Probabilistic RPV Integrity Assessment: Baseline Probabilistic Benchmark – Tools Verification

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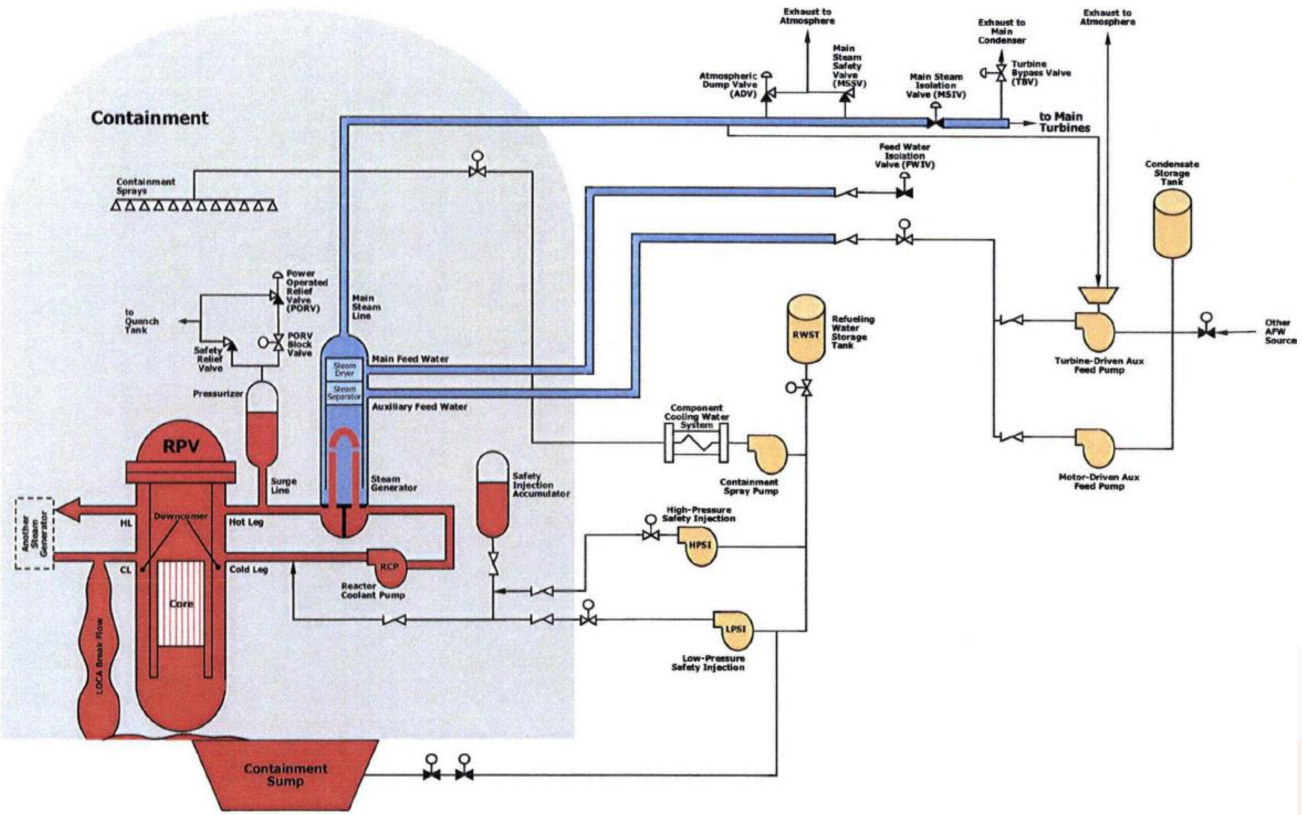
Background on Pressurized Thermal Shock (PTS)

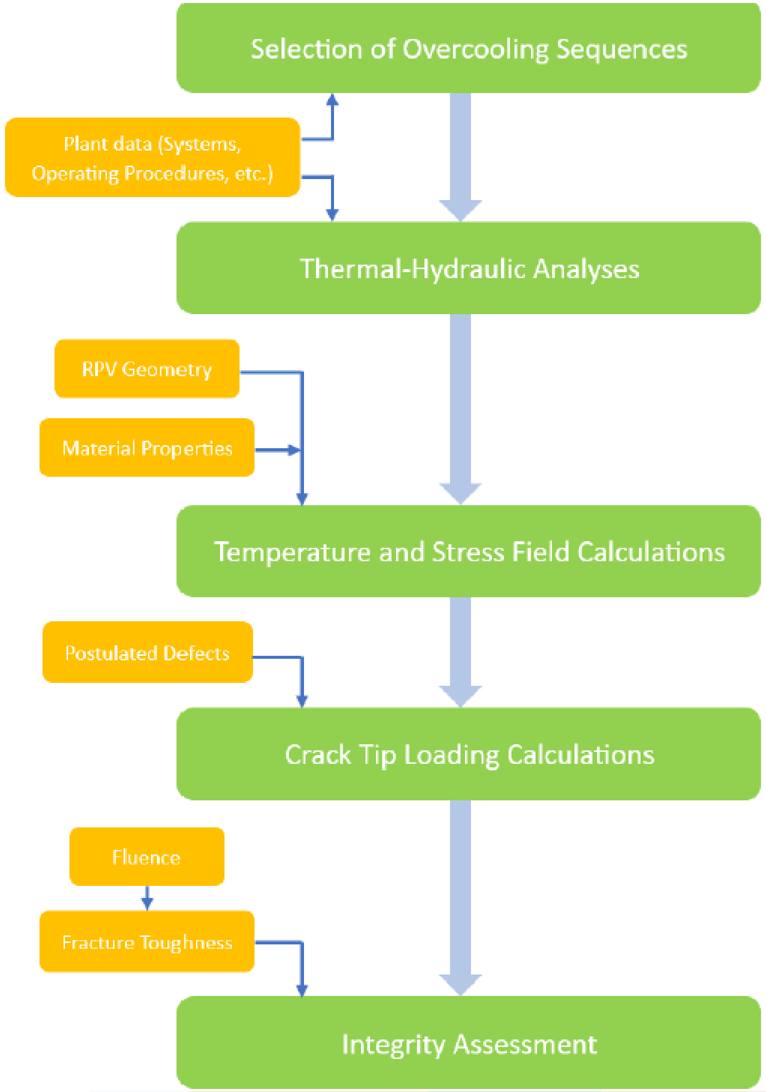
- PTS may occur when emergency core cooling water is injected into pressurized RPV under any of postulated initiating events
- Rapid cooling of RPV internal surface causes thermal tensile stresses $\sigma_T(r,t)$ in addition to pressure-induced stresses
  - Thermal stress magnitude depends on a temperature gradient through the RPV wall
- RPV integrity assessment for PTS events is one of the challenges for safety analyses for LTO of aged NPPs:
  - Thermal stresses due to PTS transient in combination with pressure loads,
  - Reduced material toughness due to neutron irradiation,
  - Presence of flaws in high stress areas



Background on APAL

- Current RPV integrity assessments for PTS scenarios are mostly based on deterministic calculations of margins against brittle fracture
  - Demonstration of sufficient margins may be a difficult task

- APAL project (Advanced PTS Analysis for LTO):
  - Multidisciplinary project (incl. TH analyses)
  - Further development of probabilistic and deterministic analysis methods for assessing PTS and RPV safety margins
  - Explicit consideration of distributed parameters (fracture toughness, fluence, chemical composition, flaw size)
  - Impact of thermal hydraulic (TH) uncertainties and different LTO improvements on the RPV safety assessment
  - Quantification of safety margins
  - Development of best-practice guidance


Selection of Overcooling Sequences

Plant data (Systems, Operating Procedures, etc.)

Thermal-Hydraulic Analyses

RPV Geometry

Material Properties

Temperature and Stress Field Calculations

Postulated Defects

Crack Tip Loading Calculations

Fluence

Fracture Toughness

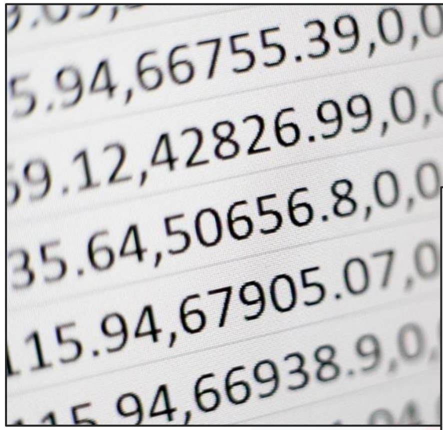
Integrity Assessment

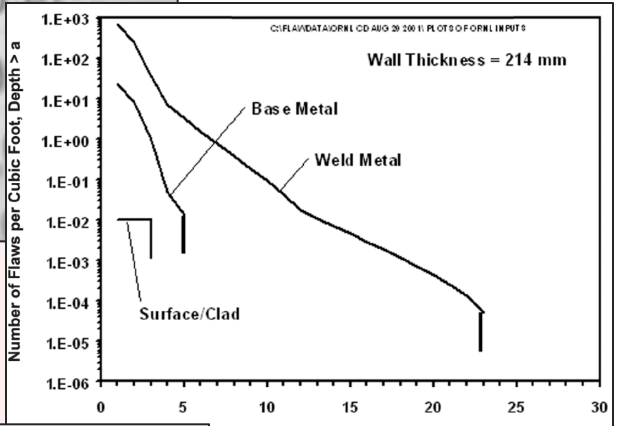
Baseline Probabilistic Benchmark - Tools verification

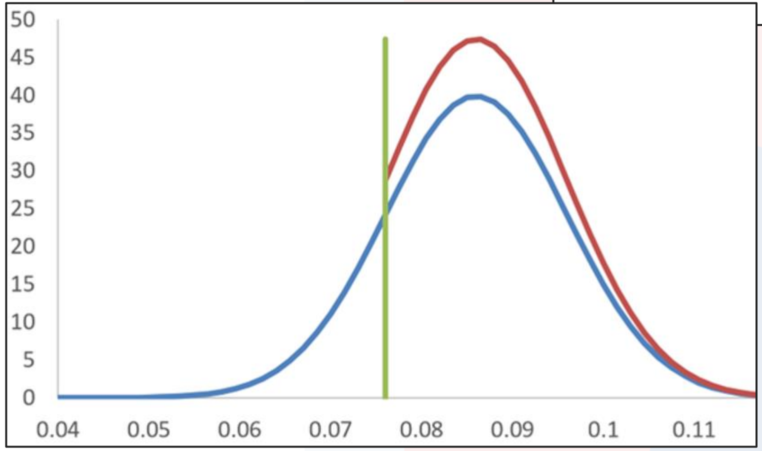
- Probabilistic analyses are complex involving many uncertainties
- Variety of probabilistic tools used in APAL
  - Mostly, in-house tools (coded in MATLAB, Python) and FAVOR
- Tools verification based on pre-defined data:
  - Based on experience from previous projects, an important prerequisite in probabilistic assessments before moving to analyses with partner-specific transient data
  - Comparison between different probabilistic codes for verification of their performance and accuracy
  - Also, some ambiguities with interpretation of certain input data were identified and adjusted

Verification of basis for used probabilistic tools

- **Random number generator (RNG) performance**
- **Generation of flaw size distribution**
- **Generation of data from a truncated distribution**
- **Verification of conditional probability of initiation (CPI) for provided K_I and adjusted reference temperature (ART)**

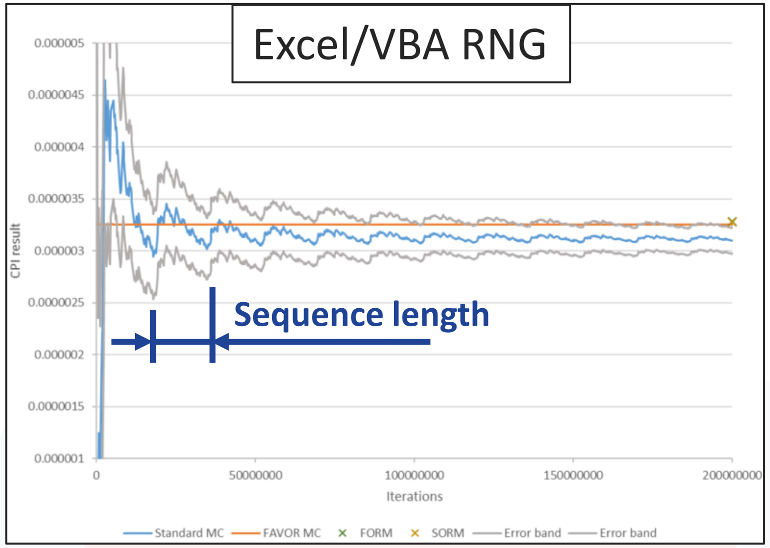




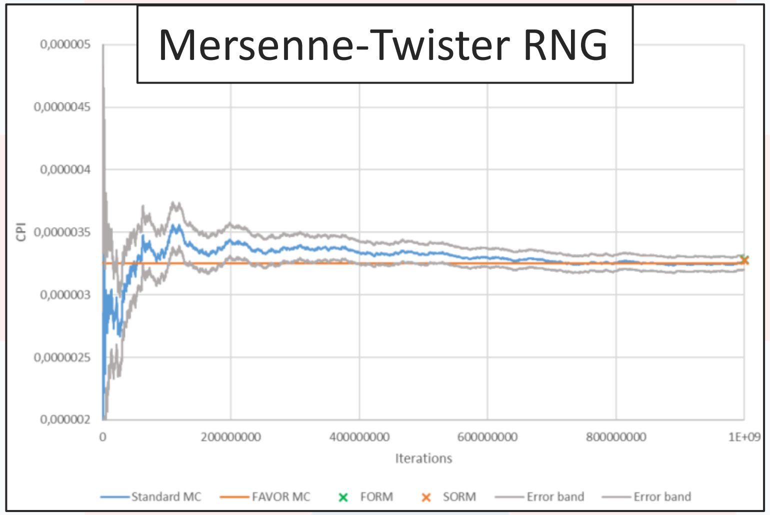


Random number generator (RNG) performance

- Monte Carlo Simulation (MCS) tools require appropriate RNGs
- Verification of RNGs in probabilistic tools used in APAL for eliminating uncertainty related to insufficient RNGs
- Sequence length (or period) of RNGs is one of the main characteristics, especially for targeting low probabilities
- Standard RNGs in common software tools may be insufficient
  - e.g. RND() in Excel/VBA RNG has a sequence period of about 1.6e7
  - RAND() uses Mersenne-Twister RNG with much longer sequence
- Targeting probabilities of 10^{-9} requires at least 10^{11} simulations with standard MCS


Excel/VBA RNG

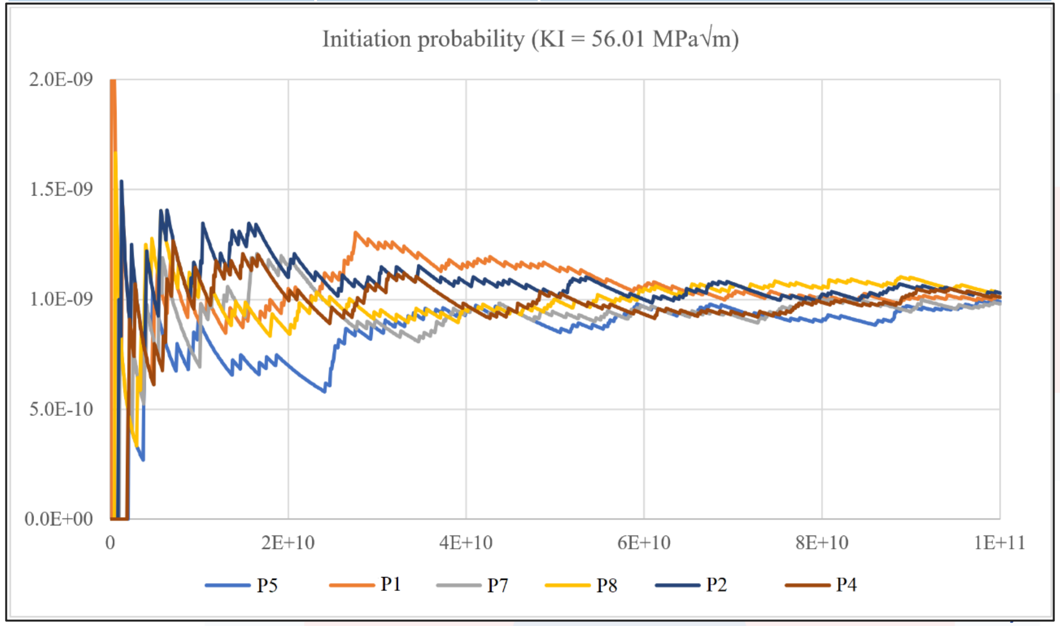
Sequence length


Mersenne-Twister RNG

RNG performance - Verification

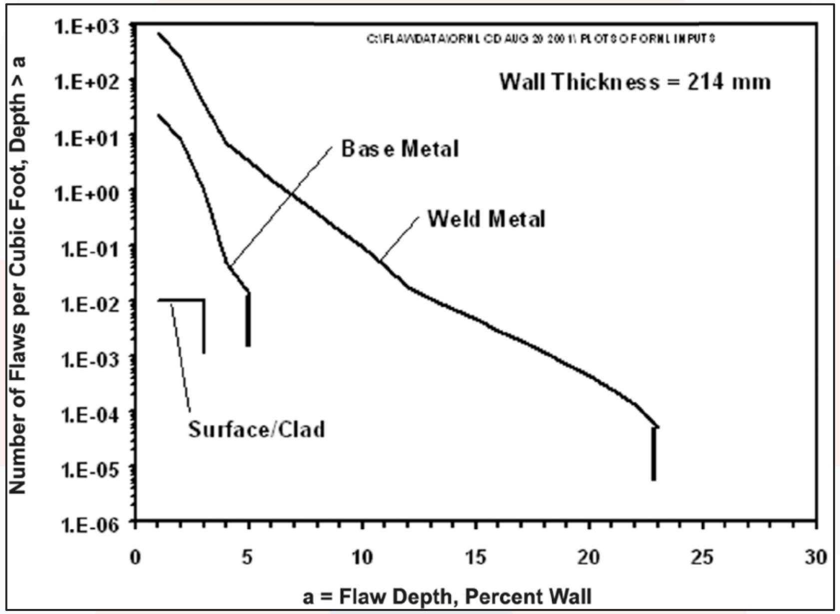
- Benchmark cases for RNG verification:
  - Evaluate fracture initiation probability by solving the limit state function $K_{IC} - K_I$
  - K_{IC} probabilistic parameter (normal distribution, $\mu = 80\ \mathrm{MPa}\sqrt{\mathrm{m}}$, $\sigma = 4\ \mathrm{MPa}\sqrt{\mathrm{m}}$)
  - K_I deterministic parameter
  - Taking the inverse of the normal cumulative distribution it can be analytically shown:
    1. For $K_I = 61.975\ \mathrm{MPa}\sqrt{\mathrm{m}}$, CPI= $3.3 \cdot 10^{-6}$
    2. For $K_I = 56.01\ \mathrm{MPa}\sqrt{\mathrm{m}}$, CPI= $1.0 \cdot 10^{-9}$
  - These cases were evaluated using Monte Carlo tools with chosen RNGs using 10^8 and 10^{11} samples.

Partner	Sequence Length	Method
P1, P2, P5	$4.3 \cdot 10^{6001}$	Mersenne-Twister
P7	$4.3 \cdot 10^{6001}$	WELL19937c (similar to Mersenne-Twister)
P8	$1.0 \cdot 10^{12}$	Lehmer (Park-Miller) linear congruential generator
P10, P3, P6	$2.3 \cdot 10^{18}$	Based on a composite of two multiplicative linear congruential generators using 32-bit integer arithmetic
P11	$3.4 \cdot 10^{38}$	Permuted Congruential Generator (64-bit, PCG64)



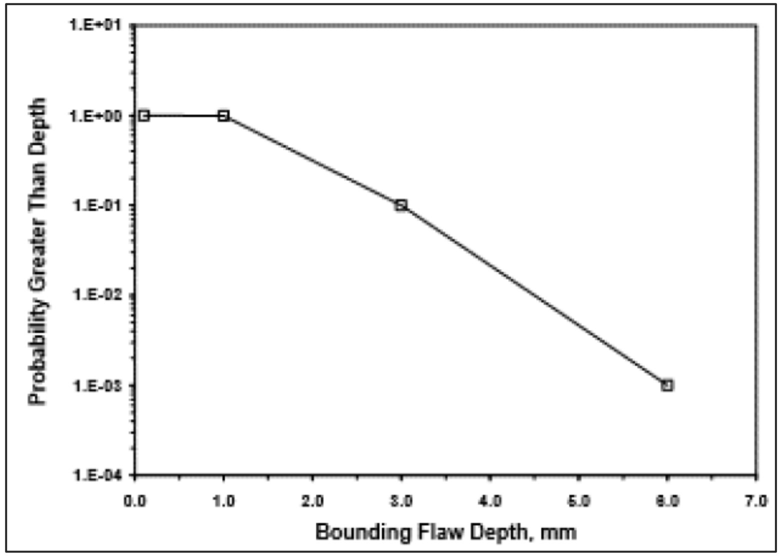
Generation of tabulated data for UCC (and TCC)

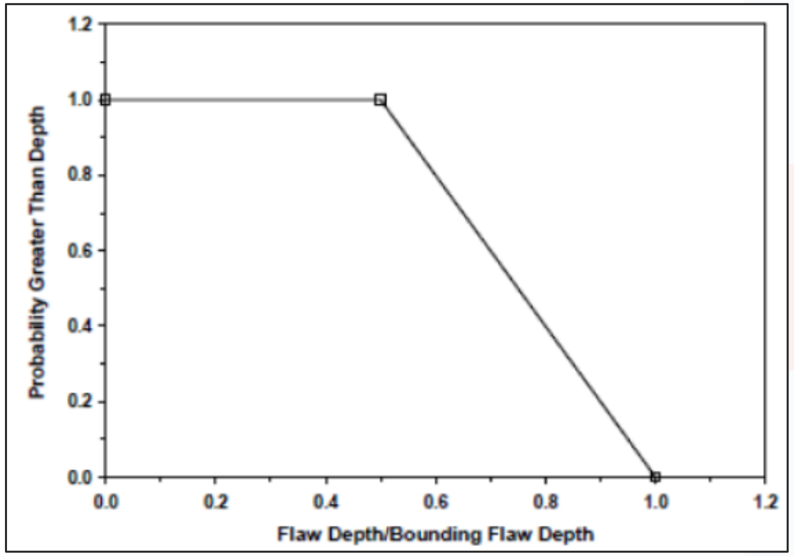
- One of the challenges in APAL was related to development of a realistic flaw distribution for underclad (UCC) and through-clad (TCC) cracks to be used in probabilistic analyses
- Significance of UCC cracks for RPV failure probabilities had previously been underestimated in comparison to other flaw types
- Information in open literature for statistically validated basis and UCC flaw distribution is very limited

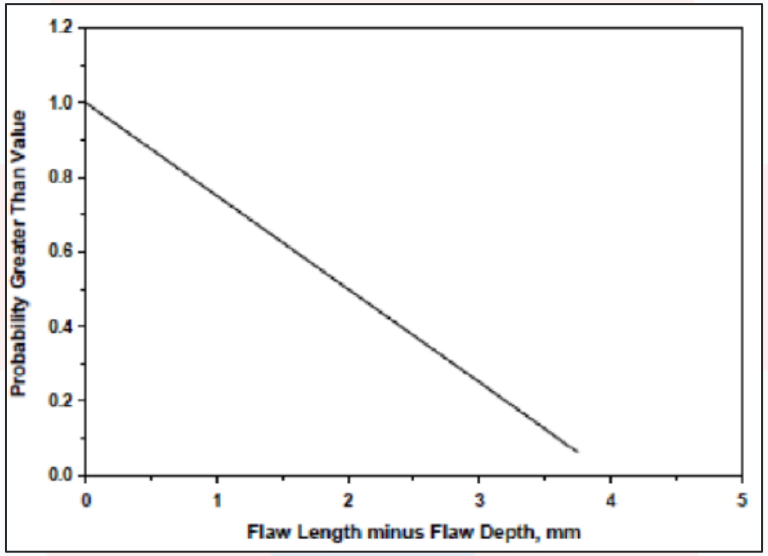


PNNL flaw distribution model for UCC

- PNNL flaw distribution model for UCCs (NUREG-1874) was used as the basis in APAL
- Parametric definition of PNNL:
  - the conditional distribution for the bounding (maximum) flaw depth,
  - the conditional distribution of the through-wall flaw depth (as a fraction of the bounding depth)
  - the conditional uniform distribution of the length
- Not suitable for an arbitrary probabilistic code
- Contains some ambiguities requiring certain interpretation and assumptions
- **Generic tabulated** distribution of UCC flaw depth (in terms of CDF) is required for codes used in APAL

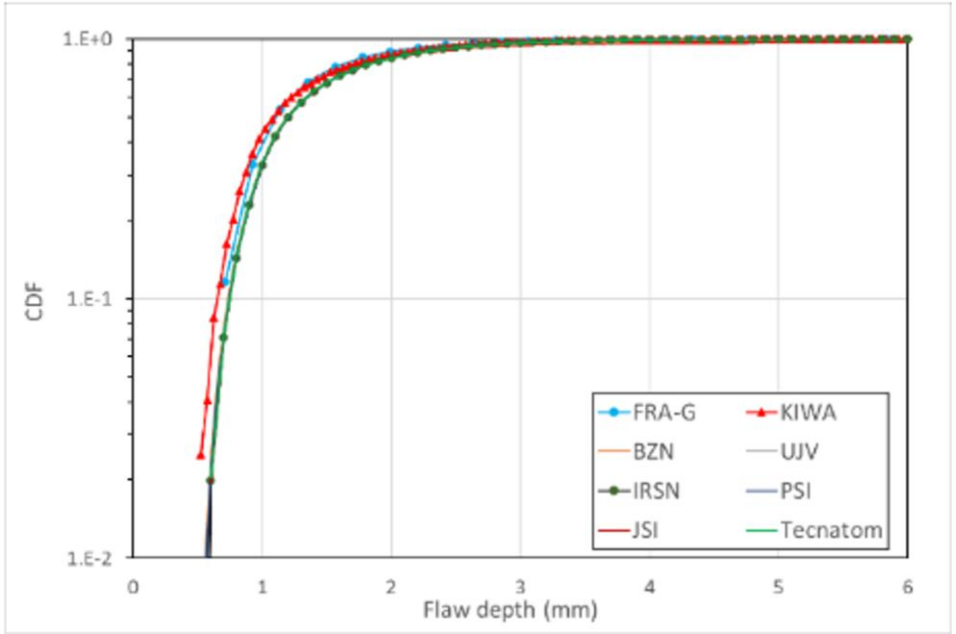


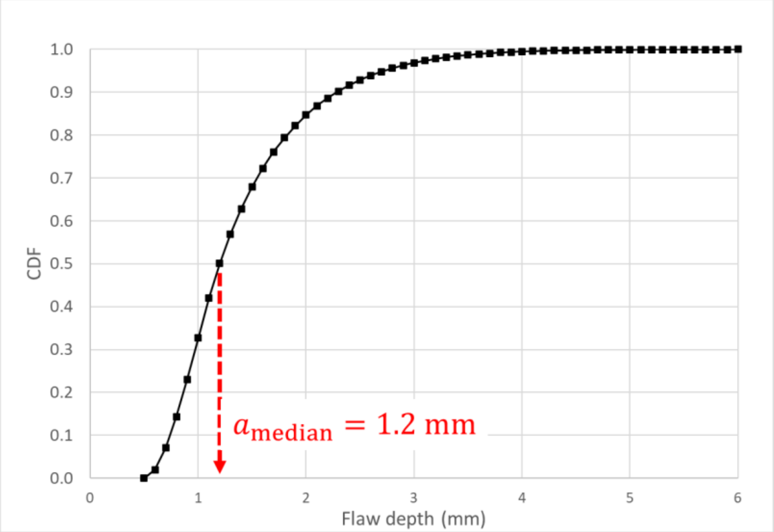




Generation of tabulated data for UCC (and TCC)

- Development of generic CDF for UCC flaw depth as a round-robin exercise:
  - Individual interpretations, assumptions and mathematical treatment of PNNL model
- Mostly, Monte Carlo simulations were used
  - Some partners used a direct integration approach
- Good agreement between partners
  - Minor differences in the obtained CDFs may be related to different assumptions and mathematical treatment of the PNNL model
- One CDF was selected for further use in APAL
  - Median UCC flaw depth is $a_{\text{median}} = 1.2$ mm
  - UCC flaw length is defined as ratio $2c/a = 6$ (or $2c/a = 3$ for optional analyses)
- Through-clad crack (TCC) depth distribution was defined as UCC+6 mm (cladding thickness)

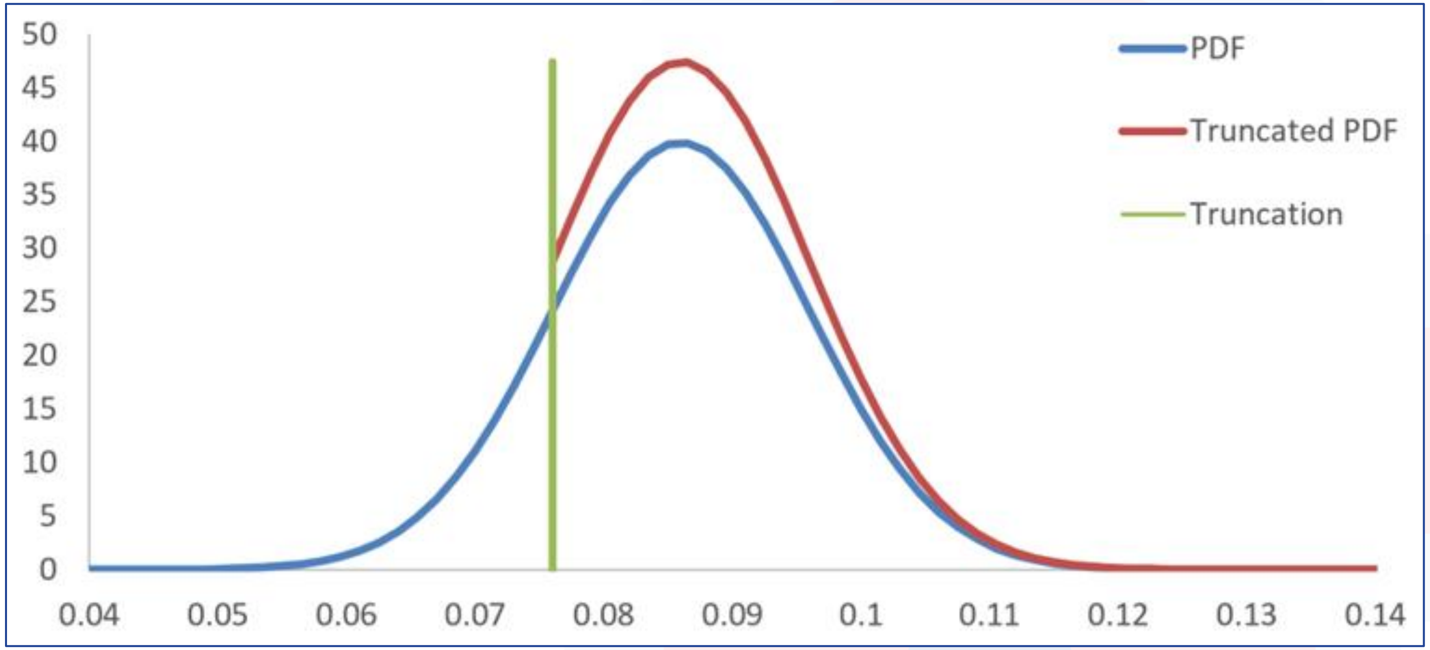




Data generation from truncated distributions

- Some distributed parameters must be truncated to avoid non-physical samples
  - Based on experience from previous international probabilistic benchmarks it has been shown that incorrect treatment of truncated distributions may lead to errors in probabilistic analyses.

- Three different approaches for truncating a normal distribution were investigated in APAL:
  - **Use a truncated normal distribution** (recommended method)
  - **Re-sample values** outside of truncation limits. Considered as a good alternative method but may lead to increased computational time
  - **Cut-off all values** outside of the truncation limits and set these values to the truncation limit (used in FAVOR)

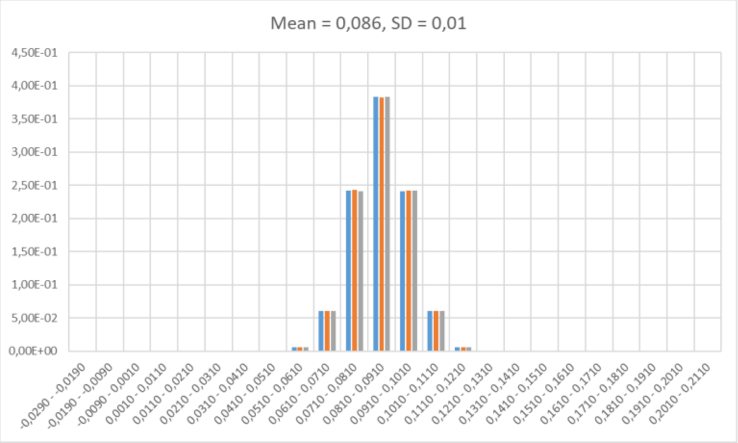


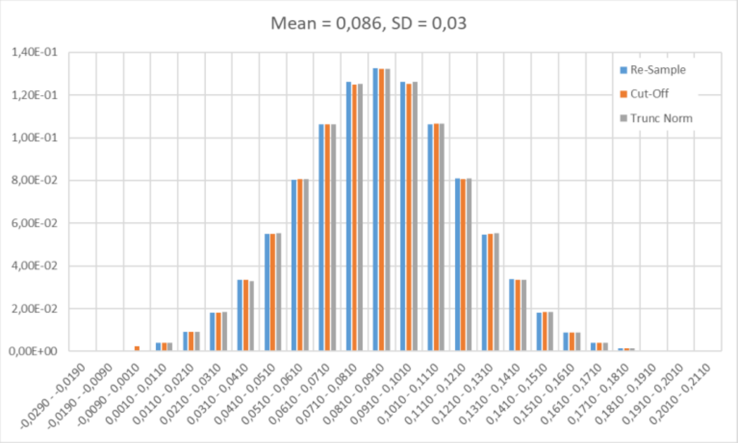
Data generation from truncated distributions

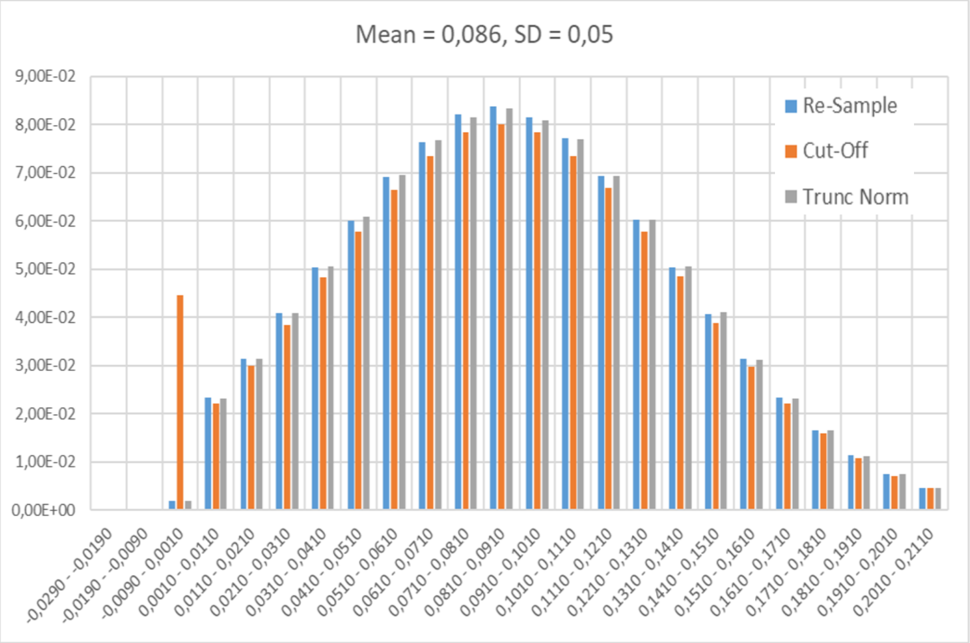
Case	MV [%]	SD [%]	One-sided truncation [%]	Trunc. reached for -X SD	Prob. Cu < 0	Effect of truncation
1	0.086	0.01	0	8.6	3.9858e-18	Small
2	0.086	0.03	0	2.9	0.0020741	Medium
3	0.086	0.05	0	1.7	0.04271622	Large

Case	Re-Sampling		Cut-Off		Truncated Distribution	
	MV	Scatter	MV	Scatter	MV	Scatter
1	0.0860	0.0100	0.0860	0.0100	0.0860	0.0100
2	0.0862	0.0297	0.0860	0.0300	0.0862	0.0297
3	0.0908	0.0455	0.0869	0.0481	0.0907	0.0455

- Re-sampling gives a good agreement with a correctly defined truncated distribution for small coefficient of variation (COV=SD/MV)
- Cut-off approach can give a large error for large COV
  - Better agreement for small COV





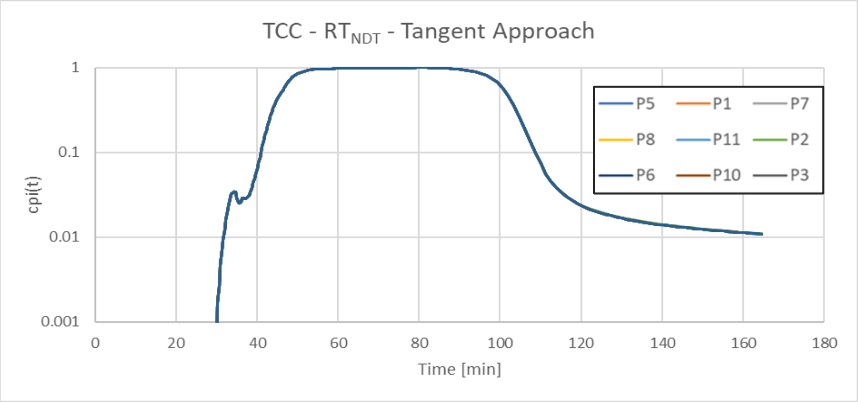


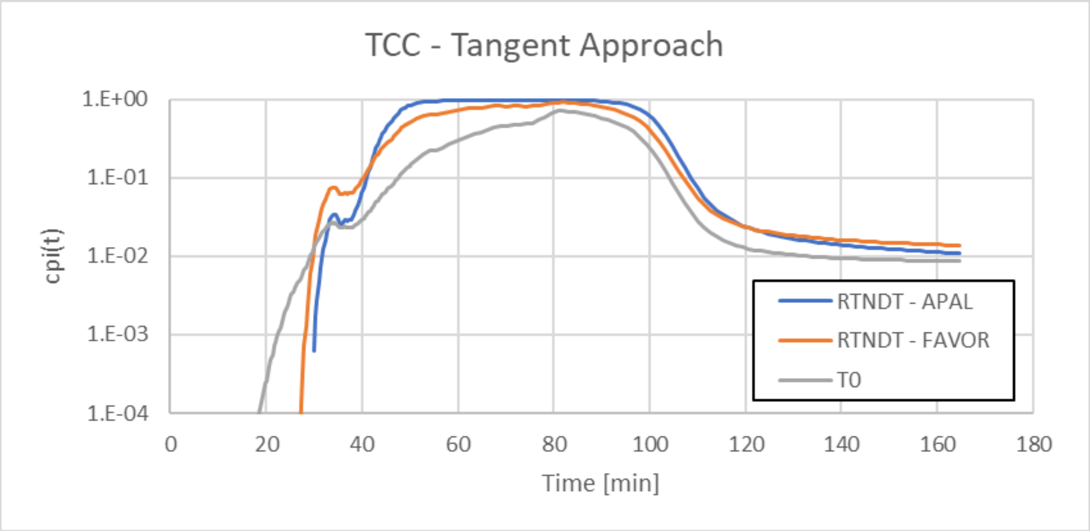
Verification of CPI for provided K_I and ART

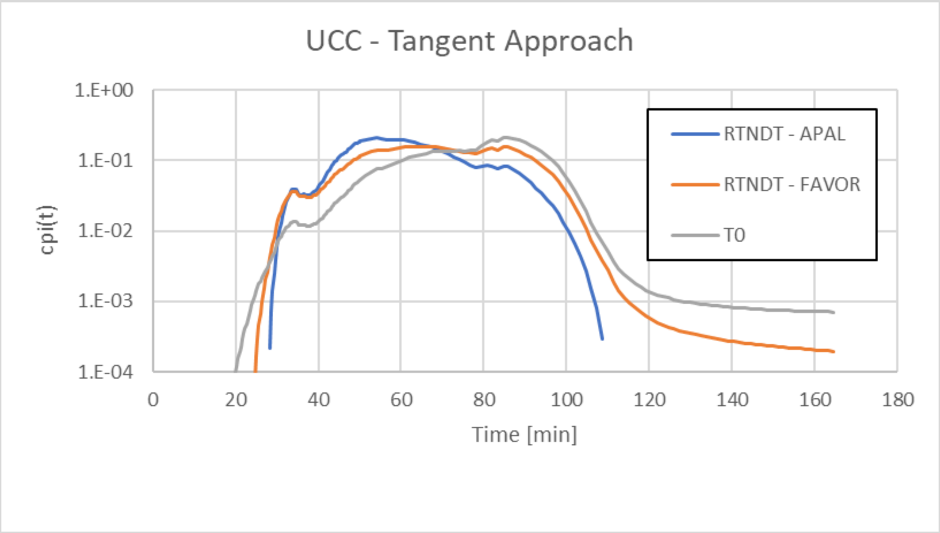
- Aim: Verification of probabilistic tools for a defined transient over time t by evaluating the CPI and instantaneous $cpi(t)$ for given ART and pre-defined stress intensity factors $K_I(t)$ and crack tip temperature $T(t)$
- Pre-defined data (same for all partners):
  - K_I for TCC and UCC cracks (inside and outside plume)
  - Temperatures at the crack tips
  - ART for each case
- Limit conditions:
  - Tangent approach
  - Simplified WPS (Max WPS approach)
- Calculate CPI by using fracture toughness concepts:
  - RT_{NDT} (ASME) - normal distribution with truncation at ±3 SD)
  - T_0 (Master Curve) –Weibull distribution
  - RT_{NDT} (FAVOR) - Weibull distribution

Verification of CPI for provided K_I and ART

Crack	RT_{NDT}		T_0	
	Tangent Approach	Max WPS Approach	Tangent Approach	Max WPS Approach
TCC circum. crack	9.933E-01	7.169E-03	7.308E-01	1.873E-02
UCC axial crack	2.114E-01	1.647E-02	2.140E-01	9.217E-03







- Perfect agreement between different codes for CPI and cpi(t)
- Different MCS codes and analytical solutions
- CPI values for Max WPS are lower compared with Tangent approach
- Different shapes of cpi(t) curves for analysed fracture toughness concepts, specifically for UCC:
  - RT_{NDT} and T_0 concepts result in similar final CPIs but occur at different times through the transient

Summary

- Preparatory steps, including tools verification (considered in this presentation) and round-robin assessments with cross-checking of analysis results (see next presentation), performed in probabilistic benchmarks in APAL allowed for:
  - Verification of different codes and provided methods
  - Demonstration of good agreement between different codes for pre-defined input data
  - Verification and adjustment of some initially defined parameters
  - Improvement of code performance

- Generic CDF for UCC flaw depth was established based on parametric PNNL flaw distribution model

Thank you for your attention!