Comparison of Non-Standard Simulation Methods for Performing Extremely Low Probability Assessments

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Context: Leak Before Break (LBB)

- **In 1985, the NRC proposed a Modification of General Design Criterion (GDC) 4 Requirements for Protection of Dynamic Effects of Postulated Pipe Ruptures in 10 CFR Part 50.**
  - The proposed amendments would modify GDC 4 to allow for the demonstration of piping analyses to serve as a basis for excluding consideration of dynamic effects associated with certain pipe ruptures.
  - These analyses constitute what is commonly referred to as the leak-before-break (LBB) concept.
- **The final rule requires a deterministic fracture mechanics analysis**
- **The supporting safety analysis must demonstrate that a substantial range of stable pipe crack sizes can exist with detectable leaks**
- **That the probability of fluid systems piping rupture is extremely low under conditions consistent with the design basis for the piping.**
- **The definition of “extremely low probability” of pipe rupture is given on the order of 10^{-6} per reactor year when all pipe rupture locations are considered.**
- **This probability includes the probability of an initiating event occurring such as an earthquake or an accident.**

Context

- **Presently, the Standard Review Plan (SRP) 3.6.3 does not allow for assessment of piping systems with active degradation mechanisms, such as Primary Water Stress Corrosion Cracking (PWSCC), which has occurred in systems that have previously been granted LBB exemptions**
- **A long-term goal has been to develop a modular-based, probabilistic fracture mechanics code capable of determining the probability of rupture for Reactor Coolant System (RCS) components.**
  - The need for this modular-based code is strongly driven by the need to quantitatively assess an LBB-approved piping system's compliance with GDC-4 on an interval (time) basis.
  - Based on the terminology of GDC-4, this program and code is entitled Extremely Low Probability of Rupture (xLPR).

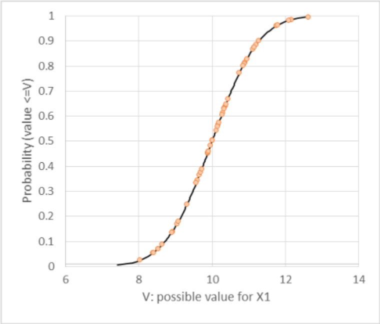
Current Status of PFM Codes

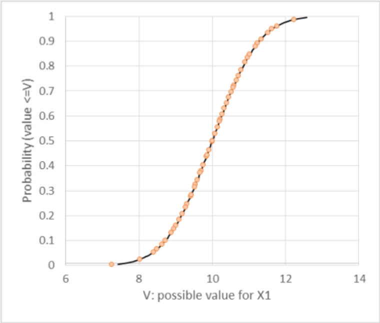
- **xLPR 2.0 has been completed**
  - It employs the GoldSim® platform for the probabilistic calculations
  - It is a fully QA'ed code for use in regulatory assessments
  - Because of this overhead each simulation, which covers the entire pipeline life, takes approximately 4 seconds
- **Because the ability to comply with GDC 4 implies, for a simple random sampling method, 5 to 10 million simulations would be needed alternative strategies have been developed**
  - Simple random sampling
  - Latin Hypercube Sampling (LHS)
  - Importance Sampling
  - Adaptive Importance sampling *
- **The focus of this paper is on the adaptive importance sampling**

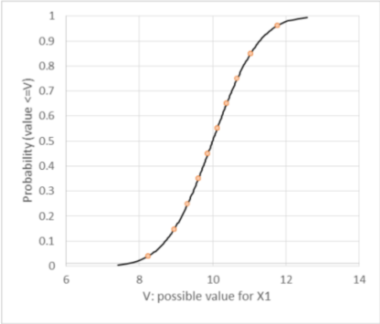
**Details of these topics can be found in PSAM 103: "Efficient sampling strategies to estimate extremely low probabilities", C. Sallaberry, R. Kurth, F. Brust, E. Twombly*

An Overview of DPD and LHS

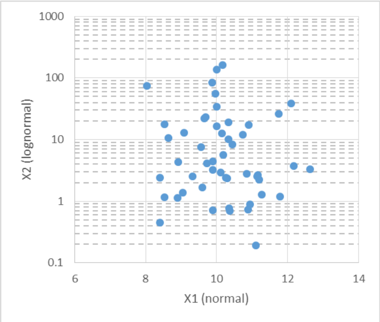
SRS | **LHS** | **DPD**

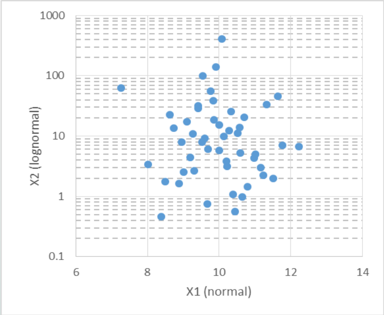


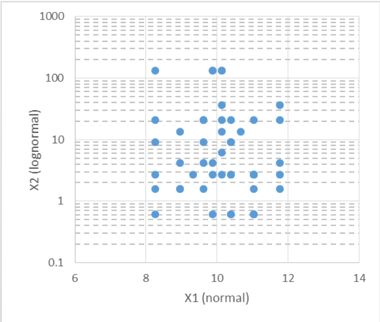




Densely cover of each input with LHS. Helps if extreme value are needed







Better multi-dimensional coverage for DPD. Helps in conjoint influence

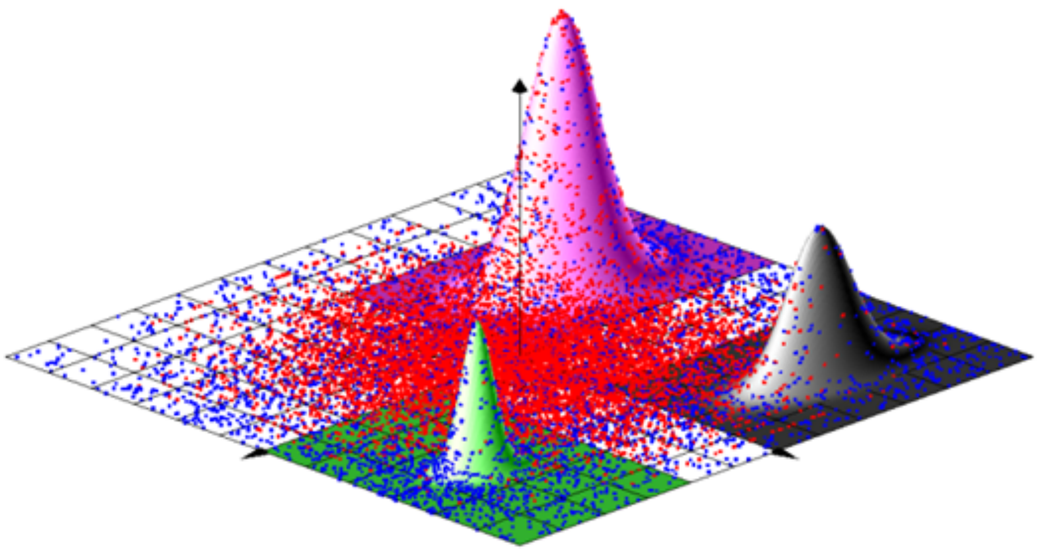
Sample problems

- **The details of the methodology, which is labeled GRC (Golden Rule Clustering since the method is based on the Fibonacci sequence)**
- **Instead we illustrate the application to two problems:**
  - A theoretical problem to illustrate the GRC method
  - An analysis of the a piping problem where
    - Time to first crack initiation
    - Time to first leakage
    - Time of pipe failure

    are calculated

Adaptive Sampling GRC: Theoretical PRoblem

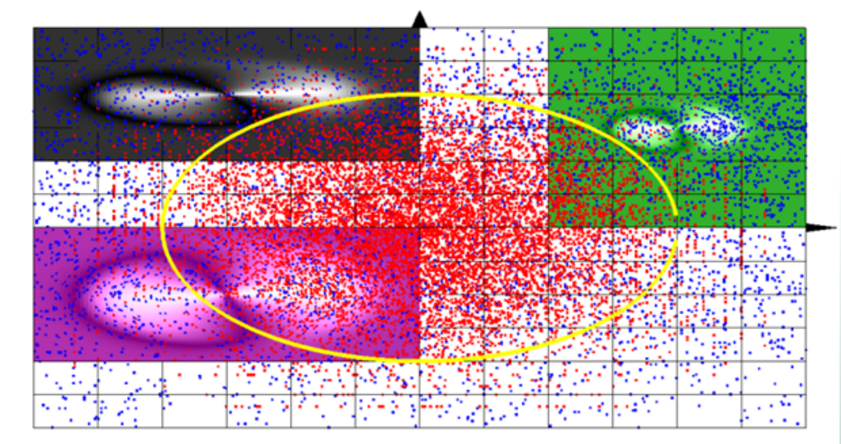
- **GRC method is**
  - Variance reduction technique
  - Purpose is to oversample the region of interest and under-sample the regions with no events.

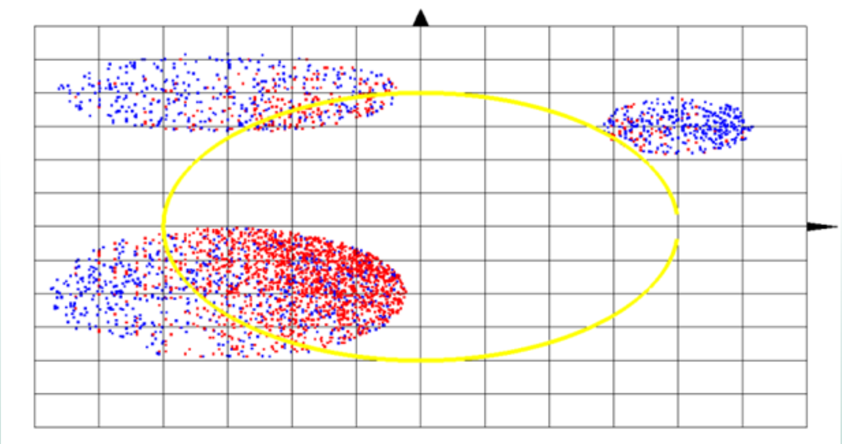


  - In the theoretical problem Three areas of interest, more than two standard deviations from the centroid, need to have their probability of occurrence estimated

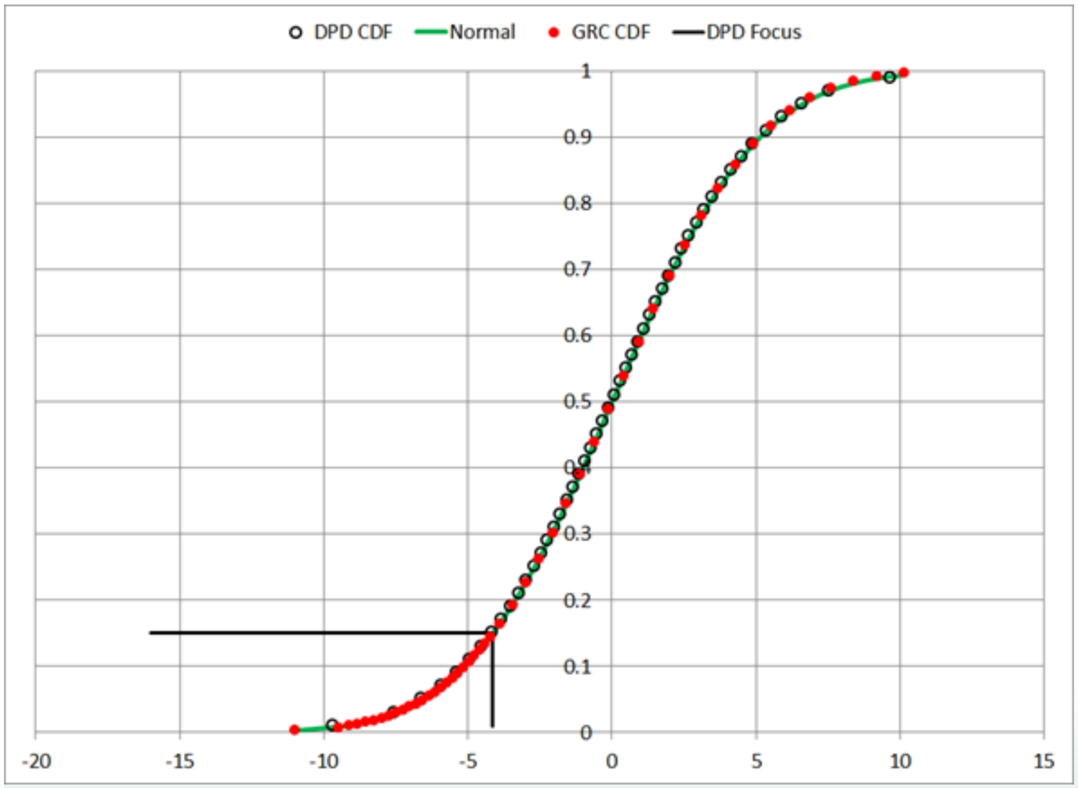
GRC Adaptive Sampling

- For the theoretical problem we wish to find the peaks
- Adaptive sampling focuses the inputs on the areas where the response is "of interest"
- In the picture on the bottom left the 3D surface is projected onto the X-Y plane
  - Red points are SRS
  - Blue points are adaptive
- On the bottom right the values below a lower limit are removed



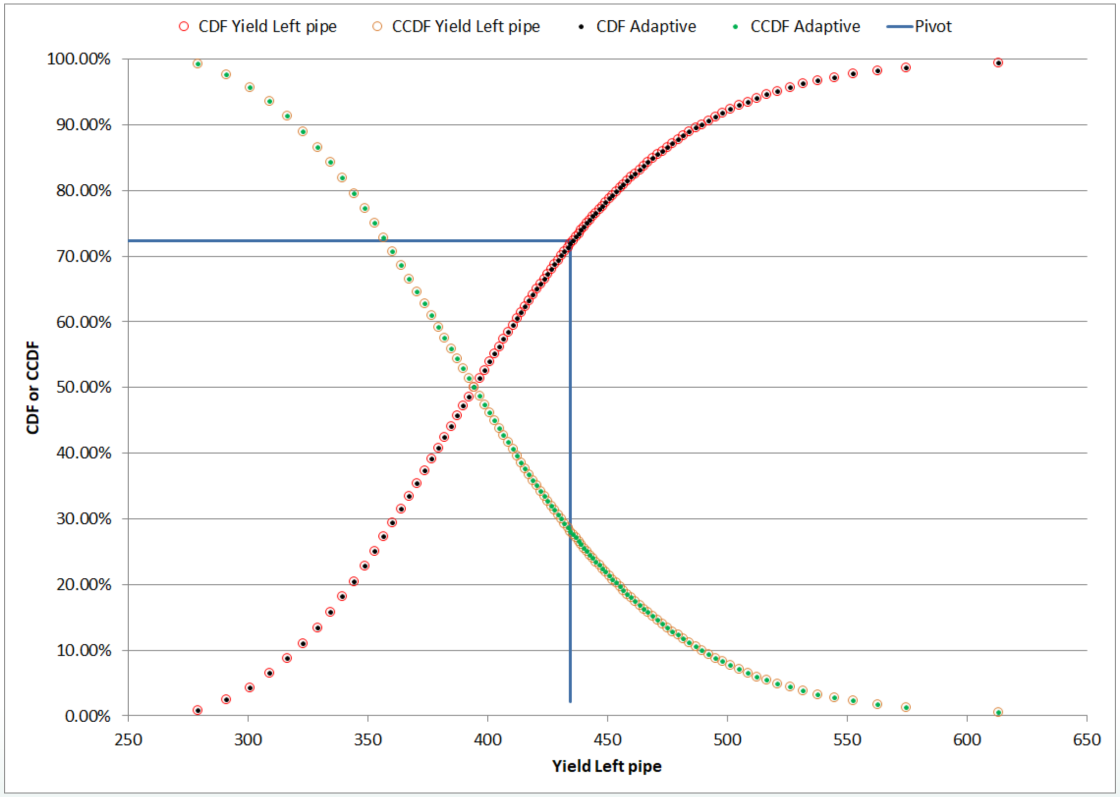


Focusing the Input Sampling



- A comparison of the normal distribution theoretical CDF, the DPD representation, and the GRC representation are shown to the left
- Both the DPD and GRC lie on the theoretical line. A good start.
- The DPD points, shown as an open black circle, are uniformly spaced along the x axis and then moved to the conditional mean value
- The GRC points depend on the value of the input when a response of interest is found
    - For this sample the input was at ~15% value
    - 50% of the GRC points are placed below this value, the remainder above

Focusing the Input Sampling

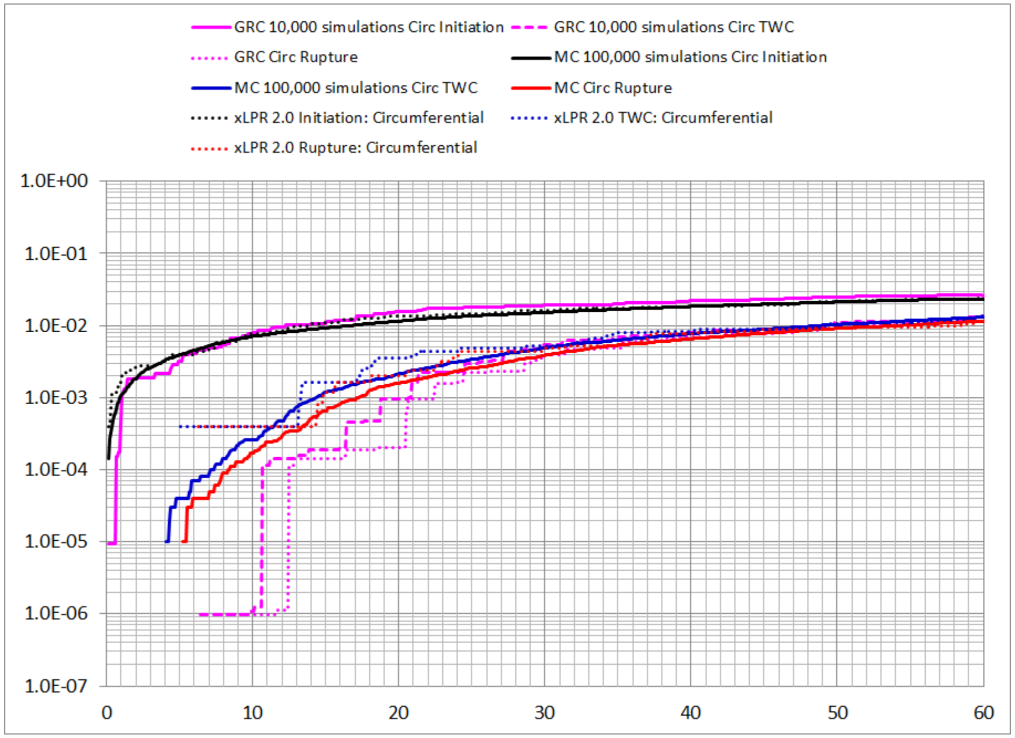


- The CDF and CCDF are shown for the yield strength
- The "pivot" point is near the mean
- The points are the DPD values after the adaptive algorithm has been applied
- Clearly there will be more samples taken near the pivot point when the sampling is based on the simple random sampling of the interval not on the value of the CDF
- The DPD PDF are used to find the weighting value for the response

Application of the GRC method to Nuclear Piping

- **Because the focus of GRC 4 is on an *extremely low probability of rupture* three quantities are examined**
  - Time to first crack initiation
  - Time to first leakage
  - Time of rupture
- **Because of the QA requirements of xLPR the GoldSim® platform cannot implement the GRC method**
- **Therefore, a preprocessor to xLPR has been written which implements the GRC method**
- **This preprocessor is call PROMETHEUS and has been released as a beta version, PROMETHEUS 1.0**

Comparison of results



- A comparison of the results for a probabilistic analysis is shown
  - 2,500 simulation using SRS with LHS xLPR 2.0 (dotted line)
  - 100,000 SRS sample (dashed line)
  - 2,500 GRC sample (solid line)
- All 3 methods converge to sample 60 year result

- **GRC result estimates the 100,000 SRS result through the entire range**
  - The uncertainty is larger
  - The ability to estimate the 1 in 100,000 point allows the xLPR code to focus sampling using standard importance sampling methods

Conclusion

- **The use of a variety of sampling methods have been studied to allow efficient analysis schemes to be developed to**
  - Estimate extremely low probabilities of a variety of events
  - Identify the areas of the input space which lead the events of interest
- **Much smaller sample sizes can be used to identify areas of interest for focused sampling**
- **Comparison of the methods shows that**
  - The SRS, LHS, and DPD methods all lead to statistically equivalent mean results
  - The GRC method finds very low probability events more efficiently but the cost is larger uncertainty
- **The use of the GRC method allows less efficient (based on the necessary number of simulations) to be focused on the regions of the input space leading to rare events**
- **This focus increases the efficiency of these codes**