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The Main Results of Structural Materials Research for Safe Long-Term Operation of LWR NPPs from the Viewpoint of Dissemination Activities

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One of the main points of any project implementation is the dissemination of the obtained results among the nuclear community, young researchers, public, stakeholders, etc. Communication and dissemination activities are considered as high-priority elements in European collaborative research projects. The article briefly presents EUROATOM project "STRUctructural MATerials Research for Safe Long-Term Operation of LWR NPPs" (STRUMAT-LTO), that was started in September 2020, describes its goals, main steps, expected outputs, approaches used for dissemination and communication activities and brief status update on interim results after 2 years' implementation. In general, the deployment of the STRUMAT-LTO project was dedicated to studying synergetic effects of Ni-Mn-Si on RPV embrittlement at high fluences by exploiting unique RPV model steels irradiated in LYRA-10 irradiation experiment and assessing the Embrittlement Trend Curves for LTO and Master curve approach for LTO. All these activities are aimed at finding a solution to justify safe LTO until 80 years of operation.

Keywords: STRUMAT-LTO, reactor pressure vessel, dissemination activity, LYRA-10, long-term operation, embrittlement, ageing management, fluence, synergetic effects.

Introduction

The majority of the current nuclear energy in the European Union (EU), Ukraine, as well as all over the world, is produced from generation II and III reactors. However, ~60% of the existing reactors have been operating for more than 30 years, which means that these reactors are close to the end of their original design life. This capacity cannot be fully replaced by new nuclear reactors immediately. To deal with this situation, long-term operation (LTO) of existing nuclear power plants (NPPs) has been identified as a promising way to achieve the intermediate decarbonisation targets in energy transition towards 2050 and is a common practice in a significant number of countries with established nuclear programmes. LTO approval for any reactor requires a comprehensive structural integrity analysis and ageing management procedures to ensure safe operation of the units for the extended operation period. These scenarios introduce many technological and scientific challenges to both

utilities (to prepare for LTO license extension) and regulators (to prepare the required regulatory framework to approve LTO license extension).

Embrittlement of reactor pressure vessels (RPVs) mainly caused by neutron irradiation is a critical issue for LTO of light-water reactors (LWRs), which are the dominant type of currently operating reactors and particularly include pressurized water reactors (PWRs). RPVs are practically non-replaceable. With increasing reactor lifetime, RPVs are exposed to higher neutron fluences causing potentially greater embrittlement and thus reducing ductility.

Substantial research has been performed in various international collaborative research projects, such as "Treatment of long term irradiation embrittlement effects in RPV safety assessment" (LONGLIFE) [1], "Prediction of the effects of radiation for reactor pressure vessel and in-core materials using multiscale modelling – 60 years foreseen plant lifetime" (PERFORM60) [2] etc., which have helped to improve the understanding of many open issues in RPV ageing phenomena, including flux effect and influence of chemical/microstructural heterogeneities on RPV embrittlement. Despite all previous research efforts on RPV embrittlement, there are several open issues that require further research to understand the unfavourable synergy between Ni, Mn and Si that affects the microstructure and mechanical properties of RPVs at high fluences to elucidate late irradiation effects.

In order to cover existing open issues, new project "STRUctructural MATerials Research for Safe Long-Term Operation of LWR NPPs" (STRUMAT-LTO) has been initiated by 18 scientific organisations from different EU countries including Ukraine and supported by European Commission with corresponding grant.

In this context, the STRUMAT-LTO project is strategically intended to address the remaining gaps in the RPV embrittlement research to support safe LTO (including > 60 years). So, it is obvious that STRUMAT-LTO scientific results should be achievable by scientific community and utilities as well. Usually, this goal will be reached by effective execution of project tasks and dissemination of project results.

1. The main aspects of dissemination activities within the STRUMAT-LTO project

One of the main points of any project implementation is the dissemination of the obtained results among the nuclear community, young researchers, public and other stakeholders. Communication and dissemination activities are considered as high-priority elements in European collaborative research projects funded under the European Horizon 2020 and EURATOM programmes.

In general, term "dissemination" can be explained as "delivering and receiving the message", "engagement of an individual in a process" and "transfer of a process or product" [3]. Thus, before the dissemination process will start it is needed to define a several main key points (KP):

KP1 What exactly should be disseminated from a project content (as a core objective)
KP2 To whom (target audiences)
KP3 By which way/tools/methods/means.

What exactly should be disseminated (KP1) is important matter because one the difficulty of any project may be misunderstanding between outputs of a project (expected from the viewpoint of a project team) and awareness of target audience that is wide enough and comprises the public, newsmakers, scientists, students, postdocs etc. All described points should be clearly identified at the beginning of any project by the project team that has to share vision and common understanding of what it is needed to disseminate together with a way of describing this activity.

The next important question is definition of target audience (KP2) or by the other words it is needed to understand to whom the obtained outputs (final or intermediate) will be interesting and correspondingly disseminated. This requires some analysis of various potential stakeholders that could be interested to get the results of the project. Term "target audience or group" can be used to describe the different groups of stakeholders connected to the project.

Finally, when there is an understanding of the results to be disseminated and identification of target audience, the methods and tools for dissemination need to be defined.

The first and main task of any dissemination process is a definition of the aspect – to whom it may concern? The project team usually understand what they are trying to achieve but that the target audience may not. It is essential, therefore, that project team has a shared vision and common understanding of what should be disseminated together with a way of describing this to those that are outside the project and who may stand to benefit from projects results and work. It is important to identify who stakeholders are and then to be able to map them to one of the categories outlined in the awareness, understanding, and action model.

Dissemination activities may be implemented by three different ways [3]:

Dissemination by awareness (awareness of people about the work of project - this may be useful for those target audiences that do not require a detailed knowledge of your work but it is helpful for them to be aware of your activities and outcomes);

Dissemination by understanding (deep understanding of a project's work by a number of groups/audiences that need to be targeted directly with dissemination considering what a project has to offer);

Dissemination by action (action refers to a change of practice resulting from the adoption of products, materials or approaches offered by a project. These

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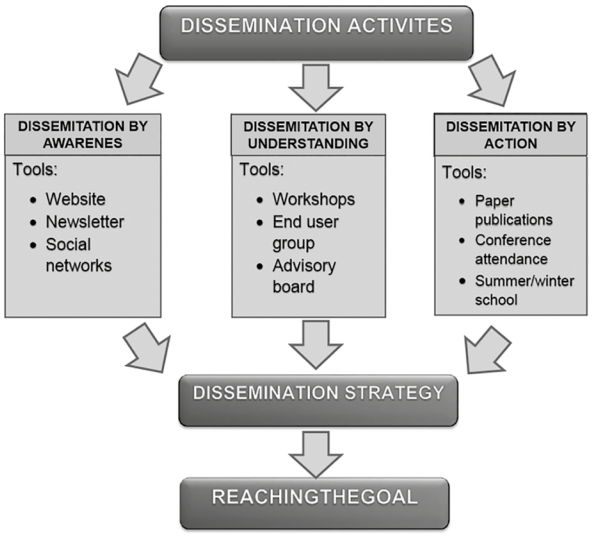

Figure 1 – Dissemination flowchart

groups/audiences will be those people that are in a position to "influence" and "bring about change" within their organisations. These are the groups/audiences that will need to be equipped with the right skills, knowledge and understanding of the project work in order to achieve real change).

Each way of dissemination requires corresponding tools. Thus, before the dissemination strategy for STRUMAT-LTO has been developed the flowchart for definition of target audience and tools of dissemination was created (see Figure 1).

Based on the aforementioned aspects the dissemination strategy and communication plan have been developed within the STRUMAT-LTO project at the earliest stage of project implementation and presented in the corresponding reporting document [4].

2. Dissemination strategy

The purpose of the Dissemination Strategy [4] is to establish and agree upon the strategic approach for communication actions focused on STRUMAT-LTO project information and dissemination of the project results at various levels: level of the EURATOM R&D programme, at project and partner levels, and at public media level for the whole duration of STRUMAT-LTO.

The main ideas regarding "what exactly should be disseminated from a project content (KP1)" may be announced as dissemination of the following results:

study on synergetic effects of Ni-Mn-Si on RPV embrittlement at high fluences (especially for LTO > 60 years);

unique LYRA-10 irradiation experiment;

assessment of the Embrittlement Trend Curves (ETCs) for LTO and Master curve approach for LTO, etc.

The definition of "to whom (target audiences) (KP2)" with corresponding targeted messages has been identified as presented in Table 1 before the Dissemination Strategy [4] development was started.

The "methods and tools (KP3)" in general could be defined as a set of actions like participations in conferences and workshops, organization of training courses, exchange program for PhD students/postdocs/young scientists, publication of project results in scientific journals and conference proceedings, activities dedicated to Education and Training. Based on these general aspects the Dissemination Strategy [4] of STRUMAT-LTO outlined the following events:

Table 1 – Target group/audiences and main messages

Target group/audiences	Targeted messages
Regulators	Solid scientific basis for decision making over RPV embrittlement within LTO licensing process
Technical support organisations (TSO)	Knowledge generated by STRUMAT-LTO to support the TSOs for safety assessment during the LTO licensing process
Operating organization (NPP Owners)	Research data generated by STRUMAT-LTO helps in validating the existing ETCs to justify safe operation of NPP units for a period more than 60 years
Academic and R&D institutes (Master and PhD students, postdoctoral researchers, trainees, young scientists and young engineers, etc.)	Project results will foster research to improve understanding of ageing mechanisms, especially synergetic effects of Ni-Mn-Si in low Cu RPV steels at high neutron fluencies by validation and improvement of existing ETC, etc. Getting results of experimental research and numerical simulation to produce data and increase knowledge to better grasp ageing phenomena and deterioration mechanisms of NPP RPV.
Small and Medium Enterprises	Increased ability to deliver high quality service based on in-depth knowledge of the properties of materials exposed to radiation
General public	Enhanced safety during LTO of NPPs

Paper publications and presentations at conferences (e.g. ASME Pressure Vessels and Piping Conference (PVP Conference), Structural Mechanics in Reactor Technology (SMiRT Conference), International Conference on Nuclear Engineering (ICONE Conference), European Conference on Fracture (ECF Conference), Nuclear Materials Conference (NuMAT) etc.);

Scientific Advisory Board meetings (4 meetings over the project period);

Consortium meeting (twice per year);

End User Group meetings (Utilities, Regulators & TSOs - twice per project duration);

Progress meetings 1 and 2 combined with End User Group and Scientific Advisory Board meetings;

Dissemination Workshops 1 and 2 (for project participants and target groups - about 20 lecturers & contributors for workshop and about 30 participants from target audience);

Summer school for target groups (for presenting the main results of work package implementation, demonstration of mechanical testing on LYRA-10 specimens in hot cells and presenting common results of the project).

One of the important parts of any project implementation for dissemination results is developing and permanent supporting of website and pages in the social networks (e.g. LinkedIn, ResearchGate etc.). These aspects are indicated in the Dissemination Strategy [4] and implemented in the framework of STRUMAT-LTO at the beginning of project deploying (see Figures 2 - 4).

The overall objective of dissemination is to make the STRUMAT-LTO project results easily available to the identified target groups, enabling stakeholders to use the project results in their own work. The communication and dissemination activities are continuing over the whole period of project implementation.

All of these disseminating steps should be adequately assessed by specific indicators such as so-called "key performance indicators" (KPI). These KPIs are created and included in the Dissemination Strategy [4]. Over the first half of project implementation, these KPIs reached and even exceeded some criteria. The current status of their quantity evaluation is presented in Table 2.

The aforementioned KPIs show that the main source of information and interest to the project is the project *website*. It is absolutely understandable because the majority of the project information and news is presented exactly on the site. Reading this news, it is really possible to follow the current status of project implementation. This article also allows to understand the current status of STRUMAT-LTO that is briefly presented below.

Figure 2 – STRUMAT-LTO Website [5]

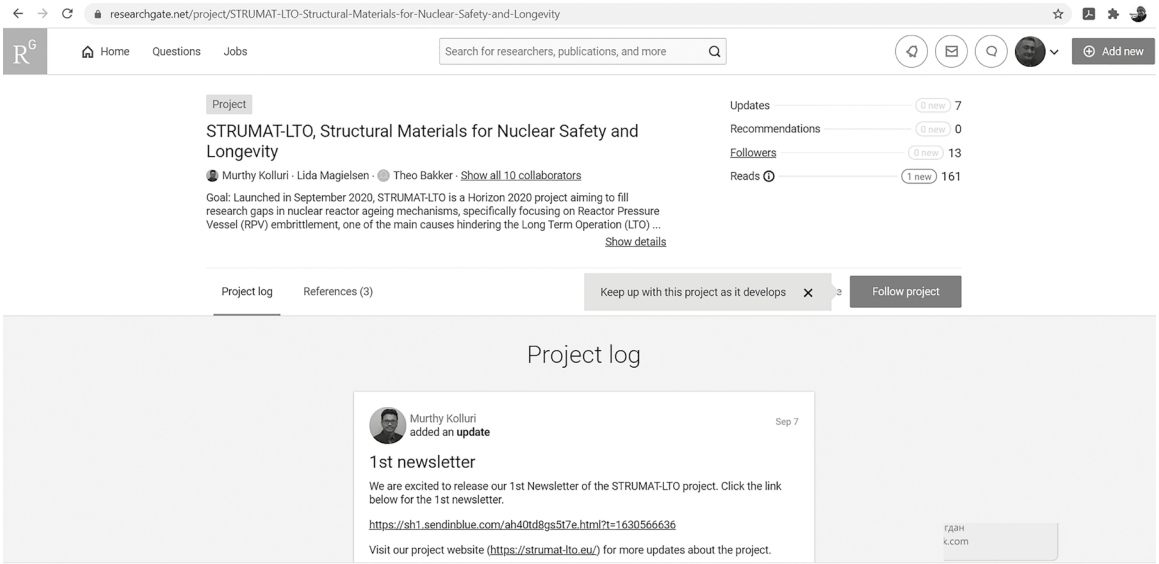

Figure 3 – STRUMAT-LTO at ResearchGate [6]

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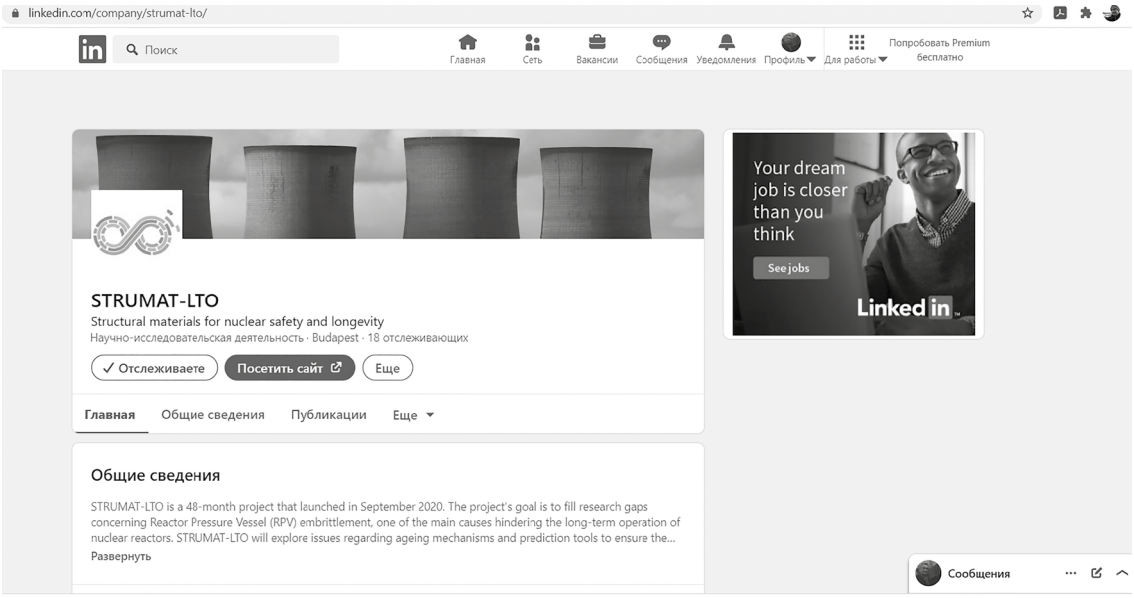

Figure 4 – STRUMAT-LTO at LinkedIn [7]

Table 2 – Current status of KPIs quantity evaluation

Channels	KPIs	KPI statistic (for 1st half of the project, December 2022)
Public website	At least 5000 views from 20 countries	5 426 visitors, 6 383 sessions, 27 countries
Social media	At least 500 views	112 visitors on the project LinkedIn page
Newsletters	Around 600 subscribers	30 subscribers
Event participation	Participation in at least 3 events	Planning for the next period
Training and education activities (summer school)	At least 30 attendees	Planning for the next period
Dissemination Workshops	At least 30 attendees	Planning for the next period

3. The main STRUMAT-LTO results over the first half of project implementation

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 Nuclear Research and Consultancy Group (NRG) and Joint Research Center (JRC) ran in the High-Flux-Reactor, Petten. Starting from the beginning of the project the activities have been deployed within five research Work packages, Dissemination & Education and Administrative ones (see Figure 5).

Sufficient progress up to the first half of project implementation was met at each work package (WP). The main steps implemented are: withdrawing samples from LYRA-10, their distribution among institutions and testing (Figure 6) etc.

In the framework of *"WP1 Embrittlement behaviour of RPV steels at high fluences"* within the first two years of the project, the majority (~90%) of the reference and Post Irradiation Examination (PIE) testing planned within WP1 has been finished: specifically, Tensile testing (Task 1.2), KLST testing (Task 1.3), and thermal annealing (Task 1.5). This also means ~50% of total reference and PIE tests planned within the whole project (see Figure 7) is finished. The analysis of the test results helps in understanding the embrittlement behaviour of RPV steels at high fluencies and effectiveness of thermal annealing in recovery after high fluence irradiation [1], [2].

Main deliverables and milestones (MS) achieved in this period include:

MS1. Final test matrix

MS2. Transport of reference and PIE specimens to the partners as per agreed test matrix

MS5. Transport of tested PIE specimens for further testing at partners' locations.

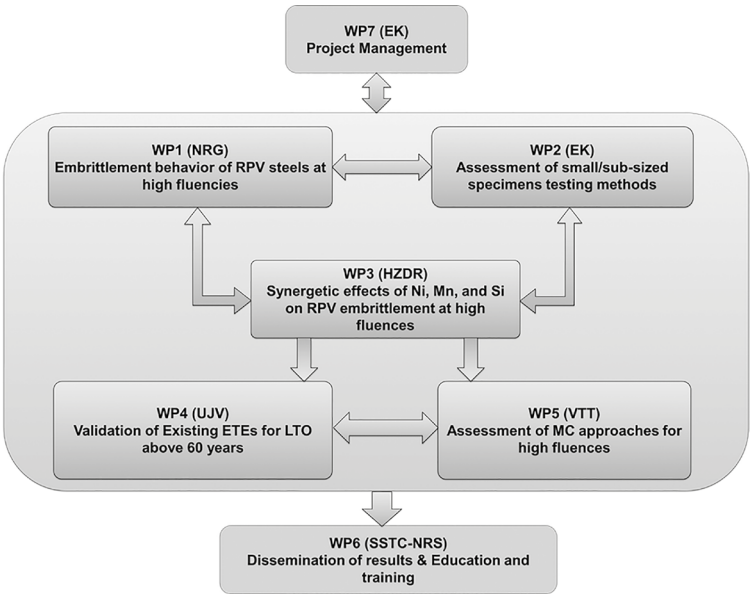

Figure 5 – STRUMAT-LTO work packages

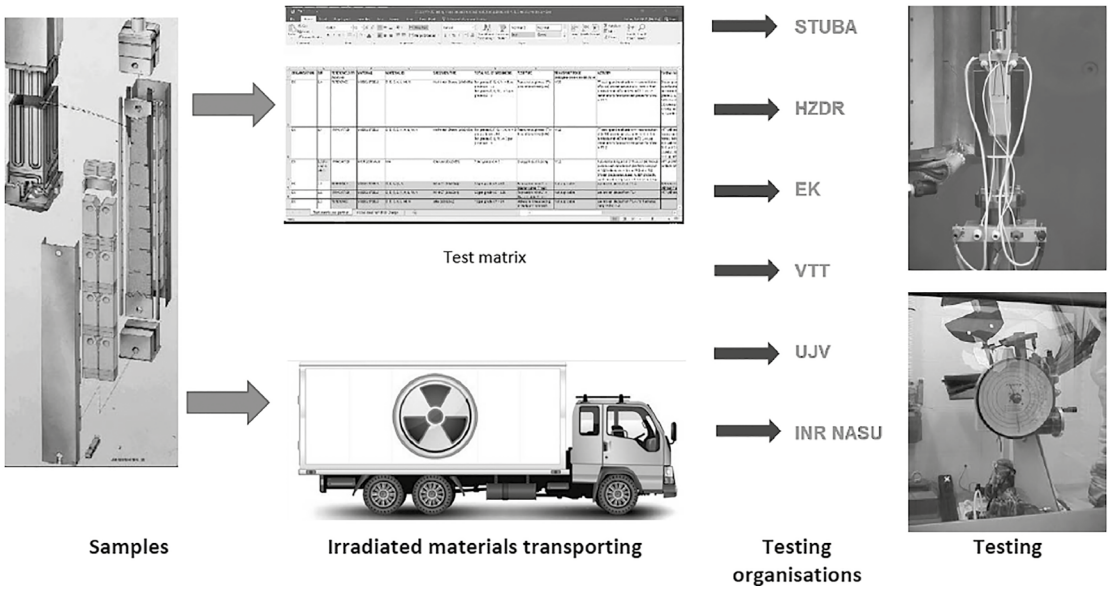

Figure 6 – The main steps implemented within STRUMAT-LTO

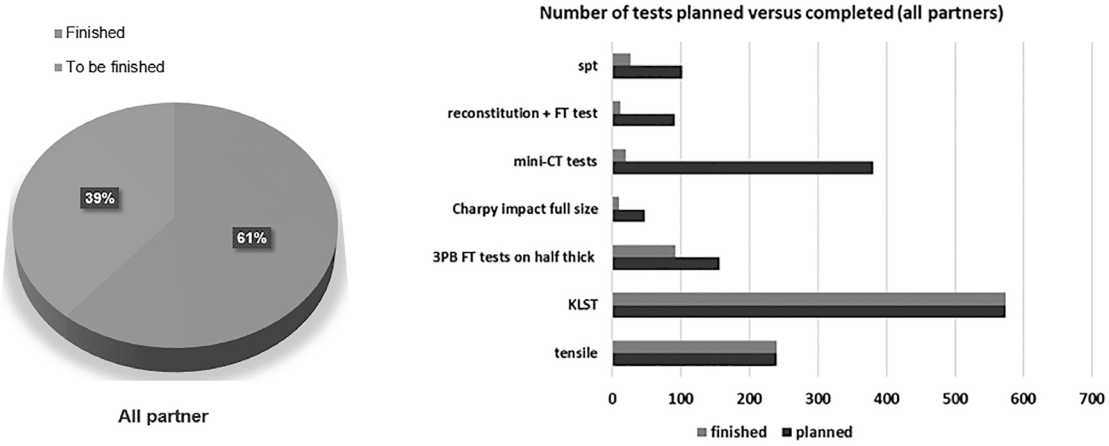

Figure 7 – Number of planned versus completed tests within STRUMAT-LTO

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Another important achievement was reporting of all LYRA-10 materials and irradiation documents, such as irradiation report, dosimetry report, report on origin and manufacturing of the LYRA-10 specimens, specific fluences, previous reference test data, to have a solid basis for analysing the PIE test results of the project.

"WP2 Assessment of small/sub-sized specimens testing methods" uses small size specimens cut from the remnants of the Charpy specimens tested at WP1. Two types of tests considered: fracture toughness measurement using mini compact tension specimens and small punch testing. While testing within WP1 is continuing, the WP2 organized Round Robin testing on the production and use of mini compact tension specimens and small punch testing. The small punch testing was successfully finished, where the participating institutes demonstrated the validity of the test method by comparing the results obtained from various labs (Figure 8 shows small punch testing specimens, Figure 9 shows small punch testing specimen production, Figure 10 represents a comparison of test results). The round robin results have been published at ASME PVP 2022 conference [1] and in ASTM journal [2]. The mini compact tension testing is currently in progress and results coming soon.

The objective of *"WP3: Synergetic effects of Ni, Mn and Si on RPV embrittlement at high fluences"* is to identify and explain synergetic effects of VVER-1000 typical alloying elements in terms of irradiation-induced microstructures and mechanical property changes.

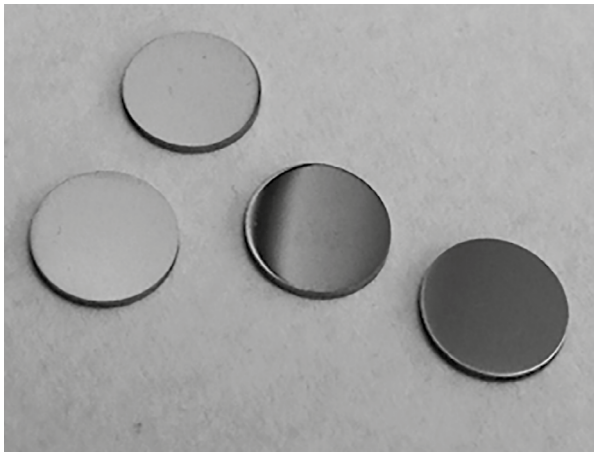


Figure 8 – Small Punch specimens prepared

Figure 9 – Spark cutting of small punch testing

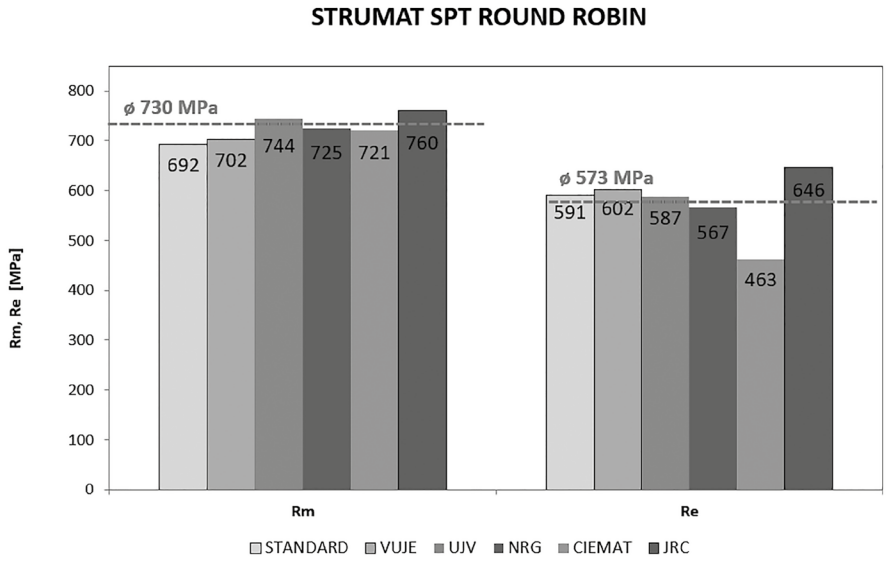


Figure 10 – Comparison of results obtained by different laboratories in the frame of the WP2 small punch test Round Robin task

The approach is based on the application of complementary microstructural characterization techniques such as Light Optical Microscopy, Scanning Electron Microscopy with Electron Backscattering Diffraction, Transmission Electron Microscopy, Atom Probe Tomography, Positron Annihilation Spectroscopy and Small-Angle Neutron Scattering. Therefore, the following tasks has been implemented:

1. Test matrix and characterization of the initial microstructure
2. Characterization of irradiation-induced nano-features
3. Correlation with mechanical properties and identification of synergetic effects of Ni, Mn and Si.

Recently, the teamwork of different labs using various microstructural investigation techniques for task 1 was completed. Various transitions electron microscopy images of model steel B are shown in Figure 11 as an example. Sample preparations and research of the irradiated material conditions is continuing.

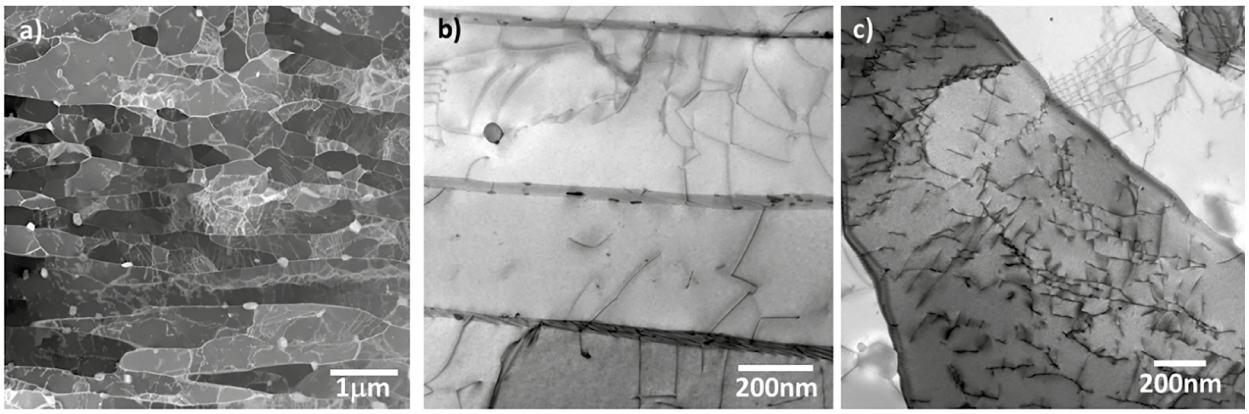
All obtained results are used in the framework of *"WP4: Validation of Existing ETCs for LTO above 60 years"* and main first step was made by issuing the report dedicated to "Collection and expert analysis of available ETCs applicable to VVER and PWR" that describes and presents information about available ETCs (official, regulatory as well as literature proposed), comparison and analysis with respect to their origin, applicability, chemical content and fluence dependencies. This analysis concentrated mainly on the studied effects within the project – effect of alloying elements Ni, Mn and Si and also on the prediction of material embrittlement for high neutron fluences expected for 60+ years of operation.

Due to the long-term irradiation, RPV material may age unevenly depending on microstructural properties or show atypical behaviour causing larger scatter than predicted by the standard Master Curve approach. These aspects will be considered in details within the *"WP5: Assessment of MC approaches for high fluences"* with focusing on the factors affecting fracture toughness at high fluences and selection of suitable materials/methods for analysis of high-fluence materials; on determination of lower boundary fracture toughness curve for high-fluence materials; on the correlation between conventional TK shifts from Charpy testing and T0 values from sub-size specimens etc. These activities are being continued.

The results of each work package will be presented continuously at different international conferences, meetings and other public events together with publishing in a scientific journals [8]-[12] and newsletters [13]-[14].

4. Interconnection of STRUMAT-LTO with sister's projects

As already mentioned above, STRUMAT-LTO aims at performing a wide range of mechanical tests and microstructural analyses to study synergetic effects of three alloying elements and irradiation embrittlement behaviour of the RPV steels under high fluences in general, and to validate existing ETCs, master curves approaches and small/sub-sized specimen testing methods for RPV material irradiated to high fluences. Standardization of small/sub-size specimen testing is not the primary purpose of the STRUMAT-LTO project. However, the use of small specimens cut from the irradiated broken remnants will increase the amount of information and allow the evaluation of the fracture toughness. On the other hand, the FRACTESUS [15] project deals with testing and standardization of irradiated small sized specimens. The goal of the FRACTESUS is to establish a foundation of small specimen fracture toughness validation and demonstration to address different concerns of national regulatory authorities. Exchanging the information on the testing of irradiated small/sub-sized specimens between



a) Weak Beam Dark Field image of the lath structure

b) Bright Field image of a detail of the lath boundaries with small V rich precipitates

c) detail of the dislocation structure within laths

Figure 11 – Images of steel structure under microscope

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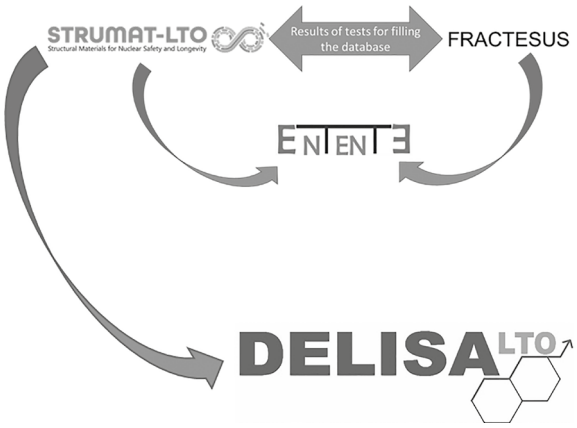

Figure 12 – Interconnection with sister projects

the FRACTESUS and STRUMAT-LTO projects will be beneficial for both projects. To facilitate this information exchange, the representatives of the FRACTESUS will be invited periodically to STRUMAT-LTO meetings and vice-versa. Finally, the ENTENTE project [16] aims at developing innovative data management tools to maximise access to RPV embrittlement data for utilisation of the results in the multiscale modelling programmes. The ENTENTE database will be improved upon the existing SOTERIA Platform to test industrial reference cases and to provide open access to this wealth of accumulated knowledge. The DELISA-LTO project (https://delisa-lto.eu/) started since June 2022 and corresponding interconnections in part of exchange results are also envisaged for DELISA-LTO and STRUMAT-LTO.

General interconnection among the projects is presented in Figure 12.

The four projects will regularly share knowledge and general results, during the meetings, conferences exchanges, seminars etc. In particular, the combined STRUMAT-LTO and FRACTESUS PVP 2023 symposium on miniature testing will take place in 2023.

Conclusions

Long-term operation of generation II and III NPP units is very challenging and demanding issue that push nuclear scientific community to look for ways to understand and justify the ability of RPV to operate up to 60 and even 80 years. The RPV is practically non-replaceable and with extending reactor lifetime the RPV is exposed to higher neutron fluence causing potentially more embrittlement and thus reducing ductility.

Substantial research has been performed in various international collaborative research projects, such as LONGLIFE, PERFORM60, SOTERIA and now is continued in the framework of STRUMAT-LTO.

One of the main points of any project implementation is the dissemination of the obtained results among the nuclear community, young researchers, public and other stakeholders. Communication and dissemination activities are considered as high-priority elements in European collaborative research projects funded under the European Horizon 2020 and EURATOM programmes.

For STRUMAT-LTO, the dissemination activity has been started immediately after the kick-off meeting was held and the Dissemination strategy [4] was developed within first three month. This strategy defined:

the strategic approach for communication actions focused on the dissemination of the project results at various levels (level of the EURATOM R&D programme, at project and partner levels, and at public media level for the whole duration of STRUMAT-LTO);

events needed for dissemination results (paper publications and presentations at conferences, different types of meetings);

educational tools (e.g. summer/winter school for target groups, dissemination workshops etc.);

interconnection among work packages and actions;

creating and supporting website, social networks;

and key performance indicators to assess the project's success etc.

Over the first half of project implementation, these KPIs reached and even exceeded some criteria showing the sufficient interest to current status of the project and expected results. These KPIs also indicate that the project goes ahead successfully and the main source of information and interest to the project is website (www.strumat-lto.eu). Nevertheless, public social networks (e.g. LinkedIn, ResearchGate etc.) allow enough quickly inform the stakeholders and target audience about current or upcoming events, news etc.

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Основні результати проєкту STRUMAT-LTO щодо вивчення структури матеріалів для забезпечення довгострокової експлуатації АЕС з легководними реакторами з погляду розповсюдження результатів діяльності

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Одним із основних аспектів реалізації будь-якого проєкту є поширення отриманих результатів серед спільноти атомників, науковців, молодих вчених, громадськості та інших зацікавлених сторін. Діяльність з комунікації та поширення результатів вважається завданням високого пріоритету в усіх європейських дослідницьких проєктах. У цій статті стисло представлено новий проєкт ЄВРАТОМу «Дослідження структури матеріалів для забезпечення безпечної довгострокової експлуатації АЕС з легководними рекаторами» (STRUMAT-LTO), розпочатий у вересні 2020 року, описано його цілі, основні кроки, підходи, які використовуються для поширення результатів та комунікаційної діяльності і описані проміжні результати після 2 років впровадження проєкту. Загалом, розгортання проєкту STRUMAT-LTO присвячено дослідженню таких аспектів, як-то вплив синергетичних ефектів таких хімічних елементів як Ni-Mn-Si у металі на крихкість корпусу реактора за високих флюенсів, отримання унікальних результатів експерименту опромінених зразків LYRA-10 та оцінка тенденції зміни крихкої міцності залежно від опромінення. Усі ці дії спрямовані на пошук рішення для обґрунтування безпечної понадпроєктної експлуатації енергоблоків АЕС у країнах Європи та в Україні до 80 років.

Ключові слова: STRUMAT-LTO, LYRA-10, довгострокова експлуатація, корпус реактора, окрихчення, синергетичний ефект, управління старінням, флюенс.

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