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FRACture mechanics TEsting of irradiated RPV steels by means of SUb-sized Specimens : FRACTESUS PROJECT

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Abstract

This work presents the overall structure of the FRACTESUS project and the progress carried out so far. The project is part of the EURATOM work programme 2019-2020, topic NFRP-04: Innovation for Generation II and III reactors. The project developments will contribute to the long-term safe operation of nuclear power plants, addressing the goals of the European Union in terms of sustainable and green energy, where the decarbonisation of the energy system is a priority. FRACTESUS intends to demonstrate the reliability of measuring the fracture toughness of reactor pressure vessel steels by means of sub-sized specimens (e.g., 0.16 CT or mini CT specimens). This will allow, among others, to notably increase the number of specimens available in the surveillance programs of the nuclear power plants.

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Keywords:

1. Introduction

Most of the nuclear power plants in operation in Europe are in the second half of their lifetime and need to comply with higher safety standards as defined in the Nuclear Safety Directive. The reactor pressure vessel (RPV) is one of

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the largest and most difficult components to be replaced in the nuclear reactor, its failure under normal or accidental scenarios being excluded by design. It is also the main barrier against the release of radioactive material into the environment. Therefore, ensuring the structural integrity of the vessel is of crucial importance for the safe operation of nuclear power plants (Shah and MacDonald, 1993). As a result, from the birth of the nuclear power plants, surveillance programmes were established to periodically monitor the fracture toughness of the RPV steel, generally using Charpy specimens (10 x 10 x 55 mm^3) placed in a surveillance capsule inside the proper RPV. For historical reasons, the Charpy impact test is the most common technique within the nuclear industry, meaning that fracture toughness is calculated indirectly. In addition, for many reactors currently in operation, the amount of material available in the surveillance capsules may not be sufficient for the continuation of the surveillance programmes and thus for the long-term operation of the corresponding nuclear power plants.

In this context, the FRACTESUS project proposes an innovative approach using miniature fracture test specimens obtained from broken Charpy specimens to directly measure fracture toughness, thus reducing the material required for monitoring tests. FRACTESUS (Lambrecht, 2019) was launched in October 2020, following its approval under the EURATOM 2019-2020 programme, section NFRP-04: Innovation for second and third generation reactors. FRACTESUS, which has a duration of 48 months, is aligned with the objectives pursued by the European H2020 framework programme, such as the continuous improvement of nuclear safety, security and radiation protection, and the contribution to the long-term decarbonisation of the European energy system in a safe and efficient manner. In addition, FRACTESUS also fulfils the three H2020 priorities: "Excellent Science", "Industrial Leadership" and "Societal Challenges".

The reference specimen selected by the consortium is the miniature compact tensile specimen (abbreviated as mini CT, 0.16 CT or MCT) (10x9.6x4 mm^3), which allows up to eight specimens to be machined from a single broken Charpy specimen. The final objective lies in the determination of the transition temperature (T_0) by using mini CT specimens, which has already been applied in previous works (Server et al., 2018; Yamamoto et al., 2014) with promising results. In addition, the use of other miniature specimens, such as the Small Punch Test (SPT) (Altstadt et al., 2021; EN 10371:2021, 2021), whose geometry has even smaller dimensions (10x10x0.5 mm^3) and allows more than 35 samples to be machined from a single broken Charpy specimen, is also considered as an in-kind contribution.

In this way, 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 a number of benefits, such as a) the direct assessment of fracture toughness rather than a semi-empirical approach based on Charpy measurements; b) the ability to characterise the local properties of a heterogeneous material; c) the significant increase in the monitoring database, providing greater confidence in the data, and; d) a reduction of the volume of irradiated material.

Moreover, the FRACTESUS project will also benefit Gen III+ and future nuclear systems. Structural materials for future nuclear systems, and in particular for Gen IV and fusion systems, will have to handle harsh irradiation conditions. Qualification programmes are a major constraint on the deployment of new materials and technologies. These qualification programmes should be performed in dedicated irradiation machines (material test reactors or accelerator-based irradiation devices, e.g. MINERVA, MYRRHA, DONES) and be fully representative of the defined operational conditions. The irradiation space in these devices is generally limited, so qualification programmes can also benefit from the FRACTESUS project.

The FRACTESUS project aims to demonstrate to nuclear authorities and regulators the applicability and reliability, of the use of mini CT specimens for the characterisation of the fracture behaviour of irradiated RPV materials. In the following sections, a brief description of the project will be given and the main progress of the project to date will be presented.

2. Project description

22 organisations from Europe (19), Japan (1), the USA (1) and Canada (1) participate in FRACTESUS, as presented in Table 1. In order to structure the project, the work is broken down into six work packages (WPs), whose scheme is described by the diagram shown in Figure 1.

An important step is the acceptance of data derived from miniature specimens within procedures or regulations. With this aim, WP1 (led by NNL) aims to identify and collect the various concerns of regulatory authorities regarding the use of mini CT specimens in reactor surveillance programmes. It also aims to identify possible limitations in the current regulations.

VTT leads WP2, which is in charge of material selection and specimen fabrication (Arffman, 2021). The steels selected in the project meet several requirements, such as the availability of a large database of characterised material under baseline and irradiated conditions (typically more than 400 data available), an open database, a material sensitive to irradiation and with high availability. On the other hand, the mini CT specimen dimensions are shown in Figure 2, where it should be noticed that even though this is the standard specimen for FRACTESUS, some partners will use slightly different dimensions.

Table 1. List of FRACTESUS project participants.

Participant	Acronym	Country
1	SCK CEN	Belgium
2	NRI	Czech Republic
3	VTT	Finland
4	CEA	France
5	IRSN	France
6	FRA-G	Germany
7	HZDR	Germany
8	KIT	Germany
9	BZN	Hungary
10	MTA EK	Hungary
11	KTU	Lithuania
12	NRG	Netherlands
13	STUBA	Slovakia
14	CIEMAT	Spain
15	UC	Spain
16	PSI	Switzerland
17	NNL	United Kingdom
18	UoB	United Kingdom
19	CCFE	United Kingdom
20	CRIEPI	Japan
21	ENT	United States
22	CNL	Canada

The coordination of the experimental campaign is carried out within WP3, led by HZDR. Fracture mechanics tests will be carried out with mini CT specimens of irradiated and unirradiated material at different temperatures and include a fractographic analysis of the fracture surfaces. WP3 will also be complemented with other tests based on miniaturised specimens, such as SPT or microhardness measurements.

The modelling activity (WP4) will be performed in support of the tests and is led by CEA. In this numerical modelling work package, the final goal is to provide a robust modelling strategy for the interpretation of experimental data and recommendations/suggestions in support of the use of mini CT specimens in the assessment of the fracture toughness of RPV steels.

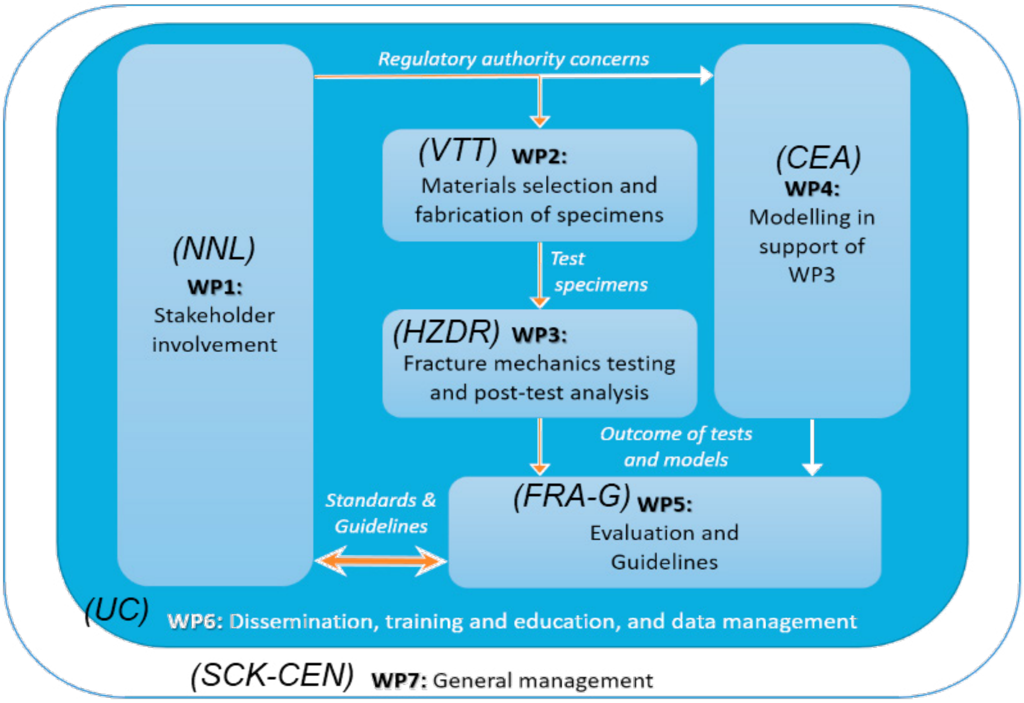

Figure 1. The organisation of the FRACTESUS Project, with the different WPs involved.

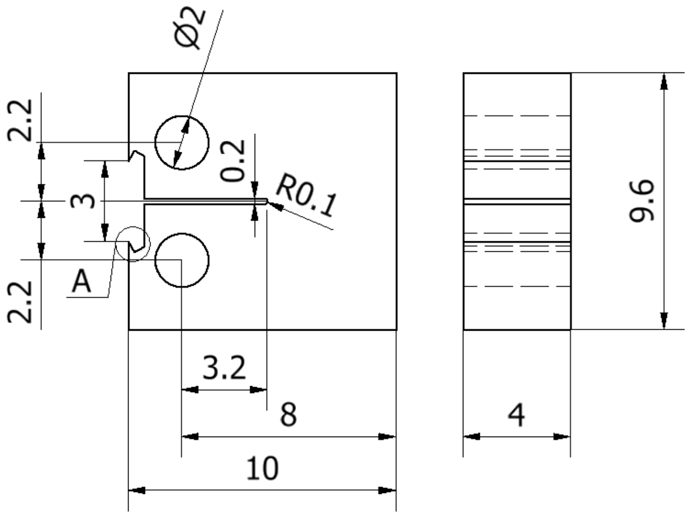

Figure 2. Test specimen dimensions (mini CT), as proposed for the project.

All results (tests and simulations) will be subsequently summarised, discussed and evaluated by WP5, an activity led by FRA-G. A detailed comparison will be made between the results of the mini CT and the standard size specimens, with the aim of developing good practice guidelines, which could ideally be included in future versions of codes or standards. This activity also seeks to create synergies with other national or international projects under development.

It should always be borne in mind that the project is only possible thanks to the EU taxpayer and therefore it is necessary to maximise the benefit of the project for the whole of Europe. In this sense, the project is planning for the communication and dissemination activities (WP6, led by the University of Cantabria) to reach the general public through open access dissemination. In addition, WP6 will be in charge, together with WP1 and WP7, of the management of the experimental data generated during the project, as well as the public exposition of these data and the corresponding publications in open repositories.

Finally, the overall management of the project is led by SCK CEN, through WP7.

3. Selection of materials

One of the first and most crucial steps forward of the project during the first year was the selection of the material for obtaining mini CT specimens. Table 2 lists the main 14 steels that will be studied in the project (more RPV steels will be included throughout the project), all of them being of great relevance to the nuclear energy industry. In addition to fulfilling the criteria mentioned above, the steels were selected in order to cover the widest possible range of variability in terms of mechanical behaviour. With this aim, steels with different chemical compositions were pursued, with emphasis on the amounts of Cu, P, Ni or Mn, kind of material (BM, base metal or WM, weld metal) and treatment/ageing of the steel, either thermal or by neutron irradiation. Furthermore, the prepared steel matrix covers a wide range of reference temperatures (T_0), ranging from -134ºC to +8ºC, and even higher for irradiated materials. Therefore, the material properties of the material selected are representative of a reasonable range of RPV materials.

Table 2. List of materials studied together with the main properties searched for.

Material	Type	Cu (%)	P (%)	Ni (%)	Mn (%)	Neutron flux (E19 n/cm²)	T_o (°C)
15Kh2MFAA	BM	0.05	0.01	0.1	0.49	0	-104
15Kh2MFAA	BM	0.05	0.01	0.1	0.49	I1 = 20 (E>0.5MV) (at 270°C)	TBD
15Kh2MFAA	BM	0.05	0.01	0.1	0.49	I1A (Annealed at 470°C)	TBD
15Kh2MFAA	BM	0.05	0.01	0.1	0.49	I1A I2 = 20 (E > 0.5MeV) (at 270°C)	TBD
A533B (JRQ)	BM	0.14	0.018	0.83	1.39	0	-71
A533B LUS (JSPS)	BM	0.24	0.028	0.43	1.52	0	+8
ANP-4	BM	0.05	0.006	0.84	0.85	4 (at 280°C-286°C)	-78
SA 533 B1 (MVE)	BM	0.041	0.005	0.632	1.42	0	-119
SA508 Cl.3	BM	0.04	0.008	0.93	1.37	0	-43
10KhMFT	WM	0.11	0.047	0.14	1.16	IA	-11.6
10KhMFT	WM	0.11	0.047	0.14	1.16	1.6 (I) (at 270°C)	74.4
73W	WM	0.31	0.005	0.6	1.55	0	-64
73W	WM	0.31	0.005	0.6	1.55	1.5 (E>1MeV) (at ~288°C)	34
ANP-5	WM	0.22	0.015	1.11	1.14	0	-38

4. Experimental programme

A large part of the project, almost 2 years, is being devoted to fracture testing with mini CT specimens in both irradiated and non-irradiated conditions, with the only difference being that the latter must be carried out in hot cells.

The fracture characterisation of the project steels in the transition regime will be determined by the master curve methodology, the main guidelines of which are given in ASTM E1921 (ASTM International, 2021).

The first step in the experimental campaign is to detect possible problems or inconsistencies arising from the testing of miniaturised specimens. In this sense, Round Robin (RR) exercises are being carried out, where the same material is tested by different laboratories for comparative purposes. Table 3 presents the test matrix prepared for the RR of unirradiated material. The nominal number of tests to be performed for each material and laboratory is 16, which allows the determination of T_0 with sufficient accuracy, for which the single temperature or multi-temperature methods in ASTM E1921 will be used.

Table 3. Test matrix prepared for the RR of non-irradiated material.

Round Robin No.	Material	T_0 (°C)	Testing participant				
			1	2	3	4	5
1	15Kh2MFAA	-104	SCK CEN	CRIEPI	HZDR	VTT	
2	A533B (JRQ)	-71	NRI	CRIEPI	PSI	CCFE	MTA-EK
3	73W	-64	SCK CEN	CIEMAT	HZDR	VTT	UoB
4	SA508 Cl.3	-43	SCK CEN	CIEMAT	KIT	NRG	UoB
5	ANP-5	-38	SCK CEN	FRA-G	HZDR	CCFE	UC
6	A533B LUS (JSPS)	+8	SCK CEN	CRIEPI	UC		

Similarly, a RR will be carried out with irradiated material in which 7 laboratories will participate; in this case, only steel 73W will be used. Complementary to the RR exercise, some participating laboratories will perform additional tests. In total, it is estimated that 656 fracture toughness tests with mini CT will be carried out in FRACTESUS. These experiences, together with supporting research, will provide validation for miniature testing techniques and experience with which to develop guidelines for determining the reference temperature using miniature specimens.

The first results obtained so far from mini CT specimens in unirradiated conditions on RR materials have been obtained, revealing a good agreement with those obtained from the larger specimens.

5. Project status

The project started in October 2020. Since its inception, five virtual meetings have been held with WP leaders, and multiple virtual meetings have been held with WP leaders to discuss technical aspects of the project. Achievements so far (June 2022) have been:

- Dissemination channels are already available: public website (https://fractesus-h2020.eu/) and profiles on ResearchGate, Twitter and LinkedIn and Facebook.
- The project roadmap has been defined with the Data Management Plan (Cicero and Arroyo, 2021).
- Testing protocols and reporting formats have been described (Cicero et al., 2021a).
- The selection of the project steels and the test matrix has been finalised (Arffman, 2021).
- Round Robin tests on unirradiated mini CT specimens have started, obtaining the first results for the corresponding reference temperatures.
- An article has been published in a JCR-indexed journal (Altstadt et al., 2021), and the project has been disseminated at national (Cicero et al., 2021b) and international conferences (Cicero et al., 2020)(Brynk et al., 2021).

6. Conclusions

Miniature 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, the possibility of measuring local toughness to detect heterogeneities, etc.

Despite this, the use of mini CT specimens still faces a number of obstacles to its acceptance by regulatory bodies. However, the FRACTESUS project, developed by a consortium of 22 European and international partners, aims to demonstrate the capabilities and robustness of these characterisation techniques. It started in October 2020 and will run for 48 months. Its ultimate aim is to address the various concerns of the regulatory authorities in order to be able to introduce these miniature specimens into codes and regulations, and thus into monitoring programs.

With the results obtained so far on non-irradiated material, the reference temperature (T_0) obtained from mini CT specimens has been shown to agree with those obtained from specimens with standard dimensions.

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