INL/CON-19-52847
PREPRINT

Demonstration of BISON/TRACE Coupling (CRAB) Through Validation Case LOFT L2-5

Global/Top Fuel 2019

Russell Gardner, Cody Permann, Matthew Bernard, Richard Williamson

September 2019

Demonstration of BISON/TRACE Coupling (CRAB) Through Validation Case LOFT L2-5

Russell Gardner[1], Cody Permann[2], Matthew Bernard[3], Richard Williamson[4]

[1]Idaho National Laboratory, 2525 Fremont Ave, Idaho Falls, ID 83402, russell.gardner@inl.gov
[2]Idaho National Laboratory, 2525 Fremont Ave, Idaho Falls, ID 83402, cody.permann@inl.gov
[3]Nuclear Regulatory Commission, 11555 Rockville Pike, Rockville, MD 20852, matthew.bernard@nrc.gov
[4]Idaho National Laboratory, 2525 Fremont Ave, Idaho Falls, ID 83402, richard.williamson@inl.gov

ABSTRACT

The postulated pressurized water reactor (PWR) accident known as a large-break loss of coolant accident (LOCA) is still of great concern to the current nuclear reactor fleet.

Research through experiments, modeling, and simulation is active in the field of LOCAs and new modeling tools are under continuous development. The BISON fuel performance code, developed at the Idaho National Laboratory (INL), is one such tool that has been very active in the development of models and the simulation of accidents. With recent model developments, Bison has been used to simulate LOCA cladding burst experiments and full integral LOCA experiments with favorable results. Bison is a thermomechanical code that must be fed boundary conditions (BC) for phenomena occurring outside of the fuel rod. These BCs include moderator or outer cladding temperature, coolant pressure, and rod linear power or neutron flux. These BCs can be supplied from a function or, preferably, another coupled code. Bison is built on the Multiphysics Object Oriented Simulation Environment (MOOSE) framework which allows for ease of code coupling. A framework is currently in place that allows codes external to MOOSE to communicate with MOOSE applications as if they were a MOOSE application. Through a recent MOOSE/BISON development, with collaboration from the U.S. Nuclear Regulatory Commission (NRC), BISON has been coupled with the NRC system code TRAC/RELAP Advanced Computational Engine (TRACE).

Simulation results of the initial validation loss of flow test (LOFT) L2-5 case from this research will be presented.

1. INTRODUCTION

BISON [1] is a parallel, multidimensional, finite-element-based fuel performance code built on the Multiphysics Object Oriented Simulation Environment (MOOSE) framework, and has been under continuous development at Idaho National Laboratory (INL) since 2008. BISON has the capability to simulate a wide range of fuels—including light water reactor (LWR), metallic, and tristructural isotropic (TRISO) particle fuel, and includes material models for multiple LWR accident tolerant fuel (ATF) concepts. More recently, BISON development and validation efforts for transient analysis have been ongoing, with simulations from loss of coolant accidents (LOCAs) and reactivity insertion accidents (RIAs), as reported in [2–5].

BISON has recently been coupled to the U.S. Nuclear Regulatory Commission's (NRC's) nuclear reactor systems code "TRACE" via a MOOSE-wrapped application. TRACE represents the NRC's flagship thermohydraulic analysis tool and is used extensively for licensing evaluations. Through the MOOSE-wrapped application, TRACE is seen as a native MOOSE application, which allows BISON/TRACE to leverage the MOOSE transfer system and time-stepping capabilities that are already in place.

The coupling of TRACE and BISON for LOCA simulations represents a first-of-its-kind capability. TRACE has been used extensively for stand-alone LOCA simulation and analysis, but does not include important fuel and cladding thermomechanics. An example of this is that the fuel-cladding gap is assumed stationary during a simulation, meaning that fuel thermal expansion and swelling, as well as cladding creep, are not properly accounted for. The evolution of the gap is important to heat transport out of the fuel rod. BISON, on the other hand, does have a suite of models that account for the thermomechanical behavior of the fuel and cladding, including models to account for high temperature cladding creep and failure for both LOCA and RIA.

What BISON lacks in LOCA simulations is the ability to simulate the evolving multiphase coolant conditions during an accident, including how the coolant behavior affects heat transport from the rod. It is noted that for stand-alone use, BISON does include a simplified 1D homogeneous coolant channel model, but it is limited in comparison to TRACE's capability.

The coupling of TRACE with BISON combines the strengths of both codes, resulting in a significantly improved simulation capability. Another advantage, from a user standpoint, is that the TRACE/BISON coupling allows for one set of inputs to be used for the simulation of reactor start-up, normal operations, and followed by accident scenarios.

2. COMPREHENSIVE REACTOR ANALYSIS BUNDLE (CRAB) CONCEPT

CRAB is a comprehensive code suite for non-LWR reactor confirmatory analysis that has recently been proposed by the NRC [6]. The fundamental concept is to integrate existing NRC software with advanced codes under current development within the U.S. Department of Energy (DOE) Nuclear Energy Advanced Modeling and Simulation (NEAMS) and the Consortium for Advanced Simulation of Light Water Reactor (CASL) programs, along with other commercial and international codes, in a common framework built around MOOSE. BISON is one of the two fuel performance codes that will be used in this suite. The work presented here represents an early demonstration of this concept where TRACE and BISON are fully coupled using MOOSE, through an early CRAB validation effort based on the LOFT L2-5 LOCA experiment, as recommended by the NRC. A graphical depiction of the CRAB concept is shown in Figure 1.

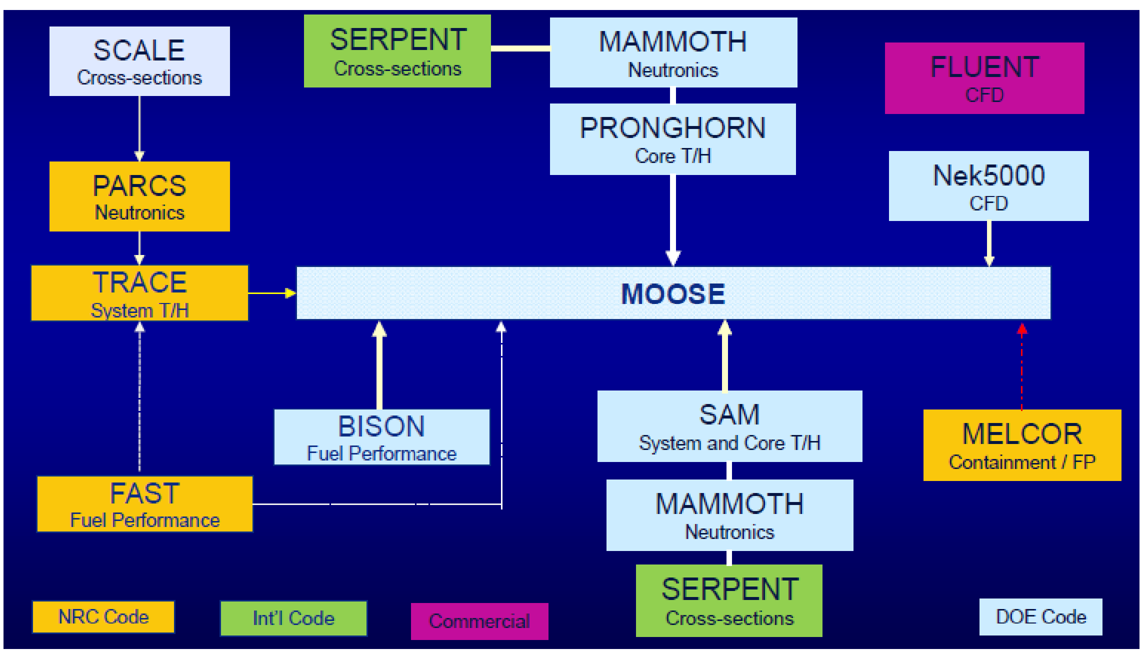

Figure 1. A graphical overview of the CRAB concept. Used with permission from the NRC.

2.1 TRACE/BISON Coupling

While in development, the TRACE/BISON coupling was known as “RedCRAB” and these two names may be used interchangeably throughout this report.

RedCRAB is a “MOOSE-Wrapped App,” meaning that its primary purpose is to provide a MOOSE-native application programmer interface (API) to an existing application—in this case, TRACE. The purpose of providing the wrapping interface is to allow the existing application to be used interchangeably with MOOSE-native applications to build up larger coupled multi-physics solves. RedCRAB, therefore. contains the necessary objects for interacting with TRACE’s API and transferring data back and forth between the TRACE and MOOSE data structures, which is more informally known as “glue code.” RedCRAB extends two key interfaces from MOOSE to enable much of the application interaction and data transfers, namely “ExternalProblem” and “ExternalMesh.” The former object encapsulates a single TRACE “solve,” while the latter encapsulates the notion of a TRACE spatial solution. Once these two objects are fully implemented, the existing application gains access to the advanced capabilities within the MOOSE framework regarding coupling and solution transfers. Figure 2 depicts a graphical representation of the RedCRAB application. At first glance, one can see that both TRACE and BISON are contained within the application. This is accomplished by individually compiling each independent application through MOOSE’s unified build system. This gives RedCRAB full access to all objects in all coupled applications. The ExternalMesh object is depicted as a one-to-one representation of TRACE’s course mesh within the RedCRAB application space. From there, existing transfers can transform data directly to BISON with minimal effort. Several quantities are exchanged on the ExternalMesh—liquid coolant temperature, vapor coolant temperature, coolant void fraction, coolant pressure, and coolant saturation temperatures. All of these fields come from TRACE and are passed to BISON. Additionally, RedCRAB contains a specialized “FineMeshTransfer” object that bypasses the ExternalMesh interface. The spatial fields that are exchanged through the FineMeshTransfer objects are the cladding temperature (from BISON) and the heat transfer coefficients (from TRACE) of both phases of the coolant.

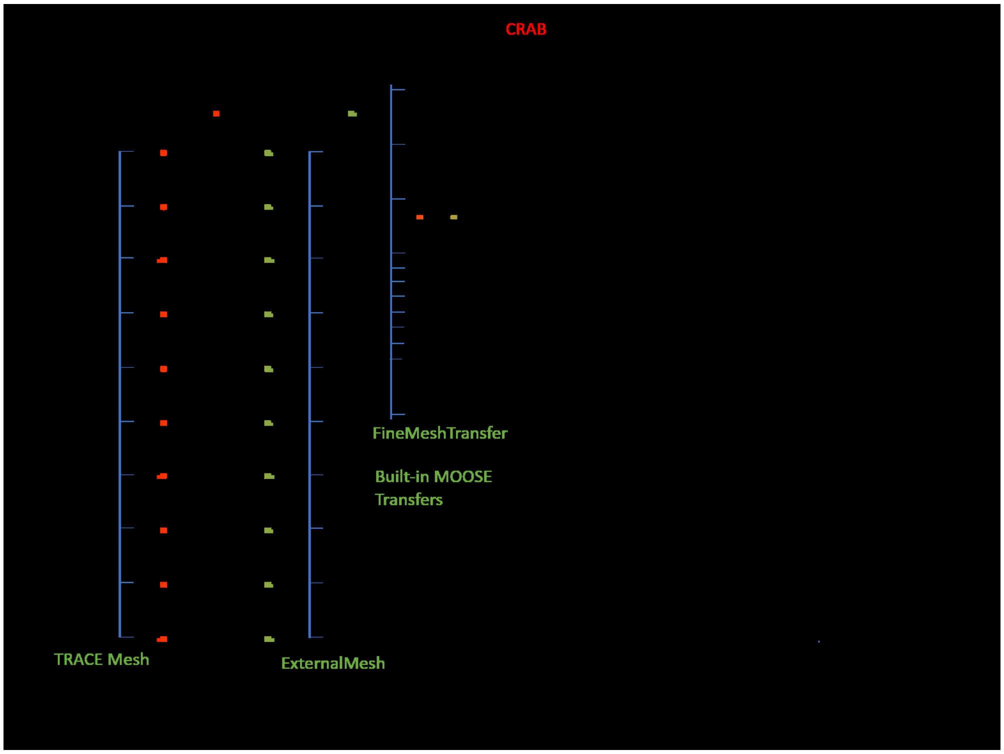

Figure 2. Simplified graphical overview of the TRACE/BISON coupling.

The time-stepping between the two codes was a bit of a challenge as MOOSE/BISON has the ability to advance at a very small time-step to a very large one (implicit). TRACE, on the other hand, is held to small time-steps (explicit). The current method to cope with the differences in time schemes is that BISON picks the end time of a time-step and then reports it to TRACE. TRACE then solves to that time end point with time-steps dictated in the TRACE input file for that time segment. As TRACE approaches the end time, another new development known as the "delta limiter" will override the TRACE time-step as necessary so that TRACE does not overshoot the BISON imposed end time. A second time-step development for this coupling was a new time-stepper called "CrabWalk" that allows the user to override the normally used MOOSE adaptive time-stepping and specify the time-step over a set period of time. An example of this might be that a user needs a time-step of 0.05 seconds during the simulation times of 1000 seconds to 2000 seconds, but then needs the adaptive time-stepping outside of 1000 to 2000 seconds. Although simple, this feature was important for studies that helped the development team's understanding of this coupled solve.

3. ASSESSMENT CASE LOFT L2-5 BACKGROUND

LOFT was a series of transient experiments conducted at INL's LOFT facility, which is located to the west of Idaho Falls, Idaho, and was sponsored by the NRC as part of their Water Reactor Safety Research Program. The LOFT reactor is a ½-scaled pressurized water reactor (PWR) with a maximum rating of 50 MWt. The active core length was 1.68 m and was made up of 1300 fuel rods configured as five 15x15 square assemblies and four triangular assemblies. A cross section of the core can be seen in Figure 3.

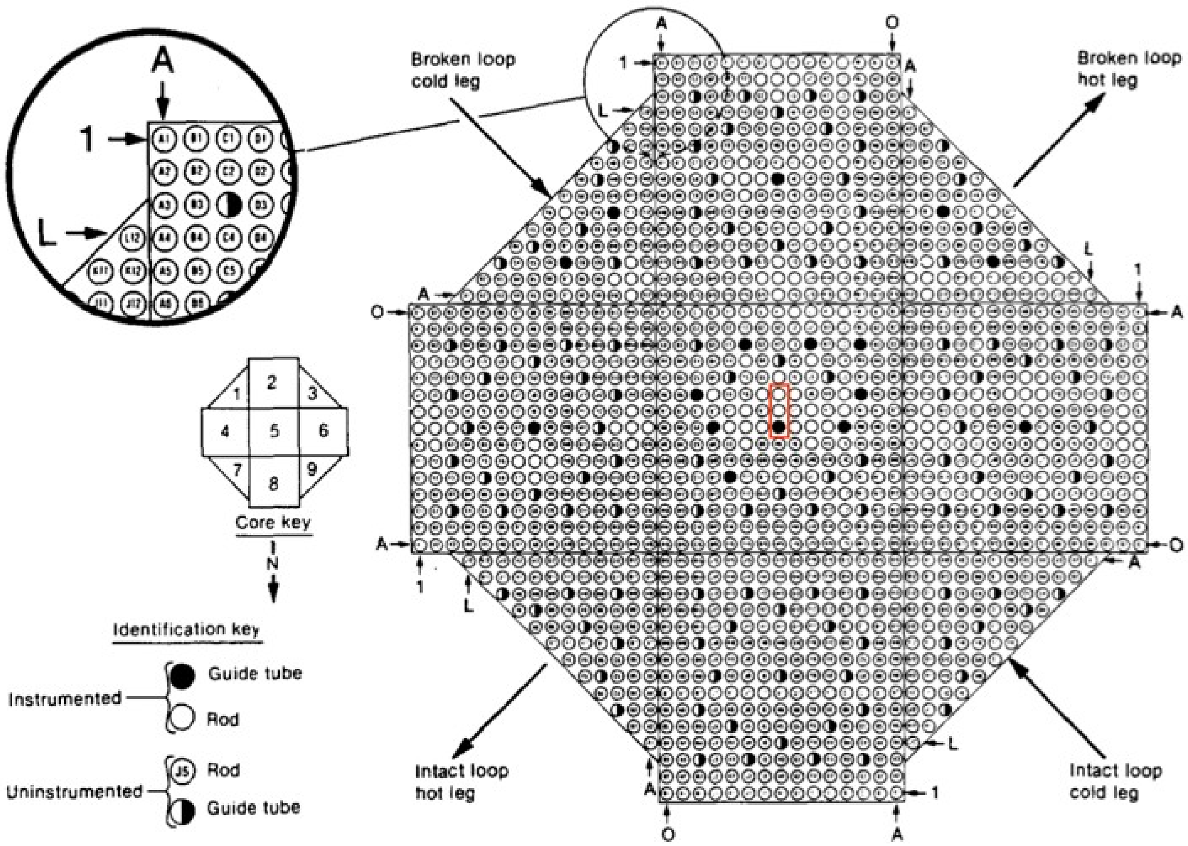

Figure 3. Cross-sectional layout of the LOFT core. The red box in the center of the core highlights the fuel rods considered in this report. Rods are identified as 5H06, 5H07, and 5H08 as listed from top to bottom [7].

The LOFT reactor was designed to replicate the same physical, chemical, and metallurgical properties that are found in a commercial PWR. Between 1976 and 1983, it was the host of 40 nuclear and non-nuclear tests, including 24 nuclear experiments on small-, intermediate-, and large-break LOCAs. The experiment simulated here, L2-5, was a large-break LOCA. Data from these experiments helped the overall understanding of these transients and went on to be the technical basis for nuclear operation procedures and the creation of models for the thermal-hydraulic system codes [7].

As stated previously, LOFT was designed to mimic a commercial PWR as closely as possible. Where LOFT differed and was special was in the primary coolant system (PCS). The PCS consisted of two loops connected to the reactor. One was designed as a normal loop and called the intact loop, while the second could be opened and was called the broken loop. A diagram of the LOFT systems is given in Figure 4.

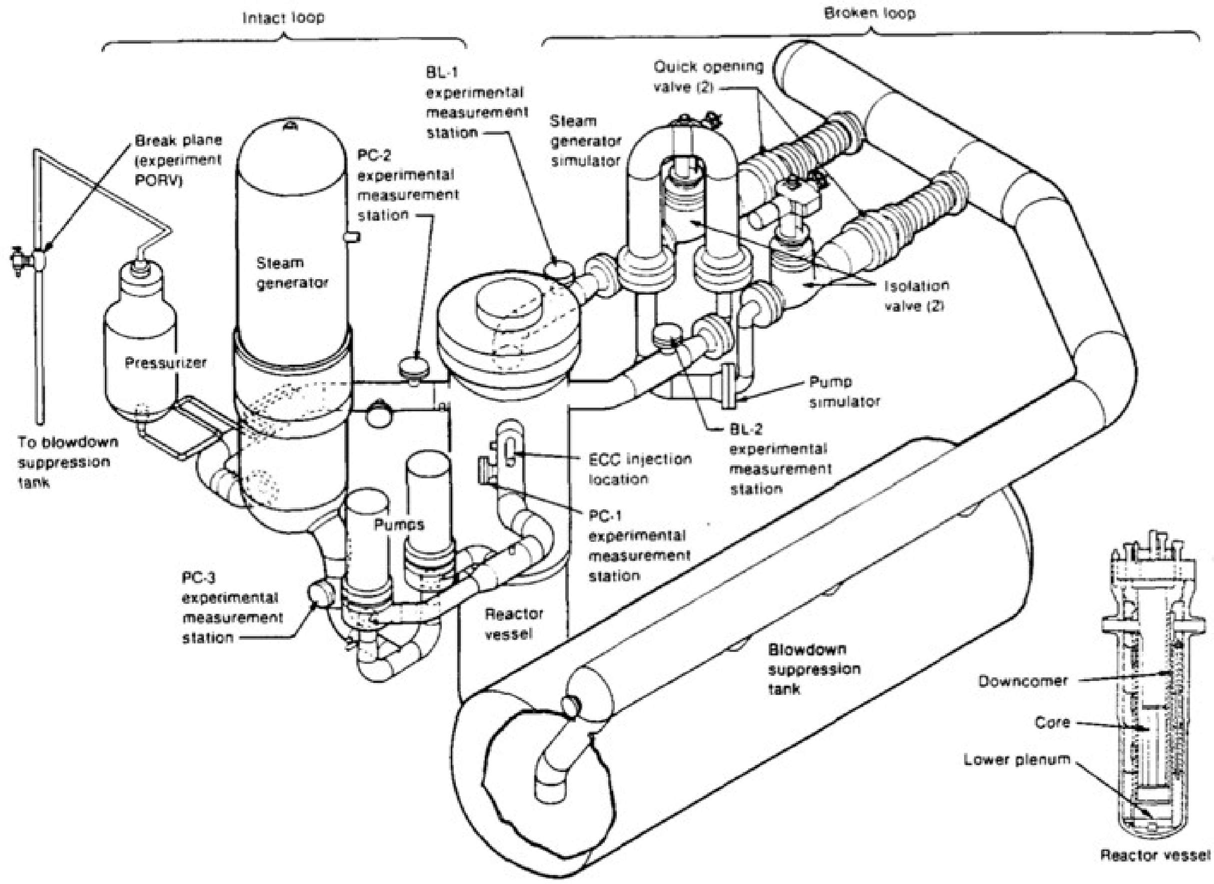

Figure 4. Layout of the LOFT reactor system components [7].

3.1 TRACE/BISON Simulation Method

This simulation was run in two distinct parts—normal operations and transient operations—with one set of input files. This was done using the MOOSE controls system, which allows a user to activate and deactivate blocks in the input file while the simulation is underway. This was used in this simulation to change coolant boundary conditions and engage TRACE when the LOCA began. The following four inputs were required for this simulation: (1) a BISON input; (2) a TRACE input; (3) a MOOSE-wrapped-app input; and (4) a TRACE transient restart file obtained from a steady-state TRACE run. All TRACE inputs were provided by the NRC.

A BISON input file and mesh were developed using information from the LOFT reports listed in [7]. The reactor was brought to about 10 MW for a short time-period, and then dropped to zero for instrument calibration. The reactor was then brought to 36 MW and held for approximately 25 hours before the LOCA was initiated.

To simulate the normal reactor operations time-period, BISON was run in a stand-alone manner, meaning that BISON and TRACE were not in communication. The coolant pressure was held at a constant 14.95 MPa and the coolant conditions (i.e., coolant temperature and heat transfer coefficient [HTC]) were modeled using BISON's internal 1D coolant channel model.

When the simulation progressed to the point where the LOCA was initiated, the MOOSE multi-app and transfer systems were initiated through the MOOSE controls, which also started TRACE and the BISON/TRACE coupling. TRACE and the actual transfers were started slightly before the LOCA (e.g., by 0.4 seconds) to allow an initial transfer such that parameter fields were populated when the boundary condition swap occurred. Another 0.2 seconds after the RedCRAB transfers began, the LOCA was initiated, and the BISON coolant boundary conditions were changed from constant pressure and the use of the BISON coolant channel model to being informed by TRACE. For this simulation, TRACE informed BISON on coolant liquid and vapor temperature, coolant liquid, and vapor HTCs, coolant pressure, and the coolant void fraction. BISON passed temperature from the cladding back to TRACE for updating the coolant conditions. The simulation continues for 120 seconds after LOCA initiation. Note that the actual termination of the LOFT L2-5 experiment was at 107 seconds.

3.2 TRACE/BISON LOFT L2-5 Results

As stated previously, all coolant properties during the LOCA were provided by TRACE. BISON was ultimately responsible to compute heat flux from the cladding, but that included heat addition due to decay heating, heat transfer from the fuel through the fuel-clad gap, heat transfer through the thermally resistive zirconium oxide layer, and any additional heat provided from the exothermic reaction of the conversion to zirconium oxide. The core of the LOFT reactor was heavily instrumented. Three rods in the center of the core were chosen for simulation comparison. Rods 5H06 and 5H07 each had four thermocouples (TC) attached to the cladding at varying heights. Rod 5H08 was a guide tube that had power detection along it axially and is the source of the axial power profile in the BISON input. For the comparison of RedCRAB against the experiment data, "PointValue" postprocessors were made in the BISON input file to output the cladding outer wall temperature at the heights specified in the experiment reports.

Figure 5 through Figure 8 are from the TCs on the 5H06 rod, which is two rods south of the center of the core. The blue lines represent the simulation results, while the red lines are from the experiment reports [7]. The vertical red line represents uncertainty in the reporting instrument. The report only had experimental values for 30 seconds for most of the TCs, which is why the red lines stop short in three of the graphs.

Overall, the RedCRAB simulation results compare well with the experimental data. Figure 5 shows the RedCRAB results and experimental data from TE-5H06-024, which was the hottest TC at a maximum of 1077 K, as recorded in LOFT L2-5. RedCRAB predicted a maximum temperature of 1071 K. It is important to note that the LOFT reports state that no cladding failure was seen in L2-5; thus, extremely high temperatures were not expected in this simulation. Figure 5 also has a comparison to a TRACE stand-alone run. The TRACE input file for this run was identical to the RedCRAB run, but it was executed with a TRACE executable only. The comparison made here shows the improved overall simulation capability by using the advanced model in BISON and by coupling it to TRACE.

Figure 8 has an interesting and easily noted feature in that the experiment TC 037 experiences a sudden, rapid temperature drop early in the LOCA. The report explains that there was a top-down quench initiated at approximately 15 seconds that lasted for 5 seconds. This was not in the TRACE input file; thus, the RedCRAB simulation does not reflect it. TC 037 is the highest elevation TC on rod 5H06, which is why it sees a more drastic temperature drop. From looking at Figure 5, Figure 6, and Figure 7, one can see that there is a small corresponding temperature drop in the experimental results at approximately 15 seconds. As with TC 037, the drop seen by the other TCs is not reflected in the simulation.

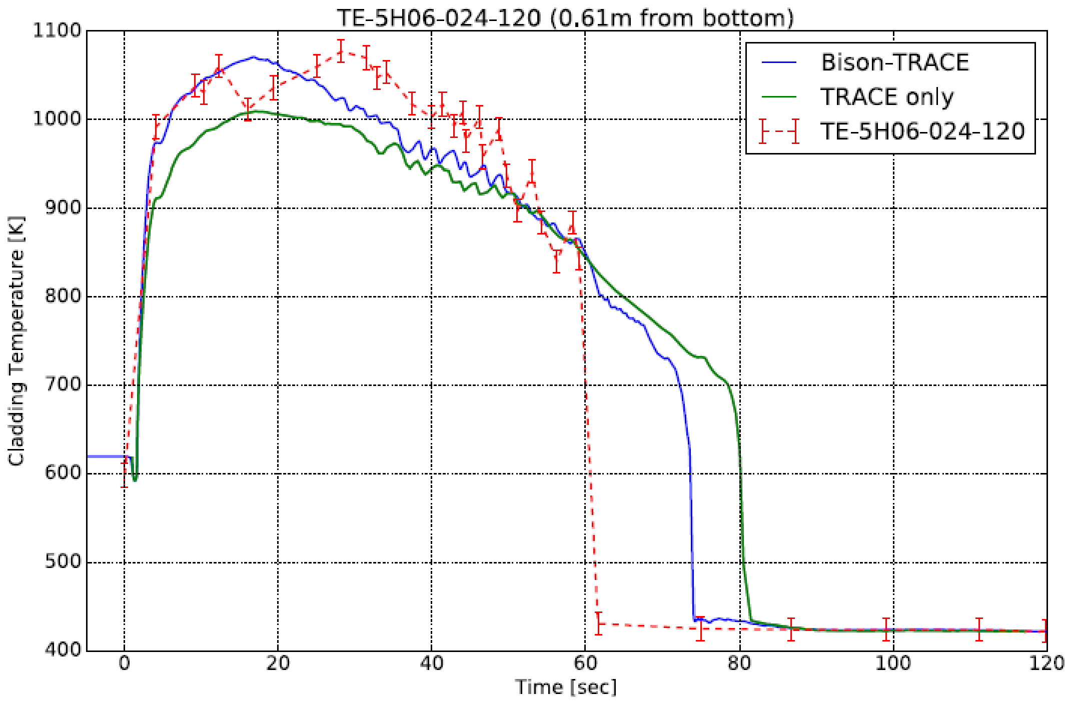

Figure 5. RedCRAB calculation results from TC TE-5H06-024 compared with a TRACE only simulation.

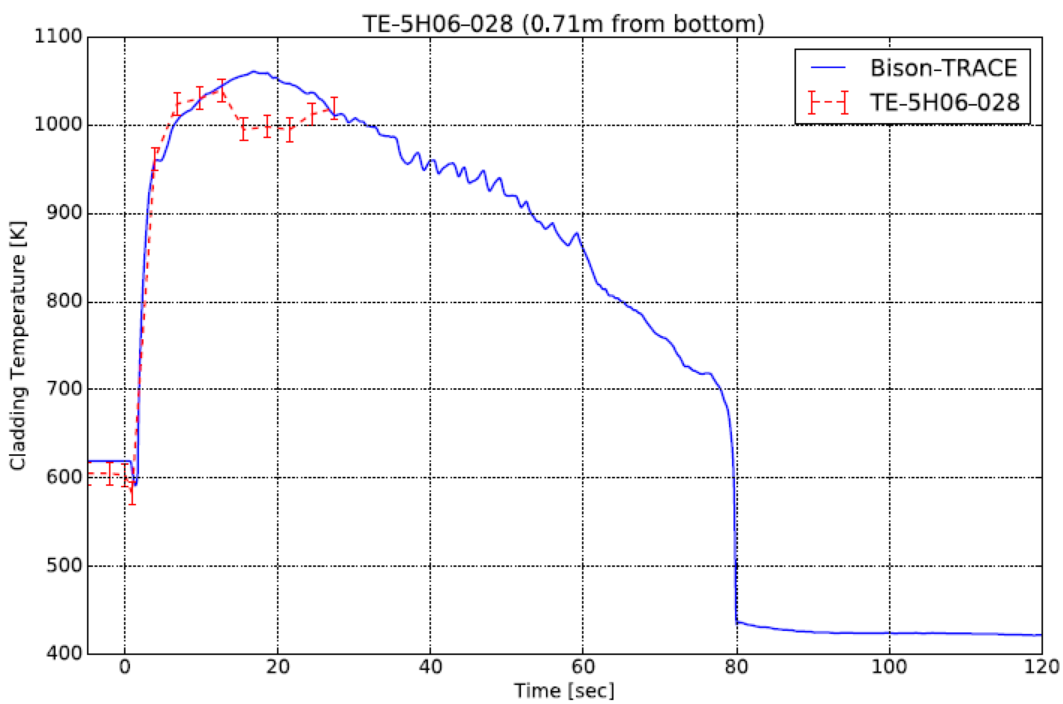

Figure 6. RedCRAB calculation results from TC TE-5H06-028.

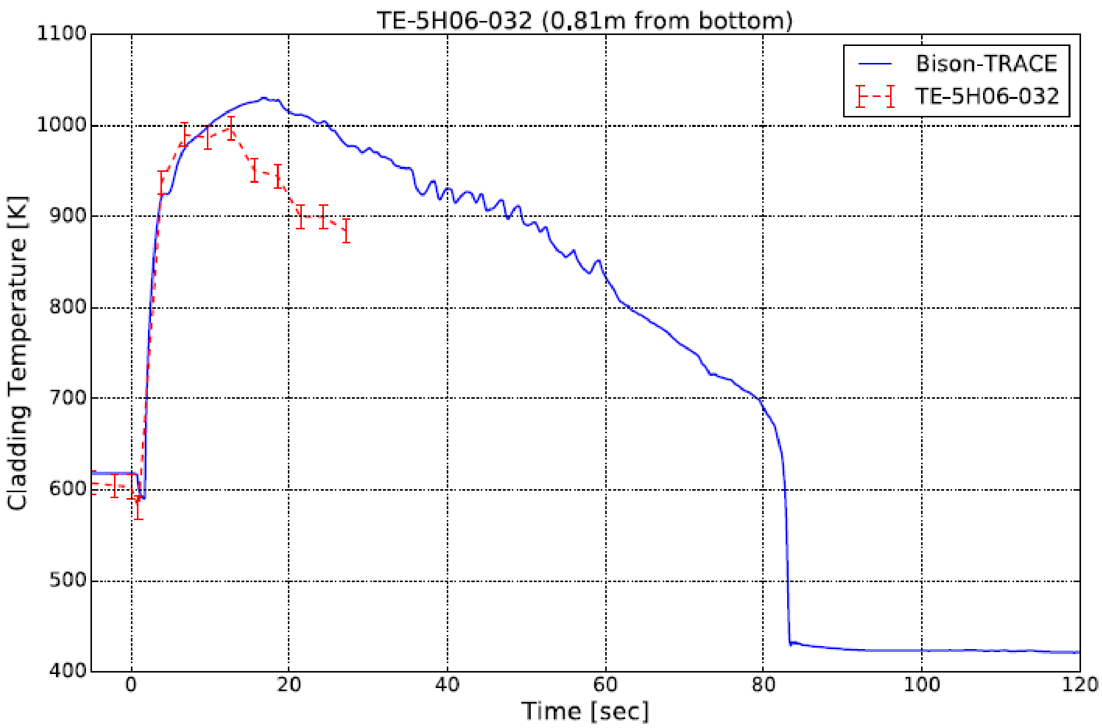

Figure 7. RedCRAB calculation results from TC TE-5H06-032.

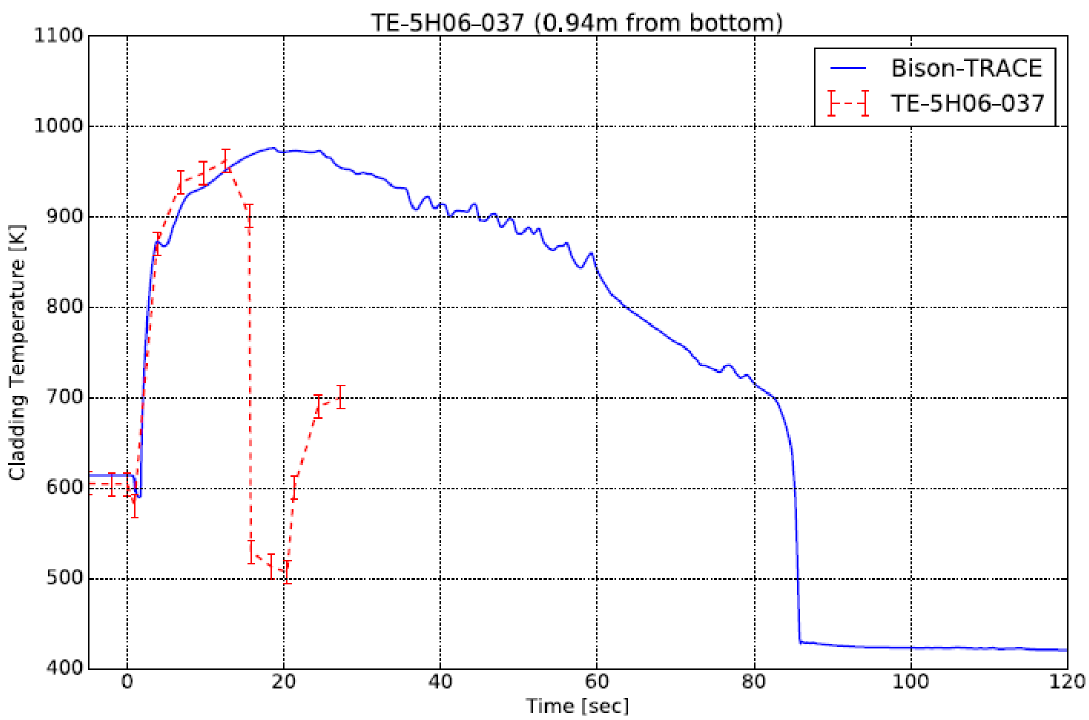

Figure 8. RedCRAB calculation results from TC TE-5H06-037.

Figure 9 shows a compilation of the RedCRAB calculations for all the TC locations for rods 5H06 and 5H07. The progression of the quench front is clearly evident in this plot.

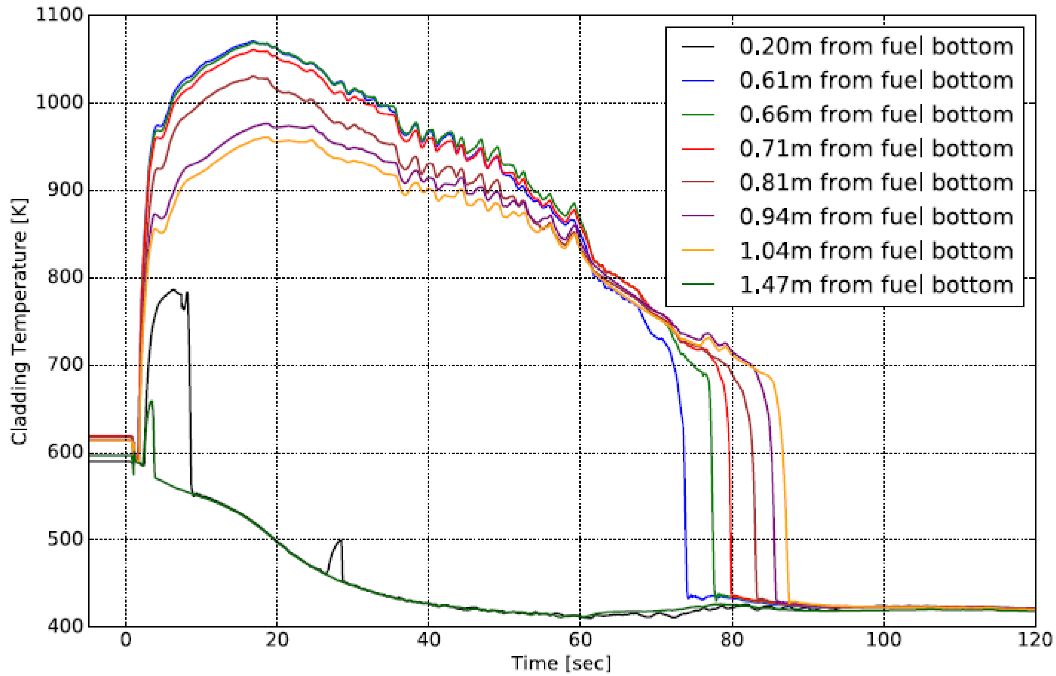

Figure 9. RedCRAB calculation results from all LOFT TCs for rods 5H06 and 5H07.

4. CONCLUSIONS

A collaborative effort between INL and the NRC has been undertaken to couple BISON and TRACE within INL's MOOSE computational platform. This collaboration supports early development within the CRAB, a concept recently proposed by the NRC to integrate the suite of legacy NRC software with modern, advanced simulation tools.

In the early stages of this work, the NRC suggested the simulation of the LOFT L2-5 experiment as a first validation case for the coupled TRACE/BISON capability. NRC had a well-vetted TRACE input description for this experiment, and the consensus of the development team was that this additional effort would be worthwhile and give increased credibility to any further simulations. This validation case was completed, and comparisons made between measurements and simulation results. Comparisons were generally very reasonable, with explanations provided for significant differences.

The coupling of TRACE and BISON for LOCA simulations represents a first of its kind capability. TRACE has been used extensively for stand-alone LOCA simulation and analysis, but does not include important fuel and cladding thermomechanical behavior. BISON includes this behavior, but is not designed to simulate the evolving multiphase coolant conditions during the accident. Coupling of TRACE and BISON combines the strengths of both codes, resulting in a significantly improved simulation capability.

ACKNOWLEDGEMENTS

This work was sponsored by the U.S. Department of Energy, Office of Nuclear Energy, Nuclear Energy Advanced Modeling and Simulation (NEAMS) and the Consortium for Advanced Simulation of Light Water Reactors (CASL) under DOE Contract No. DE-AC07-05ID14517. Accordingly, the U.S.

Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for U.S. Government purposes.

The Idaho National Laboratory would like to extend its thanks to the U.S. Nuclear Regulatory Commission for their help and guidance throughout this project.

REFERENCES

1. Williamson, R. L., J. D. Hales, S. R. Novascone, M. R. Tonks, D. R. Gaston, C. J. Permann, D. Andrs, R. C. Martineau (2012). “Multidimensional multiphysics simulation of nuclear fuel behavior,” *J. Nucl. Mater.*, 423: 149–163.

2. Gamble, K. A., R. J. Gardner, R. L. Williamson (2017). “BISON FY17 Accident Capability Development,” Consortium for Advanced Simulation of Light Water Reactors Technical Report CASL-U-2017-1389-000, July 2017, Oak Ridge National Laboratory, Oak Ridge, TN, USA.

3. Williamson, R. L., C. P. Folsom, G. Pastore, S. Veearaghavan (2016). “Reactivity Insertion Accident (RIA) Capability Status in the BISON Fuel Performance Code,” Consortium for Advanced Simulation of Light Water Reactors Technical Report CASL-X-2016-1104-000, July 2016, Oak Ridge National Laboratory, Oak Ridge, TN, USA.

4. Folsom, C. P., R. L. Williamson, G. Pastore, W. Liu (2017). “Development of an RIA Experimental Benchmark for BISON,” Consortium for Advanced Simulation of Light Water Reactors Technical Report CASL-U-2017-1403-000, August 2017, Oak Ridge National Laboratory, Oak Ridge, TN, USA.

5. Williamson, R. L., G. Pastore, K. A. Gamble, R. J. Gardner, J. Tompkins, W. Liu (2017). “Development of a LOCA Experimental Benchmark for BISON,” Consortium for Advanced Simulation of Light Water Reactors Technical Report CASL-U-2017-1422-000, September 2017, Oak Ridge National Laboratory, Oak Ridge, TN, USA.

6. Bajorak, S. (2019). Private communication. March 2019.

7. Nalezny, C. L. (1983). “Summary of Nuclear Regulatory Commission’s LOFT Program Experiments,” U.S. Nuclear Regulatory Technical Report NUREG/CR-3214, July 1983, Idaho National Engineering Laboratory (now Idaho National Laboratory), Idaho Falls, ID, USA.