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EPRI/INL TCF Project on LOCA Analysis Tool: Statement of Work

20 August 2023

Technical Report

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ABSTRACT

Through the U.S. Department of Energy's Technology Commercialization Fund, Electric Power Research Institute and Idaho National Laboratory are partnering to develop an analysis tool focused on loss-of-coolant accident behavior of light-water reactor fuel rods. This tool will involve a coupling of RELAP5-3D and Bison. This report gives details of the work to be performed in this partnership. It is hoped that industry and national laboratory experts, including the Collaborative Research on Advanced Fuel Technology's Technical Expert Group, will provide feedback on the planned work.

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ACRONYMS

CRADA	cooperative research and development agreement
CRAFT	Collaborative Research on Advanced Fuel Technology
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
INL	Idaho National Laboratory
LOCA	loss-of-coolant accident
LWR	light-water reactor
MOOSE	Multiphysics Object-Oriented Simulation Environment
NEAMS	Nuclear Energy Advanced Modeling and Simulation
NFIR	Nuclear Fuel Industry Research
SCIP	Studsvik Cladding Integrity Program
SOW	statement of work
TEG	Technical Expert Group
TREAT	Transient Reactor Test

1. INTRODUCTION

The U.S. commercial nuclear industry is interested in and has committed significant resources to increasing the nuclear fuel burnup limit to enable longer cycle operation to improve fuel economics and reduce spent fuel. Less data is available for fuel at higher burnup than at more typical burnup levels, and this introduces uncertainty regarding fuel performance in these conditions. One item of particular importance is the behavior of high burnup fuel during transients, such as a postulated loss-of-coolant accident (LOCA). Experimental data shows high burnup fuel is susceptible to fragmentation under transient conditions and under LOCA conditions. Fragmented fuel may relocate in the fuel rod and disperse to outside of a fuel rod if the cladding ruptures. This issue has been identified by regulators as a key barrier to extending fuel burnup.

The U.S. Department of Energy (DOE), Electric Power Research Institute (EPRI), and Idaho National Laboratory (INL) have begun a project to address some of the knowledge gap. The project aims to develop a computational tool able to evaluate high burnup fuel behavior under LOCA conditions. This tool will be composed of INL's system thermal hydraulics code, RELAP5-3D, and INL's finite element-based fuel performance code, Bison. These codes, coupled together, will provide novel capabilities for exploring high-burnup fuel behavior.

A statement of work (SOW) for this project was developed as part of a cooperative research and development agreement (CRADA) between EPRI and INL/Battelle Energy Alliance, LLC. The scope of work, to be completed within a 2-year period, consists of the following seven major tasks:

1. Coordinate with the CRAFT Technical Expert Group (TEG) on planned activities, align activities with those recommended by the TEG, and revise plans based on feedback from the TEG
2. Define areas where technical data is required to guide code development
3. Develop and implement improved models for cladding ballooning, fuel fragmentation, and relocation of high burn up fuel in Bison under LOCA conditions
4. Complete and document coupling of RELAP5-3D and Bison.
5. Verify and validate the coupled capability
6. Develop and document best estimate plus uncertainty capability
7. Issue final report demonstrating capability.

The purpose of this document is to provide more details than the original SOW on model development approaches to be undertaken for the listed tasks. The original SOW describes key objectives without technical details. This document will serve as a project guide as the development and analysis activities proceed.

The project team includes experts in light-water reactor (LWR) fuel, LOCA analysis, thermal-hydraulics, and system analysis. At INL, RELAP5-3D developers, Bison developers, and management are represented.

2. TASK DETAILS

2.1 CRAFT Statement of Work Review and Input

Industry input is desired to refine project goals so that they are in alignment with the industry's needs. An initial step in this interaction was taken on May 11, 2023, at INL. EPRI and INL experts met to discuss development priorities and strategy. The meeting was attended by key contributors, as well as the national technical director of the DOE's Advanced Fuels Campaign, Dr. Dan Wachs, who leads a CRAFT TEG. The meeting focused on details of development approaches, and several suggestions were made that are captured in items contained in this report.

As the technical details of the project scope are being defined, the development team would like to seek review and input from the wider CRAFT group.

2.2 Define Areas where Technical Data Is Required

In the time since this project was proposed, a considerable amount of work has been undertaken in Bison to better model fuel in accident conditions. Associated with that work, several sources of technical data have been explored. These include data on topics such as fission gas release, the formation of high burnup rim structure, and the axial relocation of fuel made possible when the cladding balloons. This being the case, the need to identify sources of data has lessened. However, it is still necessary to assess the applicability of available data and to utilize more data as it becomes available.

Four areas for data include:

1. Data associated with high burnup structure and fuel fragmentation.

   Three primary driving forces for fuel fragmentation are being evaluated by the scientific community. Transient fission gas and thermally induced internal stress have been evaluated. Less understood is the impact of a pellet's microstructural changes at high burnup on fragmentation. Microstructure changes are complex, but for the purpose of this evaluation can be divided into two major regions, high burnup rim structure and the remainder of the pellet.

2. Database of experimental LOCA cases.

   Integral LOCA tests have been conducted by different laboratories, and some of the data is in the public domain. These tests were conducted at different conditions and with different experimental apparatus. The representativeness of these LOCA test data needs to be assessed with respect to expected LOCA conditions in actual power plants.

   (a) In-pile (PBF, Halden, others)
   (b) Out-pile (REBEKA, QUENCH, Argonne National Laboartory, Oak Ridge National Laboratory, Studsvik)

   The bulk of the high burnup test data were generated by the Studsvik Cladding Integrity Program (SCIP). Their datasets include both fuel fragmentation and cladding ballooning/burst data. Access to SCIP data is being pursued outside of this project.

3. EPRI proprietary technical data

   EPRI conducted high burnup core design evaluations and separate effect tests to characterize fuel fragmentation. Fuel fragmentation studies focus on mechanistic understanding and data generated, such as fission gas distribution, pellet internal stress, high burnup fuel microstructure, and distribution of fuel fragments, and are useful data for model development.

4. Data available through coordination with CRAFT

   The project welcomes any additional data and/or input from the CRAFT community.

2.3 Develop and Refine Bison Models for Higher Burnup Application

Bison is a finite element-based fuel performance code. While traditional behaviors are well established, additional development is needed to include high burnup effects, particularly potential fuel fragmentation. Effects such as the power history will be incorporated, as appropriate. Bison models that require development or refinement include:

1. Formation of high burnup structure

   The Nuclear Energy Advanced Modeling and Simulation (NEAMS) program is developing a high burnup rim structure model using monodispersed pores filled with xenon gas. Porosity as a function of local burnup is defined by experimental observations, and pore pressure is informed by the existing fission gas model. The code will include an ability to correct porosity as warranted.

2. Fuel fracture and pulverization

   The Bison code currently includes a pulverization model developed from the EPRI Nuclear Fuel Industry Research (NFIR) data, which is primarily based on fuel disks irradiated in the Halden Program. The current effort will focus on a more mechanistic approach that combines microstructure evolution and propagation of multiple stress-driven cracks using the phase-field method. A combination of lower scale Marmot models, informed by engineering scale Bison calculations, is being pursued.

3. Transient fission gas release

   The existing NEAMS transient fission gas release model approach calculates fission gas release from freshly exposed gas pores due to fuel fragmentation. While fission gas release by this mechanism is valid, experimental data from EPRI and SCIP experiments showed visible fragmentation is not needed for transient fission gas release. A different approach may be needed considering these observations.

4. Gas communication within the fuel rod

   Gas movement inside the fuel rod can influence how a rod balloons, possibly leading it to burst. Integral tests using relatively short fuel segments showed a large variation in depressurization of the top plenum upon rod burst. This suggests gas communication away from the balloon and burst region may be slow, and ballooning may be primarily driven by local transient fission gas rather than by gas from the plenum. The Bison team is looking to implement an empirical model based on computational fluid dynamics flow through pellet pores and cracks to account for early stages of gas communication with the fuel rod plenum volume. Transient fission gas released locally will be combined with plenum gas.

   An outstanding question on gas communication is knowing when the high burnup rim structure starts to fragment. The fragmentation of the high burnup rim structure may lead to free gas communication. This aspect should be considered in potential gas communication models to be implemented in Bison.

5. Cladding ballooning and burst

   Many LOCA codes adopt a form of the Erbacher high temperature cladding creep model. The creep equation used in the model is based on uniaxial tensile tests. However, the Zircaloy creep rate is phase dependent, and different alloys have different alpha to beta transition temperatures. In addition, uniaxial tests are not representative of the biaxial loading condition a rod experiences in a LOCA. Efforts at modifying the equation to account for these factors have been met with limited success, as there is still disagreement in the predicted strain relative to recent ORNL experiments. Additional scope is being pursued to include the effects of the heating/loading rate that is currently not part of the model. It is not assured these efforts will resolve the issue, and additional experimental data may be needed.

Fission gas release of high burnup fuel that operates at high power is predicted to have much higher operational fission gas release and thus significantly higher rod internal pressure. Under the current burnup limit, the rod internal pressure is comfortably below the cladding deformation limit during the blow down phase of a LOCA. With the higher operational fission gas release, the rod internal pressure can exceed the system pressure, and thus, the fuel cladding may deform plastically. This mode of deformation will be incorporated into the Bison model. It is important to account for this effect since the initial deformation may impact the cladding ballooning behavior and likely the burst location later in the transient if the rod does not burst on the initial temperature rise from the stored energy.

Fuel rod burst can be determined using four independent criterion or a combination of any of the four.

(a) Hoop stress exceeds burst stress
(b) Temperature exceeds rupture temperature
(c) Plastic strain rate exceeds a threshold, 0.0278/s
(d) Total inelastic hoop strain exceeds a value of 0.336.

Bison currently simulates a singular fuel rod. The Multiphysics Object-Oriented Simulation Environment (MOOSE) framework contains a MultiApp system that allows the simultaneous analysis of multiple fuel rods, but these rods do not interact with one another. During a LOCA, it is possible for adjacent fuel rods to balloon and contact one another and affect the subchannel geometry for cooling. To account for this phenomenon, support will be added to Bison to enable the simulation of a 3x3 array of fuel rods that may balloon independently. The mechanical interaction between multiple ballooning rods will be analyzed. The initial approach will utilize the existing layered capability in Bison, with a stretch goal of exploring three-dimensional interactions.

6. Axial fuel relocation

The current scope of work is focused on fuel relocation without cladding burst, and relocation with burst is a stretch goal. A key reason to focus on the no-burst scenario is to evaluate potential effects of high burnup rim structure fragments relocated to the ballooned region. Of primary interest is whether the extra heat energy from the fuel fragments can increase local cladding temperature enough to cause cladding burst that otherwise would not occur. The bulk of the fuel pellets have demonstrated a resistance to fragmentation while pressurized. The timing and mechanisms of high burnup rim structure disintegration are still unclear. Simple models based on gas bubbles have been evaluated and may be applicable to the high burnup rim structure.

An existing model in Bison accounts for relocation of bulk pellet fragments. The existing axial relocation model treats the fuel as a binary system of fragments denoted as large and small. Large fragments are assumed to form due to the thermal gradients that occur during normal operation with the small fragments assumed to be due to pulverization mechanisms. Currently, fuel moves axially if the computed packing fraction based upon the binary system and the available volume in the cladding at an axial location is large enough to accommodate additional fuel. The algorithm does allow for the possibility where a single fuel pellet may crumble into the ballooned region, and the rest of the bulk fuel above can axially relocate while maintaining its cylindrical form.

The current approach for accounting for the thermal conductivity in layers with relocated fuel is to smear the thermal conductivity over the entire fuel region from centerline to cladding. One alternative to explore is to use the original thermal conductivity in the radial region where fuel has not relocated axially and adjust thermal conductivity between the outer edge of mostly intact fuel and the cladding, where relocated fuel exists.

2.4 Couple RELAP5-3D and Bison

INL will implement necessary models and coupling between Bison and RELAP5-3D to support high burnup LWR LOCA analysis.

This task involves enabling and testing features in RELAP5-3D to accommodate cladding deformation. This will involve re-nodalization of the affected flow channel upon Bison informing RELAP5-3D of ballooning.

RELAP5-3D treats three-dimensional flows as three separate one-dimensional flows, but it does not include second order effects such as turbulence. Nevertheless, the approach provides reasonably good approximations to the flows between flow channels. These features will be exercised in this task.

A generic PWR model is already available and will be used in the coupling development. Other plant configurations with or without high burnup core design could be set up with moderate effort.

The coupled code will enable an integrated simulation that not only allows feedback of individual fuel rod geometry changes in the LOCA progression but also interaction with other rods and fuel structures. With these capabilities, cladding ballooning with fuel relocation into the region could be evaluated more accurately.

The coupled capability also offers an opportunity to evaluate cooling conditions at grid locations. This may include enhanced heat transfer and lower power/burnup that may result in lower local cladding temperature and reduced balloon strain. Experimental data shows the existence of a strain threshold where fuel could be held in place and thus limit fuel relocation inside a rod. Heat transfer could be calculated either directly by numerical simulation or using experimental correlations.

Collaboration with others with experience in this area will be sought. For example, feedback from users of the TRACE-Bison coupling development/tool will be helpful. Similarly, while not widely used, limited RELAP5-3D and Bison coupling was developed at INL, and it will be useful to explore challenges that were overcome and lessons learned from this effort.

2.5 Verification, Validation, and Quality Assurance

Verification of the Bison, RELAP5-3D, and coupled Bison/RELAP5-3D capabilities developed in previous tasks will occur as part of this task. Comparisons to analytical models, with closely prescribed boundary conditions, steady state conditions, etc., as necessary, will be made. Comparisons to fuel vendor simulation results would be very useful.

Comparisons to experimental data will also be completed. These comparisons will be based on legacy and/or planned transient testing data supporting burnup limit extension. The tool is to be applicable to relevant LOCA experiments and conditions, including those to be performed in the Transient Reactor Test (TREAT) Facility and hot cell furnaces.

Given the need at INL for a tool of this kind, verification and validation work will involve potential internal users. It is anticipated that the tool will be a meaningful step forward in experiment design analysis.

2.6 Develop Best Estimate Plus Uncertainty Capability

INL will perform benchmark analysis against data sets selected jointly by EPRI and INL from the experimental database to assess model uncertainty. It is understood that the uncertainties associated with modeling rod response to LOCA are high. This database used in this effort will likely include hot cell furnace tests, in-pile LOCA tests conducted at Halden, and other experimental data sets.

This task will focus on a more efficient implementation of parametric and sensitivity studies of test cases to establish the associated uncertainty for core design. Capability extension to a wider range of accident conditions, enhanced statistical capability, and core design optimization tools will be possible if time and funding allow. Procedures here will be rigorously documented.

2.7 Prepare Final Report

This report will detail assumptions, correlations, models, uncertainty, and other outcomes specific to this work.

3. CONCLUSION

This report reviews the technical work planned as part of a joint EPRI/INL project to develop a tool for analysis of LOCA conditions in LWRs. This tool will be composed of Bison for fuel performance coupled to RELAP5-3D for thermal hydraulics. A number of enhancements to models are anticipated. Feedback about these tasks is welcomed.