xLPR PIB Meeting
Computational Framework and Alpha Program Plan

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

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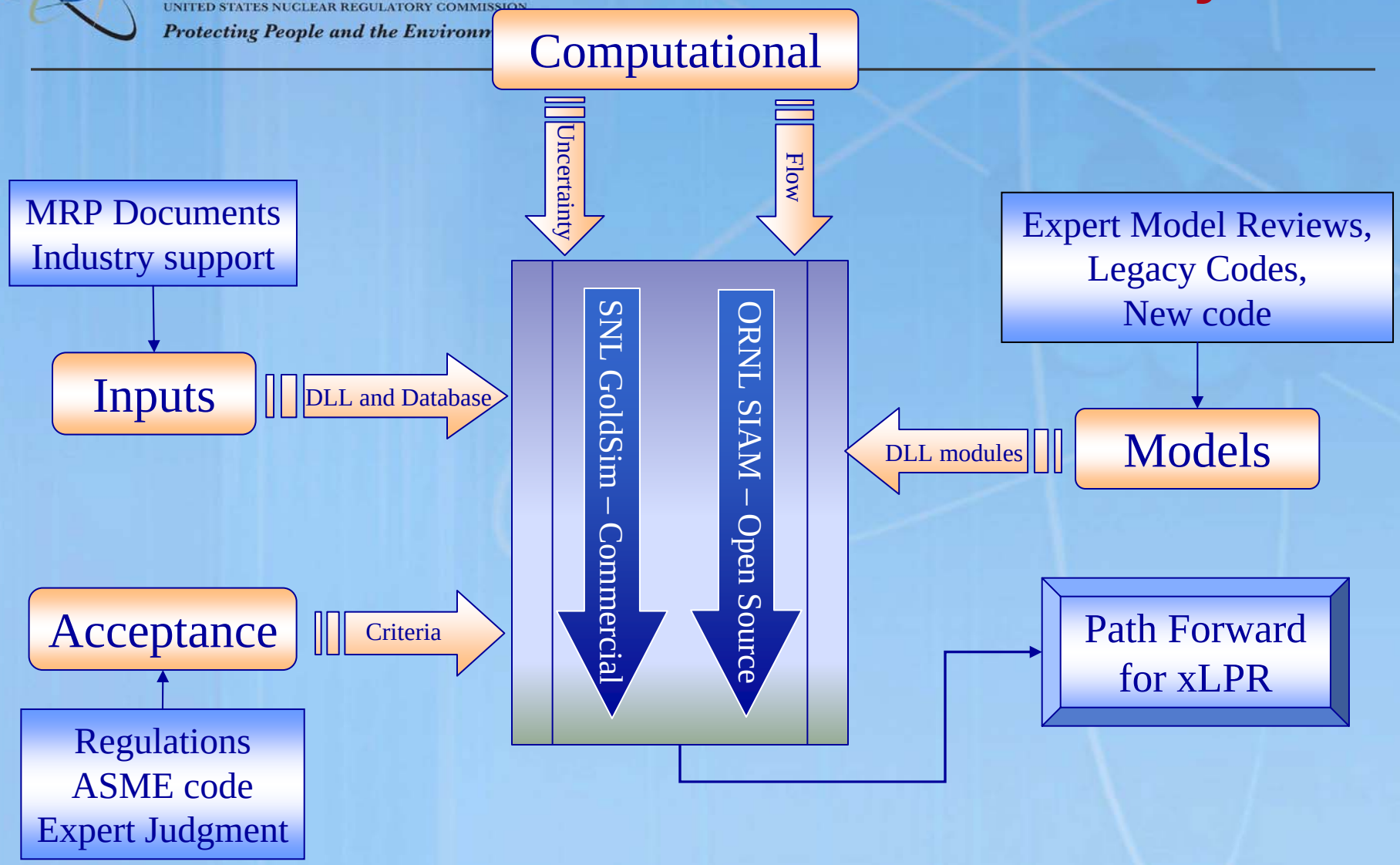
Computational Architecture

- We need to determine the required xLPR code architecture within the program timeline and the following constraints:
  - Comprehensive with respect to known challenges,
  - Vetted with respect to scientific adequacy of models & inputs,
  - Flexible to permit analysis of a variety of in-service situations
  - Adaptable to accommodate evolving and improving knowledge

Computational Architecture

- To meet this goal, we have decided to proceed down parallel paths to test two architectures
  - Commercial Software
  - Open Source software
- Each code will use the same “modules”, inputs, etc
- Each will be assessed based on the criteria in last slide
  - Probably need assessment document – PIB developed??
- It is envisioned both NRC contractor and Industry contractor will perform evaluation
  - Need to discuss

Pilot Study



Whole process guided by Project Integration Board

GoldSim

- GoldSim is a general-purpose simulation software program
- Some of GoldSim's key features include:
  - Quantitatively address the inherent variability and uncertainty
  - Superimpose the occurrence and consequences of discrete events
  - Build top-down models
  - Dynamically link external programs into GoldSim
  - Directly exchange data with databases
  - Insert graphics, notes and hyperlinks
  - Create custom designed graphical interfaces
  - Carry out sensitivity analyses
  - Save your models as player files using GoldSim Player (a free download)
  - Utilize powerful extension modules

GoldSim for xLPR

- GoldSim is a simulation software for modeling complex dynamic systems and supports decision and risk analysis by simulating future performance while quantitatively representing the uncertainty and risks inherent in all complex systems

- GoldSim software is an Object-oriented modeling environment with specialized functions, native Monte-Carlo capabilities and run controller features (manages all linked runtime software via DLL interface)

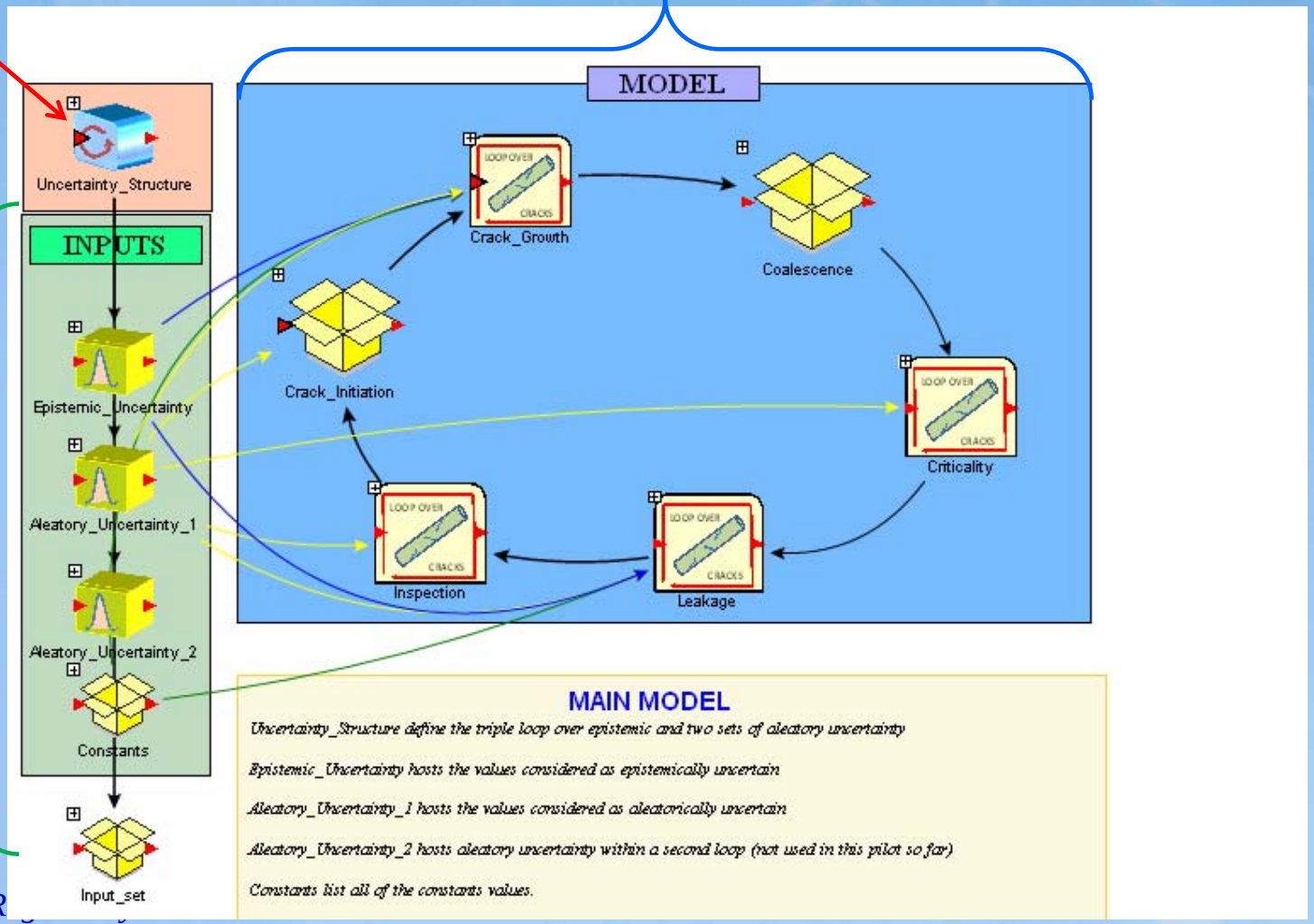
- Use GoldSim for Alpha xLPR Model and Pilot Study to
  - Develop a probabilistic framework
  - Sample uncertain parameters
  - Pass uncertain and constant parameters to modules (DLLs)
  - Receive and process output from module, e.g., link modules together
  - Compile, display and save model results

xLPR pilot - GoldSim

Uncertainty Structure

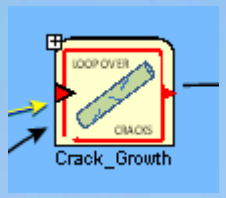
Model

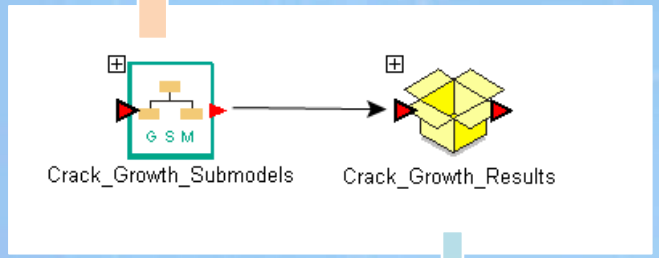
Inputs

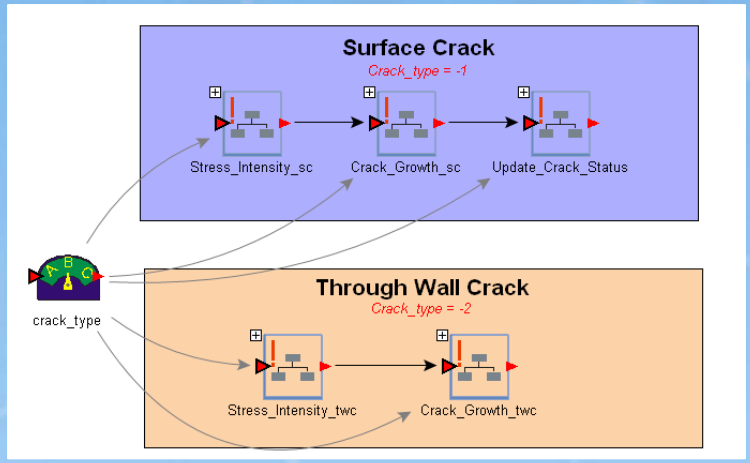


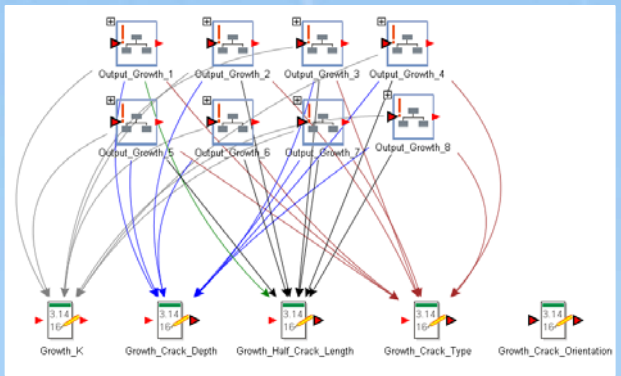
Crack Growth Modules

- Conditional Container – called for each crack
- Cracks treated differently according to their type (Surface Crack or Through wall crack)
- Results of properties saved for each crack









GoldSim Status

- Skeleton alpha version of xLPR complete and running
- Still incorporating temporary modules
  - COD
  - Inspection
  - Critical flaw size
- Alpha version complete by year end

Background on SIAM-PFM

Structural Integrity Assessments Modular - Probabilistic Fracture Mechanics (SIAM-PFM)

- **Develop a *general computational platform* for NPP primary circuit components**
- **Provide a *systematic basis* for risk-informed assessments**
- **Integrate *advanced fracture mechanics* techniques applicable to pressurized structures**
- **Enable contributions by multiple organizations within a *modular software architecture***

SIAM-PFM – Status

- The SIAM-PFM Development Team for the xLPR Pilot Project consists of:
  - Ms. Hilda Klasky – software engineer researcher
  - Dr. Kalyan Perumalla – computer science researcher
  - Dr. Paul Williams – computational fracture mechanics

ORNL will be adding a new member to the team in November:
Srikanth Yoginath – Computer Science Modeling and Simulation Group Computational Sciences and Eng. Div.

SIAM-PFM Status - Summary

- Front-end demonstration platform has been developed – available for review and comment.
- Established international interest in collaboration.
- Two new staff members have joined the SIAM-PFM team.
- Software QA tools have been put into place: Mercurial and Trac.
- Layered software architecture (MVC) has been implemented.
- QA-based coding practices for traceable documentation, code review, prototyping, and incremental unit testing have been established.
- The object-oriented design and analysis phase has begun.
  - Algorithmic decomposition for the xLPR pilot project is proceeding.
  - Model layer classes for the xLPR pilot project are now being coded.

SIAM-PFM Status - Schedule

- We expect to have an initial demonstrator by the end of January 2010.
- We expect to have an xLPR Pilot Project prototype ready for demonstration by the first of May 2010.
- The prototype will include some level of capability to also perform RPV beltline analysis.

Alpha Version of Program Plan

- Purpose and Scope
  - Written by computational group to aid in development of framework and architecture
  - Explanation of models/modules selected by computational group and used for framework development
    - These modules used as placeholders until models group finalizes modules
  - The document is “living” and will be modified as we go from alpha to beta to version 1.0
  - This document will also evolve into the technical basis for xLPR

Alpha Version Module Development

- Modules were either extracted from legacy code, or written for this purpose
- Computational group took the liberty of selecting alpha version modules
- Framework being written so alpha modules can be easily replaced with beta modules

Outline

- Section 1. Overall Flow
- Section 2. Time History Development
- Section 3. Geometry and Material Properties
- Section 4. Loads
- Section 5. Time Loop
- Section 6. Crack Initiation and Placement
- Section 7. Crack Growth
- Section 8. Crack Coalescence
- Section 9. Crack Stability
- Section 10. Leak Rate/Detection
- Section 11. Inspection
- Section 12. Mitigation and Remediation
- Section 13. Outputs
- Section 14. Sample Problem
- Section 15. References

May cause biggest challenges going from alpha to beta

Initiation and Crack Placement

- **Crack Initiation (Section 6.2)**
  - **Pre-existing defects not active in the alpha model**
  - **PWSCC initiation includes for uncertainty by using Poisson's arrival rate model**
  - **Other initiation mechanisms will not be included in alpha model**
    - **e.g., Fatigue, IGSCC, flow enhanced corrosion**

- **Crack Placement (Section 6.3)**
  - **Calculations done using a Crack Placement Module**
    - **Stress based criterion for crack placement (Amzallag, et al, 2001)**
    - **Includes uncertainty in crack placement model**

PWSCC Initiation

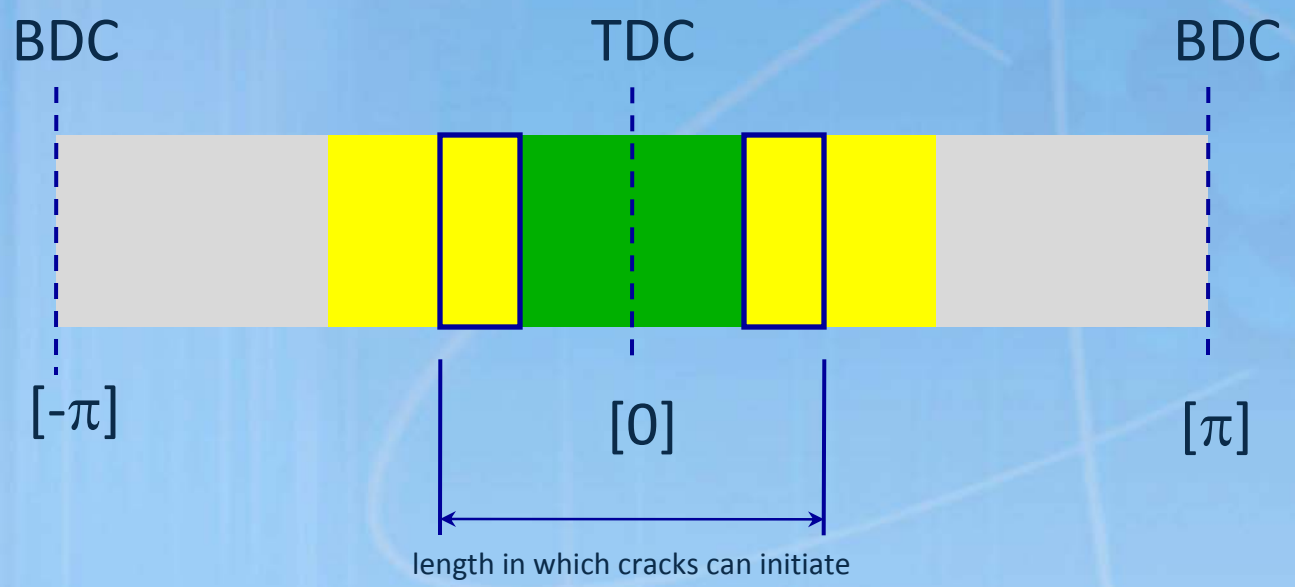
- **Crack Initiation will be determined at time=0**
  - **Inputs**
    - **Arrival Rate, λ**
    - **The arrival rate, λ, will be uncertain**
    - **Outputs - Time to initiation**

$$P\left(N(t+\tau)-N(t)=k\right)=\frac{e^{-\lambda\tau}\left(\lambda\tau\right)^{k}}{k!}$$

Where

$N(t+\tau)-N(t)$	=	number of events in time interval $(t, t+\tau)$.
τ	=	time interval
λ	=	arrival rate
k	=	number of cracks

Crack Placement



Region 1: local ID stress > yield strength

Region 2: 0 <= local ID stress <= yield strength

Region 3: local ID stress < 0

fraction of region 2 in which cracks can initiate

Leak Rate and Detection

- In order to calculate leak rate the following information is needed
  - Crack size (length)
  - Crack opening displacement (at loads) and shape
  - Fluid conditions
  - Crack morphology parameters
  - A leak rate model

Leak Rate Model

- SQUiRT - Seepage Quantification of Upsets In Reactor Tubes has been developed to incorporate the Henry-Fauske two phase flow model and the single phase models.

- Most recent versions of SQUiRT also include COD-crack morphology models

- For the alpha version of xLPR, an older version of SQUiRT will be used that does not have single phase flow or COD-crack morphology models

Leak Detection and Mitigation

- For the alpha version of xLPR, the leak detection limit will be an input (sampled).
- The calculated leak rate will be compared against sampled leak detection limit.
- If the leak rate exceeds the limit, the data is recorded, but the time loop is not exited.
- The effect of leak detection will be calculated after the simulation is complete
- It is assumed that a leaking flaw will be completely removed from the analyses

Inspection

- Credit for in-service inspection will be included in alpha version of xLPR

- Probability of detection and inspection schedule will be input

$$POD\left(\frac{x}{t}\right)=\frac{e^{\beta_1+\beta_2\left(\frac{x}{t}\right)}}{1+e^{\beta_1+\beta_2\left(\frac{x}{t}\right)}}$$

- Probability of repair assumed equal to 1. Flaw sizing uncertainty is ignored

Inspection

- For the alpha version of the code, a simplified inspection scheme will be implemented
  - The probability of non-detection (as sampled from the POD) will be assigned to each flaw present in the analyses at the inspection times
  - The PND as a function of time is then used to modify the failure probabilities to credit for inspection
  - This process assumes that all flaws found by inspection are fully mitigated and removed from the analyses
  - Also, if one flaw is found, all flaws in the simulation are assumed repaired

Pre-emptive Mitigation

- Two options for pre-emptive mitigation – Stress based mitigation and full PWSCC mitigation
- Mitigation time will be a user input – deterministic
- A probability of mitigation effectiveness may be added, which will evoke a random number to determine if the mitigation is effective

Stress Mitigation

- Weld residual stress distribution for mitigated state would be input by user
- Using the “new” ID stress, the crack initiation arrival rate beyond the mitigation time would be

$$\lambda_{mitigated} = \left(\frac{\sigma_i}{\sigma_u} \right)^{-4} \lambda$$

- The crack growth after mitigation would be driven by the operating loads and the sampled mitigated weld residual stress

Full PWSCC Mitigation

- For this option, a mitigation time is input, and both crack initiation and growth will not occur in the future
- Probability of mitigation effectiveness will still apply

Summary

- Alpha version of code underway
  - Modules chosen by computational group, and used as placeholders until Models group modules complete
  - What are the topics which may cause pain in moving from Alpha to Beta?
- Program plan written to describe alpha version and guide computational group in developing framework and architecture
  - Detailed discussions tomorrow