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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

Developing a sustainable and large-scale nuclear fusion power plant represents one of the most ambitious technological goals of the 21st century. Among the various postulated solutions, magnetic confinement—particularly through tokamaks—stands out as the most advanced and extensively investigated approach. One of the key issues related to the tokamak operation is the need of a plasma pulsed regime. This mode of operation results from the fundamental challenge of keeping the time-varying current needed to generate and sustain the plasma via the central solenoid. Consequently, the Thermal-Hydraulic (TH) systems belonging to the heat removal chain, i.e., the Breeding Blanket (BB) and the Balance of Plant (BoP), must be engineered to cope with these rapid power fluctuations and dynamic boundary conditions.
This factor poses major design challenges for the development of both ITER experiment and EU-DEMO tokamak fusion reactor. Within Europe's fusion-energy roadmap, the ultimate goal is to build EU-DEMO, the first fusion power plant intended to produce electricity for the grid. The mission of the supporting R&D activity is to fill the gaps between today's experimental devices (such as ITER experiment) and a complete commercial reactor, by integrating every critical technology needed for a full-scale power plant. The European roadmap relies on a stepwise programme foreseeing the preliminary construction and operation of ITER. Unlike EU-DEMO, ITER will not generate electricity; instead, it will demonstrate the feasibility of a tokamak fusion device, addressing some of the main technological challenges, i.e., plasma control, heating, tritium handling, and Test Blanket Modules (TBMs). In addition, it will supply the experimental data necessary to guide EU-DEMO BB design. A major difference between ITER and DEMO lies in their blankets. DEMO will deploy a full-coverage BB around the plasma chamber, whose main functions will be heat removal, tritium breeding and neutron shielding. ITER, by contrast, will not be fitted with a complete BB; instead, it will host TBMs tasked with testing and validating different blanket concepts in fusion-relevant conditions. Data collected from these TBMs will be crucial for finalizing the development of the DEMO BB. In Europe, two leading BB concepts are under investigation: the Water-Cooled Lithium-Lead (WCLL) and the Helium-Cooled Pebble Bed (HCPB) options. So far, the WCLL solution has been preferred, i.e., more studied, since it leverages well-proven water-coolant based technology coming from the R&D and operation of Pressurized Water Reactors (PWR). Thus, the WCLL BB option simplifies integration with existing infrastructure, reduces development risks, and enhances overall operational safety.
Given the complexity of a DEMO-class BB, extensive TH analyses are indispensable. Such studies evaluate the component performance, robustness, and safety under both steady-state and transient scenarios. In this context, the Nuclear Engineering Research Group (NERG) of Sapienza University of Rome, in collaboration with ENEA, has embarked on a comprehensive simulation activity aimed at supporting the development of both ITER and DEMO by using the System Thermal-Hydraulic (STH) code RELAP5/Mod3.3.

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