23 DESCRIPTION OF THE RESEARCH PROJECT

Project Proposal: **Digital twins of fatigue damage caused by induced flows in piping dead legs**
Principal Investigator: **Prof. Dr. Leon Cizelj**

Objective of the project

Develop reliable digital twins predicting the induced flows in piping dead legs and especially their competitive interaction at the frontline, which may be responsible for the thermal fatigue cracking in decades of operation.

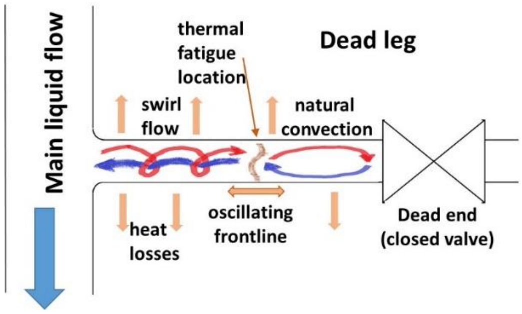

Fig. 1: Sketch of the horizontal piping dead leg with induced flows and location of thermal fatigue crack.

23.1 Scientific background, problem identification, and objective of the proposed research

Decarbonizing the energy sector remains among the key objectives of the green transition. At COP28 (2023, United Arab Emirates), 25 high-level country representatives, including Slovenia, endorsed the goal of tripling global nuclear generation capacity by 2050. This initiative gained momentum at COP29 (2024, Azerbaijan), with six additional countries joining the declaration. The United States also participated in COP29, presenting a strategy to triple its nuclear generating capacity [1]. The strategy emphasizes constructing new gigawatt-scale reactors, the long-term operation of existing ones, and accelerating the development and deployment of small modular reactors.

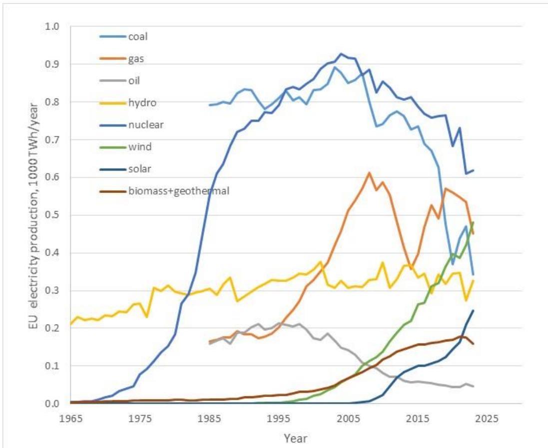

Fig. 2: Electricity production in EU by source (1965-2023) [2]

The nuclear power is the primary low-carbon electricity source in the European Union (EU) since the mid-1990s (Fig. 2, [2]). A notable decline in nuclear electricity production is noted especially in 2022: it was caused mainly by the unexpected **damage in piping dead legs** in French nuclear power plants. Yet, nuclear energy persisted as the EU's principal electricity source and the largest low-carbon electricity energy.

The damage in piping dead legs was detected during the routine 10-year in-service inspection of the Civaux 1 reactor in October 2021. Removal of the safety injection system pipe and metallurgical examinations revealed **Stress Corrosion Cracking (SCC)**. Inspection of similar instances in similar French nuclear power plants, combined with outage delays due to COVID-19, led to 32 out of 56 reactors being offline during part of 2022, and in about 80 TWh less generated electricity than in 2021 [3].

Similar cracks in the piping dead legs were detected because of leaking coolant in the French Civaux 1 [4] nuclear power plant, in 1998, Belgian Doel 1 and Doel 2 NPP in 2018 [5], and in Slovenian Krško in 2023 [6]. The common thread in these events is the most probable root cause of the cracking: **thermal fatigue,** caused by **induced flows and consequent (unexpected) mixing of cold and hot fluids in the piping dead leg**. Thermal fatigue in Civaux 1 was experienced within the first years of plant operation. In Doel and Krško, the remaining three events developed after 30 or more years of plant operation. Doel and Krško events are similar in the crack location and design of the pipe. Both Civaux 1 events, while different in the pipe configurations and crack locations, are similar to Krško and Doel events in the developed flows and, in part, also crack growth mechanisms.

The pipes affected in the above events were part of the safety injection systems, which are not active during the plant operation and are therefore insulated by a closed valve, as shown in Fig. 1. The section of the pipe between the operating system and the insulation valve is called the **dead leg**. An open end of the dead leg is connected to the operating system and exposed to the main liquid flow and its pressure and temperature. The end near the insulation valve might be affected by the heat losses depending on the length and thermal insulation of the dead leg section. Fluid flow near the open end of the dead leg could be induced by the flow in the main system. At the same time, the heat transfer through the wall could establish natural circulation vortices in the dead leg (Fig. 1). Both types of induced flows and their competitive interaction are responsible for the conditions leading either to stress corrosion cracking (e.g., steady high temperature of the pipe wall), thermal fatigue (e.g., temperature oscillations), or a combination thereof.

The safety injection systems are dormant during normal plant operation and are activated in the case of need. While the repair strategies (e.g., cut and replace, sometimes redesign of the pipe and/or insulation) are rather straightforward and effective, **the reliable prediction and/or preclusion of such events remains beyond the state of the art**. The cracks in the above-mentioned events were neither expected nor predicted. They were found after the leaks or after unplanned detailed examinations triggered by the leaks in similar pipes. This has prevented optimal responses and considerably elevated costs related to the repair and lost capacity.

The main objective and expected added value of this project are to develop reliable digital twins predicting the induced flows in piping dead legs and especially their competitive interaction at the frontline (Fig. 1), which may be responsible for the thermal fatigue cracking in decades of operation. Such digital twins will be essential to minimize both operational risks (e.g., loss of production) and the risks of losing a safety-related system, and will therefore enable essential tools for maintaining plant reliability and safety.

The practical value of digital twins predicting the damage in piping dead legs is to enable more economical and safer utilization of nuclear power plants in long-term operation. It is worth mentioning that, according to the Power Reactor Information System (PRIS) maintained by the International Atomic Energy Agency, [7], the average age of the roughly 100 GW worth of nuclear power plants in the EU reached 38 years in 2024, with approximately one-third already operating beyond their originally designed lifespan. Further, the natural convection part of the digital twins may contribute, beyond this project, to the design and safe long-term operation of passive heat transfer operational and safety systems in the future nuclear power plants including many of the envisioned small and modular reactor designs.

The digital twins to be developed in this project will contribute to the green transition by sustaining and supporting the long-term operation of the existing and future nuclear power plants in the coming decades.

23.2 State-of-the-art in the proposed field of research and survey of the relevant literature

Two distinct mechanisms are, in principle, responsible for the cracking in the dead legs of (safety injection) pipes: **Stress Corrosion Cracking** (SCC), which requires the participation of stresses, a corrosive environment and is usually thermally activated, and **Thermal Fatigue** (TF), which develops as a consequence of fluctuating temperatures in pipes. Their combination is of course possible and is usually termed **Corrosion Fatigue**. This research project proposal primarily focuses on understanding and predicting **Thermal Fatigue**.

The magnitude of the published and unpublished research on thermal fatigue is in line with the importance of this problem for the long-term operation of nuclear reactors. Consequently, we did not attempt a comprehensive literature review in the sections below. Rather, we focused on very recent publications, deemed sufficient to indicate the state of the art and opportunities to be followed in the proposed project. Selected related papers by the members of the project team are mentioned, where relevant, and, in particular in Section 23.2.4.

23.2.1 Thermal Fatigue

Development of a comprehensive digital twins simulating thermal fatigue damage in dead-end pipes requires the interaction of the following research fields:

- **Fluid mechanics and heat transfer** in the liquid coolant, combined with the heat transfer to and in the solid pipe wall, provide time-dependent temperature fluctuations in the pipe walls. This turns out to be the most challenging part: the combination of large computational domains, a wide range of Reynolds numbers, and long times that need to be analysed is thoroughly discussed in the sections below.
- **Structural mechanics** is needed to answer the question of whether the amplitudes and frequencies of the strains caused by the temperature fluctuations can result in thermal fatigue. In terms of continuum mechanics, the fatigue design curve indicates the number N and amplitude S_a of stress (or strain) cycles that lead to the initiation of a macroscopic fatigue crack. As a rule of thumb, the temperature fluctuations of several tens of °C with the frequency of about 1 per few hours could result in high cycle thermal fatigue of nuclear-grade stainless steel in a quarter of a century of operation. We should stress that we look for statistically rare events with sufficient amplitude, which then need years or even decades to cause damage to the material.
- **Fracture mechanics** is used to predict the growth of the macroscopic crack. The ductile stainless steels, which are used for the safety-related piping in nuclear power plants, are rather fracture tolerant. As a consequence, sophisticated nonlinear methods are needed to arrive at reliable answers.

An example of “fatigue life” simulation study for a stainless steel subjected to cyclic thermal loads is given in [8]. Another recent example of a comprehensive thermal fatigue simulation of a simple pipe with an elbow, with fluid mechanics, heat transfer, and structural mechanics response, can be found in a recent paper by Zhou et al. [9].

In most practical cases it turns out that analyses of time-dependent fluid mechanics and heat transfer are the most challenging parts of the thermal fatigue studies, as they provide the actual thermal loads. Consequently, these aspects constitute the central focus of this research proposal. However, structural and fracture mechanics analyses are incorporated into the project as a crucial, albeit minor, component that ultimately determines the significance of the fluctuations predicted by the heat and fluid flow analyses.

While we further confine the proposed research to water coolants within steel pipes in nuclear power plants, the outcomes will have broader applicability across various engineering fields. Thermal fatigue is an important issue in sodium-cooled reactors [10], where higher temperature differences than in water-cooled reactors are observed, and heat transfer in liquid sodium is more efficient than in water.

23.2.2 Phenomena in piping T junctions

The common geometry of interest in thermal fatigue studies is the T-junction configuration, as illustrated in Fig. 1. Numerous experimental and numerical studies addressing this geometry can be found in the literature. This proposal provides a brief list of references, predominantly from the past two years, indicating the state of the art and current challenges. Papers by Isaev et al. [12] and Angele et al. [13] provide two examples of the most recent experiments conducted on T-junction geometries. Additionally, several other authors focus on numerical simulations of thermal fatigue in T-junctions, including Isaev et al. [14] and Miyoshi et al. [15]. A detailed review of these studies and their literature review sections reveals that most experiments and simulations assumed that the main flow in the large pipe of the T-junction is combined with the side flow from the smaller perpendicular pipe. Both flows exhibit different temperatures and their mixing results in thermal fatigue in the downstream leg.

The issues surrounding dead leg T-junctions are relatively recent. For instance, a review paper summarizing the results of EU project THERFAT [16], which explored the thermal fatigue in T-junctions in 2005, concluded that: "*... the dead end ... is not considered fatigue significant.*" The events described in Section 23.1 proved this conclusion wrong. Most real-world problems with degradation emerged in the dead leg section of the piping flows, where the net flow from the dead leg is zero. A notable exception is discussed in [11], where the surge line connecting the primary coolant loop and the pressurizer in the PWR reactor is analysed for thermal fatigue. The pressurizer serves as a vessel that absorbs the thermal expansion of the primary coolant. The net flow rate through the surge line is close to zero, and the temperature fluctuations at the T-junction of the main pipe and the surge line were found too small to cause thermal fatigue.

The recent understanding of the relevant phenomena in the dead leg piping T junctions is as follows (Fig. 1): the first flow pattern emerges near the open end of the dead leg, exposed to the forcing flow in the main system. A swirling flow enters through the open end of the dead leg around the perimeter of the pipe wall, and the return flow comes back through the central region of the pipe. On the other side of the dead leg, near the insulation valve, heat losses through the dead leg walls are significant. These losses are substantial enough to generate a natural circulation vortex near the closed end. Thermal stratification near the insulation valve may lead to temperature differences of 50 K.

Under certain, currently unclear conditions, **the competitive interaction of both flow patterns may result in oscillatory motion of the front line** between them (Fig. 1). The different temperatures of the well-mixed swirl flow and the natural convection vortex can result in thermal fatigue-driven crack initiation and growth of the crack in the pipe within the path of the oscillating frontline. In such conditions, the typical temperature fluctuations in the pipe could reach about 50 K at frequencies of one or fewer fluctuations per minute, which is sufficient for the initiation and growth of thermal fatigue cracks in long-term operation stretching over decades.

These two flow patterns, and their competitive interaction resulting in oscillating frontline, were also found to be plausible explanation of the thermal fatigue leak at the Doel Nuclear Power Plant [5].

In this research proposal, our objective is to analyse T-junctions with dead legs. The newly initiated experimental benchmark, as discussed by Angele et al. [13], aims to simulate dead leg flows. However, the experiments involve a tiny flow in the pipe leg that is intended to represent the dead leg. Moreover, this experiment considers the vertical orientation of the "nearly-dead leg" section, while the problems in Belgian and Slovenian nuclear reactors occurred in horizontal dead legs. We consider the horizontal orientation of the dead legs the central case of our project proposal. We may also attempt to study inclined or vertical dead legs, at least for verification of the digital twin performance.

23.2.3 Modelling temperature fluctuations using Computational Fluid Dynamics

The primary tool for numerical simulations of the induced flows and temperature fields in the dead leg sections of the piping systems are computer codes for Computational Fluid Dynamics. The fundamental balance equations, encompassing the conservation of mass, momentum, and internal energy in liquids (commonly referred to as Navier-Stokes equations), are solved in a computational domain that is discretized into finite volumes or elements.

The tool foreseen to be used for the proposed research is the open-source code OpenFOAM (https://openfoam.org/). This code offers efficiently parallelized solvers of Navier-Stokes equations, many different turbulence models, and several different numerical schemes, and contains modules for conjugate heat transfer. The conjugate heat transfer model allows the simultaneous solution of the Navier-Stokes equations in the fluid domain and the heat conduction equation in the solid domain of the dead leg pipe.

The primary challenge of the thermal fatigue simulations are very long times that need to be simulated to properly describe the oscillatory nature of the turbulence inside the dead leg. While a typical time step in such simulations is between 10^{-4} to 10^{-2} seconds, depending on the details of the CFD model, the overall period of interest often extends over several minutes to several hours. We are interested in statistically rare large-temperature fluctuations: the averages and variances usually reported in such CFD simulations are not sufficiently informative. Consequently, the preferred type of CFD models is based on RANS (Reynolds Averaged Navier Stokes) models of turbulence, known for their capability to yield reasonably accurate results on relatively coarse grids. Given that RANS models must operate in transient mode (referred to as U-RANS, with U denoting Unsteady), the computational loads remain substantial even with moderately coarse meshes comprising several million points. This necessitates supercomputers equipped with thousands of CPU cores to handle the computational demands effectively.

The applicability of U-RANS models for industrial T-junctions with dead legs has not been systematically investigated to date. Addressing this gap is a **key opportunity and one of the**

objectives of the proposed project. Typically, U-RANS models are developed and validated using more precise Large Eddy Simulation (LES) models of turbulence, which capture smaller turbulence structures than U-RANS models. However, more accurate LES requires even more computational time. Various problems with significantly simplified T-junction geometries have been recently addressed with LES approach [17], [18]. They however considered forced flow and not the dead legs. Also, the study of the pressurizer surge line mentioned above [11], was performed with LES. One viable approach for the present project are hybrid U-RANS - LES methods [20], which could represent an acceptable compromise between the accuracy and computational time.

The most accurate simulations of turbulent flows are Direct Numerical Simulations (DNS). These simulations capture all the details of the turbulence but are too expensive for most real-world simulations. Possible approaches toward DNS of a simple T-junction were recently reported [19], and the models were examined for possible thermal fatigue simulations [20]. However, these attempts are still far from practical applications.

23.2.4 The project team and research related to thermal fatigue

The members of the project team have contributed significantly to the research topics related to this project and are well connected with the relevant research teams abroad. Examples of contribution to computational fluid mechanics and heat transfer include RANS, LES, and DNS simulations of various flows with heat transfer in various complex geometries with or without conjugate heat transfer ([20], [21], [22] and [23]).

Relevant contributions to structural and fracture mechanics include random thermal loads in the thermal fatigue assessment of nuclear piping [24], including uncertainty assessment [25], and computational multiscale modelling of intergranular cracking [26], [27].

The members of the project team have recently been involved in the root cause analysis of the Krško 2023 leak case. Our recent research on the dead leg T-junction with metallographically confirmed through-wall high-cycle fatigue crack is detailed in [28]. U-RANS models were utilized to simulate the induced flow in the dead leg of the safety injection line. The primary outcome of this study was the qualitative prediction of two distinct flow patterns inside the dead leg (Fig. 1).

This research proposal is, to a significant extent, inspired by the experience gained from the root cause analysis of the Krško 2023 leak case in [28] and the challenges encountered there.

23.3 Objectives of the proposed research

The **key challenge** is our incomplete understanding of the mechanisms responsible for the development of both induced flows and especially their competitive interaction at the frontline (Fig. 1). The **overarching objective** is therefore to develop reliable digital twins predicting the induced flows in piping dead legs and especially their competitive interaction at the oscillating frontline, that may be responsible for the thermal fatigue cracking in decades of operation.

The following objectives need to be achieved to this end:

Objective 1: develop a simulation model of the open end of the dead leg, where fluid flow in the main pipe induces **penetrating swirl flows in the dead leg** (Fig. 1). The intensity of the vortex intrusion into the dead-end pipe depends mainly on the flow conditions in the main system and the detailed geometry of the T-junction. Variations in these geometries will provide information of significance for behaviour of existing and newly designed piping systems and will enable the quest for the minimization or maximization of induced flows. Either weak or strong induced swirl flows might prove beneficial for avoiding or preventing thermal fatigue.

Objective 2: characterize and model the mechanisms influencing flows driven by **natural convection** near the closed end of the dead leg. Natural circulation is primarily influenced by the orientation (horizontal, vertical, or inclined) and thermal insulation (heat losses) of the dead leg. Variations in the orientation and adjustments in thermal insulation will impact the intensity of natural circulation. This, in turn, will impact the temperature fluctuations and may assist in avoiding or preventing thermal fatigue. It is noted however that more insulation will increase the temperature of the pipe and may contribute towards favourable conditions for stress corrosion cracking.

Objective 3: The most challenging objective is to investigate, understand and model the **competitive interactions between the swirl flow and the natural convection** possibly resulting in oscillations of the frontline (Fig. 1). The starting point will be dead leg cases with both flow patterns observed simultaneously. Currently, aside from some indications from measurements in NPP Doel, there is no conclusive evidence of such quasi-periodic motions. Additionally, the range of geometric and boundary conditions where such fluctuations might occur is unknown. As a result, selecting the type of numerical approach that will effectively capture and predict these phenomena remains uncertain. We will try to capture the phenomena with more efficient, but less accurate Unsteady Reynolds-Averaged Navier-Stokes (U-RANS) models. We aim to employ accurate Large Eddy Simulation (LES) approaches too, where high computational costs will likely represent the main obstacle.

Objective 4: The **structural and fracture mechanics** models will be developed to provide estimates of fatigue life and crack growth. These methods, primarily Finite Element Method (FEM) and Extended Finite Element Method (XFEM) are rather well developed and available in the commercial codes. The challenge at hand will be the integration with Computational Fluid Dynamics results into a functional Multiphysics digital twin.

Objective 5: Verification and validation of the digital twin with available **experimental data**. In collaboration with our industrial partner, NPP Krško, we will refine temperature measurements along the length and perimeter of the recently installed safety injection pipe, which has replaced the cracked pipe. The primary objective is to attain accurate temperature measurements at various points on the outer surface of the pipes. In addition, the data available in relevant experiments and literature or from our foreign project partners will be utilized for this purpose.

23.4 Detailed description of the work programme

The project will be organized in 6 work packages (WP), which are described in the subsections below. Three are related to the modelling of particular physical phenomena and Objectives 1, 2, and 3:

- WP1: Penetrating swirl flows (Objective 1); section 23.4.1.
- WP2: Natural convection flows (Objective 2); section 23.4.2.
- WP3: Competitive interactions between the swirl flow and natural convection (Objective 3); section 23.4.3.

Further three are “horizontal” and are designed to support the first 3 WPs:

- WP4: Models, tools, computing, integration (Objectives 1-4); section 23.4.4.
- WP5: Verification and validation (Objective 5); section 23.4.5.
- WP6: Project management and dissemination; section 23.4.6.

23.4.1 Penetrating swirl flows (WP1)

The penetrating swirl flow is an isothermal fluid mechanics problem determined by the mass and momentum balance equations. Turbulent flow in the main pipe is the sole driving force of the flow induced in the dead leg. The spatial orientation of the T-junction is not relevant, as the buoyancy does not exist or is negligible.

An essential part of this WP involves analysing the induced flow in the dead leg derived from simulations in computational domain that contains well-resolved flow in the main system pipe. In the subsequent step, a crucial aspect of the planned approach entails removing the main pipe in the T-junction and replacing it with boundary conditions that effectively induce swirl flow within the dead leg, as shown in Fig. 3. This will improve efficiency of the further simulations, but will require specifying boundary conditions for the mean velocity flow and the fluctuating part of the velocity, also known as turbulent kinetic energy, in turbulence models. The detailed specification of these boundary conditions will depend on the type of turbulence modelling used. Boundary conditions for LES simulations are more intricate, as they are expected to contain physically consistent velocity fluctuations. In RANS modelling, it is typically sufficient to specify boundary conditions for the turbulent kinetic energy (*k*), and other turbulent variables described with transport equations (ε, ω,...).

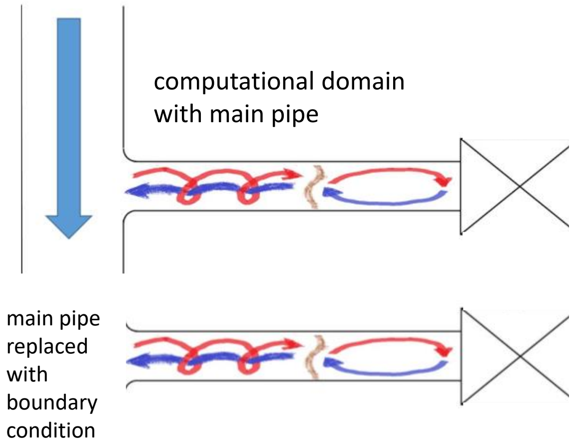

Fig. 3: Two types of computational domains to be considered in simulations.

Furthermore, our simulations will include sensitivity analysis of the T-junction's inlet nozzle shape and its potential influence on promoting or suppressing swirl (vorticity) within the deal leg. Minor modifications of the T-junction geometry, such as placing an appropriate obstacle near the junction, can significantly alter the induced flow in the dead leg by changing the shape of the flow separation. Specifically, asymmetric obstacles usually enhance swirling flow in the dead legs, while symmetric main flow and geometry tend to reduce induced flows. We anticipate that the removal of the main pipe from the computational domain, and its replacement with a boundary condition, will need to be specific for each instance of the T-junction geometry.

As part of our comprehensive study, we will also examine the geometries of various T-junctions in injection lines within the geometry of the nuclear power plant injection lines. This involves safety injection lines with available temperature measurements. By combining these aspects, our objective is to gain valuable insights into the behaviour of induced swirling flows in dead legs, providing essential knowledge for enhancing the safety and efficiency of nuclear power plant systems.

23.4.2 Natural convection flows (WP2)

Isothermal cases in Section 23.4.1 will serve as a starting point for the heat transfer analyses. The most relevant heat transfer mechanism for thermal fatigue analyses appears to be heat loss through the dead leg walls. In the few meters long dead legs of injection pipes in pressurized water reactors, these heat losses occur at coolant pressure of 15 MPa and temperatures between 100 and 300 °C, assuming weakly insulated dead leg. Significant differences in water densities at such temperatures (around 20%) result in strong buoyancy forces, even in horizontal dead legs. Our simulations in [28] have shown that natural circulation vortices can be established inside the couple-of-meters-long horizontal 15 cm diameter pipe. The intensity of the natural circulation is governed by the heat losses from the uninsulated or weakly insulated dead leg. Such large density differences are difficult to establish in experiments. Consequently, CFD simulations are seen as a crucial tool for analysing such flows.

Different natural circulation conditions are established in vertical dead legs. A vertical dead leg, exposed to heat losses, and connected at the top of the hot main pipe, will experience unstable stratification and intensive natural convection. The dead leg connected to the main pipe at the bottom side will experience stable stratification and possibly higher temperature differences. It is not straightforward to predict which configuration is more prone to thermal fatigue: a cooled vertical dead leg at the top will likely experience higher velocities but lower temperature differences. Stable stratification in the cooled vertical dead leg at the bottom will exhibit weaker velocity fields with higher temperature differences. In the case of an appropriate perturbation mechanism, higher temperature differences might show a larger potential for thermal fatigue. Configurations with inclined dead legs will likely end up with similar dilemmas.

The details of heat losses have been identified as the primary source of uncertainty in [28]. Thermal insulation of minor pipes in NPP is weak or non-existent. Furthermore, the complex geometry of piping system penetrations through thick concrete walls and ventilation air-currents may lead to poorly quantified heat losses. Some outside sections of the pipes might be cooled with the naturally circulated air, and some of them with forced air convection of unknown intensity. This results in rather rough estimates of the heat fluxes on the outer surface of the dead legs. We expect that efficient thermal insulation will, in general, reduce the potential for the thermal fatigue. Nevertheless, this assumption needs to be confirmed with simulations.

Most of the CFD studies relevant to the thermal fatigue of dead legs can be conducted without considering heat transfer in the solid walls of the dead legs. Many experiments focused on CFD of heat transfer in T-junctions are performed with pipes having negligible heat capacities or are equipped with thermocouples on the inner side of the pipe walls. However, part of the validation for our models will rely on a comparison with measurements conducted on the outer wall of the safety injection line dead leg of the industrial partner in the project - NPP Krško. Consequently, we will include pipe walls in some of our models. This will enhance the validation of the models and also enable us to perform complete thermal fatigue analyses, incorporating the computation of wall temperatures, stresses, and eventually the number of cycles contributing to thermal fatigue.

23.4.3 Competition between swirl and natural convection flows (WP3)

One of the central tasks, and arguably the most uncertain and challenging one in the proposed research, involves the analysis of dead legs, which exhibit a combination of induced flows near the open end and natural circulation near the closed end of the pipe, as illustrated in Fig. 4. This combination could potentially serve as a source of thermal fatigue, especially if the boundary between both flow patterns shows spatial fluctuations.

Currently, we are unable to predict which systems may display fluctuating boundaries between the two flow patterns. We anticipate rather chaotic transitions, characterized by rapid shifts from one stable state to another. Dynamic systems of this nature are usually sensitive to detailed boundary and initial conditions. We intend to test systematically most of the parameters in our CFD models:

- Variations of the turbulence models, including various versions of U-RANS and LES models (see Section 23.4.4).
- Variations of the heat losses specified as boundary conditions, which govern the intensity of natural convection.
- Velocity field boundary conditions at the open ends of the dead legs that govern the intensity of the induced swirl flow.
- Influence of the numerical schemes, including various spatial and temporal discretization schemes that affect numerical diffusion in the simulations.
- Mesh density, which affects solutions even for non-chaotic systems.

The majority of these analyses will involve time-consuming simulations, requiring days or weeks and utilizing thousands of CPU cores. Collaboration with other research groups abroad and comparison with measurements at NPP Krško might allow us to identify conditions that result in the oscillatory interactions of the induced swirl flow and the natural convection in the dead leg.

23.4.4 Models, tools, computing, integration (WP4)

It is too early to link the specific mathematical models and numerical tools to description of particular physical phenomena in work packages WP1, WP2, and WP3. This is the reason that the testing, comparison, selection and calibration of these methods is placed in a dedicated work package.

The basic mathematical model comprises of:

- mass, momentum, and energy equations for the fluid phase,
- heat conduction equation for the solid phase,
- structural and fracture mechanics equations and fatigue design curves.

Computational Fluid Dynamics (CFD) is a crucial component of the proposed research. We will conduct CFD simulations using the open-source code OpenFOAM. This code will be used for fluid mechanics simulations described in WP1, for natural convection and conjugate heat transfer analyses in WP2, as well as for simulations of interactions between the induced flow and natural convection flow patterns in WP3. The structural part of the simulations will employ as an input the solid wall temperature fields of the selected dead legs from CFD simulations to predict the stresses.

Structural and fracture mechanics analyses will be performed using a separate tool, Abaqus (https://www.3ds.com/), and will be combined with fatigue design and crack growth rate (Paris law) curves from ASME standards.

The CFD code OpenFOAM is applicable in T-junction geometries, which can be considered a medium complexity domain. If we successfully replace the main pipe in the T-junction with consistent kinematic boundary conditions, we will achieve significant geometry simplification and a notable reduction in computational load.

Most of our attempts will be based on Unsteady Reynolds Averaged Navier Stokes (U-RANS) models of turbulence with selected cases analysed with hybrid URANS-LES models. Particularly for the modelling planned in WP1 and WP2, with many sensitivity analyses, this approach will be the optimal solution. More accurate but time-consuming Large Eddy Simulation (LES) models will be applicable in

WP1, offering a narrower range of modelling options. While we anticipate using discrete meshes with several million points for U-RANS simulations, the number of mesh points for equivalent LES computations may increase to several tens of millions.

Turbulence modelling in dead legs will require selecting appropriate turbulence models for both LES and RANS approaches. The number of options for LES is wide - without references to particular models: WALE, Smagorinsky subgrid model, one equation eddy-viscosity models, dynamic one equation eddy-viscosity models, wall-modelled LES... The number of options for U-RANS is even wider: Isotropic eddy-viscosity turbulent models: Linear (k-omega SST, k-epsilon, v2f...), Non-linear (quadratic or cubic k-epsilon model, EARSM), Reynolds Stress models... Our starting points will be "standard" turbulence models: WALE for LES and k-omega-SST for U-RANS simulations. Depending on mesh density, we will examine a broad range of options on the same meshes: from simple "laminar" options with zero turbulent diffusivity to various U-RANS and LES models.

A non-negligible part in such simulations is always numerical diffusivity, which depends on the accuracy of spatial and temporal discretization. We will use only second-order accurate schemes in LES and U-RANS simulations; however, even these are not completely immune to numerical diffusion, as first-order schemes are automatically added at locations where velocity or temperature fields exhibit short-wavelength and high-frequency oscillations. Quantifying numerical diffusion is challenging but can be examined through modifications of discretization schemes.

Boundary conditions at the open ends, especially inflows, require specifications of turbulent velocity fields. For LES simulations, which capture a significant range of turbulent eddies, this means using "synthetic turbulence generators." These approaches are expected to be more practical and efficient than additional periodic domains, which are the most frequent choice in the most accurate DNS and LES models but are also difficult to apply in more complex geometries. Specification of inflow turbulence for U-RANS models is less complex but also less accurate.

For transient simulations spanning several hundred seconds of real-time, we can anticipate simulation times measured in days for around one thousand CPU cores for U-RANS cases and months for LES simulations. We plan to utilize several thousand CPU cores for LES simulations, some of which will be obtained from our computer clusters. In addition, we will rely on the supercomputer Vega, which is part of the Slovenian supercomputing infrastructure.

23.4.5 Verification and validation (WP5)

This work package will concentrate on accurate measurements of the outer wall temperatures at several points on the safety injection lines of NPP Krško, which were recently replaced due to leaking thermal fatigue crack. We are seeking thermometers with low thermal capacity that can be securely affixed to the pipes, ensuring efficient thermal contact. The thermometers must be thermally insulated on the air side to accurately measure the pipe wall temperature rather than the air temperature. Both the thermometers and insulation should function effectively at temperatures close to 300 °C and must not induce local corrosion on the pipes or cause other potential safety issues. Installation of these thermometers will take place during the refueling outage. Data of the industrial partner will be combined with available temperature measurements obtained on NPP Doel safety injection lines, data from relevant experimental devices [13] and from our research partners abroad.

The second set of measurements useful for V&V is coming from the dead-end pipe displacement sensors installed in NPP Krško. Displacements measured by these sensors correspond to the integral temperature changes of the steel pipes due to the temperature expansion or contraction, but also to other fluctuations. According to the preliminary analyses, displacements are highly correlated with the temperature fluctuations measured at several points along the corroded safety injection pipe.

23.4.6 Project management and dissemination (WP6)

The anticipated long computational times call for parallelization both in the computations and in the research activities in the anticipated work packages. To this end, the **project management team** will consist of the work package leaders and the principal researcher. This team will ensure the flow of information between the WPs, the optimal management of the risks and, last but not least, the dissemination of the results and challenges encountered with the partner research teams.

The **dissemination** of the results will entail the traditional publications in journals and conferences. It will also go beyond that traditional channels. The anticipated results, namely, advancement of our prediction capabilities for thermal fatigue piping dead ends, are considered of interest for various research communities, nuclear, and other process industries.

The industrial partner - NPP Krško – will benefit through the developed tools for predictive analyses of dead leg pipe sections connected to the primary coolant loop, and later possible also the dead leg sections connected to other plant systems, which might be less important from the safety point of view, but still relevant for the long-term power plant operation. These analyses will enable more optimal in-service inspection and maintenance schedules. The industrial partner will participate in disseminating the results within the nuclear industry, including light water reactor operators and designers of advanced and small modular reactors.

Results of the project will be beneficial for nuclear thermal hydraulic, structural and fracture mechanics communities. Broader fields, where results of the project could be relevant, include metal cooled nuclear reactors, passive heat transfer systems (also in advanced and small modular reactors), high temperature thermal storage systems, solar thermal systems, and water supply systems(where dead legs could facilitate development of biological contamination.

The principal researcher and the project management team will disseminate the results of the project in these communities with active participation in international alliances, e.g., European Industrial Alliance for Small and Modular Reactors and Sustainable Nuclear Energy Technology Platform, and in cooperation with the foreign project partners.

23.5 Available research equipment over 5.000 €

Two computational clusters with cumulative 6,000computational cores. Computers are operated by research teams of Reactor Engineering division and Reactor Physics division of Jožef Stefan Institute (total ~25 users). HPC Vega in Maribor (Slovenia) with 120,000 computational cores on 960 nodes and 60 GPU nodes. We already have access to the equipment and we are using it for our most computationally intensive simulations.

23.6 Detailed implementation plan and timetable

23.6.1 The research team

The very interdisciplinary research team needs to cover different aspects of computational fluid, structural and fracture mechanics, and heat transfer, and seniority levels. Opportunities to include for Ph.D. and M.Sc. students are also noted.

The funded portion of this project proposal amounts to roughly 62-person months (p-m) of work. External funding for roughly 20 p-m PhD and MSc students is foreseen:

WP1, Penetrating swirl flows: leader M. Draksler, (senior researcher, 2 p-m), 2 researchers (8 p-m), PhD student (PhD thesis), MSc student (MSc thesis).

WP2, Natural convection flows: leader B Mikuž, (senior researcher 2 p-m), 1 researcher (6 p-m), PhD student.

WP3, Competitive interactions between the swirl flow and natural convection: leader M. Draksler (senior researcher, 3 p-m), 3 researchers (16 p-m), PhD student, MSc student.

WP4, Models, tools, computing, integration: leader I. Tiselj (senior researcher, 3 p-m), 5 researchers (6 p-m).

WP5, Verification and validation: leader I. Tiselj (senior researcher, 3 p-m), 2 researchers (6 p-m).

WP6, Project management and dissemination: leader L. Cizelj (senior researcher, 3 p-m), all WP leaders (4 pm).

23.6.2 Timeline

		months						
WP	**Task**	**1-6**	**7-12**	**13-18**	**19-24**	**25-30**	**1-36**	**Leader**
1	Full simulations U-RANS and LES							
1	Sensitivity analyses (geometry, mesh density, turbulence models)							
1	**MILESTONE Boundary conditions simulating main pipe**		**Month 12**					
1	Reduced domain simulations U-RANS and LES							Draksler
2	Natural convection simulations (U-RANS)							
2	Natural convection simulations attempts (LES)							
2	**MILESTONE Natural convection simulations completed**				**Month 24**			Mikuž
3	**MILESTONE model combined swirl and natural convection flows**			**Month 15**				
3	simulations (U-RANS)							
3	sensitivity studies (mesh density, numerical schemes, …)							Draksler
3	structural and fracture mechanics studies							Costa
4	models, tools, computing, integration							Tiselj
5	verification, validation							
5	**MILESTONE verification and validation completed**						**Month 3**	Tiselj
6	management and dissemination							Cizelj

23.6.3 Expected deliverables

Expected deliverables include 3 papers in the SCI journals (fields of nuclear engineering, fluid mechanics, and/or heat transfer), presentations at 3 international conferences (nuclear thermal-hydraulic, and/or nuclear engineering), two dedicated presentations for the industrial partner, a public lecture at the Jožef Stefan Institute, and complete database with computational results.

23.6.4 Risk management

The most important risk, sorted from the most impactful to the least impactful, including the basic mitigation strategies, are:

- **Long computational times.** CFD transient simulations requiring millions to tens of millions of time steps on meshes with several million to tens of millions of finite volumes will demand significant computational resources. **Mitigation:** Carefully balance the pursuit for better accuracy with the capabilities of available supercomputers. Utilize increasingly larger and accessible computing resources: ~1,000 CPUs on the local supercomputer and ~10,000 CPUs on Slovenia's central HPC Vega. Explore options for accessing European HPC infrastructure.

- **Chaotic nature of the simulated phenomena.** The probability that the simulated phenomena are at least to some degree chaotic is considerable. For such systems, the accuracy of prediction will decrease with time regardless of the computational power invested in the solution. If the problem is demonstrated to be chaotic with sufficient certainty, even the largest supercomputers may not suffice for long-term predictions. **Mitigation**: Shift the focus of simulations to identify and, if possible, remove the source of chaotic behaviour. Alternatively, clearly define the limits of the predictive capability of the digital twin.
- **Access to data for verification and validation:** Parts of the measurement data from the Slovenian nuclear power plant Krško may not be publicly available. **Mitigation**: While all the data will remain accessible to the research team for validation purposes, reports related to verification and validation may not be made entirely public or may require more data from other public sources (partners, international projects…). In any case, reports related to other aspects of the digital twin, e.g., model descriptions, numerical setups, and simulation results, will be published.
- **Availability of M.Sc. ans Ph.D. students:** This project proposal allocates approximately 25% of work to students. These students may not be available at the start or even at the later stages of the project. **Mitigation**: strengthen the research group with members of Reactor Engineering Division, who are not listed in the current project team.

23.7 Selected references

Members of the project team are listed in **bold**.

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