compared to the reported values and FALCON. In the REP Na-10 case the resulting calculated maximum increase in radial average fuel enthalpy was 118 cal/g in BISON, 109 cal/g in FALCON and a reported value of 98 cal/g by IRSN. These values result in an 8% difference between BISON and FALCON and a 20% difference from the reported value.

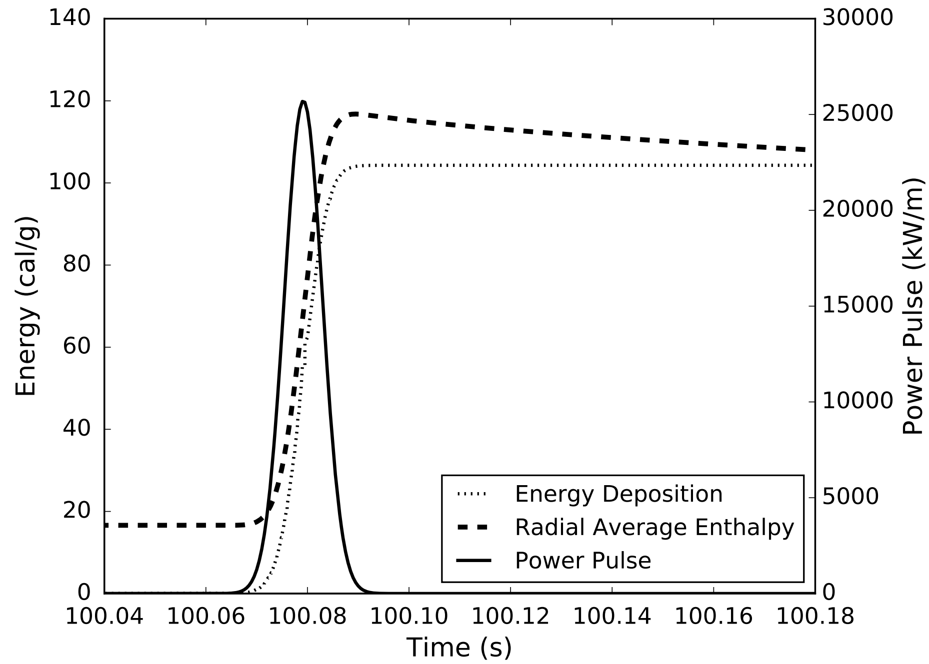
Table 3: Comparison of of peak fuel radial average enthalpy

Case	BISON	FALCON	Reported Value
REP Na-2	217	200	199
REP Na-3	136	118	124
REP Na-5	116.8	115	108
REP Na-10	118	109	98

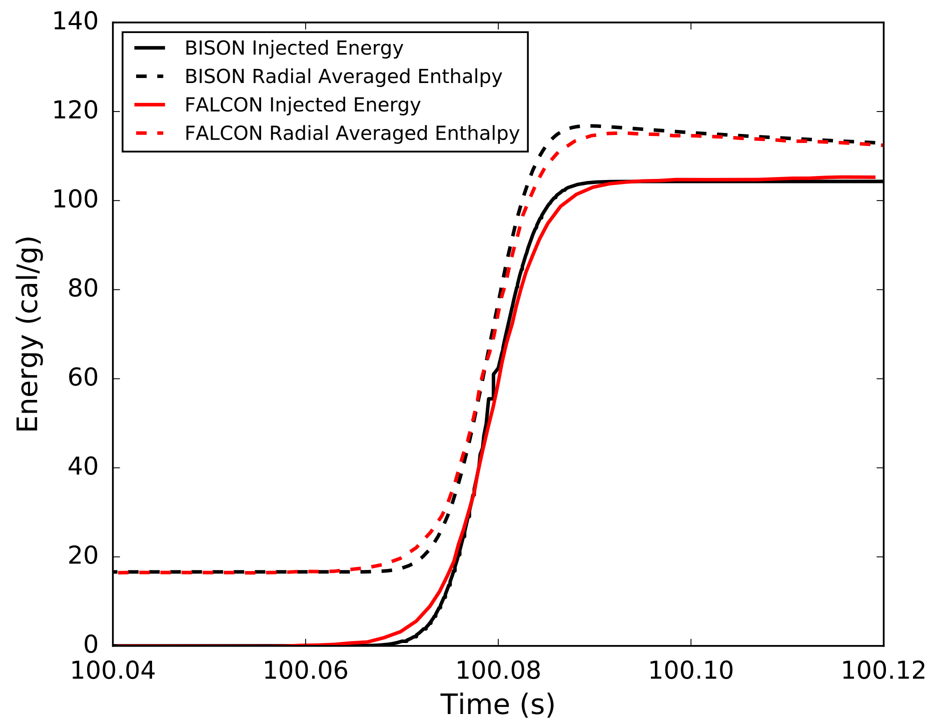
Figures 2 and 3 show the calculated fuel and cladding temperatures from BISON as well as comparisons between BISON and FALCON. Figure 2b shows very good agreement between BISON and FALCON on the fuel centerline and cladding inside surfaces for REP Na-3 and Figure 3b shows similar agreement for the cladding inner and outer surface temperatures for REP Na-10. For all cases the agreement between BISON and FALCON for the fuel centerline temperature was within 5% and and the maximum fuel temperature was within 10%. Similar results were found for the maximum cladding inner temperature with agreement typically well under 10%.

While BISON compared very well with FALCON on thermal results, mechanical results showed greater deviation from both FALCON and measured values. Figures 4 and 5 show comparisons between BISON and FALCON on calculated hoop strain during the RIA including post-RIA residual clad displacement comparisons to both FALCON and measurements. BISON tends to under-predict the total hoop strain, as shown in Figures 4a and 5a, while Figures 4b and 5b show that the residual clad diameter and radial displacement are also significantly under-predicted compared to measured results. Oscillations in the post-test measurements in Figure 4b are due to cladding ridging at the pellet-pellet interfaces, and are not seen in the BISON results due to the smeared fuel approximation. Note that all results presented thus far were performed assuming frictionless contact between the fuel and cladding. This assumption is known to be inadequate, but was required due to inadequacies in the BISON frictional contact model. Axial elongation comparisons were thus delayed until contact model improvements are completed.

There are a number of postulated reasons for the discrepancies in the mechanical results. As previously stated, the frictionless contact option greatly impacts the axial displacement predictions, but also influences the plastic hoop strain estimation in BISON. Likely the most significant factor influencing the calculated hoop strain and residual hoop strain is the initial fuel-to-clad gap width prior to the RIA [15]. BISON calculates this gap based on results from the

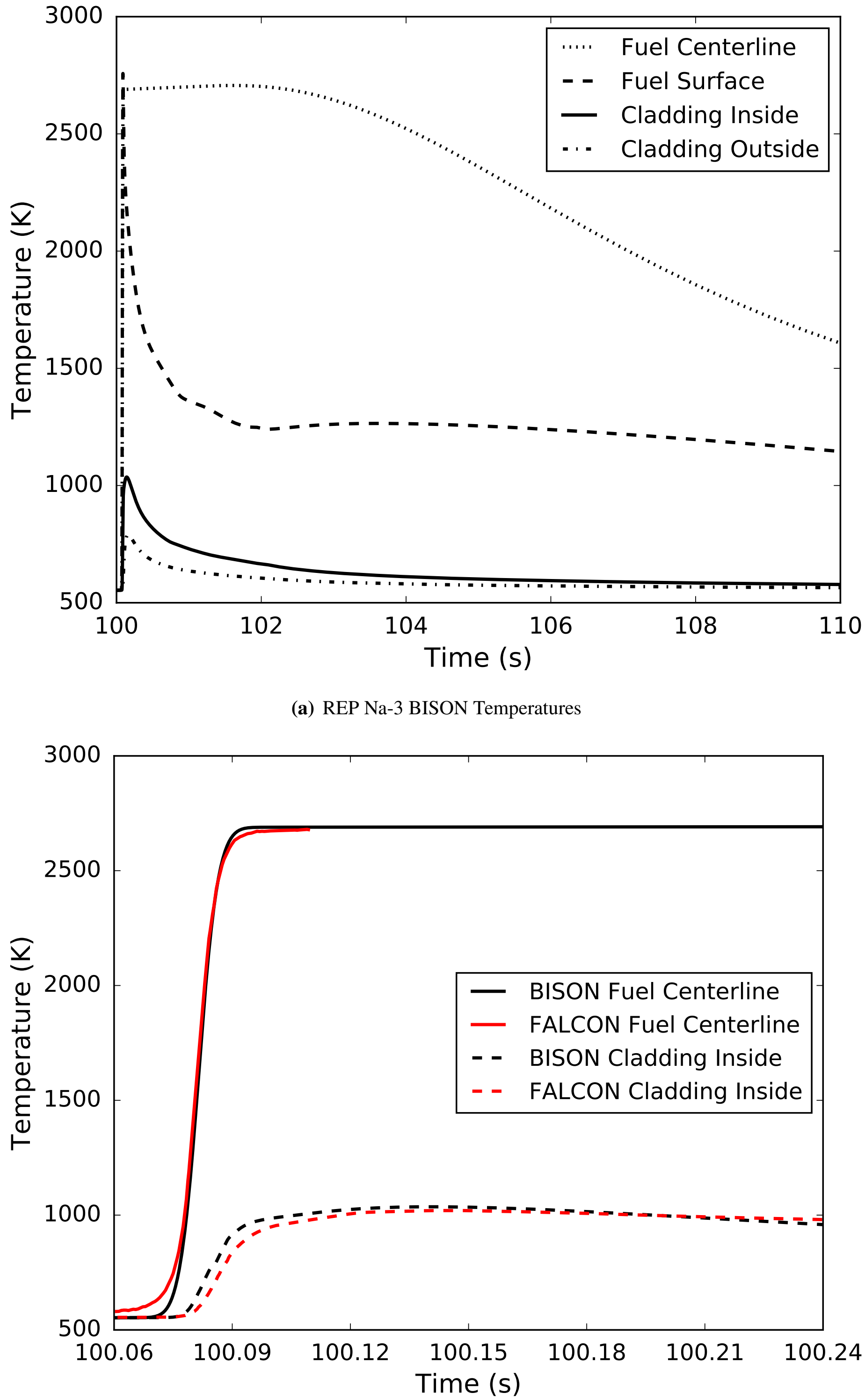


(a) BISON Energy and Power Calculations



(b) BISON and FALCON Comparison

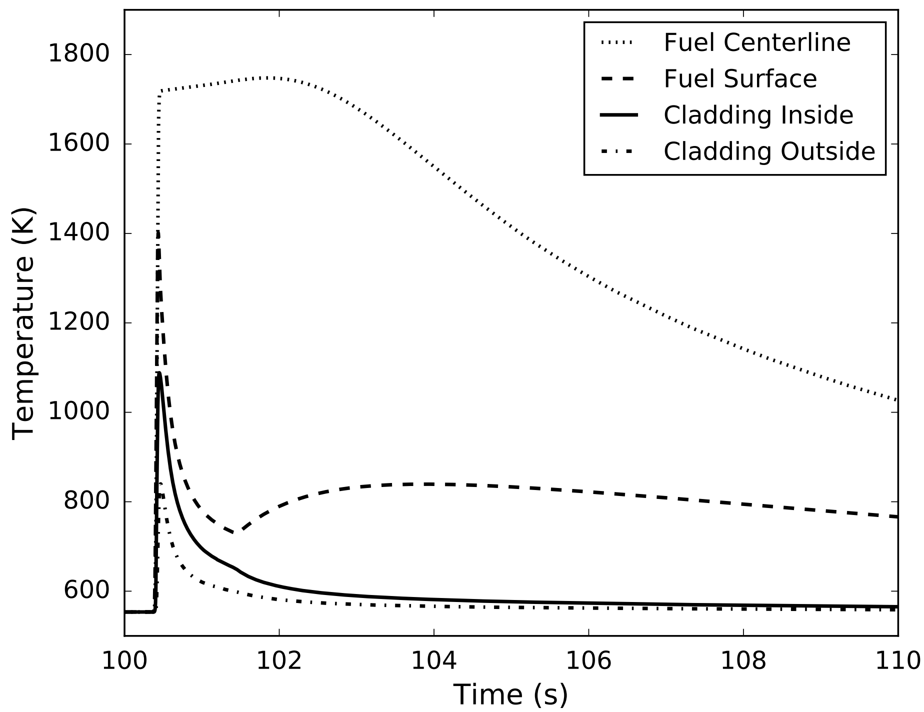
Figure 1: REP Na-5 a) BISON power pulse, energy deposited, and radial average enthalpy calculations b) BISON and FALCON comparisons for energy deposited and radial average enthalpy



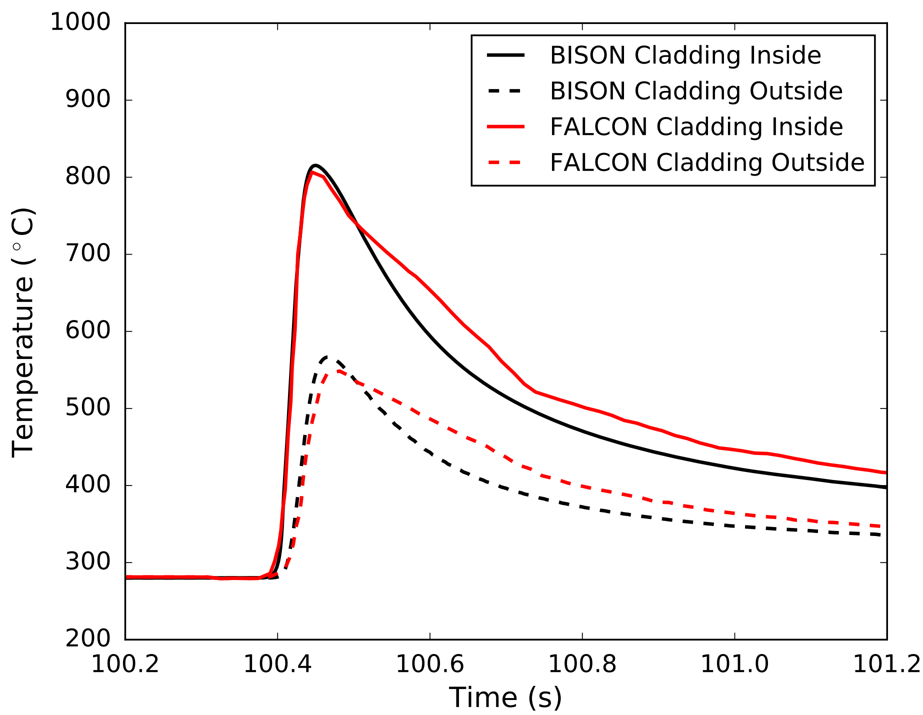
(a) REP Na-3 BISON Temperatures

(b) REP Na-3 BISON/FALCON Comparisons

Figure 2: Temperature calculations and comparisons to FALCON for REP Na-3



(a) REP Na-10 BISON Temperatures



(b) REP Na-10 BISON/FALCON Comparisons

Figure 3: Temperature calculations and comparisons to FALCON for REP Na-10

base irradiation simulation, which indicate a gap opens between the fuel and cladding during cooling from operational conditions. Both FALCON and SCANAIR begin with no initial fuel-to-cladding gap.

It is noted that a very recent improvement in BISON regarding the creep and plasticity models has improved convergence issues that were in part contributing to the convergence difficulties using frictional contact. Following this improvement, frictional contact has been applied to the REP Na-3 case with success. As expected, the energy, thermal, and fission gas release results were very similar between the frictionless and frictional contact cases. The maximum mean hoop stress was 1.2% vs. 1.1% for the frictionless and frictional cases, respectively. The residual hoop stress increased from 0.4% for the frictionless case to 0.48% for the frictional case, but is still much less than calculated by FALCON at 1.1%. Where previously no comparison was made to axial displacements due to the frictionless contact requirement, the results in this case show very good agreement with FALCON and experimental results. The maximum clad axial displacement calculated in BISON was 6.3 mm compared to 5.1 mm calculated by FALCON and 6 mm measured during the experiment. The residual axial displacement was 3.6 mm, 3.4 mm, and 3.5 mm for BISON, FALCON, and measured results, respectively. The fuel maximum axial displacement from BISON was 11.8 mm compared to only 5.4 mm in FALCON, but the residual fuel axial displacement was 3.7 mm in BISON, 0 mm in FALCON, and 3 mm measured. Inclusion of frictional contact in the BISON model provides greater overall agreement with FALCON and experimental results for the REP Na-3 case and will be included in the other CABRI cases in future work.

The predictions for fission gas release (FGR) during the transient are very promising. BISON predicted a final FGR of 7.1% compared to the measured value of 5.5% for REP Na-2, and 9.8% compared to 13.7% for REP Na-3. A plot of the FGR history for REP Na-2 is shown in Figure 6a along with the fuel centerline temperature plotted on the right ordinate. The inset shows the FGR and fuel temperature during the time period of the pulse. Figure 6b shows similar results for REP Na-5 with BISON predicting only 5.3% compared to the measured 15%. The initial large increase in FGR is highly correlated to the fast increase in fuel temperature resulting in micro-cracking and a burst release of fission gas. Note that traditional FGR models typically only account for diffusion-based FGR and will thus tend to strongly under-predict FGR during the short duration of a RIA event. This is demonstrated in Figure 6 by comparison with the results from a purely diffusion based model that differs from the complete BISON model only in that the specific transient (micro-cracking) capability is deactivated. In the REP Na-2 case the FGR still increases due to diffusion-based FGR because of the very high temperatures in the fuel reaching between 2700-3000 K. Hence, the recently developed transient release capability of the BISON model may represent an important step towards better capturing FGR during RIAs. Comparisons of fission gas release are not reported for the REP Na-10 case since the rod burst during the experiment.

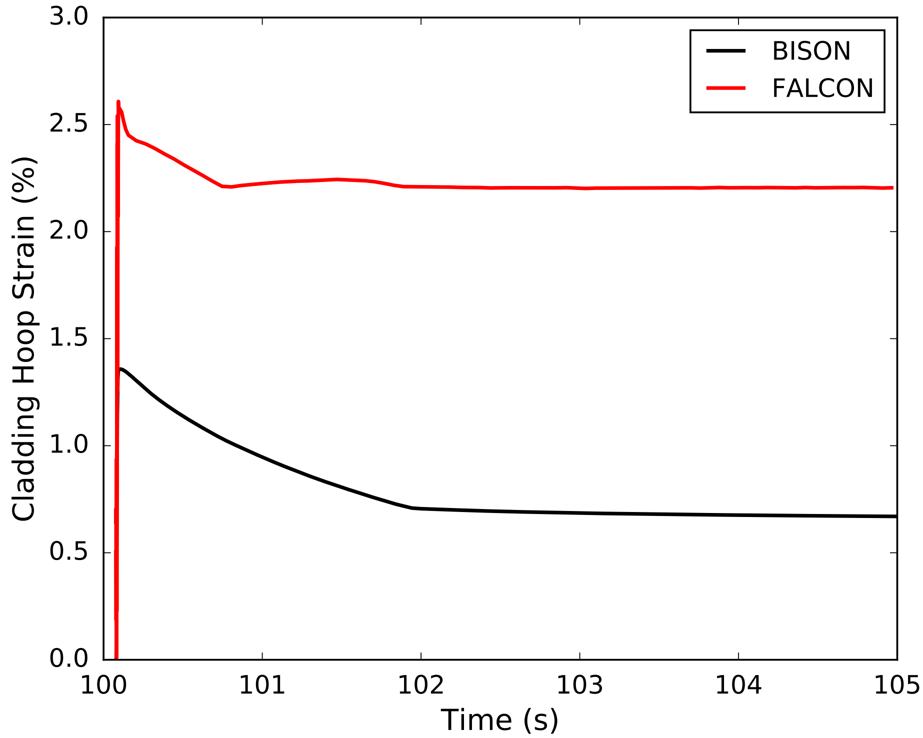
3.2 NSRR Water Cases

This section describes results of a preliminary study on the evaluation of NSRR RIA tests using BISON. As noted above, this work is being performed under NEAMS funding but outlined in this RIA benchmark report for completeness.

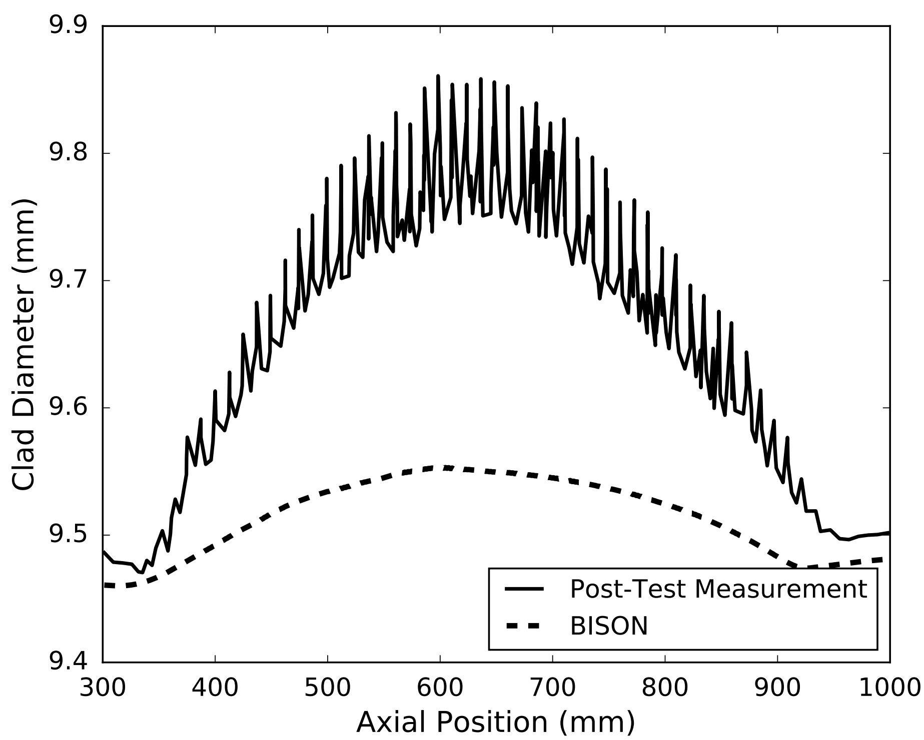
Base irradiation cases for the FK series were prepared, and results of base irradiation calculations were used to provide initial conditions for modeling the RIA transients. Specifically, the gap size, radial power and burnup profiles and fast neutron fluence from BISON calculations were used to determine the pre-transient conditions for the RIA cases. A frictionless model was used for modeling fuel clad contact, and constant clad outer surface temperature was used as the thermal boundary condition.

Figure 7 shows the power pulses for the test cases FK-1 through FK-9. Results of temperature predictions on NSRR FK cases calculated by BISON along with FALCON predictions are summarized in Table 4. Results of clad hoop strains calculated by BISON are shown in Table 5 in comparison to FALCON results [16]. Figure 8 provides calculated temperature histories at the fuel centerline, fuel outer surface, and clad inner surface for test case FK-3. It shows the typical thermal response during a RIA; the pellet outer surface has an initial temperature peak during the power pulse, and then decreases rapidly while the centerline features a more gradual temperature reduction.

BISON calculations on the fuel temperatures match closely to FALCON results for most cases, except for a few cases on peak rim temperature predictions. The calculated clad hoop strains by BISON, however, in general, are smaller than measurements and FALCON code results. As mentioned above, this could be caused by the gap size used for

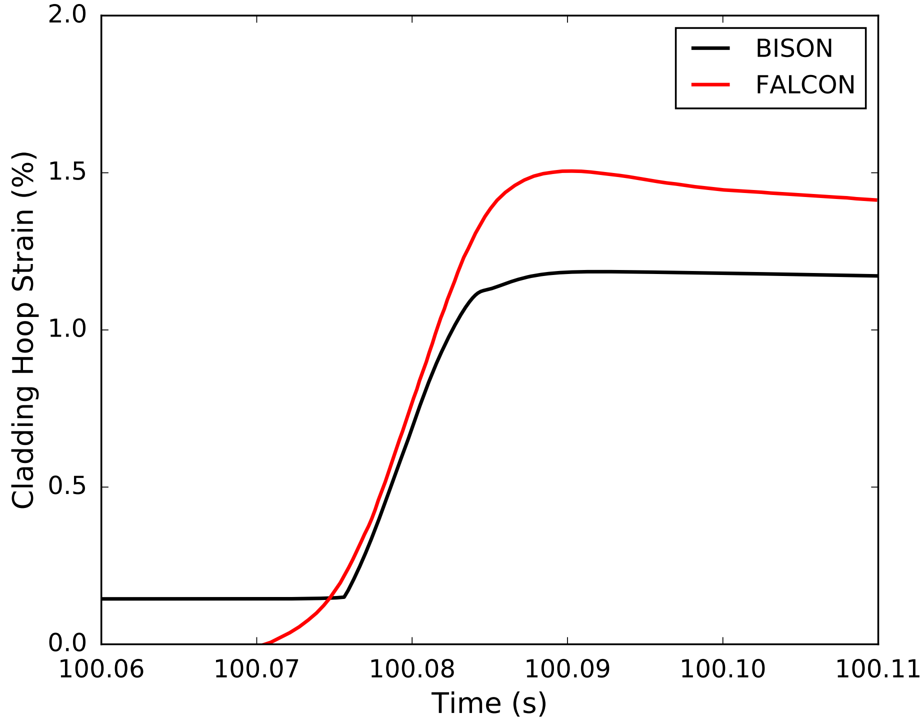


(a) REP Na-2 Hoop Strain

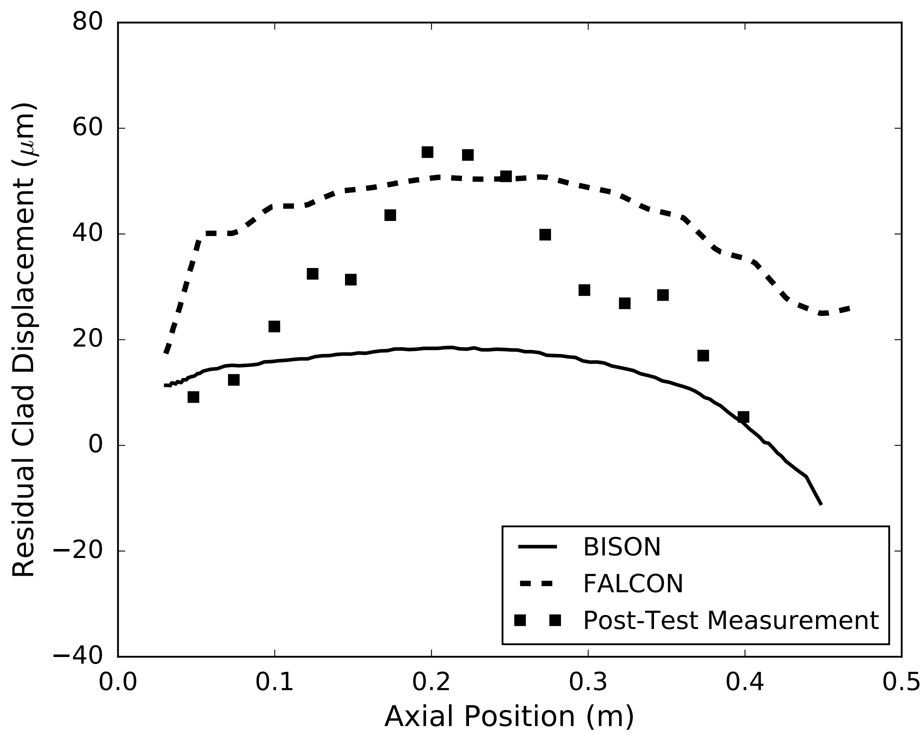


(b) REP Na-2 Post-RIA Clad Diameter

Figure 4: BISON mechanical calculations and comparisons to FALCON and measured results. a) REP Na-2 hoop strain comparison with FALCON, b) REP Na-2 post-RIA clad diameter comparison against measured results

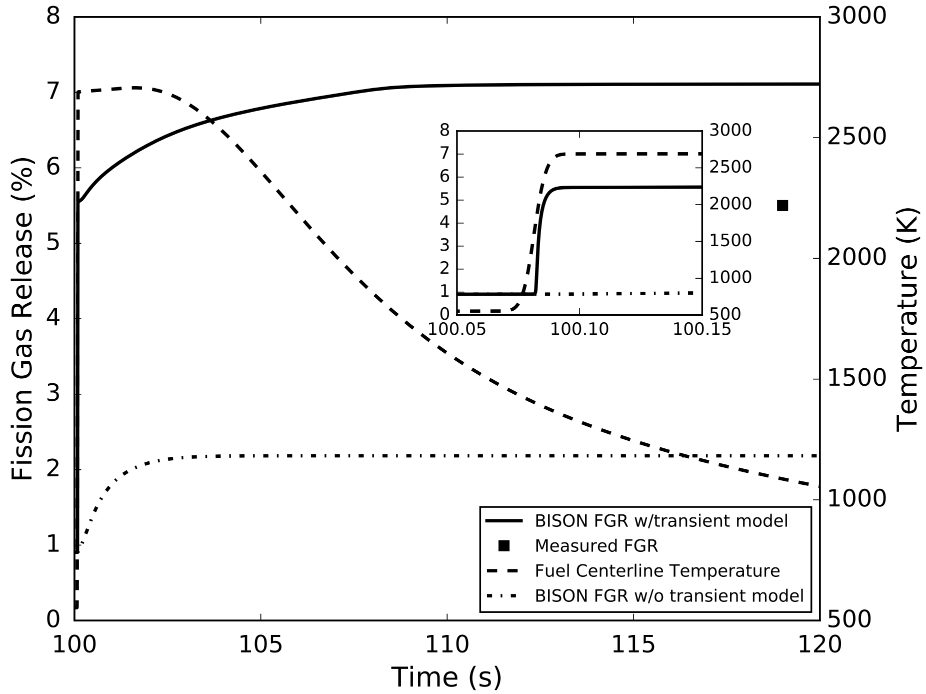


(a) REP Na-3 Hoop Strain

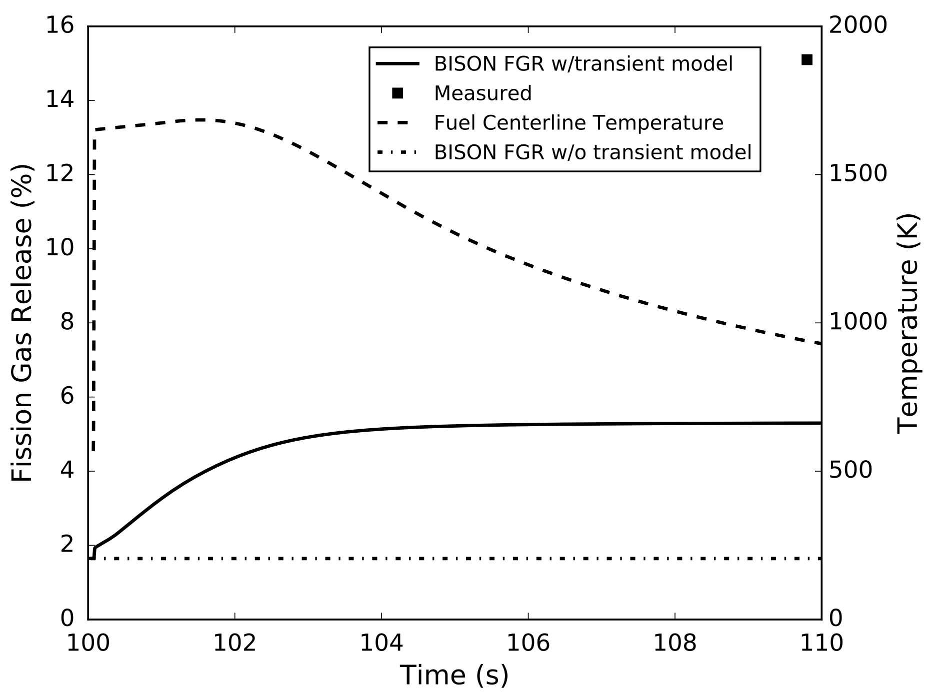


(b) REP Na-3 Post-RIA Clad Displacement

Figure 5: BISON mechanical calculations and comparisons to FALCON and measured results. a) REP Na-3 hoop strain comparison with FALCON, b) REP Na-3 post-RIA clad radial displacement comparison against FALCON and measured results



(a) REP Na-2



(b) REP Na-5

Figure 6: Fission gas release results plotted with fuel centerline temperature compared against measured FGR results post-RIA. Plotted for comparison is the BISON FGR results during the RIA with the transient FGR model turned off.

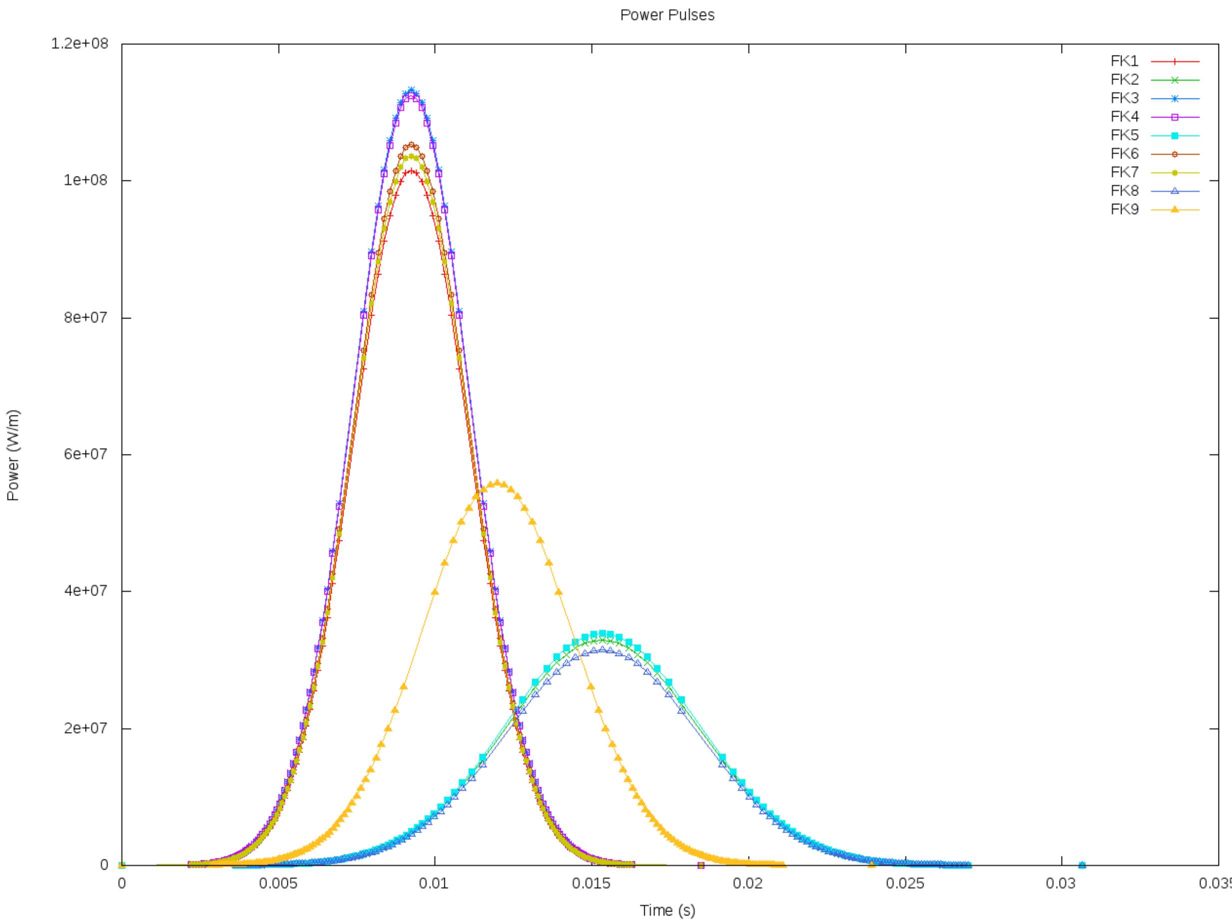
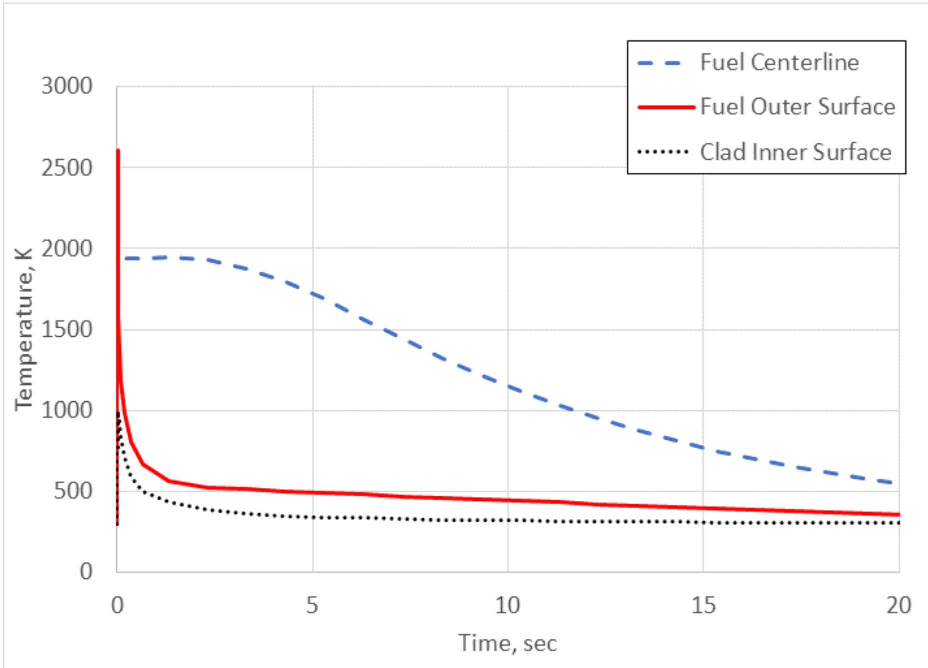


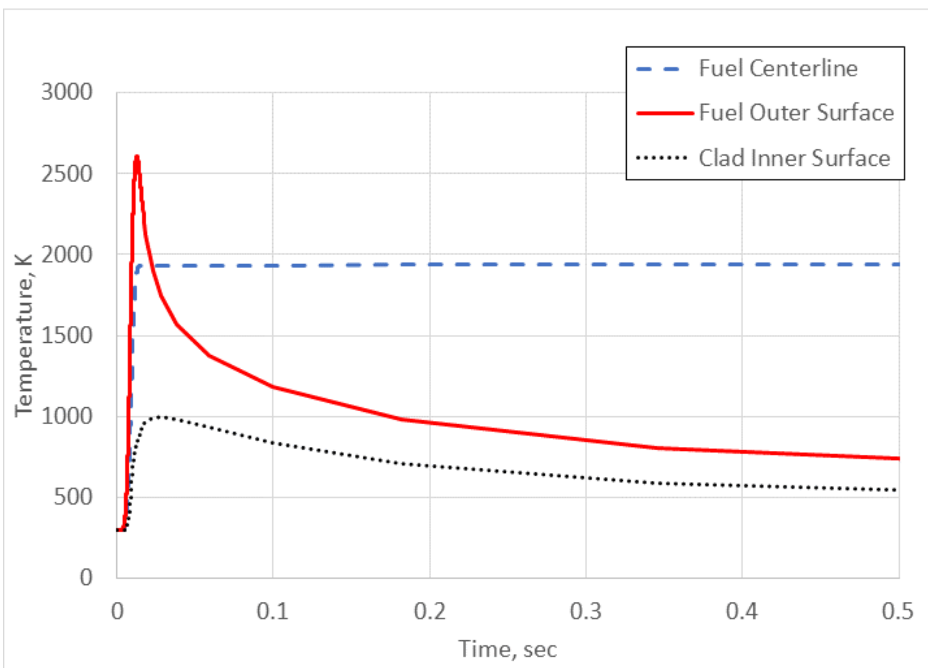
Figure 7: Power Pulses for the NSRR BWR RIA Tests.

Table 4: Summary of Fuel Temperatures of the FK cases

Case	Burnup (GWd/tU)	[H_{fail}] H_p (cal/g)	Peak Clad Inner Surface Temperature (°C)	Peak Rim Temperature by FALCON (°C) [14]	Peak Centerline Temperature by FALCON (°C) [14]	Peak Rim Temperature (°C)	Peak Centerline Temperature (°C)
FK-1	45	130	671	2529	1569	2586	1523
FK-2	45	70	410	1360	880	1519	867
FK-3	41	145	728	2691	1737	2758	1672
FK-4	56	140	737	2747	1591	2690	1623
FK-5	56	70	421	1290	852	1519	867
FK-6	61	[70] 131	623	2696	1510	2712	1535
FK-7	61	[62] 129	614	2648	1509	2662	1514
FK-8	61	65	277	1339	788	1552	811
FK-9	61	[86] 90	384	2007	1146	2076	1092



(a) 0-20 sec



(b) 0-0.5 sec

Figure 8: Temperature at fuel centerline, fuel outer surface, and clad inner surface for test case FK-3

Table 5: Summary of Clad Hoop Strains of FK cases

Case	[H_{fail}] H_p (cal/g)	Peak SED or SED at failure (MJ/m^3)	Calculated Peak Hoop Strain by FALCON [16] (%)	Calculated Peak Hoop Strain (%)	Measured Residual Strain (%)	Calculated Residual Hoop Strain (%)
FK-1	130	3.86	1.30	0.84	0.85	0.08
FK-2	70	2.28	0.4	0.66	0	0.00
FK-3	145	4.04	1.55	0.84	1.47	0.07
FK-4	140	3.89	1.75	0.84	1.25	0.07
FK-5	70	2.28	0.41	0.66	0	0.00
FK-6	[70] 131	3.85	1.7	0.84	Failed	0.07
FK-7	[62] 129	3.85	1.6	0.84	Failed	0.09
FK-8	65	2.02	0.6	0.62	0	0.00
FK-9	[86] 90	3.68	1.0	0.83	Failed	0.06

the pre-transient conditions from BISON calculations at the end of base irradiation, which is larger than the gap size assumed in FALCON analyses.

The current thermal boundary condition can be used for the prediction of the Pellet Clad Mechanical Interaction (PCMI) phase in the RIA since the cladding outer surface temperature changes little during the power pulse. In some tests (FK-1, FK-3, FK-4, and FK-9), cladding temperature escalation was observed after the power pulse phase, which was considered to be caused by Departure from Nucleate Boiling (DNB). The coolant channel model was tested for the modeling of DNB in a RIA, and it was found that the model predicts a Critical Heat Flux (CHF) not sufficient to trigger a DNB, which is consistent with the observation that the pool boiling heat transfer CHF is lower than the transient CHF reported in separate effect tests [17], and the heat transfer correlation would need to be empirically scaled to match the measurements. The determination of suitable boundary conditions for the modeling of DNB in a RIA is still undergoing.

A frictional model was tested but failed to converge, and therefore a frictionless model was used instead, and for this reason, no comparison to measurements on the axial fuel elongation was performed.

4 Summary

Several general observations can be made concerning BISON validation for RIA behavior based on the CABRI and NSSR cases studied thus far:

- BISON tends to slightly over-predict the estimated fuel radial average enthalpy compared to FALCON and reported values (predicted using SCANAIR). The results typically agree within 10% of FALCON and reported values, with slightly higher differences for REP Na-3 FALCON and REP Na-10 SCANAIR results.
- BISON agrees very well with FALCON on temperature predictions. The maximum fuel temperature (located in the high burnup rim region) and the maximum temperatures calculated for the fuel centerline and cladding inside temperatures were all within 10% of FALCON, with many of the results well within 5%.
- In general the mechanical results do not show similar close agreement with FALCON or measured values. BISON generally under predicts the max hoop strain in the cladding outer surface.
- Similar to the total hoop strain in the cladding, the plastic strain accumulation is also under-predicted. This is evident in Figures 4b and 5b showing the residual displacement or clad diameter.
- The fission gas release calculations show good agreement with measured values, with only REP Na-5 showing a sizable difference.

- Important details concerning the FALCON modeling procedure and results are not known and many assumptions were necessary to facilitate comparisons. Access to the original CABRI data is clearly desirable to improve confidence in the validation process.

With regards to BISON under-prediction of cladding hoop strains, it is again important to emphasize that the post base-irradiation conditions have a significant impact on mechanical results. One of the most significant initial conditions prior to the RIA test is the fuel-to-clad gap distance. In all cases the BISON base-irradiation calculation predicted fuel-to-clad gaps of 14.9-17.5 μm at CZP conditions after the base irradiation. Those gaps were reduced to between 9.6-14 μm at HZP conditions prior to the transient. All these cases were for high-burnup fuel (excluding REP Na-2) which should result in a closed or very small gap after the base-irradiation. Reducing this initial fuel-to-clad gap will have a direct impact on the total strain and plastic strain calculations in BISON bringing them in closer agreement with FALCON and measured results. For example, assuming no initial gap on REP Na-3, hand calculations were performed on the results from the cladding hoop strain (Figure 5a) to add the 16.4 μm gap to the displacement thus estimating the resulting total hoop strain. The results are shown in Figure 9 and the magnitude of the results compare much better to the FALCON results.

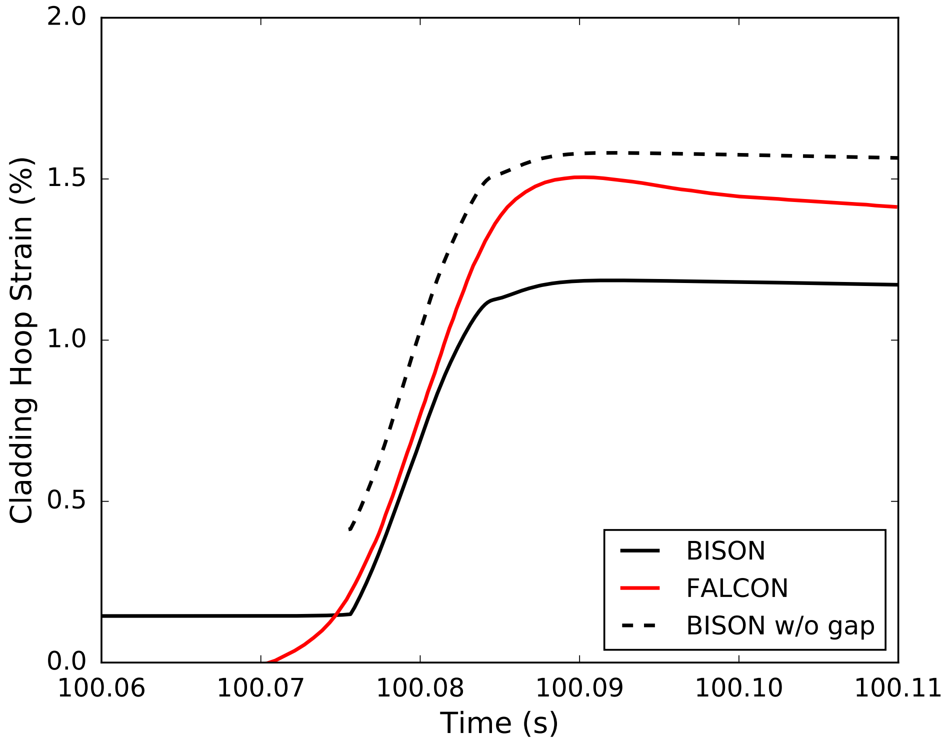


Figure 9: BISON and FALCON calculated cladding hoop strain evolution with the estimated BISON results assuming no initial fuel-to-cladding gap

5 Recommended Future Work

With regards to improving and advancing the BISON RIA validation effort, the following recommendations are made:

- Including frictional contact will permit validation of axial displacement predictions to experimental measurements and FALCON calculations. Frictional contact will also improve plastic strain predictions in the cladding.
- Considering individual fuel pellets rather than a smeared fuel column (discrete pellet meshing) will provide more prototypic results and better comparisons to measured data such as in Figure 4b.

- For preirradiated fuel, including fuel creep and smeared cracking during the base irradiation will improve initial conditions for the RIA analysis.
- Fuel-clad bonding occurs with high-burnup cases and results in a much different estimation of the fuel-to-cladding gap after the base irradiation. During cold zero power conditions this could likely result in a closed gap between the fuel outer surface and the cladding inner surface with gaps opening up inside the fuel cracks. Understanding and accounting for this could likely have a large impact on the estimation of pellet-clad-mechanical-interactions during RIAs and other transient events.
- Implementing a failure model for RIA applications to predict when and where failure occurs during fast transients.
- Only a small set of cases have been considered thus far with additional cases needed to improve confidence in using BISON for RIA analysis. The RIA Challenge Problem Implemmentation Plan identifies additional priority cases [1].

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