SAND2014-19200PE

Extremely Low Probability of Rupture (xLPR) Project

Framework overview

Rémi Dingreville

Sandia National Laboratories

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

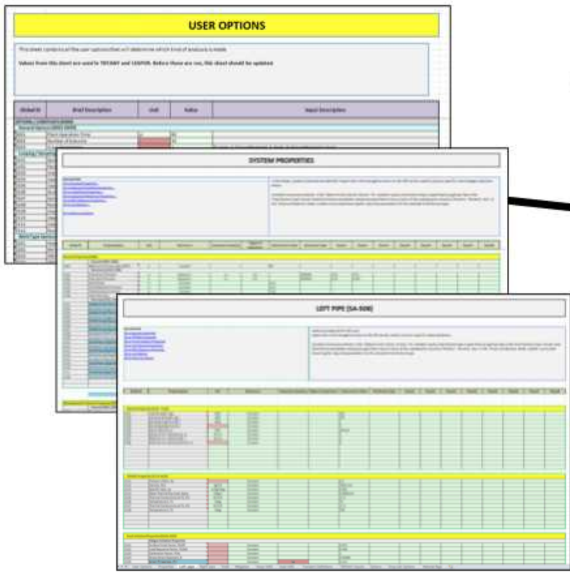
xLPR External Review Board Meeting

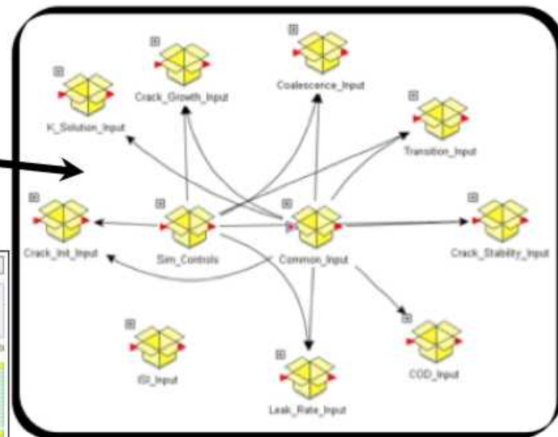
October 29-30, 2014

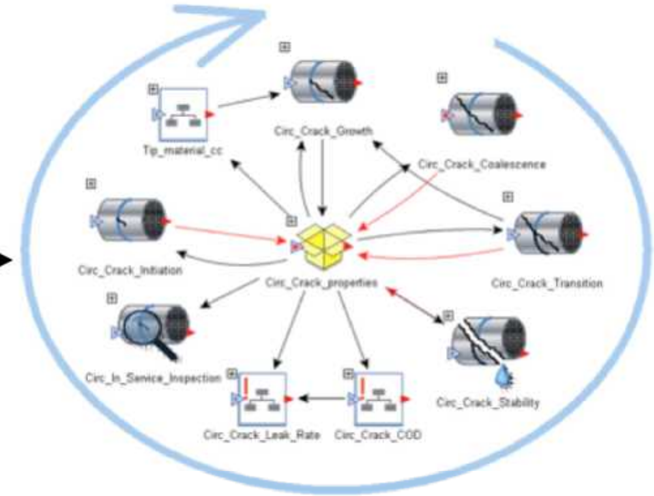
xLPR v2.0 Framework overview

- **GoldSim software:**
  - Dynamic, probabilistic simulation software that serves as the integrating shell linking various modules used in the xLPR model.
- **Input interface:**
  - Interface between user and global structure.
  - Uncertainty distribution associated with each input defined in the Input spreadsheet
- **Deterministic model:**
  - Linking the sub-models to the Framework (Dynamic Link Libraries).
- **Sampling structure:**
  - Defines the number and order of realization and appropriate values to sue based on uncertainty.
  - Outer epistemic loop, and inner aleatory loop.
  - [LHS vs. RS]x[DPD vs. no DPD]x[No importance vs. importance vs. adaptive] for each loop.
- **Landing platform:**
  - Tie up the Interface, Sampling Structure and Deterministic models under the same umbrella.
  - List all inputs and user selected options required by the model to run.

The Framework is constructed using a landing platform to allow a parallel development of the physical models , the interface and sampling methodologies







User interface

Defined by the **input group** and Excel spreadsheets hosting distributions for input parameters.
Pre-defined inputs.

Landing platform

Definition of all input variables as well as simulation controls.

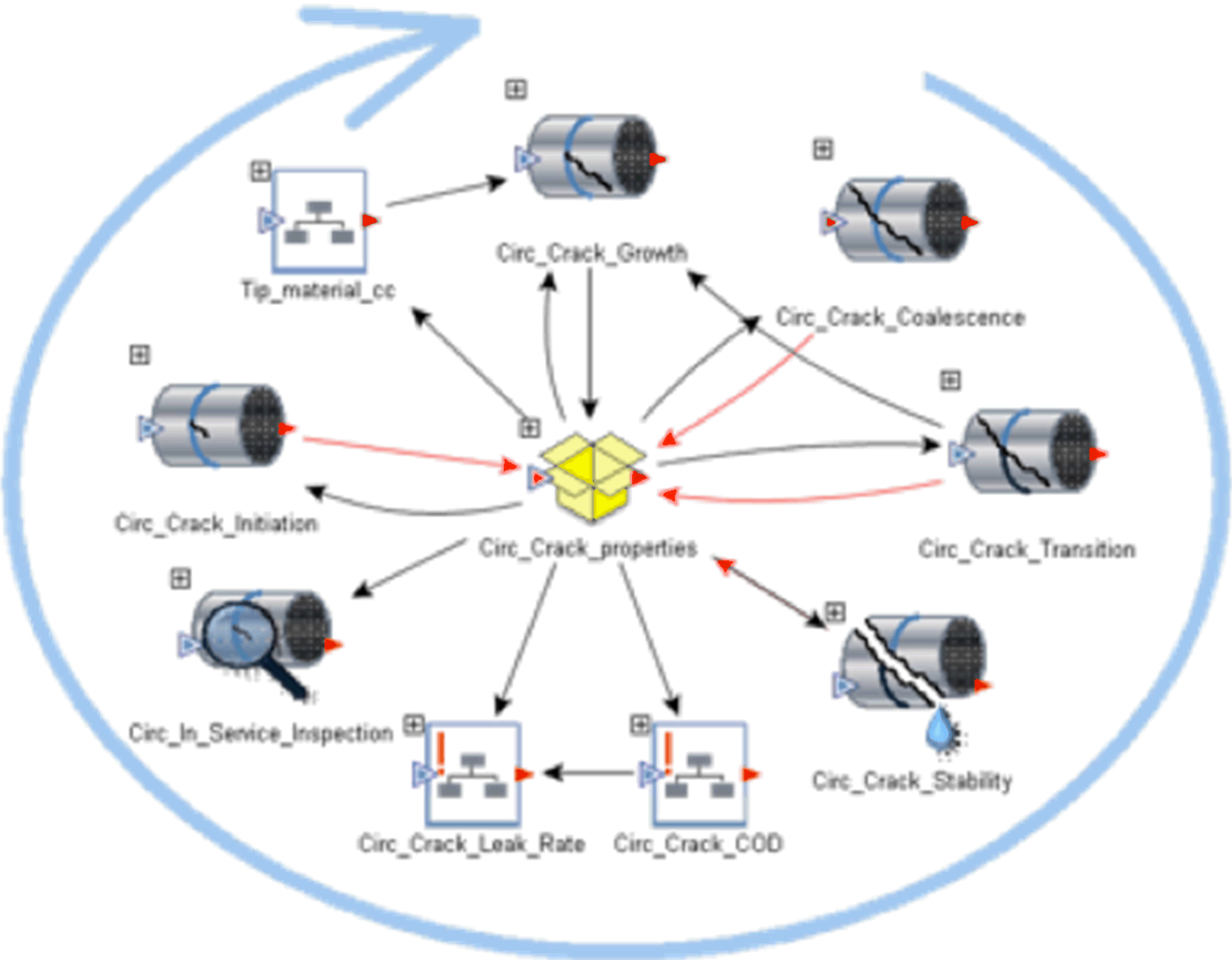
In collaboration with the **input group** (simulation settings) and the **model group** (input/ output of each model).

Physical (deterministic) models

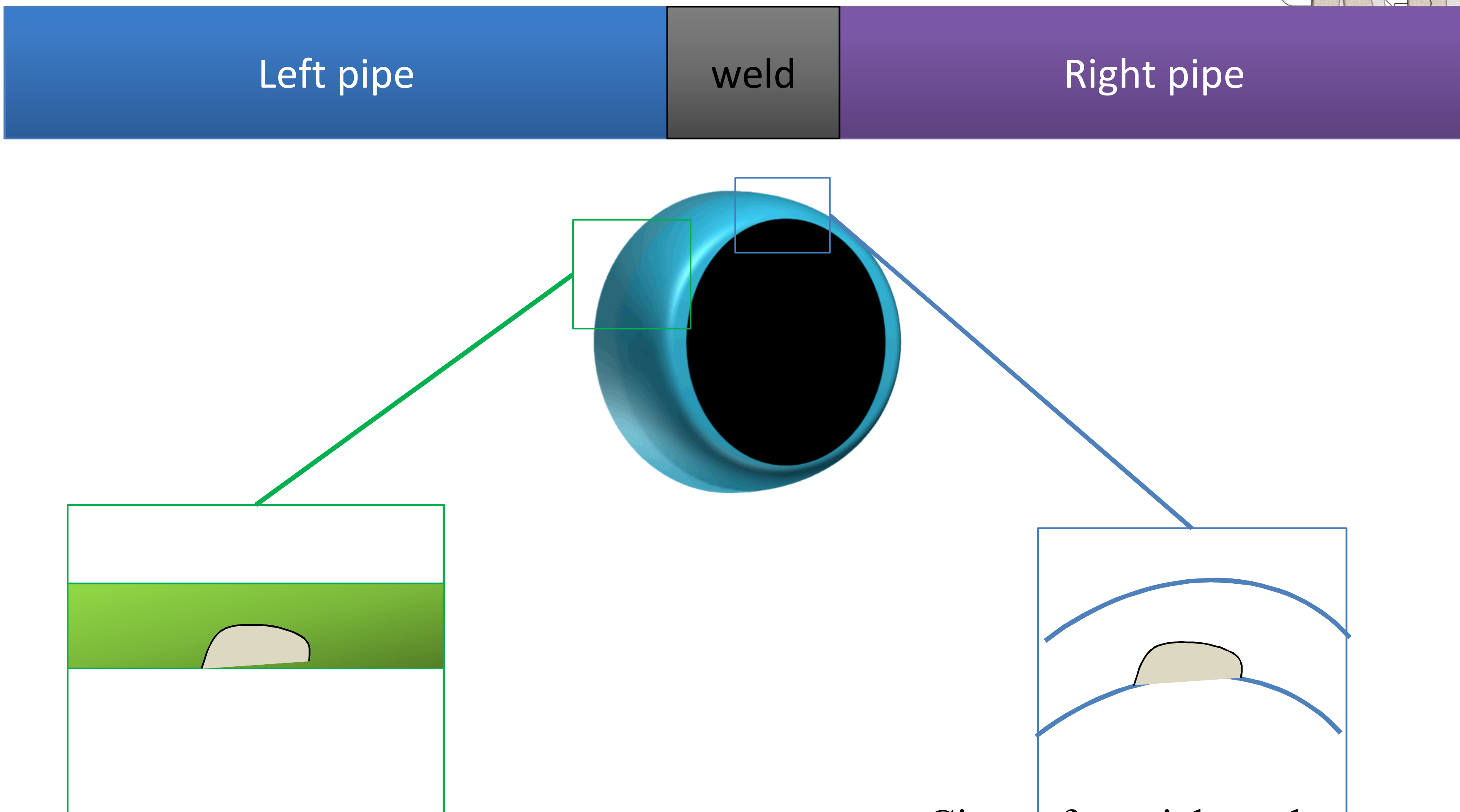
Definition of all input variables as well as simulation controls.

Each container host module developed by the **model group** and compiled as a DLL.

Deterministic model



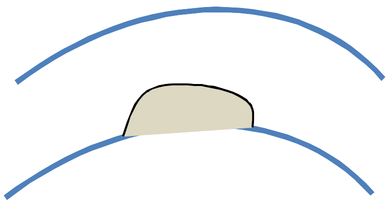
Crack modeling



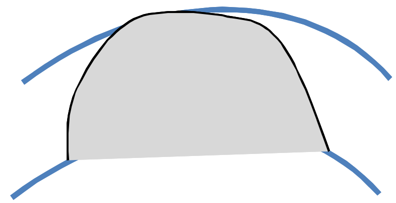
Axial cracks
(developed in different planes – do not coalesce)

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

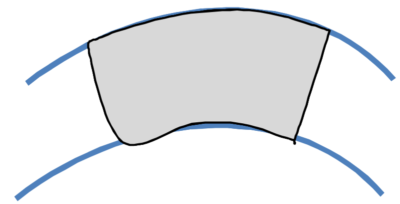
Crack modeling



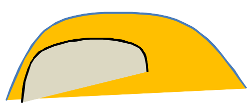
Surface crack (SC)



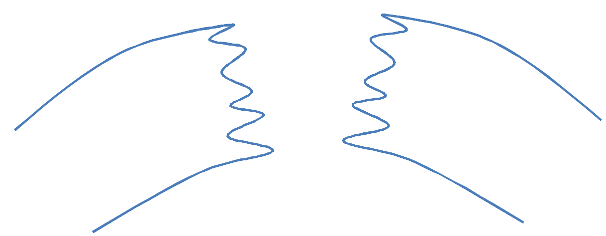
Transitioning crack (TC)



Through wall crack (TWC)



Coalesced crack
(only circ. Crack)



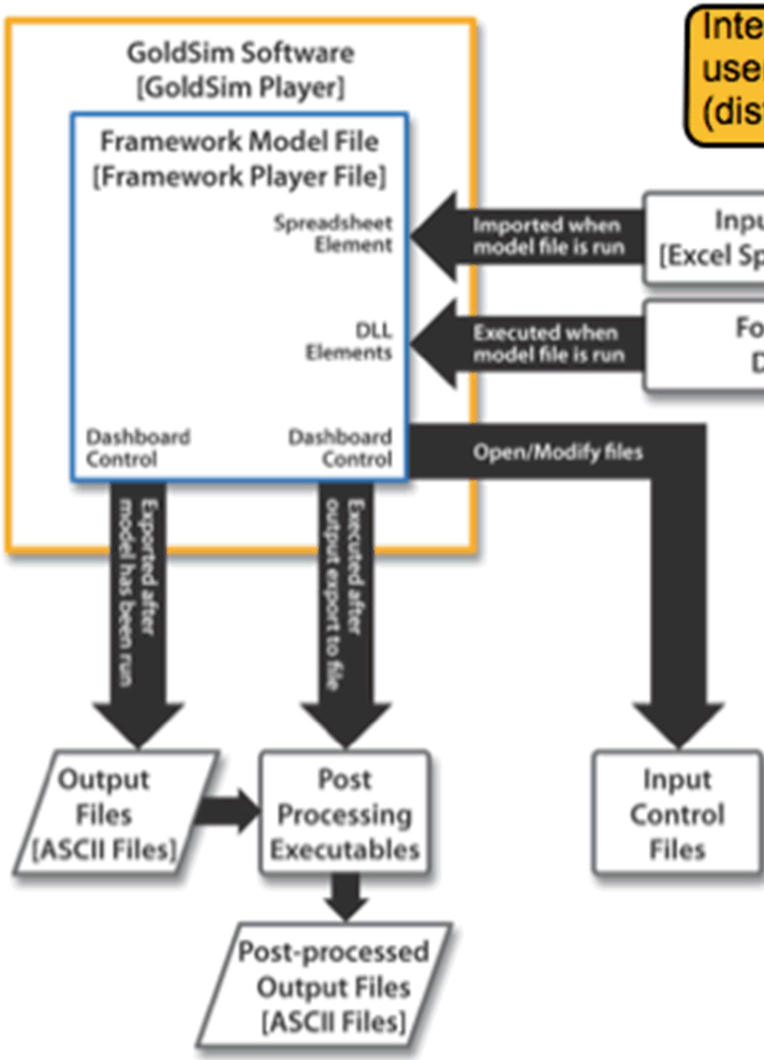
Rupture

GoldSim software

- Dynamic, probabilistic simulation software that serves as the integrating shell linking various modules used in the xLPR model.

GoldSim was chosen as the probabilistic framework to integrate the various components of this effort and to perform probabilistic analysis in a QA manner

Object oriented to allow development of algorithms via graphical elements with specific properties (dashboard).



Interaction with Excel to read user-defined information (distribution, etc.).

Interaction of any module defined as Dynamically Linked Libraries (DLL).

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

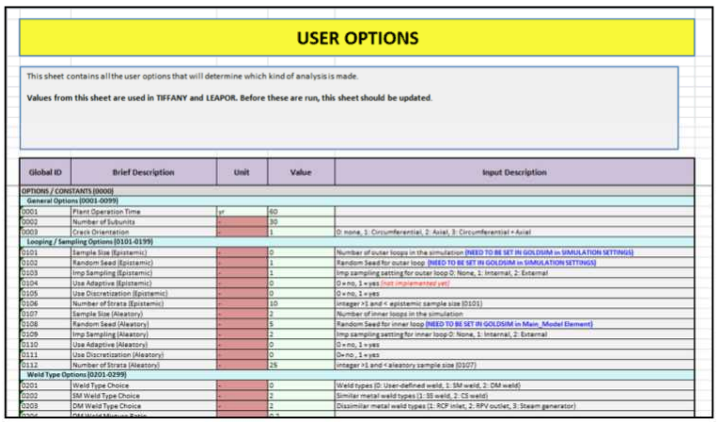
ELECTRIC POWER RESEARCH INSTITUTE

User interface

- Interface between the user and global structure.
- Uncertainty distribution associated with each input defined in the Input spreadsheet.

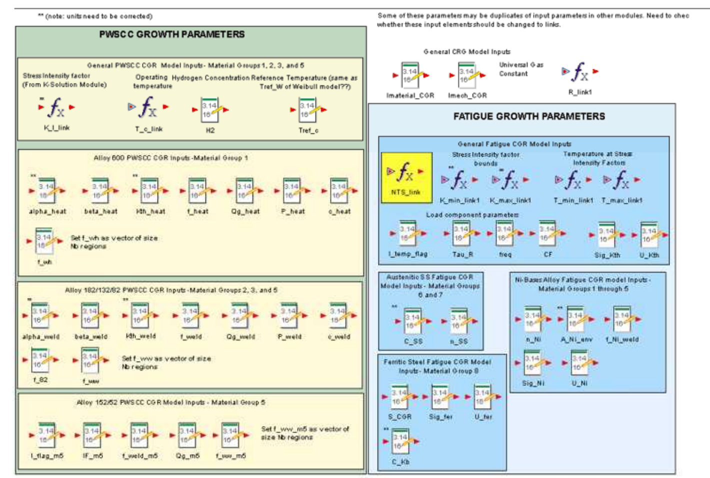
The Framework collects the user-defined probability distributions (input), samples and allocates them accordingly to each physical module

Input distributions
Are defined within the input Excel worksheet. User can also select uncertainty type (aleatory/epistemic).

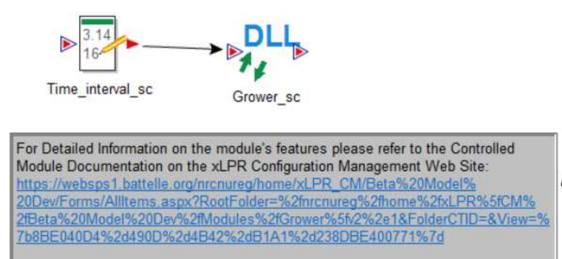


Uncertain input values are sampled automatically by the code.

Sampled model inputs
Are associated with appropriate unit in the landing platform.



Sample input are sent to the module compiled as a DLL.



Input database worksheet: user options

USER OPTIONS

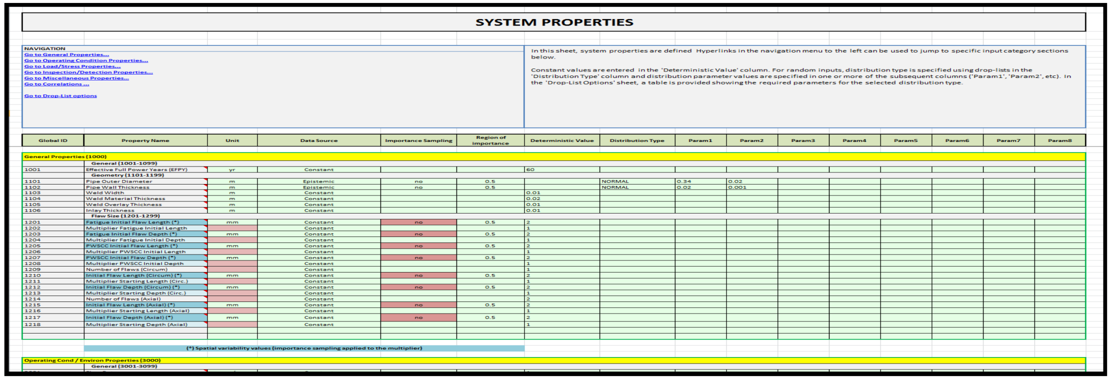
This sheet contains all the user options that will determine which kind of analysis is made.

Values from this sheet are used in TIFFANY and LEAPOR. Before these are run, this sheet should be updated.

Global ID	Brief Description	Unit	Value	Input Description
OPTIONS / CONSTANTS (0000)				
General Options (0001-0099)				
0001	Plant Operation Time	yr	60	
0002	Number of Subunits	-	30	
0003	Crack Orientation	-	1	0: none, 1: Circumferential, 2: Axial, 3: Circumferential + Axial
Looping / Sampling Options (0101-0199)				
0101	Sample Size (Epistemic)	-	0	Number of outer loops in the simulation (NEED TO BE SET IN GOLDSIM in SIMULATION SETTINGS)
0102	Random Seed (Epistemic)	-	1	Random Seed for outer loop (NEED TO BE SET IN GOLDSIM in SIMULATION SETTINGS)
0103	Imp Sampling (Epistemic)	-	1	Imp sampling setting for outer loop 0: None, 1: Internal, 2: External
0104	Use Adaptive (Epistemic)	-	0	0 = no, 1 = yes *(not implemented yet)*
0105	Use Discretization (Epistemic)	-	0	0 = no, 1 = yes
0106	Number of Strata (Epistemic)	-	10	integer >1 and < epistemic sample size (0101)
0107	Sample Size (Aleatory)	-	2	Number of inner loops in the simulation
0108	Random Seed (Aleatory)	-	5	Random Seed for inner loop (NEED TO BE SET IN GOLDSIM in Main_Model Element)
0109	Imp Sampling (Aleatory)	-	2	Imp sampling setting for inner loop 0: None, 1: Internal, 2: External
0110	Use Adaptive (Aleatory)	-	0	0 = no, 1 = yes
0111	Use Discretization (Aleatory)	-	0	0= no , 1 = yes
0112	Number of Strata (Aleatory)	-	25	integer >1 and < aleatory sample size (0107)
Weld Type Options (0201-0299)				
0201	Weld Type Choice	-	0	Weld types (0: User-defined weld, 1: SM weld, 2: DM weld)
0202	SM Weld Type Choice	-	2	Similar metal weld types (1: SS weld, 2: CS weld)
0203	DM Weld Type Choice	-	2	Dissimilar metal weld types (1: RCP inlet, 2: RPV outlet, 3: Steam generator)
0204	DM Weld Mixture Ratio	-	0.3	

- All user options will be read from Excel into GoldSim with the exception of the epistemic sample size, epistemic random seed, and aleatory random seed.

Input database worksheet: system properties



SYSTEM PROPERTIES

NAVIGATION
Go to General Properties...
Go to Operating Condition Properties...
Go to Load/Stress Properties...
Go to Inspection/Detection Properties...
Go to Miscellaneous Properties...
Go to Correlations ...

Go to Drop-List options

In this sheet, system properties are defined Hyperlinks in the navigation menu to the left can be used to jump to specific input category sections below.

Constant values are entered in the 'Deterministic Value' column. For random inputs, distribution type is specified using drop-lists in the 'Distribution Type' column and distribution parameter values are specified in one or more of the subsequent columns ('Param1', 'Param2', etc). In the 'Drop-List Options' sheet, a table is provided showing the required parameters for the selected distribution type.

Global ID	Property Name	Unit	Data Source	Importance Sampling	Region of importance	Deterministic Value	Distribution Type	Param1	Param2	Param3	Param4	Param5	Param6	Param7	Param8
General Properties (1000)															
	General (1001-1099)														
1001	Effective Full Power Years (EFPY)	yr	Constant			60									
	Geometry (1101-1199)														
1101	Pipe Outer Diameter	m	Epistemic	no	0.5		NORMAL	0.34	0.02						
1102	Pipe Wall Thickness	m	Epistemic	no	0.5		NORMAL	0.02	0.001						
1103	Weld Width	m	Constant			0.01									
1104	Weld Material Thickness	m	Constant			0.02									
1105	Weld Overlay Thickness	m	Constant			0.01									
1106	Inlay Thickness	m	Constant			0.01									
	Flaw Size (1201-1299)														
1201	Fatigue Initial Flaw Length (*)	mm	Constant	no	0.5	2									
1202	Multiplier Fatigue Initial Length		Constant			1									
1203	Fatigue Initial Flaw Depth (*)	mm	Constant	no	0.5	2									
1204	Multiplier Fatigue Initial Depth		Constant			1									
1205	PWSCC Initial Flaw Length (*)	mm	Constant	no	0.5	2									
1206	Multiplier PWSCC Initial Length		Constant			1									
1207	PWSCC Initial Flaw Depth (*)	mm	Constant	no	0.5	2									
1208	Multiplier PWSCC Initial Depth		Constant			1									
1209	Number of Flaws (Circum)		Constant			1									
1210	Initial Flaw Length (Circum) (*)	mm	Constant	no	0.5	2									
1211	Multiplier Starting Length (Circ.)		Constant			1									
1212	Initial Flaw Depth (Circum) (*)	mm	Constant	no	0.5	2									
1213	Multiplier Starting Depth (Circ.)		Constant			1									
1214	Number of Flaws (Axial)		Constant			2									
1215	Initial Flaw Length (Axial) (*)	mm	Constant	no	0.5	2									
1216	Multiplier Starting Length (Axial)		Constant			1									
1217	Initial Flaw Depth (Axial) (*)	mm	Constant	no	0.5	2									
1218	Multiplier Starting Depth (Axial)		Constant			1									

(*) Spatial variability values (importance sampling applied to the multiplier)

Operating Cond / Environ Properties (3000)															
	General (3001-3099)														

- List all the variables used in the model by category.
- Defines variable units.
- List uncertainty type and associated distribution.

Input database worksheet: materials properties

LEFT PIPE (SA-508)

NAVIGATION
Go to general properties
Go to TIFFANY Properties
Go to Crack Initiation Properties
Go to Crack Growth Properties
Go to Miscellaneous Properties
Go to correlations
Go to Drop-List options

material properties for left pipe
Hyperlinks in the navigation menu to the left can be used to jump to specific materials below.

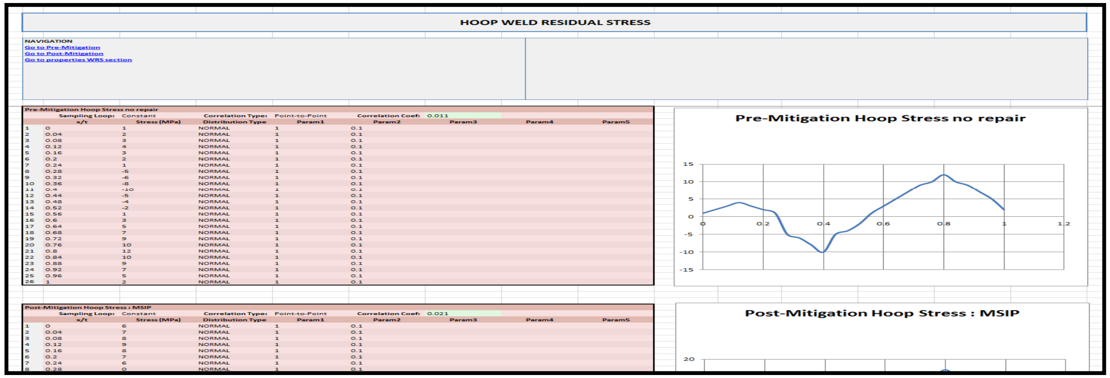
Constant values are entered in the 'Deterministic Value' column. For random inputs, distribution type is specified using drop-lists in the 'Distribution Type' column and distribution parameter values are specified in one or more of the subsequent columns ('Param1', 'Param2', etc). In the 'Drop-List Options' sheet, a table is provided showning the required parameters for the selected distribution type.

Global ID	Property Name	Unit	Data Source	Importance Sampling	Region of importance	Deterministic Value	Distribution Type	Param1	Param2	Param3	Param4	Param5	Param6	Param7	Param8
General Properties (2101 - 2110)															
2101	Yield Strength, Sigy	MPa	Constant			250									
2102	Ultimate Strength, Sigu	MPa	Constant			400									
2103	Ramberg-Osgood Coef, F	MPa	Constant			1									
2104	Ramberg-Osgood Coef, n		Constant			0									
2105	Elastic Modulus, E	MPa	Constant			195100									
2106	Material Init J-Resistance, Jic	N/mm	Constant			0									
2107	Material Init J-Resist Coef, C	N/mm	Constant			0									
2108	Material Init J-Resist Exponent, m		Constant			0									
TIFFANY Properties (2111-2120)															
2111	Poisson's Ratio, Nu		Constant			0.3									
2112	Density, Rho	kg/m3	Constant			7833.413									
2113	Specific Heat, Cp	kJ/kg/Cdeg	Constant			0.502									
2114	Mean Thermal Exp Coef, Alpha	Cdeg-1	Constant			0.0000144									
2115	Thermal Conductivity at T1, kT1	W/m/K	Constant			17.3									
2116	Temperature 1, T1	Cdeg	Constant			70									
2117	Thermal Conductivity at T2, kT2	W/m/K	Constant			17.3									
2118	Temperature 2, T2	Cdeg	Constant			700									
Crack Initiation Properties (2121-2155)															
	Fatigue Initiation Properties														
2121	Surface Finish Factor, FSURF		Constant			0.973									
2122	Load Sequence Factor, FLOAD		Constant			0.438									
2123	Calibration Factor, FCAL		Constant			1									
2124	Stress-Strain Exponent, B		Constant			0.52083									
2125	Strain Threshold, STH		Constant	no		0.112									

User Options / Properties / Left pipe / Right pipe / Weld / Mitigation / Hoop WRS / Axial WRS / Transient Definitions / TIFFANY Inputs / Options / Drop-List Options / Material flags

- List all materials properties for selected materials.
- Defines variable units.
- Protected to prevent user from making changes unintentionally.
- User selects which material is to be used for the left pipe / right pipe / weld / and mitigation (inlay or overlay). Assigned to individual tabs.

Input database worksheet: WRS



HOOP WELD RESIDUAL STRESS

NAVIGATION
Go to Pre-Mitigation
Go to Post-Mitigation
Go to properties WRS section

Pre-Mitigation Hoop Stress no repair

Sampling Loop: Constant | Correlation Type: Point-to-Point | Correlation Coef: 0.011

	x/t	Stress (MPa)	Distribution Type	Param1	Param2	Param3	Param4	Param5
1	0	1	NORMAL	1	0.1			
2	0.04	2	NORMAL	1	0.1			
3	0.08	3	NORMAL	1	0.1			
4	0.12	4	NORMAL	1	0.1			
5	0.16	3	NORMAL	1	0.1			
6	0.2	2	NORMAL	1	0.1			
7	0.24	1	NORMAL	1	0.1			
8	0.28	-5	NORMAL	1	0.1			
9	0.32	-6	NORMAL	1	0.1			
10	0.36	-8	NORMAL	1	0.1			
11	0.4	-10	NORMAL	1	0.1			
12	0.44	-5	NORMAL	1	0.1			
13	0.48	-4	NORMAL	1	0.1			
14	0.52	-2	NORMAL	1	0.1			
15	0.56	1	NORMAL	1	0.1			
16	0.6	3	NORMAL	1	0.1			
17	0.64	5	NORMAL	1	0.1			
18	0.68	7	NORMAL	1	0.1			
19	0.72	9	NORMAL	1	0.1			
20	0.76	10	NORMAL	1	0.1			
21	0.8	12	NORMAL	1	0.1			
22	0.84	10	NORMAL	1	0.1			
23	0.88	9	NORMAL	1	0.1			
24	0.92	7	NORMAL	1	0.1			
25	0.96	5	NORMAL	1	0.1			
26	1	2	NORMAL	1	0.1			

Post-Mitigation Hoop Stress : MSIP

Sampling Loop: Constant | Correlation Type: Point-to-Point | Correlation Coef: 0.021

	x/t	Stress (MPa)	Distribution Type	Param1	Param2	Param3	Param4	Param5
1	0	6	NORMAL	1	0.1			
2	0.04	7	NORMAL	1	0.1			
3	0.08	8	NORMAL	1	0.1			
4	0.12	9	NORMAL	1	0.1			
5	0.16	8	NORMAL	1	0.1			
6	0.2	7	NORMAL	1	0.1			
7	0.24	6	NORMAL	1	0.1			
8	0.28	0	NORMAL	1	0.1			

- Universal weight function selected. Up to 26 locations can be used to represents the WRS profile. In the GUI if distribution selected, the mean is displayed.
- For each 26 locations, stress can be entered as a constant or distribution.
- Pre and post mitigation WRS defined for both Hoop and Axial.
- 3 WRS profiles defined in Hoop WRS tab and 3 defined in Axial WRS tab; only defined profiles that will be used.
- Weld type (DM, SM, or user option), weld properties, and weld repair state (0%, 15%, 50%) can be defined to assign the appropriate geometry and material properties to the problem.

Input database worksheet: transients

TRANSIENT DEFINITIONS

Transient #1			
Point	Time (s)	Temp (Cdeg)	delta P (MPa)
1	10	3.09	0.31
2	20	5.88	0.59
3	30	8.09	0.81
4	40	9.51	0.95
5	50	10.00	1.00
6	60	9.51	0.95
7	70	8.09	0.81
8	80	5.88	0.59
9	90	3.09	0.31
10	100	0.00	0.00

Transient #2			
Point	Time (s)	Temp (Cdeg)	delta P (MPa)
1	10	3.13	0.31
2	20	6.18	0.62
3	30	9.08	0.91
4	40	11.76	1.18
5	50	14.14	1.41
6	60	16.18	1.62
7	70	17.82	1.78
8	80	19.02	1.90
9	90	19.75	1.98
10	100	20.00	2.00
11	110	19.75	1.98
12	120	19.02	1.90
13	130	17.82	1.78
14	140	16.18	1.62
15	150	14.14	1.41
16	160	11.76	1.18
17	170	9.08	0.91
18	180	6.18	0.62
19	190	3.13	0.31
20	200	0.00	0.00

Transient #3			
Point	Time (s)	Temp (Cdeg)	delta P (MPa)
1	10	3.14	0.31
2	20	6.24	0.62
3	30	9.27	0.93
4	40	12.20	1.22
5	50	15.00	1.50
6	60	17.63	1.76
7	70	20.07	2.01
8	80	22.29	2.23
9	90	24.27	2.43
10	100	25.98	2.60
11	110	27.41	2.74
12	120	28.53	2.85
13	130	29.34	2.93
14	140	29.84	2.98
15	150	30.00	3.00
16	160	29.84	2.98
17	170	29.34	2.93
18	180	28.53	2.85
19	190	27.41	2.74
20	200	25.98	2.60
21	210	24.27	2.43
22	220	22.29	2.23
23	230	20.07	2.01
24	240	17.63	1.76
25	250	15.00	1.50
26	260	12.20	1.22
27	270	9.27	0.93
28	280	6.24	0.62
29	290	3.14	0.31
30	300	0.00	0.00

Transient #4			
Point	Time (s)	Temp (Cdeg)	delta P (MPa)
1	10	3.14	0.31
2	20	6.26	0.63
3	30	9.34	0.93
4	40	12.36	1.24
5	50	15.31	1.53
6	60	18.16	1.82
7	70	20.90	2.09
8	80	23.51	2.35
9	90	25.98	2.60
10	100	28.28	2.83
11	110	30.42	3.04
12	120	32.36	3.24
13	130	34.11	3.41
14	140	35.64	3.56
15	150	36.96	3.70
16	160	38.04	3.80
17	170	38.89	3.89
18	180	39.51	3.95
19	190	39.88	3.99
20	200	40.00	4.00
21	210	39.88	3.99
22	220	39.51	3.95
23	230	38.89	3.89
24	240	38.04	3.80
25	250	36.96	3.70
26	260	35.64	3.56
27	270	34.11	3.41
28	280	32.36	3.24
29	290	30.42	3.04
30	300	28.28	2.83
31	310	25.98	2.60
32	320	23.51	2.35
33	330	20.90	2.09
34	340	18.16	1.82
35	350	15.31	1.53
36	360	12.36	1.24
37	370	9.34	0.93
38	380	6.26	0.63
39	390	3.14	0.31
40	400	0.00	0.00

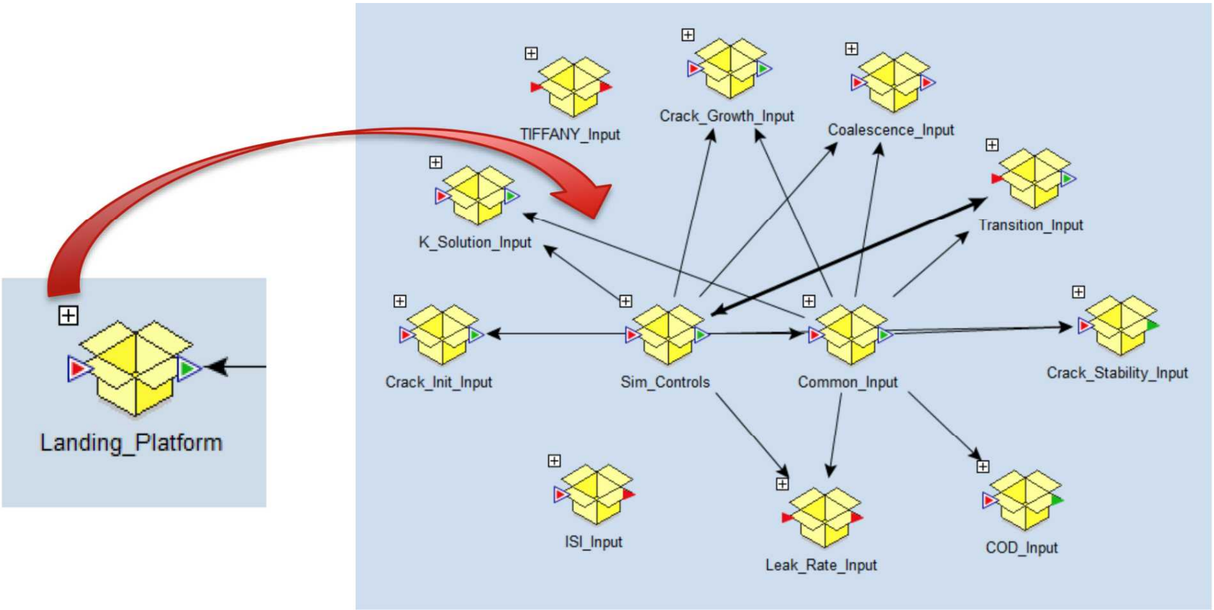
Transient #5			
Point	Time (s)	Temp (Cdeg)	delta P (MPa)
1	10	3.14	0.31
2	20	6.27	0.63
3	30	9.37	0.94
4	40	12.43	1.24
5	50	15.45	1.55
6	60	18.41	1.84
7	70	21.29	2.13
8	80	24.09	2.41
9	90	26.79	2.68
10	100	29.39	2.94
11	110	31.87	3.19
12	120	34.23	3.42
13	130	36.45	3.64
14	140	38.53	3.85
15	150	40.45	4.05
16	160	42.22	4.22
17	170	43.82	4.38
18	180	45.24	4.52
19	190	46.49	4.65
20	200	47.55	4.76
21	210	48.43	4.84
22	220	49.11	4.91
23	230	49.61	4.96
24	240	49.90	4.99
25	250	50.00	5.00
26	260	49.90	4.99
27	270	49.61	4.96
28	280	49.11	4.91
29	290	48.43	4.84
30	300	47.55	4.76
31	310	46.49	4.65
32	320	45.24	4.52
33	330	43.82	4.38
34	340	42.22	4.22
35	350	40.45	4.05
36	360	38.53	3.85
37	370	36.45	3.64
38	380	34.23	3.42
39	390	31.87	3.19
40	400	29.39	2.94
41	410	26.79	2.68
42	420	24.09	2.41

- 20 transients defined.
- Copied in worksheet to be used by TIFFANY add-in.
- User will input transient definitions (up to 20) into one of the three transient types (type I only, type I and II, type III), additional inputs allows the framework to schedule the transients.

Landing platform

- Tie up the Graphical Interface, Sampling Structure and Deterministic models under the same umbrella.
- List all inputs and user selected options required by the model to run.

Landing platform: Imports inputs values from the GUI interface and Excel input spreadsheet into a common "hub"



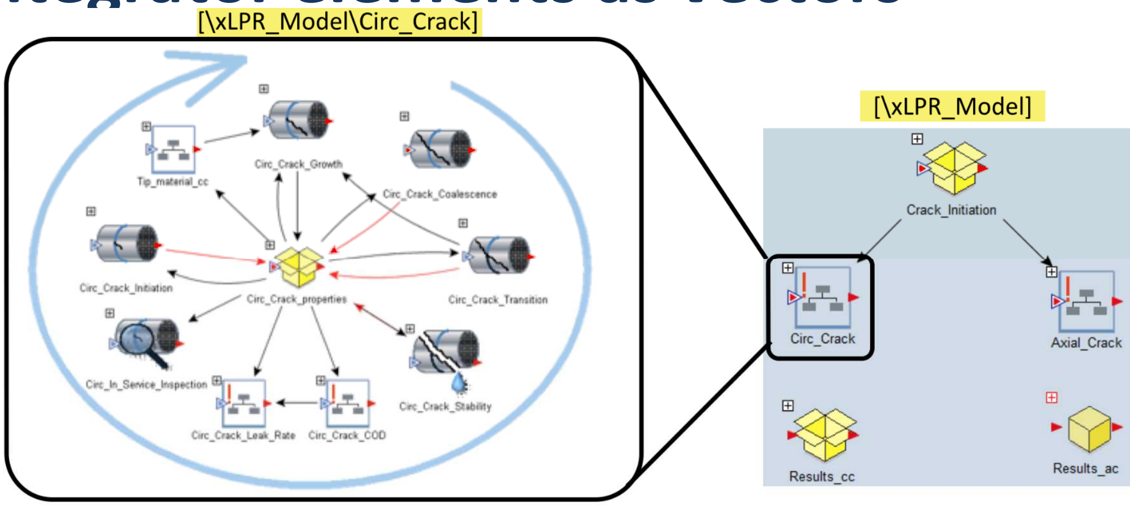
[\xLPR_hub\LandingPlatform]

- The landing platform lists and organizes the inputs used by each model.
- These containers only include data defined in the GUI and Excel input spreadsheet.
- Sim controls have model options such as circ and/or axial; model choices; fatigue and/or PWSCC.
- Common input are inputs from the input spreadsheet that are common to many of the modules.

Landing platform: Time interval calculations

- Time is split in discrete time intervals (up to 5 based on operating modes and mitigation times).
- For each time interval (PWSCC), logic script defines: T, pressure, Zn concentration, OD/ID, pipe thickness, normal operating stresses
- For fatigue, logic script defines time intervals where all the following values constant: DO, stresses (min/max), rise time, etc...
- Transient calculation: allows to define how many event (and type) per time step as a function of start/end time, front/back loading, cycles per event, events per year.

Deterministic model: structure using on state variable integrator elements as vectors

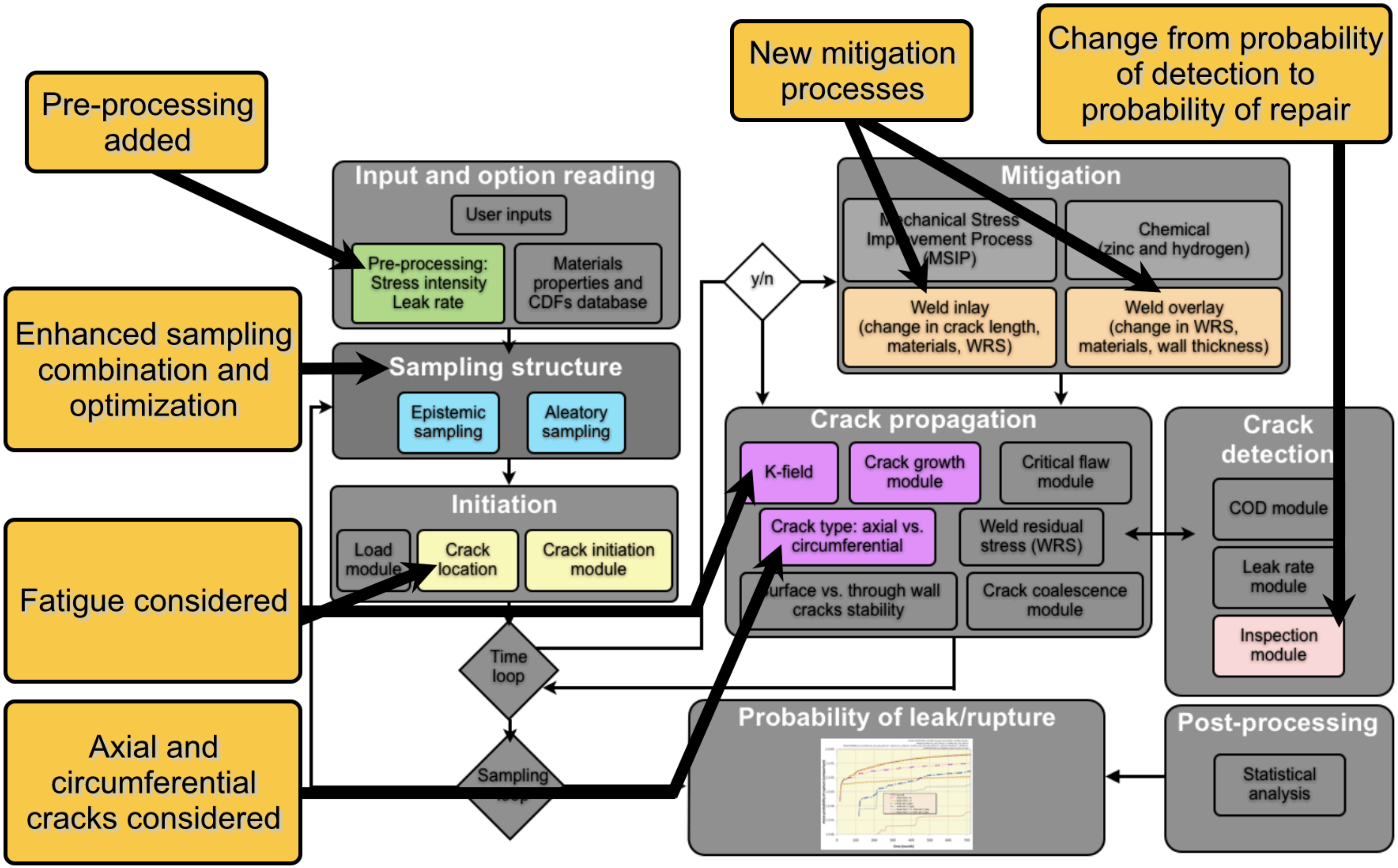


- Circumferential and axial crack evolution have been implemented.
- Deterministic model linked to sampling scheme.
- **State variables** and **Integrator element** used to track crack properties (type, position, depth, inner/outer diam half-length) changing over time.
  - Time histories saved and growth calculation using current props as input without recursive error.
  - Rate of change in variables, discrete changes.
- **Vector structure for state variables:**
  - Crack sorted by occurrence time.
  - Pipe subdivided in N regions (i.e. maximum 2N cracks possible for each realization in one sim).
- Time loop starts at coalescence and finishes with crack growth. Crack growth rate for variable applied at the end of time step.

Deterministic model

- **Linking the sub-models to the Framework (Dynamic Link Libraries).**

In xLPR v2.0 several modules have been changed and improved based on the lessons learned from xLPR v1.0



Crack definition and tracking

- **Crack attributes:**
  - Pipe subdivided in N regions (i.e. maximum 2N cracks possible for each realization in one sim.
    - Current N = 30, but can be set up to 100 segments.
  - Maximum of 2N cracks possibles (N circumferential, N axial).
  - At each time step, a crack may be defined by 6 properties:
    - Crack type.
    - Crack orientation (circ. vs. axial).
    - Crack position (center of segment).

- **Crack type** provides information about the status of a crack using a relative integer value representing different possible crack aspects:
  - 0: No crack appeared (default and initial at t=0).
  - -1: Surface crack (circ. and axial) Starting status when originating
  - -2: Transitioning crack (circ. and axial) Extending from inner to outerbut radial lengths different.

Crack definition and tracking

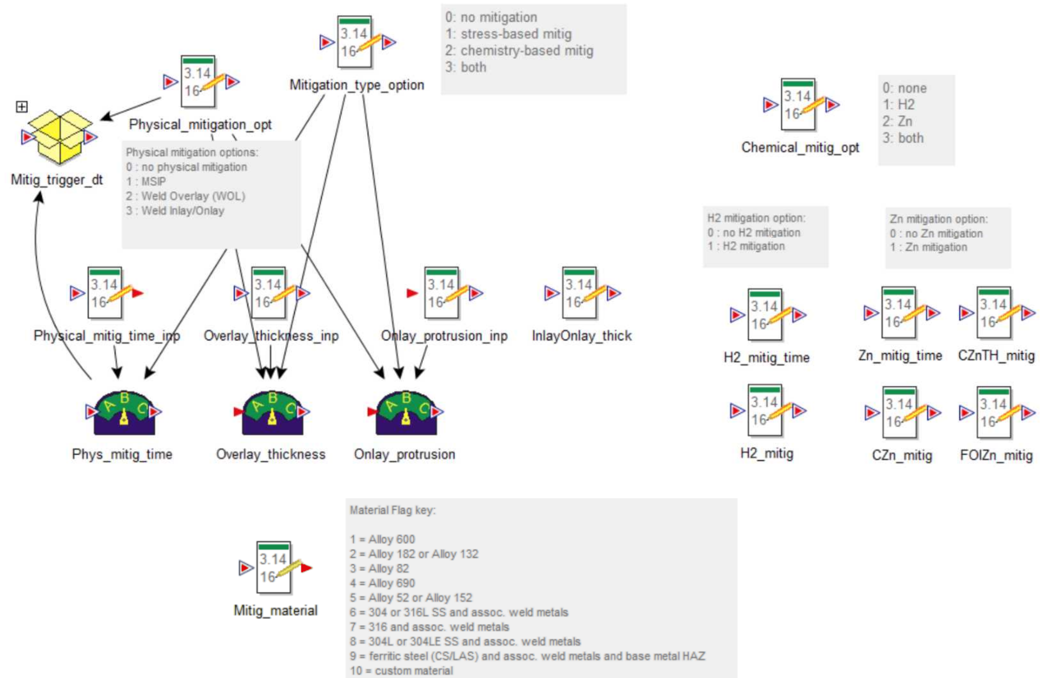
- **Crack position** ([radians] for circ.; [m] for axial) used to track center of crack.
  - Position of an axial crack center always starts at the center of the pipe segment and does not change regardless of different pipe material on left and right of weld: No asymmetrical growth.

- **Crack depth** represents the depth of the crack from the inside of the pipe toward the outside.
  - Dimensionless and expressed as fraction of pipe wall thickness.
  - Used for both circ. and axial cracks (only for surface cracks).

- **ID half-length** represents the crack along pipe inner radius.
  - Used for both circ. and axial cracks whether surface, transitioning or through-wall.
  - Normalized to dimensionless number:
    - Axial: normalized by πR (R = inner radius)
    - Circ.: Normalized by π

- **OD half-length** represents the crack along pipe outer radius.
  - Used for both circ. and axial cracks when they are transitioning or becoming through-wall.
  - Normalized to dimensionless number

Mitigation: GoldSim implementation

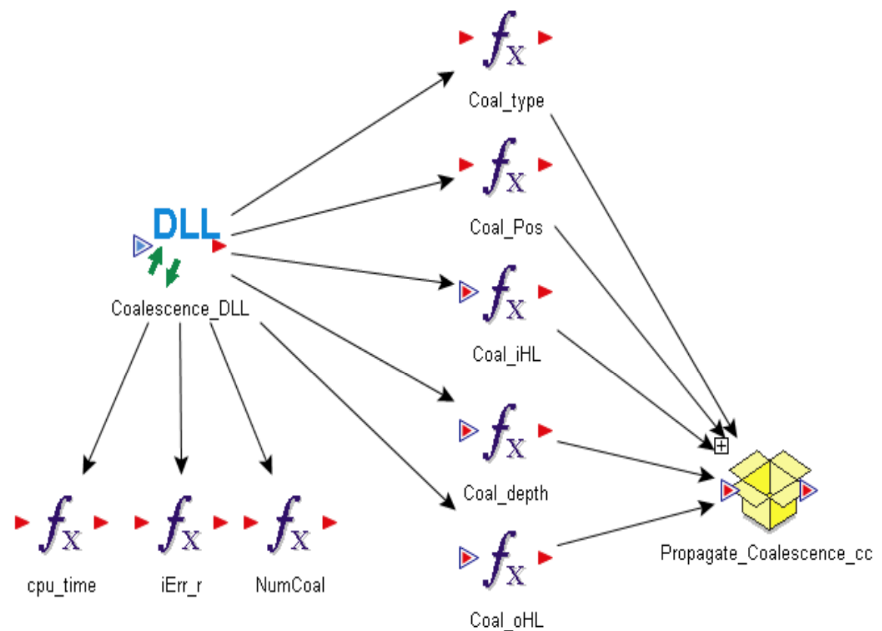


[\xLPR_Hub\Landing_Platform\Sim_Controls\Mitigation]

- Performed prior the simulation starts.
- Logic implemented to identify appropriate mitigation time.
- Depending on the type of mitigation various internal state variable are redefined (e.g. stresses [MSIP], WRS, geometry, crack location [inlay/onlay].

Crack coalescence: GoldSim implementation

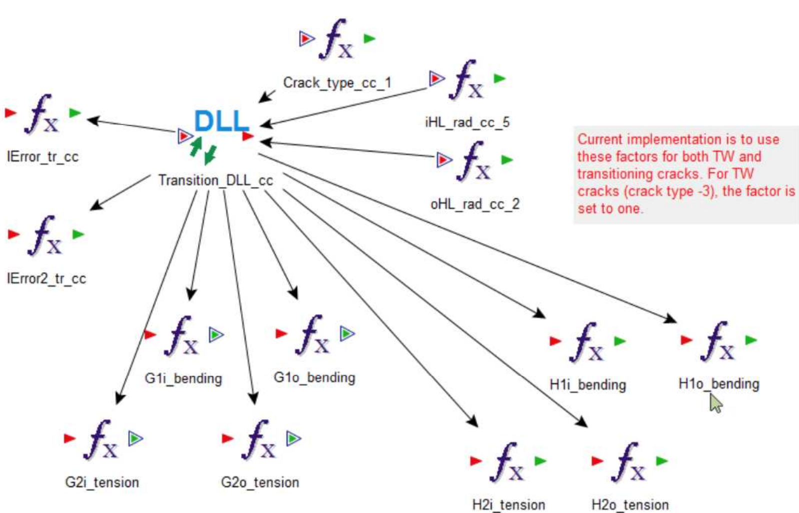
- The purpose of this module is to perform the function of simulating crack coalescence of circumferential (no axial) cracks at a given time step.
- For each time step after an active crack has been found the coalescence module is invoked by the coalescence DLL wrapper via the Framework.
- Attribute modified:
    - Crack type, depth, location, ID/OD half length, # of coalescence events
- Crack keeping the information is the one that is the closest to the zero reference (coalescer vs. coalescee). This approach is different from what was done in xLPR v1.0.

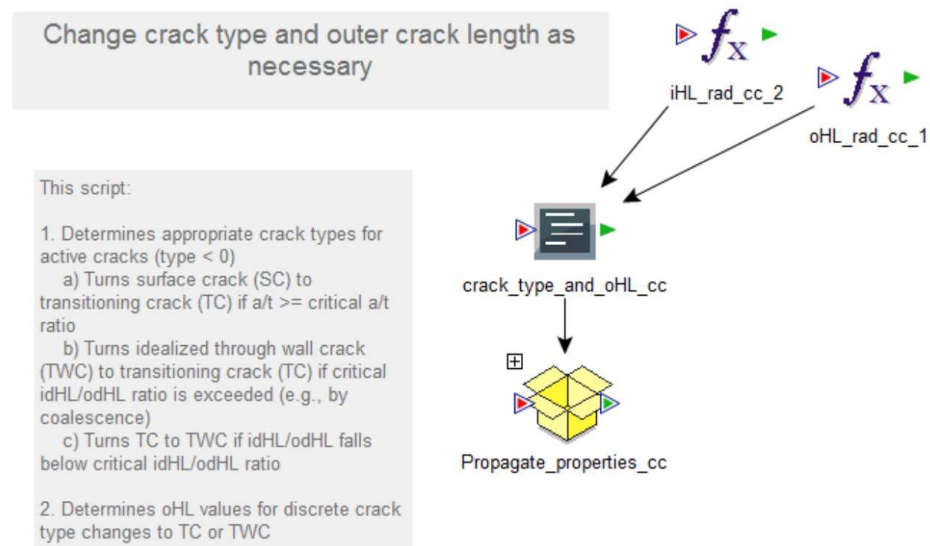


[\xLPR_Model\Circ_Crack\Circ_Crack_Coalescence]

Crack transition: GoldSim implementation

- Transition updates crack type from SC to TC and TC to TWC based on ratio of inner and outer half-lengths (crack type change).
- Calculates initial OD half-length (crack type change).
- Logic implemented to set non-dimensional depth to 1 (crack type change).
- Calculates correction factors for transitioning cracks (crack transition).
- Using current crack properties (causality sequence changed).



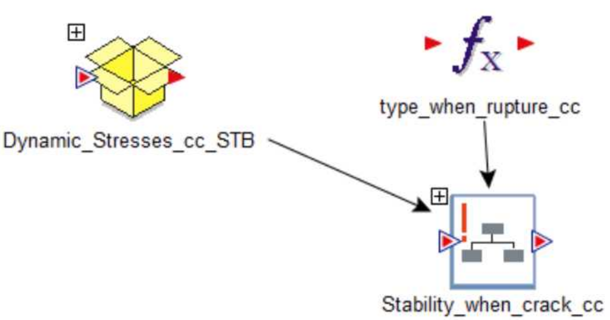


[\xLPR_Model\Circ_Crack\Circ_Crack_Transition\Crack_type_changes_cc]

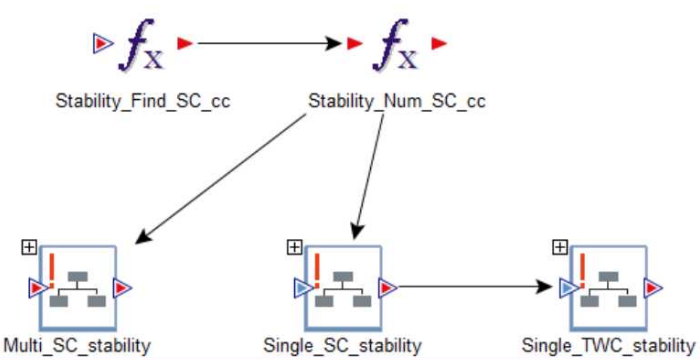
[\xLPR_Model\Circ_Crack\Circ_Crack_Transition\Crack_Transition_module_cc]

Crack stability: GoldSim implementation

- For each time (+ predicted time steps) step after an active crack has been found the stability module is invoked by the stability DLL wrapper via the Framework.
- Logic implemented to determine if a crack becomes a TWC or if we have rupture.
- If only SC, multiple NSC model used (rupture)
- If at least one TWC: Single SC fail (SC to TWC) and single TWC fail model (rupture)
- Multiple crack NSC criterion used to evaluate if pipe ruptured (as opposed to transitioning crack).
- Seismic consequences tracked:
  - If multiple SC or single TWC gives rupture, track time and continue with nominal
  - If single SC gives rupture, check resulting TWC for rupture. If so track time and continue with nominal.



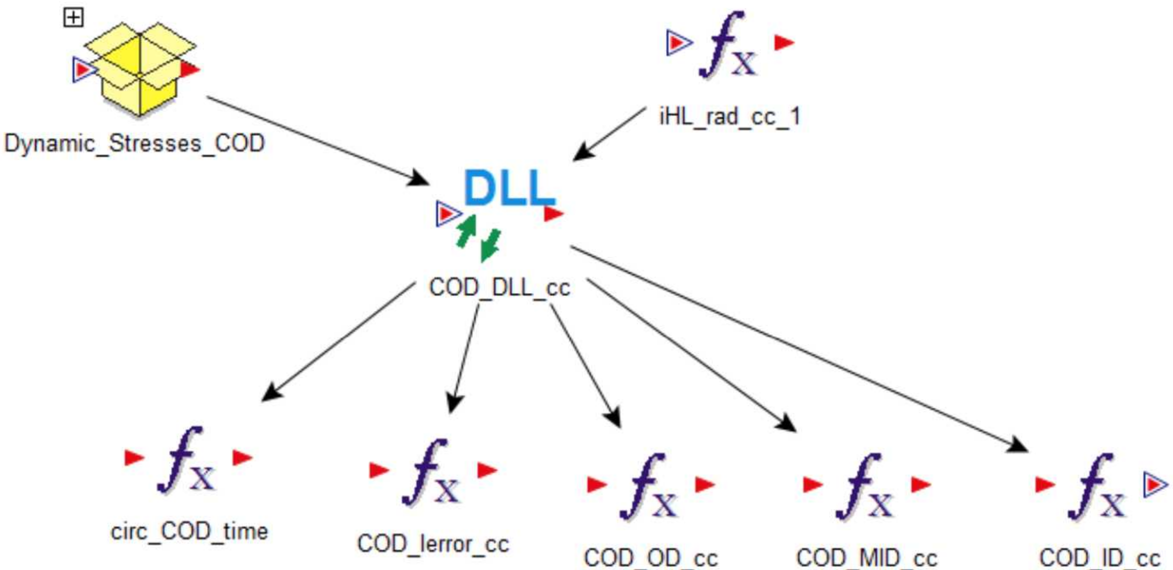
[\xLPR_Model\Circ_Crack\Circ_Crack_Stability]



[\xLPR_Model\Circ_Crack\Circ_Crack_Stability\stability_when_crack_cc]

COD: GoldSim implementation

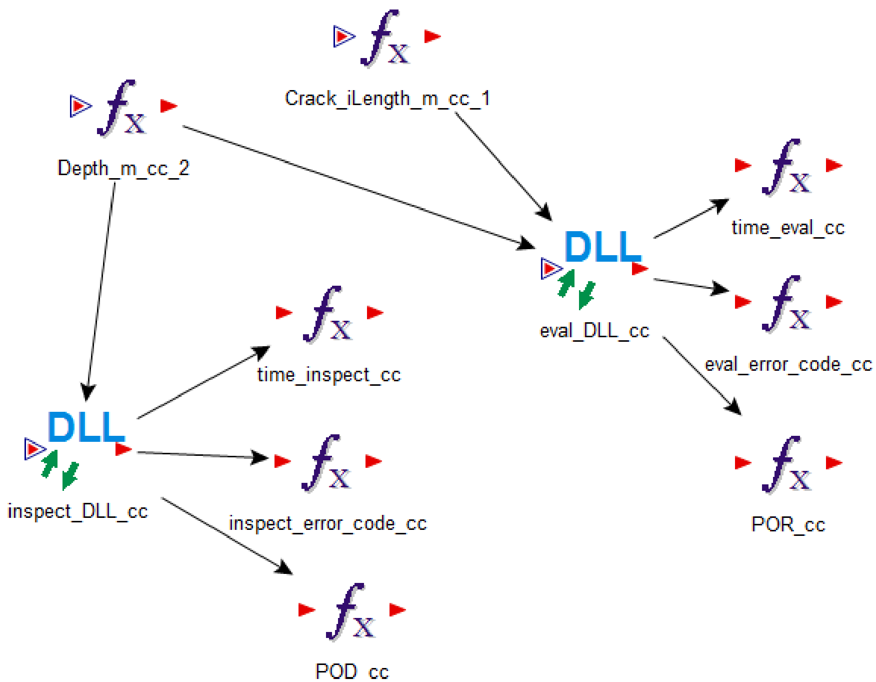
- Leak rate estimated via lookup tables calculated as pre-processor (LEAPOR).
- Options are available for crack morphology (only PWSCC and Fatigue are pre-defined morphologies currently implemented).



[\xLPR_Model\Circ_Crack\Circ_Crack_COD]

ISI: GoldSim implementation

- DLLs wrapping for circ and axial have been created and tested. All tested have been passed.
- Calculates the probability of detection AND probability of repair for each crack (two different routines from the same DLL).

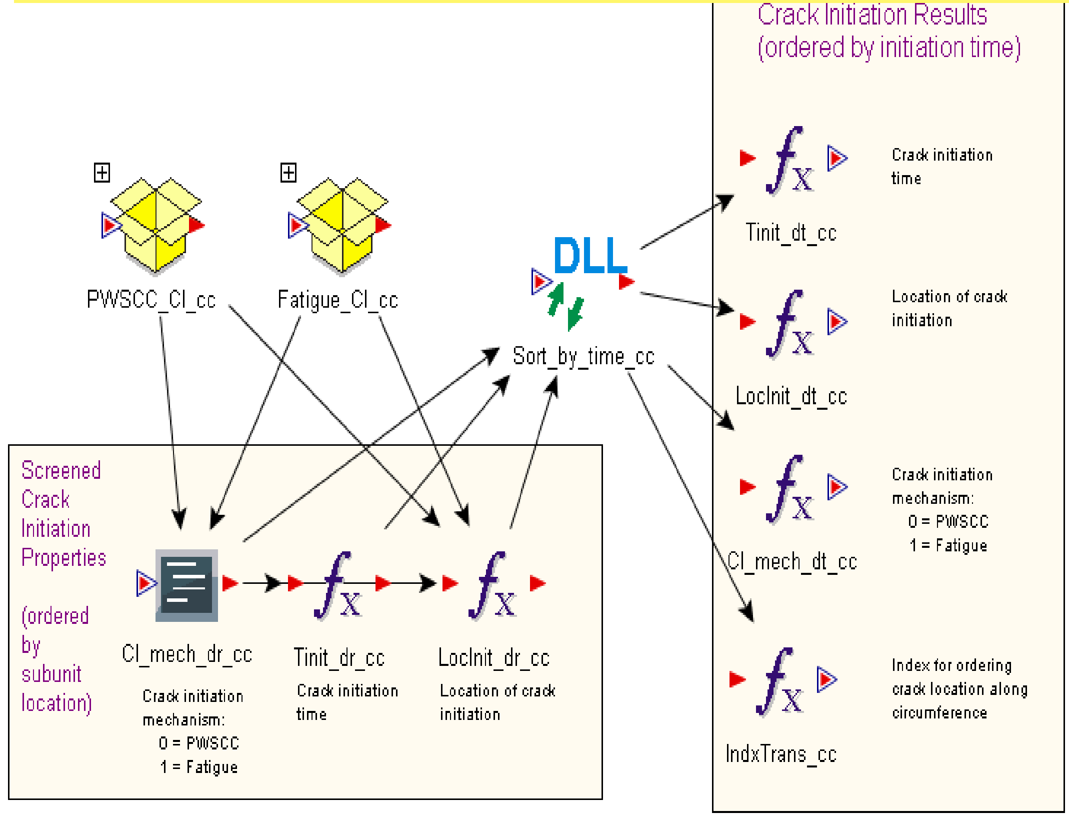


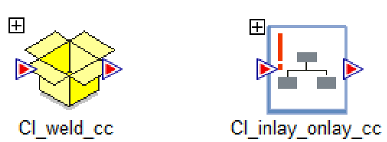
[\xLPR_Model\Circ_Crack\Circ_In_Service_Inspection]

Crack Initiation: GoldSim implementation

- DLLs wrapping PWSCC and fatigue crack initiation have been created and tested. All tested have been passed.
- Logic implemented to define crack initiation time intervals.
- Logic implemented to ensure that multiple cracks initiated within time step will all be triggered.
- For inlay/onlay: call crack initiation with inlay properties and adjust crack initiation times after inlay mitigation is applied.

[\xLPR_Model\Circ_Crack\Circ_Crack_Initiation\CI_Modules_cc\CI_weld_cc]

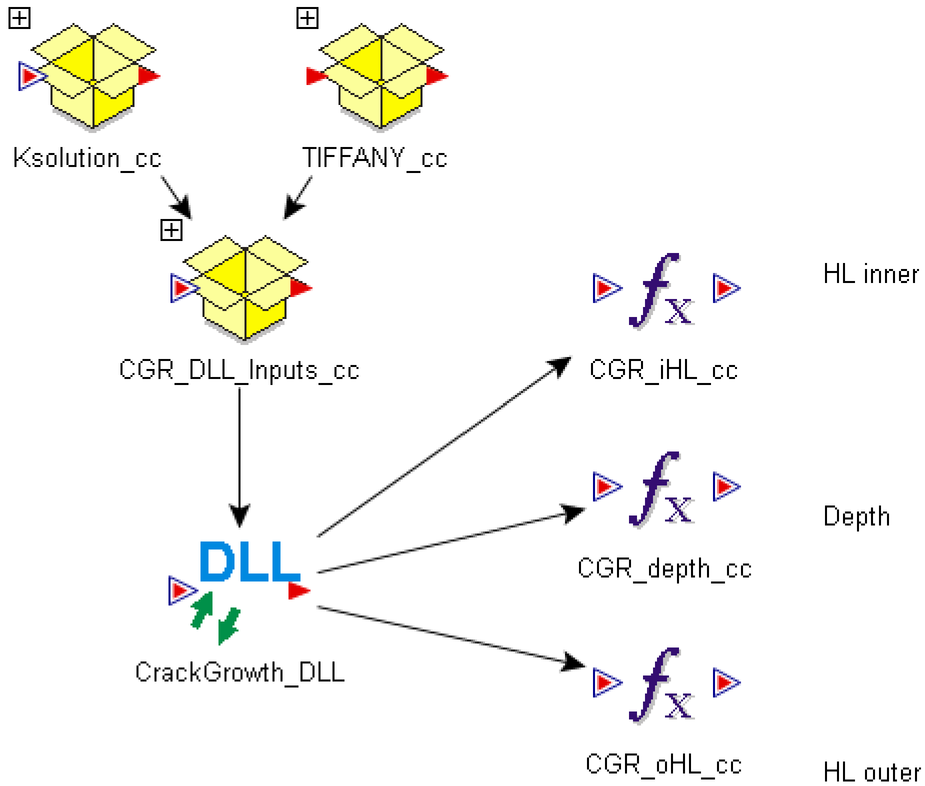




[\xLPR_Model\Circ_Crack\Circ_Crack_Initiation\CI_Modules_cc]

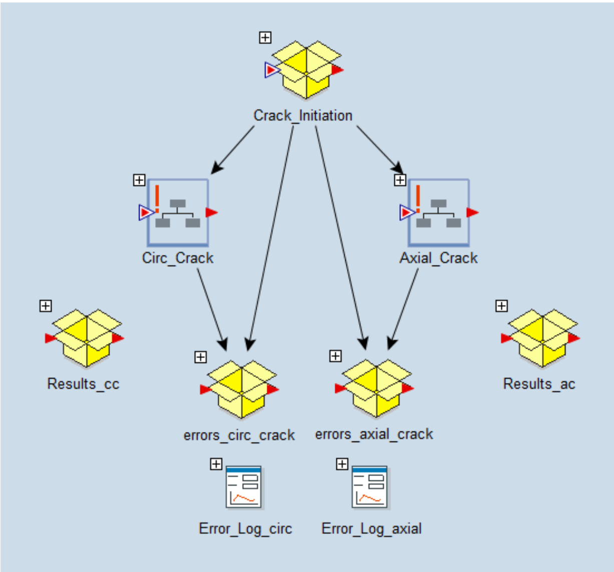
Crack growth/K-sol: GoldSim implementation

- Two crack growth mechanisms are considered:
  - PWSCC
  - Fatigue
- Script to identify materials where each crack tip is located as a function of time, inlay/onlay/overlay, and crack depth to define correct materials properties for crack growth.
- Fatigue K-solution is read from look-up table created by TIFFANY.
- Stress intensity factor vectorized by crack tip.



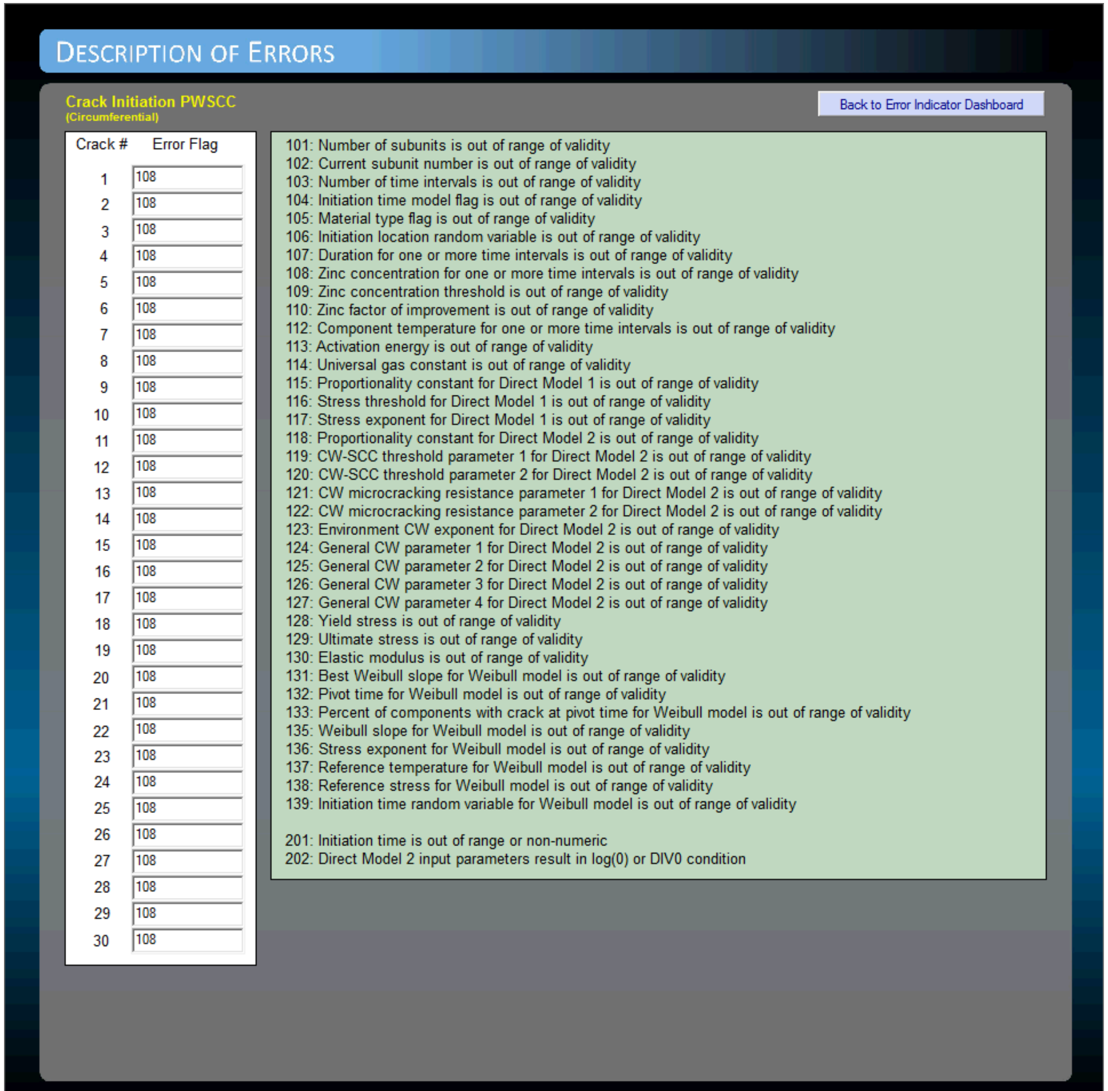
[\xLPR_Model\Circ_Crack\Circ_Crack_Growth]

Error dashboard



- Individual error tracking dashboards for circumferential and axial cracks

Error dashboard



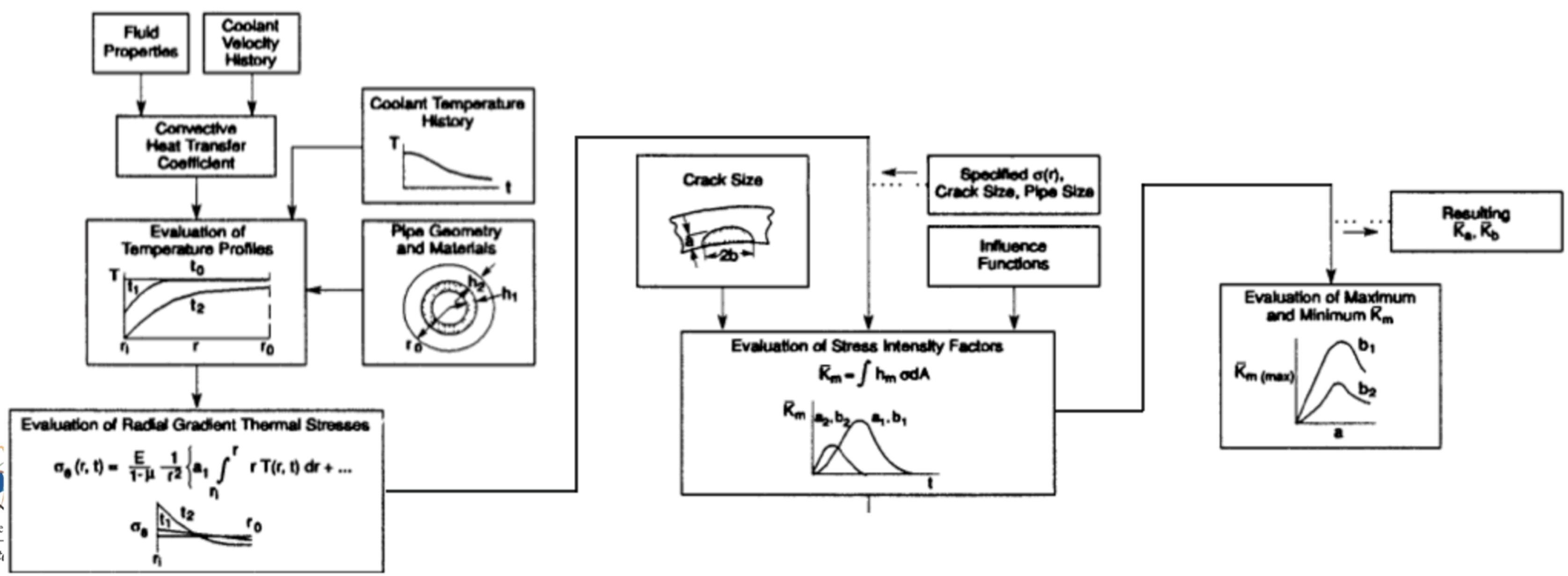
- Error elements tracked per module per subunit
- List of error code meanings provided for each module
- Time history results available for each error element
- Additional development and debugging continuing with testing

Pre-processing

- Generate look-up tables for changes in stresses and K values for fatigue crack initiation and fatigue crack growth during transients.
- Generate look-up tables for leak rate.
- Look-up tables to be interpolated by the Framework.

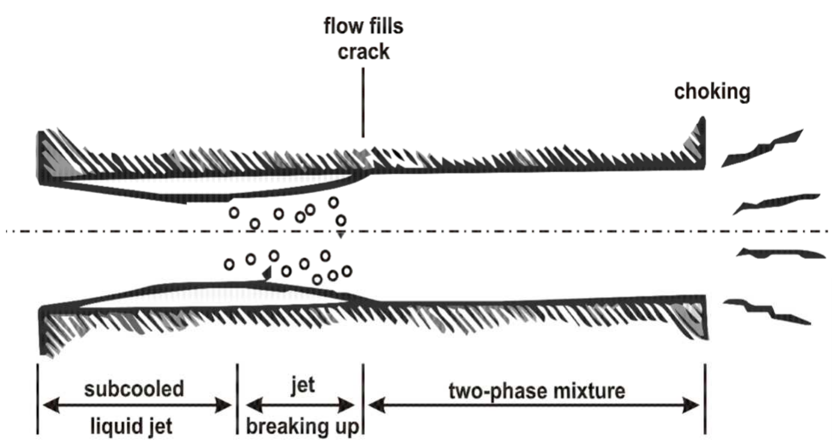
TIFFANY functionality

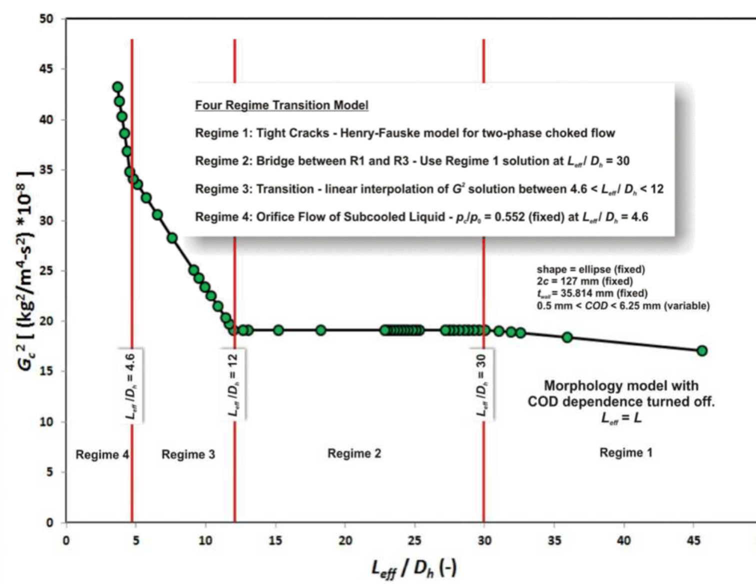
- **Stress intensity factor (fatigue crack growth):**
- **TIFFANY (T**hermal stress **I**ntensity **F**actors **F**or **ANY** coolant history) developed by SIA is used to estimate bounds for SIF.
- TIFFANY estimates SIF bounds for associated temperatures which are subsequently used by Goldsim to linearly interpolate the appropriate estimates for the SIF at a given temperature.
- Used to estimate fatigue crack growth and could potentially replace SIF module used in xLPR v1.0 for PWSCC crack growth.



LEAPOR functionality

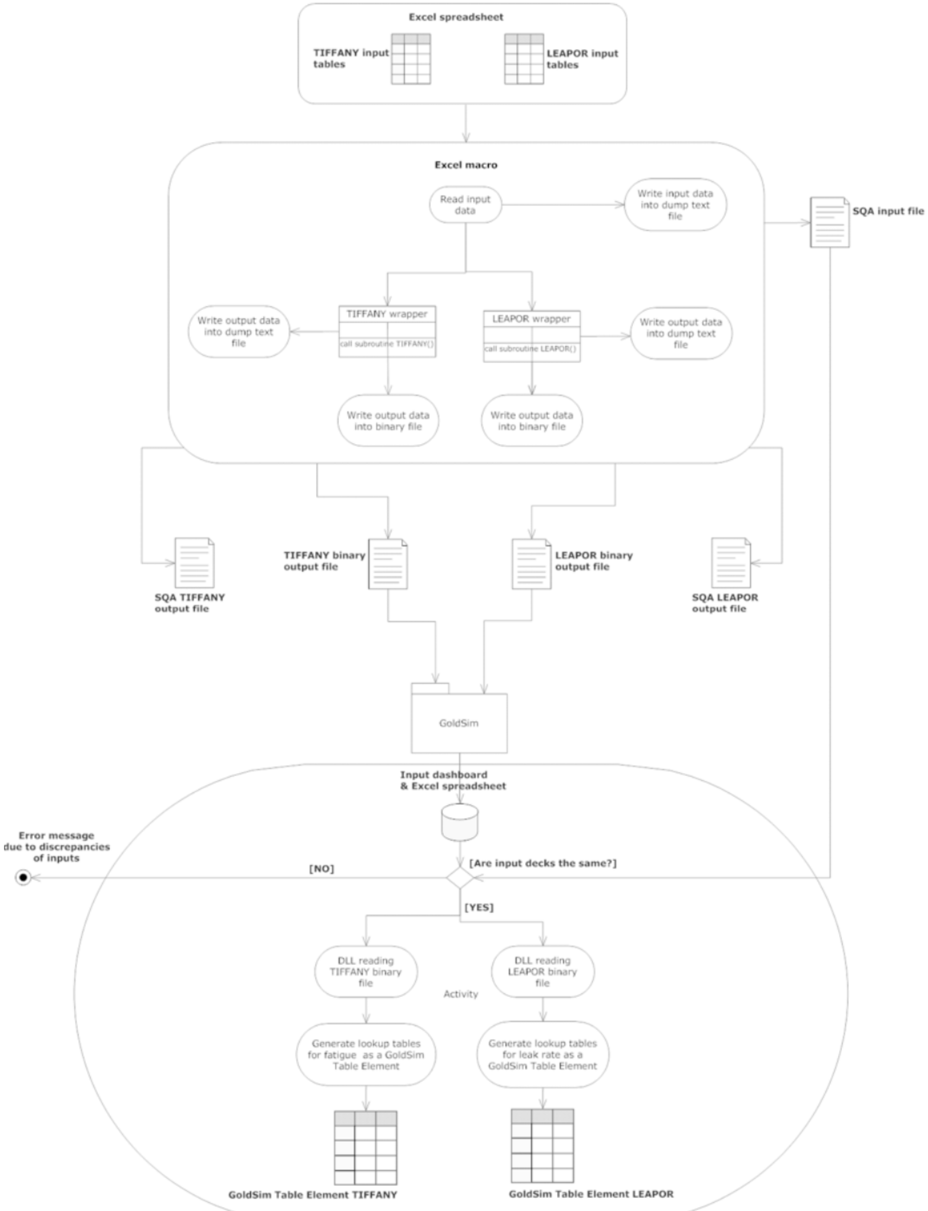
- **LEAPOR (LE**ak **A**nalysis of **P**iping **O**ak **R**idge) developed by ONRL is used to calculate leakage rates through tight cracks.**TIFFANY (T**hermal stress **I**ntensity **F**actors **F**or **ANY** coolant history) developed by SIA is used to estimate bounds for SIF.
- Saving on computational cost by generating "3D" lookup tables according to crack length, minimum COD and each thickness each defined for a given temperature and pressure.
- Used to estimate fatigue crack growth and could potentially replace SIF module used in xLPR v1.0 for PWSCC crack growth.
- Orifice flow in regime 4.



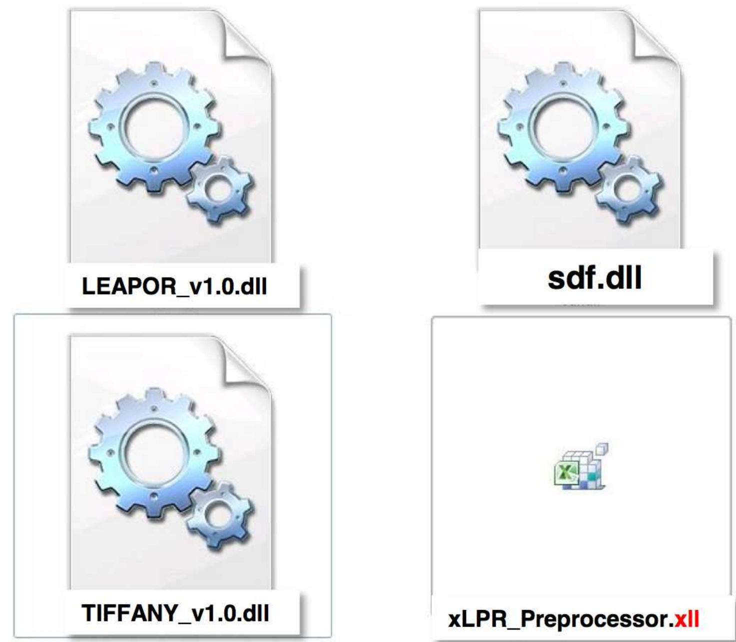


(1) R.E. Henry, "The Two-Phase Critical Discharge of Initially Saturated or Subcooled Liquid," *Nuclear Science and Engineering* **41** (1970) 336-342.
(2) R.E. Henry and H.K. Fauske, "Two-Phase Critical Flow at Low Qualities, Part II: Analysis," *Nuclear Science and Engineering* **41** (1970) 92-98.

Preprocessing flowchart



- In addition to the xLPR-2.0 Inputs Database Excel workbook, four files are required in the xLPR application directory and DLLs subdirectory.



EPRI ELECTRIC POWER RESEARCH INSTITUTE

TIFFANY and LEAPOR execution

- TIFFANY and LEAPOR embedded as a DLL subroutine and an Excel add-in to link the xLPR 2.0 inputs database and TIFFANY / LEAPOR.
- Output generated by TIFFANY and LEAPOR transmitted as a binary file to the GoldSim software.
- Additional files containing all the input data used for the runs. Two text files containing calculated results from TIFFANY and LEAPOR.
- **TIFFANY:**
  - Developed execution logic to use weld material properties and operating data as specified in Dashboard and other worksheets.
  - For each execution, TIFFANY produces 34 look-up tables for each transient, each operating period and each transient type.
  - Implemented logic for pre- and post-mitigation runs.
- **LEAPOR:**
  - Developed data gathering logic (similar to TIFFANY).
  - Pipe outer diameter and wall thickness used to establish discretization of COD , crack length, and wall thickness.
  - For each execution, LEAPOR produces 16 lookup tables.

Sampling structure

- Defines the number and order of realization and appropriate values to sue based on uncertainty.
- Outer epistemic loop, and inner aleatory loop.
- [LHS vs. RS]x[DPD vs. no DPD]x[No importance vs. importance vs. adaptive] for each loop.

In xLPR v2.0, the sampling strategy is optimized and dissociated from the uncertainty characterization giving the user flexibility on the sampling method to be used

- The two loops considered (one can be ignored by setting the sampling size to 1). For each loop, the user can select from the following options:
  - Simple random sampling or Latin Hypercube Sampling (LHS).
  - Discretization Probability Distribution (DPD).
  - Importance sampling applied to selected values.
  - Use of optimization instead of importance sampling for selected values (in development).
- Possibility of creating 12 sampling combination: [LHS vs. RS]x[DPD vs. no DPD]x[No importance vs. importance vs. adaptive] for each loop (totaling 12^2 combinations).
- 2 importance techniques (gamma-clustering (Emc^2) and importance sampling (Goldsim)) and one adaptive method (DPD adaptive (Emc^2)) are considered for xLPR v2.0.

Output

- **Office of Nuclear Reactor Regulation (NRR) leading effort to develop xLPR Acceptance criteria.**

Extremely Low Probability of Rupture (xLPR) Project

Uncertainty representation

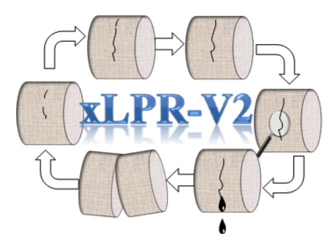
Rémi Dingreville

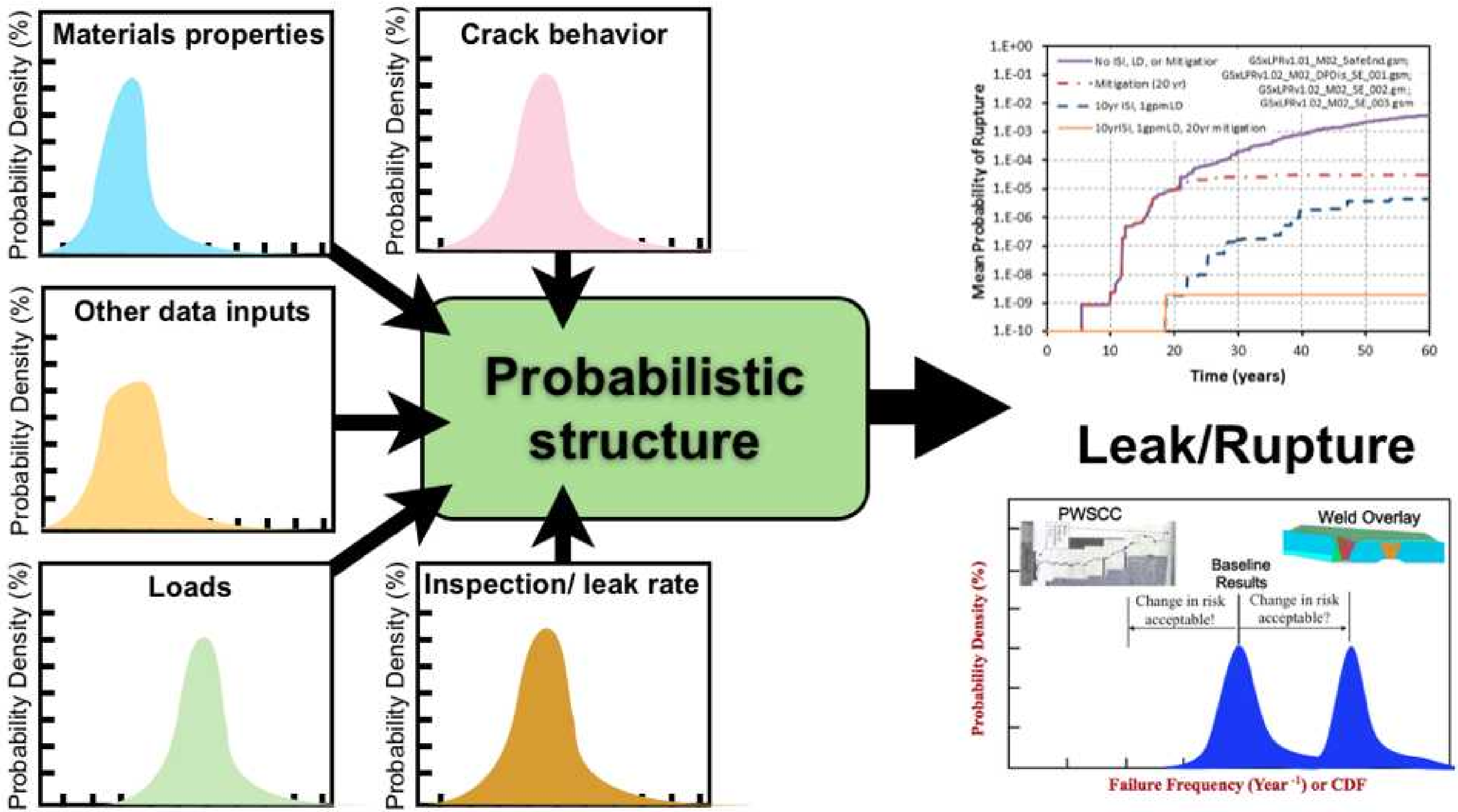
Sandia National Laboratories

xLPR External Review Board Meeting

October 29-30, 2014

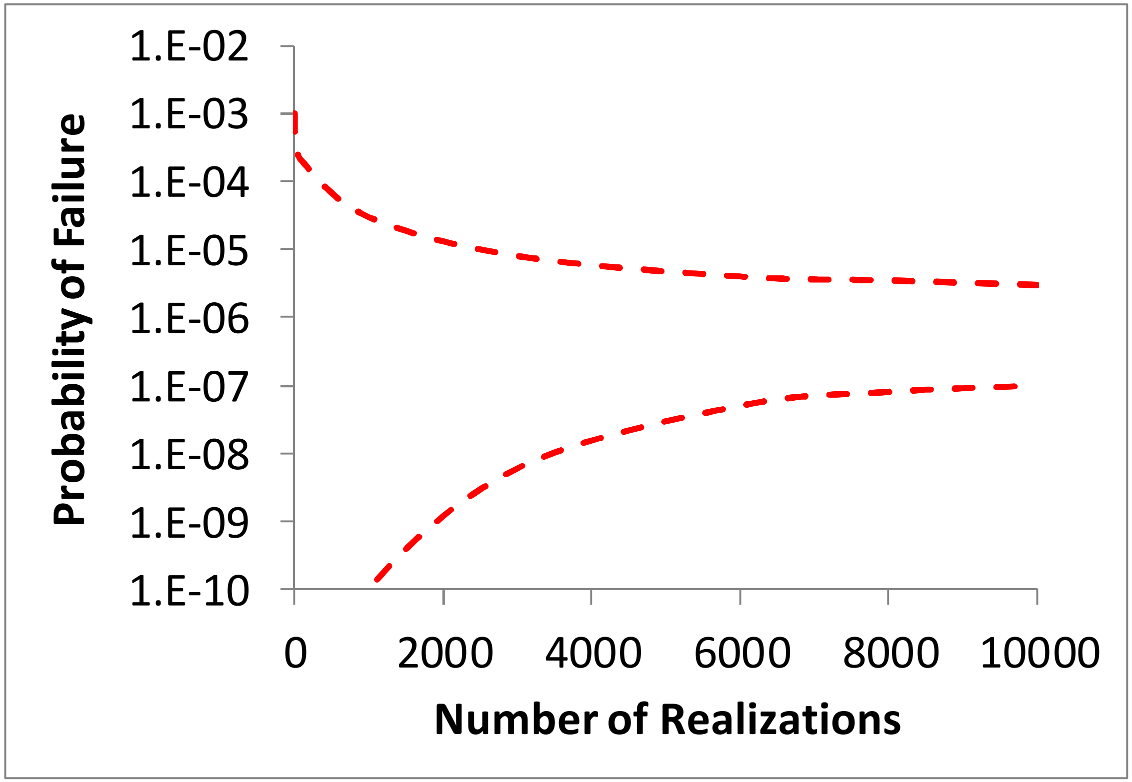
xLPR is a probabilistic assessment tool that can be used directly to demonstrate compliance with 10CFR50App-A GDC-4 requirement of extremely low probability of failure





Objectives of the uncertainty representation in xLPR version 2.0

- To capture uncertainty in model predictions
- To reduce uncertainty in predicted pipe rupture frequency
- To be efficient



Objectives of the uncertainty representation in xLPR version 2.0

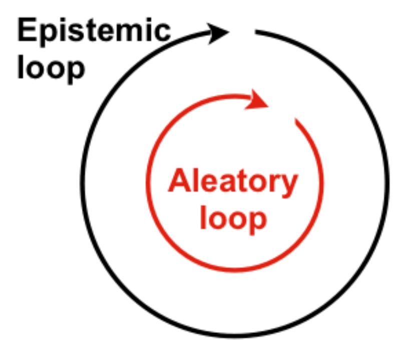
- Aleatory uncertainty
  - Well-defined distributions in which parameters may be sampled in a random or stochastic manner
- Epistemic uncertainty
  - Uncertainty in model parameter values due to uncertainty in the model, lack of knowledge, or lack of well-defined distributions
- User chooses which parameters are aleatory and which are epistemic
- Inner aleatory loop
- Outer epistemic loop
  - Allows evaluation of epistemic (model) uncertainty

Aleatory (Irreducible)

- Crack size
- POD detection
- Material properties
- Crack growth parameters (Q/R,c,P)

Epistemic (Lack of knowledge)

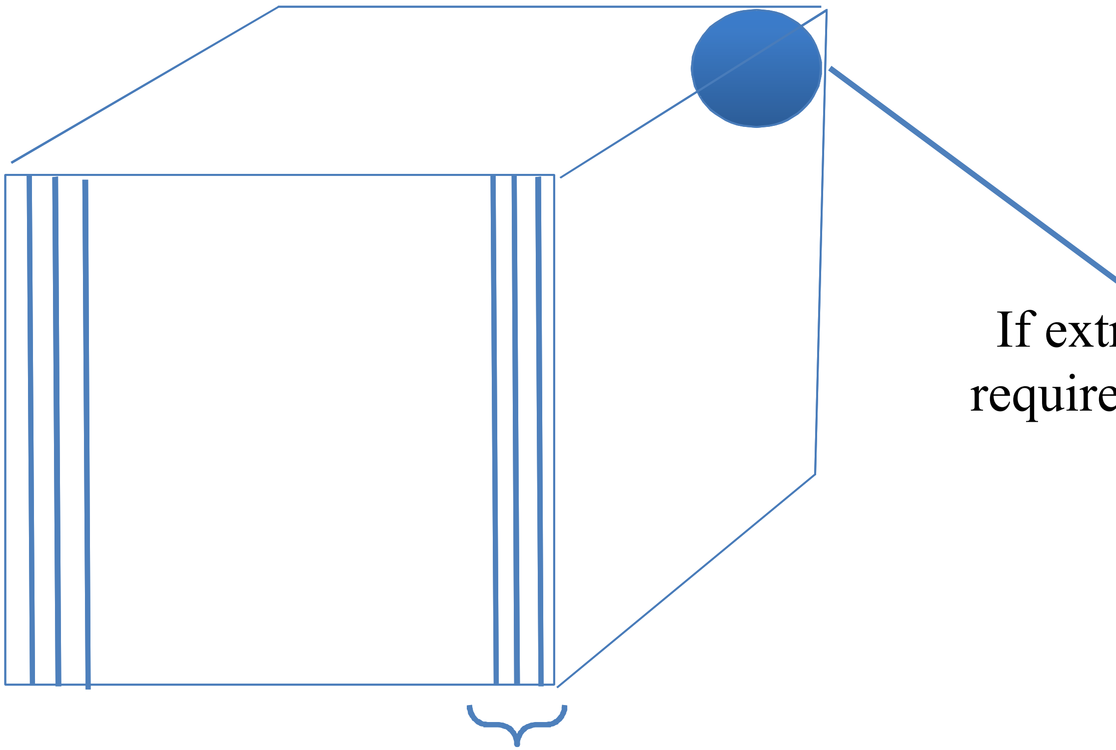
- Loads
- WRS
- Crack growth (fweld)
- Crack initiation parameters
- POD parameters



RS vs. LHS vs. DPD

- **R**andom **S**ampling is the original Monte Carlo approach.
  (usually not recommended for xLPR analysis)
- **L**atin **H**ypercube **S**ampling: dense stratification of each input (projection of input space to one value) – better if variables are important *by themselves* and extreme values for input are needed
- **D**iscrete **P**robability **D**istribution: better multidimensional coverage – better if variables are important *conjointly* and a reasonable range of values (not extremes) is required/ sufficient.

RS vs. LHS vs. DPD



If extreme values of x_1 are required, DPD may be better

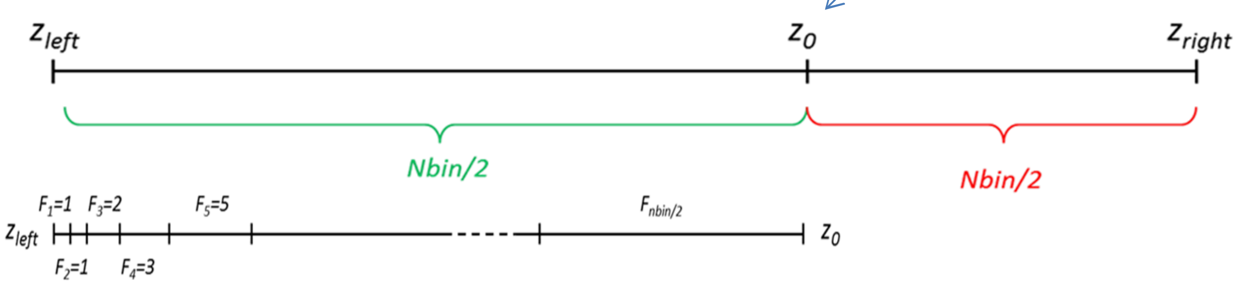
If extreme values of x_1 are required, LHS may be better

Discrete probability distributions (DPD) can be used to increase the resolution of regions of interest within probability distributions for importance sampling

- **DPD uses discrete values from probability distributions**
  - **Each value can be equally probable or of different likelihood**

- **DPD can be used in <u>importance sampling</u>**
  - **For example, a Fibonacci series works well for interrogating tails of distributions**
  - **The strength of the Fibonacci series can be controlled by an exponent γ between 0 and 1 on the F value**

A value z_0 is selected to split
The strata into two groups



$$F_{n+2} = F_n + F_{n+1}$$

Fibonacci series is used to generate strata of unequal size with focus on the tail

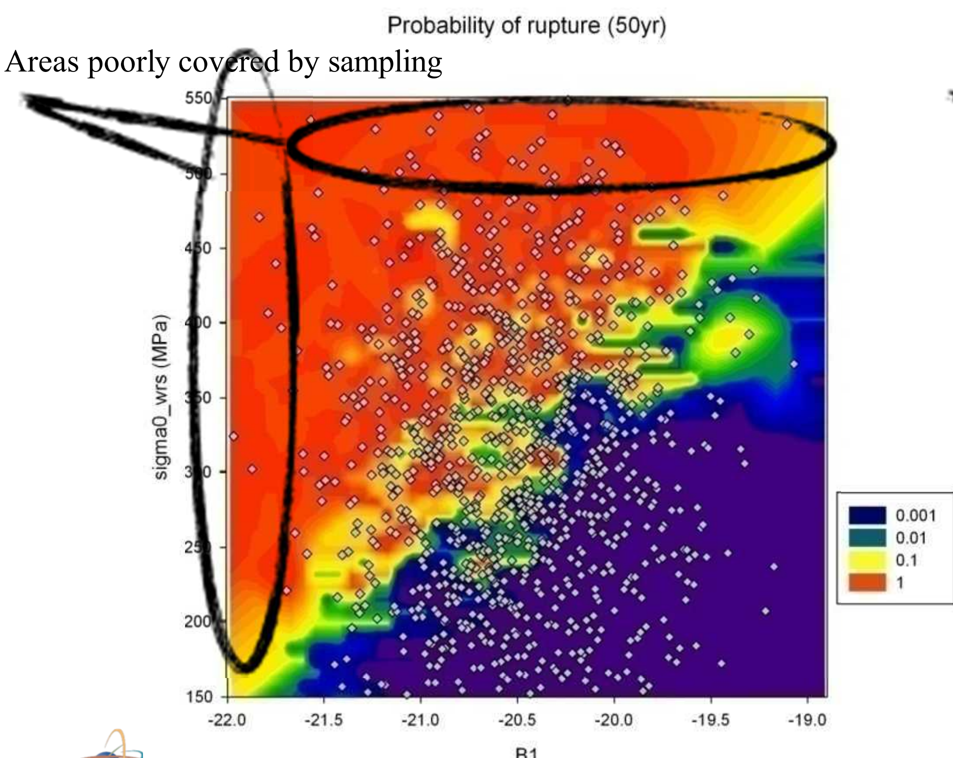
Importance smapling

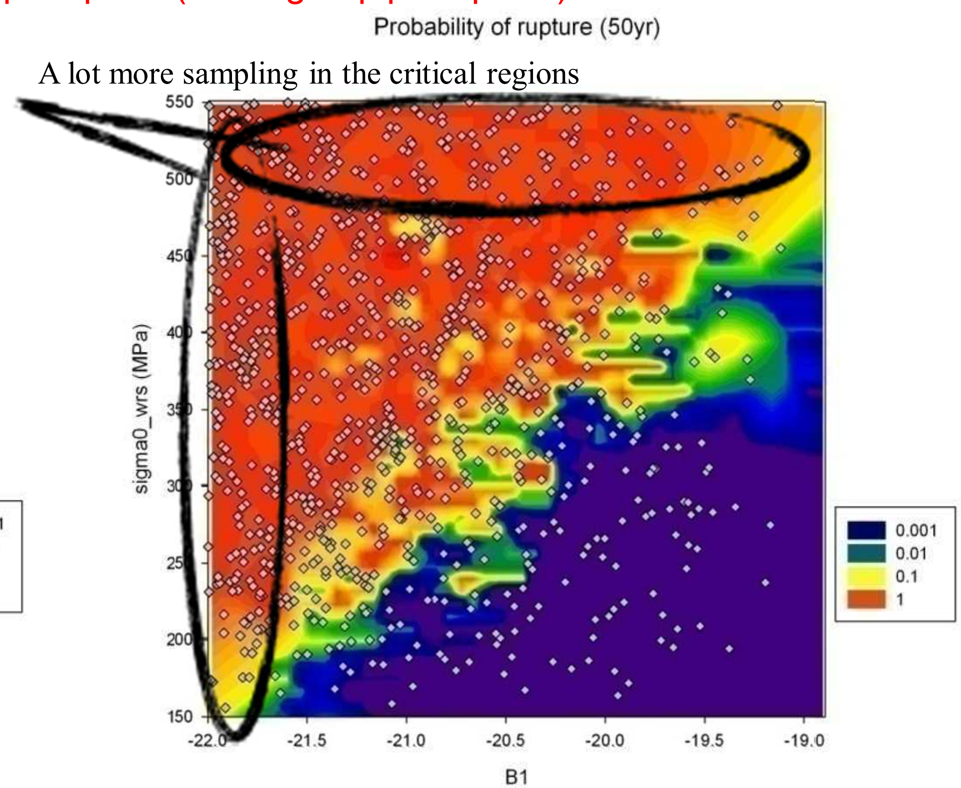
- When the sample size is not big enough to cover the required extreme values of some input, Importance sampling may be used
- Requires to know:
  - Which input variables are important
  - Which area of these inputs variables needs to be over-covered.
- May be a necessary step when dealing with extremely low values
- Cannot be applied to all variables ! (selection must be made)
- For now, only internal approach available. In the future, external and adaptive approach will be added.

xLPR v1.0 and the pilot study underlined the importance of focusing sampling on regions of interest to accurately estimate extremely low probabilities

- **For example, looking at the probability of rupture as a function of two variables (crack initiation and weld residual stress) using regular sampling vs. importance sampling highlights the shortcoming of regular sampling.**

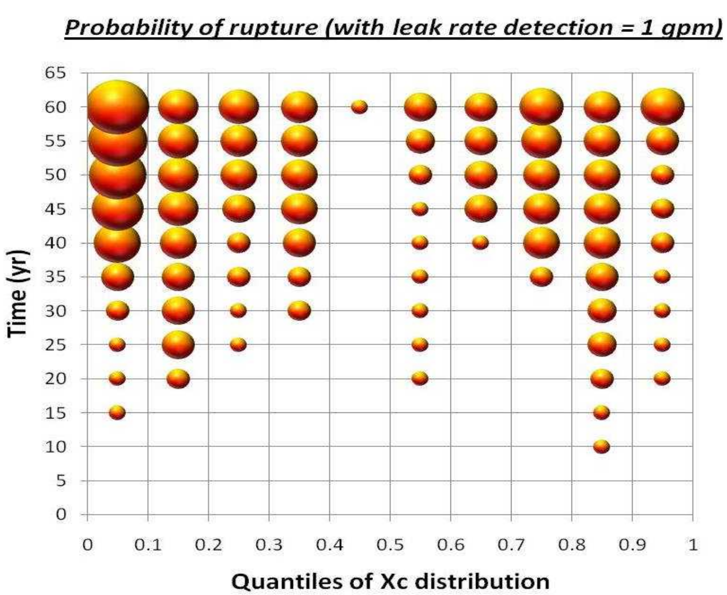
In red: region of interest in the input space (leading to pipe rupture)

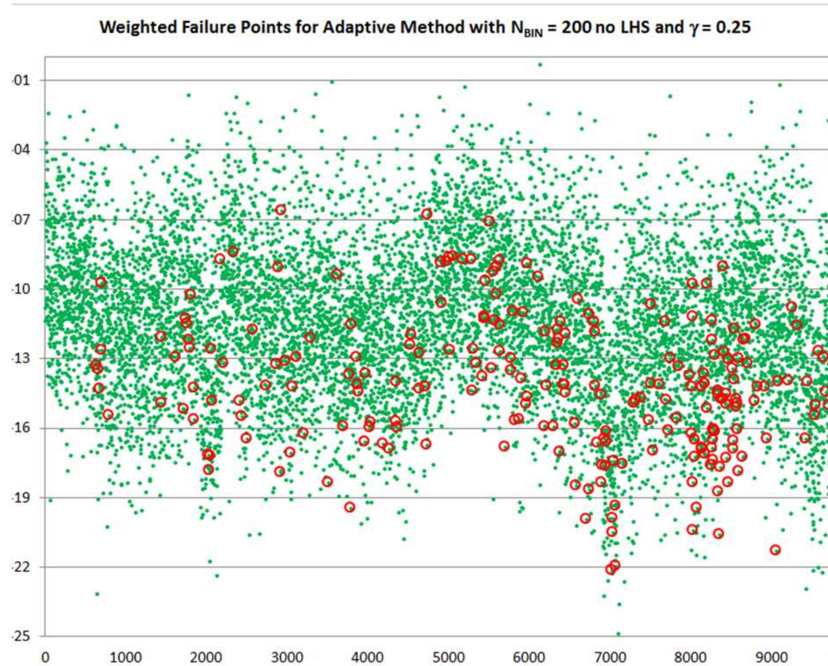




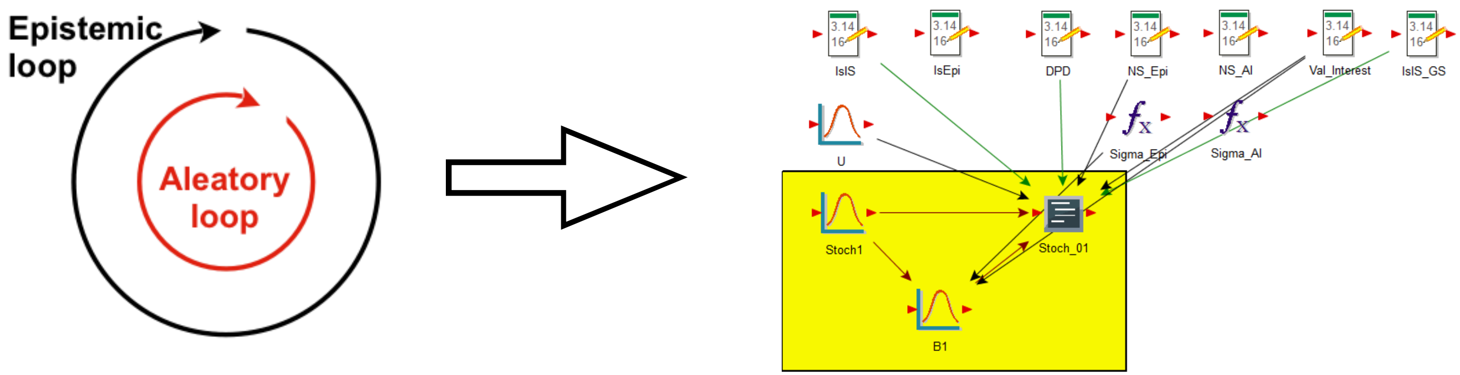
Adaptive sampling promotes importance sampling by using model results to identify and focus on sampling space that leads to pipe rupture

- In xLPR v2.0, the sampling strategy is not uniquely based on the user knowledge; rather adaptive and optimized strategies are adopted to cover relevant regions of the input space
- Adaptive sampling can cover more densely disparate regions in the input space, and reduces the number of samples needed to confidently estimate low probability (~10^{-6})
- Criteria? All variables at play? Exactly what is plotted below? Shows progression? Are red circles pipe ruptures? Adaptive DPD only?





In xLPR v2.0, the sampling strategy is optimized and dissociated from the uncertainty characterization giving the user flexibility on the sampling method to be used



- **The two loops considered (one can be ignored by setting the sampling size to 1). For each loop, the user can select from the following options:**
  - Simple random sampling or Latin Hypercube Sampling (LHS).
  - Discrete Probability Distribution (DPD).
  - Importance sampling applied to selected values.
  - Use of optimization instead of importance sampling for selected values (in development)
- **Possibility of creating 12 sampling combination: [LHS vs. RS]x[DPD vs. no DPD] x[No importance vs. importance vs. adaptive] for each loop (totaling 12^2 combinations).**

Adaptive DPD can be used to predict pipe rupture with orders of magnitude fewer realizations than Monte Carlo

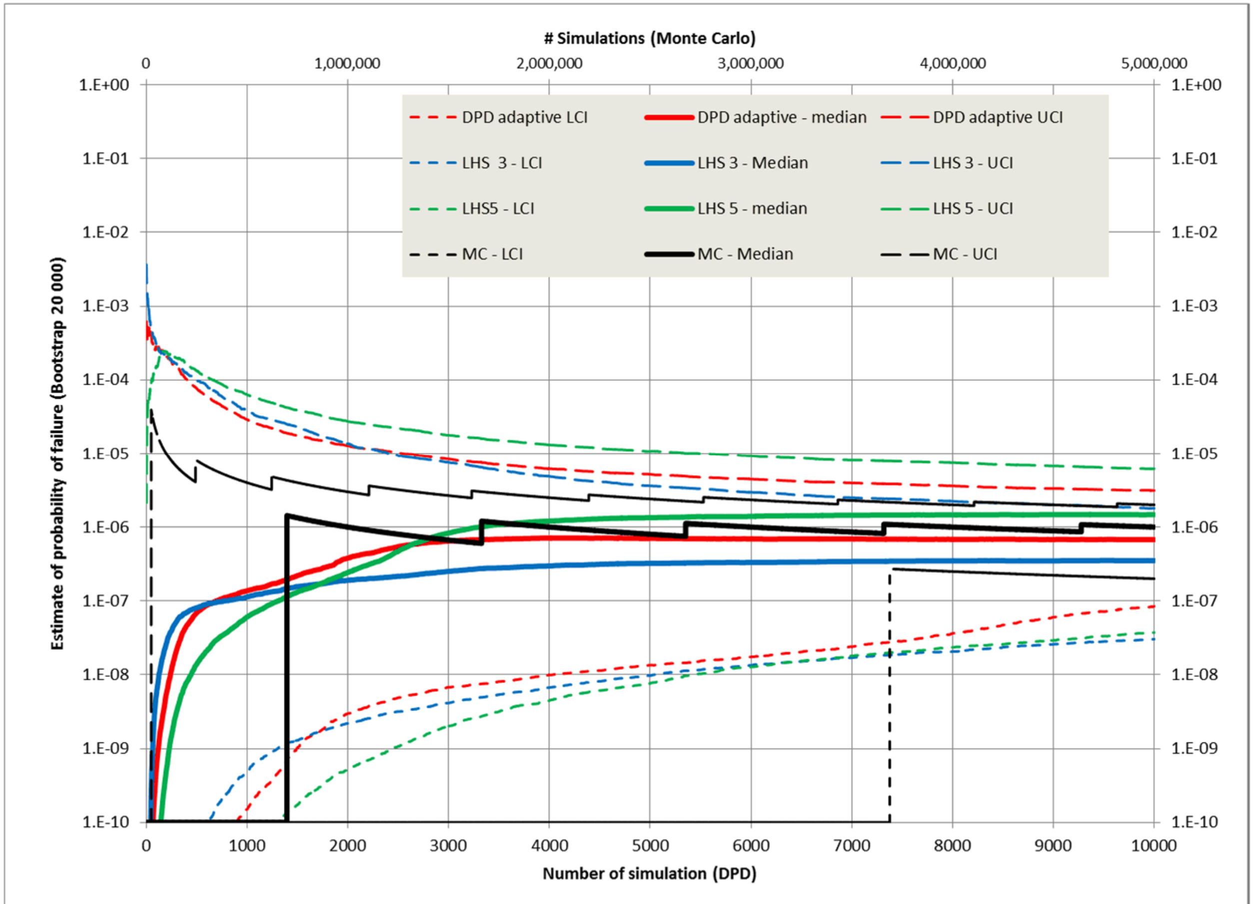
- **In this example, to predict pipe rupture with high confidence**
  - **Adaptive DPD needs 10,000 to 20,000 realizations**
  - **Monte Carlo needs at least 4,000,000 realizations (i.e., >200 times more)**

Graph compares xLPR v1.0 median and 95th confidence intervals for:

- DPD adaptive (red) up to 10,000 realizations
- Monte Carlo (black) up to 5,000,000 realizations
- LHS 3
- LHS 5

DPD adaptive:

- More efficient
- Much better resolution



U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Extremely Low Probability of Rupture (xLPR) Project

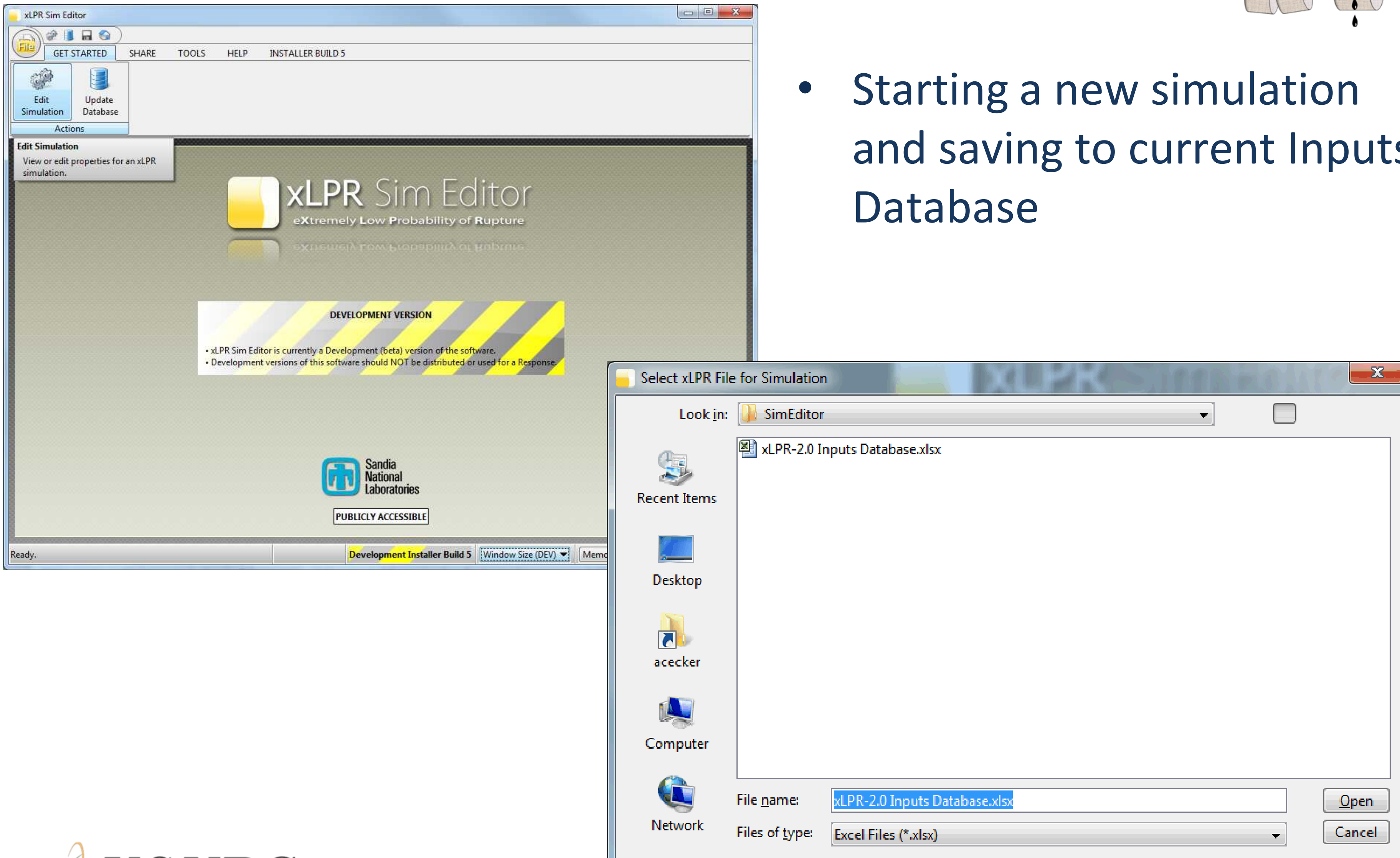
Upcoming advanced

Rémi Dingreville
Sandia National Laboratories

xLPR External Review Board Meeting
October 29-30, 2014

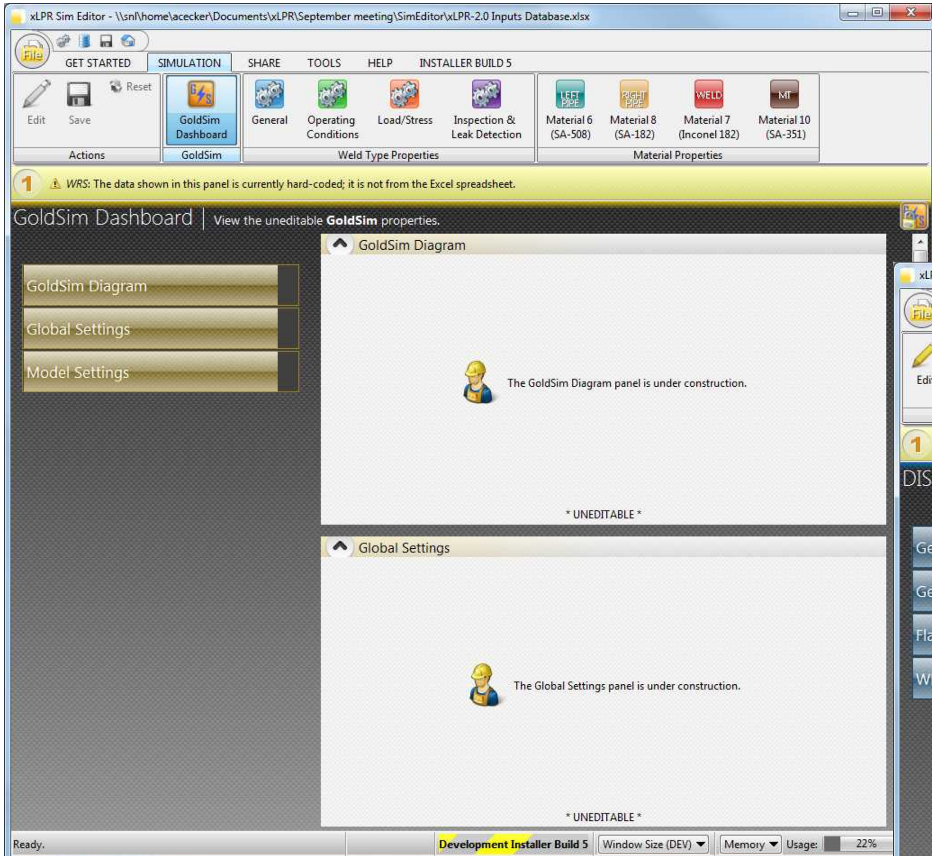
xLPR simulation editor

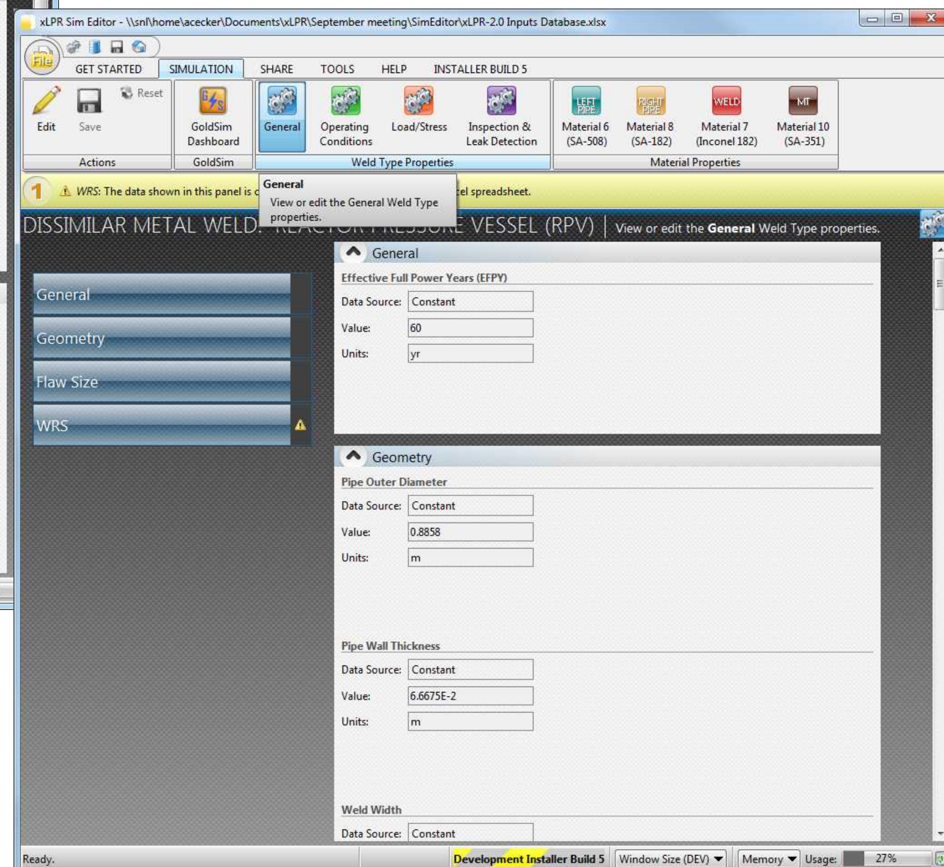
- Starting a new simulation and saving to current Inputs Database



xLPR simulation editor

- General properties window

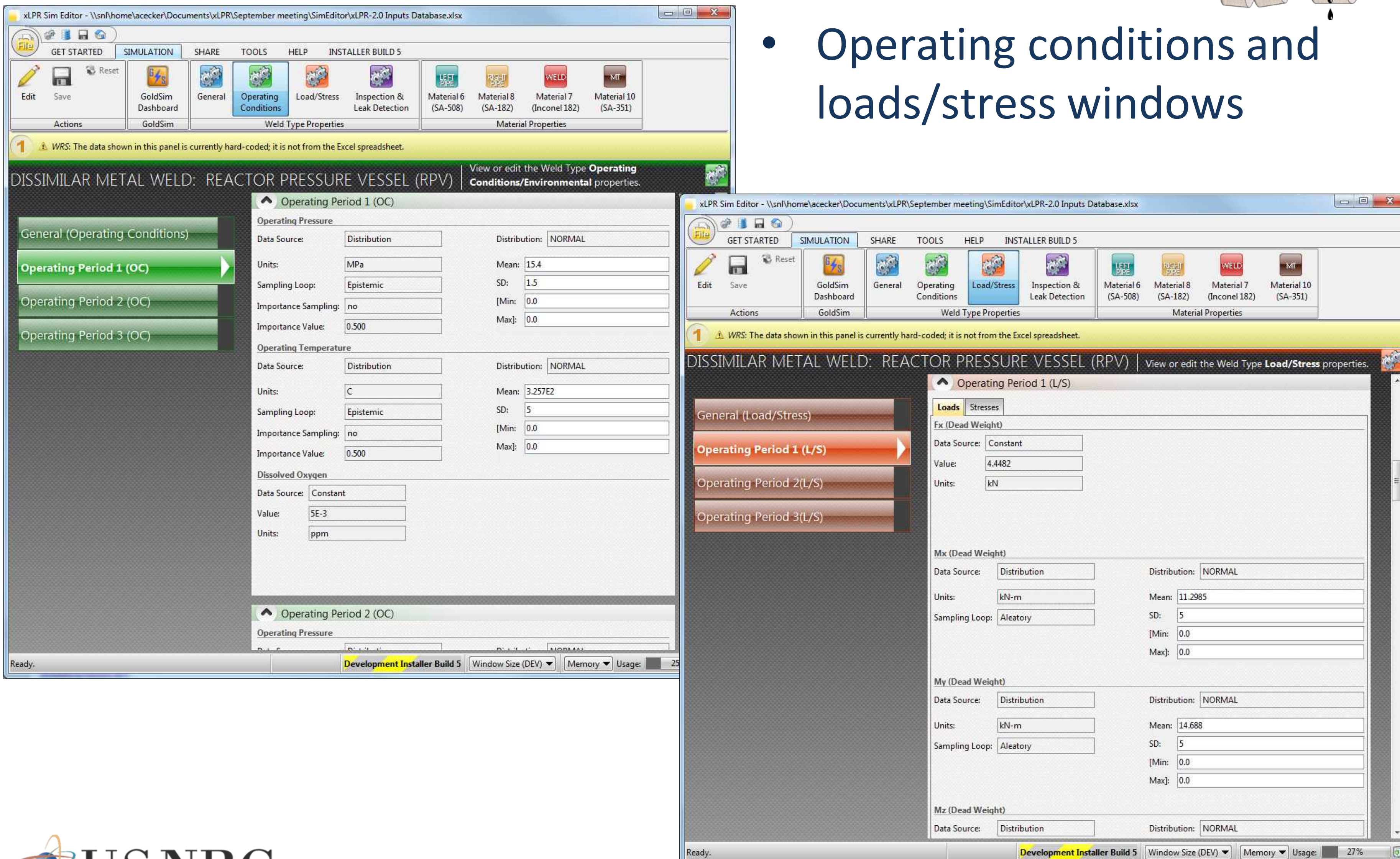




U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

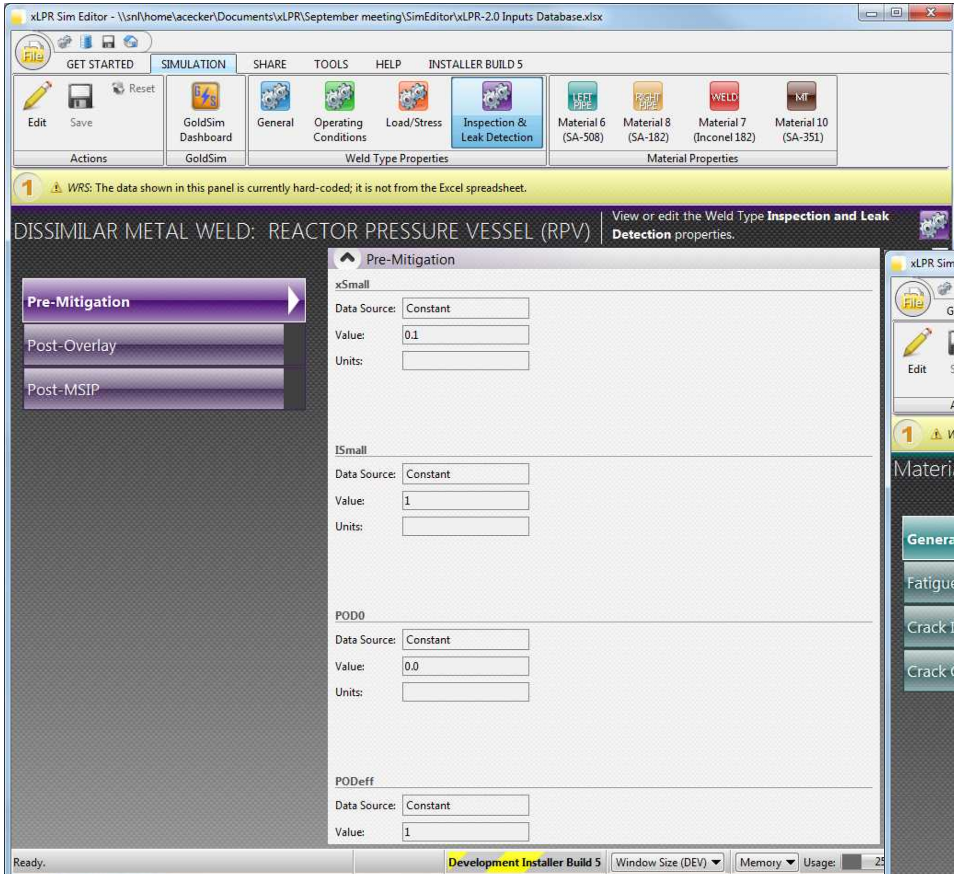
EPRI ELECTRIC POWER RESEARCH INSTITUTE

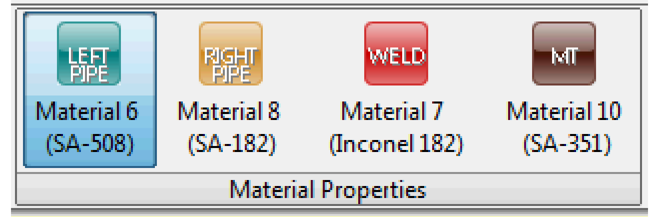
xLPR simulation editor

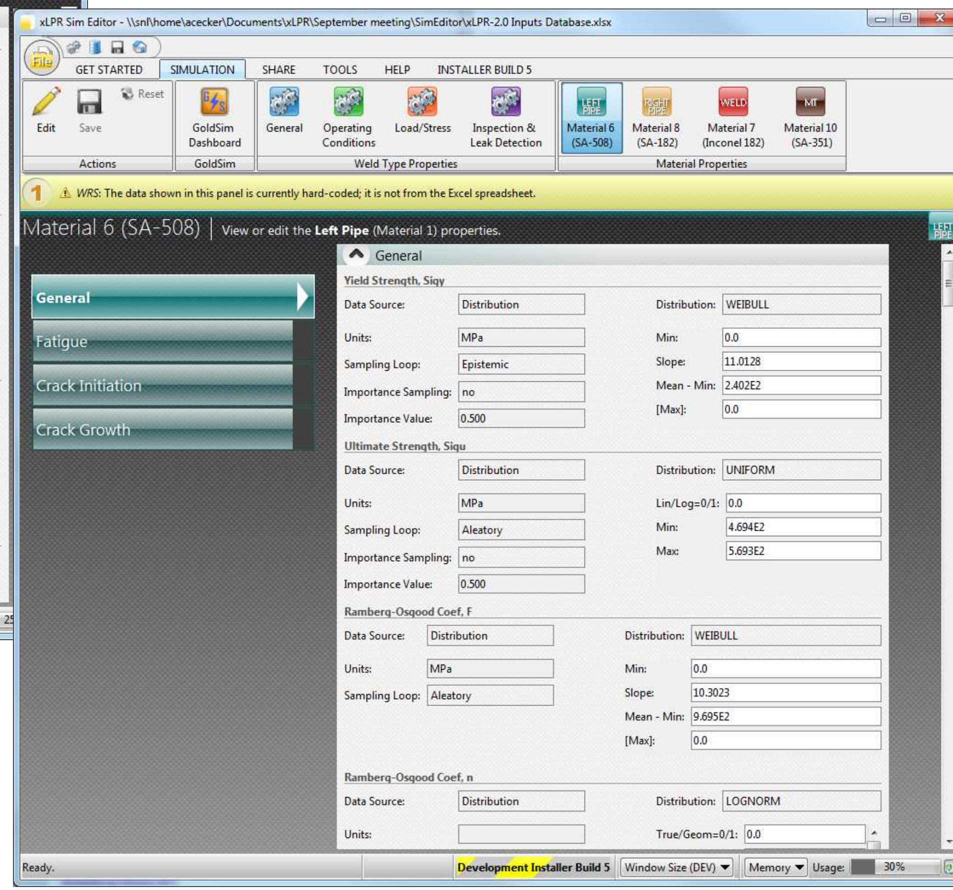


- Operating conditions and loads/stress windows

xLPR simulation editor







- Inspection & Leak Detection and Material properties windows

xLPR simulation editor

- Clarifications for user including consistent display of information, inputs, and options, descriptions of inputs, general instructions at "Get Started" command, and clear distinction among sets of commands (e.g. Reset, Save, Update)
- Determine user interaction with default distribution parameters, further explanation of these parameters, warning message for invalid distribution parameters, relationship between constant and distribution mean values
- Specific requirements for changes on a per-module basis
- Generation of PRO-LOCA input deck based on xLPR input deck