INNOVATIVE STRUCTURAL MATERIALS FOR FISSION AND FUSION

# The INNUMAT project

Jarir Aktaa

INNUMAT Workshop, Nov. 16-17th, 2023, Madrid, Spain

This project has received funding from the European Union`s Horizon EURATOM 2021 NRT 01 nuclear research and training programme under grant agreement No 101061241.

# INNUMAT Core Team

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[3] *Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT)*
[4] *Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA)*
[5] *Framatome (FRAMATOME)*
[6] *Ansaldo Nucleare SPA (ANN)*
[7] *Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile (ENEA)*
[8] *Agencia Estatal Consejo Superior de Investigaciones Científicas (CSIC)*
[9] *Kungliga Tekniska Hoegskolan (KTH)*
[10] *Studiecentrum voor Kernenergie - Centre d'Étude de l'énergie Nucléaire (SCK CEN)*
[11] *Joint Research Centre - European Commission (JRC)*

# Euratom call 2021 – Topic 4

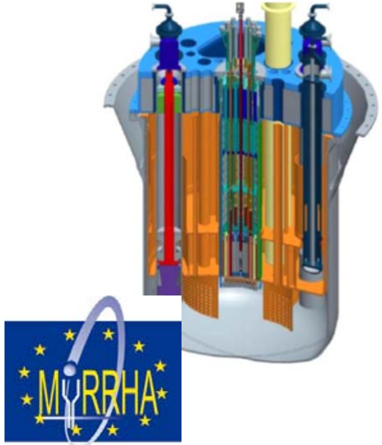
## Advanced structural materials for nuclear applications

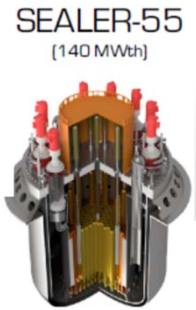
Expected outcome

- Development and qualification of **innovative materials solutions** with superior **corrosion**, **temperature** and **irradiation resistance** for the expected operating conditions of advanced fission technologies (including Research Reactors or SMRs).
- Development of solutions for **crosscutting** aspects of materials for **fission** and **fusion** technologies, **modelling** and **reduced activation** steel.
- Exploration of the **potential** of advanced nuclear **materials solutions** (also from new manufacturing technologies covered within Horizon Europe research programme) for use in **other energy technologies** that require exposure to high temperatures, high pressure and corrosive fluids

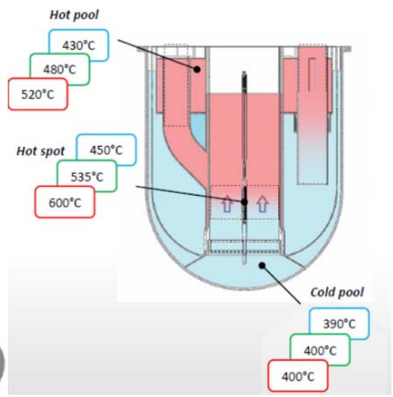
# Structural materials for fission applications

**Gen IV lead cooled fast reactors (LFR)**



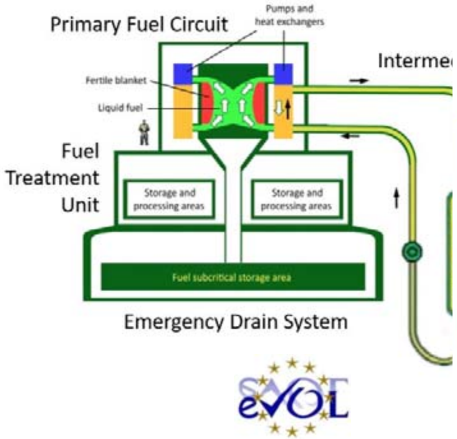



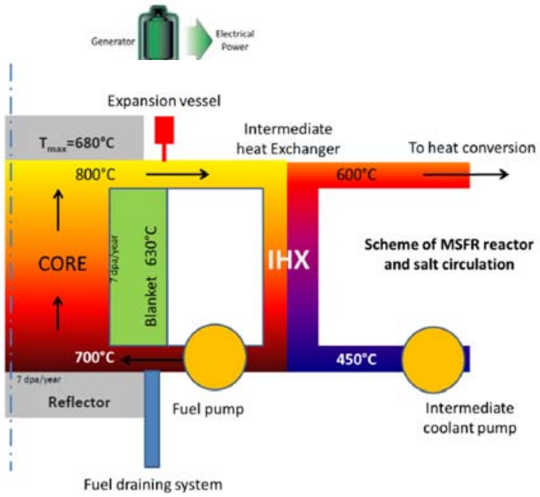

SMR




ALFRED

**Gen IV molten salt fast reactors (MSFR)**




**Challenges:**

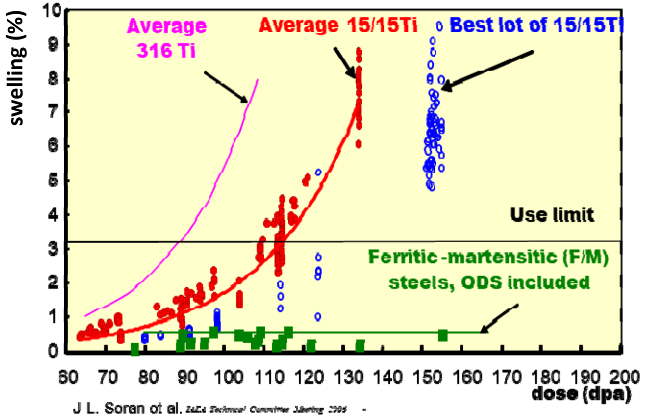
- Lead, eutectic lead-bismuth and molten salts are aggressive environments
  - ➢ Corrosion, erosion
  - ➢ Alteration of properties (LME, CAF…)
- Thermal stability and HT strength
- High dose irradiation: dpa, transmutation, activation

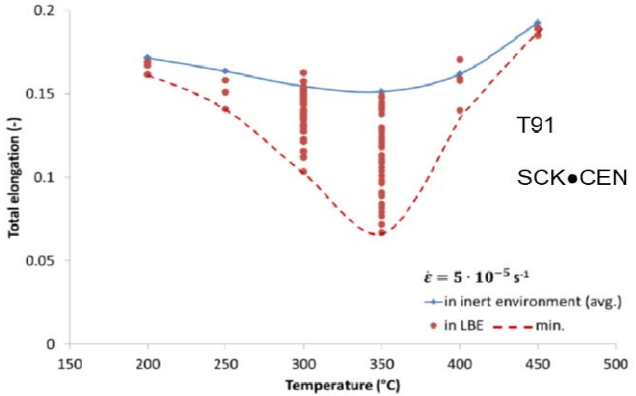
# Structural materials for fission applications

## Gaps and limits

- Ferritic/martensitic steels suffers from LME (outcome of the MATTER project)
  → Excluded as structural material candidate for MYRRHA
- Austenitic steel welds are susceptible for LMC & LME (outcome of the GEMMA project)
  → Need to protect load bearing welds
- Ni base alloys not suitable for core applications (He production → swelling and embrittlement)

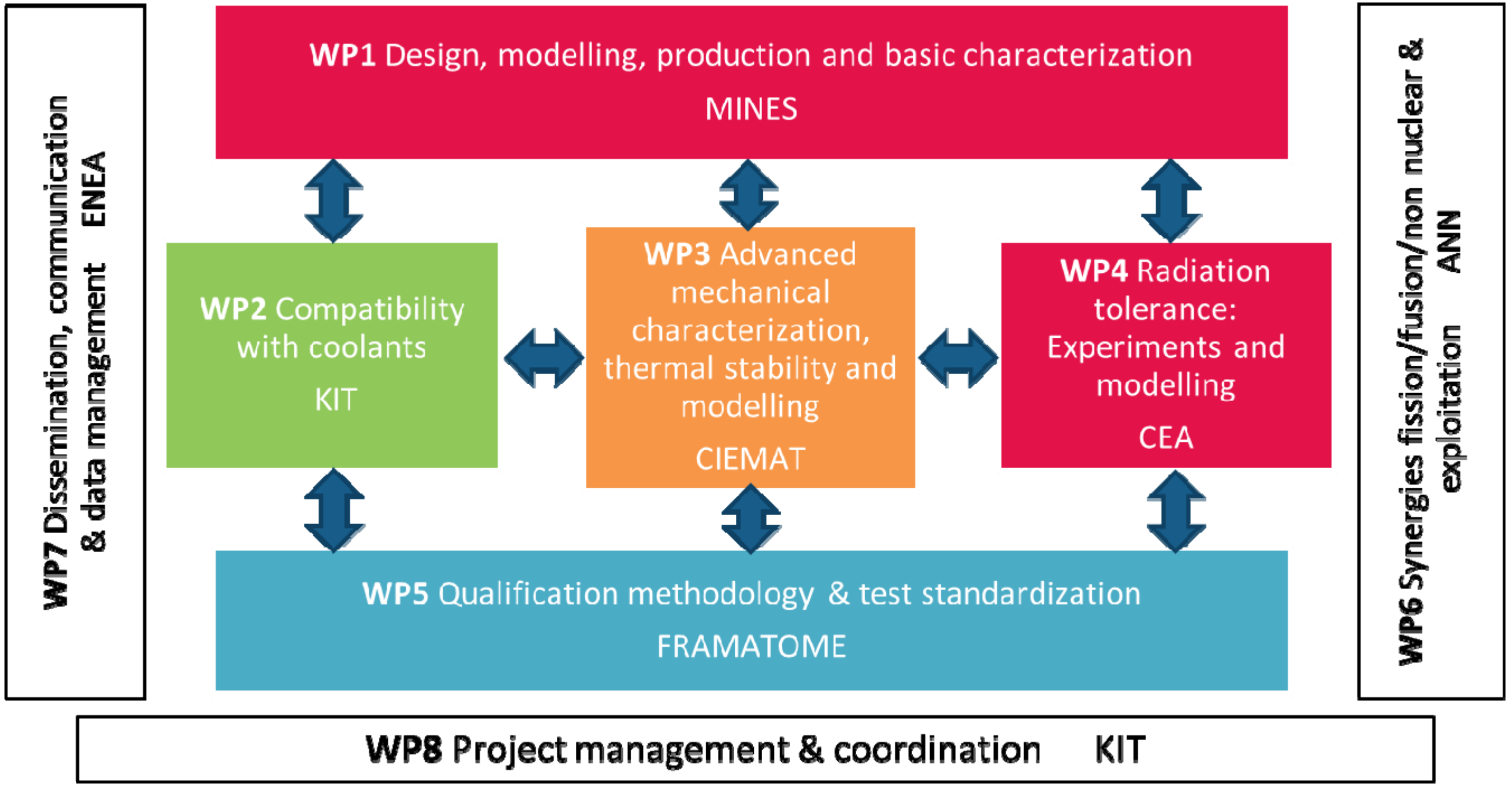
  ⇒ Innovative structural materials/material solutions are required



# Euratom call 2021 – Topic 4

## Innovative structural materials for fission and fusion - INNUMAT



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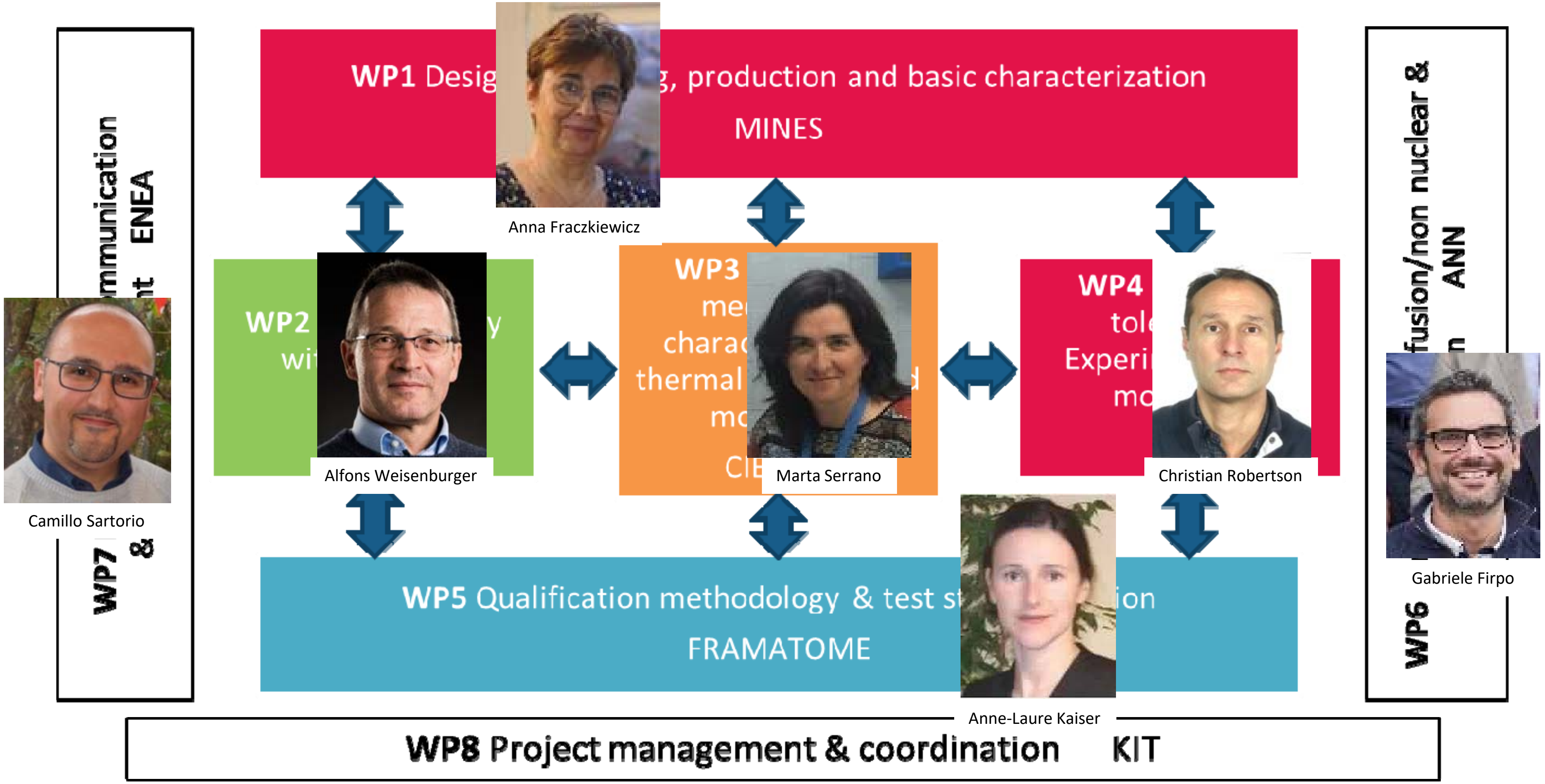
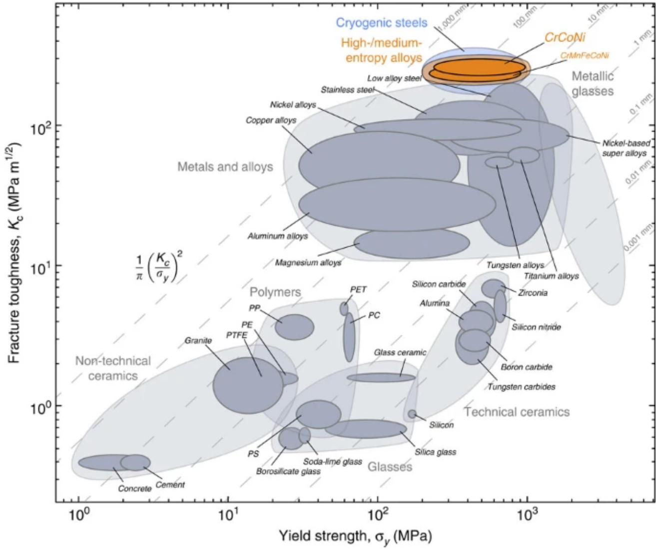


# INNUMAT

## Materials

- **HEAs**
- ?




Gludovatz et al., Nature Commun., 2016

## Materials

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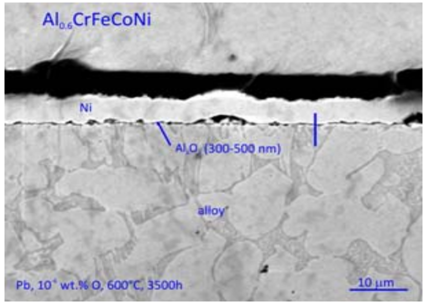
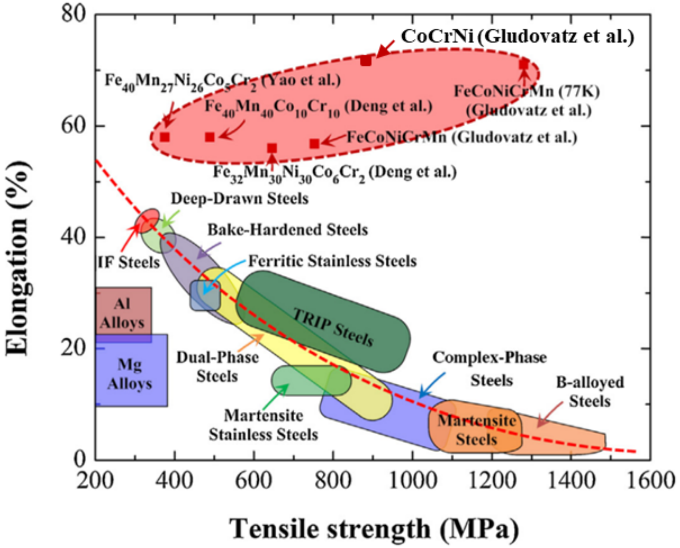
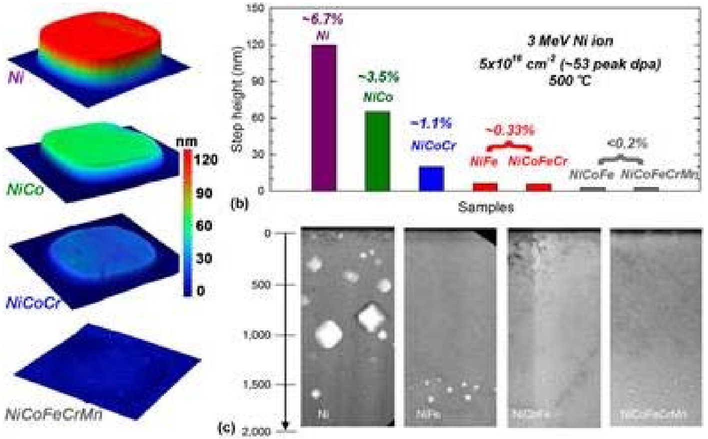



Jianu et al., Euromat, 2017




Ye et al., Materials Today, 2016

Irradiation induced swelling:
HEA ≈40 times less than pure Ni

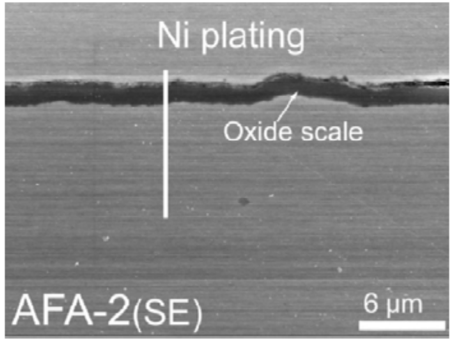



Jin et al., Scr. Mater., 2016

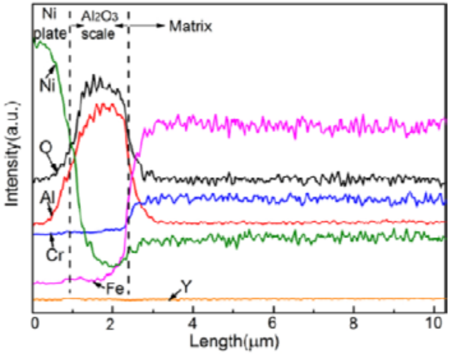
# INNUMAT

## Materials

- HEAs
- **AFA steels**
- ?




*After 1h in steam environment at 1200°C*




Shi et al., Corros. Sci., 2020

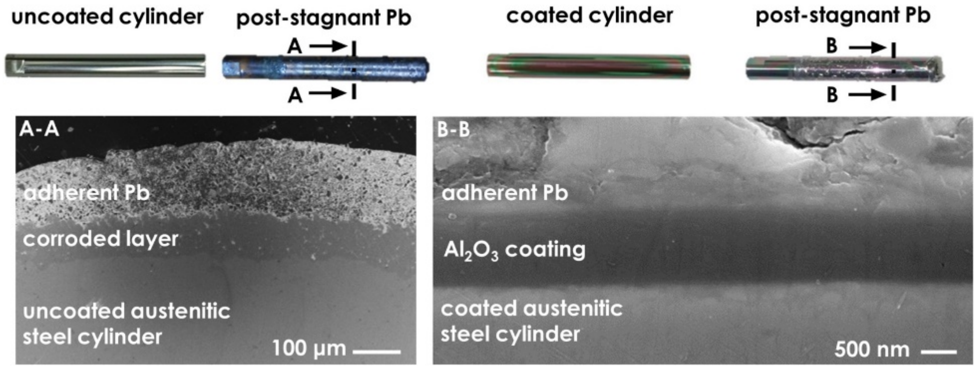
| SYSTEMS ↓ / PHASES → | | ESNII demonstrator: As licensed (phase I) | ESNII demonstrator: Evolving (phase II) | FOAK (prototype) | Commercial deployment |
|---|---|---|---|---|---|
| ADS (MYRRHA) | Periodically Replaced Components | Cladding: 1.4790; structures: 316L(N) | Coated 15-15Ti (FeAl, FeCrSi, FeTa, MAX phases, ..) or AFA | N/A | |
| | Permanent Structural Components | 316L(N) | | | |
| LFR (ALFRED) | Periodically Replaced Components | Cladding and structures: ($Al_2O_3$ coated) 15-15Ti (AIM1) | Cladding and structures: $Al_2O_3$ Coated 15-15Ti or AFA | Cladding: AFA or FeCrAl ODS Structures: AFA | AFA or FeCrAl ODS, or (coated) Mo-ODS, or $SiC_f$/SiC |
| | Permanent Structural Components | 316L(N) | | AFA or ferritic steel lined with AFA | |

Malerba et al., SRA of JPNM, 2019

# INNUMAT

## Materials

- HEAs
- AFA steels
- **Coated 15-15Ti**
- ?




F. García Ferré et al., Corr. Sci., 2017

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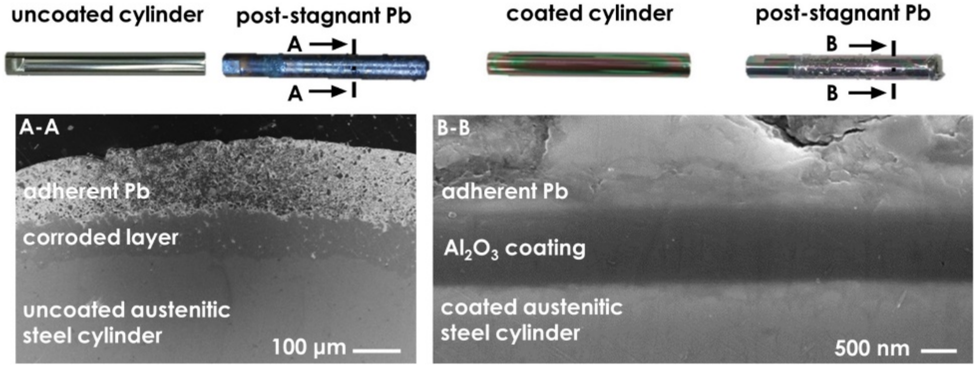
Malerba et al., SRA of JPNM, 2019

# INNUMAT

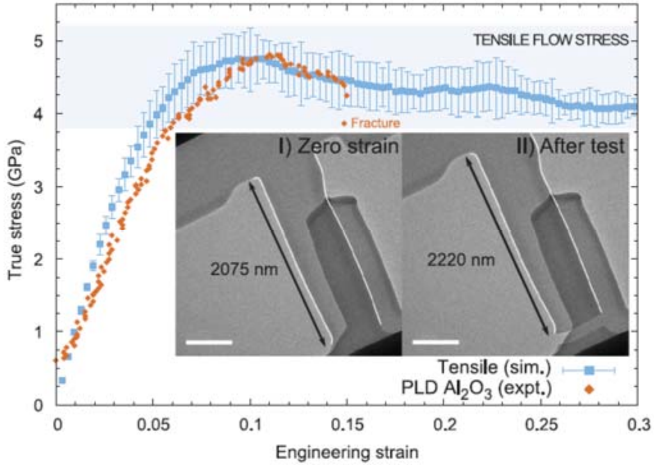
## Materials

- HEAs
- AFA steels
- **Coated 15-15Ti**
- ?




F. García Ferré et al., Corr. Sci., 2017

In-situ TEM vs. atomistic simulation: Plasticity in amorphous alumina by bond switching



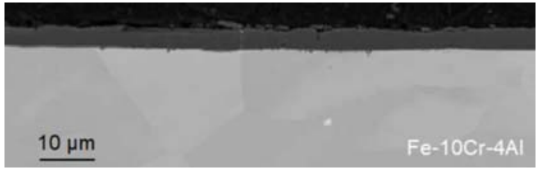

Frankberg et al., Science, 2019

# INNUMAT

## Materials

- HEAs
- AFA steels
- Coated 15-15Ti
- **Weld overlay**

AISI 316L tube with weld overlay (Fe-10Cr-4Al-RE)




Fe-10Cr-4Al-RE: Exposed to liquid lead at 800°C, protektive self-healing alumina


Weld overlay thickness: 210-220 μm
Excellent ductility: bend test 180°

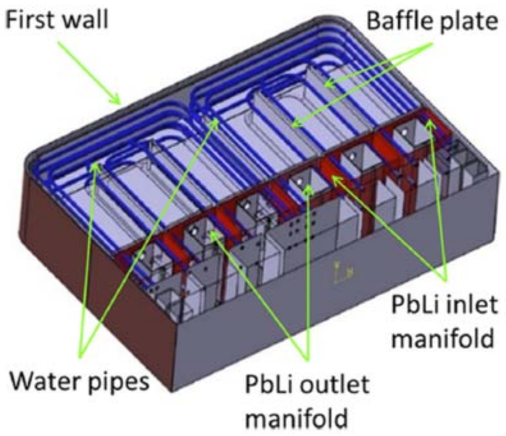
Peter Szakálos, SNETP Forum, 2021

# INNUMAT

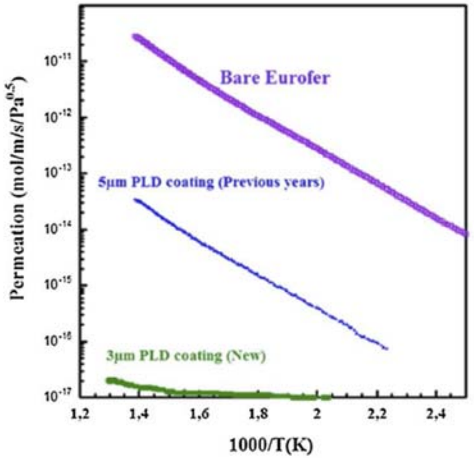
## Materials

Fission:
- HEAs
- AFA steels
- Coated 15-15Ti
- Weld overlay

Fusion:
- **Coated EUROFER**
- ?




**DEMO** Water Cooled Lead Lithium (WCLL) breeding blanket module




Permeation of deuterium in PLD alumia coated EUROFER

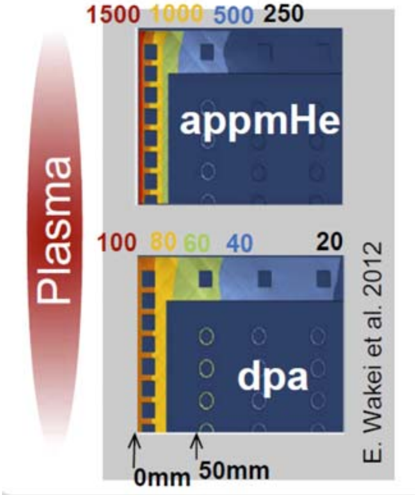
M. Utili, Fusion Eng. Des. 2021

# INNUMAT

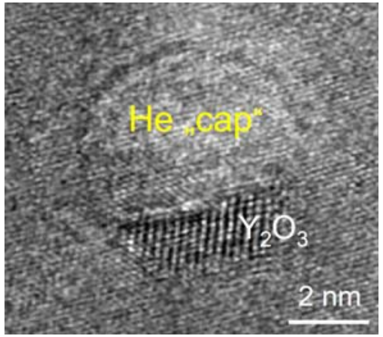
## Materials

Fission:
- HEAs
- AFA steels
- Coated 15-15Ti
- Weld overlay

Fusion:
- Coated EUROFER
- **ODS steel**




Only few centimeters have a high He/dpa ratio




A. Ryazanov et al; JNM, 2013

Trapping of He at ODS particles (1000 appm He impl. at 500°C)

# INNUMAT - materials and applications

## Materials

Fission:
- HEAs
- AFA steels
- Coated 15-15Ti
- Weld overlay

Fusion:
- Coated EUROFER
- ODS steel

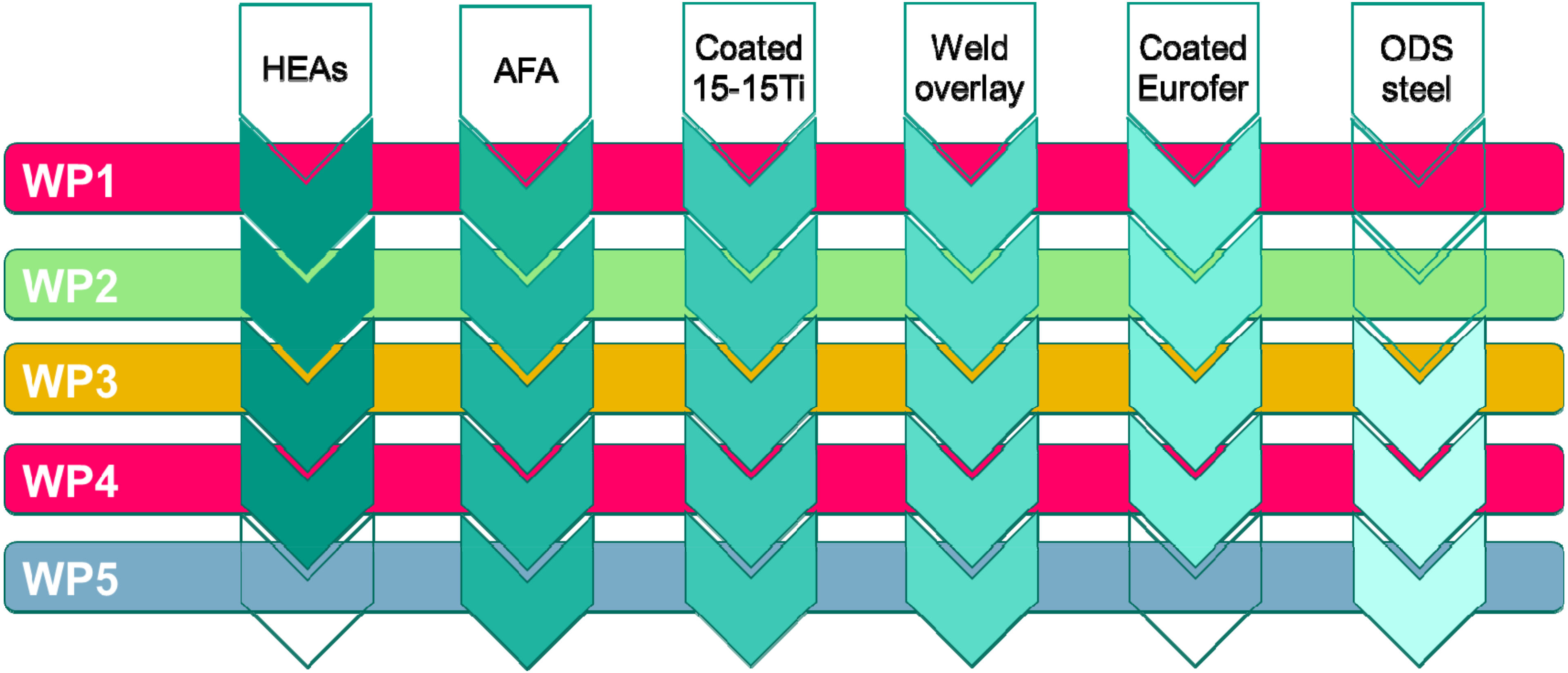
## Reactor applications

- Fission molten salt reactor
- Fission heavy metal cooled reactor
- Fusion DEMO

(Fission molten salt reactor and fission heavy metal cooled reactor:) incl. respective SMRs

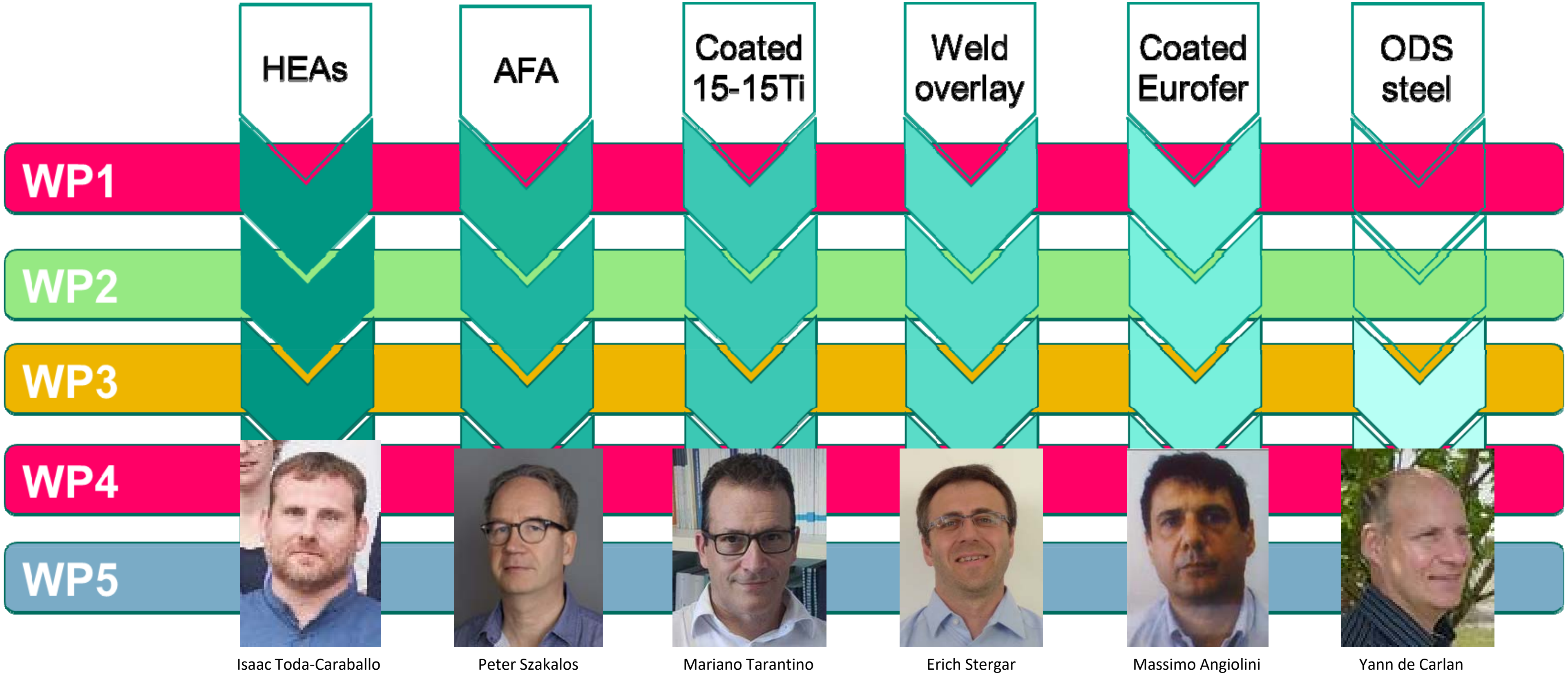
# INNUMAT – research tracks

## WPs and research tracks – matrix structure



# INNUMAT – research tracks

## WPs and research tracks – matrix structure



# INNUMAT – research tracks

**Common goals**

- Increase of technology readiness level (TRL) with respect to
  - Compatibility with coolants
  - HT mechanical behavior and thermal stability
  - Radiation tolerance
- Deep, beyond state of the art understanding of main mechanisms determining corrosion, mechanical behavior, aging, and degradation of properties due to irradiation supported by comprehensive modeling at different scales
- Use of computational and experimental high throughput methods in materials design and screening
- Establish accelerated qualification roadmaps including guidelines for standardization of SSTT, among others small punch testing (SPT)

# INNUMAT – HEAs research track

**Specific objectives**

- Develop Co-free HEAs based on the FCC CrFeMnNi system with reduced activation and irradiation induced swelling
- Explore novel BCC-HEAs with improved ductility maintaining their good HT strength, corrosion and swelling resistance
- Increase TRL to the level of industrial deployment (4-5)
- Develop computational tool to design HEA compositions for the targeted nuclear applications based on predictive advanced modelling of thermodynamic, mechanical, corrosion and irradiation properties supported by novel machine learning techniques

# INNUMAT – HEAs research track

## Approach

- Produce in the 1st year 3 *reference* HEA/CCAs of the FCC CrFeMnNi family based on existing knowledge in WP1
- Conduct comprehensive characterization and modeling on them in WP2 (corrosion), WP3 (mechanical behavior) and WP4 (radiation resistance)
- Feed the alloy design in WP1 with the results for building a consolidated modeling tool for designing *new* FCC and BCC HEAs
- Produce at the beginning of the 2nd half of the project 2-3 *new* alloys designed based on the knowledge collected so far.
- Conduct complete characterization on them in WP2, WP3, and WP4
- Use the results to further improve the computational tool for designing HEAs

# INNUMAT – consortium

INNOVATIVE STRUCTURAL MATERIALS/MATERIAL SOLUTIONS

| | HEAs | AFA | Coated 15-15Ti | Weld overlay | Coated Eurofer | ODS steel |
|---|---|---|---|---|---|---|
| | Numerical design | | Surface treatment methods | | | |
| **Development & production** | MINES, UN, CEA, CSIC, WUT, CCFE | KIT, KTH, Sandvik, UN | IIT, ENEA | KTH, SCK CEN, Sandvik, Uddcomb | IIT, ENEA | EUROfusion |
| | Advanced modelling of properties | | | | | |
| | Pb, PbBi, Molten salts | | | | PbLi | |
| **Compatibility with coolants** (corrosion & LME) | KIT, ULille, UN,CEA, CIEMAT, INCDFM, CCFE | KTH, RATEN, SCK CEN, ENEA, KIT , ULille, UN | KIT, SCK CEN, ULille | KIT, KTH, CVR, SCK CEN | CIEMAT, ENEA | |
| | Advanced modelling of properties | | Non-destructive examination | | | |
| **High temperature behavior** (creep, fatigue, thermal ageing) | Bangor, PSI, CIEMAT, VTT, JACOBS, JRC, MINES, KIPT, KIT, CSIC, HZDR, UN | PSI, CIEMAT, JRC, HZDR, CSIC, KIT, POLITO, UN | SCK CEN, ENEA, IIT, Fraunhofer, POLITO | KTH, SCK CEN, WUT, RATEN | IIT, ENEA. Fraunhofer, POLITO | HZDR, CIEMAT, CCFE, KIT, EK |
| | Advanced modelling of properties | | | | | |
| ***Radiation tolerance*** ion & neutrons microstructural & microchemical evolution - Small Punch tensile (neutron irrad.) | KIT, HZDR, CEA, CIEMAT, UR, EDF, UHEL, SCK CEN | KIT, HZDR, CEA, CIEMAT, UR, SCK CEN | IIT, CNRS, SCK CEN | SCK CEN | ENEA, IIT, SCK CEN | CEA, STUBA, PSI |
| **Qualification methodology** Small Punch micro tensile & creep | CIEMAT, KIT, HZDR, JRC, NCBJ, CCFE, VTT, WUT | CIEMAT, KIT, HZDR, JRC, NCBJ, CCFE, SCK CEN, WUT | SCK CEN, WUT | SCK CEN, WUT, CCFE | SCK CEN, WUT | CIEMAT, HZDR, CCFE, WUT |

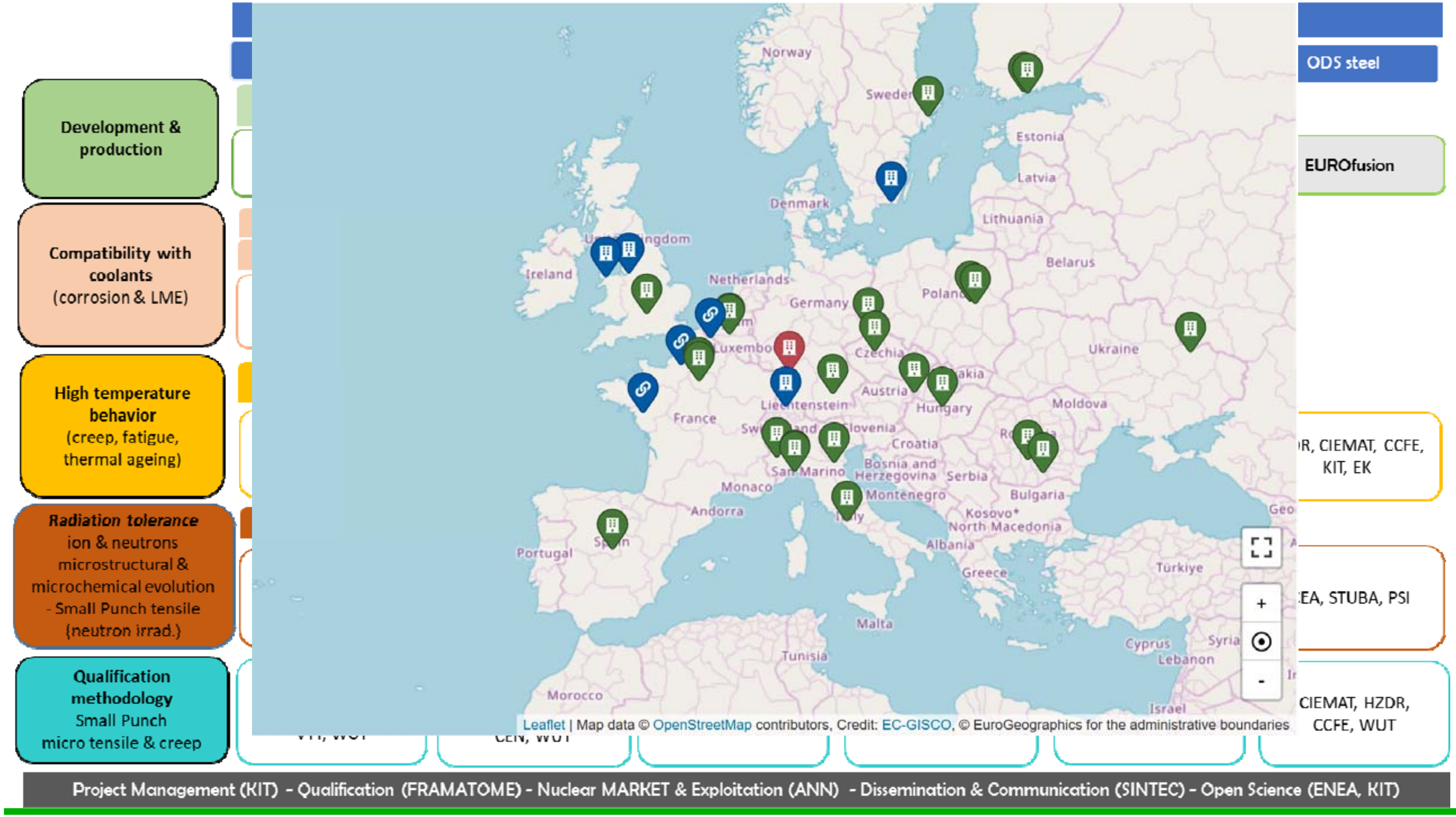
Project Management (KIT) - Qualification (FRAMATOME) - Nuclear MARKET & Exploitation (ANN) - Dissemination & Communication (SINTEC) - Open Science (ENEA, KIT)

**36** Partners from **15** countries:

- **20** Research institutions
- **9** Universities
- **7** private organizations

Collaboration with the OFFER consortium is intended.

# INNUMAT – consortium

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# INNUMAT – consortium & budget

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| | Advanced modelling of properties | | | | | |
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| Qualification methodology Small Punch micro tensile & creep | CIEMAT, KIT, HZDR, JRC, NCBJ, CCFE, VTT, WUT | CIEMAT, KIT, HZDR, JRC, NCBJ, CCFE, SCK CEN, WUT | SCK CEN, WUT | SCK CEN, WUT, CCFE | SCK CEN, WUT | CIEMAT, HZDR, CCFE, WUT |

Project Management (KIT) - Qualification (FRAMATOME) - Nuclear MARKET & Exploitation (ANN) - Dissemination & Communication (SINTEC) - Open Science (ENEA, KIT)

**36** Partners from **15** countries:

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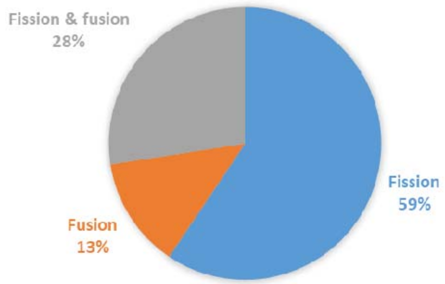
Collaboration with the OFFER consortium is intended.

Total budget: **10.953 Mio€**

Gra. EU funding: **7.816 Mio€** (75% fission & 25% fusion)

**45** deliverables & **21** milestones



# INNUMAT – certified labelling

## CERTIFICATE
## SNETP LABEL

Date of certificate issuance: *24/09/2021*
Certificate number: *2021ESN0016*

The SNETP Scientific Committee during its meeting held on *24 September 2021* awarded the SNETP Label to the project idea identified as **INNovative strUctural MATerials for fission and fusion** (INNUMAT) with the technical content reviewed and published through SOIP.

Signed for and on behalf of the SNETP Scientific Committee.

SNETP LABEL

**SNETP AISBL**
Avenue des Arts, 53
1000 Brussels – Belgium
VAT N° : BE 0843 497 746
Company Registration: 0843 497 746
secretariat@snetp.eu

SNETP
Sustainable Nuclear Energy Technology Platform

EERA European Energy Research Alliance
Coordinating energy research for a low carbon Europe

## **Certificate of EERA Consortium**

The EERA Joint Programme on NUCLEAR MATERIALS (JPNM) hereby certifies that the research project proposal described below has been developed by a consortium involving EERA members in accordance with its own vision and rules.

The procedure for accepting project proposals developed as part of this EERA Joint Programme on NUCLEAR MATERIALS is described apart. It has been approved by the Steering Committee of the JPNM and acknowledged by the EERA Operative Executive Committee (ExCoOp), which implies a **total endorsement of the EERA AISBL**.

Being in accordance with these rules, the proposal will **substantially contribute to meet the research targets set in the research agenda of this Joint Programme and support the EU SET-Plan objectives**.

On successful evaluation, the project will be allowed and obliged to use the EERA JPNM logo in all communications.

**Acronym of the project proposal:** **INNUMAT**

**Name of the project proposal: "INNovative strUctural MATerials for fission and fusion"**

**Responsible person from the EERA Joint Programme, involved in the proposal:**

**Name: Jarir AKTAA**

**Organization: KIT**

**Role in the project proposal: Coordinator**

**On behalf of the Joint Programme Management Board, the Joint Programme coordinator**

**Name: Lorenzo MALERBA**

**Organization: CIEMAT**

**Date: 30 September 2021**

Signed by MALERBA LORENZO - X1142174V on 30/09/2021 with a certificate issued by AC FNMT Usuarios

**Signature:**

EERA is an official part of the EU SET-Plan.
http://setis.ec.europa.eu/
With the support of

# Thanks of your attention!