

The ENEA logo features the word "ENEA" in a bold, white, sans-serif font. To the left of the text is a stylized graphic of a sun or starburst with rays emanating from it, set against a dark blue background with a grid pattern.

AGENZIA NAZIONALE
PER LE NUOVE TECNOLOGIE, L'ENERGIA
E LO SVILUPPO ECONOMICO SOSTENIBILE

Workshop MATISSE

Compatibility of structural materials under high temperature thermal flux with Helium Cooling System for Fusion Reactor and Coolant Purification System.

M. Utili (ENEA Brasimone)

marco.utili@enea.it

ENEA Brasimone

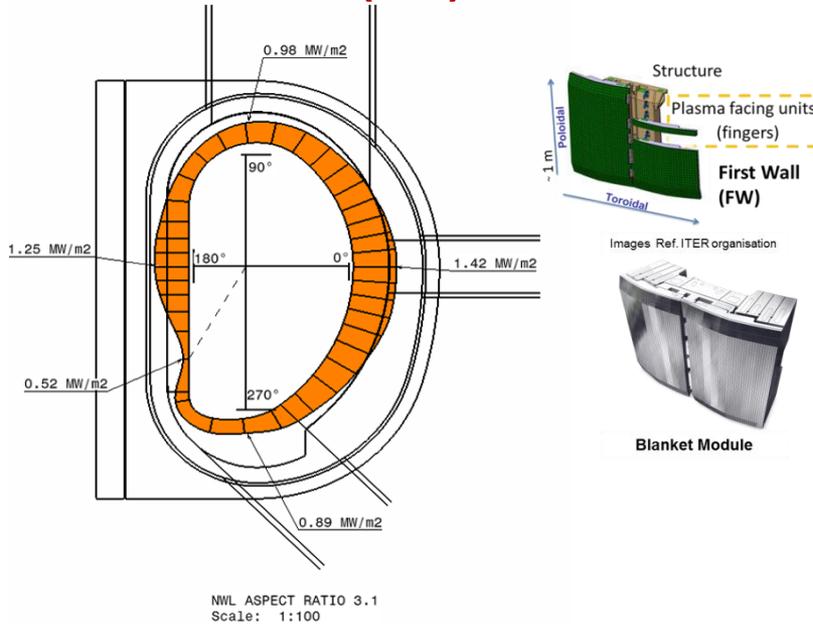
■ Scope

With the aim to promote a closer integration of research efforts between fission and fusion research communities in the domain of research on material properties for high temperature Reactor the following topics will be discussed:

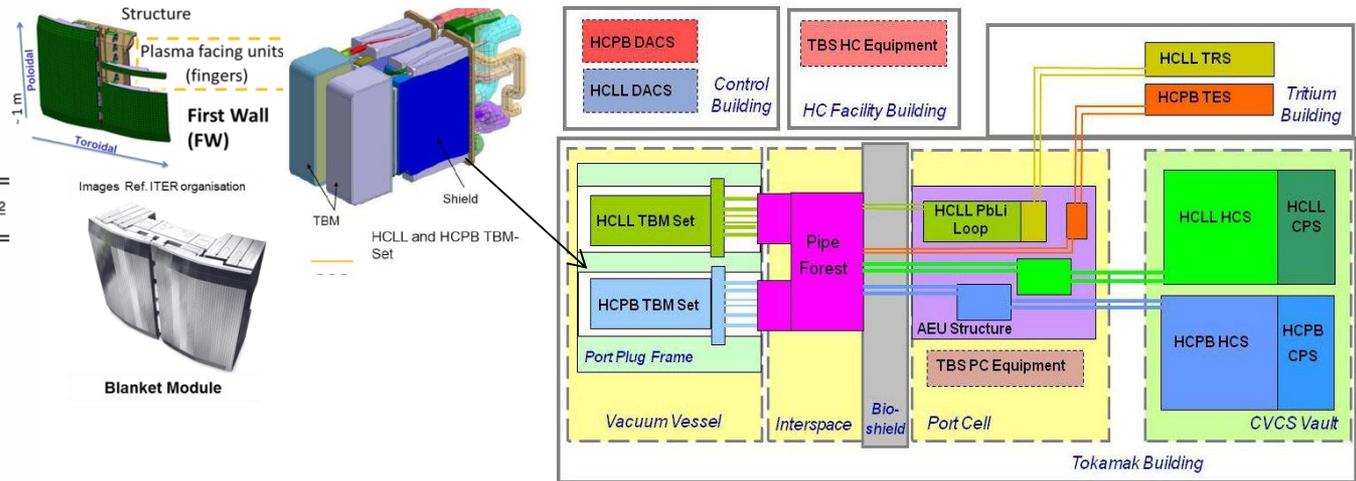
- Helium cooling system of ITER and DEMO and Coolant Purification System;
- Candidate material/system used to remove the high thermal flux with Helium cooling system;
- Experimental activities carried out in ENEA for the design of Helium cooling system of ITER and DEMO

Fusion Technologies - Helium systems in FUSION Reactor

First Wall (FW)



Breeder Blanket - Auxiliary Systems



- ❑ 0.5-1.2 MW/m² nominal surface heat flux
- ❑ Volumetric heat load is 10 MW/m³
- ❑ 14.1 MeV neutron flux
- ❑ Candidate Material: tungsten, Beryllium, EUROFER (martensitic steel)

- ❑ Helium Cooling System (Tmax 550° C, P 80bar)

- ❑ Coolant Purification System (T 20-300° C, P 80bar)

- ❑ Tritium Extraction System (T 550° C, P 8bar)

- ❑ Lead Lithium Loop (T 450° C, P 8bar)

Steel Composition

% wt	C	Cr	Mo	Mn	W	V	Si	Nb	Fe	density (g/cm ³)
EUROFER 97	0.1	8.8	0.003	0.44	1.15	0.2	0.05	0.002	89.3	7.8

The Helium Cooling System for both European TBM concepts (HCLL and HCPB) has the role to Remove the heating power from TBM of ITER, HCLL/HCPB/DCLL Breeder Blanket concepts of DEMO

The Coolant Purification System, for both the European TBM, has the role to extract the permeated tritium from the primary circuit and impurities from He, keeping controlled chemistry.

TBS present two main differences with respect to gas fission reactors:

- carbon based impurities in HCS are lower, due to the absence of a graphite based core;
- the temperature of the coolant is much lower, so we have a lower corrosion rate of the HCS structural materials

Instead, the FW of the Divertor works at high temperature (up to 1000° C) and pressure 80bar.

GFR - Gas Fast Reactor

GFR fuel cladding operative conditions

Temperature	<ul style="list-style-type: none"> • Normal: 600-1000°C • Incidental 1600°C • Accidental: 2000°C
Irradiation dose	<ul style="list-style-type: none"> • ≈ 80 dpa (in SiC) at EOL
Stresses (hoop)	<ul style="list-style-type: none"> • < 100 MPa (desired) at EOL
Coolant	<ul style="list-style-type: none"> • Impure He at ≥ 70m/s

Clad structural and functional requirements

600-1000 °C 2700 EPFD	Ensuring heat transfer, leak tightness and structural integrity
Up to 1600° A few hours	Retaining fission gas
Up to 2000°C < 1 hour	Keeping safe core geometry enabling cooling-down

SiCf/SiC for GFR fuel cladding



TLR	1	2	3	4	5	6	7	8	9
TLR function	Technology Down-Selection		Final Selection & Integration		Full Scale Integrated Testing		Full-Scale Demonstration		
Development phase	Clad Candidate Pre-Selection		Concept Definition & Feasibility		Design Improvement & Evaluation		Qualification & Demonstration		
Achievement									

completed SP3 on SiCf/SiC for GFR fuel cladding will work there

- Proof-of-concept feasibility study
- Design improvement

V-alloys for SFR/GFR fuel cladding

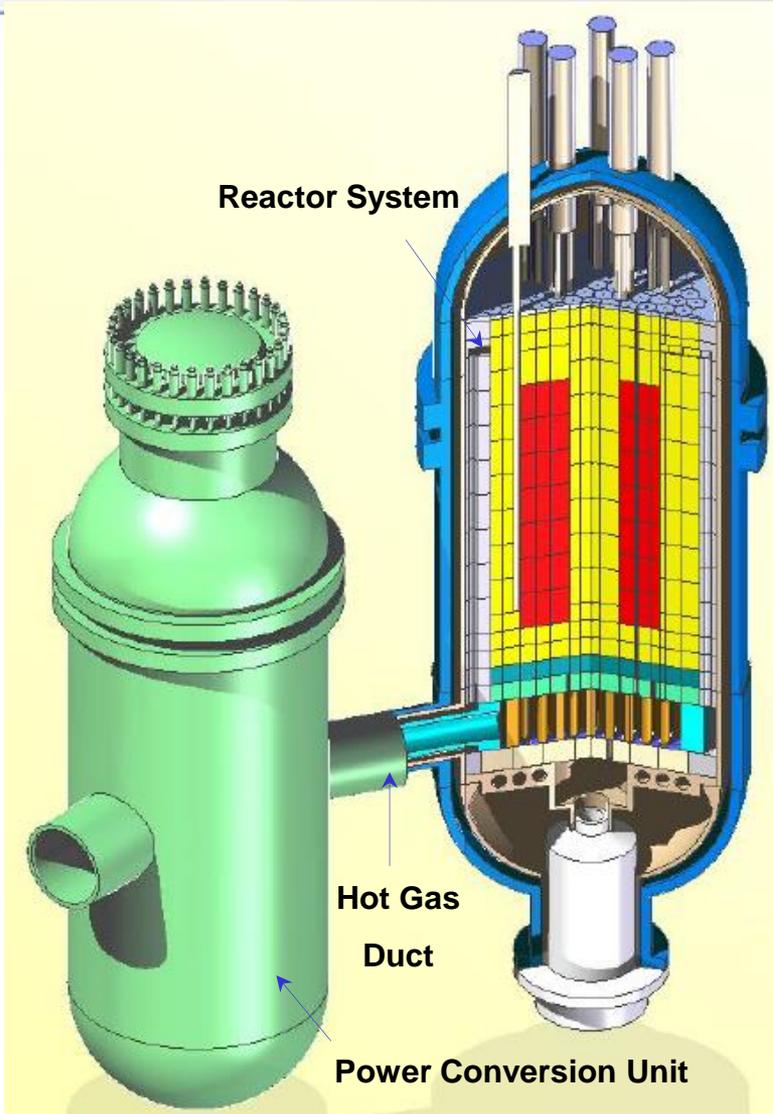


TLR	1	2	3	4	5	6	7	8	9
TLR function	Technology Down-Selection		Final Selection & Integration		Full Scale Integrated Testing		Full-Scale Demonstration		
Development phase	Clad Candidate Pre-Selection		Concept Definition & Feasibility		Design Improvement & Evaluation		Qualification & Demonstration		
Achievement									

completed SP3 on V-alloys for fuel cladding will work there

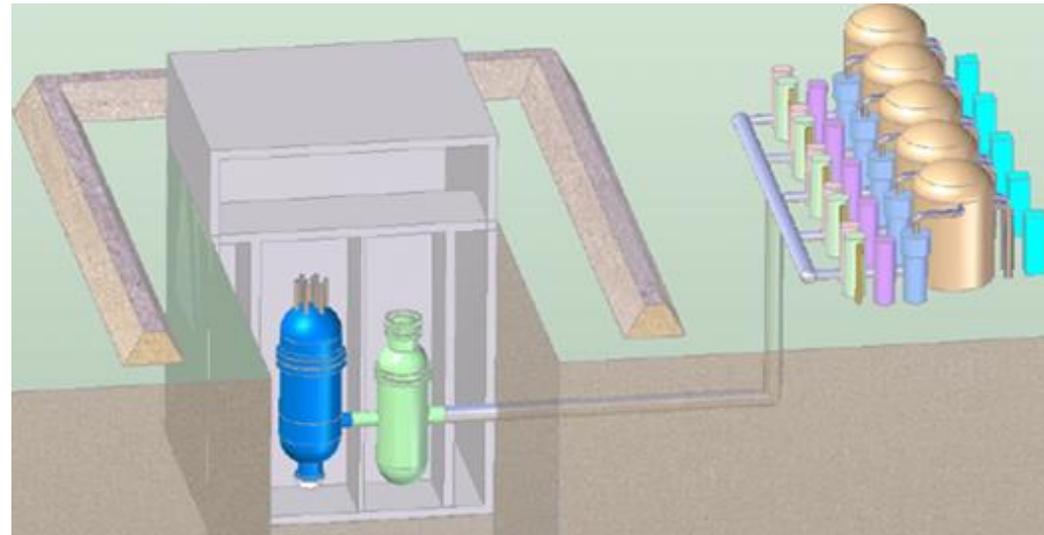
- Proof-of-concept feasibility study
- Design improvement

VHTR (Very High Temperature Reactor)



Configuration of NHDD (KAERI)

- 200 MW_t (VHTR)
- High T. (950°C), High P.(7MPa)
- NHDD : Nuclear Hydrogen Development and Demonstration



HE-FUS 3 – HCS system

HE-FUS 3 loop has a closed eight-shaped arrangement, supplying the helium flow to the a experimental Test Section connected to the plant.

The activity of the HE-FUS3 facility is to perform experimental test campaigns on thermal-mechanics and thermal-hydraulics, both in normal and off normal conditions, in support to the HCBP DEMO Blanket design. The loop was designed to operate at the following operative modes:

- 1. Long term isothermal cooling flow;**
- 2. Slow thermal cycling flow;**
- 3. Fast cold thermal shock flow;**
- 4. LOCA/LOFA**

- Max T: 500 ° C
- Max P: 8 MPa
- Max He mass flow-rate: 1.4 kg/s
- Total Installed power: 1.5 MW
- Max heating removal capacity: 1.3 MW



HE-FUS 3 DESIGN CONDITIONS

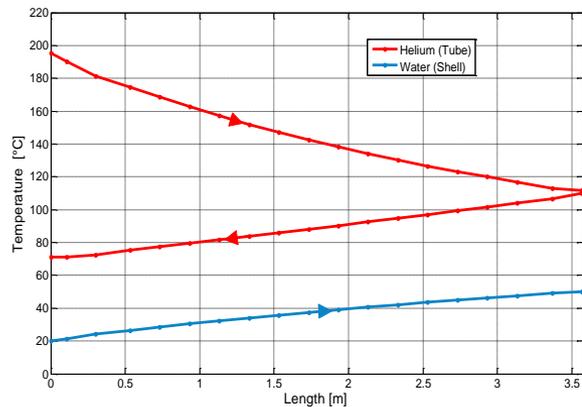
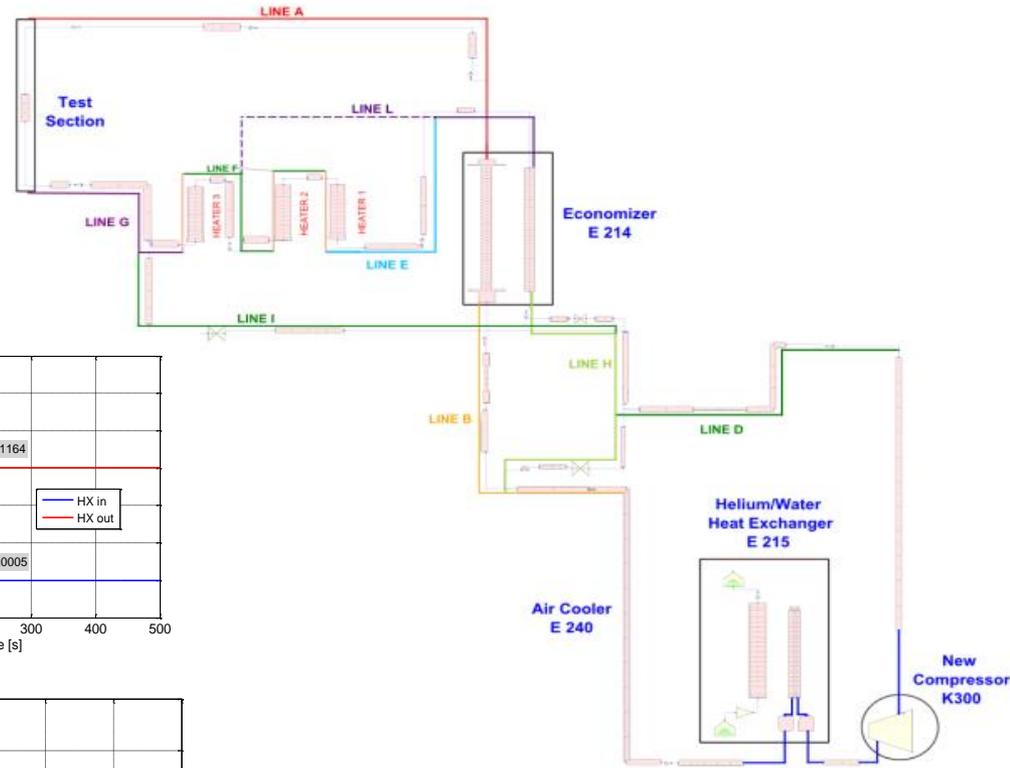


DESIGN PRESSURE	10.5 MPa	
DESIGN TEMPERATURE	530 ° C	
OUTLET TEMP. TO TEST SECTION	530 ° C	
INLET TEMP. TO COMPRESSOR	100 ° C	
COMPRESSOR HELIUM FLOW RATE	0.05-0.35 kg/s	<i>0.2-1.4 kg/s</i>
MAX COMPRESSOR SPEED	16.000 rpm	<i>40000 rpm</i>
HEATERS ELECTRICAL POWER	210 kW	
ECONOMISER THERMAL POWER	564 kW	
AIR COOLER THERMAL POWER	280 kW	
HELIUM TANK CAPACITY	3 m ³	
NEW ELECTRICAL POWER		<i>1000 kW</i>
HELIUM/WATER EXCHANGER THERMAL POWER		<i>900 kW</i>

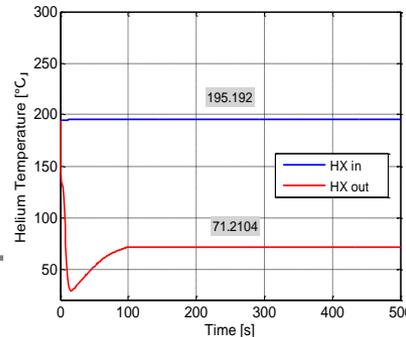
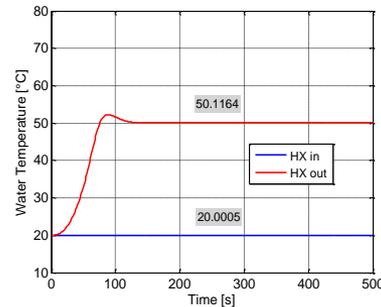
Modelling of HCS system

From a RELAP5 nodalization of HE-FUS3 facility, created to simulate a previous loop configuration, an updated model of the new configuration loop has been developed using RELAP5-3D code, as illustrated in Figure.

HE-FUS3 was qualified to perform tests simulating off-normal LOCA/LOFA accidental conditions on the HCPB/HCLL Blanket mock-up

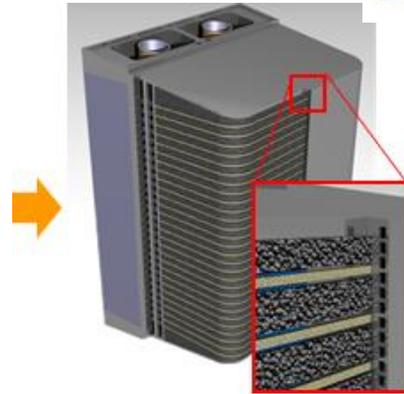
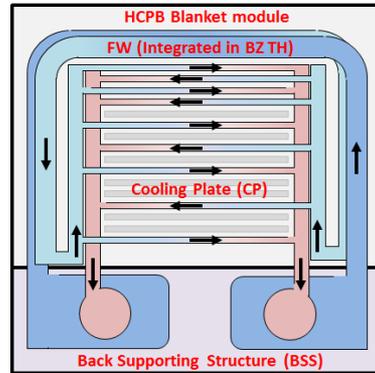


Helium (U-tubes side) and Water (shell side) temperature profile along the HX E215 active length.

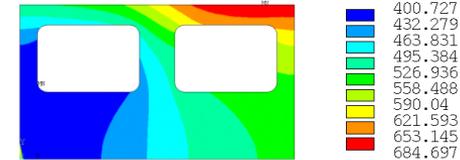


stationary state

Experimental activities performed



Breeding Blanket Project



- ❑ **HELICHETTA** represents a portion of a single breeder cell made in stainless steel AISI 316, anticipating further tests on martensitic steel structure, for starting the thermomechanical tests on breeder prismatic cell at high temperature ($< 840^{\circ} \text{C}$) and at different mechanical constraints.
- ❑ **HELICA (HE-FUS3 Lithium Cassette)** reproduces a single breeder Lithiate pebble bed cell (Li_4SiO_4 and Li_2TiO_3), to check the feasibility of the test section design, the related fabrication techniques of martensitic steel (T 91) structure and the reliability of large flat electrical heaters.
- ❑ **HEXCALIBER (HE-FUS3 Experimental Cassette of Lithium Beryllium Pebble Beds)** reproduces a medium scale portion of the HCPB module with a martensitic steel (T91) structure, with two Lithiate ceramic breeder cells and two Beryllium pebble beds cells, heated by couples of flat electrical heaters.
- ❑ **HETS (High Efficiency Thermal Shield)** Reproduces the cooling Divertor system of DEMO

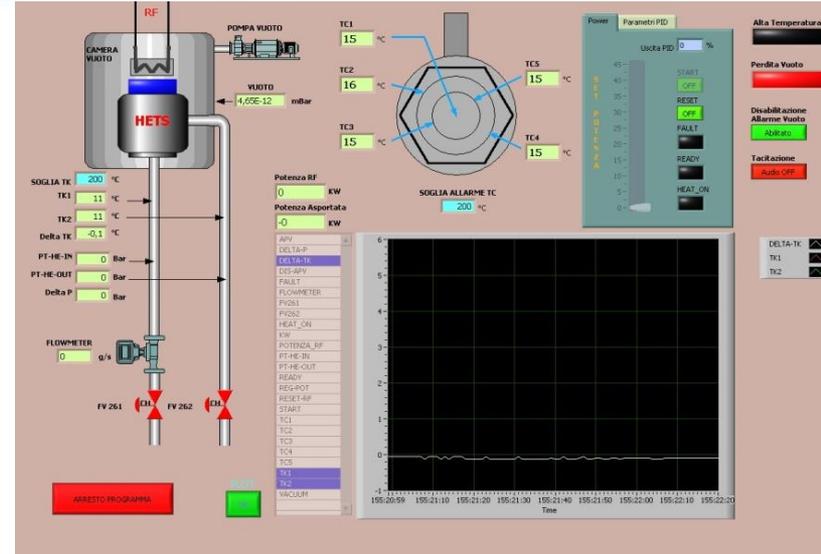
- ❑ The incident heat flux was obtained by a RF inducting equipment coupled to an inductor coil installed just over the HETS.



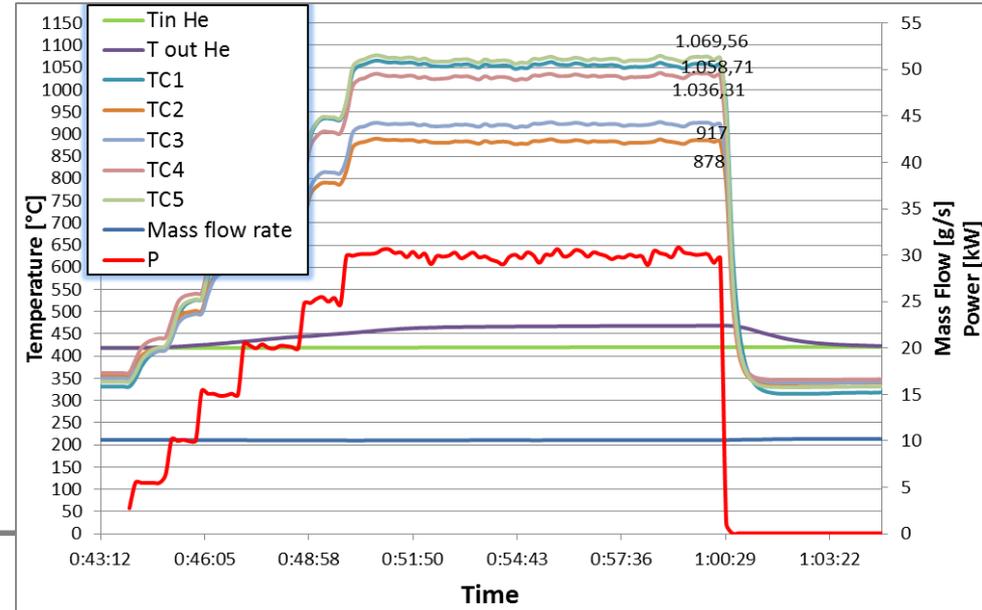
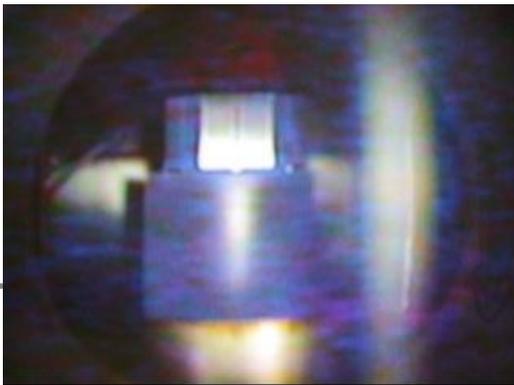
Testing vacuum chamber with HETS module installed

RF heater equipment

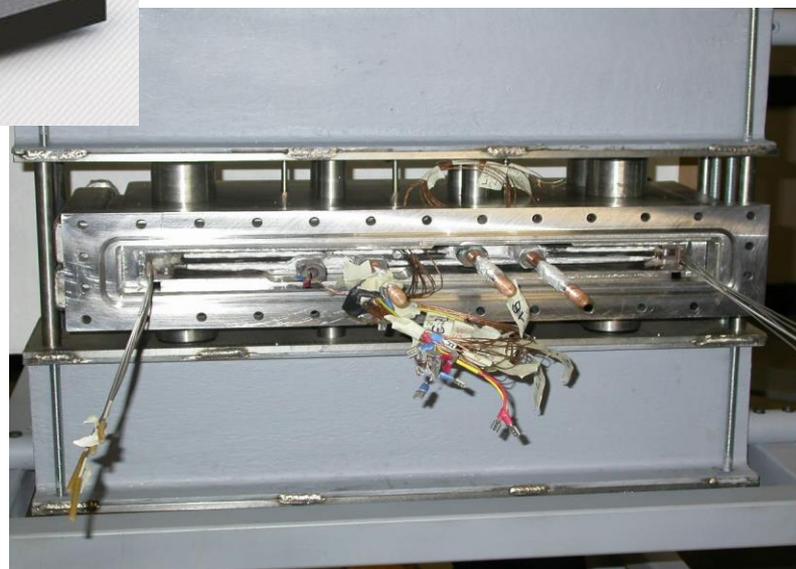
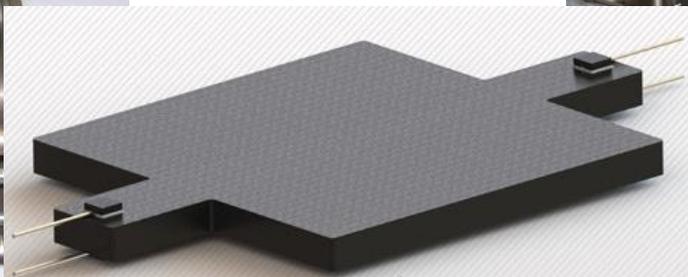
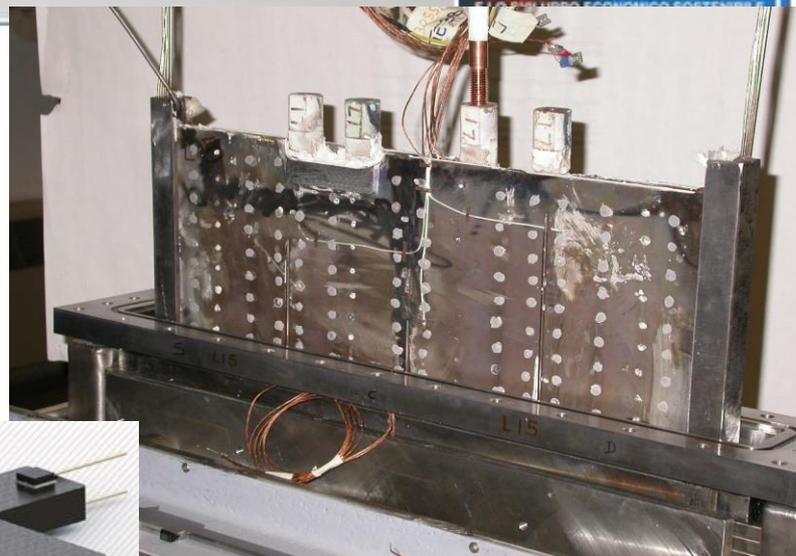
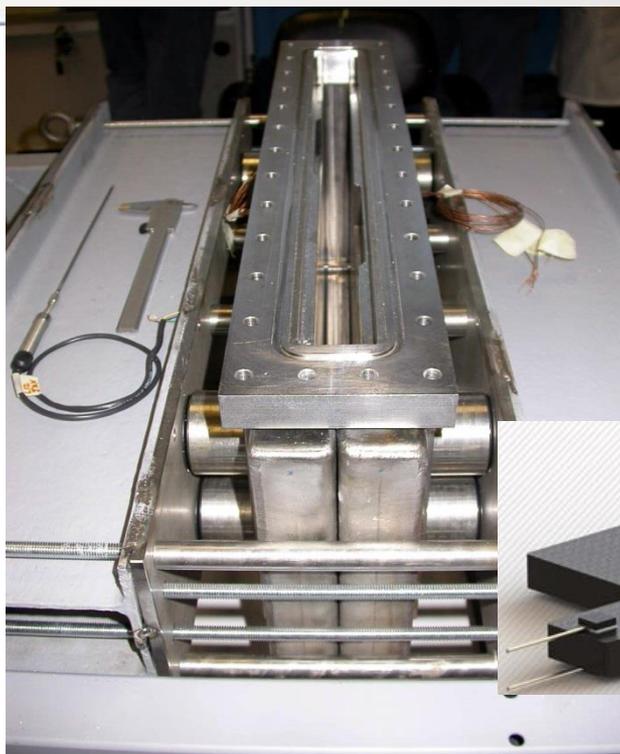
HETS



The maximum heat power transmitted and completely removed was about 3.3MW/m².



HELICA MOCK-UP

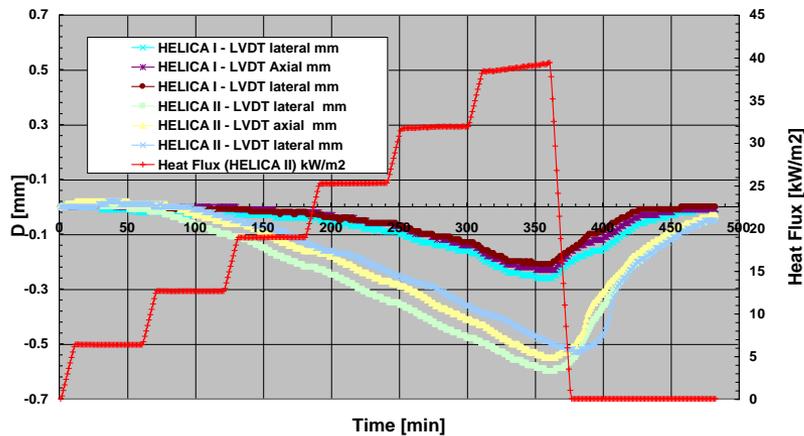


- ▶ Heating Plate made of silicon nitride with an integrated ceramic heating conductor
- ▶ Maximum temperature of 1000 °C
- ▶ Power density up to 1.5 MW/m²

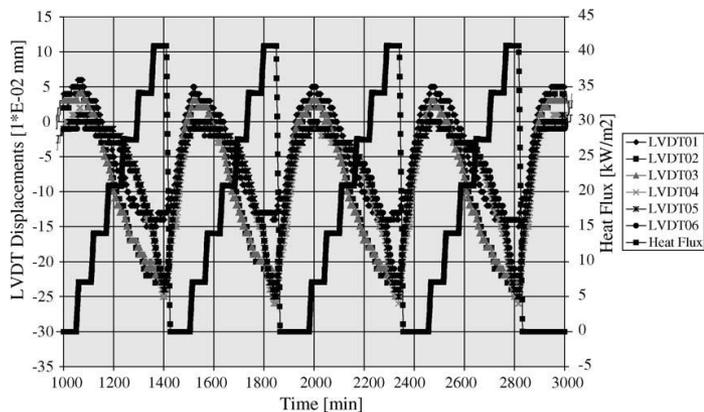
Testing of HCPB-TBM mock-ups

HELICA - Aim of the activity: thermo-mechanical characterisation of Li_4SiO_4 pebble bed for HCPB blanket development

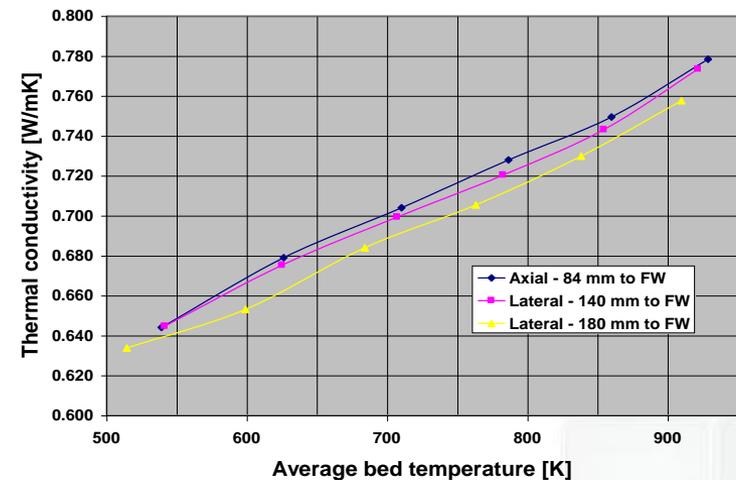
HELICA I - II tests - LVDT Displacements



Strain of the pebble bed under thermal cycle



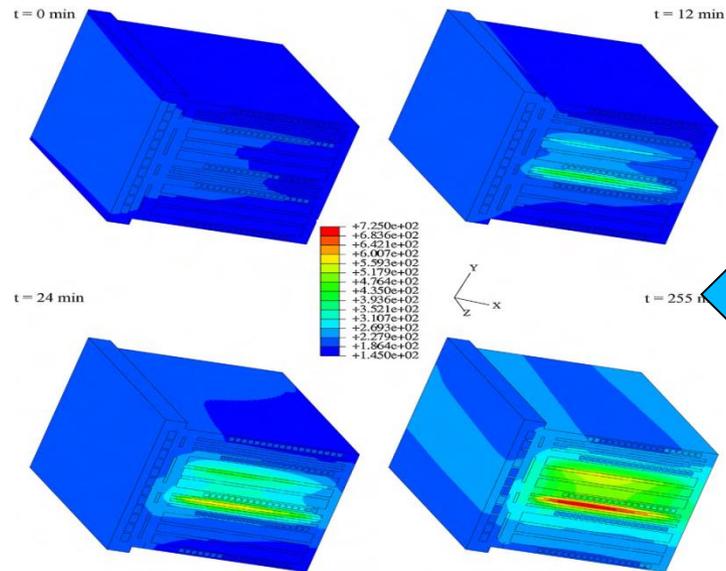
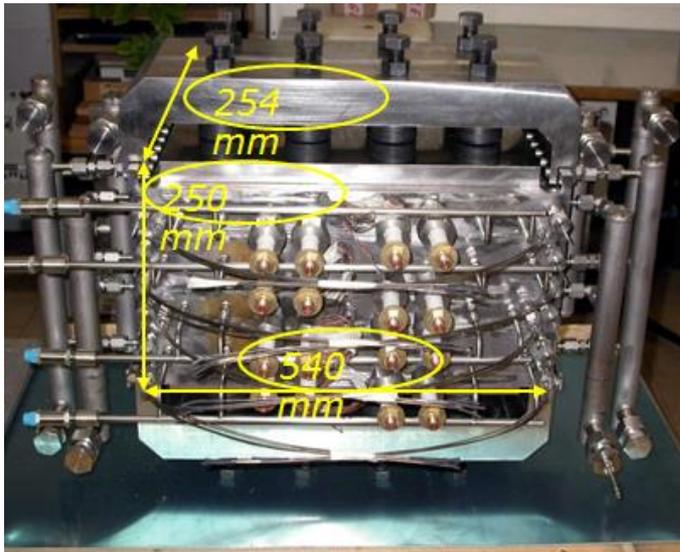
Li_4SiO_4 - Thermal conductivity



Thermal conductivity of Li_4SiO_4 in pebble form vs bed temperature

Testing of HCPB-TBM mock-ups

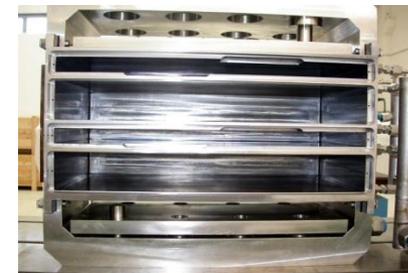
EXCALIBER: Aim of the activity: thermo-mechanical characterisation of HCPB-TBM mock-ups in ITER relevant conditions



Thermo-
mechanical
Characterisation of
box

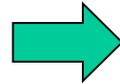
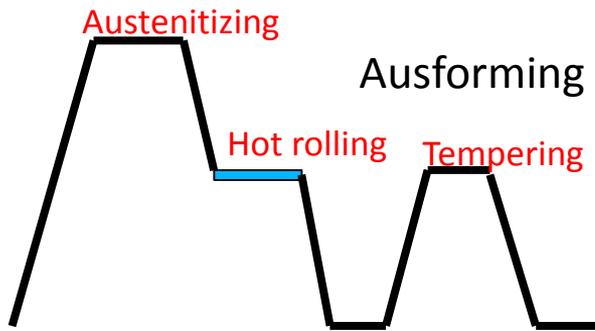
Hexcaliber (HCPB-TBM mock-up)

Procedurre for welding of EUROFER
and Characterisation



HEXCALIBER welded box

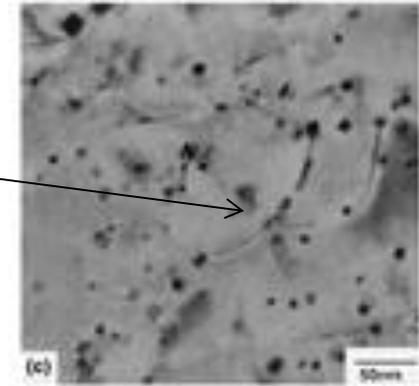
- (EUROFER-HT) Modification of EUROFER and/or development of new steels for higher Operation temperatures (650°C) In cooperation with industry, possible by thermo-mechanical treatments and/or change in chemical composition



Dislocations pinning by nano precipitation

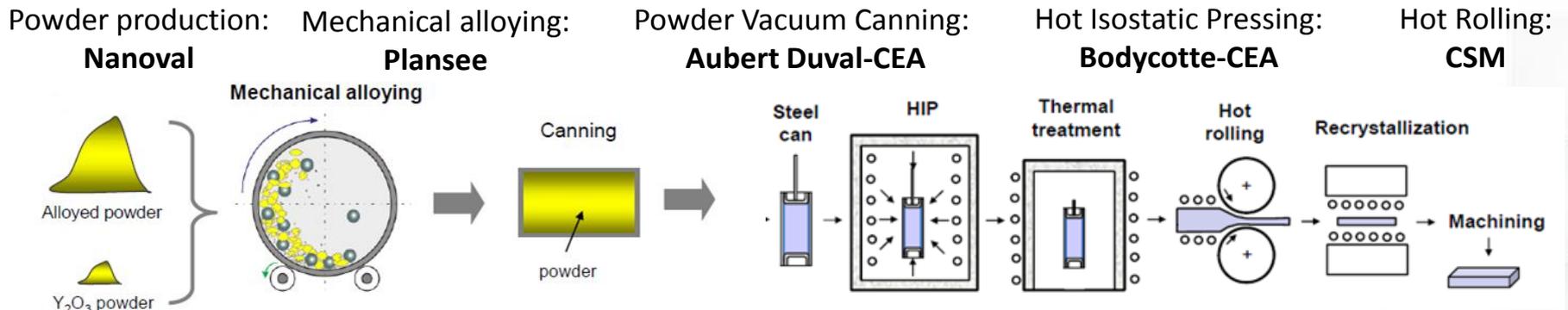


Increase of creep-strength



- ODS steels

Explore large-scale and alternative production routes for milling and thin plates;
Production of a 100 kg batch of ferritic ODS: 14Cr-1W-0.2Ti-0.2Y₂O₃



Tritium and impurities removal from helium **MEDIUM** scale without tritium

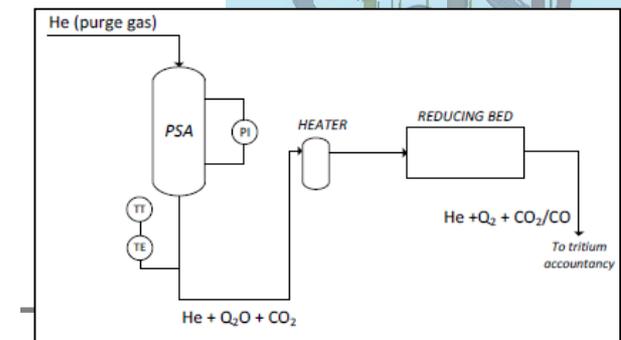
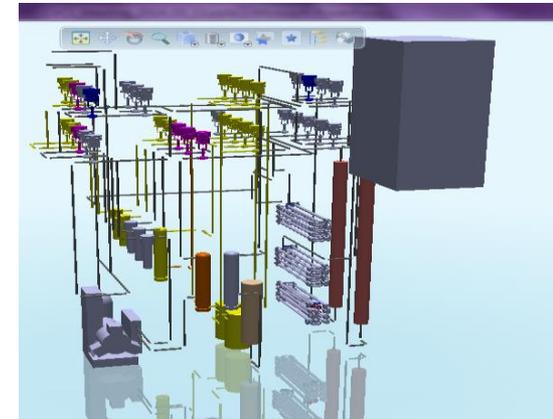
The stage processes of the CPS are four: three for the purification of Helium and the last one for the tritium separation from water (St909 alloy).

Processes for the helium purification

- ❑ Oxidation of Q2 to Q2O using a metal oxide (Cu₂O-CuO or only CuO);
- ❑ Adsorption of Q2O and CO₂ by a PTSA (Pressure Temperature Swing Adsorption);
- ❑ Adsorption of residual impurities by a heated getter.

Operating conditions at the inlet of CPS	
Inlet Temperature	70 °C
Inlet Pressure	8.2 MPa
Feed Flow rate	50-100 Nm ³ /h
H ₂ partial pressure	1000 Pa
H ₂ O partial pressure	30-50 Pa
Maximum concentration of other impurities expected (CO, CO ₂ , N ₂ , CQ ₄ , O ₂)	10 vppm

- ❑ Recovery of tritium gas from tritiated water stored on molecular sieve by: desorption of water trapped under a carrier gas (the purge feed, used to regenerate the adsorber during PTSA) and in line reduction of water vapour on a “hot metal” bed.



CPS – HCPB/HCLL – experimental facility

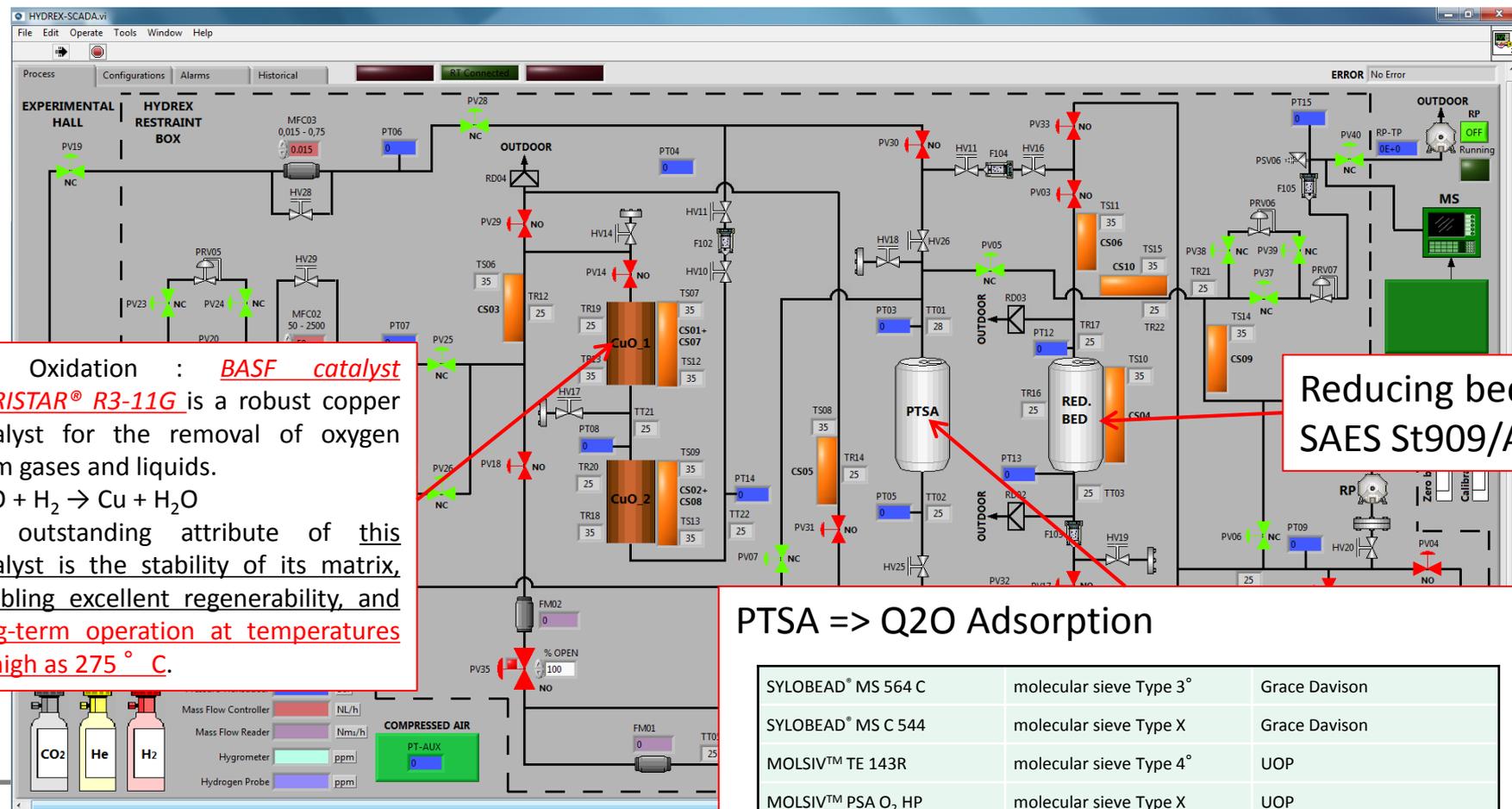


An experimental facility, called HYDREX, was designed and built in ENEA Brasimone in order to qualify the CPS system – scale 1:1. The facility is available in 2017-2019 for experimental qualification of purification systems.

	Adsorption		Rigeneration	
	Nominale	Progetto	Nominale	Progetto
Pressure He	10 - 17 bar (g)	17,2 bar (g)	1 - 4 bar (g)	17,2 bar (g)
Temp. He	RT (1)	-10 / 300 ° C (2)	200 / 450 ° C	-10 / 500 ° C
Flow rate He	1,5 / 7 Nm ³ /h	1 / 10 Nm ³ /h	75 / 350 NI/h	50 / 2500 NI/h
H ₂ O Concentration	15 / 300 ppm	-	-	-
H ₂ Concentration	-	-	50 / 100 ppm	-
CO ₂ Concentration	10 ppm	-	-	-

CPS – HCPB/HCLL – experimental facility

An experimental facility, called HYDREX, was designed and built in ENEA Brasimone in order to qualify the CPS system – scale 1:1. The facility is available in 2017-2019 for experimental qualification of purification systems.



Q2 Oxidation : **BASF catalyst PURISTAR® R3-11G** is a robust copper catalyst for the removal of oxygen from gases and liquids.
 $\text{CuO} + \text{H}_2 \rightarrow \text{Cu} + \text{H}_2\text{O}$
 An outstanding attribute of this catalyst is the stability of its matrix, enabling excellent regenerability, and long-term operation at temperatures as high as 275 ° C.

Reducing bed:
SAES St909/Al

PTSA => Q2O Adsorption

SYLOBEAD® MS 564 C	molecular sieve Type 3°	Grace Davison
SYLOBEAD® MS C 544	molecular sieve Type X	Grace Davison
MOLSIV™ TE 143R	molecular sieve Type 4°	UOP
MOLSIV™ PSA O ₂ HP	molecular sieve Type X	UOP