BADGER Orientation and Size Increments used for Debris Generation Calculations

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1 Purpose and Scope

ENERCON developed the BADGER software to calculate debris quantities generated for a range of break locations, sizes, orientations, and material-specific zones of influence (ZOIs). For any break smaller than a double ended guillotine break (DEGB) (i.e., a partial break), the ZOI is represented by a hemisphere centered on a weld at the edge of the pipe. Because these types of breaks could occur anywhere along the circumference of the pipe, breaks are analyzed at various angles around the pipe. Partial breaks are also analyzed in various size increments.

Typically, the debris generation calculations prepared by ENERCON use 45° increments for orientation at each partial break size. The partial break size increments that are typically used in these debris generation calculations are:

- 0.5 inch
- 2 inch
- 4 inch
- 6 inch
- 8 inch
- 10 inch
- 12 inch
- 14 inch
- 17 inch
- 20 inch
- 23 inch
- 26 inch

Since GSI-191 failures are more likely to occur at larger break sizes, the Vogtle debris generation calculation was refined to evaluate additional breaks at larger sizes to more accurately calculate the conditional failure probability (CFP). The revised calculation had the same sizes listed above for smaller breaks, but included 1-inch increments for breaks between 14 inches and 27 inches, and 0.5-inch increments for breaks between 27 inches and 31 inches.

During the NARWHAL NRC audit the week of May 16, 2016, the NRC staff reviewed the Vogtle debris generation results, and questioned whether the size and orientation increments are sufficient to accurately calculate the bounding quantity of debris at each weld location and the overall risk associated with GSI-191. For example, a bounding quantity of debris generated may be present somewhere between a 6-inch partial break evaluated at 45° and 90°. Further, the quantity of debris sufficient to cause a failure may be found between a 4” and a 6” break. This NRC comment was primarily based on observations from the STP pilot project where the risk quantification (using the RoverD methodology) was dependent on an accurate identification of the smallest break that fails at each weld, which is very sensitive to the analyzed break size and orientation increments.

To address the NRC’s question, this white paper specifically evaluates the following three questions:

1. Are there any significant spikes or trends in debris quantities that are missed by using larger orientation and size increments?
2. What is the maximum quantity of debris that could be missed by using 45° increments?
3. How much difference do the size and orientation increments make on the risk quantification using a) the CFP approach and b) the threshold break approach?

2 Potential for Missed Spikes or Trends

The potential for significant debris quantity spikes or trends between the orientation and size increments was evaluated by running a BADGER sensitivity calculation using the model for a 4-loop Westinghouse plant with low density fiberglass insulation. The existing data included breaks at 45° intervals for 4-inch, 6-inch, 8-inch, and 10-inch break sizes at 100 different weld locations. The sensitivity evaluation included breaks at 15° intervals and 0.25-inch intervals between 6 inches and 8 inches for the same set of breaks.

Figure 1 shows an example 6” break with the calculated debris quantities at each orientation. As shown in this figure, there is a slightly larger maximum quantity of debris generated between the 90° and 135° increments than was captured in the original data. However, the increase is not significant. Based on a review of the 6-inch and 8-inch breaks, the maximum quantity of debris generated at the worst case orientation was approximately 2% higher on average with the 15° increment data compared to the 45° increment data. The maximum increase was approximately 10% (3 ft^3) for a 6-inch break (on Weld 11204-021-27-RB).

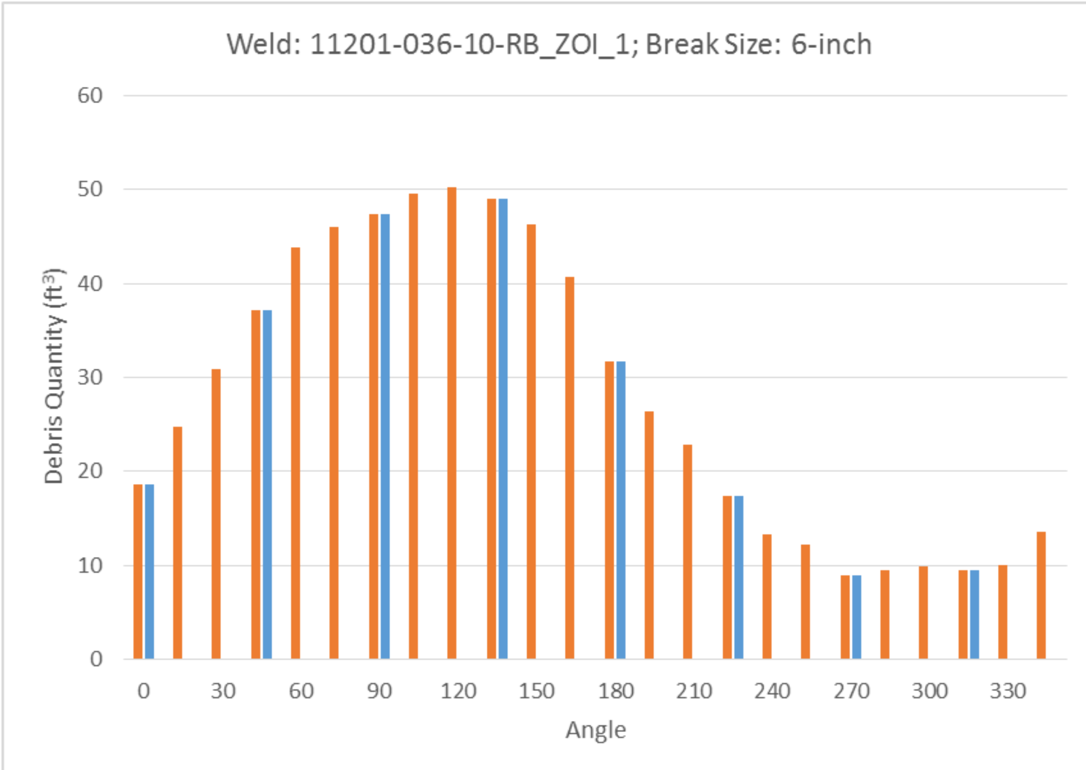

Figure 1 – Orientation Data for a 6" Partial Break (Weld 11201-036-10-RB)

The data from the break size increment is shown in Figure 2. As shown, there are not any outliers of debris generated when using 0.25" size increments vs. 2" increments. Also, as expected, there is a trend of decreasing quantity of debris generated as the break size decreases.

Figure 2 – Size Increment Data for 0° Orientation Partial Breaks (Weld 11201-036-10-RB)

Figure 3 shows the location of this weld in containment and Figure 4 shows the combined size and orientation data for all breaks evaluated between 6 and 8 inches at this weld.

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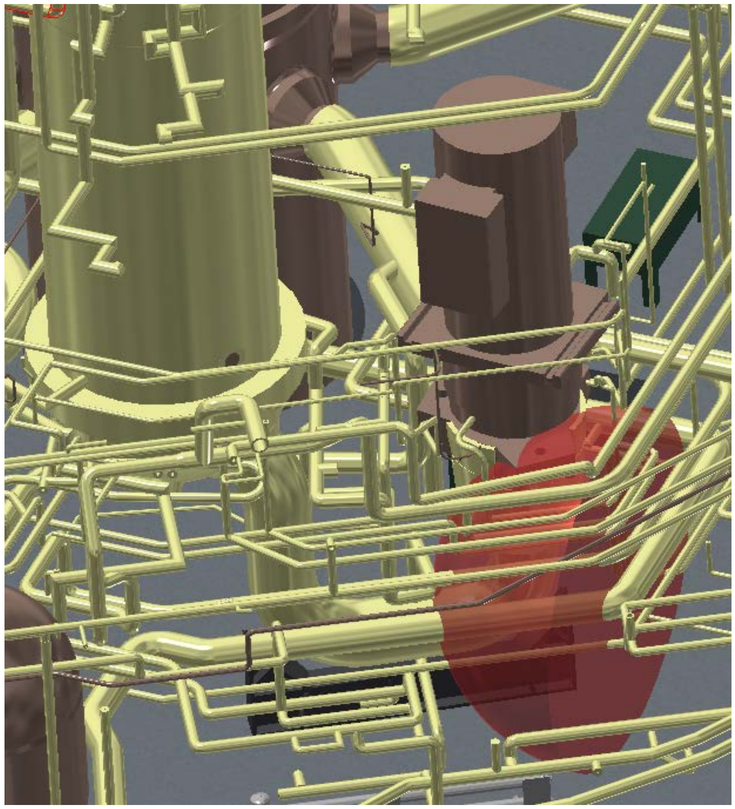
Figure 3 – Location of Weld 11201-036-10-RB

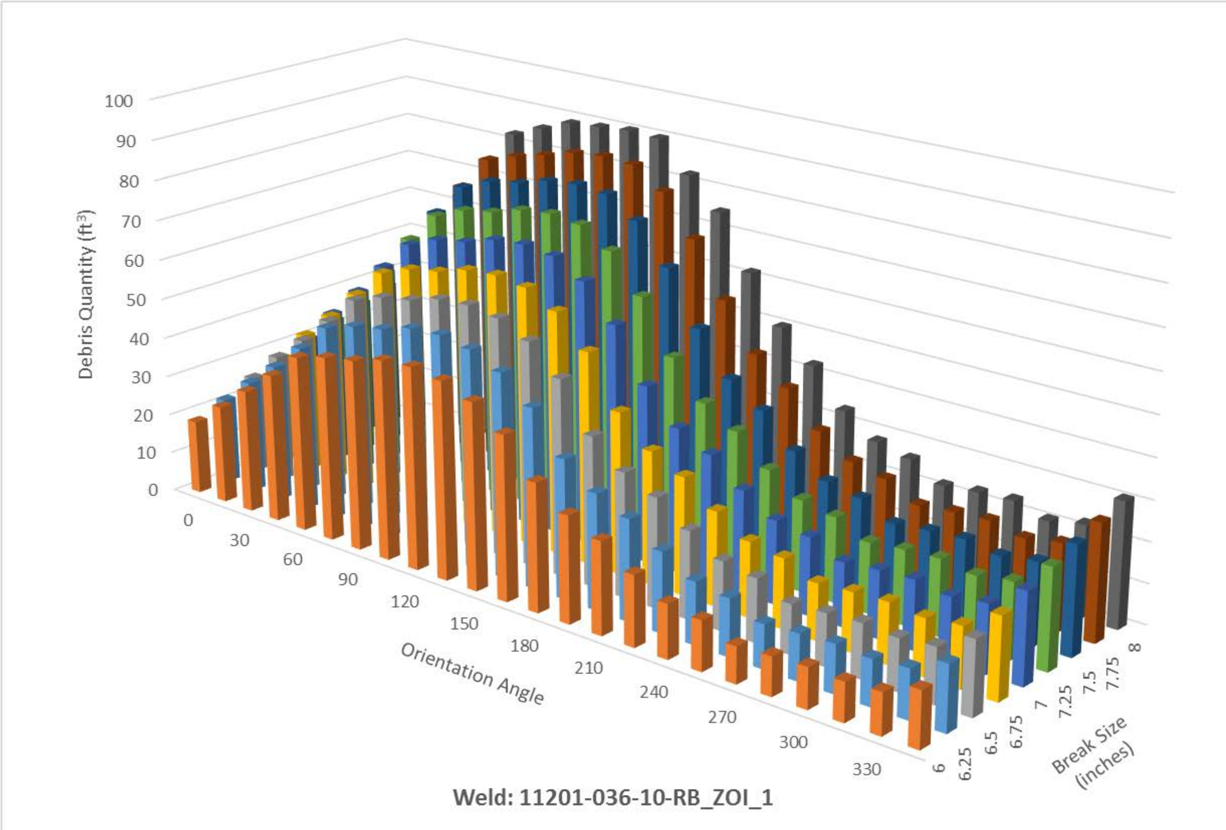

Figure 4 – Size and Orientation Increment Data for Range of Partial Breaks (Weld 11201-036-10-RB)

Figure 5 shows another example of a 6" break with the calculated debris quantities at each orientation. As shown in this figure, there are not any data points that produce a larger maximum quantity of debris generated than was captured in the original data.

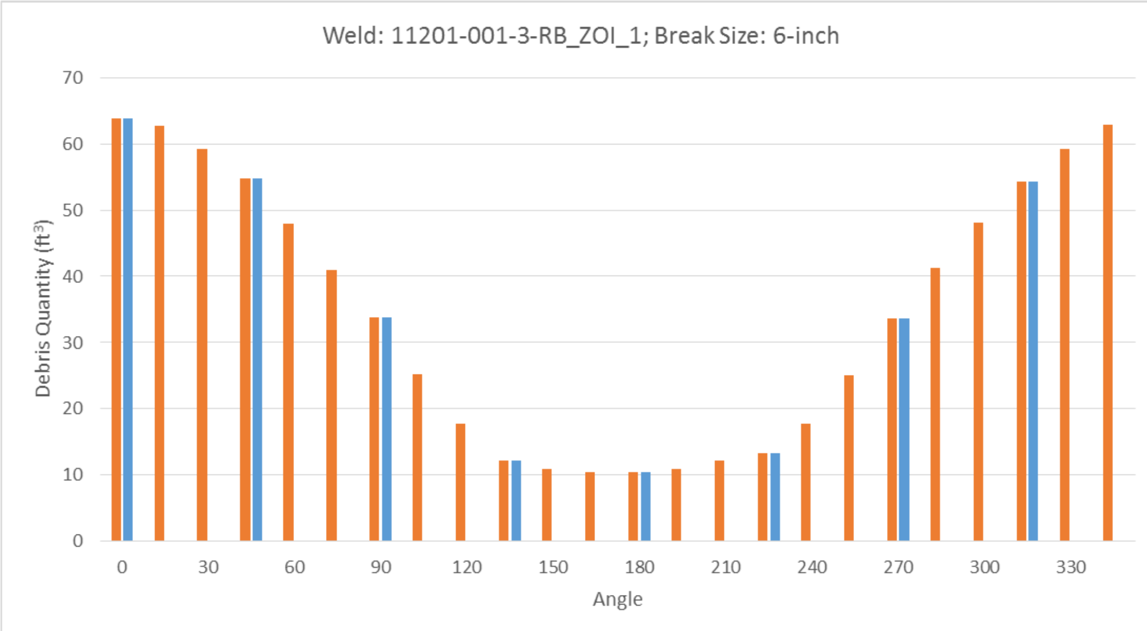

Figure 5 – Orientation Data for a 6" Partial Break (Weld 11201-001-3-RB)

The data from the break size increment is shown in Figure 6. As shown, there are not any outliers of debris generated when using 0.25" size increments vs. 2" increments. Also, as expected, there is a trend of decreasing quantity of debris generated as the break size decreases.

Figure 6 – Size Increment Data for 0° Orientation Partial Breaks (Weld 11201-001-3-RB)

Figure 7 shows the location of this weld in containment and Figure 8 shows the combined size and orientation data for all breaks evaluated between 6 and 8 inches at this weld.

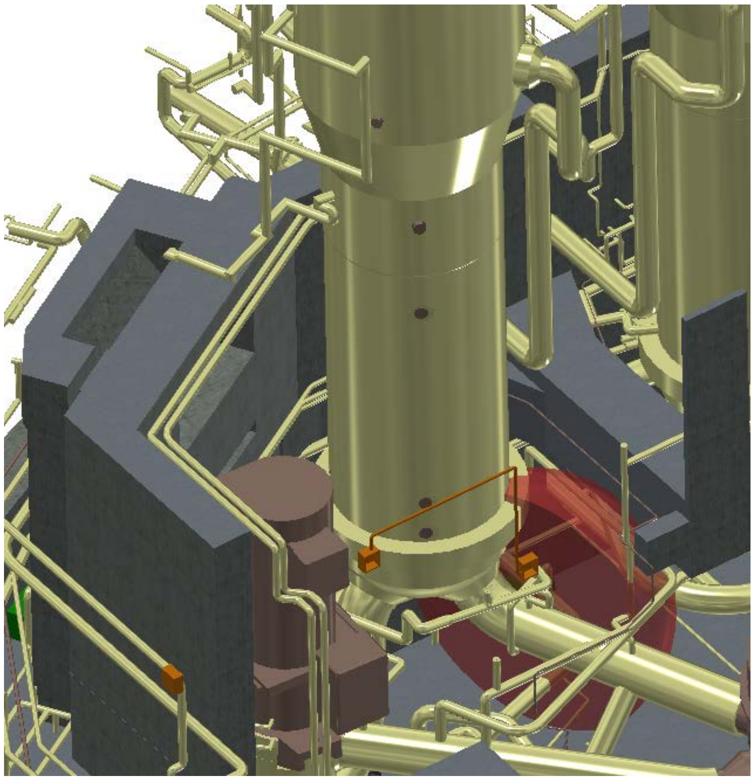

Figure 7 – Location of Weld 11201-001-3-RB

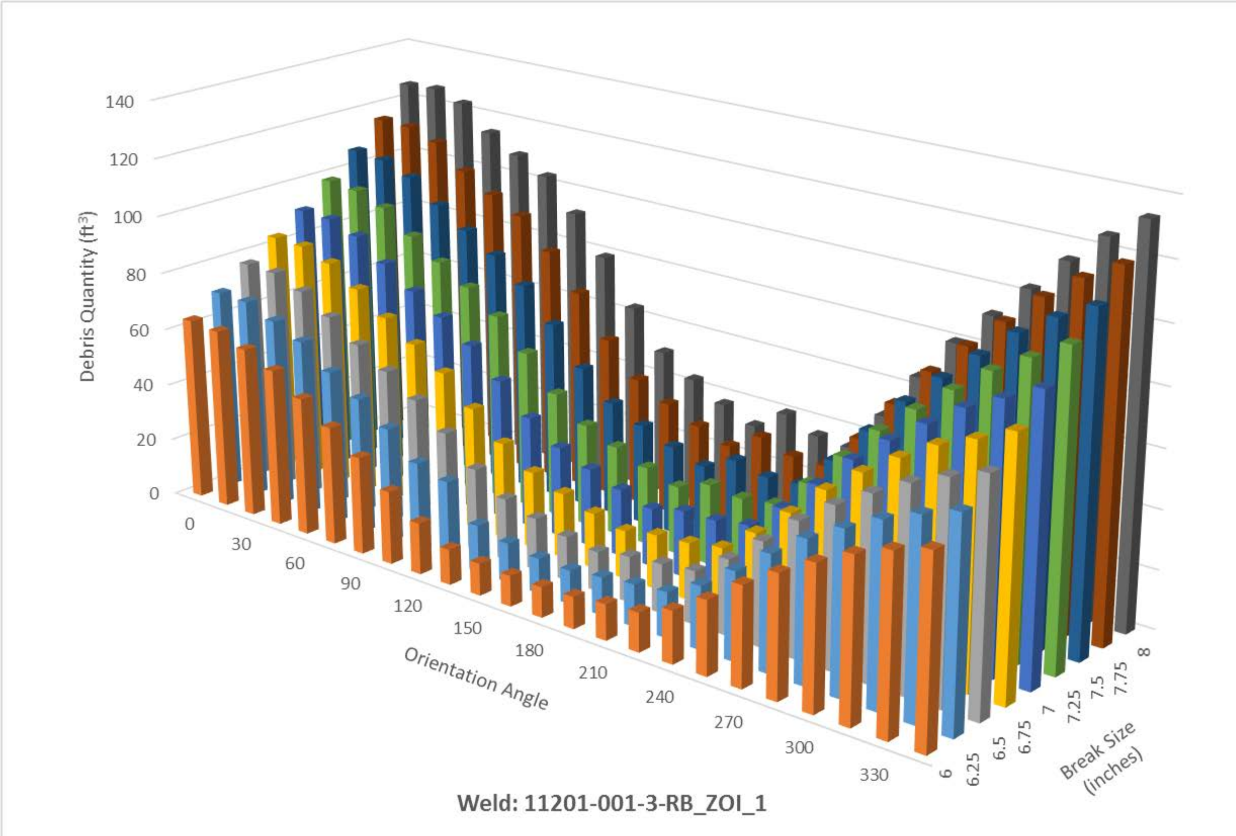

Figure 8 – Size and Orientation Increment Data for Range of Partial Breaks (Weld 11201-001-3-RB)

3 Maximum Quantity of Debris that Could Hypothetically be Missed

The sensitivity case discussed in the previous section demonstrated that there are not any significant spikes or trends in the quantities of debris generated between the break orientation and size increments. Furthermore, it can also be demonstrated that missing a hypothetical 'wedge' of debris that may exist when using the 45° increments is not significant.

As shown in Figure 9, there is significant overlap in the partial break ZOIs, and essentially any debris source in the vicinity of the weld would be captured by at least three of the 45° orientation hemispheres.

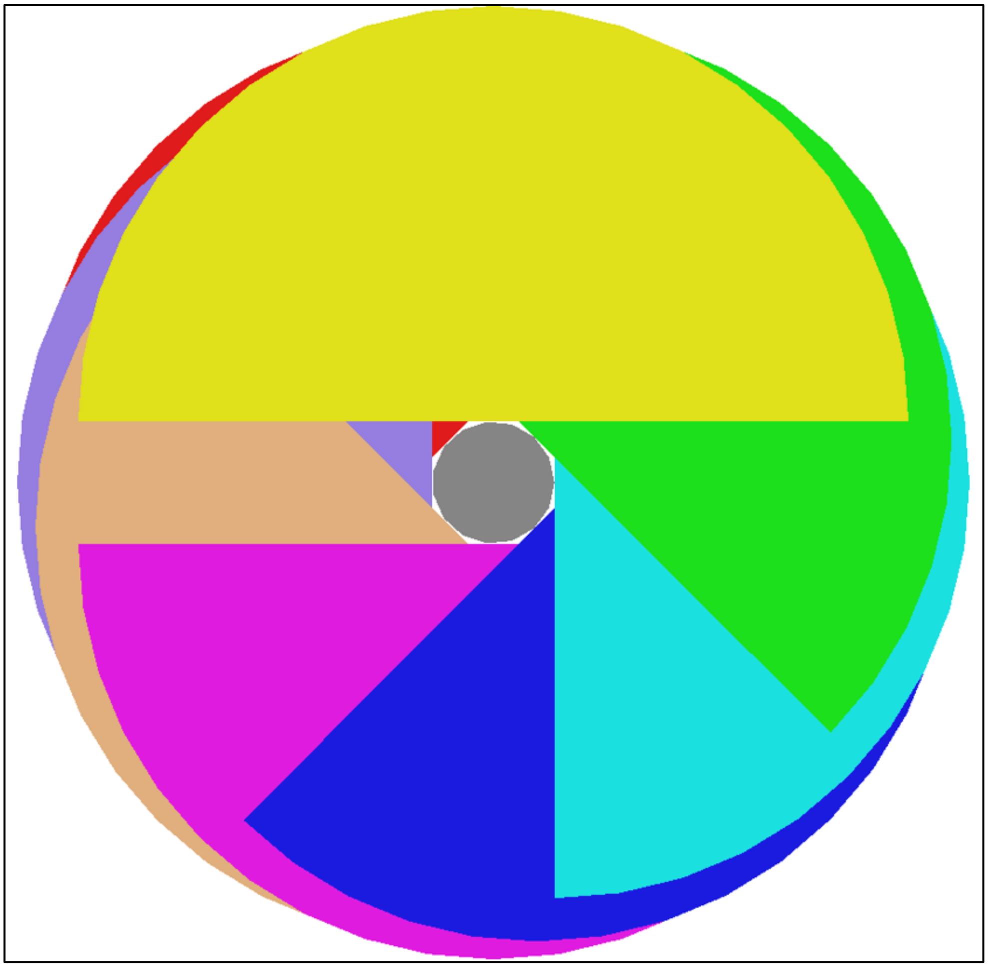

Figure 9 – 45° Increment Visualization

Since debris sources are not uniformly distributed around the entire circumference of a weld, it is hypothetically possible that a pair of insulation ‘wedges’ could exist in an exact location where half of the two wedges is missed by either of the two adjoining 45° orientation hemispheres. In the hypothetical example shown in Figure 10, the insulation (represented by the brown rectangle) is all on one side of the pipe oriented at a 22.5° increment (i.e., right in the middle of the 45° increment ZOIs represented by the green and yellow semicircles). As shown in this figure, there are two wedges of insulation that would both be captured by a ZOI oriented at a 22.5° increment (shown by the hatched region in the figure), but only one of these wedges is captured by either of the ZOIs oriented at the 45° increments.

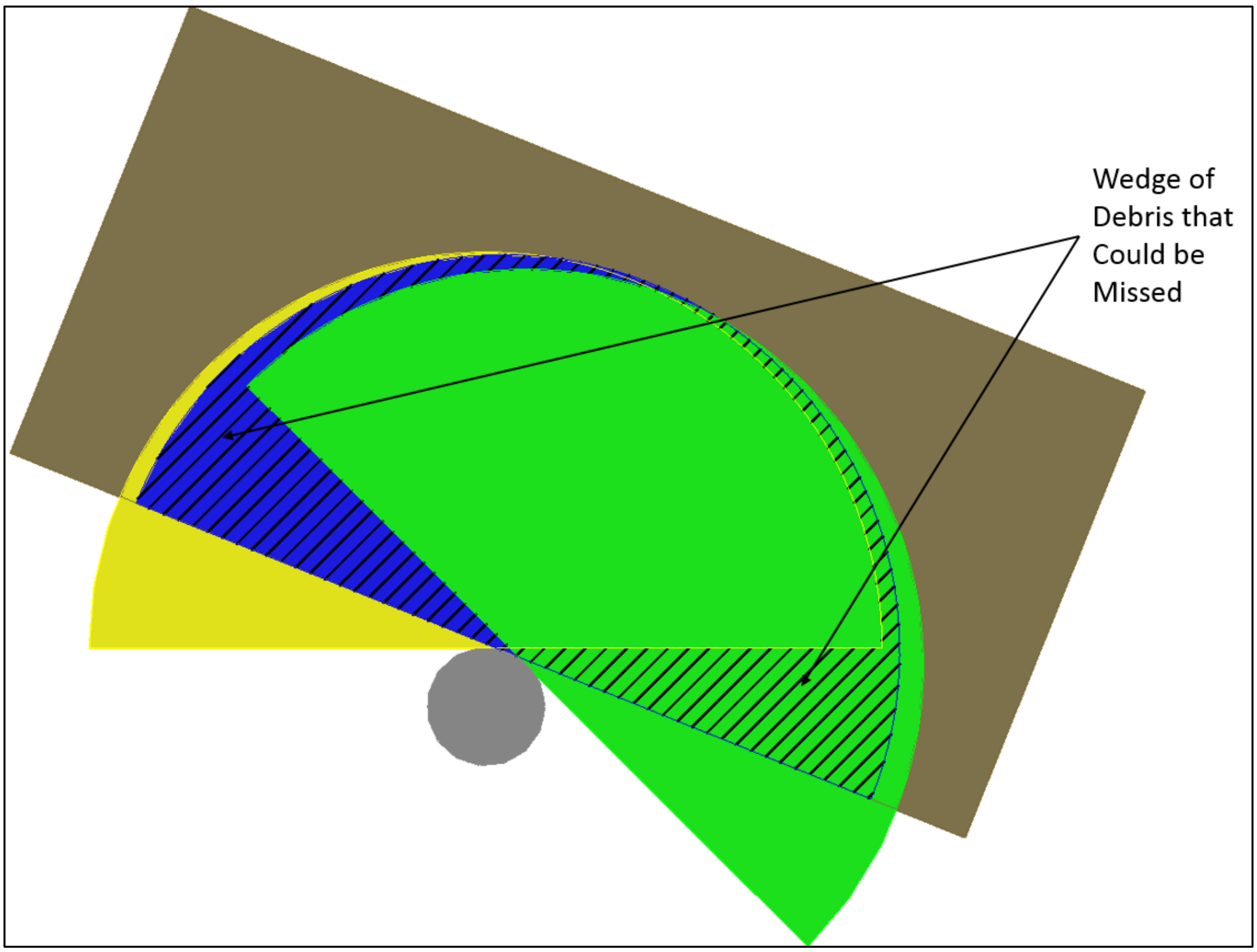

Figure 10 – Wedge of Debris

The amount of debris that could possibly be missed in the wedge (the hatched area in the figure above) can be calculated by using a 3D CAD example. To show that the quantity of debris missed is not significant, an example of a 4-inch partial break on a 29” pipe was examined with a 17D ZOI for fibrous debris[1]. As shown in Figure 11, the three hemispheres are oriented around the pipe at 0°, 22.5°, and 45°.

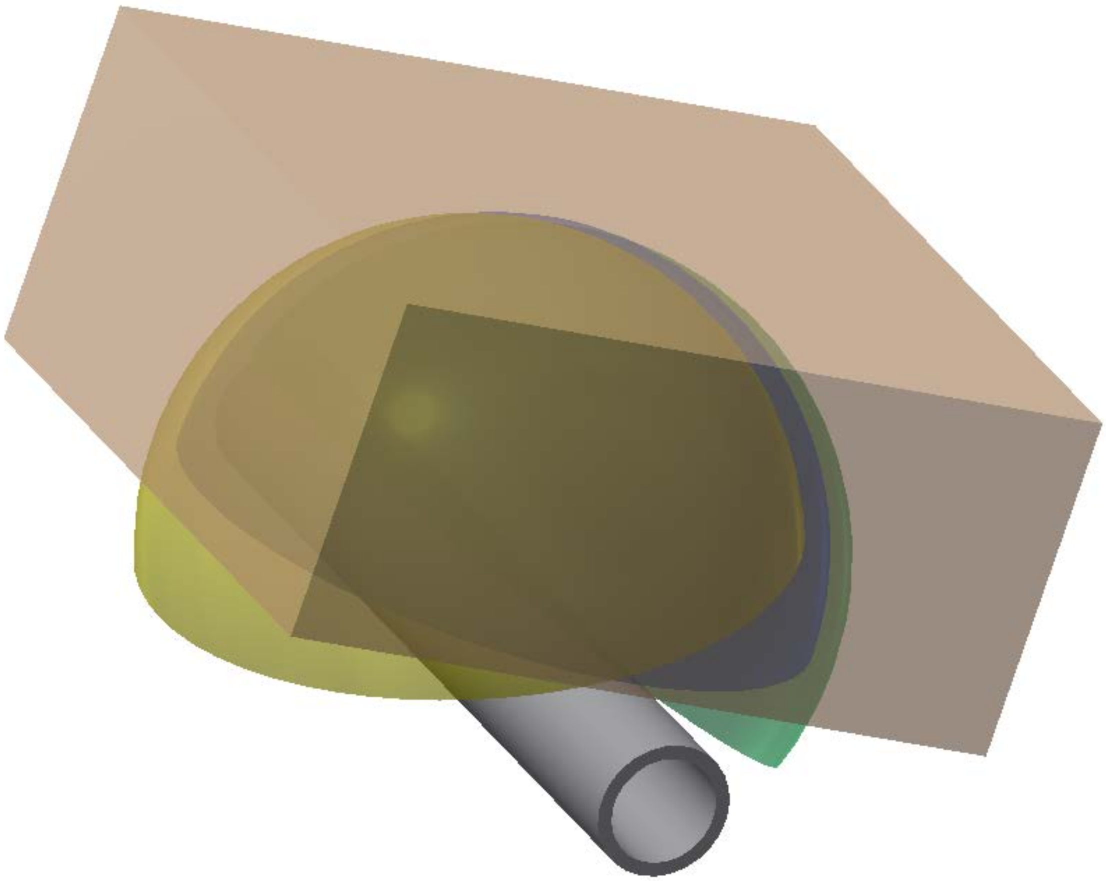

Figure 11 – 3D CAD Example of Hemisphere Orientations (4-inch Partial Break; 17D ZOI)

The amount of debris generated in each hemisphere is shown in Table 1.

Table 1 – Debris Generated in 3D CAD Example

Hemisphere Orientation	Amount of Debris Generated (ft^3)
0°	327.9
22.5°	380.0
45°	327.9

[1] Note that a 4-inch break was selected for this example due to the potential concern of missing a failure for a relatively high frequency break. Although larger breaks could potentially have a larger “missed” volume, the effect on risk would be lower due to the lower initiating event frequency associated with larger breaks.

It should be noted that this is a very conservative example assuming that the volume of the two wedges (for a 4-inch break with a 17D ZOI) is completely filled with insulation. Since the amount of fine debris is typically the debris of concern, the amount of fine debris in the hemispheres at 0° and at 22.5° can be calculated with the following equations [1]:

$$F_{LDFG\ fines}(C)\left|\begin{array}{l}(0D \leftrightarrow 4D) = 0.2\\ (4D \leftrightarrow 15D) = -0.01364 * C + 0.2546\\ (15D \leftrightarrow 17D) = -0.025 * C + 0.425\end{array}\right.$$

$$F_{LDFG\ smalls}\ (C)\left|\begin{array}{l}(0D \leftrightarrow 4D) = 0.8\\ (4D \leftrightarrow 15D) = -0.0682 * C + 1.0724\\ (15D \leftrightarrow 17D) = -0.025 * C + 0.425\end{array}\right.$$

$$F_{LDFG\ large}(C)\left|\begin{array}{l}(0D \leftrightarrow 4D) = 0\\ (4D \leftrightarrow 15D) = 0.0393 * C - 0.157\\ (15D \leftrightarrow 17D) = -0.215 * C + 3.655\end{array}\right.$$

$$F_{LDFG\ intact}(C)\left|\begin{array}{l}(0D \leftrightarrow 4D) = 0\\ (4D \leftrightarrow 15D) = 0.0425 * C - 0.170\\ (15D \leftrightarrow 17D) = 0.265 * C - 3.505\end{array}\right.$$

Where D is the break diameter and C is the average centroid magnitude value. BADGER calculates the distance between the break location and the centroid of each interference based on the center of mass, and calculates the *Centroid Distance* (in units of break size) with the following equation:

$$C(Break\ Size) = \frac{\sum_{i=1}^{n} C_i \times V_i}{V_{Total} \times Break\ Size}$$

Where:

- C_i is the distance between the ZOI center and the centroid of the interference
- V_i is the volume of the interference
- n is the number of interferences
- V_{Total} is the total volume of the debris within the ZOI

The average centroid magnitudes were calculated in the 3D CAD example. The average centroid magnitudes for the hemispheres oriented at 0° and 22.5° were calculated to be 11.2D and 11.0D, respectively.

The percentage of fines, small pieces, and large pieces generated within the hemisphere oriented at 0° is:

$$F_{LDFG\ fines}\ (11.32D) = -0.01364 * 11.2 + 0.2546 = 0.10$$

$F_{LDFG\ smalls}\,(11.32D) = -0.0682 * 11.2 + 1.0724 = 0.31$

$F_{LDFG\ large}\,(11.32D) = 0.0393 * 11.2 - 0.157 = 0.28$

The percentage of fines, small pieces, and large pieces generated within the hemisphere oriented at 22.5° is:

$F_{LDFG\ fines}\,(11.0D) = -0.01364 * 11.0 + 0.2546 = 0.10$

$F_{LDFG\ smalls}\,(11.0D) = -0.0682 * 11.0 + 1.0724 = 0.32$

$F_{LDFG\ large}\,(11.0D) = 0.0393 * 11.0 - 0.157 = 0.28$

The amount of debris missed in the wedge between the hemispheres at 0° and 22.5° is shown in the table below.

Table 2 – Amount of Fines, Smalls, and Large Debris Generated

Debris Size	Debris Generated (0° Orientation)	Debris Generated (22.5° Orientation)	Difference in Debris Generated
Fines	32.8 ft^3	38.0 ft^3	5.2 ft^3
Smalls	101.6 ft^3	121.6 ft^3	20.0 ft^3
Large	91.8 ft^3	106.4 ft^3	14.6 ft^3

Conservatively assuming all of the small and large pieces are exposed to recirculation pool flow (i.e., no holdup in upper containment or transport to inactive cavities) with a 10% erosion fraction, the total quantity of fines generated within the wedge is (5.2 ft^3+0.10*20.0 ft^3+0.10*14.6 ft^3) = 8.7 ft^3. This quantity of fine debris is very small (latent debris is typically on the order of 12.5 ft^3 of fines), and indicates that there is no significant concern related to missing failures of smaller breaks due to the 45° orientation increments.

Also, as noted in Section 2, the maximum quantity of "missed" debris from a much more realistic set of conditions for 6 inch breaks was only 3 ft^3 total.

4 Impact on Risk Quantification

As discussed in Section 1, the RoverD approach used by the STP pilot project is very sensitive to the effects of break orientation and size increments on the smallest break that fails at each weld. The non-pilot plants are not planning to use the RoverD methodology and can generally be divided into plants using a CFP approach and plants using a threshold break approach.

With the CFP approach, GSI-191 failures are quantified for different size ranges where each break in a given size range is treated as equally likely; the frequency and failure probability for each size range is then combined to calculate the CFP value for a PRA category (e.g., large breaks) [2]. The CFP values are then entered into the PRA model to calculate ΔCDF and ΔLERF.

As a simple illustration of the impact that the break orientation and size increments have on the risk quantification using the CFP approach, the example debris quantities described in Section 2 are used. Simplistically assuming that 100% of the fiber debris generated would transport to the strainer for each break, and the acceptable fiber debris limit is 100 ft^3, the CFP value for breaks in the 6 to 8 inch size range is simply the number of breaks that exceed the debris limit divided by the total number of breaks evaluated. Using the 2-inch and 45° size and orientation increments, a total of 70 breaks failed out of 1,600 breaks evaluated giving a CFP of 0.044. Using the 0.25-inch and 15° size and orientation increments, a total of 361 breaks failed out of 21,600 breaks evaluated giving a CFP of 0.017. This simple calculation was repeated for several different sensitivity cases using different portions of the same overall data set as shown in Table 3.

Table 3 – CFP Values Calculated for Various Orientation and Size Increments

Case	Orientation Increments	Size Increments	Number of Breaks	Number of Failures	CFP	Smallest Failure
1	1 (0°)	2 (6”, 8”)	200	15	0.075	8
2	2 (0°, 180°)	2 (6”, 8”)	400	24	0.060	8
3	3 (0°, 120°, 240°)	2 (6”, 8”)	600	26	0.043	8
4	4 (0°, 90°, 180°…)	2 (6”, 8”)	800	33	0.041	8
5	6 (0°, 60°, 120°…)	2 (6”, 8”)	1,200	57	0.048	8
6	8 (0°, 45°, 90°…)	2 (6”, 8”)	1,600	70	0.044	8
7	12 (0°, 30°, 60°…)	2 (6”, 8”)	2,400	101	0.042	8
8	24 (0°, 15°, 30°…)	2 (6”, 8”)	4,800	207	0.043	8
9	1 (0°)	3 (6”, 7”, 8”)	300	15	0.050	8
10	2 (0°, 180°)	3 (6”, 7”, 8”)	600	24	0.040	8
11	3 (0°, 120°, 240°)	3 (6”, 7”, 8”)	900	26	0.029	8
12	4 (0°, 90°, 180°…)	3 (6”, 7”, 8”)	1,200	33	0.028	8
13	6 (0°, 60°, 120°…)	3 (6”, 7”, 8”)	1,800	57	0.032	8
14	8 (0°, 45°, 90°…)	3 (6”, 7”, 8”)	2,400	70	0.029	8
15	12 (0°, 30°, 60°…)	3 (6”, 7”, 8”)	3,600	101	0.028	8
16	24 (0°, 15°, 30°…)	3 (6”, 7”, 8”)	7,200	207	0.029	8
17	1 (0°)	5 (6”, 6.5”, 7”, 7.5”, 8”)	500	18	0.036	7.5
18	2 (0°, 180°)	5 (6”, 6.5”, 7”, 7.5”, 8”)	1,000	27	0.027	7.5
19	3 (0°, 120°, 240°)	5 (6”, 6.5”, 7”, 7.5”, 8”)	1,500	32	0.021	7.5
20	4 (0°, 90°, 180°…)	5 (6”, 6.5”, 7”, 7.5”, 8”)	2,000	37	0.019	7.5
21	6 (0°, 60°, 120°…)	5 (6”, 6.5”, 7”, 7.5”, 8”)	3,000	66	0.022	7.5
22	8 (0°, 45°, 90°…)	5 (6”, 6.5”, 7”, 7.5”, 8”)	4,000	82	0.021	7.5
23	12 (0°, 30°, 60°…)	5 (6”, 6.5”, 7”, 7.5”, 8”)	6,000	122	0.020	7.5
24	24 (0°, 15°, 30°…)	5 (6”, 6.5”, 7”, 7.5”, 8”)	12,000	247	0.021	7.5
25	1 (0°)	9 (6”, 6.25”, 6.5”, 6.75”…)	900	27	0.030	7.25
26	2 (0°, 180°)	9 (6”, 6.25”, 6.5”, 6.75”…)	1,800	40	0.022	7.25
27	3 (0°, 120°, 240°)	9 (6”, 6.25”, 6.5”, 6.75”…)	2,700	48	0.018	7.25
28	4 (0°, 90°, 180°…)	9 (6”, 6.25”, 6.5”, 6.75”…)	3,600	54	0.015	7.25
29	6 (0°, 60°, 120°…)	9 (6”, 6.25”, 6.5”, 6.75”…)	5,400	100	0.019	7.25
30	8 (0°, 45°, 90°…)	9 (6”, 6.25”, 6.5”, 6.75”…)	7,200	124	0.017	7.25
31	12 (0°, 30°, 60°…)	9 (6”, 6.25”, 6.5”, 6.75”…)	10,800	184	0.017	7.25
32	24 (0°, 15°, 30°…)	9 (6”, 6.25”, 6.5”, 6.75”…)	21,600	368	0.017	7.25

Figure 12 through Figure 14 show the sensitivity of CFP to variations in the number of size and orientation increments. Note that the purple dot/bar in these figures represent the standard size and orientation increments used for the existing BADGER debris generation calculations. In general, these trends show that the CFP quickly levels off as more orientation increments are added. Although there is a relatively significant difference between 1, 2, and 3 orientation increments, there is very little difference in the conditional failure probability between 3 orientation increments and 24 orientation increments. Increasing the number of size increments results in a large percent decrease in CFP, although the magnitude difference is only a 2-3% change, which would have a relatively minor effect on ΔCDF.

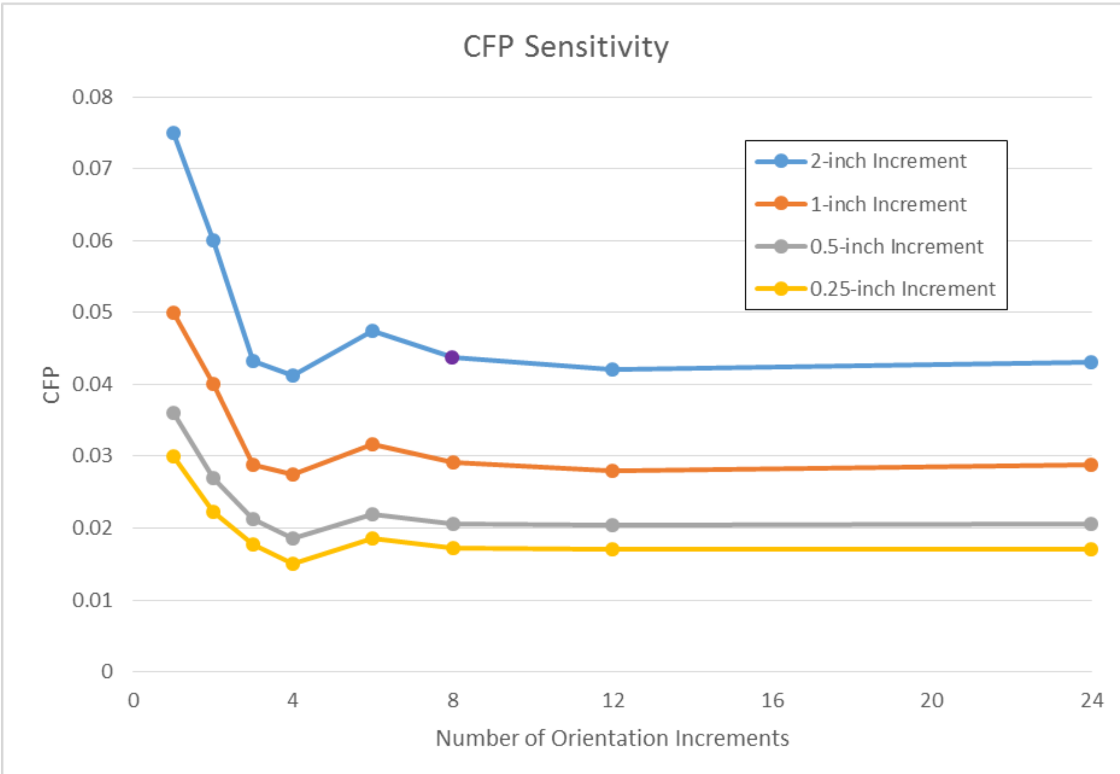

Figure 12 – Sensitivity of CFP to the Number of Orientation Increments

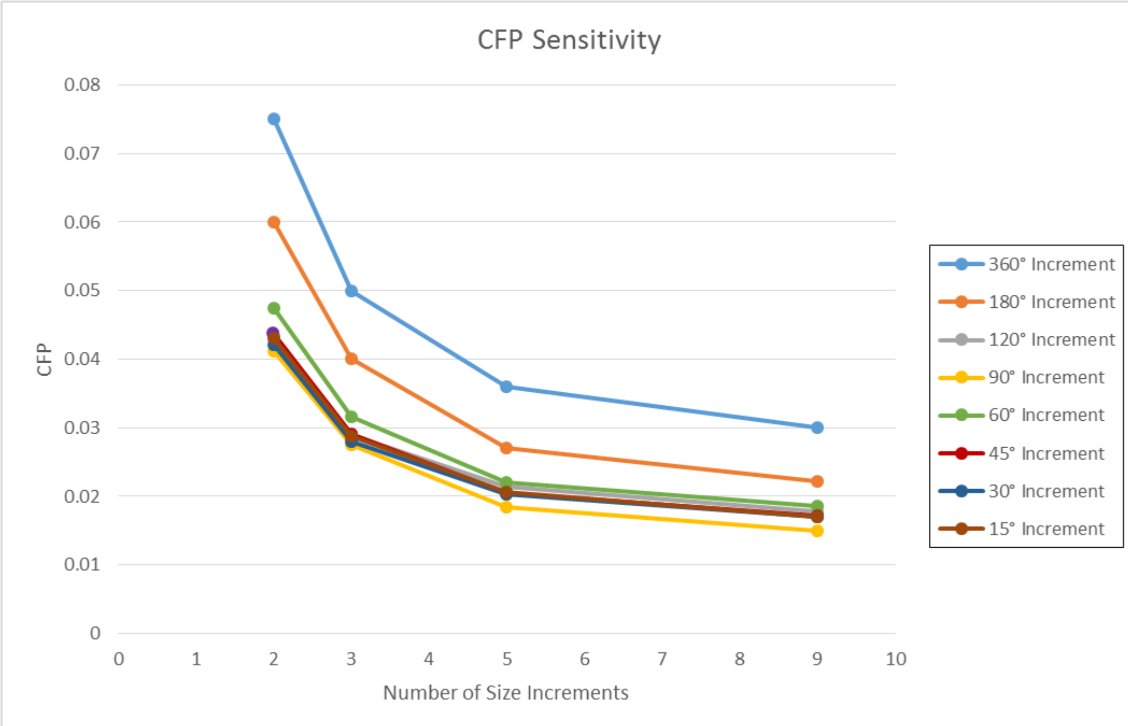

Figure 13 – Sensitivity of CFP to the Number of Size Increments

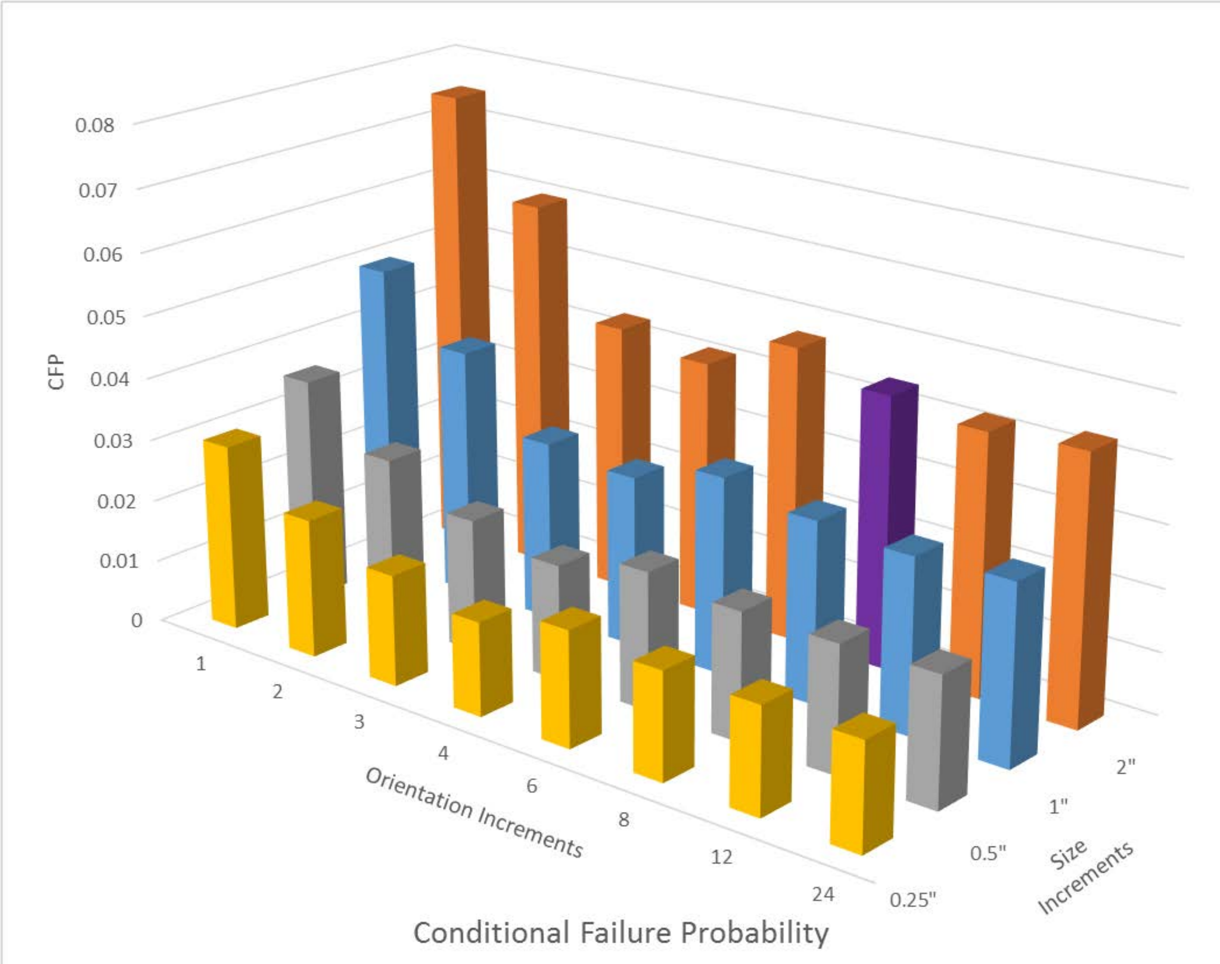

Figure 14 – Sensitivity of CFP to Size and Orientation Increments

Although refining the break size and/or orientation increments in BADGER would provide a slightly more accurate result, it would not significantly change the overall risk quantification for plants that use the CFP approach.

For plants implementing the threshold break approach, the size and orientation increments have a much more significant effect on the results (similar to the RoverD approach). As shown in Table 3 and Figure 15 through Figure 17, the smallest break that fails corresponds to the most refined size increments. The methodology for the threshold break approach is to use the largest break size that does not fail as the threshold break size (i.e., the threshold break is one size step below the smallest break that fails). In this example, the threshold break size based on the standard 2-inch size increments would be 6-inches (i.e., an 8-inch break is the smallest break that fails and a 6-inch break is the largest break that doesn't fail). When more size and orientation increments are evaluated, it can be seen that the threshold break size increases from 6-inches to 7-inches (i.e., with 0.25-inch size increments, a 7.25-inch break is the smallest break that fails and a 7-inch break is the largest break that doesn't fail).

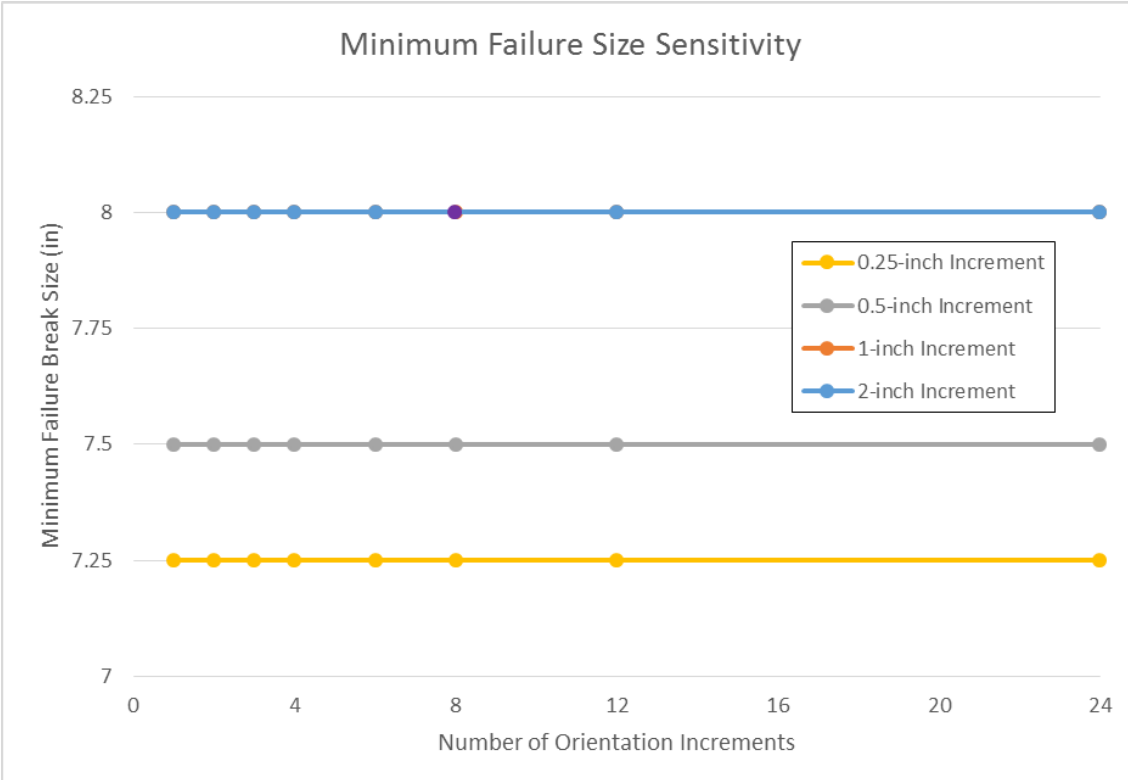

Figure 15 – Sensitivity of Smallest Failure to the Number of Orientation Increments

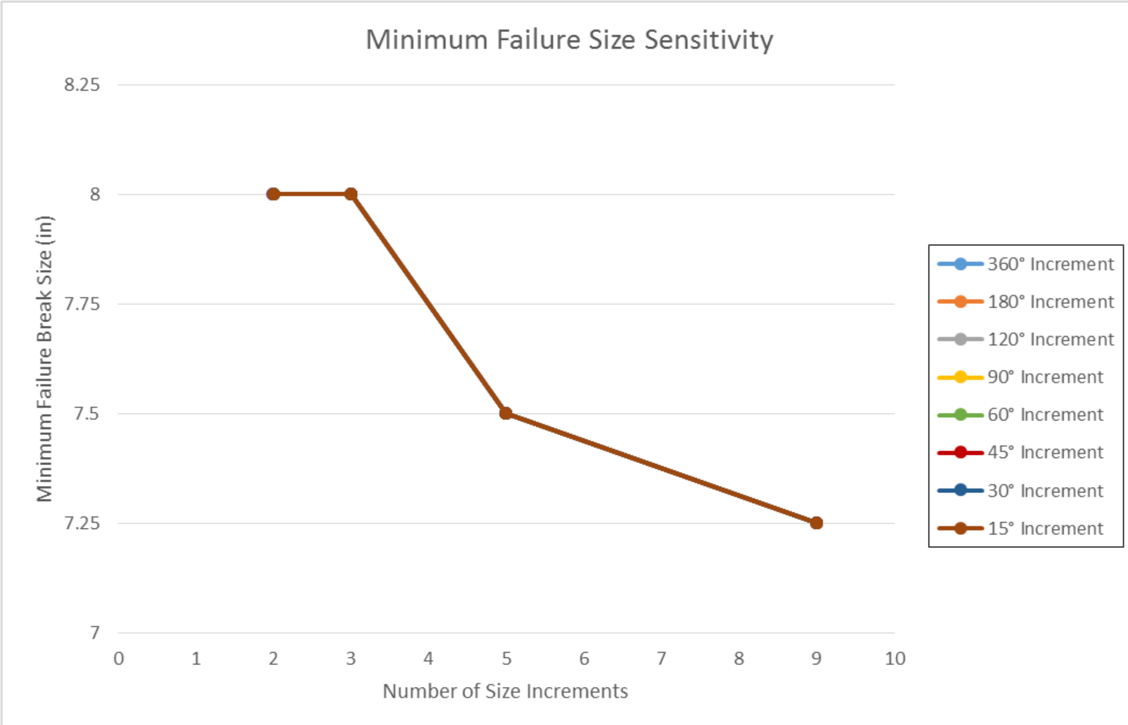

Figure 16 – Sensitivity of Smallest Failure to the Number of Size Increments

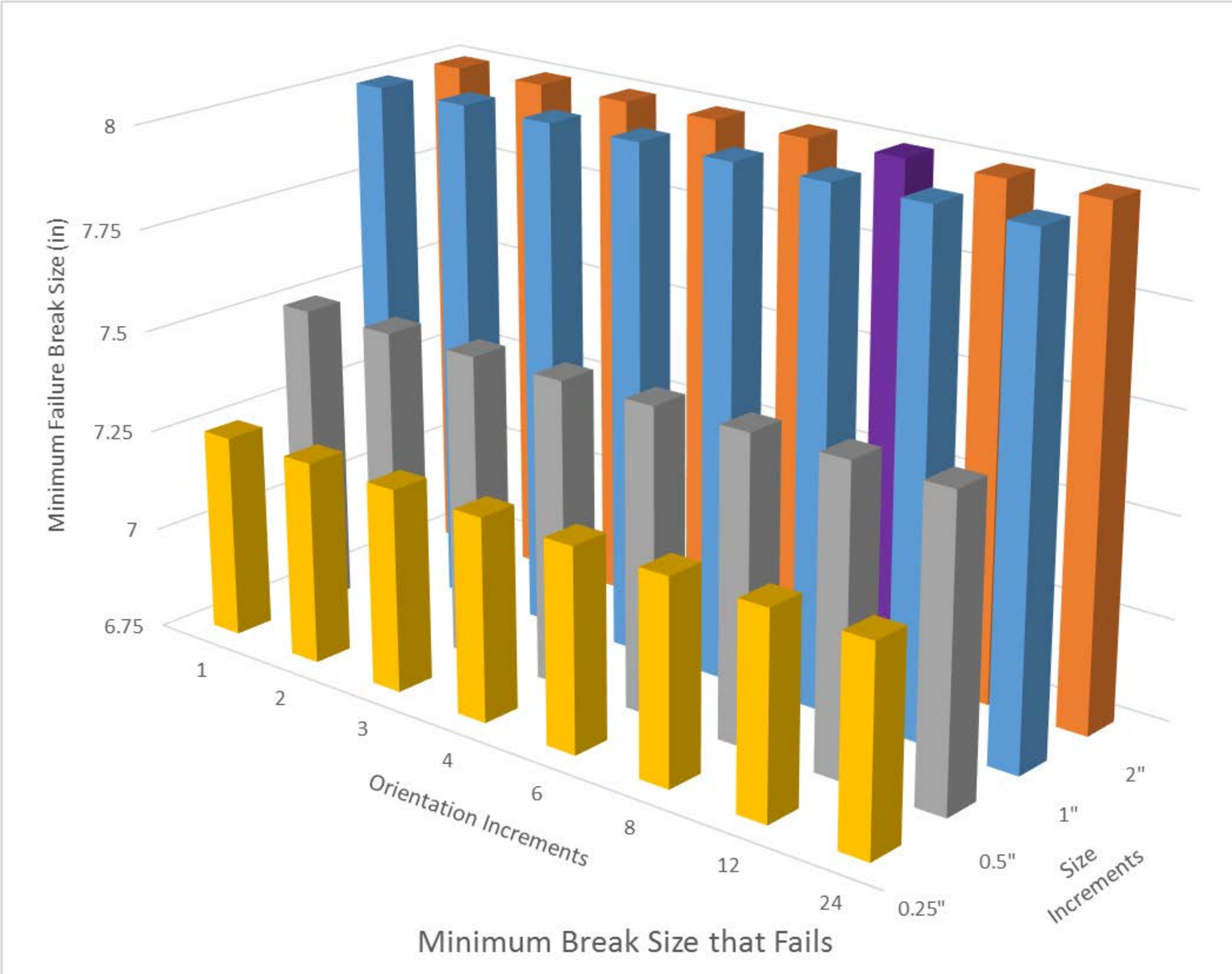

Figure 17 – Sensitivity of Smallest Failure to Size and Orientation Increments

5 Conclusion

Refining the break orientation and break size increments in BADGER will not have a significant impact on the debris generation results. When the break orientation is refined to 15° increments compared to 45° increments, there may be a slight increase in debris generated as shown in Figure 1. However, this increase is generally very small. Also, as demonstrated in Section 2, there are not any significant spikes or trends in the quantities of debris generated between the break size increments (see Figure 2 and Figure 4). The amount of debris that can be generated in the hypothetical 'wedge' of debris that may exist when using the 45° increments was shown not to be significant in Section 3. In the 3D CAD example evaluated in Section 3, it was shown that the amount of fine debris that could be missed when evaluating a 4-inch partial break with a 17D ZOI on a 29-inch pipe was 8.7 ft^3, which is very small (latent fiber is typically on the order of 12.5 ft^3 of fines). When examining the impact on risk quantification that refining the break size and orientation would have, it was demonstrated in Section 4 that refining the break size and/or orientation increments in BADGER would provide a slightly more accurate result. However, it would not significantly change the overall risk quantification for plants that use the CFP approach. For plants implementing the threshold break approach, the results shown in Section 4 illustrate that defining the threshold break as the largest break size that does not fail is conservative. If desired, the threshold break size can be refined by analyzing more break sizes and orientations for the location(s) where the smallest failures are observed.

6 References

[1] GSI191-CALC-001, "Insulation ZOI Size Distribution," Revision 3, July 18, 2016.

[2] GSI191-CALC-006, "Methodology for Distributing LOCA Frequencies and Calculating GSI-191 Conditional Failure Probabilities," Revision 0, July 8, 2016.