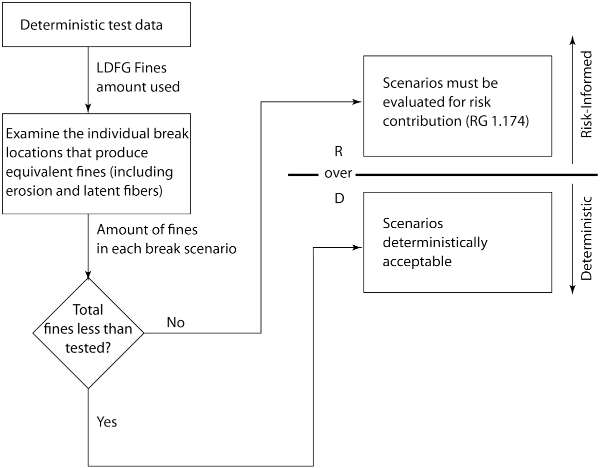
STP Risk over Deterministic (RoverD):

Test-Based Debris Risk Assessment

RoverD motivation

1. Reduce reliance on analysis
   - Correlations may have epistemic uncertainty that is difficult to quantify
   - Complexities in the engineering analysis may make results less 'transparent'
2. Reduce scope of review
   - Deterministic test data used to screen out many scenarios
   - Risk-based review scope limited to fewer scenarios
   - Use of test data consistent with (for example) fuel testing approach by establishing a limit for debris loading
3. Add confidence to conclusions regarding risk significance
   - Relegates *ALL* failures above the deterministic threshold to core damage
   - Deterministic test produces a conservatively high threshold

RoverD flow charts



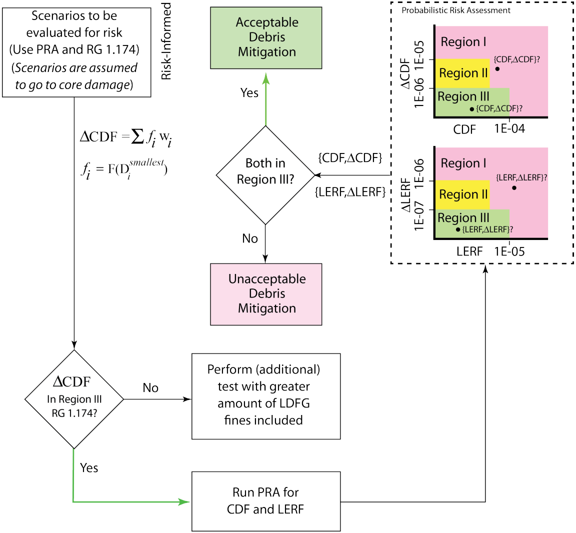
Results of break location & debris analysis

1. CASA Grande is used to exhaustively sample break size & orientation at each location and sum:
   - The amount of fine debris generated and transported
   - The amount of fine debris from latent debris
   - The amount of debris from fiber erosion
2. For each location, find out if the amount of fine fiber transported to the sump is more than the tested amount:
   - If not, record the amount created for a DEGB case for margin analysis (Deterministic category)
   - If so, record the smallest break size that exceeded the tested amount for risk analysis (Risk-informed category)

Results of break location & debris analysis

1. Two- or three-train scenarios in the deterministic and risk-informed categories (628 total Class 1 weld locations analyzed):
   - 45 locations are in the risk-informed category
   - 583 locations are in the deterministic category
2. Single train scenarios are also included in the evaluation

RoverD flow charts

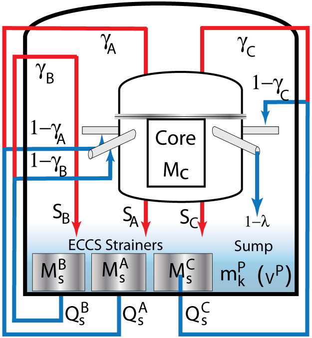


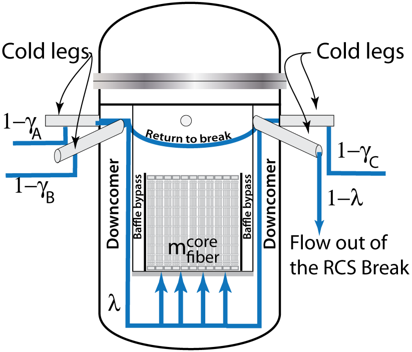
RoverD method overview

1. Use deterministic strainer test data
   - Coatings failure, chemical effects head loss, fiber loading head loss consistent with deterministic approaches
   - Note amount of fine debris from break, latent fiber, and erosion
2. Use deterministic core fiber loading data
   - Coatings failure, chemical effects head loss, fiber loading head loss consistent with deterministic approaches
   - Determine the amount of fiber (based on the amount available from above) bypassed to the core
   - Ensure the amount bypassed and collected on the core is less than the acceptable tested amount
3. Obtain the smallest break size from the CASA Grande generation and transport methodology at each weld that produces more fine fiber in the sump than in the strainer test (these are the risk-informed scenarios)
4. Derive a total failure frequency based on the smallest break sizes from NUREG 1829 to assign to ΔCDF and ensure the total ΔCDF is in Region III of RG 1.174
   - Ensure ΔLERF (using the PRA with the ΔCDF) is in Region III of RG 1.174
   - Ensure defense in depth and safety margin requirements of RG 1.174 are met

Fiber penetration uncertainty analysis

Containment flow paths and nomenclature



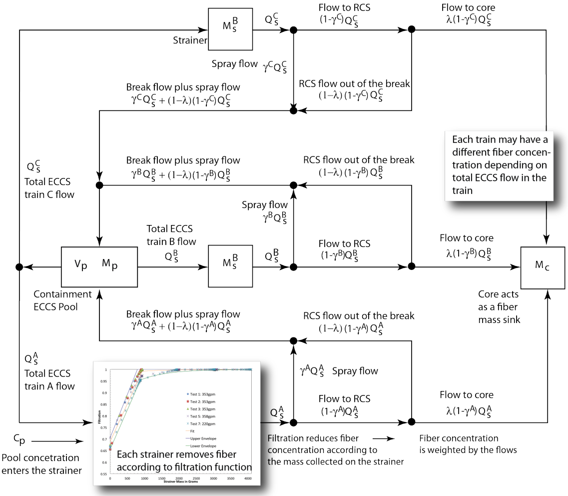


Fiber mass conservation

As showing the previous slide, the fiber mass is conserved at three locations, the ECCS sump pool, the strainers, and the core. The flow network that supports the mass conservation is shown on the following slide and can be described with time-dependent mass conservation equations shown in further slides.

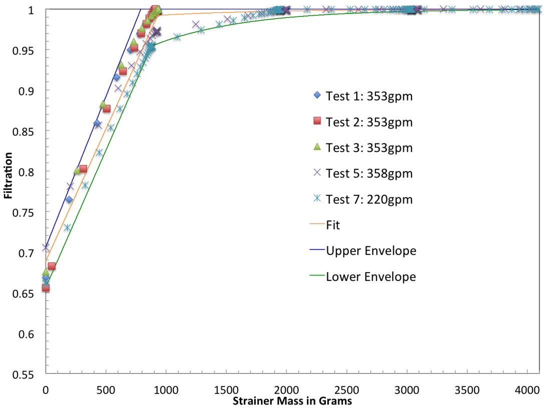
Because of the filtration function associated with the strainers' ability to capture and retain debris, the conservation equations are non-linear. The filtration function shown in graphical form as well.

Fiber mass conservation



Fiber penetration measured data

The filtration efficiency was measured for a prototypical module and the data are shown plotted against accumulated strainer fiber with bounds of uncertainty



Fiber mass conservation

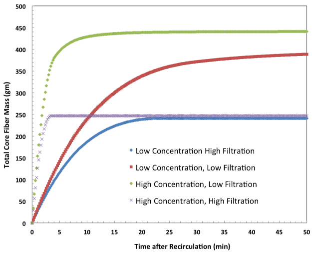
Fiber mass conservation equations (based on previous figure). Equations are implemented in a Python routine that uses "lsoda" from the scipy.integrate.ode class library.

$$\begin{aligned}
\frac{d}{dt}M_s^k(t) =& Q_s^k(t)C_p(t)f(M_s^k(t)), \\
\frac{d}{dt}M_c(t) =& Q_c(t)C_p(t)\frac{\sum_k \left[\left(1-f(M_s^k(t))\right)\left(1-\gamma^k\right)Q_s^k(t)\right]}{\sum_k\left[(1-\gamma^k)Q_s^k(t)\right]}, \\
0 =& \frac{d}{dt}M_p(t) + \frac{d}{dt}\sum_k M_s^k(t) + \frac{d}{dt}M_c(t).
\end{aligned}$$

Fiber penetration sensitivity

Upper lower and limits of fiber concentration were tested at the high bound of filtration uncertainty and low bound of filtration uncertainty. Uncertainty calculations show that the maximum (15 gm/FA) will not be reached $(441\ gm)/(193\ FA) \ll 15$ gm/FA

$C_p(t=0)$ gm/GAL	**lower**: $f(M_s^k(t=150 \text{ min.}))$	**upper**: $f(M_s^k(t=150 \text{ min.}))$
High (0.832)	441	247
Low (0.158)	400	241



ΔCDF

1. RoverD screening stage: For each weld location with a break producing more fine fiber in the sump than tested, record the smallest break size (note that some locations may not have a scenario exceeding the tested fiber fines)
2. Determine ΔCDF from NUREG 1829 LOCA frequencies based on the following principles:
   - In the limiting case for which every weld and every break above (smallest) diameter x is considered "bad" (that is, at that break size, more fines come to the sump than were tested), the break frequency should equal to the NUREG 1829 exceedence frequency at x,
   - RoverD should depend on the number of welds in the RoverD risk-informed category. In particular, frequency should increase if welds are added to the set of "bad" welds.
3. We refer to this as "top-down" adherence to NUREG 1829 published frequencies

Plant ΔCDF analysis (strainer)

For any weld i in pipe a category (indexed by n) with a smallest break size D_i^{small} the frequency for all pipe categories, each having TW_n total locations:

$$F(D_i^{small}) = \frac{f(D_i^{small})}{TW_{Cat(D_i^{small})}}.$$

$Cat(D_i^{small})$ is the pipe category corresponding to D_i^{small}. For example, if Category 1 is 1-inch pipes and category 2 is 2-inch pipes, then for a break of 1.75in, $Cat(1.75in) = 2$.

If R_n is the set of all welds in the risk-informed category associated with pipes of category n then, the frequency of unacceptable events due to weld breaks in pipes of category n can be written as:

$$\sum_{i \in R_n} F(D_i^{small}).$$

The overall frequency (Φ) of events in the risk-informed category for a plant state is given by:

$$\Phi = \sum_{n=1}^{NP} \sum_{i \in R_n}^{I} F(D_i^{small}).$$

Plant ΔCDF - plant states

Example of two plant states; two or more trains in operation and; one train operation:

If f_2 is the success frequency for two or more trains operating and f_1 is the success frequency for single train operation, the total frequency, $\hat{\Phi}$, for both operating states:

$$w_j = \frac{f_j}{\sum_j f_j};\ j = 1, 2,$$

$$\Phi_j = w_j \sum_{n=1}^{NP} \sum_{i \in R_n}^{I} F(D_i^{small}),$$

$$\hat{\Phi} = \sum_j \Phi_j.$$

ΔCDF uncertainty analysis

ΔCDF was checked at all quantiles for Geometric aggregation and Arithmetic aggregation given in the NUREG 1829 tables. In addition, the frequency at DEGB-only for the same quantiles was assessed

			Continuum Break Model			
Quantile	Case 1 GM	Case 1 AM	Case 2 GM	Case 2 AM	$\hat{\Phi}$ (GM)	$\hat{\Phi}$ (AM)
5^{th}	2.64E-10	6.47E-09	3.68E-09	2.36E-08	3.08E-10	6.69E-09
50^{th}	7.50E-09	1.68E-07	8.30E-08	4.92E-07	8.47E-09	1.72E-07
95^{th}	3.43E-07	4.79E-06	1.81E-06	1.24E-05	3.62E-07	*4.89E-06*
Mean	1.17E-07	1.56E-06	5.10E-07	3.93E-06	*1.22E-07*	*1.59E-06*
			DEGB-Only Model			
5^{th}	9.83E-11	8.18E-09	1.14E-09	1.66E-08	1.12E-10	8.29E-09
50^{th}	2.86E-09	2.07E-07	2.64E-08	3.90E-07	3.16E-09	2.09E-07
95^{th}	1.47E-07	7.06E-06	6.85E-07	1.21E-05	1.54E-07	*7.13E-06*
Mean	5.12E-08	2.06E-06	2.03E-07	3.61E-06	*5.32E-08*	*2.08E-06*

Plant $\Delta LERF$ analysis (strainer)

1. The STP RCFCs are capable of maintaining containment cooling without dependency on ECCS
2. Independence of containment failure from the concerns raised in GSI-191 allow an accurate estimate of ΔLERF based on ΔCDF:

$$\Delta LERF = LERF_{MOR}\left(\frac{\Delta CDF}{CDF_{MOR}}\right)$$

   where values of CDF_{MOR} and $LERF_{MOR}$ are the average values obtained from the PRA model of record
3. IF $\Delta LERF$ is in Region III of RG 1.174, THEN the (strainer) risk related to $\Delta LERF$ is acceptable

Plant $\Delta LERF$ analysis results

The ΔLERF values for the geometric mean model for both continuum break and DEGB-only assessments are substantially below 1E-07. However, the values for the arithmetic mean are higher as expected due to the very high estimates that result from the arithmetic mean aggregation in NUREG-1829.

Model	ΔLERF using $\hat{\Phi}$ (GM)	ΔLERF using $\hat{\Phi}$ (AM)
Continuum break model	*7.67E-09*	9.99E-08
DEGB-only model	*3.34E-09*	*1.31E-07*

In-vessel analysis

1. The risk due to core loading effects needs to be assessed against strainer penetration test data
   - Cooling effectiveness for fiber blockage
   - Boron precipitation for blockage from the lower plenum
2. Thermal-hydraulic analysis for adequate cooling for all hot-leg breaks and small cold leg breaks under bounding blockage scenarios
3. At the amount of the fiber assumed in the strainer test, the amount that penetrates the strainer and arrives in-vessel is less than 15 gm/FA (WCAP-16793)

RoverD analysis results

1. There are 45 locations (welds) in the risk-informed category and with the exception of one, all are in the RCS loop piping
2. The maximum frequency (smallest break size that exceeds the tested amount of fiber) is a DEGB of the 16 inch surge line
3. In-vessel fiber loading is not exceeded for any scenarios equal to, or less than, the tested fiber amount using bounds of the data measurements
4. All welds that exceed the tested amount of fiber have been either mitigated or replaced
5. All results using quantiles from NUREG 1829 geometric mean aggregation, both the RoverD continuum break model or DEGB-only break model ΔCDF are less than 1E-06 (RG 1.174 Region III)
6. Using quantiles from NUREG 1829 arithmetic aggregation, the mean and 95^{th} quantiles exceed 1E-06 (RG 1.174 Region II)