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Changing the World's Energy Future

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Abstract

The Bison fuel performance code has been under development at Idaho National Laboratory by various programs within the U.S. Department of Energy since 2009. As part of any fuel performance code development, validation is necessary. To this end, several Halden experiments have been used. Early on, the focus was on validating the thermal mechanical behaviour, including pellet cladding mechanical interaction and fission gas release models implemented in Bison. Support for design-basis accident capabilities began in approximately 2014. Also in 2014, the development of models for accident tolerant fuel (ATF) concepts also began. This includes doped-UO_2 fuel for which Halden has some experiments with temperature and fission gas release measurements. The Bison team has been fortunate to have two senior developers be secondees to Halden for a year: the late Dr. Giovanni Pastore from May 2015 to April 2016 and the now retired Dr. Richard Williamson in 2018. The paper will provide examples of Bison validation using Halden data for standard UO_2 fuel under normal operation and loss-of-coolant accident condition, and ATF concepts. A tribute to the legacy that both the late Giovanni and retired Richard left on the Bison code is provided.

1. Introduction

The Bison fuel performance code [1] has been under development at Idaho National Laboratory under various programs within the U.S. Department of Energy (DOE) since 2009. This development has been supported through the Nuclear Energy Advanced Modeling and Simulation (NEAMS) and Consortium for Advanced Simulation of Light Water Reactors (CASL) programs, as well as various Laboratory Directed Research and Development (LDRD) projects. Contributions to the code have also been made by collaborators from universities, other national laboratories, and industry partners. As part of any fuel performance code development, validation is necessary. To this end, several Halden experiments have been used. In the early days, the focus was on validating the thermal mechanical behaviour, including pellet cladding mechanical interaction, and fission gas release models implemented in Bison. Therefore, experiments such as IFA-431, IFA-432, IFA-515, IFA-519, IFA-534, IFA-535, IFA-562, IFA-597.3, and IFA-636 have been used. The selection of cases was primarily identified through their inclusion in many International Atomic Energy Agency international benchmarks such as Fuel Modelling at Extended Burnup (FUMEX)-II and FUMEX-III [2–3].

Support for design-basis accident capabilities began in approximately 2014. This includes loss-of-coolant accident (LOCA) capabilities such as high-temperature cladding creep and oxidation, Zircaloy phase transition, cladding failure, and fuel fragmentation, relocation, and dispersal. Naturally, this led to the Bison development team’s participation in the FUMAC-coordinated research project [4]. The integral experiments used for code comparisons as part of this project were several rods from the IFA-650 LOCA test series. Also in 2014, the development of models for accident tolerant fuel (ATF) concepts also began. This includes doped-UO_2 fuel for which Halden has some experiments with temperature and fission gas release measurements. These include IFA-677 and IFA-716.

The Bison team has been fortunate to have two senior developers be secondees to Halden for a year. From May 2015 to April 2016, the late Dr. Giovanni Pastore had the privilege to spend a year at Halden interacting with experimentalists and gaining insight into the data used for validation activities. This interaction supported the first validation of gadolinia capabilities in Bison to the IFA-681 test series. In 2018, the now retired Dr. Richard Williamson had the same opportunity and was able to get back to his technical roots after establishing himself in a more program manager role. His work focused on improving the Bison UO_2 creep model.

This paper will provide an example of Bison validation to the various Halden examples including normal operation, LOCA, and ATF. A tribute to the legacy that both the late Giovanni and retired Richard left on the Bison code and the development team in general will also be presented.

2. Bison Overview

The Bison fuel performance code is a finite element-based computational software used to evaluate the performance of a wide variety of nuclear fuel concepts in 1, 1.5, 2, 2.5, or three dimensions. The code is built upon the Multiphysics Object-Oriented Simulation Environment (MOOSE) [5] which provides fundamental physics modules (e.g., solid mechanics, heat transfer, and contact) as well as the underlying computational solvers and supported finite element types through third-party libraries, PETSc [6] and libMesh [7]. Bison supports both steady state and transient analyses with timesteps ranging from milliseconds to months, enabling fuel performance analyses that encompass both normal operation and design-basis accidents such as reactivity insertion accidents and loss-of-coolant (LOCA) accidents. To date, simulations have been conducted using Bison for research reactor fuel plates, metallic fast reactor fuels [8–9], TRI-structural ISOtropic fuel particles [10–12], accident tolerant fuel (ATF) concepts for light-water reactors (LWRs) [13–15], LWR fuels [16–18], and fast reactor mixed-oxide (MOX) fuels [19].

Since the beginning, development of Bison has employed a multiscale model development philosophy. Where appropriate, empirical and semi-empirical models are implemented to represent various physical phenomena and thermophysical properties of interest. In application regimes outside of the validity of the empirical models or areas in which empirical models are not available due to lack of data, atomistic and mesoscale simulations are used to develop correlations that are physics-based for use in Bison. The fission gas behaviour in Cr_2O_3-doped UO_2 [14] is a good example of the multiscale approach in action applied to data available from Halden.

3. Secondees to Halden

The Bison development team has had many contributors throughout its lifetime. Two long-term members of the team had the opportunity to be secondees at Halden for a year: Dr. Giovanni Pastore from May 2015 to April 2016 and Dr. Richard Williamson in 2018. Figure 1 provides photographs of Giovanni and Richard as a reminder to those who have worked with them over the years. Both Giovanni and Richard were key faces at Enlarged Halden Programme Group meetings.

Figure 1. Photographs of Dr. Giovanni Pastore (left) and Dr. Richard Williamson (right).

3.1 Dr. Giovanni Pastore

Giovanni started as postdoctoral researcher in the Bison team in 2012 after earning his master's degree in nuclear engineering (2008) and PhD cum laude (2012) from the Politecnico di Milano in Italy. In 2013, Giovanni was converted to a full-time staff member at INL. From 2017 until his departure from INL in 2020, Giovanni led the team developing Bison. His contributions to the code had a tremendous impact on credibility of the predictions. His work on fission gas transport and release was instrumental in improving Bison code predictions. Through an internal LDRD project at INL, he initiated the implementation of capabilities for LOCAs. During his time at INL, he was twice the principal investigator for a U.S. DOE Scientific Discovery through Advanced Computing (SciDAC) project, was the INL principal investigator for a DOE Integrated Research Project on hydride behaviour in spent fuel, and was the DOE chief investigator on an International Atomic Energy Agency Coordinated Research Project on accident tolerant fuels.

Besides INL, Giovanni worked at the Halden Reactor Project in Norway as a secondee, Massachusetts Institute of Technology as a visiting scientist, University of Tennessee-Knoxville as a research professor, and Newcleo, an advanced reactor startup in Italy. As a secondee at Halden, he interacted with experimentalists and gained insight into the data used for validation activities. This interaction supported the first validation of gadolinia capabilities in Bison to the IFA-681 test series. Sadly, Giovanni passed away in 2023.

3.2 Dr. Richard Williamson

Richard spent his entire professional career, spanning over 40 years, at INL. He has extensive experience in many key areas of computational methods research and model development, including nonlinear thermo-mechanics, fracture mechanics, shock wave and detonation, and thermal plasma spray. From 2009 to 2016, Richard led the team developing Bison. He later served as the technical lead of the Fuels Area within the NEAMS program, which has funded a significant portion of the Bison development efforts. Richard was given the INL Laboratory Director's Award for Exceptional Scientific Achievement in 2014. In 2018, he spent a year at Halden as a secondee focusing on UO_2 creep and improving the model available in Bison. Richard ended his career as an INL Laboratory Fellow in 2022, one of the most prestigious titles that can be bestowed upon an employee at the laboratory. His time at Halden influenced his post-retirement activities as he and his wife are currently serving as senior missionaries for The Church of Jesus Christ of Latter-day Saints in Norway.

4. Validation of Bison Using Halden Experiments

Exposure to the wealth of data generated at the Halden reactor over the years by the Bison development team has primarily been through international benchmarks [2–4]. An initial summary of the validation status of Bison was published in 2016 [16], which highlighted the current state of Bison LWR capabilities at that time. The paper described the material and behavioural models available in Bison and its application to several validation cases. Some of these experiments were from Halden: IFA-431, IFA-432 IFA-515.10, IFA-534, IFA-535, IFA-562.2, and IFA-597.3. The primary validation metrics in this publication were fuel temperature, fission gas release, and cladding profilometry during base irradiation and ramps.

More recently, publications on the initial validation of the LOCA capabilities in Bison [17–18] became available. The first focused on cladding behaviour including ballooning and rupture. Key metrics of interest included rod internal pressure evolution, rupture time, and cladding profilometry. The second focused on model developments for fuel behaviour during a LOCA such as fuel fragmentation and relocation. The metric of interest in this publication included comparisons to gamma scans indicating fuel relocation. The Halden cases used in these activities were from the IFA-650 series. Rods 2, 4, 9, 10, and 14 have been analysed. Comparisons to the distribution of particle sizes are the subject of the ongoing Bison work funded by the NEAMS program.

These cases for LWR analyses that have been added over the years are included in an automated validation suite for Bison. Since Bison itself is continuously under development (new features added directly into Bison or inherited from updates to the underlying MOOSE modules), nightly execution of the validation suite is performed. Automated updating of the accompanying plots and documentation is a subject of current development.

The ability of the Bison team to access Halden experimental data has been invaluable. Whether via the legacy interface or the more recent database at Halden, extracting experiment design details and data recorded during irradiation has proven to be essential in our validation work. With the transition to locally hosted copies of the Halden database, we look forward to continuing to review and learn from the decades of Halden experiments.

The subsections here provide highlights from various publications on the Bison validation efforts against selected Halden reactor experiments.

4.1 Normal Operation

Fuel performance under normal operation is concerned with the beginning-of-life and through-life analysis of temperature and fission gas predictions. Recent work provided updated comparisons to the IFA-431 and IFA-432 [20] beginning-of-life temperature measurements [21]. These updated comparisons utilize an improved treatment of the gap conductance across the fuel to cladding gap in UO_2 fuel rods. The updated predicted versus measured plots are shown in Figure 2. The key observation is that the new gap conductance models yield a reduction in uncertainty between the Bison simulation and thermocouple measurements. Overall, the predicted temperatures are decreased under all conditions using the new models from Toptan et al. [21].

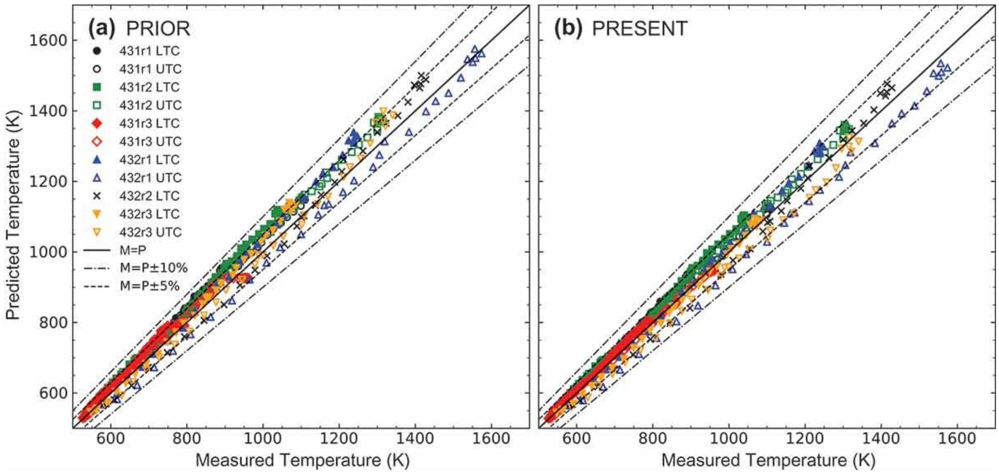
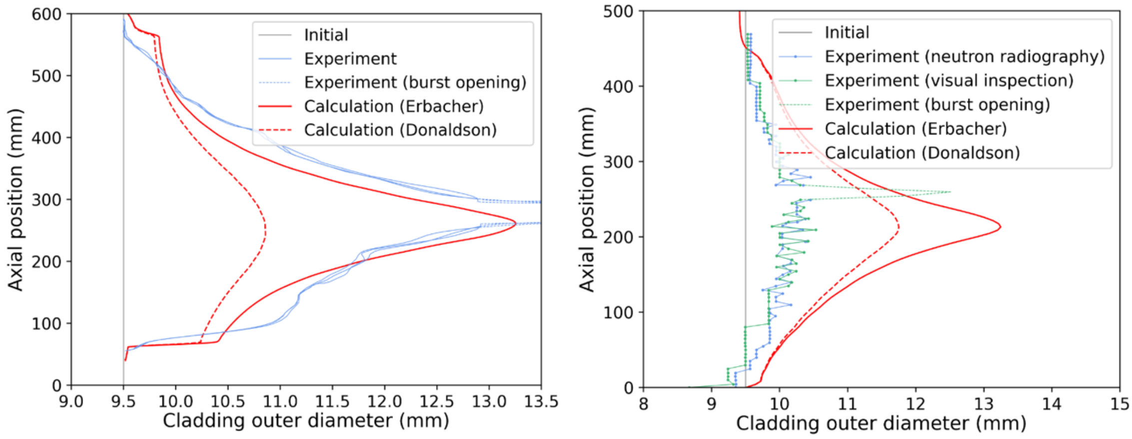


Figure 2. Predicted versus measured temperatures for the beginning-of-life rise to power for IFA-431 and IFA-432. LTC and UTC refer to lower thermal couple and upper thermal couple, respectively. M=P is the measured equals predicted line.

4.2 Loss-of-Coolant Accidents

Initial work [17–18] presented the initial validation of the LOCA capabilities in Bison. Through the NEAMS program, continued development is ongoing in improving the models for fuel fragmentation, relocation, dispersal, and high-temperature cladding creep originally highlighted in the previous publication. Every year, a report is published through NEAMS that highlights the impact of that year's improvements. Since the initial publications, research has been conducted in two specific areas: high-temperature cladding creep and fuel fragmentation. Recent work [22] has exercised different high-temperature creep models against the experimental measurements for cladding profilometry comparisons to IFA-650.2 [23] and IFA-650.10 [24]. A comparison is shown in Figure 3 between the two different high-temperature creep models (denoted as Erbacher and Donaldson) against the experimental profilometry data. It is found for the fresh fuel case in IFA-650.2 that the Erbacher model more accurately matches the experimental measurements; whereas for the irradiated IFA-650.10 model, the Donaldson model has better comparisons with the experiment. The primary difference between the Erbacher and Donaldson models is the grain size dependence on the creep rate.



(a) (b)

Figure 3. Cladding profilometry predictions using two different high-temperature creep correlation calculations (a) IFA-650.2 and (b) IFA-650.10.

In terms of validating axial relocation algorithms, Gamble [25] built upon the original publications [17–18] by extending the validation of IFA-650.4 [26], IFA-650.9 [27], and IFA-650.14 [28] by incorporating sensitivity analysis in the predictions. Figure 4 reproduces selected plots from [25] showing fuel mass fraction predictions as a function of axial comparison for IFA-650.4 and IFA-650.9 with comparisons to the gamma scan taken 6 weeks after the conclusion of the experiments. Solid curves correspond to simulations using the plastic instability criterion, whereas dashed lines represent the overstrain criterion. Coloured lines correspond to different correlations for computing the size and number of large-scale fragments. Details of these models can be found in [25]. The sensitivity analysis determined the emissivity for radiative heat transfer was the parameter that had the strongest sensitivity on the mass fraction predictions.

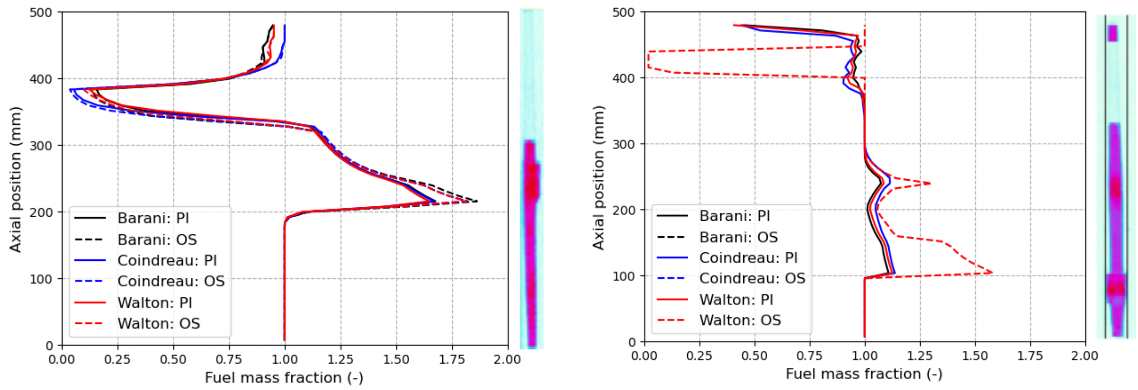


Figure 4. Fuel mass fraction predictions using three different large fragment correlations and two different failure criteria (PI: plastic instability, OS: overstrain) for (a) IFA-650.4 and (b) IFA-650.9. Curves correspond to the average of 200 different simulations assuming sensitivity on axial relocation model parameters and the emissivity between fuel rod and heater post-blowdown.

4.3 Doped UO_2

Cr_2O_3-doped UO_2 is a promising candidate for the replacement of standard UO_2 in conventional LWRs due to its larger grain size which is intended to provide benefits on fission gas retention and reduced creep. Atomistic scale simulations were conducted to gain insight in the impact the chromia dopant has on fission gas diffusivities. Cooper et al. [14] proposed an equation of the form:

(1)

where is the temperature, , , and represent the intrinsic, irradiation-enhanced, and athermal contributions to fission gas diffusivity for undoped UO_2, and , , , and are constants that have different values depending upon assumptions in the lower length scale fitting. Details can be found in [14]. Two cases were considered, denoted as Case A and Case B. For Case A, K, eV, and eV. For Case B, K, eV, and eV.

Integral simulations of the Cr_2O_3-doped fuel rods in the Halden IFA-716.1 [29] test was performed with Bison. Several different variations of the fission gas diffusivity were evaluated for fuel behaviour during Halden tests: (i) the standard UO_2 empirical (Turnbull) model (blue lines), (ii) Case A (solid black lines), and (iii) Case B (dashed black lines) of the lower length scale (LLS)-informed diffusivity model. For the empirical undoped UO_2 (Turnbull) model, a smaller (5.5 μm) grain radius, typical of undoped UO_2, was tested in addition to the large grains (35 μm for Rod 1 and 29.5 μm for Rod 6) reported in the actual fuel. This was done to investigate the effect of the grain size on FGR in the calculations. For all other diffusivity cases, only the large grain size was used.

Figure 5 reproduces the fission gas predictions originally published in [14]. As can be seen, the LLS Case A and Case B models bound the experimentally measured fission gas release. This highlights the importance of utilizing physics-based analyses for physical properties of novel concepts in which experimental measurements are limited.

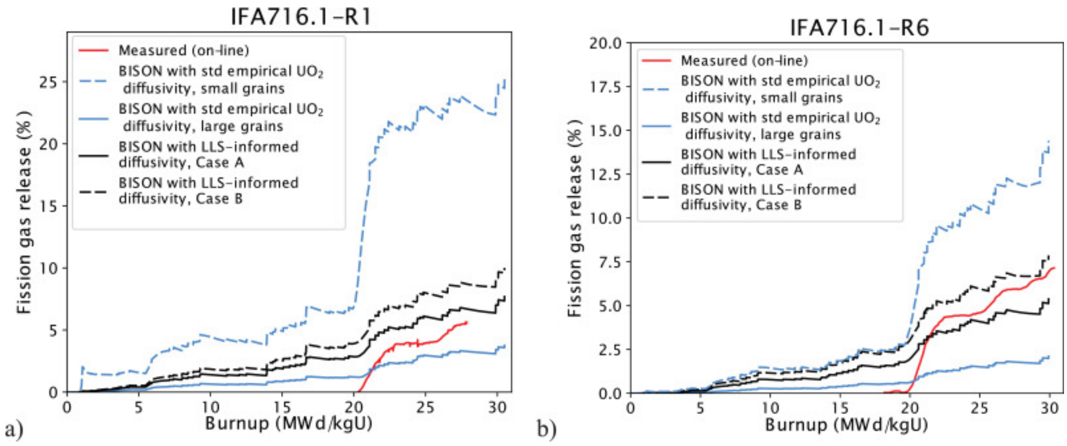


Figure 5. Fission gas predictions using the various assumptions for fission gas diffusivities for IFA-716.1 (a) Rod 1 and (b) Rod 6.

5. Conclusions

The Halden Reactor Project has been instrumental in the development and validation of the Bison fuel performance code. Initial exposure was through international benchmarks completed prior to the development of the code. Since then, the use of the data from Halden has steadily increased to include additional cases. The use of select experiments has been highlighted in this paper. The ability to have two former senior members of the team to spend a year as secondees was invaluable in gaining insight into how the Halden reports are drafted and the best practices when using the available documentation and data. With the transition to locally hosted copies of the Halden database, we look forward to the continued ability to review and learn from the decades of Halden experiments.

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