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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 provides an overview of the FRACTESUS project (Euratom work programme 2019-2020). The European Union has defined clear short and long-term objectives to achieve its energy transition towards sustainable energy and a climate neutral economy by 2050. The success of this transition relies on the combination of energy efficiency and low carbon energy in all sectors of the economy. In all electricity mix scenarios up to 2050, one needs to rely on a combination of existing nuclear power plants, long-term operation, new nuclear build and future nuclear systems. The safety and operability of nuclear systems heavily rely on strategies where the integrity of structural materials plays an essential role.
Due to material availability and/or irradiation constraints, the use of small sized specimens to obtain reliable measurements of the fracture resistance is needed by the nuclear industry to comply with safety directives. Measurement of fracture toughness using small-sized specimens has already been shown to be possible in both unirradiated and irradiated conditions. However, significant work is still required to achieve European regulatory acceptance. The goal of FRACTESUS is to join efforts to establish the foundation of small specimen fracture toughness validation and demonstration to address the different national regulatory authority concerns.

Keywords: nuclear power plants; long-term operation; fracture toughness; structural integrity; small sized specimens; irradiated steel; irradiation embrittlement.

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1. Introduction

The FRACTESUS project (Lambrecht (2019)) was submitted for evaluation in September 2019 by the EURATOM Work Programme 2019-2020, section NFRP-04: Innovation for Generation II and III reactors. The project was positively evaluated and reached the stage of Grant Agreement preparation in February 2020, with the kick-off meeting being expected in October 2020 and a project duration of 48 months. The project frame in the overall H2020 programme has the aim of continually improving nuclear safety, security and radiation protection, notably contributing to the long-term decarbonisation of the energy system in a safe, efficient and secure way. FRACTESUS also adheres to the three H2020 priorities being "Excellent Science", "Industrial Leadership" and "Societal Challenges".

Most of the nuclear power plants in operation in Europe are in the second half of their operational lives and need to comply with increased safety levels as defined by the Nuclear Safety Directive. In most manuals on ageing management for Nuclear Power Plants (NPP), reactor pressure vessel (RPV) ageing is rated number one on the list of safety concerns for the following reasons (Shah and MacDonald (1993)):

- the RPV is the primary barrier against the release of radioactive material into the environment,
- failure of the vessel in normal and accident scenarios is excluded by design,
- it cannot be replaced,
- it suffers from hardening and toughness degradation as a result of thermal ageing and radiation exposure.

RPV degradation has been recognized as an essential area of study from the beginning of the Nuclear Programme in Europe. Consequently, surveillance programmes were put in place to monitor embrittlement, typically using Charpy-sized specimens (10x10x55 mm^3) made of representative materials to be irradiated in realistic conditions in surveillance capsules. Although Charpy impact testing cannot provide a direct measurement of the fracture toughness, the Charpy technology was originally chosen due to space limitations and the fracture mechanics knowledge available in the 1960s. Those surveillance capsules are now practically exhausted with many reactors having no more surveillance material available in the reactor, insufficient archive material to extend their surveillance programmes, and, thus, no capacity to enable the appropriate surveillance specimen testing to support long-term operation.

Owing to improved characterisation and non-destructive techniques, the presence of local material heterogeneity and small defects in large forgings such as the reactor head, reactor vessel, steam generator or pressurizer has been identified. Such issues have led to major concerns for the operators and regulatory bodies, leading to very long outages of existing NPPs or serious delays in NPP construction (ASN (2017a), ASN (2017b)). To address the issue of local material properties, the use of accepted small size specimens is essential (ESNI (2018), Gérard et al. (2016)).

In this context, the FRACTESUS consortium proposes an innovative approach using small-sized specimens to measure fracture toughness directly. The reference small specimen is the miniature Compact Tension specimen (10x10x4 mm^3) allowing up to eight specimens to be machined from a single broken Charpy specimen. This approach (e.g., Yamamoto et al. (2014), Chaouadi et al. (2016), Server et al. (2018)) is designed to increase the safety level (and reduce uncertainties) significantly through:

- Direct fracture toughness evaluation rather than a semi-empirical approach based on Charpy measurements;
- Significantly increasing the surveillance database, providing an increased confidence in the data;
- Characterisation of local material properties in the case of material inhomogeneity.

This innovative approach also addresses the requirements for decarbonisation, security of energy supply and increased competitiveness of European nuclear energy through cost-effective long-term operation. The long-term operation of an NPP becomes possible if it can be supported by extended surveillance programmes. The development of such programmes, incorporating previously irradiated and broken Charpy specimens in the surveillance capsules, provides a high return on investment. The broken Charpy specimen material will be used to analyse vessel embrittlement using miniature Compact Tension specimens. Long-term operation of an NPP allows the retention of a secure energy supply while maintaining low carbon emissions.

This being said, this project will also benefit Gen III+ and future nuclear systems. Structural materials in future nuclear systems and, in particular, Gen IV and fusion systems, will need to cope with harsh irradiation conditions. Qualification programmes provide a major constraint in the deployment of new materials and technologies. These qualification programmes need to be performed in dedicated irradiation machines (Materials 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 benefit from this project.

The following sections describe the project approach, extracting part of the contents of the original project proposal (Lambrecht (2019)).

2. Materials and Methods

22 organisations from Europe (19), Japan (1), USA (1), and Canada (1) participate in FRACTESUS, as seen in Table 1. In order to structure the project, the work is broken down into work packages. The methodology described here also follows this WP structure (see Figure 1).

Table 1. List of participants of FRACTESUS project.

Participant	Participant name	Short	Country
1	Studiecentrum voor Kernenergie / Centre d'Étude de l'Énergie Nucléaire	SCK CEN	Belgium
2	ÚJV Řež, a.s.	NRI	Czech Republic
3	Teknologian tutkimuskeskus VTT Oy	VTT	Finland
4	Commissariat à l'Énergie Atomique et aux Énergies Alternatives	CEA	France
5	Institut de Radioprotection et de Sureté Nucléaire	IRSN	France
6	Framatome GmbH	FRA-G	Germany
7	Helmholtz-Zentrum Dresden-Rossendorf eV	HZDR	Germany
8	Karlsruher Institut für Technologie	KIT	Germany
9	Bay Zoltan Alkalmazott Kutatási Közhasznú Nonprofit Kft.	BZN	Hungary
10	Magyar Tudomanyos Akademia Energiatudomanyi Kutatokozpont	MTA EK	Hungary
11	Kauno Technologijos Universitetas	KTU	Lithuania
12	Nuclear Research and Consultancy Group	NRG	Netherlands
13	Slovenska Technicka Univerzita v Bratislave	STUBA	Slovakia
14	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas	CIEMAT	Spain
15	Universidad de Cantabria	UC	Spain
16	Paul Scherrer Institut	PSI	Switzerland
17	National Nuclear Laboratory Limited	NNL	UK
18	The University of Birmingham	UoB	UK
19	Culham Centre for Fusion Energy (United Kingdom Atomic Energy Authority)	CCFE	UK
20	Central Research Institute of Electric Power Industry	CRIEPI	Japan
21	Oak Ridge National Laboratory	ORNL	USA
22	Canadian Nuclear Laboratories	CNL	Canada

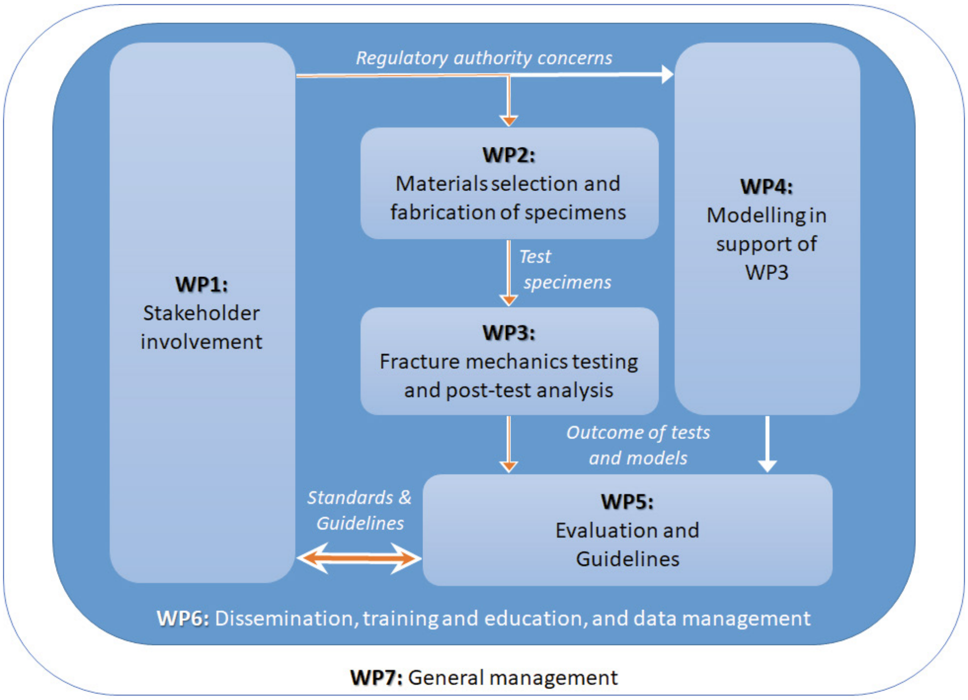

Fig. 1. Organisation of FRACTESUS project, with the different work packages involved.

To ensure a valuable output of the project, it is intended to make a continuous effort to address the stakeholder concern by regularly involving the regulatory bodies, code and standardisation committees, the End Users Group (EUG) and the Scientific Advisory Committee (SAC) (see below for details on the EUG and the SAC). This activity fits into WP1, which is led by NNL.

In the material selection and test matrix development (WP2, led by VTT), material will be carefully selected based on established criteria, prioritising materials which have:

- well characterised material in baseline and irradiated condition (typically more than 400 data available),
- open data available,
- significant sensitivity to irradiation and material availability.

Testing activities will be developed within the WP3 framework, led by HZDR, and will consist of fracture mechanics testing in the transition region using 0.16 C(T) specimens on both irradiated and unirradiated RPV steels, fractographic analyses, and other small specimen test techniques (e.g., small punch, depth sensing micro hardness tests), among other activities.

The machining (WP2) and testing (WP3) of irradiated material will be shared by different laboratories to share the costs and evaluate the repeatability and reproducibility. The procedure will be agreed upfront and any deviation will be carefully evaluated.

Modeling activity (WP4) will be performed in support of the material testing, led by CEA. It will also be of great interest to address the current limitations in code and standards when small specimens are involved. Rationalised experimental data supported by modeling activity will be used in the dialogue with code and standard committees to implement changes that will facilitate the use of small specimens, while maintaining or improving the confidence levels in the results. This last activity belongs to WP5, and it is led by FRA-G.

It must always be borne in mind that the project is only possible thanks to the EU taxpayer and therefore one needs to maximise the benefit of the project for all of Europe. In this sense, the project will perform communication and dissemination activities (WP6, led by the University of Cantabria) to reach out to the overall public by dissemination in open access. Training and Education activities will be advertised well beyond the project community thanks to a well-established network. Keeping in mind the start of the digital era with big data, artificial intelligence and decentralised access to information, the project will employ a data management plan to maximise open research data and ensure data sustainability well beyond the end of the project so that data will remain accessible, searchable and reusable independently of the system used.

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

The project has, additionally, three transversal entities: the End User Group (EUG), the Scientific Advisory Committee (SAC) and the Standardisation Committee (STC).

The EUG comprises personnel who are employed within a company with an interest in the FRACTESUS programme, but who are not part of the FRACTESUS consortium. These individuals will act as a point of contact for their company and will provide feedback on the output of FRACTESUS. The list of companies in which the EUG members are employed are the following: EDF SA (France), Westinghouse (USA), EDF Energy (UK), PAKS Nuclear Power Plant (Hungary), Tractebel (ENGIE) (Belgium), Ringhals AB-Vattenfall (Sweden) and Rolls-Royce (UK).

The SAC comprises experts in the field, acting independently of their company. Their membership is on a named basis (i.e., they cannot be replaced by another employee in their company). They will be responsible for reviewing the FRACTESUS plan, reviewing the outputs of the programme, and providing advice to the group. The members of the SAC are independent consultants or employees of the following organisations: PEAI Consulting (USA), ATI Consulting (USA), Ringhals AB-Vattenfals (Sweden) and the Swiss Federal Nuclear Safety Inspectorate (Switzerland).

Finally, the STC comprises members of the FRACTESUS consortium who also have some outside involvement in Standards Committees such as ASTM and ISO. They will be involved in the initial WP1 work outlining current standards / guidance and identifying any shortfalls of those standards in relation to the fracture toughness testing of small specimens. Furthermore, the STC will be responsible for advising the ASTM/ISO committees on how best to implement the results of FRACTESUS into the current standards, following the outcome of FRACTESUS and in particular WP5: Evaluation and Guidelines.

3. Results

The FRACTESUS project will demonstrate the reliability and the enhanced confidence of using small size specimens to measure the fracture resistance of structural (particularly nuclear) materials, providing an innovative method to characterise high-performance materials against critical situations (structural failures). This will allow the European nuclear industry to operate in safer and more efficient conditions, especially in the case of operating Gen II reactors (concerning LTO issues) and future GEN III reactors (at both design and operation stages).

Moreover, once demonstrated, the regulatory and standardisation bodies will also be able to incorporate this innovation into nuclear regulations, standards and procedures.

The high-level knowledge developed during the project has another important and final impact, consisting of the generation of a highly skilled fracture characterisation community that will provide expertise in the field to the European nuclear industry and will lead the topic internationally. FRACTESUS will also generate high quality fracture data subjected to a Data Management Plan that will be FAIR (Findable, Accessible, Interoperable and Re-usable) and Open Access, when possible.

The main results of the project (corresponding to part of the deliverables) are shown in Table 2.

4. Conclusions

Miniaturised CT specimens provide a wide range of possibilities and advantages when dealing with fracture characterization of RPV steels. Some of them would be the multiplication of data points, the (re)use and subsequent valorization of already tested specimens (Charpy specimens, mainly), the reduction of the volume of material to be irradiated in the future, and the possibility to measure local toughness to detect heterogeneities and/or toughness gradients (e.g., welds), among others. Despite its great potential for fracture characterisation, the use of sub-sized specimens, and particularly the use of miniaturised CT specimens, encounters a number of obstacles for its acceptance by national and international regulatory bodies as an assessment and design tool of structural components in NPP.

With the aim of demonstrating the capacities and the soundness of these characterisation techniques, the FRACTESUS project will start its activity in October, 2020. The goal of the project is to join European and International efforts to establish the foundation of small specimen fracture toughness validation and demonstration to achieve the change in code and standards required to address the various national regulatory authority concerns. FRACTESUS is involving regulatory bodies, code and standardisation committees, the industry and the international community at a very early stage, in order that the consortium can optimize the available resources and expertise.

Table 2. Some project results according to FRACTESUS deliverables list.

Result	Deliverable	WP
Report: current status of sub-size fracture toughness standards and testing, including all stakeholder concerns.	D1.1	1
Report: Estimation of mechanical properties of unirradiated and irradiated RPV steels based on small specimen test technologies	D.3.2	3
Report: Qualification of 0.16 C(T) fracture toughness testing on well characterised irradiated material	D.3.3	3
Report: Finite element simulations to compare C(T) and MC(T)*	D.4.1	4
Report: Comparison of fracture toughness results from standard and sub-sized specimens	D.5.4	5
Report: Guidelines for Master Curve testing with miniature specimens	D.5.7	5
FRACTESUS special sessions at international conferences	D6.4 and D6.6	6
FRACTESUS seminar	D6.5	6

* Note: MC(T) specimens correspond to 0.16 C(T) geometry

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References

ASN, 2017a. L'ASN présente sa position sur l'anomalie de la cuve du réacteur EPR de Flamanville. Available online: https://www.asn.fr/Informer/Actualites/L-ASN-presente-sa-position-sur-l-anomalie-de-la-cuve-du-reacteur-EPR-de-Flamanville (accessed on 17-03-2020).

ASN, 2017b. Anomalie de la concentration en carbone de l'acier : après contrôle, l'ASN a autorisé les réacteurs concernés à redémarrer, 2017b. Available online: https://www.asn.fr/Informer/Actualites/Anomalie-de-la-concentration-en-carbone-de-l-acier-redemarrage-des-reacteurs (accessed on 17-03-2020).

Chaouadi, R., van Walle, E., Scibetta, M., Gérard, R., 2016. On the use of miniaturized CT specimens for fracture toughness characterization of RPV materials. Proceedings of ASME PVP2016, Vancouver, British Columbia, Canada, paper PVP2016-63607.

ESNI, 2018. Assessment of the safety case for the reactor pressure vessel of the Beznau unit 1 nuclear power plant. Available online: https://www.ensi.ch/en/documents/assessment-of-the-safety-case-for-the-reactor-pressure-vessel-of-the-beznau-unit-1-nuclear-power-plant/ (accessed on 17-03-2020)

Gérard, R., De Smet, M., Chaouadi, R., 2016. Materials properties of reactor pressure vessel shells affected by hydrogen flaking, Proceedings of ASME PVP2016, Vancouver, British Columbia, Canada, paper PVP2016-63901.

Lambrecht, M., 2019. Fracture mechanics testing of irradiated RPV steels by means of sub-sized specimens, Proposal Acronym: FRACTESUS, Euratom work programme 2019-2020, Topic Identifier: NFRP-04: Innovation for Generation II and III reactors, Types of Action: Innovation actions.

Server, W., Sokolov, M., Yamamoto, M., Carter, R., 2018. Inter-Laboratory Results and Analyses of Mini-C(T) Specimen Testing of an Irradiated Linde 80 Weld Metal, Proceedings of ASME PVP2018, Prague, Czech Republic, paper PVP2018-84950.

Shah V.N., MacDonald, P.E., 1993. Aging and Life Extension of Major Light Water Reactor Components, 1st ed. Elsevier Science, Amsterdam, Netherlands.

Yamamoto, M., Kimura, A., Onizawa, K., Yoshimoto, K., Ogawa, T., Mabuchi, Y., Viehrig, H.W., Miura, N., Soneda, N., 2014. A round robin pogram of Master Curve evaluation using miniature C(T) specimens - 3rd report: Comparison of T_0 under various selections of temperature conditions, Proceedings of ASME PVP2014, Anaheim, California, USA, paper PVP2014-28898.