RESEARCH REPORT

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Loss-of-coolant accident simulations in FIDES-II LOC-HBu benchmark with the U.S.NRC's FAST fuel performance code

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Loss-of-coolant accident simulations in FIDES-II LOC-HBu benchmark with the U.S.NRC's FAST fuel performance code	
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Summary

As part of the NEA's Second Framework for Irradiation Experiments (FIDES-II), a Joint ExPerimental Programme (JEEP) named Loss-of-Coolant High Burnup (LOC-HBu) is ongoing. This programme involves in-pile loss of coolant accident (LOCA) fuel experiments at Idaho National Laboratory's TREAT facility. Focused on light water reactor fuel performance at high burnup, the LOC-HBu aims to expand knowledge on fuel fragmentation, relocation and dispersal during LOCA events.

In connection with the LOC-HBu JEEP, a modelling and simulation (M&S) exercise was organized. The goal of this exercise is to improve M&S vs. experimental integration and to facilitate community involvement in experiment design and interpretation. The LOC-HBu M&S exercise is based around a fresh fuel commissioning test named LOC-C-4 which had not yet been conducted when the modelling benchmark was ongoing. Further goals of the exercise are to simulate both the thermal-hydraulics and fuel performance, to predict fuel rod ballooning and burst behaviour, and to study the impact of rod internal pre-pressurization and plenum size on ballooning and burst. The thermal-hydraulic boundary conditions are provided for the participants so it is not imperative to perform thermal hydraulics analysis. The commissioning tests are not part of the FIDES-II but only the actual tests on high burnup fuel are.

VTT participated in the M&S exercise by simulating five LOCA cases with the U.S. NRC's fuel performance code FAST 1.2.1. The code was used at VTT for the first time.

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1. Introduction

As part of the NEA's Second Framework for Irradiation Experiments (FIDES-II), a Joint ExPerimental Programme (JEEP) named Loss-of-Coolant High Burnup (LOC-HBu) is ongoing. This programme involves in-pile loss of coolant accident (LOCA) fuel experiments at Idaho National Laboratory's TREAT facility.

In connection with the LOC-HBu JEEP, a modelling and simulation (M&S) exercise was organized. The goal of this exercise is to improve M&S vs. experimental integration and to facilitate community involvement in experiment design and interpretation. The LOC-HBu M&S exercise is based around a fresh fuel commissioning test named LOC-C-4 which had not yet been conducted when the modelling benchmark was ongoing. Further goals of the exercise are to simulate both the thermal-hydraulics and fuel performance, to predict fuel rod ballooning and burst behaviour, and to study the impact of rod internal pre-pressurization and plenum size on ballooning and burst. The thermal-hydraulic boundary conditions are provided for the participants, so it is not imperative to perform thermal hydraulics analysis. The commissioning tests are not part of the FIDES-II but only the actual tests on high burnup fuel are.

VTT participated in the M&S exercise by simulating five LOCA cases with the U.S. NRC's fuel performance code FAST 1.2.1 (Geelhood et al., 2024). The code was used at VTT for the first time. FAST is a merger of NRC's legacy codes FRAPCON (steady-state) and FRAPTRAN (transients).

In Section 2, the modelling benchmark is introduced, and in Section 3, the applied modelling assumptions listed. Some examples of results are listed in Section 4, and finally, lessons learned from first FAST simulations listed in Section 5. As this is a pre-test benchmark, comparison to experimental results cannot be done.

2. Modelling benchmark

In the M&S exercise, six cases under the planned experimental conditions of the LOC-HBu programme are examined. Case 1 consists of simulating both the thermal-hydraulics and fuel performance experiment, whilst cases 2 through 6 are fuel performance simulations only. Those cases list different rod conditions (Table 1) to study their effects on cladding behaviour during LOCA. Detailed description of the problem alongside the thermal hydraulics and fuel performance boundary conditions were provided by INL (Armstrong et al., 2025). The total simulation time was 500 s. Case 1 was not simulated by VTT, only the fuel performance simulations (Cases 2-6) were conducted.

The fuel in LOC-C-4 experiment will be PWR-sized rodlet consisting of fresh UO_2 fuel in Zircaloy-4 cladding with a ceramic insulator pellet on the top and bottom of the active fuel stack. The fuel rodlet contains an enlarged diameter plenum region to allow for increased free volume (Armstrong et al., 2025).

Table 1. Summary of the LOC-HBu M&S exercise cases.

<table>
<tr><th>Case #</th><th>Fuel Length (cm)</th><th>Rod Free Volume (cm^3)</th><th>Rod Internal Pressure @ 293.15 K (MPa)</th><th>Peak Cladding Temperature* (°C)</th><th>Notes</th></tr>
<tr><td>1</td><td rowspan="6">25</td><td rowspan="4">15.9</td><td rowspan="2">10</td><td rowspan="6">900</td><td>FP & TH: Nominal rod pressure</td></tr>
<tr><td>2</td><td>FP: Nominal rod pressure</td></tr>
<tr><td>3</td><td>5</td><td>FP: Lower rod pressure</td></tr>
<tr><td>4</td><td>15</td><td>FP: Higher rod pressure</td></tr>
<tr><td>5</td><td>10</td><td rowspan="2">10</td><td rowspan="2">FP: Reduced plenum</td></tr>
<tr><td>6</td><td>5</td></tr>
</table>

3. Modelling assumptions

The key modelling assumptions are listed as follows:

- Cases 2-6 were calculated with the convective boundary condition using coolant temperature, pressure, and heat transfer coefficient (HTC) in FAST
- The rod was divided into 24 axial nodes, and the insulator pellets at both ends were not modelled.
- The coolant pressure was assumed constant throughout the length of the rod. The provided upper capsule pressure by INL was specified in the input file for this purpose.
- A maximum of 200 timesteps is allowed in FAST transient calculations. A solution timestep of 0.2 s is used as recommended in the manual to achieve convergence successfully.
- The convective boundary condition profile was condensed and specified at four axial elevations in the input file.
- The external plenum volume option in FAST is used to model the enlarged diameter plenum part.
- The provided rod plenum temperature was used as an input for the external plenum temperature, which has to be supplied by the user in FAST.
- The cladding strain reported in the results is the hoop strain.
- The fuel centreline temperature and the cladding outside temperature at the mid-height of the fuel rod is reported from the centre of node 12.

4. Results

The requested outputs were defined in the benchmark specifications (Armstrong et al., 2025) and the results were gathered into Excel templates provided by INL. For all cases, INL requested that all time-dependent outputs should be provided up to time of predicted rod failure, or 500 seconds if no failure is predicted.

A summary of the predicted burst time results for cases 2-6 is presented in Table 2.

It is seen that when the internal pressure is increased (Case 3 int. pressure < Case 2 < Case 4), the predicted burst occurs earlier (expected result).

When the free volume is increased (Case 6 free volume < Case 5 < Case 2) while keeping the same rod internal pressure, the predicted burst is delayed.

Table 2. Cases 2-6 time to burst results.

Modelled Cases	Predicted burst time (s)
Case 2	44.8
Case 3	55.8
Case 4	40
Case 5	44.4
Case 6	42.6

The burst location for all cases occurs at 0.2212 m elevation, corresponding to node 22 in the fuel rod.

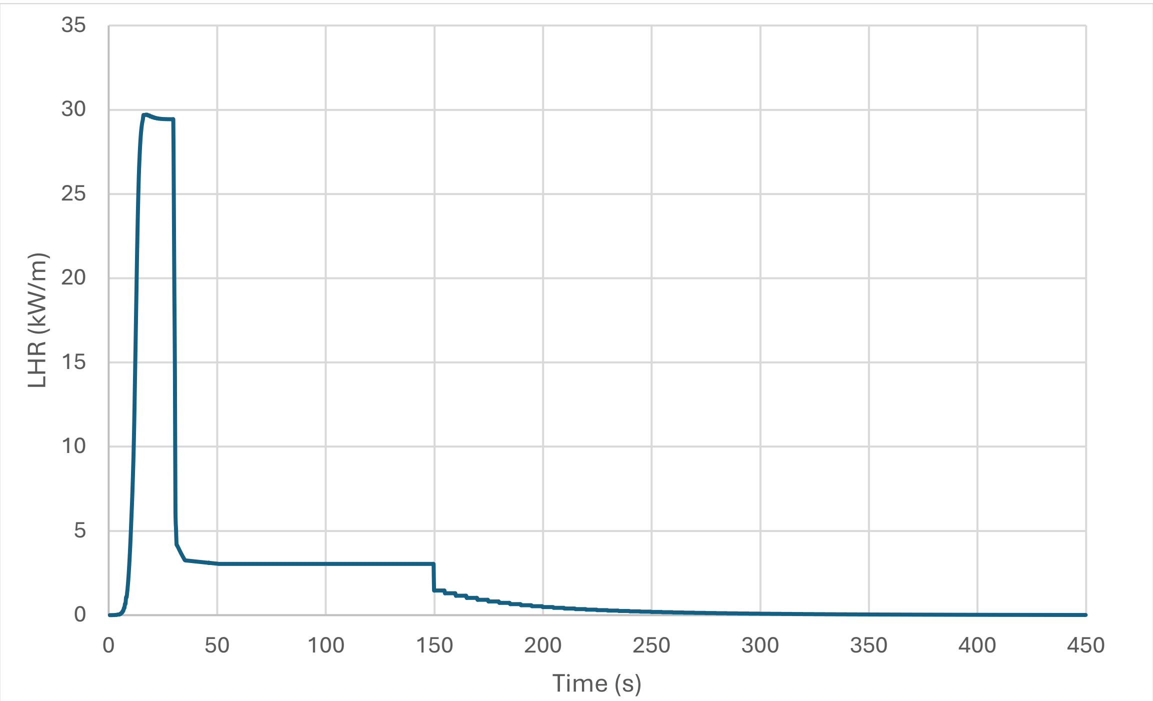

Figure 1. Average power vs time for all simulated cases.

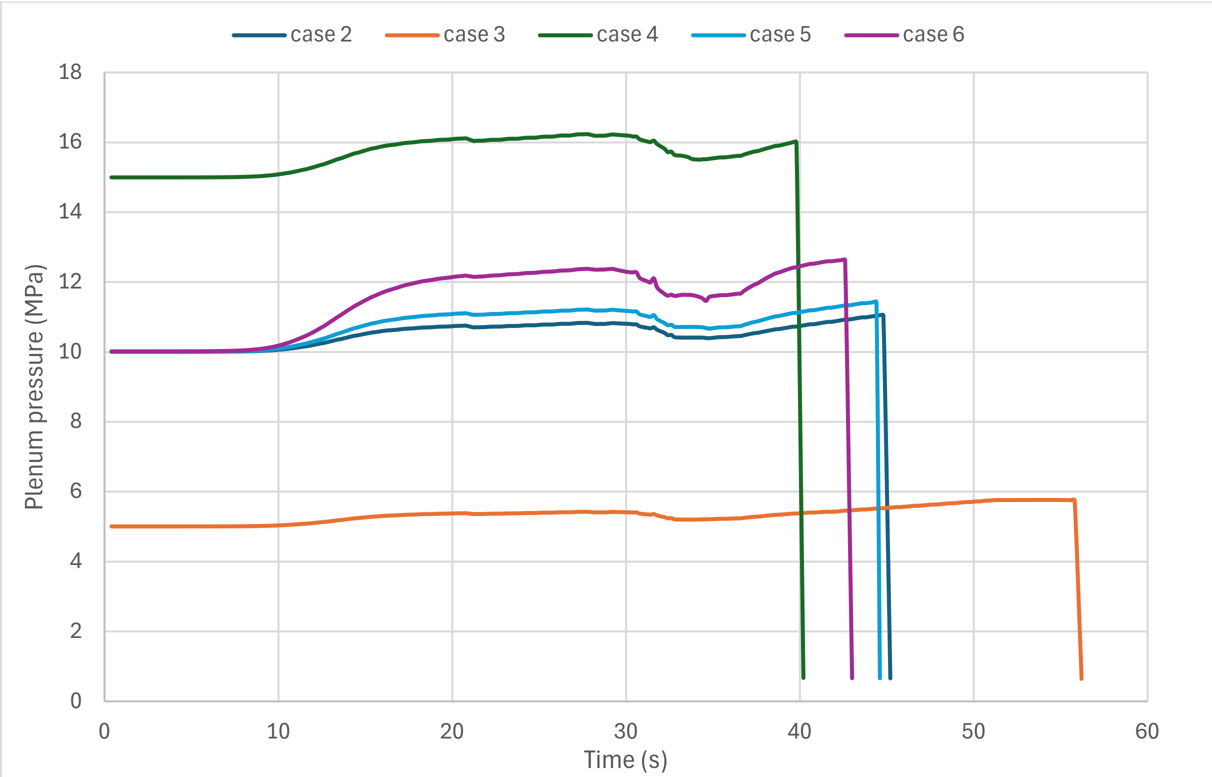

Figure 2. Cases 2-6 results - plenum pressure vs time.

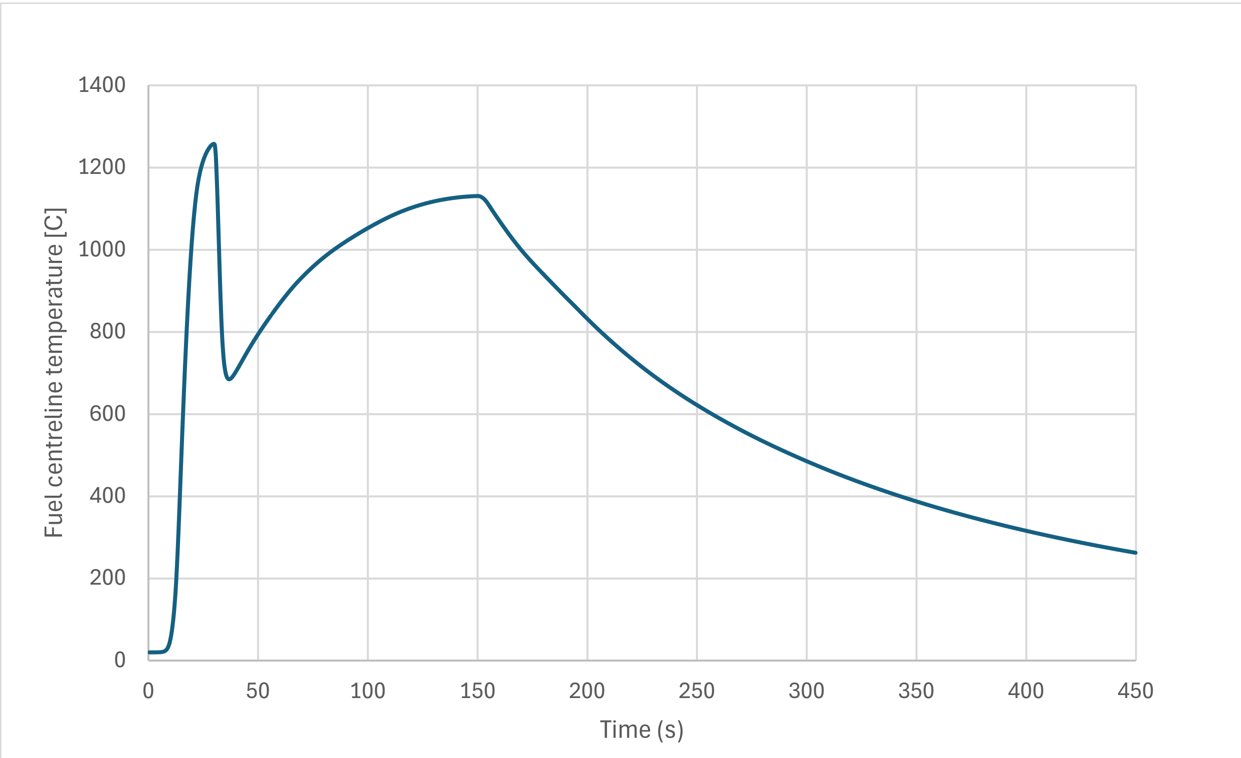

Figure 3. Fuel centreline temperature at rod mid height for Case 2.

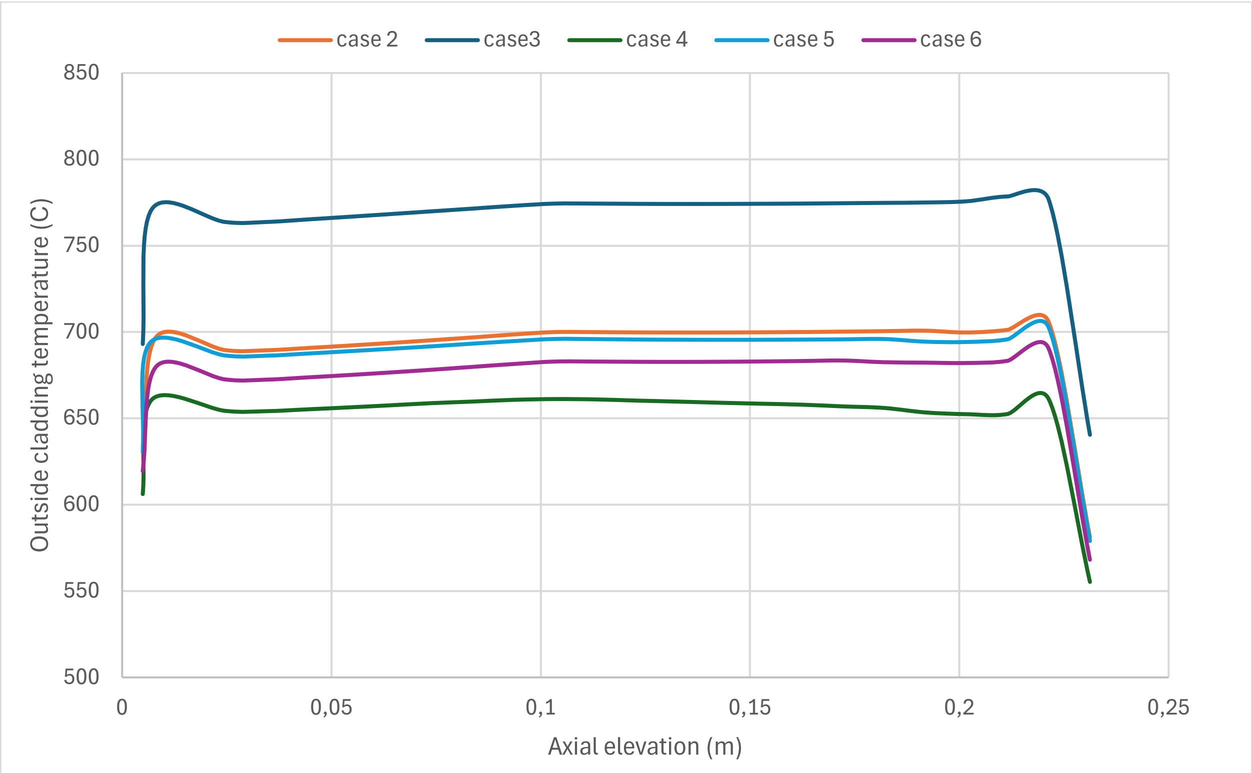

Figure 4. Cases 2-6 Axial profiles of outside cladding temperature for cases 2-6 at the burst time.

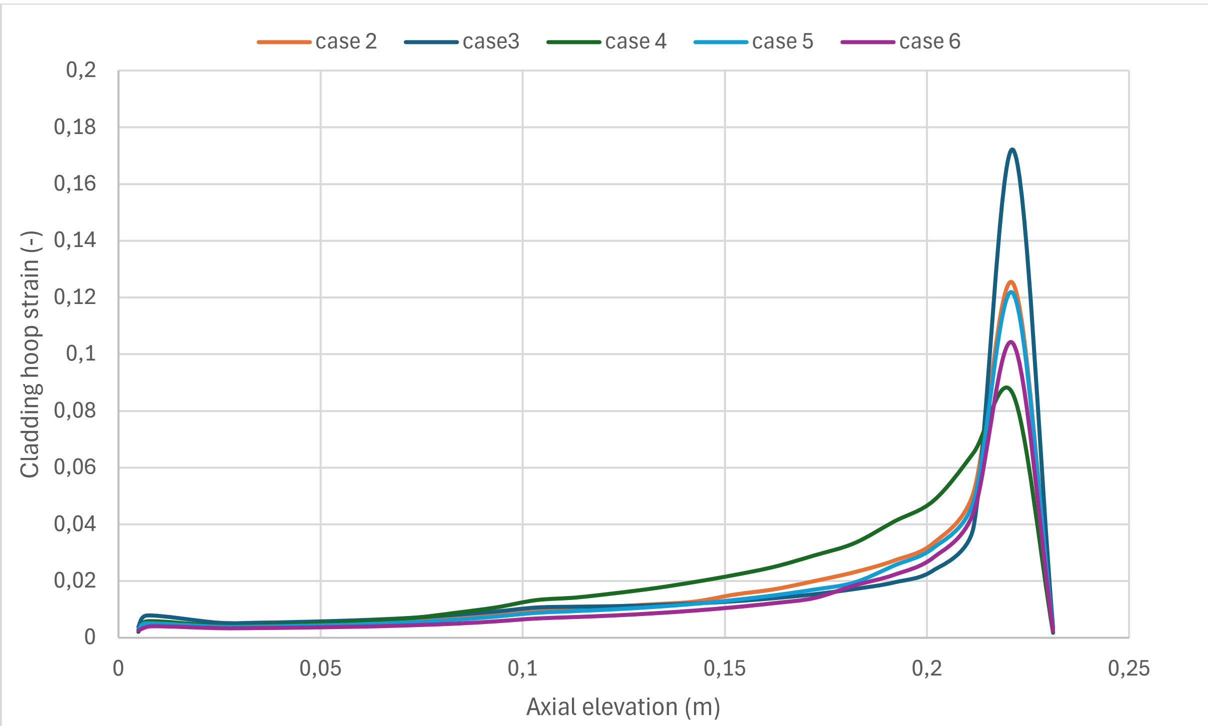

Figure 5. Axial profile of cladding hoop strain in cases 2-6 at the burst time.

5. Learnings and notes from using the FAST fuel performance code

In the following, lessons learned and open questions from the first use of the FAST code at VTT are listed.

- Since FAST is a Fortran-based fuel performance code, lines in the input file should not be longer than 72 characters or even less. This was limited to four values per line with two decimal places in few cases for the code to parse the input file correctly.

- The first value in the problem time cannot be 0 s, it should always be larger than 0.0 s.

- The axial power profile in FAST is limited to a maximum of seven axial locations. Therefore, the axial power profile had to be condensed.

- Several errors were noted with the input file generator:
  - The “Advanced Coolant” sheet in the FAST input generator, used to specify the boundary conditions, has tables for each parameter such as the Cladding temperature, Clad/Coolant HTC, Coolant temperature. These tables, however, are limited to a maximum of 21 columns, limiting the number of axial positions that can be used to provide boundary conditions to 21 along the length of the fuel rod. If the number of axial positions exceeded the maximum number of columns of these tables, a loose chunk of the boundary conditions was generated outside of the correct boundary block (the boundary blocks start with &-letter in the input file).
  - The input generator does not generate the timestep in the input file correctly.
  - The input file flagged an error when initially trying to generate the file with the cladding wall temperature dataset as an input.

- By default, a maximum of 200 timestep pairs is allowed. It is mentioned in the manual that “defsize” can be used to increase it, but it was not specified in the manual how.

- When simulating a LOCA event, the timestep solution should be 0.2 s to achieve convergence successfully.

- When specifying the thermal hydraulics boundary conditions (cladding wall temperature, coolant pressure, heat transfer coefficient) in the input file, the format of the datasets should be: the number of timesteps, the number of axial elevations, then the timesteps themselves, then the elevations themselves, then the corresponding values listed for each timestep at all elevations.

- To specify constant values at all axial zones, use two axial zones, one with elevation at 0.0 and the second with elevation of totl+cpl (fuel rod length + plenum length).

- When listing the values for boundary conditions (cladding temperature, pressure), there should always be a comma after each value (,), even after the very last value at the end. This is particularly important for the cladding wall temperature.

- The excel input generator failed to produce the input file for the convective boundary condition that requires the coolant temperature, pressure, heat transfer coefficient and mass flow rate. This generated an error message shown in the image below. The input file therefore was generated manually by editing a template.

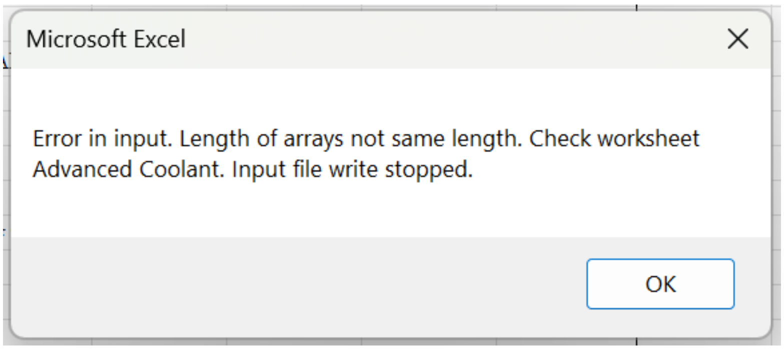

Figure 6. An error message from the FAST input generator.

- Eventually, the final results were calculated with both fuel rod plenums (top and bottom) being modelled as one large plenum volume at the top, and the enlarged plenum modelled separately. Adding a separate plenum at the bottom resulted in unrealistic results, where failure occurs at the bottom of the fuel rod. It should be noted that all boundary conditions were provided along the axial length of the fuel rod starting from elevation level 0 m (the bottom of the fuel rod). An assumption why the error occurred when the bottom plenum was modelled is that perhaps the boundary conditions were not properly defined at the bottom plenum region. One possible solution could be to provide the boundary conditions (coolant temperature, pressure and HTC) starting from elevation below zero by negative axial elevation corresponding to the bottom plenum length. However, this assumption was not tested; it remains just speculation.

- An error was noted in the output file: the elevation of the axial node 22 (the node just before the last node) was shifting position, i.e., changing the value of its axial elevation, resulting in an unrealistic situation where its elevation was less than in the node before that. The underlying reason for this issue was not resolved, and the axial profiles in this report are plotted at time of burst with the axial elevation before the bug occurs.

6. References

Armstrong, R., Folsom, C., Jensen, C., Bosland, L., 2025. LOC-HBu M&S Exercise, Problem Description Report, Idaho National Laboratory, Idaho Falls, Idaho, INL/RPT-24-82202, April 2025

Geelhood, K.J., Colameco, D.V., Luscher, W.G., Kyriazidis, L., Goodson, C.E., Corson, J., Whitman, J.J., Wray, D.F., 2024. FAST-1.2.1: A Computer Code for Thermal-Mechanical Nuclear Fuel Analysis under Steady-state and Transients. PNNL-35701