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Overview of the system-level thermal-hydraulic analysis performed at Sapienza to support the development of a Water-Cooled Lead-Lithium Breeding Blanket for Tokamak Fusion Reactors

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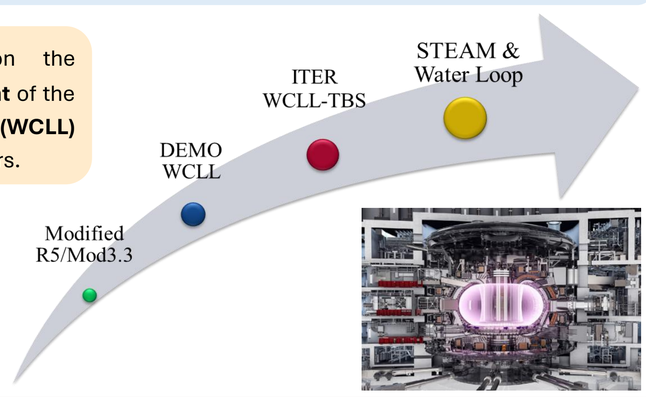
Activity Framework

Activity conducted in the frame of the **EUROfusion Consortium**, within a collaboration between **NERG of Sapienza University of Rome** & the **Experimental Engineering Division of ENEA (Brasimone R.C.)**. Since 2015, research works carried out by the joint research team associated to **Work Packages Breeding Blanket** (**BB**) and **Balance of Plant** (**BoP**).

Goal: The research activity was focused on the **conceptualization** and **thermal-hydraulic assessment** of the **cooling system** for the **Water-Cooled Lead-Lithium (WCLL) blanket option**, involving **ITER** and **DEMO** fusion reactors.

Main Topics: Fusion reactor design; Thermal-hydraulics; System codes; Transient analysis; Control systems; Management strategy for accident mitigation.

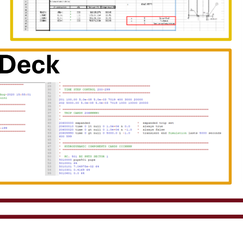


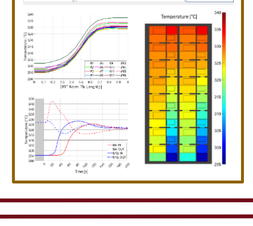
Modified R5/Mod3.3

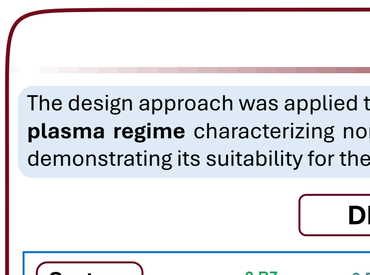
To carry out the BB PHTS transient analysis, RELAP5/Mod3.3 was used, since fully validated to perform LWRs transient analysis. Since it missed some features to properly model the fusion power plants, a modified version of the code, more suitable for fusion reactors, was developed, verified and the preliminary validated.

Workflow

1. **Plant Description** (CAD, PFD, P&ID, etc.)
2. **Engineering Handbook Definition**
3. **Input deck preparation**: Nodalization (control volumes, junctions, heat structures); Control system; Boundary conditions.
4. **Post-processing and result analysis** (MATLAB)







Code Modifications

1. **Lead-lithium** and **HITEC©** working fluids, with their thermophysical properties (EUROfusion database)
2. **Heat transfer correlations** for new working fluids (Seban-Shimazaki, Cheng-Tak, Ushakov, Mikityuk, Kazimi-Carelli, Graber-Rieger, Sieder-Tate,)
3. **Helicoidally tubes** heat transfer correlations (Mori-Nakayama and Zukauskas) and dedicated dry-out point (thermal crisis) control loop

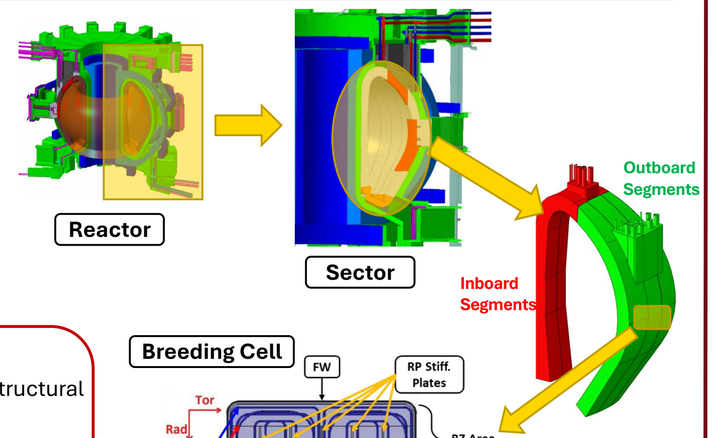
VERIFICATION: Simple Thermal-Hydraulics problems were run to verify the effectiveness of the features implemented in the code.

VALIDATION: Comparison among simulation results and experimental data coming from facilities where heat transfer phenomena were tested.

What is a Breeding Blanket?

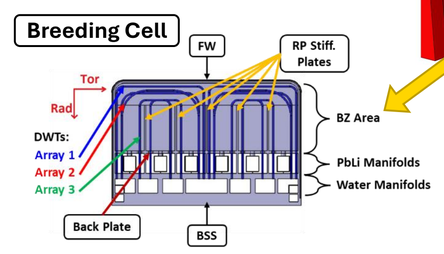
In a fusion power plant, the BB is a key reactor component, accomplishing several functions: **cooling device**, **tritium breeder** and **neutron shield**. In a top-down scheme, it is divided in **sectors**, **segments** and **breeding cells** (system elementary units). It is composed of two principal subsystems: the **First Wall** (**FW**) and the **Breeding Zone** (**BZ**), each one provided with an independent cooling circuit.

- DEMO WCLL Reactor
- Sector (1 of 16)
- Segment (1 of 5)
- Breeding Cell (1 of 100)



WCLL BB relies on:

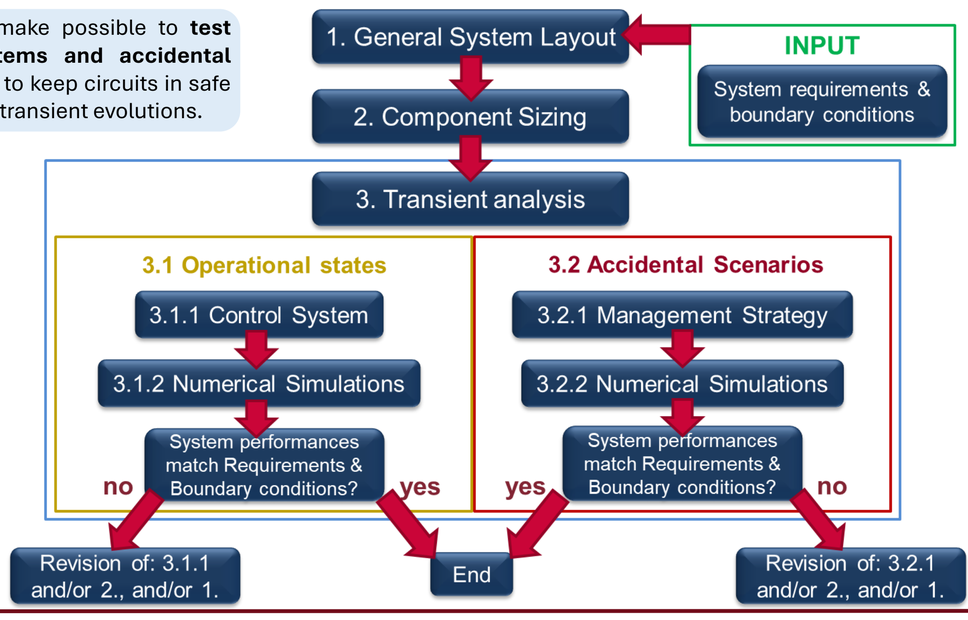
- **Ferritic-martensitic steel** (**EUROFER-97**) as structural material, because of its reduced activation;
- **Liquid lead-lithium** enriched at 90% in Li^6 as breeder, neutron multiplier and tritium carrier;
- **Pressurized water** as coolant (295–328 °C and 15.5 MPa).
- A **tungsten** layer to cover the plasma facing surface.



BB cooling system design approach

The design process was articulated in several steps. Starting from the **system requirements** and **boundary conditions**, a **preliminary layout** was defined, together with the **sizing of all the main circuit components**. **Transient analysis** was then used to refine and improve the project. Indeed, it allows to fully characterize the **system performances** not only in **nominal conditions** but also in a wide range of **operational and accidental scenarios**.

Numerical simulations make possible to **test and tune control systems and accidental management strategies** to keep circuits in safe conditions in considered transient evolutions.

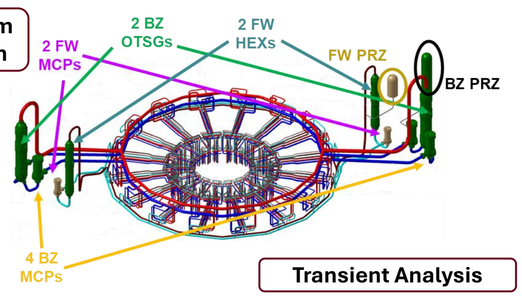


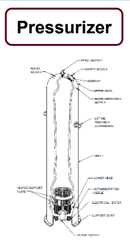
Outcomes of Design Activity (Sizing and Transient Analysis)

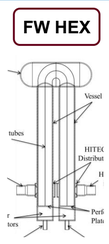
The design approach was applied to the **WCLL technology** considering both **ITER** and **DEMO reactors**. The activity proved to be quite challenging since the system layout was strongly driven by the peculiarities of a nuclear fusion reactor, i.e., the **pulsed plasma regime** characterizing normal operations. The design rationale was adopting well proven nuclear equipment (PWRs), by developing innovative solution for the circuit layout, adapting the component sizing to the fusion environment, and demonstrating its suitability for the new working conditions. Finally, the **transient analysis** demonstrated the appropriateness of the developed design when withstanding a wide range of selected operational and accidental scenarios.

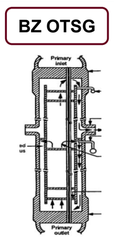
DEMO WCLL BB Primary Heat Transfer System

System Design



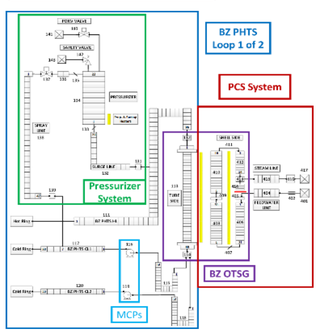




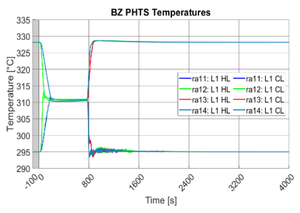


Transient Analysis

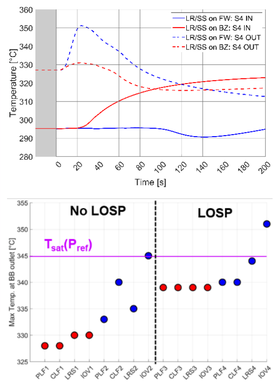
R5/Mod3.3 Model



Pulsed Plasma Regime:
Goal: keep the primary system mean temperature despite the plasma power variation (100% - 1% and vice versa).

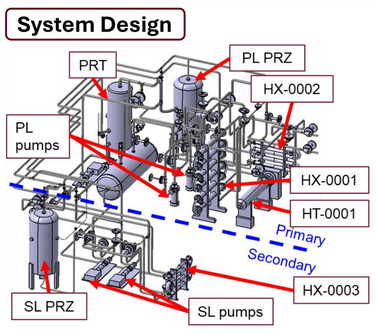


Accidental Analysis:
Goal: keep the BB cooling function avoiding the occurrence of thermal crisis within the component for all the transient investigated: LOCA, LOFA, LOHS, etc. Also, the Loss of Off-Site Power (LOSP) occurring in combination with Postulated Initiating Events (PIE) was considered.

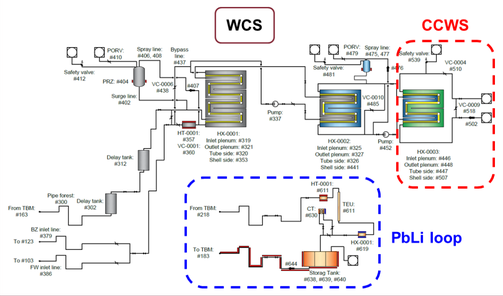


ITER WCLL Test Blanket Module Water Cooling System

System Design

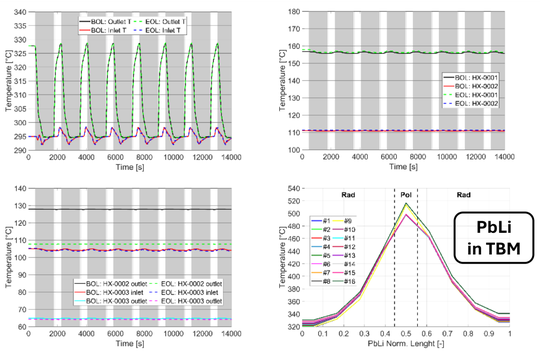


R5/Mod3.3 Model

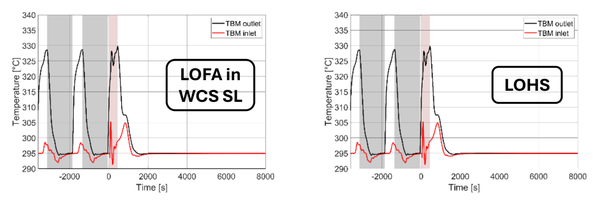


Transient Analysis

Normal Operation State:
Goal: keep the TBM water inlet conditions despite the plasma pulsed regime (100% - 1% and vice versa).



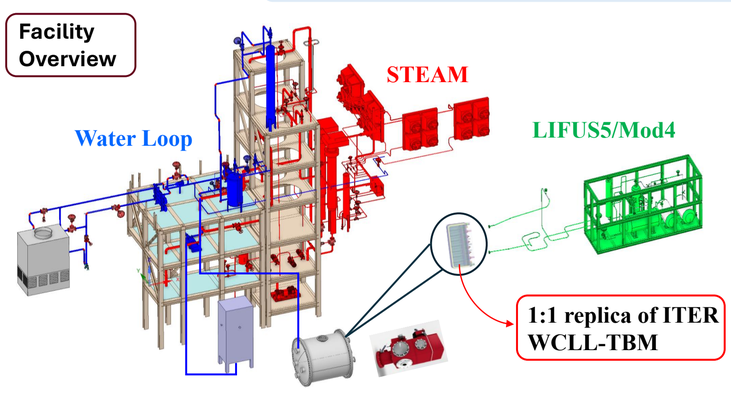
Accidental Analysis:
Goal: Demonstrate that WCS control system can keep the TBM cooling function for a plasma pulse (no triggering of Fast Plasma Shutdown System), i.e., a minor WCS accident does not interfere with ITER global operation.



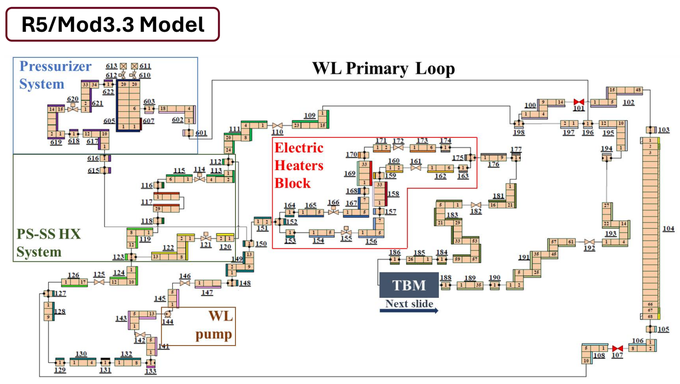
W-HYDRA

The **strategic objective** is to have an experimental infrastructure to investigate **DEMO WCLL technology**, including components of blanket primary and secondary cooling systems (e.g., **SG mock-up**). The facility will be hosted in ENEA RC of Brasimone. It is composed of three facilities: **STEAM**, **Water Loop** and **LIFUS5/Mod4**, each targeting key aspects of the design validation and safety analysis for the WCLL BB.

Facility Overview



R5/Mod3.3 Model



Transient Analysis

Pretest calculations: STH transient analysis used to characterize the behavior of the facilities composing the W-HYDRA experimental setup (now in the procurement phase).

LOFA in WL PL