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PROBABILISTIC BENCHMARK WITHIN THE APAL PROJECT – RESULTS AND CONCLUSIONS

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ABSTRACT

Most of the nuclear power plants (NPPs) in Europe are currently in the second half of their designed lifetime. One of the important aspects limiting safety analyses for lifetime extension and long-term operation (LTO) is the reactor pressure vessel (RPV) integrity assessment for pressurized thermal shock (PTS). Current PTS analyses are based on deterministic assessment and conservative boundary conditions. Therefore, demonstration of sufficient safety margin against fast fracture initiation and quantification of margin in terms of risk of RPV failure become a challenging task requiring advanced probabilistic assessments. The APAL (Advanced PTS Analysis for LTO) EU project is aimed at addressing these challenges by further development of analysis methods for evaluation of RPV safety margins. The impact of thermal hydraulic (TH) uncertainties and various improvements for LTO onto the RPV safety assessment are investigated in the project. One of the main tasks within the APAL project is related to probabilistic fracture mechanics analyses allowing an explicit consideration of all distributed parameters involved in the safety assessments. Prior to embarking upon the probabilistic safety margin assessments related to LTO improvements and TH uncertainties, it is necessary to conduct a baseline benchmark for performance verification of probabilistic approaches and tools used by different APAL partners. This paper addresses on-going activities in the probabilistic benchmark for performance verification by presenting key results and conclusions from this work.

INTRODUCTION

The work with probabilistic margin assessments within the APAL project is divided into two main tasks: the probabilistic benchmark related to different LTO improvements and the probabilistic benchmark related to uncertainties in TH data. The main objective and the result that should be evaluated from these probabilistic benchmarks is the conditional probability of initiation (CPI) and the conditional probability of failure (CPF) for a selected transient. In the safety margin assessment, three basic margin definitions are highlighted: in terms of maximum allowable adjusted reference temperature (ART), RPV lifetime and failure frequency.

This work is currently on-going but prior to initiation of probabilistic benchmark assessments, it is necessary to conduct a baseline benchmark for performance verification of probabilistic approaches and tools used by different APAL partners. The baseline benchmark for performance verification consists of several checks and round robin analyses described in the following sections. The main results and conclusions from the baseline benchmark for performance verification are summarized in this paper.

PROBABILISTIC BENCHMARK – INITIAL TESTS AND VERIFICATIONS

Check random number generator

When doing Monte Carlo Simulations (MCS) it is important that the probabilistic parameters included are randomly sampled throughout the entire simulation. The random parameters are obtained from a random number generator (RNG) which is an algorithm that produce a sequence of numbers which occurs in a seemingly random fashion although not truly being random. Most RNGs starts from an initial value, commonly denoted ‘starting seed’ from which the sequence is calculated.

There are many different RNGs with different qualities and it is important to ensure that the sequence length, or period, of the RNG used is long enough that the values does not start repeating before a simulation is complete. In order to verify that appropriate RNGs are used within APAL, each partner have provided the name or source of the RNG as well as the period. In addition, two benchmark cases, each with different conditional probability of initiation (CPI), are performed.

Each case studied can be solved analytically and consists of a normally distributed fracture toughness with a mean value of 80 MPa$\sqrt{\mathrm{m}}$ and a standard deviation of 4 MPa$\sqrt{\mathrm{m}}$. The first case has a deterministic stress intensity factor of 61.975 MPa$\sqrt{\mathrm{m}}$ resulting in CPI = $3.3\cdot10^{-6}$. For this case, the partners are asked to use a sampling size of 10^8. The second case has a deterministic stress intensity factor of 56.01 MPa$\sqrt{\mathrm{m}}$ resulting in CPI = $1.0\cdot10^{-9}$. For this second case, the partners are asked to use a sampling size of 10^{11}.

Each partner has provided information of the RNGs used by their tools which is shown in Table 1. All RNGs are considered to have adequately long sequence lengths based on this information.

Table 1: RNGs used by partners.

Partner	Sequence Length	Method
P1, P2, P5	$4.3\cdot10^{6001}$	Mersenne-Twister
P7	$4.3\cdot10^{6001}$	WELL19937c (similar to Mersenne-Twister)
P8	$1.0\cdot10^{12}$	Lehmer (Park-Miller) linear congruential generator
P10, P3, P6	$2.3\cdot10^{18}$	Based on a composite of two multiplicative linear congruential generators using 32-bit integer arithmetic
P11	$3.4\cdot10^{38}$	Permuted Congruential Generator (64-bit, PCG64)

The benchmark case requiring 10^{11} samples is shown in Figure 1. As it can be noted in the plot, there is no periodic behavior and all partner’s results converge towards CPI = $1.0\cdot10^{-9}$ as expected. The same could be seen in the first benchmark case with a smaller sampling size. It is concluded from these verifications that the tools used by all partners have sufficient RNGs.

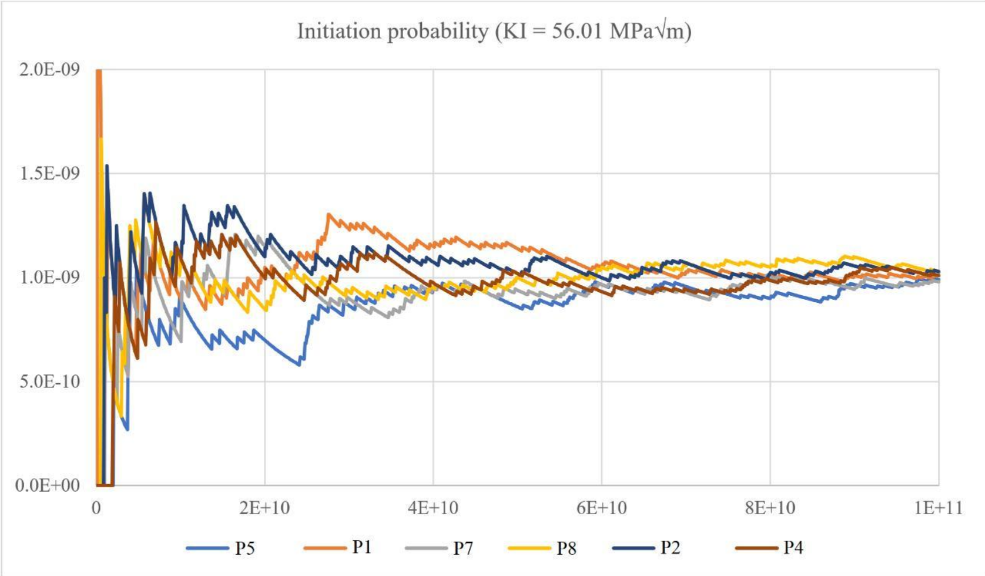

Figure 1. Convergence plot for verification of RNGs for $K_{\mathrm{I}} = 56.01\ \mathrm{MPa}\sqrt{\mathrm{m}}$.

Check generation of tabulated data for different crack configurations

One of the challenges within the APAL project was related to developing a realistic flaw distribution for under-clad (UCC) and through-clad (TCC) cracks that can be used in probabilistic analyses. Significance of UCC cracks for calculated RPV failure probabilities had previously been underestimated in comparison to defects located in welds, base metal and cladding. Therefore, there is limited and scarce information available in open literature about statistically validated basis and distribution parameters for UCC cracks.

One of the widely recognized UCC flaw distribution models has been developed by PNNL based on insights from literature review along with a treatment of the uncertainties in estimating the distribution parameters, see EriksonKirk, M.T., Dickson, T.L. (2010). The PNNL UCC distribution model, as presented in Figure 2, includes the following parameters; the maximum (or bounding) through-wall depth of UCC flaws, the conditional distribution of the through-wall depth expressed as a fraction of the bounding depth dimension and the conditional distribution of the length for UCC flaws.

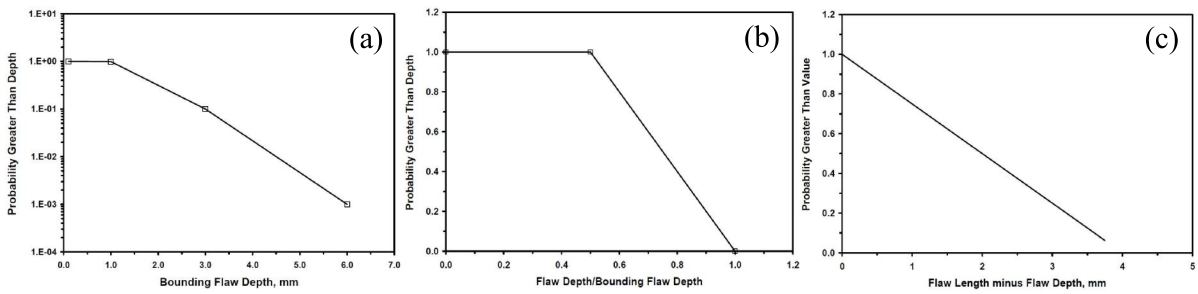

Figure 2. The UCC flaw distribution model developed by PNNL with the parameters; (a) the bounding flaw depth, (b) the ratio between the flaw depth and the bounding flaw depth, (c) the flaw length.

Figure 2(a) shows the conditional distribution for the bounding flaw depth dimension truncated at the maximum bounding flaw depth of 6 mm. This bounding depth is assumed to be related to details of the cladding procedure. Ranges for the bounding flaw depths (0-1 mm, 1-3 mm and 3-6 mm) and their probabilities are based on the French work cited in EriksonKirk, M.T., Dickson, T.L. (2010) regarding vessel-to-vessel variability for the bounding flaw depth. Thus, the distribution of bounding flaw depths over the range of 0-6 mm is described by uniform distribution of the logarithm of the probability.

The conditional distribution of UCC flaw depth is assumed to be relatively uniform and is described by a uniform distribution over the range of 50-100% of the bounding flaw depth as shown by Figure 2(b). The uniform distribution is a reflection of the lack of information on measured flaw depth dimensions. The undertaken approach in the PNNL model, therefore, conservatively assigns a large fraction of the flaws to have depth equal to about the bounding flaw depth. Figure 2(c) presents the PNNL conditional uniform distribution of UCC flaw length. This distribution implies that the maximum flaw length is bounded by a dimension of 10 mm. Within the APAL project a flaw length has been treated deterministically and defined by the length/depth ratio $2c/a = 6$.

The PNNL flaw distribution model is provided in such way that does not allow direct use with an arbitrary probabilistic code. One of the aims with the APAL project was to assess and compare the results produced by various probabilistic codes that have been developed or used by different APAL partners. Therefore, a generic tabulated distribution of UCC (and TCC) flaw depth (in terms of cumulative distribution function (CDF)) needed to be developed from the PNNL distribution model (see Figure 2) that can be used as input to an arbitrary probabilistic tool.

A development of the generic CDF of UCC flaw depth has been set up in the APAL project as a round-robin exercise where the involved partners individually interpreted, made necessary assumptions and mathematically treated the PNLL flaw distribution model, see Figure 2. Most of the partners have used Monte Carlo simulation methods for sampling the UCC flaw depth and length from the PNNL model whereas several partners have used direct integration approach.

Regardless the used approach, the obtained CDFs of UCC flaw depth have demonstrated a good agreement between the APAL partners as shown in Figure 3(a). Minor differences in the obtained CDFs may be attributed to the assumptions that have been taken for interpretation and mathematical treatment of the conditional distribution for the bounding flaw depth, see Figure 2(a). Thus, some partners have assumed that the bounding flaw depth is uniformly distributed in the range 1-6 mm, thereby neglecting the intermediate bounding flaw depth of 3 mm. One of the obtained CDFs, judged to be based on most rigorous assumptions, have been selected for further use in probabilistic assessments withing the APAL project. The chosen CDF of UCC flaw depth is presented in Figure 3(b). The median flaw depth from this distribution is $a_{\mathrm{median}} = 1.2$ mm. For assessments of TCC flaw growth, the TCC flaw depth distribution was obtained by adding 6 mm cladding thickness to the UCC depth distribution.

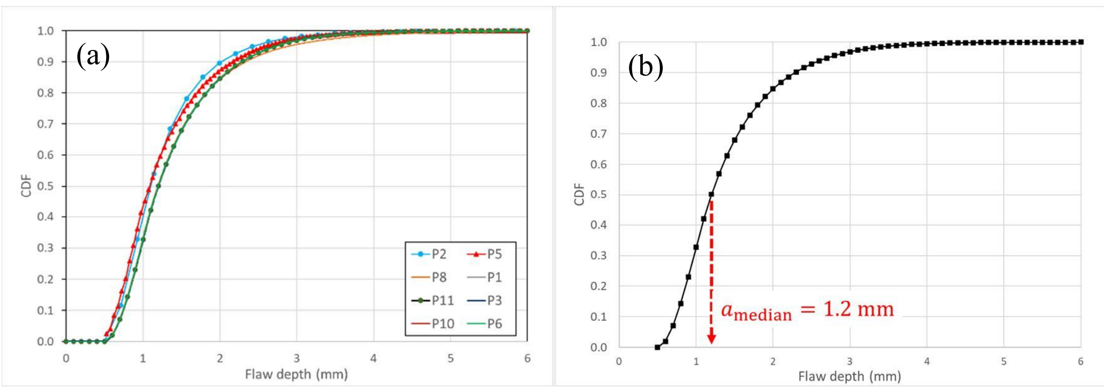

Figure 3. The calculated CDFs of UCC flaw depth; (a) CDFs from different APAL partners, (b) the CDF of UCC flaw depth chosen for probabilistic assessments in APAL.

Check generation of data from a truncated distribution

Some distributed parameters need to be truncated due to physical or practical reasons. Previously completed international benchmarks have shown that incorrect handling of truncated distributions can lead to major errors in the probabilistic analyses. It is therefore important to check that the tools to be used within APAL can handle the truncations considered within the project.

In APAL, truncation is included for several parameters to avoid non-physical samples, all of which are normally distributed. A truncation of ±3 standard deviations is included for fracture toughness as well as on the chemical components and the additive error function for the reference temperature shift formula used to define the adjusted reference temperature (ART).

Several verifications are made at different sampling sizes for MCS ranging from 10^4 to 10^{10} samples in order to verify that the tools used by all partners gives adequate results. This is done by comparing histograms. Three different methods are compared:

1. Only considering the fracture toughness as a probabilistic parameter
2. Only considering the ART parameters as probabilistic
3. Considering both the fracture toughness and the ART parameters as probabilistic (up to seven probabilistic parameters).

The comparisons between the different partners resulted in very good agreement at higher sampling sizes as shown in Figure 4.

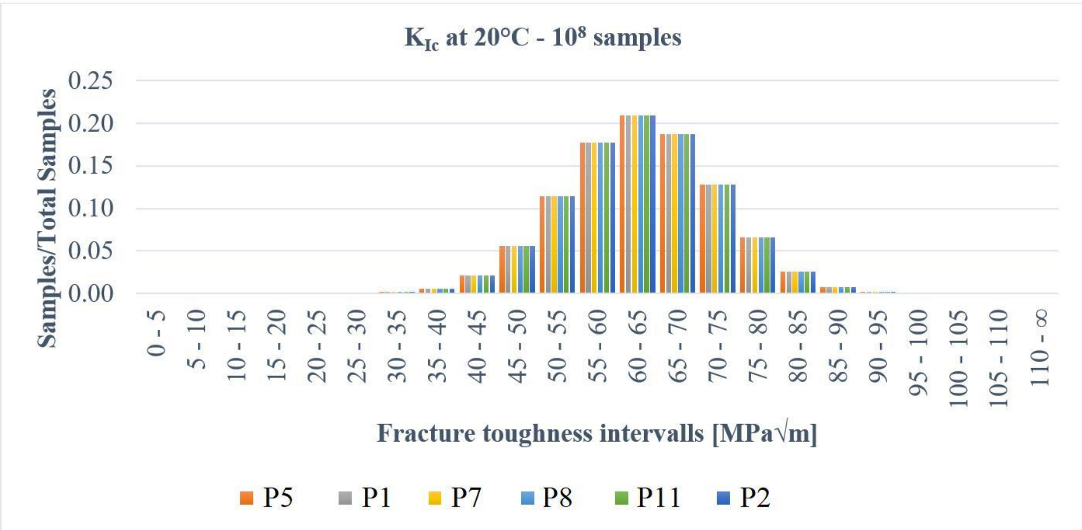

Figure 4. Comparison of results from different partners for method 1; only considering the fracture toughness probabilistically.

Only a few partners provided results exceeding a sampling size of 10^8 as a sampling size of 10^{10} may be very time consuming and may also lead to memory issues if the code is not developed to handle the amount of data required properly.

Check CPI for Provided K_I and ART

Analyses are made for a transient over the time, *t*, where all partners calculates the conditional probability of initiation (CPI) as well as instantaneous conditional probability of initiation (cpi(*t*)) for a given ART as well as pre-defined stress intensity factors $K_I(t)$ and temperatures at the crack tip, $T(t)$.

Analyses are made for two different limit conditions:

- The Tangent Approach - Initiation is assumed to occur if K_I exceeds the fracture toughness, K_{Ic}.
- The maximum Warm Pre-Stressing (WPS) Approach – The WPS effect is assumed to prevent initiation if K_I is lower than it has been earlier during the transient regardless of temperature. This can be seen as a simplified and very generous WPS Approach.

Three different concepts for describing the fracture toughness transition region are considered:

- The RT_{NDT} Concept according to ASME Code Case N-830-1 (2021) using normal distribution as defined within APAL.
- The RT_{NDT} Concept as defined within the FAVOR software using a Weibull distribution.
- The T_0 Concept according to Master Curve (see ASTM E1921 (2021)).

A good agreement is seen between al partners by studying cpi(t) in Figure 5 using the Tangent Approach for the RT_{NDT} Concept. Similar agreement in results are seen for the T_0 Concept.

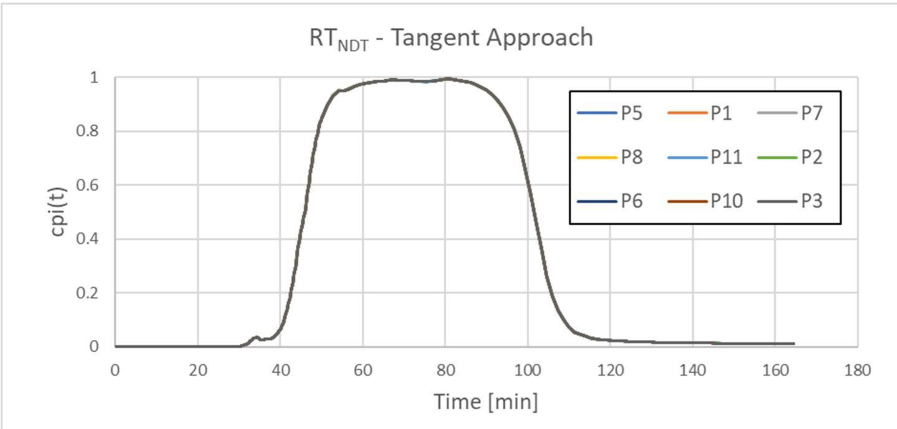

Figure 5. Comparison of cpi(t) between partners using the Tangent Approach for the RT_{NDT} Concept.

The three different concepts for treating the transition region and distribution of K_{Ic} are compared in Figure 6 which shows that the RT_{NDT} Concept using a normal distribution results in the highest CPI while the T_0 Concept results in the lowest.

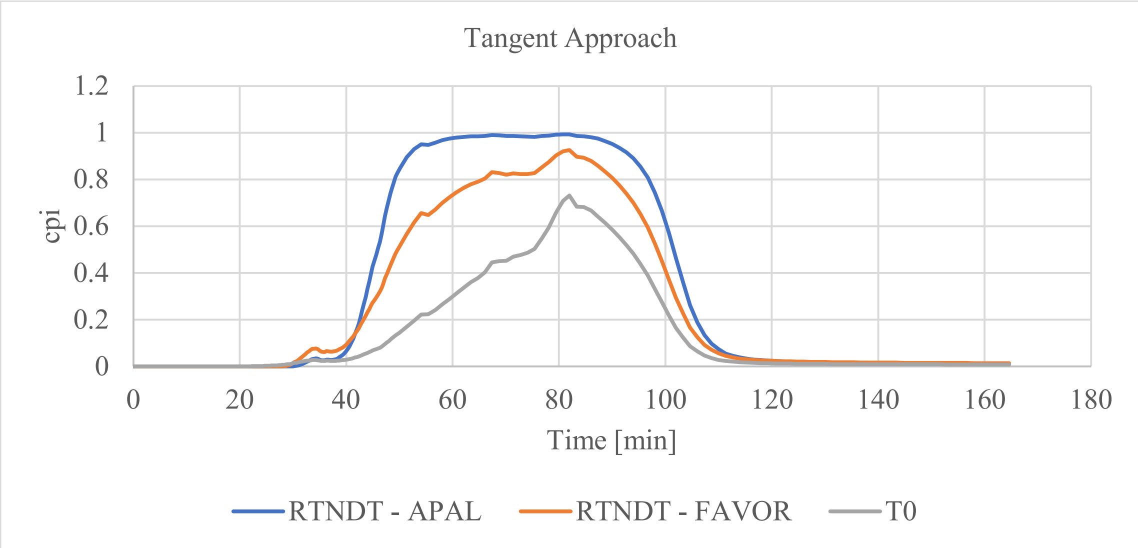

Figure 6. Comparison of K_{Ic} concepts.

Check CPF for Provided K_I and ART

This non-mandatory part of APAL is a continuation of the CPI case above. Here, crack arrest is studied and the conditional probability of failure (CPF) describes the probability of a crack growing through more than 75 % of the RPV wall during the transient.

When the crack initiates, it is redefined as an infinitely long crack. Pre-defined stress intensity factors and temperatures are given for a growing crack exceeding 75% of the wall thickness. For the original case studied based on the CPI benchmark, most partners did not get any crack arrest. All the analyses where crack initiation occurred led to failure.

Other more relevant cases are studied by using different ART values. In Figure 7, a histogram of final crack depths is shown for an ART value of 60°C. The bottom most bar is for non-initiated cracks where the original crack depth of 10 mm remains after the analyses, the top most bar represents cracks that have grown through more than 75 % of the wall thickness. In-between it can be seen that a number of simulations have reached a final crack arrest between 129 – 192 mm.

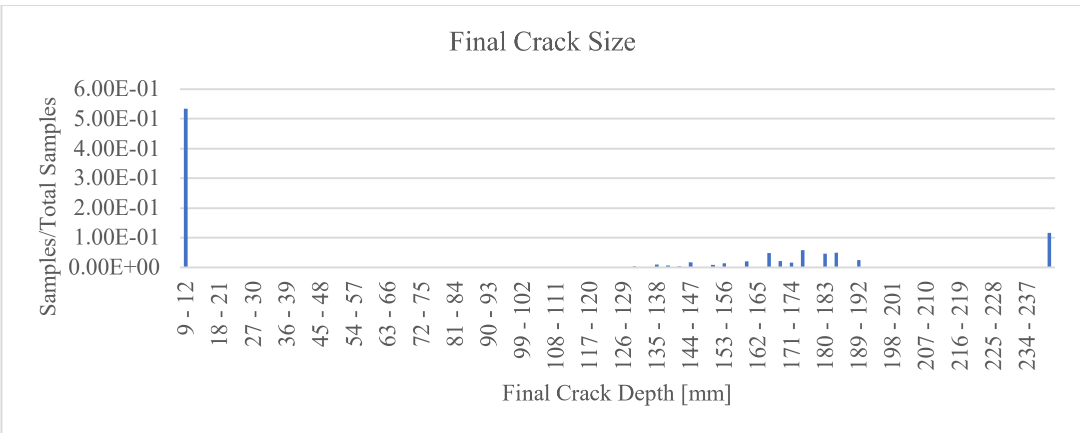

Figure 7. Final crack depths for an example case using ART = 60°C.

PROBABILISTIC BENCHMARK – ROUND ROBINS

Besides the verification of different analysis tools used by APAL partners, several round robin benchmarks have been carried out in the APAL project. Description of two initial benchmarks are provided in this paper.

Round Robin 1 – Prediction of ART

This round robin benchmark is aimed at predicting ART for increasing fluence level. The analyses have been carried out for several positions through the RPV wall considering fluence attenuation through the wall according to

$$F = F_0 \cdot e^{-0.125x} \tag{1}$$

where F is the neutron fluence at the location x from the cladding/weld interface in cm, and F_0 is the neutron fluence at the cladding/weld interface. No attenuation is considered through the cladding.

The ART calculations have been performed for both weld and base materials and utilizing both the RT_{NDT} and T_0 fracture toughness concepts. Similar to the previous presented analyses, this round robin benchmark was not based on the user specific data.

As expected, the results from all partners are in very good agreement as shown in Figure 8. The curves represent the mean values along with 5% and 95% quantiles of ART for a location of ¼ from the cladding interface.

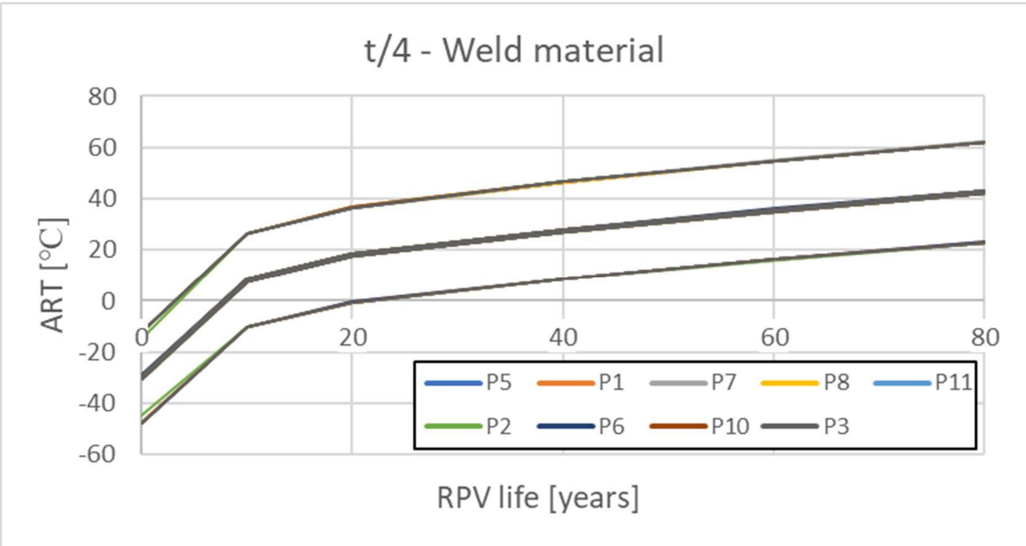

Figure 8. Mean ART value as well as 5% and 95% quantiles as a function of RPV life.

One partner has obtained a different standard deviation, leading to some discrepancies in the quantiles for RPV life at 0 years. It is related to assuming no shift before plant operation was started. Indeed the shift function leads to zero shift at zero years, but it also includes an additive error function that is time independent and does provide a small shift.

Figure 9 shows a variation of ART values at different positions through the RPV wall and for different RPV lifetimes. It can be seen that limiting ART values alternate between the weld and base materials depending on the position through the RPV wall and the RPV lifetime. Higher ART values are obtained for the weld material close to the inner surface, but for deeper positions, the base metal leads to higher ART values. As the RPV lifetime is increased, ART increases faster for the weld than the base material and the transition between the materials becomes deeper, see Figure 9.

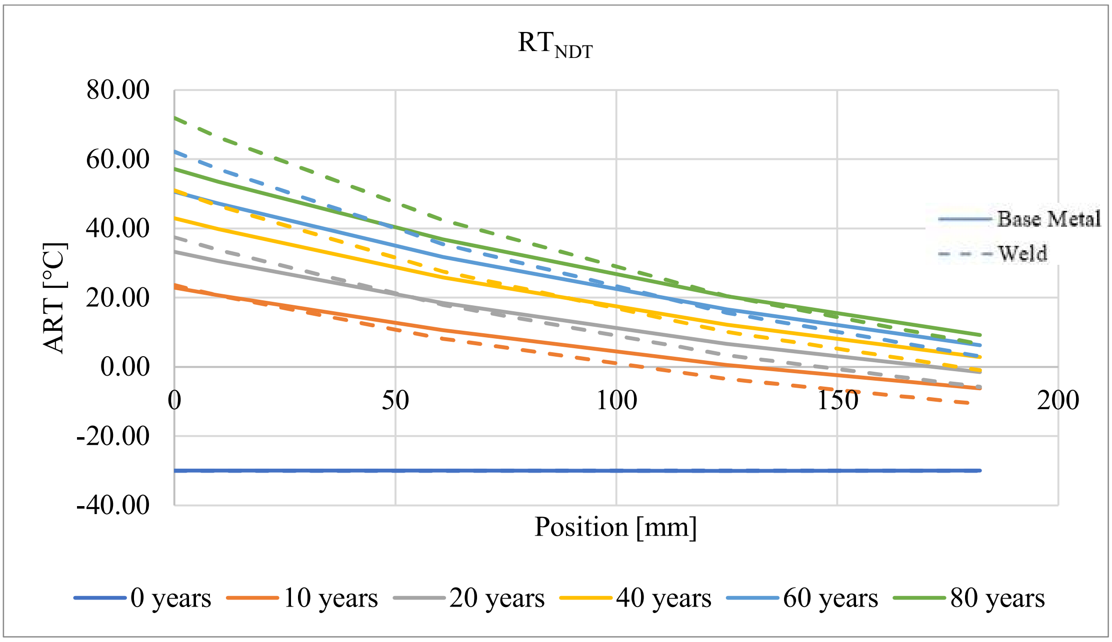

Figure 9. Comparison between weld and base metal at different positions through the RPV wall and at different times.

Round Robin 2 – Calculate allowable ART and years of operation for given probability

This round robin benchmark aims at calculating CPI values for various crack geometries (TCC, UCC and embedded cracks), orientations within the RPV wall (axial and circumferential), crack tip locations and sizes. The geometry for TCC and UCC cracks is shown in Figure 10. The work with this benchmark is still on-going, therefore the embedded cracks have been excluded from presented results. TCC cracks have been assumed having the depth of 16 mm (including 6 mm cladding thickness) and the length of 60 mm. UCC cracks had the depth of 10 mm and the length of 60 mm. All cracks have been located in the core weld at the vertical distance of -2.638 m from the centerline of a cold-leg nozzle.

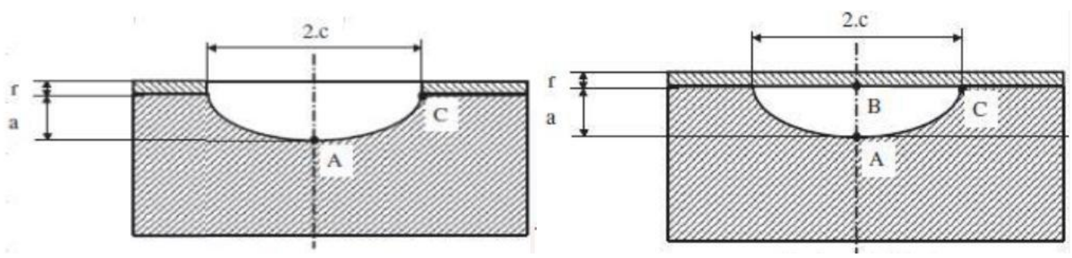

Figure 10. TCC and UCC crack geometries.

Two different probabilistic margin assessments (PMA) have been performed within the benchmark:

- PMA1: Determine a maximum allowable ART considering fracture toughness as a probabilistically distributed parameter and ART as a deterministic parameter.

- PMA2: Determine a maximum allowable RPV lifetime considering both the fracture toughness and ART as probabilistically distributed parameters.

The maximum allowable ART and RPV lifetime are calculated for a CPI probability of $2.28{\cdot}10^{-4}$ which is the combined probability of the baseline assumption of 10^{-6} and the assumed transient occurrence frequency of $4.39{\cdot}10^{-3}$. The results from the PMA1 and PMA2 in terms of evaluated maximum allowable ART and maximum allowable RPV lifetime are presented in Figure 11 and Figure 12, respectively, for the tangent and simplified WPS limit conditions.

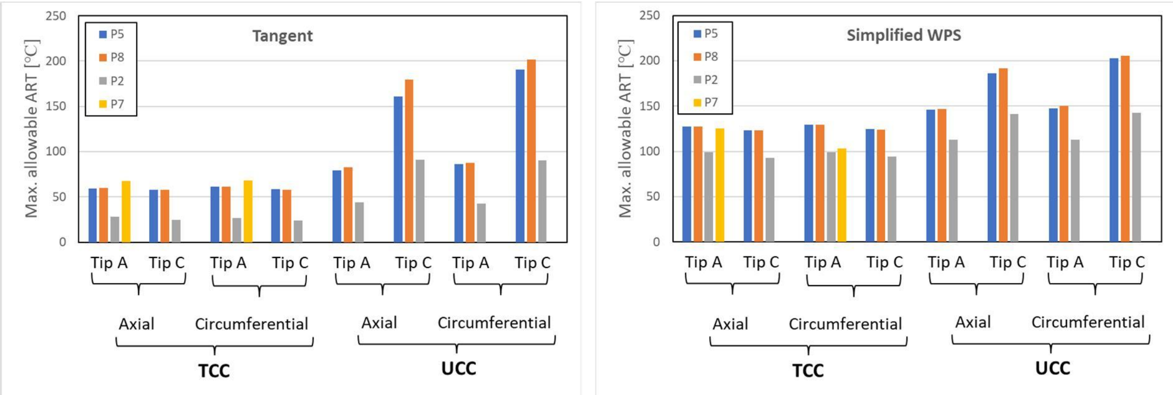

Figure 11. Results for maximum allowable ART corresponding to allowable CPI=$2.28 \cdot 10^{-4}$. The results are based on RT_{NDT} fracture toughness concept.

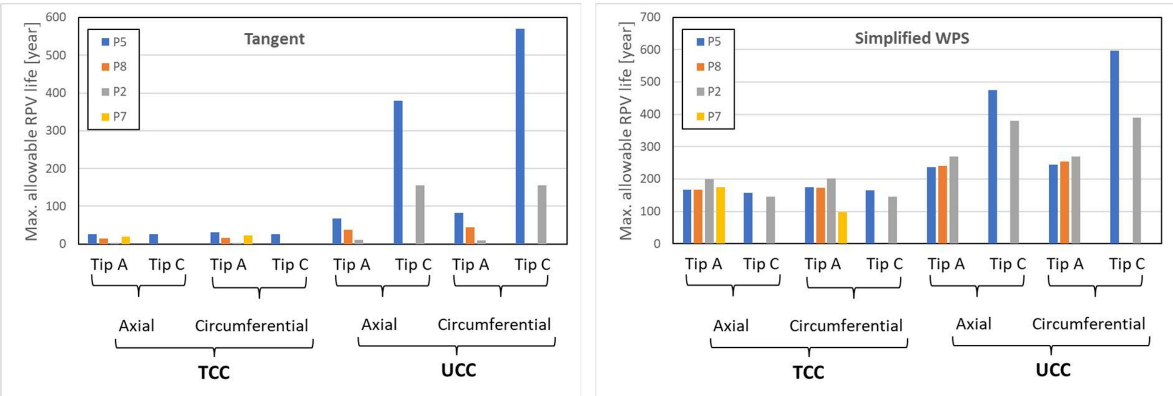

Figure 12. Results for maximum allowable RPV lifetime corresponding to allowable CPI=$2.28 \cdot 10^{-4}$. The results are based on RT_{NDT} fracture toughness concept.

In this benchmark, the APAL partners used user-specific TH data, calculated temperatures, stresses and KI values obtained from their own analyses which explains some differences in results. However, the following trends can be seen from the plots. Lowest magnitudes for maximum allowable ART and RPV lifetime are predicted for TCC cracks evaluated by the tangent limit condition. The magnitudes of maximum allowable ART and RPV lifetimes are similar regardless TCC crack orientation and crack tip locations (deepest tip A or surface tip C). For UCC cracks, higher magnitudes of maximum allowable ART and RPV lifetimes have been calculates, especially at the surface crack tip C both for axial and circumferential cracks. From the assessments based on the simplified WPS limit condition substantially greater magnitudes of maximum allowable ART and RPV lifetime have been calculated.

CONCLUSIONS

The on-going work within the probabilistic baseline benchmark for performance verification is summarized in this paper. The benchmark consists of initial tests and verification of used methods and probabilistic techniques, e.g. adequate generation of random numbers, development of a generic tabulated distribution of UCC (and TCC) flaw depth, adequate treatment of truncated distributions and evaluation of CPI and CPF quantities for given K_I and ART distributions.

Further, the benchmark includes a series of round robin assessments dealing with prediction of ART values at increasing fluence level and evaluation of maximum allowable ART and RPV lifetime for given CPI of $2.28 \cdot 10^{-4}$ considering the fracture toughness and ART as distributed probabilistic parameters. The work with round-robin assessments is on-going, so only part of the results and observed trends has been included in the paper.

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