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REVIEW ARTICLE

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Increase of nuclear installations safety by better understanding of materials performance and new testing techniques development (MEACTOS, INCEFA-SCALE, and FRACTESUS H2020 projects)

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Abstract. Research to better understand the phenomena influencing materials and components' performance is important for increasing the safety of Generation II and III nuclear plants. A crucial step for improving nuclear safety is the development of new experimental techniques that can provide the necessary data. The three H2020 projects presented in this paper, MEACTOS (2017–2022), INCEFA-SCALE (2020–2025), and FRACTESUS (2020–2024), cover the steps needed to realize those safety improvements. The goal of the MEACTOS project is to improve the resistance of critical locations, including welds, to environmentally-assisted cracking through optimizing surface machining and treatments. The project is currently in its final stage, and the complete analysis of the data is finished. The objective of INCEFA-SCALE is to improve predictions of component fatigue lifetime when subjected to Environmentally-Assisted Fatigue (EAF). The strategy consists of producing guidance on how to appropriately accommodate variable amplitude and plant-relevant loading in EAF assessments. Increasing the understanding of the EAF mechanism based on substantial testing, characterization, and analysis program will support the INCEFA-SCALE strategy. The FRACTESUS project will validate the use of miniaturized compact tension specimens by comparing the results of master curve-oriented fracture toughness tests performed with small and large specimens. The round-robin exercises will use irradiated and non-irradiated Reactor Pressure Vessel (RPV) materials. The material selection process is complete in time for the project to enter the testing phase. The output of the project will be beneficial from a long-term operation perspective and a saving in the material amount needed for RPV surveillance programs. Even though each project is devoted to different research areas, common aspects are clearly visible. All three projects investigate phenomena that are relevant to the performance and safe operation of the nuclear plant. Moreover, each project will provide valuable databases and analyses of test results for materials relevant to components in the nuclear plant. The output of these projects will be of great value to the nuclear industry. This paper presents the current progress for each project, emphasizing the common research domains between the projects.

1 Introduction

Most of the nuclear power plants (NPPs) in operation worldwide have already exceeded half of their initially planned service time, and the average age of the currently operating reactors is over 30 years. Over the last 30 years, the progress in material science may allow an increase in the operating lifetime of those NPPs beyond what was initially planned. The long-term operation (LTO) perspective for the existing NPPs fleet is crucial for satisfying the still-growing demand for electricity in modern societies.

The safety of nuclear installations is of the utmost importance in any activity related to LTO implementation. Therefore, many research activities are focused on this topic, including the projects financed within the H2020 Euratom program. To accurately inform the service time of NPPs, the Nuclear Industry is investigating the complex phenomena that influence and limit the performance of materials in nuclear applications. The output of such research is very important, not only from the LTO perspective but also for designing new NPPs.

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This paper presents an overview and current status of three H2020 projects oriented on the safety increase of generation II and III reactors, namely MEACTOS (2017–2022), INCEFA-SCALE (2020–2025), and FRACTESUS (2020–2024). All three projects investigate phenomena that relate to material performance and safe operation of NPPs, i.e., environmentally-assisted cracking (EAC), fracture, and fatigue of materials. It is impossible to produce materials without flaws in large-scale component manufacturing methods. Therefore, the fracture toughness of materials has to be investigated. In the case of cyclical loading, the alternating stresses and strains can initiate and propagate new and existing flaws. This underlines a need for research on the fatigue of materials. Moreover, conditions that may influence material degradation mechanisms at the surface of components, such as coolant environments and surface conditions, must be considered. When assessing material performance, the surface and subsurface state of parts and components is vital to improving resistance to cracking in service. In the case of materials used to build reactor pressure vessel (RPV) and internal reactor components, neutron irradiation induces changes in material microstructure which has a noticeable influence on their mechanical properties. Generally, long exposure of metallic materials to neutron irradiation increases their brittleness, which has to be monitored during service time. In the case of RPV, which is essential for preventing the release of radionuclides and safe operation of the NPP, surveillance specimens are used to monitor neutron irradiation-induced changes in material properties. Due to the limited capacity of surveillance capsules in nuclear reactors testing methods should prioritize the efficient use of the available space. Miniaturization of testing specimens is not straightforward, and additional analyses are required to introduce corrections to correlate laboratory testing to real structure performance. Translation of the laboratory results from tests on relatively small specimens requires deep scientific understanding. Two main research paths are visible in the projects described in this paper:

- Better understating of phenomena related to fracture and fatigue of materials used to build reactor components (environmental, surface, and scaling effect),
- Development of new testing techniques that allow for precisely determining mechanical properties with a relatively small amount of material needed (optimization of material usage in surveillance programs, upscaling from laboratory to real size components, new specimen designs).

The following sections will briefly describe each project with an emphasis on their common research domains.

2 MEACTOS – Mitigation of environmentally assisted cracking through optimization of surface

Environmentally Assisted Cracking (EAC) is one of the major failure modes occurring in light water reactors (LWRs), affecting safety and nuclear energy production. The condition of surfaces exposed to the primary coolant plays the main role in the susceptibility of components to EAC. Despite its relevance, many national and international guidelines and standards do not address the surface condition of critical components in NPPs [1].

The MEACTOS project aimed to address this critical issue by identifying and quantifying the link between EAC initiation susceptibility and the surface layer produced by various surface machining and treatment techniques. The specific surface conditions to be considered including those resulting from current procedures of fabrication and in-service repair for nuclear components as well as from mitigation techniques, which can be applied in-service or as a final treatment during fabrication.

The improvement in the resistance of alloys to surface and subsurface cracking is related to optimizing the residual stresses induced by machining and the microstructure. Operating experience and studies have shown that producing compressive residual stress in the surface/near-surface regions improves the resistance to EAC [2,3].

MEACTOS aimed to quantitatively assess advanced surface machining and treatment techniques to produce surface modifications via generating a compressive residual stress layer [4,5] and/or an improved microstructure [6–8] over those presently attained with current nuclear industry processes.

The effect of the surface machining and treatment technique on the material's EAC initiation behavior was quantified using accelerated testing methods developed in previous projects funded by the European Commission: NUGENIA+ projects MICRIN+ (MItigation of CRack INitiation) and ASATAR (Development and Analysis of the Suitability of Accelerated Testing methods for Assessing the long-term Reliability of environmentally assisted cracking of nuclear components). These methods are constant extension rate tensile testing (CERT) using tapered specimens [9] and multiple factor acceleration testing using notched tensile specimens [10]. The link between laboratory testing and component behavior has been examined in terms of EAC models.

The structure of the project and the relations between work packages are shown in Figure 1. In addition, this figure shows the project relationships between the work packages and the structure of the project and includes the projects of the NUGENIA+ call, on which the MEACTOS project has been based.

During the first project workshop, where state-of-the-art (SOTA) materials, manufacturing techniques, and test procedures were discussed, the consortium agreed on the interest in evaluating advanced manufacturing techniques according to two approaches: one as a possible mitigation technique, applicable as a treatment in those components where cracks have been reported in service and on the other hand as manufacturing techniques for new components. In terms of mitigation techniques, it was decided to also test a technique applied commercially to mitigate the effects of EAC, such as peening. Shot peening was included as a previous step in understanding other commercial techniques, such as cavitation, jet, or laser peening.

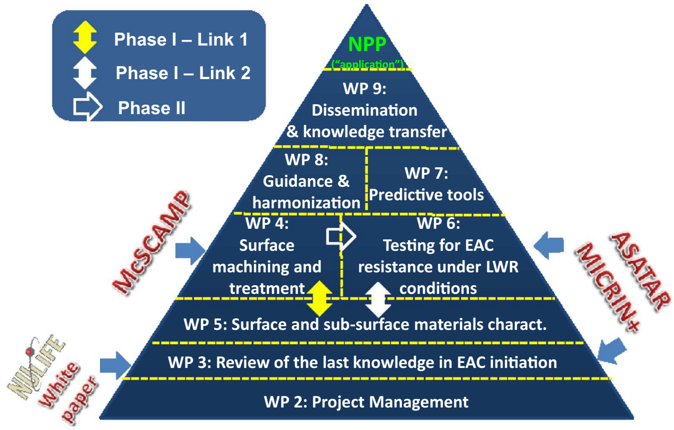

Fig. 1. WP structure of MEACTOS project and interaction with previous projects from NUGENIA+ call.

A comparison of the EAC resistance of surfaces machined by conventional practices with those obtained by advanced methods was made. Firstly, cryogenic CO_2 and cryogenic CO_2 + MQL (Minimum Quantity of Lubricant) machining was considered. The use of cryogenic CO_2 improved the roughness of the surface, as well as the level of residual stresses. However, it was observed that the surface hardness was increased markedly, which has been shown to be detrimental to the crack resistance of stainless steels in high-temperature oxygenated aqueous environments. Therefore, based on the recommendations of the partner responsible for advanced machining (Nuclear Advanced Manufacturing Research Center, NAMRC), the use of cryogenic CO_2 as coolant/lubricant was replaced by supercritical CO_2.

The possible benefits in terms of lubrication and behavior of the machined layer were evaluated throughout the project. Some preliminary results provided by NAMRC regarding machining maps using supercritical CO_2 + MQL indicate the possibility of generating compressive residual stresses under a certain combination of machining parameters (tool feed, lube/coolant injection nozzle diameter, flow rate, etc.).

Figure 2 compiles the decisions made in the SOTA workshop regarding materials to be tested, machining processes, additional surface treatments, and testing environments. The experimental campaign was divided into two phases. In the first one (screening phase), the objective was to determine threshold stress for crack initiation, and in the second phase (verification and validation), the aim was to obtain crack initiation times in-service conditions.

The results of both experimental campaigns served to feed the models of Work Package 7:

- EngInit: model proposed by SCK CEN, which defines cracking when a certain damage index has been reached. That model requires mechanical and environmental variables, such as strain rate, level of plastic deformation, and stress.
- ACETMA: purely empirical model proposed by CVR, based on some "acceleration factors" related to mechanical and/or environmental variables determined during the screening phase (task 6.1). These acceleration factors were used to determine initiation times for specimens tested in various service conditions and were determined during the verification and validation testing phase (task 6.2).
- Local Model: model proposed by EDF. This phenomenological model was applied exclusively to the Alloy 182 and is based on the preferential grain boundary oxidation as the main degradation mechanism. The model is implemented in the "Coriolis" finite element program developed by EDF in recent years and takes into account geometric, thermodynamic as well as kinetic parameters.

The main conclusions obtained from MEACTOS project are summarized below:

- The proposed machining with supercritical CO_2 does not seem to have any benefit compared to the traditional procedures in the case of stainless steel in any of the environments tested, even after applying a thickness reduction of around 14% by cold rolling. However, for Alloy 182, although with considerable dispersion in the results, machining with supercritical CO_2 slightly improves the behavior in LWR environments.
- Even with comparable results in terms of resistance to cracking, machining with CO_2 has environmental benefits since it reduces pollution and waste management of petroleum products. Likewise, from the operational point of view, it allows "in-situ" machining of components and the robotization of the process.
- In all cases, the outermost surface shows an ultrafine grain layer, which thickness depends on the process applied. Although affected by a notable dispersion in the results, the thickness of the layer varies in the direction from advanced machining through conventional machining and finally to manual polishing. At least for A 182, the improvement of resistance to crack initiation varies in the same direction, so, in principle, for this alloy, the crack resistance relies on the microstructure of this nanostructured layer more than on the possible residual stresses induced by machining.

Experimental results and calibrated models were used to prepare guidelines for mitigating EAC in Alloy 182 and 316L stainless steel in LWR environments by optimizing surface treatment. The project output was presented to the community at the final workshop. Partners will disseminate those results themselves once the project has finished.

3 INCEFA-SCALE – extrapolation of environmentally assisted fatigue results from laboratory to real components

Fatigue assessments are an important part of justifying the structural integrity of the nuclear plant, and hence their safe operation. There are multiple codes that provide methods for accounting for the fatigue behavior of the materials of plant components under relevant operating conditions [11–14]. For cases beyond the perceived

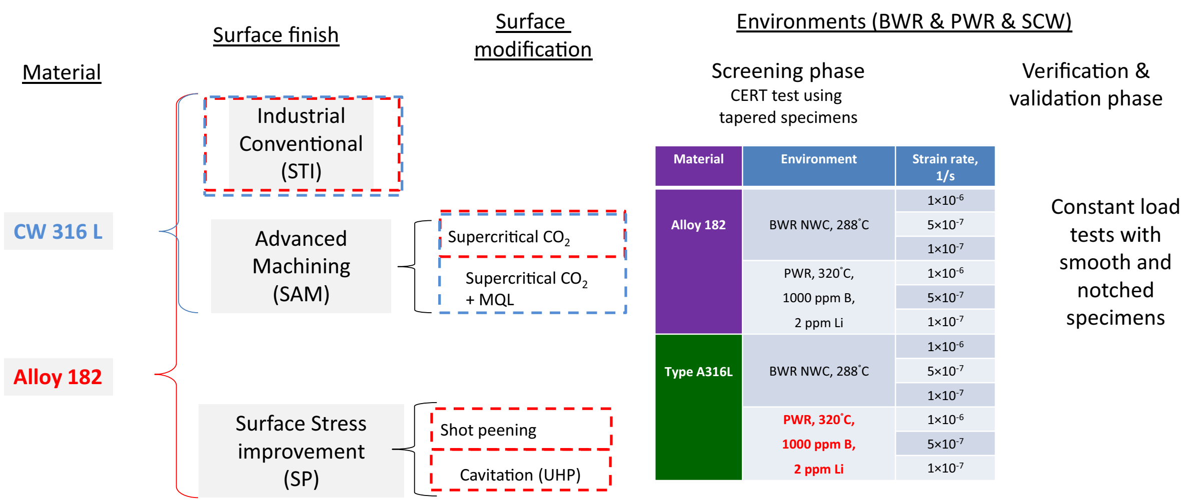

Fig. 2. Scheme of materials/test conditions carried out in the two experimental phases of the project.

scope of the codes, the technical basis for the methods may be presented separately. Environmentally-Assisted Fatigue (EAF) is one example where NUREG/CR-6909 presents the methods for accounting for an LWR environment [15].

There appears to be a discrepancy between the plant operational experience and the potential difficulty of obtaining an acceptable fatigue assessment result using the EAF methods [16]. This discrepancy has been the subject of substantial research efforts to understand the contribution of surface finish [17,18], strain rate [19], and thermo-mechanical fatigue [19]. These areas have yielded improved methods incorporated into codes, reducing this gap but not completely closing it.

A potential research area under investigation focuses on the effect of Variable Amplitude (VA) fatigue and how it is handled within the available codes. Taking the ASME Boiler and Pressure Vessel Code (BPVC) as an example, loading history (including VA loading) is intended to be accounted for in the application of adjustment factors on life and stress or strain to the mean air curve when forming the design fatigue curves [15]. However, a detailed treatment of the effect of loading history within an EAF assessment was not presented in NUREG/CR-6909, which creates a gap in dealing with this behavior [15].

The method defined in NUREG/CR-6909 for accounting for VA loading within the ASME BPVC is to use the modified Goodman relationship to account for mean stress effects on the best-fit curve [15]. The fatigue design curve is constructed by the application of adjustment factors that are considered to account for material variability and data scatter, size and geometry, surface finish, and the loading sequence. Once the relevant alternating stress intensities are calculated, Miner's rule is applied to these design curves for each cycle in the VA waveform to calculate partial usage factors [15]. The environmental cumulative usage factor (CUF_{en}) is calculated by applying the environmental effect F_{en} associated with each cycle in the VA waveform to the partial usage factors. The failure criterion is when the CUF_{en} reaches unity.

Research has indicated that the effect of VA loading on fatigue lifetime may be accounted for by understanding the material's behavior and resulting mean stress [20,21]. Therefore, a potential over-conservatism may exist within the current code method where the use of a mean stress correction combined with the loading history transference factors could double account for the effect of VA loading. Work on alternate methods that appear to better account for VA fatigue than current codified methods is already underway [22]. However, data studying the effect of VA fatigue on other materials in nuclear plant-relevant environments is very limited, and further work would be necessary to justify the adoption of such alternative methods.

Further opportunities to address the gap between material behavior in laboratory testing and plant experience investigation of multi-axial fatigue, notch sensitivities, and their incorporation into an EAF assessment [16]. Although methods are available to account for the complex loading states produced by such features and multi-axial loads, experimental data capable of differentiating or supporting their use is limited and unable to differentiate between the more advanced methods.

The goals of INCEFA-SCALE are to improve assessments of fatigue lifetimes of NPP components when subjected to EAF loading and provide guidance on the transferability of laboratory-scale testing results to component-scale behavior.

INCEFA-SCALE will achieve these goals by:

- Developing a better understanding of material performance through characterization of laboratory-tested fatigue specimens and data mining of the MatDB database (the JRC administered database in which INCEFA-PLUS and other data are already stored);
- Novel testing focused on defining the effects of Variable Amplitude (VA) loading, surface finish, notches, and multi-axial loading on the fatigue lifetime of 316L stainless steel;
- Delivering guidance, based on the technical output of the project, on the transferability of laboratory-scale

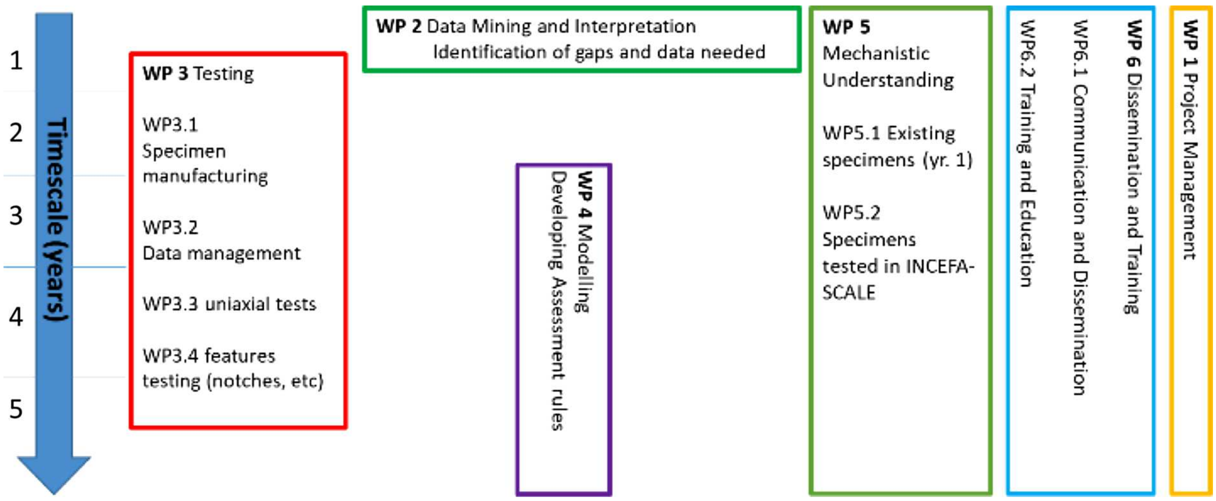

Fig. 3. INCEFA-SCALE work package structure plus timescales for WP activities.

data to component scale and plant-relevant loading conditions.

The INCEFA-SCALE project comprises six Work Packages (WP), illustrated in Figure 3.

The interactions between the INCEFA-SCALE WPs shown in Figure 4 highlight the substantial level of integration and collaboration within the project. Collaboration between the WPs will be essential to the success of INCEFA-SCALE. The WPs will need to inform and effectively define requirements between each other. For example, the collaborative definition of the test conditions in WP3 supports the ongoing work in WP4 and WP5. As test data becomes available from WP3, the assessment methods investigated in WP4 will evolve and may require future testing in WP3 to change so that further development can take place. An integral part of this way of working is the development of the existing experimental methods in WP3 and WP5 to support the provision of the information required to inform fatigue assessments.

The study of VA loading in INCEFA-SCALE is new to many of the testing laboratories and has required improvements in experimental control and data acquisition, as well as new procedures for extracting information from fracture surfaces developed through round-robin programs [23].

The integration of WP2 into WPs 3, 4, and 5 will allow the developments of INCEFA-SCALE to be placed into context with the global position of fatigue for the nuclear industry and ensure decisions made by these WPs are fully informed. This approach will maximize the impact, usefulness, and success of INCEFA-SCALE.

Since the project kick-off in September 2020, there have been several full project meetings and multiple further virtual gatherings of sub-groups with interests in mechanistic understanding, testing, data mining, and modeling activities. Key achievements at the time of writing are:

- A collaboration with EPRI through a non-disclosure agreement (NDA) (under development) has been agreed upon.
- WP2 has completed the development of a software application that will facilitate data mining activities using the information stored in MatDB. Additionally, significant external data will become available for examination from external collaborators, i.e., EPRI. Since work continues to overcome commercial challenges to the International Fatigue Database Agreement, further data will eventually be forthcoming from the US Nuclear Regulatory Commission (USNRC) and the Japanese Nuclear Regulation Authority (NRA).
- The WP 3, 4, and 5 members have combined thoughts on the aims of the respective WPs and the prioritization of the study areas.
- The WP3 uniaxial testing has started with support from the recently established Expert Panel and Data Management Committee.
- WP3 features testing is being defined by a Working Group specifically brought together to define and prioritize the scope of testing.
- WP4 modeling and assessment has kicked off and defined the scope of the WP. Discussions will occur throughout 2022 to create a clear plan for WP4 to deliver its aims.
- WP5 characterization continues to progress and support the INCEFA-SCALE aims. A round robin for striation counting has reached completion and issued a common method for calculating striation spacing [23]. The WP team is now in the process of engaging with the consortium to analyse pre-test specimens.
- WP6 has set up project dissemination channels consisting of a public website (https://incefascale.unican.es), ResearchGate, Twitter, and LinkedIn presences.

4 FRACTESUS – miniaturization in fracture toughness testing in surveillance programs

Acronym FRACTESUS stands for "Fracture mechanics testing of irradiated RPV steels by means of sub-sized

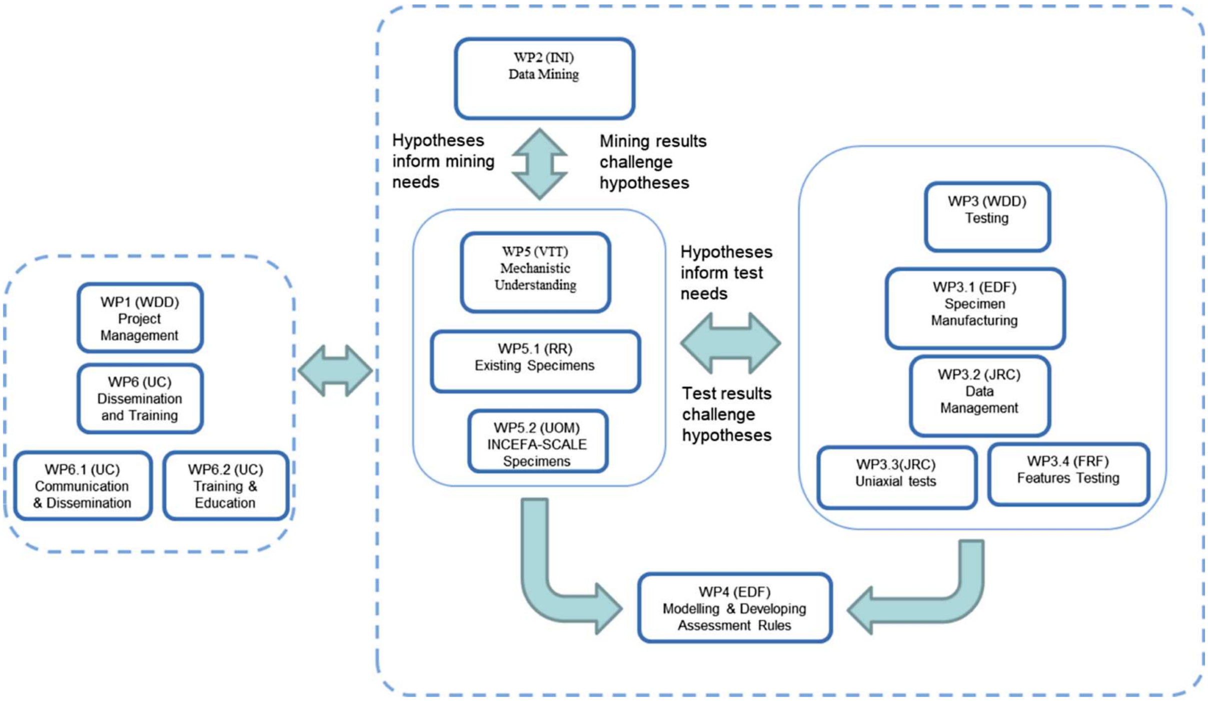

Fig. 4. INCEFA-SCALE work package inter-dependencies.

specimens". The project started in October 2020 and is planned for 4 years. Twenty-one partners supported by the Scientific Advisory Committee and End User Group are engaged in the research, which is aimed to validate the usage of miniature compact tension (MCT) specimens in Master Curve (MC) oriented fracture toughness (FT) testing. Details on the project consortium, its main aims, and its current status can be found on its official website [24].

As was already mentioned, many reactors operating today are close to the end of their initially planned service time. However, in many cases, their service time might be noticeably prolonged (long-term operation – LTO perspective), which is beneficial from the point of view of a still growing demand for electric power. In such cases, the remaining surveillance material usage has to be optimized, and miniaturized specimens have to be periodically tested, instead of large ones, to control if the irradiation-induced change of material mechanical properties is below the limits described in appropriate safety codes. As it is shown in Figure 5, MCT specimens allow for saving a noticeable amount of material. They might also be produced from already tested larger specimens, giving an opportunity for the re-usage of the surveillance material.

The usage of miniaturized specimens, especially for FT testing, is not straightforward. There are many concerns raised by various stakeholders regarding the reliability of the MCT test of RPV materials. The successful implementation of the FRACTESUS project is possible only if all the stakeholders' concerns have been considered at the very beginning of the project. Although miniature specimen usage is permitted even in the current MC standard [25], there are still many concerns related to the reliability of the results, briefly described in [26], and the current Technology Readiness Level (TRL) of MCT testing is estimated to 5. The first results of inter-laboratory trials show successful implementation of MCT specimens [27,28]. However, there are still many open questions that have to be answered before enabling the movement of this technology to TRL 7. That is the ambition of the FRACTESUS project. For instance, various laboratories use slightly different specimen geometries and the different locations of clip gauges, which might affect FT results and Master Curve reference temperature T_0 determined in accordance with ASTM E1921 standard. Production of miniaturized specimens, especially in hot cell conditions, is also challenging. Moreover, in the case of miniaturized specimen usage, an allowable testing temperature range is much limited compared to larger counterparts made of the same material. Furthermore, the potential inhomogeneity of material might have a much larger influence on the final testing results when only a small volume of material is used for specimen preparation. Having all those concerns in mind, the reliability of MCT testing has to be proved for various types of RPV steels, taking into account their initial properties, as well as properties change during exploitation, to convince stakeholders of their application.

The work in the project is planned within seven main Work Packages (WP), as schematically presented in Figure 6. Details of the structural organization of the project and main deliverables are presented in [29].

The work on identifying the knowledge gaps and the main stakeholders' concerns is foreseen in WP1. First of all, the project Scientific Advisory Committee (SAC) and End User Group (EUG) have been set up to provide the

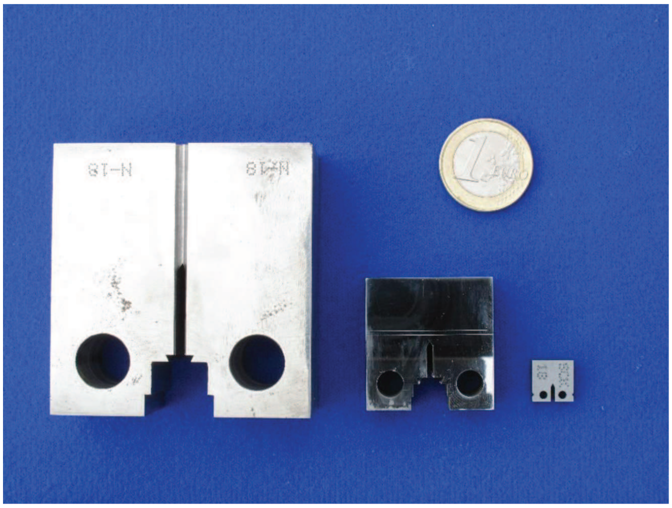

Fig. 5. Standard and miniaturized specimens for FT testing. MCT specimen is the rightmost.

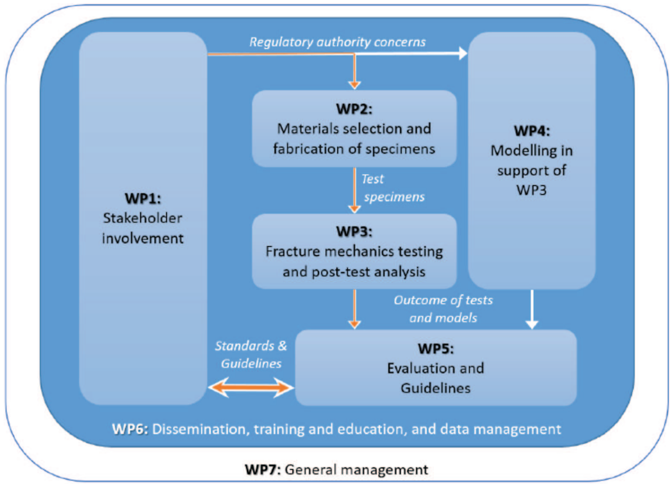

Fig. 6. Organisational structure of FRACTESUS.

expertise and to assess whether the information produced as a part of WP1 is appropriate to inform other work packages (WP). Work in this WP is oriented on three main areas: (1) to understand the content and limitations of current standards, (2) to understand the concerns of the various nuclear regulators, and (3) to understand the current extent of using sub-sized specimens in fracture toughness testing by operators and research organizations. All those topics, as well as initial material candidates for testing, were discussed at the 1st SAC/EUG meeting held in February 2021, and the final document collating identified concerns is now being finalized.

WP2 of the FRACTESUS project is devoted to the selection of materials for both irradiated and unirradiated specimens and MCT specimens machining. Having in mind the main stakeholders concerns, identified in WP1, the final test matrix has been prepared [30]. More than 650 MCT specimens are planned to be tested within WP3 of the FRACTESUS project. Materials for testing have been selected, taking into account already existing, reliable database of fracture toughness (FT) results, availability of materials for testing within numerous round-robin exercises planned in the project, and the coverage of a wide spectrum of properties (expected T_0 and upper shelf energy). It is worth noticing that not only base materials (BM) but also welds will be tested.

The general assumptions of the FRACTESUS material selection and testing processes are described in [26]. The main part of the testing campaign is focused on the round robin (RR) exercise, where seven selected materials will be tested. Specimens for each material will be produced and tested by at least three institutions. The results from MCT testing will be compared to the results obtained in large specimen tests. Due to the evolution of the MC standard from its introduction in 1997, the results for large specimens for the materials selected to be tested were reprocessed according to the current version of the standard with the usage of the same software [31]. Thus, the results delivered from MCT tests will not be biased by the calculation methodology. It is very important due to the complexity of MC calculations. More unirradiated and irradiated RPV materials, widely used in the nuclear industry, will be tested by the project partners. Finally, guidelines for MCT usage will be developed within WP5 in the final stage of the project. In addition to MCT testing, some project partners will provide in-kind contributions related to miniaturized specimen testing techniques, such as small punch tests [32]. At the date of this paper's writing, the unirradiated specimen preparation task is being finalized, and the first series of specimens have been tested in accordance with MC standards. Initial preparation of the irradiated 73W material, which has to be tested independently by seven different institutions, has also started.

The results comparison between large and MCT specimens will be supported by the numerical modeling planned in WP4. The first large task in WP4 is a numerical RR exercise. The institutions involved in this task have to provide the results of numerical modeling for a compact specimen of 25 mm thickness (1T-CT) and MCT specimens according to the RR specification with strictly imposed parameters for the most important model features (geometry, loading steps, material law, meshing near the crack tip, output data format). However, some options were left to be freely chosen by each institution (FEM code, model symmetry, meshing outside of crack tip region, way of loading introduction in the model) in their simulations. This task will allow identifying all the discrepancies related to the specific code usage and an individual interpretation (human factor) of RR specification before further usage of the models in the activities directly supporting experimental results interpretation. At the moment of the paper preparation comparison of the results delivered by nine institutions is ongoing.

Similarly to the other two projects described in this paper, dedicated WPs related to the results dissemination (WP6) and general project management (WP7) are also present in the FRACTESUS project.

5 Summary

The three H2020 projects described in this paper aim to increase the safety of nuclear reactors. Safety-oriented research activities have to focus on a better understanding of the material's resistance to complex degradation mechanisms involving static and dynamic loading. These research activities must also integrate how environmental and surface conditions influence these materials' degradation mechanisms. Moreover, new material testing techniques have to be developed and validated to optimize material usage and correlation of the properties determined in laboratory conditions with large components and structure behavior. The output of multidirectional research activities is important to ensure a longer and more reliable service of currently operated nuclear power plants and will also be taken into account during new facilities design. The results delivered in MEACTOS, INCEFA-SCALE, and FRACTESUS projects will have an influence on providing electric power in a safe and sustainable way to meet the ever-growing demand of modern European and worldwide societies.

MEACTOS investigated the influence of various machining techniques on EAC. It was proved that advanced surface machining methods have nearly the same impact on EAC initiation behavior as standard methods, i.e., they are not inferior. In combination with benefits like higher cutting speed and less pollution by lubricants, those methods are, therefore, a promising alternative to standard procedures. They can be used for future applications or if standard methods cannot be applied (e.g., robots for pipe repair).

INCEFA-SCALE is improving the safety of nuclear plant operations by improving fatigue assessments and working towards resolving the discrepancy between operating experience and the perceived difficulty in achieving an acceptable fatigue assessment result. This goal will be achieved through improving the understanding of the behavior of materials subject to fatigue loading through material characterization, improved experimental methods for studying EAF, and the provision of new methods and guidance for accounting for plant-relevant loading conditions in fatigue assessments.

The work planned in the FRACTESUS project is related to the validation of a new FT testing technique that can be used in surveillance programs for RPV materials and is aimed at a better understanding of scaling effect phenomena in FT testing. The output of the project is expected to elevate the TRL of MCT testing technology from 5 to 7. That will be an important step before its final implementation by the NPPs operators.

Conflict of interests

The authors declare that they have no competing interests to report.

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Data availability statement

This article has no associated data generated and/or analyzed.

Author contribution statement

TOMASZ BRYNK: coordinator of the FRACTESUS project, Writing – original draft, Writing – review and editing, Visualization, Project Administration. FRANCISCO JAVIER PEROSANZ LOPEZ: coordinator of the MEACTOS project, Writing – review and editing. ALEC MCLENNAN: coordinator of INCEFA-SCALE, Writing – review and editing

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