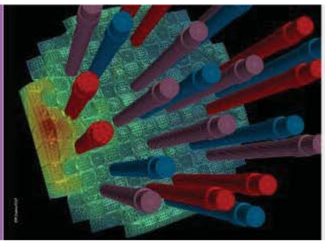


FISA 2022

30 May - 3 June 2022
Lyon, France

Reactor Performance, system reliability: Long-Term Operation

Marta Serrano CIEMAT, Sebastian Lindqvist VTT, Madalina Rabung, Fraunhofer ZFP, Akos Horvath, EK-CER, Murthy Kolluri, NRG

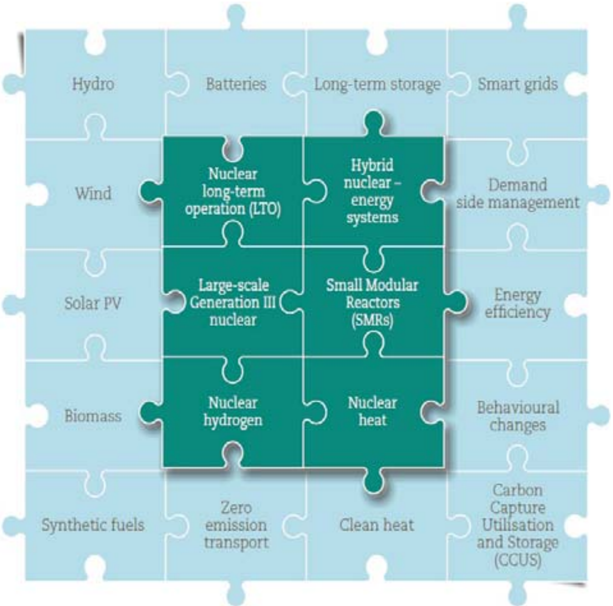
ENTENTE – ATLASplus – NOMAD – STRUMAT-LTO

20min

Contents

- Introduction
- Reactor pressure vessel
- Primary circuit
- Non destructive diagnosis

Introduction



Nuclear technologies and applications in future low-carbon energy systems
[*Meeting Climate Change Targets: The Role of Nuclear Energy OECD 2022 NEA No. 7628*]

- The nuclear sector can support climate change mitigation efforts in a variety of ways
  - **Long term operation**
  - Large-scale Generation III nuclear new builds
  - Generation IV and small modular reactors (SMRs)
  - nuclear hybrid energy systems,
  - Nuclear hydrogen
  - Nuclear heat

Introduction

- Long term operation
  - The operating time frame for a nuclear power plant is ultimately governed by the ageing of critical structures, systems and components (SSCs)

the following SSCs may become life-limiting

- Reactor pressure vessel (LWR)
- Reactor coolant system piping, welds and core internals (LWRs, PHWRs);
- large, civil and concrete structures, such as the containment building (LWRs, PHWRs)
- large sections of the plant's electrical cable system (LWRs, PHWR).

ENTENTE — Euratom 2019-2020 Grant agreement No 900018 — European Database for Multiscale Modelling of Radiation Damage

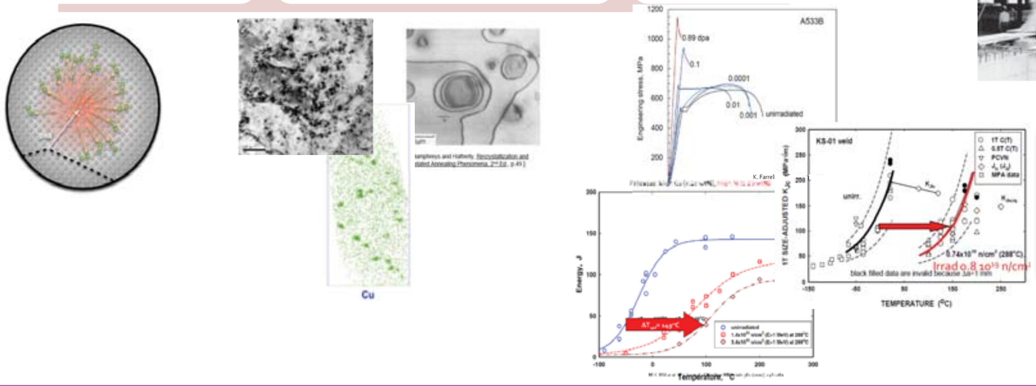
STRUMAT-LTO — Structural Materials for Nuclear Safety and Longevity

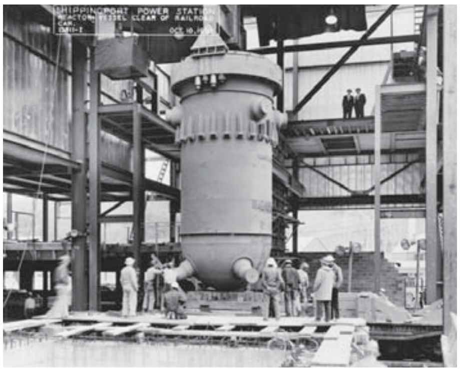
NOMAD — Nondestructive Evaluation (NDE) System for the Inspection of Operation-Induced Material Degradation in NPP

Introduction

- The Reactor Pressure Vessel (RPV)
  - **The problem** -> Neutron embrittlement

Neutron irradiation → Microstructural damage → Mechanical properties

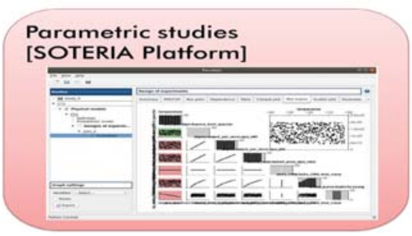


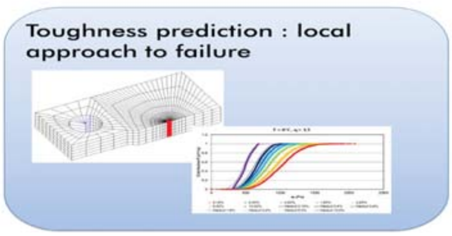


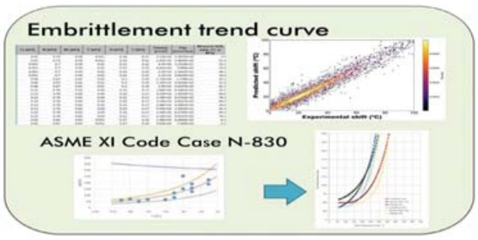
Large and not (economically) replaceable component

ENTENTE - Objectives

- ENTENTE "European Database for Multiscale Modelling of Radiation Damage" aims to design a **new European experimental/modelling materials database** to collect and store highly-relevant data on **radiation damage of Reactor Pressure Vessel** (RPV) steels
- Specific objectives
  - Design and maintain a unique experimental/modelling database for model validation and calibration
  - Collect previous data and enrich the database with microstructural and mechanical data on neutron irradiated RPV materials to fill gaps
  - Development of advanced models based on data analytics/mining and previous knowledge
- Exploitation objectives
  - Improve the SOTERIA Platform
  - Encourage the dissemination of results
  - Foster International collaboration







http://rdgroups.ciemat.es/web/materiales/entente

ENTENTE - Consortium

- 27 partners, (Coordinator CIEMAT)
  - Industrial partners (EDF, CRIEPI, FRA-G, UJV, NNL);
  - R&D centres (CIEMAT, BZN, CEA, HZDR, IMDEA, SCK•CEN, CCFE); Universities (CNRS, CHALM, KTH, UC, UBRIS, UWAR, UMAN, UA, UPC, UPM)
  - SME (SINTEC, PHIMECA), as well as TSO (VTT, SSTC NRS, IRSN).
- 12 countries: Spain, France, UK, Germany, Finland, Sweden, Belgium, Italy, Hungary, Czech Republic, Ukraine and Japan.

ENTENTE
Grant agreement ID: 900018

DOI
10.3030/900018

Start date 1 September 2020
End date 31 August 2024

Funded under
Euratom

Total cost
€ 4 938 147,94

EU contribution
€ 4 000 000

Coordinated by
CENTRO DE INVESTIGACIONES ENERGETICAS, MEDIOAMBIENTALES Y TECNOLOGICAS-CIEMAT
Spain

ENTENTE - Implementation

Implementation

WP1 (CIEMAT) - Management

WP5 (CIEMAT) - Dissemination, exploitation and training

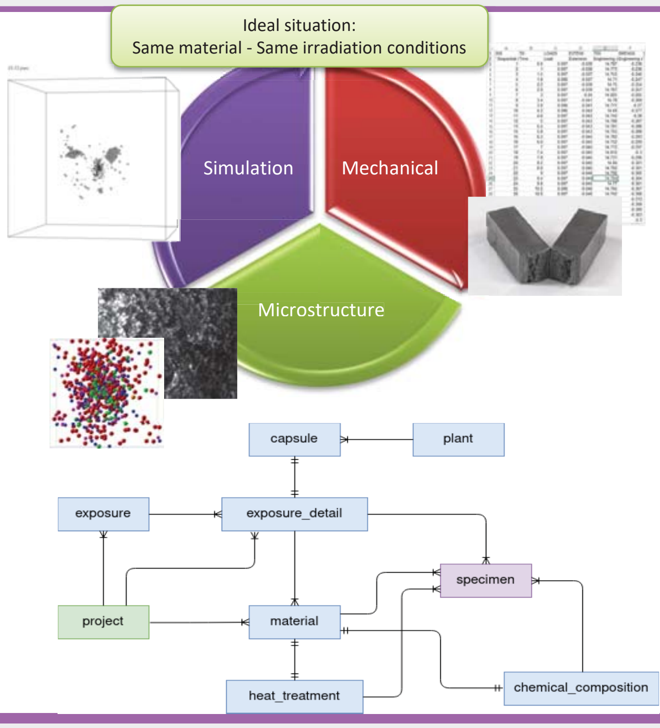
WP2 (EDF) - Model/experiment database
Database design
Data collection
SOTERIA PLATFORM

WP3 (CEA) - Generation of experiment/modelling data
Dedicated experiments and models
Atomistic -> Fracture

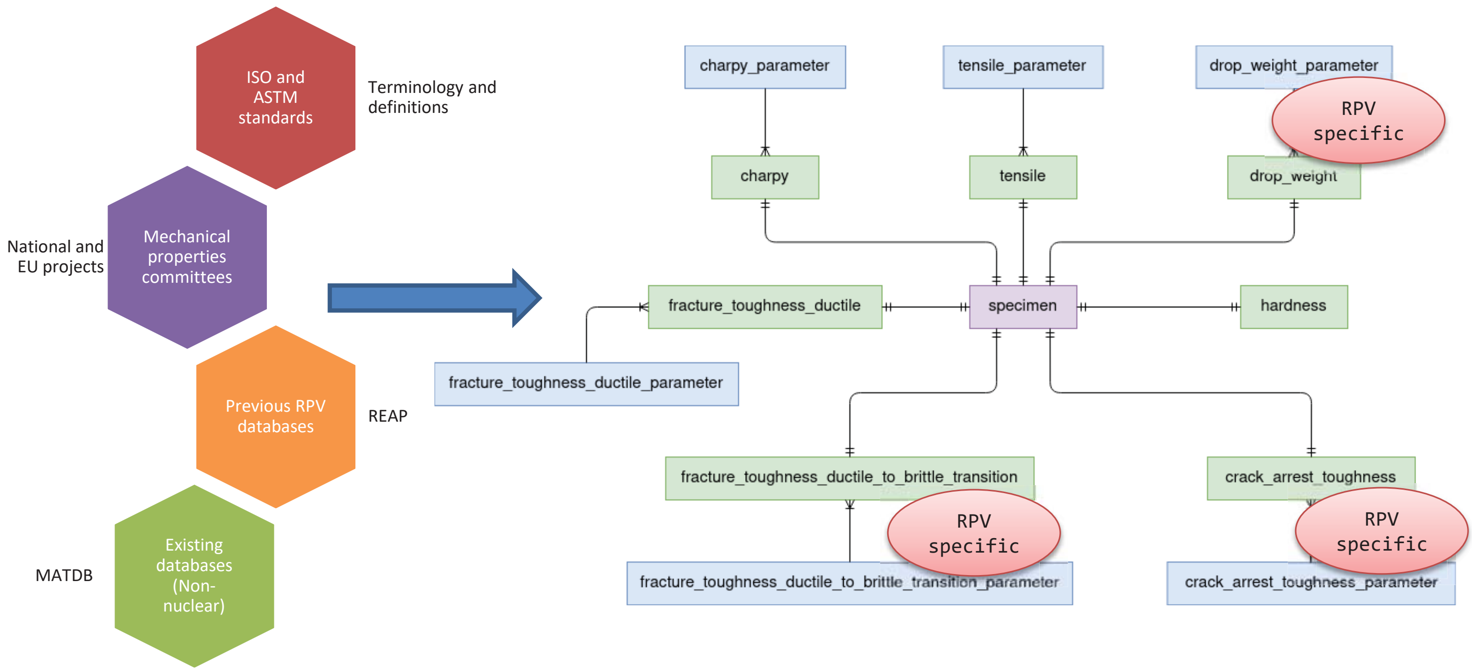
WP4 (VTT) - Accelerated model and analysis approaches
ICME approaches
Artificial networks and Machine learning.
Hybrid atomistic

ENTENTE – Relevant Results

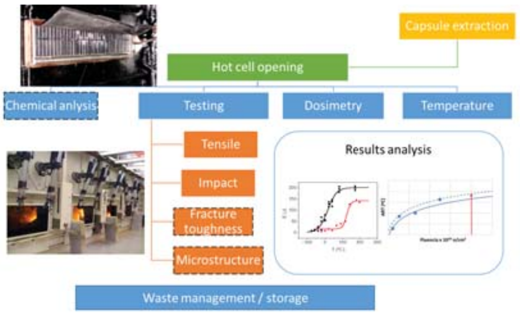
- ENTENTE Database
  - The ENTENTE database is composed of a high-level part, which acts as the core that connects to other modules.
  - These modules refer to specific techniques (e.g., mechanical properties, SEM or APT).
  - This modular structure facilitates data ingestion, and its later exploitation, as different techniques can be treated independently, but they all share a common high-level layer.



ENTENTE – Relevant Results

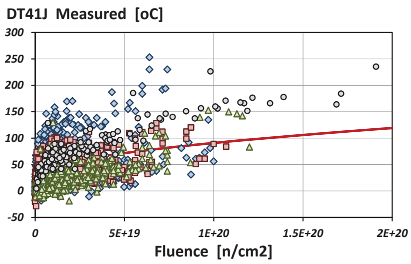


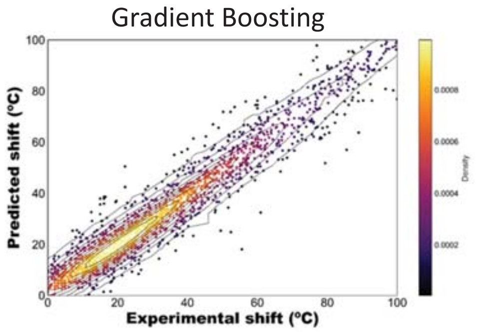
ENTENTE – Relevant Results

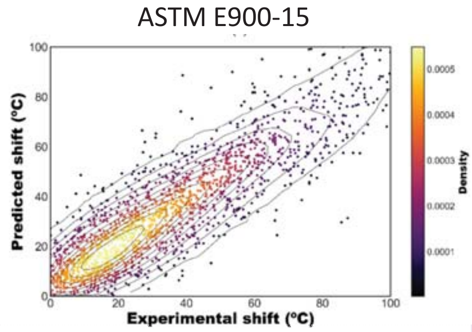


Prediction of the Transition-Temperature Shift Using Machine Learning Algorithms

Available surveillance data from nuclear power plants.
Collected to support ASTM's E900 effort -> ASTM PLOTTER excelfile
4438 transition temperature shifts







Ferreño, D.; Serrano, M.; Kirk, M.; Sainz-Aja, J.A. Prediction of the Transition-Temperature Shift Using Machine Learning Algorithms and the Plotter Database. Metals **2022**, 12, 186. https://doi.org/10.3390/met12020186

STRUMAT-LTO Objectives

High level objectives	Specific objectives (SO)	WP
Address remaining scientific gaps and open issues in RPV embrittlement to support safe long term operation of European NPPs including the scenario of LTO > 60 years	**SO1:** Quantitative characterization of RPV embrittlement and recovery in PWR and VVER-1000 steels at high fluences resembling 60 – 80 years of reactor operation	WP1, WP2
	SO2: Perform exclusive investigation of synergetic effects of Ni, Mn and Si on RPV materials embrittlement at high fluences	WP1, WP2, WP3
Assess and improve prediction tools (ETEs) and surveillance test methods in improving the RPV embrittlement assessment for increased safety for LTO of NPPs	**SO3:** Validation of existing ETEs for LTO above 60 years and a proposal for modifications when needed	WP4
	SO4: Assessment of Master curve (MC) approaches for fracture toughness characterization at high fluences	WP5
	SO5: Assessment and application of small specimen testing methods, i.e., fracture tests with mini 0.16 CT specimens, and small punch test (SPT), to investigate high fluence materials	WP2
Bridging the gap by knowledge transfer from experts retiring in this field to the next generation of young nuclear scientists	**SO6:** 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	WP6
Dissemination and outreach activities to maximise impact of the project results	**SO7:** Dissemination of the projects results to all stake holders in LTO business, including academic and R&D institutes, Utilities, SMEs, TSOs and regulators, to maximise the overall impact and to pave way for safe LTO of European NPPs.	WP6

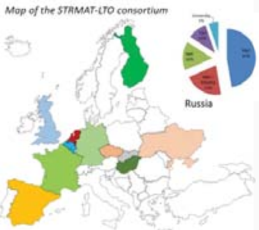
https://strumat-lto.eu/

STRUMAT-LTO Consortium

18 partners, (Coordinator EK-CER, Scientific coordinator NRG)

- R&D institutes: EK-CER, NRG, HZDR, CIEMAT, UJV, BZN, VTT, JRC, UKAEA, VUJE, CNRS, KINR, FhG-IZFP
- TSO: SSTC-NRS
- SMEs: LGI, ARB-NPPS, IPP Centre LLC
- University: STUBA

11 countries: Hungary, The Netherlands, France, Germany, Spain, Czech Republic, Finland, Belgium, United Kingdom, Slovakia, Ukraine



STRUMAT-LTO
Grant agreement ID: 945272

DOI
10.3030/945272

Start date 1 September 2020
End date 31 August 2024

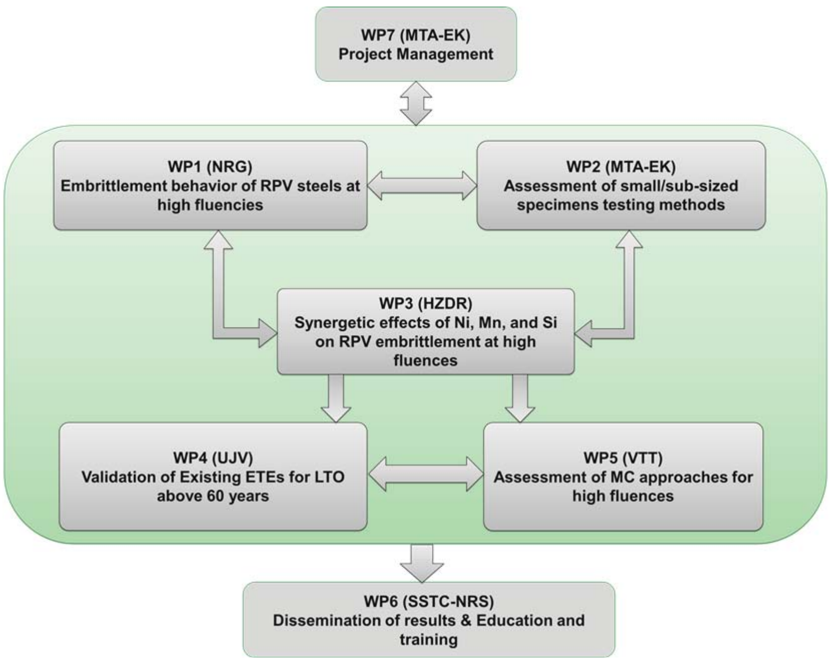
Funded under
Euratom

Total cost
€ 4 466 997,50

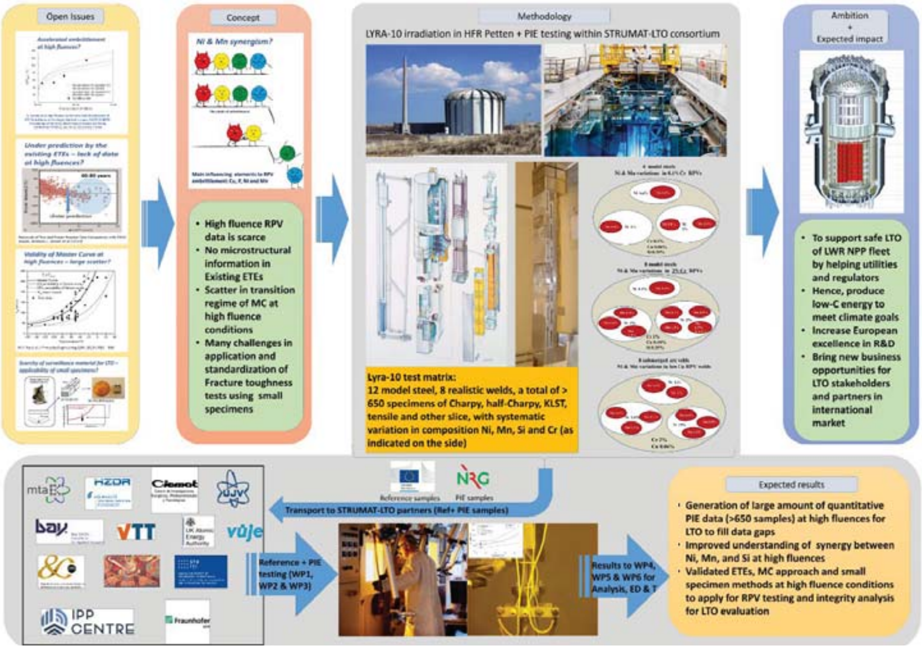
EU contribution
€ 3 965 029,25

Coordinated by
ENERGIATUDOMANYI KUTATOKOZPONT
Hungary

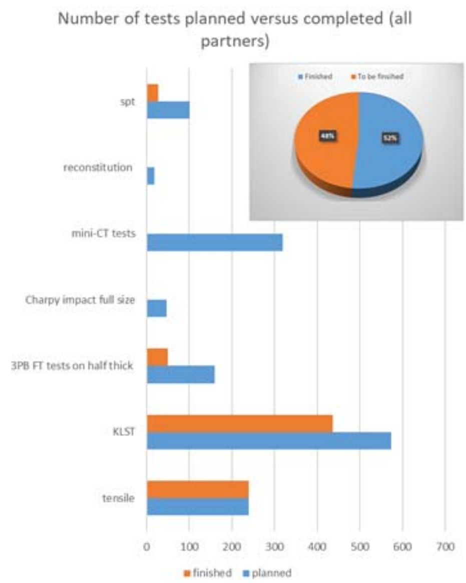
STRUMAT-LTO Implementation



STRUMAT-LTO concept and methodology



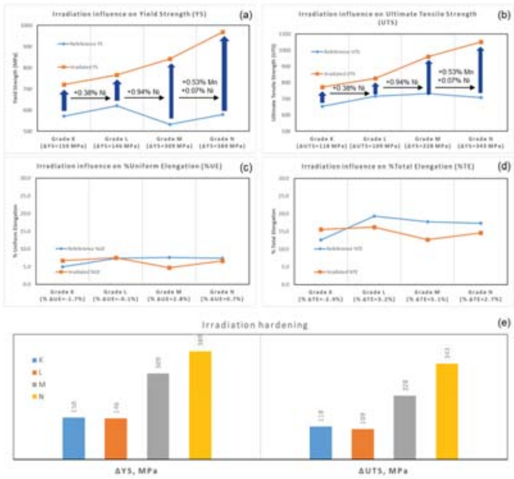
Achievement Sep 2020- Mar 2022:
Large part of PIE campaign finishend

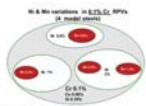


STRUMAT-LTO Relevant results

- A total of 118 samples (12 TENSILE + 106 KLST). The results of this research showed that:
  - No big change in irradiation induced hardening was observed with increase of Ni from ~0.6% to 1.0 %.
  - A large increase in irradiation induced hardening was observed in both model steels (M & N) containing high Ni content.
  - No significant change in %UE and a slight decrease in %TE was observed in all model steels after irradiation

Tensile testing results of PWR model steels





Test type	Steel grade	Number of specimens tested and testing laboratory			
		Unirradiated		Irradiated	
Tensile	K	1	NRG	2	NRG
	L	1		2	
	M	1		2	
	N	1		2	
KLST	K	9	JRC	8	
	L	9		15	
	M	11+15	JRC + NRG	15	
	N	9	JRC	15	

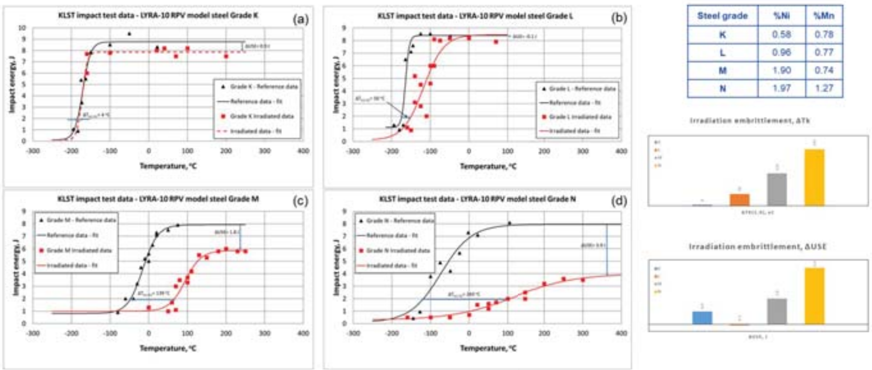
Steel grade	Nominal fast fluence (x 10^{20} n.cm^{-2})	
	Tensile	KLST
K	1.18	1.15
L	1.05	1.16
M	1.06	1.15
N	1.09	1.17

Model steel	C	Si	Mn	Cr	Ni	Mo	V	Cu	S	P
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

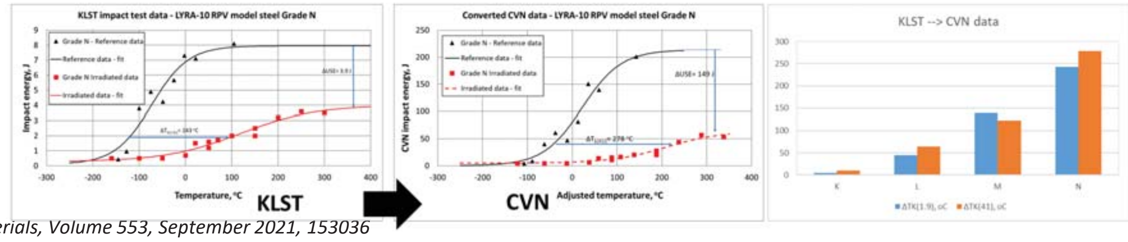
STRUMAT-LTO Relevant results

- The **shift in transition temperature** measured by KLST testing, ΔTk(1.9J) **increased proportionally with Ni** content for the model steels containing a constant Mn of ~0.8% (K, L, M)
- On the other hand a large increase in ΔTk(1.9J) and a decrease in upper shelf energy, ΔUSE was observed for model steel N with an **increase in Mn from ~0.8 to ~1.3** (compared to model steel M) for the same amount of Ni, indicating a **synergetic effect of Ni and Mn on the embrittlement behavior at these high neutron fluences**
- the combined effect of Ni and Mn on the shift in transition temperature follows a similar trend as observed for **Ringhals 3 and 4 RPV welds**

KLST testing results of PWR model steels



Data conversion from small to standard specimens



M. Kolluri et. al., Journal of Nuclear Materials, Volume 553, September 2021, 153036

NOMAD Objectives

- NOMAD **Nondestructive Evaluation (NDE) System for the Inspection of Operation-Induced Material Degradation in Nuclear Power Plants**
- The objective of NOMAD is the development, demonstration and validation of a non-destructive evaluation (NDE) tool for the local and volumetric characterisation of the embrittlement in operational reactor pressure vessels (RPVs). In order to address these objectives, the following steps will be taken:
  - Development and demonstration of an NDE tool for the characterisation of RPV embrittlement, especially accounting for material heterogeneities and exceeding the existing information from surveillance programmes
  - Extension of the existing database of RPV material degradation by adding correlations of mechanical, microstructural and NDE parameters as well as including quantification of reliability and uncertainty.
  - Application of the developed tool to cladded material resembling the actual RPV inspection scenario

https://www.nomad-horizon2020.eu/

NOMAD Consortium

- 10 partners (Coordinator Fraunhofer)
  - Industrial partners (Tecnatom, SVTI);
  - R&D centres (Fraunhofer, SCK CEN, CER, PSI);
  - Universities (Coventry Univ.);
  - SME (HEPENIX), as well as TSO (VTT).
- 7 countries: Germany, Belgium, Finland, Spain, UK, Swiss, Hungary.

NOMAD
Grant agreement ID: 755330

DOI
10.3030/755330

Closed project

Start date 1 June 2017
End date 28 February 2022

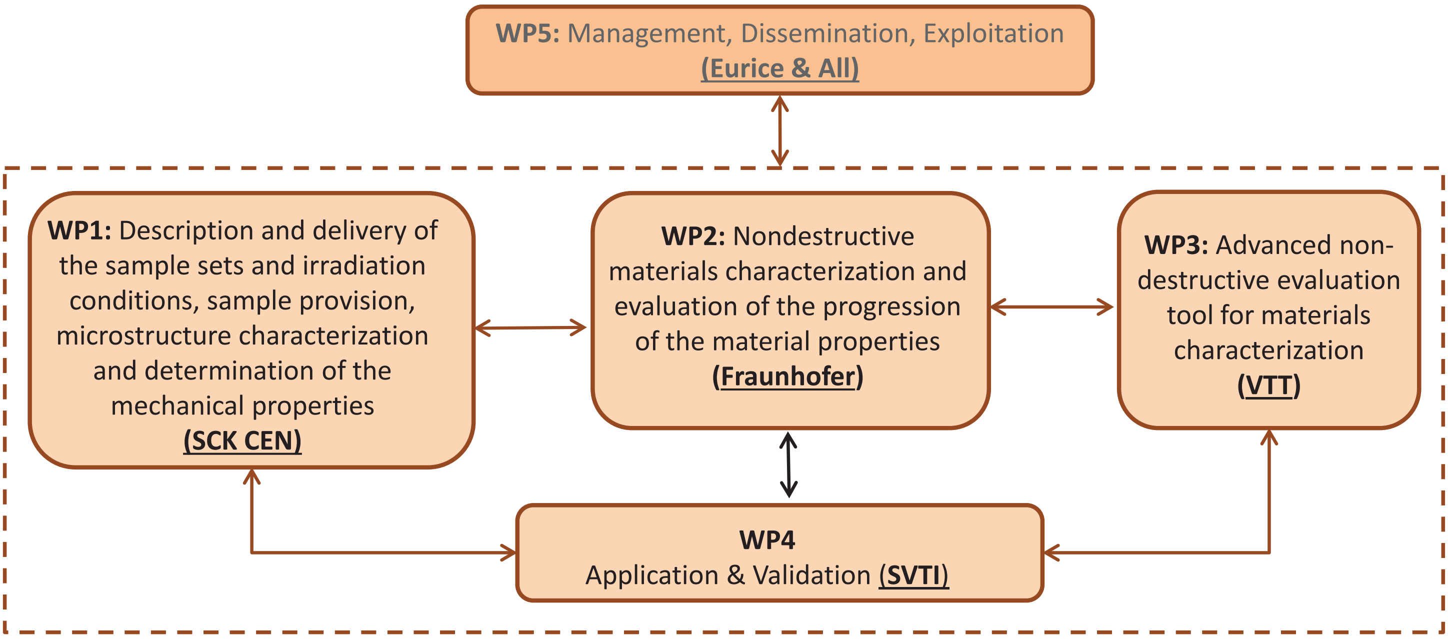
Funded under
Euratom

Total cost
€ 4 881 168,75

EU contribution
€ 4 881 168,75

Coordinated by
FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV
Germany

NOMAD Implementation

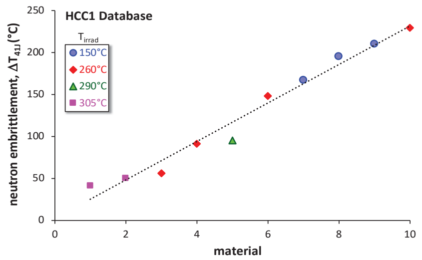


NOMAD Relevant results

Materials / Irradiation

- Materials of Western and Eastern RPV design, weld and base materials

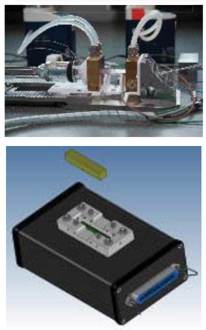
Neutron irradiation
- high neutron flux
- different fluences / temperatures
- Different sample geometries



Application of six NDE methods to irradiated non-cladded and cladded samples

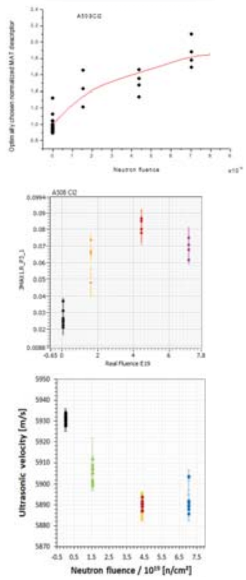
Micromagnetic techniques

Electrical techniques

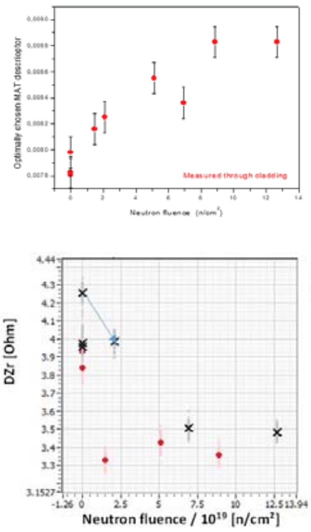


Ultrasonic technique

Charpy

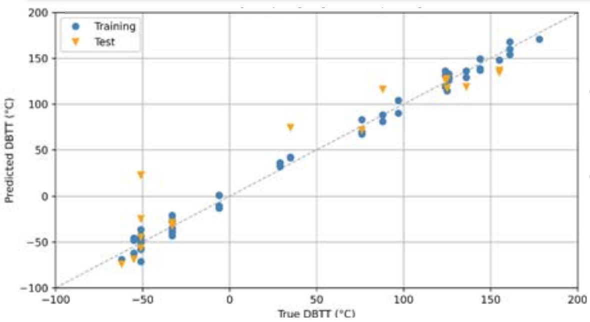


Blocks



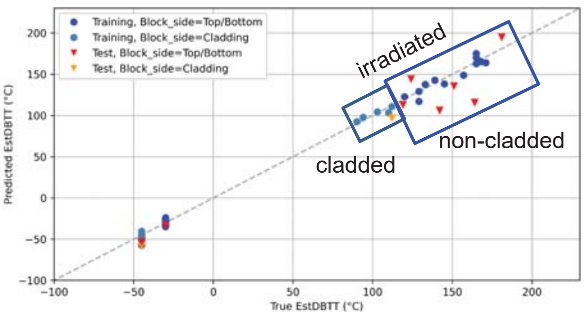
NOMAD Relevant results

Prediction of DBTT by AI-driven NDE tool



Charpy's

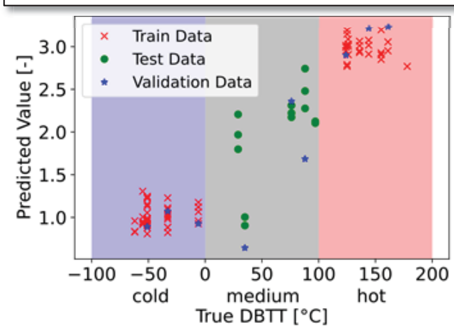
Training
(MAE = 6,59°C
R^2 = 0,99)
Test
(MAE = 15,95
R^2 = 0,92)



Blocks

Training
(MAE = 4,06°C
R^2 = 1)
Test
(MAE = 17,8°C
R^2 = 0,93)

Validation of the NOMAD tool for Charpy samples



Linear regression model **trained on classes "cold" and "hot"**, and **tested on class "medium"**

Additional data on irradiated cladded blocks (class "medium") needed for the validation of the NOMAD tool for cladded material

Introduction

- Long term operation
  - The operating time frame for a nuclear power plant is ultimately governed by the ageing of critical structures, systems and components (SSCs)

the following SSCs may become life-limiting

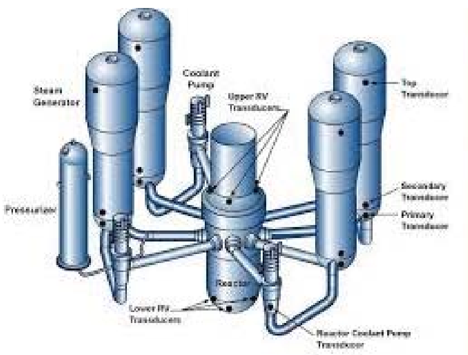
- Reactor pressure vessel (LWR)
- Reactor coolant system piping, welds and core internals (LWRs, PHWRs);
- large, civil and concrete structures, such as the containment building (LWRs, PHWRs)
- large sections of the plant's electrical cable system (LWRs, PHWR).

→ ATLAS+

Advanced Structural Integrity Assessment Tools for Safe Long Term Operation

Introduction

- Reactor coolant system piping & welds
  - **The problem** **->safety assessment of acceptable degradation and defects in piping components for LTO.**
- The PWR primary system piping constitutes a barrier to the release of fission products and activated species to the containment during normal, off-normal, accident and test conditions.
- The large diameter primary system piping (main coolant piping) carries the hot coolant from the reactor pressure vessel to the steam generators and then provides cold coolant back to the vessel.
- The other piping facilitates plant operation and plays a role in mitigating any off-normal or accident conditions.
- Therefore, maintaining the structural integrity of this piping is essential to the safe operation of a PWR plant.



ATLAS+ Objectives

- ATLAS+ **Advanced Structural Integrity Assessment Tools for Safe Long Term Operation**
- Specifically this project will focus on developing:
  - innovative quantitative methodologies to transfer laboratory material properties to assess the structural integrity of large piping components,
  - an enhanced treatment of weld residual stresses when subjected to long term operation,
  - advanced simulation tools based on fracture mechanics methods using physically based mechanistic models,
  - improved engineering methods to assess components under long term operation taking into account specific operational demands,
  - integrated probabilistic assessment methods to reveal uncertainties and justify safety margins.

ATLAS+ Consortium

In-kind contributions are provided by
Oakridge Consulting International Incorporated (OCI, Inc.),
Mitsubishi Heavy Industries, Ltd (MHI) and University of Soul.

ATLASplus
Grant agreement ID: 754589

DOI
10.3030/754589

Closed project

Start date	End date
1 June 2017	30 November 2021

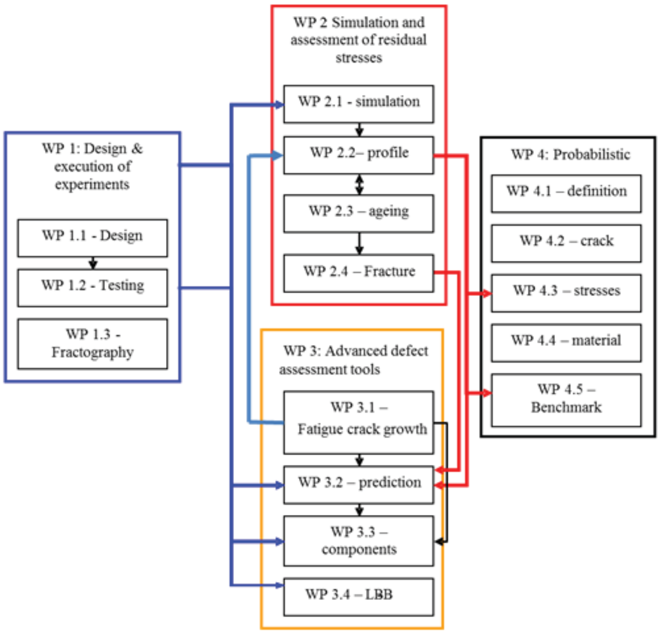
Funded under
Euratom

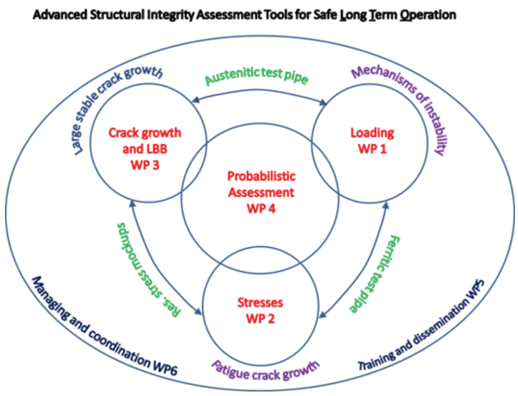
Total cost
€ 7 195 162,59

EU contribution
€ 3 930 863,92

Coordinated by
TEKNOLOGIAN TUTKIMUSKESKUS VTT OY
Finland

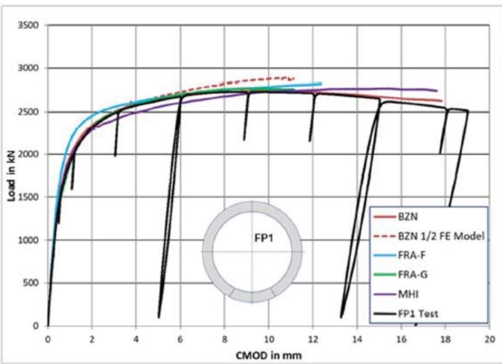
ATLAS+ Implementation

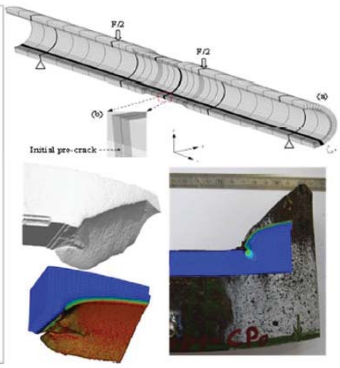


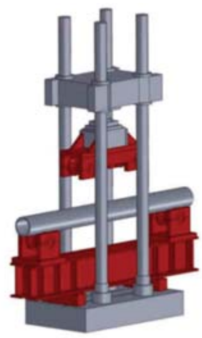


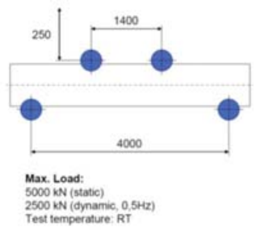
ATLAS+ Relevant results

- Most of the participating organizations were able to develop a reasonable approach for prediction of ductile fracture in large and mid-scale mock-ups that are representative of real nuclear components. Performed benchmarks revealed a robust implementation of GTN type LA models in different FE codes and their capability to take into account both the constraint and transferability effects.
- The models were calibrated based on small scale specimen data (C(T) and SE(T)) and validated based on the large scale experimental data.



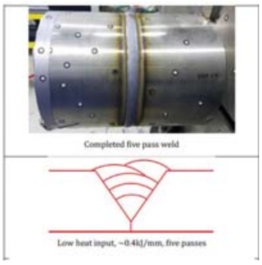






ATLAS+ Relevant results

- WP2 primarily focuses on modelling and measuring residual stresses. Thick and thin-walled (manufactured with low and high heat-input) narrow-gap gas tungsten arc-welds (GTAW) (AISI 316L), fully circumferential and 120° patch overlay welds, and thick walled thermally aged NGGTAW were manufactured, and the residual stress profiles were measured with different techniques vital to minimize uncertainty.
- The FEM 2D and 3D residual stress predictions agreed with the experimental results determined with several techniques and the results were repeatable.



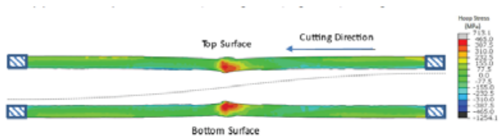


Figure 42. Hoop residual stresses on the longitudinal-normal plane of a low HI thin-walled AISI-316L pipe girth weld measured using the contour method.

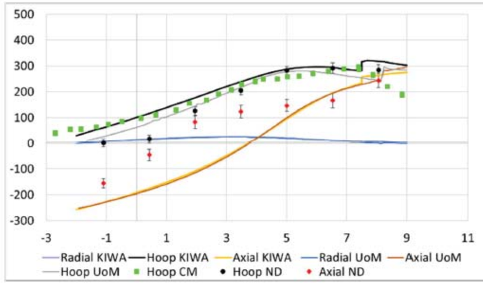


Figure 46. Line plots of the axial, radial, and hoop stresses on a through-wall line at the weld centreline of a high HI 3-pase weld in an AISI 316L pipe, showing both measured stresses (contour method and neutron diffraction) and predicted stresses.

ATLAS+ Relevant results

- Final report available at: https://cris.vtt.fi/en/publications/final-project-report-atlas-advanced-structural-integrity-assessme
- Honorable mention: A best practice guidance document on LBB. The best practice guidance document takes into account and highlights LBB methodologies from various codes and assessment procedures developed and utilised in different countries. This enables the user to be well informed when performing a LBB assessment and effectively provides a template for carrying out LBB assessments. The guidance contains two types of LBB methodologies. The two types of methodologies and the strong emphasis on undertaking sensitivity studies are considered to be an enhancement on some of the current LBB methodologies and practices.
- WP1, WP2 and WP3 → New best-practice simulation models for assessing ductile tearing and residual stresses in industrial components were validated based on high-quality experimental data.
- The probabilistic round robin analyses had initially large differences, but after refining of the parameters acceptable agreement between the partners was achieved despite the different fracture assessment methodologies applied and differences in the limit states. The results have made it possible to better understand how different assumptions and parameters influence a probabilistic assessment.

Summary

- This presentation show the main results of 4 EURATOM-funded projects aligned with the SNETP-NUGENIA Technical area 4 – System and component integrity
  - Three projects devoted to the ageing management of the reactor pressure vessel from different perspectives:
    - Data management and modelling approaches
    - Irradiation embrittlement and hardening evaluation of highly irradiated materials
    - Non destructive diagnosis of irradiation embrittlement
  - One project dealing with the best practice guidance document on LBB (leak before break) and probabilistic assessment of primary piping
- Relevant results are already available
- Well-consolidated consortiums