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INTRODUCTION

Reactivity Initiated Accidents (RIA) are design basis accidents that can adversely impact core coolability. In the unlikely event sufficient reactivity is inserted into the reactor core by the ejected/dropped control rod, prompt energy deposition into the fuel can occur. If sufficiently high, such deposition can lead to fuel rod failure or, at extreme levels, expulsion of UO_2 fragments or molten UO_2 material from the fuel rod. This results in a release of fission product and fuel into the coolant, potentially compromising core coolability and threatening the pressure boundary of the primary coolant system.

Design basis RIA is an industry-challenging problem that the Consortium for the Advanced Simulation of Light Water Reactors (CASL) aims to address. The CASL RIA Challenge Problem Charter [1] states, "The Pressurized Water Reactor (PWR) Rod Ejection Accident and Boiling Water Reactor Control Rod Drop Accident are postulated accidents with consequences that are important to nuclear safety (fuel rod integrity and core coolability). Currently, each reload core design must be analyzed to meet regulatory acceptance criteria. The goal of CASLs ModSim capability for RIA is to model the event at a higher fidelity, with validation to existing tests, to better model the transient neutronics and the progression of the fuel and cladding thermal-mechanical behavior. These improved analytical capabilities can be used to better inform reload core design, limits on fuel assembly discharge burnup, restrictions on placement of fuel in the reactor, control rod insertion limits, operating margin, and performance sensitivities." In support of that charter, BISON, a fuel performance code, is used to demonstrate the simulation of thermal-mechanical behavior in light water reactor (LWR) fuels during RIAs. The combination of mechanical, thermal, and thermal-hydraulic phenomena present during an RIA makes a multiphysics code such as BISON a valuable tool for modeling these scenarios.

This paper highlights many BISON-associated activities relevant to RIA capability development and validation efforts. These efforts have been performed under both the CASL and Nuclear Energy Advanced Modeling and Simulation (NEAMS) programs.

BISON DEVELOPMENTS FOR RIA ANALYSIS

BISON [2] is a modern, finite element-based, multidimensional fuel performance code under development at Idaho National Laboratory since 2009. In addition to being the fuel performance code adopted by CASL, BISON is used in multiple Department of Energy Office of Nuclear Energy programs, as well as by industry and academia. Recent work has demonstrated that BISON is capable of simulating LWR fuel under normal operating conditions [3], in addition to special conditions such as missing pellet surfaces [4]. More recently, BISON was demonstrated in transient analyses such as loss-of-coolant accidents (LOCA) [5, 6] and RIAs [7, 8].

This work was made possible by capability enhancements necessary for modeling the complicated thermo-mechanical response of fuel rods during RIA and LOCA transients. Many of the enhancements are cross-cutting for both LOCA and RIA. A good summary of the LOCA enhancements are documented in the CASL LOCA Challenge Problem report [9], and capability enhancements more relevant to RIA scenarios are highlighted in this paper.

A Zircaloy cladding plasticity model applicable to high temperatures and strain rates was implemented into the BISON code [10]. Rapid increase in reactor power during an RIA causes a very fast increase in fuel temperature and expansion into the cladding. Rapid thermal expansion of fuel into the cladding can impose large stresses on the cladding, exceeding the yield stress and imparting permanent plastic deformation on the cladding. Accurately predicting the cladding plastic strain is important because, historically, post-test measurement of residual strain in the cladding is one of the few metrics available to validate the mechanical parameters of RIA tests.

An RIA failure model based on critical strain energy density (CSED) [11] was also developed for BISON. The plasticity model in BISON calculates the strain energy density (SED) in the cladding and compares it against the CSED model to determine whether failure has occurred. These capabilities were added to BISON so the SED in the cladding could be calculated and compared to the CSED model [12].

A time increment control was implemented to improve the numerical solution in the presence of non-linear material behavior, such as plasticity and creep, during accident scenarios. In particular, a time step criterion physically based on the material's strain rate was implemented. The criterion limits the time step length in order to guarantee that the increment of inelastic strain during the time step is kept under a pre-defined limiting value. Due to time discretization in the presence of non-linear material behavior, the new criterion enables automated control of the numerical error, thereby improving the accuracy of the numerical solution.

More recently, a mechanistic model for predicting the release of gaseous fission products in fast transient conditions was added in BISON to improve fission gas release (FGR) prediction for RIAs [13].

INTEGRAL TEST VALIDATION

The capabilities added to BISON for addressing RIA problems have been demonstrated by comparing BISON's integral test simulation results with the experimental results, and also benchmarked against the Falcon fuel performance code. These cases are summarized below.

CABRI Cases

The CABRI test reactor is a pool-type LWR with a central area that accepts the insertion of a test device. The central area, originally designed to study fast reactor transients, contained a sodium coolant loop that was recently converted into a water loop. Numerous cases were selected from multiple CASL and NEAMS programs for application in validation efforts. These tests include CABRI REP cases Na-2 through Na-5, in addition to Na-10, with UO_2 fuel and Zircaloy-4 cladding tested in sodium coolant. The CIP3-1 case with UO_2 fuel and ZIRLO^{TM} cladding was selected, though the experiment has not been run. It is scheduled to be completed with the upgraded CABRI water loop capabilities. In collaboration with the IRSN, a SCANAIR/BISON comparison benchmark was completed on the CIP0-1 case [7], a UO_2 fuel with ZIRLO^{TM} cladding performed in sodium coolant. Details of each test are summarized in TABLE I.

Full details of the CABRI case results can be found in [8, 14, 15], with certain highlights shown here. A primary regulatory acceptance criterion for the RIA is that fuel temperature and radial average enthalpy (RAE) responses remain within established limits. BISON demonstrated that it can accurately predict these parameters, as shown (for case REP Na-5) in Fig. 1.

TABLE I: CABRI REP and CIP Test Summary [16-18]

Test	**REP Na-2**	**REP Na-3**	**REP Na-4**	**REP Na-5**	**REP Na-10**	**CIP0-1**	**CIP3-1**
Fuel type	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2	UO_2
Cladding type	Std Zy-4	Std Zy-4	Std Zy-4	Std Zy-4	Std Zy-4	ZIRLO	ZIRLO
Initial enrichment (^{235}U/U %)	6.85	4.5	4.5	4.5	4.5	4.5	4.5
Internal gas pressure (MPa, 20°C)	0.101	0.31	0.301	0.302	0.301	0.304	2.35
Active length (mm)	1004.9	441	563	564	559	540.7	540.7
Max. burnup (GWd/tU)	33	54	62	64	63	75	72
Corrosion thickness (μm)	10	35-60	60-80	15-25	60-100	70-90	60-110
Pulse width FWHM (ms)	9.6	9.5	76.4	8.8	31	32.4	9
Energy deposit (cal/g)	207	122	95	104	108	99	115
Cladding OD (mm)	9.51	9.55	9.51	9.51	9.51	9.50	9.50
Cladding thickness (mm)	0.637	0.596	0.578	0.578	0.575	0.5715	0.5715
Pellet OD (mm)	8.05	8.19	8.19	8.19	8.19	8.192	8.192
Pellet height (mm)	11.99	13.69	13.74	13.74	14.25	9.83	9.83
Diametral fuel-cladding gap (μm)	186	164	164	164	164	165	165
Coolant type	Sodium	Sodium	Sodium	Sodium	Sodium	Sodium	Water
Coolant pressure (MPa)	0.5	0.5	0.5	0.5	0.5	0.5	15.5
Coolant temp. (°C)	280	280	280	280	280	280	280

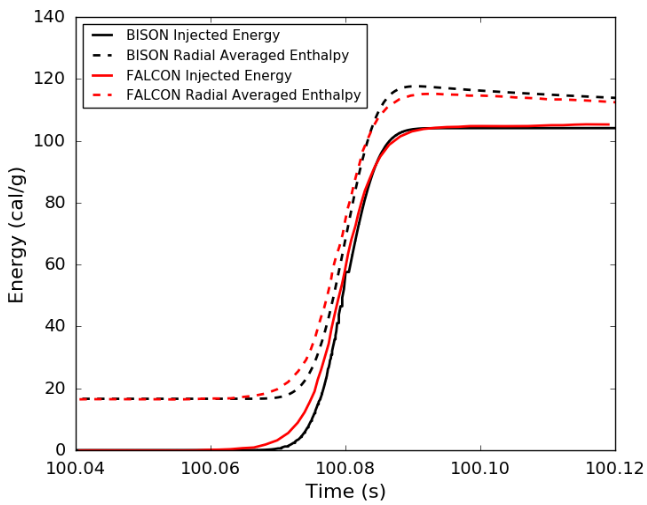

Fig. 1: BISON and Falcon comparison for energy deposited and RAE for REP Na-5

The BISON, Falcon, and reported values for peak fuel RAE are summarized in TABLE II, and the BISON and Falcon peak fuel centerline and maximum fuel temperatures are tabulated in TABLE III. Energy, RAE, and temperature comparisons with the Falcon and experimental/reported values show excellent agreement for many of these cases.

TABLE II: Comparison of peak fuel RAE (cal/g) increase from 20°C

Case	BISON	Falcon	Reported Value
REP Na-2	209	200	199
REP Na-3	136.7	118	123.5
REP Na-4	87.7	71.9	85.9
REP Na-5	117.6	115	108
REP Na-10	119	109	98

TABLE III: Comparison of peak fuel temperatures (K)

Case	BISON		Falcon	
	Centerline	Max	Centerline	Max
REP Na-2	2647	3134	2775	2948
REP Na-3	1965	2643	1960	2480
REP Na-4	1671	-	1625	-
REP Na-5	1770	2300	1757	2387
REP Na-10	1820	2114	1662	2046

While BISON compared very well with Falcon in regard to thermal results, the mechanical results showed greater deviation from both Falcon and measured values. There are a number of postulated reasons for this. 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 [19]. BISON calculates this gap based on results from the base irradiation simulation, which indicates a gap opening up between the fuel and cladding during cooling from operational conditions. Both the Falcon and post-irradiation examinations of these cases—all of which are medium to high burnup—have no initial fuel-to-cladding gap in their respective analyses and simulations.

Even with the larger deviation in mechanical results compared to the thermal results, BISON accurately calculated the SED for failure prediction and the total elongation of the cladding. Fig. 2 shows SED prediction for BISON compared to a CSED failure model for each case. Fig. 3 shows BISON and Falcon predictions of peak cladding elongation during the test, compared to the measured results. In all cases BISON does a good job at predicting failure or matching with experimental results. An overview of the mechanical parameters is shown in Table 2 of [12].

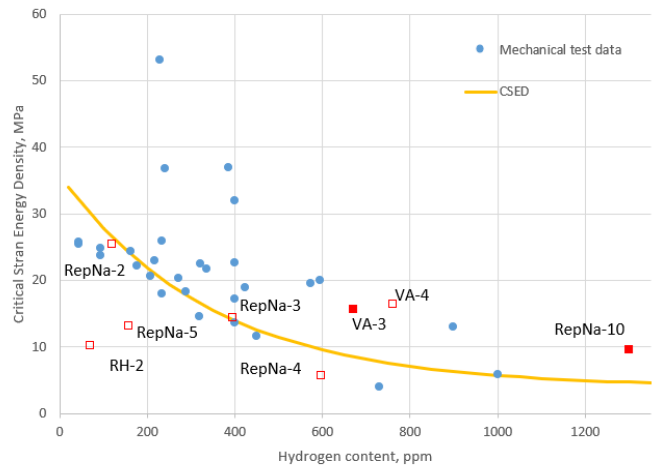

Fig. 2. SED calculated by BISON, compared to the CSED (as a function of total hydrogen content) failure model; solid symbols represent failure cases, and hollow symbols represent non-failure cases.

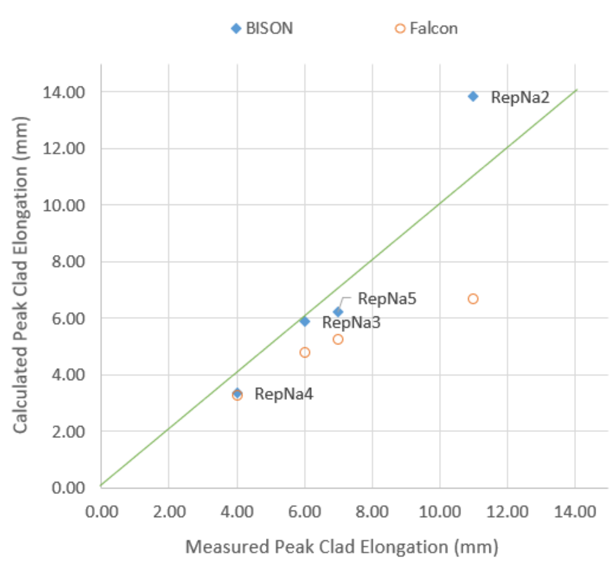

Fig. 3. Comparison between calculated and measured peak clad elongation for BISON and Falcon

The predictions for FGR during the transient are very promising. BISON predicted a final FGR of 6.7%, compared to the measured value of 5.5% for REP Na-2, and 10.3% compared to the 13.7% for REP Na-3. A plot of the FGR history for REP Na-2 is shown in Fig. 4, with the fuel centerline temperature plotted on the right ordinate. The inset shows FGR and fuel temperature during the time period of the pulse. In this figure, the initial large increase in FGR is highly correlated to the fast increase in fuel temperature resulting in microcracking and a burst release of fission gas. Note that traditional FGR models typically only account for diffusion-based FGR and tend to strongly underpredict FGR during the short duration of an RIA event. This is demonstrated in Fig. 4 via comparison with results from a purely diffusion-based model that solely differs from the original BISON model in terms of the specific transient (microcracking) capability being deactivated. In the REP Na-2 case, FGR still increases due to diffusion following the initial burst release, due to very high fuel temperatures reaching between 2700–3000 K. Hence, the recently developed transient FGR model in BISON may represent an important step towards better capturing fuel behaviors during RIAs.

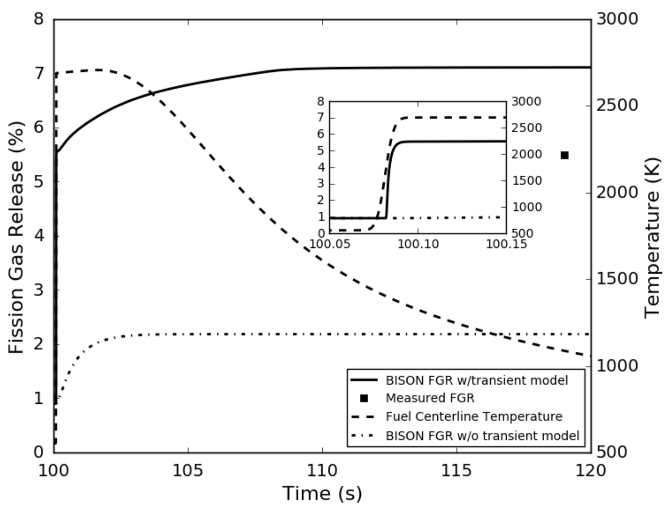

Fig. 4. CABRI REP Na-2 FGR results plotted with the fuel centerline temperature compared with the measured FGR results post-RIA. Plotted for comparison are the BISON results for FGR during the RIA with the transient FGR model turned off.

NSRR Cases

NSRR is a modified Training, Research, Isotopes, General Atomics (TRIGA) Annular Core Pulse Reactor (ACPR) with a dry space located in the center of the core. In a simulated RIA test, a single instrumented fuel rod in a water-filled capsule is placed in the center of the core and then pulse irradiated. A large number of experiments on simulated RIAs have been performed at the NSRR test facility to evaluate fuel rod behavior and failures for different energy depositions, burnups, fuel designs, and coolant conditions. Some cases with medium and high burnups were selected for the validation of BISON. These include cases FK-1 through FK-9, VA-3, VA-4, and RH-2. Full details of these cases can be found elsewhere [8, 12], with key characteristics summarized in TABLE IV.

The results from the validation of the NSRR cases can be seen in previously published work [8, 12]. The calculated temperature histories for test case FK-3 at the fuel centerline, fuel outer surface, and clad inner surface are shown in Fig. 5.

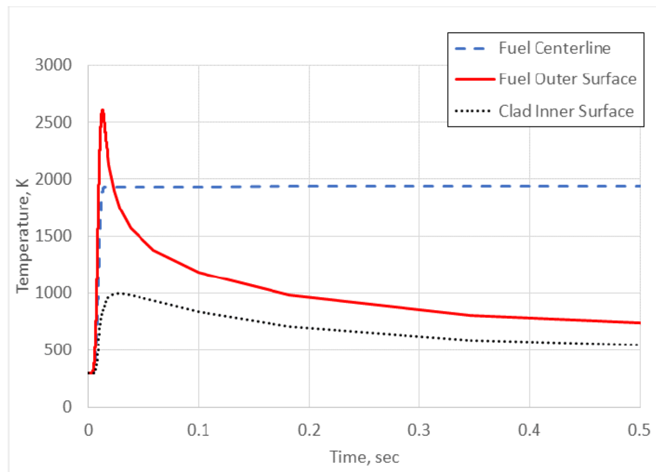

Fig. 5. Temperature at the fuel centerline, fuel outer surface, and clad inner surface for case FK-3

Results of temperature predictions for NSRR FK cases calculated by BISON, along with the Falcon predictions, are summarized in Table 4 of reference [8]. Results of clad hoop strains calculated by BISON are shown in Table 5 of reference [8], in comparison to the Falcon results.

For most cases, BISON calculations on the fuel temperatures closely match the Falcon results, except in a few cases involving peak rim temperature predictions. However, the calculated clad hoop strains by BISON are generally smaller than the post-test measurements and Falcon code results. As mentioned, this may be because the gap size used in the pre-transient conditions for the BISON calculations at the end of base irradiation is larger than the gap size assumed in the Falcon analyses.

TABLE IV: NSRR Test Summary [20, 21]

Test	FK1	FK2	FK3	FK4	FK5	FK6	FK7	FK8	FK9	VA-3	VA-4	RH-2
Cladding type	Zry2	Zry2	Zry2	Zry2	Zry2	Zry2	Zry2	Zry2	Zry2	ZIRLO	MDA	M5
Coolant type	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O
Coolant temp. (°C)	20	20	20	20	20	20	20	20	20	285	249	278
Coolant pressure (MPa)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	6.8	4	6.4
Clad thickness (mm)	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.57	0.57	0.57
Fuel density (%TD)	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
Initial enrichment (^{235}U/U %)	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	5	5	5
Burnup (GWd/tU)	45	45	41	56	56	61	61	61	61	71	77	67
Internal gas pressure (MPa, 20°C)	0.3	0.3	0.3	0.5	0.5	0.1	1.5	1.5	1.5	0.1	0.1	0.1
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)	130	69.8	145	140	131	131	129	64.8	89.8	108	109	90
Pulse width FWHM (ms)	4.5	7	4.5	4.3	7.3	4.3	4.3	7.3	5.7	4.4	4.4	4.4
Failure enthalpy (cal/g)	-	-	-	-	-	70	62	-	86	82	-	-

CONTROL ROD EJECTION ACCIDENT DEMONSTRATION

As part of the efforts to address CASL RIA Challenge Problems, BISON was used to model a full-length PWR rod with power and thermal-hydraulic conditions generated by other codes in the CASL suite. A control rod ejection accident was simulated in VERA, a core simulator tool. VERA provided the rod power, and COBRA-TF provided the thermal-hydraulic boundary conditions. This demonstration showed the flexibility of BISON in being coupled with other codes for multiphysics simulation of a design basis accident in a PWR. Details on this demonstration problem can be found in [22, 23].

CONCLUSIONS

BISON has proven capable of simulating RIAs with reasonable accuracy compared to other codes and experimental results. A total of five CABRI REP Na cases and two CABRI CIP cases were completed, and nine NSRR FK, two NSRR VA, and an NSRR RH case were analyzed.

In general, BISON provides good results for both fuel RAE and fuel temperature predictions—both used as regulatory acceptance criteria for RIA transients. BISON shows reasonable agreement with Falcon on predicted mechanical results such as cladding hoop strain. BISON provides accurate SED calculations that can be used for failure predictions, with BISON successfully predicting the non-failed rods (REP Na-2 through Na-5) and the failed rod (REP Na-10). Frictional contact modeling allows for comparisons with clad elongation, showing very good agreement with the post-test measurements and Falcon results. The addition of the transient FGR model shows very promising results for predicting FGR following fast transients such as RIAs.

BISON still underpredicts many of the mechanical parameters, such as residual cladding displacement at the end of the RIA, when compared against experimental results. This can be partly explained by the initial fuel-to-cladding gap prior to the RIA, but additional work and development needs to be implemented to improve these results.

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