

The STRUMAT-LTO project is finishing by the end of August 2024. It involved four years of intensive testing, analytical and dissemination activities conducted by the STRUMAT-LTO team gathered from 18 institutions.



Figure 1. Project Partners

Over these years, the synergetic effects of nickel, manganese, and silicon (Ni-Mn-Si) on RPV embrittlement and the applicability of Embrittlement Trend Equations (ETEs) and master curve testing methods at high fluences relevant for LTO beyond 60 years have been investigated within the STRUMAT-LTO project. To achieve the objectives, the STRUMAT-LTO project used a unique set of RPV steel specimens with systematic variations in Ni, Mn and Si, irradiated in the LYRA-10 experiment conducted by NRG and JRC in the Petten High Flux Reactor. The LYRA-10 experiment included more than 650 test specimens with various geometries, involving tensile, mini-Charpy (KLST) and Charpy, representing a variety of PWR and VVER-1000 base metal (12 grades) and VVER-1000 weld metal (8 grades) RPV steels. Lyra-10 samples achieved a nominal fluence ($E > 1$ MeV) of 1.11×10^{24} n.m⁻² and an average irradiation temperature of ~ 286 °C.

The work within STRUMAT-LTO was organized into five scientific work packages (WP1-5) and a dissemination, education, and training work package (WP6).

The **WP1 “Embrittlement behavior of RPV steels at high fluences”** and **WP2 “Assessment of small/sub-sized specimens testing methods”** are focused on extensive post-irradiation mechanical testing of all base metal and weld metal RPV steel grades. Specifically, WP1 is focused on bulk mechanical testing of tensile, mini-Charpy (KLST) and fracture mechanics testing on single edge notched bend (SEN(B)) specimens. On the other hand, WP2 is focused on using remnants of broken test pieces from WP1 to perform miniature testing techniques, such as mini-CT, small punch test methods, hardness and micromechanical testing, and reconstitution. A total of ~ 1600 mechanical tests excluding hardness and indentation are planned in WP1 and WP2, of which 98% of tests have been successfully finished (see Figure 2), being a great achievement of the project. The results from WP1 and WP2 are supplied to WP3 for the assessment of synergetic effects of Ni, Mn and Si on RPV embrittlement in correlation with microstructural damage mechanisms, to WP4 for validation of existing ETEs for LTO above 60 years and to WP5 to study the suitability of the master curve technique for these high fluence materials. The highlights in each of these WPs are outlined further in this newsletter.

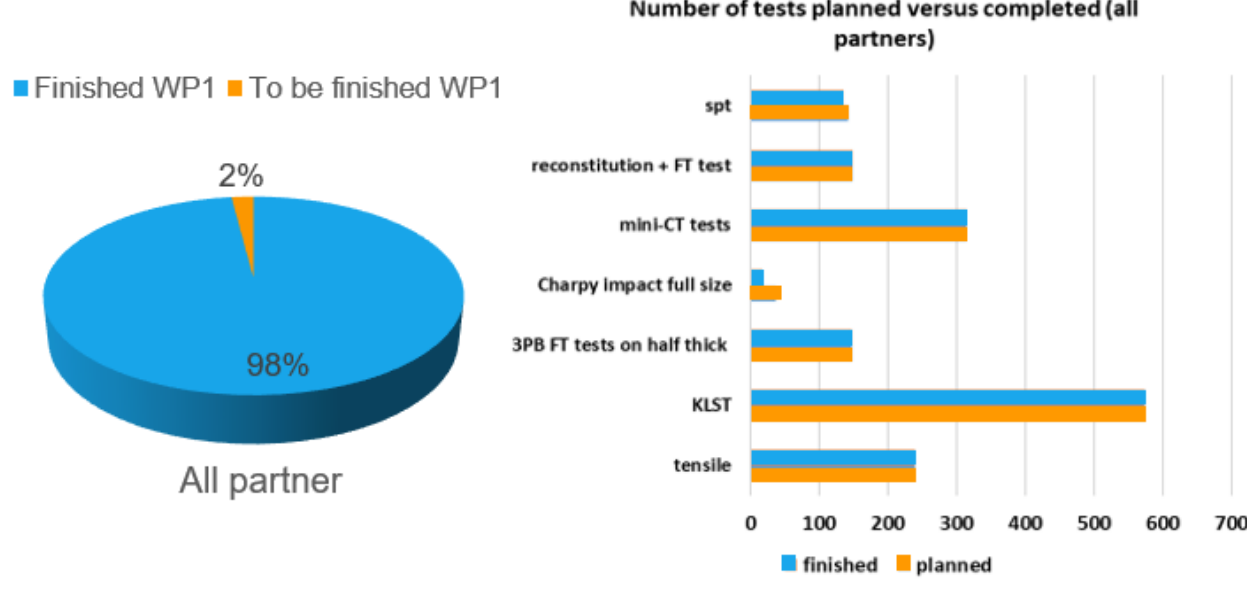


Figure 2. Planned versus completed tests within STRUMAT-LTO (status as of July 2024)

Over these years, the synergetic effects of nickel, manganese, and silicon (Ni-Mn-Si) on RPV embrittlement and the applicability of Embrittlement Trend Equations (ETEs) and master curve testing methods at high fluences relevant for LTO beyond 60 years have been investigated within the STRUMAT-LTO project. To achieve the objectives, the STRUMAT-LTO project used a unique set of RPV steel specimens with systematic variations in Ni, Mn and Si, irradiated in the LYRA-10 experiment conducted by NRG and JRC in the Petten High Flux Reactor. The LYRA-10 experiment included more than 650 test specimens with various geometries, involving tensile, mini-Charpy (KLST) and Charpy, representing a variety of PWR and VVER-1000 base metal (12 grades) and VVER-1000 weld metal (8 grades) RPV steels. Lyra-10 samples achieved a nominal fluence ($E > 1$ MeV) of 1.11×10^{24} n.m⁻² and an average irradiation temperature of ~ 286 °C.

In addition to the above-mentioned bulk mechanical testing, WP1 also investigated the effectiveness of thermal annealing in recovery of tensile properties of these highly irradiated RPV steels. The results showed that almost full recovery in tensile properties can be obtained after thermal annealing at ~ 475 °C irrespective of composition (see Figure 3), which is promising for applying this technology for certain types of RPV steels as a mitigation measure for LTO. Further investigation on the re-irradiation behavior of annealed RPV steels is needed to prove this technology for low-Cu RPV steels.

It is worth mentioning that WP2 started with two Round-Robin exercises on fabrication and testing of mini-CT and SPT specimens in hot cell environment to harmonize the testing procedures between different laboratories (NRG, EK CER, UJV, VTT) before proceeding to testing of LYRA-10 samples (irradiated and unirradiated). Both mini-CT and SPT testing results demonstrate a good agreement between different laboratories (see Figure 4).

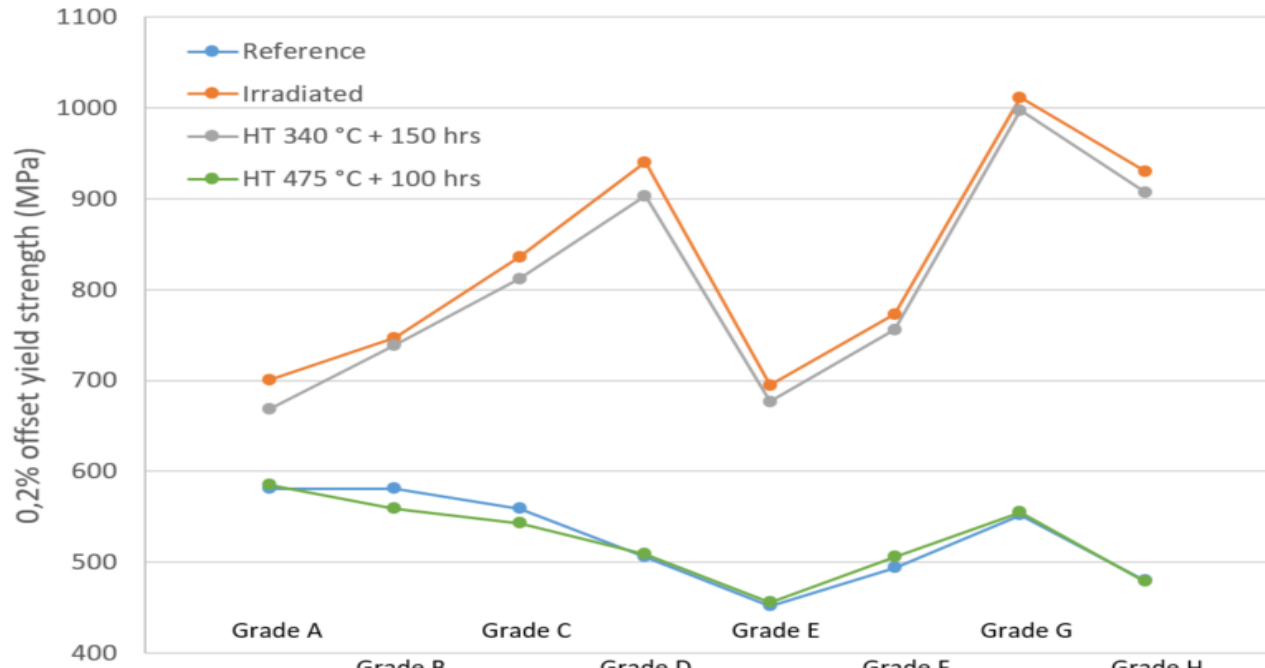


Figure 3. Effectiveness of the thermal annealing in recovery of tensile properties of VVER-1000 model steels investigated in STRUMAT-LTO

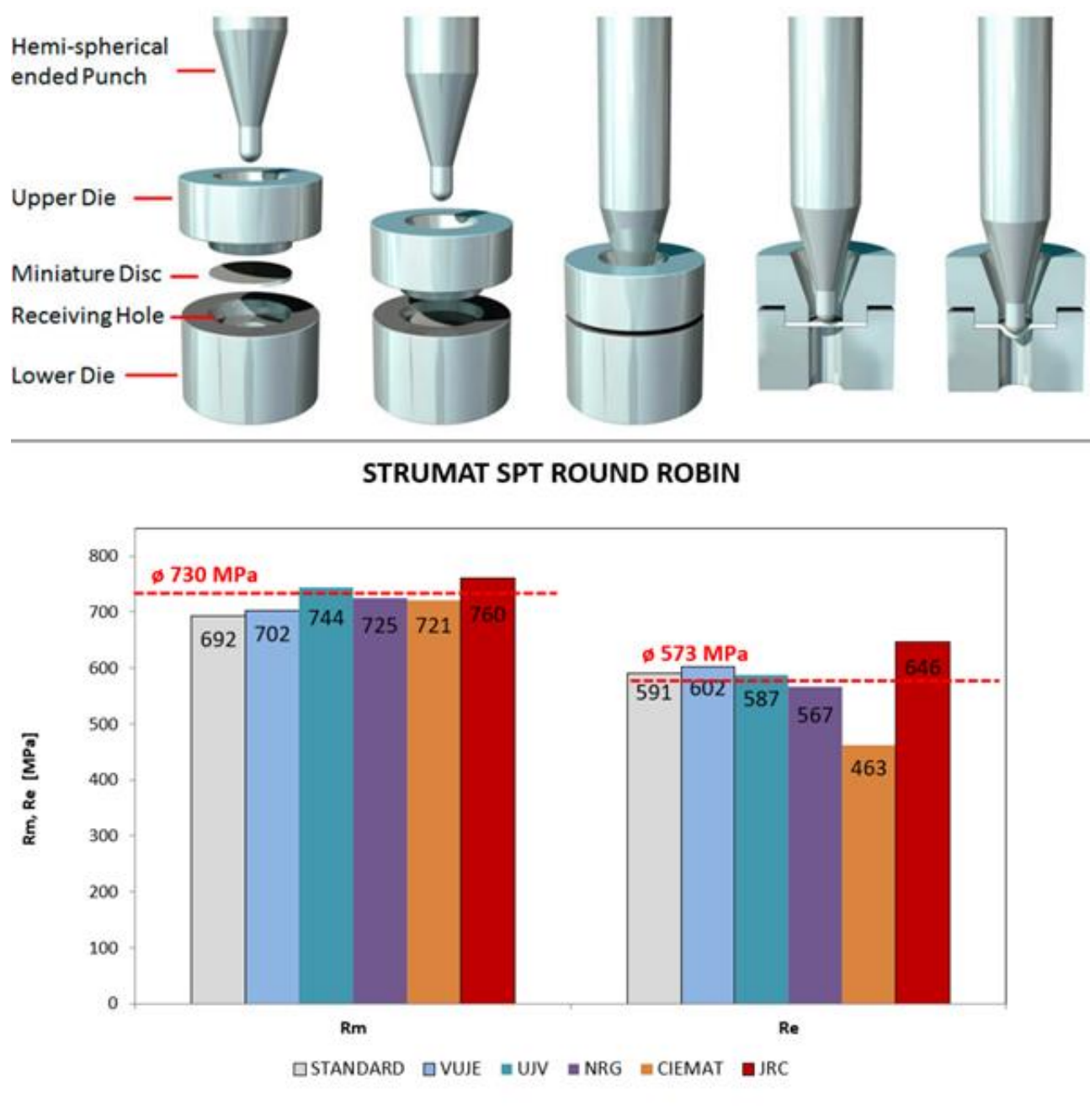


Figure 4. Comparison of SPT Round-Robin test results

Master curve testing on Mini-CT specimens provided required additional data points, when combined with data from SENB specimens from WP1, for obtaining valid reference temperature values for the investigated RPV steel grades in reference and irradiated conditions. In addition, SPT results on investigated steels demonstrated increase in strength properties after irradiation, and the results in general are in good agreement with standard tensile test results. These results pave the way for application of the SPT test method for the assessment of the mechanical properties using small quantities of material. A total of 12 model steels and 2 RPV welds were tested in the unirradiated reference condition and 9 different model steels were tested after irradiation. The effect of irradiation and chemical composition (Mn, Ni) on the change in the correlation coefficient was observed and studied within a separate package regarding the synergetic effects of Ni, Mn and Si on RPV embrittlement. These results can be used for improving the existing SPT standards with respect to the correlation coefficient used for converting SPT results to tensile results.

Identification and explanation of **“Synergetic effects of Ni, Mn and Si on RPV embrittlement at high fluences”** in WP3 provide a link between the irradiated microstructure and mechanical property changes for highly irradiated VVER-1000 type steels. The approach is based on the application of complementary microstructural characterization techniques to study base and weld materials with intentionally varied contents of Ni, Mn and Si. The research included the selection of suitable materials and their distribution among partners. The chemical composition of model steels is presented in Figure 5 and specimens in Figure 6.

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

Figure 5. Chemical composition of model steels (in mass %)

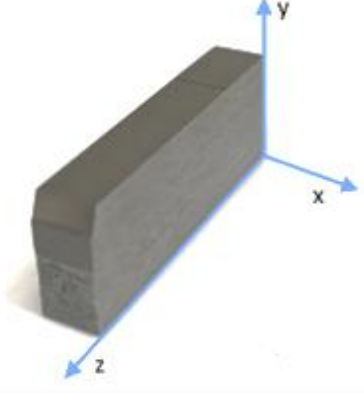


Figure 6. Tested fracture toughness specimens

One of the aims was to provide a quantitative description of the microstructural features appearing in the material at the initial state: i.e. the grain structure, dislocation structure, and the type, size and number density of precipitates/inclusions for the selected materials were determined. The degree of heterogeneity in the microstructure is an important aspect.

The studied materials and experimental ones are presented in Table 1, with distribution of the materials among partners.

Table 1

Partner	Reference material	Activity
NRG	Model steels K, L, M and N	TEM
HZDR	Model steels A, B, C, F, G and H	SEM/EBSD, EDX
CIEMAT	Model steels A, B, C, F, G and H	SEM, (S)TEM
VTT	Model steels A, B and C (F, G and H)	Hardness, LOM, SEM, (S)TEM
CNRS	Model steels A, B, C, F, G and H	APT
STUBA	Model steels A-H, K, L, M and N	PAS

The investigation of the irradiation-induced microstructure conditions revealed the following:

- Increase in vacancy-type defects by a factor of 10 / possibly associated with Mn and Ni (PAS);
- Small loops (PAS, TEM);
- Very low density of needle-shape precipitates (TEM);
- Mn, Ni, Si (Cu, P) rich clusters observed in all irradiated materials (APT, SANS).

The effect of bulk chemical composition on irradiation-induced microstructure: Ni increases the cluster number density and size, Mn has a strong effect on the cluster number density.

A synergy between Mn and Ni was observed. Si has no clear effect. A reasonably good correlation of irradiation hardening with irradiation-induced solute clusters was observed.

All experimental efforts were performed for validation of the existing Embrittlement Trend Equations (ETEs), and corresponding actions were undertaken for package **“Validation of Existing ETEs for LTO above 60 years”**. The work started with the collection and expert analysis of available ETEs for VVER-1000 and PWR RPV steels to be applicable for materials irradiated in the LYRA-10 project. All available (official, regulatory as well as literature proposed) ETEs were collected, compared and analyzed with respect to their origin, applicability, chemical content and fluence dependencies. This analysis was concentrated mainly on the effect of Ni, Mn and Si alloying elements and also on the prediction of material embrittlement for high neutron fluencies expected for 60+ years of operation. The ETE prediction from the following codes and standards was analyzed for STRUMAT-LTO steels: PNAE G-7-002-86 code, IAEA VERLIFE, Ukrainian approach (before 2018) and SOU NAEK 087:2023, US NRC Regulatory Guide 1.99, EONY Model (2007) - 10CFR50.61a, ASTM E900-15 and ASTM E900-21, French RSE-M and OKMC (multiscale modelling based trend equation). The predictions from many of these ETEs were found non-conservative because the neutron fluence from LYRA-10 is very high, representing approximately 120+ years of operation, and many of the steels investigated here are also outside the chemical validity limits for the above-mentioned ETEs.

These aspects are considered in detail within the **“Assessment of MC approaches for high fluences”** with the goal of investigating the effect of high fluence on the scatter in the fracture toughness obtained with small specimens. The main focus was made on the factors affecting fracture toughness at high fluences and the selection of suitable materials/methods for analysis of high-fluence materials; on determination of lower boundary fracture toughness curve for high-fluence materials; and on the correlation between conventional TK shifts from Charpy testing and T₀ values from sub-size specimens etc. Finally, conclusions are presented as follows:

- at high fluences and for large T₀ shifts (<300 °C) and high T₀ values (< 150 °C), the homogeneity/inhomogeneity varies for different materials, i.e., the high fluence does not systematically affect the homogeneity;
- the correlation between T₀ and T_{41J} follows a 1:1 relation closely at lower absolute values, T_{0Q} < 75 °C. At higher values, T_{41J} gives an increasingly larger estimate.

The T_{0Q} results for high-Ni/Mn welds from the literature show similar shifts compared to results from this study for welds with the same equivalent content of Ni and Mn.

All results achieved over these past years have been shared via dissemination activities and tools that started with developing a dissemination strategy that actually worked as a road map. All dissemination actions were performed as sharing information via articles and conference presentations, LinkedIn (project’s page and private one), [Website](#), Newsletters etc.

Two significant events (Dresden, October 2023 (see Figure 7) and Budapest, July 2024 (see Figure 8)) were provided as **Dissemination Workshops (DWS)** in a conference format that comprises presentation from the STRUMAT-LTO expert team and presentations from young researchers as well.



Figure 7. Dissemination WS#1 in Dresden



Figure 8. Dissemination WS#2 in Budapest

Interconnection with sister projects #ENTENTE, #FRACTESUS and #DELISA-LTO was successfully managed by:

- Meetings with presentation of results
- Common session during the conference
- Presenting the results at the STRUMAT-LTO Summer School (May 2024)

STRUMAT-LTO Summer School “Testing and evaluation of LWR RPV embrittlement to support LTO” was held at the beautiful location under the Vltava river at UJV premises in Prague on 27-31 May. 25 young researchers and scientists attended the Summer School and 15 experts from the STRUMAT-LTO team presented and demonstrated the testing results obtained within the project and highlighted their importance for further safety justification of RPV for LTO for 60++ years. The Summer School was divided into two parts: theoretical and practical (Figures 9-12)



Figure 9. Theoretical part



Figure 10. Practical part



Figure 11. Hot cells



Figure 12. Samples

There have been more than 30,000 views of the public website from 50 countries, about 500 visitors and 100 followers on the project LinkedIn and 32 subscribers on the newsletter.

Dissemination Workshop No. 1 with 45 attendees and Workshop No. 2 with 40 attendees, as well as Summer School for 25 students, were held successfully.

Upcoming events: more articles are planned to be published by the end of the year 2024 and the final report on dissemination results should be prepared until 31/08/2024.

We are happy to receive your comments and suggestions and feel free to forward this newsletter to your network.

We look forward to hearing from you!

Akos Horvath, STRUMAT-LTO Coordinator

Murthy Kolluri, STRUMAT-LTO Scientific Coordinator

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