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BENCHMARKING OF PROBABILISTIC PRESSURIZED THERMAL SHOCK ASSESSMENTS WITH DIFFERENT MARGIN APPROACHES

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ABSTRACT

In the APAL project (Advanced PTS analyses for long term operation, 2020-2024) advanced pressurized thermal shock (PTS) assessment methods for the reactor pressure vessel (RPV) were developed to allow for a quantification of safety margins. This paper summarizes the results of a probabilistic benchmark and highlights the features of three different margin approaches. Three different margin concepts are evaluated within the benchmark: based on the maximal allowable adjusted reference temperature, based on the maximal allowable RPV lifetime, and based on the reliability theory. The benchmark allows to verify a good agreement in the probabilistic fracture assessment, while the impact of the thermal-hydraulic transient input data is significant. The different margin concepts provide different quantifications of the safety margins. Despite the differences between those margins, results show that they are related to each other or correlated and show globally the same tendencies.

INTRODUCTION

For the safety assessment of the reactor pressure vessel (RPV), the resistance of the structure against failure has to be demonstrated. This includes the resistance against brittle fracture even in case of a (pressurized) thermal shock (PTS) as a result from emergency cooling after a loss of coolant accident (LOCA), and even in case of an existing crack in the vessel wall. Besides ensuring the vessel integrity, it is also of interest to quantify and assess the remaining safety margin.

The PTS assessments can be either deterministic or probabilistic. In the deterministic assessment, the philosophy is to impose conservative assumptions or safety factors on input quantities and to verify the integrity even for these extreme parameter combinations. In the probabilistic assessment, the uncertainties

in some input parameters are quantified by distribution functions, which allows to compute a probability of failing the deterministic assessment criterion, which can be compared with an acceptance criterion.

Within the APAL project (https://www.apal-project.eu/), the different participants compared different computational codes for the for the deterministic and probabilistic PTS analysis (the focus here is on the latter). The main types of computational codes involved in the PTS assessment are the thermal-hydraulic (TH) codes for the simulation of the LOCA and the details of the time evolution of TH parameters during PTS, and the fracture mechanic (FM) codes for the assessment of the crack. Probabilistic fracture mechanic codes directly compute the probability of crack initiation. The involved APAL partners and their codes applied within this benchmark study are listed in Table 1.

Table 1: Institutions and codes

Institution	Abbrev.	TH Code	FM Code
Bay Zoltán	BZN	RELAP	In-house PFM code
Framatome Germany	FRA-G	KWU-MIX	ABAQUS
GRS	GRS	ATHLET	PROST
IPP Center	IPP	RELAP	SIF-Master
Jožef Stefan Institute	JSI	RELAP	FAVOR/in-house PFM code
Kiwa	Kiwa	RELAP	ISAAC/in-house PFM code
Paul Scherrer Institut	PSI	TRACE	FAVOR
Tecnatom	Tecnatom	TRACE	FAVOR
ÚJV Řež	UJV	RELAP	PROVER

This comparison shows that many different tools are involved in this study, which differ in specific capabilities and assumptions. This leads to significant differences already in the evolution of TH parameters of the PTS transient, as well as to additional differences in the crack assessment. Therefore, a decent level of differences is to be expected. While one interest in this activity is to investigate the significance of these differences, the other interest is to apply and compare different margin concepts.

BENCHMARK DEFINITION

The plant and RPV type, the anticipated LOCA transient and the procedure have been described in the preceding deterministic benchmark, see Angermeier et al. (2024). In the cases selected for this presentation, through-cladding cracks (TCC) of 16 mm total depth and underclad cracks (UCC) of 10 mm depth beneath the cladding are assumed, in axial and circumferential directions. An option for approximating the UCC by embedded cracks (EC), which is required by the capabilities of certain FM codes, is also considered.

The scope of this paper is restricted to fixed crack sizes and does not consider uncertainties in the crack size parameters. Uncertainties are considered for the fracture toughness, the fluence, the initial reference temperature and the chemical composition of the RPV steel (concentration of Ni, Cu and P). Details are provided in Shipsha et al. (2024b) and von Unge et al. (2024). The detailed definition of the benchmark is given in Suryaprakash et al. (2024).

Probabilistic PTS assessments address computation of crack initiation or RPV failure frequency (per year). The frequency of crack initiation (FI) is the frequency of PTS event occurrence multiplied by conditional probability of crack initiation (CPI), all treated as statistical distributions.. Similarly, the frequency of RPV failure (FF) is the frequency of a propagation of a non stable-arresting crack (i.e. crack arrest is considered and an initiated but stable-arrested crack does not add to the failure frequency) reaching a defined portion of the RPV wall thickness or leading to plastic collapse of the RPV. The primary PTS

acceptance criterion according to US NRC (2018) stipulates the acceptable through-wall crack frequency (TWCF) $< 10^{-6}$ vessel failures per reactor-operating year. For simplicity, within the benchmark the allowable conditional probability of initiation (CPI) of $2.28 \cdot 10^{-4}$ was defined in APAL based on the 10^{-6} PTS acceptance limit in combination with the mean value of the probability of occurrence $4.39 \cdot 10^{-3}$ of the selected transient (ICAS T2 transient from Pistora et al., 2016).

Three different fracture toughness concepts were evaluated in the probabilistic benchmark assessments in APAL, see Shipsha et al., 2024a, for further details. This paper presents the results based on the RT_{NDT} concept as defined in ASME Section XI Appendix A for the transition region, where the lower bound (LB) crack initiation fracture toughness curve, K_{Ic} is defined as follows:

$$K_{Ic}^{LB} = 36.5 + 3.1e^{0.036(T - RT_{NDT} + 55.5)} \quad (1)$$

For this fracture toughness concept defined for APAL, K_{Ic} quantity is assumed to be normally distributed with a truncation at ±3 standard deviations. The mean value (MV) and standard deviation (SD) are defined for crack initiation as follows.

$$K_{Ic}^{MV} = K_{Ic}^{LB}/0.7, \qquad K_{Ic}^{SD} = 0.15K_{Ic}^{MV} \quad (2)$$

The reference temperature RT_{NDT} is defined as the initial reference temperature, RT^{0}_{NDT}, combined with the reference temperature shift, ΔRT_{NDT}:

$$RT_{NDT} = RT_{NDT}^{0} + \Delta RT_{NDT} \quad (3)$$

Initial reference temperature RT^{0}_{NDT} was assumed as normally distributed without truncation, with a mean value of -30℃ and standard deviation of 9℃. The formulation of the shift ΔRT_{NDT} can be found in Shipsha et a. (2024a).

Two limit conditions, namely the Tangent approach and the maximum Warm Pre-Stressing (WPS) approach were investigated in the APAL project:

1. Tangent approach: Initiation is assumed to occur when K_{I} exceeds the fracture toughness, K_{Ic}.
2. Maximum WPS (Baseline WPS, “Max. K”) approach: WPS effect is assumed to prevent initiation, provided that K_{I} remains lower than previous values observed during the transient regardless of temperature. It can be seen as a simplified and very generous WPS approach.

MARGIN CONCEPTS

As explained in the benchmark definition, the basic quantity provided by the probabilistic assessment in consideration of the uncertainties represented by distribution functions is the conditional probability of initiation (CPI). Already the CPI for a given assumption of RPV embrittlement (either by a fixed ductile-brittle transition temperature DBTT, or an uncertainty-affected shift based on an assumed lifetime) quantifies the safety margin of the RPV.

Additional details are provided when not only the absolute value of the CPI is obtained, but when also the uncertainties relevant for calculating this CPI are identified. A straight-forward way to do this is to compute or to estimate the most probable failure point (MPFP) and to provide its coordinate in the standard normal space (u-space), which yields the MPFP u-vector. This vector can be interpreted as the number of standard deviations beyond the median of the distributed parameters that dominate the scenarios leading to failure.

To transfer the margin in terms more accessible for operation, it is useful to compare the CPI to the acceptance criterion, and vary either the reference temperature RT_{NDT} (if it is an input parameter) or the

lifetime (if it is an input parameter). This quantifies the maximal allowable reference temperature (MART) or lifetime, respectively. The relation between these different margins is shown in Figure 1.

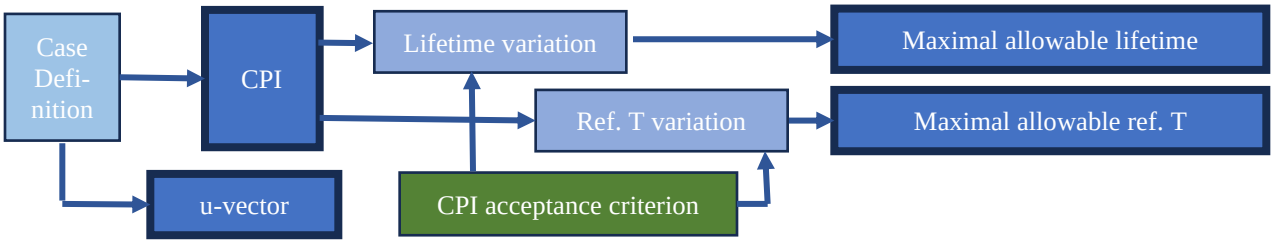

Figure 1. Relation between different margin concepts.

REFERENCE TEMPERATURE RESULTS

The option with the reference temperature input allows to study the predicted CPI in dependency on reference temperature for the participating partners. The result comparison for the postulated circumferential TCC is shown in Figure 2. The two WPS criteria (tangent criterion and the max. K WPS approach) are included, representing the extremal points in the spectrum of possible WPS criteria.

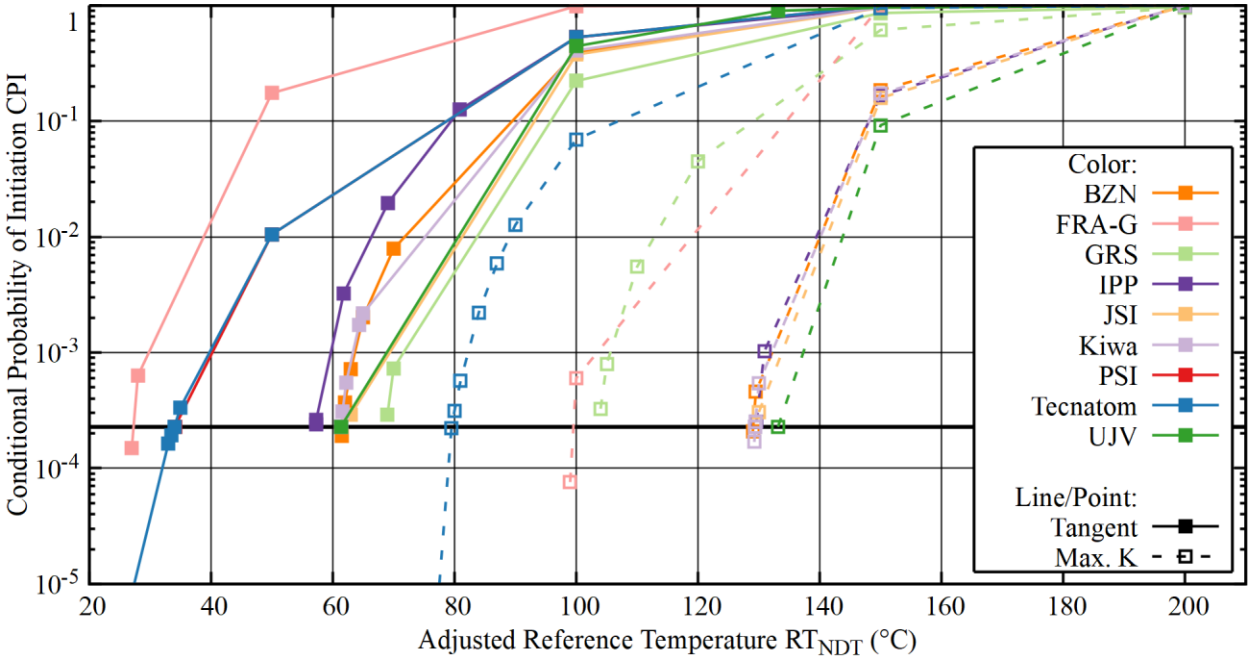

Figure 2. Conditional probability of initiation as a function of the adjusted reference temperature.

All participants compute a zero CPI for low reference temperatures, a steep increase of the CPI at a specific threshold and an approach to one for high reference temperatures. The CPI of the max. K WPS approach is lower than the CPI of the tangent approach; meaning that the threshold for non-zero CPI is higher for max. K WPS than for tangent. The differences in TH code and possibly also FM code are reflected in the difference between the participants; participants with the same codes (e.g. Kiwa and BZN; Tecnatom, UJV and PSI) obtain very similar results.

The threshold value is very close to the acceptable CPI. For the comparison of the margin concept of maximal allowable adjusted reference temperature, the crossing value is computed for each participant.

The resulting maximal allowable reference temperatures of this benchmark case are compared in Figure 3, together with the results for axial orientation and the UCC and EC.

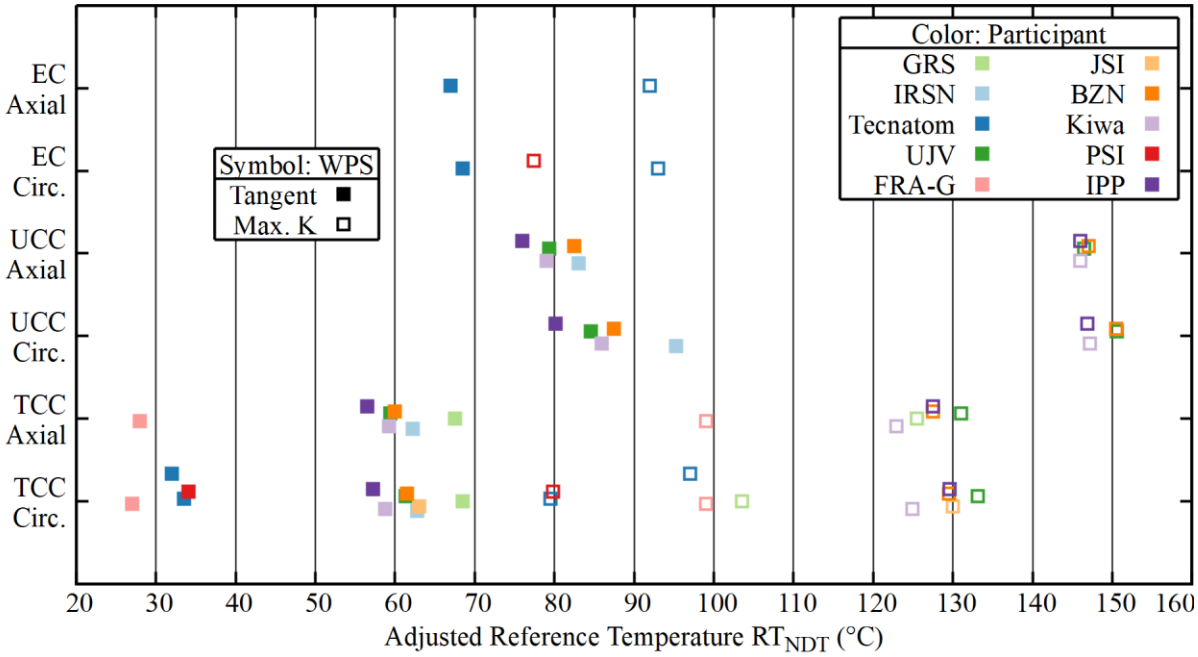

Figure 3. Maximal allowable adjusted reference temperature.

This shows that the shape of postulated crack (TCC vs. UCC vs. EC) influences significantly the safety margin, while the crack orientation (axial vs. circumferential) has a smaller impact (the axial orientation has in most cases a slightly lower safety margin). It should be noted, that this observation can depend on the analysed PTS transient (transient analysed within APAL exhibited relatively small pressure and not significant cold plume). The different TH codes lead to a visible scattering in the margin.

LIFETIME RESULTS

As a more complex case, the reference temperature was treated as a probabilistic, implicit parameter, dependent on fluence and a shift formula. The fluence is directly related to the RPV operating lifetime, therefore, the CPI can be expressed as a function of lifetime. The results are shown in Figure 4 for the postulated circumferential TCC.

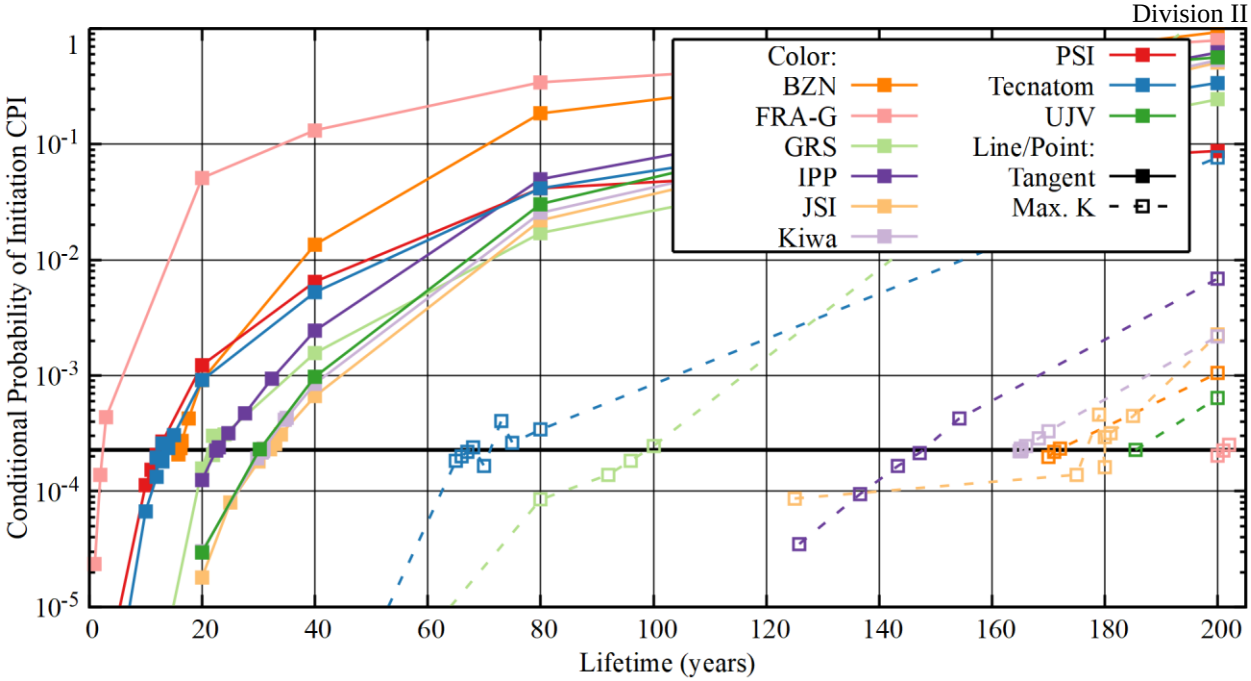

Figure 4. Conditional probability of initiation as a function of the lifetime.

Qualitatively, this result is very similar to the dependence between CPI and reference temperature (see Figure 2): The CPI increases as a function of lifetime, approaching unity for high ages of the RPV. The computed CPI vary depending on the applied TH and FM codes, and the tangent criterion leads to higher CPI than the max. K WPS. A significant difference is the behaviour for small CPI: The lifetime-based approach does not exhibit a threshold behaviour below which CPI is exactly zero; instead, the CPI is constantly decreasing for smaller operating times.

At specific ages (such as 40 and 80 years), the computed CPIs can be compared between the participants, which corresponds to the analysis of the vertical scattering at selected moment in lifetimes in Figure 4. The scattering in the logarithmic scale becomes smaller as the RPV life increases, from about three orders of magnitude at 20 years to about one order of magnitude at 200 years. It should be noted that the order of the participant's predicted CPI also changes – GRS and PSI have medium to high CPI for early years, and low CPI at 200 years.

To better understand the relevant mechanisms and the influences of the different uncertainties, the u-vectors can be deduced from the simulation. This u-vector contains the coordinates of initial reference temperature, Cu-, Ni-, and P-concentration, the fluence ϕ, the shift error Err, and the fracture toughness (K_{Ic}). Two participants provided this information, and the comparison of the MPFP coordinates is shown in Figure 5 for 20, 40, 80, and 200 years, respectively.

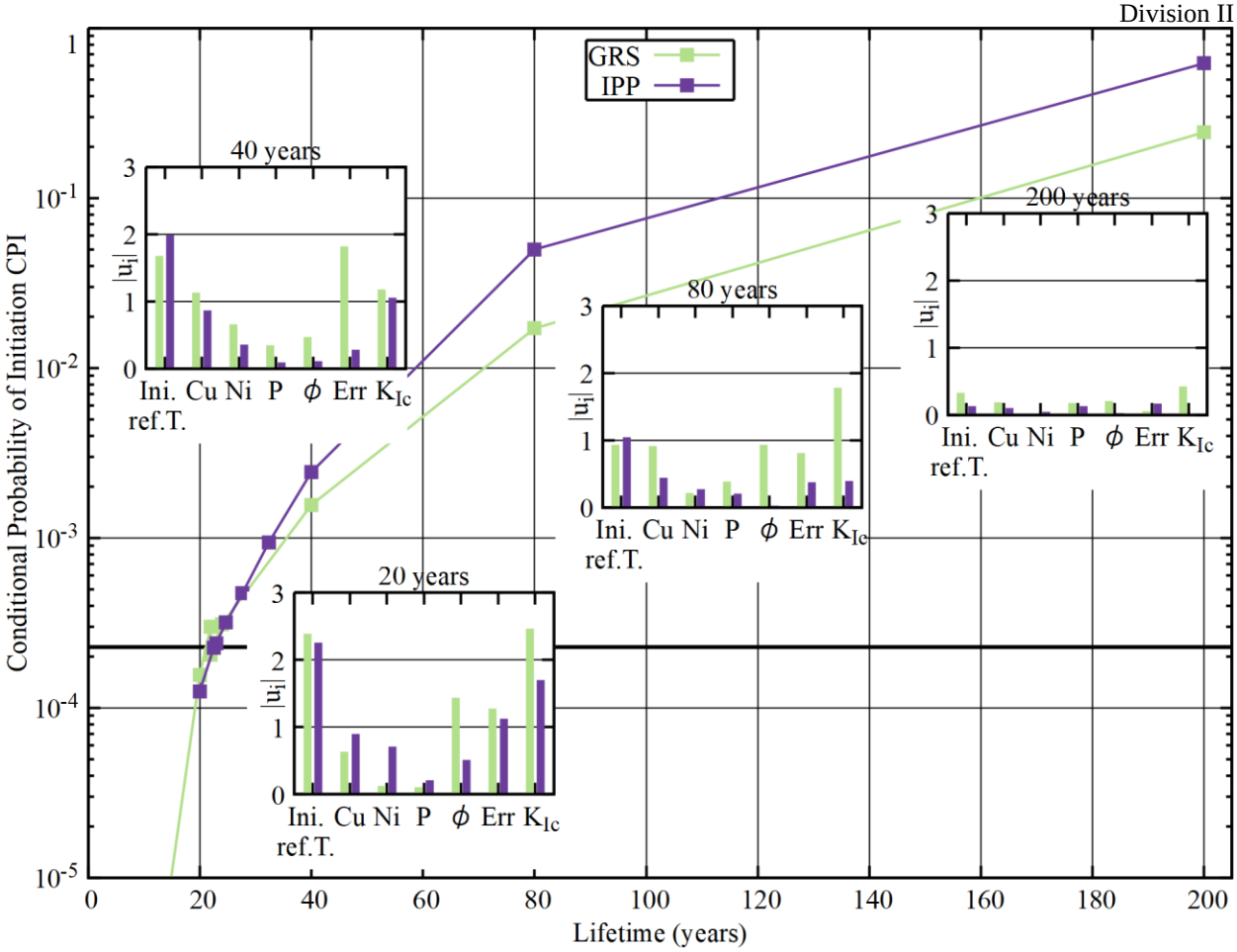

Figure 5. u-vector of the MPFP at specific lifetimes.

This representation affirms that the distance from the MPFP to the median becomes smaller as the CPI increases (the absolute height of the bars decreases), and reveals that the relevant uncertainties change with the RPV lifetime (the relative height of variable's bar at one age can be interpreted as a measure of relevance). At 20 years, extreme combination of initial reference temperature and fracture toughness have to occur simultaneously to allow for crack initiation. At 40 years, fluence error and Copper (and Nickel) concentration become also relevant. At 80 years, the influence of the initial reference temperature is already reduced, and at 200 years, the CPI is so high that the MPFP is close to the median, leading to very small $|u_i|$-values.

The intersection between the CPI acceptance level and the computed CPI in Figure 4, but also in Figure 5, defines the maximal allowable lifetime. This quantity is compared in Figure 6, together with the other crack shapes and orientations.

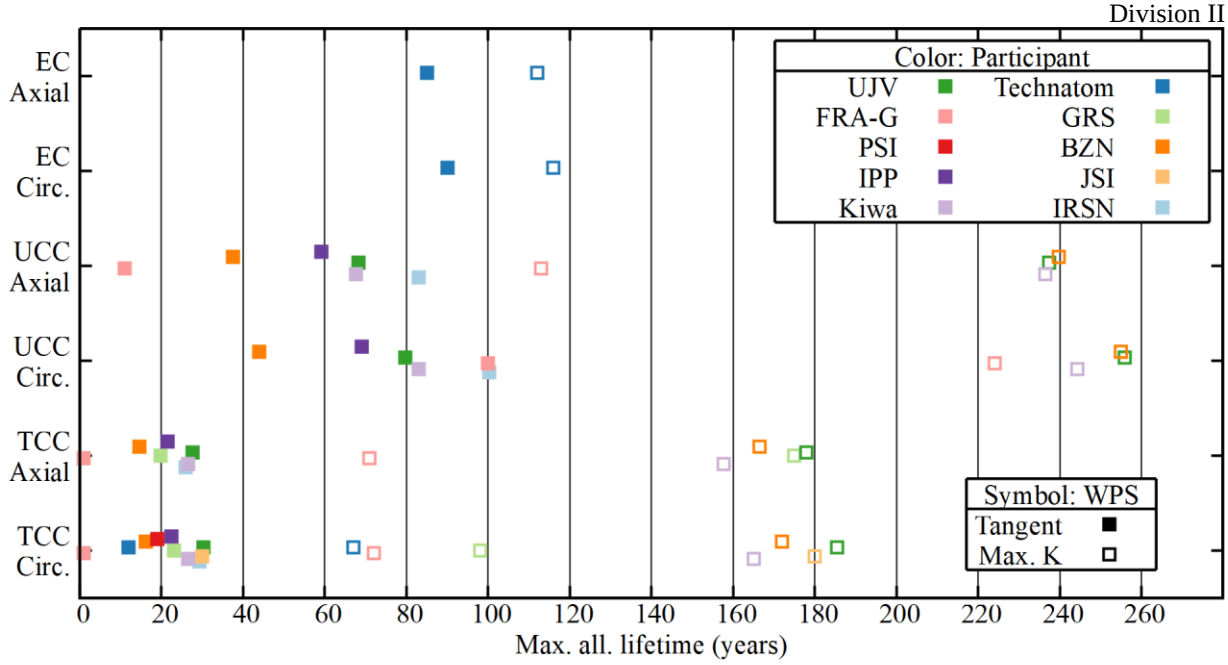

Figure 6. Maximal allowable lifetime.

These results show that, with the conservative tangent criterion, the maximal allowable lifetime is very small, in the range of about 10 to 30 years for most partners. This result renders the selected benchmark case unrealistic for contemporary RPVs, but very suitable for the study of long-term operation (LTO) improvement assessments, which was another key point in APAL. For this study, the conclusions about the influence of TH and FM codes and the benefit of different margin concepts are not affected by the maximal allowable lifetime.

The observation about the lower margin for the axial orientation (see the discussion of the maximal allowable adjusted reference temperature above) is confirmed. The TCC margins are smaller than the UCC margins, and the EC margins are higher than most UCC margins (for the tangent criterion). The scattering in maximal allowable lifetime is very high for the max. K WPS approach, which is caused by the lack of numerical robustness of this approach. For LTO discussions, the max. K WPS leads to lifetimes that are in many but not all cases much higher than those relevant for LTO considerations.

RELATION BETWEEN DIFFERENT MARGINS

While the margins give different information, it is worth to study the relation between the introduced margins concepts. The circumferential TCC with both initiation criteria for all partners provide a set of cases for a graphical comparison. This comparison is provided to show the relation between the probabilistic maximal allowable reference temperature with the probabilistic maximal allowable lifetime and the deterministic maximal allowable adjusted reference temperature (see Angermeier et al., 2024) in Figure 7.

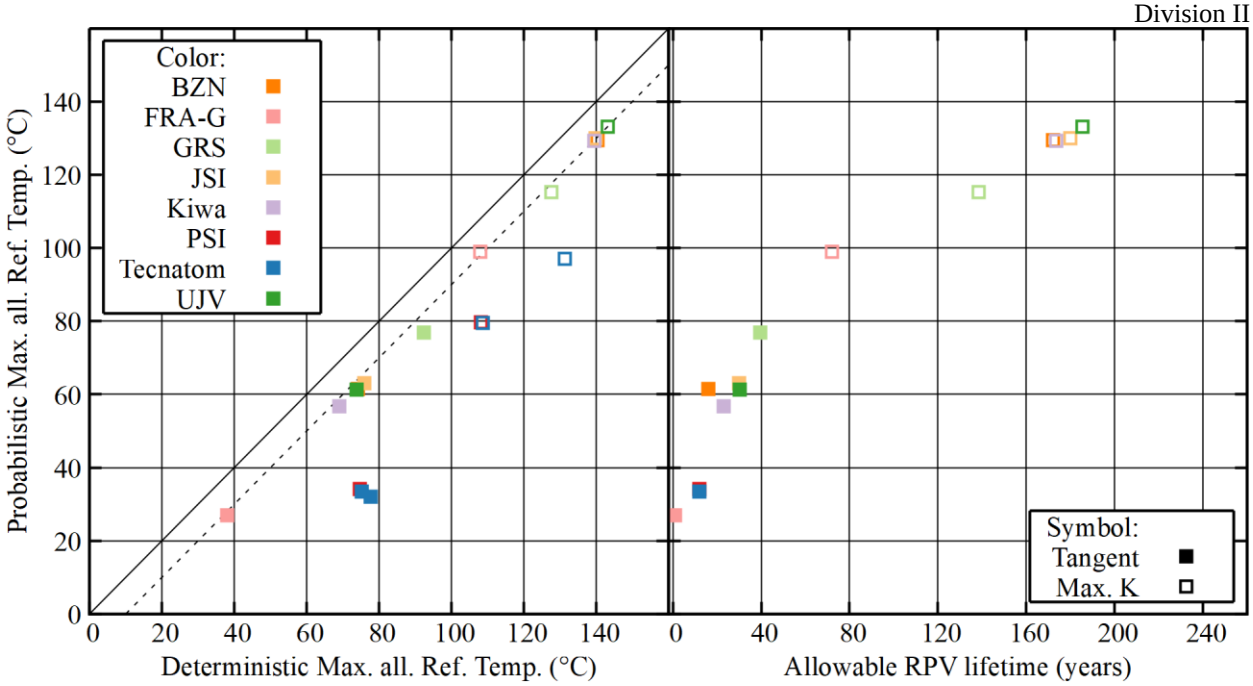

Figure 7. Probabilistic max. all. ref. temperature as a function of the deterministic max. all. ref. temperature and allowable lifetime.

In this comparison, there is demonstrated monotonic relation between the three margins. The difference between the probabilistic and deterministic maximal allowable reference temperature is about 10 °C – except for participants using a slightly modified fracture toughness due to their FM code. The relation between allowable reference temperature and lifetime is non-linear. It should be noted that, in this specific case definition, the probabilistic margin is lower than the deterministic margin, meaning that the probabilistic computation of the MART is more conservative than the deterministic computation. This result is caused by the use of the fracture toughness as the only one distributed input parameter in this specific probabilistic assessment, when the CPI acceptance criterion of $2.28 \cdot 10^{-4}$ is stricter than two standard deviations below the mean value, which corresponds to the deterministic fracture toughness value.

SUMMARY AND CONCLUSION

In the presented benchmark study, probabilistic PTS assessments performed with different FM codes and based on transients obtained with different TH codes are compared. This variation allows to study the influence of the code differences, but also to compare different margin concepts on a variety of simulations.

The safety margin in the PTS assessment is expressed in terms of CPI, in terms of (MPFP) u-vector, in terms of maximal allowable reference temperature, and in terms of maximal allowable lifetime. While the CPI alone provides only few information on the safety of an RPV in a specific state, the analysis of the u-vector enriches this by pointing out relevant mechanisms (or input parameters) leading to possible crack initiations. The concepts of maximal allowable reference temperature, and even more of maximal allowable lifetime are very suitable to quantify the safety margin and to study the impact of differences in transients, codes, and improvement measures.

ACKNOWLEDGEMENT

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