NRG

Long term operation: New insights into the ageing of light water reactor pressure vessel (RPV) steels

- Investigation of RPV embrittlement at high fluences (Murthy Kolluri)
- Pressurized Thermal Shock (Lorenzo Stefanini)

KIVI presentation, 16-04-2021

NRG

Nuclear. For life.

EU DuC = X

Investigation of RPV embrittlement at high fluences for safe long term operation of LWRs

Results from STRUMAT project at NRG

KIVI presentation, 16-04-2021

Murthy Kolluri <kolluri@nrg.eu>

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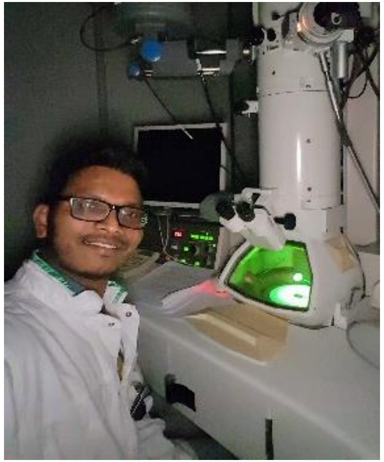
Speaker introduction

Murthy Kolluri

- Born In India and live in Zaandam with my wife and 2 kids
- Masters in materials engineering from IISc Bangalore (2006)
- PhD from TU Eindhoven (2011) on '*In-situ* characterization of interface delamination in microelectronic components'
- Senior research consultant – materials at NRG (~10 years)
- Specialization: Radiation damage in structural materials, fracture mechanics, interface delamination, FEM, materials characterization and metallurgy.
- Hobbies: Badminton, Running, Cycling and Cooking.

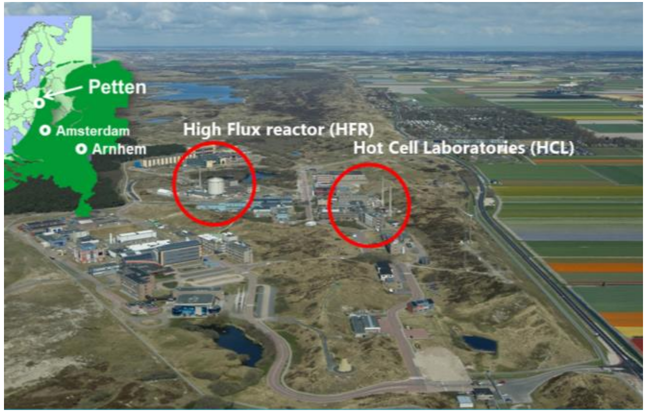


Contents

Nuclear. For life.

NRG Introduction

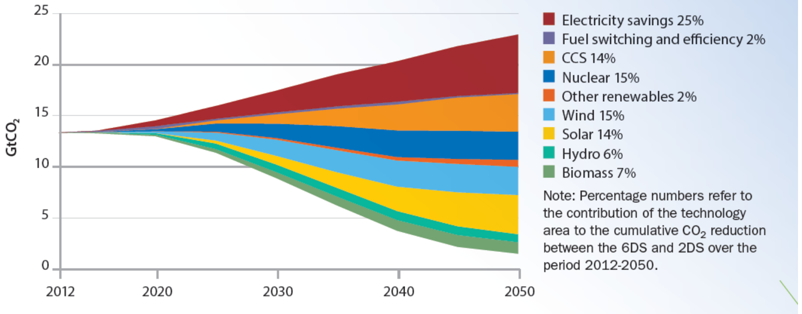
- NRG is based in 2 locations in the Netherlands: Petten and Arnhem
- Main business areas: (a) Advancing Nuclear Medicine and (b) Ensuring Nuclear Performance
- Global market leader in producing medical isotopes. 30000 patients benefit per day.
- NRG performs nuclear research and innovation projects 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

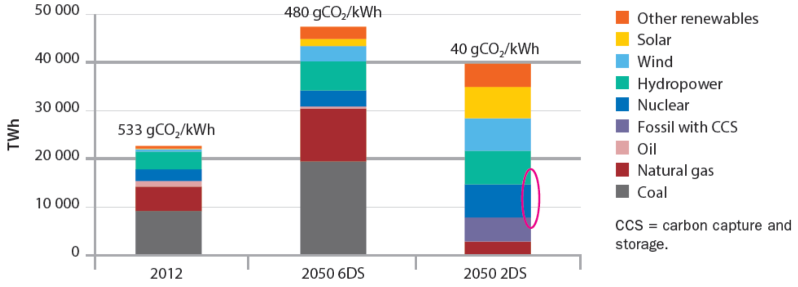
Importance of LTO – climate goals

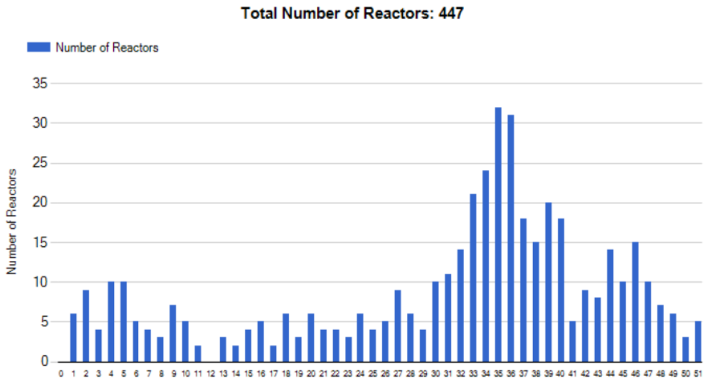
Figure 9: Emissions reductions required in the power sector by 2050 to move from the 6°C scenario (6DS) to the 2DS



Source: IEA (2015c).

Figure 10: Shares of different technologies in global electricity production until 2050 in the 2DS

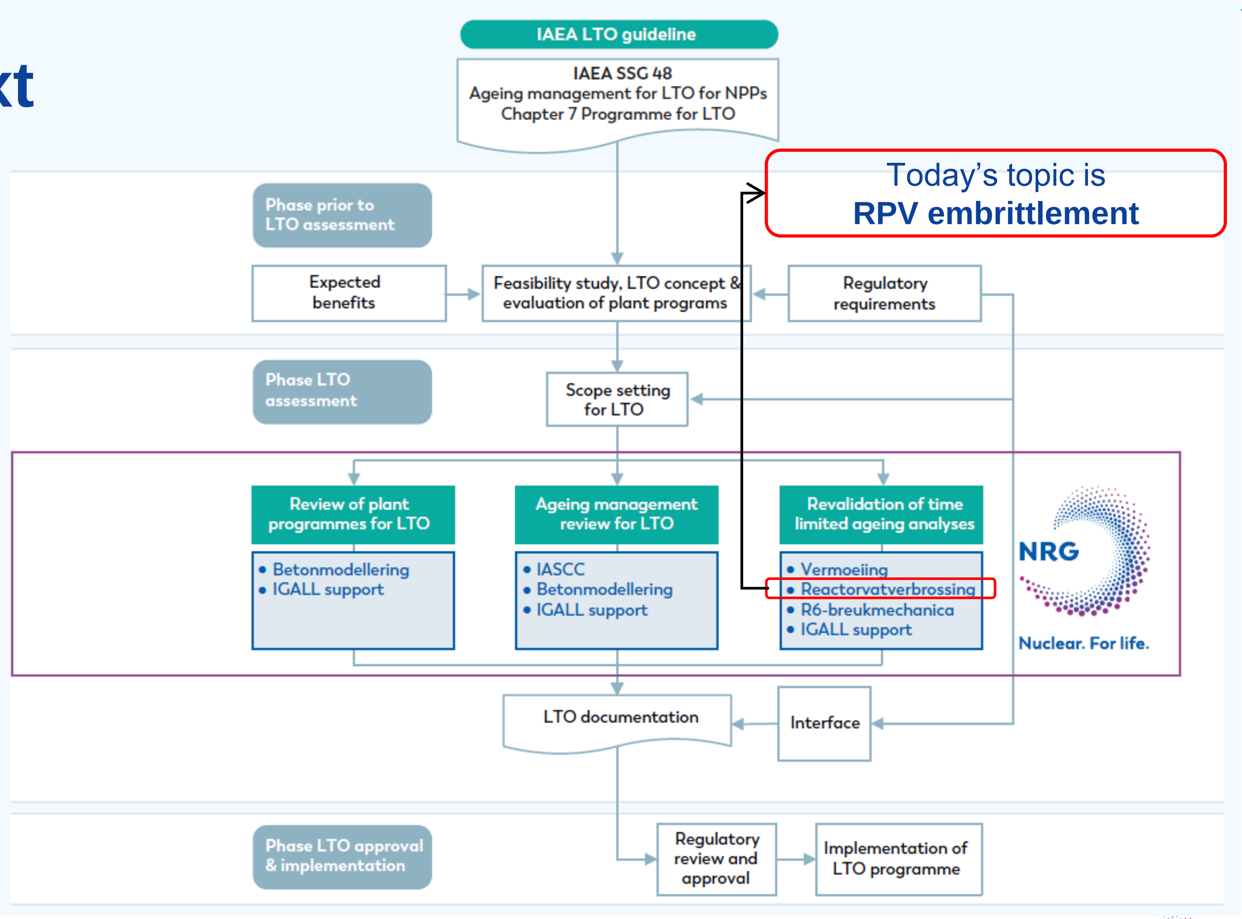




- The share of nuclear energy is vital in the energy mix to reach climate goals.
- Worldwide ~7/10 operating reactors are >30 years old.
- LTO of existing fleet (on top of new constructions) is mandatory to meet the target contribution of nuclear energy share.
- LTO up to 60 in Europe and even up to 80 years in U.S. is envisaged (/granted to several reactors).

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 challenges to be addressed



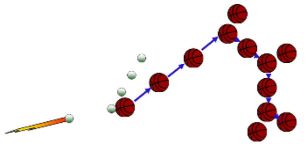
Schematic illustration of the LTO-program and de connection with the research theme's at NRG.

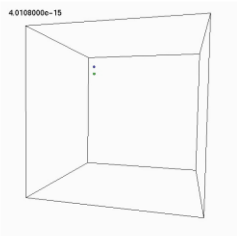
Damage mechanisms - embrittlement

Two important contributions

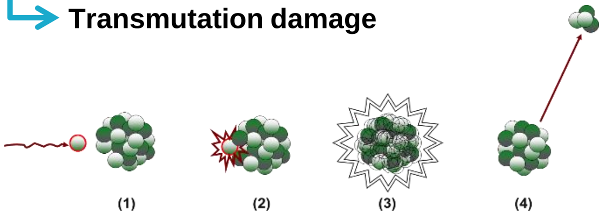
- Thermal ageing
- Radiation damage

Displacement damage





Transmutation damage



Binary collisions

1

PKA cascades, He production

2

1A **point defects, small clusters, He atoms**

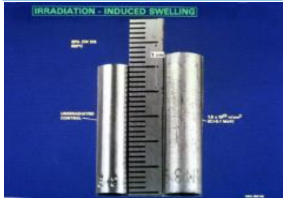
3 **mobility**

100 A **voids, bubbles, precipitates, dislocation loops**

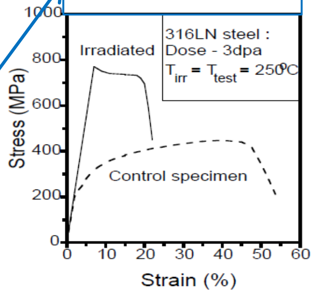
Influencing factors:

- Neutron spectrum
- Steel composition
- Time and Temperature

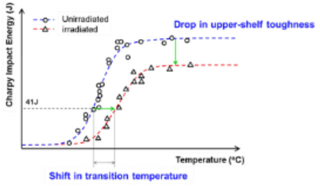
Swelling



Hardening



Embrittlement

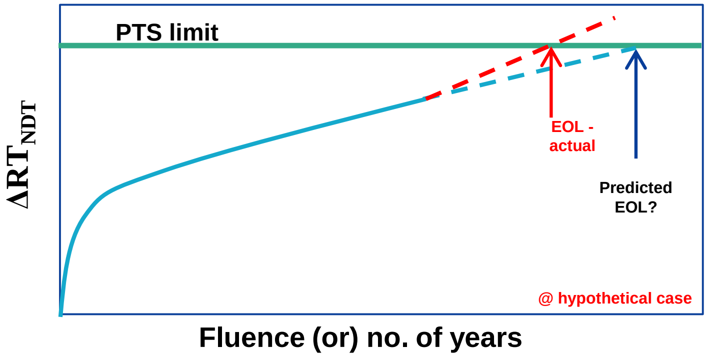


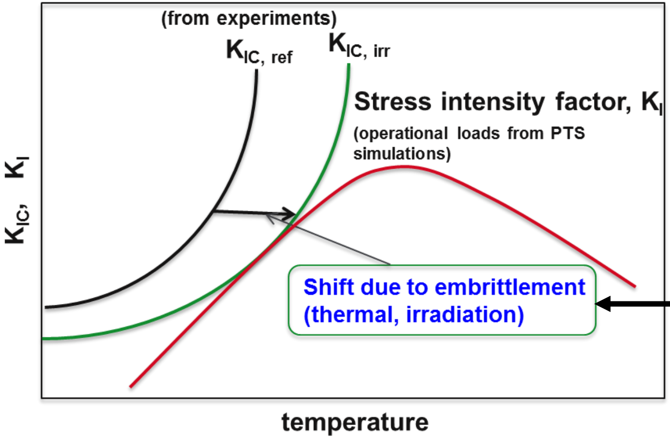
RPV embrittlement → RPV life

RPV embrittlement:
- Thermal ageing
- Neutron irradiation

Under prediction at higher fluences/ long operation times:
- Sparse data
- new irradiation damage mechanisms

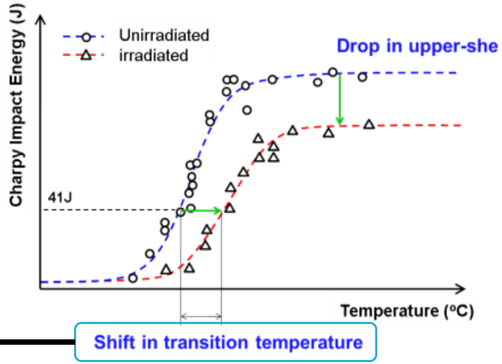
Prediction by embrittlement trend curves





$$RT_{NDT}^{irr} = RT_{NDT} + \Delta T_{41J}$$

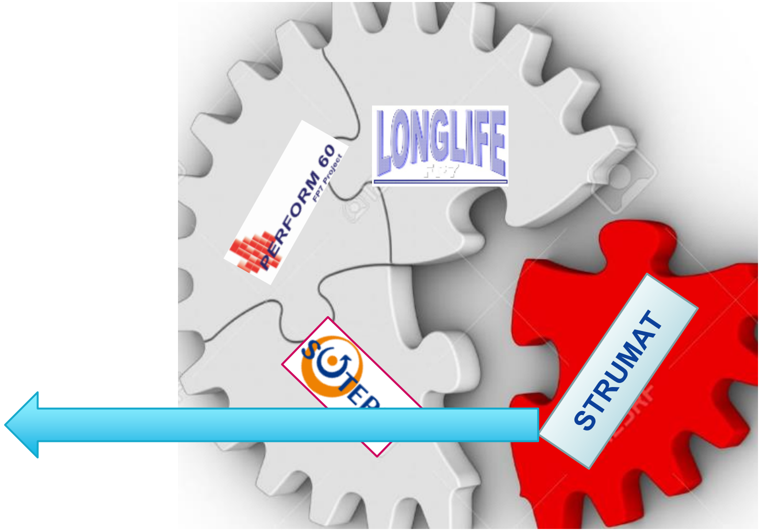
$$K_{IC} = A + B\left[e^{C(T - RT_{NDT}^{irr})}\right]$$



RPV-LTO: Former work & Open issues

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

- **Flux effects**
- **Initial microstructure, heterogeneities**
- **Prediction models for radiation effects** in RPV materials
- **Long term thermal aging and irradiation**
- **New embrittlement mechanisms (LBPs**?) and **Synergetic effects of Ni, Mn and Si** at **high fluences**
- Validity of existing **Embrittlement Trend Curves for LTO >60 years**
- Applicability of **miniature testing techniques**



RPV embrittlement program at NRG

STRUMAT: RPV embrittlement program at NRG: Objectives

STRUctural **MAT**erials research program on parameters influencing the material properties of RPV steels for safe long term operation of LWRs

STRUMAT-EZS
Dutch national funded project (2014 - present)

→

STRUMAT-LTO (pilot)
NUGENIA in-kind collaboration project (2018-2020)

→

STRUMAT-LTO
H2020 project 19 international partners (2020-2024)

+

FRACTESUS
H2020 project 21 international partners (2020-2024)

Overall objective:

STRUMAT program is aimed **<u>to address these remaining gaps and open issues in RPV embrittlement</u> research <u>to support safe long term operation of NPPs</u>**, 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 realistic welds (Low Cu RPV materials: irradiated in LYRA-10 to fluences representative of 60-80 years of LWR operation)

FRACTESUS: Archive RPV materials for mini-CT qualification

NRG

Equipment developed within STRUMAT project

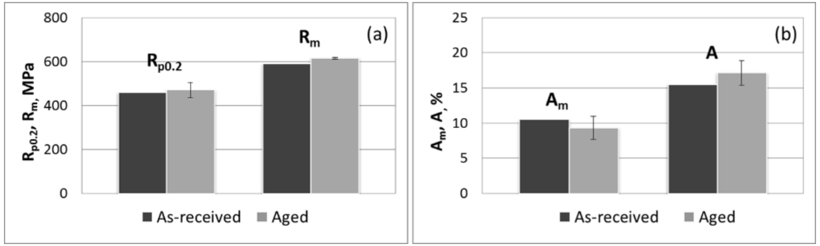
- In-cell reconstitution setup to reproduce specimens from broken pieces of Charpy size specimens
- Fracture mechanics setups for master curve testing as per ASTM E1921 standard on various specimen geometries
  - Single edge notched bending (SENB) of 3 point bend specimen
  - Mini-CT
  - KLST size

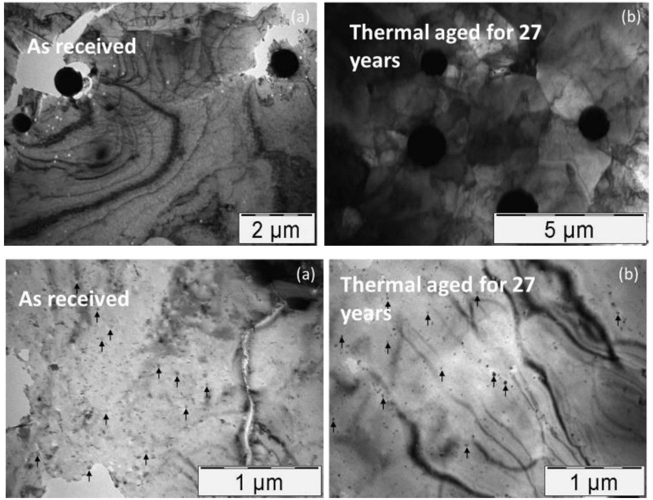
Stud welding machine

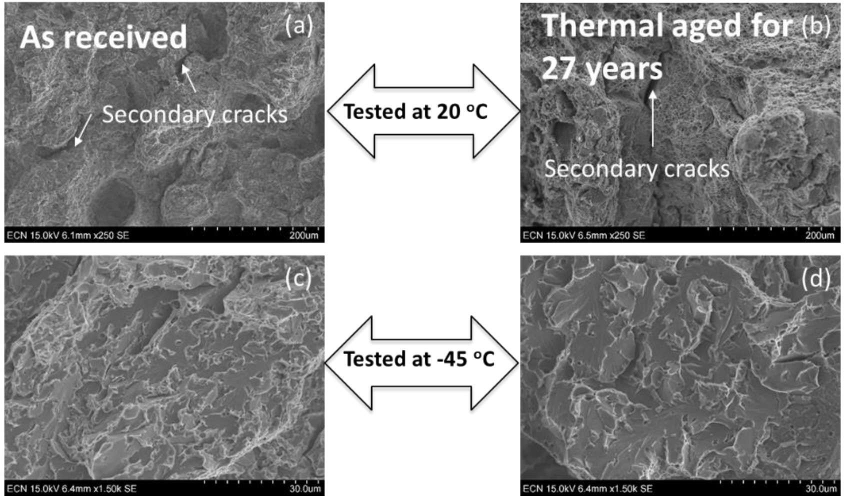
Milling machine and tools

Results: Effect of long term thermal ageing (27 years) in VVER-440 RPV surveillance samples

- VVER-440 surveillance specimens from ANPP after long term (27 years) thermal ageing at 290 °C
- No significant influence of thermal ageing on mechanical and microstructure

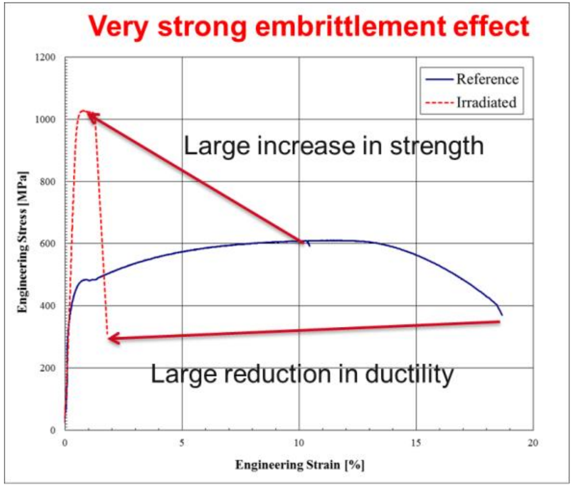


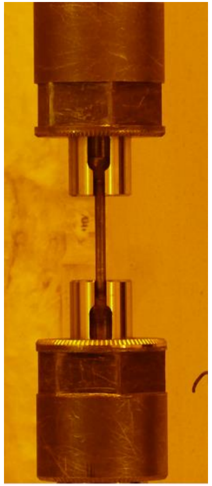


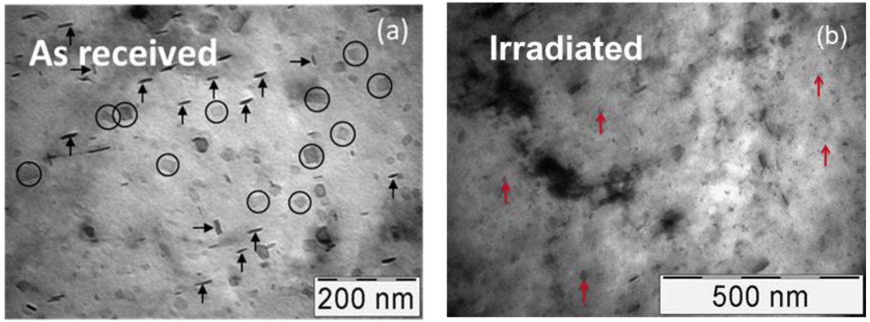


Results: Effect of high fluence irradiation in VVER-440 RPV surveillance samples

- VVER-440 surveillance specimens from ANPP after High fluence irradiation at 270 °C upto
- Large influence on mechanical and microstructure properties
- Significant hardening + embrittlement
- High density of irradiation induced precipitates in the microstructure



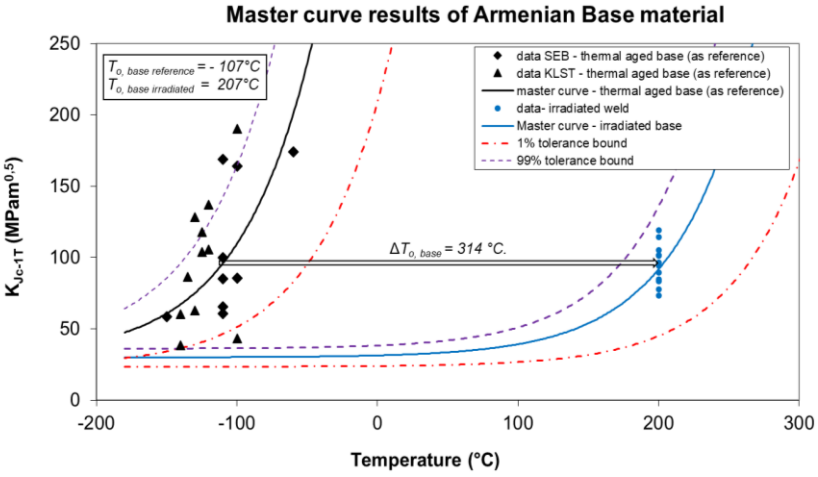


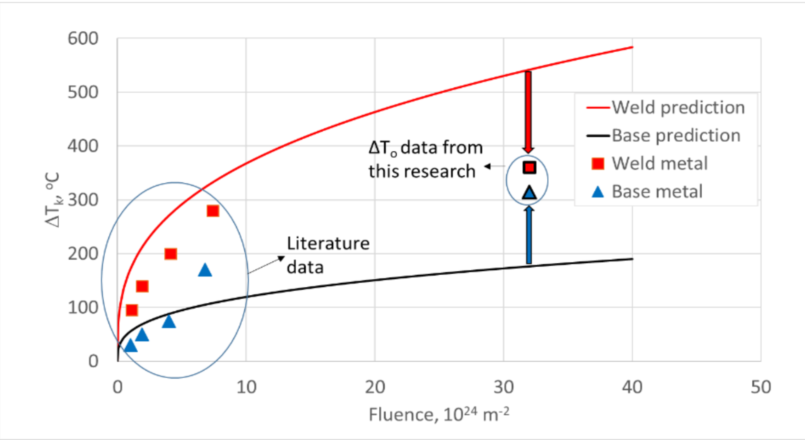


High density fine precipitates throughout the microstructure of irradiated specimens

Results: Effect of high fluence irradiation in VVER-440 RPV surveillance samples

- Large embrittlement can be seen via large Shift in transition temperature (ΔT)
- Under prediction at high fluences in the base metal



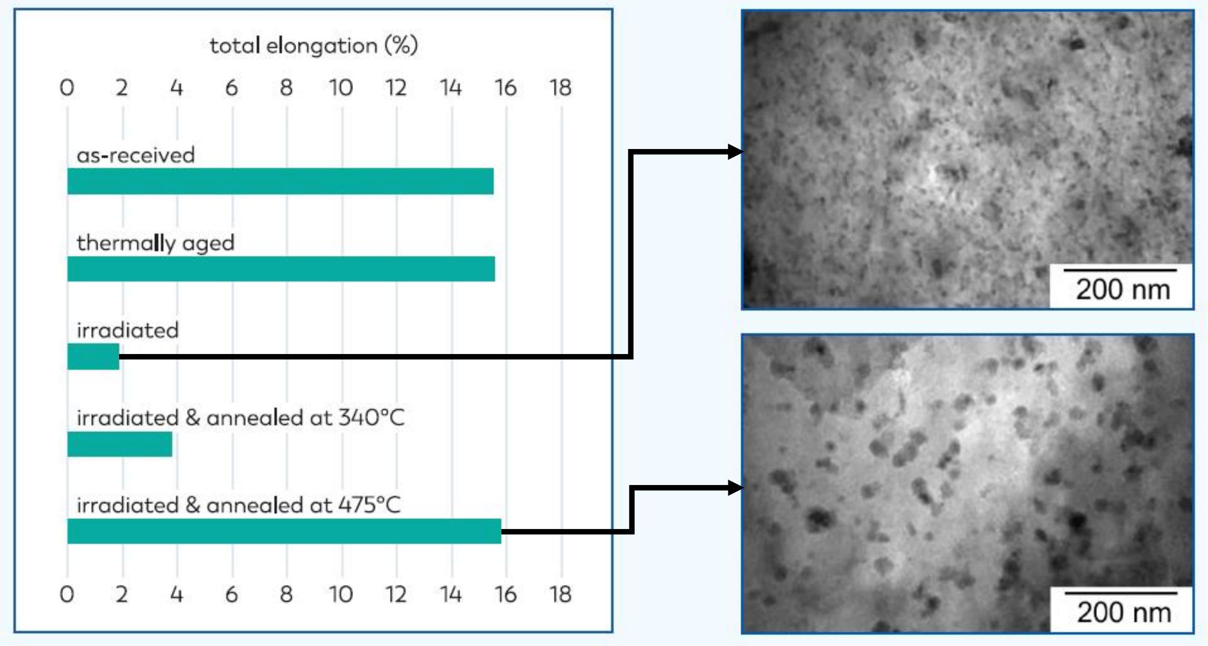


Results: Effect of recovery annealing in high fluence irradiated VVER-440 RPV surveillance samples

- The effectiveness of recovery annealing at two different temperatures of the highly irradiated weld was investigated.

- Recovery annealing at 475 °C results in significant recovery of mechanical properties, disappearance of the radiation-induced “black-dot” damage.

- This is an excellent news for LTO preparation

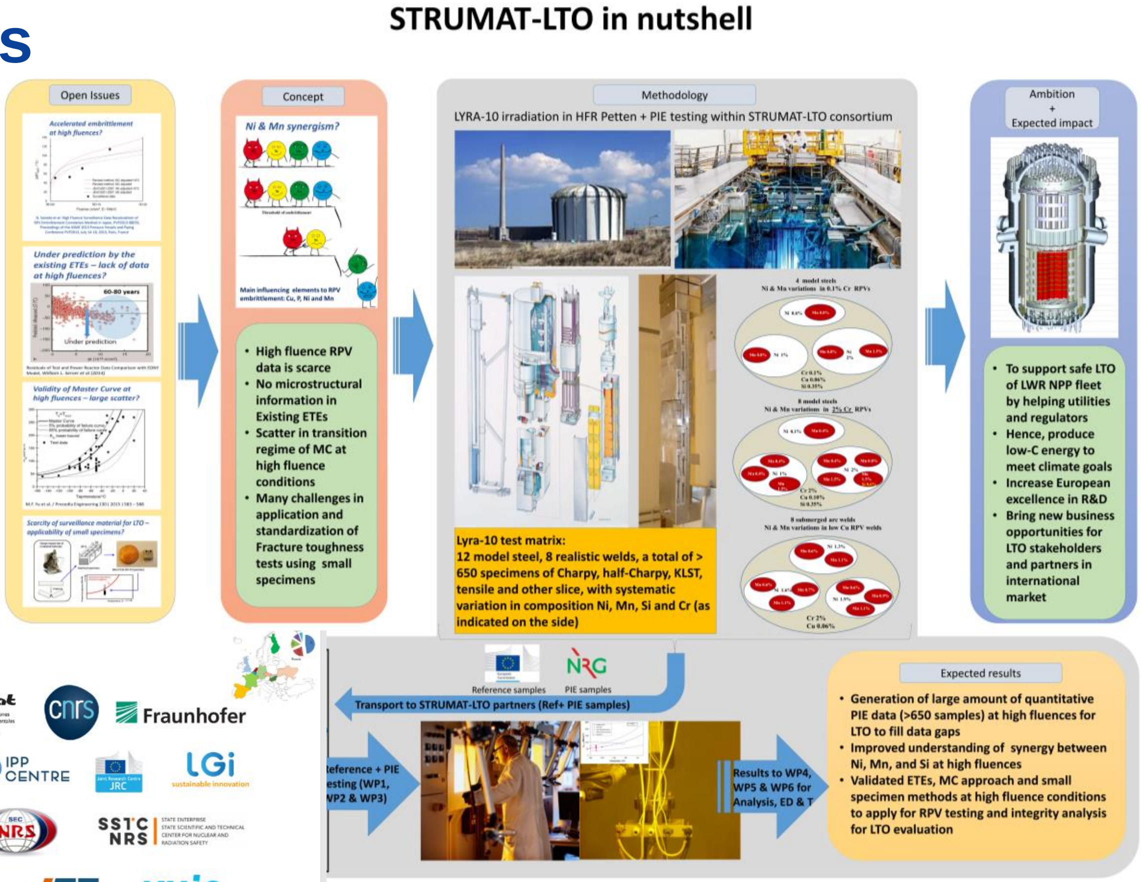


NRG
Ensuring Nuclear Performance

Work in progress

- Large PIE campaign on LYRA-10 samples within STRUMAT-LTO project co-funded by H2020 to address remaining challenges in this area

- Standardization of mini-CT test methods within FRACTESUS project co-funded by H2020



Acknowledgements and export control note

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Export control note

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Questions?

Thank you for your attention