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Structural MATerias research on parameters influencing the material properties of RPV steels for safe long-term operation of PWR NPPs

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ABSTRACT

This article provides a comprehensive overview of the STRUMAT-LTO project. Embrittlement of the reactor pressure vessel (RPV) due to neutron irradiation and high temperature conditions impose critical challenges for long-term operation (LTO) of pressurized water reactors (PWRs). Significant amount of past research conducted on RPV ageing phenomena has helped to enhance the understanding of the flux effect and the impact of chemical/microstructural heterogeneities on RPV embrittlement. Nonetheless, several unresolved questions regarding RPV embrittlement persist, such as the conflicting viewpoints on the underlying mechanisms that lead to accelerated embrittlement at high fluence conditions in certain low-copper (Cu) RPV steels and the synergistic effect between nickel, manganese, and silicon (Ni-Mn-Si). Also, the accuracy of embrittlement trend curves (ETCs) for LTO beyond 60 years and the applicability of the master curve approach at high fluences for small/sub-sized specimens require further study. The aim of the STRUMAT-LTO is to address the above-mentioned scientific gaps in RPV embrittlement by employing a unique set of RPV steel specimens constituting systematic variations in Ni, Mn, and Si content, which are irradiated to high fluences resembling reactor operation beyond 60 years within the LYRA-10 experiment at high flux reactor (HFR) in Petten. The STRUMAT-LTO project has received funding from the Euratom research and training programme 2019–2020 under grant agreement n°945272. The project has a duration of 48 months.

1. Introduction

To meet the climate targets defined by the EU, nuclear energy will play a fundamental role. Nuclear energy in the EU, as well as other parts of the word, is produced mainly by Generation II reactors and to a lower (but increasing) extent by Generation III reactors. However, ~67% of these reactors have been operating >30 years and will reach the end of their original design life in <10 years (https://pris.iaea.org/PRIS/WorldStatistics/OperationalByAge.aspx). This capacity cannot be immediately replaced due to long licensing and construction times. Long-term operation (LTO) of existing nuclear power plants (NPPs) has been identified as a promising way to achieve the intermediate decarbonisation targets in the energy transition towards 2050 in an economic manner (FORATOM position paper, 2019) and is common practise in a significant number of countries with established nuclear programmes. On the other hand, LTO up to 80 years has become a norm in US. In the recent years, US NRC has granted license extension up to 80 years to some NPPs, namely for Surry units 1 and 2, Peach bottom units 3 and 4, Turkey point units 3 and 4 (https://www.nrc.gov/reactors/operating/licensing/renewal/subsequent-license-renewal.html), through the so called subsequent license renewal (SLR) procedure. Currently, several other SLR applications are under review at US NRC for LTO up to 80 years.

LTO approval of any reactor requires a comprehensive structural integrity analysis and ageing management procedures according to international safety standards (International Atomic Energy Agency, 2015; https://www.nrc.gov/reactors/operating/licensing/renewal/slr/

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Nomenclature

APT	Atom Probe Tomography
CT	Compact Tension
DBTT	Ductile-to-brittle transition temperature
ETCs	Embrittlement Trent Curves
FM	Fracture Mechanics
HFR	High Flux Reactor
LBP	Late Blooming Phases
LTO	Long-Term Operation
MC	Master Curve
NPP	Nuclear Power Plant
PAS	Positron Annihilation Spectroscopy
PIE	Post Irradiation Examination
PWR	Pressurized Water Reactor
RPV	Reactor Pressure Vessel
SANS	Small Angle Neutron Scattering
SEM	Scanning Electron Microscopy
SPT	Small Punch Test
TEM	Transition Electron Microscopy
WP	Work Package

guidance.html) to ensure safe operations of the units for the extended operation period. These scenarios introduce many technological and scientific challenges to both utilities (to prepare for LTO licence extension) and regulators (to prepare required regulatory framework to approve LTO license extension). One of the critical issues of LTO of LWRs, in particular pressurized water reactors (PWRs), is the embrittlement of the reactor pressure vessel (RPV), which is a non-replaceable safety relevant structural component. The mechanical properties of RPV degrade over time due to its exposure to neutron radiation and high temperatures. Utilities need to prove to the regulators that the structural integrity of the RPV will be maintained for the extended period of operation during both normal operating conditions and emergency scenarios, such as pressurised thermal shock when emergency core cooling is triggered. LTO assessment requires prediction of RPV damage for the proposed period of life extension and a surveillance testing program in tandem to monitor the validity of the RPV damage predictions used for the specific reactor.

RPV damage predictions are usually performed by using so called embrittlement trend curves (ETCs) published in relevant codes and standards such as 10 CFR 50.61 (ECFR). The existing ETCs have been developed based on large amount of data generated from standard surveillance programs that largely represent 40 to 60 years of operational life of RPV, thus their applicability at high fluences conditions in LTO regime beyond 60 years need to be validated. In order to do this a deeper understanding on radiation induced damage mechanisms in RPV steels at high fluence conditions relevant for LTO beyond 60 years need to be developed.

Even though, several research projects in previous EURATOM framework programmes (PERFECT, PERFORM60, SOTERIA, NULIFE, LONGLIFE (PERFECT; PERFORM 60; SOTERIA; NULIFE; LONGLIFE) increased the understanding of RPV ageing phenomena such as the flux effect and the influence of chemical/microstructural heterogeneities in RPV embrittlement, still several issues, as addressed in (The NUGENIA Association, 2015), remain open. One of the open issues mentioned in The NUGENIA Association, 2015, is the high fluence behaviour and synergetic effects of Ni, Mn and Si at high fluences. In literature, evidence can be found of accelerated embrittlement at high neutron fluences (ca. 6×10^{23}n.m^{-2}, E > 1 MeV) for certain low copper (Cu) RPV steels relevant for LTO (Odette et al., 1995; Odette and Lucas, 2001; Eason et al., 2006; Sprouster et al., 2016; Burke et al., 2004; Styman et al., 2015). There is no full consensus on the mechanisms causing the accelerated embrittlement at high fluences. Some experts (Odette et al., 1995; Odette and Lucas, 2001; Eason et al., 2006; Sprouster et al., 2016) suggest the formation of Mn-Ni-Si clusters while others imply the evolution of already existing clusters (Burke et al., 2004; Styman et al., 2015). The individual and synergetic effect of Ni, Mn and Si on the embrittlement of low-Cu RPV steels needs to be further clarified.

Once the above is achieved, ETCs need to be validated/adapted so

Table 1
Chemical composition of RPV base material model steels in LYRA-10 (in mass %).

Model	C	Si	Mn	Cr	Ni	Mo	V	Cu	S	P
A	0.11	0.28	0.43	2.22	<0.02	0.71	0.10	0.09	0.008	0.010
B	0.11	0.26	0.38	2.19	0.99	0.70	0.10	0.10	0.008	0.010
C	0.12	0.24	0.38	2.13	2.00	0.69	0.10	0.10	0.008	0.010
D	0.11	0.23	0.83	2.13	2.00	0.68	0.10	0.09	0.008	0.009
E	0.12	0.33	0.77	2.16	1.02	0.70	0.10	0.10	0.008	0.009
F	0.12	0.33	1.37	2.15	1.02	0.70	0.10	0.10	0.008	0.010
G	0.11	0.32	1.36	2.06	1.99	0.69	0.10	0.10	0.008	0.009
H	0.12	0.51	1.31	2.07	2.00	0.69	0.10	0.10	0.008	0.010
K	0.17	0.35	0.78	0.10	0.58	0.64	–	0.07	0.005	0.009
L	0.18	0.35	0.77	0.08	0.96	0.63	–	0.05	0.005	0.010
M	0.16	0.37	0.74	0.09	1.90	0.61	–	0.05	0.005	0.010
N	0.16	0.33	1.27	0.07	1.97	0.63	–	0.06	0.005	0.010

Table 2
Chemical composition of RPV realistic welds in LYRA-10 (in mass %).

Code	C	Mn	Si	P	S	Cr	Ni	Mo	V	Co	As	Cu	Sn	Sb
A	0.07	0.57	0.18	0.011	0.007	2.07	1.30	0.59	0.09	0.02	0.004	0.06	0.005	<0.001
B	0.06	0.56	0.31	0.007	0.009	2.04	1.59	0.60	0.09	0.02	0.004	0.06	0.005	<0.001
C	0.05	0.60	0.32	0.007	0.010	1.95	1.87	0.58	0.08	0.02	0.004	0.06	0.005	<0.001
D	0.06	0.72	0.29	0.006	0.009	2.01	1.57	0.59	0.09	0.02	0.004	0.06	0.004	<0.001
E	0.05	0.89	0.30	0.006	0.009	2.00	1.94	0.57	0.09	0.02	0.004	0.06	0.004	<0.001
F	0.06	1.07	0.29	0.006	0.009	2.04	1.26	0.58	0.09	0.02	0.004	0.06	0.004	<0.001
G	0.06	1.07	0.30	0.007	0.0010	2.04	1.57	0.59	0.09	0.02	0.004	0.06	0.005	<0.001
H	0.06	1.08	0.32	0.007	0.0010	1.98	1.89	0.58	0.09	0.02	0.004	0.06	0.005	<0.001

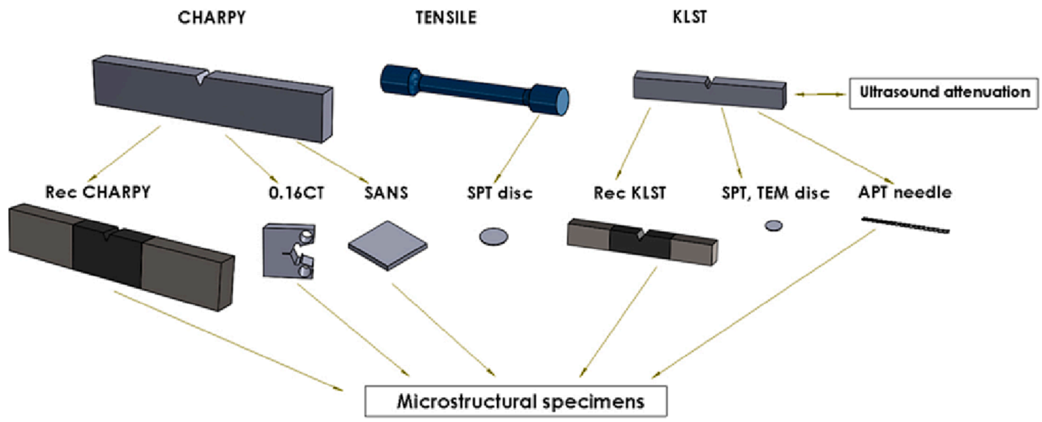

Fig. 1. Reconstituted specimen that can be can be manufactured from already tested normal-sized Charpy specimens.

Table 3
List of participants of the STRUMAT-LTO project.

	Participant organisation name	Short name	Type	Country
1	Energiatudományi Kutatóközpont EK-CER	EK-CER	R&D	Hungary
2	Nuclear Research and consultancy Group	NRG	R&D/ Industry	The Netherlands
3	LGI consulting	LGI	SME	France
4	Helmholtz-Zentrum Dresden-Rossendorf ev	HZDR	R&D	Germany
5	Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas	CIEMAT	R&D	Spain
6	UJV Rez, a. s.	UJV	R&D/ Industry	Czech Republic
7	Bay Zoltan Alkalmazott Kutatasi Kozhasznu Nonprofit kft.	BZN	R&D	Hungary
8	Teknologian Tutkimuskeskus VTT oy	VTT	R&D/ Industry	Finland
9	Joint Research Centre-European Commission	JRC	R&D	Belgium
10	United Kingdom Atomic Energy Authority	UKAEA	R&D	United Kingdom
11	VUJE as	VUJE	R&D/ Industry	Slovakia
12	State Enterprise State Scientific and Technical Center for Nuclear and Radiation Safety	SSTC NRS	TSO	Ukraine
13	Centre National de la Recherche Scientifique	CNRS	R&D	France
14	Institute for Nuclear Research of NAS of Ukraine	INR NASU	R&D	Ukraine
15	Slovenska Technicka Univerzita v Bratislave	STUBA	University	Slovakia
16	Limited Liability Company Analytical Research Bureau for NPP safety	ARB-NPPS	SME	Ukraine
17	IPP Centre LLC	IPP CENTRE LLC	SME	Ukraine
18	Fraunhofer Gesellschaft Zur Foerderung der Angewandten Forschung e.v	FhG-IZFP	R&D	Germany

that they can be used for RPV embrittlement prediction for LTO beyond 60 years. The existing ETCs mostly under-predict irradiation embrittlement for high fluences and are mainly based on empirical or semi-mechanistic models which do not explicitly consider the effect of microstructural properties and chemical elements (The NUGENIA Association, 2015). Due to lack of surveillance data at high neutron fluences, the effect of Ni, Mn and Si are not adequately described in both VVER and PWR ETCs.

Finally, the structural integrity of the RPV is demonstrated by means of the surveillance programme of each NPP. Most standard surveillance programmes, especially of PWR type reactors, may not contain sufficient amount of surveillance specimen for the LTO beyond the original design life of 40 years. A promising solution for the lack of surveillance material are test methods based on sub-sized/small specimens to characterize irradiation induced shifts in fracture toughness reference curves as well as shifts in DBTT. Manufacturing of small size 0.16 compact tension (CT) specimens from remnants of Charpy impact specimens after testing seems to be an appropriate method. Another potential method is Small Punch Test (SPT) to obtain additional mechanical properties of these materials, like tensile properties, shifts in DBTT etc. Comparison of DBTT shifts from small or standard size specimens with shifts in the reference temperature (T_0) needs to be studied. Applicability of the sub-sized small specimen test methods needs to be further studied and standardised.

Large irradiation and PIE programmes that are aimed to generate required material property data at high fluence conditions for RPV steels have been organised in U.S (https://www.nrc.gov/docs/), in order to help decision makers in preparing required regulatory framework for LTO beyond 60 years. In the similar context, European commission has funded several EU level research programmes on LWR RPV materials, namely STRUMAT-LTO (STRUMAT-LTO), FRACTESUS (FRACTESUS) and ENTENTE (ENTENTE), to address these remaining open issues and to comply with the increased nuclear safety standards of the European NPPs fleet by the Nuclear Safety Directive and to prepare decision makers for possible lifetime extension of European NPPs beyond 60 years. Each of these programmes is focussed on addressing specific open issues. For instance, FRACTESUS project is aimed to demonstrate the applicability of miniaturized compact tension specimens in fracture toughness testing of the RPV steels under hot cell conditions. ENTENTE project is focussed on building a European database for multi-scale modelling of radiation damage including the damage mechanisms from atomic and microscopic levels to model continuum behaviour for integrity assessments. On the other hand, STRUMAT-LTO project aims to address the synergetic effects of Ni, Mn and Si on RPV embrittlement and the applicability of ETCs and master curve testing methods at high fluences to support safe long-term operation of European NPPs, including the scenario of LTO > 60 years.

This paper will provide an overview of the STRUMAT-LTO objectives and project approach, extracting parts of the original project proposal (Horváth and Kolluri, 2019-2020).

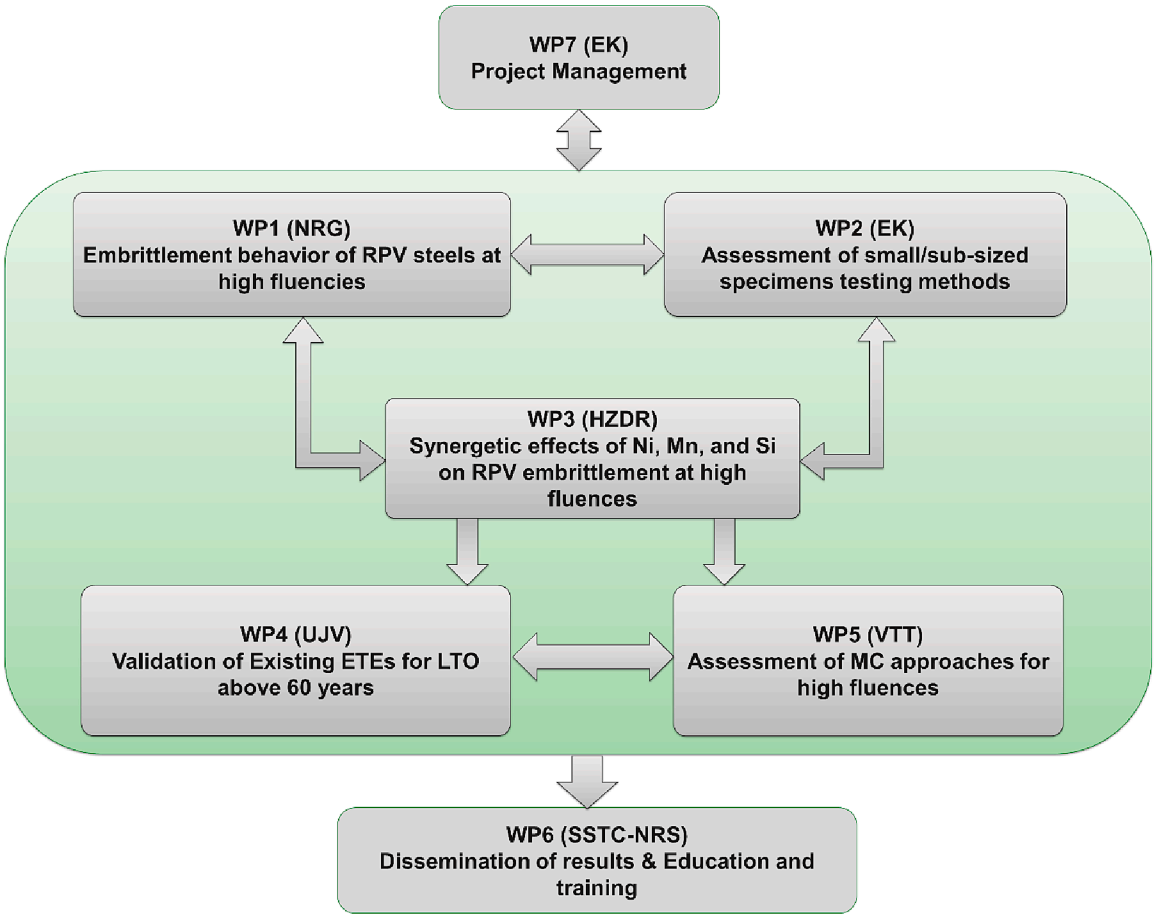

Fig. 2. Work package structure of STRUMAT-LTO Project.

2. Materials and methods

2.1. Project specific objectives

In this section, the 7 specific objectives determined for the STRUMAT-LTO project are presented. These objectives are defined such to provide a deeper understanding of the ageing mechanisms (especially the synergetic effect of Ni-Mn-Si in low Cu RPV steels at high neutron fluences), facilitate the validation and improvement of existing ETCs and investigate the applicability of sub-sized testing methods for LTO. In addition, STRUMAT-LTO intends to bridge gaps in knowledge transfer between retiring and new generations researches in the LTO community.

Quantitative characterization of RPV embrittlement and recovery in PWR and VVER-1000 RPV steels at high fluences resembling 60 – 80 years of reactor operation

The available data for RPV steel embrittlement beyond 40 years is limited (Server et al., 2014; W. e. a. Server, 2013). Within the STRUMAT-LTO project, this data gap is intended to be filled by performing mechanical tests and microstructural analysis on representative RPV materials (both base and weld metals) irradiated to fluence values relevant for LTO. STRUMAT-LTO has obtained access to the valuable set of RPV specimens from the LYRA-10 irradiation experiment. LYRA-10 was a joint irradiation experiment carried out by NRG and JRC ran in the High-Flux-Reactor (HFR), Petten. The LYRA-10 (Ballesteros et al., 2012) irradiation constituted following 3 different categories of RPV model steel specimens resembling western PWR and VVER-1000 RPVs with systematic variation in Ni, Mn and Si contents (Tables 1 and 2).

- Model steels A-H shown in Table 1 represent VVER-1000 base metal RPVs
- Model steels K-N shown in Table 1 represent western PWR base metal RPVs (Kolluri et al., 2021; Laot et al., 2022)
- Realistic welds A-H shown in Table 2 represent VVER-1000 weld metal RPVs

The specimens were irradiated at an average temperature of 286 °C and to a nominal fast high fluence (E > 1 MeV) of 1.11×10^{20}n.cm^{-2} to resemble reactor operation times of 60 + years for PWR / VVER-1000 type reactors. Irradiation lasted for 16 HFR cycles (~467 full power days at a nominal reactor power level of 45 MW) to achieve the target fluence. Note that the nominal flux value is ~ 2.75×10^{12} n.cm^{-2}.s^{-1}, which is slightly more than two orders of magnitude higher than the design flux values of a typical PWR RPV. Flux effects on embrittlement of low Cu RPV steels is a topic of research for long time. For example, LONGLIFE-FP7 and SOTERIA-H2020 projects have investigated flux effects on RPV embrittlement for different types of RPV steels. This knowledge will be employed during the analysis of PIE results within STRUMAT-LTO project. For each type of RPV steel, a variety of specimens were included in the LYRA-10 experiment, constituting Charpy, half-thick Charpy, miniature Charpy (KLST type), tensile test specimen and small slices for miniature and microstructural investigations. An extensive post-irradiation examination (PIE) campaign of the LYRA-10 specimens will be performed in this project. In addition, as the current knowledge and data on recovery annealing treatment and re-irradiation behaviour of low-Cu and high-Ni RPV steels is limited, the influence of thermal annealing on the recovery of mechanical properties of highly irradiated low Cu RPV steels will be investigated. Based on the findings, a proposal will be made for further studies on annealing and re-irradiation behaviour of highly irradiated low-Cu and high-Ni RPV materials for LTO beyond 60 years.

Perform exclusive investigation of synergetic effects of Ni, Mn and Si on RPV materials embrittlement at high fluences

Mn, Ni and Si are usually observed in the solute clusters which contribute to irradiation hardening and embrittlement of RPV steels (Almirall et al., 2019; Mühlbauer et al., 2019). Many studies indicate that these solute clusters could result from an irradiation-induced mechanism (dragging of solute atoms by point defects). In such a case, a monotonous evolution of the microstructure and hardening with fluence is expected. However, from a thermodynamic point of view Mn, Ni and Si can precipitate to form stable phases (Sprouster et al., 2016). In this case, Mn, Ni and Si could result in enhanced hardening and embrittlement at high doses (Bergner et al., 2009). Thus, it is important to study the impact of these solutes especially in materials irradiated up to high dose values. This is particularly important for RPV steels consisting considerable amounts of Ni, in the context of LTO (Kuleshova et al., 2016).

To address this need, a combination of microstructural analysis methods (SEM, TEM, SANS, APT, PAS) will be employed on selected LYRA-10 specimens to investigate irradiation defects and the synergistic effects between Ni, Mn and Si on the irradiated microstructure.

Validation of existing ETCs for LTO above 60 years and a proposal for modifications when needed

need PAS, SANS, TEM..

Currently, ETCs do not include information about the microstructure of the RPV steels (The NUGENIA Association, 2015). Mostly, the ETCs are developed base on surveillance data representing 40 years of reactor operation. Surveillance data representing RPV embrittlement beyond 40–50 years of reactor operation is scarce. Also, some theoretical studies predict existence of a new embrittlement mechanism – late blooming phases (LBP) – that could substantially increase the embrittlement rate after approximately 40 to 60 years of operation for materials with high content of Ni (and most probably also Mn). There are supporting evidences in the literature showing accelerated embrittlement rate at high fluences for RPVs containing high Ni and Mn (Bergner et al., 2009). Thus, still there is a lack of understanding on the physical damage mechanisms of RPV steels in the most relevant fluence range for LTO.

Any evidence of new or accelerated embrittlement mechanisms at high fluences will call for modification of existing ETCs and consequently impact the potential NPP life extension. In fact, recent studies proved that several existing ETCs under-predict RPV embrittlement at fluences representing 60–80 years of reactor operation (The NUGENIA Association, 2015). Consequently, life assessment predictions by the existing ETCs do not cover current efforts for plant life extension to a sufficient level. For this reason, this specific objective is aimed to validate existing ETCs using PIE data generated from LYRA-10 specimens and to propose improvements.

Assessment of Master curve (MC) approaches for fracture toughness (FT) characterization at high fluences

Application of the MC approach to characterize shifts in transition temperature (T_0) of RPV surveillance specimens has gained increased acceptance in the U.S. as well as in many European countries (in some countries use of MC approach is compulsory with regards to RPV integrity assessment, e.g., Finland (Radiation and Nuclear Safety Authority (STUK), 2020). Underlying reason for this change is following: (i) MC approach is a physical-based approach and (ii) all structural integrity calculations of RPVs are based on fracture toughness (FT) values, while currently many countries in Europe use indirect-empirical relations (as published in nuclear codes and standards) to translate DBTT (T_k) shifts determined from Charpy impact tests to T_0 shifts in FT MC.

Application of Master Curve instead of DBTT

MC approach fundamentally relies on two assumptions: (i) the scatter in FT data follows a characteristic Weibull distribution in the ductile–brittle transition region and (ii) the shape of the MC in the transition regime is virtually identical, only the absolute position on the temperature axis varies. The validity of the MC approach and underlying assumptions needs to be further assessed at high fluences relevant for LTO to be able to use this approach in the context of European regulatory framework for structural integrity assessment of RPVs. This is because RPV material may age unevenly after high fluence irradiation due to inherent inhomogeneity in the microstructure (Zurbuchen et al., 2009), which may lead to atypical behaviour causing larger scatter in transition regime than predicted by the standard MC approach. This can also raise ambiguity on validity of existing correlation between transition temperature shifts determined from Charpy impact tests and FT tests.

These irregularities need to be analysed, in addition to the relation to the microstructure and its effect on the applicability of miniature specimens. To address these issues, the goal here is to investigate the effect of high fluence on the scatter in the FT results obtained with small specimens for MC evaluation. Results from FT tests of full size Charpy and mini-CT specimens from selected RPV welds from the LYRA 10 irradiation programme will be used to assess the effect of irradiation embrittlement on the scatter in the ductile-to-brittle transition region of MC at high neutron fluences.

Assessment and application of sub-sized/small specimen testing methods i.e., fracture tests with mini 0.16 CT specimens, and small punch test (SPT), to investigate high fluence materials

The use of sub-sized/small specimen testing methods is a promising way to overcome the problem of limited material from RPV surveillance programmes. In particular FT testing using sub-sized CT specimens (0.16 CT, 4 mm thickness) is a promising way, since they can be manufactured from already tested normal-sized Charpy specimen (see Fig. 1).

The feasibility of FT testing using sub-sized specimens has been generally demonstrated for un-irradiated material in a Japanese-USA lead Round Robin programme (Yamamoto et al., 2014), but only for a number of cases for irradiated steels (Nanstad and Sokolov, 2016). Using sub-sized specimens from irradiated steels bring along several technical challenges (remote controlled machining in hot cell, installation in the test rig, using mini pins, application of extensometers, testing scatter, etc.). Due to these difficulties, the use of mini-CT specimens to evaluate FT properties of irradiated RPV steels needs further investigation. In this regard, STRUMAT-LTO will maintain strong cooperation with the planned FRACTESUS (Cicero et al., 2020; FRACTESUS) project to acquire any new developments made in the specimen design and testing technology of 0.16 CT specimens.

The SPT is used to evaluate mechanical properties and this method has been recently standardized by ASTM (ASTM, 2020) and EN (CEN, 2017). The issue of scatter of the results is still open, especially in the case of irradiated steels, where the specimens have to be machined in a hot cell. Another difficulty is performing such tests in hot-cell conditions, as most manipulators are not sensitive enough to handle such small specimens.

Despite these challenges, small specimen FM testing is seen as candidate solution to collect enough fracture mechanical data for evaluation of synergetic effects of alloying and polluting elements in RPV steels and to evaluate MC for LTO. Within STRUMAT-LTO, the applicability of FT testing using small specimens (mini-CT and SPT) will be assessed and more FT data from available irradiated specimens which can be used for MC and ETC evaluations will be produced. For this purpose, sub-sized CT specimens and SPT discs will be machined from irradiated Charpy and KLST LYRA-10 specimens for further testing.

Small samples testing

Podporenie knowledge transfer

Education and training of young researchers in the field, especially PhDs, Post-docs and young researchers, to bridge gaps in knowledge transfer between retiring and new generations

Ensuring the transfer of knowledge between retiring and new members of the nuclear workforce is one of the most significant challenges in nuclear industry. This increasing need for establishing successful retention, knowledge transfer and capacity building programmes has been agreed by both veteran and young experts at IAEA's 62nd General Conference (https://www.iaea.org/newscenter/news/bridging-the-gap-knowledge-transfer-to-next-generation-of-nuclear-workforce). Similarly, this need of bridging knowledge gap between generations was identified at EU level and the European Nuclear Education Network Association (ENEN) is working on enhancing research, education and training in nuclear technology, and supporting the activities of other educational networks. To support this unique need, STRUMAT-LTO is aimed for education and training of young researchers including PhDs, Post-docs by involving them in executing various tasks within the project under the guidance of experts in the field. Additionally, a summer school for young researchers in the field and a dissemination workshop will be organised in the project where experts deliver lectures and share their experiences and knowledge in the field. Large number of travels grants will be provided to encourage students to attend the summer school and workshop.

Dissemination of the projects results to nuclear stakeholders

The final specific objective for the STRUMAT LTO project is to involve all relevant nuclear stakeholders (e. g. academic and R&D institutes, utilities, Technical and scientific support organizations, regulators, other EU consortiums, experts etc.) from the beginning of the project. This will help to understand actual needs from the utilities and regulatory points of view, so that technical and scientific tasks can be tuned to address these needs accordingly, and to maximize the overall impact of the project's results.

3. Project structure

Vyuzitie SANS a PAS

In total 18 international organizations will contribute to the STRUMAT-LTO project as can be viewed in Table 3. In order to structure the project, the work is divided into 7 work packages (WPs) (Fig. 2).

The testing of irradiated tensile, Mini-Charpy/KLST, Charpy, half-Charpy, Mini-CT, SPT test specimens from LYRA-10 and corresponding reference specimens in WP1 and WP2 as per the agreed test matrix, will lead to quantitative PIE data on hardening and embrittlement behaviour of PWR and VVER-1000 RPV steels at fluences resembling>60 years of reactor operation to fill the existing data gaps. To investigate synergetic effects of Ni, Mn and Si on RPV embrittlement at high fluences, microstructural analysis characterization by SEM, TEM, SANS, APT, PAS etc. will be performed on selected specimens from LYRA-10 in WP3 combined with mechanical testing results of WP1 and WP2. These results will provide a comprehensive understanding of the synergetic effects as well as individual role of Ni, Mn and Si on RPV embrittlement at high fluences for low Cu RPV steels.

In WP4, analysis of transition temperature shift results (both T_o and T_k) from WP1 and WP2 in combination with microstructural information from WP3 will be used to assess and validate existing ETCs to propose improvements to support LTO beyond 60 years. Also, the results of WP5 will lead to an improved understanding on the applicability of the MC method at high fluences, especially in view of the scatter in the transition region with the analysis of the MC testing results of WP1 and WP2. The sub-sized / small specimen test methods applied in WP2, will enhance the current understanding of the applicability of such test methods for FT evaluation and in addition, more PIE data points will be produced.

Knowledge transfer to younger generations in the RPV-LTO research topic will be attained by organizing activities such as a summer school. Also, 40 k€ from the STRUMAT-LTO budget is reserved for student grants and young scientist from the beginning of the project. Finally, to maximise the overall impact of the project 2 end user group meetings, 2 dissemination workshops, 4 scientific advisory board meetings, and one summer school for young engineers will be organised and project results are continuously published in peer-reviewed journals and as conference papers, through the interaction with other project consortia working in the field.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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