STRUMAT-LTO
Structural Materials for Nuclear Safety and Longevity

Influence of Ni, Mn and Si on irradiation induced shifts in transition temperature of VVER-1000 RPV model steel specimens irradiated in LYRA-10

INSEFA-scale seminar, 19-Sep-2023, Virtual presentation
(Presented at ASME PVP, 16–21 July 2023, Atlanta)

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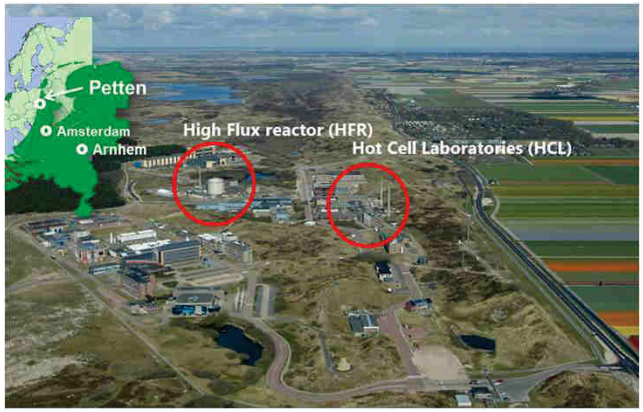
1. NRG Introduction

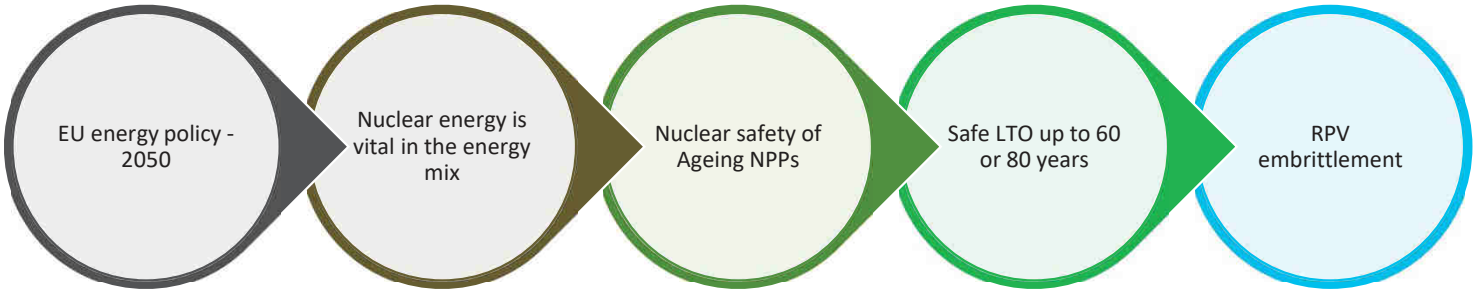
- NRG is based in 2 locations in the Netherlands: Petten and Arnhem
- Main business areas: (a) Advancing Nuclear Medicine and (b) Ensuring Nuclear Performance
- We are the global market leader in producing medical isotopes. 30000 patients benefit per day.
- We perform nuclear research and innovation projects employing our unique knowledge and infrastructure to help industry as well as government for safe, reliable and efficient use of nuclear technology.
- Important nuclear infrastructure: (a) High Flux Reactor and (b) Hot Cell Laboratories in Petten.



For more details go to www.nrg.eu/en

2. Research context

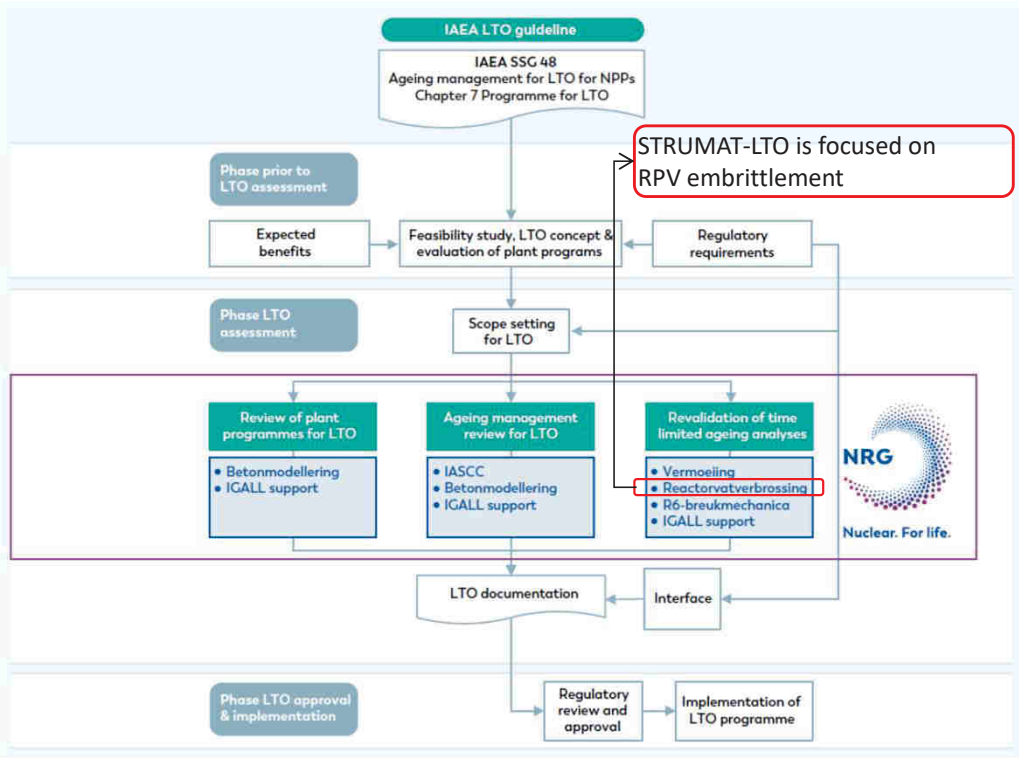
RPV embrittlement is one of the critical issue for safe Long Term Operation of LWR NPPs



Positioning of STRUMAT-LTO project relating the EU R&D needs to meet goals of European initiatives on energy transformation and a link to previous European projects on this topic is shown in the above figure

Research context

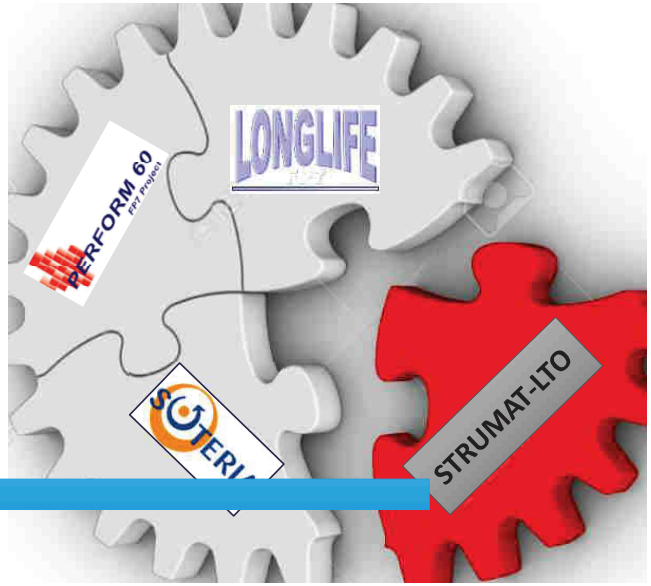
- Ageing management review and revalidation of time limited ageing analysis (TLAA) of critical systems, structures and components are mandatory (e.g. IAEA safety guidelines)
- Reactor Pressure Vessel (RPV) embrittlement is a critical issue for LTO of NPPs
- Several open challenges to be addressed



3. Former work and Open issues

(from NUGENIA position paper, May 2015 and other literature)

1. Flux effect on embrittlement mechanisms
2. Initial microstructure, heterogeneities
3. Prediction models for radiation effects in RPV materials
4. High fluence behavior and Synergetic effects of nickel, manganese and silicon (Ni-Mn-Si) at high fluences
5. Validity of Embrittlement Trend Equations (ETE) for LTO beyond 60 years
6. Lack of surveillance material and applicability of miniature specimens for surveillance testing



4. STRUMAT-LTO: Objectives

STRUctural **MAT**erials research program on parameters influencing the material properties of RPV steels for safe **Long Term Operation** of LWRs

Dutch national funded project (2014 - present) → NUGENIA in-kind collaboration project (2018-2020) → EU funded H2020 project 18 international partners (2020-2024)

Overall objective:

STRUMAT-LTO project is strategically aimed **to address the aforementioned remaining gaps and open issues in RPV embrittlement research to support safe long term operation of European NPPs**, including the scenario of LTO > 60 years.

Research on VVER-440 RPV surveillance samples
(High Cu RPV materials: surveillance specimens from Armenian NPP)

Research on VVER-1000 and PWR RPV model steels and VVER 1000 realistic welds
(Low Cu RPV materials: irradiated in LYRA-10 to fluences representative of 60-80 years of LWR operation)

Present work

Specific Objective of the research presented here:

Influence of Ni, Mn and Si contents on the embrittlement of **VVER-1000 RPV model steels** irradiated to high fluences.

Key figures: STRUMAT-LTO

STRUMAT-LTO: STRUctural MATerials research on parameters influencing the material properties of RPV steels for safe Long Term Operation of LWR NPPs

Project Information

STRUMAT-LTO

Grant agreement ID: 945272

DOI

10.3030/945272

Start date
1 September 2020

End date
31 August 2024

Funded under
Euratom

Overall budget
€ 4 466 997,50

EU contribution
€ 3 965 029,25

Coordinated by
ENERGIATUDOMANYI KUTATOKOZPONT
Hungary

Work package (WP) structure

T7.1	Project coordination
T7.2	Project office
T7.3	Scientific Advisory Board

WP7 (MTA-EK)
Project Management

T1.1	Test matrix and specimen transport
T1.2	Tensile tests
T1.3	Impact testing
T1.4	Reconstitution and Fracture toughness (FT) tests
T1.5	Thermal annealing of Low Cu RPVs

WP1 (NRG)
Embrittlement behavior of RPV steels at high fluencies

T2.1	Mini CT specimens
T2.2	Small Punch Testing
T2.3	Supplementary tests for validate the use of small specimen testing

WP2 (MTA-EK)
Assessment of small/sub-sized specimens testing methods

T3.1	Test matrix and characterization of the initial microstructures
T3.2	Characterization of irradiation-induced nanofeatures
T3.3	Correlation with mechanical properties (from WP1 and WP2) and identification of synergetic effects of Ni, Mn and Si

WP3 (HZDR)
Synergetic effects of Ni, Mn, and Si on RPV embrittlement at high fluences

T5.1	Pre-screening of FT data
T5.2	Analysis of fracture toughness and impact data
T5.3	Analysis of the various fracture toughness characterization methods to determine a lower boundary fracture toughness curve for high-fluence materials
T5.4	Fracture toughness by local approach

T4.1	Collection and expert analysis of available Embrittlement Trend Equations (ETE) for VVER-1000/PWR RPV steels to be applicable for Lyra-10 irradiation materials and conditions
T4.2	Check of the consistency of chemical factors (CF) in Embrittlement Trend Equations with test results of embrittlement of irradiated materials with different Ni, Mn and Si contents in Lyra-10
T4.3	Check of the possible extension of available Embrittlement Trend Equations beyond the fluence of $6x10^{23}$ m-2 (En > 0.5 MeV) for VVER-1000 RPV materials and beyond the fluence $6x10^{23}$ m-2 (En > 1 MeV) for PWR RPV steels

WP4 (UJV)
Validation of Existing ETEs for LTO above 60 years

WP5 (VTT)
Assessment of MC approaches for high fluences

WP6 (SSTC-NRS)
Dissemination of results & Education and training

T6.1	Dissemination strategy
T6.2	Public Communication
T6.3	Dissemination, training, education

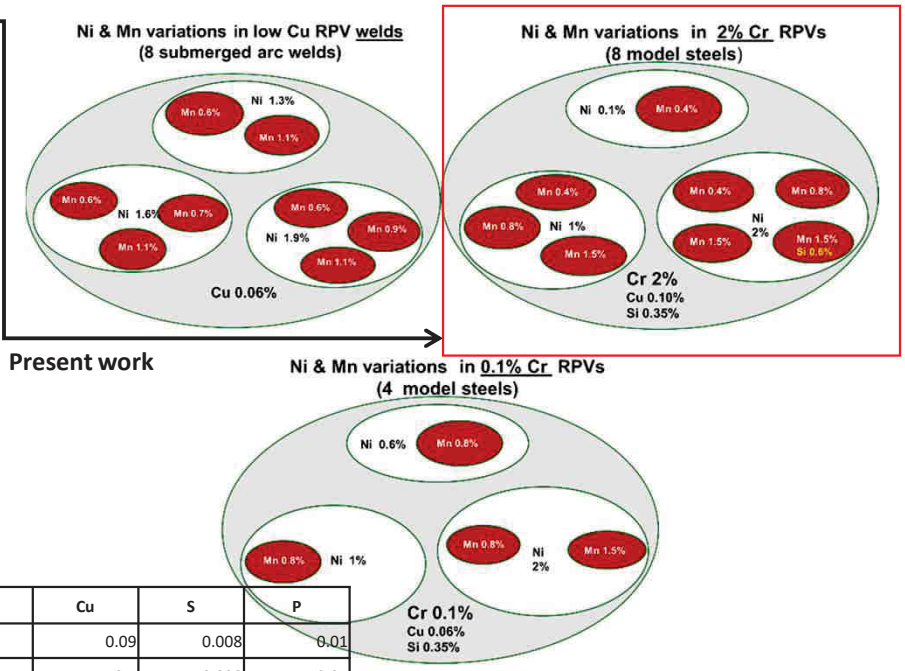
5. Experimental methodology: RPV materials Irradiated in LYRA-10c

LYRA-10 was a joint NRG-JRC experiment in HFR Petten to investigate **synergistic interactions between Ni, Mn and Si for low Cu RPV** steels at high fluence to validate LTO

- 16 HFR cycles (finished in Jan 2018)
- Nominal fluence (E > 1 MeV): 1.11 x 10^{24} n.m^{-2}
- Average irradiation temperature: ~286 °C

5. Experimental methodology: RPV materials Irradiated in LYRA-10

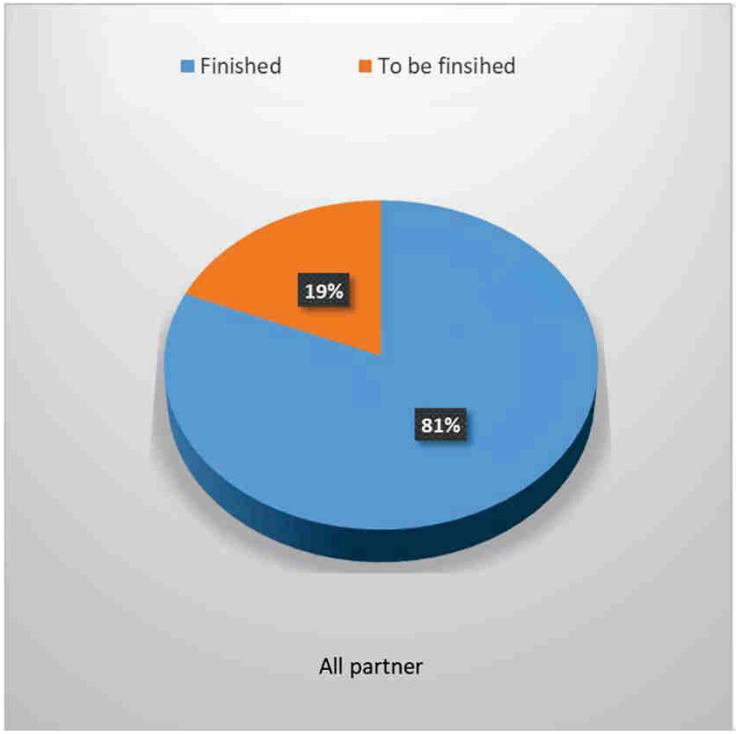
- 12 model steels (8 VVER 1000 + 4 PWR)
- 8 realistic welds (8 VVER 1000)
- VVER-1000 weld
- Several additional RPV slices for microstructure examination
- Test specimens for tensile, Charpy and KLST
- >650 irradiated specimens

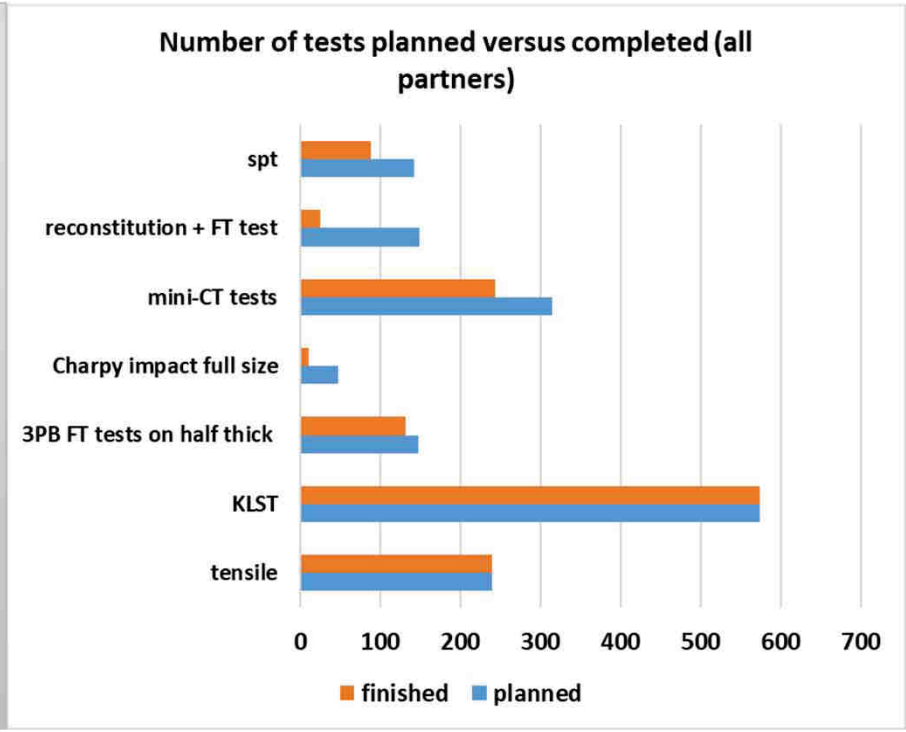


Present work: 8 VVER-1000 model steels

Steel Id.	C	Si	Mn	Cr	Ni	Mo	V	Cu	S	P
A	0.11	0.28	0.43	2.22	<0.02	0.71	0.1	0.09	0.008	0.01
B	0.11	0.26	0.38	2.19	0.99	0.7	0.1	0.1	0.008	0.01
C	0.12	0.24	0.38	2.13	2	0.69	0.1	0.1	0.008	0.01
D	0.11	0.23	0.83	2.13	2	0.68	0.1	0.09	0.008	0.009
E	0.12	0.33	0.77	2.16	1.02	0.7	0.1	0.1	0.008	0.009
F	0.12	0.33	1.37	2.15	1.02	0.7	0.1	0.1	0.008	0.01
G	0.11	0.32	1.36	2.06	1.99	0.69	0.1	0.1	0.008	0.009
H	0.12	0.51	1.31	2.07	2	0.69	0.1	0.1	0.008	0.01

5. Experimental methodology: RPV materials Irradiated in LYRA-10

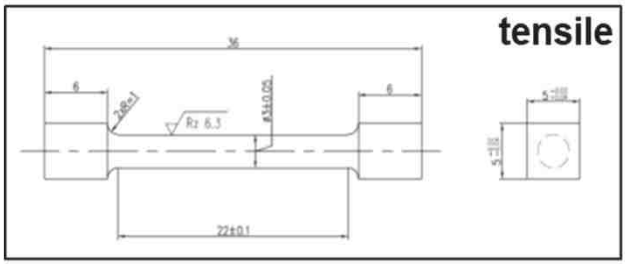


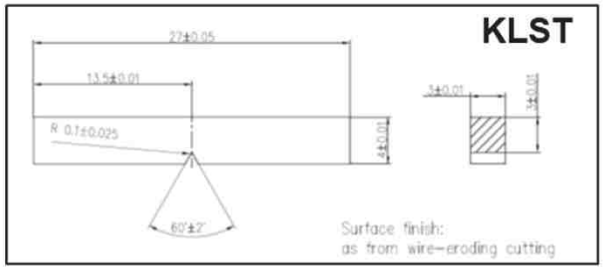


In total 1300 (81%) out of 1600 tests planned within the total project are finished.

5. Experimental methodology: Test matrix of the present work

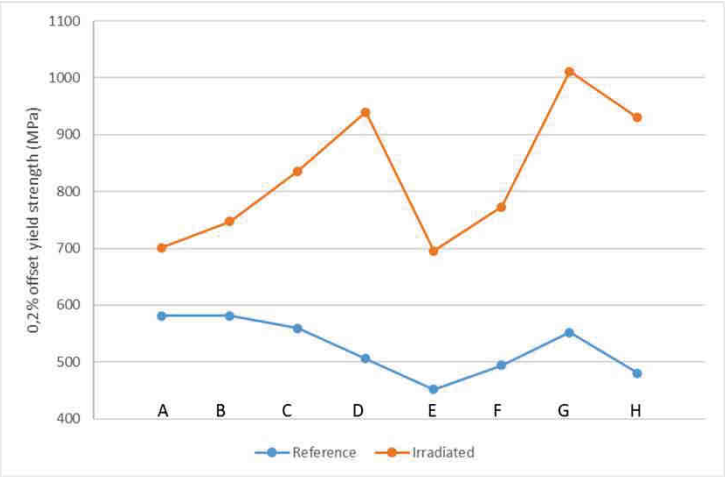
VVER-1000 Model steel grade	Nominal fluence E>1 MeV (n/m2)		(wt.%)		
	KLST	Tensile	Ni	Mn	Si
A	1.14432E+24	8.1E+23	0.02	0.43	0.28
B	1.189E+24	8.9E+23	0.99	0.38	0.26
C	1.21241E+24	1.0E+24	2.00	0.38	0.24
D	1.14809E+24	1.1E+24	2.00	0.83	0.23
E	1.19292E+24	1.2E+24	1.02	0.77	0.33
F	1.21643E+24	1.2E+24	1.02	1.37	0.33
G	1.15087E+24	1.1E+24	1.99	1.36	0.32
H	1.19581E+24	1.2E+24	2.00	1.31	0.51

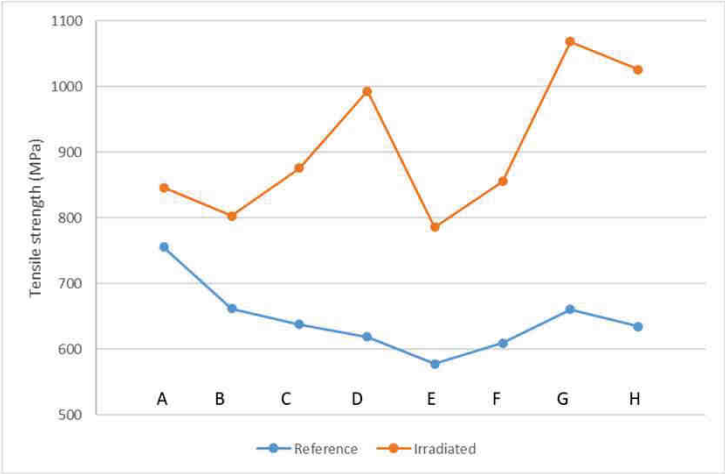




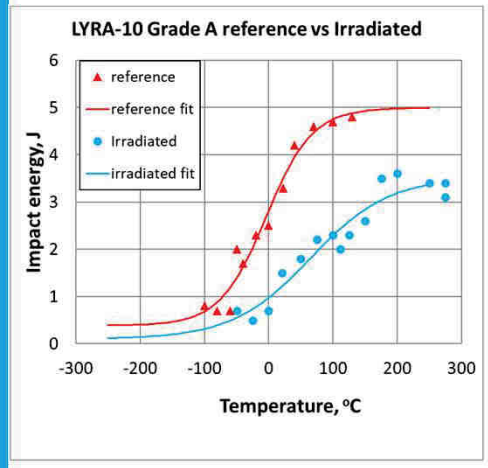
A total of **<u>32 tensile (at RT)</u> and <u>194 KLST impact</u>** tests were performed at **NRG, JRC and UJV** including reference and irradiated specimens

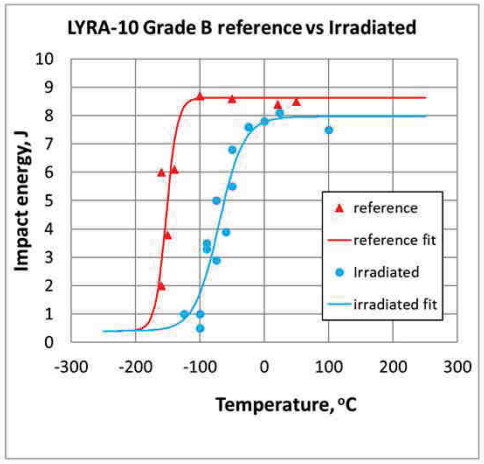
6. Results and discussion: Tensile properties (RT)

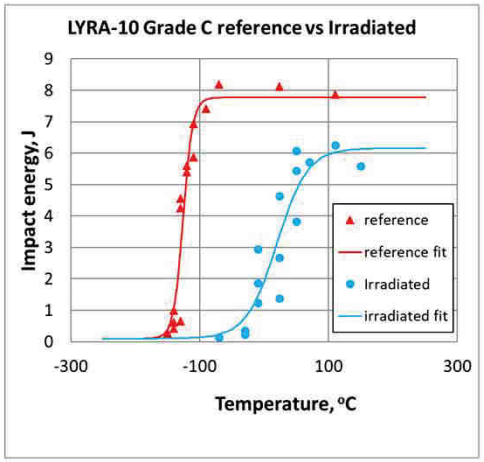


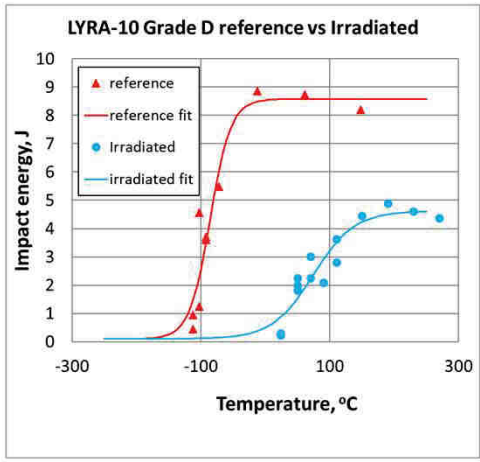


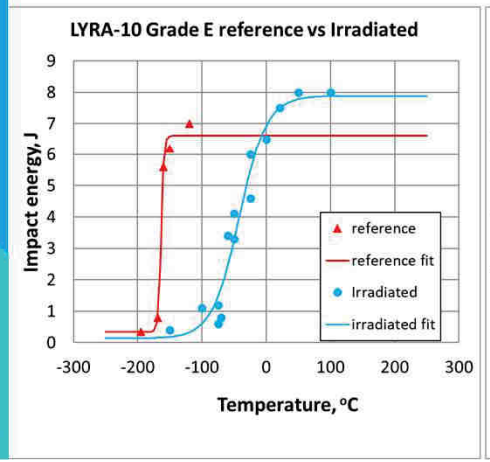
6. Results and discussion: DBTT properties (KLST)

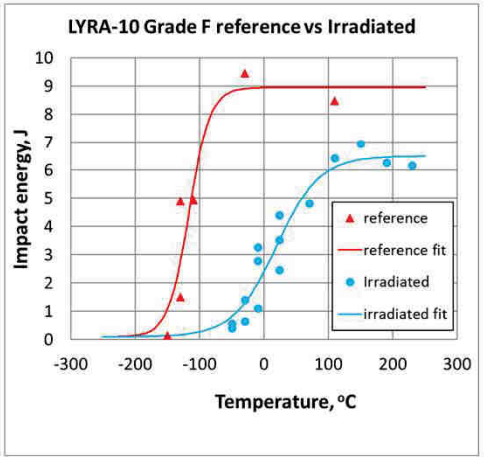


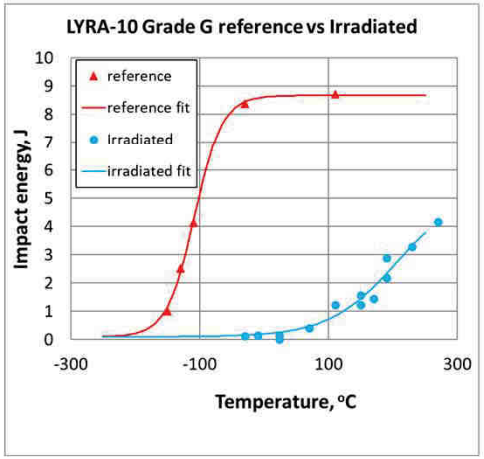


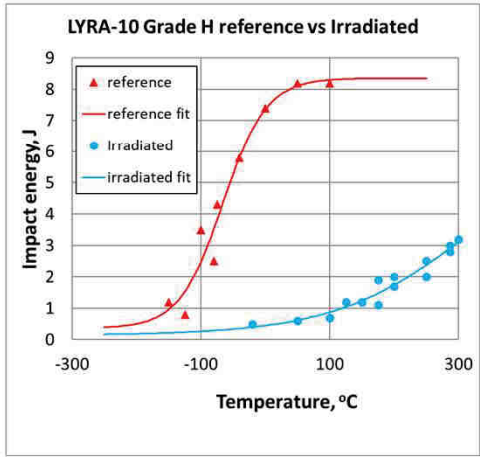




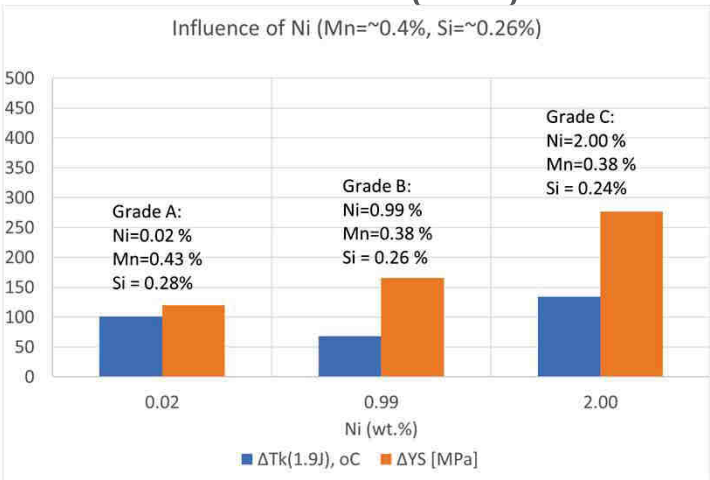


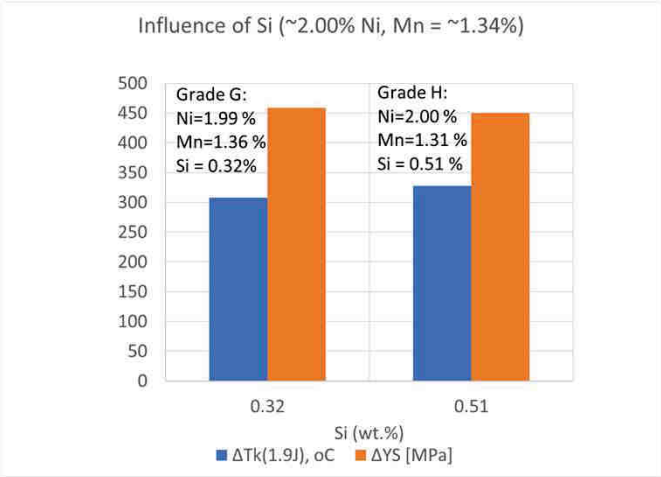


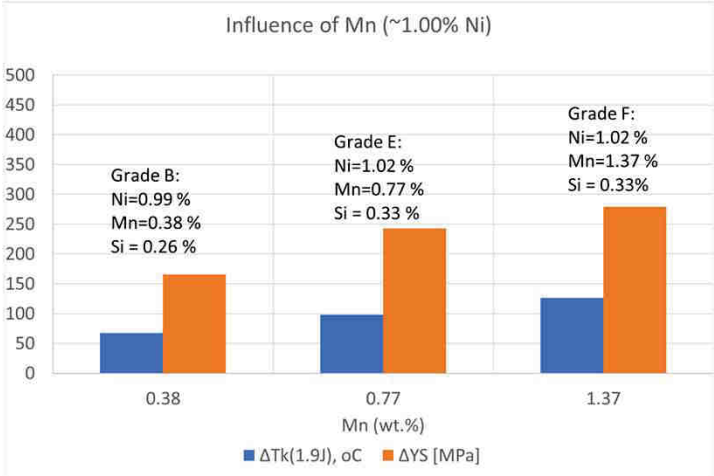


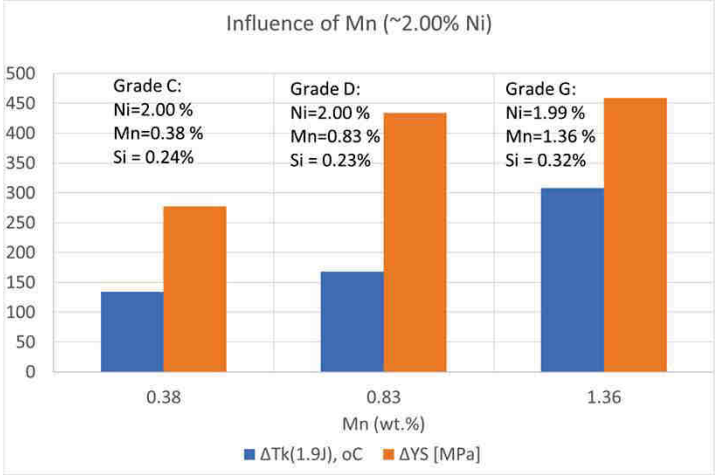


6. Results and discussion: Influence of Ni, Mn and Si on $\Delta T_{k(1.9J)}$ and ΔYS

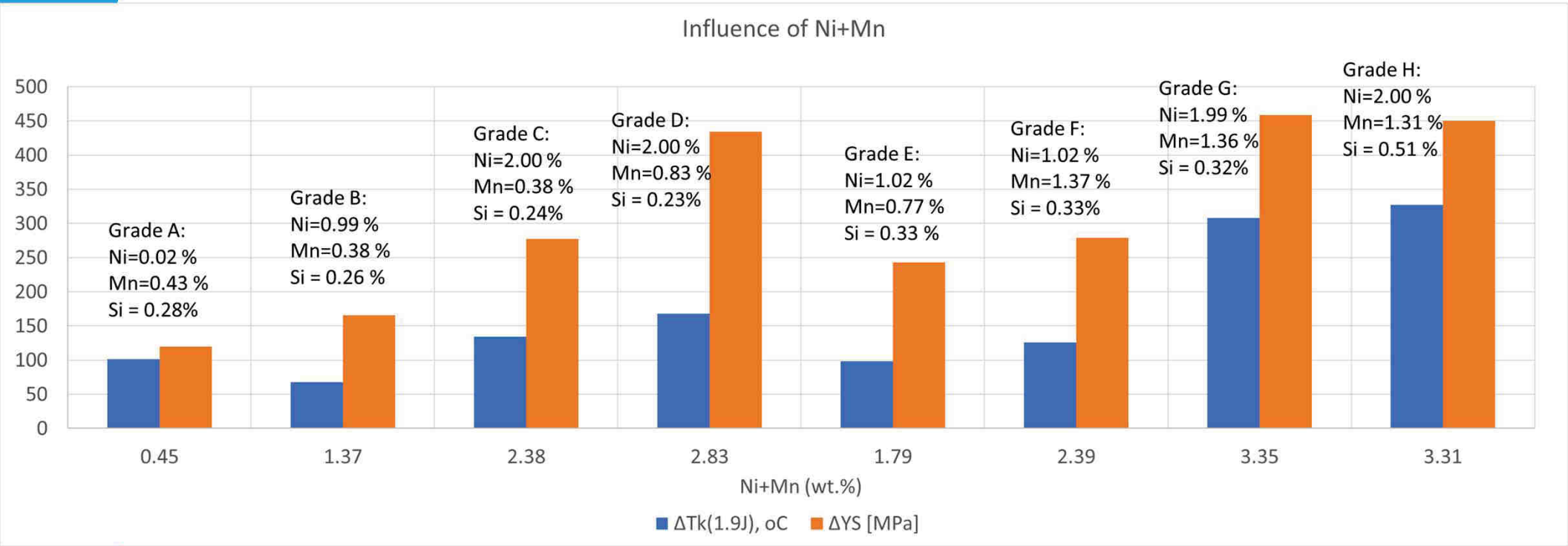








6. Results and discussion: Influence of Ni+Mn on $\Delta T_{k(1.9J)}$ and ΔYS



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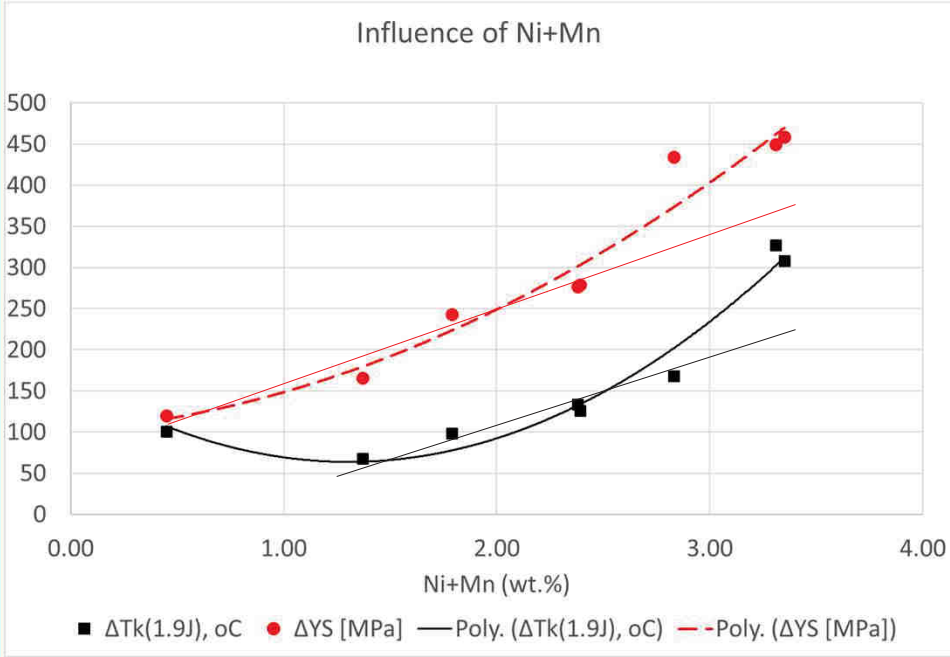
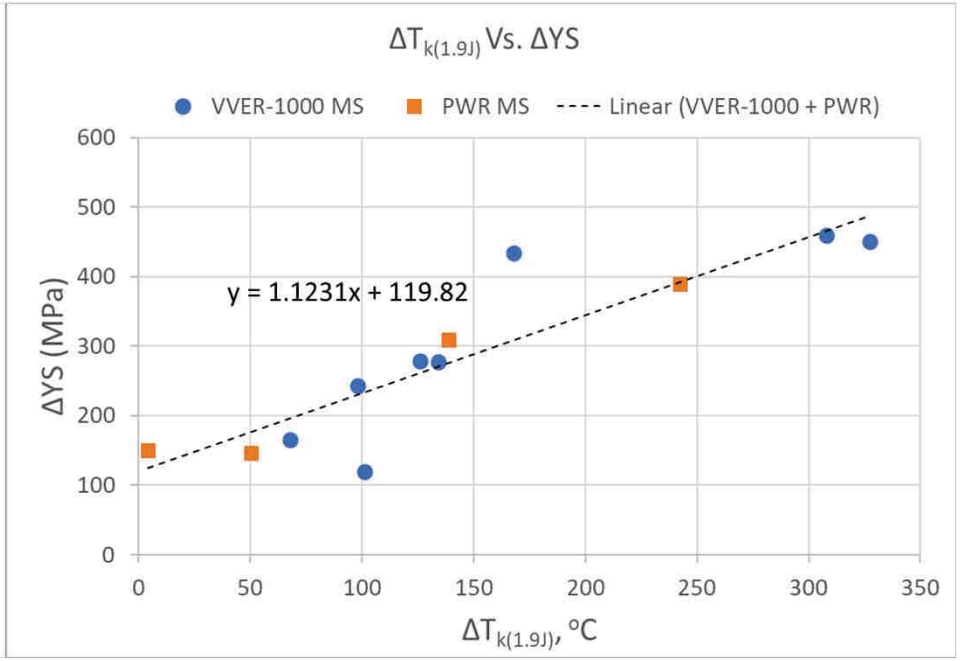




6. Conversion of KLST data into full size Charpy data

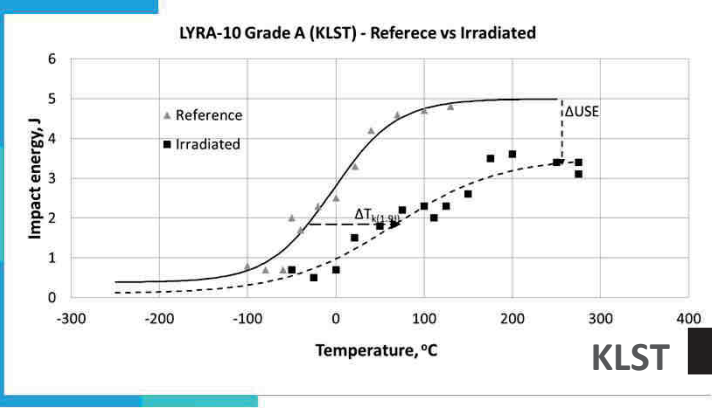
- All the measured KLST data points have been converted into the full size Charpy impact data using the following phenomenological equation published by Kim Wallin (*Int. Jl. of Pr. Ves. and Pi 183 (2020) 104080*)

$$\Delta T_{35J/cm^2} = -51.4.\ln\left\{2.\left(\frac{B}{10\ mm}\right)^{0.25} - 1\right\}$$

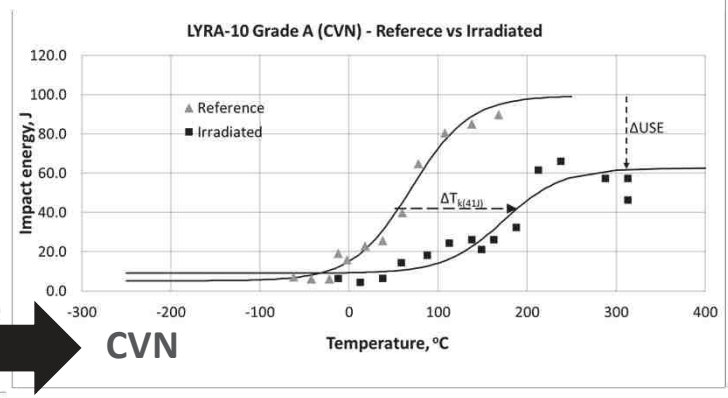
$$KV^*_{10-USE} \approx 1.89.KV^*_{B\times b-USE} + \left(\frac{b}{2.18\ mm}\right)^2 + \left(\frac{KV^*_{B\times b-USE}}{16.45}\right)^2 - \frac{\left(\frac{KV^*_{B\times b-USE}}{3.95}\right)^2}{b} + \left(\frac{KV^*_{B\times b-USE}}{1.89.b}\right)^2 - 1.67.b - KV^*_{B\times b-USE}.\frac{b}{8.86} \quad \left[\frac{J}{cm^2}, mm\right]$$

$$KV^*_{10} \approx KV^*_{B\times b} + \left(\frac{KV^*_{B\times b}}{KV^*_{B\times b-USE}}\right)^4.(KV^*_{10-USE} - KV^*_{B\times b-USE}) \quad \left[\frac{J}{cm^2}\right]$$

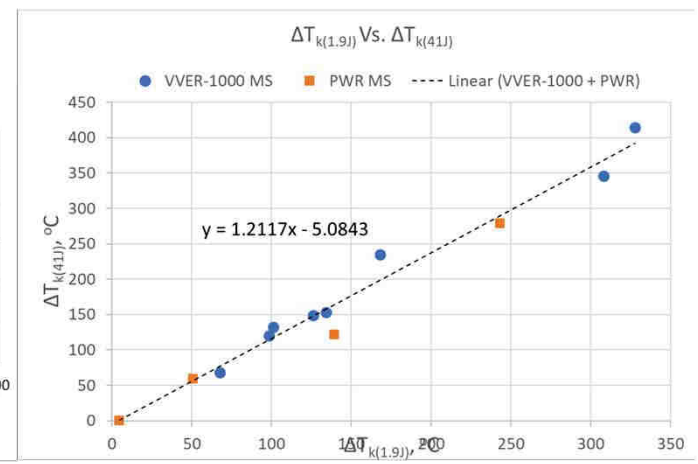
- The converted CVN data was fitted with sigmoidal curves to deduce the $\Delta T_{k(41J)}$ and ΔUSE values
- $\Delta T_{k(41J)}$ are used to check the validity of the 2 selected ETEs



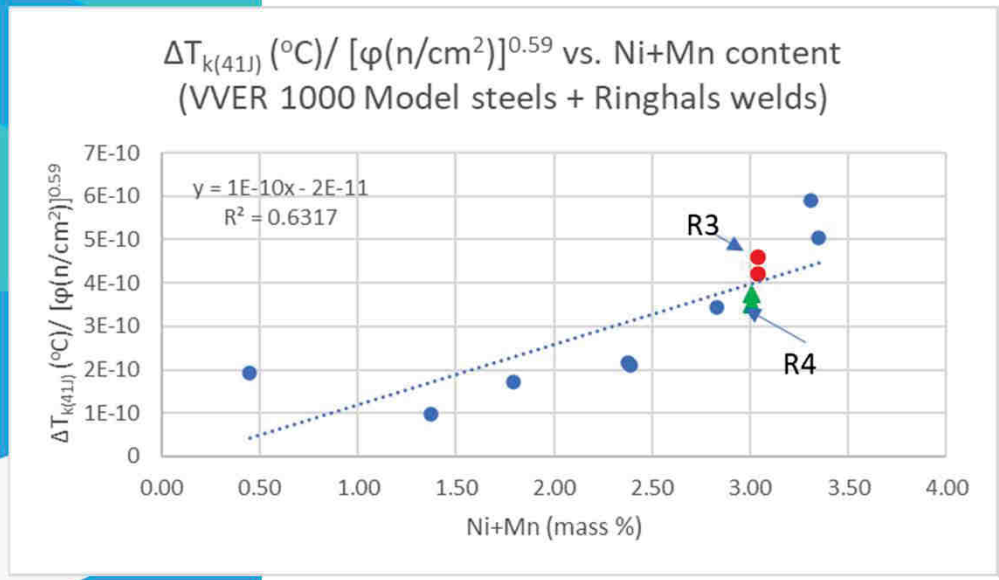
KLST

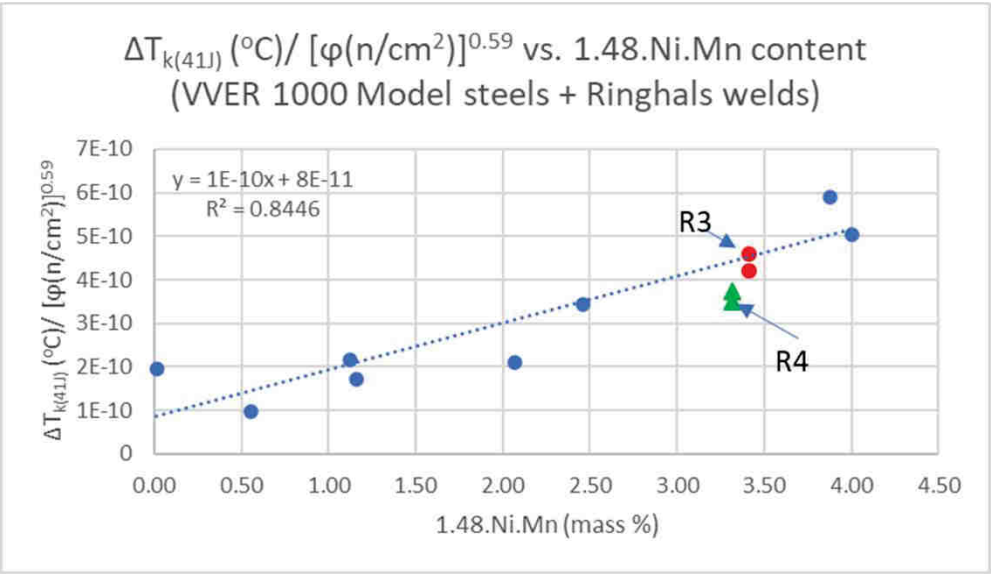


CVN

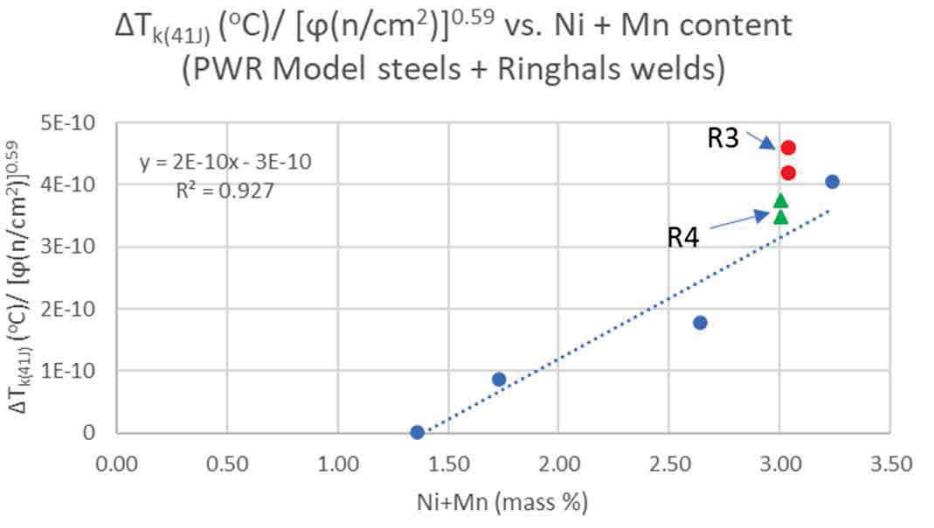


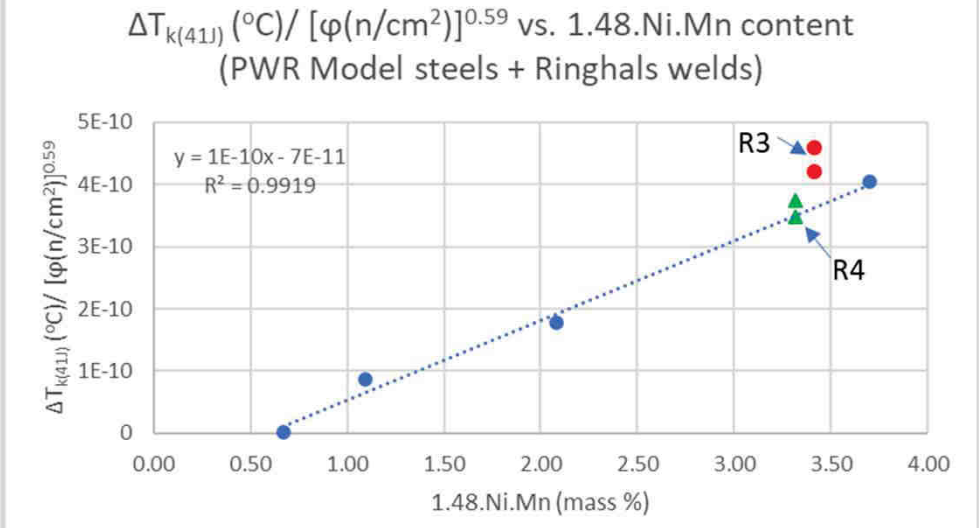
VVER-1000 model steels vs. Ringhals welds





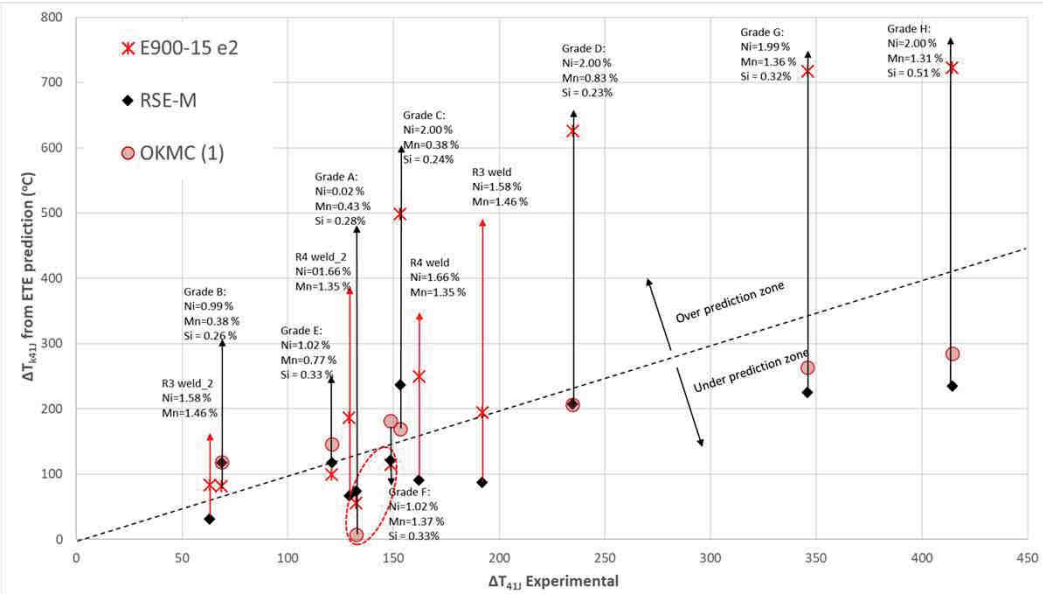
PWR model steels vs. Ringhals welds





6. Prediction of shift in transition temperatures

- Following 3 embrittlement trend equations (ETEs) are used to predict the shift in Charpy transition temperature, $\Delta T_{k(41J)}$ by feeding composition and fluence information:
  - ASTM E900-15 e2: $\Delta T_{k(41J)}$ = F (irr. T, fast fluence (E >1MeV), %Cu, %Ni (max 1.7%), %P and % Mn)
  - RSE-M code (FIS): $\Delta T_{k(41J)}$ = F (irr. T, fast fluence (E >1MeV), %Cu and %Ni (max 1.4%)).
  - OKMC model
- RSE-M code well predicted the $\Delta T_{k(41J)}$ values for steels B, C, E but under-predicted for rest of the steels of which grade A and F are within the validity range and rest are outside the validity range.
- In case of E900-15, large over prediction was observed for all steels containing higher Ni content (D, G, H), while good agreement was obtained for steels B, C & Ringhals welds.
- OKMC model well predicted the $\Delta T_{k(41J)}$ below 200 °C except for grade A which has very low Ni (<0.02%)



(1) N. Castin et al., Materials Today Physics 27 (2022) 100802.

7. Summary and conclusions

- Influence of Ni-Mn contents on the embrittlement of VVER-1000 RPV model steels irradiated to high fluences has been studied
- The results obtained from variations in Ni and Mn contents of VVER-1000 model steels showed that the combined effect of Ni and Mn is higher than sum of their separate contributions at higher Ni and Mn contents indicating the presence of a synergetic effect between Ni and Mn.
- Further microscopic investigations are planned to understand the underlying damage mechanisms causing this behavior.
- Mini-Charpy data was converted to CVN data and obtained $\Delta T_{k(41J)}$ data has been used to check the validity of 3 selected ETEs, RSE-M, ASTM E900-15 and EKMC models.
- RSE-M code well predicted the $\Delta T_{k(41J)}$ values for steels B, C, E but under-predicted for rest of the steels of which grade A and F are within the validity range and rest are outside the validity range.
- In case of E900-15, large over prediction was observed for all steels containing higher Ni content (D, G, H), while good agreement was obtained for steels B, C & Ringhals welds.
- EKMC model well predicted the $\Delta T_{k(41J)}$ below 200 ^{o}C except for grade A which has very low Ni (<0.02%)

8. Acknowledgements

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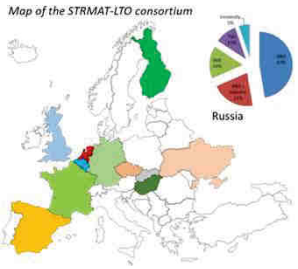

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Thank you!

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