Questions and Answers

from the

U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research Public Meeting to Discuss Release of the Extremely Low Probability of Rupture Probabilistic Fracture Mechanics Code

April 23, 2020

The table below provides responses to questions submitted during the subject meeting. The original questions have been edited for clarity.

No.	Question and Answer
1	Question: On Slide 6 of the agenda item, "Program History and Perspectives," presentation, it states that around 120 formal documents have been developed. Are all the Extremely Low Probability of Rupture (xLPR) code documents available on the U.S. Nuclear Regulatory Commission (NRC)'s public website? Answer: Most of these documents are part of the "quality assurance pedigree" set of documents that will be made available through the future, fee-based xLPR User Group. Although these documents provide the most granular details of the inner-workings of xLPR, most questions should be addressed by the information contained within the higher-level documents, such as the User Manual.
2	Question: For multiple cracks, were proximity rules applied conservatively (e.g., high, moderate, or low)? Answer: Coalescence is included in xLPR for circumferential cracks, and the user has the flexibility to set the proximity rules to reduce unnecessary or undesired conservatisms.
3	Question: Do the software calculations also consider plant transients as inputs? Answer: xLPR provides the user with extensive capabilities to include a range of both normal operational and design-basis transients as either deterministic events or as sampled inputs to reflect the uncertainty in their frequency and magnitude.
4	Question: Does xLPR model weld fabrication flaws, initiated fatigue cracks, or both? Answer: xLPR can model pre-existing cracks or cracks initiated by either fatigue or stress-corrosion cracking (SCC).

No.	Question and Answer
5	Question: How are inputs entered in GoldSim? Are inputs controlled in a spreadsheet, a database, or external text files? Answer: The inputs to GoldSim are primarily entered using a spreadsheet. A companion software tool, called the Sim Editor, provides database support and assists the user in populating the spreadsheet.
6	Question: Is the weld fabrication defect size distribution the same as that for WinPRAISE, as derived from the Rolls-Royce PRODIGAL code? Answer: Fabrication defects are not directly modeled in xLPR. However, there is an "initial flaw" option, which allows the user to model several surface cracks present at the beginning of the simulation. The number and size of these cracks can be sampled from user-defined probability distributions.
7	Question: Is the leakage rate module linked to LEAPOR or SQUIRT, or is it a self-standing module? Answer: LEAPOR, a modified version of SQUIRT, is used with a preprocessor to generate leak rate look-up tables based on user-defined temperature, pressure, and thickness values prior to running xLPR. xLPR inputs these look-up tables at run time. There is also a standalone version of LEAPOR with a graphical user interface, LEAPOR-SA, that is available for use independent of xLPR.
8	Question: Can xLPR be used on pipe-like reactor vessel internal components (e.g., core spray and jet pump risers)? Answer: xLPR can model pipe-like configurations that can be resolved into a basic butt-weld geometry where cracks are initiated from the inside surface of the weld.
9	Question: How does xLPR handle the interaction between SCC and fatigue? Does xLPR calculate the crack growth separately and then add the contributions together? Answer: Yes, in xLPR SCC and fatigue are modeled separately and their contributions to the total crack growth are additive in each time step. The two mechanisms are not currently modeled in a multiplicative or synergistic way; however, due to the flexibility of xLPR's modular design, such synergistic effects could be considered as future enhancements to xLPR depending upon their safety impacts.
10	Question: Is semi-elliptical the only crack shape available for surface cracks? How about a tight crack? Does the user need to assume the crack shape and orientation first? Answer: In general, semi-elliptical is the only surface crack geometry currently modeled in xLPR. Both axially- and circumferentially-oriented cracks can be modeled.

No.	Question and Answer
11	Question: Concerning the in-service inspection input parameters, are the probability of detection curves input as distributions? Answer: Yes, the probability of detection curves are nominally defined as logistic curves. The individual parameters defining those curves can be input as constant or distributed values.
12	Question: Are SCC and fatigue considered separate and, therefore, don't impact each other? Answer: Please see the response to Question 9.
13	Question: What are the definitions of crack probability and leak probability in Slide 12 of the agenda item, "xLPR Version 2 Code Overview and Features," presentation? Answer: Crack probability is the probability for the first crack to occur, while leak probability is the probability of having leakage (equivalent to having a through-wall crack) for the first time. These probabilities reflect the first amongst circumferential and axial cracks if both orientations are considered.
14	Question: Is it possible to access the results from different steps of the calculations (e.g., results from just the stability module or the transition module)? Answer: The model is not set up to display all results by default due to the large amount of data that would need to be stored. However, with GoldSim Pro, it is possible to create new elements to display any specific results. It is also possible to set any existing element to display time-dependent results. It is recommended to only use these capabilities when needed and for deterministic or small sample size cases.
15	Question: Is each user supposed to perform case-specific validation of the code or, if the code is used within the applicable range of input parameters, the user can assume it is validated? Answer: A detailed validation of the code within the general range of applicability established during code development was performed. However, if the code is applied outside this range of applicability, it is incumbent upon the user to address any validation gaps to the extent appropriate to the specific problem being addressed. Within the original range of applicability, the user is still responsible for assessing whether the completed validation satisfies the needs of the specific problem.

No.	Question and Answer
16	Question: Can user-specified material property curves be entered, including fatigue curves and other environmental degradation curves? Answer: Material properties that can be specified by the user include: tensile properties, fracture toughness parameters, thermal parameters, fatigue crack initiation model parameters, SCC initiation model parameters, fatigue crack growth model parameters, and SCC growth model parameters.
17	Question: Is the code applicable for non-U.S. materials (e.g., water-water energetic reactor-type steels)? Answer: The xLPR code has been designed to be as generic and flexible as possible. However, the material models require parameters of specific form (e.g., Ramberg-Osgood parameters, J-R parameters, and subcritical crack growth parameters). Although selected material property values are available, the user is responsible for determining the appropriate values for the particular application.
18	Question: Does the code address both circumferential and axial flaws? Answer: Yes, xLPR can model flaws that are circumferentially-oriented, axially-oriented, or both.
19	Question: Can changes in material toughness over time (e.g., thermal aging or irradiation) be addressed? Answer: xLPR currently does not model changes to material properties over time. However, the user could perform a bounding analysis.
20	Question: Is the methodology of probabilistic fracture mechanics like the FAVOR code? What are the differences? Answer: The xLPR and FAVOR methodologies differ in the quantification and treatment of uncertainties and in the numerical implementation. In general, the modeling of uncertainties in xLPR is broader than in FAVOR, as xLPR allows for almost any input variable to be sampled, which is not the case in FAVOR. Furthermore, xLPR's computational framework allows for the separation of aleatory and epistemic uncertainties via a nested loop implementation, as well as advanced sampling techniques, which are not available in FAVOR. Because of the simplified implementation, the FAVOR code can produce reliable, converged estimates of vessel failure at lower computational cost than xLPR.

No.	Question and Answer
21	Question: As a follow-up to the question on proximity rules, are ASME B&PV Code proximity rules already programmed into xLPR as a selectable option, or must any proximity rules be defined and coded by the user? Answer: The user may input "coalescence distance rule" values to determine the distance between cracks prior to coalescence. For surface cracks, either an absolute distance or distance to maximum depth ratio may be entered. For through-wall cracks, an absolute distance may be entered.
22	Question: Deterministic and probabilistic approaches were compared. What failure probability would you typically associate with deterministic approaches in common codes like the ASME B&PV Code, Section XI? Answer: There have been no attempts to date to calculate the failure probabilities for any ASME B&PV Code, Section XI analyses. However, it's suspected that the failure probabilities would be low due to the conservative nature of the code.
23	Question: Does xLPR account for how the moments change in the pipe system with the change in flexibility of the piping, or does it just use the uncracked pipe design stresses? This behavior promotes more fracture stability in the pipe system. Answer: The xLPR code does not currently model pipe system flexibility, and the loads come from the un-cracked pipe system. However, due to the flexibility of xLPR's modular design, such effects could be considered as future enhancements to xLPR depending upon their safety impacts.
24	Question: How is crack opening time modelled? Is it an instant opening to the crack opening displacement or crack opening area, or does it allow for some transition time to a fully open crack? Answer: The crack opening displacement is calculated for the conditions present during each incremental time step (e.g., material property parameters, loads, temperatures, and crack length), but the underlying material behavior and the evolution of crack morphology are not time-dependent phenomena.
25	Question: Why do the aleatory probabilities for each epistemic q-value remain relatively stable from 20 years and after? Are any mechanistic phenomena affecting this outcome? Answer: In the example shown, there are no underlying mechanistic phenomena affecting the results. Mechanical stress mitigation, which is an external change, was applied at 20 years, which explains the sudden change in behavior.

No.	Question and Answer
26	Question: Does the code consider material anisotropy effects, such as in A106 carbon-steel material pipes? Answer: Material anisotropy effects are not currently included in xLPR. The material properties are not defined directionally, and cracks are only treated in axial and circumferential orientations.
27	Question: How did you perform the 4,000 verification tests mentioned on slide 13 of the agenda item, "xLPR Version 2 Code Overview and Features," presentation? Answer: Testers independent from the programmers executed both static and dynamic test cases to verify that all xLPR software requirements were met in accordance with established acceptance criteria. Verification testing was performed at the individual software component level and then with all the software components integrated together as a system.
28	Question: Does this version of xLPR allow for input parameters for cast austenitic stainless steels, such as grain boundary conditions, and how that might impact crack initiation and growth? Answer: Grain boundary conditions are not currently an input to xLPR. However, the user may specify custom fatigue or SCC initiation and growth model parameters.
29	Question: Primary water stress-corrosion cracking (PWSCC) has been frequently mentioned. Is intergranular stress-corrosion cracking for boiling-water reactors also covered? Answer: Intergranular stress-corrosion cracking is not presently addressed within xLPR, but its incorporation is certainly on the list of potential future enhancements. We look forward to engaging with the boiling-water reactor community to investigate this opportunity.
30	Question: Is the surface crack failure criterion based on net-section-collapse or elastic-plastic fracture mechanics (EPFM)? If EPFM, does it account for recent concepts of toughness decreases with increasing flaw depth? Answer: Surface crack stability is based on net-section-collapse. Toughness decreases caused by moment reduction due to the crack length have been previously studied. For PWSCC, the cracks grow so quickly that, for cracks long enough to cause a significant moment reduction, the impact on the probability of rupture is insignificant. Therefore, the current strategy is more conservative. For the large-diameter piping system where such a model would have the most impact, the probability of rupture is already well below the limiting condition, so from a risk standpoint, this is a second-order effect.

No.	Question and Answer
31	Question: Does xLPR assume normal operation, or does can it include the impact of fault transients? Answer: Please see the response to Question 3.
32	Question: Can you make the chat questions and responses available after the presentations? Answer: The questions and responses have been made available as part of the NRC meeting summary.
33	Question: Is the code validated for thin-walled piping (e.g., tubes) nickel-based materials? Answer: The models, assumptions, and analytical methods currently implemented within xLPR reflect the behavior of thick-walled pressure boundary components.
34	Question: Can the user combine SCC and fatigue in ways other than by simple summation? For example, can fatigue be assumed to accelerate SCC? Answer: Please see the response to Question 9.
35	Question: Can the user input time-dependent crack aspect ratios for each time step? If so, are any guidelines available for these inputs? Answer: This is not currently an option in xLPR. The user can directly input initial crack aspect ratios, however.
36	Question: Can the user apply its own crack initiation and propagation models? Answer: The crack initiation and growth model forms cannot be changed, but the inputs to those models (for both fatigue and SCC) can be modified by the user.
37	Question: Is PWSCC and fatigue synergy considered? Summing the two phenomena assumes independence. How significant might be the synergy? Answer: Please see the response to Question 9.
38	Question: Is it possible to call the xLPR code from an external code like MATLAB? Answer: xLPR is run by GoldSim, and it is possible to execute GoldSim externally, for example, using a batch script. The GoldSim documentation can be consulted for further information. However, running xLPR directly within GoldSim is the most effective approach.

No.	Question and Answer
39	Question: Previous software (i.e., PRO-LOCA 4.X) calculated the leakage non-conservatively when weld residual stresses (WRS) are relevant. How is this handled in xLPR? Answer: PRO-LOCA 6.0 and 7.0 and xLPR Version 2 (V2) use similar WRS and leak rate models. Indeed, the impacts of WRS on through-wall crack opening predictions, which affect leak rate, are not currently addressed in these models. The NRC Office of Nuclear Regulatory Research is currently sponsoring efforts to develop a model to address such impacts, which will be assessed for future inclusion in a later version of xLPR.
40	Question: Are all the WRS solutions axisymmetric? When going to thinner-walled pipe (i.e., non-light-water reactor piping), the transient stop-start local stresses can be purely tensile through the thickness, giving a quicker initial leak location. Answer: The current WRS solutions are from axisymmetric finite element analyses.
41	Question: Does xLPR allow for a reduction of displacement-controlled, elastically calculated stresses if the total failure stress is above yield of the uncracked pipe? This is more important to circumferential surface cracks and is an aspect that ASME B&PV Code Section XI committees are just beginning to look at. Answer: xLPR includes a deterministic input which the user can use to adjust and study the impact of displacement-controlled (e.g., thermal expansion) stresses. This input adjusts the stresses used for calculation of SCC and fatigue through-wall crack growth, through-wall crack stability, and crack opening displacement.
42	Question: Is the code limited to running one problem at a time, or can multiple cases (i.e., "batch" files) be run simultaneously? Answer: xLPR is currently limited to running one problem at a time. Multiple, different analysis cases would need to be evaluated sequentially.
43	Question: xLPR means "extremely low probability of rupture." How low can probability values can be analyzed with high accuracy? Answer: Generally, having 10 to 20 instances of an event in a Monte Carlo analysis gives an accurate enough estimate. xLPR can easily be used to run 100,000 realizations, leading to stable probability in the range of 1E-4. With some modifications, the code can be used to run 1,000,000 realizations to go to 1E-5 probabilities. Furthermore, some probabilities are estimated by applying correction factors (such as for the impact of inservice inspections) and can have lower probabilities estimated accurately.

No.	Question and Answer
44	Question: For a surface crack, as the length over depth ratio approaches one, the highest crack-driving force is not at the center or ends of the surface crack but at about 30 to 45 degrees from the center. Do the xLPR K-solutions account for this phenomenon? Answer: xLPR currently only includes K-solutions at the 0- and 90-degree locations. The crack shape remains elliptical throughout the entire calculation.
45	Question: Previous software, such as PRO-LOCA 4.X and perhaps xLPR V1, are quite slow when low probabilities are calculated. Using PRO-LOCA 4.X, computer central processing unit times could be more than 24 hours (or even weeks) to get an accurate result. Is xLPR V2 much faster than PRO-LOCA 4.X? Answer: The simulation time in any probabilistic fracture mechanics code depends on the options and mechanisms considered as well as the amount of accuracy desired. When using GoldSim Pro, xLPR can be run in parallel on up to four processors, which can be extended to a hundred with an additional GoldSim module. Distributed processing can significantly reduce the amount of time for large sample sizes.
46	Question: Can the user perform model averaging if unsure about the choice of a single model? Answer: xLPR currently does not include the ability to average the results from multiple models, so this would have to be performed by the user in post-processing. However, some of the material flags (leading to different growth and initiation models) can be set as uncertain with a discrete distribution to potentially emulate model averaging.
47	Question: When using importance sampling, which results are used as an initial driver of the solution? Answer: The importance sampling method implemented in xLPR is not an optimization method, and thus it is not linked to any specific results. It is up to the user to select the appropriate inputs in order to apply importance sampling. Most of the inputs are available for importance sampling.
48	Question: It was just shown that the normal distribution is capped by minimum and maximum values. How is the loss in "probability" accounted for since the integral is not equal to one anymore? Answer: For any truncated distribution, the integral is re-normalized between the quantiles considered, so that the shape of the distribution is respected, and the integral is equal to one. This feature is an inherent part of the GoldSim software.

No.	Question and Answer
49	Question: Which version of the GoldSim Player is xLPR using? Is it the latest version, GoldSim 12? Answer: xLPR was verified and validated using GoldSim 11.1. While there is a newer version of GoldSim (e.g., 12.1), GoldSim Technology Group provides access to prior versions of the GoldSim Player for free and to GoldSim Pro if a license is purchased. Official support for GoldSim 12 is currently being considered under the xLPR maintenance program.
50	Question: The test cases used for PRO-LOCA 4.X were in some cases unrealistic and generated probabilities that were too high. Were more realistic data used when verifying and testing xLPR V2? Answer: xLPR validation included comparisons against the best-available data from PWSCC events that occurred in-service both in the U.S. and internationally.
51	Question: Will a list of attendees be provided? Answer: A list of the meeting attendees has been made available as part of the NRC meeting summary.
52	Question: One thing that strikes me is the number of variables that are available for the user to specify the input value for. It seems to be a much larger set than is required for the FAVOR code. Has the xLPR team developed a set of accepted, default values? Answer: The xLPR development team has prepared sets of recommended inputs; however, many of these inputs are case-specific and an acceptable input for one case may not be acceptable for another. Should it be determined that the recommended inputs are not suitable for analyzing a particular case, then xLPR allows the user to modify the recommended inputs or provide its own inputs. This flexibility makes xLPR suitable for a broad range of applications.
53	Question: How many inspections and at what intervals do the calculations consider? Is that a variable that the user can change? Answer: The user can schedule when the inspections occur, either by frequency or at specific points in time during the simulation.

No.	Question and Answer
54	Question: It seems like the loss-of-coolant accident frequency obtained based on the case study is for a specific location (e.g., hot leg). What if the user is interested in the plant-level loss-of-coolant accident frequency as an input to the probabilistic risk assessment? Is it recommended that the user run xLPR for all the possible locations and somehow aggregate the results together? Answer: The user would first need to make sure that all possible degradation mechanisms are properly modelled and used in the determination of the weld-specific probabilities throughout the plant. Once those analyses are complete, the plant-level break frequencies could be estimated. It's also important to keep in mind that a loss-of-coolant accident could be caused by non-piping related breaks, and these also need to be factored into a plant's loss-of-coolant accident frequency.
55	Question: Do the inspection inputs consider limited coverages? Answer: The inspection inputs do not explicitly consider limited coverage as defined in spatial areas. Limited coverage would need to be addressed through the probability of detection inputs and through independent or dependent inspection treatment, which is a user option.
56	Question: As a potential application of xLPR, what are the NRC's plans with respect to revising its regulatory requirements, standard review plans, or both? Answer: The NRC staff is currently applying xLPR to study the impacts of PWSCC in leak-before-break analyses. Results from these studies will be used to determine whether any changes to NRC's current regulatory framework are necessary.
57	Question: What is the NRC's and the Electric Power Research Institute (EPRI)'s plan to continue to maintain and update xLPR? For example, in 5 years better models and data will probably be available. Is there a plan or process in place to incorporate these into a revised version of xLPR? Answer: xLPR is already under an active maintenance program. This program was applied to prepare xLPR V2.1, which will be the initial public release. Going forward, the maintenance program will be used to address known issues and prepare updated releases. NRC and EPRI also plan to establish a User Group to help support xLPR maintenance needs far into the future and expect that this will become the forum for planning and implementing new models and other enhancements.

No.	Question and Answer
58	Question: Regarding using this code with balance-of-plant systems and other piping degradation mechanisms, what are EPRI's thoughts regarding the use of CHECWORKS for flow-accelerated corrosion and mechanical erosion vs. xLPR? Answer: EPRI is investigating the possibilities of utilizing CHECWORKS as an input for a future xLPR model. Particularly, using CHECWORKS data in place of the crack initiation and growth modules could prove beneficial, but the investigation is in the early stages.
59	Question: How does one join the xLPR User Group? Answer: Details regarding the planned xLPR User Group will be forthcoming later this year.
60	Question: A follow-up note on the system flexibility change with through-wall crack size: (1) the applied moments decrease as the crack length gets longer, and (2) this change in flexibility also causes the moments generated from seismic loading to decrease dramatically as well. Answer: To augment the response to Question 30, seismic loading only lowers the probability of rupture. Since the probability of rupture is already extremely low, this conservative assumption is adequate. It may be useful to include this effect in future versions of xLPR to improve accuracy.
61	Question: is there a plan to make xLPR forward compatible with new versions of GoldSim? If not, does this mean that after some period xLPR may not be able to run if GoldSim stops supporting the old versions? Answer: Please see the response to Question 49.
62	Question: It is risky to rely on the 32-bit version of Excel. Eventually it will become discontinued. Answer: Official support for 64-bit versions of Excel is currently being considered under the xLPR maintenance program. Preliminary investigations indicate that 64-bit versions work with GoldSim, but not with the xLPR preprocessor.
63	Question: Does the new version of the code consider weld fabrication flaws? Answer: Please see the response to Question 6.
64	Question: Is the weld defect distribution taken from the same source as WinPRAISE? Answer: Please see the response to Question 6.

No.	Question and Answer
65	Question: I believe the WinPRAISE defect distributions may be derived from the obsolete PRODIGAL code. Although the PRODIGAL defect distributions had good pedigree, the data sources are now old. Have there been, or will there be, any new weld fabrication flaw expert elicitations to take credit for improved modern tungsten inert gas welding practices and non-destructive examination resolution? Answer: Please see the response to Question 6.
66	Question: What range of pipe weld sizes does xLPR cover? Answer: The xLPR models were generally developed for large-diameter piping. It is up to the user to ensure that all inputs selected are within the range of applicability for the xLPR models.
67	Question: Can you please send me the instructions or webpage link with the instructions as to how my company could obtain a copy of xLPR? Answer: An overview of the process for requesting a copy of the code was given in the "Process for Requesting a Copy of the Code" presentation. A copy of that presentation is available under NRC Agencywide Documents Access and Management System Accession No. ML20119A470. A future announcement will be made when that process has been activated.