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Deterministic benchmark definition for the Advanced Pressurized thermal shock Analysis for Long term operation (APAL) project

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ABSTRACT

The APAL project has been launched in order to improve the nuclear power plant safety in Europe by commuting efforts to share a common understanding on evaluation of safety margin for nuclear reactor pressure vessel (RPV), valid for old and new plants. The impact of thermal hydraulic uncertainties and improvement for long term operation (LTO) onto the RPV safety assessment are investigated to preclude RPV break (fast fracture) in case of emergency cold water safety injection event in aged nuclear power plant.

The deterministic benchmark definition is the paradigm for safety assessments and integrity analysis of the RPV in order to quantify safety margin against fast fracture (DEFI-PROSAFE, 2018). The deterministic fracture mechanic assessment has to be well defined; understood and correctly applied therefore a benchmark is required 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 includes 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. The common understanding of the procedures will be verified within the mandatory parts of the benchmark and solutions are provided at each step to allow own verification of the proposed models.

The beginning of the benchmark is educational and contains a series of pre-requisite analyses for each step of the assessment Fig.1 to allow verification of each partners models and tools before moving to the main part. There, temperature and stress distributions are calculated for several sets of transients to investigate impact of LTO or TH-uncertainties from Wilks, see Porner (2019) on RPV break preclusion margin.

This paper presents the deterministic benchmark definition (work package WP3) of the APAL project.

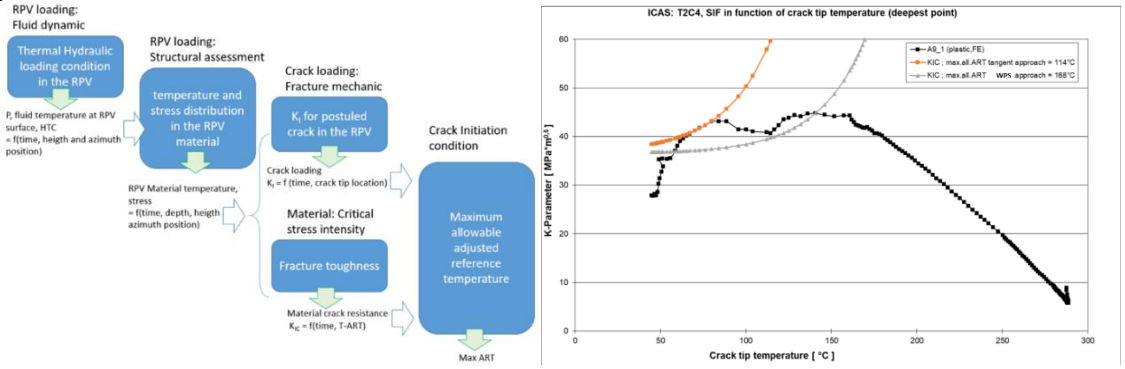


Figure 1. Flow chart of the calculation chain for RPV fracture mechanics safety assessment (left), example of maximum allowable ART determination from ICAS

INTRODUCTION

The first benchmark performance contains a series of pre-requisite analyses to allow partners to verify and validate their tools before they move to the benchmarks in tasks 3.4 (LTO) and 3.5 (TH

uncertainties) for margin assessment, which require much more computation. This is to avoid misunderstanding in the different steps and to allow re-definition of the parts of the benchmark or input parameters if needed. The steps are separated into fracture-mechanics and margin assessment. The overall benchmark structure is quite simple: a common Fracture mechanics assessment approach is the Pre-Requisite (PR) analysis, so this is the first step: PR-Det-1 (part 1), educational to learn state of the art (SOA) solutions (reference); PR-Det-2 (part 2), to compare other solutions with reference results for base case scenario, starting with the structural assessment (SA), see Spisák, 2024 and the fracture mechanic analysis (FMA), see Angermeier (2024). In a second step the margin assessment is performed following the same verified approach between base case scenario and LTO improvements or for TH-uncertainties.

Table 1. Overview of deterministic benchmark (some non-mandatory tasks are not presented)

	Pre-requisite (**PR**)			**Margin** assessment	
	Part 1 Verification	**Part 2 (PR-Det.2)** Comparison of TH-code		**LTOs improvement**	**TH uncertainties**
Scenario	Not required, data are made available to partners	APAL-ICAS T2 Base Case			
TH global (system code)		System code results (RELAP, TRACE, ATHLET …)		9 LTO improvements or human actions	59, 93, 130 variants
TH mixing or CFD		Mixing code (ECC-MIX, KWU-MIX) or CFD results (Fluent)		Some LTOs	93 variants
Temperature & Stresses (SA)	Pre-defined, i.e. provided!	Simplified 1D/2D ***Task 3.1*** ***PR Det.2.0***	Sophisticated 3D FEA ***Task 3.1*** ***PR Det.2.0***	1D /2D Simplified, Sophisticated 3DFEA (selected LTOs, ***Task 3.1***	1D / 2D(cold plume) simplified ***Task 4.1***
Crack type	UCC, TCC	TCC, UCC (for non FAVOR user), Buried (for FAVOR/CAPAL user only)			
K_I model	Referenced K_I: ***PR-Det 1.1.1*** And individual for comparison: ***PR-Det 1.1.2***	***PR-Det 2.1*** Ref. K_I Or Individual K_I	same	Same ***Task 3.4***	Same ***Task 3.5***
K_{IC} model + Limit condition+ Max all. ART	RT_{NDT}, T_0 Tang.: ***PR-Det 1.2.1*** WPS: ***PR-Det 1.2.2***	***PR-Det 2.2***	same	Same ***Task 3.4***	Same ***Task 3.5***
Crack arrest	***PR-Det 1.3***	***PR-Det 2.3***	same	Not mandatory	Not mandatory

Task 3.3:

BASIC DATA AND MODELS FOR FRACTURE MECHANICS SAFETY ANALYSIS

The **RPV geometry** considered for APAL is based on ICAS / UPTF, see Figure 2. a four-loop, 1300 MWe pressurized water reactor (PWR) of Grafenrheinfeld built by Siemens/KWU. A general description of UPTF is given in the report of Nuclear Energy Agency (1999). Location of core weld=-2638mm from nozzle center line, outer radius at core weld elevation=2684mm, thickness ferritic=243 mm, cladding=6mm.

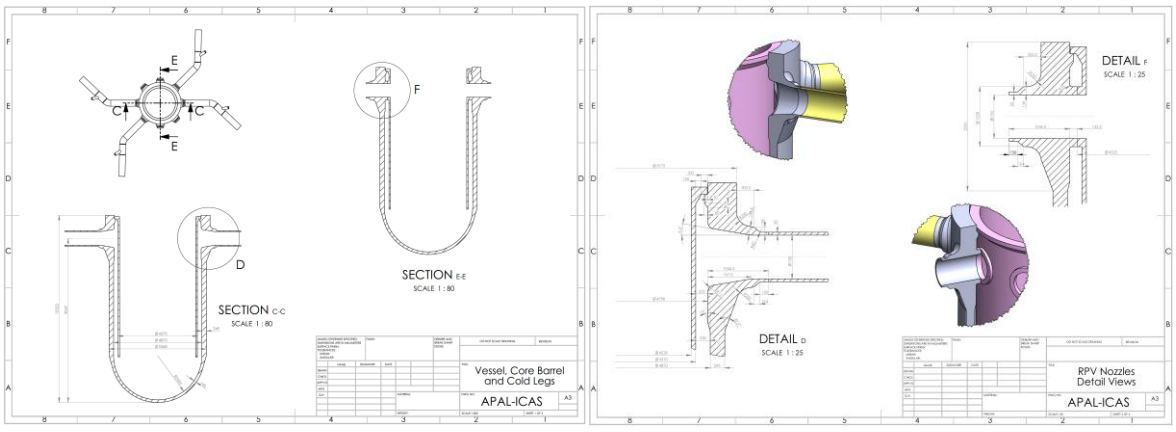


Figure 2. RPV main geometry considered in APAL (fictional RPV)

It is assumed for simplification of the SA: the ferritic base and weld material have the same **physical and technological properties**; the materials are isotropic.

Table 2 Ferritic and austenitic material properties

	Ferritic 22 NiMoCr 3 7					Austenitic cladding 1.4551				
T [°C]	20	100	200	300	350	20	100	200	300	400
E [GPa]	206	199	190	181	172	200	194	186	179	172
Poisson's ratio ν [–]	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Thermal cond. [W/(m·K)]	44.4	44.4	43.2	41.8	39.4	16	16	17	17	18
Spec. Heat. Cap. C_p [J/(g·K)]	0.45	0.49	0.52	0.56	0.61	0.5	0.5	0.54	0.54	0.59
Mean thermal exp. α [10^{-6}/K] With T_{ref} = 20 °C	10.3	11.1	12.1	12.9	13.5	15	16	17	19	21
$R_{p0.2}$ [MPa]	450	431	412	392	--	Considered constant 320				
E_T [GPa]	Considered constant at 20									
density [kg/m³]	Considered constant at 7800									

The initial temperature (starting temperature) of a SA calculation with transient loading (starting usually from full power) is usually not related to the reference temperature T_{ref} required by any particular finite elements method (FEM) software. The initial temperature is related to the stress-free temperature in some FEM software (such as Marc, Abaqus), but not in all commercial software. A manual of any relevant FEM software shall be consulted (read the friendly manual RTFM) on what regards reference temperature T_{ref} and stress-free temperature T_{sf}, because the implementation of thermal stresses differs among various FEM codes. The formula for converting the TEC (usually given with a reference temperature of 20 °C) to a new T_{ref} is given as formula (11) of TECDOC (2010), see also M. Niffenegger (2012).

Deterministic **fracture toughness** descriptions are provided for crack initiation and crack arrest in the brittle to ductile transition regime. Equations for lower bound (5% percentile) an mean value (50% percentile) are reproduced for historical RT_{NDT} concept in Table *3* and in Table 4 for state-of-the-art Master-Curve concept considering T_0. The values $RT_{T0} = T_0 + 19.4K$ is set by imposing that the ASME K_{Ic} curve indexed with RT_{T0} in place of RT_{NDT} will bound the majority of the actual material fracture toughness data. $K_{IC\ ASME}$ and $K_{IA\ ASME}$ are intended to be a lower bound with 95% confidence (i.e. p = 5%), so corresponding to minus two standard deviations. Standard deviations for K_{IC} and K_{IA} of 15% and 10% respectively (of the mean value) were provided in PROSIR(2016) and this will be also considered within APAL.

Table 3. Equations to describe the fracture toughness according to the RT_{NDT} concept

Against crack initiation	Historical Fracture toughness K_{IC} indexed with RT_{NDT}
K_{IC} lower bound	$K_{Ic\ ASME} = 36.5 + 3.1 \exp[0.036\ (T\text{-}RT_{NDT} + 55.5)]$
K_{IC} median	$K_{ICmean,\ ASME} = 1/0.7\ K_{Ic\ ASME}$
For crack arrest	
K_{IA} lower bound	$K_{Ia\ ASME} = 29.4 + 1.4 \exp[0.026\ (T\text{-}RT_{NDT} + 88.9)\ ]$
K_{IA} median	$K_{Ia\ mean,\ ASME} = 1/0.8\ K_{Ia\ ASME}$

Table 4. Fracture toughness according to the Master Curve concept and direct measure of Temperature index T_0 (ASTM E 1921)

Fracture toughness index	T_0
K_{IC} lower bound	$K_{Jc}^{p=0.05} = 25.2 + 36.6 \cdot \exp[0.019(T - T_o)]$
K_{IC} median	$K_{Jc}^{p=0.5} = 30 + 70 \cdot \exp[0.019(T - T_o)]$
For crack arrest	
K_{IA} lower bound	$K_{Ia}^{p} = K_{Ia}^{mean}(1 - 0.18M_p)$ with M_p = 1.64
K_{IA} median	$K_{Ia}^{mean} = 30 + 70 \cdot \exp[0.019 \cdot (T - T_{KIa})]$ where $T_{KIa} = T_0 + 44.97\exp[-0.00613 \cdot T_0]$

The fracture toughness upper limit is set to 220 MPa√m and is only kept for the deterministic benchmark purpose since we are interested by the margin in the brittle fracture assessment. It must be noted that the upper limit for the upper shelf is given arbitrary, since the state of the art reflects that the

historical limit (cut) of 220 MPa√m may not be adequate every time. The proper definition of the upper shelf limit can now be considered with limitation of ductile tearing in ASME Code case 830 (2021).

The **flaw type postulated** within APAL is underclad crack (UCC) due to its potential presence in some cladded RPV forging. The through clad crack (TCC) are postulated in addition to consider unknown degradation mechanism leading UCCs to develop through the cladding. Both are idealized with semi elliptical shape to allow simplified evaluation of the loading along the crack front with stress intensity factor (SIF) solutions. The dimensions of the postulated crack are a = 10 mm, 2c = 60 mm, and r = 6 mm, the latter being the stainless-steel cladding thickness. The state of the art reference K_I solution considering explicitly the discontinuous stresses at clad interface is by Marie and Chapuliot (2008) for TCC and UCC elastic. The plastic correction required for the UCC is according to Marie and Nédelec (2007).

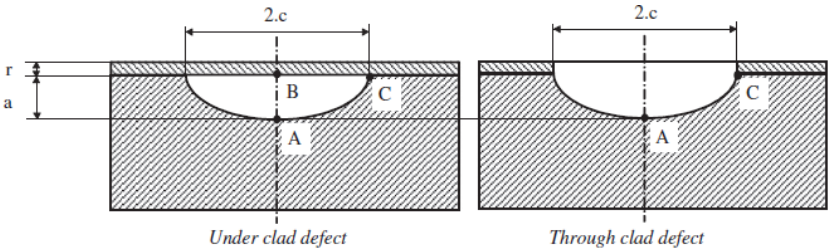
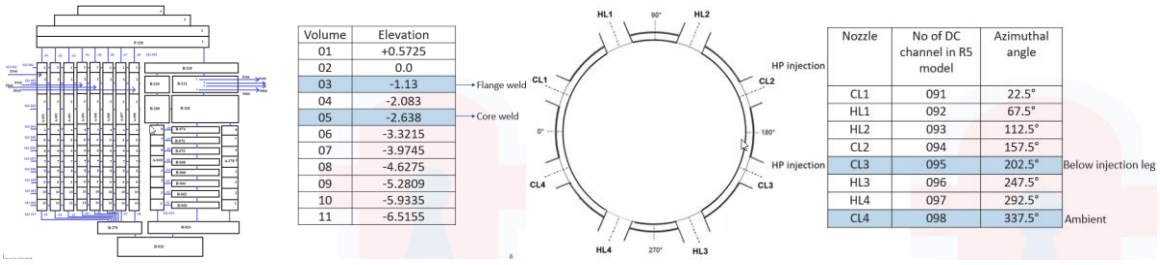


Figure 3 idealized flaw types (UCC, TCC) and geometry convention (crack tip A,B,C, a, 2c, r)

Fully embedded (buried) defect are common in welds and base metal, this flaw type is postulated and idealized considering fully elliptical flaw model with a height of 20 mm and a total length of 120 mm, located at a distance from the clad-base/weld interface of 5 mm. This type of flaw has been incorporated in APAL afterword to allow benchmark comparison using available software's FAVOR/CAPAL without modification (SOA SIF models for fully embedded flaw).

The **RPV loading scenario** investigated R&D ICAS T2: 50 cm² break/leak in hot leg i.e. small break LOCA (SB-LOCA) is re-used and updated for APAL considering loss of off-site power. Global system codes and mixing codes were applied. Reduced welding residual stresses (WRS) are considered additionally to other stresses for brittle fracture assessment in weld after post-weld-heat-treatment (PWHT) according to the German KTA 3201.2 (2017) standard: constant 56 N/mm² for circumferential stresses and $\sigma_R(x,s) = 56 \cdot \cos\left(2\pi \cdot \frac{x}{s}\right)$ N/mm² for axial stresses.

In the part 2, partners will go their own way for evaluation, they consider their own selected TH-output (data from system analysis only, data from local mixing analysis) and perform their structural analysis which may be simplified (1D, 2D with simplified plume according to IAEA (2010) or sophisticated with 3D FEM). The own SA performance is allowing to investigate the impact of their choice (TH input, SA, SIF solution) up to the final fracture mechanics safety assessment of the maximum allowable adjusted reference temperature (max. all. ART) for the RPV model. Each partner will come up with max. all. ART for "their" APAL base case scenario, which will be later required to evaluate margin once LTOs impact and TH uncertainties will be investigated.



Volume	Elevation
01	+0.5725
02	0.0
03	-1.13
04	-2.083
05	-2.638
06	-3.3215
07	-3.9745
08	-4.6275
09	-5.2809
10	-5.9335
11	-6.5155

Nozzle	No of DC channel in R5 model	Azimuthal angle	
CL1	091	22.5°	
HL1	092	67.5°	
HL2	093	112.5°	
CL2	094	157.5°	
CL3	095	202.5°	Below injection leg
HL3	096	247.5°	
HL4	097	292.5°	
CL4	098	337.5°	Ambient

Figure 4. RELAP5 nodalisation and elevation from nozzle axis (mm)– APAL orientation of inlet/outlet nozzles

The thermal-hydraulic definitions are supplied by WP2 (TH task) in the form of digitized tables of bulk coolant temperature, convective heat-transfer coefficient, and internal pressure, all as functions of elapsed time for the transient. The time step (TH, SA) will be one of the sensitivity study. Results from combined system analyses by code RELAP + mixing code KWU-MIX, i.e. sophisticated 4D (3D + time) TH input are provided to partners willing to perform their own 3D SA assessment based on KWU-MIX (including merging plume).

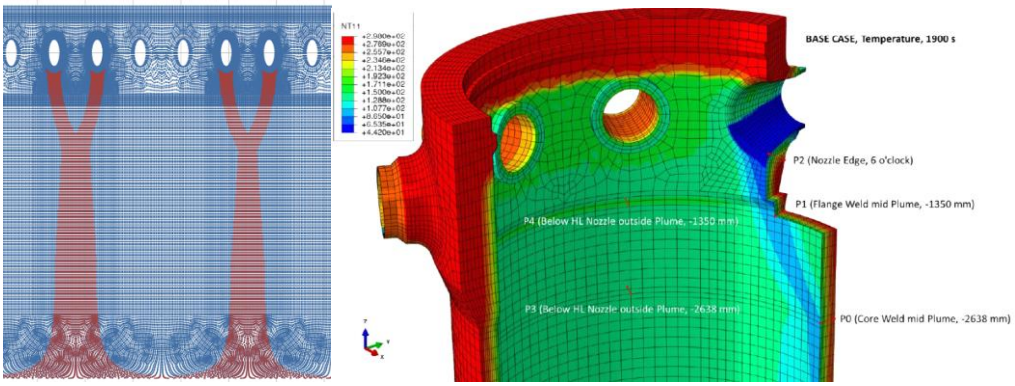


Figure 5. Base Case KWU-MIX TH results as input data for SA (left), sophisticated SA results with most interesting locations (right)

Post-processing for results system code RELAP5 (Data-kwu76-WP34d.xlsx) is performed for the SA (Task3.1) according to Table *5*. Locations: below injection leg = DC channel 095; ambient = 098.

Table 5 Variation of RELAP data

Variant	**Evaluation of RELAP data**	
	Elevation (height)	**Azimuth (circumference)**
#1 / 0D – average	Average	average
#2 / 1D – core weld	-2638 mm (V05)	average
#3 / 2D – core weld/cold leg	-2638 mm (V05)	Below injection leg (095)
#4 / 2D – core weld/ambient	-2638 mm (V05)	Ambient (098)
#5 / 1D – flange weld	-1130 mm* (V03)	Average
#6 / 2D – flange weld/cold leg	-1130 mm* (V03)	Below injection leg (095)
#7 / 2D – flange weld/ambient	-1130 mm* (V03)	Ambient (098)

* not the real elevation for FW, but kept due to RELAP nodalisation

All these data represent one transient scenario and were calculated using same software. The variants differ only in the way how the data were averaged to provide inputs for 1D FEM structural calculations. TH results are averaged over the whole inner surface of the down-comer for 0D-average. TH results are averaged over the circumference of the beltline region of the RPV for 1D-core weld and 1D-flange weld. These data are relevant especially for Part 2, where the partners will perform their own structural assessment with their own tools considering TH data (bulk):

- simplified solution using 1D structural assessment
- sophisticated solution (3D structural assessment) with detailed 3D TH-Output considering System + local Mixing (full CFD is non-mandatory).

PR-DET 1.1: DETERMINATION OF SIF WITH PROVIDED TEMPERATURE, STRESSES AND PRESSURE PROFILES

PR-Det 1.1.1: SIF solution provided

The objective is to use the reference SIF solutions with explicit consideration of stresses in cladding and base metal applied with input data provided. The stresses and temperature are provided to allow K_I calculation in the pre-requisite (educational) part (Part 1). These data are provided from a simplified structural assessment considering APAL-ICAS-T2 preliminary transient for an arbitrary location and

are supplied in the form of digitized tables in a file. Stresses without / with weld residual stresses (WRS) were provided. Pressure loading on crack face shall be considered for TCC. E-modulus ratio of 0.85 is kept constant for sake of simplicity. Both crack orientations shall be considered. Flaw location in base metal and in weld (with weld residual stresses) shall be considered. Mandatory: TCC, UCC elastic, UCC with plastic correction, TCC a/c=0 if crack arrest is performed.

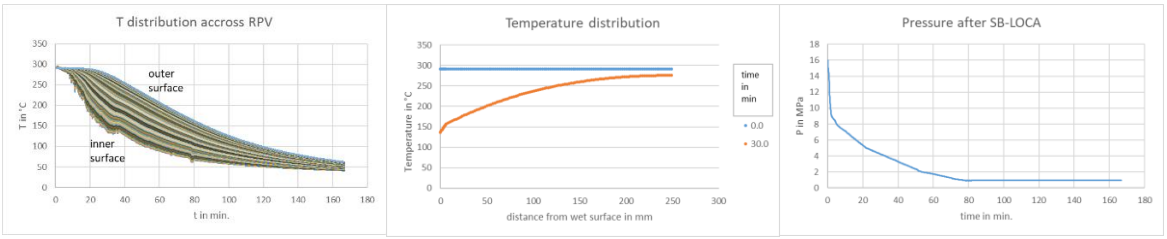


Figure 6. Temperature to be considered for PR-Det. Part 1

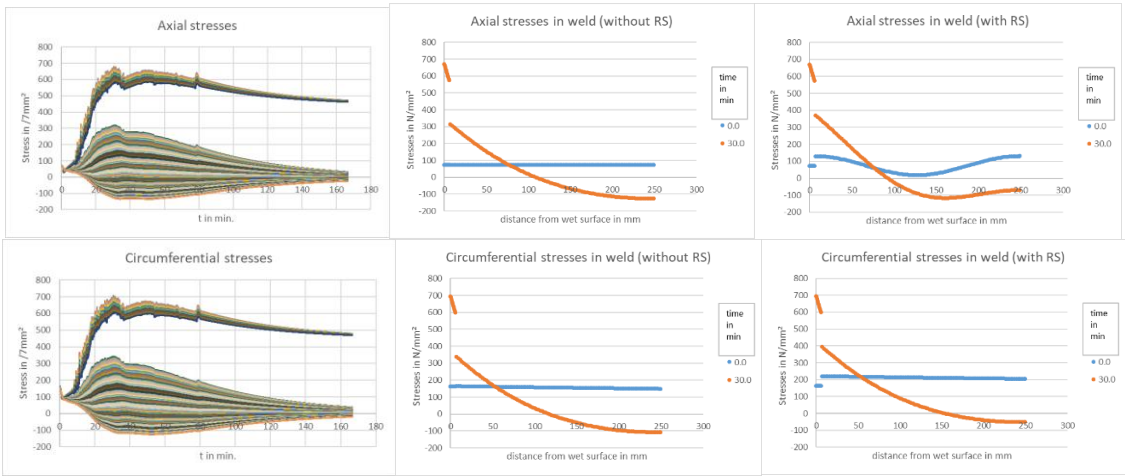


Figure 7. Stresses to be considered for PR-Det. Part 1

Output: SIF results shall be provided for both crack tips A (deepest point) and C (interface clad-base/weld metal) in function of time.

PR-Det 1.1.2: Individual/own SIF solutions

Since partners may use third party software (FAVOR/CAPAL/PASCAL) with own SIF solution different from the reference ones and without possibility to add the reference solution to the source code, the previous task is repeated with the SIF solution intended to be used in the probabilistic benchmark. It is necessary for proper comparison and evaluation of bias compared with the reference SOA solutions for TCC and UCC (with plastic correction) crack type. For partner using third party software buried flaw shall be investigated.

PR-Det 1.1.3: SIF Sensitivity study (non-mandatory)

Consideration of buried crack (for non-commercial software user), TCC nozzle (crack shape: axial straight crack front in base metal), a/c=0 or circular with a/c=1. Stresses profiles from 3D non-uniform FEM structural assessment considering mixing TH loading shall be considered. This will be provided from D3.1.

PR-DET 1.2: DETERMINATION OF MAX. ALL. ART CONSIDERING CRACK INITIATION

The max. all. ART is the value (calculated from PTS fracture mechanics safety assessment) being shifted in order to find the highest index fulfilling the limit condition (tangent or WPS). Partners will have to compute K_{Ic} = f(T at considered crack tip) for each crack tip for increasing RT_{NDT} and T_0

(starting from 0 °C) and perform the assessment of max. all. ART using the limit condition for the different approaches: tangent and WPS (simplified max WPS and sophisticated WPS for some partners). The required results are: max. all. ART (RT_{NDT} and T_0 concepts) for Tangent approach, WPS approach; corresponding K_{IC} (ASME), K_{IC} (Master curve 5% Lower Bound) and time of initiation. The non-mandatory tasks are: use of WPS model for K_{IC}, size correction for T_0 considering basic UCC size, embedded crack (for partners not using FAVOR/CAPAL), other location: nozzle crack, flange weld.

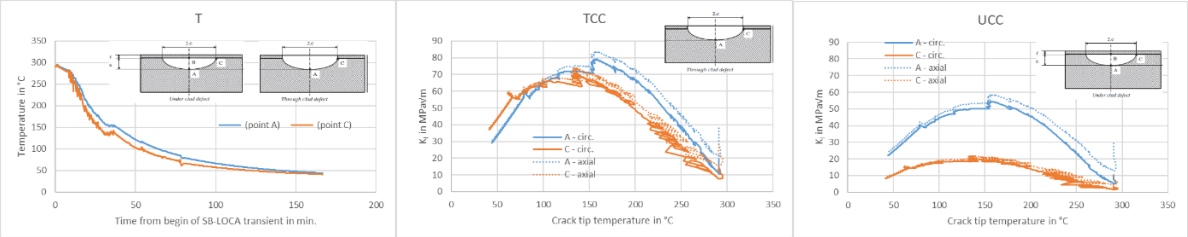


Figure 8. Input data for PR-Det 1.2

PR-Det 1.2.1: Tangent Approach

The max. all. ART can be obtained iteratively by increasing the RT_{NDT} index by a computational aging step of 1K (starting from non-irradiated T_0 or RT_{NDT}) and comparing the resulting K_{IC} curve with crack loading path for all times of the transient. Other ways shall be explained. Once the condition for crack initiation is achieved considering $K_I = K_{IC}$ (T, $RT_{NDT\,j}$) then max. all. ART is equal to estimated RT_{NDT} last index.

The tangent approach (no WPS) is considered using ASME curve: determination of max. all. ART ($RT_{NDT}{}^{a\,tan}$) with $K_I <= K_{IC}$; using Master Curve concept: determination of T_0 max allowable ($T_0{}^{a\,tang}$) with $K_I <= K_{IC}$ (5% Lower Bound). Comparison between max. all. ART for RT_{NDT} concept and MC concept i.e. $RT_{NDT}{}^a$ and $T_0{}^a$ can be done considering $RT_{T0}{}^a = T_0{}^a + 19.4K$.

PR-Det 1.2.2: WPS Approach

The conditions for the flaw not to be in a WPS state is: "*in a rising applied-KI field, the driving force at the flaw tip must exceed some portion to the previously-established maximum applied-K_I (designated as K_I(max)) experienced by the flaw during the transient up to the current point in time under consideration – applied- KI (τ) ≥ 1 ∗ KI(max) (τ) "*

The max. all. ART is obtained iteratively by increasing the RT_{NDT} index by a fictional "computational aging" step of 1K (starting from -33 °C non-irradiated T_0 or RT_{NDT}) and comparing the resulting K_{IC} curve with crack loading path for all times of the transient. Once the condition for crack initiation is achieved considering $K_{Imax} = K_{IC}$ (T, $RT_{NDT\,j}$), with K_{Imax} being the maximum value of K_I achieved at the crack tip during the transient, then max. all. ART is equal to estimated RT_{NDT} last index. The global maximum SIF is considered as simplified formulation: no fracture for a loading level lower than maximum loading at hot temperature. Using ASME curve: determination of max. all. ART ($RT_{NDT}{}^{a\,WPS}$) with $K_{Imax} <= K_{IC}$; using Master Curve concept: determination of max. all. T_0 ($T_0{}^{a\,WPS}$) with $K_{Imax} <= K_{IC}$ (5% Lower Bound). A verification considering $RT_{NDT}{}^{a\,WPS}$ combined with KFRAC for the transient will be performed by some volunteers (at least 2 using the same WPS model).

PR-Det 1.2.3/1.2.4: non-mandatory tasks with regards to WPS and ductile tearing

Alternative Approach is applied with different model to quantify the magnitude of the WPS effect, codified K_{IC} WPS (for example Chell, KFRAC), WPS 90% $K_I$max (VERLIFE) or other national approach. Consideration of ductile initiation (tearing) is considered following CC-830 R1 approaches (T_0 based) for evaluation of ductile crack initiation risk at nozzle corner.

PR-DET 1.3: DETERMINATION OF MAX. ALL. ART CONSIDERING CRACK ARREST (NON-MANDATORY)

Allowance of crack initiation and arrest during the base case scenario is investigated. Data are provided, including temperature fields, K_I for TCC for initial geometry a=10mm 2c=60 mm. After initiation a K_I matrix considering a fully surface extended (a/c=0) growing crack geometry is provided for several crack depths (starting with 10 mm up to $0.75t_{ferritic}$). RT_{NDT} is considered constant across thickness, azimuth, height. Limit condition are K_{IC}, K_{IA} ASME (5% Lower Bound). K_{IC} , K_{IA} both max = 220 MPa√m (only cleavage fracture consideration, no tearing check after arrest).

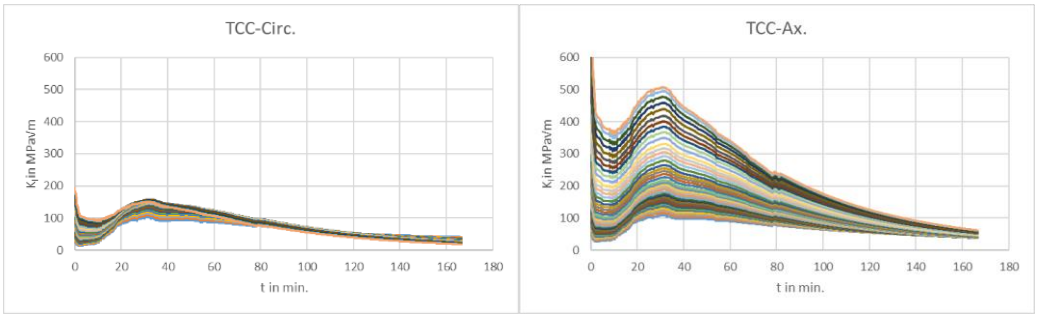


Figure 9. KI matrix for TCC extended (a/c=0) and increasing crack depth

PR-DET 1.4: CRACK ARREST ANALYSIS IN CYLINDRICAL PART OF RPV (NON-MANDATORY)

K_{IC} ASME, K_{IA} (5% Lower Bound) at each potential crack tip location and each time of the transient shall be calculated, considering crack growth step of 0.5 mm. Basic approach for crack arrest analysis is: starting point: max. allowable ART+20 K from previous task considering WPS (so initiation is ensured) ; consideration of surface (ferritic material) and deepest point for crack initiation ; once $K_I >= K_{IC}$ then TCC with a/c=0 ; crack growth immediately and stopped if $K_I <= K_{IA}$; fluence, chemical composition considered as constant upon thickness for this analysis, so the RT_{NDT} is considered constant too (starting with RT_{NDT} = max. all. ART $_{WPS}$ + 20K, re-initiation if $K_I > K_{IC}$, re-arrest if $K_I<K_{IA}$).

Output: Crack arrest results for first arrest (size of crack at first arrest, K_I shall be equal to K_{IA}!) for verification, check for further initiation for t>ti considering $K_I >= K_{IC}$ for tangent approach; considering WPS (no-initiation by K_I decrease with K_I(t>ti) < maximum K_I (t between initiation and end of transient). Present full results and diagrams (K_I, K_{IC}, K_{IA}) timely dependent + crack tip temperature dependent. Repeat the previous analysis but increasing starting ART by 1 K up to achieving the $ART_{no\ arrest}$ at which a stable crack arrest does not occur; max. all. ART $_{arrest}$ = $ART_{no\ arrest}$ -1 K ; Full results and diagram considering max. all. ART $_{arrest}$. Sensitivity studies with consideration of RT_{NDT} profile across thickness (RT_{NDT} at crack tip), with/without WPS after crack stop, T_0 basis for K_{IC}, $K_{IA,}$ check of plastic collapse and ductile tearing at crack stop.

PR-DET 2: EVALUATION OF MAX. ALL. ART BASED ON DIFFERENT TH CALCULATIONS AND INDIVIDUAL STRUCTURAL AND FM METHODS

After reconciliation and verification of the tools for SA and fracture mechanics assessment (FMA) (especially K_I TCC + UCC) is performed, qualified partners will share efforts to determine the max. all. ART from the different TH calculations output made available from WP2. All partners shall use the same methodologies as intended in WP4 probabilistic (part of the verification pre-requisite). All intermediate results shall be documented (task 3.1/4.1 for SA and task 3.3 for fracture mechanics assessment) and final results of max. all. ART shall be summarized in tabular form (see template **Fehler! Verweisquelle konnte nicht gefunden werden.**) for each variant of the base line assessment.

The mandatory base line for the assessment of max. all. ART is:

- Axial and azimuthal location:
  - inside plume at height of core weld -2638mm from nozzle centerline (system code)
  - inside merging plumes at elevation of core weld -2638mm (local mixing)
- Crack types: TCC (shape 1) + UCC plastic, embedded/buried (FAVOR/CAPAL user group)
- Crack tips:
  - TCC (deepest point + point close to clad/base fusion line (FL)
  - UCC (deepest point + point close to FL in ferritic base/weld metal)
  - for FAVOR user group: embedded/buried crack (point close to FL)
- With/without weld residual stress
- both limit condition (tangent, simplified WPS max.)
- both fracture toughness concept (RT_{NDT}, Master Curve)

PR-Det in 2.0: Stress and temperature profiles (i.e. D3.1)

The mechanical analysis (structural assessment) is performed with increasing level of effort for the base case transient. The different type of TH results will be shared to the structural assessment. Preliminary assessment is based on the same TH-data from RELAP (Data-kwu76-WP34d.xlsx) to allow verification between partners. Simplified TH loading will be treated considering decreasing simplification (TH result variants Table 3) and increasing level of effort in the SA. It results in SA assessment considering axisymmetric cooling with: 1D SA for each location, 2D or 3D geometry with thickness transition and both location included with axisymmetric cooling. Decreasing the simplification results to non-uniform cooling consideration with: 2D SA for each elevation with both cold plumes and ambient regions, additional stresses due to cold plume considering eq.4.3 from IAEA TECDOC or with 2D FEA (ring), full 3D geometry and 3D TH. With System code RELAP results the width of the plume is set to 1/8 of the RPV inner circumference since only code with local mixing models are able to evaluate the cold plume strength properly. Boundary conditions for the simplified assessment are: Generalized plane strain, Thermal outside adiabatic (or HTC=1 W/m² K, $T_{outside}$ = 40°C), $P_{outside}$ = 0 MPa.

The sophisticated assessment consists in the consideration of detailed (local) boundary condition from detailed TH analysis from local mixing code able to consider cold plume merging or CFD mapped to 3D FEA mesh for the full RPV geometry analysis. Comparison of sophisticated analysis with simplified SA (1D / 2D / 3D with system code results; 1D and 2D with local mixing results for T/HTC/cold plume width) shall be performed with the goal to identify a safe level of simplification. Sensitivity studies: cladding thickness, mesh density, residual stress.

For the consideration of individual TH the performance of SA (and sub-sequent analysis SIF, max. all. ART) shall focus on the aforementioned mandatory base line.

PR-Det 2.2: Determination of SIF (i.e. D3.3)

Tasks are similar to PR-Det 1.2 considering mandatory base line.

PR-Det 2.3: Determination of max. allowable ART (i.e. D3.3)

Tasks are similar to PR-Det 1.3 considering mandatory base line.

PR-Det 2.4: Non mandatory: determination of crack arrest (i.e. D3.3)

Tasks are similar to PR-Det 1.4 considering mandatory base line limited to TCCs.

MARGIN ASSESSMENT

Benchmark for tasks 3.4 considering LTOs improvement identified in WP2

Improvements listed in Table 6 will be investigated with regards to max. all. ART.

The SA and FMA are performed considering the mandatory baseline case. Intermediate results are documented in task 3.3 and final results shall be tabulated in a template for the different configurations.

Table 6. TH transient variants for LTO improvement investigation

LTO improvement / Human action	Simulated change
1. Heating of water in the HPIS tanks	Heated from 15 °C to 45 °C
2. Heating of water in the ACCs	Heated from 20 °C to 50 °C
3. Heating of water in the LPIS tanks	Heated from 15 °C to 45 °C
4. Decreasing the HPSI head	Decreased down to 75% (in 5% decrements)
5. Decreasing the HPSI capacity	Decreased down to 75% (in 5% decrements)
6. Reduction of HPIS flow (operator action)	Reduced at 1800 s to one pump
7. Decreasing of ACC pressure	Decreased from 26 bar to 20 bar (JSI and PSI: in 2 bar steps)
8. Different cooldown rate (operator action)	Changed from 100 K/h to 200 K/h
9. Isolation of ACCs (operator action)	Isolated at 500 s

Analysis with RT_{NDT} concept/$K_{IC\ best\ estimate}$ as well as MC concept/T_0 $K_{IC\ 50\%}$ shall be performed. The margin in max. all. ART against crack initiation can be made in a relative way by comparison with the max. all ART obtained with the base case: horizontally (difference between lower bound toughness and best estimate toughness) or vertically (difference between TH variant and base case TH). The "best" LTO's improvements to minimize the risk of brittle fracture of the RPV can be identified looking at the highest positive margin. The negative margins help to identify the PTS contra-productive measures and to propose counter measures.

Benchmark for task 3.5 TH uncertainties

The Wilks' method provides a non-parametric (distribution-free) method to estimate the desired tolerance limit with a prescribed confidence that the estimate is conservative. Several runs will be considered: for N=59 simulations (fulfilling the tolerance limit and the confidence level of 0.95), N=93 and N 130 simulations. Proceed in analogy to PR-Det 2 and calculate max. all. ART for all N transients and report results for all configurations defined by the mandatory baseline case. The run leading to the minimum from all max. all. ART is the "true" bounding envelope transient for which TH parameter can be identified using reverse engineering. A ranking of all runs based on max. all. ART has to be done as well as a counting for each range. Sensitivity study on range width shall be performed. Margin considering lower bound (P=0.95), best estimate and base case shall be determined. As sensitivity study (non-mandatory) an engineering artificial "envelope" transient (created) can be investigated.

CONCLUSIONS

A sound technical basis including experiences and conclusions from past projects with pre-requisite verification sub-tasks were defined to clear misunderstanding and ensure a limited bias propagation into the final assessment of the max. all. ART for safety margin assessment. The realisation also support exchange and knowledge transfer to engineers interested in RPV brittle fracture safety assessment.

DEFINITIONS USED IN APAL

Base case TH data set = new conservative transient (in the meaning to be conservative for a FM 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.)
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
Statistical TH data sets = set of 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)
Long term operation (LTO) improvements = set of transients concerning TH improvement to RPV brittle fracture assessment for long term operation resulting from task 2.3 (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 K_{IC} curve (RT_{NDT} concept, indirect) as well as for the index from the Master Curve (direct measurement of T_0 + margin = RT_0).
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. RT_{NDT} or max. allow. RT T_0, depending on the adopted concept (RT_{NDT} 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 (base case) due to the change of a given parameter.
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 aging (mandatory task, penalizing and allowing further operation after plant inspection) 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 (may not allow further operation after plant inspection)
Limit condition (or limit state): WPS or tangent approach; initiation or unstable (non-arresting) crack growth (or too deep crack, i.e., plastic collapse).

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