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# Sensitivity analysis of FeCrAl cladding and $U_3Si_2$ fuel under accident conditions

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## Introduction

The purpose of this milestone report is to highlight the results of sensitivity analyses performed on two accident tolerant fuel concepts: $U_3Si_2$ fuel and FeCrAl cladding. The BISON fuel performance code under development at Idaho National Laboratory was coupled to Sandia National Laboratories' DAKOTA software to perform the sensitivity analyses. Both Loss of Coolant (LOCA) and Station blackout (SBO) scenarios were analyzed using main effects studies. The results indicate that for FeCrAl cladding the input parameters with greatest influence on the output metrics of interest (fuel centerline temperature and cladding hoop strain) during the LOCA were the isotropic swelling and fuel enrichment. For $U_3Si_2$ the important inputs were found to be the intergranular diffusion coefficient, specific heat, and fuel thermal conductivity. For the SBO scenario, Young's modulus was found to be influential in FeCrAl in addition to the isotropic swelling and fuel enrichment. Contrarily to the LOCA case, the specific heat of $U_3Si_2$ was found to have no effect during the SBO. The intergranular diffusion coefficient and fuel thermal conductivity were still found to be of importance. The results of the sensitivity analyses have identified areas where further research is required including fission gas behavior in $U_3Si_2$ and irradiation swelling in FeCrAl. Moreover, the results highlight the need to perform the sensitivity analyses on full length fuel rods for SBO scenarios.

## Case Description

The BISON fuel performance code [1] was coupled to the DAKOTA [2] sensitivity analysis software to perform main effects sensitivity analyses under LOCA and SBO conditions. To obtain appreciable burnup prior to the transients, the rods were subject to a representative base irradiation history, which is shown in Figure 1. Two systems were considered, $UO_2$ fuel with FeCrAl cladding and $U_3Si_2$ fuel with Zircaloy-4 cladding. The rodlets used in these analyses contained 10 discrete fuel pellets with a rod diameter of 9.5 mm. In the $UO_2$/FeCrAl rodlet, the cladding was thinner to accommodate for the neutronic penalty introduced by using steel claddings while the fuel diameter was correspondingly increased. The initial gap thickness was the same for each rodlet.

After the base irradiation the $UO_2$/FeCral rodlet was at a burnup of 53 MWd/kgU and the $U_3Si_2$/Zircaloy-4 rodlet was at 47.67 MWd/kgU. At the conclusion of the base irradiation, the LOCA was simulated by turning the power off over 2 seconds and transitioning to decay heat, while subsequently dropping the inlet mass flux to 1 kg/m$^2$-s and reducing the coolant pressure to atmospheric over 10 seconds. The LOCA was terminated after 90 seconds due to numerical instabilities likely caused by cladding strains. The scenario is similar for the SBO except the coolant pressure was maintained at 15.5 MPa and the inlet mass flux was dropped to 100 kg/m$^2$-s to simulate the minimal flow rate introduced by the backup cooling system. The duration of the SBO was 24 hours.

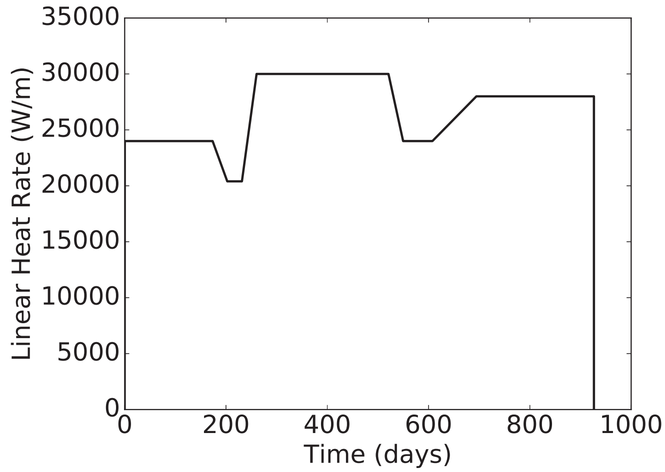


Figure 1: Representative base irradiation power history prior to initiation of the transients.

Due to the lack of experimental data and limited knowledge of which material models are of most importance during accident scenarios for ATF concepts, sensitivity analyses have been employed. In these main effects studies we have chosen select input parameters for which we have assumed an associated uncertainty to investigate their importance on the uncertainty in fuel centerline temperature and cladding hoop strain during the LOCA and SBO scenarios. The material properties and behavior models varied for the $UO_2$/FeCrAl rodlet are summarized in Table 1 including the minimum, mean, and maximum values. For the inputs listed as a scaling factor this is a constant multiplied by the value obtained from the correlation in the code, essentially increasing or decreasing the calculated value by a percentage. Table 2 summarizes the inputs varied for the $U_3Si_2$/Zircaloy-4 rodlet. In main effects studies, every combination of the various inputs is required yielding 243 simulations for the each of the LOCA and SBO scenarios for both rodlets. In total these analyses required 972 simulations.

Table 1: Parameters varied in the main effects analysis including their minimum, mean, and maximum values for the $UO_2$/FeCrAl rodlet.

| | **Minimum** | **Mean** | **Maximum** |
|---|---|---|---|
| Thermal creep scaling factor | 1.0 | 50.5 | 100.0 |
| Irradiation creep scaling factor | 1.0 | 5.5 | 10.0 |
| Volumetric swelling scaling factor | 0.8 | 1.0 | 1.2 |
| Young's Modulus scaling factor | 0.8 | 1.0 | 1.2 |
| Fuel enrichment(%) | 5 | 6.5 | 8 |

Table 2: Parameters varied in the main effects analysis including their minimum, mean, and maximum values for the $U_3Si_2$/Zircaloy-4 rodlet.

| | **Minimum** | **Mean** | **Maximum** |
|---|---|---|---|
| GB diffusion coefficient scaling factor | 1.0 | 5000.5 | 10000.0 |
| IG diffusion coefficient scaling factor | 1.0 | 5000.5 | 10000.0 |
| Thermal conductivity scaling factor | 0.8 | 1.0 | 1.2 |
| Gas swelling scaling factor | 0.8 | 1.0 | 1.2 |
| Specific heat capacity scaling factor | 0.95 | 1.0 | 1.05 |

# Results and Analysis

The results of the main effects study for the $UO_2$/FeCrAl rodlet during the LOCA and SBO are shown in Figures 2 and 3 respectively. The $U_3Si_2$/Zircaloy-4 results are summarized in Figures 4 and 5. For the $UO_2$/FeCrAl rodlet the main effects study highlights the importance of the swelling scaling factor and the fuel enrichment. The centerline temperature and cladding hoop strain are both positively correlated with the swelling rate. Contrarily, the fuel enrichment is negatively correlated with centerline temperature but positively correlated with the hoop strain. Higher enrichment leads to a higher burnup within the fuel, particularly in the rim region at the periphery of the pellet. The swelling correlation in BISON is burnup dependent, thus, increased enrichment results in larger fuel swelling. Larger fuel swelling results in contact between the fuel and cladding earlier in the LOCA transient resulting in a decreased centerline temperature. Subsequently, the harder the contact occurring between the fuel and cladding the larger the strain. Interestingly, the large scaling factors on the thermal and irradiation creep appear to have no influence, indicating that the creep strain remains significantly low in the C35M FeCrAl alloy used in these simulations. It is prudent to note that the range of centerline temperature and cladding hoop strain is small, 2.5 K and 0.3% respectively.

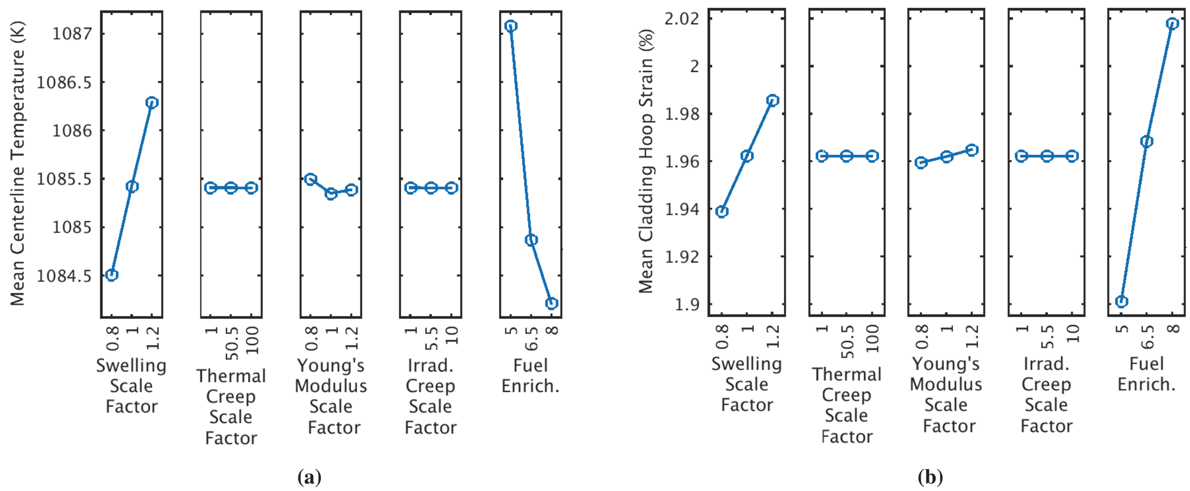


Figure 2: Main effects results for (a) fuel centerline temperature and (b) cladding hoop strain for the $UO_2$/FeCrAl rodlet during the LOCA transient.

The main effects study for the $UO_2$/FeCrAl rodlet for the SBO scenario is shown in Figure 3. The variation in the centerline temperature and cladding hoop strain was low because of the size of rodlet used. A 10-pellet rodlet can still be cooled quickly by the minimal flow provided by the backing up cooling system because BISON's coolant channel model takes the bottom of the rodlet as the coolant inlet. The shortness of the rod results in adequate cooling despite the conditions of the SBO. Running the sensitivity analyses on full length rods are expected to change the results shown here. Despite the shortness of the rodlet, it was found that the cladding hoop strain had strong positive correlations between the Young's modulus and swelling factor. Comparing this to the LOCA case it can be concluded that at the end of the SBO there is no contact between the fuel and cladding because the Young's modulus correlates with the strain. Whereas, in the LOCA case shown previously, the Young's modulus has no effect indicating contact had been established at the end of the transient.

The results of the main effects study for the $U_3Si_2$/Zircaloy-4 rodlet during the LOCA are shown in Figure 4. In this case the range of the output metrics is much larger than the $UO_2$/FeCrAl system indicating that uncertainty in $U_3Si_2$ behavioral models have a more significant impact on the centerline temperature and hoop strain. As expected the significant uncertainty assumed on the intergranular diffusion coefficient results in large variations in the centerline temperature and cladding hoop strain. The larger diffusion coefficients give rise to increased strain due to greater fission gas release to the plenum increasing the internal pressure and inducing larger strain on the cladding. In addition, increasing the thermal conductivity results in lower temperatures and strains. Surprisingly, uncertainty in the specific heat capacity has a significant correlation with the centerline temperature for such a long duration transient. Usually,

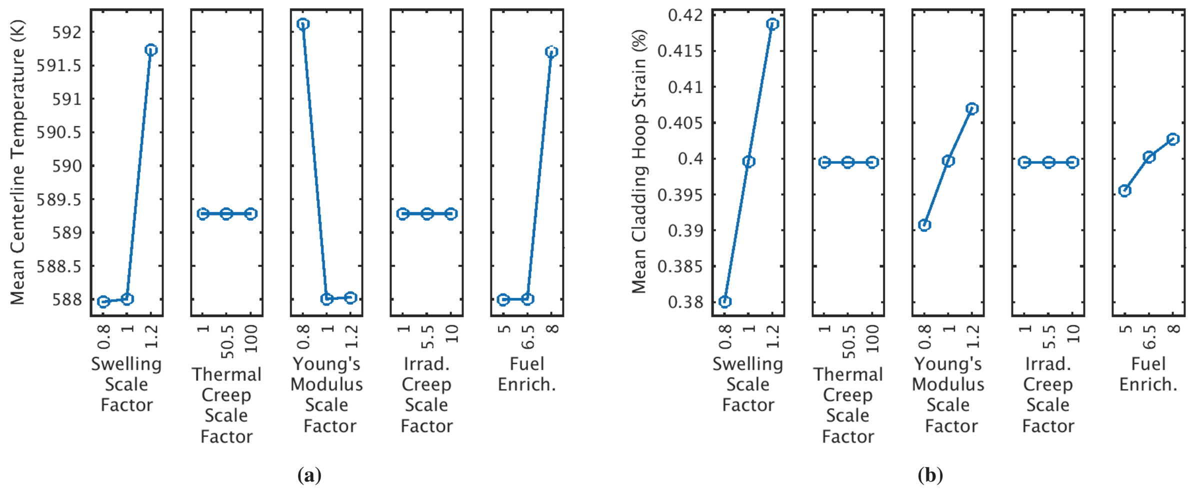


Figure 3: Main effects results for (a) fuel centerline temperature and (b) cladding hoop strain for the $UO_2$/FeCrAl rodlet during the SBO transient.

the specific heat only has an effect during very short duration transients (e.g., reactivity insertion accidents). The plots indicate that the grain boundary diffusion coefficient and gaseous swelling have minimal effects. It is anticipated that at very high burnup (>60 MWd/kgU) gaseous swelling would be the most dominant behavior due to the rapid increase in gaseous swelling at high burnup. In this study the burnup after the base irradiation was approximately 5.01% FIMA (47.67 MWd/kgU) which is just above the threshold for gaseous swelling of 5% FIMA in the current BISON model.

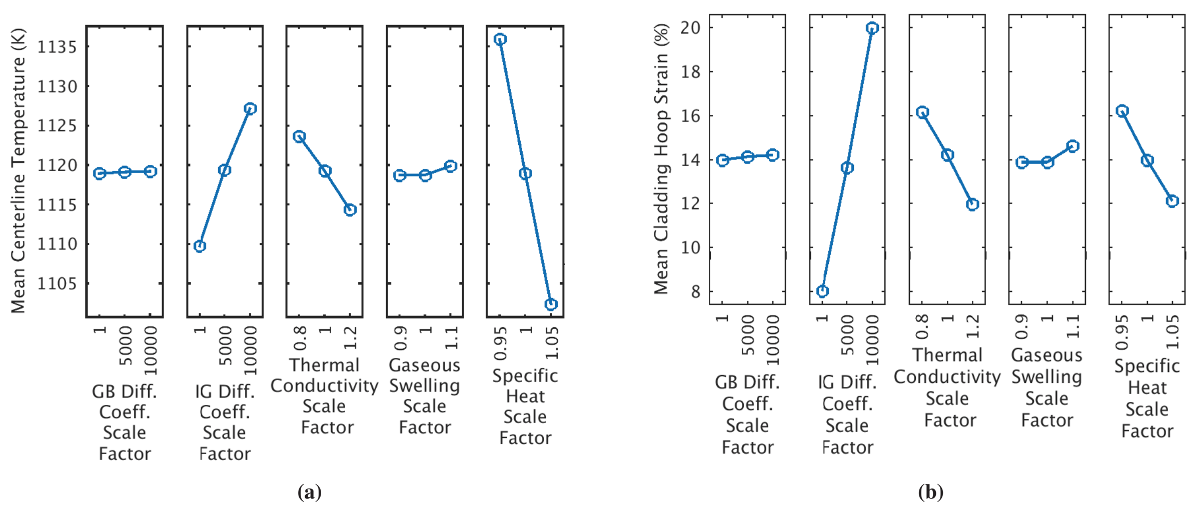


Figure 4: Main effects results for (a) fuel centerline temperature and (b) cladding hoop strain for the $U_3Si_2$/Zircaloy-4 rodlet during the LOCA transient.

The $U_3Si_2$/Zircaloy-4 system experienced minute variation in the centerline temperature and cladding hoop strain with respect to the uncertainties in the inputs for the SBO case as shown in Figure 5. Strong correlations are still observed for the intergranular diffusion coefficient and fuel thermal conductivity. An important observation is that for the SBO transient, which lasted 24 hours, compared to the LOCA that lasted 90 seconds, the specific heat has no correlation with the output parameters. This is expected for the long duration transients.

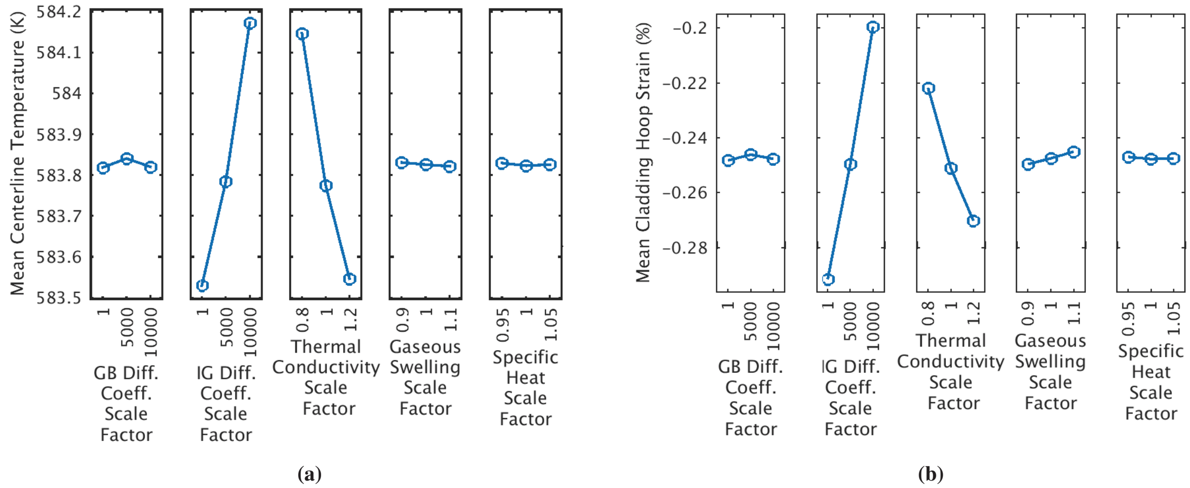


Figure 5: Main effects results for (a) fuel centerline temperature and (b) cladding hoop strain for the $U_3Si_2$/Zircaloy-4 rodlet during the SBO transient.

## Publications

The results presented in this report were summarized in a conference paper submitted to the TopFuel 2016 conference where it was accepted for a technical presentation.

## Conclusion

This report documents recent work in the application of sensitivity analysis to $U_3Si_2$ fuel and FeCrAl cladding under Loss of Coolant and Station Blackout conditions. The results indicate that during accident scenarios the isotropic swelling, Young's modulus, and fuel enrichment are of greatest importance for FeCrAl, whereas the intergranular diffusion coefficient, thermal conductivity, and specific heat are of greatest importance for $U_3Si_2$. Although insight into the behavior of $U_3Si_2$ and FeCrAl fuel under accident conditions have been completed, additional work is required including:

- Extending the sensitivity analyses to include variance-based indices (e.g., polynomial regression or polynomial chaos expansions) that provide additional detail into which model parameters are of greatest importance.
- Extending sensitivity analyses to include reactivity insertion accidents.
- Performing sensitivity analyses on a full length rod under accident conditions.

## References


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