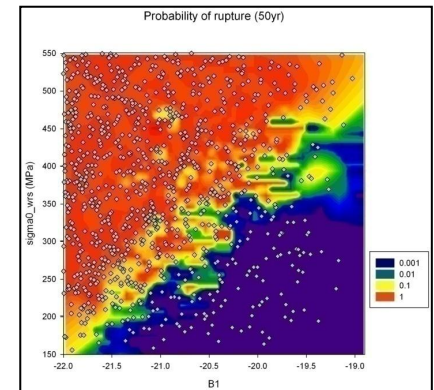
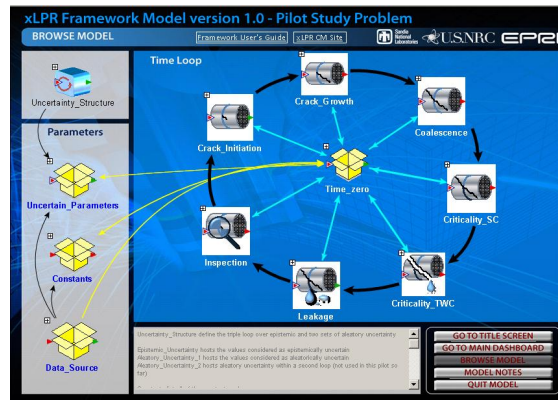
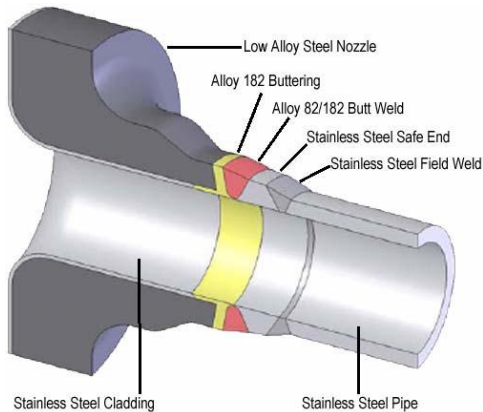


Uncertainty and Parameter Sensitivity Analyses for the U.S. NRC: Understanding and Verification of the Extremely Low Probability of Rupture (xLPR) in Reactor Primary System Pressure Piping

Patrick D. Mattie⁺, Cédric J. Sallaberry⁺, David L. Rudland^{*} and Jon C. Helton⁺

⁺: Sandia National Laboratories

^{*}: U.S. Nuclear Regulatory Commission



ASME 2012 Verification & Validation Symposium
May 2-4, 2012 . Las Vegas, NV

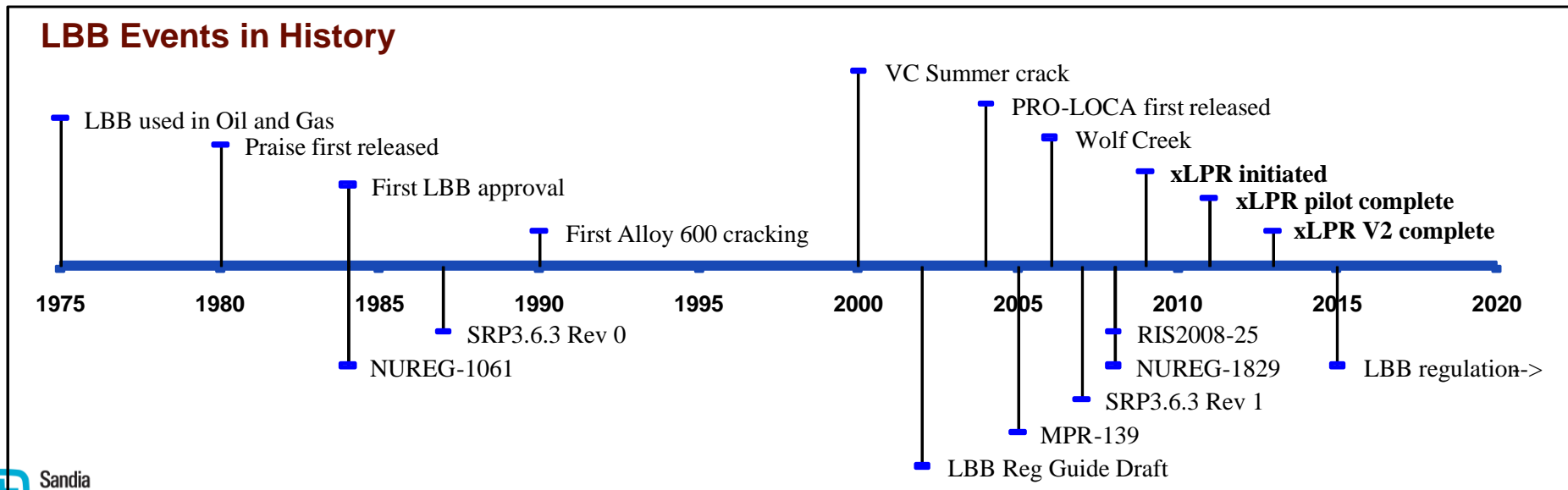
Extremely Low Probability of Rupture Rationale

- 10CFR50 Appendix A GDC-4 allows local dynamic effects of pipe ruptures to be excluded from design basis if pipe ruptures have extremely low probability of occurrence
- Local dynamic effects include pipe whipping and discharging fluids. Effect is to eliminate need for whip restraints and jet impingement shields
- Conservative flaw tolerance analyses developed and incorporated in SRP3.6.3 to demonstrate leak-before-break (LBB) and satisfy GDC-4

Extremely Low Probability of Rupture

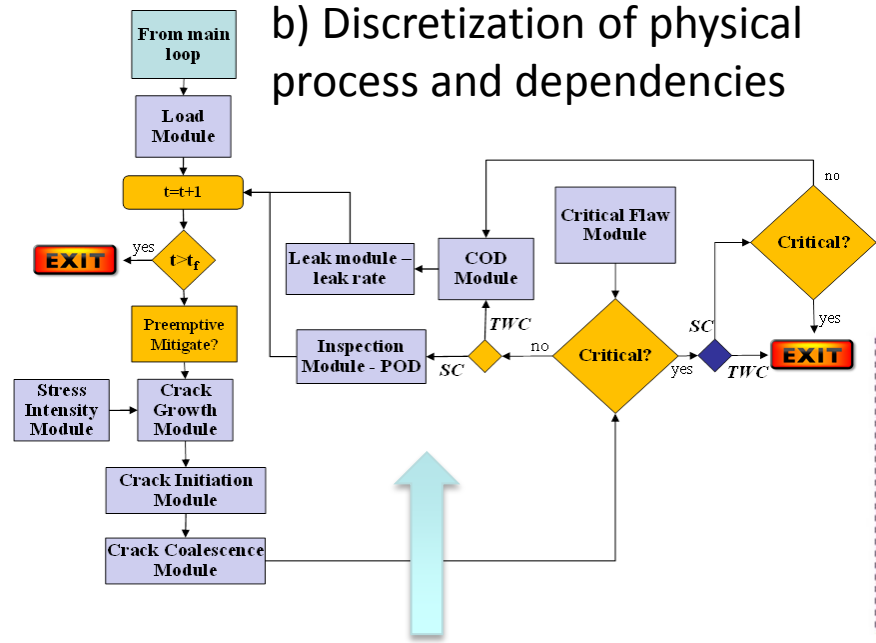
LBB Historical Review

- PWRs have LBB approvals for reactor coolant loop (RCL) piping
 - Some PWRs have LBB for RCL branch piping
- SRP 3.6.3 stipulates no active degradation. PWSCC is active in LBB approved lines
- Qualitative: mitigations and inspections – Short Term
- Quantitative: probabilistic evaluation – Long Term

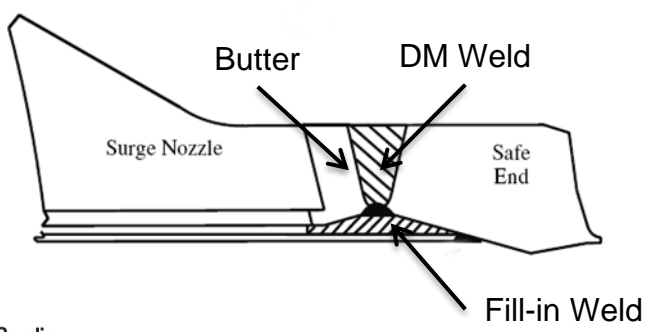


Extremely Low Probability of Rupture General Description

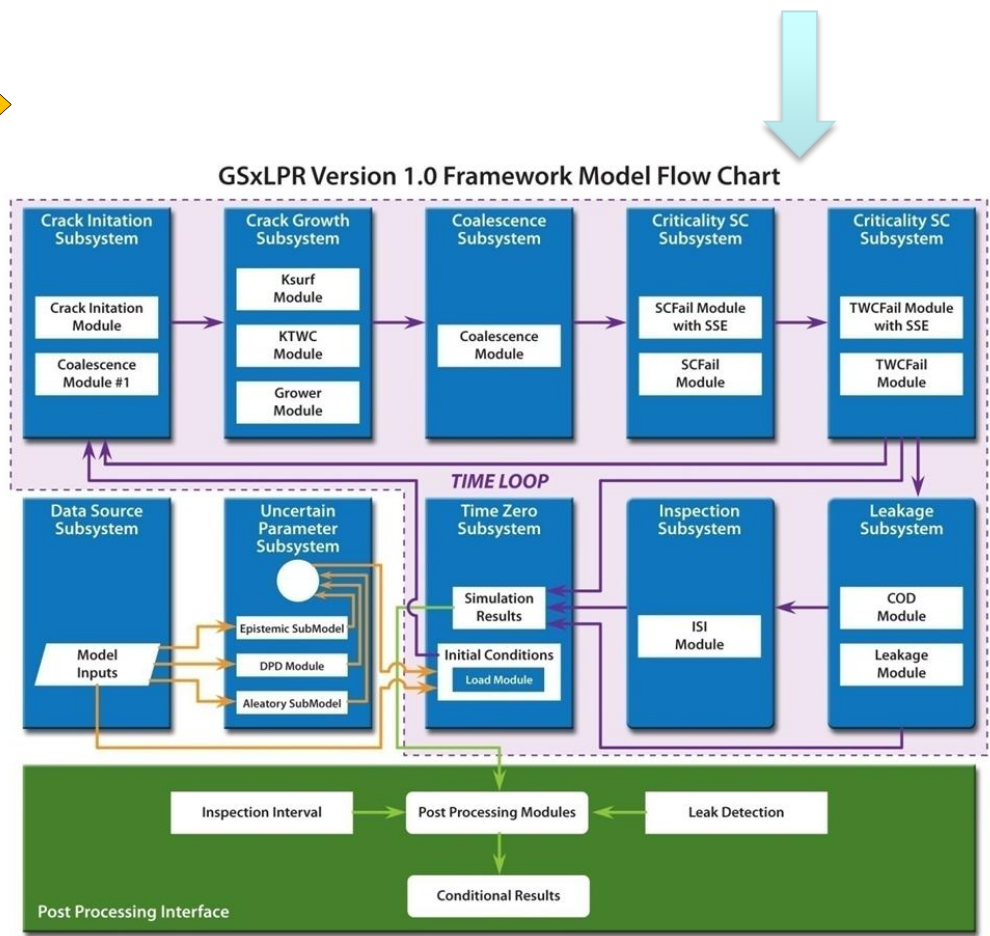
b) Discretization of physical process and dependencies



a) Surge Nozzle Problem



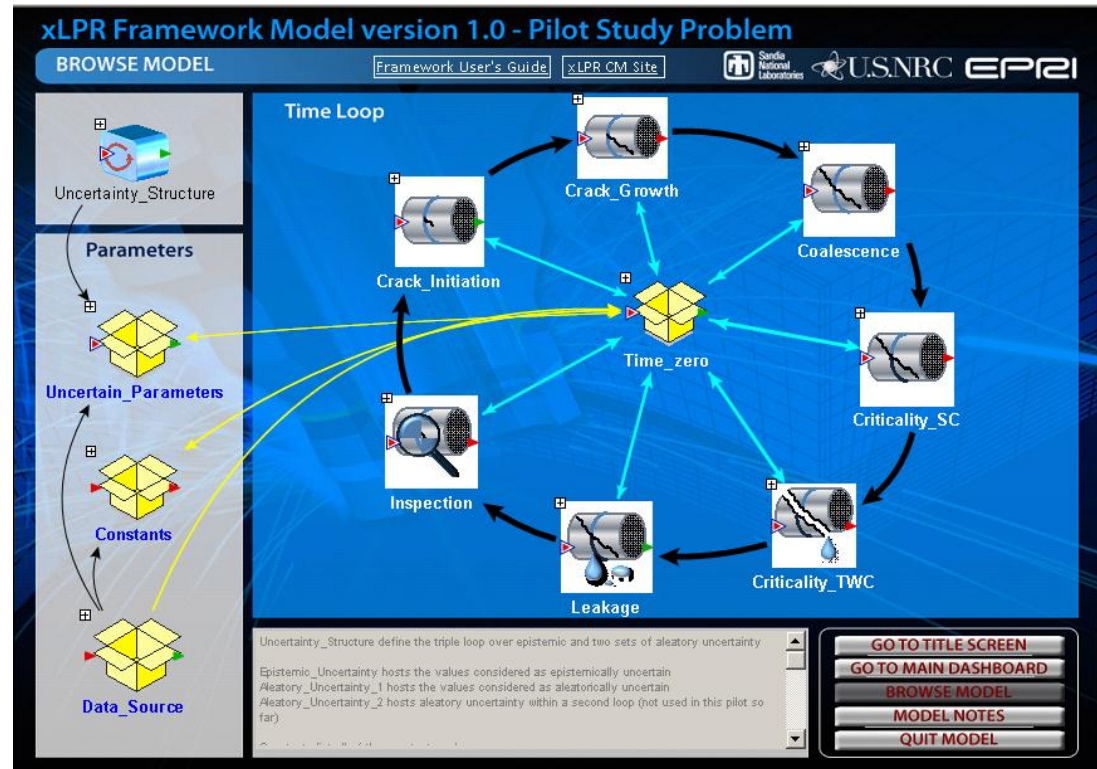
c) Translation to computational and code architecture



Extremely Low Probability of Rupture Numerical Implementation

- At each time step, the framework calls each appropriate module, following a loop:

- checking for new crack
- growing existing cracks
- coalescing cracks
- checking for criticality of surface cracks (SC)
- checking for criticality of through wall cracks (TWC)
- estimating potential leak rate
- Estimating probability of finding a crack through inspection



xLPR project Team Members

Computational Group

David Rudland – U.S. NRC
 Bruce Bishop – Westinghouse
 Nathan Palm – Westinghouse
 Patrick Mattie – Sandia National Laboratories
 Cedric Sallaberry – Sandia National Laboratories
 Don Kalinich – Sandia National Laboratories
 Jon Helton – Sandia National Laboratories
 Hilda Klasky – Oak Ridge National Laboratory
 Paul Williams – Oak Ridge National Laboratory
 Robert Kurth – Emc²
 Scott Sanborn – Pacific Northwest National Laboratory
 David Harris – Structural Integrity Associates
 Dilip Dedhia – Structural Integrity Associates
 Anitha Gubbi – Structural Integrity Associates

Inputs Group

Eric Focht – U.S. NRC
 Mark Kirk – U.S. NRC
 Guy DeBoo – Exelon
 Paul Scott – Battelle
 Ashok Nana – AREVA NP Inc.
 John Broussard – Dominion Engineering
 Nathan Palm – Westinghouse
 Pat Heasler – Pacific Northwest National Laboratory
 Gery Wilkowsky – Emc²

Acceptance Group

Mark Kirk – U.S. NRC
 Glenn White – Dominion Engineering Inc.
 Aladar Csontos – U.S. NRC
 Robert Hardies – U.S. NRC
 David Rudland – U.S. NRC
 Bruce Bishop – Westinghouse
 Robert Tregoning – U.S. NRC

Models Group

Marjorie Erickson – PEAI
 Gary Stevens – U.S. NRC
 Howard Rathbun – U.S. NRC
 David Rudland – U.S. NRC
 John Broussard – Dominion Engineering
 Glenn White – Dominion Engineering
 Do-Jun Shim – Emc²
 Gery Wilkowsky – Emc²
 Bud Brust – Emc²
 Cliff Lange – Structural Integrity Associates
 Dave Harris – Structural Integrity Associates
 Steve Fyfitch – AREVA NP Inc.
 Ashok Nana – AREVA NP Inc.
 Rick Olson – Battelle
 Darrell Paul – Battelle
 Lee Fredette – Battelle
 Craig Harrington – EPRI
 Gabriel Ileybare – EPRI
 Frank Ammirato – EPRI
 Patrick Heasler – Pacific Northwest National Laboratory
 Bruce Bishop – Westinghouse

Program Integration Board

Craig Harrington – EPRI
 Aladar Csontos – U.S. NRC
 Robert Hardies – U.S. NRC
 Denny Weakland – Ironwood Consulting
 David Rudland – U.S. NRC
 Bruce Bishop – Westinghouse
 Eric Focht – U.S. NRC
 Guy DeBoo – Exelon
 Marjorie Erickson – PEAI
 Gary Stevens – U.S. NRC
 Howard Rathbun – U.S. NRC
 Mark Kirk – U.S. NRC
 Glenn White – Dominion Engineering Inc.



Model description

- The xLPR model considers 36 uncertain input variables and 51 constants
- The model architecture has capability to separate aleatory and epistemic uncertainty
- Each input variable can be optionally designated as aleatory or epistemic
- The main purpose of the code is to estimate extremely low probability of events (10^{-6} or lower)

Application and use of Uncertainty Analysis (UA) and sensitivity Analysis (SA)

Beyond their traditional use in any complex system analysis, Uncertainty Analysis (UA) and Sensitivity Analysis (SA) have been valuable in two specific domains:

- Verification and Validation of xLPR model at a system level
- Selection of region of the input hyperspace driving the extremely low probabilities

Uncertainty and Sensitivity as a V&V tool

V&V at module level vs. system level

- **Traditional Verification and Validation can be applied separately to test each module composing the complex system:**
 - For most of the modules considered, data and/or other code exists allowing to check results generated within a given input set
 - The physics may be simple enough so that the effect of each input variable is known upfront
- **Usually this approach cannot be applied at the system level if model is too complex**
 - Theoretical results are usually not known (that's why the complex system are developed).
 - Few events available to compare, including extensive field data or laboratory testing – and information may be proprietary
 - Some positive effect in one module may become negative in another module – some input variables may have different or opposite effect depending the module they are used in

Uncertainty and Sensitivity as a V&V tool

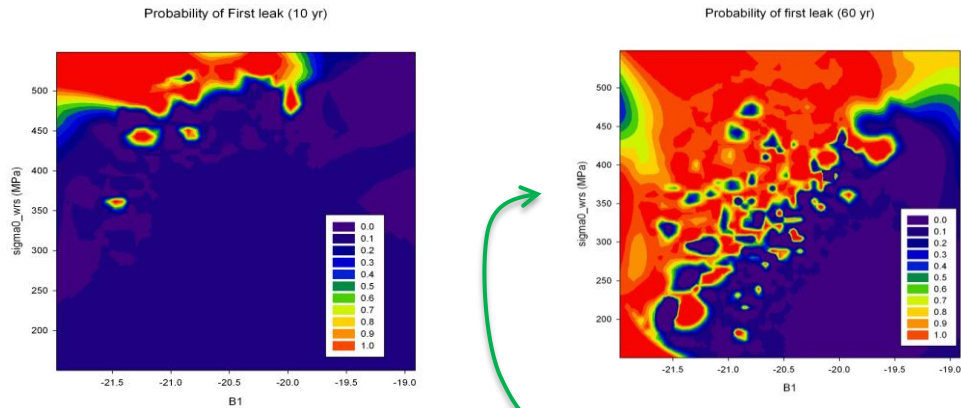
V&V at the system level

- Uncertainty analysis and Sensitivity Analysis can be considered as powerful tools when studied model is too complex:
 - They can inform about the effect of single or conjoint variables
 - Sampling allows to test the models in variety of conditions that may not have been considered upfront, testing on the validity of modules in extreme cases and also validity of input set considered (e.g. there may be nonphysical unrealistic combinations)
 - Scatterplots, coefficients of determination, sign and importance of regression coefficients (relative to each other) are indicators that experts can look and study to check whether the system performs as expected or differently, which may help tracking software or model implementation errors and validity of modeling assumptions.

Use of Sensitivity Analysis to check xLPR at system level (1)

Example of influence of two parameters (sigma0_wrs and B1) on the probability of having a through wall crack (TWC)

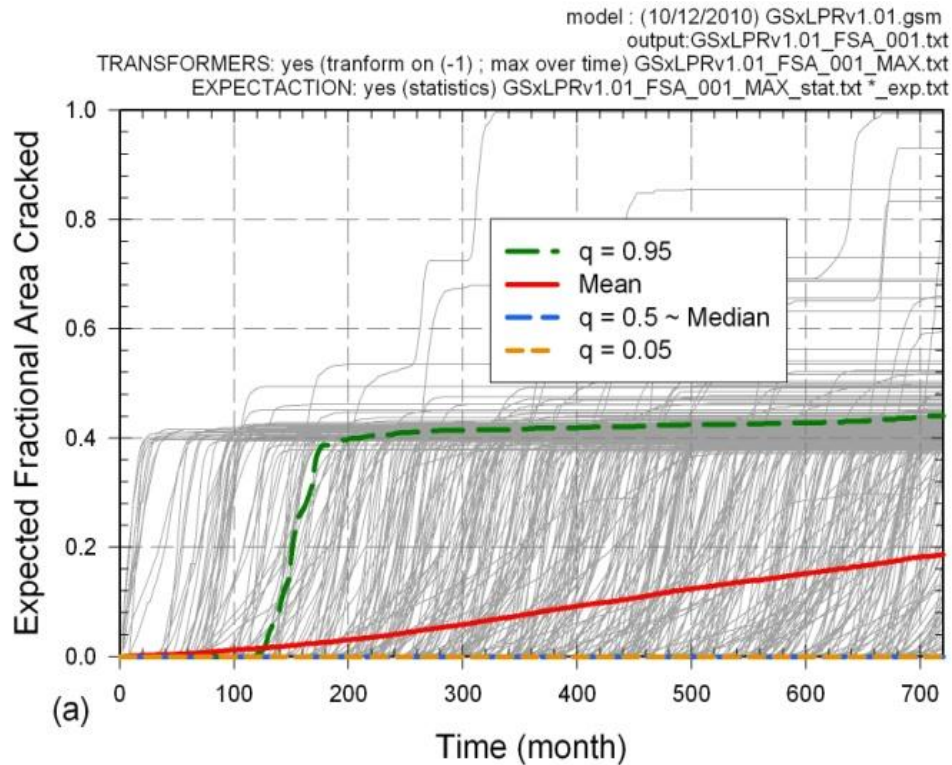
These types of results have been presented to experts to confirm that this is the influence they expect to see (or have observed).



PROBTWC: 10 yr				PROBTWC: 30 yr				PROBTWC: 50 yr				PROBTWC: 60 yr			
var.	R ²	R ² inc.	SRRC	var.	R ²	R ² inc.	SRRC	var.	R ²	R ² inc.	SRRC	var.	R ²	R ² inc.	SRRC
SIGOWRS	0.09	0.09	0.10	SIGOWRS	0.31	0.31	0.37	SIGOWRS	0.39	0.39	0.42	SIGOWRS	0.40	0.40	0.55
B1	0.10	0.01	-0.03	B1	0.39	0.09	-0.20	B1	0.53	0.14	-0.31	B1	0.55	0.15	-0.34
RANDP07	0.11	0.01	-0.02	ODRAND	0.40	0.00	-0.04	FWELD	0.54	0.01	0.06	FWELD	0.55	0.01	0.07
TEMP	0.11	0.01	-0.02					RANDP06	0.54	0.00	-0.05	RANDP05	0.56	0.00	0.04
								RANDP01	0.54	0.00	0.04	RANDP03	0.56	0.00	-0.04
								RANDP05	0.55	0.00	0.04	RANDP06	0.56	0.00	-0.04
								ODRAND	0.55	0.00	-0.04	XC	0.56	0.00	0.04
								PRESS	0.55	0.00	0.04				
								XC	0.55	0.00	0.04				



Use of Sensitivity Analysis to check xLPR at system level (2)



Extreme values are valuable to track potential bugs and/or nonphysical combination of inputs, or solutions outside range of model validity

General behavior and statistics on uncertain results can be checked against knowledge about what results are expected to be.

Classical Use of UA and SA

- Uncertainty and Sensitivity Analysis are used to understand the behavior of complex systems treated probabilistically to take uncertainties into account:
 - They give a range of potential values that can be summarized with statistics in order to help making informed decisions
 - They estimate which are the important input parameters driving the uncertainty in the output of interest and allow to direct research towards them to reduce overall uncertainty.
 - With separation of aleatory and epistemic uncertainty, they can also indicate which part of the uncertainty in the system is due to inherent randomness and which part is due to (theoretically) reducible lack of knowledge.

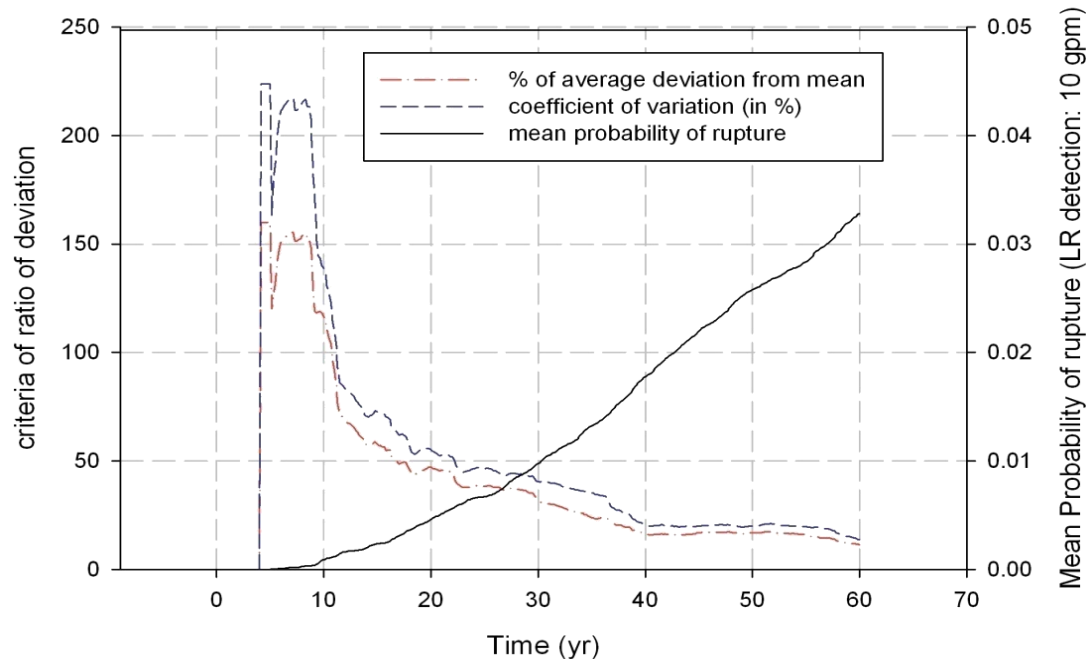
Use of SA within context of low probability

- When extremely low probability estimate are performed, Sensitivity and Uncertainty analysis have an additional (and very important) use.
- Often extremely low probability, in the order of 10^{-5} or lower would require accordingly large sample size (that can be millions of estimate of more)
- Due to computational cost, such large sample size are not practical. More sophisticated techniques such as importance sampling or optimization have to be used.
- Sensitivity and Uncertainty analysis help defining which input parameters should be considered in importance sampling and optimization and also which output parameter to be used in optimization

Example of application – Importance Sampling

1 – limit of regular sampling

- With traditional sensitivity analysis, the lower is the probability, the less accurate is the technique. As rule of thumb, a sample of size n has an accuracy of $1/\sqrt{n}$.
- If the probability is in the order of 10^{-6} only one in 1,000,000 runs will lead from 0 to a handful of realization of interest at best



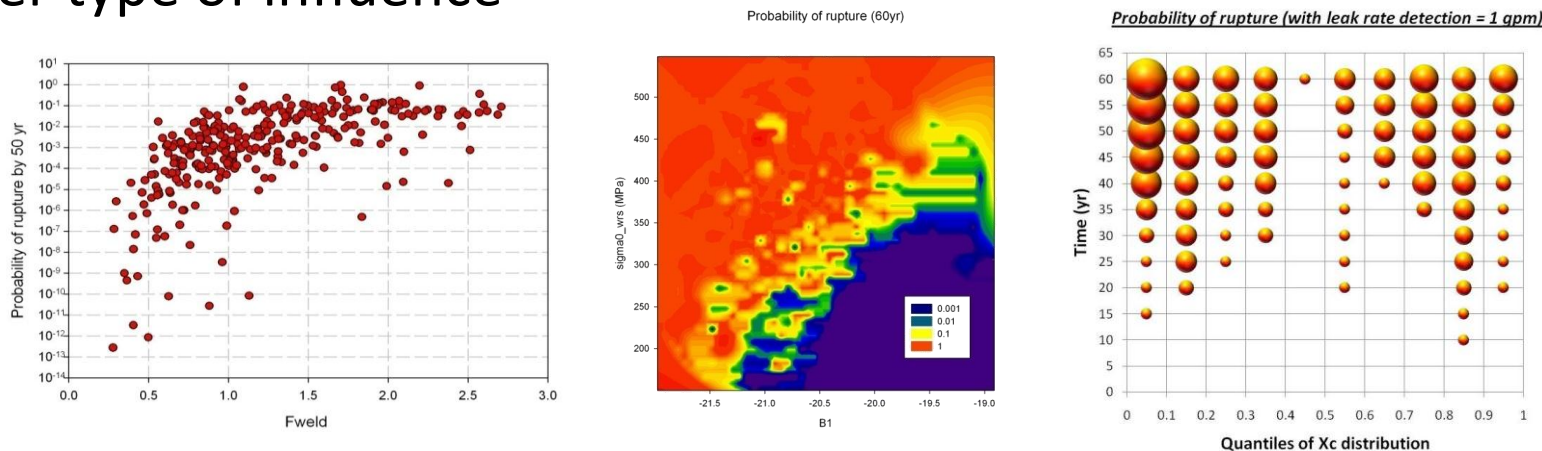
Example of application – Importance Sampling

2 – selection of important parameters

- Stepwise regression can tell which parameters may be important and what part of their distribution is influential

PROBRUP: 10 yr				PROBRUP: 30 yr				PROBRUP: 50 yr				PROBRUP: 60 yr			
var.	R ²	R ² inc.	SRRC	var.	R ²	R ² inc.	SRRC	var.	R ²	R ² inc.	SRRC	var.	R ²	R ² inc.	SRRC
SIGOWRS	0.09	0.09	0.10	SIGOWRS	0.30	0.30	0.36	SIGOWRS	0.42	0.42	0.54	SIGOWRS	0.44	0.44	0.58
B1	0.10	0.01	-0.03	B1	0.38	0.08	-0.18	B1	0.57	0.15	-0.33	B1	0.61	0.17	-0.36
RANDP07	0.11	0.01	-0.02	ODRAND	0.38	0.00	-0.04	FWELD	0.58	0.01	0.07	FWELD	0.62	0.01	0.09
TEMP	0.11	0.01	-0.02	FWELD	0.39	0.00	0.04	RANDL17	0.58	0.00	0.04	RANDP05	0.62	0.00	0.04
												ODRAND	0.62	0.00	-0.04

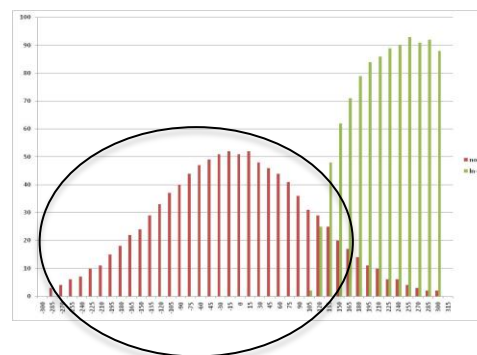
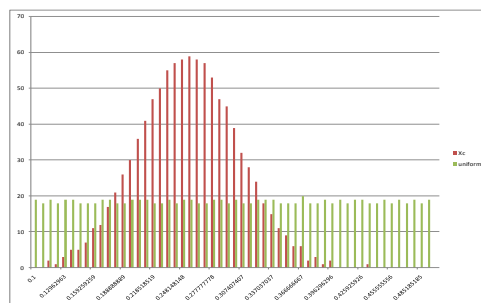
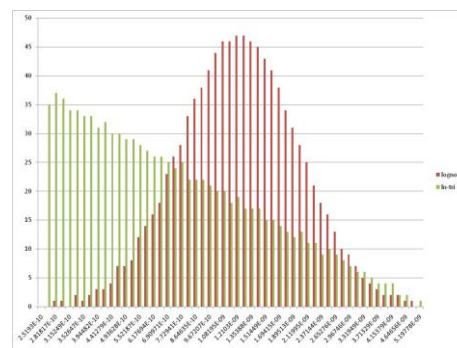
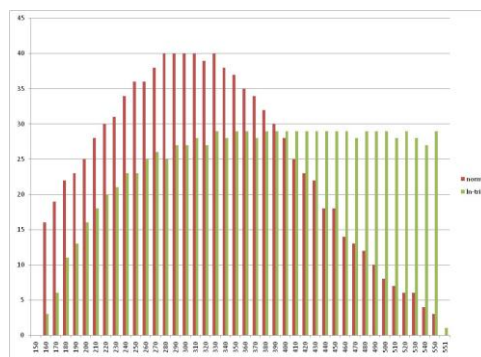
- Scatterplot and more sophisticated techniques can show other type of influence



Example of application – Importance Sampling

3 – application of importance sampling (1)

- Importance sampling (in green) is applied to emphasize the region of interest for each selected input parameters

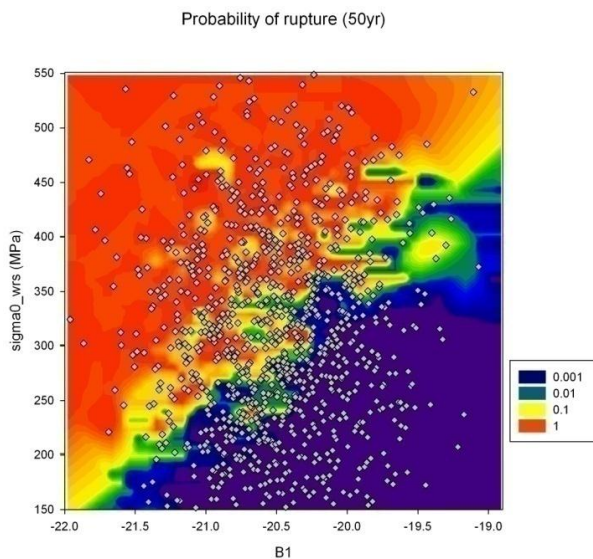


If part of the original distribution is not included, additional corrective term may be required

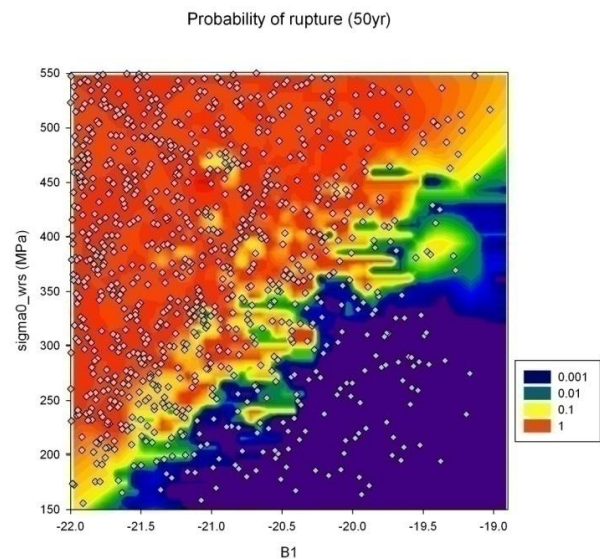
Example of application – Importance Sampling

3 – application of importance sampling (2)

- The resulting sampling can be tested upfront on previous results to check its validity
- In the following example, a comparison is made on the coverage of regular sampling and importance sampling of the region of interest (in red)



Regular Sampling

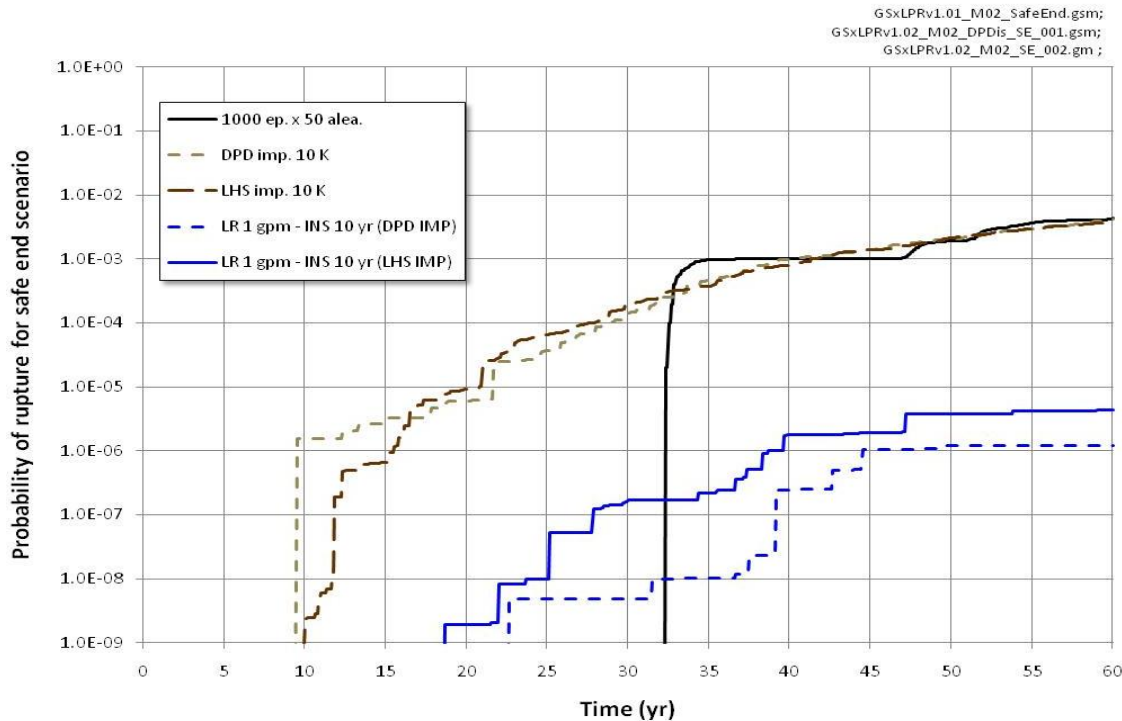


Importance Sampling

Example of application – Importance Sampling

4 – results and comparison (1)

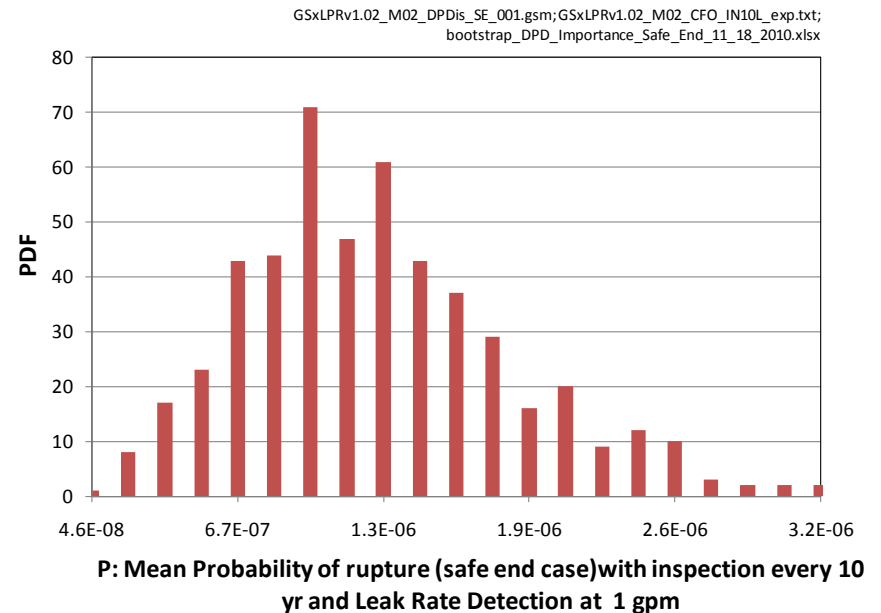
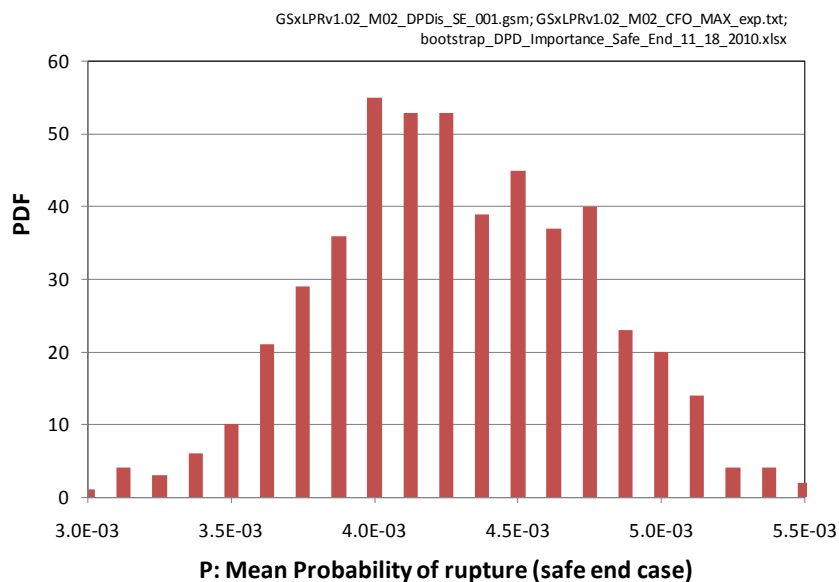
- As a result, importance sampling was successful in estimating probabilities in the order of 10^{-9} (blue lines) to 10^{-6} (dash beige and brown lines) while traditional sampling of same size (black line) was only relevant around 10^{-3} probability



Example of application – Importance Sampling

4 – results and comparison (2)

- Adapted bootstrap method (corrected on each realization weight) shows that results up to 10^{-6} are stable using a sample of size 10,000



Conclusion

- In Probabilistic Assessment of Complex system such as xLPR, sensitivity and uncertainty analysis have been shown to be valuable tools at different steps of the development
 - For checking validity and verify generated results – as well as code, data, and model implementation
 - As classical tool for a better understanding the system and presenting more complete and insightful results for the decision maker
 - As necessary part of optimizing the code in order to estimate extremely low probability of rupture
- In the subsequent versions of xLPR, sensitivity and uncertainty analyses will continue to be used and improved to improve their usefulness.