Probabilistic RPV Integrity Assessment: Definition of Baseline Probabilistic Benchmark

Vignesh Suryaprakash
Framatome GmbH, Germany

Sebastien Blasset, Ralf Tiete, Katharina Angermeier, Petter von Unge, Peter Dillstrom, Klaus Heckmann, Vladislav Pištora, Miroslav Pošta, Oriol Costa, Carlos Cueto- Felgueroso, Jerome Roy

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Intro (1/2)

- APAL aims to investigate the impact of thermal hydraulic uncertainties and improvement for long term operation (LTO) onto the RPV safety assessment
- In WP3 and WP4 of APAL, these impacts were quantified based on a deterministic and probabilistic benchmark respectively
- The benchmarks were well defined, understood and correctly applied to improve the confidence in the safety assessment results
- The benchmark definition is based on existing plant data (ICAS 2012) and state of the art research results
- It included RPV geometry, thermal hydraulic (TH) loading, type of cracks, state of the art stress intensity factor models, residual stresses, fracture toughness models, warm-prestress (WPS), procedures for crack initiation and arrest as well as margin definition

Intro (2/2)

- The probabilistic margin assessment consisted of five main tasks:
  - Task 4.1: Structural assessment
  - Task 4.2: Definition of a probabilistic fracture mechanics benchmark ➡ This presentation
  - Task 4.3: Baseline probabilistic benchmark performance
  - Task 4.4: Probabilistic benchmark related to LTO improvements
  - Task 4.5: Probabilistic benchmark related to thermal hydraulic uncertainties

General Terms (1/3)

- Baseline case = benchmark case with methods, models and set of parameters to be investigated by all partners (mandatory)
- Base case TH data set = new conservative transient (in the meaning to be conservative for the safety assessment) for T2 from ICAS including accumulator, named now APAL-ICAS T2, this is the reference transient
- Best-estimate TH data set = transient results from task 2.3 "best-estimate solution" from "Wilks set" is a solution of TH calculations for the APAL transient with all input parameters (both plant parameters and model parameters, as well as human factor parameters) set to their best estimates if they are available. (Otherwise, the conservative value is applied.)
- Average transient data set = transient results from task 2.3 from "Wilks set", the term "Wilks set" implies random selection of parameters. This is in contradiction "all input parameters set to their best estimates", hence we select "some average" transient from the Wilks set.
- Base line assessment = basic assessment considering base case TH loading for structural assessment, RPV location of interest at core weld below cold leg with safety injection
- Enveloping TH data set = results from task 2.3 (enveloping solution from Wilks set of TH calculations) and will be evaluated in task 4.5 (margin assessment related to TH uncertainties), from Wilks set
- Statistical TH data sets = set of all transients (i.e. coming from Wilks method) resulting from task 2.3 and will be evaluated in task 3.5 (margin assessment related to TH uncertainties)

General Terms (2/3)

- Long-term operation (LTO) improvements = set of transients concerning TH improvement to RPV brittle fracture assessment for long term operation resulting from task 2.1 and will be assessed in task 4.4 (margin assessment related to LTO improvement)

- ART = adjusted reference temperature (from indirect or direct measurement), this is the name chosen for the index of the KIC curve (RTNDT concept, indirect) as well as for the index from the Master Curve (direct measurement of T0 + margin = RT0).

- max. ART = This is the (calculated from PTS fracture mechanics safety assessment) value being shifted in order to find the highest index fulfilling the limit condition (tangent or WPS). The max. all. ART can be max. all. RTNDT or max. allow. RT T0, depending on the adopted concept (RTNDT or Master Curve)

- margin (in…against … between … and …due to ...) = the term margin alone does not mean anything, the relation leading to a margin must be always specified. Specifically, in the APAL project the definition of the margin is given by: margin in maximum allowable reference temperature (max. all. ART) against RPV failure (situation leading to crack initiation or non-arresting crack), this is given by the comparison (difference) of maximum allowable ARTs between situation A and situation B due to the change of a given parameter.

- Inherent margin = Unquantifiable positive bias in results of some method, calculation, assessment, measurement, etc.

- RPV failure = within the APAL project, this is the name of the situation obtained if a postulated crack could initiate under given combination of loading and ageing (mandatory task, penalizing) or if a propagating crack cannot stop or growths up to some given proportion of RPV thickness (e.g. 75%) under given combination of loading and aging (aging is non-mandatory task), i.e. RPV failure = crack growth up to 75% of the RPV wall thickness

- Limit condition (or limit state): WPS or tangent approach; initiation or unstable (non-arresting) crack growth (or too deep crack, i.e., plastic collapse).

General Terms (3/3)

- cpi (t) = instantaneous conditional probability of initiation at time t in the selected transient
- CPI = final conditional probability of initiation for a selected transient
- CPF = final conditional probability of failure for a selected transient
- FI = frequency of crack initiation
- FF = frequency of failure

Failure Frequency

- The frequency of initiation FI is the frequency of the event that one crack initiates.

- The frequency of failure FF is the frequency of a propagating non-arresting crack (i.e. crack arrest is taken into account and an initiating but arresting crack does not add to the failure frequency) reaching a defined portion of the RPV wall or leading to plastic collapse of the RPV. The latter case (considering a crack can arrest) is the more realistic.

- We have to set an allowable FI or FF for margin assessment:
  - base line = $1\text{x}10^{-6}$

- Primary PTS acceptance criterion according to Regulatory Guide 1.230: acceptable TWCF < $1\ \text{x}10^{-6}$ vessel failures per reactor-operating year.

- For correlation of FI or FF with CPI or CPF, the yearly occurrence of base case transient has been defined in DEFI-PROSAFE

- Allowable CPI or CPF of $2.22 * 10^{-4}$

Yearly occurrence of base case transient taken from DEFI-PROSAFE

Group of scenarios	Representative scenario	mean value of frequency	5% quantile	50% quantile	95% quantile
		[1/year]	[1/year]	[1/year]	[1/year]
medium LOCA	ICAS T2	4.39×10^{-3}	5.28×10^{-4}	2.43×10^{-3}	1.43×10^{-2}

Basic data for RPV probabilistic fracture assessment

An overview of the parameters in the probabilistic assessment and the type of uncertainty of these parameters

Material data - RPV Geometry

- There are several sources that can serve as basis for uncertainties on RPV geometry:
  - Fabrication of shells/plates with a specified tolerance
  - The geometry is measured with a given uncertainty
  - Weld geometry is related to welding process
  - The thickness of the cladding may vary (especially at weld location)
- Uncertainties on RPV geometry are usually not considered in PFM.
- For the APAL benchmark no uncertainties on RPV geometry were considered, the RPV dimensions was fixed.

Material data – Chemical properties

- The chemical composition of RPV ferritic steel was specified (direct measurement: ladle analysis; component), see for example the material 22NiMoCr37. The uncertainties on each element relevant for the embrittlement model was quantified
- For the APAL benchmark the chemical composition was of importance, when CPI and CPF were calculated for a pre-defined lifetime or if ART was assumed to be distributed in connection with ART shift.
- The chemical composition has an influence on the reference temperature shift
- Best-estimate and uncertainties for chemical composition were treated as normally distributed

	% copper (Cu)	2 SD uncertaintie s	% phosphorus (P)	2 SD uncertaintie s	% nickel (Ni)	2 SD uncertaintie s
Base metal	0.086	0.02	0.0137	0.002	0.72	0.1
Welds	0.120	0.02	0.0180	0.002	0.17	0.1

Material data – Technological properties

- The inherent variability of material properties within one forging is correlated with the process of manufacturing, therefore it is logical that variation in the properties occurs in a forging even if it has been considered historically as “homogeneous” and isotropic. Such simplification was required in the past due to the level of knowledge and technical capability of measurement.

- In the past the beltline HAZ material was part of the RPV embrittlement surveillance program. According to KTA 3203 and ASTM E185 it is not required anymore, as the base metal is assumed to deliver higher reference temperatures than this HAZ.

- Within the APAL project, structural assessments were performed without any variability or uncertainty of thermal and mechanical properties for base, weld metal or HAZ below the cladding.

Material data – Fluence

- The profile of the fluence is spread in azimuthal and axial direction on RPV inner (wet) surface, the fluence is increasing with the time of operation. These profiles are needed for a probabilistic assessment, when multiple flaws are assessed in regions with different level of neutron fluence.
- Within APAL's benchmark, assessment of multiple flaws was not mandatory. For margin assessment approaches, where a correlation between lifetime and max. neutron fluence and uncertainty in fluence was required, the definition provided in DEFI-PROSAFE was used.
- The information on fluence profile on the inner surface for assessing multiple flaws in different sub-regions of the RPV (e.g. FAVOR approach). Such an assessment was non-mandatory within APAL's benchmark.
- A fluence attenuation occurs through the RPV wall. This can be considered for detailed analysis of the embrittlement distribution across the RPV thickness (especially for crack arrest). The attenuation formula from PROSIR was considered

Years of operation	Max. neutron fluence (normal distribution)	
	Mean value (MV)	Standard deviation
10	$3.0 \cdot 10^{23}$	10% of MV
20	$5.0 \cdot 10^{23}$	10% of MV
40	$7.5 \cdot 10^{23}$	10% of MV
60	$10.0 \cdot 10^{23}$	10% of MV
80	$12.5 \cdot 10^{23}$	10% of MV

Material data – Reference temperature

- The knowledge of the shift of the reference temperature due to ageing by neutron embrittlement was required for certain margin assessments (PMA 2 and 3) and non-mandatory crack arrest assessment. The intention was to have a summary of the available shift formulas in the D3.2, only some of them (specific for the material under consideration) for base metal, HAZ and weld were considered for the benchmark.
- The embrittlement shift formulas given in PROSIR, RSE-M and 10CFR50.61a were used in APAL
- It must be emphasized:
- Each formula was been developed based on a given dataset of experimental results, therefore some formulas can deliver “better” prediction considering one nuance of material
- Each prediction model has an epistemic uncertainty (linked with the level of knowledge) which has to be added (added error function in the probabilistic assessment of predicted reference temperature at a given year of operation).
- The reference temperature at a given EFPY shall account for errors in the initial value (begin of operation) and the error in the shift formula
- The degradation shift is always positive

Material data – Fracture toughness

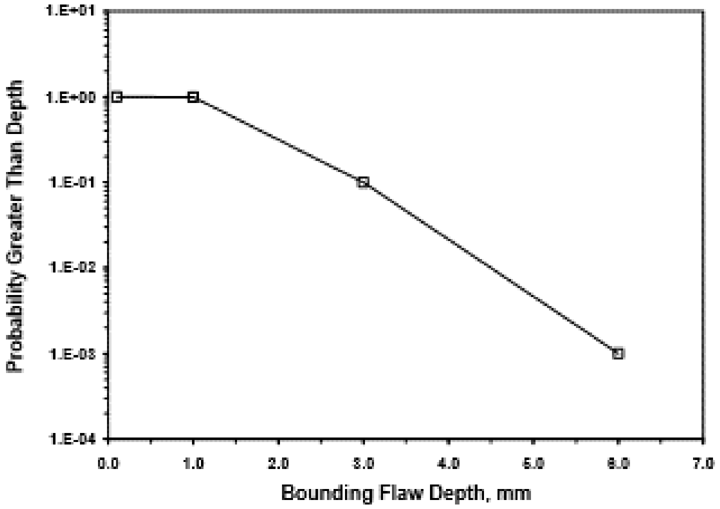
- Master-Curve: Direct use 5%-quantile from Weibull distribution (and ASME CC-830 R1 for K_{Ia})
- RT_{NDT} concept: K_{IC} ASME and K_{IA} ASME are intended to be a lower bound with 95% confidence (i.e. p = 5%); K_{IC} and K_{IA} normal distributed

Basic data – Flaw types (1)

- Flaw types
    - Underclad crack (UCC) due to its potential presence in some cladded RPV forging
    - Through clad crack (TCC) are postulated in addition to consider unknown degradation mechanism leading UCCs to develop through the cladding
    - Fully embedded (buried) defect are common in welds and base metal
- Assessment of fully embedded flaws is used for FAVOR/CAPAL software to allow comparison with UCC assessment

Basic data – Flaw distribution

- The flaw-characterization for inner surface- breaking flaws applicable to weld and plate (base metal) material.
- The distribution for UCC was based on NUREG 1806 data Moreover, a distribution function was generated for crack depth and length distribution.
- For TCC the same distribution was applied but adding the cladding thickness of 6 mm on distributed crack depth.

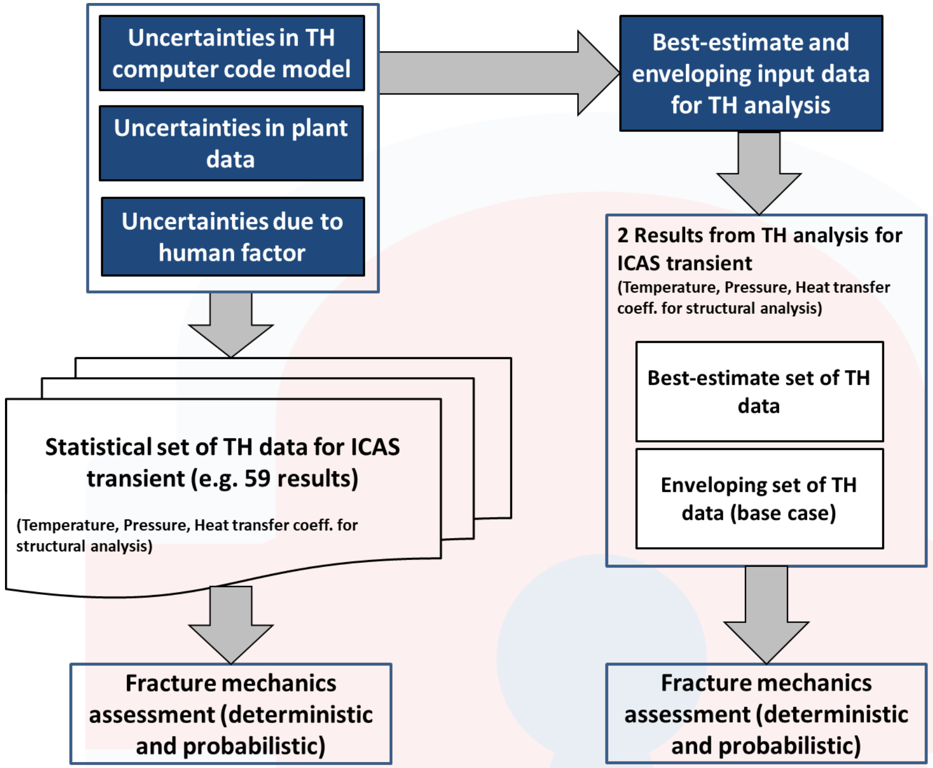


Basic data – RPV Loading (1)

- RPV loading scenario R&D ICAS T2 transient (50 cm² break/leak in hot leg, i.e. small break LOCA) is re-used and updated for APAL
- Global system codes and mixing codes were applied to determine thermal-hydraulic (TH) data for the transient (temperature, pressure, heat transfer)
- Reduced welding residual stresses (WRS) in weld after post-weld-heat-treatment

Basic data – Load distribution

- In WP 2 the uncertainties in the TH analysis were described.
- The Wilks method requires that 59 simulations of the APAL-ICAS transient T2 be performed in order to obtain figures of merit with a 95% likelihood of not being exceeded at a confidence level of 95%.
- The best-estimate and enveloping transient from Wilks method was used in the fracture mechanics analyses in order to determine margin related to TH uncertainties. Moreover, it was recommended to assess all 59 transients to verify the best-estimate and enveloping TH data set in terms of fracture mechanics results (e.g. max. allowable ART). The propagation of TH data sets from WP2 uncertainty analysis to either WP3 and WP4 is shown in figure.
- Uncertainties in the loading profile may become important, when different regions of loading (in azimuthal and axial direction) are assessed, e.g. for multiple flaws. The sources of these uncertainties are mainly related to variation of cold plume width, movement of cold plume overlapping of cold plumes. The determination of these uncertainties require more sophisticated thermal hydraulic mixing analyses (e.g. CFD calculations).
- On the other hand, the basic approach to postulate flaws in the region of highest loading can be seen as conservative approach to cover uncertainties on loading profile. If flaws in different regions are assessed, a covering (enveloping) loading for each region may be taken into account. The simplified approach to use covering loading due to variation in azimuthal and axial direction for PFM was used for APAL benchmark.



Uncertainties in TH computer code model

Uncertainties in plant data

Uncertainties due to human factor

Best-estimate and enveloping input data for TH analysis

Statistical set of TH data for ICAS transient (e.g. 59 results)

(Temperature, Pressure, Heat transfer coeff. for structural analysis)

2 Results from TH analysis for ICAS transient

(Temperature, Pressure, Heat transfer coeff. for structural analysis)

Best-estimate set of TH data

Enveloping set of TH data (base case)

Fracture mechanics assessment (deterministic and probabilistic)

Fracture mechanics assessment (deterministic and probabilistic)

Basic data – Crack initiation limit condition (1/2)

- There are different limit conditions for crack initiation that can be used. The historical lower bound approach is the tangent limit condition. The max. all. ART for analyzed sequence corresponds to the allowable stress intensity factor curve (K_{IC}) shifted horizontally up to the point where it becomes a tangent to the crack loading path of the sequence of PTS.
- By the “tangent point” we mean the point, in which in the conventional inequality $K_I \leq K_{IC}$ becomes an equality, once the equality $K_I = K_{IC}$ is reached.

$$max.all.ART = \sup\left\{ART: \forall t\ K_J(t) \leq K_{Jc}(ART, T(t))\right\}$$

- This equation defines ART for one transient, one fixed crack and one point on the crack front using the tangent approach and “crack initiation” as a failure criterion. A maximum probability of crack initiation is provided using the Tangent approach following the FAVOR approach.

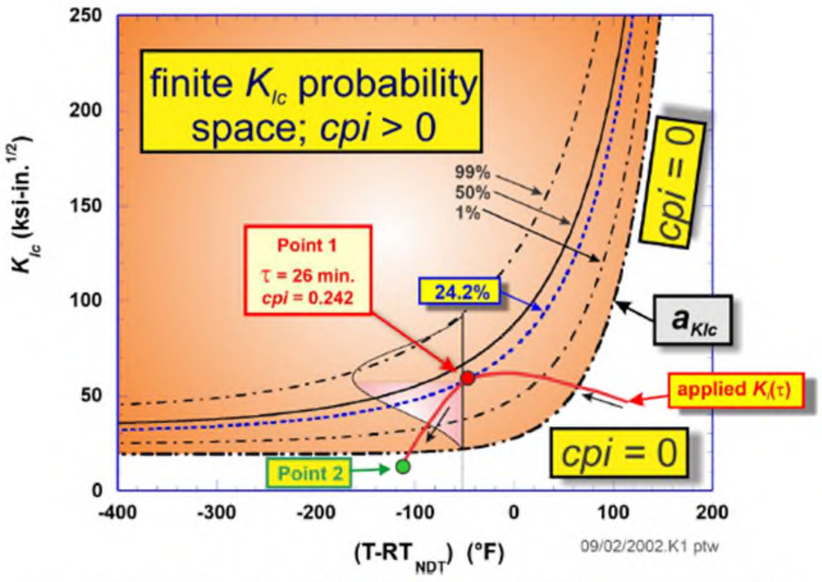


Figure 14: Interaction of the applied KI time history and the Weibull K_{IC} statistical model.

Basic data – Crack initiation limit condition (2/2)

- The best-estimate approach is considering a limit condition with WPS benefit
- For the APAL project a simplified approach was chosen as provided in FAVOR code. The maximum allowable reference temperature for analyzed sequence corresponds to the allowable stress intensity factor curve (KIC) shifted horizontally up to the point where it intersects at a certain point relative to the maximum value of KI during the PTS event if warm pre-stressing (WPS) approach is applied.
- If a flaw is in a state of WPS, it is not eligible for initiation (or re-initiation if it has arrested) until it leaves the WPS state.
- Three conditions can be stated for a flaw not to be in the state of WPS and, thereby, to be eligible for initiation. These three conditions are:
  - Condition (1): the applied-K_I is greater than K_{Ic}(min), where K_{Ic}(min) is defined by the fracture toughness model for the temperature at the flaw tip;
  - Condition (2): a rising applied-KI field – the time-rate-of-change of the applied-KI is positive ($dK_I /dt > 0$);
  - Condition (3): in a rising applied-KI field, the driving force at the flaw tip must exceed some portion of the previously-established maximum applied-KI (designated as K_I(max)) experienced by the flaw during the transient up to the current point in time under consideration – applied- $K_I (t) \geq K_I$(max)
- This is the “FAVOR approach”. All the three conditions must be fulfilled simultaneously for a flaw to be eligible for initiation. The flaw initiates, if and only if all the three conditions are met together with cpi > 0.

Margin Definition

- Two types of margin:
  - Explicit margin: Difference between maximum allowable value for data of interest (e.g. ART) determined by PTS analysis (either probabilistic or deterministic) and predicted value for data of interest (e.g. material ART for expected EoL).
  - Implicit margin: Margin that is implicitly due to used conservative boundary conditions (e.g. flaw postulate, loading condition, SIF solution). The quantification of implicit margin can be done by comparison of results with different approaches, e.g. using SIF solution A versus SIF solution B or comparison for different inputs (assessment with conservative input data versus assessment with relaxed/best-estimate input data).
- Coming from deterministic approaches, historically, the explicit margin of a PTS analysis is quantified in terms of difference between material ART and max. allowable ART from PTS analysis. For probabilistic fracture mechanics there are mainly two quantifications used: In terms of ageing (e.g. max. all. ART) or in terms of risk of failure. But even for those two types of quantification several probabilistic approaches are possible with different levels of uncertainty consideration.
- In DEFI-PROSAFE, a methodology was developed to assess the maximum allowable ageing of the RPV in terms of maximum allowable ART (max. all. ART) which can be used to make comparison and assess margin. The principle is to determine the max. all. ART for which a given probability of failure is calculated.

Margin Assessment

- Within APAL several probabilistic margin approaches (PMA) were discussed and defined:
    - Margin definition in terms of maximum allowable ART
        - PMA 1 (DEFI-PROSAFE approach): Determine max. allow. ART for a given defined allowable failure frequency with ART being a fixed input parameter for PFM. In the end the correlation of ART with FF (from several PFMs) will lead to determination of maximum allowable ART and margin can be determined in terms of ART. Using the uncertainties in ART, the maximum allowable ART can be compared to mean value or a certain quantile.
    - Margin definition in terms of lifetime
        - PMA 2: Determine max. allow. lifetime for a given defined allowable failure frequency. The lifetime of the RPV defines the initial ART and the ART shift (both are treated distributed) as input for the PFM. In the end the correlation of a lifetime with FF (from several PFMs) will lead to determination of maximum allowable lifetime and margin can be determined in terms of lifetime. This approach can also be used for determination of allowable ART, if the lifetime is correlated with mean value or quantile of sampled ART.
    - Margin definition in terms of failure frequency
        - PMA 3: Determine failure frequency for a given RPV lifetime. This approach quantifies the safety in terms of failure frequency to be compared with an allowable (acceptable) failure frequency for further operation.
- PMA 1 had the disadvantage of losing some uncertainty treatment in relation to RPV specific material behavior (embrittlement), whereas PMA 2 and 3 used the full scope of probabilistic fracture mechanics. But on the other hand, PMA 1 was preferred to quantify potential margin gain obtained solely by lowering the uncertainty in the loading path (e.g. related to TH uncertainties) independently of the type of RPV, as a bias resulting from uncertainties in material embrittlement was excluded.
- PMA 1 and 2 were used to compare deterministic with probabilistic assessment and to quantify implicit margin of a deterministic PTS analysis. All the approaches were also used to quantify the difference in explicit margin related to LTO improvements.

Margin Assessment

- After successful performance of benchmark for the base case transient, impact on margin assessment was performed:
  - Benchmark for LTO improvement identified in WP2
  - Benchmark for TH uncertainties (results from Wilks analysis)

Thank you for your attention!
Questions?

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