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STATE-OF-THE-ART OF LONG-TERM OPERATION IMPROVEMENTS RELEVANT FOR PTS ANALYSIS

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ABSTRACT

The APAL project (Advanced PTS analyses for LTO) has been launched in October 2020 with funding from EURATOM Work Programme 2019-2020 and with a duration of four years. The main objectives of APAL are the development of advanced probabilistic PTS assessment method, the quantification of safety margins for LTO improvements and the development of best-practice guidance.

The project will address multidisciplinary and multi-physics challenges related to RPV safety assessment of PTS. The first package (WP1) of the project, which is the focus of this paper, aims to identify the state-of-the-art of LTO improvements that may have an impact on the results of PTS analysis.

INTRODUCTION

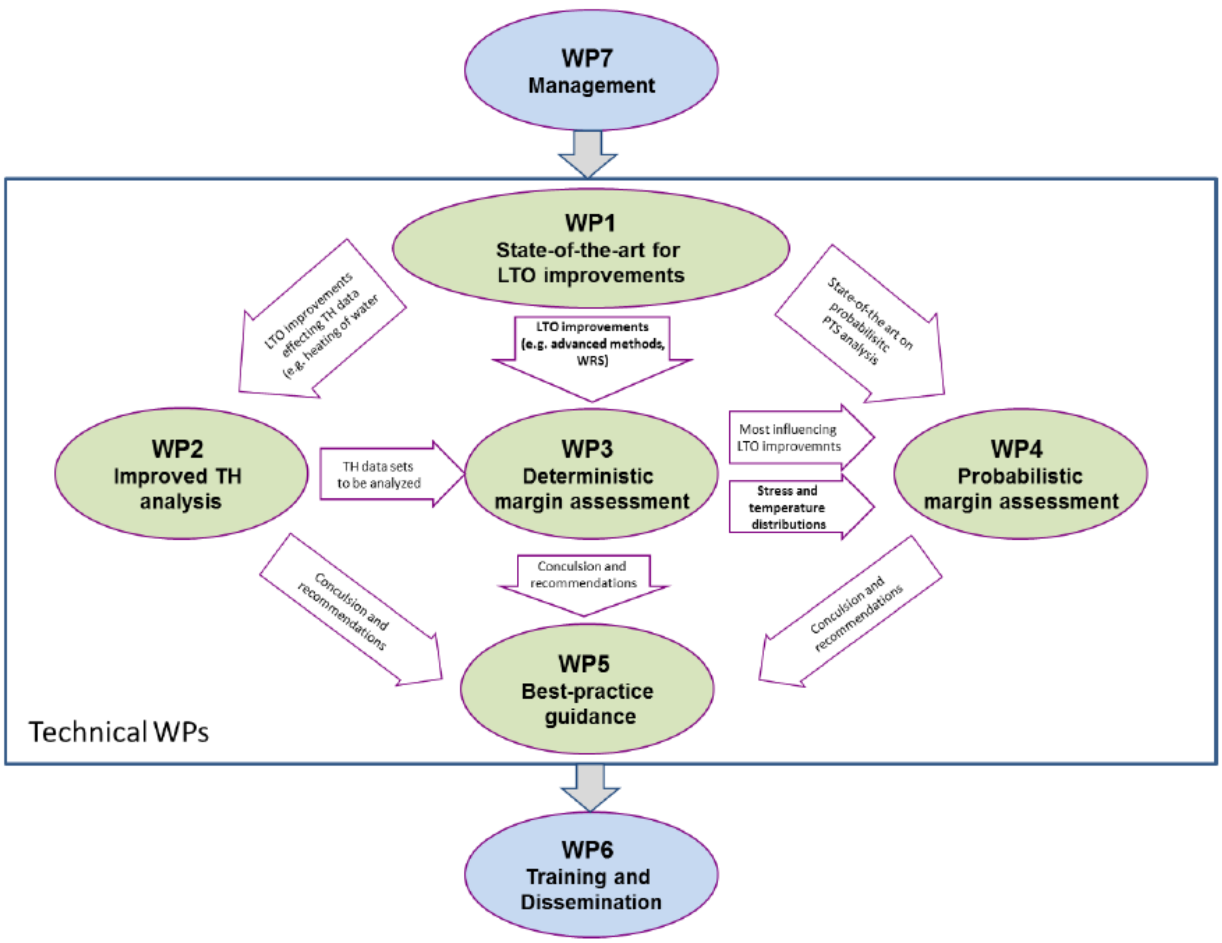
The reactor pressure vessel (RPV) is a key component of a nuclear power plant (NPP), and its integrity must be ensured throughout its entire operating time including long-term operation (LTO) in accordance with applicable regulations.

The dominant degradation mechanism of the RPV material is embrittlement due to neutron irradiation, especially in the core (beltline) area. If a flaw of critical size exists in an embrittled RPV and if certain severe system transients occur, the flaw could propagate very rapidly through the vessel, possibly resulting in a through-wall crack, which challenges the integrity of the RPV.

The pressurized thermal shock (PTS) is characterized by rapid cooling (i.e., thermal shock) of the reactor downcomer and internal RPV surface, followed sometimes by re-pressurization of the RPV. Thus, the PTS event poses a potentially significant challenge to the structural integrity of RPV in pressurized-water reactors (PWRs) and water-cooled water-moderated energy reactors (WWERs).

Currently in the European Union, PTS analyses are based on deterministic assessments and conservative boundary conditions. This type of PTS analyses is reaching their limits in demonstrating the safety of PWRs and WWERs facing LTO, and they need to be enhanced. However, inherent safety margins exist, and several LTO improvements applicable to the NPP, as well as advanced methods of PTS analyses, may be able to increase these safety margins. Additionally, the quantification of the safety margins in terms of risk of RPV failure by advanced probabilistic assessments becomes more and more important, because the probabilistic methods ensure more comprehensive assessments in PTS analysis, and they enable the quantification of uncertainties of the results.

To address this challenge, the project Advanced PTS Analyses for LTO (APAL) has been launched in October 2020 with funding from EURATOM Work Programme 2019-2020 under grant agreement No. 945253 and with a duration of four years. The main objectives of the APAL project are the development of advanced probabilistic PTS assessment methods, quantification of safety margins for LTO improvements, and the development of best-practice guidance. The planned work to achieve these objectives is divided into six technical work packages (WPs). The interaction of WPs within APAL is shown in the diagram below:



The first work package (WP1) consists of an extensive literature review and collection of partners' experiences to identify the state of the art of LTO improvements that may have an impact on the results of PTS analysis. This WP1 was already completed, and its summary report is publicly available on the APAL web site (website: https://apal-project.eu/). This paper presents the main results of WP1.

After establishing the LTO improvements, thermal-hydraulic (TH) calculations are performed, including uncertainty quantification relevant to the PTS assessment (WP2). The impact of both LTO improvements and human factor on the results of TH analysis will be quantified and later assessed by subsequent structural and fracture-mechanics benchmarks within WP3 and WP4. Moreover, the consideration of uncertainties in TH analysis (due to plant data, used computer codes and human factor) and their impact on the entire PTS analysis will be addressed.

The third work package (WP3) consists of performing deterministic structural and fracture-mechanics analyses to quantify the safety margins related to both LTO improvements and uncertainties in TH analyses. The analyses to be used for deterministic margin assessments by the APAL partners will first be tested on a common deterministic benchmark.

In the fourth work package (WP4), probabilistic margin assessments based on probabilistic fracture-mechanics analyses will be performed. The assessments will enable the quantification of safety margins in terms of risk of RPV failure. An advanced probabilistic PTS assessment will be performed by including the TH uncertainties in the subsequent structural and probabilistic fracture-mechanics analyses. An appropriate benchmark for the probabilistic fracture-mechanics analysis will be defined in accordance with the benchmark performed for deterministic margin assessment. In addition, a link between deterministic and probabilistic margin assessment will be established.

In the fifth work package (WP5), recommendations and conclusions will be gathered from the work to define the best practices for advanced PTS analysis for LTO. Close cooperation with APAL Advisory Board (AB), regulatory bodies, and end users (NPP owners, suppliers, etc.) during the project will help to increase the acceptance of the best-practice guidance. For that purpose, several workshops will be organized (WP6) to discuss the best-practice guidance with regulatory bodies and the end users in order to analyse potential barriers, integrate feedback, and obtain broad acceptance of the best-practice guidance for an advanced PTS analysis for LTO within the nuclear community.

WP6 is aimed at ensuring consistent communication for optimal project visibility, dissemination of project results to all relevant stakeholders (including an end-user workshop and a final seminar), education and training activities, as well as strategic planning and operational support of project exploitation.

In relation with WP1, four LTO improvements have been defined a priori to be reviewed/investigated in more detail, resulting in the following sub-tasks in WP1:

- Residual stress distributions for welds (WRS) and cladding.
- Warm pre-stress (WPS) approach applied in PTS.
- Thermal-hydraulic (TH) analysis (including definition of human factor).
- Probabilistic PTS analysis.

In addition, another sub-task is dedicated to the investigation of further potential LTO improvements relevant to PTS analysis.

The state-of-the-art reviews within each subtask include:

- Collection of existing solutions/approaches for assessment of LTO improvements.
- Collection of existing assessments.
- Identification of gaps and possible improvements.

Within each sub-task the initial activity consisted of preparing a technical questionary covering the relevant issues. Involved partners had to complete the questionnaires based on their experience in the analysis carried out in their countries. Additional information from some partners was provided to get a better understanding of specific assessments or LTO improvements. Based on the compilation of answers, additional information and discussions during various task meetings, the state-of-the-art of the investigated LTO improvements have been summarized. Moreover, common understanding of best practice on some topics have been agreed between the partners. Finally, some gaps and conclusions were collected to be assessed in WP2, WP3 and WP4 in order to eventually incorporate in the best-practice document for PTS analysis (WP5).

RESIDUAL STRESS DISTRIBUTIONS FOR WELDS (WRS) AND CLADDING

The beltline region of an RPV is fabricated using either forged-ring or rolled-plate segments. RPVs made with forgings have only girth (circumferential) welds, and plate-type vessels have both girth and longitudinal (axial) welds. The vessels are typically constructed of special pressure vessel ferritic steels. The heavy-section steel wall is lined with an internal cladding of stainless steel. After welding and cladding, the RPV is subject to a post weld heat treatment (PWHT), partially relieving weld residual stresses.

The level of the maximum weld residual stress depends mainly on the parameters of the stress relieving heat treatment (temperature and time of tempering) and the material properties of the weld. Cladding residual stress is produced in the cladding after PWHT. This residual stress is due to the difference in the thermal expansion coefficients between the cladding and base materials. Thus, the residual stresses in the vessel arise both during the welding process and clad manufacturing.

Methodologies to determine RS

There are three main methodologies to determine RS, which differ in the level of difficulty to obtain them:

- Take RS from standards.
- Calculate RS from a detailed FEM analysis.
- Determine RS based on measurements.

RS from standards

In order to provide a reasonable and practical way to deal with RS in the case of RPV assessments, several standards and codes solutions for RS profiles in welds and cladding are available. These distributions were in general obtained in the absence of crack(s).

A fair similarity has been observed between the WRS distributions proposed in the standards and technical literature for RPV assessments which are compiled in Section 4.3.3.1 of Deliverable D1.6. The shape of WRS is often assumed to be cosinusoidal with an amplitude between 45 MPa and 56 MPa for PWRs, and of 60 MPa for WWER vessels according to the IAEA guidelines.

The cladding residual stresses are generally approximated using a stress-free temperature (T_{sf}), which should be chosen to produce appropriate levels of residual stress at room temperature. The value of stress-free temperature depends on material properties, the manufacturing procedure and the influence of the hydraulic pressure test.

A more detailed procedure can be found in the Russian Standard MRKR-SKhR-2004 which contains recommendations on how to perform the calculation of residual stresses for WWERs due to welding and cladding manufacturing processes and heat treatment.

Calculate RS from a detailed FEM analysis.

As a rule of thumb, commercial FEA codes or specific codes focussed on welding simulations are usually used. This RS numerical simulation is still a challenging task since a lot of input data is required:

- Material (stress-strain curves, creep curves, mechanical and thermal properties in a wide range of temperatures, phase transformation).
- Welding processes information (welding conditions, bead dimensions, heat profiles).
- Post weld heat treatment (temperature, time, heating and cooling rates).
- Hydro-pressure test (pressure and time duration).

For direct FE simulation some assumptions and simplifications are often used. That it is why weld simulations are still scarcely used in industrial applications. Performing detailed FE calculation of RS is out of the scope of the APAL project. Nevertheless, some sensitivity studies focussed on the effect of RS magnitudes on the PTS results are recommended for WP3 and WP4 of APAL.

Determine RS based on measurements

One valuable method for characterization of RS is measurements performed on a reference component to collect empirical data for application on similar components. Measurements are also used to validate numerical models used for predicting the residual strain and stress states for specific components and welding conditions, including effects of pressure tests and operational loads.

The reference component may be a cut-out piece from a never operated or a decommissioned pressure vessel, or a representative mock-up. Aspects such as whether an actual cut-out piece has been in service or not, post-weld heat treatment, pressure test, and operational conditions could potentially imply a significant difference. Conditions from events after the as-welded state and post-weld heat treatment will always be difficult to include. There may also be a deviation in actual material properties unless archived original material is available. Inadequate documentation may constitute uncertainty concerning the actual procedures during manufacturing decades ago.

APAL partners gather significant experience in the measurement of residual stresses in components, which is detailed in Deliverable D1.6. Strain relieving methods appear to account for most of the experimental experience among the project participants, although X-ray and neutron-based methods receive increasing attention.

STATE-OF-THE-ART FOR WARM PRE-STRESS (WPS)

The inclusion of warm pre-stress (WPS) effect in RPV assessment can reduce over-conservatism and enable more accurate evaluations of the safety margins against limiting conditions, which may occur during PTS events. However, the inclusion of WPS effect in PTS analyses is currently not uniform across the different European countries, nor is the position of national regulators regarding its acceptance.

Different standards or methodologies are used in participating countries in APAL to consider WPS effect in PTS analyses. Section 5.3 of Deliverable D1.6 summarizes the different approaches. The main differences consist in the following aspects: possibility of WPS application for monotonical or non-monotonical unloading, consideration of the so-called Case 1 (i.e., increased fracture toughness curve) in WPS approach, application of different WPS models for Case 1 and application of additional safety margins.

Section 5.3.1 of Deliverable D1.6 summarizes the analysis of the considered WPS approaches/models in terms of their predictive capability. This analysis is included in a separate paper presented at this conference by M. Zarazovskii et al.

STATE-OF-THE-ART FOR THERMAL-HYDRAULIC (TH) ANALYSIS

The goal of the thermal-hydraulic (TH) analysis is the determination of the local pressure, temperature, and heat transfer coefficient histories in the downcomer region that affect the RPV wall by thermal and mechanical loading.

Thermal-hydraulic Phenomena Relevant for PTS

As stated above, PTS events are characterized by rapid cooldown of the primary coolant, particularly in the downcomer, and by the subsequent cooldown of the RPV wall leading to thermal stresses in the RPV wall loaded (usually) at the same time by inner pressure. This cooldown is often nonuniform (asymmetric), which causes additional thermal stress and RPV load. The nonuniformity is caused typically by emergency core cooling system (ECCS) injection or/and by rapid asymmetric cooling down via steam generators.

Experimental Activities and Validation

Because of their importance and complexity of modelling, the thermal-hydraulic phenomena relevant to PTS effects have been extensively studied both experimentally and numerically. The available investigations can be subdivided into separate-effect studies and combined-effect/integral system studies. The separate-effect studies deal only with a single aspect of PTS, like free surface flow or generic condensation. The integral system studies are performed in realistic reactor configurations and examine the interaction of all relevant effects. Because of their complexity and cost, only few data on the combined-effect studies are available.

The experimental data base related to TH phenomena important for analysing PTS is huge. However, many of the experimental campaigns were conducted at a time when the used measurement techniques had not yet evolved into such a state of maturity as they are today. For a detailed understanding of the flow and heat transfer behaviour, there still is a need for adequate experimental results to develop correlations and validate modelling approaches. Particularly, computational flow dynamics (CFD) techniques are showing great promise in this area, but more experimental data is needed, specifically in the area of multi-phase flow and direct contact condensation, in order to validate these tools and use them in safety assessments.

Thermal-hydraulic Analysis Methodologies

Several options are available for the thermal-hydraulic analysis of the system thermal-hydraulics and detailed flow distribution in the downcomer for PTS scenarios. These include system thermal-hydraulics analysis codes, CFD analysis codes, and regional mixing codes.

Systems codes use a one-dimensional nodalisation of the various components of the reactor's primary and secondary cooling circuits. By their design, systems codes traditionally had limited success in predicting local flow behaviour where three-dimensional effects are important. In an effort to address these limitations, codes such as CATHARE (CEA), ATHLET (GRS), RELAP5-3D (US DOE) and TRACE (US NRC) now incorporate dedicated three-dimensional components. The 3D components in systems codes are based on many of the same simplifying assumptions and flow regime maps used for 1D components. One important limitation is in the absence of modelling of turbulent mixing and dispersion.

Some of the most important phenomena are simulated by mixing-analysis codes, examples of which are CFD programs or mechanistic-model programs. CFD programs solve the conservation equations for mass, momentum, and energy by approximating the differential equations by finite-difference equations.

Mechanistic-model (regional mixing) programs simplify the conservation equations by the use of boundary-layer approximations or integral methods for solving the differential equations. Both types of programs rely partly on correlations for closure of the conservation equations. An advantage of the mechanistic-model programs is the speed at which the mixing analyses are performed. The ability to perform hundreds of analyses in a time span on the order of minutes makes it possible to perform best-estimate-plus uncertainty analyses. They are also applicable to probabilistic fracture mechanics (PFM).

Finally, CFD modelling enables detailed prediction of volumetric temperature fields in the reactor pressure vessel. Some APAL partners plan to use CFD methods as an alternative to mixing codes or in addition to these mixing analysis codes, or to consider coupling of system and CFD codes.

PTS Accident Scenarios

A large spectrum of postulated plant transients and accidents can lead to PTS. Selection of the transients for deterministic analysis can be based on analysis and engineering judgment using the design basis accident analysis approach, combined with operational experience. An alternative approach to the selection of transients is the probabilistic risk assessment. At least the following groups of initiating events should be taken into account:

- Loss of Coolant Accidents (with different break sizes of in both cold and hot leg) which are characterized by rapid cooldown should be considered).
- Stuck open pressurizer safety or relief valve (after an overcooling transient caused by a stuck open pressurizer safety or relief valve, possible reclosure can cause a severe re-pressurization).
- Primary to secondary leakage accidents (different sizes for both single and multiple steam generator tube ruptures up to the full steam generator collector cover opening in VVER design should be considered).
- Large secondary leaks (transients with secondary side de-pressurization caused either by the loss of integrity of the secondary circuit or by the inadvertent opening of a steam dump valve can cause significant cooldown of the primary side).
- Inadvertent actuation of high-pressure injection or make-up systems (this kind of accident can result in a rapid pressure increase in primary system).
- Accidents resulting in cooling of the RPV from outside (in some NPPs, there are several possible sources capable to flood the whole reactor cavity).

Best-Estimate Plus Uncertainty (BEPU)

For general thermal-hydraulics applications, most countries have developed methodologies for uncertainty quantification (UQ). For the most part, this includes forward propagation of uncertainties and, in some cases, methods for calibration of prior uncertainties have been demonstrated. The most common approach to forward propagation of uncertainties is the use of Wilks formula, which allows one to identify 95% confidence intervals with a relatively small number of random samples or code runs. Other approaches are, however, also used, e.g., Latin hypercube sampling and sampling of surrogate models. The Wilks method is planned to be used in APAL WP2.

Human Interactions

In many cases, the effect of operator actions has been included in PTS analyses. These are typically at fixed times (either assuming realistic timing of operator actions, or assuming conservative timing of actions). The impacts of failure of the operator to successfully complete an action or the time required to complete the action are relatively unexplored in Europe. In APAL project, human performance is considered in WP2.

STATE-OF-THE-ART OF PROBABILISTIC PTS ANALYSIS AND RELEVANT STATISTICAL TOOLS

To get an overview of the different types of assessment for probabilistic PTS analysis used by the partners the questionnaire of this sub-task focused on the following points:

- Methods for calculation of probability (Monte Carlo, FORM/SORM), including convergence criteria for the former.
- Methods for sampling of distributed parameters.
- A summary of distributed input data and basis for distribution parameters.
- Methods for considering the whole spectrum of PTS scenarios.
- The scope of the assessment and treatment of RPV loading (1D, 2D or 3D analysis, regions of RPV analysed, cold plume effects, etc.).
- Events considered, such as initiation, failure, arrest.
- Fracture mechanics models used.
- An overview of performed applications.

Detailed information of the outcome of the identification of the state-of-the-art on probabilistic PTS analysis is given in APAL public summary report Deliverable D1.6. An overview of the different types of assessment for probabilistic PTS analysis used by the partners involved in the APAL project is given in a separate paper presented at this conference by R. Tiete et al.

IDENTIFICATION OF FURTHER LTO IMPROVEMENTS HAVING AN IMPACT ON PTS AND SELECTION FOR ASSESSMENT

In addition, further potential LTO improvements relevant for PTS analyses applied or considered in participating countries were investigated in this sub-task. This covers the improvements relating to the PTS transients, RPV materials, plant procedures and software, as well as methods of PTS analyses. Detailed information of LTO improvements already implemented or planned in participant countries is given in APAL public summary report Deliverable D1.6.

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