PROBABILISTIC FRACTURE MECHANICS CODE

Agenda

Introduction and Opening Remarks

Extremely Low Probability of Rupture (xLPR) Code Overview

Deterministic Models Overview

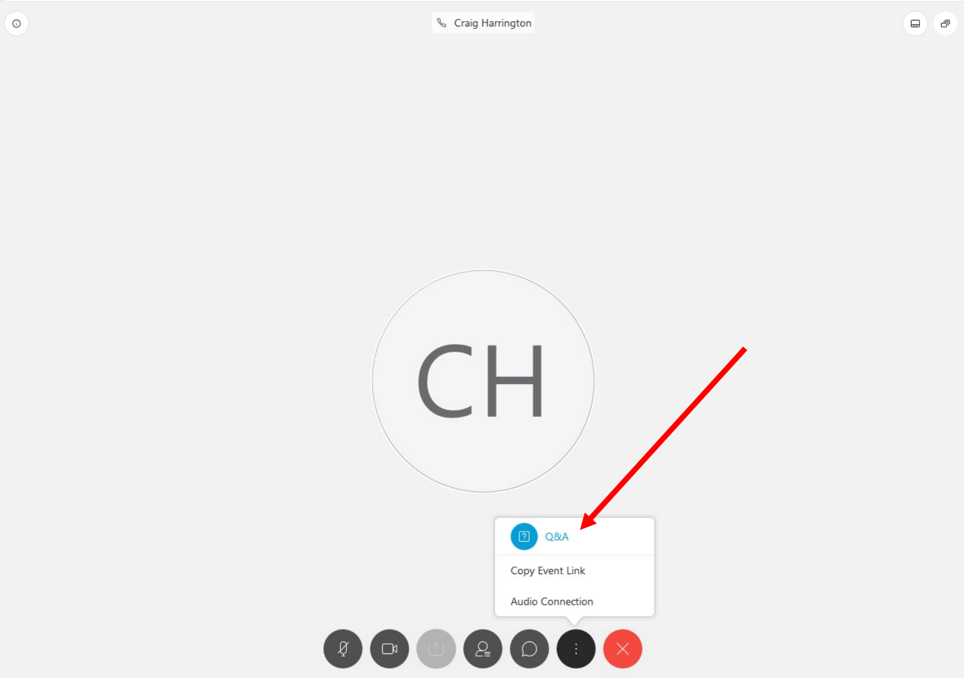
Questions and Answers

Closing Remarks

Introduction and Opening Remarks

WEBEX Q+A

Webex Internet Browser



Webex Desktop Client

xLPR V2.1 REQUEST PROCESS

- A pre-release public meeting was held on April 23, 2020
- xLPR Version 2.1 (V2.1) available soon (announcement to be made)
- xLPR V2.1 will be available for request from U.S. Nuclear Regulatory Commission (NRC) and Electric Power Research Institute (EPRI) websites

Starting from NRC.gov

- Navigate to [About NRC > How We Regulate > Research Activities > Obtaining the Codes
- Select "xLPR" – read and follow the link

Starting from EPRI.com

- Click on search icon at top right
- Type "xLPR" in the search page
- Press [Enter]
- Select "xLPR V2.1" from the search results

- Code is free, but applicant must sign End User License Agreement

From NRC.gov

Research Activities

The regulatory research program sponsored by the U.S. Nuclear Regulatory Commission (NRC) addresses issues in the three arenas of nuclear reactors, nuclear materials, and radioactive waste. The research program is designed to improve the agency's knowledge where uncertainty exists, where safety margins are not well-characterized, and where regulatory decisions need to be confirmed in existing or new designs and technologies. The NRC's annual Regulatory Information Conference (RIC) provides a forum for presentations and discussions about the agency's research activities. Information gained from the research program is documented in our NUREG-series publications and is used in developing regulatory guides. Some of these publications provide documentation and information on the use of technical computer codes that are used in research, modeling, and analysis.

RELATED INFORMATION

Level 3 PRA Project

Human Factors Research (video) EXIT

For more information on research activities see the following:

- Nuclear Reactor Safety Research
- Nuclear Materials Safety Research
- Radioactive Waste Safety Research
- Fire Research Program
- The Radiological Protection Computer Code Analysis and Maintenance Program (RAMP)
- Digital Instrumentation and Controls (I&C) Research
- State-of-the-Art Reactor Consequence Analyses (SOARCA)
- Computer Codes
- Obtaining the Codes
- Probabilistic Flood Hazard Assessment
- Accident Sequence Precursor (ASP) Program

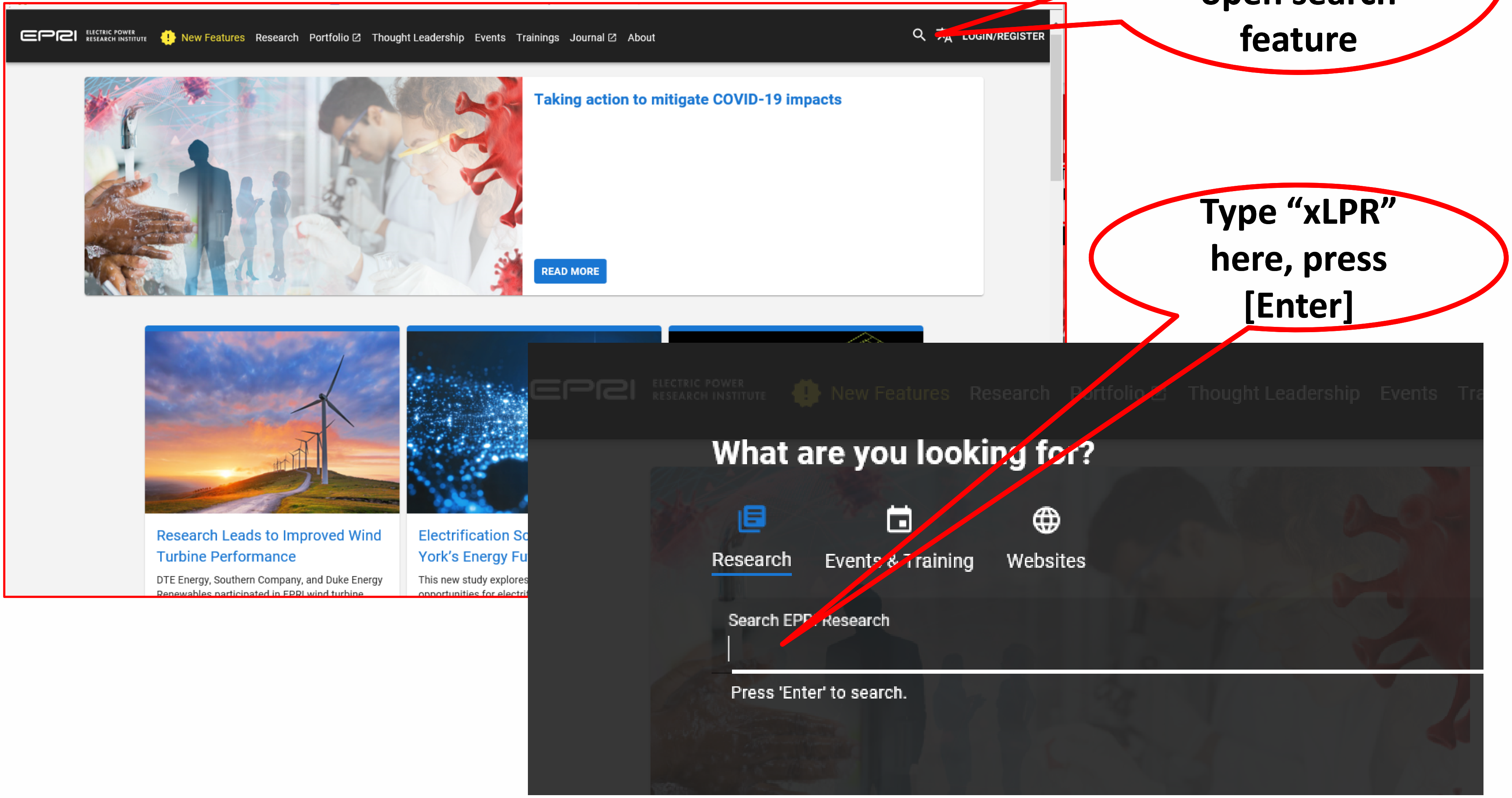
For information related to the research program, please see FY2020-22 Planned Research Activities and

About NRC

Research

Access Obtaining the Codes page

EPRI.com Homepage



Taking action to mitigate COVID-19 impacts

Research Leads to Improved Wind Turbine Performance

DTE Energy, Southern Company, and Duke Energy Renewables participated in EPRI wind turbine

Electrification Sc
York's Energy Fu

This new study explores
opportunities for electri

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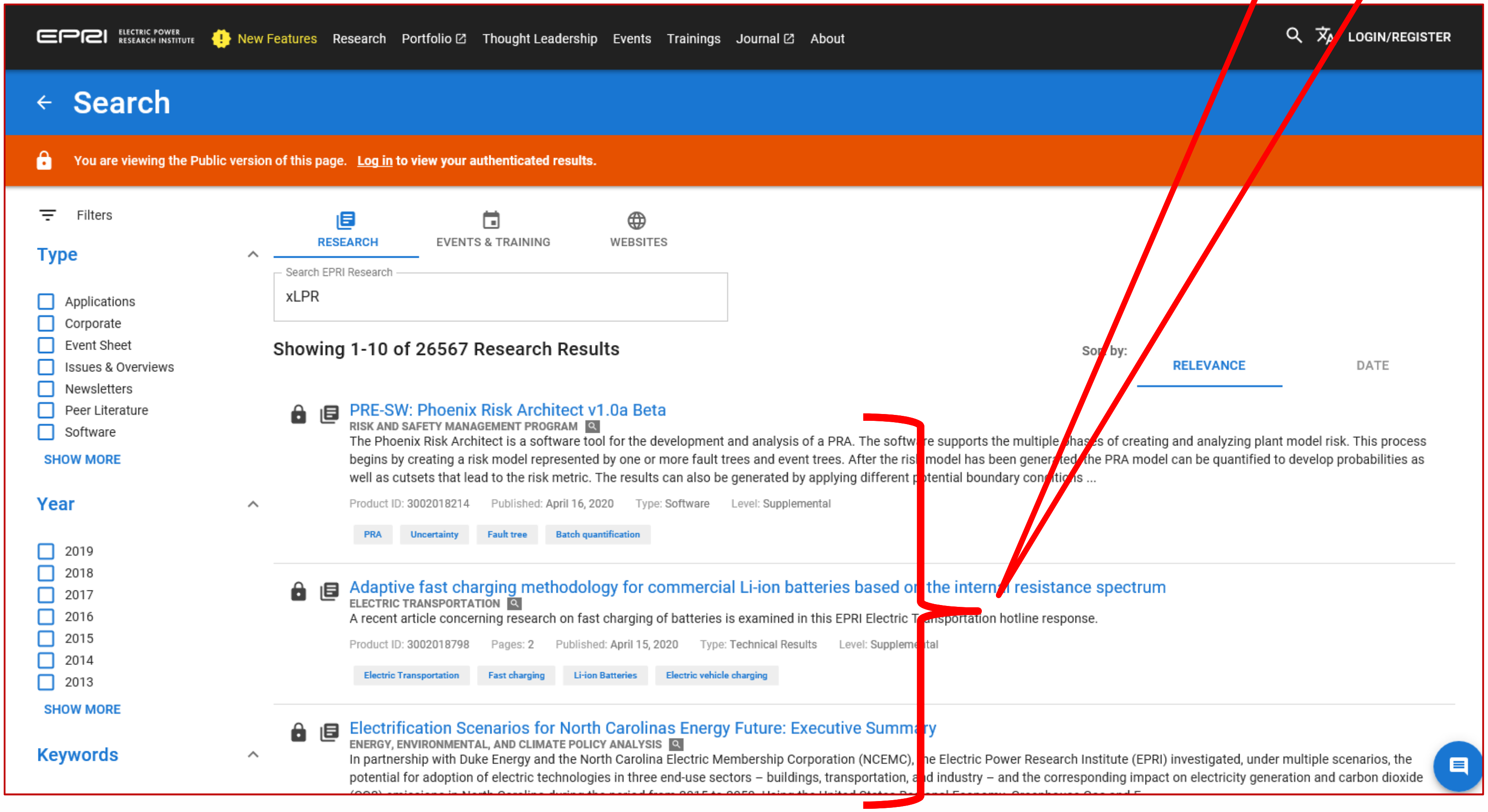
Type “xLPR” here, press [Enter]

Search Results

Select “xLPR V2.1” from search results



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Showing 1-10 of 26567 Research Results

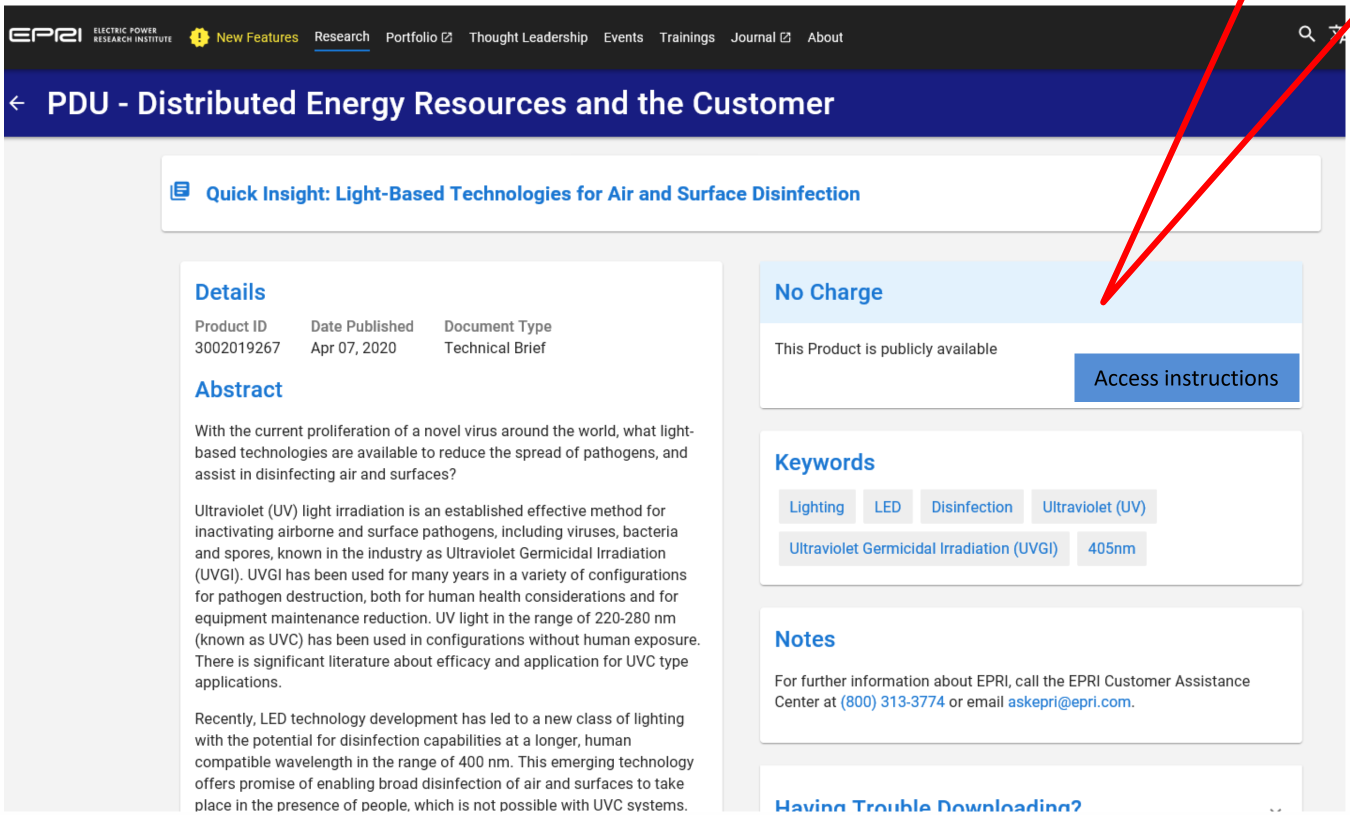
PRE-SW: Phoenix Risk Architect v1.0a Beta
RISK AND SAFETY MANAGEMENT PROGRAM
The Phoenix Risk Architect is a software tool for the development and analysis of a PRA. The software supports the multiple phases of creating and analyzing plant model risk. This process begins by creating a risk model represented by one or more fault trees and event trees. After the risk model has been generated the PRA model can be quantified to develop probabilities as well as cutsets that lead to the risk metric. The results can also be generated by applying different potential boundary conditions ...
Product ID: 3002018214 Published: April 16, 2020 Type: Software Level: Supplemental
PRA | Uncertainty | Fault tree | Batch quantification

Adaptive fast charging methodology for commercial Li-ion batteries based on the internal resistance spectrum
ELECTRIC TRANSPORTATION
A recent article concerning research on fast charging of batteries is examined in this EPRI Electric Transportation hotline response.
Product ID: 3002018798 Pages: 2 Published: April 15, 2020 Type: Technical Results Level: Supplemental
Electric Transportation | Fast charging | Li-ion Batteries | Electric vehicle charging

Electrification Scenarios for North Carolinas Energy Future: Executive Summary
ENERGY, ENVIRONMENTAL, AND CLIMATE POLICY ANALYSIS
In partnership with Duke Energy and the North Carolina Electric Membership Corporation (NCEMC), the Electric Power Research Institute (EPRI) investigated, under multiple scenarios, the potential for adoption of electric technologies in three end-use sectors – buildings, transportation, and industry – and the corresponding impact on electricity generation and carbon dioxide

xLPR V2.1 Abstract page

Follow instructions here to initiate Request process



PDU - Distributed Energy Resources and the Customer

Quick Insight: Light-Based Technologies for Air and Surface Disinfection

Details

Product ID	Date Published	Document Type
3002019267	Apr 07, 2020	Technical Brief

Abstract

With the current proliferation of a novel virus around the world, what light-based technologies are available to reduce the spread of pathogens, and assist in disinfecting air and surfaces?

Ultraviolet (UV) light irradiation is an established effective method for inactivating airborne and surface pathogens, including viruses, bacteria and spores, known in the industry as Ultraviolet Germicidal Irradiation (UVGI). UVGI has been used for many years in a variety of configurations for pathogen destruction, both for human health considerations and for equipment maintenance reduction. UV light in the range of 220-280 nm (known as UVC) has been used in configurations without human exposure. There is significant literature about efficacy and application for UVC type applications.

Recently, LED technology development has led to a new class of lighting with the potential for disinfection capabilities at a longer, human compatible wavelength in the range of 400 nm. This emerging technology offers promise of enabling broad disinfection of air and surfaces to take place in the presence of people, which is not possible with UVC systems.

No Charge

This Product is publicly available

Keywords

Lighting, LED, Disinfection, Ultraviolet (UV), Ultraviolet Germicidal Irradiation (UVGI), 405nm

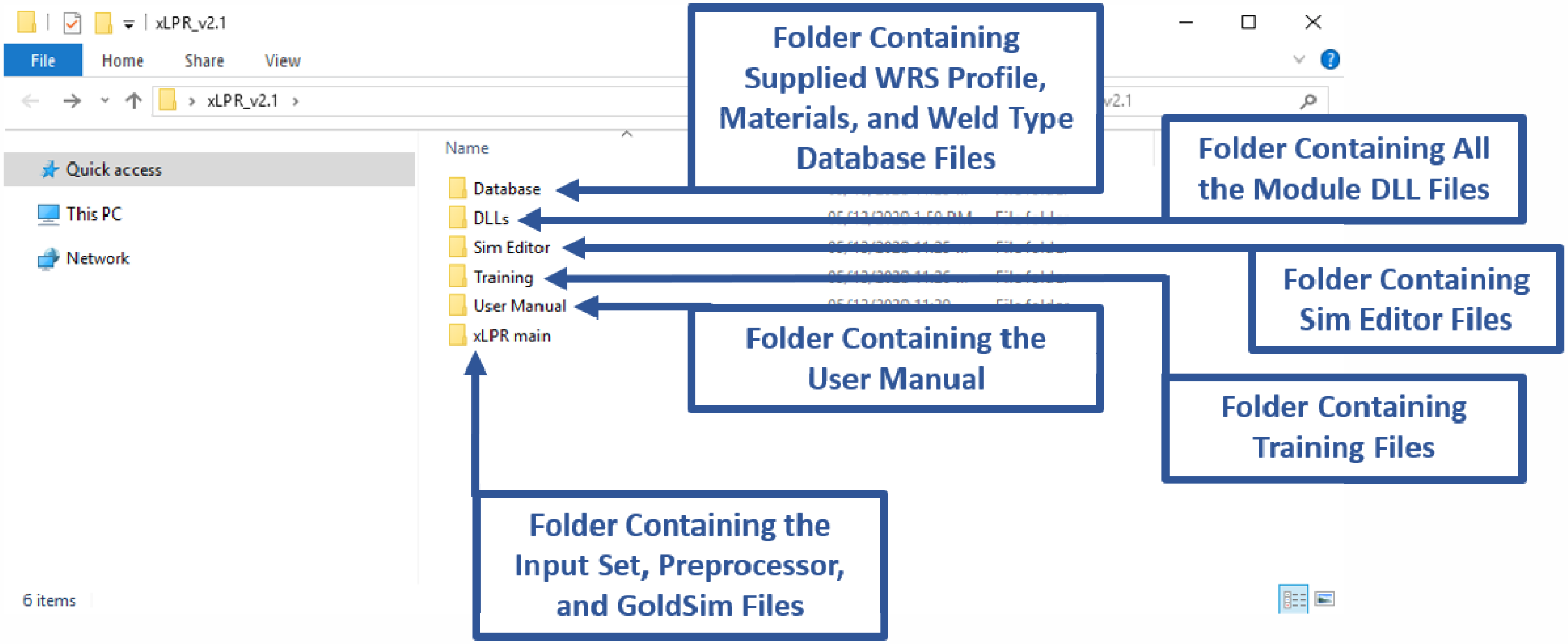
Notes

For further information about EPRI, call the EPRI Customer Assistance Center at (800) 313-3774 or email askepri@epri.com.

Having Trouble Downloading?

xLPR V2.1 RELEASE PACKAGE

- The xLPR V2.1 release contains the following:



Folder Containing Supplied WRS Profile, Materials, and Weld Type Database Files

Folder Containing All the Module DLL Files

Folder Containing Sim Editor Files

Folder Containing Training Files

Folder Containing the User Manual

Folder Containing the Input Set, Preprocessor, and GoldSim Files

TRAINING MATERIAL FOR xLPR USERS

- Available to Everyone
  - Video recording and presentation materials from this meeting
  - Video recording and presentation materials from April 23, 2020, pre-release meeting
  - xLPR development reports (pending)
- Available to xLPR users
  - User manual
  - Training manuals with links to pre-recorded videos

xLPR-TRN-Theory

- Module-focused theory training presentations are provided in xLPR-TRN-Theory (Training Manual, xLPR Code Theory)
- Includes links to pre-recorded version of the course

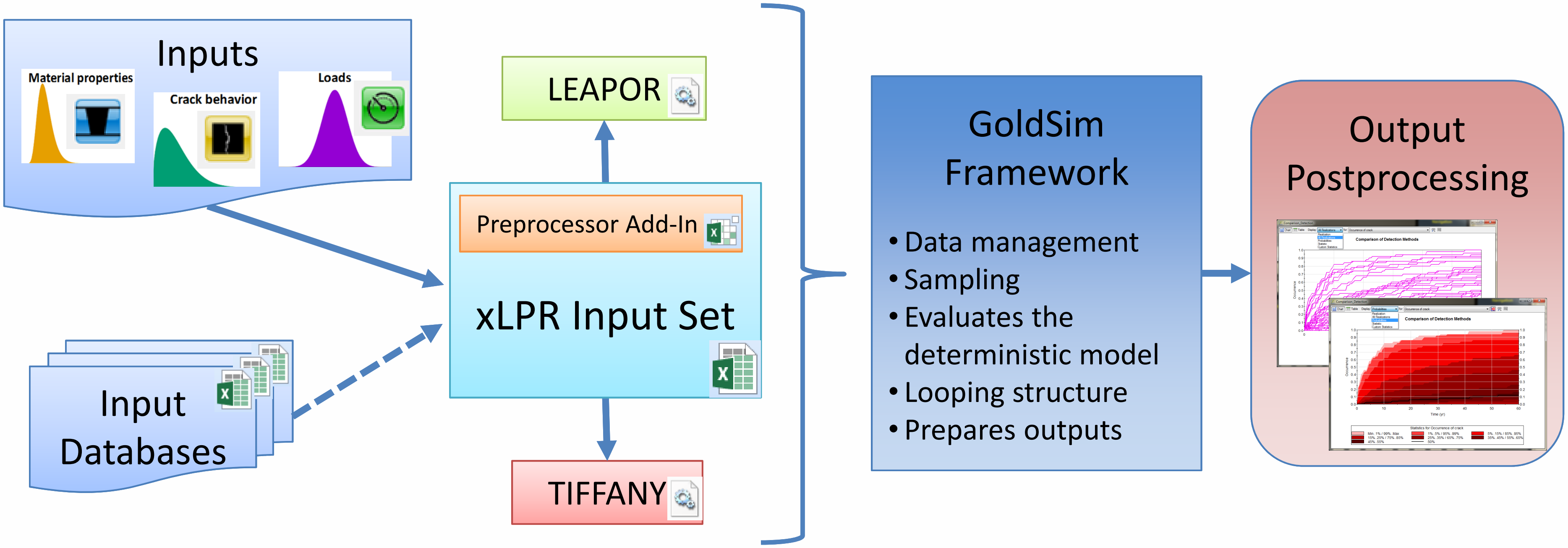
Summary of Topics	
Lesson 1: Overview (18 slides)	Lesson 9: Crack Transition (22 slides)
Lesson 2: Welding Residual Stresses (56 slides)	Lesson 10: Circ. TW Crack Stability (24 slides)
Lesson 3: K-Solutions (20 slides)	Lesson 11: Circ. Surface Crack Stability (19 slides)
Lesson 4: PWSCC Initiation (49 slides)	Lesson 12: Axial Crack Stability (21 slides)
Lesson 5: PWSCC Growth (36 slides)	Lesson 13: ISI Model Parameter Dev. (65 slides)
Lesson 6: Fatigue Crack Initiation and Growth (27 slides)	Lesson 14: ISI Param. Implementation (31 slides)
	Lesson 15: Circ. Crack Opening Disp. (39 slides)
Lesson 7: Transient Modeling (26 slides)	Lesson 16: Ax. Crack Opening Disp. (38 slides)
Lesson 8: Crack Coalescence (13 slides)	Lesson 17: Leakage Rate Calculations (58 slides)

xLPR RELEASE TECHNICAL SEMINAR SERIES

- This is the first of four technical seminars
- Focus is high-level overview of xLPR and its underlying deterministic models
- Remaining seminars targeted for users of the code:
  - Setting up the Inputs (Tentatively July 1st)
  - Running the Simulation (Tentatively July 15th)
  - Accessing Results (Tentatively July 29th)

xLPR Overview

xLPR OVERVIEW



Inputs

Material properties

Crack behavior

Loads

Input Databases

LEAPOR

Preprocessor Add-In

xLPR Input Set

TIFFANY

GoldSim Framework

- Data management
- Sampling
- Evaluates the deterministic model
- Looping structure
- Prepares outputs

Output Postprocessing

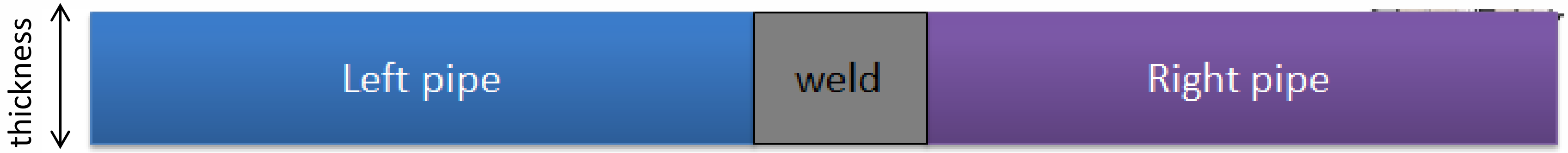
INPUTS AND PRE-PROCESSING

- A custom “Sim Editor” Java application provides a more user-friendly way to create the inputs spreadsheet
- An Excel spreadsheet stores possible inputs to xLPR
  - Material-specific libraries are included for ease of use
- TIFFANY generates look-up tables for stresses and stress intensity factors (K-values) based on defined plant transients (for fatigue initiation and growth models)
  - “Thermal stress Intensity Factors For ANY coolant history”
- LEAPOR generates look-up tables for leak rate calculations
  - “Leak Analysis of Piping – Oak Ridge”

GOLDSIM FRAMEWORK

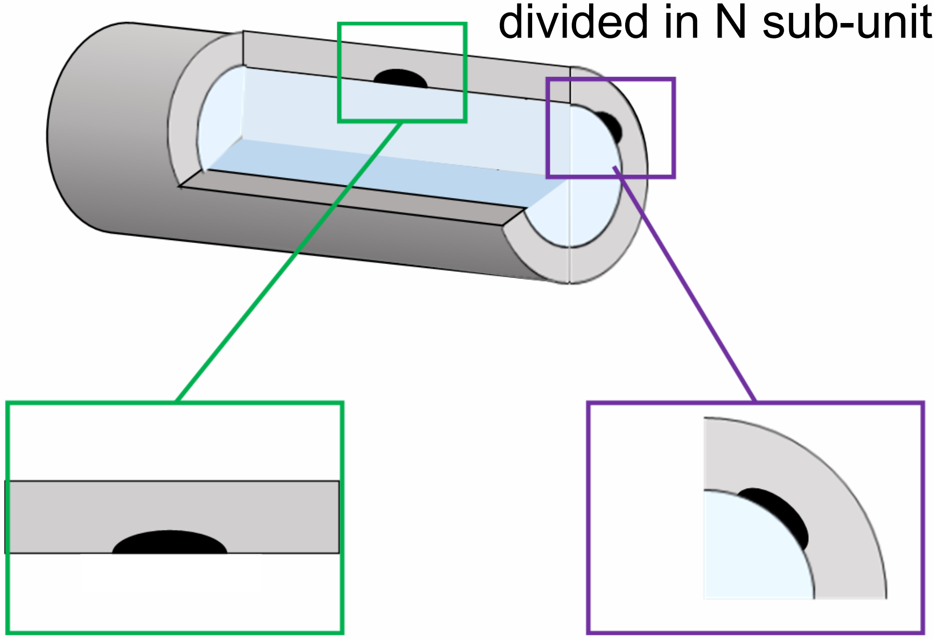
- The xLPR Framework is a GoldSim model that serves as the integrating shell linking the deterministic submodels
- GoldSim is a graphical-based probabilistic programming environment that embeds a dynamic simulation engine within a Monte Carlo simulation framework
  - Includes random sampling engines
    - Simple Random Sampling (SRS), Latin Hype importance sampling (IS)
  - Includes tools for parallelization
  - Maintains realization-specific information
  - Creates probabilistic graphical outputs

xLPR COMPONENT GEOMETRY MODELING



- Dissimilar metal welds are primary location of interest
- Idealized as distinct material groups
- All flaws initiate in the weld
- Axial flaws may grow into adjacent base metals

Circumference of pipe divided in N sub-units

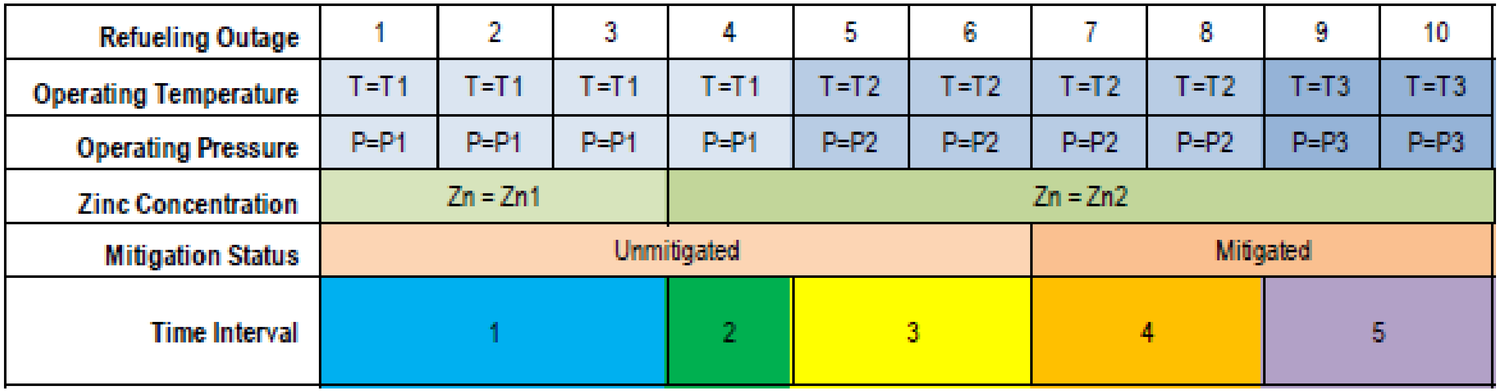


Axial cracks
(developed in different planes – do not coalesce)

Circumferential cracks
(all in the center of the weld – may coalesce)

TIME-EVOLUTION

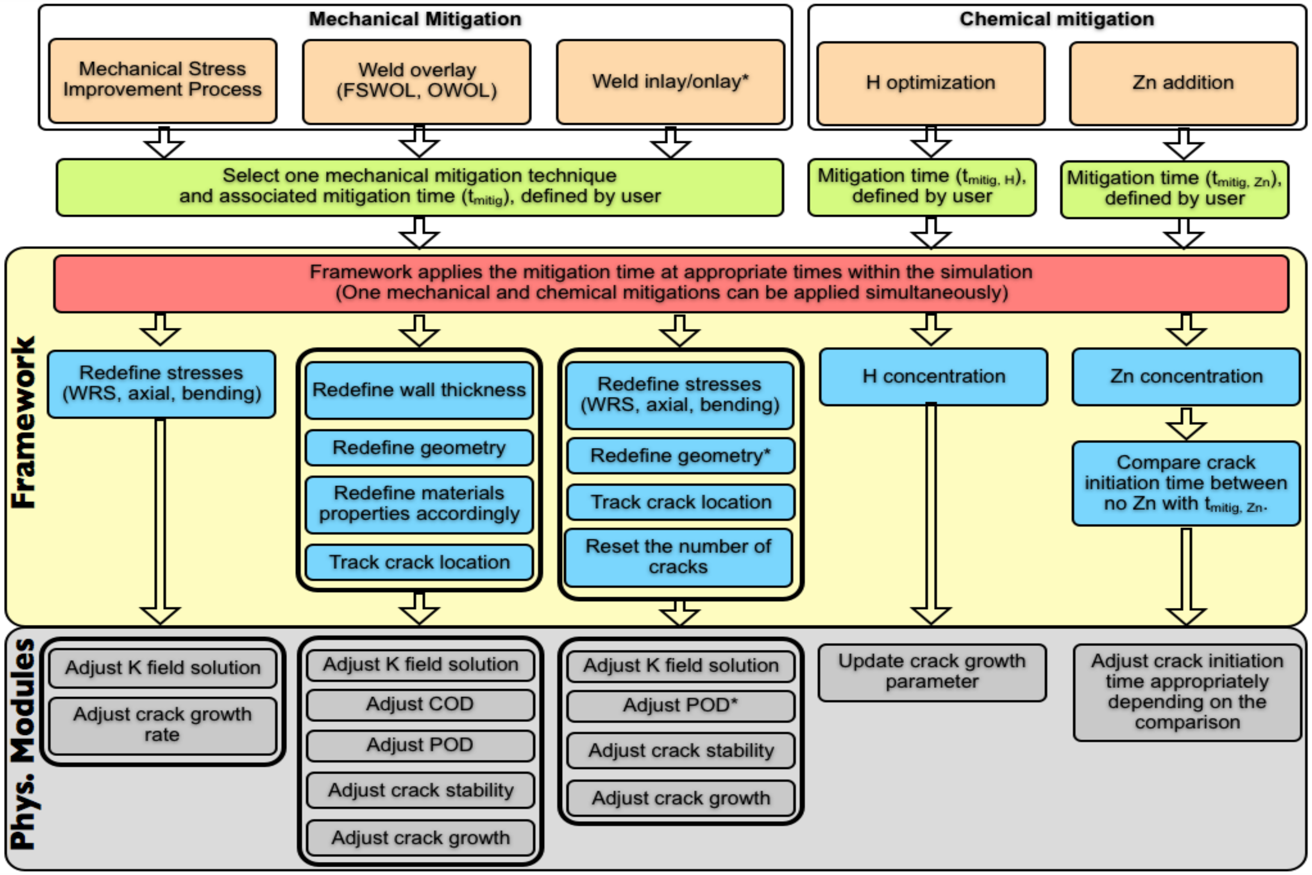
- Default one-month time steps
- Inputs applied based on operating period and mitigation status
  - Up to three operating periods may be represented
    - Defined by changes in pressure, temperature, dissolved oxygen, loads/stresses
  - Pre- and post-mitigation
    - Hydrogen (H2) and zinc (Zn) concentration, pipe geometry (presence of inlay/overlay), welding residual stress (WRS) profiles, inservice inspection (ISI) model parameters, weld/mitigation material properties



Refueling Outage	1	2	3	4	5	6	7	8	9	10
Operating Temperature	T=T1	T=T1	T=T1	T=T1	T=T2	T=T2	T=T2	T=T2	T=T3	T=T3
Operating Pressure	P=P1	P=P1	P=P1	P=P1	P=P2	P=P2	P=P2	P=P2	P=P3	P=P3
Zinc Concentration	Zn = Zn1			Zn = Zn2						
Mitigation Status	Unmitigated						Mitigated			
Time Interval	1			2	3		4		5	

MITIGATION MODELING

- A variety of mitigation techniques are included:
  - Weld overlays and inlays
  - Mechanical stress improvement (MSIP)
  - Chemical additions
- Mitigation may change:
  - Loading
  - Material
  - Environmental conditions
- Reflected as changes to module inputs



Mechanical Mitigation

Mechanical Stress Improvement Process

Weld overlay (FSWOL, OWOL)

Weld inlay/onlay*

Chemical mitigation

H optimization

Zn addition

Select one mechanical mitigation technique and associated mitigation time (t_{mitig}), defined by user

Mitigation time ($t_{mitig,\ H}$), defined by user

Mitigation time ($t_{mitig,\ Zn}$), defined by user

Framework

Framework applies the mitigation time at appropriate times within the simulation (One mechanical and chemical mitigations can be applied simultaneously)

Redefine stresses (WRS, axial, bending)

Redefine wall thickness

Redefine geometry

Redefine materials properties accordingly

Track crack location

Redefine stresses (WRS, axial, bending)

Redefine geometry*

Track crack location

Reset the number of cracks

H concentration

Zn concentration

Compare crack initiation time between no Zn with $t_{mitig,\ Zn}$.

Phys. Modules

Adjust K field solution

Adjust crack growth rate

Adjust K field solution

Adjust COD

Adjust POD

Adjust crack stability

Adjust crack growth

Adjust K field solution

Adjust POD*

Adjust crack stability

Adjust crack growth

Update crack growth parameter

Adjust crack initiation time appropriately depending on the comparison

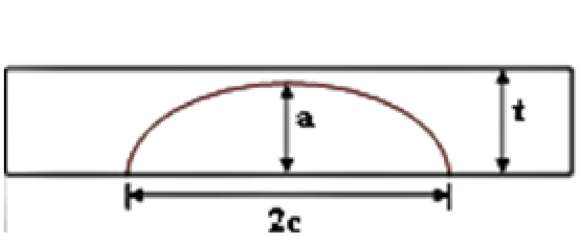
xLPR REFERENCES

- xLPR-GR-FW, “Computational Framework Development, Testing, and Analysis,” Version 1.0, January 2020.
- xLPR-UM-2.1, “User Manual for xLPR Version 2.1,” Version 1.0, May 2020.
- xLPR-TRN-Theory, “Training Manual, xLPR Code Theory,” Version 1.0, May 2020.
  - Pages 12-21 (Overview)
- xLPR-GR-IG, “Inputs Group Report,” Version 1.0, December 2017.

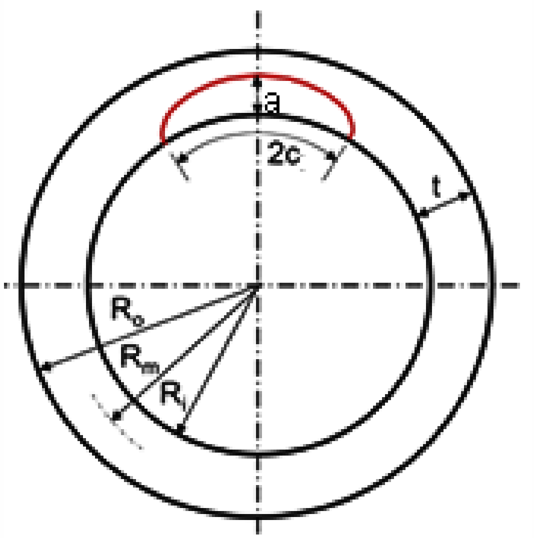
Deterministic Models Overview

FLAW TYPES IN xLPR

Part Through-Wall

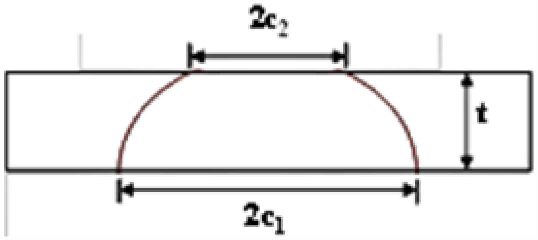


Axial

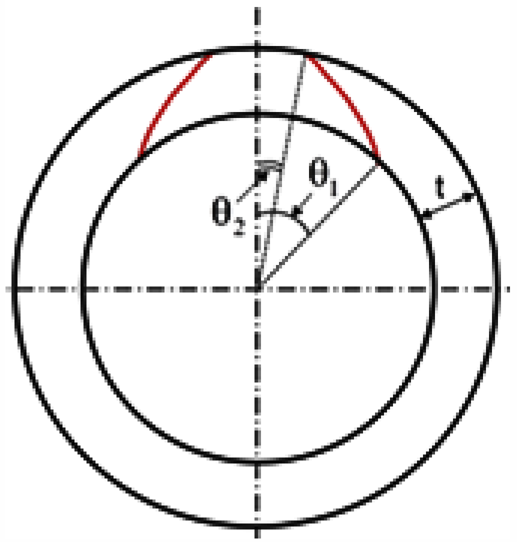


Circumferential

Transitioning Through-Wall

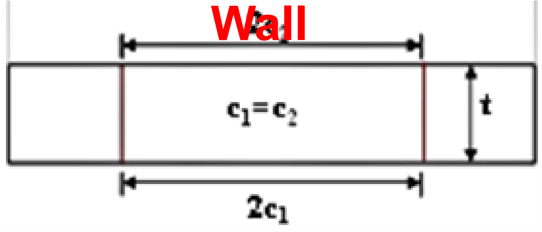


Axial

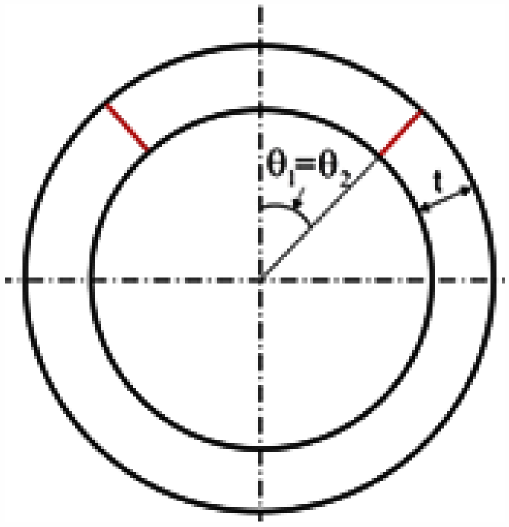


Circumferential

Idealized Through-Wall



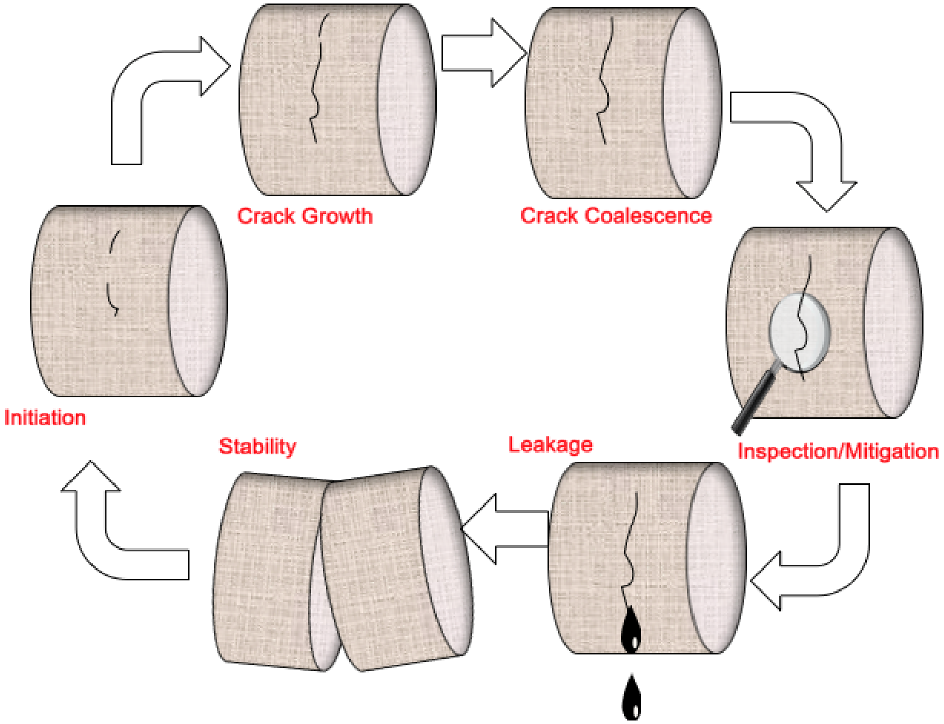
Axial



Circumferential

SIMULATED COMPONENT LIFE CYCLE

- xLPR uses submodels to simulate:
  - Crack initiation
  - Stress intensity factors
  - Crack growth
  - Coalescence
  - Transition
  - Crack Opening Displacement
  - Leak Rate
  - Crack stability
  - In-Service Inspection
- Each deterministic model is calibrated and validated against field/lab data



COMPONENT LOAD AND STRESS MODELING

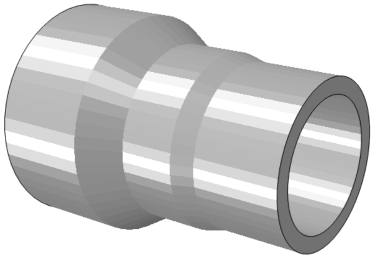
- Normal operating loads:
  - Pressure, deadweight, sustained thermal loads (e.g., thermal stratification loads)
  - Welding residual stresses
- Transient stresses:
  - Type I: Temperature-pressure time-transient – heat-up and cool-down transients or any normal/upset thermal transient. May include piping system global load due to thermal expansion
  - Type II: Thermal stratification transient (always associated with Type I)
  - Type III: Mechanical transient
  - Earthquake loads – low frequency with loads significantly higher than operational
- Transient Scheduling:
  - Up to 20 transients
  - User controlled (start time, end time, frequency, front-back loading, number of cycles)

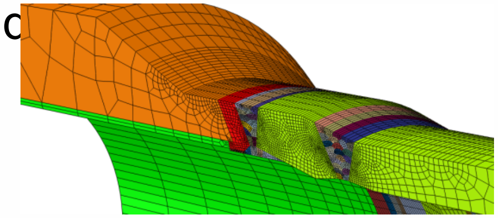
WELD RESIDUAL STRESS MODELING

- xLPR users can develop and implement their own WRS fields for nozzles that are different from those supplied
- WRS profiles are defined at 26 points through thickness of weld
  - Expressed as percent through-wall (may be scaled for pipe geometry)
  - Axisymmetric solutions
  - Both axial WRS (for circumferential cracks) and hoop WRS (for axial cracks) are considered
  - Before and after mitigation
- WRS profiles can be input as constant or normally distributed
  - For distributed inputs, the user can set a point-to-point correlation coefficient to mitigate the “saw-tooth” effect from sampling

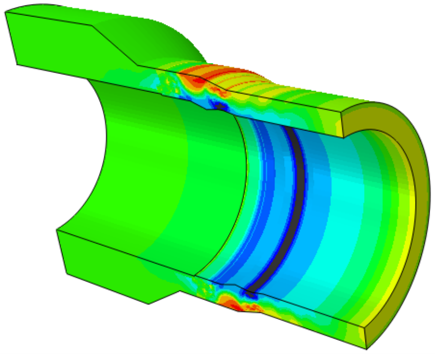
WELD RESIDUAL STRESS MODELING

- xLPR provides users with several example WRS profiles
- Three archetypical dissimilar metal welds studied wit finite element analysis (FEA):
  - Westinghouse reactor pressure vessel nozzle weld
  - Westinghouse steam generator nozzle weld
  - Babcock & Wilcox reactor coolant pump nozzle weld





- Modeled repair options:
  - No weld repair, 15% weld repair, 50% weld repair
- Modeled mitigation options (based on literature solutions):
  - None
  - Weld overlay (full-structural and optimized)
  - MSIP
  - Inlay



- Modeled uncertainty derived from variation betwee independently produced models considering the same general assumptions

LOAD AND STRESS REFERENCES

- xLPR-MSGR-WRS, “Welding Residual Stress Modeling Development for xLPR Version 2.0,” Version 1.0, October 2016.
- xLPR-TRN-Theory, “Training Manual, xLPR Code Theory,” Version 1.0, May 2020.
  - Pages 22-50 (Welding Residual Stresses)
- xLPR-UM-2.1, “User Manual for xLPR Version 2.1,” Version 1.0, May 2020.
  - Appendix E.2 (Stress)

STRESS INTENSITY FACTOR SOLUTIONS

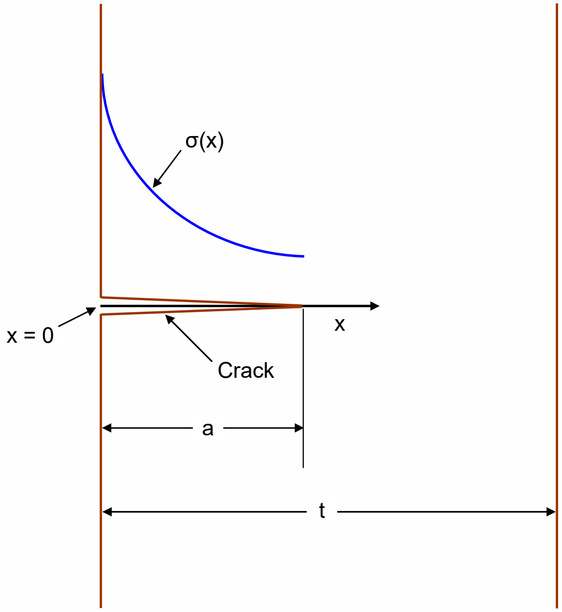
- Universal weight function method to calculate K_I:
  (expression shown is for part-through-wall cracks)

$$K_I\left(a,\sigma\left(x\right)\right)=\int_0^a m\left(x,a\right)\sigma\left(x\right)dx$$

$\sigma\left(x\right)=$ normal stress distribution at crack location

$a=$ crack depth

$m\left(x,a\right)=$ mode I weight function



- Calculated for:
  - Semi-elliptical part-through-wall cracks
  - Idealized through-wall cracks
  - Crack transition module applied for transitioning cracks

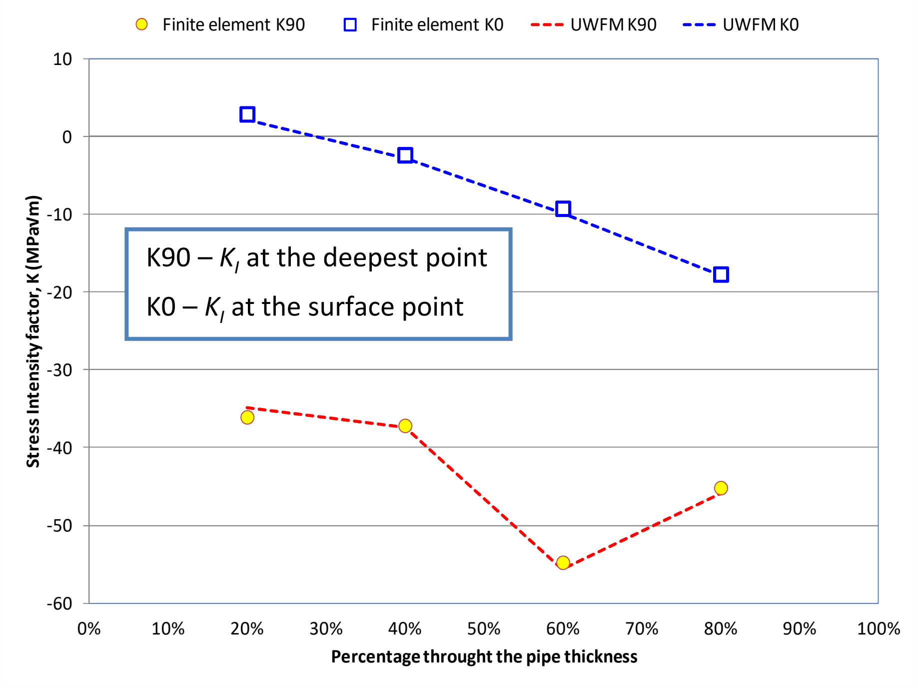
[Xu et al., PVP2011-57911, 2011]

[Zheng et al., EFM, 1997]

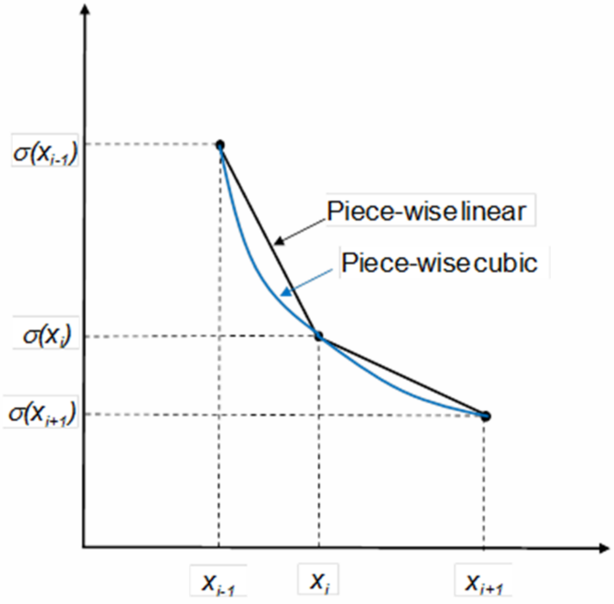
STRESS INTENSITY FACTOR SOLUTIONS

- Stress intensity factor calculated in closed-form using Universal Weight Function and piece-wise linear representation of actual stress distribution

- Accuracy confirmed with detailed FEA for highly non-linear



[Xu et al., PVP2011-57911, 2011]



$$\sigma_i(x) = k_i x + b_i \quad (i = 1, \ldots, n)$$

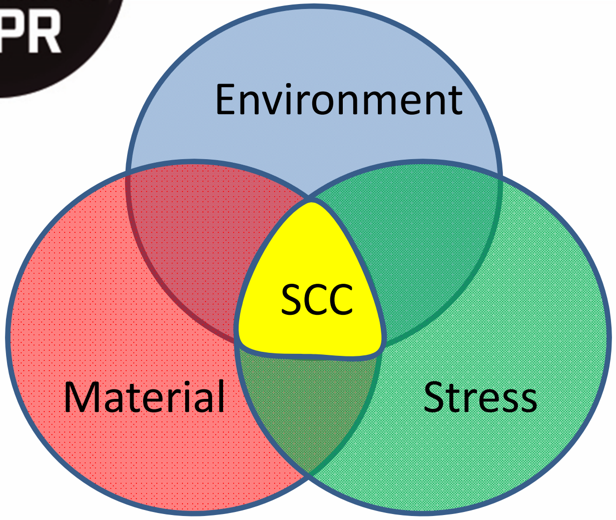
STRESS INTENSITY FACTOR
DUE TO TRANSIENTS AND CYCLIC LOADS

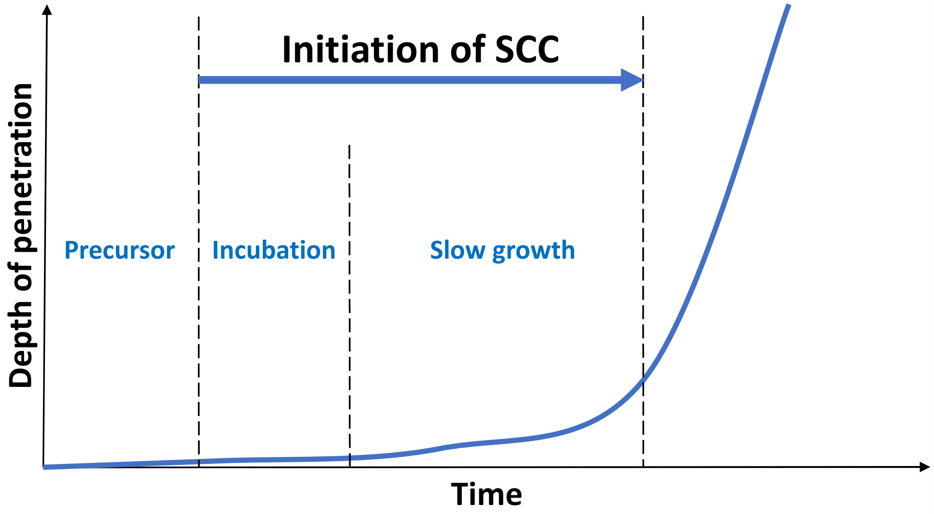
- Computes:
  - Cyclic stress intensity factors due to transients and cyclic loads
  - Transient rise-time
  - Cyclic stress at the pipe inner surface
- Treats radial gradient thermal stresses and thermal transients
- Considered three transient types:
  - Type 1 - Thermal transient
  - Type 2 - Stratification transient *(membrane and bending stresses input to TIFFANY)*
  - Type 3 - Mechanical transient *(membrane and bending stresses input to TIFFANY)*
- Builds look-up tables (TIFFANY outputs) as a function of crack shape for each transient
  - Look-up tables are read and interpolated by the Framework
- Outputs are used for fatigue crack initiation and growth

K SOLUTION REFERENCES

- xLPR-MSGR-KSol, “Surface and Through-Wall Crack Stress Intensity Factor Module Development,” Version 1.0, June 2016.
- xLPR-MSGR-TIFF, “Cyclic Stress Intensity Factors Due to Operating Transients – Module Development (TIFFANY),” Version 1.0, January 2016.
- xLPR-TRN-Theory, “Training Manual, xLPR Code Theory,” Version 1.0, May 2020.
  - Pages 51-61 (K-Solutions)
  - Pages 122-135 (Transient Modeling)
- xLPR-UM-2.1, “User Manual for xLPR Version 2.1,” Version 1.0, May 2020.
  - Appendix E.3 (K Solutions Modules)
  - Appendix E.4 (TIFFANY Preprocessing Module)

STRESS-CORROSION CRACKING (SCC) AND FATIGUE INITIATION

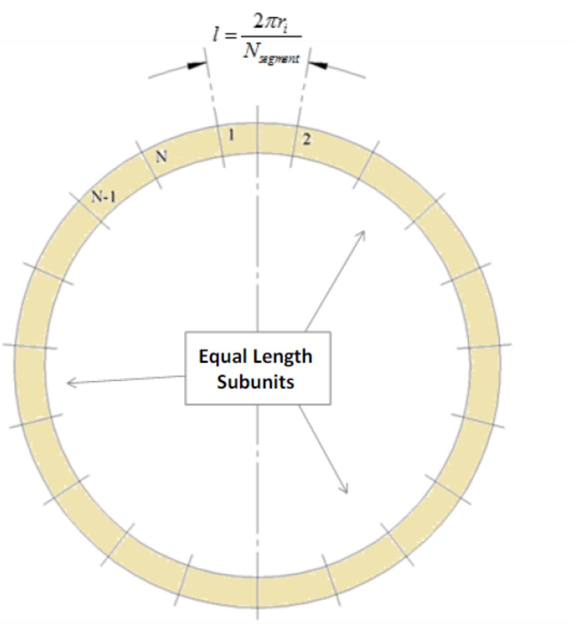




- For the purposes of xLPR, “initiation” is defined as the emergence of a flaw of engineering scale
  - Simulation of micro-sized flaws is not addressed in xLPR
- Crack initiation mechanisms considered:
  - Primary water stress-corrosion cracking (PWSCC) - 3 models available
  - Fatigue
  - Pre-existing flaws
- Operating experience, plant-specific data, and lab data used to calibrate models
- Incremental damage is calculated for each time interval and a Miner’s rule type of approach is used to calculate cumulative damage over time

CRACK INITIATION LOCATION

- Component is modeled with N equal length subunits
- All subunits have the same length in radians
- Subunit 1 is centered at zero radians, at top dead center of the weld
- Each subsequent subunit has one of its bounds coincidental with the bound of the previous subunit
- No subunits have finite overlap
- Initiation models are evaluated on a per-subunit basis
- Initiation is modeled separately for SCC and Fatigue
  - Initiation time is based on whichever is modeled to occur first (SCC or Fatigue)
- Circumferential location of the crack within a subunit is determined by sampling uniformly over the circumferential bounds of the current



CRACK INITIATION MODELS

PWSCC

- **Direct Model 1** is in accordance with Env. Deg. references (Amzallag 1999, Daret 2005)
  - Material index approach
  - Initiation time is calculated directly as a function of temperature and surface stress
- **Direct Model 2** is in accordance with EPRI 1019032 and 1025121 (Garud)
  - Cold work SCC initiation (CW-SCC) model
  - Initiation time is calculated directly as a function of temperature, surface stress, level of cold work, and mechanical material properties
- **Weibull model** is a classic approach for reliability engineering and failure analysis
  - Statistical approach using plant data
  - The Weibull model determines initiation time by sampling from a Weibull distribution

Fatigue

Fatigue initiation model is based on probabilistic fatigue life curves similar to those developed in NUREG/CR-6909 and CR-6674

$$\boxed{\ln(N) = C_0 + C_{env} - \frac{1}{b}\ln(\varepsilon_a - \varepsilon_\infty) - \ln(f_{surf}) + \ln(f_{load}) + \ln(f_{cal})}$$

N = number of cycles to initiation

C_0 = scaling parameter (sampled input)

ε_∞ = endurance limit strain (sampled input)

ε_a = strain amplitude (calculated)

C_{env} = deterministic environmental term (calculated)

f_{surf} =surface finish effect parameter (sampled input)

f_{load} =load sequence effect parameter (sampled input)

f_{cal} =calibration parameter (sampled input)

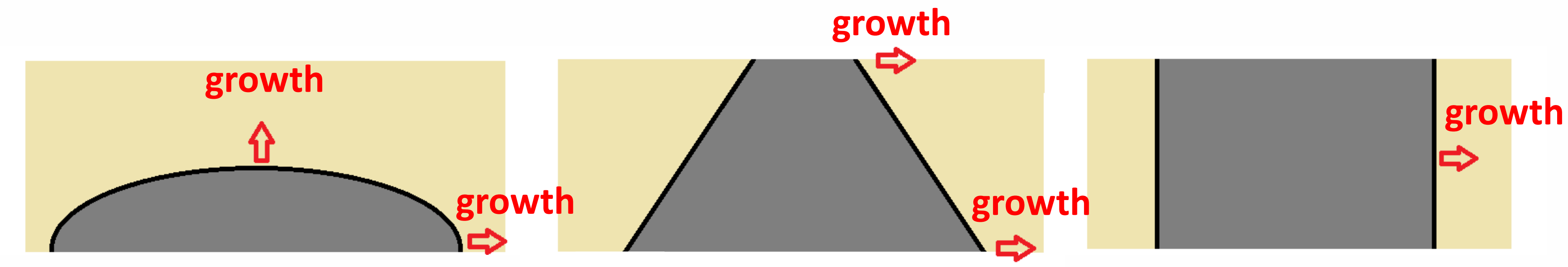
[Chopra et al., *NUREG/CR–6909*, 2007]

CRACK INITIATION REFERENCES

- xLPR-MSGR-CI, “PWSCC & Fatigue Crack Initiation Module Development,” Version 1.0, August 2016.
- xLPR-TRN-Theory, “Training Manual, xLPR Code Theory,” Version 1.0, May 2020.
  - Pages 62-87 (PWSCC Initiation)
  - Pages 107-121 (Fatigue Crack Initiation and Growth)
- xLPR-UM-2.1, “User Manual for xLPR Version 2.1,” Version 1.0, May 2020.
  - Appendix E.5 (Crack Initiation (CI) Module)

CRACK GROWTH MODELING CHOICES

- Idealized flaw shapes (semi-elliptical, straight) are assumed for crack representation
- PWSCC and fatigue growth mechanisms are assumed to be independent from one another.
- **Missing dependencies:** some known dependencies are not accounted for explicitly and are instead part of the crack growth rate (CGR) model uncertainty:
  - Orientation, cold work and residual plastic deformation, differences in growth near weld interfaces (heat affected zone, dilution zone…)



PWSCC CRACK GROWTH MODEL

- Dependencies: $\dot{a}_{\text{PWSCC}} = \frac{1}{IF} f_{K_I} f_T f_{H_2} f_{\text{comp}} f_{\text{flaw}}$
  - Stress intensity factor (K) dependency: $f_{K_I} = \alpha \left(K_I - K_{th}\right)^{\beta}$
  - Temperature dependency: $f_T = \exp\left(-\frac{Q}{R}\left[\frac{1}{T} - \frac{1}{T_{ref}}\right]\right)$
  - H_2 dependency: $f_{H_2} = f\left(\log_{10}\left(\left[H_2\right]\right), T\right)$
  - Component-to-component (f_{comp}) and within-component variation (f_{flaw}) factors
- CGR model parameters have been developed for Alloy 600 and Alloy 82/182/132 (including and excluding effect of H_2)
- Other alloys can be modeled using the “custom model” for model forms compatible with the expressions shown above

[White et al., *TMS AM 2005*, 2005]

FATIGUE CRACK GROWTH MODEL

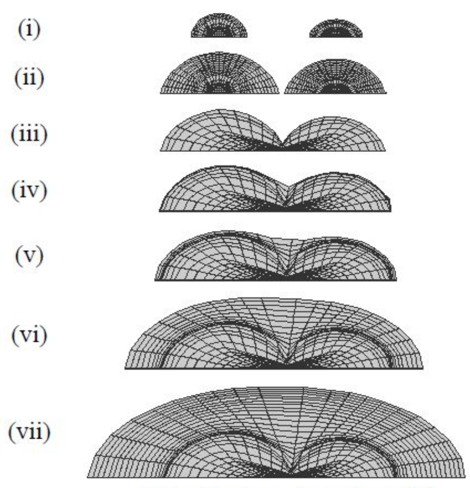
- Material-specific models:
  - Ni-based alloy in accordance with NUREG/CR-6721
  - Austenitic stainless steel in accordance with American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code Case N-809
  - Ferritic steels in accordance with ASME B&PV Code Case N-643-2
- Models use Paris law with additional dependencies
- Model considerations
  - Nominal temperature (calculated from min and max temperatures)
  - Load ratio ($R = K_{min}/K_{max}$)
  - Stress intensity factor range ($\Delta K = K_{max} - K_{min}$)
  - Rise time
  - Stress intensity factor range threshold
  - Scheduling of transients in component life-time will dictate when fatigue crack growth is applied

[Chopra et al., *NUREG/CR–6721*, 2010]

[Eason et al., *Welding Research Council Bulletin*, 1995]

COALESCENCE MODEL

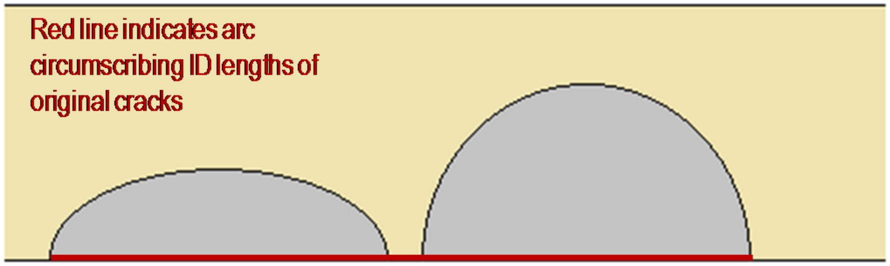
- **Rule-based pairwise coalescence:**
  - Rule-based model is applied to determine whether or not coalescence will occur
  - Rules vary for different pairwise combinations based on crack type
  - All instances of coalescence occur between two cracks at a time
  - Three or more cracks close enough to coalesce at the same is considered extremely rare
    - This is handled by two or more sequential instances of pairwise coalescence
- **Crack interaction:**
  - All circumferential cracks are assumed to be coplanar
  - Axial cracks do not interact with each other or with circumferential cracks



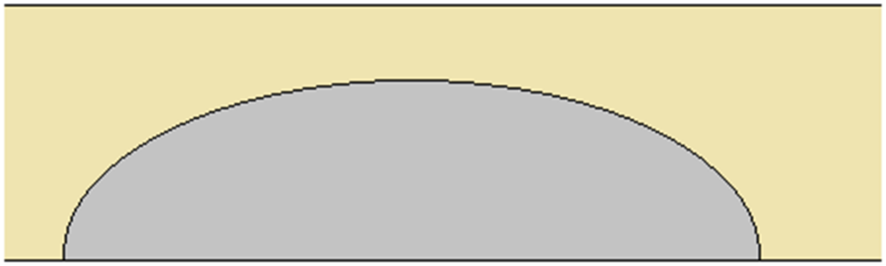
(a) Coalesced crack model

[Kikuchi *AIMS Mat. Sci.*, 2016]

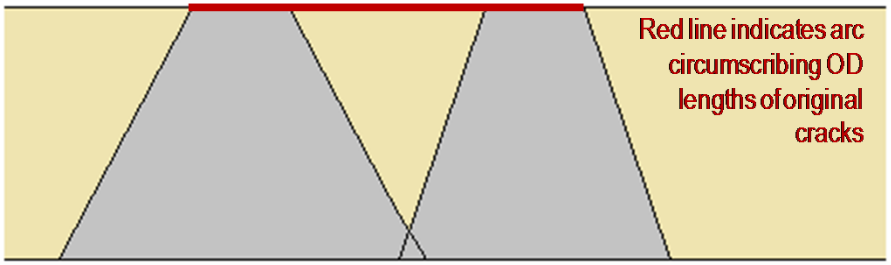
COALESCENCE RULES



Surface crack + Surface crack



Coalesced surface crack



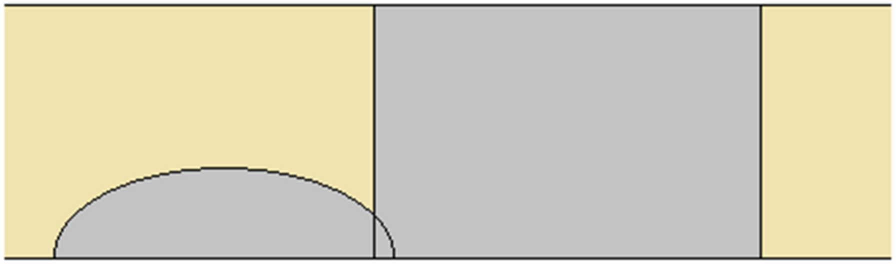
Transitioning crack + Transitioning crack

Coalesced transitioning crack

Through-wall crack + Transitioning crack

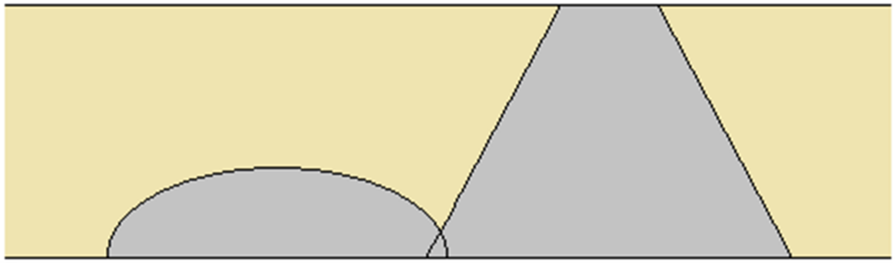
Coalesced through-wall crack

COALESCENCE RULES

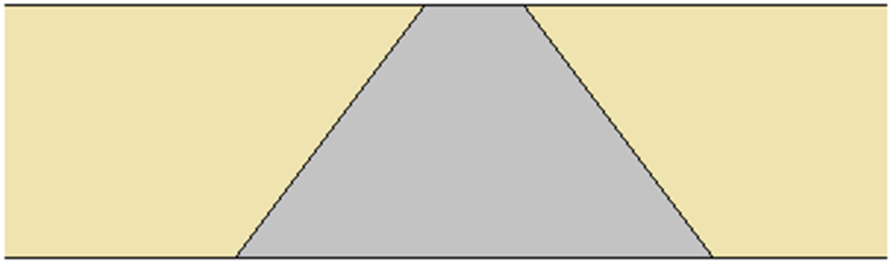


Surface crack + Through-wall crack

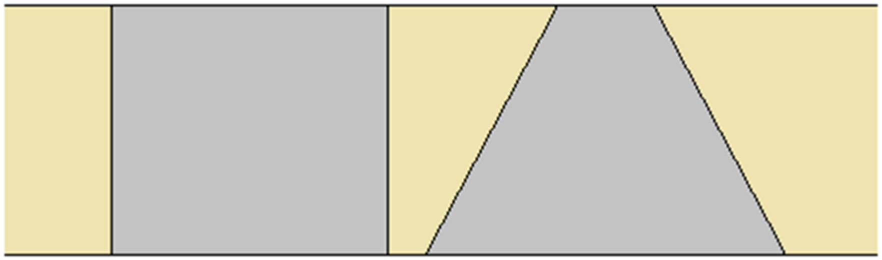
Coalesced transitioning crack



Surface crack + Transitioning crack



Coalesced transitioning crack



Through-wall crack + Transitioning crack

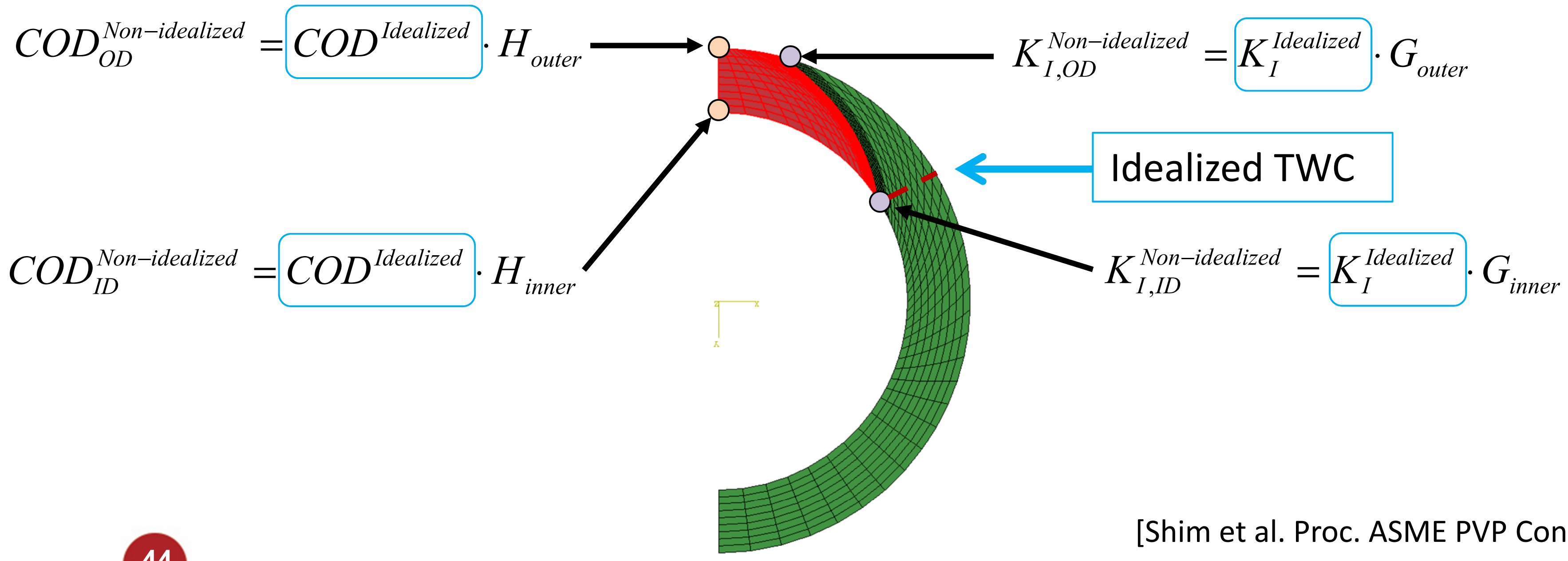
Coalesced transitioning crack

CRACK GROWTH AND COALESCENCE REFERENCES

- xLPR-MSGR-CGR, “PWSCC & Fatigue Crack Growth and Coalescence Module Development,” Version 1.0, June 2016.
- xLPR-TRN-Theory, “Training Manual, xLPR Code Theory,” Version 1.0, May 2020.
  - Pages 88-106 (PWSCC Growth)
  - Pages 107-121 (Fatigue Crack Initiation and Growth)
  - Pages 136-143 (Crack Coalescence)
- xLPR-UM-2.1, “User Manual for xLPR Version 2.1,” Version 1.0, May 2020.
  - Appendix E.6 (Crack Growth Rate (CGR) Module)
  - Appendix E.7 (Crack Coalescence Module)

SURFACE CRACK TO THROUGH-WALL CRACK TRANSITION

- Crack transition model developed to better approximate leak rate response as crack grows through-wall
- Correction factors are applied to K solutions (“G”) and crack-opening displacement (COD) solutions (“H”) to approximate non-idealized through-wall flaws



$$COD_{OD}^{Non-idealized} = \boxed{COD^{Idealized}} \cdot H_{outer}$$

$$K_{I,OD}^{Non-idealized} = \boxed{K_{I}^{Idealized}} \cdot G_{outer}$$

Idealized TWC

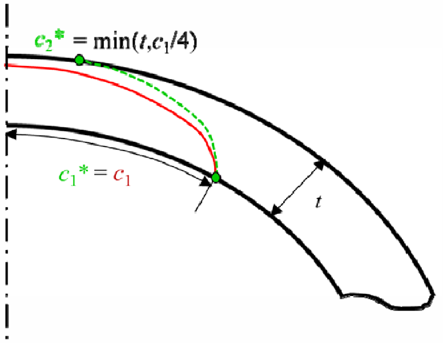
$$COD_{ID}^{Non-idealized} = \boxed{COD^{Idealized}} \cdot H_{inner}$$

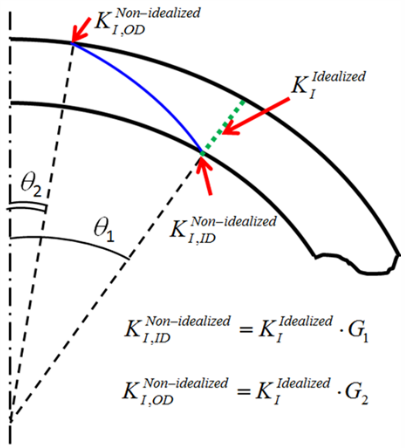
$$K_{I,ID}^{Non-idealized} = \boxed{K_{I}^{Idealized}} \cdot G_{inner}$$

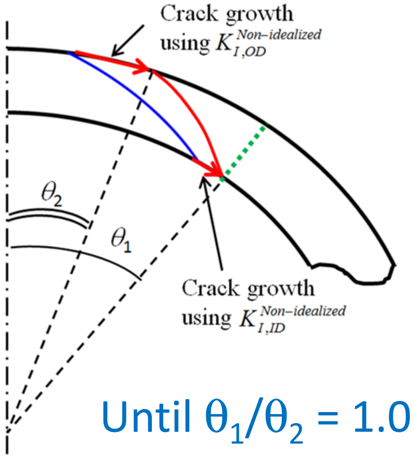
[Shim et al. Proc. ASME PVP Conf., 2011]

TRANSITIONING THROUGH-WALL CRACK EVOLUTION

Circumferential crack

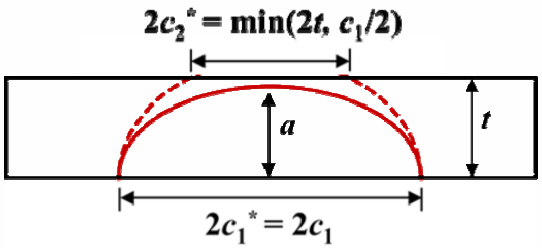


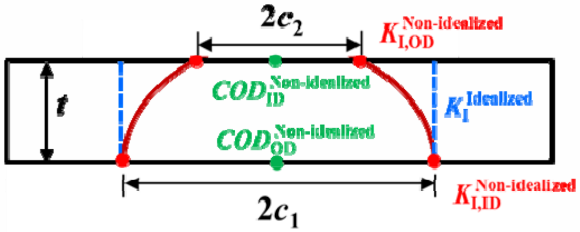


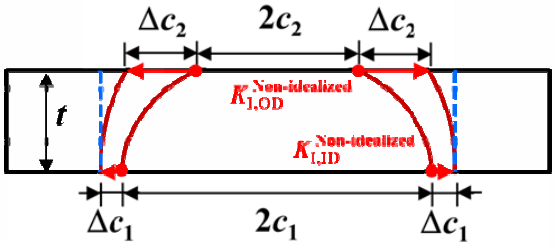


Until $\theta_1/\theta_2 = 1.05$

Axial crack







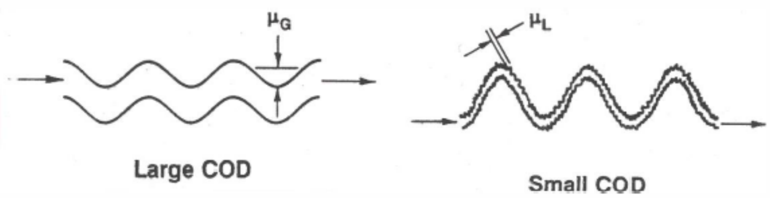
Until $c_1/c_2 = 1.05$

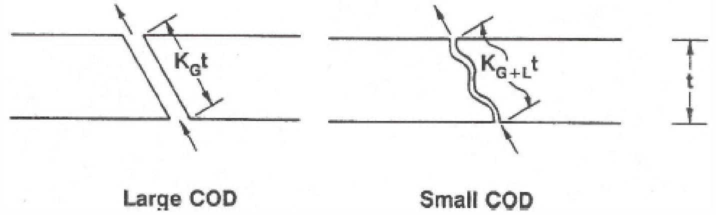
CRACK TRANSITION REFERENCES

- xLPR-MSGR-CTM, “Surface-to-Through-Wall Crack Transition Module Development,” Version 1.0, April 2016.
- xLPR-TRN-Theory, “Training Manual, xLPR Code Theory,” Version 1.0, May 2020.
  - Pages 144-155 (Crack Transition)
- xLPR-UM-2.1, “User Manual for xLPR Version 2.1,” Version 1.0, May 2020.
  - Appendix E.8 (Crack Transition Module)

CRACK OPENING DISPLACEMENT MODELING

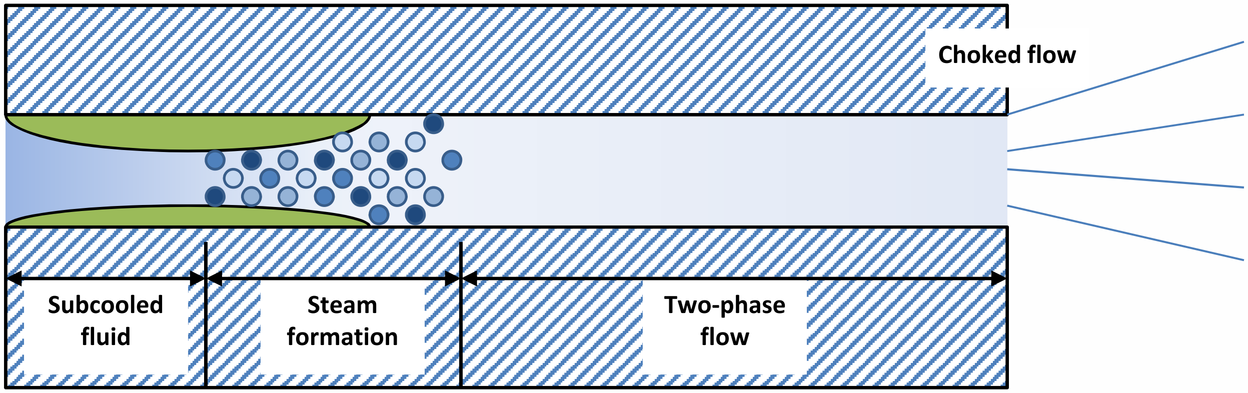
- COD is required for leakage prediction
- COD models for circumferential and axial through-wall cracks
  - Based on General Electric / EPRI methodology
  - Both models use influence function fits to FEA results with elastic and plastic contributions
  - Implemented as look-up tables with respect to component geometry, crack length, and hardening exponents
  - Solutions at outside diameter, inside diameter, and mid-thickness
- Circumferential model is applicable for bending, tensile, and pressure loads
  - Weld residual stresses are not addressed given tendency to balance in axial direction
- Axial model is applicable for pressure loads
  - Weld residual stresses are included as an equivalent effective pressure based on thro





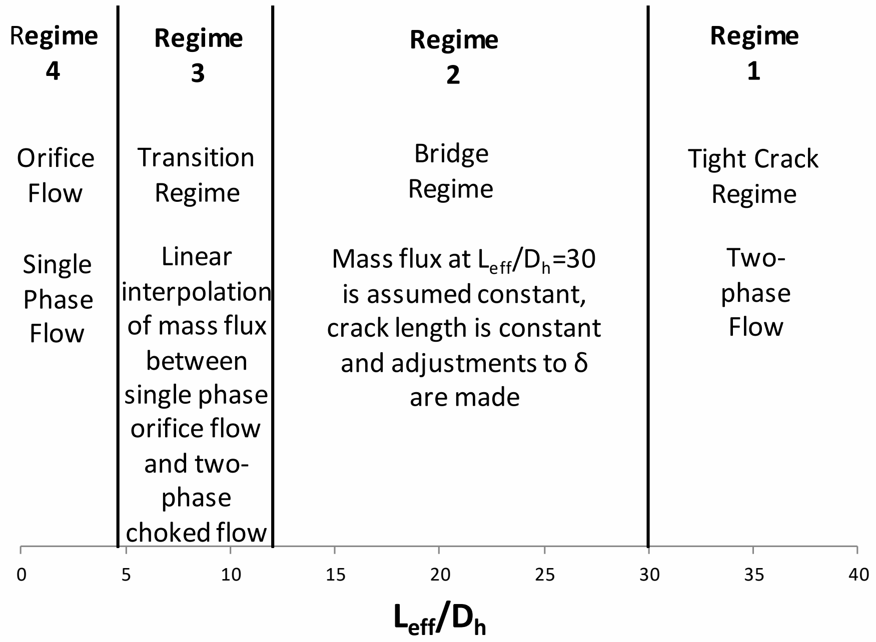
LEAK RATE MODEL

- LEAPOR produces look-up tables that are used to determine leakage rate based on the results of the COD calculation
  - Includes thermohydraulic model for tight cracks where fluid flashes to steam (Henry-Fauske model for two-phase flow)
  - Also includes orifice flow model (single phase subcooled liquid)
  - Surface roughness, number of turns, and actual flow path length are key crack morphology parameters
  - Leak rates are calculated assuming an idealized crack shape
- Two use modes available: single use mode and preprocessing mode

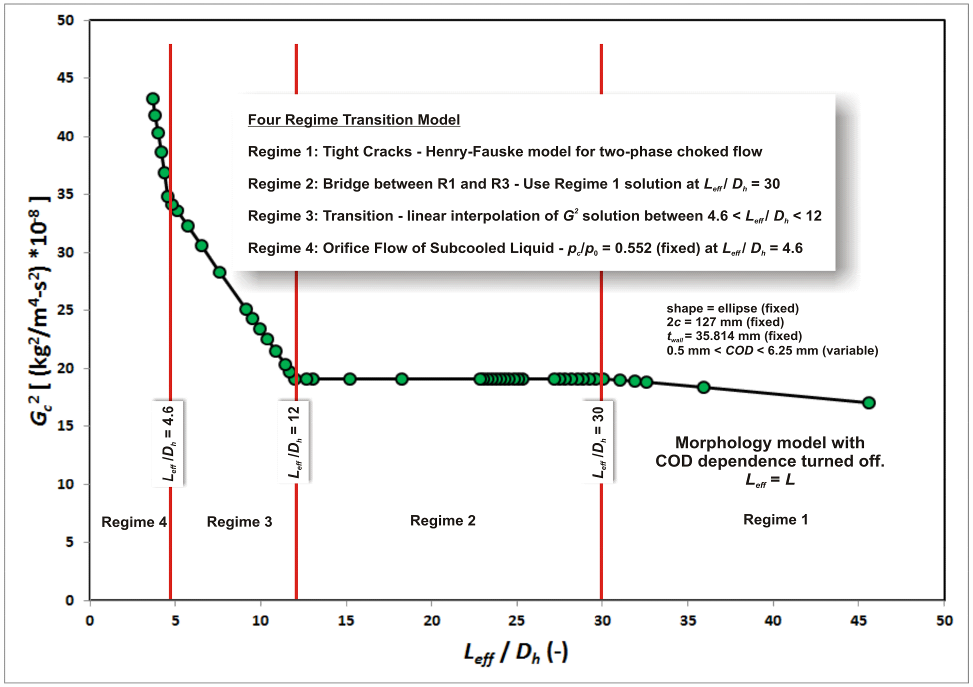


LEAK RATE MODEL FLOW REGIMES

- Four fluid flow regimes are defined to produce smooth transition between tight crack and orifice flow regimes



Regime 4	Regime 3	Regime 2	Regime 1
Orifice Flow	Transition Regime	Bridge Regime	Tight Crack Regime
Single Phase Flow	Linear interpolation of mass flux between single phase orifice flow and two-phase choked flow	Mass flux at L_{eff}/D_h=30 is assumed constant, crack length is constant and adjustments to δ are made	Two-phase Flow



Four Regime Transition Model

Regime 1: Tight Cracks - Henry-Fauske model for two-phase choked flow

Regime 2: Bridge between R1 and R3 - Use Regime 1 solution at $L_{eff}/D_h = 30$

Regime 3: Transition - linear interpolation of G^2 solution between $4.6 < L_{eff}/D_h < 12$

Regime 4: Orifice Flow of Subcooled Liquid - $p_c/p_0 = 0.552$ (fixed) at $L_{eff}/D_h = 4.6$

COD AND LEAK RATE REFERENCES

- xLPR-MSGR-COD, “Summary of the xLPR Version 2.0 Crack Opening Displacement (COD) Modules,” Version 1.0, April 2016.
- xLPR-MSGR-LRM, “Leak Rate Module Development (LEAPOR),” Version 1.1, September 2016.
- xLPR-TRN-Theory, “Training Manual, xLPR Code Theory,” Version 1.0, May 2020.
  - Pages 243-263 (Circumferential Crack Opening Displacement)
  - Pages 264-283 (Axial Crack Opening Displacement)
  - Pages 284-313 (Leakage Rate Calculations)
- xLPR-UM-2.1, “User Manual for xLPR Version 2.1,” Version 1.0, May 2020.
  - Appendix E.10 (Crack Opening Displacement)
  - Appendix E.11 (Leak Rate Module)

COMPONENT STABILITY MODELING

- Multiple stability modules are included in xLPR
  - Circumferential cracks:
    - SC_fail and TWC_fail
  - Axial cracks:
    - Axial_SC_fail and Axial_TWC_fail (Combined in AxCS documentation)
- Models generally output:
  - Predicted rupture (true/false)
  - Ratio of current applied loads to critical loads (for surface cracks)
  - Ratio of current crack size to critical crack size (for through-wall cracks)
- Rupture due to seismic conditions is considered:
  - If seismic conditions exceed stability limits, then rupture (given seismic conditions) is recorded, but realization progresses
  - If normal operating plus transient loads exceed stability limits, then rupture is recorded and time-evolution for realization is ended

CIRCUMFERENTIAL CRACK STABILITY MODELING

- Surface Cracks:
  - If one or more surface cracks exists, a multiple net-section-collapse (NSC) model is used to evaluate stability (Li and Rahman)
    - Applicable for one or more circumferential cracks
    - Surface cracks are modeled as constant-depth
  - No elastic-plastic fracture mechanics (EPFM) model is implemented for surface cracks
- Through-Wall Cracks:
  - If there is at least one through-wall crack, both NSC and EPFM models are used
    - Through-wall cracks are modeled as idealized through-wall
    - Performed on each flaw individually
  - NSC model (Kanninen and Zahoor)
    - Also considers all circumferential flaws (part-wall and through-wall) present in the component
  - LBB.ENG2 EPFM model (Brust and Gilles)
  - Solution that yields the smallest critical crack size is used for output

AXIAL CRACK STABILITY MODELING

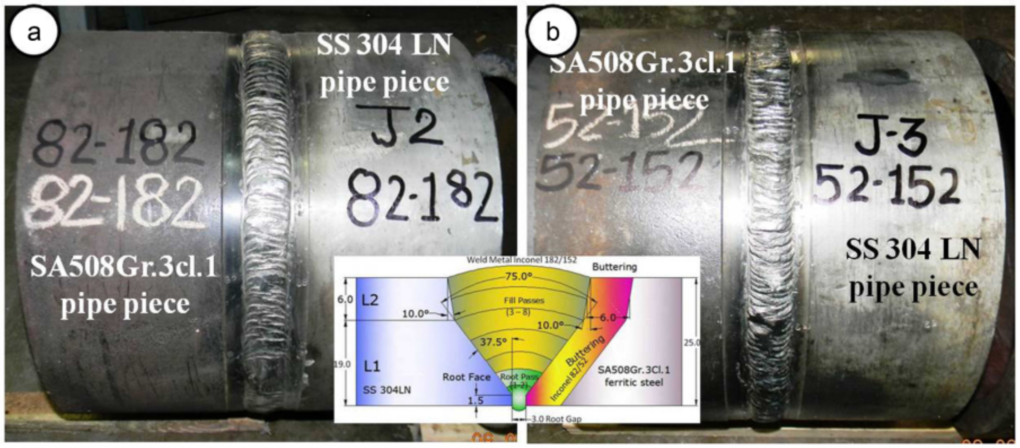
- Surface cracks:
  - Plastic collapse analysis from Ductile Fracture Handbook (Zahoor)
    - Cracks are modeled as constant-depth
- Through-wall cracks:
  - Both limit load and EPFM models are used
    - Cracks are modeled as idealized through-wall
  - Limit load solution in Ductile Fracture Handbook (Zahoor)
  - EPFM analysis in the spirit of General Electric / EPRI method (Kim, et al.)
  - Solution that yields the smallest critical crack size is used for output
- Axial crack stability is evaluated on a per-crack basis (no interaction between multiple axial cracks)

CRACK STABILITY REFERENCES

- xLPR-MSGR-Stability, “Axial and Circumferential Crack Stability Module Development,” Version 1.0, June 2016.
- xLPR-TRN-Theory, “Training Manual, xLPR Code Theory,” Version 1.0, May 2020.
  - Pages 156-168 (Circumferential Through-Wall Crack Stability)
  - Pages 169-179 (Circumferential Surface Crack Stability)
  - Pages 180-191 (Axial Crack Stability)
- xLPR-UM-2.1, “User Manual for xLPR Version 2.1,” Version 1.0, May 2020.
  - Appendix E.9 (Crack Stability)

ISI MODELING CHOICES

- **Inspection models** use probability of detection (POD) as a function of crack depth.
- **Evaluation model** uses a crack sizing model and a repair threshold to calculate probability of repair.
- **Missing dependencies:** the inspection and sizing model use only depth as an independent variable. Other crack attributes (e.g., length, COD) may also influence detectability and measured flaw size. They are instead **part of the ISI model uncertainty**.

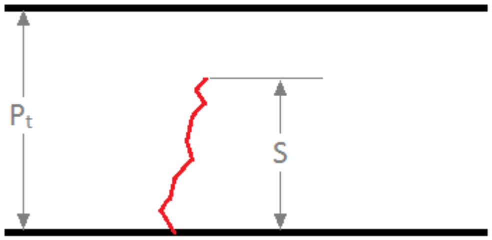


[Rathod et al. JPVT, 2015]

Materials Reliability Program: Development of Probability of Detection Curves for Ultrasonic Examination of Dissimilar Metal Welds (MRP-262, Revision 3): Typical PWR Leak-Before Break Line Locations. EPRI, Palo Alto, CA: 2017. 3002010988.

INSPECTION MODEL

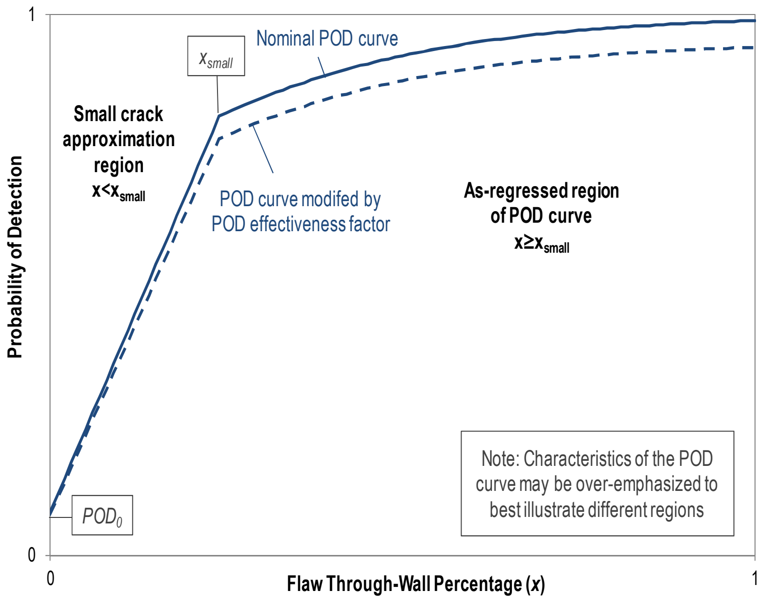
- **Flaw percentage:** $x = \dfrac{\text{flaw size}}{\text{pipe thickness}}$



- **Probability of Detection (POD)**

$$POD(x,t) = \frac{e^{(\beta_0+\beta_1 x_{POD})}}{1+e^{(\beta_0+\beta_1 x_{POD})}}$$

  - Suitable for fitting experimental data
  - Wide acceptance
  - Used for many successful applications



Note: Characteristics of the POD curve may be over-emphasized to best illustrate different regions

- **Small crack POD approximation:**
  - User-defined parameter for linear approximation

$$POD_{\text{small}} = POD_0 + \left[POD\left(x_{\text{small}}\right) - POD_0\right] \frac{x}{x_{\text{small}}}$$

EVALUATION AND REPAIR MODEL

- **Sizing model:** $M = ax + b + \epsilon$
  - *a* and *b* are random variables from model fit
  - Sizing model well-accepted approach for characterizing sizing accuracy
  - Error term ϵ

- **Probability of repair (POR):**
  - User-defined repair threshold

$$POR = p\left(M > x_{\text{repair}}\right) = p\left(\epsilon > x_{\text{repair}} - ax - b\right)$$

- The xLPR Framework models repairs as “perfect”
  - Probability of additional initiation, leakage, ruptures, etc. is zero for the remainder of the simulation

INSERVICE INSPECTION REFERENCES

- xLPR-MSGR-ISI, “In-Service Inspection (ISI) Module Development,” Version 1.0, June 2016.
- xLPR-TRN-Theory, “Training Manual, xLPR Code Theory,” Version 1.0, May 2020.
  - Pages 192-225 (Inservice Inspection Model Parameter Development)
  - Pages 226-242 (Inservice Inspection Model Implementation)
- xLPR-UM-2.1, “User Manual for xLPR Version 2.1,” Version 1.0, May 2020.
  - Appendix E.12 (In-Service Inspection)

Questions and Answers

QUESTIONS?
(RAISE HAND)

Webex Internet Browser

Webex Desktop Client

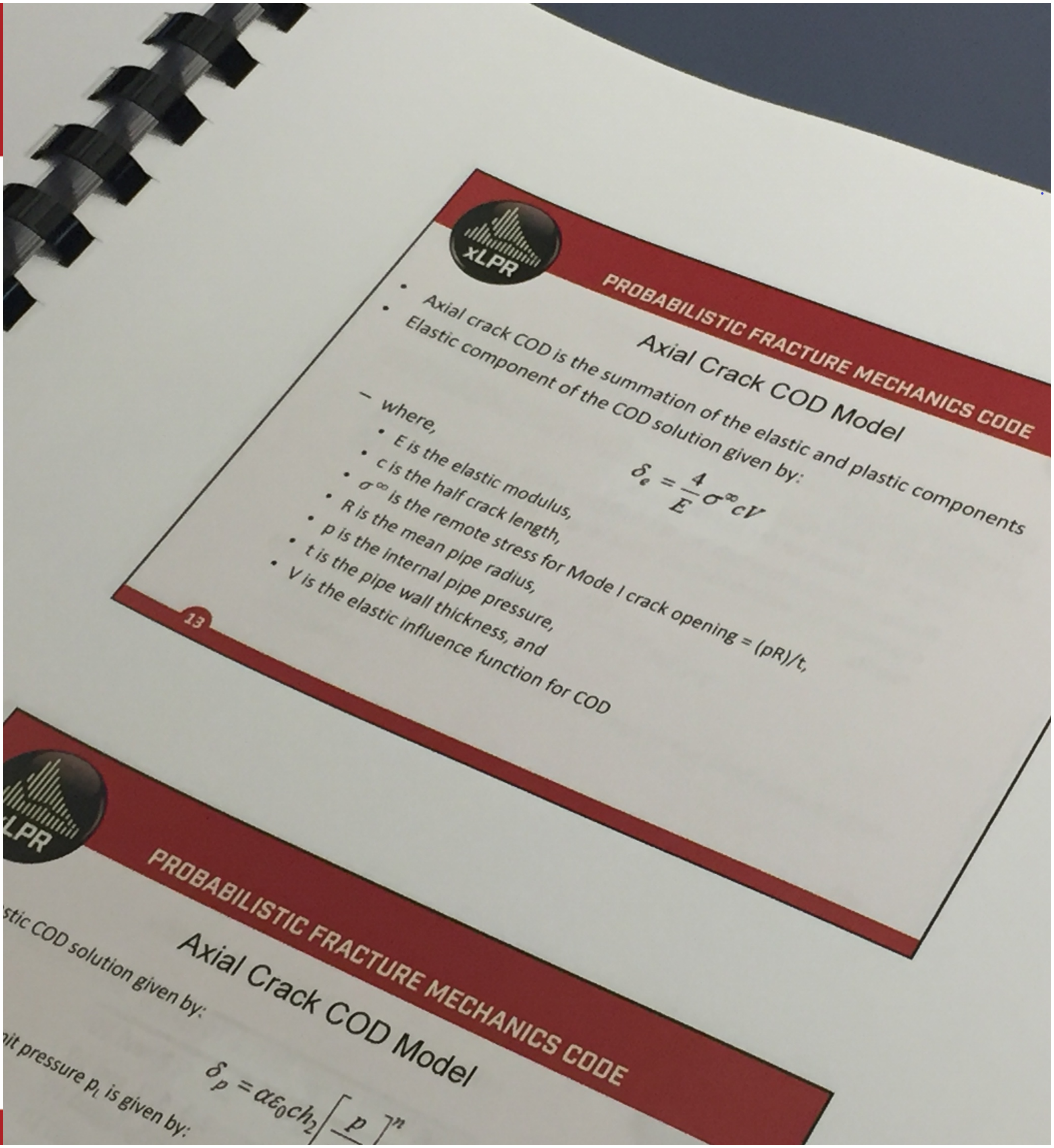
Closing Remarks

FUTURE EVENTS

1. **Setting Up the Inputs**
   Tentatively July 1st
2. **Running the Simulation**
   Tentatively July 15th
3. **Accessing Results**
   Tentatively July 29th

Recommended Review Before "Setting Up the Inputs":

- xLPR Input Set (xLPR-2.1 Input Set.xlsx)
- Inputs section (Module 3) of xLPR-TRN-Introduction
- User Manual (Section 3.3 and Appendix B)



PROBABILISTIC FRACTURE MECHANICS CODE

Axial Crack COD Model

- Axial crack COD is the summation of the elastic and plastic components
- Elastic component of the COD solution given by:

$$\delta_e = \frac{4}{E}\sigma^{\infty} c V$$

- where,
  - E is the elastic modulus,
  - c is the half crack length,
  - σ^{∞} is the remote stress for Mode I crack opening = (pR)/t,
  - R is the mean pipe radius,
  - p is the internal pipe pressure,
  - t is the pipe wall thickness, and
  - V is the elastic influence function for COD

13

PROBABILISTIC FRACTURE MECHANICS CODE

Axial Crack COD Model

stic COD solution given by:

$$\delta_p = \alpha \varepsilon_0 c h_2 \left[\frac{p}{} \right]^n$$

it pressure p_l is given by:

Questions?

xlpr@nrc.gov

xlpr@epri.com