Sensitivity Analysis of the Gap Heat Transfer Model in BISON

Rodney C. Schmidt, Laura P. Swiler, Danielle M. Perez, Richard L. Williamson
Sensitivity Analysis of the Gap Heat Transfer Model in BISON

Rodney Schmidt
Multiphysics Applications
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-1323
rcschmi@sandia.gov

Danielle Perez
Idaho National Laboratory
2525 Fremont Avenue
Idaho Falls, ID 83415

Laura Swiler
Optimization and Uncertainty Quant.
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-1318
lpwile@sandia.gov

Richard Williamson
Idaho National Laboratory
2525 Fremont Avenue
Idaho Falls, ID 83415

Abstract

This report summarizes the result of a NEAMS project focused on sensitivity analysis of the heat transfer model in the gap between the fuel rod and the cladding used in the BISON fuel performance code of Idaho National Laboratory. Using the gap heat transfer models in BISON, the sensitivity of the modeling parameters and the associated responses is investigated. The study results in a quantitative assessment of the role of various parameters in the analysis of gap heat transfer in nuclear fuel.
ACKNOWLEDGMENTS

This work was funded by the Nuclear Energy Advanced Modeling and Simulation (NEAMS) Program under the Advanced Modeling and Simulation Office (AMSO) in the Nuclear Energy Office in the U.S. Department of Energy. The authors specifically acknowledge the Program Manager of the Fuels Product Line, Dr. Steven Hayes (INL), and Dr. Keith Bradley, National Technical Director of NEAMS, for their support of this work. Finally, we thank the BISON and MOOSE development teams.
CONTENTS

1. Introduction........................................................................................................................................7
   1.1. Bison Gap-region Heat Transfer Model ........................................................................... 8
2. Main Effects Analysis......................................................................................................................10
3. Sensitivity Analysis Results .......................................................................................................11
   3.1 Analytic Model .................................................................................................................. 11
       Analytic Model Results......................................................................................................... 13
   3.2 Beginning of Life Analysis................................................................................................. 16
   3.3 Irradiated Fuel.................................................................................................................... 22
   3.4 Sensitivity Analysis: Base Irradiation Period................................................................. 24
       Discussion of Base Irradiation Case.................................................................................. 29
   3.5 Sensitivity Analysis: Base Irradiation + Experiment Period ........................................... 31
       Discussion of Base Irradiation + Experiment Case......................................................... 36
4. Conclusions......................................................................................................................................37
5. References.........................................................................................................................................40
Appendix A: Listing of the GapCladHT Fortran Code ................................................................. 43
Appendix B: Additional sensitivity analysis results for baseline irradation case......................... 47
Appendix C: Additional sensitivity analysis results for baseline irradation case + Experiment, RISo AN3 .......................................................... 52
Distribution.......................................................................................................................................57
1. INTRODUCTION

This report summarizes the result of a NEAMS project focused on sensitivity analysis of the models governing the heat transfer, particularly in the gap between the fuel rod and the cladding in the BISON fuel performance code. BISON is an implicit, parallel, fully-coupled code under development at the Idaho National Laboratory (INL) [1]. BISON is built on the MOOSE computational framework [2] which allows for rapid development of codes involving the solution of partial differential equations using the finite element method. Nuclear fuel operates in an environment with complex multiphysics phenomena, occurring over distances ranging from inter-atomic spacing to meters, and times scales ranging from microseconds to years. This multiphysics behavior is often tightly coupled and many important aspects are inherently multidimensional.

BISON is able to simulate tightly coupled multiphysics and multiscale fuel behavior, for either 2D axisymmetric or 3D geometries. BISON code validation and assessment is presented in [3].

In BISON, there are several physical processes that may affect the thermal behavior of a fuel rod during normal operation. We desire to identify those models and parameters that most significantly affect the predicted centerline temperature during a typical problem. If we can narrow our focus to a small set of models and parameters, then performing a subsequent uncertainty analysis will present a much more tractable problem.

The Bison Theory Manual [4] provides a description of the models currently coded in BISON. Discussions were held with INL staff in order to identify those models that would be expected to potentially affect the fuel rod thermal response. These discussions identified several areas, including:

- Gap heat transfer modeling
- Fuel thermal properties
- Radial distribution of heat release
- Fission product induced swelling
- Fuel densification
- Effect of UO$_2$ cracking on gap width (denoted “relocation”)

This report focuses on primarily on the first item: the gap heat transfer model. Initially, we study it in isolation from the other models. The gap heat transfer is known to be a dominant contributor to overall heat transfer uncertainty and is by itself complicated.

In this report, we present three instances of the sensitivity analysis for the gap heat transfer model. The first study involves a small, standalone code that was written to study the analytic behavior of the gap heat transfer model used in BISON. The second study involves the sensitivity of the model parameters at the beginning of life. The third study involves the sensitivity of the model parameters in highly irradiated fuel.

The outline of this document is as follows: Section 1 describes the heat transfer model used in BISON. Section 2 outlines the sensitivity analysis method and software used. Section 3
provides results for the three cases (analytic model, beginning of life, and highly irradiated fuel). Section 4 presents the conclusions.

1.1. Bison Gap-region Heat Transfer Model

Gap heat transfer models in BISON are described in Section 13.1 of the Bison Theory Manual [4]. Figure 1 illustrates the region of interest.

\[ q = h_{gap}(T_1 - T_2) \]  

(1)

where the total effective heat transfer coefficient across the gap, \( h_{gap} \) (W/m\(^2\)K, also called the gap conductance in Bison literature), is modeled as the sum of three distinct contributions: (1) conduction through the gas \( h_g \), radiation heat transfer \( h_r \), and the increase in heat transfer due to solid-solid contact \( h_s \).

\[ h_{gap} = h_g + h_r + h_s \]  

(2)

These individual contributions are modeled separately as follows

\[ h_g(T) = \frac{k_g(T_g)}{d_g + C_r(r_1 + r_2) + (g_1 + g_2)} \]  

(3)

\[ h_r(P_c) = C_s \frac{2k_1k_2}{(k_1 + k_2)} \frac{P_c}{\delta^{3/2}} \]  

(4)

\[ h_s(T) = \sigma \frac{(T_1^2 + T_2^2)(T_1 + T_2)}{\left(\frac{1}{\varepsilon_1} - 1\right) \left(\frac{1}{\varepsilon_2} - 1\right)} \]  

(5)

where
$d_g$  gap thickness
$k_g(T)$  gas thermal conductivity (as function of temperature, species)
$C_r$  Empirical roughness coefficient
$r_1+r_2$  surface roughnesses of the two surfaces
$g_1+g_2$  temperature jump distance  (see Eq. 13.3-13.6, Bison Theory Manual)
$C_s$  Empirical constant for solid-solid contact
$k_{1,2}$  thermal conductivity of materials on surface 1 and 2
$P_c$  contact pressure
$\delta$  Avg. gas film thickness, approximated as $\delta = 0.8(r_1+r_2)$
$H$  Meyer harness of the softer material
$\sigma$  Stefan-Boltzmann constant $= 5.669 \times 10^{-8}$  W/(m$^2$ K$^4$)
$\varepsilon_{1,2}$  emissivities of surface 1 and 2

Details of the Kennard model for the temperature jump distance ($g_1+g_2$) can be found in the Bison theory manual [4] section 13.1. Here we simply note that the Kennard model has a leading model coefficient that with nominal value 5756 which will be varied as part of the sensitivity study.
2. MAIN EFFECTS ANALYSIS

To perform the sensitivity analysis, we interfaced a toolkit called Dakota to the BISON fuel performance code on the High Performance Computing (HPC) machine called Fission at Idaho National Laboratory. Dakota allows a user to design computer experiments, run parameter studies, perform uncertainty quantification, and calibrate parameters governing their simulation model. A primary goal for Dakota is to provide scientists and engineers with a systematic and rapid means to obtain improved or optimal designs or understand sensitivity or uncertainty using simulation-based models. These capabilities generally lead to improved designs and better understanding of system performance [5].

One of the primary advantages that Dakota has to offer is access to a broad range of iterative capabilities through a single, relatively simple interface between Dakota and a simulator. In this context, we interfaced Dakota to BISON. To perform different types of analyses, it is only necessary to change a few commands in the Dakota input and start a new analysis. The need to learn a completely different style of command syntax and the need to construct a new interface each time you want to use a new algorithm are eliminated. For the work presented below, we were able to develop one interface between Dakota and BISON, and swap out a few lines in the Dakota input deck to run the various case studies.

There are many goals of running a computer experiment. One objective is to determine which inputs have the most influence on the output, or how changes in the inputs change the output. This is usually called sensitivity analysis. We have focused on sensitivity analysis in these studies, in contrast to uncertainty quantification, which aims at obtaining a probability distribution on the outputs given probability distributions on the inputs. In this work, no probability distributions are assumed.

In order to identify the input parameters that have the most significant influence on the output, a sensitivity analysis technique called main effects analysis is used. This technique assesses the effect of an independent variable (input parameter) on a dependent variable (output quantity), averaging across the levels of the other independent variables. Orthogonal array sampling (OAS) is used to perform the main effects study [5,6]. With orthogonal arrays, the input parameters are specified at fixed levels (e.g. low, medium, high), and the OAS design is constructed so that the sample columns (e.g. columns for particular parameter settings) are orthogonal to each other. We used a full factorial orthogonal array for these studies, which means we considered the full tensor product of all the combinations of parameter levels.

Orthogonal arrays allow one to perform main effects analysis. This is a sensitivity analysis method which identifies the input variables that have the most influence on the output. In main effects, the idea is to look at the mean of the response function when variable A (for example) is at level 1 vs. when variable A is at level 2 or level 3. If these mean responses of the output are statistically significantly different at different levels of variable A, this is an indication that variable A has a significant effect on the response. The orthogonality of the columns is critical in performing main effects analysis, since the column orthogonality means that the effects of the other variables 'cancel out' when looking at the overall effect from one variable at its different levels.
3. SENSITIVITY ANALYSIS RESULTS

This section provides results for the three case studies of the gap heat transfer model: an analytic model, beginning of life, and highly irradiated fuel.

3.1 Analytic Model

To study the equations outlined in Section 1.1, a small Fortran code (here called GapCladHT) was written to act as a fast-running surrogate for the entire BISON code, focusing only on the isolated region illustrated in Figure 1. The equations used in this simple model are as follows.

\[
T_1 = T_3 + q \left[ \frac{1}{h_{gap}} + \frac{d_c}{k_c} \right],
\]

(6)

\[
T_2 = T_3 + q \frac{d_c}{k_c},
\]

(7)

where

- \( T_1 \) = Temperature of the fuel surface
- \( T_2, T_3 \) = Temperature of the inside and outside of the clad, respectively
- \( q \) = heat flux through the surfaces (W/m²)
- \( d_c \) = clad thickness (m)
- \( k_c(T) \) = clad thermal conductivity (as function of temperature)

Inserting the models used in BISON for the three contributions to the total heat transfer coefficient (see equations (3)-(5) above) we can write

\[
T_1 = T_3 + q \left[ \frac{1}{(h_g(T)+h_c(P_c)+h_r(T))} + \frac{d_c}{k_c(T)} \right],
\]

(8)

The models and correlations used were taken directly from the equations modeled in BISON. A code listing is provided in Appendix A.

Each of the following problem conditions must be specified for a particular analysis.

- \( T_3 \) = clad outer-surface temperature
- \( q \) = heat flux
- \( d_c \) = clad thickness
- \( d_g \) = gap thickness
- \( P_c \) = contact pressure

Table 1 lists, models and parameters that were not varied during the sensitivity analysis.

Table 2 lists the six parameters whose effects were included in the sensitivity study using Dakota. The quantities kg_mult, kc_mult and ken_mult are multiplier coefficients of the
computed values for the gas thermal conductivity, clad thermal conductivity and temperature jump distance (Kennard model) respectively.

### Table 1. Specified models and parameters not varied

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Model or Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_3$</td>
<td>513 K</td>
<td>used by Bison for ifa_431_rod1 [3]</td>
</tr>
<tr>
<td>$q$</td>
<td>6.5e5 W/m²</td>
<td>See Table 3</td>
</tr>
<tr>
<td>$d_c$</td>
<td>9.5e-4 m</td>
<td>See Table 4</td>
</tr>
<tr>
<td>$P_c$</td>
<td>0.</td>
<td>Sets $h_s = 0$</td>
</tr>
<tr>
<td>$k_c(T)$</td>
<td>$7.511 + 0.02088* T - 1.45e-5<em>T^2 + 7.688e-9</em>T^3$</td>
<td>Ref. [8]</td>
</tr>
<tr>
<td>$k_g(T)$</td>
<td>$0.0468 + 3.81e-4<em>T - 6.79e-8</em>T^2$</td>
<td>Ref. [9]</td>
</tr>
<tr>
<td>$r_1 + r_2$</td>
<td>$2.8e-6$ ($2.16e-6 + 6.35e-7 = 2.795e-6$ m)</td>
<td>used by Bison for ifa_431_rod1 [3]</td>
</tr>
<tr>
<td>$g_1 + g_2$</td>
<td>Kennard model with $P_{pin} = 1.2e5$ N/m²</td>
<td>used by Bison for ifa_431_rod1 [3]</td>
</tr>
</tbody>
</table>

### Table 2. Parameters varied in the sensitivity study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>low</th>
<th>nominal</th>
<th>high</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_g$</td>
<td>1.e-6</td>
<td>1.e-5</td>
<td>1.e-4</td>
</tr>
<tr>
<td>$C_r$</td>
<td>1.0</td>
<td>3.2*</td>
<td>10.</td>
</tr>
<tr>
<td>$\varepsilon_1$, ($\varepsilon_2 = 1.0$)</td>
<td>0.0</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>$k_g\text{ mult}$</td>
<td>0.9</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>$k_c\text{ mult}$</td>
<td>0.9</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>$k_e\text{ mult}$</td>
<td>0.75</td>
<td>1.0</td>
<td>1.25</td>
</tr>
</tbody>
</table>

* value used by Bison for ifa_431-rod1 test [3]

Note that there is some uncertainty about parameter values to use for the size of the gap and the fuel thermal conductivity. The geometric parameters we chose to use for this study relative to other references are described in Figure 2 and Tables 3 and 4.

### Table 3 Comparison of fuel rod dimensions

<table>
<thead>
<tr>
<th></th>
<th>Fuel pellot radius (m)</th>
<th>Clad inner radius (m)</th>
<th>Clad outer radius (m)</th>
<th>Gap thickness (m)</th>
<th>Clad thickness (m)</th>
<th>Total gapclad (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 5.1 in [10]</td>
<td>4.70e-3</td>
<td>4.75e-3</td>
<td>5.36e-3</td>
<td>5.0e-4</td>
<td>6.1e-4</td>
<td>11.1e-4</td>
</tr>
<tr>
<td>ifa_431_rod1</td>
<td>5.34e-3</td>
<td>5.45e-3</td>
<td>6.40e-3 m</td>
<td>1.1e-4</td>
<td>9.5e-4</td>
<td>10.6e-4</td>
</tr>
<tr>
<td>Remirez et al. [11]</td>
<td>4.30e-3</td>
<td>4.33e-3</td>
<td>4.83e-3</td>
<td>0.3e-4</td>
<td>5.0e-4</td>
<td>5.3e-4</td>
</tr>
<tr>
<td>gapcladHT</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$10^{-6} \rightarrow 10^{-4}$</td>
<td>9.5e-4</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 2. Illustration of fuel rod dimensions compared in Table 3

Table 4 Comparison of fuel rod thermal conditions

<table>
<thead>
<tr>
<th></th>
<th>Fuel Heat flux (W/m²)</th>
<th>Clad outer Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 5.1 in [10]</td>
<td>~6.4e5</td>
<td>~620</td>
</tr>
<tr>
<td>ifa_431_rod1</td>
<td>variable</td>
<td>513</td>
</tr>
<tr>
<td>Remirez et al. [11]</td>
<td>4.3e5</td>
<td>750</td>
</tr>
<tr>
<td>gapcladHT</td>
<td>6.5e5</td>
<td>513</td>
</tr>
</tbody>
</table>

Analytic Model Results

Several plots are presented below to visually quantify the results from doing a main effects parameter study using Dakota and GapCladHT.

Figure 3 plots results of varying the six parameters listed in Table 2 and shows that over the ranges specified, changes in gap width have by far the largest effect on fuel surface temperature. However, changes to the roughness coefficient and gas thermal conductivity were also significant.

To better understand the relative importance of the other five parameters, a set of three additional main effects studies were performed, one for each of the three gap widths considered. These results are shown in Figures 4, 5 and 6.
Figure 3. Six-parameter main effect plots for simple GapCladHT model

The magnitude of the variations used in this study were chosen by subjective judgment of the authors as representing the current range of uncertainty for these values.

By comparing the plots in Figure 4 – 6 we can observe the following.

- Varying the roughness coefficient over the specified range was the most significant factor among the five parameters for all gap widths.
- Varying the emissivity over its entire range of possibility has only a very small impact, demonstrating that radiation heat transfer is relatively weak under these conditions. Only in Figure 6 (large gap width), where the surface temperatures are several hundred degrees higher do we begin to see some noticeable impact.
- Figure 6 shows that the gas thermal conductivity can be important as the gap width becomes large. This directly reflects that the thermal resistance due to thermal conduction across the gap scales linearly with the gap width.
Figure 4. Five-parameter main effect plots for simple GapCladHT model: gap=10^{-6} m.

Figure 5. Five-parameter main effect plots for simple GapCladHT model: gap=10^{-5} m.
3.2 Beginning of Life Analysis

To study the effect of the gap heat transfer at the beginning of a fuel rod’s life, we performed a sensitivity study of the Bison code analysis of the Halden IFA_431-rod test as described in [3]. The experiments referred to as IFA-431 and IFA-432 were heavily instrumented assemblies irradiated in the Halden Boiling Water Reactor in Norway. The tests provided a large amount of well-characterized data under realistic LWR conditions, and have been used extensively for assessing and improving fuel rod performance calculations [12]. Measurements included fuel centerline temperature histories from thermocouples located in the top and bottom end of the fuel column. All test rods contained fresh high density (95% TD) sintered UO$_2$ in Zircaloy 2 cladding. The reactor was operated at typical BWR conditions. Details concerning rod geometry and materials, power history and axial power profile, and reactor operating conditions, are given in references [13] and [14]. Although measurements were taken through an extended fuel life, the focus here is on beginning of fuel life, before more complex behavior associated with irradiation and high burnup occurs.

Table 5 lists the three parameters whose effects were included in the BISON sensitivity study using Dakota. Two of these, the roughness coefficient Cr and the Kennard coefficient were previously included in the sensitivity study described above using the gapcladHT model. In addition, a multiplier on the fuel thermal conductivity was also varied by +/- 25%. Of note is that the gap width is not specified but is part of the solution, and varies throughout the
simulation. Its value is affected directly and/or indirectly by many of the models in BISON, and thus cannot be directly studied in this context.

For this sensitivity study we concern ourselves with BISON-predicted temperatures that are nearest to the locations of two test thermocouples, here denoted “T_up_tc” (for the upper thermocouple) and “T_low_tc” (for the lower thermocouple). However, we do not compare the results of the simulation to test data, but rather look at the sensitivity of the predictions at the end of the test to changing the three parameters listed in Table 5. As before, the ranges used for this study were chosen by the subjective judgment of the authors.

Figure 7 shows main effects results for the sensitivity study when comparing to the upper thermocouple. Figure 8 is for the lower thermocouple. Qualitatively, both show almost identical results. The parameter variation with the greatest effect is the thermal conductivity of the fuel, followed by the roughness coefficient, and lastly the Kennard model coefficient. Here a point should be made concerning the results for the roughness coefficient and the coefficient for the Kennard model of the temperature jump. Note that in equation (3), both of these terms take the same form, and thus the sensitivity to both of these must be the same for the same relative change. But in the sensitivity study done here, the roughness coefficient was varied in both directions by a factor of 3X, whereas the Kennard model coefficient was only varied by a factor of (5/4)X. As mentioned, this choice reflected the subjective judgment of the authors.

Using Paraview to visualize the results of the simulation showed that during the run, the gap width shrunk quickly by about 40% and then fluctuated around that value, reflecting the power fluctuations that occurred during the test. However, the gap was never smaller than ~30% of its initial value of (1.1e-4 m) and its ending value was about 40% (i.e. ~0.5e-4 m).

<p>| Table 5  Bison input parameters varied in the sensitivity study for Halden IFA 431 Beginning of Life case |</p>
<table>
<thead>
<tr>
<th>Parameter</th>
<th>low</th>
<th>nominal</th>
<th>high</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_r</td>
<td>1.0</td>
<td>3.2</td>
<td>10.</td>
</tr>
<tr>
<td>Kennard Coefficient</td>
<td>4317</td>
<td>5756</td>
<td>7195</td>
</tr>
<tr>
<td>kf_mult</td>
<td>0.75</td>
<td>1.0</td>
<td>1.25</td>
</tr>
</tbody>
</table>
Figure 7. Three-parameter main effects plots for Bison predictions of T_up_tc

Figure 8. Three-parameter main effects plots for Bison predictions of T_low_tc
Two additional Bison-related sensitivity issues were also looked at. The first of these concerns the question of mesh refinement and mesh convergence. The radial resolution used for all of these cases was 12 radial elements in the fuel and 4 in the clad. A 2X more refined mesh was created that had 24 radial elements in the fuel, and the Bison calculation was repeated under the nominal conditions. It was found that the end-of-run temperatures changed less than 0.2 degrees (specifically, $T_{up\_tc}$ $813.932 \rightarrow 813.736$ K). This suggests that the mesh resolution was sufficient for the purposes of this study.

The second question concerns the model for how the power was radially distributed within the fuel. The default Bison model tends to yield a peaking of the power closer to the outer surface of the fuel pin instead of at its centerline. To get a preliminary sense of how important this model may be to the predicted centerline temperature, an additional run was made with this power distribution model turned off (which yields a uniform power distribution). It was found that the end-of-run temperatures at the centerline locations of interest changed about 15 degrees (specifically, $T_{up\_tc}$ $813.932 \rightarrow 828.320$ K).

Note that the results presented in Figures 7 and 8 were based on the actual power profile from Halden IFA-431 Rod 1, which had a very noisy power profile as shown in Figure 9. We were interested in seeing if we would obtain a similar sensitivity analysis with a much simpler, “smoothed” power profile which has approximately the same total power over the timeframe. This would allow us to perform studies over longer times with simpler power profiles which require less run-time in BISON. We created a simpler power profile as shown in Figure 9.

We performed the same sensitivity analysis with the smoothed power profile shown in blue in Figure 9. The results are shown in Figures 10. Note that Figure 10 is nearly identical to Figure 7 which was calculated with the actual power profile shown in red in Figure 9. The similarity of these plots leads us to conclude that using a smooth power profile for the purposes of sensitivity analysis of these parameters on centerline fuel temperature is sufficient.
Figure 9. Halden IFA-431 Rod 1 Power profile (red), equivalent flat power (green), and smoothed power profile used in subsequent studies (blue).

Figure 10. Three-parameter main effects plots for Bison predictions of T_up_tc based on smoothed power profile.
Finally, we performed one additional study in which we modified the range on the multiplier for the roughness coefficient (now 1, 2, and 4) and we added a multiplier on the gas thermal conductivity, with values (0.9, 1.0, and 1.1). The main effects plot for this analysis is shown in Figure 11.

![Main Effects Plot for T_up_tc](image)

**Figure 11.** Four-parameter main effects plots for Bison predictions of T_up_tc based on smoothed power profile.

Based on all of these sensitivity analyses, we ranked the relative importance of each of the parameters and models considered in the numerical studies presented above. Table 6 summarizes this by listing the sensitivity to changing the different parameters and models over a certain range in terms of an associated temperature change $\Delta T$. They are ordered with the largest sensitivities listed first. Note that these results depend on the variations chosen for parameters. Different ranges on the parameters will result in different sensitivities.
Table 6. Summary Results for GapCladHT or Bison parameters varied in the sensitivity study

<table>
<thead>
<tr>
<th>Parameter or Model</th>
<th>Variation Range</th>
<th>ΔT (K) change</th>
</tr>
</thead>
<tbody>
<tr>
<td>gap thickness – In Bison this is a function of all physics/models affecting fuel density/swelling. Hard to separate.</td>
<td>10^{-6} &lt; 10^{-4} m</td>
<td>~300</td>
</tr>
<tr>
<td>k_f thermal conductivity of the fuel</td>
<td>+/- 25%</td>
<td>~250</td>
</tr>
<tr>
<td>C_f roughness coefficient</td>
<td>10X</td>
<td>~70</td>
</tr>
<tr>
<td>k_g thermal conductivity of the gas in the gap</td>
<td>+/- 10%</td>
<td>~30-50</td>
</tr>
<tr>
<td>rpf active switch (on/off) controlling radial energy deposition</td>
<td>on/off</td>
<td>~15</td>
</tr>
<tr>
<td>k_c thermal conductivity of the clad</td>
<td>+/- 10%</td>
<td>~10</td>
</tr>
<tr>
<td>Temperature jump model (Kennard model)</td>
<td>+/- 25%</td>
<td>~5-10</td>
</tr>
<tr>
<td>Surface emissivity – (radiation heat transfer)</td>
<td>0 &lt; \varepsilon &lt; 1</td>
<td>&lt; ~3</td>
</tr>
</tbody>
</table>

3.3 Irradiated Fuel

To study the effect of the gap heat transfer in higher burn up situations we performed a sensitivity study of a Bison code analysis of the Risø AN3 test as described in [3]. The Risø AN3 experiment was one of the FUMEX-II priority cases [15] and was conducted at the Risø DR3 water-cooled HP1 rig. This experiment utilized a re-fabricated fuel rod from a pressurized water reactor fuel pin (CB8) irradiated in the Biblis A PWR over a duration of four reactor cycles. The re-fabricated rod (CB8-2R) was shortened and fitted with a fuel centerline thermocouple and pressure transducer [16] for use in the experiment.

As shown in Figure 12, the power history consists of two parts. The base irradiation period extends for just over three years (1198.25 days), corresponding to the time when the fuel rod was in the Biblis A PWR. The second, much shorter Risø AN3 experimental irradiation period was for only about 3 days, and is shown in greater detail in Figure 13.
Figure 12 Riso3 Power history, including the base irradiation period (~1200 days) and the experimental irradiation period (~3 days).

Figure 13 Riso3 Power history for the experimental irradiation period.
Table 7 lists the six parameters whose effects were included in the sensitivity study using Dakota. The quantities kf_mult, kg_mult are multiplier coefficients on the normal computed values for the fuel and gas thermal conductivity.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>low</th>
<th>nominal</th>
<th>high</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughness coefficient, C_r</td>
<td>1.0</td>
<td>2.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Kennard temperature jump model coefficient, C_jump</td>
<td>4317</td>
<td>5756</td>
<td>7195</td>
</tr>
<tr>
<td>Multiplier on fuel thermal conductivity, kf_mult</td>
<td>0.75</td>
<td>1.0</td>
<td>1.25</td>
</tr>
<tr>
<td>Multiplier on gap gas thermal conductivity, kg_mult</td>
<td>0.9</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Contact model coefficient, C_contact</td>
<td>5</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>

Dakota was used to perform a main effects sensitivity study of the Bison code predictions where the output metrics of interest were the mid-plane centerline temperature of the fuel and the corresponding mid-plane gap conductance. This study required that a total of 243 separate runs be made. Each run was assigned eight processors on the INL fission1 computer. Run times varied from 4-12 hours, depending on the conditions.

Data was extracted at two points in time: (1) at the very end of the base irradiation period, but just before the power ramp-down (time=103528800 sec.), and (2) at the end of the experimental irradiation period just before power ramp-down (time=103788200 sec.).

### 3.4 Sensitivity Analysis: Base Irradiation Period

This section outlines the sensitivity of the parameters to the results at the end of the base irradiation period, at 103528800 seconds, before the power ramp-down. Figure 14 shows the main effects of the parameters on the mid-plane centerline temperature, and Figure 15 shows the main effects of the parameters on the mid-plane gap conductance. Note that the thermal conductivity of the fuel is the dominant parameter for the centerline temperature, while the roughness coefficient is the dominant parameter for the gap conductance.
Figure 14. Base irradiation case: Main effects for mid-plane centerline temperature (K).

Figure 15. Base irradiation case: Main effects for mid-plane gap conductance (W/m²K).
Tables 8 and 9 show the correlation matrices for the centerline temperature and the gap conductance. The most significant correlations are highlighted in yellow. Correlations vary between -1 and 1, with -1 meaning strongly negatively correlated (as one variable increases, the other decreases) and 1 meaning strongly positively correlated. Note the correlations between the parameters are zero, which is what we should see because the main effects studies were performed with orthogonal arrays which means there are no correlations amongst the inputs (e.g. the parameter sample columns are orthogonal to each other). The thermal conductivity multiplier is strongly negatively correlated with the centerline temperature and mildly positively correlated with the gap conductance. The roughness coefficient is negatively correlated with gap conductance.

<table>
<thead>
<tr>
<th></th>
<th>rough_coef</th>
<th>c_jump</th>
<th>kf_mult</th>
<th>kg_mult</th>
<th>c_contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>c_jump</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kf_mult</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kg_mult</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c_contact</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>ctr_mid_temp</td>
<td>0.085</td>
<td>0.001</td>
<td>-0.985</td>
<td>-0.015</td>
<td>-0.003</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>rough_coef</th>
<th>c_jump</th>
<th>kf_mult</th>
<th>kg_mult</th>
<th>c_contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>c_jump</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kf_mult</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kg_mult</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c_contact</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>h_gap_mid</td>
<td>-0.905</td>
<td>-0.013</td>
<td>0.199</td>
<td>0.173</td>
<td>0.022</td>
</tr>
</tbody>
</table>

Figures 16-20 show boxplots of the data, across the various levels of the parameters. This provides more detail than the main effects plots. There is more detail about the sensitivity analysis, especially the Analysis of Variance (ANOVA) results, in Appendix B.
Figure 16: Boxplots based on roughness coefficient.

Figure 17: Boxplots based on Kennard temperature jump model coefficient.
Figure 18: Boxplots based on Fuel thermal conductivity multiplier.

Figure 19: Boxplots based on Gas gap thermal conductivity multiplier.
Discussion of Base Irradiation Case

As the roughness coefficient increases, the variance of the centerline temperature increases slightly, but the variance of gap conductance decreases noticeably, as shown in Figure 16. The opposite is true for the fuel thermal conductivity multiplier: as it increases, the variance of the centerline temperature decreases very slightly but the variance of gap conductance increases significantly, as shown in Figure 18. Note that we see the same behavior after the Risø AN3 experiment is performed (the base irradiation case + experiment). This will be presented below.

One thing that we are not sure about: the response at the fuel thermal conductivity multiplier $kf\_multiplier = 1.0$ and $1.25$ are very similar for the gap conductance. This is different than after the experiment, where we saw an increase in the gap_conductance at $kf\_multiplier = 1.25$.

The Kennard temperature jump model coefficient and the contact model coefficient do not exhibit any significant effect on either response. This is a significant finding, as these were parameters of the heat transfer model in the gap that we thought would be significant.

For the centerline temperature, the only variable that has a significant main effect is the fuel thermal conductivity. For the gap conductance, the roughness coefficient is the most significant. There are significant, though much smaller, main effects with $kf\_multiplier$ and $kg\_multiplier$. Note that for $kf\_multiplier$, we see a difference between the mean at $kf\_multiplier = 0.75$ and $1.0$ (or $1.25$), but not between $1.0$ and $1.25$. Appendix B provides supporting evidence for these ANOVA results.
Finally, note that the centerline mid-plane temperature in the base irradiation case is much smaller than the base irradiation + experiment case, but the gap conductance is higher. Table 10 shows these differences.

Table 10: Differences between base irradiation and (Base irradiation plus experiment) cases:

<table>
<thead>
<tr>
<th></th>
<th>BASE IRRADIATION</th>
<th></th>
<th>BASE IRRAD PLUS EXPERIMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ctr_mid_temp (K)</td>
<td>H_gap_mid (W/m²K)</td>
<td>Ctr_mid_temp (K)</td>
</tr>
<tr>
<td>MEAN</td>
<td>1224.75</td>
<td>35221.12</td>
<td>2196.41</td>
</tr>
<tr>
<td>MIN</td>
<td>1058.86</td>
<td>13157.30</td>
<td>1762.38</td>
</tr>
<tr>
<td>MAX</td>
<td>1432.54</td>
<td>66657.30</td>
<td>2761.34</td>
</tr>
</tbody>
</table>
3.5 Sensitivity Analysis: Base Irradiation + Experiment Period

This section outlines the sensitivity of the parameters to the results at the end of the base irradiation + experiment period, at 103788200 seconds after the RISO AN3 experiment was performed, before the power ramp-down. Figure 21 shows the main effects of the parameters on the mean mid-plane centerline temperature, and Figure 22 shows the main effects of the parameters on the mid-plane gap conductance. Note that the thermal conductivity of the fuel is the dominant parameter for the centerline temperature, while the roughness coefficient is the dominant parameter for the gap conductance. However, the thermal conductivity of the fuel plays a more significant role than it does in the baseline case (e.g. compare Figure 15 to Figure 22).

![Main Effects Plot for ctr_mid_temp](image)

Figure 21. Base irradiation + experiment case: Main effects for mid-plane centerline temperature (K).
Figure 22. Base irradiation + experiment case:
Main effects for mid-plane gap conductance (W/m² K).

The correlation matrices are shown in Tables 11 and 12.

**Table 11: Correlation matrix for ctr_mid_temp**

<table>
<thead>
<tr>
<th></th>
<th>rough_coef</th>
<th>c_jump</th>
<th>kf_mult</th>
<th>kg_mult</th>
<th>c_contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>c_jump</td>
<td>0.063</td>
<td>0</td>
<td>0</td>
<td>0.006</td>
<td>0.063</td>
</tr>
<tr>
<td>kf_mult</td>
<td>0.063</td>
<td>0</td>
<td>0.031</td>
<td>0</td>
<td>0.008</td>
</tr>
<tr>
<td>kg_mult</td>
<td>-0.123</td>
<td>0.006</td>
<td>0.031</td>
<td>0</td>
<td>0.008</td>
</tr>
<tr>
<td>c_contact</td>
<td>-0.123</td>
<td>-0.008</td>
<td>0.063</td>
<td>0.031</td>
<td>0.008</td>
</tr>
<tr>
<td>ctr_mid_temp</td>
<td>0.063</td>
<td>0.008</td>
<td>0.063</td>
<td>0.031</td>
<td>0.008</td>
</tr>
</tbody>
</table>

**Table 12: Correlation matrix for h_gap_mid**

<table>
<thead>
<tr>
<th></th>
<th>rough_coef</th>
<th>c_jump</th>
<th>kf_mult</th>
<th>kg_mult</th>
<th>c_contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>c_jump</td>
<td>0.063</td>
<td>0</td>
<td>0.031</td>
<td>0</td>
<td>0.008</td>
</tr>
<tr>
<td>kf_mult</td>
<td>0.063</td>
<td>0</td>
<td>0</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>kg_mult</td>
<td>-0.123</td>
<td>0.008</td>
<td>0.031</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>c_contact</td>
<td>-0.123</td>
<td>-0.008</td>
<td>0.031</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>ctr_mid_temp</td>
<td>-0.736</td>
<td>-0.003</td>
<td>0.483</td>
<td>0.134</td>
<td>0.174</td>
</tr>
</tbody>
</table>
Figures 23-27 show boxplots of the data, across the various levels of the parameters. This provides more detail than the main effects plots. There is more detail about the sensitivity analysis, especially the Analysis of Variance (ANOVA) results, in Appendix C.

**Boxplot of ctr_mid_temp, h_gap_mid**

![Boxplot of roughness coefficient](image)

*Figure 23: Boxplots based on roughness coefficient.*
Figure 24: Boxplots based on Kennard temperature jump model coefficient.

Figure 25: Boxplots based on Fuel thermal conductivity multiplier.
Figure 26: Boxplots based on Gas gap thermal conductivity multiplier.

Figure 27: Boxplots based on contact model coefficient.
Discussion of Base Irradiation + Experiment Case

For the centerline temperature, the only variable that has a significant main effect is the fuel thermal conductivity multiplier. This is shown in the main effects and boxplots above (Figures 21 and 25) and the ANOVA results in Appendix C. For the gap conductance, both the roughness coefficient and the fuel thermal conductivity multiplier are significant.

The Kennard temperature jump model coefficient does not exhibit any significant effect on either response.

Similar to the base irradiation case: As the roughness coefficient increases, the variance of the centerline temperature increases slightly, but the variance of gap conductance decreases noticeably (Figure 23). The opposite is true for the fuel thermal conductivity multiplier: as it increases, the variance of the centerline temperature decreases very slightly but the variance of gap conductance increases significantly (Figure 25).

NOTE: We did conduct a main effects analysis after power-down, at the very end of the simulation. We are not showing the results here since they are very similar to these results before the power-down. The major difference between these results and the results at the end of the simulation after power-down is that the roughness coefficient and the fuel thermal conductivity have switched the order of their importance on the gap conductance. After power-down, the fuel thermal conductivity is the most important parameter. But in these results before power-down, the roughness coefficient is the most important variable for the gap conductance.

Finally, note that c_contact did have a small but significant main effect on the gap conductance. If you look at the ANOVA results in Appendix C, the p-value is 0.026 for the gap conductance and c_contact. This implies that we cannot say all three means (e.g. the mean at c_contact =5, 10, or 20) are the same. If we were only looking at 5 and 10 we could not say they are statistically significantly different, but the mean of the gap conductance at c_contact=5 and c_contact = 20 are different.
4. CONCLUSIONS

In this report, we present a detailed sensitivity analysis of the heat transfer model used in the BISON code to model heat transfer in the gap between the fuel rod and the cladding. We performed three different case studies. First, we examined the analytic behavior of the gap heat transfer by developing a standalone model of the governing equations. The second study involved the sensitivity of the model parameters at the beginning of life. The third study involved the sensitivity of the model parameters in highly irradiated fuel.

In the study of the analytic model, we found the following:
- Varying the roughness coefficient over the specified range was the most significant factor among the five parameters for all gap widths.
- Varying the emissivity over its entire range of possibility has only a very small impact, demonstrating that radiation heat transfer is relatively weak under these conditions. Only with a large gap width, where the surface temperatures are several hundred degrees higher, do we begin to see some noticeable impact.
- The gas thermal conductivity can be important as the gap width becomes large. This directly reflects that the thermal resistance due to thermal conduction across the gap scales linearly with the gap width.

Note that fuel thermal conductivity does not affect the gap heat transfer directly, so this parameter is not a factor in this assessment.

We used the Halden IFA-431 rod 1 to study the sensitivity of the BISON heat transfer model parameters during beginning of life. We found the following:
- The thermal conductivity of the fuel was the most significant variable influencing the temperature at the upper and lower thermocouples, followed by the roughness coefficient.
- The thermal conductivity of the gas in the gap had a small effect, and the Kennard temperature jump coefficient had very little influence on the centerline temperatures of the thermocouples.
- Detailed analyses of the parameter influences are shown in Table 6.
- The power profile for this Halden rod was complicated with significant power cycling. We ran a smooth power profile that was similar in overall increase in fuel rod temperatures. The sensitivity analysis with the simpler power profile gave very similar results to the actual power profile and required less run-time (BISON execution time).

We used the RISO AN3 rod to study the sensitivity of the BISON gap heat transfer model parameters for highly irradiated rods. We looked at two times: a time of baseline irradiation (approximately 1200 days when the rod was at fairly constant power levels) and a final experimental time of 3 days when the rod was in the experimental reactor. Our findings:
- For the mid-plane centerline temperature, the only variable that has a significant main effect is the fuel thermal conductivity multiplier. For the mid-plane gap conductance, both the roughness coefficient and the fuel thermal conductivity multiplier are significant. This finding is true for both the baseline irradiation and for the baseline+experiment cases.
• The Kennard temperature jump model coefficient does not exhibit any significant effect on either response (centerline temperature or gap conductance). This finding is true for both the baseline irradiation and for the baseline+experiment cases.

• The contact model coefficient did not have an effect either response in the baseline irradiation case. It had a very small effect only on the gap conductance in the baseline+experiment case.

• The thermal conductivity of the gas in the gap had a small effect on the gas gap conductance for both baseline and baseline+experiment. It did not affect the centerline temperature, however.

• The centerline temperatures were significantly higher (~1000 degrees higher) for the baseline+experiment case than for the baseline case due to the much higher power during the experiment. However, compared with the baseline case, the gap gas conductance was in the mean ~ 40% lower for the baseline+experiment case.

In summary, the thermal conductivity of the fuel dominated the results in the Halden and Risø cases we studied, both at beginning of life and in highly irradiated cases. This is a significant finding, as these results suggest that for the models currently in Bison, the complicated gap heat transfer modeling is not nearly as important as may have been assumed. It points to the need to have accurate estimates of the fuel thermal conductivity when running further BISON studies.
[Blank page following section.]
5. REFERENCES


[Blank page following section.]
APPENDIX A: LISTING OF THE GAPCLADHT FORTRAN CODE

! ====================================================================================
! gapcladHT.f90
! Heat transfer across the gap and clad of a fuel rod as modeled in BISON (See BISON
! Theory manual). It will be used as a simple surrogate for BISON to help set up a
! sensitivity study.
! Created by Schmidt, Rodney C
! ====================================================================================
PROGRAM gapclad

USE input_mod
IMPLICIT NONE

! ====================================================================================

WRITE(*,*) "**************************
     Program gapclad     
**************************"

CALL read_input_file

CALL solve_problem

END PROGRAM gapclad

SUBROUTINE solve_problem

USE input_mod
USE var_mod
IMPLICIT NONE

! Variable declarations

INTEGER :: DBUG = 0  ! Debug flag for printing extra output
INTEGER :: IT      ! Main iteration index
INTEGER :: ITMAX = 25 ! Max numbed of iterations
REAL    :: TOL = 2.e-5 ! Non-linear Convergence Tolerance
REAL    :: TCHG    ! Change in T1 between iterations
REAL    :: T1old   ! Previous iterate value of T1
REAL    :: Rgap    ! Thermal resistance of the gap
REAL    :: Rcld    ! Thermal resistance of the clad

! ====================================================================================

WRITE(6,*) "Subroutine solve_problem"

! Initialize temperatures
T1 = TBC
T2 = TBC
T3 = TBC

DO IT=1,ITMAX ! Main nonlinear iteration loop

T1old = T1
CALL update(Rgap, Rcld)
T1 = T3 + qflx*(Rgap + Rcld)
T2 = T3 + qflx*Rcld

END SUBROUTINE
TCHG = ABS(T1-T1old)
IF(TCHG .le. TOL) EXIT ! Convergence
!WRITE(6,*) IT, T1, T1old
ENDDO

IF(IT.gt.ITMAX) THEN
   WRITE(6,9) "The change in T1 temperature over the last update =", TCHG
   WRITE(6,99) "ITMAX = ", ITMAX
ELSE
   WRITE(6,99) " Iterations to converge =", IT
ENDIF

WRITE(6,9) " T3 = ", T3
WRITE(6,9) " T2 = ", T2
WRITE(6,9) " T1 = ", T1

!9  FORMAT(a,F9.3)
9  FORMAT(a,F12.6)
99 FORMAT(a,I3)

! ====================================================================================
END Subroutine solve_problem
! ====================================================================================
SUBROUTINE update(Rgap, Rcld)
USE input_mod
USE var_mod
IMPLICIT NONE

! Variable declarations
REAL :: Rgap    ! Thermal resistance of the gap
REAL :: Rcld   ! Thermal resistance of the clad
REAL :: TG     ! avg gap temperature (T1+T2)/2
REAL :: TC     ! avg clad temperature (T2+T3)/2

! ====================================================================================
! ====================================================================================
! ----------------------
! Model for conduction-based heat transfer coefficient across the gap
TG = (T1+T2)/2.
TC = (T2+T3)/2.

! Compute thermal conductivity of the gas in the gap
! k_g = 0.081594 + 2.4147e-4*TC  ! Pure helium, W/m K
! k_g = 0.0468 + 3.81e-4*TC - 6.79e-8*TC*TC ! Bejan 1993
k_g = k_g * k_g_mult ! gas TC multpleiar (default 1.0)

! Compute jump distance
CALL jmp_dist(P_p, TG, k_g, g12)
g12 = g12 * ken_mult ! Kennard model multiplier (default 1.0)

h_g = k_g / (d_g + C_r*r12 + g12)
!WRITE(6,*) "h_g =", h_g

! ----------------------
! Model for linearized radiation-based heat transfer coefficient across the gap
!e_1 = max(e_1,1.e-8) ! prevent divide by zero for zero emiss.
\[ e_2 = \max(e_2, 1.e-8) \] ! prevent divide by zero for zero emiss.
\[ h_r = \frac{\text{sig} \times (T1^2 + T2^2)^2 \times (T1 + T2)}{(1./e_1 + 1./e_2 + 1.)} \]
\[ \text{WRITE}(6,) \] *"h_r =", h_r

! ----------------------
! Model for increased conductance due to solid-solid contact

IF(P_c .le. 1.0) THEN
\[ h_s = 0.0 \]
ELSE
\[ h_s = 0.0 \] ! replace with model
ENDIF

! ----------------------
! Compute the total thermal resistance of that gap due to each contribution

Rgap = 1. / (h_g + h_s + h_r)
\[ \text{WRITE}(6,) \] *"Rgap =", Rgap

! ----------------------
! Compute the thermal resistance of the clad (Assumed Zircaloy)

\[ k_c = 7.511 + 0.02088 \times TC - 1.45e-5 \times TC^2 + 7.688e-9 \times TC^3 \]
\[ k_c = k_c \times k_c \_mult \] ! clad TC multiplier (default 1.0)

Rcld = d_c / k_c
\[ \text{WRITE}(6,) \] *"Rcld =", Rcld

! ====================================================================================
END Subroutine update

! ====================================================================================
SUBROUTINE jmp_dist(P_p, TG, k_g, g12)
!
! Compute the Temperature jump distance using "Kennard's model based on a review
! by Lanning [70]" (See BISON Theory Manual pg. 51). Here implemented for
! pure helium.
!
IMPLICIT NONE
!
! Variable declarations
REAL :: g12 ! Temperature jump distance (m)
REAL :: TG ! Avg gas temperature (T1+T2)/2
REAL :: P_p ! Thermodynamic pressure of gas in the fuel pin gap (units??)
REAL :: k_g ! Therm. Conductivity of the gas in the gap
REAL :: ahe ! accomodation coefficient for helium
REAL :: amix ! accomodation coefficient for mixture
REAL :: M_he=4.0 ! Molecular weight of helium = 4.003 g/m
REAL :: uconv1 = 2.3901e-3 ! W/m-K to cal/sec-cm-K
REAL :: uconv2 = 10.0 ! Pa to dynes/cm^2
REAL :: uconv3 = 0.01 ! cm to m
REAL :: cfac
!
! REAL :: M_xe ! Molecular weight of xenon = 131.293 g/m
! REAL :: M_xe ! Molecular weight of mixture
!
! ====================================================================================
! ====================================================================================

ahe = 0.425 - 2.3e-4 * TG ! (per Eq. 13.4)
amix = ahe  ! 100% helium - per Eq. 13.6

cfac = uconv1*uconv3/uconv2 ! conversion factor

g12 = cfac * 5756.* ((2.-amix)/amix) * (k_g*SQRT(TG)/P_p) / SQRT(1./M_he)

! WRITE(6,*) "DEBUG: P_p =", P_p
! WRITE(6,*) "DEBUG: TG =", TG
! WRITE(6,*) "DEBUG: k_g =", k_g
! WRITE(6,*) "DEBUG: amix =", amix
WRITE(6,*) "DEBUG: g12 =", g12
! WRITE(6,*) ""
!===================================================================
END Subroutine jmp_dist
APPENDIX B: ADDITIONAL SENSITIVITY ANALYSIS RESULTS FOR BASELINE IRRADATION CASE

Matrix Plot of ctr_mid_temp

 Scatterplot of mid-plane centerline temperature

Matrix Plot of h_gap_mid

 Scatterplot of mid-plane heat conductance
Analysis of Variance (ANOVA) results:  
The p-value indicates if there are significant differences in the means across levels of a parameter. One needs a p-value less than 0.05 to be significant. The closer the p-value is to zero, the more significant the effect, the closer the P-value is to one, the less significant.

One-way ANOVA: ctr_mid_temp versus rough_coef

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>rough_coef</td>
<td>2</td>
<td>33632</td>
<td>16816</td>
<td>0.86</td>
<td>0.422</td>
</tr>
<tr>
<td>Error</td>
<td>240</td>
<td>4666225</td>
<td>19443</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>242</td>
<td>4699856</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 139.4  R-Sq = 0.72%  R-Sq(adj) = 0.00%

Individual 95% CIs For Mean Based on Pooled StDev

| Level | N    | Mean  | StDev  | -------+---------+---------+---------+--|
|-------|------|-------|--------|-------+---------+---------+---------+--|
| 1     | 81   | 1212.1| 137.7  | (-----------*-----------) |
| 2     | 81   | 1221.7| 138.9  | (------------*-----------) |
| 4     | 81   | 1240.4| 141.6  |             (-----------*-----------) |

Pooled StDev = 139.4

One-way ANOVA: ctr_mid_temp versus c_jump

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>c_jump</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.00</td>
<td>1.000</td>
</tr>
<tr>
<td>Error</td>
<td>240</td>
<td>4699854</td>
<td>19583</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>242</td>
<td>4699856</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 139.9  R-Sq = 0.00%  R-Sq(adj) = 0.00%

Individual 95% CIs For Mean Based on Pooled StDev

| Level | N    | Mean  | StDev  | ----+---------+---------+---------+-----|
|-------|------|-------|--------|----+---------+---------+---------+-----|
| 4317  | 81   | 1224.6| 139.9  | (------------------*-------------------) |
| 5756  | 81   | 1224.8| 139.9  | (------------------*-------------------) |
| 7195  | 81   | 1224.9| 139.9  | (-------------------*------------------) |

Pooled StDev = 139.9

One-way ANOVA: ctr_mid_temp versus kf_mult

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>kf_mult</td>
<td>2</td>
<td>4664231</td>
<td>2332116</td>
<td>15711.05</td>
<td>0.000</td>
</tr>
<tr>
<td>Error</td>
<td>240</td>
<td>35625</td>
<td>148</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>242</td>
<td>4699856</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 12.18  R-Sq = 99.24%  R-Sq(adj) = 99.24%

48
Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>81</td>
<td>1407.1</td>
<td>14.5</td>
</tr>
<tr>
<td>1.00</td>
<td>81</td>
<td>1195.6</td>
<td>10.9</td>
</tr>
<tr>
<td>1.25</td>
<td>81</td>
<td>1071.5</td>
<td>10.7</td>
</tr>
</tbody>
</table>

---

Pooled StDev = 12.2

One-way ANOVA: ctr_mid_temp versus kg_mult

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg_mult</td>
<td>2</td>
<td>1014</td>
<td>507</td>
<td>0.03</td>
<td>0.974</td>
</tr>
<tr>
<td>Error</td>
<td>240</td>
<td>4698842</td>
<td>19579</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>242</td>
<td>4699856</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 139.9  R-Sq = 0.02%  R-Sq(adj) = 0.00%

Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>81</td>
<td>1227.3</td>
<td>140.3</td>
</tr>
<tr>
<td>1.0</td>
<td>81</td>
<td>1224.6</td>
<td>139.9</td>
</tr>
<tr>
<td>1.1</td>
<td>81</td>
<td>1222.3</td>
<td>139.5</td>
</tr>
</tbody>
</table>

---

Pooled StDev = 139.9

One-way ANOVA: ctr_mid_temp versus c_contact

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>c_contact</td>
<td>2</td>
<td>30</td>
<td>15</td>
<td>0.00</td>
<td>0.999</td>
</tr>
<tr>
<td>Error</td>
<td>240</td>
<td>4699826</td>
<td>19583</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>242</td>
<td>4699856</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 139.9  R-Sq = 0.00%  R-Sq(adj) = 0.00%

Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>81</td>
<td>1225.1</td>
<td>140.1</td>
</tr>
<tr>
<td>10</td>
<td>81</td>
<td>1224.8</td>
<td>140.0</td>
</tr>
<tr>
<td>20</td>
<td>81</td>
<td>1224.3</td>
<td>139.8</td>
</tr>
</tbody>
</table>

---

Pooled StDev = 139.9
One-way ANOVA: h_gap_mid versus rough_coef

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>rough_coef</td>
<td>2</td>
<td>57996613399</td>
<td>28998306700</td>
<td>1181.36</td>
<td>0.000</td>
</tr>
<tr>
<td>Error</td>
<td>240</td>
<td>5891188815</td>
<td>24546620</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>242</td>
<td>63887802214</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 4954  R-Sq = 90.78%  R-Sq(adj) = 90.70%

Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>81</td>
<td>55390</td>
<td>7011</td>
</tr>
<tr>
<td>2</td>
<td>81</td>
<td>32411</td>
<td>4268</td>
</tr>
<tr>
<td>4</td>
<td>81</td>
<td>17862</td>
<td>2504</td>
</tr>
</tbody>
</table>

Pooled StDev = 4954

One-way ANOVA: h_gap_mid versus c_jump

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>c_jump</td>
<td>2</td>
<td>10690796</td>
<td>5345398</td>
<td>0.02</td>
<td>0.980</td>
</tr>
<tr>
<td>Error</td>
<td>240</td>
<td>63877111418</td>
<td>266154631</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>242</td>
<td>63887802214</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 16314  R-Sq = 0.02%  R-Sq(adj) = 0.00%

Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>4317</td>
<td>81</td>
<td>35479</td>
<td>16531</td>
</tr>
<tr>
<td>5756</td>
<td>81</td>
<td>35220</td>
<td>16312</td>
</tr>
<tr>
<td>7195</td>
<td>81</td>
<td>34965</td>
<td>16098</td>
</tr>
</tbody>
</table>

Pooled StDev = 16314

One-way ANOVA: h_gap_mid versus kf_mult

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>kf_mult</td>
<td>2</td>
<td>3068874043</td>
<td>1534437021</td>
<td>6.06</td>
<td>0.003</td>
</tr>
<tr>
<td>Error</td>
<td>240</td>
<td>60818928172</td>
<td>253412201</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>242</td>
<td>63887802214</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 15919  R-Sq = 4.80%  R-Sq(adj) = 4.01%

Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>81</td>
<td>30216</td>
<td>13864</td>
</tr>
<tr>
<td>1.00</td>
<td>81</td>
<td>37329</td>
<td>16794</td>
</tr>
<tr>
<td>1.25</td>
<td>81</td>
<td>38118</td>
<td>16911</td>
</tr>
</tbody>
</table>

Pooled StDev = 15919
Pooled StDev = 15919

**One-way ANOVA: h_gap_mid versus kg_mult**

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg_mult</td>
<td>2</td>
<td>1914746659</td>
<td>957373329</td>
<td>3.71</td>
<td>0.026</td>
</tr>
<tr>
<td>Error</td>
<td>240</td>
<td>61973055555</td>
<td>258221065</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>242</td>
<td>63887802214</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 16069   R-Sq = 3.00%   R-Sq(adj) = 2.19%

Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>31500</th>
<th>35000</th>
<th>38500</th>
<th>42000</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>81</td>
<td>31783</td>
<td>14418</td>
<td>(</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>81</td>
<td>35221</td>
<td>16016</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>81</td>
<td>38659</td>
<td>17614</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pooled StDev = 16069

**One-way ANOVA: h_gap_mid versus c_contact**

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>c_contact</td>
<td>2</td>
<td>30870098</td>
<td>15435049</td>
<td>0.06</td>
<td>0.944</td>
</tr>
<tr>
<td>Error</td>
<td>240</td>
<td>63856932116</td>
<td>266070550</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>242</td>
<td>63887802214</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 16312   R-Sq = 0.05%   R-Sq(adj) = 0.00%

Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>32000</th>
<th>34000</th>
<th>36000</th>
<th>38000</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>81</td>
<td>34840</td>
<td>16316</td>
<td>(</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>81</td>
<td>35126</td>
<td>16313</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>81</td>
<td>35697</td>
<td>16306</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pooled StDev = 16312
APPENDIX C: ADDITIONAL SENSITIVITY ANALYSIS RESULTS FOR BASELINE IRRADIATION CASE + EXPERIMENT, RISO AN3

Matrix Plot of \textit{ctr\_mid\_temp}

Scatterplot of mid-plane centerline temperature

Matrix Plot of \textit{h\_gap\_mid}

Scatterplot of mid-plane gap conductance
Analysis of Variance (ANOVA) results:
The p-value indicates if there are significant differences in the means across levels of a parameter. One needs a p-value less than 0.05 to be significant. The closer the p-value is to zero, the more significant the effect, the closer the P-value is to one, the less significant.

One-way ANOVA: ctr_mid_temp versus rough_coef

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>rough_coef</td>
<td>2</td>
<td>132094</td>
<td>66047</td>
<td>0.53</td>
<td>0.591</td>
</tr>
<tr>
<td>Error</td>
<td>226</td>
<td>28333028</td>
<td>125367</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>228</td>
<td>28465122</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 354.1  R-Sq = 0.46%  R-Sq(adj) = 0.00%

Individual 95% CIs For Mean Based on Pooled StDev

Level   N    Mean  StDev   -------+---------+---------+---------+--
1      81  2165.8  351.5  (---------------*---------------)
2      81  2204.2  356.3   (---------------*---------------)
4      67  2224.0  354.5           (--------------*-------------)
-------+---------+---------+---------+--
2100      2160      2220      2280

Pooled StDev = 354.1

One-way ANOVA: ctr_mid_temp versus c_jump

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>c_jump</td>
<td>2</td>
<td>1076</td>
<td>538</td>
<td>0.00</td>
<td>0.996</td>
</tr>
<tr>
<td>Error</td>
<td>226</td>
<td>28464046</td>
<td>125947</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>228</td>
<td>28465122</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 354.9  R-Sq = 0.00%  R-Sq(adj) = 0.00%

Individual 95% CIs For Mean Based on Pooled StDev

Level   N    Mean  StDev  -------+---------+---------+---------+--
4317   77  2194.7  354.2  (---------------*---------------)
5756   76  2199.5  354.2   (---------------*---------------)
7195   76  2195.1  356.3  (---------------*---------------)
-------+---------+---------+---------+--
2150      2200      2250      2300

Pooled StDev = 354.9

One-way ANOVA: ctr_mid_temp versus kf_mult

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>kf_mult</td>
<td>2</td>
<td>27973491</td>
<td>13986745</td>
<td>6429.62</td>
<td>0.000</td>
</tr>
<tr>
<td>Error</td>
<td>226</td>
<td>491631</td>
<td>2175</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>228</td>
<td>28465122</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 46.64  R-Sq = 98.27%  R-Sq(adj) = 98.26%
Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>72</td>
<td>2663.8</td>
<td>47.9</td>
</tr>
<tr>
<td>1.00</td>
<td>77</td>
<td>2164.4</td>
<td>52.9</td>
</tr>
<tr>
<td>1.25</td>
<td>80</td>
<td>1806.5</td>
<td>38.3</td>
</tr>
</tbody>
</table>

Pooled StDev = 46.6

One-way ANOVA: ctr_mid_temp versus kg_mult

Source | DF | SS     | MS     | F    | P    |
kg_mult | 2  | 20422  | 10211  | 0.08 | 0.922|
Error   | 226| 28444700 | 125862 |      |      |
Total   | 228| 28465122 |        |      |      |

S = 354.8   R-Sq = 0.07%   R-Sq(adj) = 0.00%

Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>74</td>
<td>2209.1</td>
<td>359.9</td>
</tr>
<tr>
<td>1.0</td>
<td>77</td>
<td>2194.6</td>
<td>353.9</td>
</tr>
<tr>
<td>1.1</td>
<td>78</td>
<td>2186.1</td>
<td>350.6</td>
</tr>
</tbody>
</table>

Pooled StDev = 354.8

One-way ANOVA: ctr_mid_temp versus c_contact

Source | DF | SS     | MS     | F    | P    |
c_contact | 2  | 274201 | 137100 | 1.10 | 0.335|
Error   | 226| 28190921 | 124739 |    |      |
Total   | 228| 28465122 |        |    |      |

S = 353.2   R-Sq = 0.96%   R-Sq(adj) = 0.09%

Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>81</td>
<td>2221.5</td>
<td>360.5</td>
</tr>
<tr>
<td>10</td>
<td>81</td>
<td>2215.7</td>
<td>359.0</td>
</tr>
<tr>
<td>20</td>
<td>67</td>
<td>2142.7</td>
<td>336.8</td>
</tr>
</tbody>
</table>

Pooled StDev = 353.2

One-way ANOVA: h_gap_mid versus rough_coef

Source | DF | SS     | MS     | F    | P    |
rough_coef | 2  | 17477910680 | 8738955340 | 176.91 | 0.000|
Error   | 226| 11163978209 | 49398134  |    |      |
Total   | 228| 28641888889 |        |    |      |
S = 7028    R-Sq = 61.02%    R-Sq(adj) = 60.68%

Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>81</td>
<td>32070</td>
<td>9970</td>
</tr>
<tr>
<td>2</td>
<td>81</td>
<td>18781</td>
<td>5669</td>
</tr>
<tr>
<td>4</td>
<td>67</td>
<td>10666</td>
<td>3114</td>
</tr>
</tbody>
</table>

Pooled StDev = 7028

One-way ANOVA: h_gap_mid versus c_jump

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>c_jump</td>
<td>2</td>
<td>316045</td>
<td>158022</td>
<td>0.00</td>
<td>0.999</td>
</tr>
<tr>
<td>Error</td>
<td>226</td>
<td>28641572844</td>
<td>126732623</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>228</td>
<td>28641888889</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 11258    R-Sq = 0.00%    R-Sq(adj) = 0.00%

Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>4317</td>
<td>77</td>
<td>21144</td>
<td>11375</td>
</tr>
<tr>
<td>5756</td>
<td>76</td>
<td>21121</td>
<td>11284</td>
</tr>
<tr>
<td>7195</td>
<td>76</td>
<td>21057</td>
<td>11111</td>
</tr>
</tbody>
</table>

Pooled StDev = 11258

One-way ANOVA: h_gap_mid versus kf_mult

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>kf_mult</td>
<td>2</td>
<td>7246482340</td>
<td>3623241170</td>
<td>38.27</td>
<td>0.000</td>
</tr>
<tr>
<td>Error</td>
<td>226</td>
<td>21395406549</td>
<td>94669940</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>228</td>
<td>28641888889</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 9730    R-Sq = 25.30%    R-Sq(adj) = 24.64%

Individual 95% CIs For Mean Based on Pooled StDev

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>72</td>
<td>15399</td>
<td>6226</td>
</tr>
<tr>
<td>1.00</td>
<td>77</td>
<td>18695</td>
<td>8168</td>
</tr>
<tr>
<td>1.25</td>
<td>80</td>
<td>28567</td>
<td>13107</td>
</tr>
</tbody>
</table>

Pooled StDev = 9730

One-way ANOVA: h_gap_mid versus kg_mult

55
### One-way ANOVA: kg_mult versus Error

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg_mult</td>
<td>2</td>
<td>516390034</td>
<td>258195017</td>
<td>2.07</td>
<td>0.128</td>
</tr>
<tr>
<td>Error</td>
<td>226</td>
<td>28125498855</td>
<td>124449110</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>228</td>
<td>28641888889</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 11156  R-Sq = 1.80%   R-Sq(adj) = 0.93%

| Level | N  | Mean | StDev | ---+---------+---------+---------+------|
|-------|----|------|-------|---+---------+---------+---------+------|
| 0.9   | 74 | 19261| 10006 | (---------*---------)          |
| 1.0   | 77 | 21020| 11081 | (---------*---------)          |
| 1.1   | 78 | 22946| 12212 |                  (---------*---------) |
---+---------+---------+---------+------|
17500 | 20000  | 22500   | 25000   |

Pooled StDev = 11156

### One-way ANOVA: h_gap_mid versus c_contact

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>c_contact</td>
<td>2</td>
<td>906164244</td>
<td>453082122</td>
<td>3.69</td>
<td>0.026</td>
</tr>
<tr>
<td>Error</td>
<td>226</td>
<td>27735724645</td>
<td>122724445</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>228</td>
<td>28641888889</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S = 11078  R-Sq = 3.16%   R-Sq(adj) = 2.31%

| Level | N  | Mean | StDev | ---+---------+---------+---------+-------|
|-------|----|------|-------|---+---------+---------+---------+-------|
| 5     | 81 | 19477| 11143 | (---------*---------)          |
| 10    | 81 | 20210| 11197 | (---------*---------)          |
| 20    | 67 | 24163| 10852 | (---------*---------)          |
---+---------+---------+---------+-------|
17500 | 20000  | 22500   | 25000   |

Pooled StDev = 11078
DISTRIBUTION

1 Keith Bradley  
National Technical Directory NEAMS  
Argonne National Laboratory  
9700 S. Cass Avenue  
Argonne, IL 60439

1 Jason Hales  
Idaho National Laboratory  
2525 Fremont Avenue  
Idaho Falls, ID 83415

1 Steven Hayes  
Idaho National Laboratory  
2525 Fremont Avenue  
Idaho Falls, ID 83415

1 Richard Martineau  
Idaho National Laboratory  
2525 Fremont Avenue  
Idaho Falls, ID 83415

1 Giovanni Pastore  
Idaho National Laboratory  
2525 Fremont Avenue  
Idaho Falls, ID 83415

1 Danielle Perez  
Idaho National Laboratory  
2525 Fremont Avenue  
Idaho Falls, ID 83415

1 Richard Williamson  
Idaho National Laboratory  
2525 Fremont Avenue  
Idaho Falls, ID 83415

1 MS 1318  J.R. Stewart  01441
1 MS 1318  B.M. Adams  01441
1 MS 1318  V.A. Mousseau  01444
1 MS 1318  R.M. Summers  01444
1 MS 0899  RIM - Reports Management, 9532 (electronic copy)