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Vogtle Evaluation of Timing for Random Pump Failures

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Revision 1, 8/3/2016

1. Purpose and Scope

The likelihood of strainer and core failures due to the effects of debris is highly dependent on the equipment configuration that is being analyzed (specifically the type and number of pumps running). Therefore, for a risk-informed GSI-191 evaluation, it is important to take into consideration the potential pump failure combinations due to random (not debris related) failures, along with the corresponding failure probabilities. These random failures are classified in a probabilistic risk assessment (PRA) model as failure to start (FTS) and failure to run (FTR). If a pump fails to start at the beginning of the event, this pump would have no contribution to flow rates, refueling water storage tank (RWST) drawdown timing, debris transport, etc. However, if a pump starts, but eventually fails to run, it would have some effect on the evaluation up until the point when it fails.

Preliminary evaluations for Vogtle and other licensees have treated FTR the same as FTS, and have not explicitly evaluated the effects of a pump randomly failing at some point after the start of the event. During the NARWHAL NRC audit, the staff questioned whether a late pump failure could be worse than a failure at the start of the event.

This white paper evaluates the potential issues associated with random pump failures later in the event for Vogtle, along with the impact on the overall risk calculation. Note that no operator actions to mitigate or recover from pump failures are credited in this evaluation.

2. Bounding Scenarios for FTR Timing

Vogtle has two trains for the emergency core cooling system (ECCS) and containment spray system (CSS). Each train includes a residual heat removal (RHR) pump, a safety injection (SI) pump, a charging pump, and a containment spray (CS) pump. There are four independent strainers including two RHR strainers for the two ECCS trains, and two CS strainers for the two CSS trains. The SI and charging pumps both piggyback off of the RHR pump during recirculation. The pump and strainer configuration is illustrated in Figure 1.

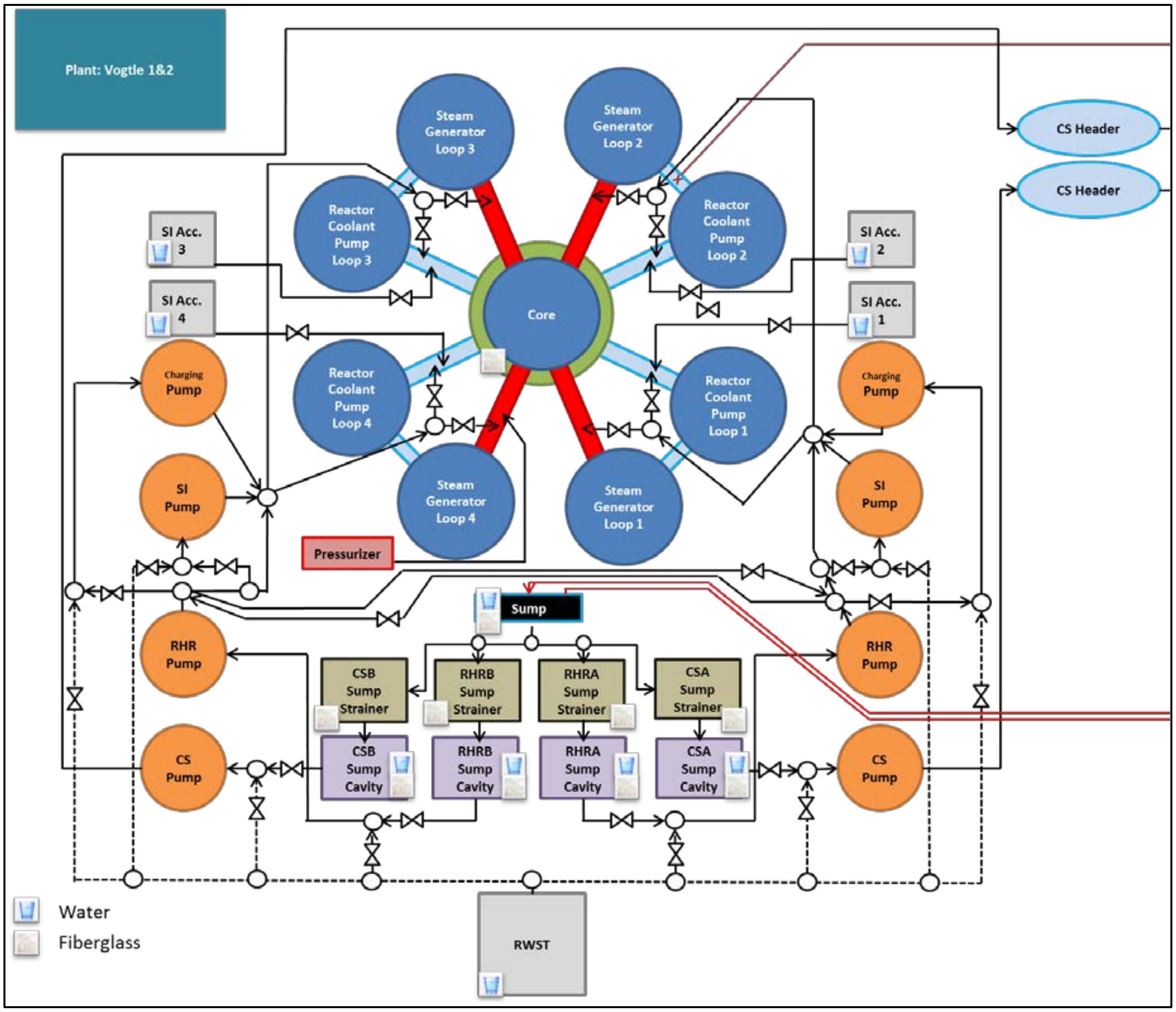

Figure 1 – Vogtle pump equipment configuration

In reality, a small break would have a higher reactor coolant system (RCS) pressure and lower break flow rate than a large break. However, to simplify the Vogtle GSI-191 evaluation, a single bounding RHR pump flow rate is used for all breaks regardless of size. Therefore, the GSI-191 effects due to random failure of the SI and charging pumps were not explicitly evaluated since these pumps piggyback off of the RHR pumps and do not change the maximum flow rate injected into the RCS. Note that if any failures are observed for small or medium breaks, the CFP values associated with single SI pump or single charging pump failures can be calculated using one of the analyzed equipment configurations described below.

However, it is important to evaluate the GSI-191 effects due to random RHR and CS pump failures. The important equipment combinations for Vogtle include:

1. No pump failures
2. Single RHR pump failure
3. Single CS pump failure

4. Single RHR pump and single CS pump failures
5. Two CS pump failures
6. Single RHR pump failure and two CS pump failures

Note that it is not necessary to evaluate two random RHR pump failures since this is assumed to automatically result in core damage without operator action regardless of the effects of debris.

The effects of pump failures are highly dependent on the plant-specific configuration and models:

- Since Vogtle has separate strainers for each of the four pumps, failure of any one pump will result in increased debris accumulation on the remaining three active strainers.
- Failure of both CS pumps at the start of the event would significantly reduce debris washdown and the total quantity of debris in the sump.
- Failure of one RHR pump prior to the start of recirculation would significantly reduce the amount of debris that penetrates the strainers and transports to core.

These are all high level effects of pump failures that are relatively easy to assess qualitatively. However, there are also some more subtle impacts that should be considered:

- Failure or early termination of both CS pumps would reduce the chemical effects from unsubmerged aluminum and concrete sources.
- Failure of any of the RHR or CS pumps prior to the start of recirculation would reduce the RWST injection flow rate and delay switchover to recirculation. Since the pool temperature is reduced by the time recirculation is initiated, failures due to degasification or loss of net positive suction head (NPSH) are less likely.

Since debris is assumed to washdown essentially immediately when containment sprays are initiated, and it is generally worse to switchover to recirculation earlier, the worst case scenario for CS pump failures is for the pump(s) to start at the beginning of the event, but fail at the start of recirculation. This maximizes debris washdown to the sump, minimizes the RWST injection time, and maximizes transport to the RHR strainers. The worst case failure timing for an RHR pump failure is also at the start of recirculation, since this minimizes the time to recirculation and maximizes transport to the other RHR strainer.

3. Pump Failure Probabilities

Table 1 (derived from the Vogtle PRA model) shows the probabilities of a single CS train failure, two CS train failures, and a single RHR train failure broken down into FTS at the beginning of the event, FTS at switchover to recirculation, FTR in the first hour, and FTR in the next 23 hours. As shown in this table, it is most likely that a single CS train or a single RHR train fails at the start of the event, although it is relatively likely that a single pump train could fail at or near the start of recirculation. Therefore, between these two points in time, the one that is worse with respect to GSI-191 effects should be used to calculate the GSI-191 conditional failure probabilities.

Table 1 – CS and RHR Train[1] Failure Probabilities

Failure	Probability	Percent Contribution[2]
1 CS Train FTS – RWST Injection	3.7E-3	65%
1 CS Train FTS – Sump Recirculation	1.1E-3	19%
1 CS Train FTR – First hour	1.9E-4	3%
1 CS Train FTR – Next 23 hours	6.6E-4	12%
Total 1 CS Train	**5.67E-3**	**99%**
2 CS Trains FTS – RWST Injection	8.5E-5	0.2%
2 CS Trains FTS – Sump Recirculation	5.17E-2	99.6%
2 CS Trains FTR – First hour	1.3E-5	0.0%
2 CS Trains FTR – Next 23 hours	1.3E-4	0.3%
Total 2 CS Train	**5.19E-2**	**99.9%**
1 RHR Train FTS – RWST Injection	4.9E-3	70%
1 RHR Train FTS – Sump Recirculation	1.1E-3	16%
1 RHR Train FTR – First hour	1.7E-4	2%
1 RHR Train FTR – Next 23 hours	7.6E-4	11%
Total 1 RHR Train	**6.98E-3**	**99%**

[1] A train failure may occur due to the associated pump failing, failure of associated valves to allow flow, or loss of electric power or cooling water to the pump.

[2] In order to limit the timing-related equipment failures to a manageable size, the pump train failures that contribute 99% of the failure probability (99.9% for 2 CS pump failures) were reviewed. Some contribution totals may exceed 99% (or 99.9%) due to rounding.

4. NARWHAL Analysis of Timing for Random Pump Failures

To evaluate the difference in pump failure timing, six NARWHAL simulations were run using the current Vogtle model:

1. Failure of CS Pump B at the start of the event
2. Failure of CS Pump B at switchover to CS recirculation
3. Failure of both CS pumps at the start of the event
4. Failure of both CS pumps at switchover to CS recirculation
5. Failure of RHR Pump B at the start of the event
6. Failure of RHR Pump B at switchover to ECCS recirculation

For all of these cases, the only failures observed were from exceeding the strainer debris limits and/or flashing.

Figure 2 and Figure 3 show the fiber accumulated on the RHR A and CS A strainers, and the CFP value as a function of break size for the various failure mechanisms when CS Pump B is assumed to fail. The graphs on the left show the data when the CS pump is assumed to fail at the start of the event, and the graphs on the right show the data when the CS pump is assumed to fail at the start of recirculation. These figures show that there is no major difference in the accumulated fiber load or CFP regardless of the random failure time for a single CS pump, although the results are slightly worse when the CS pump fails at the start of recirculation.

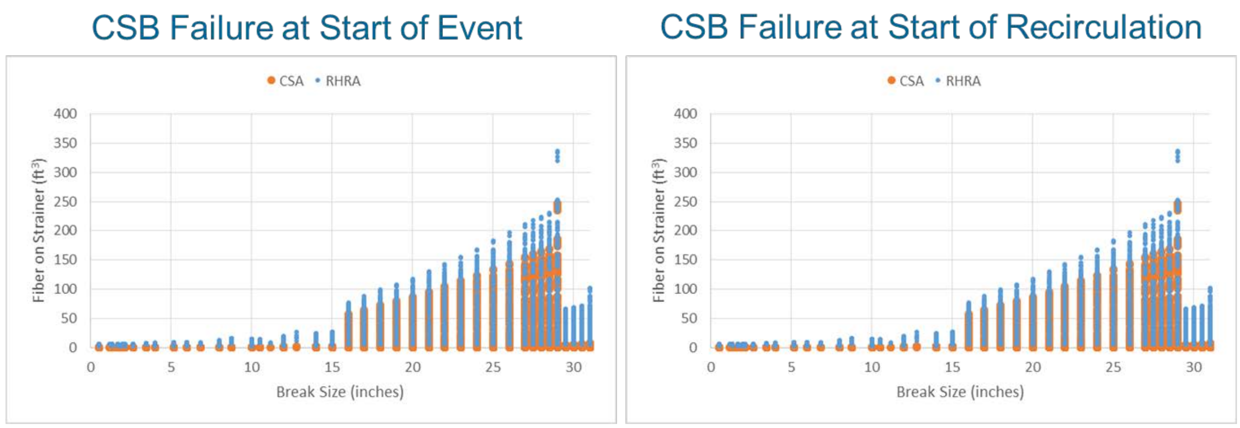

Figure 2 – Fiber Load on RHR A and CS A Strainers (Single CS Pump Failure)

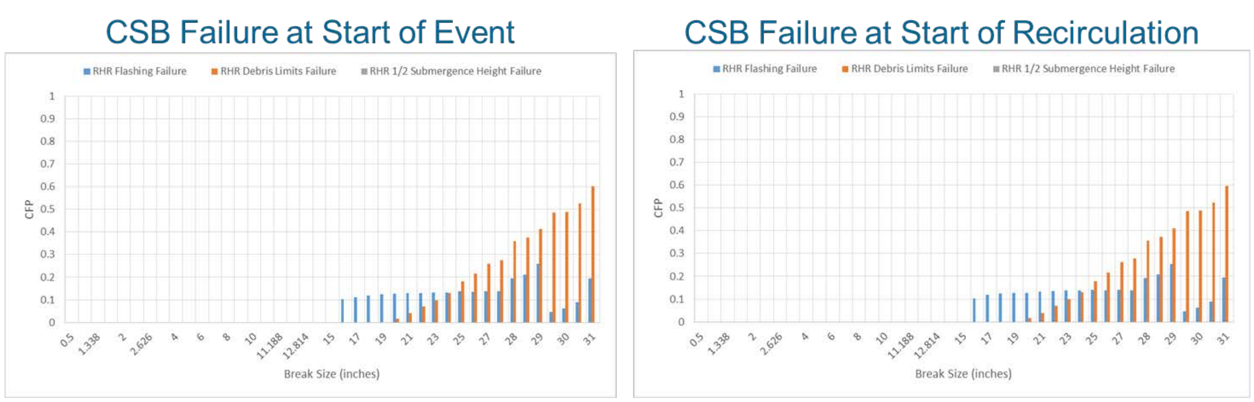

Figure 3 – Break Size-Dependent CFPs (Single CS Pump Failure)

Figure 4 and Figure 5 show similar results for the case with two CS pump failures. The time of the pump failures has a significant effect for breaks that would initiate containment sprays since failure of both pumps at the start of the event would result in significantly reduced washdown fractions compared to failure of both pumps at the start of recirculation. The additional washdown that occurs when both pumps fail at the start of recirculation results in significantly more failures due to both exceeding the debris limits and flashing as shown in Figure 5.

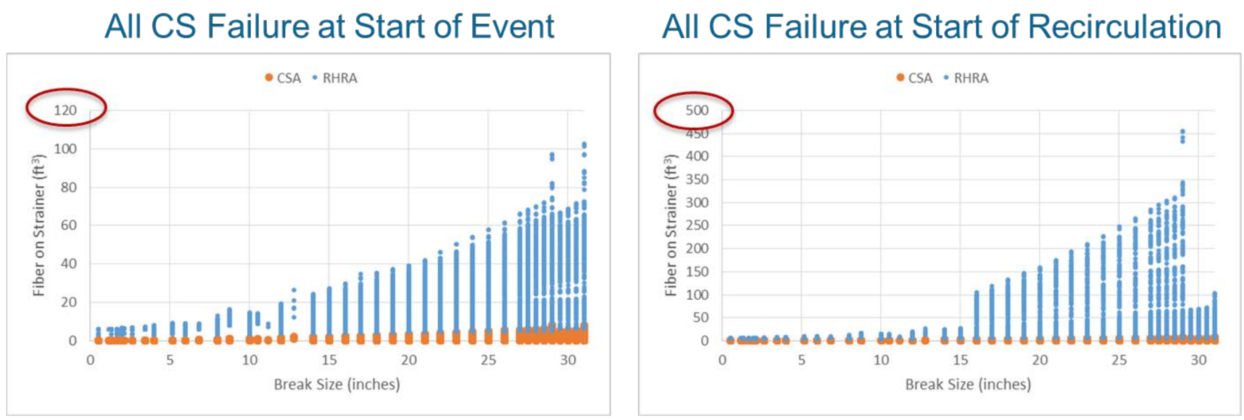

Figure 4 – Fiber Load on RHR A and CS A Strainers (Two CS Pump Failures)

Figure 5 – Break Size-Dependent CFPs (Two CS Pump Failures)

Figure 6 and Figure 7 show similar results for the case with a single RHR pump failure. The most significant difference here is the additional flashing failures shown in Figure 7 for the largest break sizes. The case with both RHR pumps running initially results in an earlier switchover to recirculation and a corresponding higher pool temperature at the start of recirculation, which leads to the additional flashing failures.

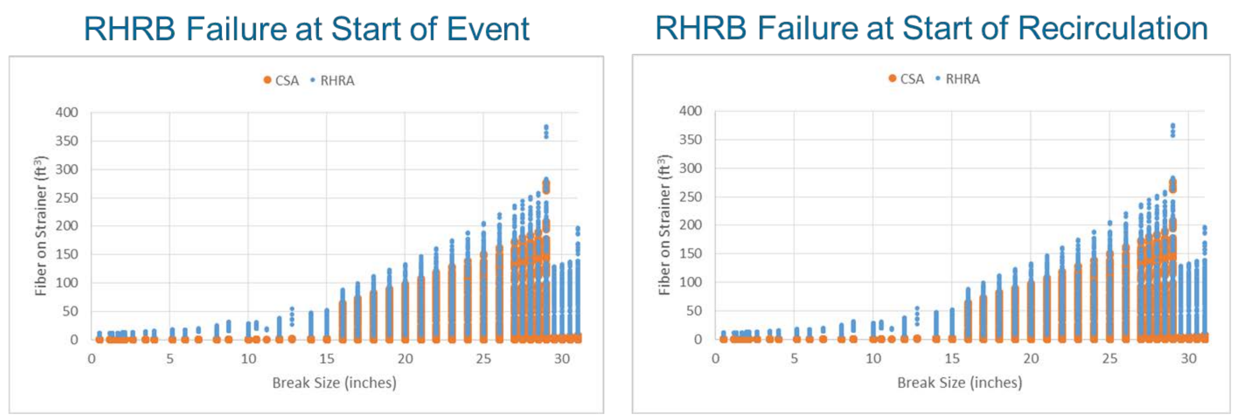

Figure 6 – Fiber Load on RHR A and CS A Strainers (Single RHR Pump Failure)

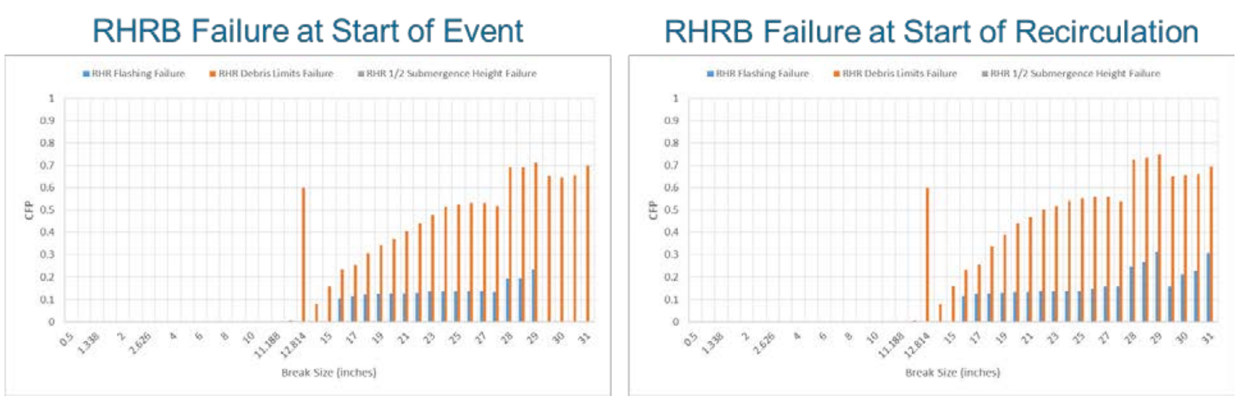

Figure 7 – Break Size-Dependent CFPs (Single RHR Pump Failure)

The CFP values corresponding to the Vogtle PRA categories (small, medium, and large LOCAs) were calculated using the built-in CFP calculator in NARWHAL Version 1.0. The required inputs are shown in Table 2 for LOCA frequency values, Table 3 for the PRA categories, and Table 4 for the size ranges within the PRA categories. Table 5 shows the resulting CFP values based on these inputs and the NARWHAL simulation results.

Table 2 – LOCA Frequency Inputs for NARWHAL CFP Calculator

Break Size	Mean NUREG-1829 Frequencies (yr^{-1})
0.5	1.9E-03
1.625	4.2E-04
3	1.6E-05
7	1.6E-06
14	2.0E-07
31	2.9E-08

Table 3 – PRA Category Inputs for NARWHAL CFP Calculator

LOCA Category	Break Size Range (in)
Small	0 - 2
Medium	2 - 6
Large	6 - 43.84

Table 4 – Size Range Inputs for NARWHAL CFP Calculator

Size Range	Size (in)
Small	0.5 - 2
Medium	2 - 6
Large(1)	6 - 15
Large(2)	15 - 25
Large(3)	25 - 43.84

Table 5 – CFP Using Log Interpolation and Mean Quantile

Case	PRA Category	Failure at Start of Injection	Failure at Start of Recirculation	Difference
Single CS Pump Failure	Small	0	0	0%
	Medium	0	0	0%
	Large	0.0120	0.0122	1.7%
Two CS Pump Failures	Small	0	0	0%
	Medium	0	0	0%
	Large	0.0069	0.0126	82.6%
Single RHR Pump Failure	Small	0	0	0%
	Medium	0	0	0%
	Large	0.0330	0.0351	6.4%

Based on NUREG-1829, the mean exceedance frequency for 6-inch breaks is 5.2E-06/year. The equipment configuration probabilities for Vogtle are approximately 91% for no pump failures, 1% for one CS pump failure, 6% for two CS pump failures, 2% for one RHR pump, and 0% for one RHR pump and one or two CS pumps. The base case CFP value (assuming no random equipment failures) is 0.0118. The overall ΔCDF can be estimated as shown below:

$$\Delta CDF_{Failure@t=0} = 5.2 \cdot 10^{-6} \cdot (0.91 \cdot 0.0118 + 0.01 \cdot 0.0120 + 0.06 \cdot 0.0069 + 0.02 \cdot 0.0330) = 6.20 \cdot 10^{-8}$$

$$\Delta CDF_{Failure@Recirc} = 5.2 \cdot 10^{-6} \cdot (0.91 \cdot 0.0118 + 0.01 \cdot 0.0122 + 0.06 \cdot 0.0126 + 0.02 \cdot 0.0351) = 6.41 \cdot 10^{-8}$$

Therefore, assuming failure of the pumps at the start of recirculation rather than at the start of the event results in a slightly higher ΔCDF value for Vogtle.

5. Conclusions

For Vogtle, the worst case failure timing for all pump failures is at the start of recirculation (earlier failures would delay the start of recirculation and later failures would result in less debris accumulation on the strainers for the pumps that do not fail). However, this has a small impact on the overall Vogtle risk (ΔCDF) results due to the relatively low probability of equipment failures and the relatively minor difference in strainer CFP for pump failures at different times (except for the case where both CS pumps fail).

In general, to address the NRC's concern, it is recommended that the worst case failure time be assumed for all random equipment failures.