GROWING SYNERGIES BETWEEN FISSION AND FUSION RESEARCH TOWARDS DEMONSTRATION PLANTS

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Introduction

The **scope** of this lecture is to identify common technologies developed in both Fusion and Fission Reactors to promote synergetic R&D programs. **In the last years**, several **platforms** have identified cross-cutting activities between fission and fusion projects in particular in the frame **of structural materials** and several research programs were developed by NUGENIA, EERA-JPNM, OECD-NEA and IAEA.

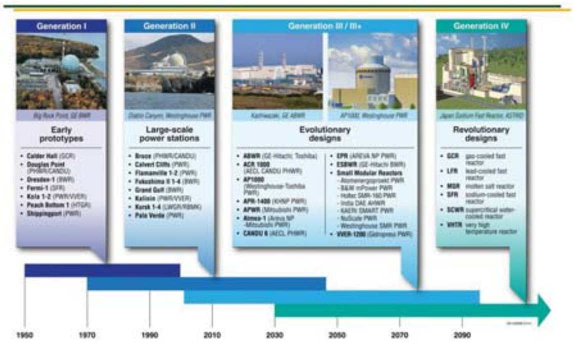
In the frame of **ORIENT-NM** project, possible collaborations were explored with international organisations, standardization, safety and data/knowledge management bodies involving different stakeholders. In particular, the task 4.3 of the project intends to secure complementarity, consistency and commonalities on research between the **EUROfusion roadmap** and the **Europea Joint Program (EJP)** SRA, thereby identifying possible **cross-cutting projects**.

Introduction

Fission Power Plant Reactor

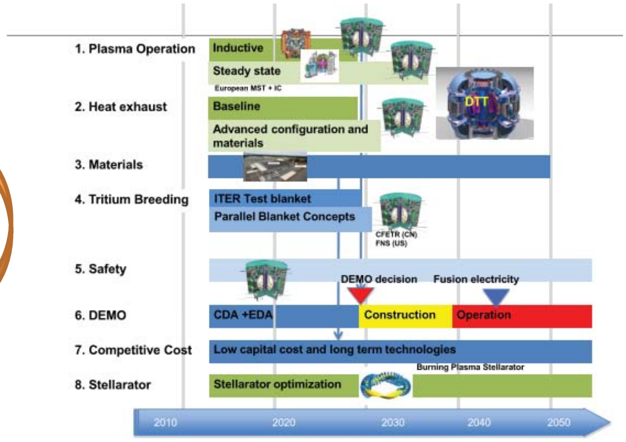
Fission Roadmap will be able to demonstrate:

- ❑ Short term: SMR-oriented features aimed at being a competitive option for the future Nuclear Power Plants
- ❑ Middle-term: potentialities to demonstrate that the LMFR/GFR large scale reactors can meet the goals set out by GIF for Generation-IV reactors.



Fusion Reactor

In a longer term, fusion has the potential to provide the baseload energy production needed to provide electricity to final users.



Synergies between Fission and Fusion R&D

A common program considers developing core technologies of coolants and auxiliary systems, evaluate structural issues, set-up a collective database for Engineering Design and share knowledge about manufacturing, technologies and codes used. The added value of interacting with **EUROfusion** is also that it is an EJP with **established QA, Engineering & Technology schemes**, the knowledge of which will be beneficial for the design of the future EJP.

Among the possible R&D program identified to grow up synergies, particular attention has to be dedicated to some open technical issues:

- ❑ **Mitigation strategies to protect materials from the aggressive environment**
- ❑ The experience and knowledge developed for **the tritium extraction system** of fission reactors can find application to fusion reactor for Water-Cooled-Lithium-Lead (WCLL) and Helium-Cooled-Pebble-Beds (HCPB) BB concepts
- ❑ Liquid **metal chemistry control** of LMFR and WCLL BB concepts of EUROPEAN DEMO Reactor
- ❑ **Liquid metal pumping system**
- ❑ **Facilities and Instrumentation**: the experience and knowledge gained in the design and operation of experimental facilities supporting liquid metal fast reactor development can be transferred to fusion reactors and vice versa.

Protective coating

Mitigation strategies to protect materials from the aggressive environment in the coolant for fast Fission reactors and Fusion Reactor: WCLL and HCPB Breeding Blanket concepts.

	Fission Coating	Fusion Coating
Function	▪ Protect materials from the aggressive environment: corrosion, erosion, LME	▪ Protect materials from the aggressive environment: corrosion, erosion ▪ Avoid tritium permeation ▪ Electrical isolation of structural materials
Loads	▪ Neutron Flux up to 100dpa ▪ Temperature up to 800°C ▪ Environments: Pb/PbBi/He/Na/H_2O	▪ Neutron Flux up to 80dpa, up to 2.010+14 (n/cm2/s) ▪ Temperature up to 550°C ▪ Environments: PbLi/He/H_2O
Materials	▪ Substrate: **AISI 316L/15-15Ti /AISI 300 series** ▪ Al2O3/ FeCrAl diff. coating, AlTiN / AFA steel	▪ Substrate: **EUROFER** ▪ Al2O3/ Multilayer
Manufacturing process	▪ PLD, ALD, Diffusion/Detonation gun/ pack cementation	▪ PLD, ALD, ECX, Packed cementation

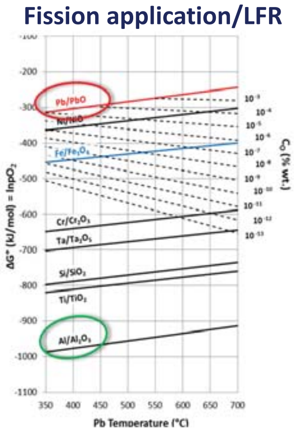
Protective coating

Experience and knowledge gained in the coating processes development can be transferred to fusion reactors and vice versa by the identification of:

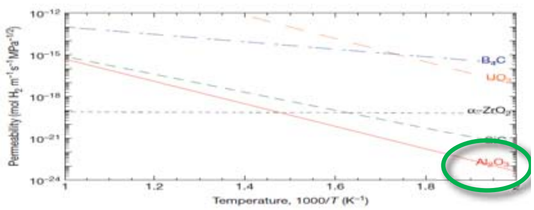
- ❑ common **coating materials** with relevant TRL: Al2O3;
- ❑ common manufacturing process: Pulsed Laser Deposition and packed cementation processes;
- ❑ common characterisation program:
  - ➢ Mechanical characterisation in Liquid Metal
  - ➢ **Irradiation program**
  - ➢ coating manufacturing

The final scope is to Demonstrate the possibility to manufacture suitable coating at relevant scale characterized at relevant operative conditions

Fission application/LFR

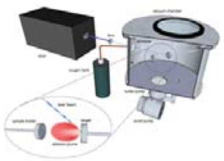


Fusion application



Protective coating

Al2O3 coating developed by Pulsed Laser Deposition (PLD)



In the *PLD* a high-power pulsed laser beam is focused inside a vacuum chamber to strike a target of the material (EUROFER/AISI). Al is vaporized from the target and as result, a high homogeneous layer of alumina is deposited.

Property @RT	Sapphire	PLD Al_2O_3	AISI 316L
v	0,24	0,295 ± 0,025	0,3
E [GPa]	345	193,8 ± 9,9	200
G [GPa]	175	75,5 ± 3,8	80
B [GPa]	240	159,2 ± 11,8	140
H [GPa]	27,8	10,3 ± 1	4
H/E	0,059	0,049 ± 0,007	0,025

Breeding Blanket Project in EUROfusion

Upgraded PLD facility

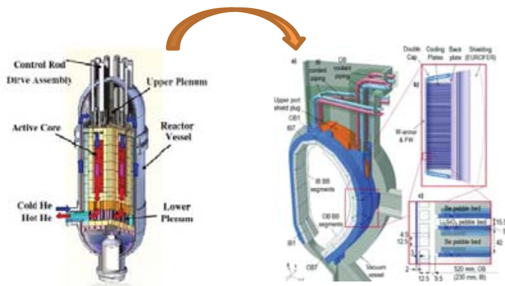
TRANSAT
TRANSversal Actions for Tritium

1" tube - 300 mm long AISI 316L coated with α - AL2O3 - 3 μm

- PLD coating investigated in the frame of Fission (**TRANSAT project**) and Fusion program (**FP8-BB EUROFUSION**): compatibility with the coolant, tritium permeations, scale up of the facility
- Coating behavior and Tritium transport proprieties has to be further investigated with the support of experimental device and **numerical tools (dynamic molecular code)** that can play an important role to support the design of system.

Tritium purification in fission and fusion reactors

- The process most widely used for the tritium removal in the Coolant Purification Systems (CPSs) of **High Temperature Gas Reactors (HTGRs)** considers the oxidation of Q_2 (Q = H, D, T) into Q_2O, in high temperature copper oxide beds, and the following adsorption of the generated tritiated water in molecular sieve beds, at room temperature.
- This process has been also proposed for the CPS of **ITER and DEMO** Test Blanket Module (TBM), in the configuration **Helium Cooled Pebble Bed (HCPB)**. Also in this case, the purification of helium from tritium foresees two steps:
  - oxidation of Q_2 into Q_2O, using copper oxide beds (Q = H, D, T);
  - removal of Q_2O from He, using molecular sieves.



G-IV HTGRs

DEMO-HCPB BB

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- In fusion reactors, the CPS has also the scope to transform the removed tritium in a suitable form for the final extraction systems. In ITER, Reducing Beds (RBs), based on use of metallic alloys, are the reference technology to transform the Q_2O trapped inside the molecular sieve beds in Q_2, which will be directed to the downstream tritium processing systems.

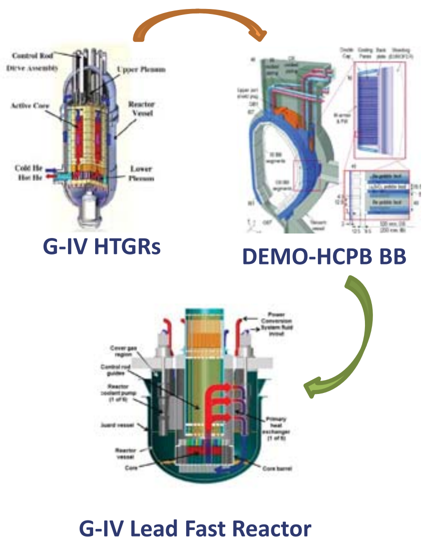
HYDREX Experimental Facility

- ❑ HYDREX (HYDRogen EXtraction) is an experimental facility, located in ENEA Brasimone Research Centre, having the scope to test processes, components and materials considered of interest for tritium extraction/purification from helium and for the purification systems of the cover gas of liquid metal cooled fast reactors.
- ❑ The performances of different types of molecular sieves, included in a PTSA column, can be studied in conditions characterized by different temperatures and pressures.
- ❑ The trapped water, released during the regeneration of the molecular sieves, can be directed to a RB, in which the performances for the reduction of H_2O into H_2 of the selected metallic getter can be studied.

HYDREX Experimental Facility

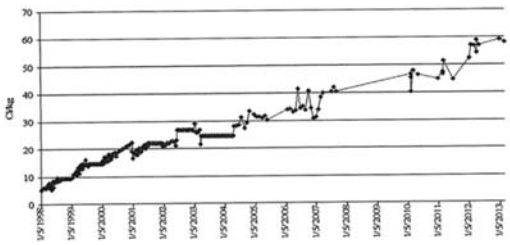
Tritium purification in GEN IV reactors

- ❑ Among the technologies selected by Generation IV International Forum (GIF) as the most interesting for the development of the future fission reactors, two are liquid metal fast reactors: Sodium Fast Reactors (SFRs) and Lead-cooled Fast Reactors (LFRs).
- ❑ In the past, the tritium concentration in the primary cover gas of SFRs using steam generators was considered very low, due to the efficiency of the cold traps for tritium removal; for this reason no dedicated device for tritium removal was considered necessary.
- ❑ However, to reduce the release of tritium in the environment at a level as low as reasonably achievable, it is necessary to consider also for SFRs the treatment of the cover gas.
- ❑ Because no significant interaction is expected between hydrogen isotopes and lead, the cold traps used for tritium purification in SFRs seem not effective for LFRs and, consequently, the treatment of the cover gas is required.
- ❑ The reference process for tritium purification considered in HTGRs and in HCPB TBM of fusion reactors can be taken into account also for the treatment of the cover gas in liquid metal fast reactors.



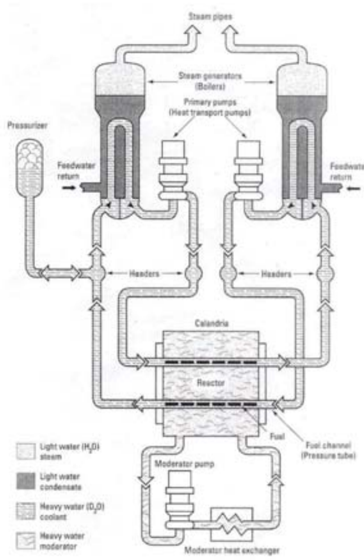
Water Detritiation Systems

- Heavy Water Reactors (HWR) use D_2O as neutron moderator and reactor coolant due to the very small absorption cross section for thermal neutrons compared to light water
- In HWR, tritium is directly generated from neutron absorption (even if it is small) by the deuterium atoms in heavy water; therefore the coolant and moderator will be contaminated with tritium
- In a CANDU 600 NPP, the HW inventory is >450,000 kg divided between moderator and coolant. The growth of tritium activity in the moderator of NPP Cernavoda Unit 1 is shown in figure.



Babcock & Wilcox Canada – Cernavoda Steam Generators Design - Project No. 7505/7506.

→ Adoption of **Water Detritiation System (WDS)**



The experience and knowledge developed for the tritium extraction system of CANDU reactors can find application to fusion reactors Breeding Blanket (BB) concepts

Fusion reactors WDS

The general procedure to recover tritium from water foresees two processes:

- **front-end process** in which the tritium is transferred from the aqueous into a hydrogen gas stream (several processes available: direct electrolysis, CECE, LPCE, VPCE)
- **back-end process** for the separation of the hydrogen isotopologues (cryogenic distillation)

Current WDS for CANDU reactors manage water flow rates up to 360 kg h^{-1} (Darlington Tritium Removal Facility DTRF). Tritiated water is processed off-line.

Darlington Tritium Removal Facility

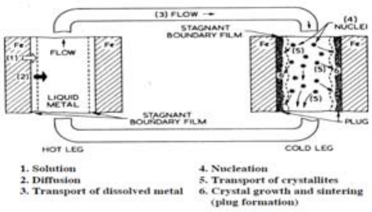
ITER, CFETR and DEMO WDS:

- **ITER WDS** is based on **CANDU WDS** design. It will process a flow rate of 20 kg h^{-1} adopting as front-end process the Combined Electrolysis and Catalytic Exchange (CECE)
- **Chinese Fusion Engineering Test Reactor (CFETR)** WDS will be based on CECE process. It will process around 500 kg h^{-1} for water-cooled BB.
- **DEMO WDS** in the case of WCLL BB must process few thousands kg h^{-1} to ensure, without anti-permeation barriers, a tritium concentration in the coolant below 1.85×10^{11} Bq kg^{-1}

In the case of DEMO, from a technological point of view, a process able to decontaminate such large amount of tritiated water is very energy consuming. → Tritium permeation should be reduced with permeation barriers

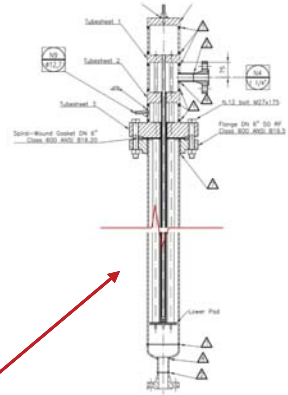
Liquid Metal chemistry

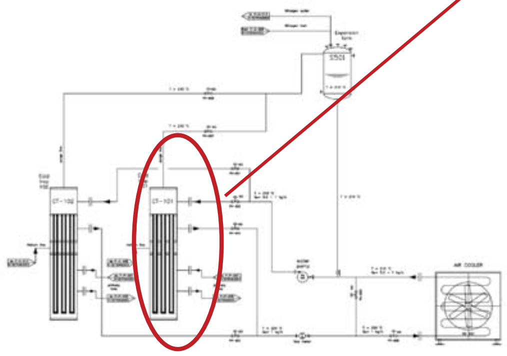
- ❑ Due to the extreme operating condition of Lead cooled fast reactor (GEN IV- Fission) and LiPb loop for the WCLL blanket (Fusion), corrosion and corrosion product transport phenomena constitute strong limitations for the loop safety (**material corrosion**, **plugging phenomena** and **region with high concentration of activated materials**).
- ❑ A system devoted to remove the corrosion product was developed in the frame of WCLL BB. The ***Cold Trap*** system consists of a heat and mass transfer device, where a **supersaturated solution of impurities is generated** as the result of the primary fluid cooling, causing the **crystallization of the impurities both on the immovable surfaces and in suspension**.

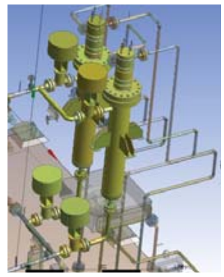


$$C_{Fe}^{S} = e^{\left(a-\frac{b}{T}\right)}$$

C_{Fe}^{S} Fe saturation concentration in LM (kg/m3)







Pumping systems for Liquid metals

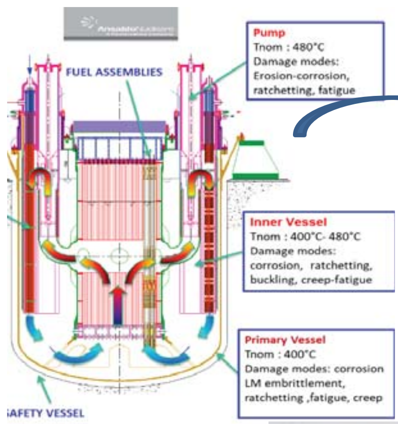
To manage liquid metal flow in the range 50-400kg/s dedicated pumping system was designed and qualified in the frame of Gen-IV LMFR. The design proposed was adapted to PbLi loop of WCLL BB Fusion reactor, based on **mechanical pump with magnetic coupling** technologies:

- ❑ **Mechanical centrifugal pump**, was considered the most promising solution due to the high efficiency (η=60%) in comparison with the electromagnetic pumps (η in the range 15-20%)
- ❑ **Magnetic coupling electrical motor with pump shaft**.

The main design parameters are:

- Rotational speed: **1000 rpm** (for outboard); 750 rpm (for inboard)
- Efficiency Electric motor estimated: 90 kW 6Poles.

Fission Gen-IV LMFR

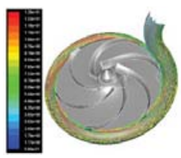


WCLL – BB DEMO

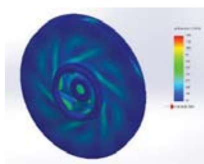
operating parameters of the pump

	Q	H
	[m³/h]	[m]
PLP	30.4	30.0
BEP	72.9	15.0

Impeller Velocity profile



Von Mises stress on impeller



Pumping systems for experimental facilities

Facility name	Fluid/ Application	Type of pump	Max. Flow Rate [kg/s]	Head [bar]	Working T [°C]	Operating Time [h]
LECOR	LBE/Fission	Vertical centrifugal	10.9	5	300	12,000
CHEOPE III	Pb/Fission	Vertical centrifugal	2.7	3	420	10,000
LIFUS II	PbLi/Fusion	Vertical centrifugal	5.4	4	300	25,000
RELA III	PbLi/Fusion	Vertical centrifugal	1.0	3	300	1,000
LECOR upgrade	Pb/Fission	Vertical centrifugal	27.2	5	500	3,000
TRIEX	PbLi/Fusion	Vertical centrifugal	1.5	2.5	530	3,000
HELENA	Pb/Fission	Horizontal centrifugal	100	3.5	480	1,000
CIRCE	LBE/Fission	Axial mechanical	81.7	1.5	500	new
TRIEX-II	PbLi/Fusion	Permanent magnet	4.9	4	530	2,500
IELLLO	PbLi/Fusion	Permanent magnet	2.5	3	400	5,000

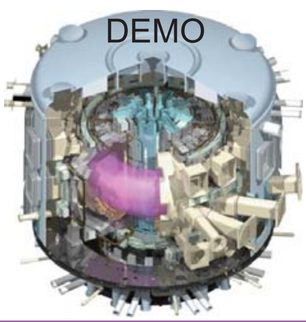
Gen-IV LFR and Fusion Experimental facilities

Experimental Facilities for Fast Reactors: IAEA database

Research Platform

- CIRCE
- NACIE
- LIFUS-5
- HELENA
- RACHEL
- PLACE
- ATHENA
- CHEMLAB
- ....

https://www.iaea.org/newscenter/news/new-iaea-database-to-support-advanced-fast-reactors-development-and-deployment



Experimental Facilities for Fusion Reactors: database is missing

- HE-FUS3
- HYDREX
- BREST
- IELLLO
- PERI-II
- PLD device
- APRIL
- ....

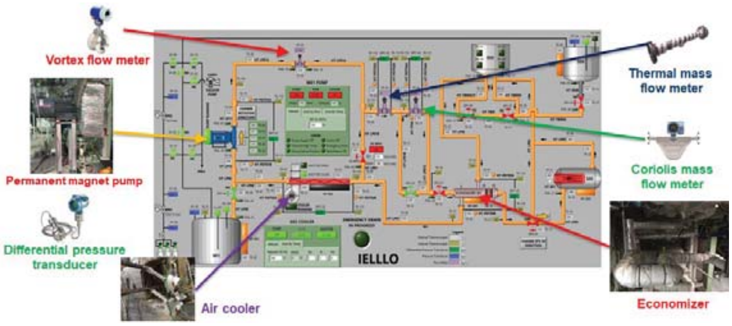
Research Platform

Instrumentation

Instrumentation plays a key role in the operation, control and management of Fusion and Fission reactors, thus the experience and knowledge gained in the design and operation of experimental facilities supporting liquid metal fast reactor development can be transferred to fusion reactors and vice versa.

Instrumentation developed for Gen-IV LFR Research facilities can be adopted to Fusion power plant, as:

- ❑ LM Mass flow meter
- ❑ LM Pressure meter
- ❑ Temperature sensors
- ❑ LM Level meter
- ❑ Neutron flux



Criteria
Measurement range (max)
Measurement range (typical)
Long term stability
Accuracy
Repeatability
Interchangeability
Tip sensitivity
Signal strength
Excitation
Cost
Noise problems
Extension cable
Best for
Worst for
Hysteresis
Self-heating

CONCLUSION

In order to growing synergies between fission and fusion research towards demonstration plants it is necessary to:

- ❑ Consider core technologies of coolants and auxiliary systems, evaluate structural issues, set-up a collective database for: Engineering Design, infrastructure, experimental facilities, instrumentations with focus on possible synergies between Gen-IV and Fusion power plant application.
- ❑ share knowledge about development and manufacturing of technologies and codes used.
- ❑ Create synergies among research Teams in order to promote exchange of knowledge and experience.

THANK YOU