Nuclear Science and Technology Symposium - SYP2022
Helsinki, Finland, 1-2 November 2022

Nuclear Technology Activities under ECO-Fusion Project – What is Needed to Design a Fusion Power Plant?

Antti Hakola, Marton Szogradi, Sixten Norrman, Timo Aalto, Markus Airila, William Brace, Juuli Huuhanmäki, Petteri Lappalainen, Anssi Laukkanen, Tapani Ryynänen, Antti Salmi, Olli Soppela, Tomi Suhonen, Tuomas Tala
VTT Technical Research Centre of Finland Ltd.
P. O. Box 1000, 02044 VTT, FINLAND
antti.hakola@vtt.fi

ABSTRACT

We discuss the activities and advances made within the *ECO-Fusion project* whose goals are to promote nuclear fusion R&D in Finland and to build a top ecosystem to involve Finnish companies in different fusion tenders and research projects. Work is carried out on several fronts, including remote maintenance, novel materials, balance-of-plant studies, safety of the fusion reactors, and ecosystem research. Links to nuclear technology are strong, a concrete example of those is applying the Apros code in transient analyses of the European DEMO reactor. Several of the developed solutions or components will find applications in other challenging environments such as fission reactors.

1 INTRODUCTION

Nuclear fusion is expected to produce baseline energy to meet the continuously growing need of clean electricity by the end of the century. The present fusion roadmap consists of first proving the scientific and technical feasibility of fusion in the international ITER reactor within the next couple of decades and then proceed to demonstrating net production of electricity in a DEMO reactor (DEMOnstration power plants). Finland is heavily involved in the R&D activities of ITER and European DEMO, both being coordinated and funded in the European level by the EUROfusion consortium. ITER and DEMO are large research programmes where tight collaboration between several different science and technology areas is required. This contribution introduces how the new Finnish *ECO-Fusion project* promotes this collaboration, with special focus put on the nuclear-technology front.

2 OVERVIEW OF ECO-FUSION

ECO-Fusion is a 3-year (2021-2023) co-innovation project, funded by Business Finland, where VTT, University of Helsinki, and four Finnish companies (Comatec, EOS Finland, Luvata, and Platom) have joined their efforts in selected areas to advance fusion-related R&D and business opportunities in Finland. The VTT part of the project is the largest in volume and scope and is carried out in tight agreement with the EUROfusion work programme. The overarching goals from the VTT side are to facilitate the entry of Finnish companies into international fusion tenders and research projects, build a world-class fusion ecosystem in Finland, and advance the technological and business expertise of the partners through selected research activities.

Meeting the set objectives means that the spectrum of activities carried out under ECO-Fusion is broad, as summarized below. ECO-Fusion consists of five work packages, with the following themes:

- WP1: development of tools for remote maintenance of fusion power plants
- WP2: development of novel materials for fusion reactors and detailed analyses of neutron-irradiated fusion materials
- WP3: experiments in existing European fusion devices and subsequent analysis activities, development of new diagnostics for fusion reactors, and full-scale power-plant modelling using Apros
- WP4: safety in fusion power plants including risk analyses, waste production, and decommissioning
- WP5: supporting studies for the benefit of companies interested in involving in the fusion ecosystem

In the following a short overview of each of the WPs and a more detailed description of the application of Apros to fusion reactors are given.

3 ADVANCES IN ECO-FUSION

3.1 Remote maintenance strategy for systems in a challenging environment

The DEMO reactor is an example of a complex environment where the necessary maintenance is challenged by the limited available space, strongly radiating environment, and heavy loads of the components to be maintained. Under ECO-Fusion strategies are being developed to ensure rapid maintenance of DEMO such that several remotely controlled and autonomous systems can operate in parallel. This combines traditional engineering design with robotics and sensor technology, development of virtual reality tools, and careful monitoring of conditions in the remote maintenance systems. Up to now, most efforts have been devoted to collecting requirements and assessing the technologies available for maintaining and inspecting the most constrained sub-systems. Here, usage of drones and crawler solutions is expected to provide added value. The remaining challenge is combination of the different systems with human interaction.

3.2 New materials for irradiation environments

In the area of materials research, the focus is on implementing Integrated Computational Materials Engineering (ICME), carried out at VTT for several years, to the fusion-reactor design. This is foreseen to yield novel capabilities to tackle various materials related research and application challenges, such as finding new ways of controlling embrittlement and radiation-induced defects. Moreover, together with industry, additive manufacturing (3D printing) with tailored processes and materials is being applied for components in future fusion reactors and thus accelerate the traditionally slow development process from ideas into final solutions. Recent R&D highlights include developing models for assessing the characteristics of irradiated BCC metals and coming up with an optimized workflow for additive manufacturing of tungsten-based materials.

3.3 Sensor development

In collaboration with Danish Technical University (DTU) VTT is developing a new silicon-based sensor concept for measuring steady state magnetic fields in high radiation environments such as those in future fusion power plants. The novel idea is based on silicon optics where μm-sized waveguides are folded on a thumb-sized chip and aligned to measure the desired magnetic field component using the Faraday rotation phenomenon. The advantage of the concept is that is does not require any electronics in the vicinity of the measurement location, but all light sources (~1500 nm) and spectrometers can be situated in remote locations while optical fibers carry the input and output for the sensor. At present, multiple versions of individual components have been designed and manufactured and are now being characterized. After the manufacturing recipes for the optimal components (e.g. straight waveguides, bends, delay lines, multiplexers) are finalized they will be joined together to enable sensor operation.

3.4 Safety in fusion reactors

Safety is an integral part of operating nuclear facilities, and fusion power plants are no exceptions to the rule. In this field VTT is contributing to several sub-areas including waste production, risk assessment, and overall plant safety. Recent advances include assessing the generation of liquid radioactive waste in a fusion power plant. Here, the most important waste streams and process options have been identified and technology readiness estimates for their further processing have been determined. Another example is related to fire safety where several high-risk areas in a power plant have been considered and simulations have been made to determine the effects of a fire on its surroundings and the possibility for releasing dangerous materials to the environment. In a recent study case, the LiPb component room of a fusion reactor was considered, and acceptable fire safety levels were possible with the designed fire protection systems.

3.5 Supporting companies interested in fusion business

The ecosystem research elaborates around the problem of Finnish companies not extensively participating in Big Science projects such as ITER or DEMO. Interviews have been conducted with Finnish companies to understand why this is the case and to identify challenges and needs of companies. For example, the actual offer phase, resource intensity of Big Science projects and not knowing the possibilities that these projects provide have been recognized. Additional input has been gathered by interviewing international Big Science consortia and companies. System dynamics modelling is an integral part in the work to improve the participation and it has been progressed as a workshop exercise with relevant experts.

4 APROS FOR DEMO DESIGN

The Advanced Process Simulation software (Apros), developed by VTT and Fortum, has been utilized heavily in transient analyses of various DEMO plant configurations [1, 2, 3]. Within EUROfusion, Apros has been applied for balance-of-plant studies and integral thermal-hydraulic models have been developed for subsequent iterations of the Helium-Cooled Pebble-Bed (HCPB) and Water-Cooled Lithium-Lead (WCLL) breeding blanket (BB) concepts. Each lumped parameter plant model entails the blanket-specific Primary Heat Transfer Systems (PHTS), the Power Conversion System (PCS) and the Energy Storage System (ESS). Control systems have been also developed, deploying the automation library components of Apros.

The helium-cooled breeding blanket PHTS features two representative (inboard and outboard) segments with adjacent piping and compressor pairs. This variant supplies the turbine with high-pressure and temperature steam achieving higher cycle efficiencies than its water-cooled counterpart [2].

The current WCLL BB model depicts a 22.5° sector of the fusion device with two identical inboard and three outboard segments. Each segment is divided into 7 regions, following the spatial discretization trends of other high-fidelity physics models. These regions compose thermal-hydraulic interfaces, first wall (FW), breeding zone (BZ) and vacuum vessel (VV) modules, which have been represented by custom-made user components in Apros [3].

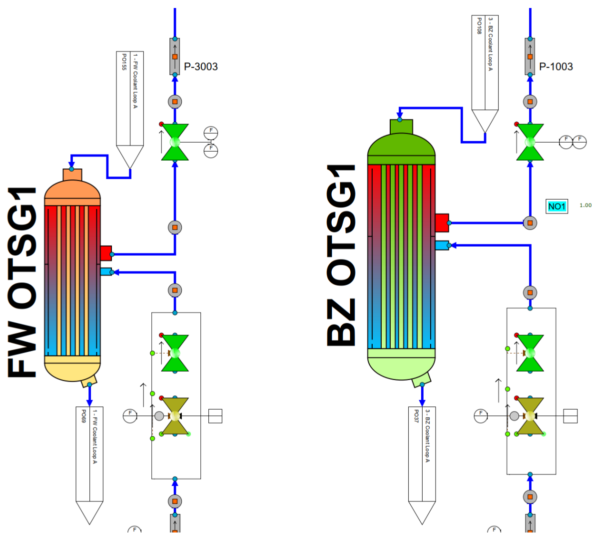

Figure 4.1 Steam generator pair of the WCLL plant in Apros.

The power conversion system employs basic process components from the Apros library, e.g. pumps, counter-current heat exchangers, high- and low-pressure turbine stages, condensers. The system is coupled to the PHTS via the steam generators. Concerning the HCPB configuration, 8 helical-coil steam generators (user components) connect the 8 helium-cooled loops to the secondary system. The WCLL plant operates with two pairs of Once-Through Steam Generators (OTSGs), each pair consisting of a FW and a BZ steam generator (see Figure 4.1).

The energy storage system integrates cold and hot molten salt (HITEC) reservoirs with the corresponding piping, electrical heater and pump stations. The purpose of the ESS is to bridge the input power gap during dwell for the PCS while only the decay heat is available from the PHTS. Thermal-hydraulic nodes, containing HITEC and helium, are using a 3-eq. solution whereas nodes, containing water, utilize a 6-eq. solution. In its last version, an argon-based pressure control system has been developed for both HCPB and WCLL models. The operation of the HCPB small ESS is illustrated in Figure 4.2 where the charge and discharge periods of the molten salt tanks are compiled. During dwell-phase the hot tanks discharges its excess enthalpy into the PCS to feed the turbine with fresh steam, during pulse the hot tank is recharged with flow coming from the cold tank.

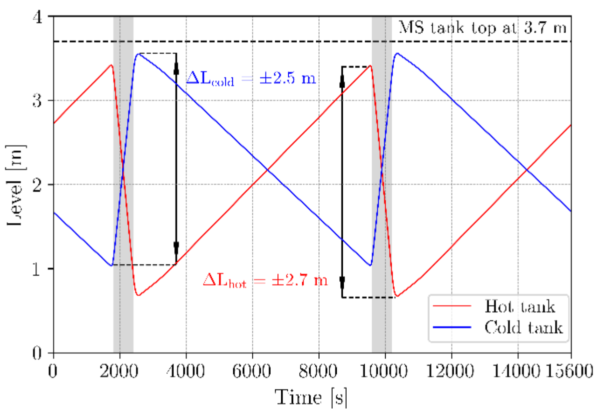

Figure 4.2 Cold and hot salt storage tank levels in the small ESS of the HCPB plant [2].

Recent activities include development and stability analyses of various steam generator concepts for the WCLL direct coupled plant. Once-Through Steam Generator (OTSG) and Internal Economizer Once-Through Steam Generator (IEOTSG) components have been conceived for the BZ and FW coolant loops, building on earlier designs. These SG-related tasks are a part of the general integral plant model updates which foresee brand new power distribution maps and a new WCLL PHTS arrangement. Figure 4.3 depicts the linear behaviour of the BZ OTSG components with respect to power and feed water mass flow rate. Strategy 1 refers to a feedwater control valve regulation where the primary system average temperature is maintained during the transient by SG feedwater flow rate control. Strategy 2 denotes another approach where the minimum (SG outlet) primary temperature is prioritized by the SG feedwater control function during power ramps.

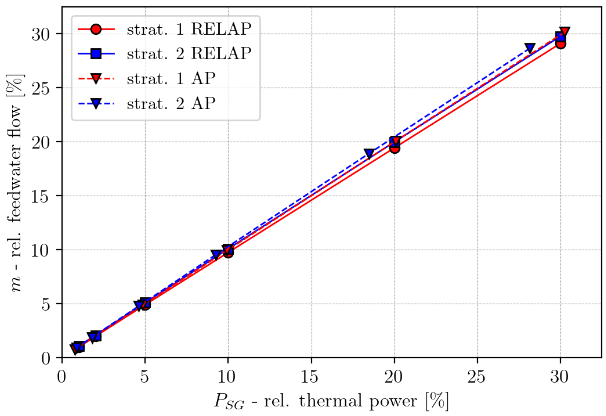

Figure 4.3 BZ OTSG relative power and feedwater flow rate trends, featuring RELAP5/Mod3.3 and Apros results.

An ongoing activity is the development of a novel multiphysics calculation chain, featuring a neutron source integrator (ASCOT-AFSI), module for burnup calculations in the reactor (Serpent) and Apros as the thermal-hydraulic block [4]. Fusion product distributions have previously been calculated for flat-top conditions in order to provide input for the coupled neutron-photon transport simulations with Serpent. These models consider heterogeneous CAD-based geometries to describe the breeding blanket. Synthetic detectors collect nuclear response data e.g. fluxes and power deposition (see Figure 4.4). Afterwards the tallies can be converted and implemented in the Apros blanket model as time-dependent power functions, defining the heating of the solid heat structures of the breeding units.

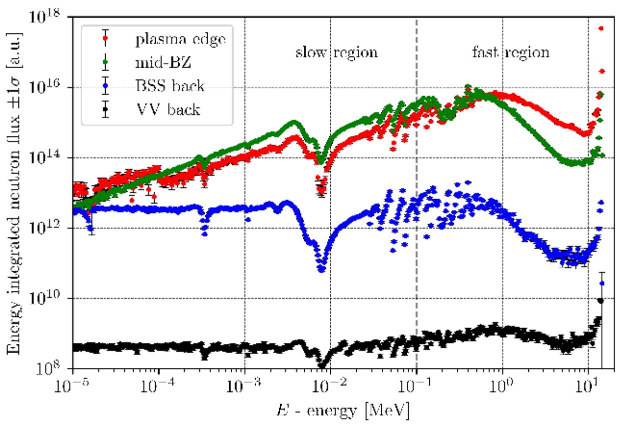

Figure 4.4 Neutron spectra at various radial planes of the equatorial breeding unit (BU) in Serpent [4].

5 CONCLUSIONS

In this paper, we have introduced the ECO-fusion project whose goals are to promote high-quality research in the field of nuclear fusion and build a top ecosystem for Finnish companies, research organizations and universities to become more active participants in Big Science projects including ITER and DEMO. Work is carried out on several fronts, including remote maintenance, novel materials, modelling for fusion reactors and power plants, plant safety, and ecosystem research. The links to nuclear technology are strong as evidenced by the application of the Apros code in transient analyses in various DEMO configurations. The project will continue until 2024 and further progress made in the different work packages will be reported after the project completion.

ACKNOWLEDGEMENTS

Part of the work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. Financial support from Business Finland is acknowledged.

REFERENCES

[1] "Apros Official website," VTT Technical Research Centre of Finland Ltd., Espoo, 2022

[2] M. Szogradi, S. Norrman, "Model development and transient analysis of the HCPB BB BOP DEMO configuration using the Apros system code," *Energies,* vol. 14(21), p. 7214, November 2021.

[3] M. Szogradi, S. Norrman, "Model development and transient analysis of the WCLL BB BOP DEMO configuration using the Apros system code," *Energies,* vol. 14(18), p. 5593, September 2021.

[4] M. Szogradi, A. Snicker, "The development of a novel particle transport and thermal-hydraulic calculation chain for the European DEMO, Submitted: 04.05.2022," *Fusion Engineering and Design,* 2022.