EUROfusion

Breeding blanket challenges and needs for technology qualification

S. D’Amico, G. Federici, G. A. Spagnuolo, F. A. Hernandez, and the DEMO Central Team

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Outline

- Breeding Blanket in DEMO power plant
  - Preamble and main functions
  - DEMO BB reference concepts and variants
- Breeding Blanket technological challenges and needs
  - Current non-neutronic testing efforts
- Conclusions and outlook

[…] *Despite its criticality to the development of fusion power, the maturity of the breeding blanket is still very low, and no breeding blanket has ever been built or tested. Large feasibility concerns and performance uncertainties exist for all concepts. R&D is then needed to fill the remaining outstanding gaps* […]

G. Federici - Testing Needs for the Development and Qualification of a Breeding Blanket for DEMO, submitted to Nuclear Fusion

Breeding Blanket in DEMO power plant: preamble and main functions

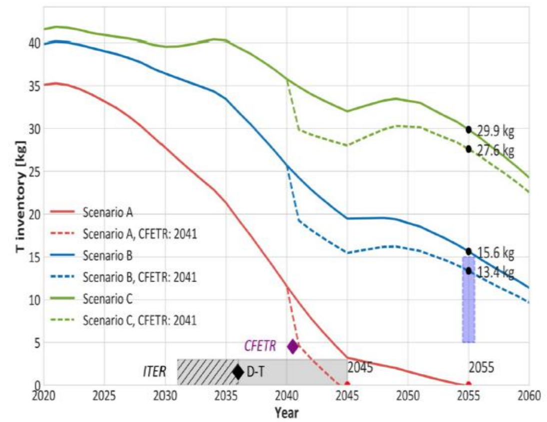
DEMO must be a representative fusion power station: it should pave the way for **commercial fusion power:**

- **breed its own tritium:** ***"a 2 GW fusion power DEMO will consume around 111 kg T/FPY, and this clearly underscore the indispensable requirement to achieve T-self-sufficiency"***

$$ {}^{6}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{4}_{2}\mathrm{He}\ (2.05\ \mathrm{MeV}) + {}^{3}_{1}\mathrm{T}\ (2.75\ \mathrm{MeV}) $$

- **produce electricity:** (~300-500 MWe) predictably and safely, with minimal environmental impact:
  - ✓ use Reduced Activation Ferritic-Martensitic 'RAFM' steel → *EUROFER*
  - ✓ minimization of tritium permeation, dust and corrosion products generation

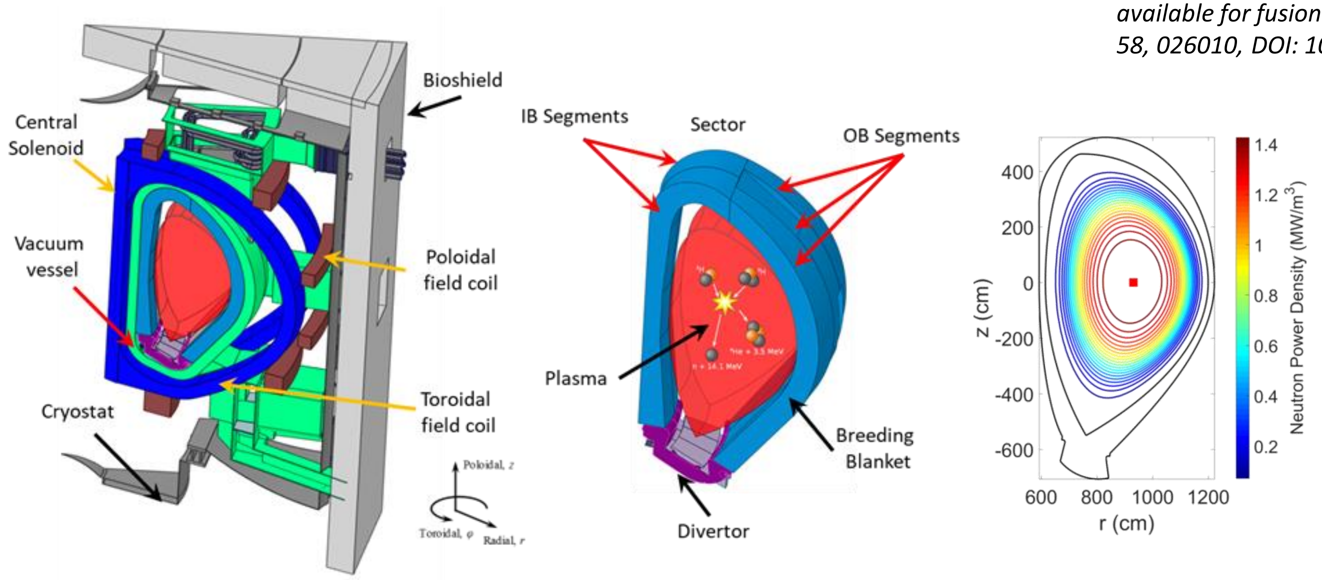
The BB is the key nuclear component: it is exposed with >85% coverage to the plasma



M. Kovari et al, (2018) Tritium resources available for fusion reactors, Nuclear Fusion, 58, 026010, DOI: 10.1088/1741-4326/aa9d25

Its top-level functions are:

- **Tritium breeding**
- **Heat removal for electrical production**
- **Contribution to nuclear shielding**

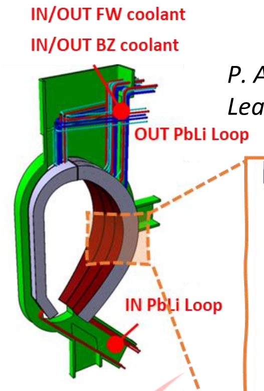


Breeding Blanket in DEMO: reference concepts

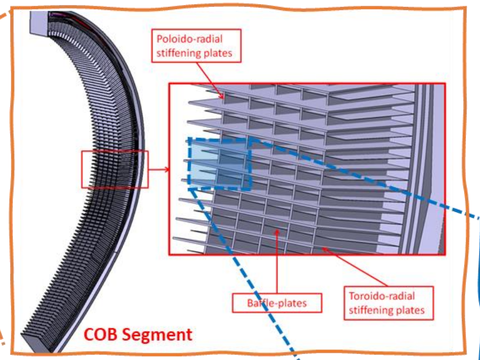
P3A2: Francisco Hernández
P1A1: Guangming Zhou
P6B1: Italo Ricapito
P6C5: Carlos Ortiz Ferrer

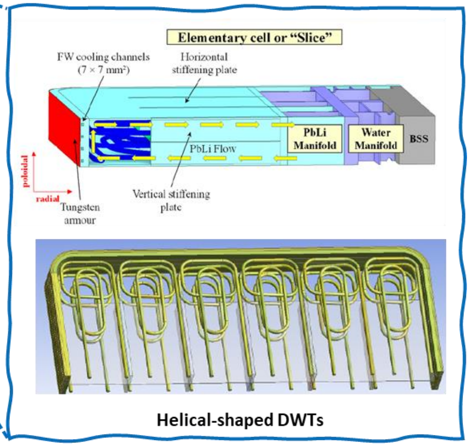
Water Cooled Lead Lithium Concept (WCLL)

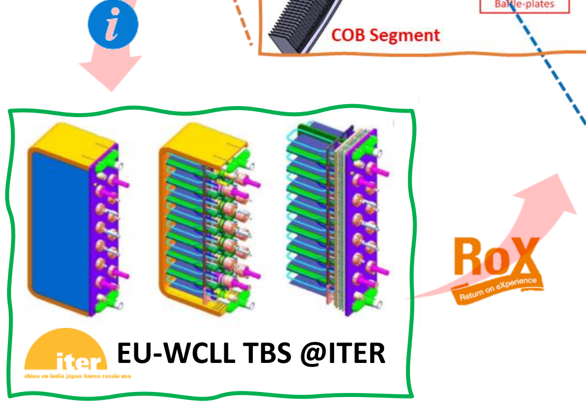
- **Structural Material**: EUROFER (RAFM steel)
- **Breeder/neutron multiplier**: PbLi (^{6}Li at 90%) liquid (~330 °C @ 0.25-1.55 MPa)
- **Coolant**: Water (295-328°C @ 15.5 MPa)
- **Plasma protection**: W layer (2 mm)
- **T extraction from recirculating PbLi**



P. Arena et al, (2023) Design and Integration of the EU-DEMO Water-Cooled Lead Lithium Breeding Blanket, Energies, 16, 2069 , DOI: 10.3390/en16042069

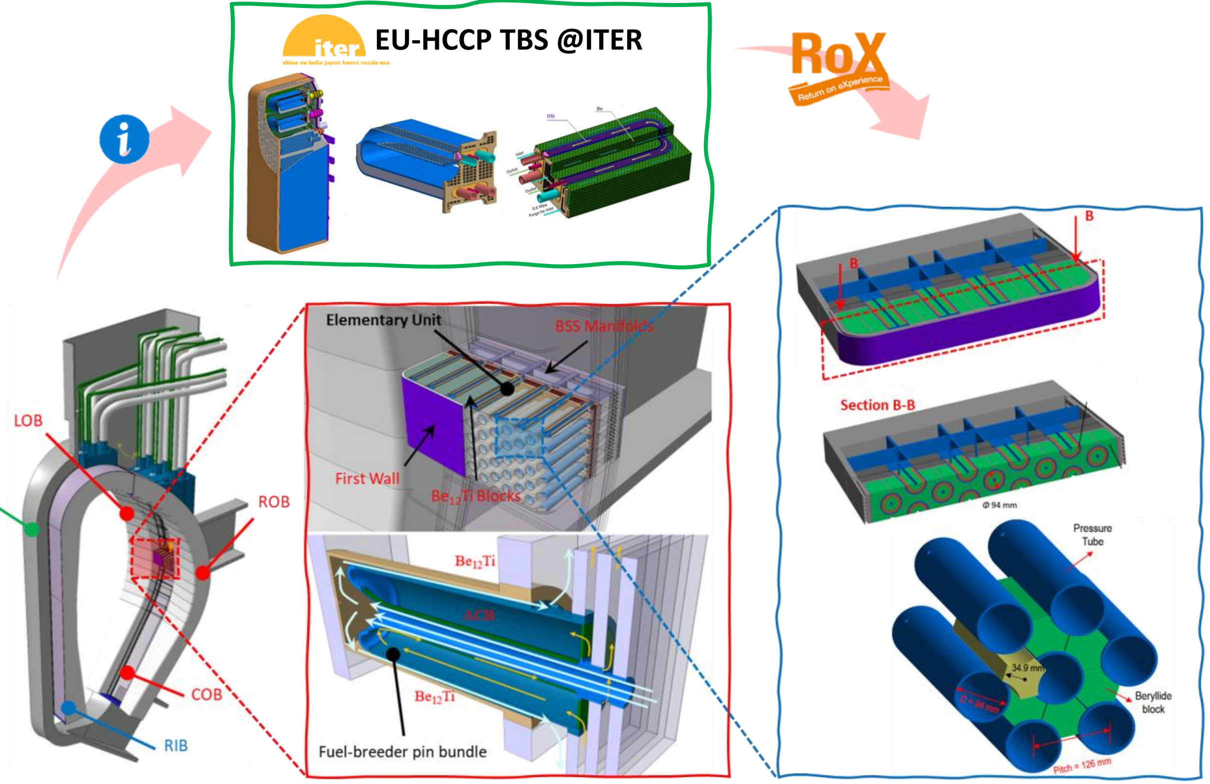






Helium Cooled Pebble Bed Concept (HCPB)

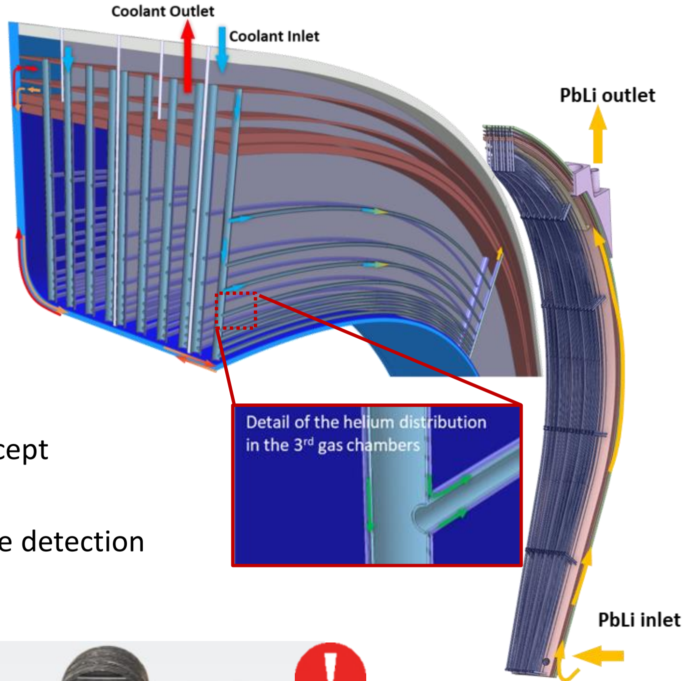
- **Structural Material**: EUROFER (RAFM steel)
- **Breeder**: ACB (Li_4SiO_4 + 35 mol% Li_2TiO_3) in form of a pebble bed, ^{6}Li at 60%
- **Neutron multiplier**: Beryllide ($TiBe_{12}$) hexagonal rods
- **Coolant**: helium 300-520°C @ 8 MPa
- **Plasma protection**: W layer (2 mm)
- **T extraction with purge Helium**: 0.1% H_2/H_2O@ ~0.2 MPa (**@8 MPa: HCPB-HP**)

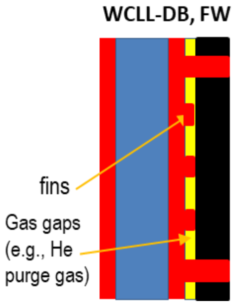


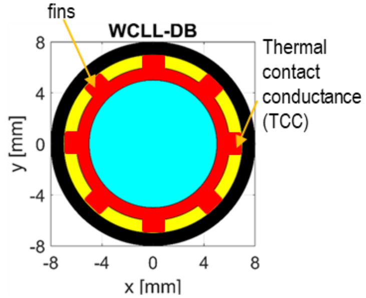
Breeding Blanket in DEMO: variants

Water Cooled Lead Lithium Concept (WCLL) – Double Bundle

- **Structural Material**: EUROFER (RAFM steel)
- **Breeder/neutron multiplier**: PbLi (^{6}Li at 90%) liquid (~330 °C)
- **Coolant**: Water (285-325°C @15.5 MPa)
- **T extraction from recirculating PbLi**
- **BZ and FW in series** ($T_{in,FW} \approx$ 315 °C)
- *Poloidal coolant tube distribution*:
  - Less tubes, less welds ↑ **reliability**
  - Less tubes, less surface ↓ **^{3}H permeation**
  - Less tubes, less water, more PbLi ↑ **TBR**
  - BB like HX/SG ↑ **TRL/RoX**
- *Double bundle of simple tubes*
  - 3-chamber as per S&T HX (K.-H. Funke) concept
  - to avoid PbLi and water interaction
  - helium to reduce ^{3}H permeation and leakage detection





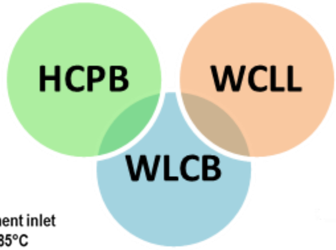


e.g., Wieland Safety Tubes: https://www.wieland-thermalsolutions.com

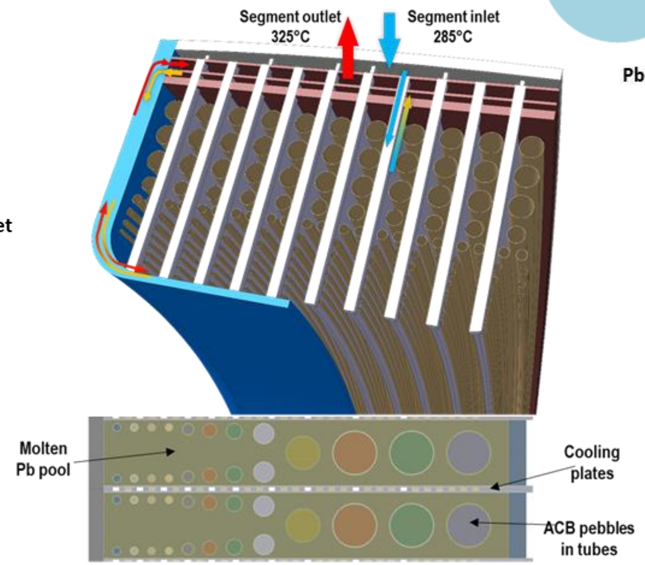
Water-cooled Lead and Ceramic Breeder (WLCB)

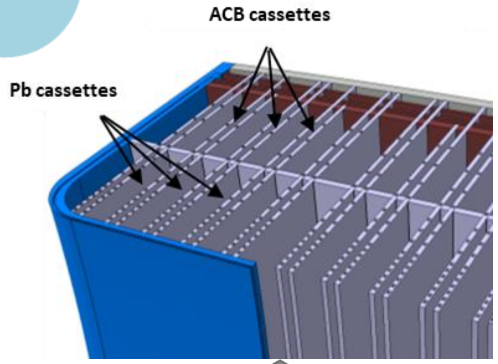
- **Structural Material**: EUROFER (RAFM steel)
- **Breeder**: ACB (Li_4SiO_4 + 35 mol% Li_2TiO_3) (^{6}Li at 60%)
- **Neutron multiplier**: molten Pb or solid Pb compound
- **Coolant**: Water (285-325°C @15.5 MPa)
- **T extraction with purge Helium**: 0.1% H_2/H_2O@ ~0.2 MPa
- **BZ and FW in series** ($T_{in,FW} \approx$ 315 °C)

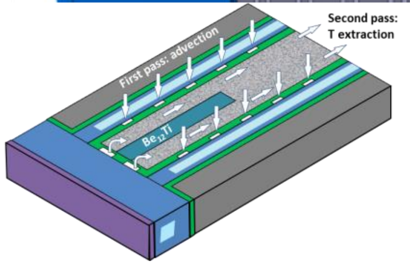
Proven T extraction
Available TER technology
Good TBR
Low T permeation



Proven water PWR tech
Excellent neutron shielding
More mature PHTS/BoP







Breeding Blanket Technological Challenges

PL 2: Gianfranco Federici
KN 4: Ambrogio Fasoli
P1A2: Alessandro Spagnuolo

Structure

EXAMPLE

- Changes in properties and behaviour of materials
  - *Effect of heat flux and cycling on fatigue or crack growth-related failure*
  - *Premature failure at welds and discontinuities*
  - *Effect of swelling, creep and thermal gradients on stresses conc.*
- Tritium permeation through the structure
  - *Effectiveness of tritium permeation barriers*
  - *Effect of radiation on tritium permeation*
- Structural activation product inventory and volatility

Solid Breeder / multiplier / structure interactions

EXAMPLE

- Solid breeder mechanical and materials interactions
  - *Strain accommodation by creep and plastic flow*
  - *Stress concentrations at cracks and discontinuities*
- Neutron multiplier mechanical interactions
  - *Beryllium/beryllide swelling (swelling driving force in beryllium)*
  - *Strain accommodation by creep in Beryllium/beryllide*
- Thermal interactions
  - *Breeder/multiplier-structure heat transfer (gap conductance)*

Coolant / liquid breeder-multiplier

EXAMPLE

- MHD pressure drop and pressure stresses
- MHD and geometric effects on flow distribution
- Helium bubble formation leading to hot spots
- Activation products in PbLi

Coolant / structure interactions

EXAMPLE

- Mechanical and materials interactions
  - *Corrosion*
  - *Failure of coolant wall due to stress corrosion cracking*
  - *Failure of coolant wall due to liquid-metal embrittlement*
- Thermal interactions
- Coolant/coatings/structure interactions

Breeder and purge

EXAMPLE

- Tritium recovery and inventory in solid breeder
- Liquid breeder tritium extraction
- Thermal conductivity changes under irradiation
- Effect of T mass transfer
- Breeder behaviour at high burn-up/high dpa

General blanket

EXAMPLE

- Tritium trapping
- Uncertainties in achievable breeding ratio
- Uncertainties in required breeding ratio
- Permeation to blanket coolant
- Failure modes and frequencies
- Nuclear heating rate predictions
- Prediction and control of radioactive effluent


CORIANDER: Comparison of Relevant Issues and Nuclear Development for Fusion Energy Research

F. Arendt, G. Böhme, L.A. El-Guebaly, G.A. Emmert, B. Haferkamp, W. Heinz, E. Hutter, R. Klingelhöfer, P. Komarek, M. Kehle, G.L. Kulcinski, M. Kuntze, E.M. Larsen, G. Leppelmeier, S. Malang, W. Maurer, C.W. Maynard, R.A. Müller, D. Perinic, J.F. Santarius, M.E. Sawan, J.E. Scharer, A. Suppan, I.N. Sviatoslavsky, W.F. Vogelsang, and L.J. Wittenberg

January 1985

FPA-84-7

FUSION POWER ASSOCIATES

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1500 Engineering Drive, Madison, Wisconsin 53706, (608) 263-2308

F. Arendt et al, ***(1985)*** *CORIANDER: comparison relevant issues and nuclear developments for fusion energy research, Fusion Power Associates, FPA-84-7*


Volume I
Summaries
PPG-909
UCLA-ENG-85-39

Volume II
Chapters 3-9
PPG-909
UCLA-ENG-85-39

Technical Issues and Requirements of Experiments and Facilities for Fusion Nuclear Technology

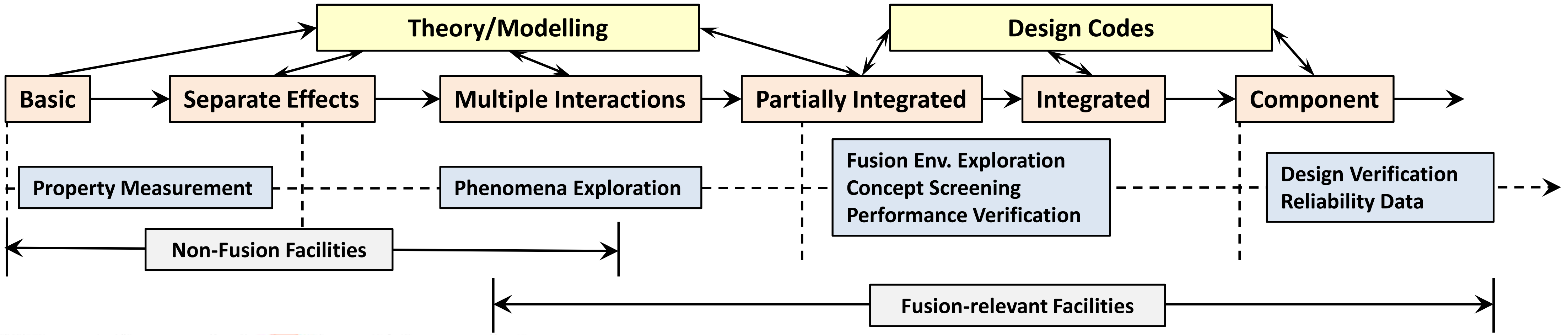
FINESSE Phase I Report

December 1985

Fusion Engineering
University of California, Los Angeles
Los Angeles, California

M. A. Abdou et al, ***(1985)*** *A Study of the Issues and Experiments for Fusion Nuclear Technology, Fusion Technology, 8:3, 2595-2645, DOI: 10.13182/FST85-A24685*

Breeding Blanket Qualification Needs



Existing or being upgraded (green) | New or to be upgraded (red)

BREEDING BLANKET & BALANCE OF PLANT

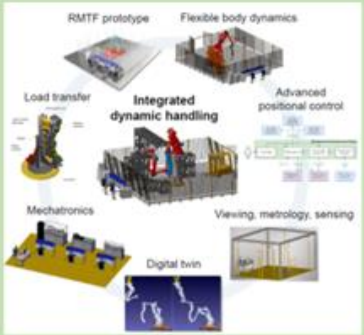
HELOKA (KIT)
MEKKA/MAPLE (KIT)
KALOS (KIT)
IELLO (ENEA)
LIFUS5 (ENEA)
WATER LOOP - WP (ENEA)
CHIMERA (CCFE)
others

BREEDING BLANKET & HHFCs

GLADES (MPG-IPP)
HADES (CEA)
WATER LOOP - WP (ENEA)
CHIMERA (CCFE)
others

BREEDING BLANKET & REMOTE MAINTENANCE

TARM (CCFE)
RMTF prototype
PHMTF, HPTF, VPTF
others



TRITIUM EXTRACTION SYSTEMS AND REMOVAL SYSTEM & FUEL CYCLE

HCPB TER Test Rig (KIT)
WCLL TER Test Rig (ENEA)
H3AT (CCFE)
DIPAK (KIT)
others

BREEDING BLANKET & MATERIALS

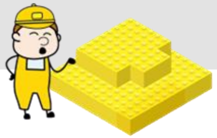
FML (KIT)
HML (FZJ)
others
LECI (CEA)
FNG (ENEA)

BREEDING BLANKET & MATERIAL TEST REACTORS

BR2 (SCK-CEN)
JHR (CEA)
LVR-15 (CVRez)
MARIA (NCBJ)
others

Adapted from G. Federici, (2022) - The European Programme towards a Demonstration Fusion Reactor, SOFT-32

Breeding Blanket Qualification Needs: ongoing R&D efforts



EXAMPLE

Non-exhaustive!

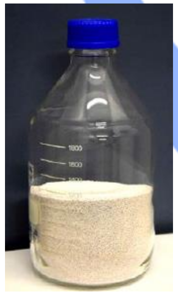
General blanket: Fabrication of (functional material) tritium breeding ceramics in pebble form

KArlsruhe Lithium OrthoSilicate UPgrade (KALOS-UP)

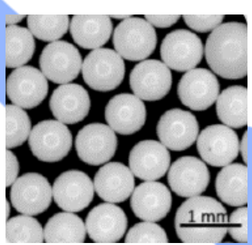
The facility uses a melt-based process to produce Advanced Ceramic Breeder (ACB) pebbles. The major interesting points are:

- the KALOS-UP facility is the **only European facility to produce ceramic breeder pebbles**
- the **semi-continuously operating** facility will be able **to cover any needs for breeder blanket mock-ups and the ITER TBMs** in the coming years
- in view of DEMO and beyond, this facility will demonstrate **the transferability to a large-scale production of ACB**
- **provision of ACB pebbles for the DEMO blanket qualification** in all accelerator driven neutron sources available along the timeline
- demonstration of ability to use the facility for **direct reprocessing and lithium replenishment of used pebbles** (long term perspective)

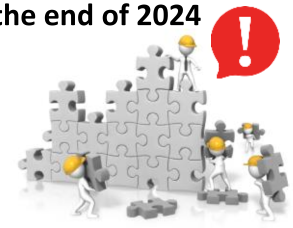
O. Leys et al, (2019) Ceramic Pebble Production from the Break-Up of a Molten Laminar Jet, Oral Presentation, ILASS–Europe 2019



Lithium orthosilicate pebbles with 35 mol% lithium metatitanate



Continuous operation by the end of 2024



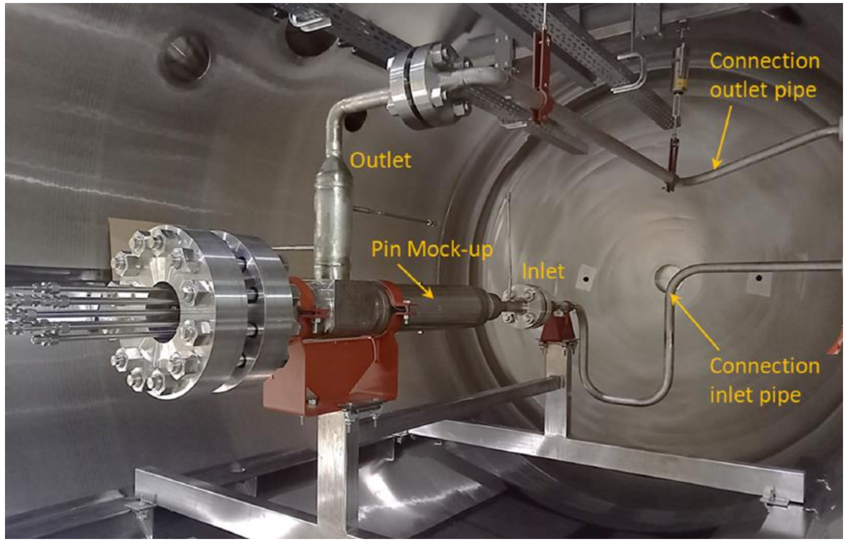
KALOS-UP Input Data for the EUROfusion Facility Review, 2023

Breeding Blanket Qualification Needs: ongoing R&D efforts

Coolant/structure: thermal interactions

Helium Loop Karlsruhe (HELOKA)

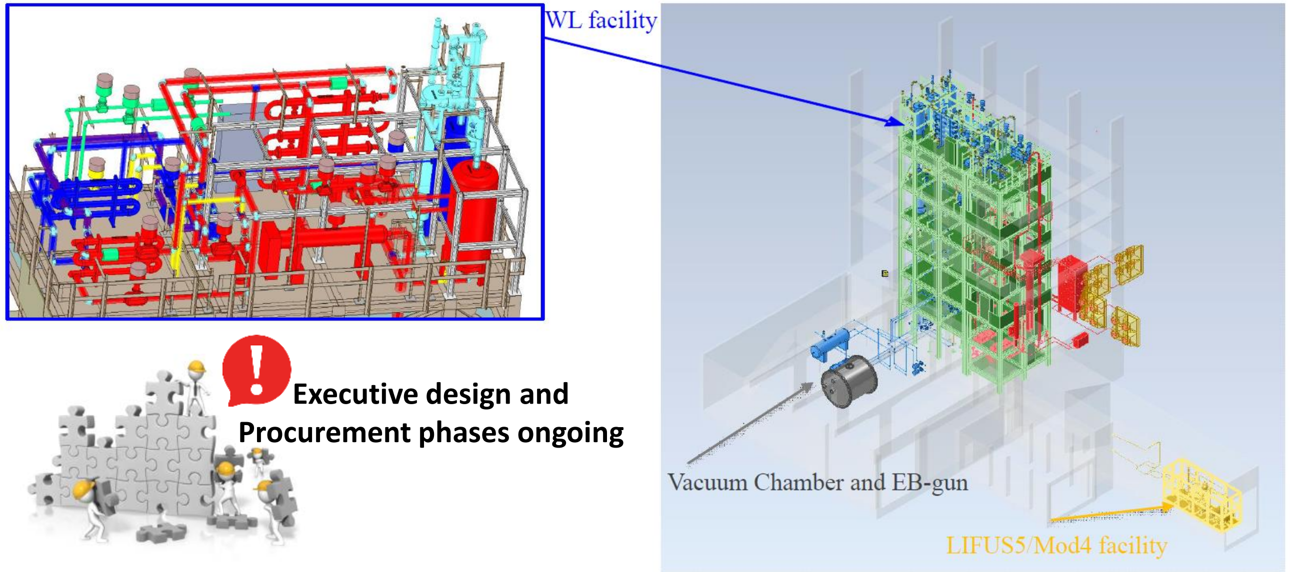
HELOKA is a test facility comprising several experimental loops using high pressure, high temperature helium as coolant and a High Heat Flux (HHF) test rig



A. Abou-Sena et al, (2022) Experimental Thermal–Hydraulic Testing of a Mock-Up of the Fuel-Breeder Pin Concept for the EU-DEMO HCPB Breeding Blanket, J. Nucl. Eng. 2023, 4, 11–27, DOI: 10.3390/jne4010002

WATER LOOP (WL)

WL as a part of the W-HYDRA platform (ENEA-Brasimone) is a large/medium scale water coolant plant that will provide water coolant at high pressure and temperature allowing multi-purpose experiments



Executive design and Procurement phases ongoing

Water Loop (WL) Input Data for the EUROfusion Facility Review, 2023

Validation of single-effect phenomena in key BB elements:

- **heat transfer** in DEMO BB relevant geometries
- **functional and pre-manufacturing qualification** (HHF + code validation)
- **development and validation of predictive tools** (extension of benchmark database)
- **qualification of flow distribution** and design robustness against uncertainties as well as operational procedures
- **preliminary assessment of structural/functional/coolant interactions**

Breeding Blanket Qualification Needs: ongoing R&D efforts

P4D1: Leo Bühler

EXAMPLE

Non-exhaustive!

Coolant/liquid breeder-multiplier interactions: liquid metal magnetohydrodynamics (MHD)

Magnetohydrodynamic Experiments in NaK Karlsruhe (MEKKA)

MEKKA uses NaK as a surrogate liquid metal: it enables experiments to be performed at room temperature (MP: -12 °C)

MEKKA Input Data for the EUROfusion Facility Review, 2023

Magnetohydrodynamic PbLi Experiment (MaPLE)

MaPLE uses prototypical eutectic PbLi (MP: 235 °C) at 300°C and enables experiments with combined MHD and buoyancy effects

Commissioning by the end of 2023

MaPLE Input Data for the EUROfusion Facility Review, 2023

MEKKA and MaPLE are unique and complementary facilities for addressing MHD challenges for liquid metal BB

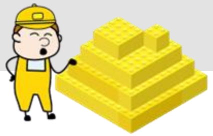
- Fundamental experiments will be performed in generic geometries for:
  - **improving the understanding of coupled multiphysics phenomena**
  - **provide insight for designers of liquid metal blankets**
- Development and validation of predictive tools (extension of benchmark database)
- Validation of design concepts of liquid metal blankets (mock-up tests)

C. Mistrangelo et al, (2023) Magneto-convective flows around two differentially heated cylinders, Heat and Mass Transfer, DOI:10.1007/s00231-023-03350-2

C. Mistrangelo et al, (2021) MHD R&D Activities for Liquid Metal Blankets, Energies, 1996-1073, DOI:10.3390/en14206640

Breeding Blanket Qualification Needs: ongoing R&D efforts

P1A3: Thomas R. Barrett



Non-exhaustive!

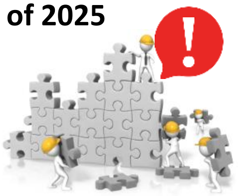
Coolant/liquid breeder-multiplier interactions: Heat Flux, MHD and EM effects

The Combined Heating and Magnetic Research Apparatus (CHIMERA) fusion technology test facility is under construction, and it will be capable of **multiple effects/partially integrated** testing of fusion component modules up to the size of the ITER Test Blanket Module box, under independent or combined conditions of in-vacuum high heat flux, static and pulsed magnetic fields, and high temperature/pressure (PWR-like) water cooling

The capacity to perform high heat flux testing at component scale, with integrated magnetic fields will allow:

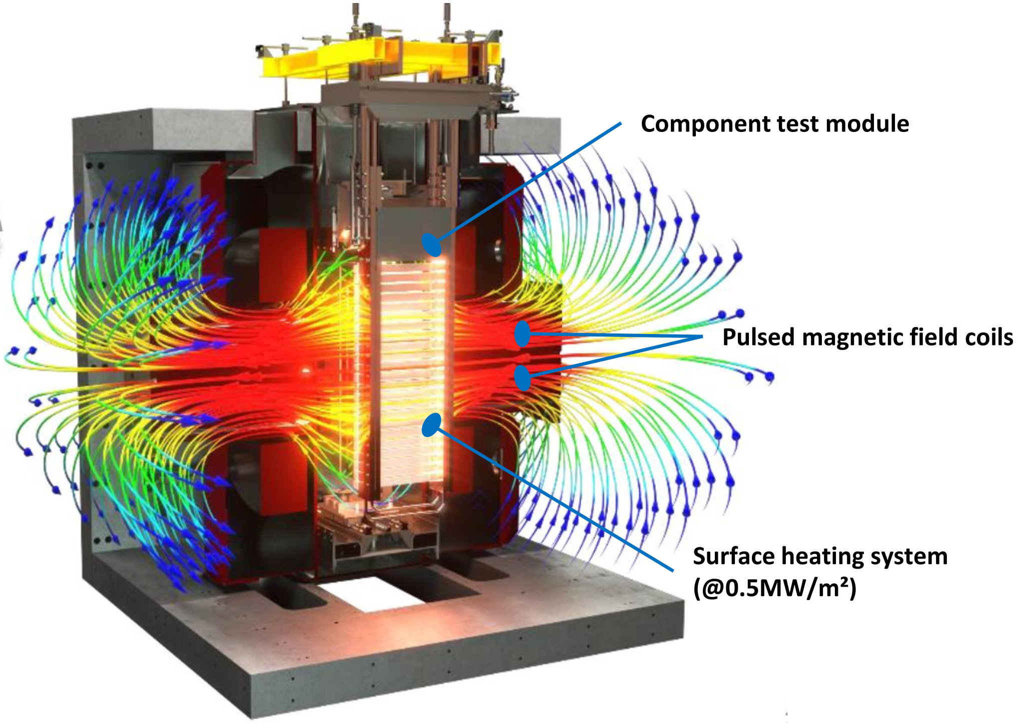
- **testing and verification** of diagnostics and equipment within magnetic fields where EM loads along with thermal and mechanical loads can be evaluated to verify comparisons with models and for design verification

Commissioning by the end of 2025



Aerial isometric view (computer-aided design) above the CHIMERA facility

T. R. Barrett et al, (2023) CHIMERA Fusion Technology Facility: Testing and Virtual Qualification, Fusion Science and Technology, DOI: 10.1080/15361055.2022.2147766



Vertical cross section showing illustration of the SC magnet field lines coloured by magnetic flux density

Conclusions and outlook

- Technology readiness of essential enabling technologies (BB, ^{3}H fuel cycle, Divertor, Materials, RH, etc.) is low: no breeding blanket has ever been built or tested

- Within the BB development there are still some knowledge gaps (design and technology R&D) that need to be urgently addressed

- EUROfusion program has undertaken a recent assessment to identify the most critical issues and facilities (existing or new) that are needed to address them: a facility review (including technology facility) is planned before the end of the year

- There are urgent priorities about design development and testing in non-nuclear environment. These include:
  - Facilities for tritium extraction & recovery (TER) from the BB breeder / purge gas
  - Facility to test and demonstrate concept and remote maintenance procedures
  - A process and a facility for the enrichment of ^{6}Li which is missing so far
  - Development of an integrated modelling/virtual qualification tool to complement and/or extend the experimental qualification activities as possible risk mitigation action

… for your kind attention!

FAIRNESS	OPENNESS	COMMITMENT	DIVERSITY
			
Transparency Collaboration Loyalty	Open doors Open hearts Open minds Open ears	Ownership Critical thinking Determination Respect	Cooperation Equal opportunities Inclusion

P2A1-Relevant Talks

P1A1: Guangming Zhou - Overview of the design activities of the EU DEMO Helium Cooled Pebble Bed breeding blanket

P1A3: Thomas R. Barrett - Preparing for the First Integrated Test of a Fusion Breeding Blanket Prototype in the CHIMERA Facility

P1A4: Anoop Retheesh - Structural Integrity Assessment of the Central Outboard Segment of the EU DEMO HCPB Breeding Blanket

PL 2: Gianfranco Federici - DEMO-Related Design Activities in Europe

P2A2: Alessandro Spagnuolo - Needs and options for qualifying fusion nuclear technologies

P2A4: Nicola Fonnesu - Measurement of tritium production in the HCPB TBM mock-up at JET during DTE2

P2B1: Alexander V. Müller - Additive manufacturing techniques for the fabrication of tungsten-based plasma-facing components

P2D1: Barry Buttler - Tritium related challenges to be overcome in order to deliver fusion power plants

P3A2: Francisco Hernández - Alternative water-cooled breeding blanket concepts for the EU DEMO: Overview on studies and perspectives

P3A5: James Dark - Multiphysics tritium transport modelling in WCLL breeding blankets: Influence of MHD effects and neutron damage

P3B3: Dieter Leichtle - Radiological protection design considerations for DEMO

P3B5: Yuefeng Qiu - Overview of recent advancements in IFMIF-DONES neutronics activities

P3C3: Elisabetta Carella - Coatings: challenges of Tritium Permeation Barriers in fusion reactors context

P3D1: Oliver Crofts - Overview of progress towards more maintainable architectures for fusion devices

P3D2: Hongtao Pan - Breeding Blanket Remote Handling System for CFETR and EU-DEMO

P4A4: Jarir Aktaa - Embrittlement of WCLL Blanket and Its Fracture Mechanical Assessment

P4D1: Leo Bühler - Liquid metal MHD research at KIT: fundamental phenomena and flows in complex blanket geometries

P4D5: Sara Pérez-Martín - The scaling methodology applied for designing HELOKA-US facility, the EU-DEMO HCPB BOP mock-up

PL 8: Joëlle Elbez-Uzan - Safety approach for future fusion power plant

PL 10: Ángel Ibarra - Overview of IFMIF-DONES: an irradiation facility relevant for fusion materials

P5B4: Beatriz Brañas - TRL analysis of IFMIF-DONES and Overview of the required validation needs

P5B5: Axel Klix - Fusion neutronics experiments utilizing the intense DT neutron generator of Technical University of Dresden

P5C3: María González - Towards the down-selection of ceramic materials for the European High Temperature DCLL BB concept based on Single Module Segments (SMS)

P5D1: Mark Gilbert - Fusion waste requirements for tritium control: perspectives and current research

P5D4: Alberto Previti - Parametric assessment of the Activated Corrosion Products on the ITER Water Cooled Lithium Lead Test Blanket System

P6A4: María Lorena Richiusa - The Integrated Engineering Design Concept of the Upper Limiter within the EU-DEMO LIMITER System

P6B1: Italo Ricapito - Tritium Transport Modelling: Current status, open points and perspectives

P6B5: Jonas Caspar Schwenzer - Tritium inventory evolution modelling for demonstration and future fusion power plants

P6C1: Christian Bachmann - Relevance of a high magnetic field to the design of the EU DEMO

P6C5: Carlos Ortiz Ferrer - The Lead Lithium Loop for the European Water-Cooled Test Blanket System (WCLL-TBS)

KN 4: Ambrogio Fasoli - Recent Progress and Plans in the EUROfusion Program

PL 11: Luciano Giancarli - Status of the ITER TBM Program and overview of its technical objectives