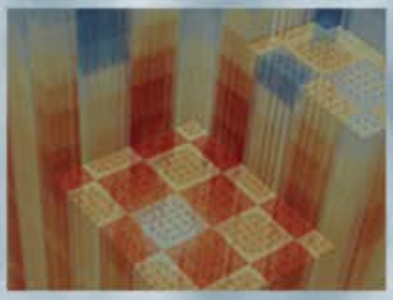
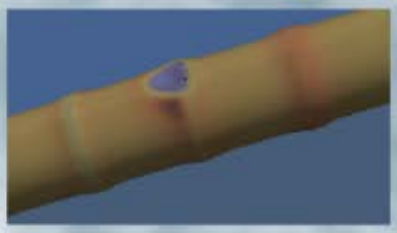
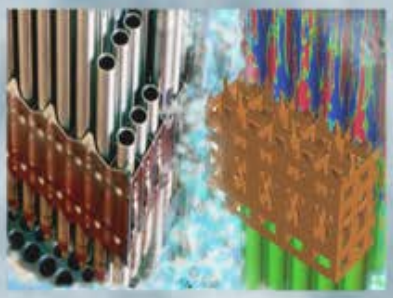
CASL-U-2015-0150-000

Pellet-Cladding Mechanical Interaction Analyses Using VERA







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PELLET-CLADDING MECHANICAL INTERACTION ANALYSES USING VERA

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ABSTRACT

A CASL Test Stand was launched in 2013 to evaluate VERA's fuel performance component, BISON-CASL, as a state-of-the-art fuel performance code for PCI analysis by guiding it through a series of fuel performance progression problems. The progression problems are performed using 2D R-Z axisymmetric models and focus on examining the thermal and mechanical responses of the fuel and cladding to an imposed axially-varying power history. The progression begins with a constant axial power profile imposed during a single cycle ramp up to power followed by steady-state operation for a short length test rod and concludes with the most complex case studied by the Test Stand: a full-length fuel rod with an axially-varying power history containing a first cycle ramp to full power steady-state operation followed by a shutdown and a second-cycle ramp to full power. The evaluation of these progression problems is performed by comparing BISON-CASL results against results from the Falcon fuel rod performance code. The results of this comparison show that while differences exists in the thermomechanical responses between the two codes, the peak inside cladding surface hoop stress calculated by the two codes are within 0.5% of one another.

Key Words: fuel performance, PCI, Falcon, BISON, CASL

1 INTRODUCTION

The Consortium for Advanced Simulation of Light Water Reactors (CASL) is developing advanced modeling and simulation (M&S) capabilities to support development of advanced reactor analysis tools which leverage high performance computing (HPC) platforms to address critical issues within commercial nuclear power plants (NPPs). In order to test the ability of these codes and their application in the industry, several Test Stands were launched by the core industry partners within CASL to serve as a primary mechanism for initial early stage deployment of CASL developed technology to key stakeholders. The EPRI Test Stand focused on evaluating the fuel performance component within the Virtual Environment for Reactor Applications (VERA), BISON-CASL, by using it to perform pellet-cladding interaction analyses (PCI), more specifically pellet-cladding mechanical interaction (PCMI) analyses since the chemical aspect of PCI is neglected. This evaluation was performed by comparing temperature and stress results to the Electric Power Research Institute's (EPRI) fuel performance code Falcon [1].

To accomplish this, an extensive set of simulations were executed in order to perform a thorough assessment of the BISON-CASL code. These simulations used a variety of different models and power histories to evaluate various aspects of the code and its ability to perform analyses similar to those typically performed by nuclear power plant operators using currently available fuel performance codes. In the absence of measured data, BISON-CASL is run alongside the Falcon

fuel performance code, and the resulting thermal and mechanical trends as a function of time are compared for parameters such as temperature, displacement, and hoop stress for select locations.

2 METHODOLOGY

2.1 Progression Problems

The objective of this Test Stand is to evaluate BISON-CASL[1] as a state-of-the-art fuel performance code by guiding it through a series of six fuel performance progression problems. The problems, model used, and purpose for each progression problem is provided in Table 1. These progression problems are performed using two-dimensional (2D) R-Z axisymmetric models (see Figure 1) and focus on examining the thermal and mechanical responses of the fuel and cladding to an imposed axially-varying power history.

Table 1. Progression problem description

Problem	Model	Purpose
1	Super-Ramp	Thermal analysis of shortened rod with a flat axial profile
2	PCI Example	Single-cycle thermo-mechanical analysis
3	PCI Example	Gap closure analysis with an elevated power history.
4	PCI Example	Thermo-mechanical analysis including down power
5	PCI Example	Thermo-mechanical analysis with additional power ramp
6	PCI Example	Thermo-mechanical analysis with down power and 2nd cycle ramp

[1] At the time this work was performed the BISON-CASL code was called Peregrine. Also note that some of the figures in this manuscript may refer to results as Peregrine results instead of BISON-CASL.

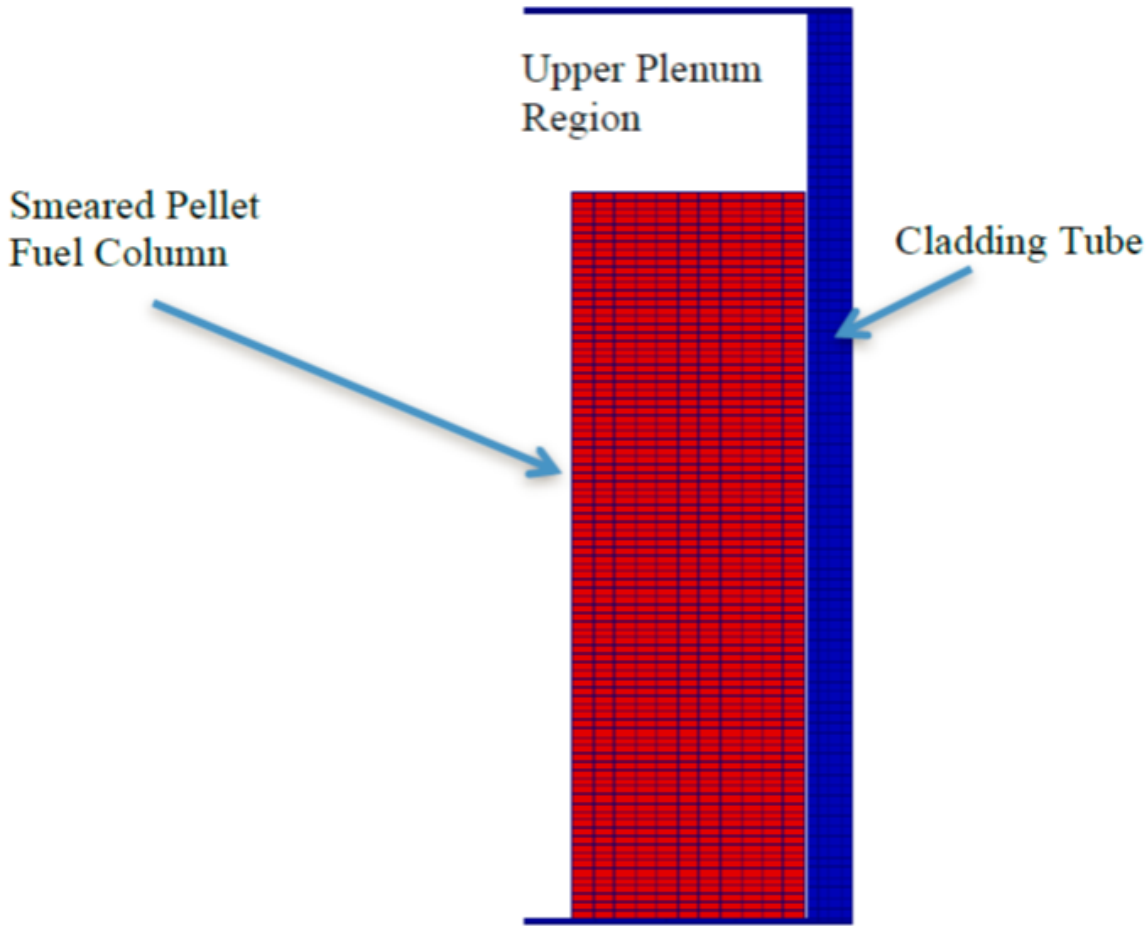

Figure 1. 2D Axisymmetric finite element fuel rod model [2]

The progression begins in problem 1 with a flat axial power profile imposed on a shortened test rod for a single cycle ramp. This case is denoted as the Super-Ramp [3], [2] case throughout this report. The power history, outer cladding surface boundary condition, and select modeling parameters for the Super-Ramp case are provided in Figure 2, Figure 3, and Table 2, respectively. Progression problems 2 through 6 use a generic PWR fuel rod example case, denoted as the PCI Example[2] case throughout this document, to investigate the thermal and mechanical responses predicted when an axially-varying power history is imposed on a full length fuel rod. The power history and select modeling parameters are provided in Figure 4 and Table 3, respectively. Note that a coolant channel model is being used for the PCI Example case instead of specifying the outer cladding surface temperature as was done for the Super-Ramp case. The imposed power history for this progression problem includes a ramp up to steady-state operation and hold for a full cycle. In progression problem 3, the power is increased to achieve gap closure and enable investigation of the thermo-mechanical responses estimated by BISON-CASL with respect to pellet-cladding contact. Progression problem 4 then appends a period of

[2] This case was used as a non-proprietary Falcon example case provided by EPRI to CASL to facilitate an open exchange between CASL entities interested in developing BISON-CASL: INL, Pacific Northwest National Laboratory (PNNL), ANATECH, Westinghouse, and the University of Tennessee in Knoxville (UTK).

down power to the power history and evaluates the thermo-mechanical response as the model ramps down from steady-state to zero power. Progression problem 5 takes progression problem 3 and appends an additional ramp period to the end of the steady-state operational period. For progression problem 6, the down power and second cycle ramp are both appended (in that order) to the end of steady-state operation for the first cycle to investigate thermo-mechanical responses under second-cycle restart conditions.

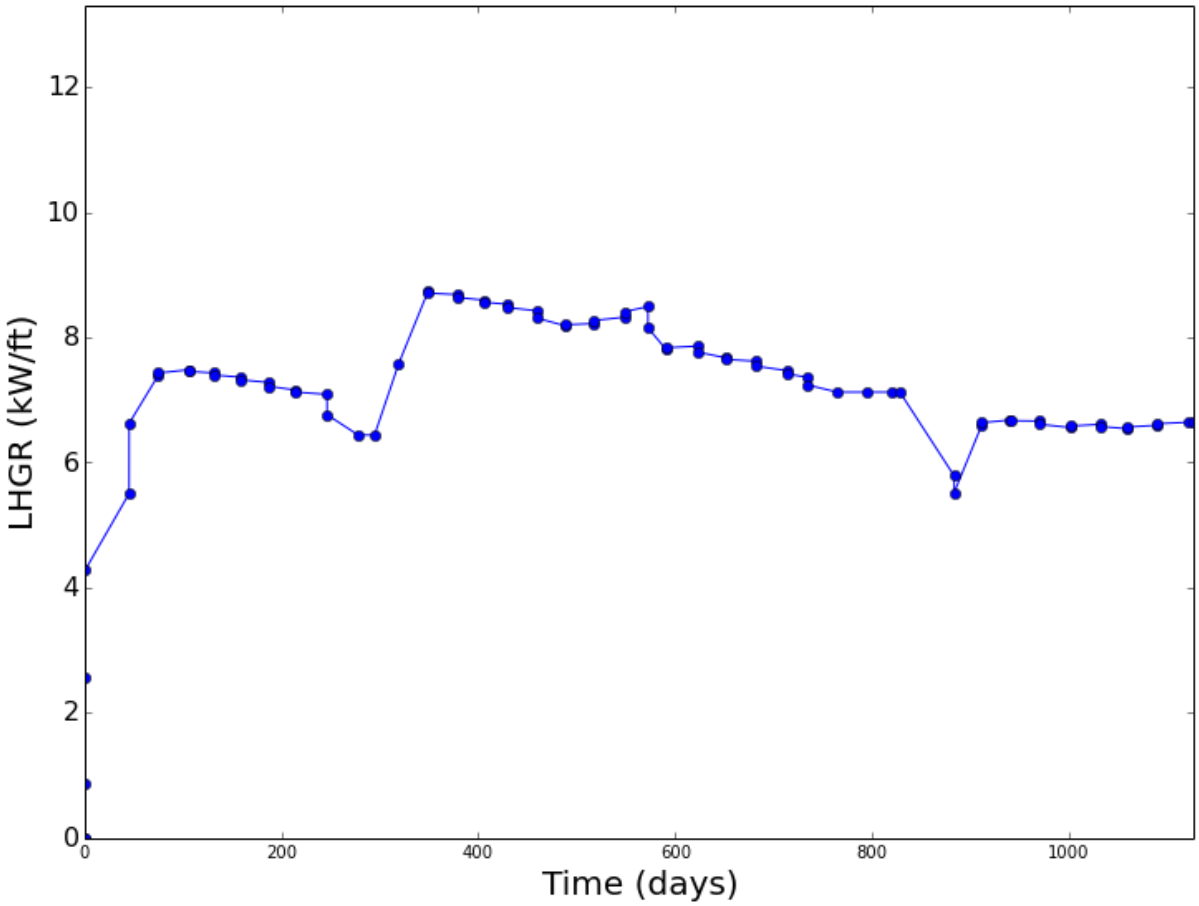

Figure 2. Power history for the Super-Ramp test case

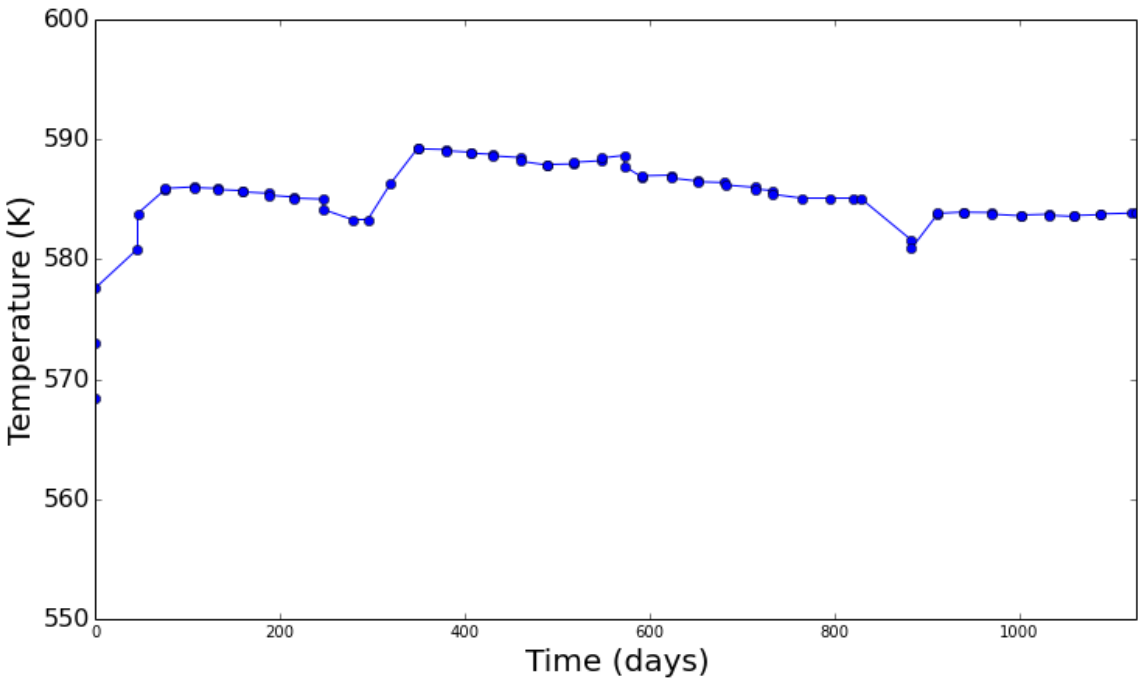

Figure 3. Bulk coolant temperature history applied uniformly as the outer cladding boundary condition for progression problem 1

Table 2. Select test conditions for the Super-Ramp test case [3], [2]

Parameter	Value
Coolant temperature at core inlet	566 K
Mass flow rate	6833 kg/s
Average system pressure	14.5 MPa
Active length of core	0.3174 m
Fuel density	10340 kg/m
Pellet outer diameter	9.138 mm
Cladding outer diameter	10.75 mm
Cladding thickness	0.74 mm

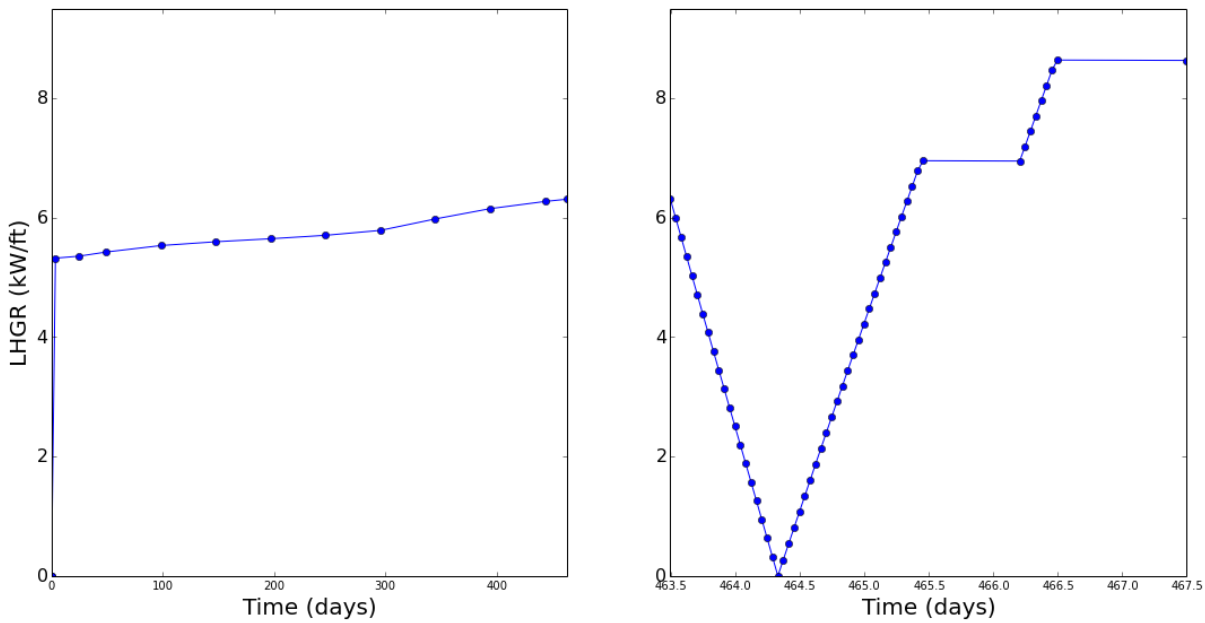

Figure 4. Power history for the PCI Example test case; the right-hand figure represents a magnification of the down power and cycle restart surrounding an outage

Table 3. Select test conditions for the PCI Example test case

Parameter	Value
Coolant temperature at core inlet	560 K
Mass flow rate	3024 kg/s
Average system pressure	15.5 MPa
Active length of core	3.6576 m
Fuel density	10465 kg/m
Pellet outer diameter	8.1915 mm
Cladding outer diameter	8.3566 mm
Cladding thickness	0.5715 mm

2.2 BISON-CASL/Falcon Comparisons

Many of the results produced during this Test Stand are displayed as comparisons between BISON-CASL and Falcon simulations, with both cases using similar inputs. Version 1.2 of the Falcon fuel performance code [1] represents the version of Falcon used throughout this Test Stand.

Considering that a number of physics models are the same in both BISON-CASL and Falcon it is a reasonable assumption that the same input in both codes would result in essentially the same output. However, because the two codes are coupled and solved with different solution methods and procedures, the results are not expected to be identical although they are expected to display similar trends with reasonably close output values. These results are also provided in this format in order to compare BISON-CASL results to an industry standard tool as well as to help identify differences between the codes that may guide developers in determining further verification and validation needs. Other differences in the way solutions are reached for these time-based analyses may highlight the potential advantages or disadvantages associated with the advanced solution methods used by BISON-CASL. Note that Falcon results are not being considered as a benchmark solution against which BISON-CASL is being measured. The Falcon results are provided to illustrate differences between BISON-CASL and an industry-standard fuel performance code with over 40 years of development history and industry use.

Output results throughout this report are plotted as a function of time (in days) or position (in meters). The various thermal and mechanical responses are reported using the International System of Units (SI). Some notable exceptions include using days instead of seconds because of time scale practicalities and kW/ft for linear heat generation rates (LHGRs) instead of W/m because of industry traditional use and familiarity.

Table 4. Comparison of material and behavioral models between BISON-CASL and Falcon

Material	Property	BISON-CASL	Falcon
Fuel	Thermal Conductivity	Falcon/NFIR	MATPRO [4] + Literature
	Heat Capacity	FPE [5]	MATPRO
	Relocation	Falcon	ESCORE

	Thermal/Irradiation Creep	Falcon	Modified MATPRO
	Smeared Cracking	Falcon	EPRI
	Thermal Expansion	MATPRO	MATPRO
	Solid Swell	Falcon	Literature
	Densification	ESCORE	MATPRO, ESCORE
	Fission Gas Release	SIFGRS	Modified Forsberg-Massih
	Radial Power/Burnup	TUBRNP	TUBRNP
Cladding	Thermal Conductivity	MATPRO	MATPRO
	Irradiation Growth	Falcon	MATPRO, ESCORE
	Thermal/Irradiation Creep	Limback/Falcon	Limback
	Thermal Expansion	MATPRO	MATPRO
Gap	Gap Conductivity	MATPRO	Literature
	Void Volume	Ideal Gas Law	Ideal Gas Law
Coolant	Single Channel Enthalpy Rise Model	CASL	EPRI

3 RESULTS

Because fuel performance results have both time and spatial dependence, and because both the Falcon and BISON-CASL codes produce output in different formats, most results are presented as a time series analysis for a single point in space or at specific points along a given geometric plane for a specified time. The first progression problem is a test reactor experimental fuel rod case derived from the Studsvik International Fuel Performance Experiments (IFPE)/Super-Ramp Project [6]. This test case represents a fuel rod (modeled as a single pellet) that is less than 1/10th the size of a commercial PWR fuel rod. This case also includes further simplification in that the power history is applied uniformly along the axial length of the rod. A comparison of the fuel centerline temperatures is provided in Figure 5. Similar to the results presented in the reference [7], Falcon is generally predicting hotter fuel temperatures than BISON-CASL. . This difference in temperature is less at the radial mid-plane in Figure 6 and is reversed at the outside of the fuel and at select cladding locations (reported in Figure 7 through Figure 8).

Note that the power history used by the BISON-CASL development team for this case was misrepresented from its source, a Falcon case file. The original Falcon input was based on constant power input where changes to power from one time point to the next are quickly ramped using a 0.1-hr ramp time. Instead, linear changes were assumed for this BISON-CASL case[3]. This difference is apparent when comparing BISON-CASL results that show ramped temperature changes where Falcon results do not (Figure 5 through Figure 8). In all cases, reasonable agreement is achieved between the codes if one accounts for the difference in power input noted above. A consistent difference in temperature is exhibited as the shape in temperature history is examined. The axial profiles at 1126 days into the simulated fuel exposure, shown in Figure 9 through Figure 10, are consistent with this assessment.

[3] The power history input can be modified to mirror the 0.1-hour ramps used by Falcon, however the Peregrine solvers had difficulty finding converged solutions using this strategy and therefore this technique was not pursued further.

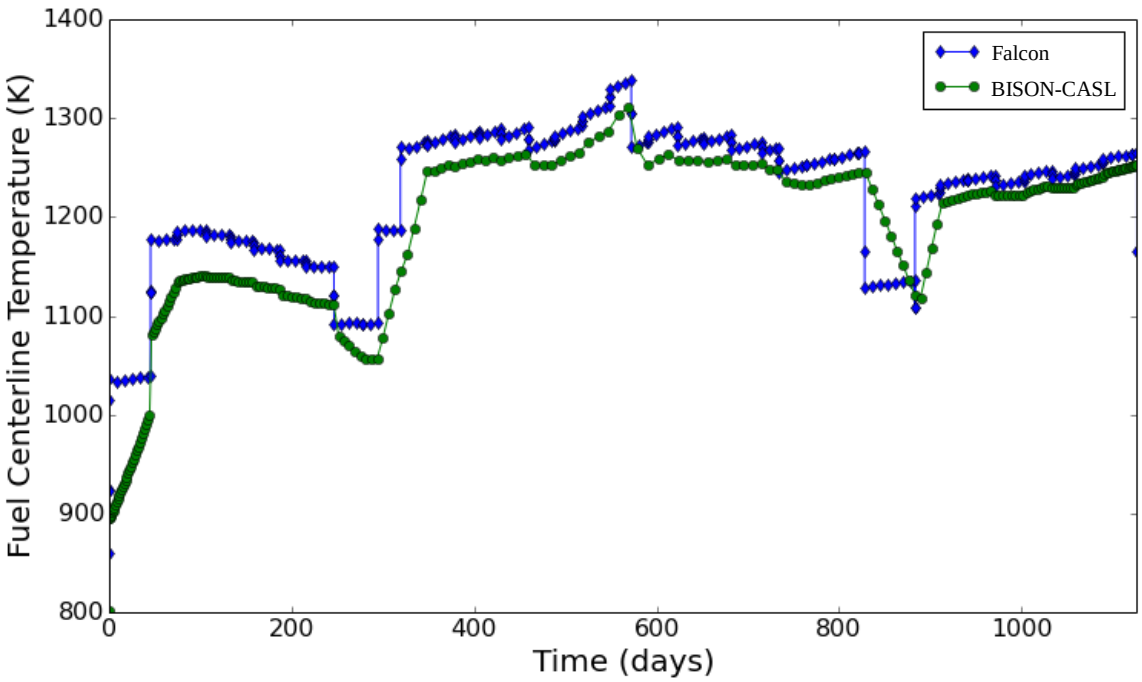

Figure 5. Fuel centerline temperature taken at a point along the axial mid-plane of the active fuel region for progression problem 1

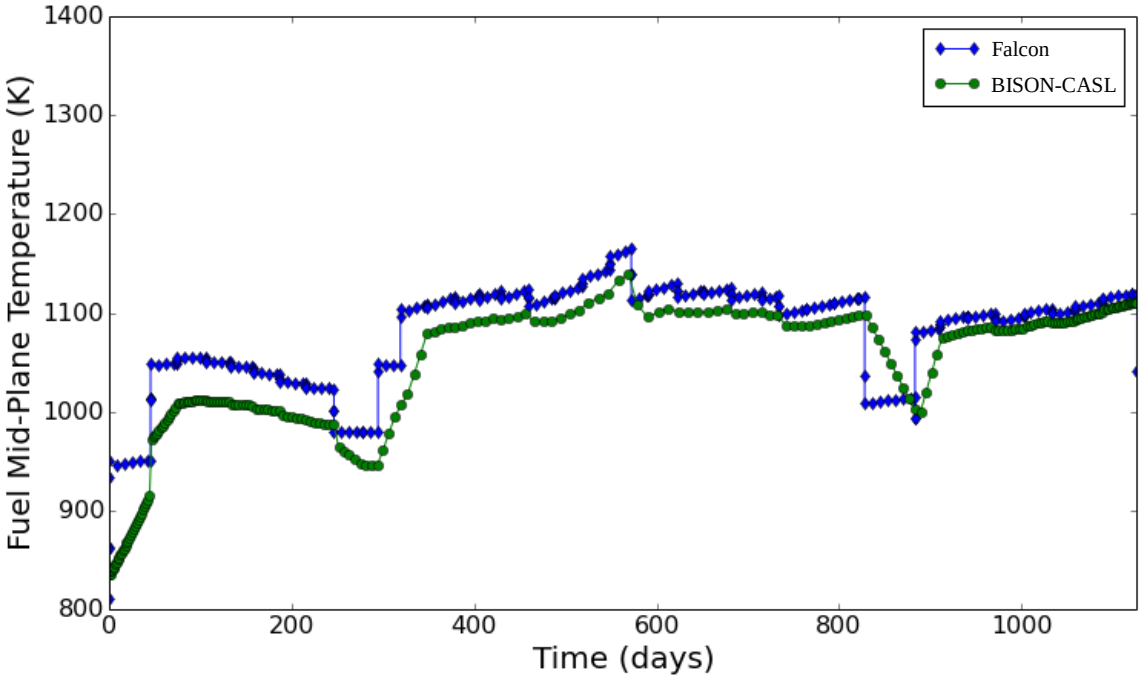

Figure 6. Fuel mid-plane temperature taken at a point along the axial mid-plane of the active fuel region for progression problem 1

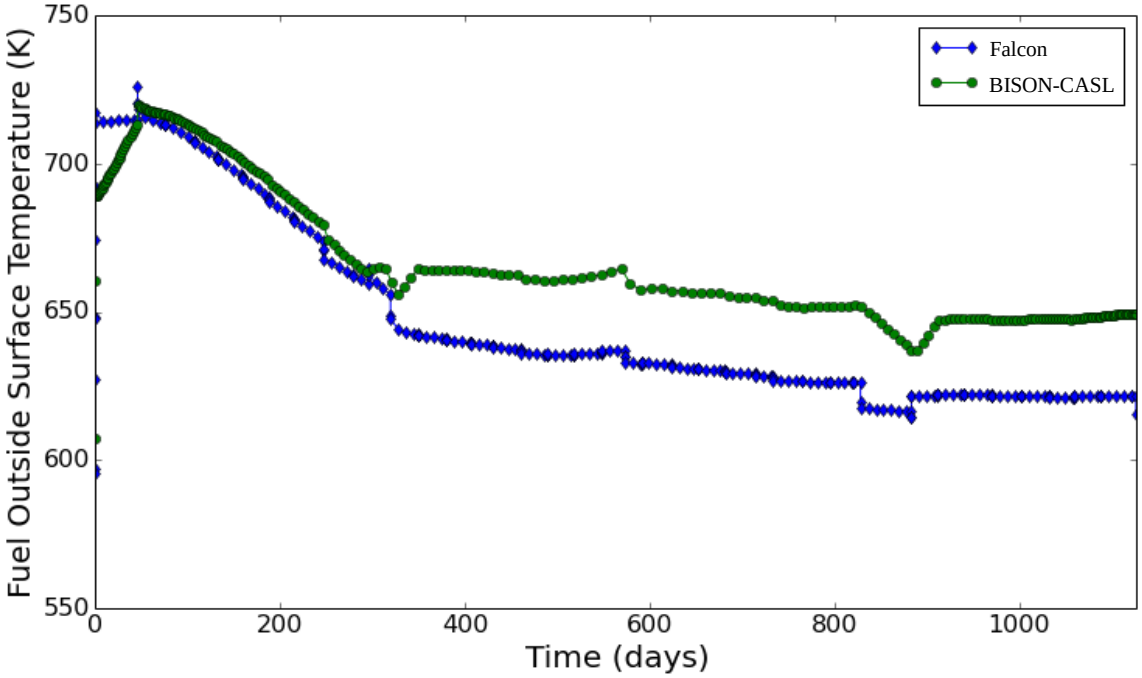

Figure 7. Fuel outer surface temperature taken at a point along the axial mid-plane of the active fuel region for progression problem 1

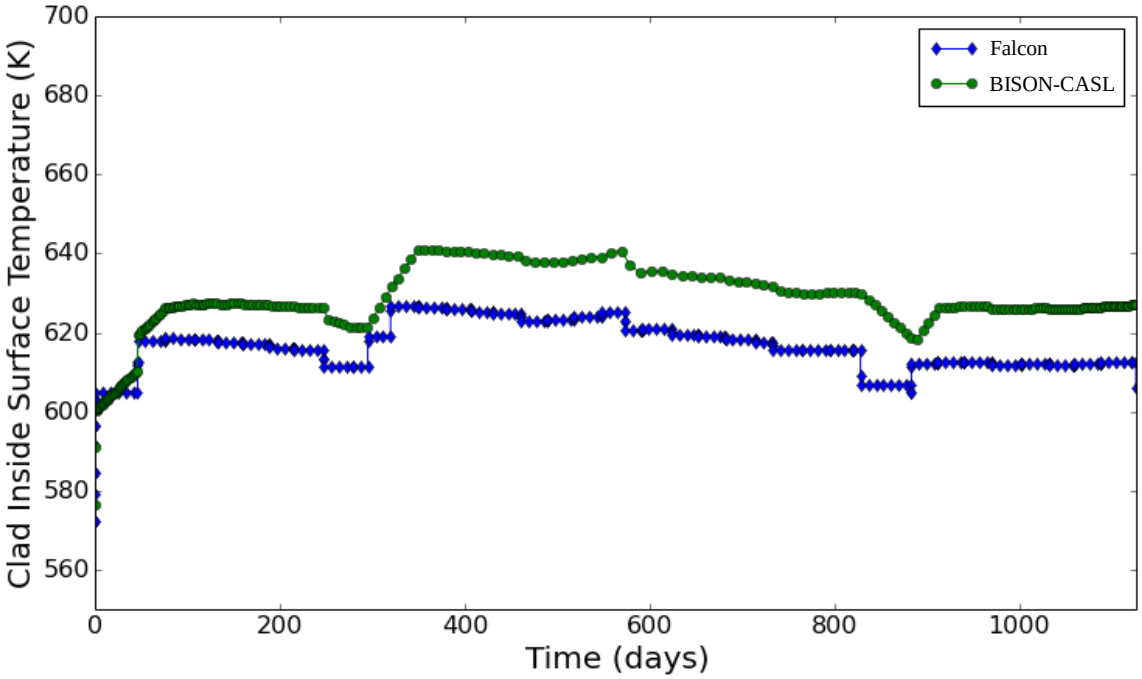

Figure 8. Cladding inner surface temperature taken at a point along the axial mid-plane of the active fuel region for progression problem 1

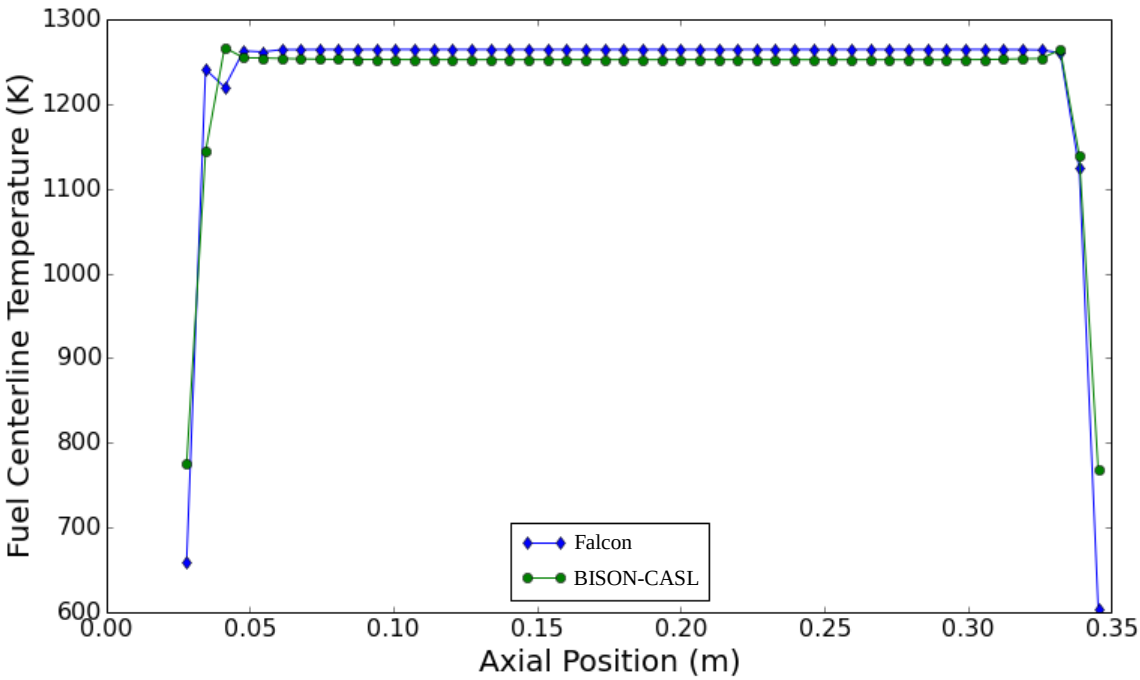

Figure 9. Axial temperature profile along the fuel centerline at 1126 days for progression problem 1

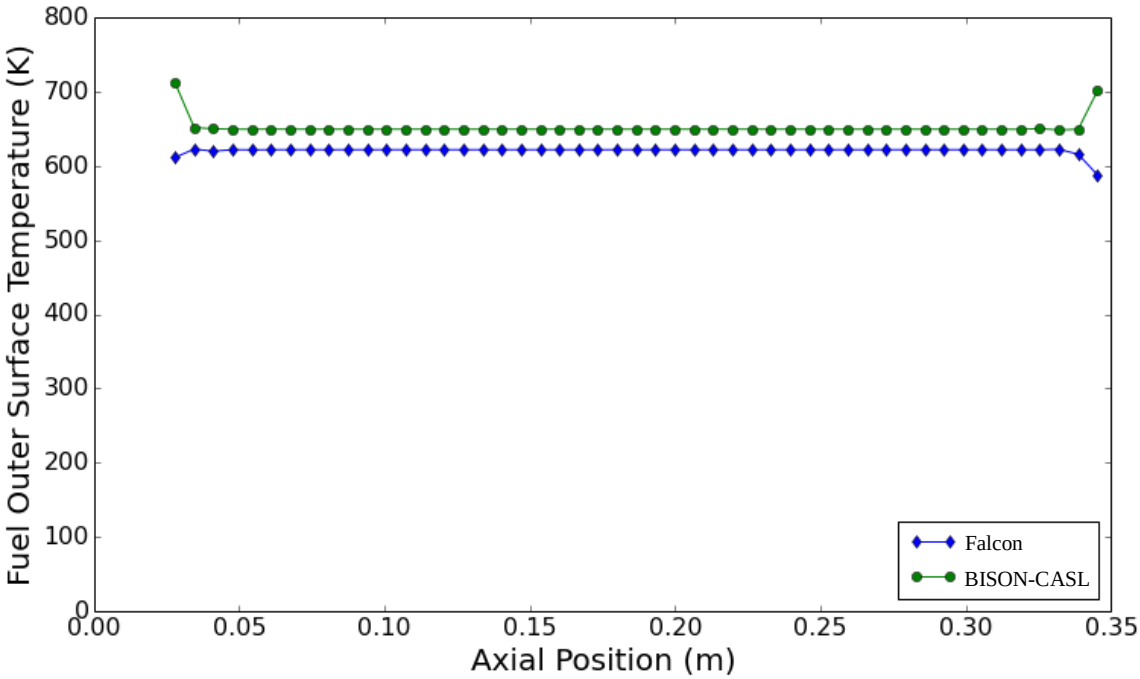

Figure 10. Axial temperature profile along the fuel outer surface at 1126 days for progression problem 1

Next, the PCI Example case is examined. Because progression problems 2 through 6 are indeed a "progression" in complexity for the PCI Example case, only the results for the final step in this progression, progression problem 6, are presented. The aid in the explanation of the results to follow, the power history during the ramp down and subsequent second cycle restart for the PCI Example case is provided in Figure 11.

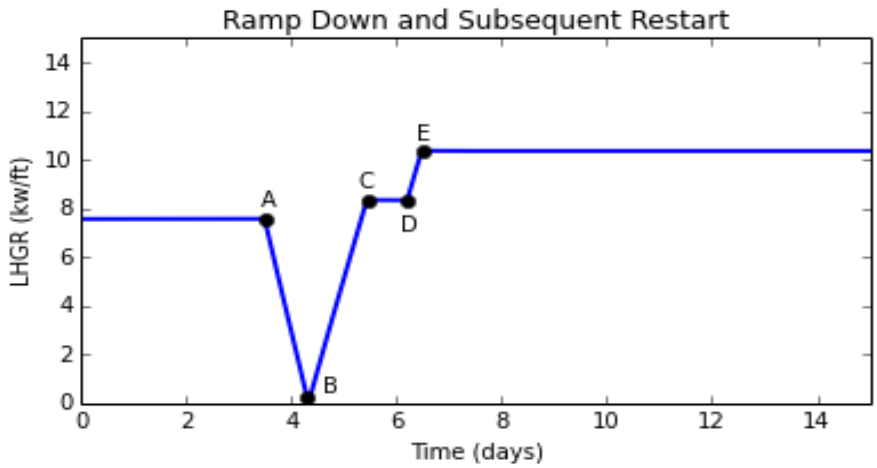

Figure 11. Power history during the ramp down and subsequent restart for the PCI Example case

Figure 12 is a plot of the fuel centerline temperature for the PCI Example case. Similar to the previous progression problems, the trends in the fuel centerline temperature throughout the ramp down and second cycle restart for both Falcon and BISON-CASL show good agreement. The magnitudes, as in the previous progression problems, differ significantly. Figure 13 plots the difference between the Falcon and BISON-CASL temperature estimates by subtracting the BISON-CASL temperature estimate from the Falcon temperature estimate. Figure 13 illustrates that the magnitude of the difference in temperature has a strong dependence on the magnitude of the temperature which is reflective of the power history. This result requires further evaluation to obtain a better understanding of what is causing this temperature difference and why it appears to be correlated to the power history.

The fuel radial mid-plane temperatures, illustrated in Figure 14, show results similar to those presented for the fuel centerline temperatures. The fuel outer surface temperature, illustrated in Figure 15, shows a difference in the trend during the second cycle restart and subsequent hold period. Beginning near the end of the second cycle power ramp (segment $\overline{DE}$) , the trends separate as Falcon, starting at a lower temperature, predicts a larger increase in temperature as a function of time until approximately day 473. This can be more clearly observed by Figure 16, which plots the difference in the fuel outer surface temperatures calculated by Falcon and BISON-CASL. When compared to Figure 13, the dependence on the magnitude of the temperature, or power, is not as strongly pronounced. It would seem that the influence of heat transferred from the cladding to the coolant has a large competing effect on determining the temperature response on the outside fuel surface at these lower temperatures. Note that similar to progression problems 2 through 5, agreement is observed between the cladding and coolant temperature results between the two codes.

Figure 17 plots the temperatures and displacements for the fuel outer surface and cladding inner surface during the ramp down and subsequent restart. This result shows good agreement between the two codes during the down power and second cycle restart, but also shows that Falcon estimates increasing fuel and cladding displacements throughout the final hold period while BISON-CASL does not estimate swelling of the fuel rod during this final hold period. This observed difference in the mechanical solution is likely the driver behind the difference in the thermal trends for this time period. It is important to note that this difference in trends does not

necessarily suggest an inconsistency between the codes. Falcon is predicting temperatures that are approximately 140 K higher during this hold period, and this difference in magnitude could be responsible for variation in this and other various physical phenomena calculated by the two codes.

Figure 18 displays the hoop stress comparison for a generic PWR rod model during the down power following cycle 1 steady-state operation as well as the second cycle restart (progression problem 6). In comparison with the Falcon analysis, notable observations from Figure 18 include:

- BISON-CASL predicts less stress relaxation during the down power (segment $\overline{AB}$) as well as the first step in power during the second-cycle restart (segment $\overline{CD}$),
- BISON-CASL predicts more stress relaxation during the final hold period after the second cycle power ramp is complete (following point E),
- BISON-CASL predicts less stress buildup during the first step increase of the second-cycle power ramp (segment $\overline{BC}$),
- BISON-CASL predicts more stress buildup during the second step increase of the second-cycle power ramp (segment $\overline{DE}$), and
- The peak inside cladding surface hoop stress predictions by the two codes are within 0.5% of each other.

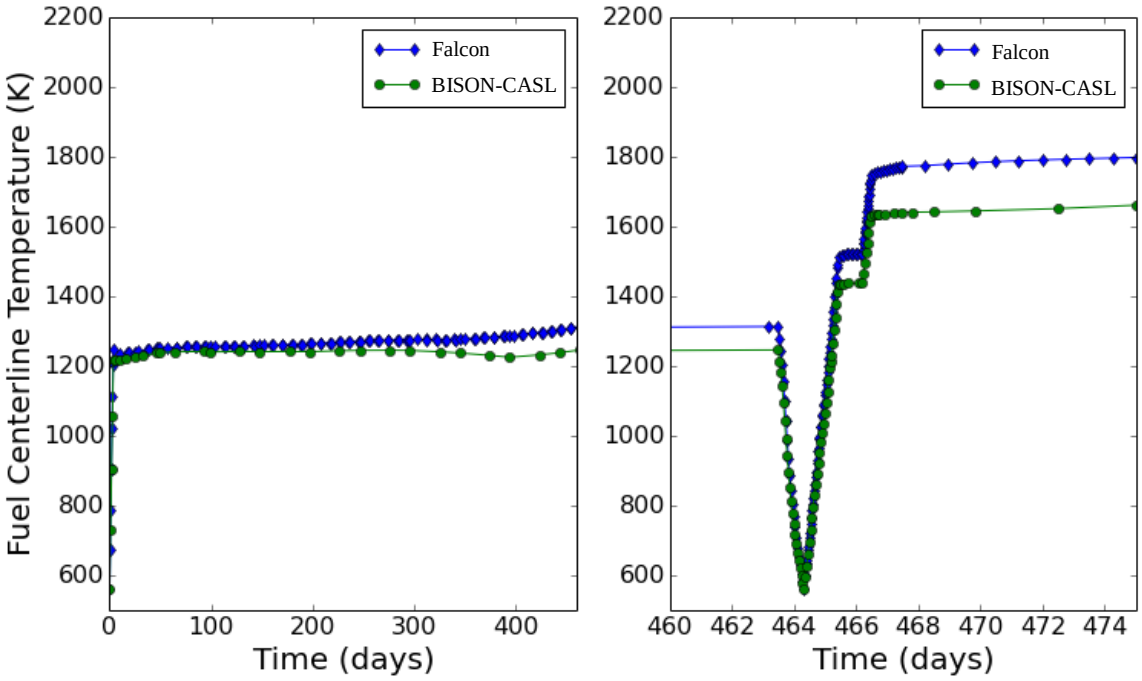

Figure 12. Fuel centerline temperature for the first cycle (left) and the down power and subsequent second cycle restart (right) taken at a point along the axial mod-place of the active fuel region for the PCI Example case

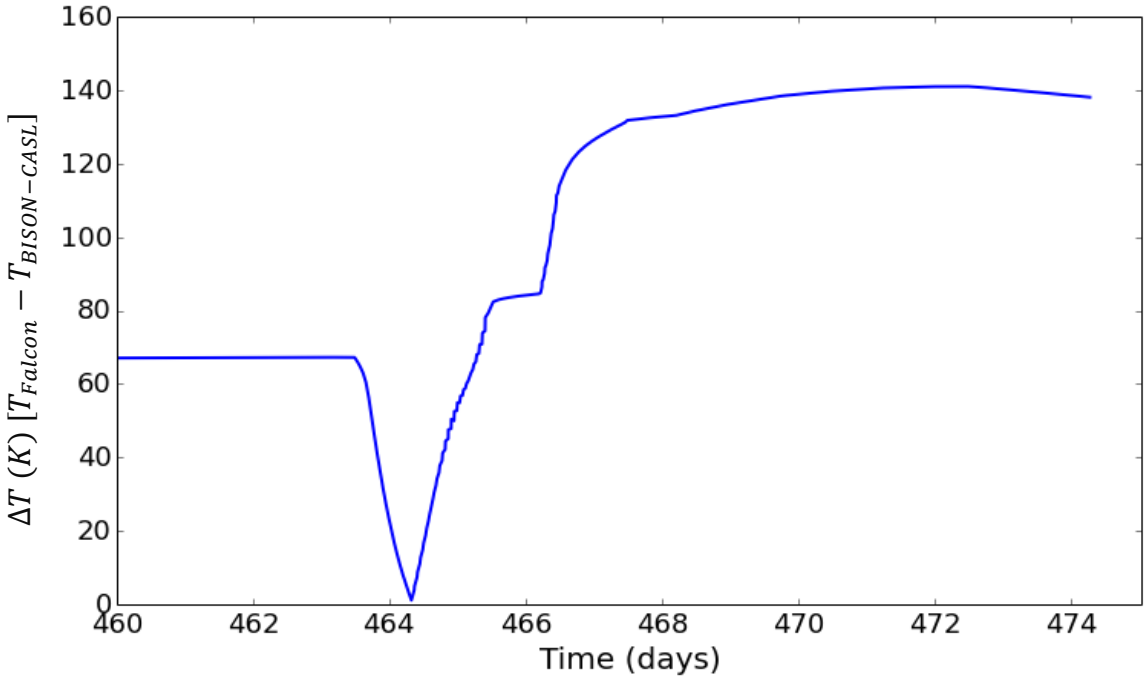

Figure 13. Fuel centerline temperature difference between Falcon and BISON-CASL for the PCI Example case

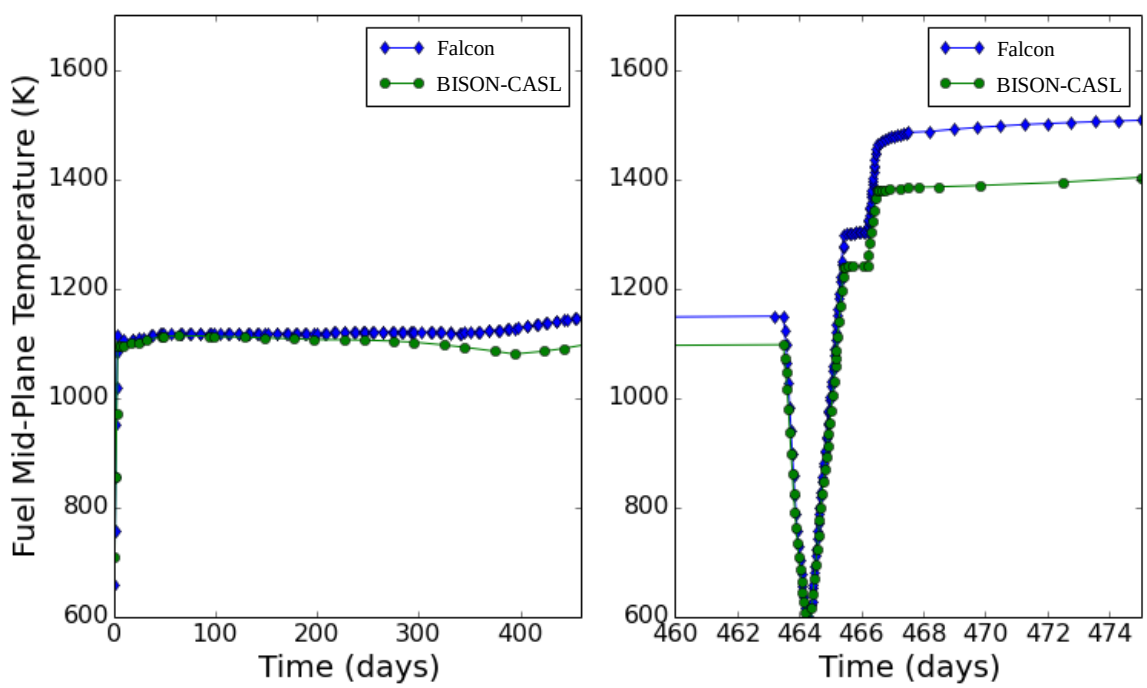

Figure 14. Fuel mid-plane temperature for the first cycle (left) and the down power and subsequent second cycle restart (right) taken at a point along the axial mid-plane of the active fuel region for the PCI Example case

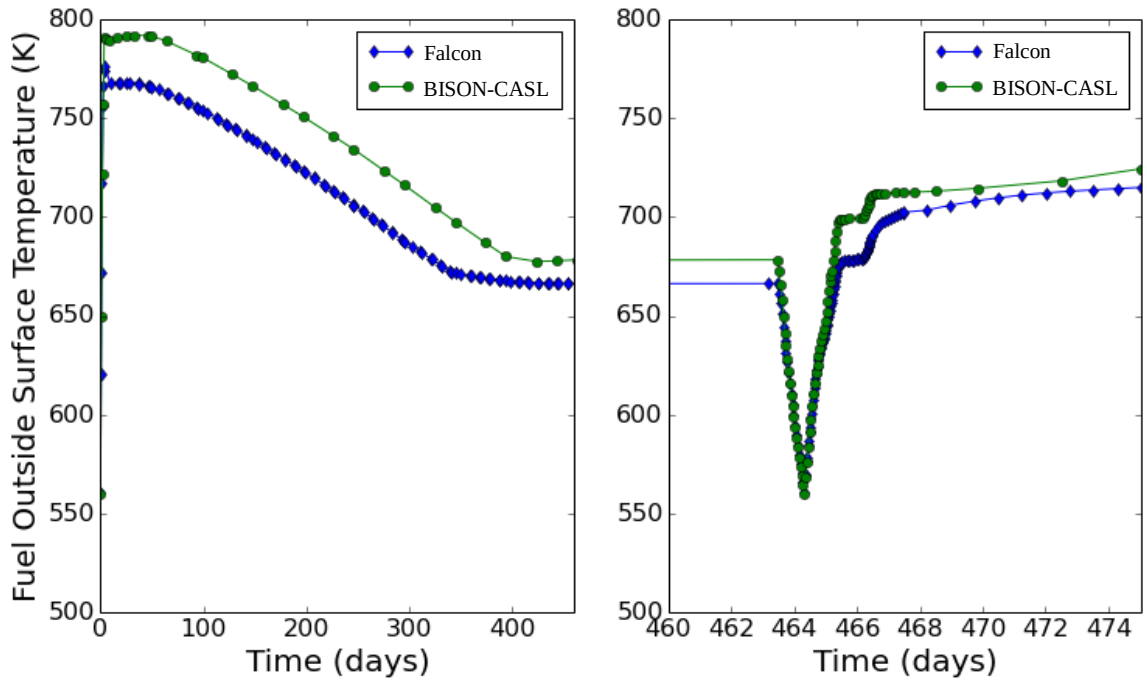

Figure 15. Fuel outer surface temperature taken at a point along the axial mid-plane of the active fuel region for the PCI Example case

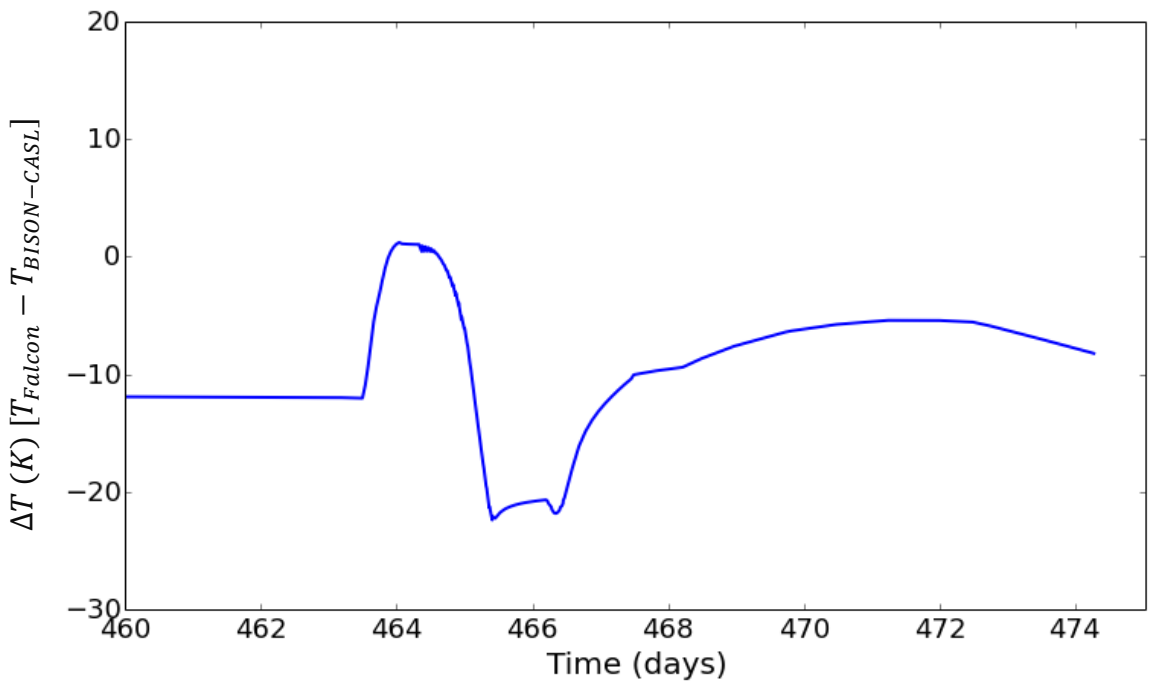

Figure 16. Fuel outer surface temperature difference between falcon and BISON-CASL for the PCI Example case

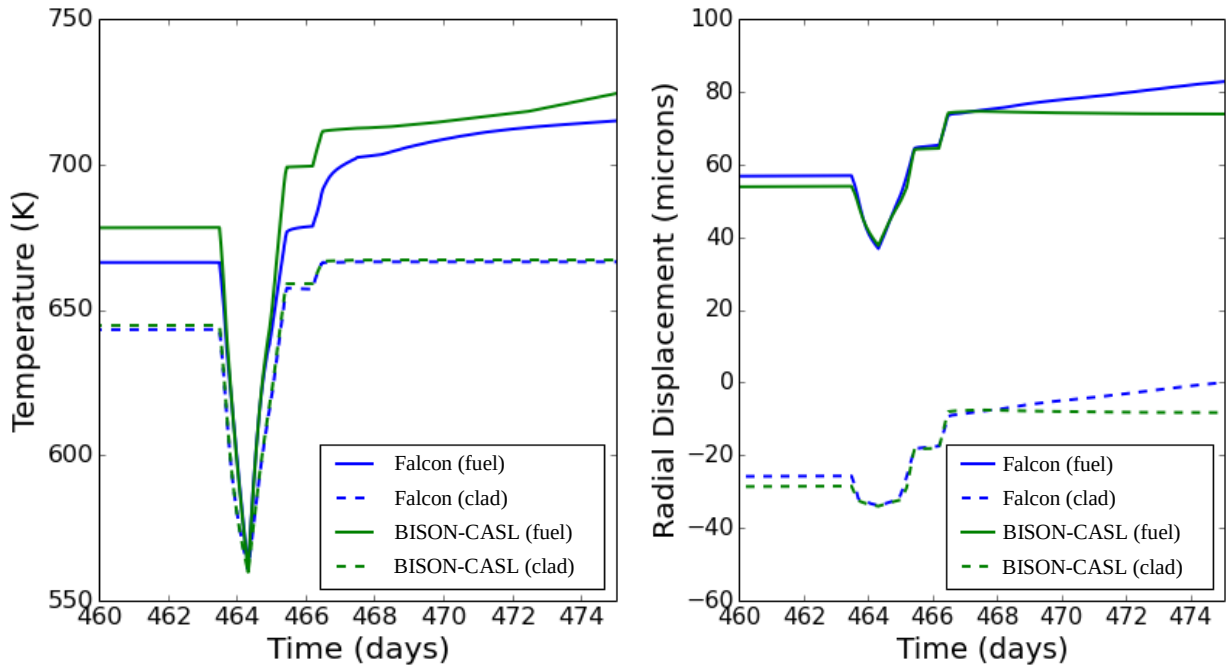

Figure 17. Temperatures (left) and displacements (right) for the fuel outer surface and cladding inner surface taken at a point along the axial mid-plane of the active fuel region for the PCI Example case

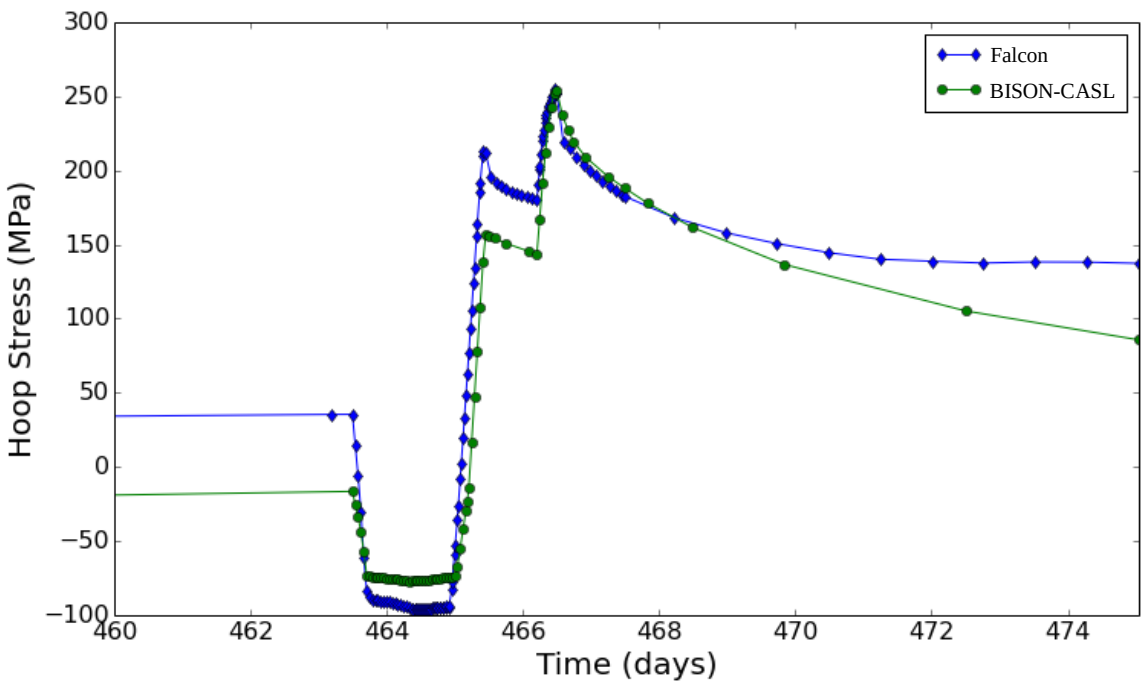

Figure 18. Cladding inside surface hoop stress taken at a point along the axial centerline of the active fuel region for the PCI Example case

4 CONCLUSIONS

The ultimate goal of this Test Stand application is to evaluate BISON-CASL with respect to its ability to perform pellet-cladding interaction (PCI) analyses. This evaluation was performed using a series of progression problems developed specifically for this Test Stand application and modeled in two-dimensional R-Z axisymmetric space. Results from the six progression problems were used to assess the position of BISON-CASL relative to industry standard codes. Note that 15 000+ core hours were used on EPRI's high-performance computing (HPC) cluster Phoebe to perform the simulations for this Test Stand. The primary conclusions derived from this Test Stand are:

- The thermal behavior within the fuel is different during the initial startup between the two codes. It appears that more energy in the form of heat exists in the fuel during Falcon simulations relative to the BISON-CASL simulations considering all temperature histories and axial temperature distributions examined by this Test Stand. This could be the result of numerous differences that exist between the two codes. Two areas identified as having a higher likelihood of exposing the reasons behind the observed differences in the results include (1) the volumetric heat generation calculation and (2) the UO_2 thermal conductivity model.
- The thermal and mechanical response trends observed by both codes are quite similar, although they vary in numerical result. This is important because the Falcon model has been validated by several sets of experimental data, and BISON-CASL should produce near equivalent results.
- Differences are observed in the magnitude of the temperature, displacement, and hoop stress estimates by BISON-CASL and Falcon for similar input cases.
- General agreement between Falcon and BISON-CASL is observed in the temperature, displacement, and hoop stress trends both spatially and temporally.
- There are no outstanding large differences in BISON-CASL results when compared to Falcon, suggesting that BISON-CASL is ready for a more through verification program.

It is important to note that multi-physics code comparisons that involving dozens of different models and parameters are difficult. Significant effort went into making the Falcon and BISON-CASL models comparable; however, this cannot be rigorously enforced to ensure a true "like for like" comparison given the differences in the solution methodology, finite element formulation, and the treatment of the various thermal, mechanical, and chemical phenomena. It is important to recognize that definitive assessments and conclusions should not be derived using only code-to-code comparisons. Data validation of the BISON-CASL results is needed to accomplish this task.

5 ACKNOWLEDGMENTS

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