FISA 2019
9th European Commission Conference on EURATOM Research and Training in Safety of Reactor Systems
4-7 June 2019
Pitesti, Romania

Innovative Gen-II/III and Research Reactors' Fuels and Materials

FISA 2019 Session II – Safety of Nuclear Installations

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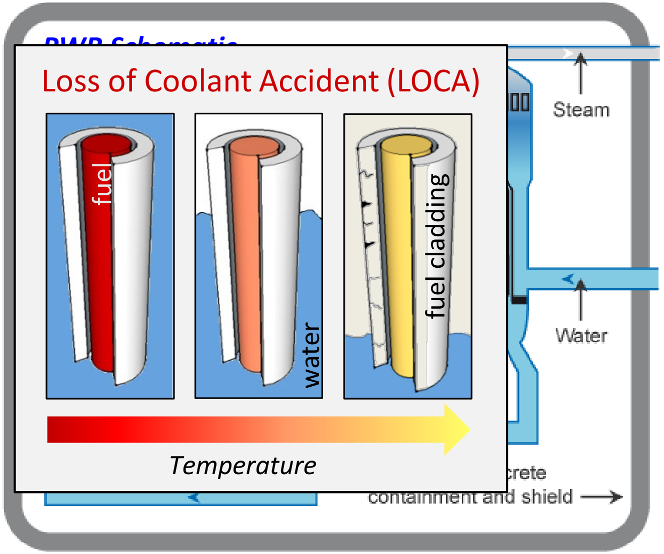
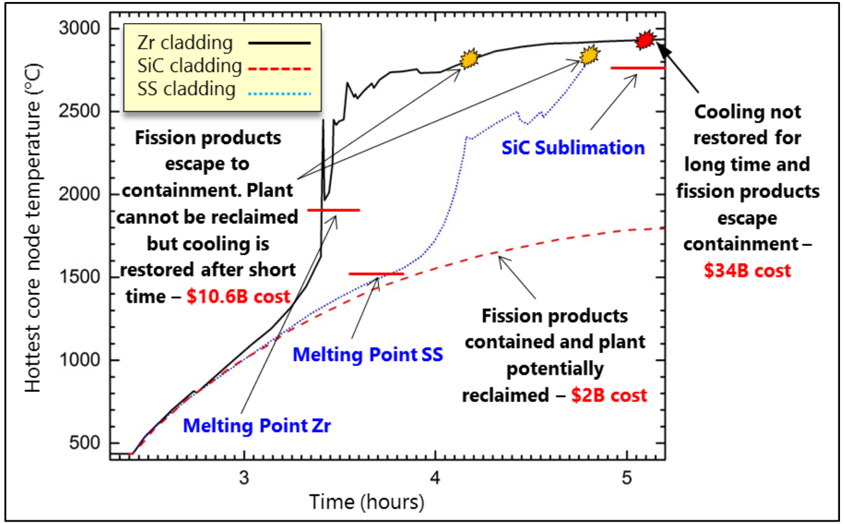
European studies to prevent structural material failures in reactors

- **IL TROVATORE** EU Project focuses on new fuel cladding materials, able to resist the **very high temperatures** which are achieved during the Loss Of Coolant Accident of a PWR Reactor.
- The goal of FP7 project **MULTIMETAL** was to collect and analyse relevant information from the field experience and tests on dissimilar metal welds as typical location of **brittle fracture**.
- In liquid metal cooled fast reactors, besides the high temperature and the brittle rupture, also **corrosion attack** has to be considered. The **MATTER** EU Project addressed all these failure causes (and others…).
- Corrosion and high temperature are also considered as the most relevant failure causes for the Supercritical Water Reactor. In **SCWR-FQP** the best performing materials for fuel clads and core structures were selected.

H2020 IL TROVATORE – Problem Setting

PWR = Pressurised water reactor





(E. Lahoda et al., Paper #10231, ANS 2014 Annual Meeting)

- Loss of coolant accident (LOCA)
- Exothermic Zr-based clad/water reactions → fuel cladding failure
- Release of fission products to power plant containment
- Release of hydrogen & possible hydrogen explosion
- Escape of radioactive fission products beyond site boundary
- Power plant loss & high remediation cost of surrounding area
- ❖ Severe societal & environmental impact!

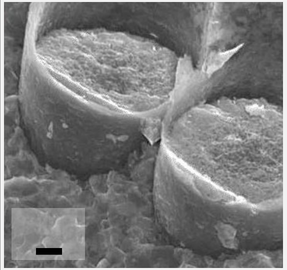
➢ Accident-tolerant fuel (ATF) clads must outperform Zr-based commercial clads during:

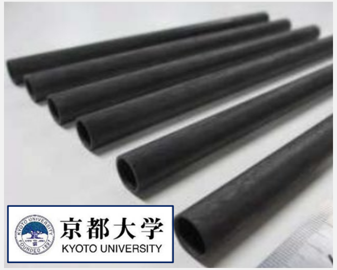
- nominal operation conditions
- design-basis transients (<1200°C)
- beyond-design-basis accidents (>1200°C)

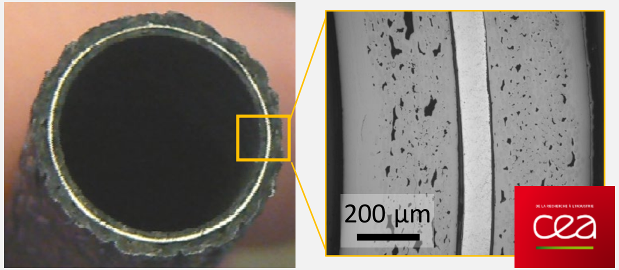
H2020 IL TROVATORE – Introduction

- **H2020 IL TROVATORE objective:** Help addressing the global societal & industrial need for **improved nuclear energy safety** in the post-Fukushima era by validating select ATF cladding material concepts **in an industrially relevant environment** (i.e., under neutron irradiation in PWR-like water)
- Candidate ATF Cladding Material Concepts:

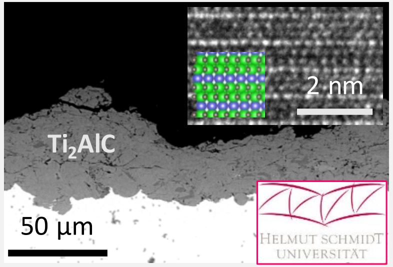
SiC/SiC Composite Clads

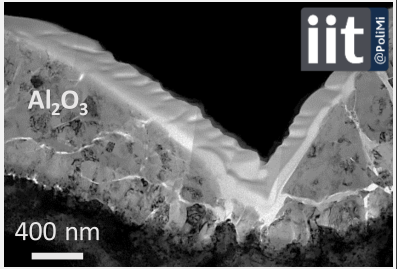






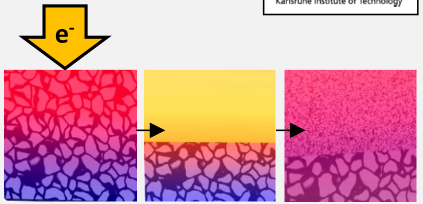
Coated & Surface-Modified Clads



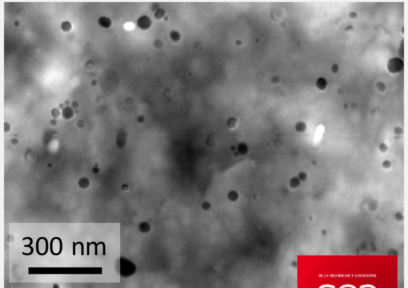


GESA Clad Surface Modification

FeCrAl-coated DIN 1.4970 SS



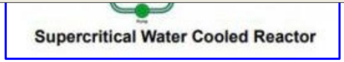
ODS-FeCrAl Clads



H2020 IL TROVATORE – Expected Impact

Expected H2020 IL TROVATORE Impact

- The strong cross-cutting character of the IL TROVATORE R&D activities can give results with strong potential impact on both Gen-II/III LWRs & Gen-IV systems, such as Gen-IV LFRs, Gen-IV GFRs, etc., as well as fusion
- Non-nuclear industrial sectors, e.g., aerospace, concentrated solar power (CSP), etc., are expected to benefit as well
- Exploitation of project results is expected to help industrial competitiveness in Europe & globally
- New products & processes, patents, standards, accelerated development of nuclear materials & tools to achieve it, e.g., ion/proton irradiation guidelines
- Open Research Data Pilot, open access publications, …
- Education & training of young scientists, new skills & competences, new jobs, …
- If successful in its quest, it will increase nuclear energy acceptance by general public
- More widespread, safer nuclear energy will help the reduction of greenhouse gas emissions → indirect environmental protection



➤ Education ... 20...

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HORIZON 2020 THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION

IL TROVATORE

INNOVATIVE CLADDING MATERIALS FOR ADVANCED ACCIDENT-TOLERANT ENERGY SYSTEMS

IL TROVATORE

Research and Innovation Action

Call Identifier: NFRP-2016-2017

Topic Identifier: NFRP-1 – Continually Improving Safety and Reliability of Generation II and III Reactors

Grant Agreement Number: 740415

Project Starting Date: 2017-10-01 | Project Duration: 54 Months

D12.3

Workshop on MAX Phases for Harsh Environments

Authors: T. Cabioc'h (UP), S. Dubois (UP), K. Lambrinou (SCK•CEN)

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 740415.

FP7 MULTIMETAL – Introduction

FP7 MULTIMETAL (Structural performance of multi-metal component)

- FP7 MULTIMETAL (Grant Agreement ID: 295968) – 01/02/12 to 31/01/15
- EU contribution: 1 683 480,98 €
- Coordinator: VTT, Finland – FP7 MULTIMETAL involved 8 beneficiaries

➢ FP7 MULTIMETAL objectives:

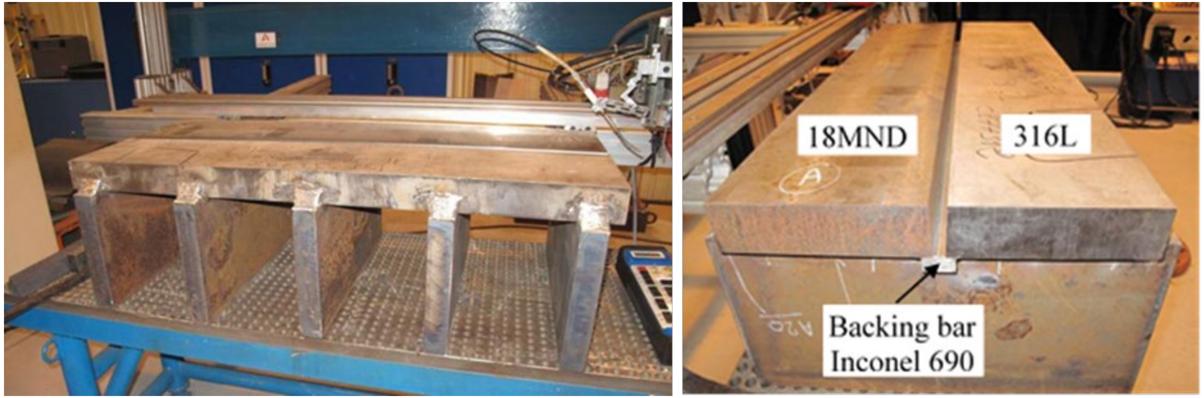
- Collect relevant information from field experience on dissimilar metal welds (DMWs) in both Western & Eastern light water reactors (LWRs)
- Augment current numerical methods for structural integrity assessment of DMWs, considering ageing-related phenomena and realistic stress distributions in the weld area
- Support modelling activities by a comprehensive material test program
- Develop a test procedure for measuring the fracture toughness of DMWs
- Provide recommendations for a best-practice approach to assess the integrity of DMWs, as part of overall integrity analyses and leak-before-break (LBB) procedures

FP7 MULTIMETAL – Main Achievements

SEVENTH FRAMEWORK PROGRAMME

Several weld mock-ups:

- In all mock-ups, the base metals were ferritic and austenitic stainless steels, while the type of groove, welding parameters and filler materials made the difference



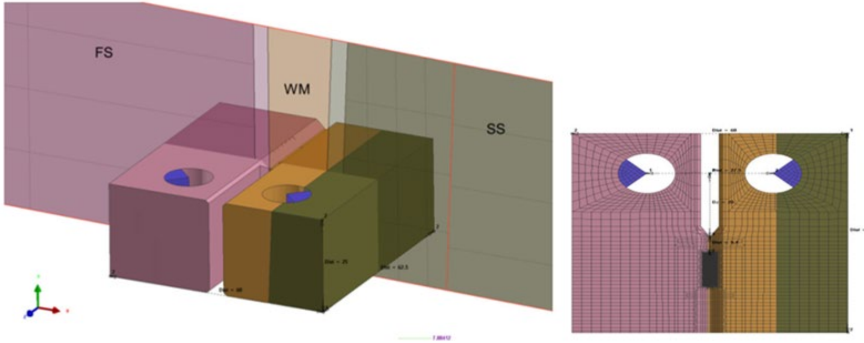
Mock-up 1 (MU1) provided by AREVA-NP

- The four mock-ups, named MU1 (Ni base filler material), MU2a, MU2b (austenitic stainless filler material) and MU3 (austenitic stainless filler material with enriched Ni content), were used for material characterization and property benchmarking

FP7 MULTIMETAL – Conclusions & Outlook

➢ **Conclusions:**

- Characterization of local tensile properties is a key issue for analyzing the toughness tests and test on mock-ups
- The use of CT specimens (subsized, if necessary) is recommended for toughness determination of DMWs; for SEN(B) specimens, rotation correction should be applied
- The use of ASTM 1820 is recommended to assess the fracture toughness of DMWs; the notch must be located at the DMW fusion line



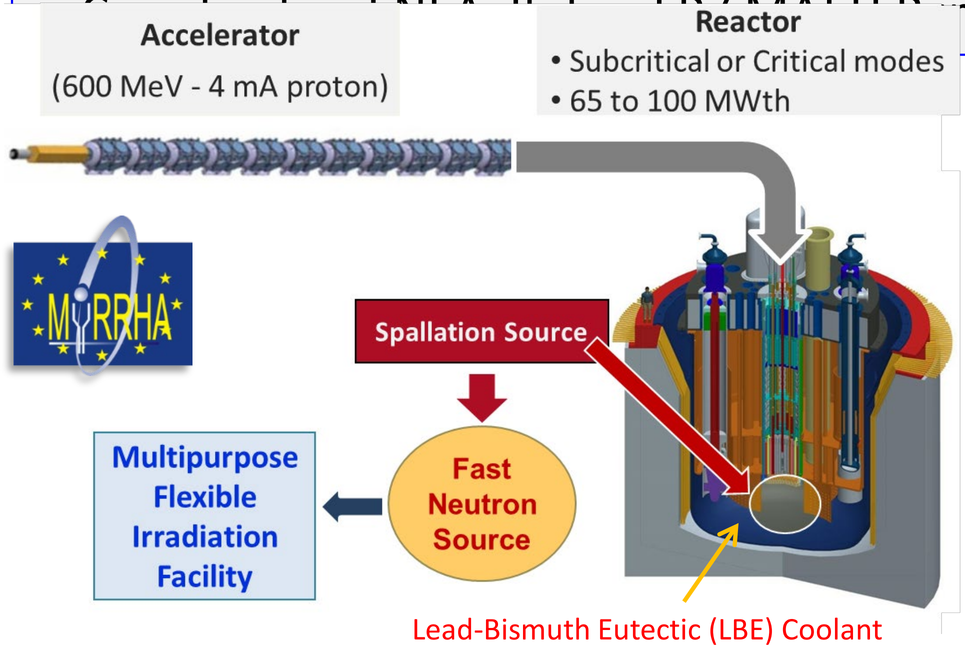
Position & meshing of CT25 specimen (MU1)

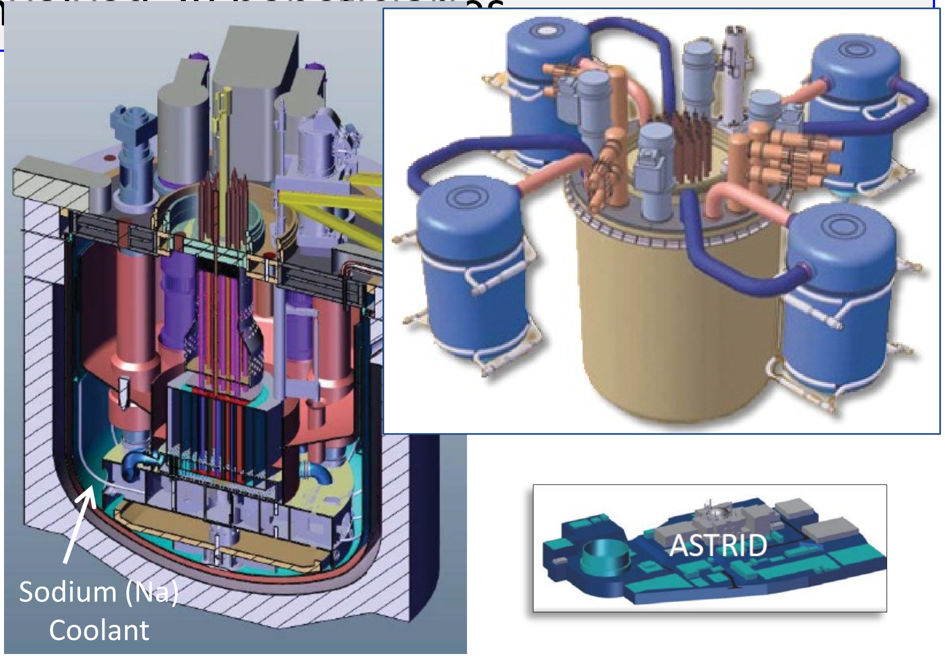
➢ **Recommendations for future work:**

- Improve guidelines for fracture toughness testing of DMWs
- Develop guidelines for applying local approaches of ductile tearing
- Develop an exemption criterion for not considering residual stresses in the fracture analysis of DMWs, on the basis of the resistance to ductile tearing and the expected level of residual stresses acting on the crack

FP7 MATTER objective:

- Materials-oriented design research for ESNII (European Sustainable Nuclear Industrial Initiative) reactors, esp. for accelerator-driven (ADS) systems MYRRHA and ASTRID

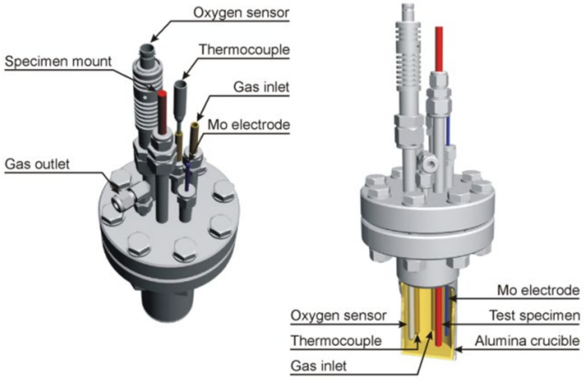


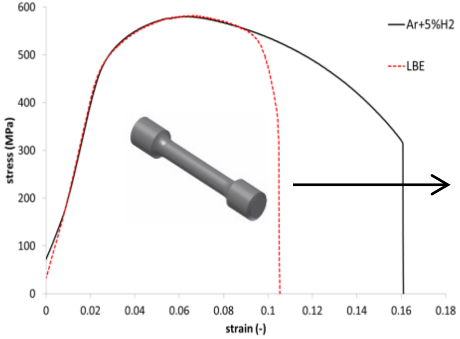


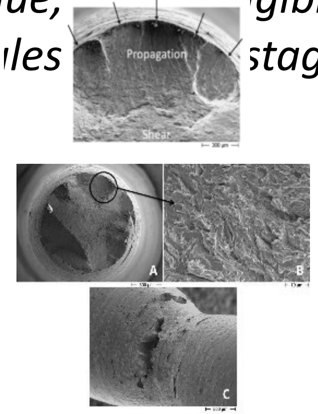
FP7 MATTER – Main Achievements

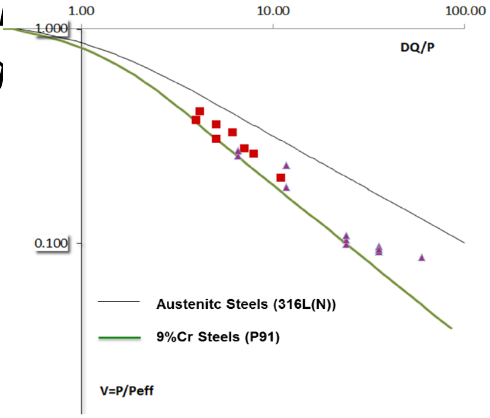
➢ FP7 MATTER achievements:

- Development of guidelines and standardized setup for more adequate heavy liquid metal (HLM) corrosion testing
- Experimental demonstration of liquid metal embrittlement of P91 by pre-wetting with HLM
- Recommendations for design rules of grade 91 ferritic/martensitic (f/m) steels regarding ratchetting, creep/fatigue, negligible creep, and weld coefficients
- *The proposed design rules for ratcheting, creep-fatigue, ... les ... stag*





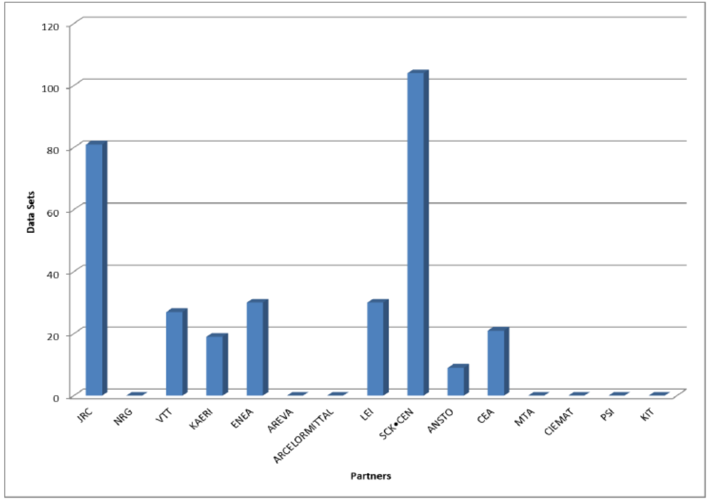




New efficiency diagram proposed for P91 and 9%Cr steels.

FP7 MATTER – Dissemination/Capitalization of Knowledge

- Experimental and scientific data were stored on MatDB repository at https://odin.jrc.ec.europa.eu (JRC)
- Workshops and Summer Schools:
  - Workshop on “Key material properties for MYRRHA and Astrid” – Rome, March 2012
  - International School on Materials UNder Extreme COnditions (MUNECO) – Madrid, June 2012
  - International school on DEsign Rules for Gen-IV Reactors and INnovative reactors (DERIVIN) – Saclay, June 2013
- 10 industries participated as project partners
- 9 PhD theses were supported within the project
- Special issue of Journal of Nuclear Materials on MATTER Project (J. Nuclear Materials **472** 2016)
- Frequent contacts with AFCEN through CEA
- Project deliverables stored in EERA-JPNM website



Partner contributions in MATTER database

FP7 MATTER – Conclusions & Further R&D Activities

- The most immediate and visible outputs of FP7 MATTER were the exclusion of grade 91 f/m steels from the MYRRHA project and the downgrade of the same steel for the ASTRID heat exchangers. These decisions were dictated by:
  - the proven steel susceptibility to liquid metal embrittlement (only for MYRRHA)
  - the unpredictable behavior of welded joints, and
  - the poor steel fatigue resistance
- Persistent doubts on the chemical compatibility of grade 91 steels with heavy liquid metals have triggered R&D initiatives towards more reliable candidate materials, namely:
  - the further development of certain ODS steel types, although extensively studied in FP7 MATTER
  - the development of austenitic materials resistant to HLM corrosion, and
  - the development of protective coatings against HLM corrosion
- The awareness of the insufficient knowledge on the corrosion mechanisms caused by liquid metals has triggered the necessity to develop a set of models able to allow design engineers to predict the corrosive behavior of both f/m and austenitic steels

➢ *Most of FP7 MATTER outputs have been taken up in H2020 GEMMA*

FP7 SCWR-FQT – Introduction

FP7 SCWR-FQT (Supercritical water reactor-fuel qualification test)

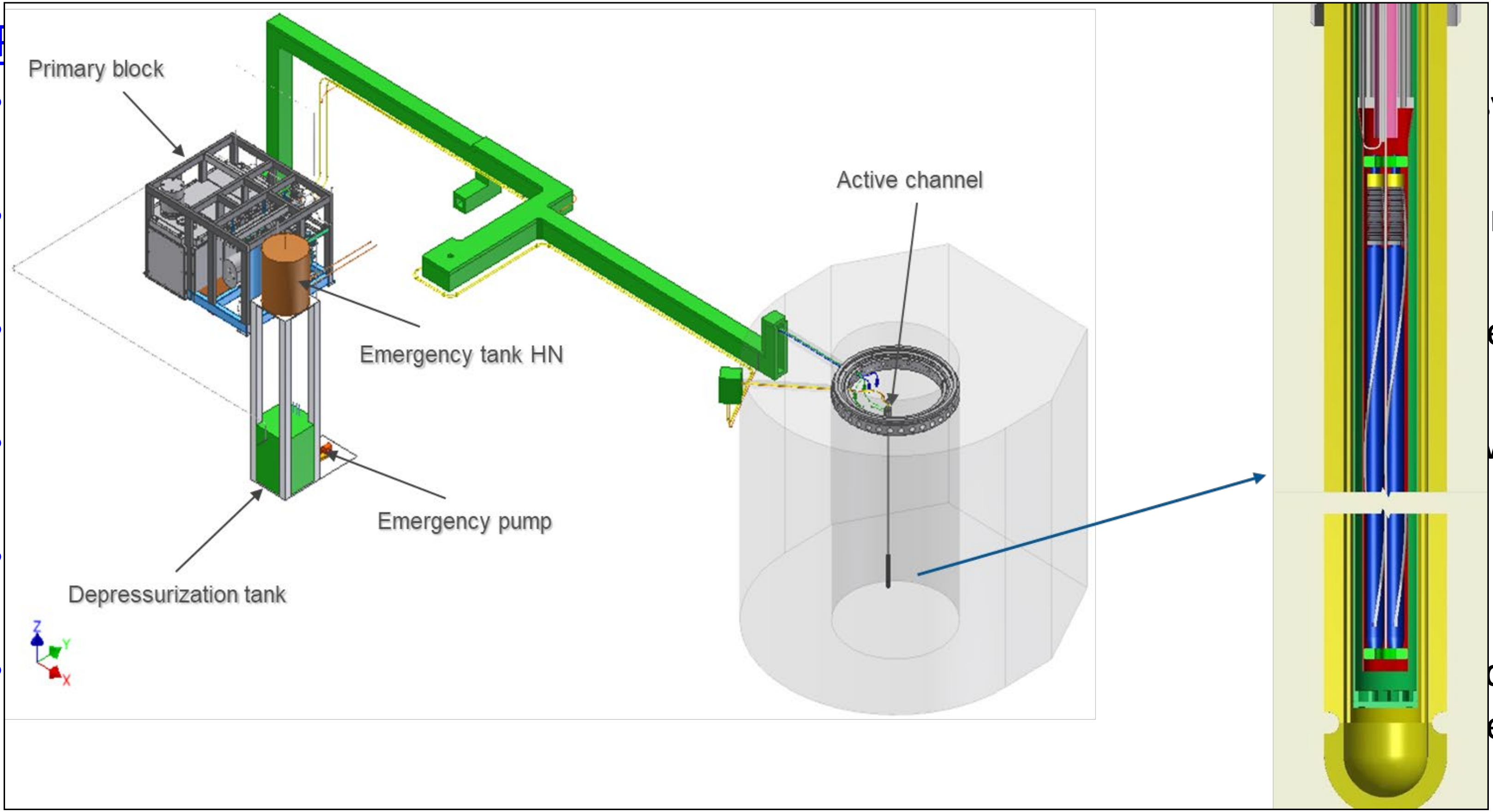
- FP7 SCWR-FQT (Grant Agreement ID: 269908) – 01/01/11 to 31/12/14
- EU contribution: 1 500 000 €
- Coordinator: CV Rez, Czech Republic – FP7 SCWR-FQT involved 7 beneficiaries

- FP7 SCWR-FQT was a collaborative project between Euratom (7 partners) and China (9 partners) (i.e., the parallel Chinese project SCRIPT). The Chinese Consortium collaborated on thermal-hydraulic steady-state and safety analyses, neutronic and structural analyses, and contributed with the out-of-pile test of the electrically heated test section in the SWAMUP facility.

➢ Main technical challenges of FP7 SCWR-FQT:
  - predictions of heat transfer
  - choice of materials for fuel and core structures
  - the largest uncertainties are expected in the evaporator where the coolant passes through the pseudo-critical point, i.e., in the region with the highest heat flux (heat transfer deterioration, temperature peaks)

FP7 SCWR-FQT – Objectives

➢ FF



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FP7 SCWR-FQT – Main Achievements

- Temperature distr
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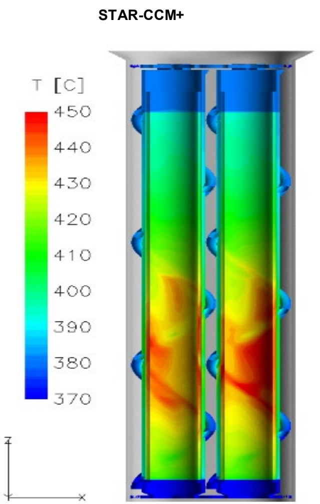
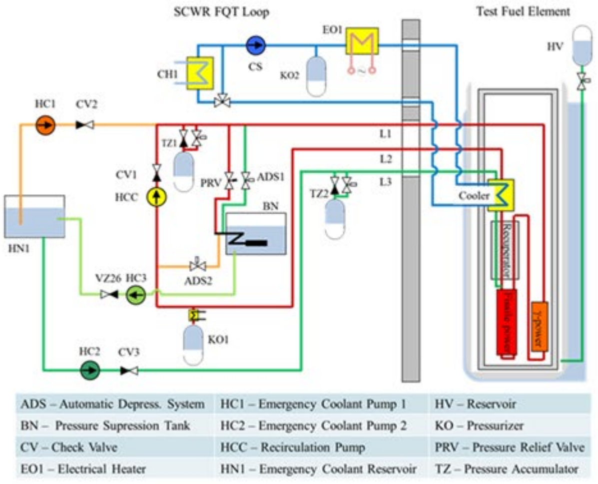
  (ANSYS CFX) resul
- Peak fuel cladding

- Passive/active safety systems design

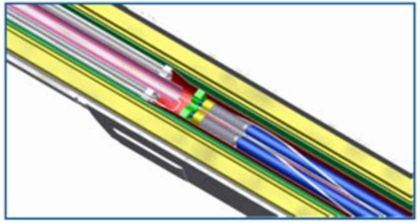
Active safety systems:	Passive safety systems:
Emergency Line Coolant Injection (ELCI) Feedwater Line Coolant Injection (FLCI)	Bladder accumulators TZ1 and TZ2 Insulation Gap Flooding System (IGFS)



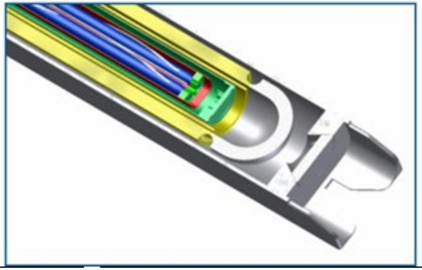
mean $T_{rod\text{-}in}$ = 419 °C
max $T_{rod\text{-}in}$ < 462 °C



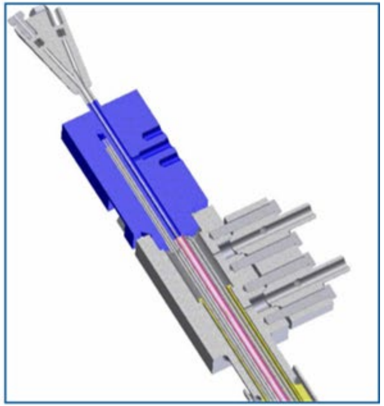
Emergency cooling line:



Insulation gap (displacer):



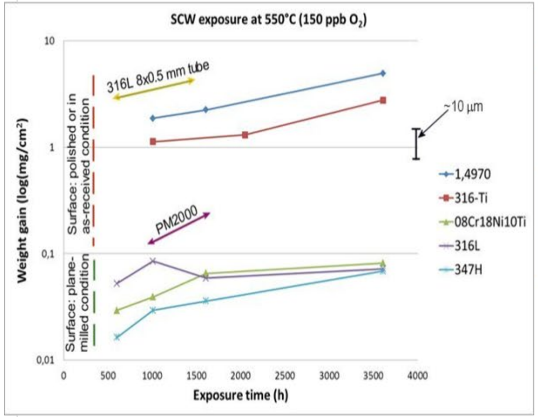
Feedwater lines:



FP7 SCWR-FQT – Main Achievements

- The 316L stainless steel was sel

550°C, 150 ppb O_2



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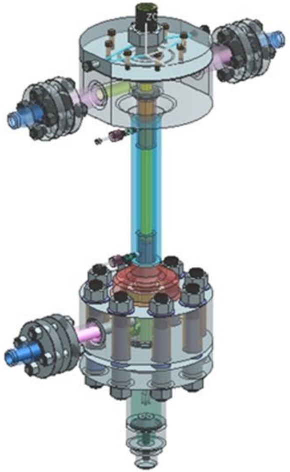
- Out-of-pile (electrically heated) validation experiment

二层平台

一层平台



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CONCLUSIONS

- The four presented EU Projects deal with material studies aimed to enhance the safety of nuclear reactors.
- IL TROVATORE (still ongoing) is focused on fuel claddings able to survive to very high temperature of PWR LOCA accident. The new or modified cladding materials are intended to replace the present ones.
- In MULTIMETAL a lot of experimental information was collected from running reactors and from new tests in order to optimize fabrication of bimetallic welds which are potentially prone to rupture.
- MATTER has evidenced important issues of F/M steel in harsh liquid metal environment. The results determined some exclusions and triggered further well targeted researches.
- SCWR-FQT identified the best performing materials in terms of «weight loss» due to high thermal flux conditions encountered in the evaporator of the Supercritical Water Reactor