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# FRACTESUS Project overview: objectives, organisation and initial findings

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**Abstract**

This paper presents an overview of the FRACTESUS project, which is part of the EURATOM work programme 2019-2020, topic NFRP-04: Innovation for Generation II and III reactors. FRACTESUS aims to prove the reliability of determining the fracture toughness of reactor pressure vessel steels using sub-sized specimens, with special emphasis on mini-CT specimens (or 0.16 CT specimens). To achieve this main goal, 22 organisations from Europe, the USA, Canada and Japan launched the project in 2020, completing the first phase of the experimental works in 2022. After providing some background information about the project objectives and organisation, the present work gathers some initial findings and conclusions obtained so far.


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*Keywords:* FRACTESUS; mini-CT specimens; fracture toughness; master curve; reactor pressure vessel steel.

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## 1. Introduction

In the European energy context, the long-term operation (LTO) of the nuclear power plants (NPPs) appears to be an attractive option to achieve the energy transition goal proposed by the European Union, which consists of the decarbonization of the energy system by 2050.

The safe operation of NPPs is of crucial importance, as any failure can have catastrophic consequences. Therefore, to achieve LTO of the NPPs, it is necessary to guarantee the structural integrity of the reactor pressure vessel (RPV) (Shah & MacDonald, 1993). The RPV is the primary safety concern for several reasons: it is the main barrier against the release of irradiation into the environment; its failure is excluded by design in normal or accidental scenarios, it cannot be replaced, and it suffers from hardening and toughness degradation.

For these reasons, NPPs have implemented surveillance programmes to periodically monitor the fracture toughness of the RPV steel to ensure safe operation. These surveillance programmes consist of removing, from time to time, some specimens from the surveillance capsule (located inside the RPV) to be tested. For historical reasons, the most common technique for monitoring the embrittlement of the RPV steel in the nuclear industry has been the Charpy impact test, which calculates fracture toughness indirectly. However, for many RPVs currently in operation, the quantities of material available in the surveillance capsules may not be sufficient for the continuation of the surveillance programmes and thus, ensure the long-term operation of such NPPs.

To address this issue, the FRACTESUS project (Cicero et al., 2020) was launched in October 2020, following its approval under the EURATOM 2019-2020 programme, section NFRP-04: Innovation for second and third generation reactors. The project proposes an innovative approach using miniature fracture test specimens obtained from broken Charpy specimens (10 x 10 x 55 $mm^3$) to directly measure fracture toughness, thus reducing the material required for monitoring tests. The reference specimen selected by the consortium is the miniature compact tensile specimen (abbreviated as mini-CT, 0.16 CT or MCT) and whose main dimensions are 10 x 9.6x 4 $mm^3$, as shown in Figure 1. The mini-CT specimen is small enough to allow up to eight specimens to be machined from a single broken Charpy specimen. The final objective of the project is to demonstrate the usability of mini-CT specimens to determine the reference temperature ($T_0$) of RPV materials, which has already been applied in previous works with promising results (Miura & Soneda, 2010; Yamamoto et al., 2014).

The use of other miniature specimens, such as the Small Punch Test (SPT), whose geometry has even smaller dimensions (10 x 10 x 0.5 $mm^3$) and allows more than thirty-five specimens to be machined from a single broken Charpy specimen, is also considered as an in-kind contribution (Altstadt et al., 2021). The project will compare the results obtained using mini-CT specimens with the test databases of standardised fracture toughness specimens. This miniaturised characterisation approach brings several benefits such as the ability to characterise the local properties of a heterogeneous material, a significant increase in the monitoring database with direct measures of fracture toughness, providing greater confidence in the data, and a reduction of the volume of irradiated material, which is especially interesting in terms of safety.

In addition, the FRACTESUS initiative will have positive implications not only for GEN II and Gen III+ nuclear systems, but also for upcoming nuclear systems. These future systems, including Gen IV and fusion systems, will require robust structural materials capable of withstanding challenging radiation conditions. However, the process of certifying these materials and technologies through qualification programmes presents a significant hurdle to their deployment. To ensure an accurate representation of the operational conditions, qualification programmes must be conducted in dedicated irradiation machines with limited space for irradiation. Therefore, the FRACTESUS project can also provide valuable support to these qualification programmes.

With all this, the FRACTESUS project goals are to prove the applicability and reliability of utilising mini-CT specimens to analyse the fracture behaviour of irradiated RPV material to nuclear authorities and regulators. This project is in line with the objectives pursued by the European H2020 framework programme, which aims to ensure the continuous improvement of nuclear safety, security and radiation protection, while also contributing to the long-term decarbonisation of the European energy system in a safe and efficient manner.

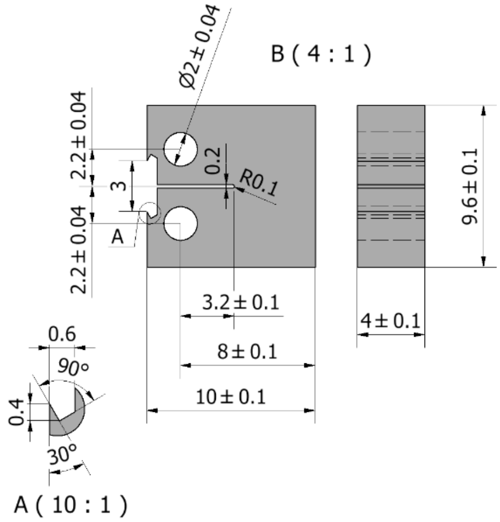



Figure 1. Geometry of the mini-CT specimens used in Fractesus. Dimensions in mm.

## 2. Fractesus project description

The FRACTESUS project involves 22 organisations from Europe, Japan, the United States and Canada, and is divided into six work packages (WPs), as shown in Figure 1 (a), while all the project participants are presented in Figure 1 (b). WP1, led by NNL, focuses on identifying regulatory authorities' concerns and possible limitations in regulations regarding the use of mini-CT specimens in NPP surveillance programmes. WP2, led by VTT, oversees material selection and fabrication of the specimens that meet specific requirements, such as having a large database of characterised material and being sensitive to irradiation. WP3, led by HZDR, focuses on performing fracture mechanics tests with mini-CT specimens of irradiated and non-irradiated materials at different temperatures, complemented by other tests based on miniaturised specimens (e.g., SPT, micro hardness tests). WP4, led by CEA, is dedicated to numerical modeling to provide a robust modeling strategy for the interpretation of experimental data. WP6, led by the University of Cantabria, is responsible for the communication and dissemination of the project and management of the experimental data generated during the project. Finally, the overall management of the project is led by SCK CEN through WP7.

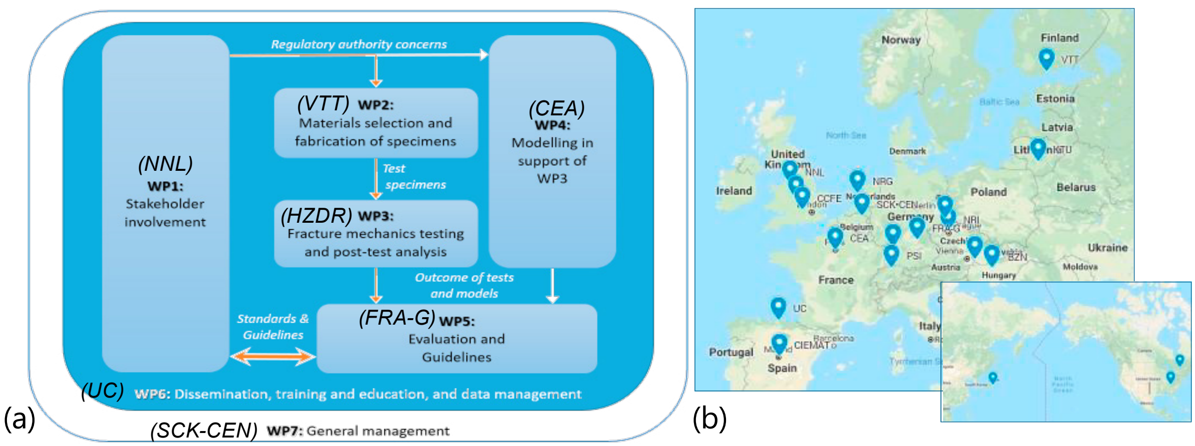



Figure 2. (a) The organisation of the FRACTESUS Project, with the different WPs involved and (b) the project participants.

The main objectives of the projects are to demonstrate the reliability and the enhanced confidence in using mini-CT specimens to measure the fracture toughness of RPV steels, to demonstrate the applicability of the mini-CT specimens in combination with the master curve approach for the characterisation of the ductile-to-brittle transition zone and to establish the foundations for the inclusion of mini-CT specimens in future codes and standards.

Therefore, by following the technology readiness levels (TRLs) proposed by the European Commission (as shown in Figure 4), and assuming the mini-CT technology is at level five, FRACTESUS aims to reach level seven, which will mean that the usability of the mini-CT specimens in NPPs will have been demonstrated.

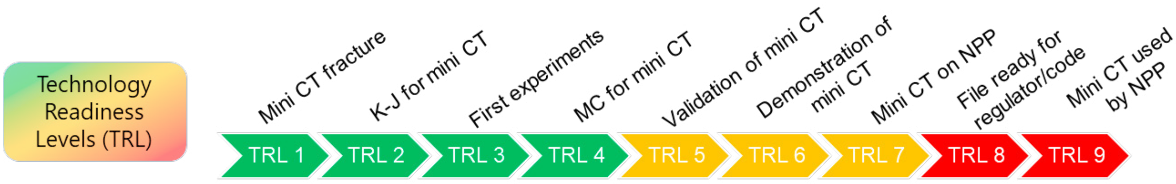



Figure 3. Technological readiness levels of the project.

## 3. Project status

During the first half of the project, significant progress has been made by the WPs, which will be discussed below. WP1, which concerns stakeholder involvement, has been completed, and several tasks were carried out under it. The Scientific Advisory Committee (SAC) and End User Group (EUG) were established and had a productive meeting. The current standard practices for fracture toughness measurements used in different countries were summarised, as well as the limitations associated with miniaturising fracture toughness specimens. A survey was conducted among nuclear regulators, operators, and research organisations in various countries to gather their viewpoints on the use of master curve techniques and mini-CT specimens. Finally, the deliverable D1.1 was completed (Swan et al., 2022), combining the contributions from all parties into one document and making recommendations on how to address stakeholder concerns using the FRACTESUS project.

WP2 involves the selection of the materials and fabrication of specimens for fracture toughness testing. Within this WP, a survey was conducted among participants to identify available materials, specimen design, and fabrication methods, and meetings were held to agree on material selections and limits on specimen design. The final test matrix for the selected materials was included in the deliverable D2.1 (Arffman, 2021). Each provider delivered the corresponding material to the testing partners, who successfully fabricated and fatigue pre-cracked mini-CT specimens from unirradiated materials. Challenges in specimen preparation were related to fatigue pre-cracking, which will be further investigated. The fabrication of unirradiated specimens, including the final specimen dimensions and the experiences and remarks from the survey, were included in the deliverable D2.2 (Arffman & Lappalainen, 2022). The fabrication and fatigue pre-cracking of irradiated specimens are ongoing.

WP3 focuses on fracture mechanics testing and post-test analysis. In the initial phase of the fracture mechanics testing with unirradiated materials, a series of round robin tests were conducted. Six interlaboratory studies were carried out with several participants using different RPV steels, including 15Kh2MFAA, 73W, A533B (JRQ), A533B LUS, SA508 Cl.3, and ANP-5. All planned round robin tests have been completed by most of the partners. The results were gathered in the deliverable D3.1 (E. Altstadt et al., 2023). Regarding the fracture mechanics testing of mini-CT specimens on irradiated RPV steels, a single round robin test on 73W has been planned along with two additional individual test series. This activity is still in progress. Another important task being performed in this WP involves fractography on tested specimens, both unirradiated and irradiated. The progress on this task can be summarised by the elaboration of a fractography procedure by NNL and HZDR, and the reports of some fractography analysis, but the activity is still ongoing. Additionally, supporting experiments based on small specimen test techniques (e.g., SPT) are being carried out.

WP4 aims to support the experimental investigation of WP3 by providing numerical simulations to understand and analyse the experimental results. Specifically, WP4 intends to provide interpretations and recommendations for the standardisation of the use of mini-CTs to safety authorities. The first stage of this WP consisted of a numerical round robin with all the participants involved in WP4, to ensure clear comparability of subsequent calculations without further post-processing of the data. With the finalisation of the round robin, all codes have been benchmarked, and they are ready for use in support of the experiments. Currently, numerical efforts are ongoing to compare the stress/strain fields with the experimental data generated in WP3 and to investigate related factors such as fracture size effect and loss of constraint and geometry factors, among others. Additionally, numerical simulations are being carried out to support experimental tests of other small specimen techniques.

WP5 is mainly focused on the evaluation of the results and the proposal of the guidelines. Currently, the project has just begun the interpretation of the results generated in WP3 and WP4. A database has been created to summarise all experimental data for internal use, and the results will be made available through open access at the end of the project. Once the evaluation is completed, the next step will be to develop guidelines for the testing procedure, including fatigue pre-cracking, side grooving, and the selection of test temperature, COD measurements, and specimen orientation. Additionally, this WP is dedicated to establishing links with ongoing national and international projects, to facilitate the scientific exchange of experience and results. The Fractesus project has established links with several ongoing projects, including STRUMAT-LTO (STRUMAT-LTO, 2020), Kleinproben (a German national project), DELISA-LTO (DELISA-LTO, 2022), and ENTENTE (ENTENTE, 2020), for potential exchange and cooperation.

WP6 is responsible for maximising the benefit of the project for the whole of Europe through communication and dissemination activities. In this sense, profiles on social and scientific networks including Twitter, LinkedIn, Facebook and ResearchGate are available. So far, three peer-reviewed JRC papers have been published (Altstadt et al., 2021; Sánchez, Cicero, Arroyo, et al., 2023; Sánchez, Cicero, Kirk, et al., 2023) and numerous contributions to national and international events have been made. Of course, this activity is still ongoing. Additionally, the project roadmap has been defined with the Data Management Plan (DPM) (Cicero & Arroyo, 2021), and the testing protocols and reporting formats have been described (Cicero et al., 2021). All the testing results will be open-access through Zenodo-OpenAIRE and the ENTENTE database by the end of the project.

Finally, the progress and management of the FRACTESUS project are overseen in WP7. The project management platform consists of a public website (https://fractesus-h2020.eu/) and a SharePoint site with restricted access for partners. The project has had several virtual meetings, including executive meetings, progress meetings and general assemblies, hosted by SCK CEN.

## 4. Experimental Round Robin activities

As briefly mentioned above, the FRACTESUS project has selected 6 steels that are highly relevant to the nuclear energy industry for its experimental round robin activities. The chosen steels meet several requirements such as having a large database of characterised material under baseline and irradiated conditions (typically with more than 400 available data), being open databases, and having materials that are sensitive to irradiation. Among the selection criteria, the amounts of Cu, P, Ni or Mn present in the steels were considered since these elements can significantly affect the mechanical and fracture properties of the materials. Likewise, steel manufactured by both forging and welding were chosen since these methods can have a significant impact on the microstructure and mechanical properties of the material. In addition, the treatments and aging to which the steels were subjected, either thermal or by neutron irradiation, were also considered. These processes can modify the mechanical properties of the materials and it is important to evaluate their effect on the fracture resistance. Finally, the matrix of selected steels was intended to cover a wide range of reference temperatures ($T_0$), which is an important parameter in the evaluation of the material fracture toughness. As shown in Table 1, all these materials cover the widest possible range of variability in terms of chemical composition, fabrication method, treatment/aging, and reference temperatures.

The FRACTESUS project aims to evaluate the fracture toughness of different steels under both irradiated and non-irradiated conditions. The fracture characterisation of the steels will be carried out using the master curve methodology, which makes it possible to determine the fracture toughness of the materials in the ductile-to-brittle transition region, by following the standard ASTM E1921 (ASTM E1921, 2021). To guarantee the quality of the results, round robin exercises are being carried out, in which the same material is tested by different laboratories for comparative purposes. Test matrices have been designed for the round robin of non-irradiated material (see Table 2) and the round robin of irradiated material (see Table 3), and it is estimated that a total of 656 fracture toughness tests will be performed with mini-CT specimens.

The preliminary results obtained from mini-CT specimens under non-irradiated conditions showed a reasonably good correlation in $T_0$ when compared with conventional specimens for the 15Kh2MFAA material, A533B LUS, and ANP-5 material, but still significant differences between partners were found, probably due to the high sensitivity of the mini-CT specimens to material heterogeneities. For example, the UC obtained a $T_0$ of -26.1 ºC and 7.2 ºC for the ANP-5 and the A533B LUS, respectively. These results are in good agreement with those obtained with large specimens, the difference between large specimens and mini-CT specimens being -11.9 ºC and 0.8 ºC for the ANP-5 and the A533B LUS, respectively. Figure 5 shows the corresponding results of the master curve analysis of the ANP-5 material.

On the other hand, some deviations were detected in the A533B JRQ and 73W material. In any case, the analysis of the results is being analysed and further investigation is still needed.

Table 1. List of materials studied at the RR activities together with the main properties in baseline conditions.

| Material | Type | Orientation | Provider | $\sigma_{y\,(RT)}$ (MPa) | $T_{41J}$ (°C) | USE (J) | C | Si | P | S | Cr | Mn | Ni | Cu | Mo |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15Kh2MFAA | BM | L-S | HZDR | 530 | –54 | 189 | 0.150 | 0.300 | 0.008 | 0.002 | 2.860 | 0.450 | 0.100 | 0.050 | 0.790 |
| A533B JRQ | BM | T-L | NRI | 480 | –25 | 194 | 0.180 | 0.250 | 0.019 | 0.004 | 0.120 | 1.380 | 0.820 | 0.140 | 0.490 |
| HSSI-73W | WM | T-L | SCK-CEN | 495 | –39 | 135 | 0.100 | 0.450 | 0.005 | 0.005 | 0.250 | 1.560 | 0.600 | 0.310 | 0.580 |
| SA508 Cl.3 | BM | R-C | CIEMAT | 470 | –41 | 230 | 0.190 | 0.220 | 0.008 | 0.001 | 0.150 | 1.360 | 0.930 | 0.030 | 0.520 |
| ANP-5 | WM | T-L | FRA-G | 604 | –12 | 145 | 0.080 | 0.150 | 0.015 | 0.013 | 0.740 | 1.140 | 1.110 | 0.220 | 0.600 |
| A533B LUS | BM | T-L | SCK CEN | 455 | 34 | 72 | 0.240 | 0.410 | 0.028 | 0.023 | 0.080 | 1.520 | 0.430 | 0.190 | 0.490 |

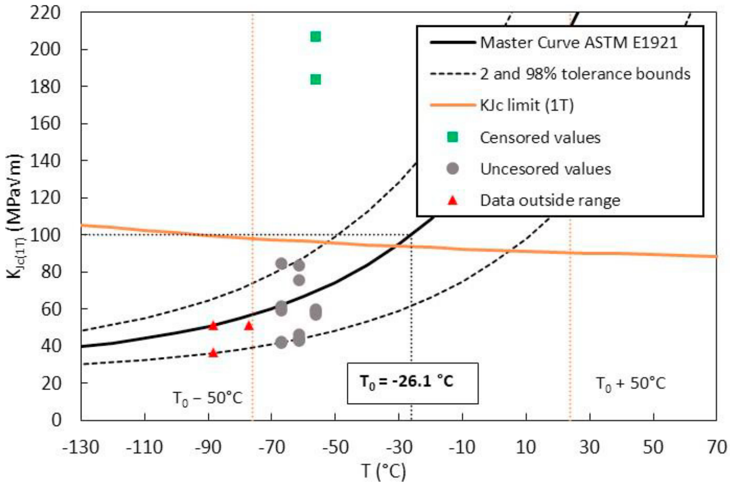
Table 2. Test matrix prepared for the RR of non-irradiated material.

| RR N° | Material | Orientation | Provider | $T_0$ (°C) | $N_{test}$ | $N_{mat}$ | Testing participant | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 1 | 2 | 3 | 4 | 5 |
| 1 | 15Kh2MFAA | L-S | HZDR | -104 | 16 | 20 | SCK CEN | CRIEPI | HZDR | VTT | |
| 2 | A533B (JRQ) | T-L | NRI | -71 | 16 | 20 | NRI | CRIEPI | PSI | CCFE | MTA- EK |
| 3 | 73W | T-L | SCK CEN | -64 | 16 | 20 | SCK CEN | CIEMAT | HZDR | VTT | UoB |
| 4 | SA508 Cl.3 | R-C | CIEMAT | -43 | 16 | 20 | SCK CEN | CIEMAT | KIT | NRG | UoB |
| 5 | ANP-5 | T-L | FRA-G | -38 | 16 | 20 | SCK CEN | FRA-G | HZDR | CCFE | UC |
| 6 | A533B LUS (JSPS) | T-L | SCK CEN | 8 | 16 | 16 | SCK CEN | CRIEPI | UC | | |

Table 3. RR prepared for the irradiated material.

| Material | $T_0$ (°C) | Orientation | Fluence [×$10^{19}$ n/cm²] | Ntest | Testing participant | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 73W | 34 | T-L | 1.5 (at ~288°C) | 16 | SCK CEN | VTT | HZDR | MTA-EK | NRI | CEA | NRG |

Figure 5. Example of a master curve analysis of the ANP-5 material.




## 4. Conclusion

Mini-CT specimens offer a wide range of possibilities and advantages for the fracture characterisation of RPV steels: multiplication of experimental data, (re)use of already tested specimens (Charpy), reduction of the volume of irradiated material for handling, possibility of measuring local toughness to detect heterogeneities, etc. However, FRACTESUS must overcome some uncertainties for the acceptance of mini-CT specimens by nuclear authorities. The final goal of the project is to address the various concerns of regulatory authorities in order to be able to introduce these miniature specimens into codes and regulations, and therefore into surveillance programmes.

In the first half of the project a number of milestones were completed, most notably the material selection matrix and the report on the current status of fracture toughness standards and testing with focus on sub-sized specimens, including stakeholder concerns. The round robin activities regarding unirradiated materials is near completion and the numerical round robin has been finalised. The preliminary results of the unirradiated round robin showed a reasonably good agreement in $T_0$ between the mini-CT specimens and larger specimens for most materials. However, the sub-set of results provided from each partner presented significant differences in some cases, most probably due to material inhomogeneities. The largest discrepancies between mini-CT specimens and larger specimens were found for the 73W and A533B JRQ materials, still under investigation. Finally, the irradiated round robin is still ongoing.

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