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DEVELOPMENT OF MULTIPHYSICS, SEMI-AUTOMATIC, AND MULTISCALE TOOLS FOR BREEDING BLANKET DESIGN

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Acronyms

ACB Advanced Ceramic Breeder

APDL ANSYS Parametric Design Language

BB Breeding Blanket

BC Bottom Cap

BSS Back Supporting Structure

BZ Breeding Zone

CAD Computer Aided Design

CS Cooling Stiffener

CSG Constructive Solid Geometry

DCLL Dual-Coolant Lithium-Lead

DEMO DEMOnstration fusion power reactor

EMBEE Embedded Elemental Edits Control

FEM Finite Element Method

FoM Figure of Merit

FPR Fusion Power Reactor

FW First Wall

HCPB Helium-Cooled Pebble Bed

HELIAS HELIcal-axis Advanced Stellarator

HeM Heterogeneous Model

HoM Homogeneous Model

HTC Heat Transfer Coefficient

ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
MCNP	Monte Carlo N-Particle
MFR	Mass Flow Rate
NWL	Neutron Wall Loading
PRD-SPPS	Prospective Research and Development – Stellarator Power Plant Studies
R&D	Research and Development
SB	Segment Box
SP	Stiffening Plate
SW	Side Wall
TBR	Tritium Breeding Ratio
TC	Top Cap
tokamak	TOroidal'naya KAmera s MAgnaitnymi Katushkami
VV	Vacuum Vessel
W7-X	Wendelstein 7-X
WCLL	Water-Cooled Lithium Lead
WLCB	Water-cooled Lead Ceramic Breeder
WP	Work Package

Abstract

Nuclear fusion reactors could be a long-term solution to the world's energy supply problem. However, this technology has several critical points that have not yet enabled its industrial deployment, such as fuel supply and the machine operating conditions from the point of view of the physical phenomena involved, either in terms of neutronics or thermohydraulics and thermomechanics.

One of the key components of a nuclear fusion reactor that will have the fuel production function for its self-sufficiency is the breeding blanket. Given the complexity of this component and the multi-physical nature of the loading conditions under which it will operate, it is easy to conclude that its design studies require a complex approach that typically consists of several phases. The first phase involves the study of the component's nuclear response that provides the thermal power data deposited by neutrons and photons in order to proceed, in the second phase, to the study from the thermohydraulics point of view. This allows to evaluate a temperature spatial distribution that is arisen in the component to be provided as input, together with the other mechanical loads, for the evaluation of the proposed design solution's structural performance. Lastly, the results obtained are compared with the reference standards to determine whether the component studied is capable of operating under the expected loading scenarios without incurring incipient structural crisis conditions or, in any case, without violating any of the imposed design requirements. This *modus operandi* is typically characterized by two major bottlenecks which are the use of different computational software and the need to start over with all the calculation when one is faced with the need to make geometric changes, thus involving a considerable computational and time burden. Hence, the objective of the following PhD thesis is to define two methodologies to study the interconnected phenomenologies involved during the deployment of the breeding blanket to arrive at a design definition and verification.

The first chapter will give a brief description of the fusion reaction, the breeding blanket, and the roadmap defined by the EUROfusion consortium for the coming years for the development of this technology. Both the study of neutron transport and the thermomechanical problem will also be explored from a theoretical point of view.

The second chapter, on the other hand, presents a multi-scale and semi-automatic

methodology coupling neutronics and thermal analysis that allows, starting from a radial power density profile and a neutron source from which it is derived, to obtain a tubular and/or plate design of a breeding blanket portion located anywhere in the reactor. The procedure, at first, is explained in detail in each of its steps, starting from the generation of a first attempt geometry through a simplified approach developed in MATLAB and then verified with ANSYS parametric design language, to its neutron analysis, using the Monte Carlo N-Particle code with use of unstructured mesh. Once the definition of the procedure and its validation are completed, it is applied to a particular breeding blanket architecture, namely the Water-cooled Lead Ceramic Breeder. The results validated the methodology and made it possible to exploit one of the generated geometries for a parametric study on the influence of the blanket material composition with respect to the tritium breeding ratio. A total of nineteen models were studied with the same neutron boundary conditions by varying the composition first of the first wall then of the breeding zone allowing noteworthy results to be obtained. It has been shown how, the use of materials with moderating qualities, can lead to a greater exploitation of tritium breeding reaction from lithium 6 in the first 40 cm of breeding zone and to a greater overall tritium breeding ratio of the local model, allowing a possible reduction of the radial breeding blanket thickness.

The third chapter describes another multi-scale and semi-automatic methodology for the study of a particular stellarator-type nuclear fusion reactor, which by nature has a very high geometrical complexity. In particular, the procedure follows a back-and-forth flow in which, starting from local thermal analyses, thermal fields are derived, which are then averaged to obtain average temperatures to be associated with the components of a less detailed global model in order to study it at the structural level while maintaining the actual boundary conditions of the system. Once the results of this analysis are derived in terms of displacements, they are then applied as boundary conditions for the local model's mechanical analysis. Lastly, it is validated from a mechanical point of view through the application of RCC-MRx code rules. The methodology was applied to a DEMO Dual-Coolant Lithium-Lead breeding blanket architecture adapted to the HELIAS 5B geometry, which was examined for this study. The results, which are not relevant from a design point of view since that it wasn't the main objective, showed how the procedure is highly versatile and functional, making it a viable alternative for future studies in the field of stellarator-type reactors.

Both activities were developed through the use of codes written with different programming languages, Python being the main one, and some of the most important have been listed and explained in the appendix.

Introduction

Nuclear fusion reactors could be a long-term solution to the world's energy supply problem. In fact, this technology has many positive sides including the emission of inert and nontoxic substances such as Helium, no radioactive waste with high decay periods, and the inherent level of safety it possesses compared to, for example, nuclear fission. In fact, unlike the latter, fusion is not a process that can be self-maintained but rather it requires certain plant conditions to be achieved in order to take place, which if not maintained over time would lead to the reactions stoppage.

However, this technology has several critical points that have not yet enabled its industrial deployment. The first among them is undoubtedly fuel supply. In particular, wanting to exploit the nuclear fusion reaction with the highest cross section, namely that between deuterium and tritium, it would be necessary to have both of these hydrogen isotopes in sufficient quantities for years to come. While deuterium is easily obtained from, for example, seawater, tritium does not exist in nature and has a decay period of about twelve years. In addition, the operating conditions of the machine, as previously mentioned, lead to the need to properly study the reactor components under extreme working conditions from the point of view of the physical phenomena involved, either in terms of neutronics or thermohydraulics and thermomechanics.

The component of a nuclear fusion reactor that will have the tritium production function for its self-sufficiency is the breeding blanket. Numerous designs have been thought of for its development, but they all have common points. In particular, it is important that there must be a material with tritium-breeding properties, which in the specific case is lithium, a neutron multiplier, a coolant to extract power from the system and a structural material. Given the complexity of a component such as the breeding blanket and given the multi-physical nature of the loading conditions under which it will operate, it is easy to conclude that its design studies, and of all other plasma-exposed fusion reactor components, require a complex approach that typically consists of several phases. Typically, the first phase involves the study of the component's nuclear response that provides the thermal power data deposited by neutrons and photons in order to proceed, in the second phase, to the study from the thermohydraulics point of view. This allows

to evaluate a temperature spatial distribution that is arisen in the component to be provided as input, together with the other mechanical loads, for the evaluation of the proposed design solution's structural performance. Lastly, the results obtained are compared with the reference standards to determine whether the component studied is capable of operating under the expected loading scenarios without incurring incipient structural crisis conditions or, in any case, without violating any of the imposed design requirements. This *modus operandi* is typically characterized by two major bottlenecks. The first is represented by the use of different computational software, one for each physical aspect of the problem, each of which is characterized by its own peculiarities and a certain degree of approximation, which therefore inevitably leads to a loss of information in the transition from one phase of the analysis to another. The second derives from the fact that, precisely because of this analytical differentiation, when one is faced with the need to make geometric changes to the proposed solutions, in most cases it will be necessary to restart from the first stage of the analysis procedure, with the obligation to carry out all the analyses in cascade again, thus involving a considerable computational and time burden. In order to overcome these problems, it is essential to study in depth existing multiphysics tools, or to proceed with their development first-hand, in such a way as to allow the coupling of the different phases of the design procedure while maintaining the level of detail in the transition from one phase to another. Hence, the objective of the following PhD thesis is to define two methodologies to study the interconnected phenomenologies involved during the deployment of the breeding blanket to arrive at a design definition and verification.

The first chapter will give a brief description of the fusion reaction, the breeding blanket, and the roadmap defined by the EUROfusion consortium for the coming years for the development of this technology. Both the study of neutron transport and the thermomechanical problem will also be explored from a theoretical point of view.

The second chapter, on the other hand, presents a multi-scale and semi-automatic methodology coupling neutronics and thermal analysis that allows, starting from a radial power density profile and a neutron source from which it is derived, to obtain a tubular and/or plate design of a breeding blanket portion located anywhere in the reactor. The procedure is then applied to a specific breeding blanket architecture, and finally a parametric study is carried out with the objective of verifying the influence of materials and/or geometries on tritium production.

The third chapter describes another multi-scale and semi-automatic methodology for the study of a particular stellarator-type nuclear fusion reactor, which by nature has a very high geometrical complexity. Specifically, the procedure allows a local portion of breeding blanket to be studied from a structural point of view while taking into account global boundary conditions through a submodeling approach.

The methodology is then applied to a particular blanket architecture demonstrating its versatility as the plant solutions adopted changes.

Lastly, in the conclusions a brief summary of the main results obtained in the studies carried out is reported. Moreover, the thesis is supplied with an appendix listing the main Python codes developed and used for both studies, with a brief explanation of how they can be applied.

Chapter 1

The nuclear fusion reaction and its exploitation for the production of electricity

1.1 The fusion reaction

The thermonuclear fusion reaction is a process that consists on bringing two populations of reacting atoms to such a temperature that, thanks to the kinetic energy conferred to the particles, the repulsive Coulomb force, acting between the protons of different nuclei, is overcome and cause the so-called strong nuclear force to prevail, thus generating a new population of nuclei produced, with higher atomic number but with total rest mass different from the sum of the rest masses of the reacting nuclei [1]. The theoretical temperature for this phenomenon to take place is around one billion degrees Kelvin, corresponding to an average energy of atoms of about 0.1 MeV. However, with a view to the exploitation of this reaction in a power plant, where high reaction rates must necessarily exist, it is sufficient to bring the populations of combustible nuclei to temperatures of about tens of millions of degrees Kelvin (≈ 10 keV), since the kinetic energy value associated with such temperatures turns out to be an average value of a Maxwellian distribution and especially due to the so-called “quantum tunneling effect”. Under the conditions described, matter is in the state of plasma or ionized gas, in which separate electrons and ions can be found, constituting a globally neutral mixture that tends spontaneously to disintegrate. The difference in mass of the nuclei produced, can be translated in two ways. Indeed, if one tries to fuse two elements lighter than Iron, experimentally it is observed that the reaction produces energy; vice versa, the exact opposite happens. It is precisely from this consideration that discussions began on what was the best reaction that could be exploited for productive purposes. There are basically four basic conditions to enable this:

- it must be a process that is as exothermic as possible;
- it would be preferable to obtain Helium 4 (${}^4_2\text{He}$) as the product of the reaction, given its nature as an inert gas and its small specific atomic mass;
- it is necessary to choose reactants with a very low atomic number to prevent the repulsive force of the nuclei from being too high;
- it is necessary to limit the number of reactants involved to two because the density of the plasma obtainable on Earth is not high enough to allow for other solutions.

The most likely reaction, i. e., the one with the largest cross section (Figure 1.1), is the one that occurs between a Deuterium nucleus and a Tritium nucleus, in which a ${}^4_2\text{He}$ nucleus and a neutron are generated [1].

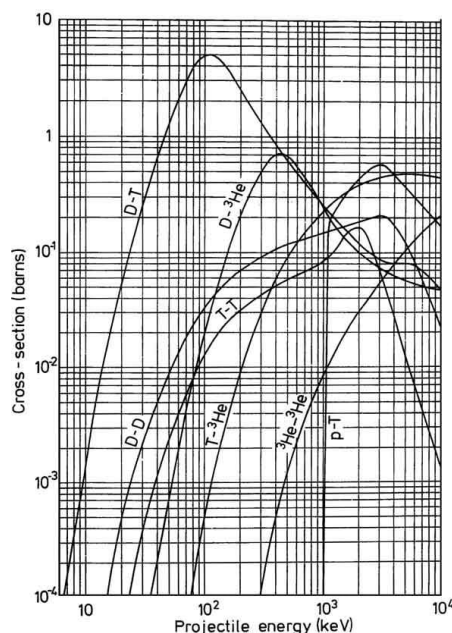
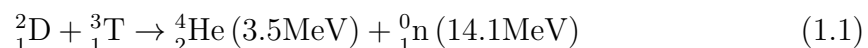


Figure 1.1: Cross-sections of different thermonuclear fusion reactions

In this reaction, the total mass of the products is less than the mass of the interacting particles, and energy release occurs according to the mass-energy equivalence principle. In particular it is distributed between the alpha particle and the neutron in inverse ratio to their respective masses:



Both Deuterium and Tritium are isotopes of Hydrogen. However, while the former is readily available in nature since it is also present in seawater, the latter is not, as it decays β^- with a half-life of 12.32 years. In view of the construction of a possible reactor using the thermonuclear fusion reaction as a source of thermal power generation, the supply of Tritium thus turns out to be a problem to be taken into account. The solution arrived at is to exploit “tritium breeding” reactions so as

to produce Tritium in situ and be able to utilize it in a short time, as it will be described in section 1.4.

1.2 Plant solutions

The nuclear fusion reactors based on the magnetic confinement can be designed according to TOroidal'naya KAmera s MAgnaitnymi Katushkami (tokamak) [2] or stellarator [3] concept. In this section, pros and cons of the two alternatives are summarized, giving an overview on their main features.

1.2.1 The tokamak magnetic confinement concept

The tokamak magnetic confinement system is characterized by planar coils (toroidal field and poloidal field coils) capable of generating, together with the central solenoid (inner poloidal field coils in figure 1.2), the magnetic cage to confine the plasma. In addition, other minor coil groups are necessary to locally adjust the plasma shape improving the confinement performances.

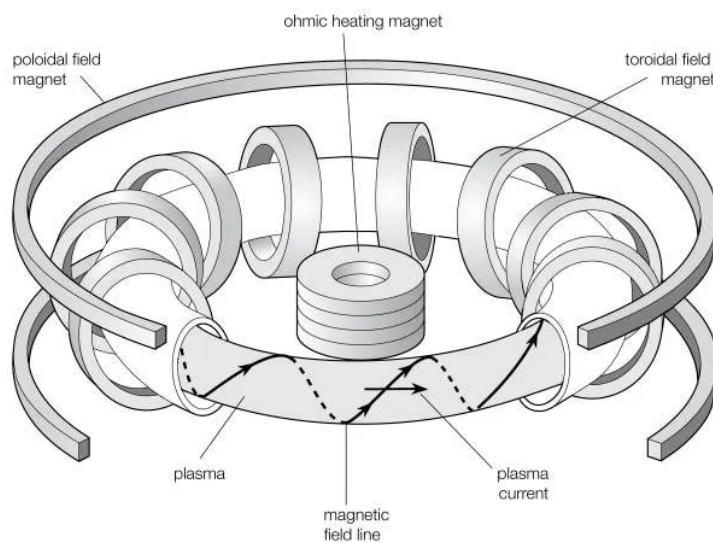


Figure 1.2: *The tokamak magnetic confinement system*

This type of system generates a purely toroidal plasma shape, with a high degree of symmetry. For this reason, the development of tokamak fusion reactors has been greatly facilitated. However, in order to guarantee the magnetic confinement of the plasma, a tokamak machine must necessarily work with a pulsed duty cycle. This is mainly due to the central solenoid operational mode, devoted to generating the plasma current which is responsible, in its turn, of the generation of the poloidal component of the confining magnetic field. Indeed, the central solenoid is fed with an increasing (over the time) current input, which must be stopped and inverted after a certain time to comply with the maximum current intensity the conductive material

can withstand. As a consequence, the steady-state working condition cannot be maintained for a long time in a tokamak machine. Hence, in case a steady state electricity production is expected to comply with the grid requirements, the power conversion system of a tokamak fusion reactor must be purposely designed, implying lot of design complications and the necessity of big auxiliary systems. Moreover, the presence of an intense plasma current (necessary to obtain the confinement) leads to the arising of plasma instabilities leading to the loss of confinement and the sudden shut-down of the machine.

1.2.2 The stellarator magnetic confinement concept

The stellarator magnetic confinement system (figure 1.3) is characterized, instead, by non-planar coils and the absence of the central solenoid. Hence, the confined plasma shows a purely helicoidal shape and, consequently, symmetries are hard to find in such a kind of system. Also, in this case there are minor coil groups (some of them are planar), necessary to locally improve the confinement. As well as in tokamak the simple shape of the plasma allows designing symmetric components, the helicoidal shape of the stellarator plasma implies that the reactor components must have a quite complicated geometric layout. This has made tokamak machines design much more advanced than stellarator ones. Anyway, since the central solenoid is missing in stellarator, this kind of system is able to sustain fusion reactions in a stationary regime, simplifying a lot the design of the power conversion system to fulfill the grid requirements. Moreover, the absence of plasma current, makes the plasma more stable than in a tokamak allowing a better management and control of the magnetic confinement system, reducing the expected number of plasma's off-normal events (such as ELMs and disruptions) leading to the loss of confinement.

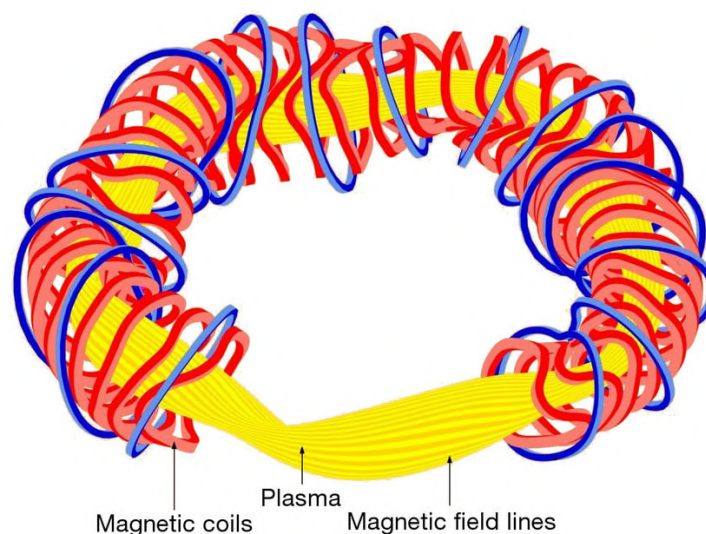


Figure 1.3: *The stellarator magnetic confinement system*

1.3 The European roadmap

In order to promote and coordinate Research and Development (R&D) activities relevant to fusion reactors development and funded by Horizon 2020 programme, the EUROfusion consortium has been created thanks to the joint effort of European universities, laboratories, industries and research centers. The EUROfusion consortium has issued in 2013 [4] and up to date in 2018 [5] a European roadmap to the realization of fusion energy, aimed at depicting the work-plan and the milestones towards the realization of the nuclear fusion power plants. The R&D programme for the realization of a thermonuclear fusion reactor has been divided by the scientific community into four phases, each of which has a specific aim, which are focused respectively on the scientific, engineering and economic feasibility and finally on the operational aspect.

The first phase of the R&D programme aims to demonstrate the scientific feasibility of the thermonuclear fusion reaction in a controlled manner. This has already been achieved through the construction and operation of tokamak machines, the most important of which is Joint European Torus (JET), located in England and in operation since 1983 [6].

The engineering feasibility phase is aimed at assessing the possibility of recovering the energy produced, verifying the performance of the structural materials, the cost-effectiveness of producing the magnetic fields for confining the plasma, and the producibility of tritium in the required quantities. The project on which the research is focusing is called International Thermonuclear Experimental Reactor (ITER) [7]. It involves the construction of the ITER reactor in Cadarache, in the south of France, which is scheduled to be operational in the next years.

At the same time as the ITER project is progressing, pre-conceptual research and design work is underway on the DEMOnstration fusion power reactor (DEMO) reactor [8], whose task will be to demonstrate the technological and commercial viability and thus the economic competitiveness of electricity generated by nuclear fusion. DEMO is the final step in the testing process and its construction data will be very close to those of the final thermonuclear fusion reactors.

Finally, the operational phase, should coincide with the construction of the first commercial reactors, known as Fusion Power Reactors (FPRs).

As far as stellarator machines are concerned, however, the feasibility of this technology on a larger scale than the laboratory scale has so far only been demonstrated through the construction of the Wendelstein 7-X (W7-X). This is the largest stellarator reactor currently in operation, located at the Max Planck Institute for Plasma Physics in Greifswald, Germany, and was built and operated by the W7-X team.

At present, the EUROfusion strategy considers the tokamak as the main reactor line whereas the stellarator is studied in parallel, albeit with a less amount of

resources employed as it represents the long-term alternative to the tokamak. Nevertheless, bringing stellarator line to maturity is one of the milestones of the EUROfusion roadmap [5] (figure 1.4). Indeed, although DEMO is already within its design phase, even if at the pre-conceptual level, the stellarator equivalent reactor called HELical-axis Advanced Stellarator (HELIAS) is still at the stage of conceptual study which is previous to the design phase. This means that the studies performed so far on HELIAS reactor, represents conceptual assessments aimed at paving the way for the future design activities. To try to bridge this gap, it was prescribed by the roadmap to export what has been done for DEMO and adapt it, as far as possible, to the stellarator machines.

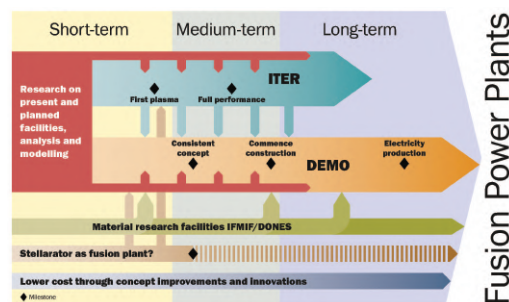


Figure 1.4: *EUROfusion roadmap timeline*

1.4 The breeding blanket

A nuclear fusion reactor is composed by in-vessel and out-vessel components [9]. Typically, the in-vessel components (blanket, divertor, limiters, heating and current drive, fueling lines, diagnostic cassettes, etc.) must be designed to withstand the intense radiation fields and neutronic spectra generated by the plasma, together with further loads exerted by a wide range of occurrences such as electro-magnetic fields, cooling fluids flowing, interfaces with adjacent systems, plasma disruptions and so on. In this context, as the blanket covers the majority of the in-vessel plasma facing surface, its design drives the development of the whole machine. Moreover, if the blanket has to breed Tritium as well, the endeavour to attain a robust enough design requires a joint effort by the whole international scientific community, because of its terrific complexity. To this end the European Commission, through the Euratom, funds research activity on the fusion technology carried out by the EUROfusion consortium. In this framework, the design of the Breeding Blanket (BB) is one of the biggest projects because of its importance in the general design of a fusion reactor like DEMO or HELIAS.

The BB is a key component for those nuclear fusion reactors devoted to produce electricity at industrial scale. It is used for the on-site production of Tritium, the basic reagent for D-T reactions, by means of tritium breeding with Lithium, which

has proved to be the most promising element for this purpose. In particular, there are two reactions involving two lithium isotopes (${}^6_3\text{Li}$ and ${}^7_3\text{Li}$) that are currently been considered (figure 1.5):

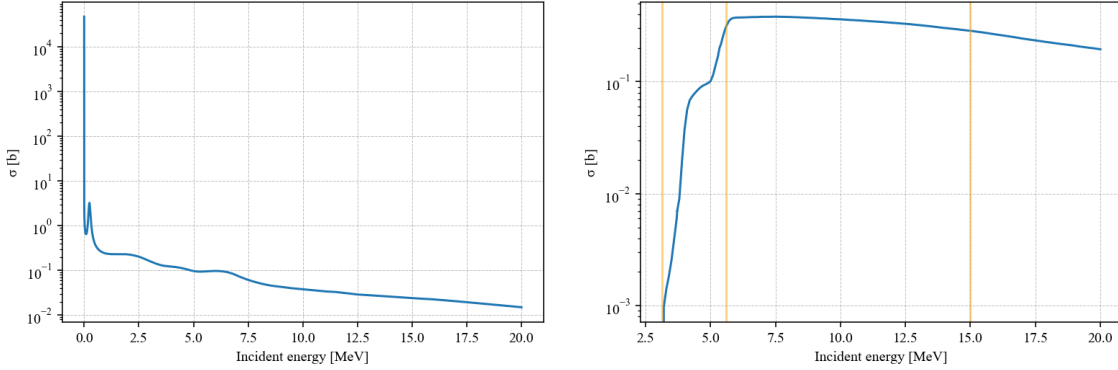
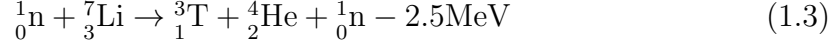


Figure 1.5: *Lithium 6 (left) and Lithium 7 (right) (z,Xt) cross sections [10]*

Hence, the BB must contain Lithium or its alloys to allow tritium breeding and, possibly, a neutron multiplier to increase the Tritium breeding efficiency. The BB is also in charge of the shielding of the Vacuum Vessel (VV) and the reactor magnets from the electromagnetic radiation and the neutrons coming from the plasma. Indeed, shielding the VV allows complying with the safety requirements on the vessel welding, whereas shielding the magnets allows them operating in super-conductive state, which is a must for the generation of the proper confining magnetic field. Last but not least, the BB is also the key component devoted to recover the energy produced by the nuclear fusion reaction, which is radiated from the plasma and transported by neutrons. Gammas and neutrons deposit their energy within the BB structures (the above said shielding requirements impose that almost all the energy must be released within BB structural and functional materials). Hence, a cooling fluid must flow through BB components, removing this power which is converted, after multiple passages, into electricity downstream the BB. Over the years, the scientific community has examined different BB concepts to adopt in fusion reactors [11], but all of them share the same basic structural characteristics:

- the First Wall (FW) is the component directly facing the plasma, mainly devoted to remove the heat power radiated from it;
- the Breeding Zone (BZ) is the region where the neutron multiplication and tritium breeding reactions take place, which consequent deposition of the neutrons kinetic energy to be removed by dedicated cooling systems;

- the Back Supporting Structure (BSS) is what acts as the primary structural support and channel through which the system's cooling fluids can flow;
- a tungsten layer to protect the FW against sputtering and erosion by charged plasma particles;
- plates of different thickness and orientation which can have various roles (typically strengthening the segment and removing heat) depending on the breeding blanket concept considered.

Concerning the European researches on the fusion technology, funded by the European Commission and carried out by the EUROfusion consortium, two BB concept have been selected, among all those analyzed, for the next conceptual design phase of the DEMO reactor: the Helium-Cooled Pebble Bed (HCPB) [12] and the Water-Cooled Lithium Lead (WCLL) [13]. Nevertheless, evaluations are ongoing about hybrid variants between these two configurations, such as the Water-cooled Lead Ceramic Breeder (WLCB) [14], which will be described in more detail in chapter 2.

1.5 Theoretical digression

For the multiphysical study of the BB, it is necessary to have a deeper understanding of the phenomena governing its operation during reactor deployment. In particular, it will be essential to analyze its nuclear, thermohydraulic and thermo-mechanical response, through the use of numerical methods that allow to outline its design trying to predict its strengths and possible criticalities in order to identify the one that may represent the best choice. In particular, in the following paragraphs a brief digression will be made on how the nuclear and thermomechanical problems are addressed, through a quick theoretical excursus aimed at making clearer what is going to be described in the following chapters.

1.5.1 The Monte Carlo method and the nuclear problem

The “Monte Carlo” is a numerical method that approximates the solution of a considered problem statistically, simulating its probabilistic processes and thus providing an answer relative to the average behavior of the physical system under investigation, by means of the central limit theorem. This method is thus significantly different from other numerical methods (finite differences, finite elements and so on), since while Monte Carlo discretizes the field function and considers a continuum the space of phases required to characterize the system, conventional numerical methods consider the field function continuous and discretize the space of phases [15, 16]. To better explain that, let's consider the problem of the nuclear particles behavior in matter. The governing equation for such

phenomenology is a differential transport equation whose solution is approximated by deterministic methods by partitioning the phase space into a number of subdomains where the reference quantities are considered constant and through which the solution of the equation can be brought back to that of an algebraic system. The Monte Carlo method provides an answer to the same problem without solving any equations but by individually simulating the path of particles, transporting them from one event to another, each separated in space and time from the other, and recording some aspect of their behavior. The average behavior of the particles in the physical system is then deduced according to the central limit theorem. It is, on the other hand, demonstrated [17] that the average answer of a Monte Carlo calculation approximates the solution of the transport integral equation, i. e., to the limit, for the number of simulated particles tending to infinity it coincides with the exact solution of that equation. It is noted that the differentials of space and time are not among the characteristic parameters of the Monte Carlo method, it is then understood how this method is particularly suitable for solving those problems, independent of time, characterized by complicated three-dimensional geometries. Thanks to the rapid improvement of hardware resources that have greatly reduced computational time, today the Monte Carlo method is used in various application as the design of nuclear fission and fusion reactors, cancer therapy, predictions on the performance of financial indices and so on. As can be seen, the applications are the most varied and particularly concern those physical systems whose nature is inherently probabilistic.

1.5.2 The MCNP code

The Monte Carlo N-Particle (MCNP) program is a computational code based on the Monte Carlo method that was created and developed by Los Alamos National Laboratory in the United States [18]. It can be used to address the neutron, photon and electron transport problem and allows the calculation of eigenvalues in critical systems. The code makes it possible to reproduce arbitrary three-dimensional geometries by schematizing them with elementary cells bounded by first and second-order surfaces and elliptic tori and cones that are fourth-order (Constructive Solid Geometry (CSG) approach), or through the use of an unstructured mesh, appropriately generated in the form of Abaqus [19] input. For neutrons all reactions predicted by the cross-section libraries are taken into account, in particular for thermal neutrons “free gas” models are also used to account for thermal agitation of the target nuclei and in some cases $S(\alpha, \beta)$ to also consider the effect of chemical bonds. For photons, the code takes into account both coherent and incoherent scattering, the possibility of fluorescent emission as a result of photoelectric absorption, absorption by the pair effect and the subsequent emission of annihilation radiation, and braking radiation. A continuum-slowning model is adopted for

electrons, and positrons, x-rays emitted by rearrangement of k orbitals and braking radiation are covered but the effects of external or self-induced electromagnetic fields are not considered.

1.5.2.1 Data and nuclear reactions

The MCNP code uses libraries of nuclear and atomic data with continuous energy spectra obtained in well-known U.S. research laboratories (Livermore, Oakridge, Los Alamos and others). The libraries include collections of nuclear data obtained experimentally and reprocessed in a form suitable for use by the program. There are nuclear data tables relating to neutron interactions, neutron-induced photons, photon interactions, activation, neutron dosimetry, and $S(\alpha, \beta)$ scattering of particles in thermal equilibrium. Over five hundred tables of neutron interactions are available, approximately for one hundred different isotopes while tables for photon interactions exist for all elements with atomic numbers between one and ninety-four i. e., from hydrogen to plutonium. For dosimetric analyses, cross sections are available for about two thousand activation reactions with about four hundred target nuclei in the fundamental or excited state; these cross sections can be used as energy-dependent response functions, but cannot be used as transport cross sections. Specific data libraries are also available at different temperatures for heavy and light water, beryllium metal, beryllium oxide, benzene, graphite, polyethylene, and zirconium.

1.5.2.2 Particle sources

MCNP allows the user to define the characteristics of the particle source. It makes available some specific energy distributions (Watt spectrum, Maxwellian, Gaussian) and allows the user to define probability distributions related to the parameters that define the source itself such as energy, position, and volume or surface direction and so on. Also contemplated is the possibility of being able to use sources created completely by the user externally to the code, by modification of subroutines intended for the purpose.

1.5.2.3 Tallies and results

The user can have the code record particular magnitudes or events (tally) correlated with current or particle flux and energy deposition, these tallies are then normalized per source particle except in a few specific cases related to criticality calculations. Quantities such as the number of fissions, of absorptions, the production of some particular nucleus as well as all those expressible as the product of flux by a cross section or a generic response function can be calculated. In fact, any quantity can be estimated that has the form

$$\int \Phi(E) f(E) dE \quad (1.4)$$

where $\Phi(E)$ is the fluence as a function of energy and $f(E)$ is a product or sum of cross sections or a user-supplied function. In addition, tallies can be defined on cell segments or surfaces without requiring them to be part of the geometry provided in the input and can be partitioned according to the energy, direction, or origin (surfaces, cells) of the particles contributing to its estimation. In the output in addition to the tally, much information is provided summarizing the performance of the simulation, various physical quantities of interest, and tables (tallies fluctuation charts) indicating the confidence level of the results (tally) by providing the outcomes of ten tests and the value of the main statistics, i. e., mean, error, variance of variance, slope, Figure of Merit (FoM) as a function of the number of stories.

1.5.2.4 Error estimation

As mentioned, each tally, i. e., the mean value of the magnitude of interest, is provided normalized per source particle; moreover, in the output, it is printed together with its own relative error R so defined:

$$R = \frac{S_{\bar{x}}}{\bar{x}} \quad (1.5)$$

where $S_{\bar{x}}$ is the standard deviation of $\bar{x}$ which is the mean value. MCNP calculates the quantities necessary for the estimation of R i. e., the mean and its standard deviation at the end of each Monte Carlo story as the various contributions to the tally from the same story are statistically correlated. It is observed that a good behavior of the tally trend with the number of stories requires that the error R is proportional to $1/\sqrt{N}$, where N is the number of stories. Estimation of the relative error allows calculation of the confidence interval associated with the mean and thus to make assessments about the truthfulness of the result obtained. In fact by virtue of the central limit theorem as N tends to infinity there is a 68% chance that the true result lies in the interval $\bar{x}(1 \pm R)$, 95% that it falls in $\bar{x}(1 \pm 2R)$ and so on. It is critically important to point out that this evaluation refers only to the accuracy of the Monte Carlo calculation and not to the accuracy of the result with respect to the physical value. This is a consequence of the uncertainties introduced by the available physical data such as the libraries of cross sections, sampling techniques i. e., the lack of actual randomness in the sequences of pseudo-random numbers, computational accuracy, and various other causes of deviation of the model from reality. Table 1.1 gives ratings regarding the degree of acceptability of the results with reference to their relative error.

It should be pointed out that the ratings given in the above table are meaningful only if the entire space of phases has been sampled in the Monte Carlo calculation.

The code to give an indication regarding the possibility of incomplete sampling of the phase space provides a FoM for each tally as the number of stories varies; this index is defined as follows:

$$\text{FoM} \equiv \frac{1}{R^2 T} \quad (1.6)$$

where T represents the computation time taken by the computer. For the same error the larger the FoM the more efficient the computation is because of the shorter time taken to reach that error value. Since R^2 is proportional to $1/N$ and T to N it becomes clear that the FoM should be constant as N increases, which is the more true the larger N is, so if examination of the tallies fluctuation charts shows a sharp decrease in the FoM then this would mean that a part of the phase space is sampled too rarely, which obviously negatively affects the evaluation of the expected value of the given magnitude and its error.

Table 1.1: *Guidelines for interpreting the relative error R*

Range of R	Quality of the Tally
0.50 to 1.00	Not meaningful
0.20 to 0.50	Factor of a few
0.10 to 0.20	Questionable
<0.10	Generally reliable
<0.05	Generally reliable for point detectors

1.5.2.5 Variance reduction techniques

Since variance is defined as the square of the standard deviation a reduction in it corresponds to a reduction in the estimated relative error R . It is noted that since R is proportional to $1/\sqrt{N}$ and T to N then it is found that $R = C\sqrt{T}$, where C is a constant dependent on the way the given tally is calculated. So in order to reduce R i. e., the variance, one can act either by increasing T (i. e., the number of stories) or by decreasing C . The first option is related to the computational capacity of the calculators and beyond a certain limit imposed on R is not feasible while the second option is to change the approach in Monte Carlo calculation as explained below.

The Monte Carlo calculation described in the previous paragraphs is the so-called “Analog Monte Carlo” and consists of following the random walks of particles without altering the probability laws to which they are subject while maintaining the analogy with the natural phenomenology of transport. Methods suitable for variance reduction have been developed that work in an alternative way: trying to follow more often particles that are “useful” for estimating results rather than all particles equally. These methods involve an alteration in the statistical weight of the particles it is therefore necessary to normalize the result for the individual random walk to its current statistical weight so that the final average result is not affected by the alteration suffered by the problem and is comparable with that obtained by

a conventional calculation. These techniques therefore, when used appropriately, make it possible to estimate the quantities of interest, with the same accuracy, in much less time than Analog Monte Carlo. The MCNP code contemplates four classes of techniques for reducing variance:

- Truncation methods. These are the simplest and consist of cutting out of the calculation all those stories that do not contribute to the formation of a tally because of their path in phase space (space cut-off; time cut-off; energy cut-off);
- Population control methods. These methods use particle multiplication techniques (splitting and Russian roulette) in order to control the number of particles that populate given regions of greatest interest in phase space;
- Modified sampling methods. These methods alter the sampling of certain quantities (emission direction, energy and so on) in order to “drive” more particles into regions of interest in phase space.
- Partially deterministic methods. These are the most complex; they modify the particle path with pseudo-deterministic techniques or control the sequence of pseudo-random numbers. It can be understood how the use of such techniques must involve special care in order not to incur serious biases.

In many cases the application of a variance reduction technique is not just a method of shortening computation time but a real necessity. An example of what has been stated is deep penetration problems, i. e., those in which it is necessary to estimate certain quantities in heavily screened areas where, that is, the population of particles is extremely sparse to obtain satisfactory results and increasing the number of stories is, therefore, not sufficient.

1.5.3 The thermomechanical problem

In order to carry out a thermomechanical analysis of a generic component it is necessary, under appropriate assumptions, to identify its thermal and mechanical state, knowing the loads to which it is subjected. If the thermal state is directly related to the temperature distribution, the mechanical state requires knowledge of the tensional and deformation fields and of the displacements [20]. However, the two problems are potentially coupled, thus causing a certain complexity in their resolution. Under appropriate assumptions, however, it is possible to decouple them in order to study them independently of each other, reducing the analytical burden. To be able to do this, the hypothesis of small displacements must be valid, i.e., assuming that the displacements are considerably smaller than the dimensions of the body considered. It will then be possible to calculate the temperature distribution inside the component and consider it as one of the stress terms for the subsequent resolution of the mechanical problem. Once both studies have been carried out, it

will finally be possible to compare the results obtained with the specific performance standards to which the component is required to obey and decide accordingly whether or not it can fulfill the task assigned to it.

1.5.3.1 The thermal problem

Given the geometry and the boundary conditions, under the assumptions of small displacements, the solution of the thermal problem leads to the determination of the temperature distribution in the body under examination. The fundamental law from which it is necessary to start is the conservation of energy equation, which describes the constraints to which our body must be subject in order for the variations of its energy to be coherent:

$$\frac{dE}{dt} = \dot{E}_{in} - \dot{E}_{out} \quad (1.7)$$

in which the time variation of energy must be equal to the net of all its forms of production and consumption. In addition to this equation, it is necessary to consider the fundamental law governing the transmission of heat by conduction in bodies and thus essentially the magnitude of heat flow ($\underline{q}''$) defined by Fourier's law:

$$\underline{q}'' = \underline{q}''_x + \underline{q}''_y + \underline{q}''_z = - \left(\lambda_x \frac{\partial T}{\partial x} \underline{i} + \lambda_y \frac{\partial T}{\partial y} \underline{j} + \lambda_z \frac{\partial T}{\partial z} \underline{k} \right) \quad (1.8)$$

where $\underline{i}$, $\underline{j}$ and $\underline{k}$ are the verses associated with the three spatial directions of the Cartesian reference system, and λ_x , λ_y and λ_z are the relative thermal conductivities. By means of a few mathematical steps we can, starting from equation (1.7), derive the expression of the heat diffusion equation:

$$\rho c_p \frac{\partial T}{\partial t} = -\nabla \cdot \underline{q}'' + q''' \quad (1.9)$$

where ρ denotes the density of the body, c_p its specific heat at constant pressure, and q''' is the heat power generated per unit volume. If we put equation (1.8) in system with equation (1.9) we obtain:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\lambda_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(\lambda_z \frac{\partial T}{\partial z} \right) + q''' \quad (1.10)$$

Furthermore, considering the assumptions of isotropy, homogeneity, and thermo-invariance of the physical and chemical properties, the three conductivities are equal to each other and the final expression we obtain is as follows:

$$\frac{\rho c_p}{\lambda} \frac{\partial T}{\partial t} = \nabla^2 T + \frac{q'''}{\lambda} \quad (1.11)$$

From this equation it will be possible to derive the trend of the thermal field as a function of space and time $T = T(x, y, z, t)$. As previously mentioned, this function

will be considered as one of the stress terms for solving the mechanical problem.

1.5.3.2 The mechanical problem

The mechanical problem aims to obtain the tensional and deformation state and the displacements to which a body is subjected due to external or internal stresses, whether thermal or mechanical in nature. The tensional state at a certain point of the body and at a certain time is represented by the stress tensor or stress matrix, which is a double tensor that can be expressed as:

$$\underline{\underline{\sigma}}(x, y, z, t) = \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix} \quad (1.12)$$

in which the elements on the main diagonal are the components of the tension vector normal to the planes defined by the main axes of the reference system considered, while the τ_{ij} (with i and j varying between x , y and z with $i \neq j$) represent the tangential components to the same planes.

The deformation state tensor can be represented as the tensional state with a 3x3 matrix and arises as a result of the application of both primary (mechanical) and secondary (thermal, neutron swelling and/or creep) loads. Its expression can be summarized as follows:

$$\underline{\underline{\varepsilon}}(x, y, z, t) = \begin{bmatrix} \varepsilon_x & \frac{1}{2}\gamma_{xy} & \frac{1}{2}\gamma_{xz} \\ \frac{1}{2}\gamma_{yx} & \varepsilon_y & \frac{1}{2}\gamma_{yz} \\ \frac{1}{2}\gamma_{zx} & \frac{1}{2}\gamma_{zy} & \varepsilon_z \end{bmatrix} \quad (1.13)$$

where the diagonal terms represent the linear deformations of the fibres along the principal axes of the reference system at a given point and instant, while γ_{ij} (with i and j varying between x , y and z with $i \neq j$) are the sliding between the fibres, initially in a condition of orthogonality between them but which due to the loads will change their arrangement. Finally, as far as displacements are concerned, they can be represented by a vector function dependent on space and time:

$$\underline{u}(x, y, z, t) = \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} \quad (1.14)$$

with u_x , u_y and u_z components of the above vector along the principal axes of the reference system, evaluated at a given point and instant. Using the assumptions of the Theory of Linear Elasticity, considering small displacements and infinitesimal deformations, the determination of the operators just described

can be simplified. In this way, the problem translates into the resolution of a complex system of algebraic-differential equations with partial derivatives, which can be summarized in the so-called Equilibrium, Strain-displacement and Constitutive Equations. The former represent the equilibrium conditions for the roto-translation of the continuum, subjected to external loads under stationary conditions. Defined b_i with i varying between x , y and z the specific volumetric forces acting in the volume under examination, it can be written:

$$\begin{cases} \frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} = -b_x \\ \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} = -b_y \\ \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_z}{\partial z} = -b_z \end{cases} \quad (1.15)$$

The Strain-displacement equations relate deformations to displacements in order to guarantee the continuity of the material in such a way that no penetrations or tears which compromise the integrity of the continuum occur:

$$\begin{cases} \varepsilon_x = \frac{\partial u_x}{\partial x} \\ \varepsilon_y = \frac{\partial u_y}{\partial y} \\ \varepsilon_z = \frac{\partial u_z}{\partial z} \\ \gamma_{xy} = \frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x} \\ \gamma_{yz} = \frac{\partial u_y}{\partial z} + \frac{\partial u_z}{\partial y} \\ \gamma_{zx} = \frac{\partial u_z}{\partial x} + \frac{\partial u_x}{\partial z} \end{cases} \quad (1.16)$$

Finally, the Constitutive equations represent the closing equations of the problem, since they depend directly on the physical characteristics of the material under consideration, such as Young's modulus E , the tangential elasticity modulus G and the Poisson's coefficient ν , each of which can be expressed as a function of the other two. These equations relate the deformations to the stresses that have generated them and can be represented explicitly through Hooke's law:

$$\begin{aligned} \varepsilon_x &= \frac{1}{E} [\sigma_x - \nu (\sigma_y + \sigma_z)] \\ \varepsilon_y &= \frac{1}{E} [\sigma_y - \nu (\sigma_x + \sigma_z)] \\ \varepsilon_z &= \frac{1}{E} [\sigma_z - \nu (\sigma_x + \sigma_y)] \\ \gamma_{xy} &= \frac{1}{G} \tau_{xy} \\ \gamma_{yz} &= \frac{1}{G} \tau_{yz} \\ \gamma_{zx} &= \frac{1}{G} \tau_{zx} \end{aligned} \quad (1.17)$$

The system of equations we arrive at consists of 21 linearly independent equations with partial derivatives, having 21 unknowns, 9 of which are the components of the stress tensor, 9 are those of the deformation tensor, while the last 3 refer to displacements. First, the components of the displacement vector are determined by defining appropriate boundary conditions related to the external constraints. Once these results have been obtained, they are substituted into the strain-displacement equations, from which it will be possible to obtain the deformation field. Finally, by means of the constitutive equations, it will be possible to determine the tensional state of the body, at the point and at the instant under examination. If we assume that the solid is homogeneous and isotropic, the resolution is greatly simplified as the equations to be solved are reduced to 15. However, the application of these equations leads to finding closed analytical solutions only if the geometry under consideration is simple and as symmetrical as possible, which is not always possible in the design of a generic component. To overcome this problem, calculation systems are used that exploit approximate numerical methods, including the finite element method, which is used in this Thesis work and briefly described in the following paragraph.

1.5.3.3 The finite element method

The Finite Element Method (FEM) is one of the most widely used numerical methods in the engineering field because it can make possible to solve the thermomechanical problem even for bodies that present a complex spatial domain and whose thermophysical properties are strongly dependent on variables such as position, temperature or time [21]. This approach basically consists in subdividing the examined body into many small elements and solving the governing equations of the studied problem within each of them, considering appropriate conditions at the interface. The discretization of the body obtained in this way is called “mesh” and the points of intersection between the lines, as well as the vertices of the elements that define the mesh, are called nodes and represent the points at which the equations will be solved. A more detailed mesh, and therefore with a greater number of nodes, will provide solutions much closer to the real case than a mesh with fewer nodes, but the analytical burden will be proportionally greater. It is therefore up to the analyst to choose the right compromise between the level of detail of the study and the time taken to carry it out. The fundamental assumption on which the FEM is based is that the values of the field function at a generic point inside the element are dependent on the nodal values by means of certain shape functions, whose analytical expression is known and depends on the type of element, which in general can be hexahedral or tetrahedral. Immediately afterwards, it will be necessary to set up a system of loads applied to the nodes, elements or surfaces, according to their nature, which is equivalent to the total external stresses

experienced by the body. The data supplied in this way will then be analyzed by a solver, which in turn will provide us with an output of the punctual characteristic for each node of the tensional state of our body.

1.5.3.4 Stress linearization and structural design criteria

Once the thermal and mechanical response of the component analyzed has been found, it is necessary to check whether or not it satisfies the structural design criteria imposed by the standards relating to its design. In particular, the most important standards relating to nuclear components (ASME [22], RCC-MRx [23], SDC-IC [24], etc) include a list of safety classes, within which the component must be classified, indicating the level of operation and how stringent the safety limits are. A component must be designed to respond, according to appropriate indicators, to at least two design scenarios, i. e., the nominal working conditions and the reference accidental scenario conditions. Clearly, the conditions it must withstand in the two different conditions must not imply the same verification criteria for both cases. The safety criteria are therefore functions of these scenarios. Once the scenarios in which the component may be encountered during its operational life have been identified, it must be verified that all the safety criteria relating to the individual safety levels within which these scenarios are classified have been met. These are conditions expressed in the form of an inequality of the type ($\sigma < \sigma_{limit}$), where σ_{limit} is the maximum permissible voltage. In order to calculate the tension to be compared with the admissible value given by the standards, it is necessary to find a value that summarizes the tensional state of the body, since the latter is described by a tensor quantity as seen in the previous chapter. The method that is followed consists in considering an invariant of the tensor of the stresses, that is an equivalent tension that has a scalar value, and in particular the one of the second order is chosen, also called Von Mises' one, since it assumes a physical sense linked to the deformation energy of the body:

$$\sigma_{VM} = \sqrt{\frac{1}{2} [(\sigma_x - \sigma_y)^2 + (\sigma_x - \sigma_z)^2 + (\sigma_y - \sigma_z)^2 + 6(\tau_{xy} + \tau_{xz} + \tau_{yz})^2]} \quad (1.18)$$

The first step consists in evaluating the spatial trend of the components of the stress tensor in the regions where they assume high values. Once these regions have been identified, paths are chosen in which the distribution of primary stresses P (usually generated by mechanical stresses), secondary stresses Q (generally caused by thermal gradients) and total stresses (P+Q) will be evaluated. In general, this distribution will not be linear. At this point, the so-called Stress Linearization procedure is carried out, i. e., the subdivision of the considered stress component into the sum of three elements:

- mean value or membrane stress;
- triangular component or bending stress;
- peak stress.

A schematic illustration of what has just been described is shown in figure 1.6:

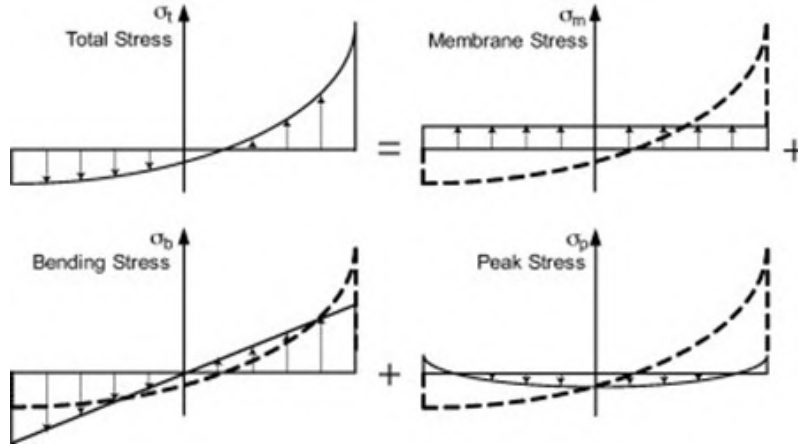


Figure 1.6: *Stress linearization*

This operation must be carried out for all components of the stress tensor, thus obtaining a sum of several terms for both the P and Q tensors. The rules work on the second-order invariant of these tensors and compare them directly with the maximum acceptable value according to the Von Mises criterion. Each of these rules must be verified for each identified path, so it is important that they are chosen wisely because there may be estimation errors by choosing less stressed areas. The choice of paths therefore requires a certain amount of experience in identifying them. It is also important to emphasize that the paths are generally not chosen at a constraint or discontinuity, since the stress values at those points tend to be infinite. Finally, the results are reviewed by the regulator, who may point out a possible error on the part of the analyst or validate the study carried out and proceed to approve the project.

Chapter 2

Neutronic and thermal loosely-coupled procedure for the breeding blanket design

2.1 Introduction

The BB study represents a complex step in the design economy of a nuclear fusion reactor. In fact, as already mentioned, this component during its normal deployment, encounters physical phenomena involving neutronics, thermohydraulics and thermomechanics, which are closely interrelated.

It therefore becomes essential to find tools to study the relationship between these various aspects and how they translate into the actual design phase of the component. To do so, this chapter will describe a methodology developed with the goal of generating a generic BZ design composed of tubular and/or slab structures starting from thermal and neutronic inputs and user-defined boundary conditions.

The focus of the methodology described below is on the preliminary phase that involves physics at the neutronic and thermal levels but does not deal with hydraulic and mechanical phenomena, which will still need to be addressed once this first phase is completed.

The entire process is governed by steps managed directly by the user alternated with fully automated ones through the use of Python, MATLAB and ANSYS Parametric Design Language (APDL) scripts. This has resulted in a workflow in which numerous phases that would normally be extremely time-consuming are handled directly by the software, resulting in a significant reduction in possible user error and a presentation of results in a format that is easily manipulable by the user.

The whole process is based on the concept of submodeling since the focus will be on the development of a small BB area, specifically an outboard equatorial portion, but which in general could be located anywhere else in the reactor. This approach is

used because with the current computational resources, tackling a design study with this level of detail for the entire machine would pose a major feasibility challenge.

In the following sections, the methodology will first be described in detail in all its steps, then it will be implemented for the study of a WLCB BB slice and finally the results of a parametric study carried out with the aim of finding the configurations of the above-mentioned BB with better performance in terms of Tritium Breeding Ratio (TBR) (i. e., number of Tritium nuclei produced per fusion reaction) will be reported.

2.2 Methodology

The methodology outlined below allows the generation, from a given radial power density (q''') profile related to a specific neutron source (obtained from neutronic analyses performed on any type of DEMO BB), of a BB slice design whose BZ is composed of tubular and/or cassette structures and Stiffening Plates (SPs).

Depending on the BB type to be implemented in the procedure, it will be necessary to make preliminary assessments about the mechanical loads to which the BB is subjected so that the number and thickness of the SPs can be decided in advance. Once the “skeleton” of the BZ has been established, it will be possible to fill it via the tubular and/or cassette structures mentioned above.

For illustrative purposes, on the basis of the particular BB chosen as an example for the application of the methodology, the model that will be used is a hybrid of tubular and cassette structures, whose BZ is divided into six regions by means of two poloidal-radial SPs equidistantly distributed from each other and the Side Walls (SWs) and a poloidal-toroidal SP that roughly divides the BZ in half. In particular, the three areas of the BZ closest to the FW will be filled by tubular structures developed in the poloidal direction that are repeated in the toroidal direction and increase in diameter in the radial direction. The fundamental unit, depicted in figure 2.1, can be identified with a tube containing the breeder, connected by fins to four other smaller tubes through which water with a cooling function flows. The water tubes also connect adjacent breeder tubes to each other.

As for the three BZ areas closest to the BSS, there are cassette structures filled with breeder and connected to several tubes with cooling function. The rest of the BZ is filled with the multiplier.

The design was chosen on the basis of considerations related to the particular type of BB that will be analyzed in the following paragraphs, however, the model has been parameterized to allow the addition of more SPs or even to consider only slab-type geometries without the use of tubes.

It is important to emphasize that, the following procedure, performs a back-and-forth thermal-neutron coupling, without verifying anything with regard

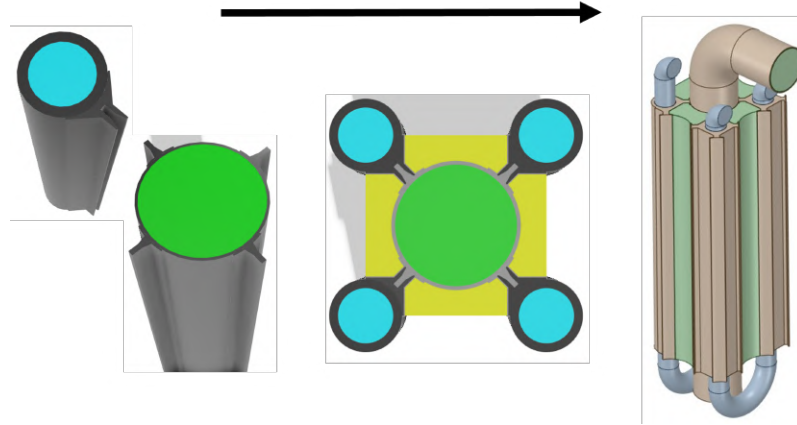


Figure 2.1: Fundamental unit of the repeated tubular structure

to the hydraulic or structural performance of the component, steps which represent the direct continuation of the application of this methodology.

In the next sections, the procedure depicted in figure 2.2 will be explained in details.

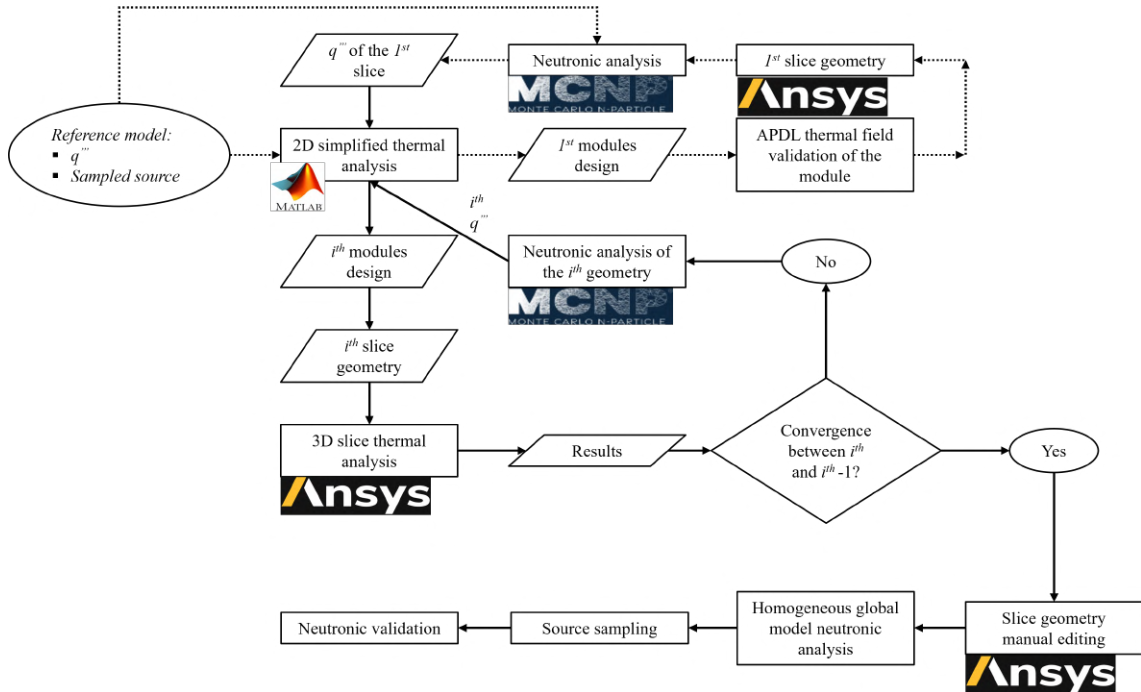


Figure 2.2: Methodology's flow chart

2.2.1 Geometry generation

The first part of the methodology is the geometry generation phase. It is structured on a procedure that involves the coupling of MATLAB and APDL software. The hybrid geometry previously mentioned will be considered, but this can potentially be adapted to any BB concept.

2.2.1.1 MATLAB 2D simplified thermal analysis

The first phase of the geometry generation part, implemented in MATLAB, aims to provide a fundamental unit configuration that is thermally valid with respect to the user-imposed boundary conditions. The operation, which can also be done in APDL, is performed on MATLAB because it has proven to be significantly faster due to its simplifications. The input data is represented by the power density distribution within the BZ, which represents the thermal load that the system must dissipate to ensure that the thermal boundary conditions are met.

The MATLAB code consists of three nested “while” loops. The innermost loop is responsible for performing thermal calculations on a two-dimensional, simplified model of a fundamental unit’s quarter as depicted in figure 2.3. The intermediate loop calculates the number of module instances that can be inserted into the available space and prevents potential geometric interferences between the pipelines themselves and with the surrounding support structures. The outermost loop finally verifies the remaining radial space available for the insertion of additional pipelines.

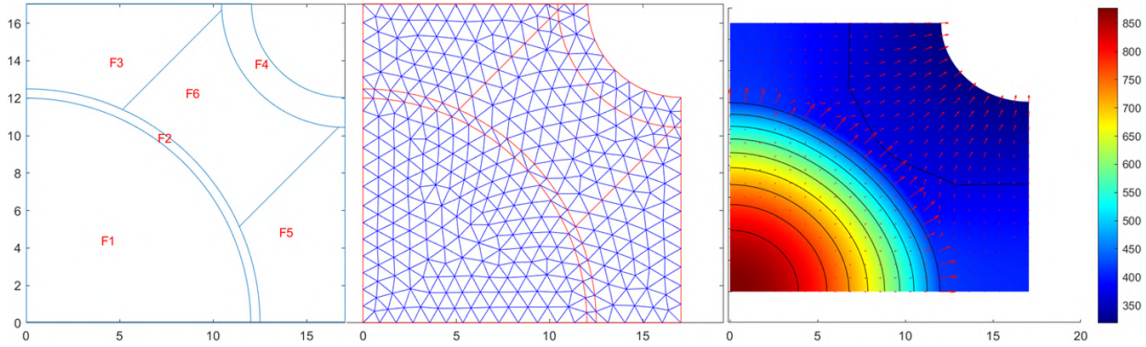


Figure 2.3: *MATLAB simplified 2D thermal analysis*

The dimensioning of the fundamental unit’s quarter module is done by evaluating the first-attempt radius of the tube containing the breeder. To do so, using equation (1.11) particularized for cylindrical geometry with transverse dimension $z \gg r$ and in the case of stationary heat transfer it is obtained:

$$T(r) = T_0 - \frac{q'''}{4\lambda} r^2 \quad (2.1)$$

where T_0 is the temperature that one wants to obtain at the breeder’s tube center. If one would want to derive the radius of the tube r_s it is enough to impose $T(r_s)$, which is the maximum temperature the tube’s material can be operated at, obtaining:

$$r_s = \sqrt{\frac{\Delta T 4\lambda}{q'''}} \quad (2.2)$$

Since the power density is a function of the radial coordinate of the point

considered relative to the plasma, to determine the value to be used in the equation, the center of the tube containing the breeder is arbitrarily positioned at a certain radial coordinate within the BZ. Once the power density value in the center of the tube is known, and the thermal gradient to be maintained within the tube is set to ensure the temperature conditions of the breeder and tube's material are met, it is possible to analytically calculate the first guess radius r_s of the tube containing the breeder.

Starting from this radius, the entire module is constructed by imposing a preliminary distance between the heat source and the heat sink with a given Heat Transfer Coefficient (HTC). This distance represents the parameter that is iteratively varied to achieve convergence of the innermost cycle.

Once internal convergence is achieved, the geometric interferences verification is carried out. When this is satisfied, the pipeline is defined, and after verifying the remaining available space in the BZ for the insertion of additional pipelines, the sizing of the next row proceeds. At the end of each complete iteration, the geometric input parameters are saved, which will then be used in the next phase of parametric generation of the entire equatorial slice for more detailed evaluations of the slice thermal field.

2.2.1.2 APDL thermal analysis and slice generation

Once the MATLAB code finds the fundamental unit's quarter module configuration that satisfies the user-imposed thermal conditions, the geometry data obtained are used as input on APDL to perform a more detailed thermal analysis in order to validate the use of the MATLAB code (figure 2.4). This step is necessary because although MATLAB appears to be a powerful and practical tool, it will still be required to exploit its results for the use of a proper tool designed for the component structural analysis and which also allows to extrapolate the local design obtaining a global one.

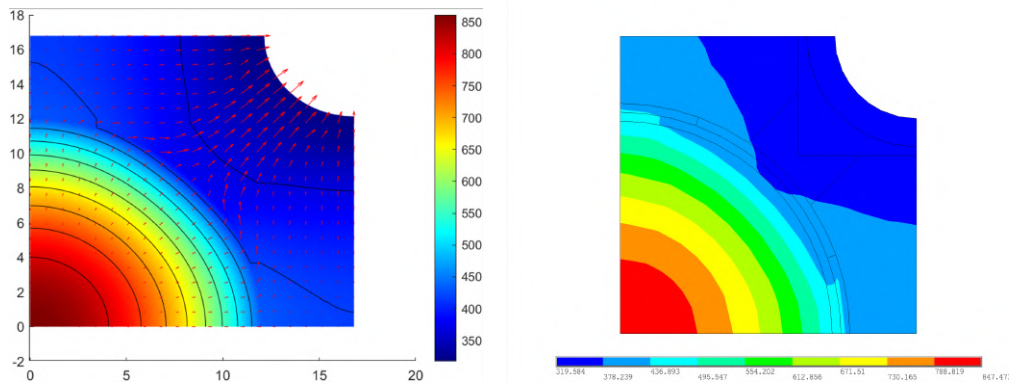


Figure 2.4: *MATLAB (left) and APDL (right) thermal results comparison*

Once it is shown that the two codes give nearly identical results an APDL

code is executed to allow the actual geometry generation following the next steps (figure 2.5):

- Creation of FW-SW, BSS and poloidal-radial SPs;
- Creation of the quarter module at a fixed distance from the FW;
- Mirroring and creation of the single fundamental unit;
- Repetition of the fundamental unit to create the tube row and check for any interpenetrations;
- Generation of subsequent rows until the space occupied by the pipes is optimized;
- Generation of the poloidal-toroidal SP dynamically according to the number of obtained tube rows;
- Cassette generation in the remaining space of the BZ.

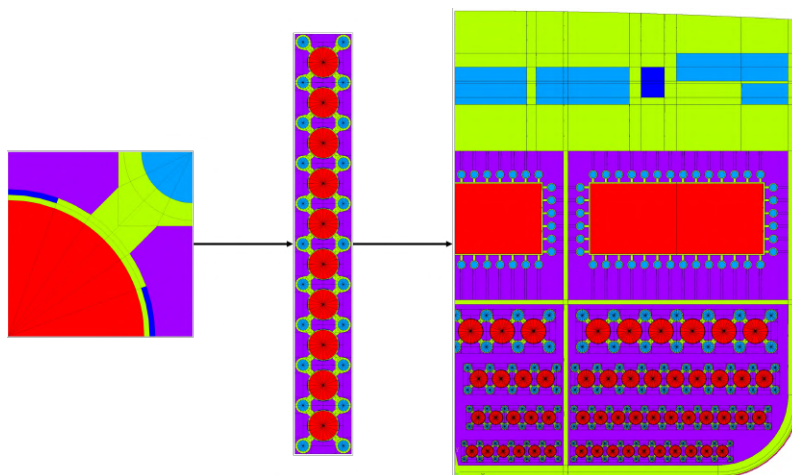


Figure 2.5: *APDL geometry generation steps*

From this point on, only half of the generated slice will be considered for toroidal symmetry reasons.

Once the zero slice configuration has been generated, it is necessary to manipulate the model so that it can be read by the MCNP software for subsequent neutronic analyses. To do so, there are two options: convert the Computer Aided Design (CAD) to CSG format through the use of software such as McCAD [25] or SuperMC [26], or by generating an unstructured mesh in the typical Abaqus-like input format. In the following discussion, the approach using unstructured mesh has been chosen, since this allows results to be derived with a considerably higher level of detail than CSG at a slightly higher computational cost (figure 2.6).

After the input has been generated in the Abaqus-like format, it will be necessary to “insert” the mesh into a specific region of the MCNP input through the use of the so-called “universes”, resulting in a hybrid with the CSG. Specifically, the mesh is inserted inside a fictitious bounding box, located in a portion of BB that extends

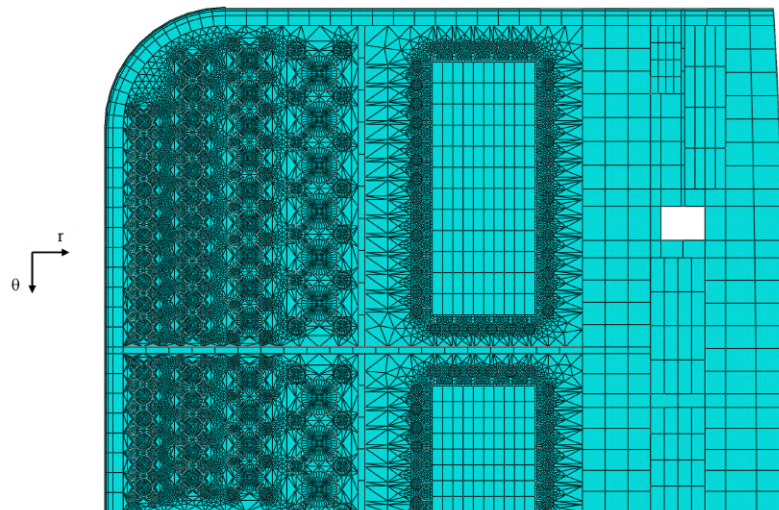


Figure 2.6: *Abaqus unstructured mesh*

in the poloidal, radial and toroidal directions exactly like the slice. In addition, in the radial direction, immediately after the bounding box there is also a homogenized model in CSG format of the VV in which the BB is contained.

At this point the geometry generation phase is completed and the neutronic analysis of the model can be carried out.

2.2.2 Neutronic analysis

The next sections will describe the two steps into which the neutronic analysis phase is divided, starting with the sampling of the local sources to be used and then moving on to the evaluation of the TBR and power density obtained in the zero slice.

2.2.2.1 Local neutron and photon sources sampling

Considering that a submodeling study is being conducted, a local neutron and photon source must be appropriately sampled to act as a driver for the neutronic problem.

To do so, it is necessary to perform another neutronic analysis on a DEMO global model with its typical source and equipped with any type of BB. For consistency, the same BB whose power density was used to generate the geometry in the previous step will be chosen.

At this point, it is necessary to locate a global model surface that matches as closely as possible the plasma front surface taken from the submodel bounding box, both in extent and location, that will be used for the tallies (figure 2.7).

Both neutrons and photons will be categorized and divided by their cosines and energies: the cosine distribution is divided into ten bins ranging from 0 to 1, while, based on the Vitamin J+ energy data structures [27], neutron energies are sampled

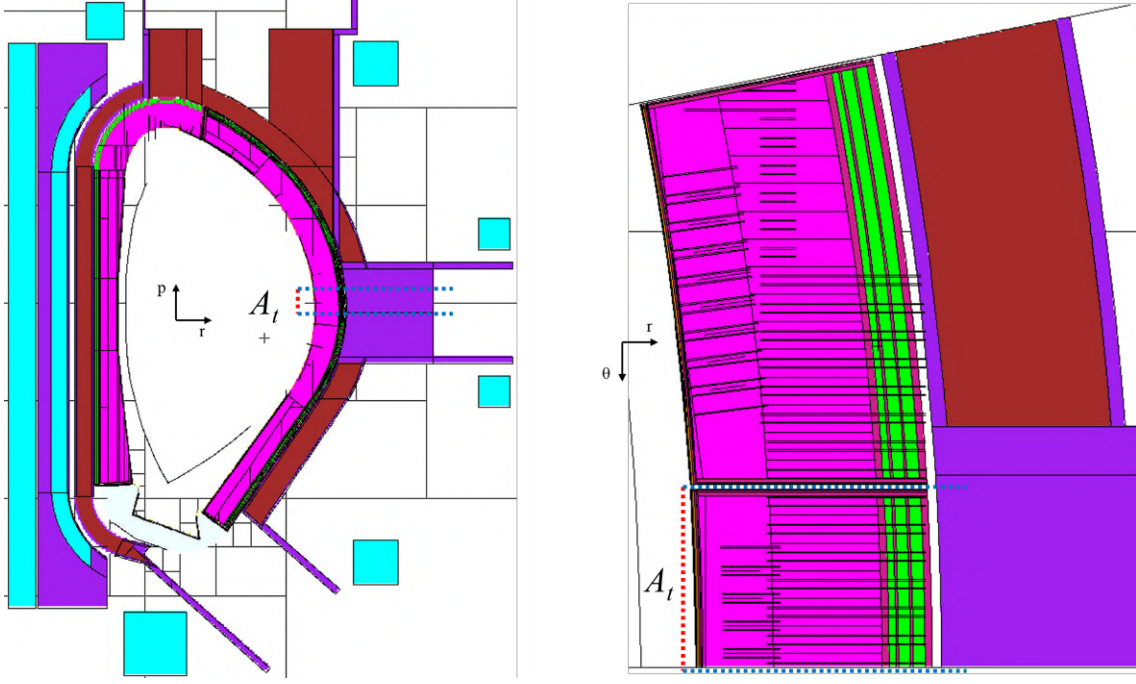


Figure 2.7: Neutronic global model

from 0.111 to 20 MeV divided into 99 bins and photon energies are sampled from 0.001 to 50 MeV divided into 43 bins. Thus, the data calculated for the submodel include a total of 1420 tally values defined $T_{i,j}$ with i and j representing respectively the cosine and energy bin.

In general, the probability p_{ij} that a particle starts from the selected surface A_t with a cosine comprised between $[\mu_i, \mu_{i+1}]$ and between the energy bin $[E_j, E_{j+1}]$ with i from 1 to I and j from 1 to J is given by:

$$p_{ij} = \frac{\int_{A_t} dA \int_{E_j}^{E_{j+1}} dE \int_{\mu_i}^{\mu_{i+1}} \varphi(\mathbf{R}_s, E, \mu) \mu d\mu}{\int_{A_t} dA \int_0^{+\infty} dE \int_0^1 \varphi(\mathbf{R}_s, E, \mu) \mu d\mu} \quad (2.3)$$

where $\mathbf{n}$ is the source surface A_t unit vector, μ is the cosine which is equal to $\Omega \cdot \mathbf{n}$, Ω is the neutron velocity unit vector and $\varphi(\mathbf{R}_s, E, \mu)$ is the particle flux. Hence, starting from the results of the dedicated global neutronic analysis $T_{i,j}$ the tally score per cosine bin R_i can be calculated as:

$$R_i = \sum_{j=1}^{E_b} T_{i,j} \quad (2.4)$$

with i from 1 to 10 and $E_b = 99$ for the neutron bins and $E_b = 43$ for the photon bins.

Moreover, the neutrons entering the surface A_t from the plasma are defined:

$$F1_{\text{net}} = \sum_{i=1}^{10} R_i \quad (2.5)$$

Consequently, the cosine emission probability C_i and the energy emission probability $E_{i,j}$ for each cosine bin can be calculated:

$$C_i = \frac{R_i}{F1_{\text{net}}} \quad (2.6)$$

$$E_{i,j} = \frac{T_{i,j}}{R_i} \quad (2.7)$$

with i from 1 to 10 and j from 1 to E_b . The obtained C_i and $E_{i,j}$ values will be used to define the local neutron and photon source for the submodel nuclear analysis. In this way, not only the direct neutrons coming from the plasma but, also, the neutrons and photons subjected to the albedo effect and entering the submodel from the FW will be taken into account. The whole operation described above was fully automated with a Python script (code A.1).

2.2.2.2 TBR and power density evaluation

Once the local neutron and photon sources have been sampled, the submodel analysis can be carried out. Boundary conditions are imposed on the extreme surfaces of the bounding box in both the toroidal and poloidal directions and are of the reflecting type (figure 2.8), i. e., both act as mirrors for neutrons and photons in order to take into account the geometric continuity in those directions.

The cross sections library chosen for the material definition is JEFF-3.3 [10].

Two analyses have to be carried out at this point, namely, one that takes into account neutron and photon transport and one only with photon transport. The reason for this approach will be better explained in the following.

For the neutron and photon transport analysis, four Embedded Elemental Edits Controls (EMBEEn) are requested, which are the equivalent of the tally in the unstructured mesh case study [18]:

- A flux-type EMBEEn6 expressed in MeV/g for calculating the energy deposited by neutrons generated in the plasma, neutrons scattered from other modules and neutrons and photons produced in the submodel due to the neutronic interaction with the materials;
- A reaction-type EMBEEn4 for the tritium produced by Lithium-6 reactions;
- A EMBEEn4 equivalent to the previous one, but for the calculation of tritium produced by Lithium 7;
- A EMBEEn4 of flux type and expressed in particles/cm², for the evaluation of neutron fluxes at different energy bins (3.1454, 5.6, 15 MeV), characteristic of the tritium-breeding reaction from Lithium 7 (figure 1.5).

Instead, for the analysis with photon transport only, just an EMBEEn6 is requested to calculate the energy deposited by photons produced due to neutronic

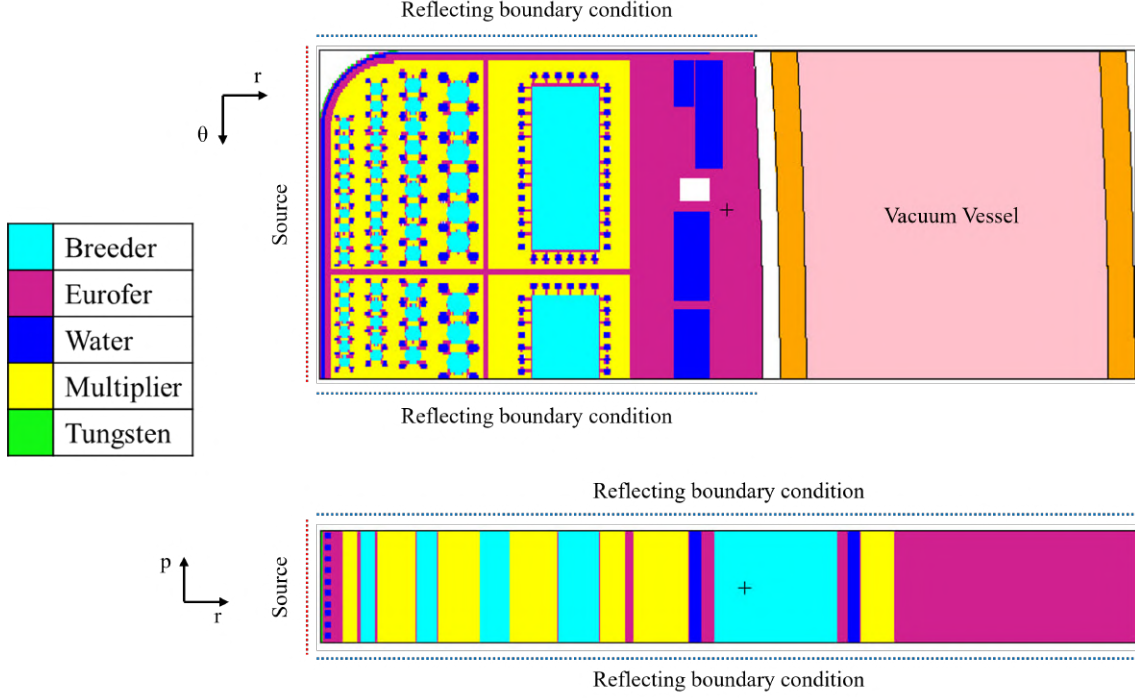


Figure 2.8: *MCNP submodel*

interactions elsewhere in the reactor and scattered into the BB slice modeled.

After the neutron and photon transport analysis of the model has been carried out, it will be necessary to manipulate the results of the EMBEES so as to obtain the power density values in W/cm^3 associated with each material and the values of TBR/cm^3 associated with the breeder material. Starting from the latter, it will be sufficient to multiply the results of the analysis with neutron and photon transport by the atomic densities expressed in $\text{b}^{-1}\text{cm}^{-1}$ of Lithium 6 and Lithium 7, respectively, since the MCNP results are given per incident neutron. As for the power density of each material, on the other hand, it will be necessary to multiply the results by the density expressed in g/cm^3 , the conversion factor equal to $1.6021773 \cdot 10^{-13}$ to go from MeV to Joule, and the intensity of the source, either neutron or photon. In fact, as mentioned before, two analyses are performed since the power deposited in the slice results from the sum of the contributions calculated from the two EMBEEn6 described above related to both the neutron and photon sources.

In order to find the local source intensities, a brief digression must be made.

Considering a reactor power of $1.998 \cdot 10^9 \text{ W}$ [5] and an energy of $17.59 \times 1.6021773 \cdot 10^{-13} \text{ Joules}$ typical of the D-T type fusion reaction, it is possible to derive the global source intensity I_g as:

$$I_g = \frac{1.998 \cdot 10^9}{2.818 \cdot 10^{-12}} = 7.090 \cdot 10^{20} [\text{part/s}] \quad (2.8)$$

In the neutron analysis of the global model carried out earlier, the A_t surface and two F1-type tally were also calculated for the neutron and photon current. Having

defined A_s the bounding box surface of the submodel to which the local source will be applied, and considering that A_t and A_s could be slightly different, it is obtained:

$$I_s^{np} = \frac{I_g F 1_{np} A_s}{A_t} [\text{part/s}] \quad (2.9)$$

$$I_s^p = \frac{I_g F 1_p A_s}{A_t} [\text{part/s}] \quad (2.10)$$

where I_s^{np} and I_s^p are the local neutron and photon source intensity, respectively.

However, the approach via unstructured mesh implies that the results obtained are associated with the centroid of each element of which the mesh is composed, which is why the operations described above can be time-consuming the higher the number of elements in the mesh. To address this problem, two Python scripts were written to fully automate the operations (code A.2), while the script reported in [28] was used to convert the output files to the “vtk” extension, so that the results could be visualized using the Paraview software [29]. At this point, the loop drawn by dashed arrow of the flow chart in figure 2.2 has been completed.

In the next step, the radial power density profile obtained from the submodel analysis is used as input to the previously used MATLAB tool in order to generate a new slice geometry and repeat all the procedure just described all over again, keeping the local sources and boundary conditions unchanged. The operation is performed until the radial power density profile of the i^{th} slice matches the $i^{th} - 1$ one. Indeed, since q''' is the starting parameter for slice generation, it will also represent the parameter considered for results convergence. When this happens, minor manual modifications to the geometry, not yet implemented in the APDL code, can be made to allow percentage points of breeder volumes within the BZ to be gained while simultaneously refrigerating zones that are particularly critical in terms of temperature, as shown in figure 2.9.

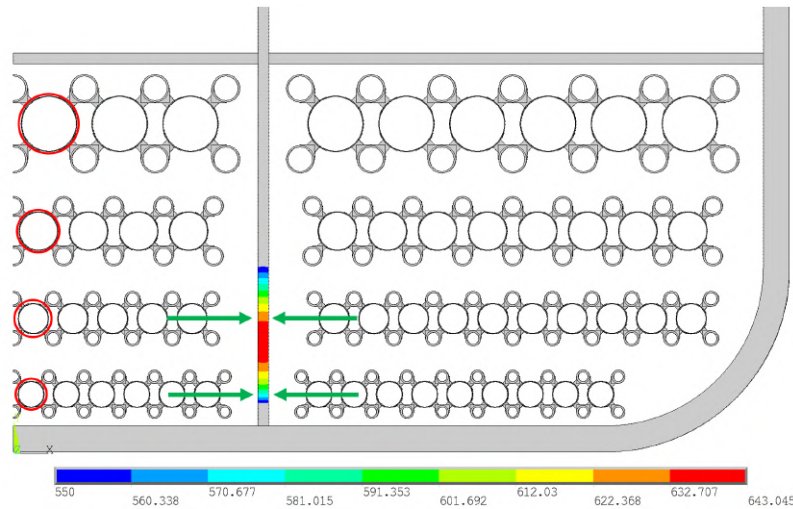


Figure 2.9: Manual modifications not implemented in APDL

Finally, a further global model analysis will need to be performed, this time with a BZ with material composition identical to the i^{th} slice found. To do so, the model used for the first sampling of local sources is considered, and instead of the materials composing the BZ, a homogeneous material with volumetric percentages weighted according to the composition of the i^{th} slice BZ is implemented. With the analysis executed, the sampled local sources are then compared: if they match with a minimum percentage deviation, then the neutron validation is considered done and the results obtained are valid.

2.3 Implementation on the WLCB geometry

In the next sections, the methodology described above will be implemented on a WLCB geometry. First, this particular BB concept will be described and then the results of the implementation will be shown.

2.3.1 Architecture description

As briefly stated in the previous chapter, the WCLL and the HCPB are the two main concept poised to be implemented as DEMO BB [30]. Nevertheless, during their pre-conceptual design phase, potential showstoppers have arisen. With the aim of overtaking them, new variants are being studied in parallel by the European scientific community [31]. Among them, the WLCB BB concept is one of the most promising [32]. It has been conceived as an hybrid concept between WCLL and HCPB BB, trying to adopt the best features from both (figure 2.10).

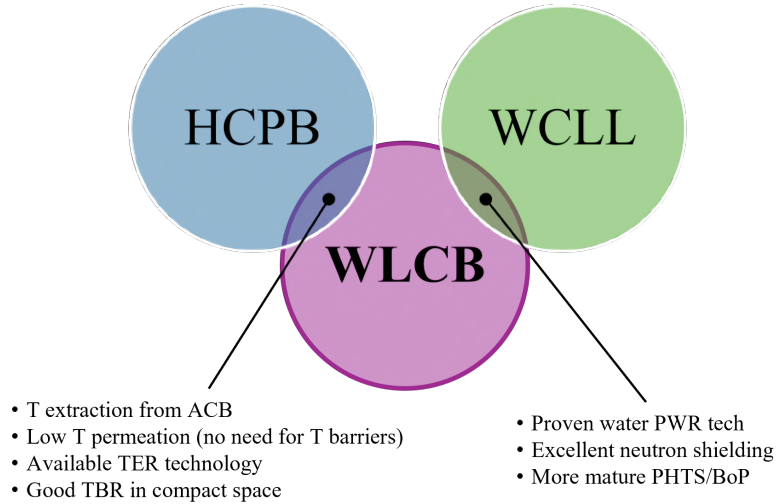


Figure 2.10: *WLCB hybrid design*

The WLCB BB slice model set up for this study will now be described in more detail. It extends a total of 135 mm in the poloidal direction, 1002 mm in the radial direction, and 742 mm in the toroidal direction since for symmetry reasons, only

half of it will be considered. It is composed of a 25 mm thick FW actively cooled via ten 7×7 mm channels in which water flows in PWR-like operating conditions. The so-called Advanced Ceramic Breeder (ACB) [33] in the shape of pebble-beds already used for the HCPB with a $\approx 90\%$ Lithium 6 enrichment is employed. Zr_5Pb_3 [34] in solid form was chosen as the multiplier to prevent the BZ from going under overpressure in the event of an accidental scenario, thus leading to an Eurofer reduction. For this reason there are only three SPs, two poloidal-radial and one poloidal-toroidal. The set of tubular and plate structures extensively described in section 2.2 was employed to contain the breeder and the cooling water used to refrigerate the BZ. The FW surface is covered with a 2 mm thick Tungsten armor. Finally, a BSS serves as a manifold for the refrigerants in the system.

2.3.2 Boundary conditions and results

The global neutron model from which the local sources were sampled and the radial power density profile was taken is the same as that used in [31] and reported in figure 2.11, and is slightly different from the submodel considered in this discussion. However, as will be shown in subsequent sections, for the purpose of local source sampling this does not significantly affect the characteristics of the incident neutrons.

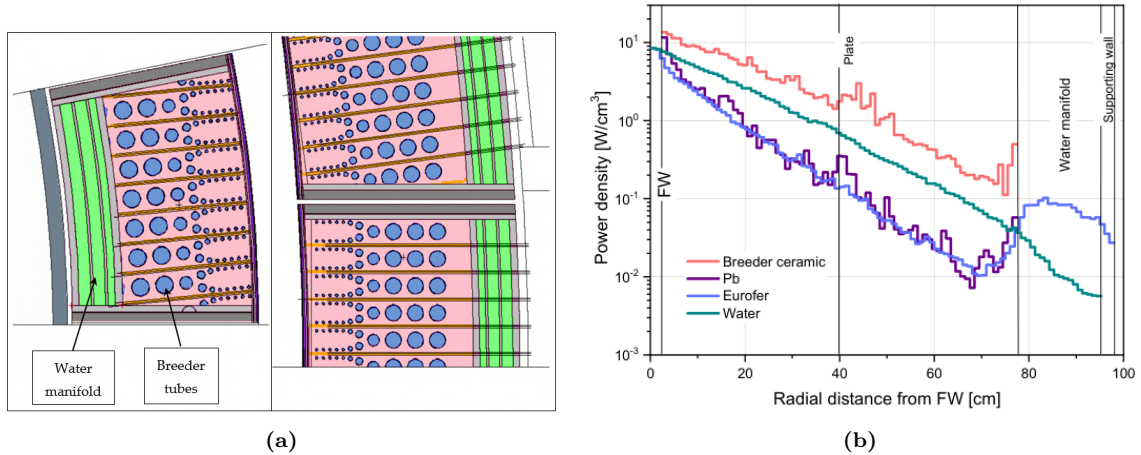


Figure 2.11: *WLCB ref. global model inboard and outboard (a) and outboard power densities (b)*

The Eurofer [35] and Tungsten [36] material properties used for evaluations performed on both MATLAB and APDL are given in tables 2.1 and 2.3 while those of ACB in table 2.2, considering its density constant with temperature $\rho = 1.65 \cdot 10^3$ [kg/m³]. All Zr_5Pb_3 properties were considered constant with temperature and in particular $\rho = 9.69 \cdot 10^3$ [kg/m³], $\lambda = 7.5$ [W/(m K)] and $c_p = 1.91 \cdot 10^2$ [J/(kg K)].

Table 2.1: *Eurofer material properties*

T [°C]	ρ [kg/m ³]	λ [W/(m K)]	c_p [J/(kg K)]	α [1/°C]	E [GPa]
0			4.35E+02		
20	7.74E+03	2.81E+01	4.49E+02	1.03E-05	2.17E+02
50	7.75E+03	2.89E+01		1.05E-05	2.15E+02
100	7.74E+03	2.98E+01	4.90E+02	1.07E-05	2.12E+02
150			5.07E+02		
200	7.72E+03	3.04E+01	5.20E+02	1.12E-05	2.07E+02
250			5.32E+02		
300	7.69E+03	3.00E+01	5.46E+02	1.16E-05	2.02E+02
350			5.63E+02		
400	7.66E+03	2.95E+01	5.87E+02	1.19E-05	1.96E+02
450			6.20E+02		
500	7.63E+03	2.96E+01	6.64E+02	1.22E-05	1.90E+02
550			7.21E+02		
600	7.59E+03	3.11E+01	7.96E+02	1.22E-05	1.70E+02
650			8.89E+02		
700	7.56E+03	3.11E+01	1.00E+03	1.22E-05	1.62E+02

Table 2.2: *ACB material properties*

T [°C]	λ [W/(m K)]	c_p [J/(kg K)]
20	9.19E-01	1.24E+03
50	9.29E-01	
100	9.46E-01	
200	9.79E-01	
300	1.01E+00	1.64E+03
350	1.03E+00	
400	1.05E+00	
450	1.06E+00	
500	1.08E+00	1.82E+03
550	1.10E+00	
600	1.11E+00	
650	1.13E+00	
700	1.15E+00	2.32E+03
750	1.17E+00	
800	1.18E+00	
850	1.20E+00	
900	1.22E+00	
950	1.23E+00	
1000	1.25E+00	

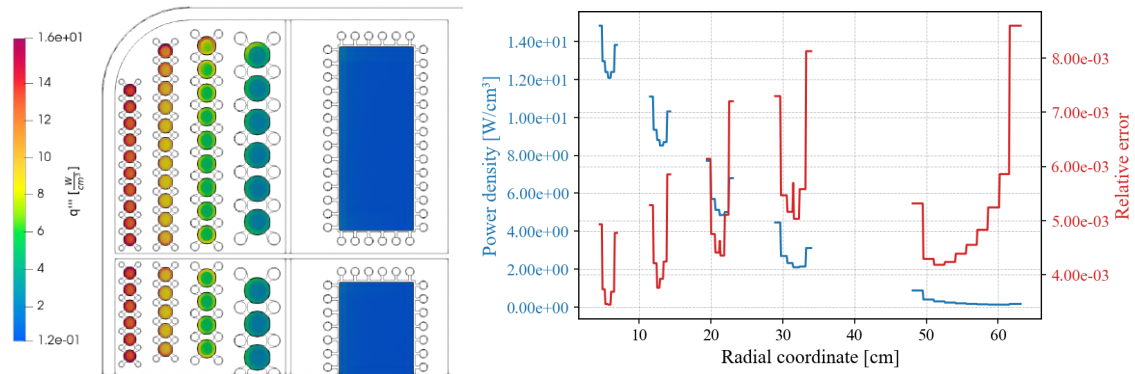
Table 2.3: Tungsten material properties

T [°C]	ρ [kg/m ³]	λ [W/(m K)]	c_p [J/(kg K)]
0	1.93E+04	1.75E+02	1.28E+02
20	1.93E+04	1.73E+02	1.47E+02
50	1.93E+04	1.70E+02	1.75E+02
100	1.93E+04	1.65E+02	2.22E+02
150	1.93E+04	1.60E+02	2.68E+02
200	1.93E+04	1.56E+02	3.15E+02
250	1.92E+04	1.51E+02	3.61E+02
300	1.92E+04	1.47E+02	4.08E+02
350	1.92E+04	1.43E+02	4.54E+02
400	1.92E+04	1.40E+02	5.01E+02
450	1.92E+04	1.36E+02	5.47E+02
500	1.92E+04	1.33E+02	5.94E+02
550	1.92E+04	1.30E+02	6.40E+02
600	1.92E+04	1.27E+02	6.87E+02
650	1.91E+04	1.25E+02	7.33E+02
700	1.91E+04	1.22E+02	7.80E+02
750	1.91E+04	1.20E+02	8.26E+02

The convective conditions used for the cooling water in the thermal analyses are $HTC = 2.15 \cdot 10^4$ [W/(m² K)] and $T_{bulk} = 310$ [°C].

The maximum allowable temperature at the center of the ACB tubes T_0 varies between 800 and 900 °C for reasons related to tritium extraction from the system [37] while the maximum allowable temperature of the Eurofer $T(r_s)$ is 550 °C [35].

Once the first attempt geometry generation is completed, the back-and-forth phase of the procedure begins. As mentioned, the use of an unstructured mesh model made it possible to obtain very detailed 3D power density distributions with very low associated relative error values (figure 2.12). A characteristic “saddle” pattern can be seen, probably given by the shielding effect that the outermost layers of ACB exert toward the innermost layers.

**Figure 2.12:** ACB submodel power density

Starting from these radial distributions, the subsequent iteration geometries were generated for a total of five submodel analyses called “i” from 0 to 4. A graphical comparison between the iteration zero slice and the last one is shown in figure 2.13. An i_{4m} analysis was also carried out modifying the i_4 model according to figure 2.9.

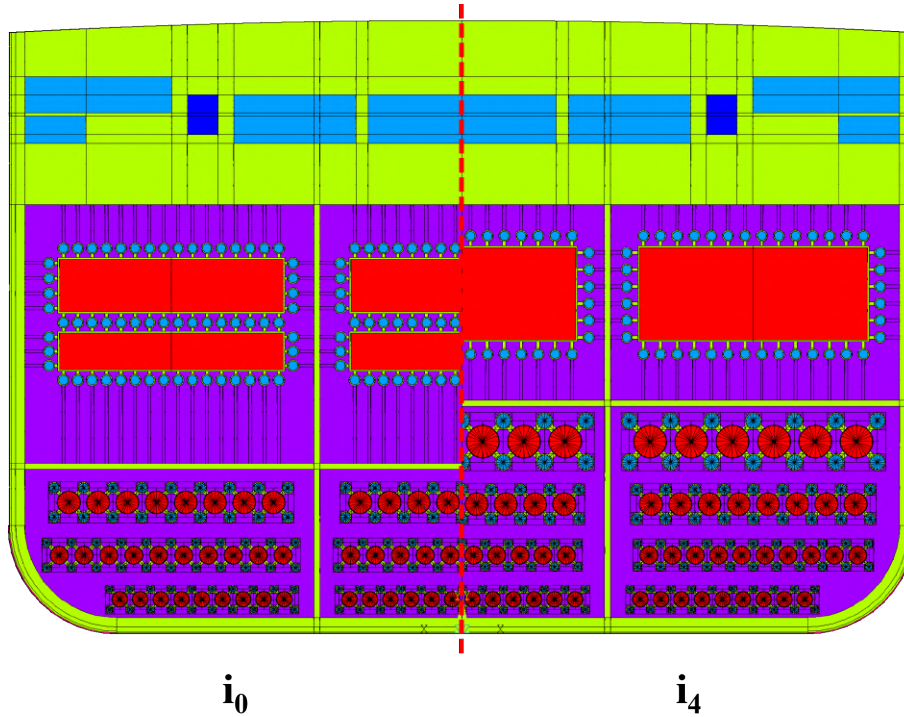


Figure 2.13: Geometry comparison between i_0 and i_4

In table 2.4 the results of the study, which were manipulated through the use of code A.2 are reported.

The final step of the procedure consists on re-sampling the local sources from a global model having a BZ with a composition which is identical to the submodel i_{4m} one in order to compare them with those used in the various iterations to demonstrate the consistency of the methodology. Through a Python script, an homogeneous BZ material was generated with 28.33% ACB, 6.61% Water, 54.66% Zr_5Pb_3 and 10.39% Eurofer composition.

The new sources sampling led to practically identical neutron analysis results to those of the i_{4m} case, as can be seen from figures 2.14 to 2.23 graphs.

Table 2.4: Iteration results comparison

Data	i_0	i_1	i_2	i_3	i_4	i_{4m}
ACB volume [cm ³]	1.45E+04	2.11E+04	1.71E+04	1.82E+04	1.77E+04	1.82E+04
ACB volume % over 750°C [%]	2.37E+01	2.63E+01	2.39E+01	2.39E+01	2.57E+01	2.79E+01
Total slice TBR [part]	3.62E-01	3.74E-01	3.74E-01	3.68E-01	3.74E-01	3.88E-01
Total slice TBR density [part/cm ³]	2.49E-05	1.77E-05	2.19E-05	2.02E-05	2.11E-05	2.13E-05
Total slice thermal power [W]	9.18E+04	9.17E+04	9.19E+04	9.20E+04	9.19E+04	9.30E+04

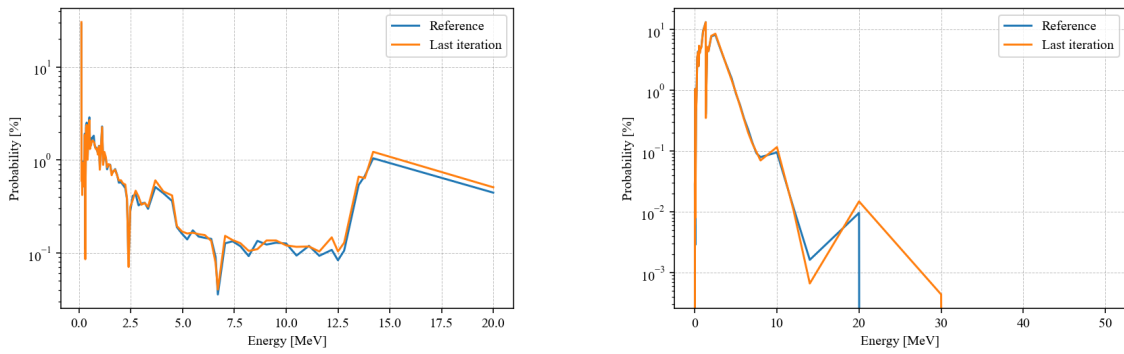


Figure 2.14: Neutron (left) and photon (right) energy probability function for $\cos 0.0 - 0.1$

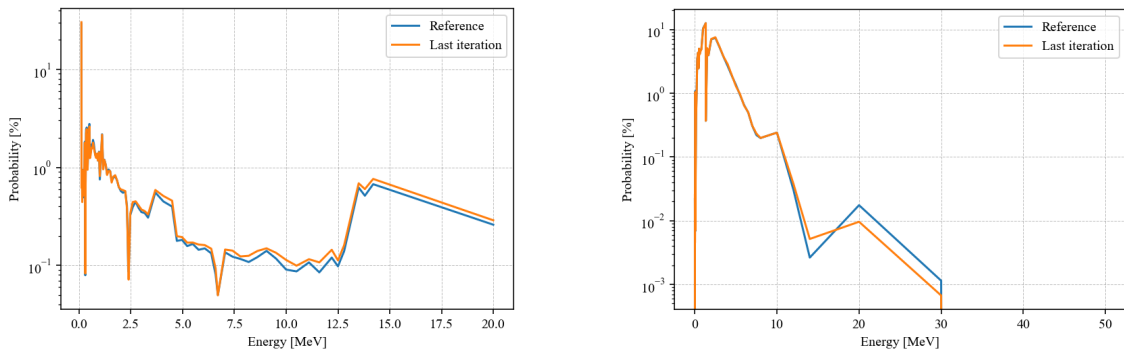


Figure 2.15: Neutron (left) and photon (right) energy probability function for $\cos 0.1 - 0.2$

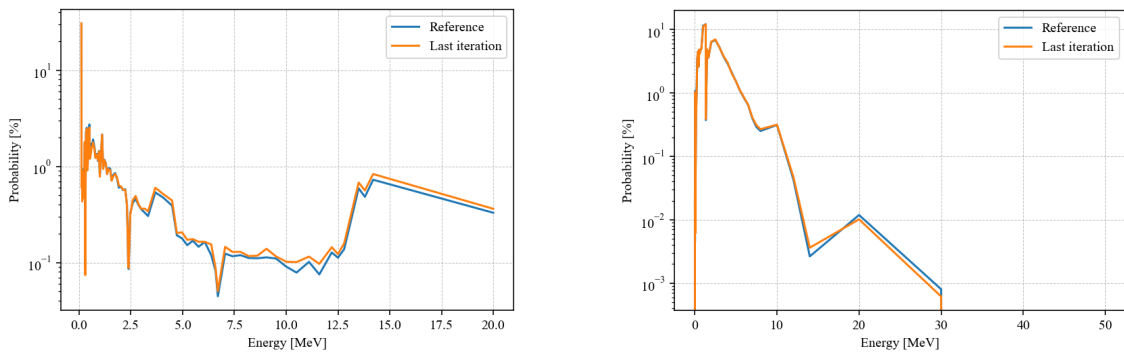


Figure 2.16: Neutron (left) and photon (right) energy probability function for $\cos 0.2 - 0.3$

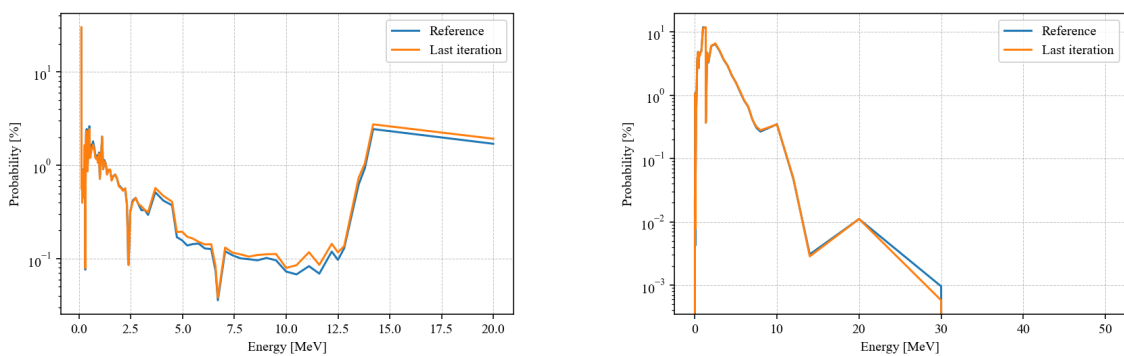


Figure 2.17: Neutron (left) and photon (right) energy probability function for $\cos 0.3 - 0.4$

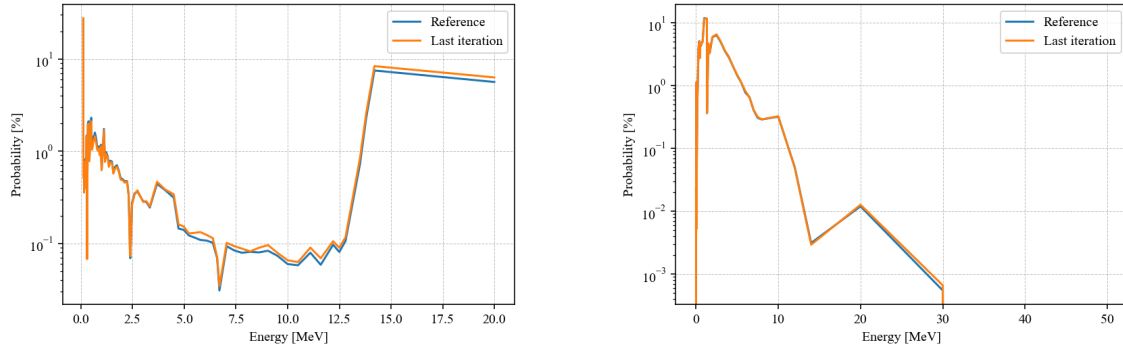


Figure 2.18: Neutron (left) and photon (right) energy probability function for $\cos 0.4 - 0.5$

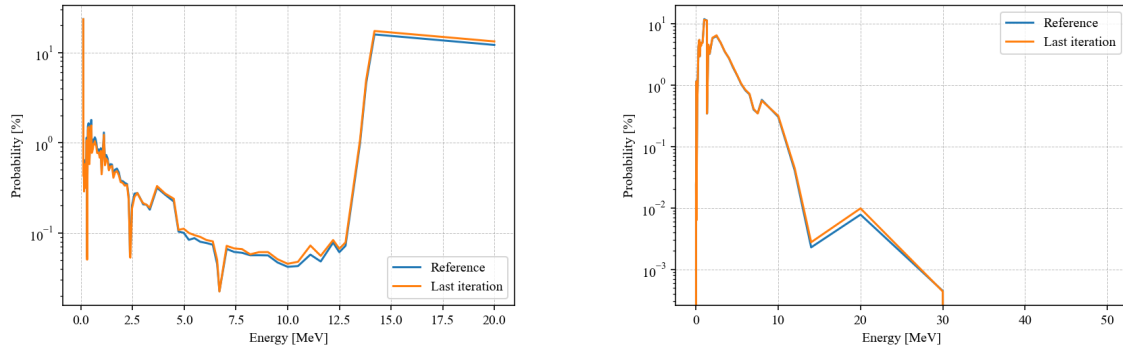


Figure 2.19: Neutron (left) and photon (right) energy probability function for $\cos 0.5 - 0.6$

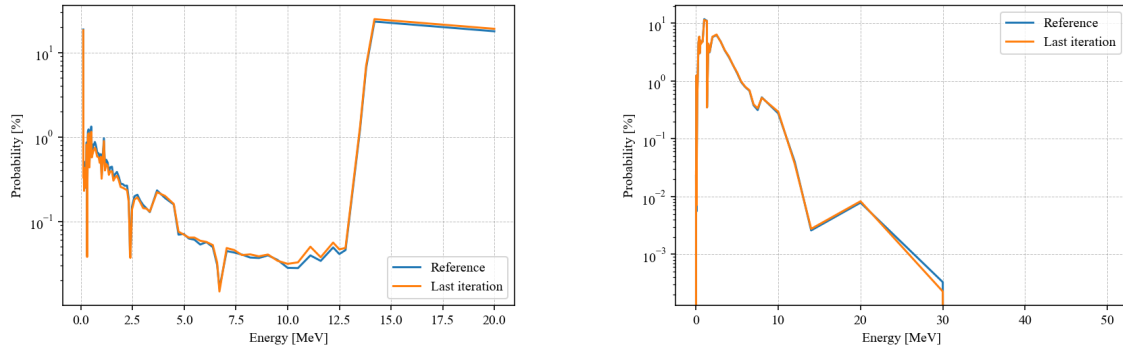


Figure 2.20: Neutron (left) and photon (right) energy probability function for $\cos 0.6 - 0.7$

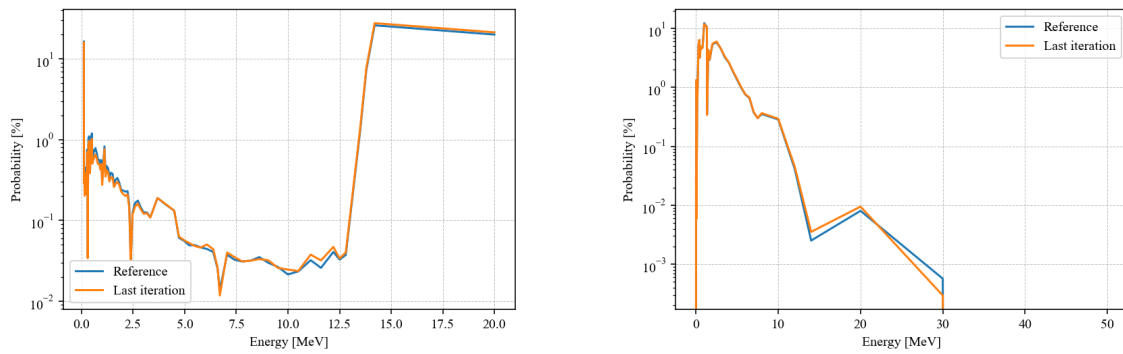


Figure 2.21: Neutron (left) and photon (right) energy probability function for $\cos 0.7 - 0.8$

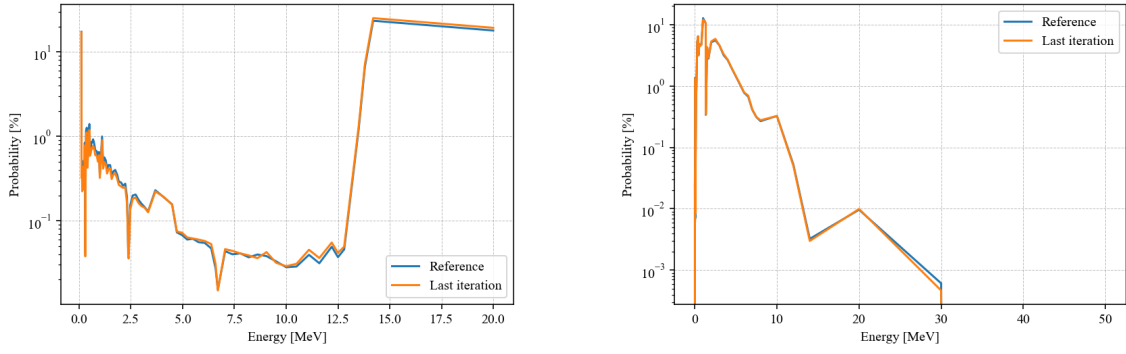


Figure 2.22: Neutron (left) and photon (right) energy probability function for $\cos 0.8 - 0.9$

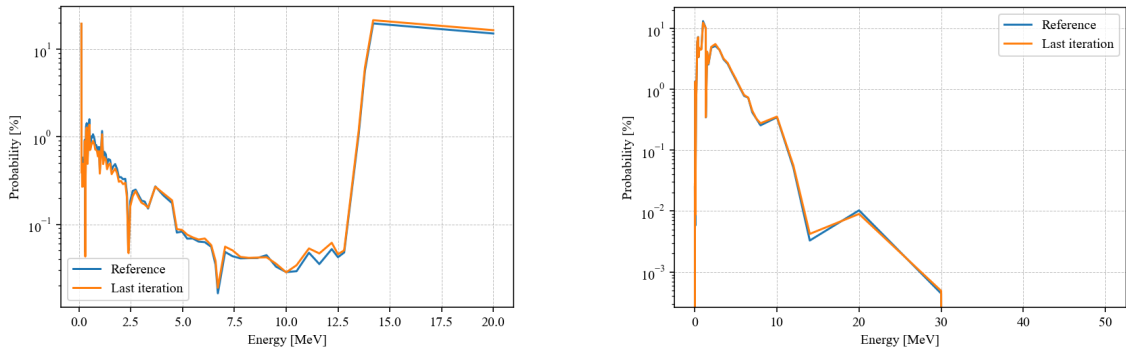


Figure 2.23: Neutron (left) and photon (right) energy probability function for $\cos 0.9 - 1.0$

2.4 Parametric activity

In parallel to the work just described, a WLCB layout without SPs has been considered as a starting point to perform more neutronic analyses to verify the influence of different parameters as the material distribution and/or composition on the slices TBR. The slice, whose geometrical characteristics are given in figure 2.24, is similar to the one considered before, except from the BSS, which here is composed by alternating poloidal-toroidal SPs and water.

A total of 19 models were analyzed and divided in 4 macro groups, which will be described in detail in the next sections.

The same neutronic boundary condition used in section 2.2.2.2 were considered in all the models with the local sources used in section 2.3.2. It is important to say however, that the objective of this activity was not to find realistic TBR absolute values, but instead to make comparison between different solutions in order to find the best ones as possible future alternatives.

In the tables that will follow, the term “FW” will indicate the complex of FW, SW and the tungsten armor (W). Instead, the BSS material composition ($1.851 \cdot 10^4$ [cm³], 46.9% Eurofer and 53.1% H₂O) circled in red in figure 2.24, was not taken into account.

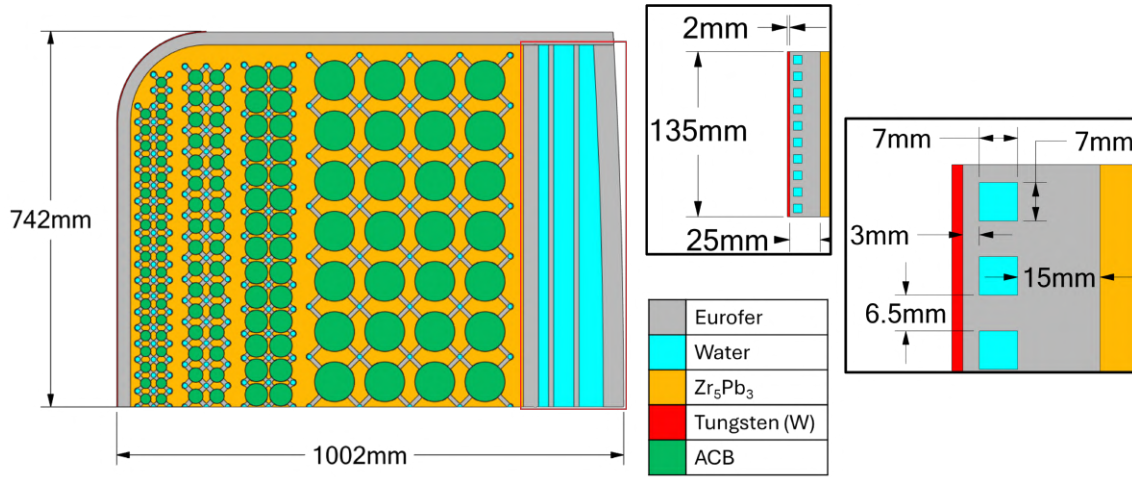


Figure 2.24: Reference WLCB slice

2.4.1 Group 1 analyses

Group 1 consists of four analyses where the FW has been modified, in terms of material composition and/or thickness:

- A1: five water channels were replaced with Lead (figure 2.25a);
- A2: five water channels were replaced with void space (figure 2.25b);
- A3: the dimensions and number of the channels has been modified according to the results of [38] (figure 2.25c);
- A4: starting from A3, the thickness of FW was increased while keeping constant the Eurofer/water ratio obtaining a BZ with the same amount of ACB but with less Zr_5Pb_3 (figure 2.25d).

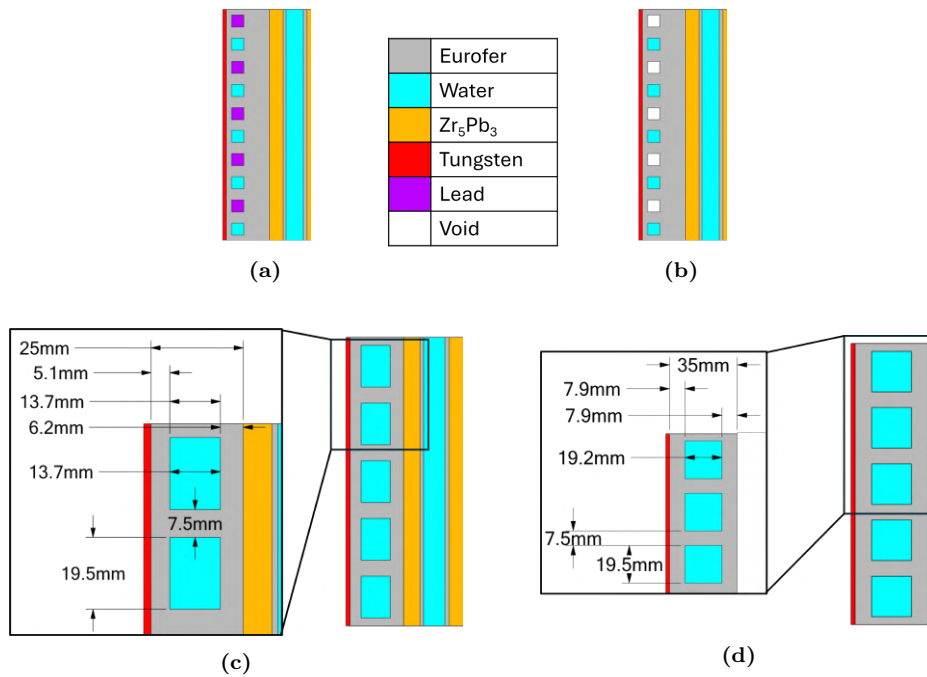


Figure 2.25: G1A1 (a), G1A2 (b), G1A3 (c), G1A4 (d) FW

The slices material composition is reported in table 2.5 while in tables 2.6 to 2.8 the results are shown.

Cases A1 and A2 showed that the first two rows of ACB tubes closer to the FW perform worse in terms of Tritium produced by Lithium 6, while the other rows are exploited more. This is due to the fact that neutrons passing through the FW encounter less water, which has a moderating effect, maintaining higher energies and thus the Tritium breeding reaction cross section decreases slightly (figure 1.5). However, looking at the value of TBR in table 2.8 one can see that these differences result in a virtually identical behavior. Case A3, on the other hand, turns out to be the most promising one since, unlike the first two, due to the higher presence of water that moderates the neutron flux by significantly increasing the Tritium reactions from Lithium 6 in the first two rows of ACB tubes, in agreement with [38]. Finally, the A4 case, generated to try to harden FW and SW by decreasing the multiplier content in BZ led to results in line with those of A3, but which are, however, worse overall than the reference case. This is probably caused by the fact that most of the neutrons reacts with the tube rows closest to FW, allowing fewer neutrons to interact with the back ones.

Table 2.5: *Group 1 slices material composition (BSS not considered)*

		Eurofer	H₂O	Zr₅Pb₃	Pb	ACB	Void	W	Vol [cm³]
Ref	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	46.96%	0.00%	37.90%	0.00%	0.00%	7.432E+04
G1A1	FW	82.84%	6.59%	0.00%	6.59%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	46.96%	0.00%	37.90%	0.00%	0.00%	7.432E+04
G1A2	FW	82.84%	6.59%	0.00%	0.00%	0.00%	6.59%	3.98%	5.711E+03
	BZ	12.39%	2.75%	46.96%	0.00%	37.90%	0.00%	0.00%	7.432E+04
G1A3	FW	60.29%	35.73%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	46.96%	0.00%	37.90%	0.00%	0.00%	7.432E+04
G1A4	FW	60.98%	36.14%	0.00%	0.00%	0.00%	0.00%	2.89%	7.869E+03
	BZ	12.72%	2.83%	45.56%	0.00%	38.90%	0.00%	0.00%	7.241E+04

Table 2.6: *Group 1 slices TBR due to Li6 reactions*

Row	Vol [cm³]	Ref	A1	A2	A3	A4
1	8.022E+02	6.995E-02	-3.04%	-3.83%	18.33%	28.26%
2	8.867E+02	7.700E-02	-0.65%	-1.05%	3.77%	1.78%
3	1.325E+03	8.087E-02	0.36%	0.42%	0.00%	-6.45%
4	1.325E+03	6.156E-02	0.64%	0.92%	-0.51%	-8.68%
5	2.864E+03	6.898E-02	0.88%	1.47%	-0.55%	-10.33%
6	2.864E+03	4.609E-02	1.25%	2.08%	-0.77%	-11.51%
7	4.496E+03	3.275E-02	1.54%	2.85%	-0.90%	-12.92%

Table 2.6 continued from previous page

Row	Vol [cm ³]	Ref	A1	A2	A3	A4
8	4.496E+03	1.449E-02	2.34%	4.10%	-1.48%	-14.20%
9	4.496E+03	6.635E-03	2.86%	5.18%	-1.95%	-15.28%
10	4.496E+03	3.141E-03	3.54%	6.15%	-1.94%	-16.95%
Total	2.805E+04	4.615E-01	0.08%	0.32%	3.03%	-2.10%

Table 2.7: Group 1 slices TBR due to Li7 reactions

Row	Vol [cm ³]	Ref	A1	A2	A3	A4
1	8.022E+02	3.070E-04	-1.33%	0.60%	7.20%	-3.08%
2	8.867E+02	2.516E-04	-1.35%	0.57%	7.02%	-3.82%
3	1.325E+03	1.878E-04	-1.35%	0.54%	6.84%	-4.36%
4	1.325E+03	1.226E-04	-1.32%	0.64%	6.82%	-4.65%
5	2.864E+03	1.220E-04	-1.31%	0.72%	7.05%	-4.62%
6	2.864E+03	8.020E-05	-1.42%	0.78%	7.26%	-4.47%
7	4.496E+03	4.434E-05	-1.46%	0.92%	8.10%	-3.42%
8	4.496E+03	1.716E-05	-1.62%	0.94%	8.78%	-2.61%
9	4.496E+03	6.617E-06	-1.66%	0.57%	9.31%	-2.85%
10	4.496E+03	2.534E-06	-1.63%	1.15%	10.20%	-1.25%
Total	2.805E+04	1.142E-03	-1.35%	0.63%	7.13%	-3.88%

Table 2.8: Group 1 total slices TBR

Row	Vol [cm ³]	Ref	A1	A2	A3	A4
1	8.022E+02	7.026E-02	-3.03%	-3.81%	18.28%	28.13%
2	8.867E+02	7.726E-02	-0.65%	-1.04%	3.78%	1.76%
3	1.325E+03	8.106E-02	0.35%	0.42%	0.02%	-6.44%
4	1.325E+03	6.168E-02	0.64%	0.92%	-0.49%	-8.67%
5	2.864E+03	6.910E-02	0.87%	1.47%	-0.54%	-10.32%
6	2.864E+03	4.617E-02	1.24%	2.08%	-0.75%	-11.50%
7	4.496E+03	3.279E-02	1.54%	2.85%	-0.89%	-12.91%
8	4.496E+03	1.451E-02	2.33%	4.10%	-1.47%	-14.19%
9	4.496E+03	6.641E-03	2.86%	5.18%	-1.94%	-15.27%
10	4.496E+03	3.143E-03	3.54%	6.14%	-1.93%	-16.94%
Total	2.805E+04	4.626E-01	0.08%	0.32%	3.04%	-2.10%

2.4.2 Group 2 analyses

Group 2 consists of five analyses were a single 15 mm plate of different multiplying and/or reflecting material [39] was placed in different zones of the BZ:

- A1: Carbon plate in figure 2.26 position 1;

- A2: Be₁₂Ti plate in figure 2.26 position 1;
- A3: MgO plate in figure 2.26 position 1;
- A4: MgO plate in figure 2.26 position 2;
- A5: MgO plate in figure 2.26 position 3.

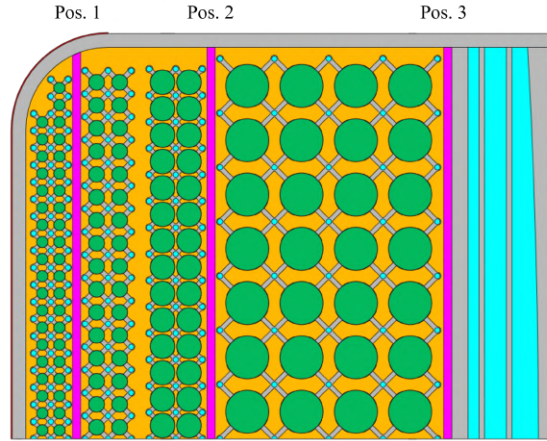


Figure 2.26: Possible plate positions in G2 analyses

Given the slices material composition in table 2.9 the analyses were carried out and the results are reported in tables 2.10 to 2.12.

The results showed practically negligible overall effects, while locally the A2 case with Be₁₂Ti plate showed a particularly high increase in TBR compared with the rest of the cases, in the immediately adjacent tube rows.

Table 2.9: Group 2 slices material composition (BSS not considered)

		Eurofer	H ₂ O	Zr ₅ Pb ₃	ACB	C	Be ₁₂ Ti	MgO	W	Vol [cm ³]
Ref	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	46.96%	37.90%	0.00%	0.00%	0.00%	0.00%	7.432E+04
G2A1	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	45.04%	37.90%	1.92%	0.00%	0.00%	0.00%	7.432E+04
G2A2	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	45.04%	37.90%	0.00%	1.92%	0.00%	0.00%	7.432E+04
G2A3	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	45.04%	37.90%	0.00%	0.00%	1.92%	0.00%	7.432E+04
G2A4	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	45.01%	37.90%	0.00%	0.00%	1.95%	0.00%	7.432E+04
G2A5	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	45.01%	37.90%	0.00%	0.00%	1.95%	0.00%	7.432E+04

Table 2.10: Group 2 slices TBR due to Li6 reactions

Row	Vol [cm ³]	Ref	A1	A2	A3	A4	A5
1	8.022E+02	6.995E-02	-0.94%	-0.22%	-0.62%	-0.15%	0.00%
2	8.867E+02	7.700E-02	1.94%	-0.22%	1.36%	-0.09%	0.05%

Table 2.10 continued from previous page

Row	Vol [cm ³]	Ref	A1	A2	A3	A4	A5
3	1.325E+03	8.087E-02	1.62%	-0.29%	-1.00%	-0.05%	0.12%
4	1.325E+03	6.156E-02	-1.72%	-0.38%	-4.16%	-0.04%	0.09%
5	2.864E+03	6.898E-02	-2.78%	-0.15%	-5.84%	0.00%	0.01%
6	2.864E+03	4.609E-02	-2.71%	7.70%	-6.24%	2.22%	0.06%
7	4.496E+03	3.275E-02	-1.59%	3.00%	-5.97%	-1.18%	-0.03%
8	4.496E+03	1.449E-02	-0.44%	-8.72%	-5.43%	-5.53%	-0.06%
9	4.496E+03	6.635E-03	0.45%	-10.34%	-5.11%	-6.82%	0.01%
10	4.496E+03	3.141E-03	1.33%	-9.74%	-4.56%	-7.01%	1.97%
Total	2.805E+04	4.615E-01	-0.56%	0.30%	-2.79%	-0.23%	0.06%

Table 2.11: Group 2 slices TBR due to Li7 reactions

Row	Vol [cm ³]	Ref	A1	A2	A3	A4	A5
1	8.022E+02	3.070E-04	0.59%	-0.16%	0.11%	-0.17%	-0.05%
2	8.867E+02	2.516E-04	1.70%	-0.20%	0.49%	-0.20%	-0.12%
3	1.325E+03	1.878E-04	9.32%	-0.12%	-2.01%	-0.13%	-0.04%
4	1.325E+03	1.226E-04	8.23%	0.08%	-2.04%	0.06%	0.04%
5	2.864E+03	1.220E-04	7.32%	0.50%	-2.12%	0.32%	0.08%
6	2.864E+03	8.020E-05	7.04%	1.36%	-2.16%	0.69%	0.05%
7	4.496E+03	4.434E-05	6.78%	4.96%	-1.99%	-1.31%	-0.04%
8	4.496E+03	1.716E-05	6.15%	3.72%	-2.45%	-1.46%	-0.06%
9	4.496E+03	6.617E-06	5.66%	2.43%	-2.89%	-2.33%	0.10%
10	4.496E+03	2.534E-06	5.33%	2.11%	-3.04%	-2.83%	0.28%
Total	2.805E+04	1.142E-03	4.63%	0.32%	-0.93%	-0.11%	-0.03%

Table 2.12: Group 2 total slices TBR

Row	Vol [cm ³]	Ref	A1	A2	A3	A4	A5
1	8.022E+02	7.026E-02	-0.94%	-0.22%	-0.62%	-0.15%	0.00%
2	8.867E+02	7.726E-02	1.93%	-0.22%	1.35%	-0.09%	0.05%
3	1.325E+03	8.106E-02	1.64%	-0.29%	-1.00%	-0.05%	0.12%
4	1.325E+03	6.168E-02	-1.70%	-0.38%	-4.16%	-0.04%	0.09%
5	2.864E+03	6.910E-02	-2.77%	-0.15%	-5.84%	0.00%	0.01%
6	2.864E+03	4.617E-02	-2.70%	7.69%	-6.24%	2.22%	0.06%
7	4.496E+03	3.279E-02	-1.58%	3.00%	-5.97%	-1.18%	-0.03%
8	4.496E+03	1.451E-02	-0.43%	-8.70%	-5.42%	-5.53%	-0.06%
9	4.496E+03	6.641E-03	0.46%	-10.33%	-5.11%	-6.82%	0.01%
10	4.496E+03	3.143E-03	1.33%	-9.73%	-4.55%	-7.01%	1.96%
Total	2.805E+04	4.626E-01	-0.55%	0.30%	-2.79%	-0.23%	0.06%

2.4.3 Group 3 analyses

Group 3 consists of six analyses in which the breeder and/or the surrounding material composition was modified:

- A1: the material of the tubes surrounding the ACB has been modified to ZrH_2 instead of Eurofer;
- A2: the ACB has been replaced with a homogeneous material composed by 95% of ACB and 5% of ZrH_2 ;
- A3: the ACB has been replaced with a homogeneous material composed by 90% of ACB and 10% of ZrH_2 ;
- A4: the ACB has been replaced with a homogeneous material composed by 70% of ACB and 30% of ZrH_2 ;
- A5: the ACB has been replaced with Li_2TiO_3 with $\rho_g = 3.08 \text{ [g/cm}^3\text{]}$
- A6: the material of the tubes surrounding the ACB has been modified to Zr instead of Eurofer.

These analyses, with the material composition reported in table 2.13, are the ones that led to the most interesting results, shown in tables 2.14 to 2.16. In cases A1 to A4, the ZrH_2 material was used first as a constituent of the ACB tubes, then as a mixed component within the breeder itself. The presence of Hydrogen gives the material an important moderating effect [40], which inevitably results in the greatest utilization of the Lithium 6 that is present in the breeder, concentrating most of the reactions in the first five tube rows, sacrificing the remaining ones. In contrast, a totally negative trend is seen for what concerns Tritium production from Lithium 7. However, since the breeder is predominantly enriched in Lithium 6 and its cross section is always greater than the Lithium 7 one, the overall effect is still positive. Also in the study, the ZrH_2 percentage was increased in a discrete way, reaching a maximum of 30%, but without conducting a more detailed study to find a possible maximum, leaving room for further improvement. Instead, in case A5, an attempt was made to use instead of ACB only Li_2TiO_3 which has a higher coefficient of thermal conductivity and a temperature at which Tritium can be extracted of $\approx 600^\circ\text{C}$, leading to promising results. Case A6 produced no particularly noteworthy results.

Table 2.13: *Group 3 slices material composition (BSS not considered)*

		Eurofer	H ₂ O	Zr ₅ Pb ₃	ACB	ZrH ₂	Li ₂ TiO ₃	Zr	W	Vol [cm ³]
Ref	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	46.96%	37.90%	0.00%	0.00%	0.00%	0.00%	7.432E+04
G3A1	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	10.91%	2.75%	46.96%	37.90%	1.48%	0.00%	0.00%	0.00%	7.432E+04
G3A2	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	46.96%	36.00%	1.89%	0.00%	0.00%	0.00%	7.432E+04

Table 2.13 continued from previous page

		Eurofer	H ₂ O	Zr ₅ Pb ₃	ACB	ZrH ₂	Li ₂ TiO ₃	Zr	W	Vol [cm ³]
G3A3	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	46.96%	34.11%	3.79%	0.00%	0.00%	0.00%	7.432E+04
G3A4	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	46.96%	26.53%	11.37%	0.00%	0.00%	0.00%	7.432E+04
G3A5	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	46.96%	0.00%	0.00%	37.90%	0.00%	0.00%	7.432E+04
G3A6	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	10.91%	2.75%	46.96%	37.90%	0.00%	0.00%	1.48%	0.00%	7.432E+04

Table 2.14: Group 3 slices TBR due to Li6 reactions

Row	Vol [cm ³]	Ref	A1	A2	A3	A4	A5	A6
1	8.022E+02	6.995E-02	11.57%	3.55%	7.04%	19.76%	12.57%	0.31%
2	8.867E+02	7.700E-02	11.76%	4.02%	7.93%	21.72%	12.09%	0.31%
3	1.325E+03	8.087E-02	7.68%	4.05%	7.94%	20.82%	10.80%	0.44%
4	1.325E+03	6.156E-02	5.96%	3.47%	6.53%	15.57%	7.83%	0.58%
5	2.864E+03	6.898E-02	0.06%	2.27%	3.87%	5.97%	3.60%	0.70%
6	2.864E+03	4.609E-02	-2.34%	-0.05%	-0.88%	-8.08%	-5.82%	1.04%
7	4.496E+03	3.275E-02	-7.85%	-3.53%	-7.56%	-22.68%	-13.23%	1.20%
8	4.496E+03	1.449E-02	-9.56%	-8.30%	-16.07%	-38.51%	-24.52%	1.61%
9	4.496E+03	6.635E-03	-11.12%	-13.49%	-24.53%	-51.16%	-35.03%	1.97%
10	4.496E+03	3.141E-03	-12.72%	-18.51%	-31.95%	-60.43%	-45.64%	2.49%
Total	2.805E+04	4.615E-01	4.53%	1.88%	3.53%	8.47%	4.30%	0.64%

Table 2.15: Group 3 slices TBR due to Li7 reactions

Row	Vol [cm ³]	Ref	A1	A2	A3	A4	A5	A6
1	8.022E+02	3.070E-04	0.12%	-5.38%	-10.71%	-31.64%	12.76%	0.29%
2	8.867E+02	2.516E-04	0.49%	-5.57%	-11.08%	-32.51%	9.36%	0.80%
3	1.325E+03	1.878E-04	0.75%	-5.93%	-11.74%	-33.93%	5.16%	1.31%
4	1.325E+03	1.226E-04	1.04%	-6.26%	-12.37%	-35.32%	0.24%	1.85%
5	2.864E+03	1.220E-04	1.25%	-7.03%	-13.76%	-38.05%	-6.16%	2.37%
6	2.864E+03	8.020E-05	1.70%	-7.65%	-15.01%	-40.84%	-15.55%	3.12%
7	4.496E+03	4.434E-05	1.91%	-8.53%	-16.62%	-44.07%	-25.74%	3.62%
8	4.496E+03	1.716E-05	2.12%	-9.47%	-18.52%	-47.90%	-37.21%	4.18%
9	4.496E+03	6.617E-06	2.36%	-10.55%	-20.40%	-51.48%	-46.49%	4.83%
10	4.496E+03	2.534E-06	2.61%	-11.31%	-22.11%	-54.11%	-54.15%	5.79%
Total	2.805E+04	1.142E-03	0.75%	-6.17%	-12.20%	-34.83%	2.67%	1.39%

Table 2.16: *Group 3 total slices TBR*

Row	Vol [cm ³]	Ref	A1	A2	A3	A4	A5	A6
1	8.022E+02	7.026E-02	11.52%	3.51%	6.96%	19.54%	12.57%	0.31%
2	8.867E+02	7.726E-02	11.72%	3.99%	7.87%	21.54%	12.09%	0.32%
3	1.325E+03	8.106E-02	7.67%	4.03%	7.89%	20.70%	10.79%	0.44%
4	1.325E+03	6.168E-02	5.95%	3.45%	6.49%	15.47%	7.82%	0.58%
5	2.864E+03	6.910E-02	0.06%	2.25%	3.84%	5.89%	3.59%	0.70%
6	2.864E+03	4.617E-02	-2.33%	-0.07%	-0.91%	-8.14%	-5.84%	1.04%
7	4.496E+03	3.279E-02	-7.84%	-3.53%	-7.57%	-22.71%	-13.25%	1.20%
8	4.496E+03	1.451E-02	-9.55%	-8.30%	-16.07%	-38.52%	-24.54%	1.61%
9	4.496E+03	6.641E-03	-11.11%	-13.48%	-24.52%	-51.16%	-35.04%	1.97%
10	4.496E+03	3.143E-03	-12.70%	-18.50%	-31.94%	-60.43%	-45.65%	2.50%
Total	2.805E+04	4.626E-01	4.52%	1.86%	3.49%	8.36%	4.29%	0.64%

2.4.4 Group 4 analyses

Group 4 consists of three analyses in which the multiplier was changed:

- A1: instead of the Zr₅Pb₃ there is void;
- A2: instead of the Zr₅Pb₃ there is ZrH₂;
- A3: instead of the Zr₅Pb₃ there is ZrH₂ until the sixth row of ACB tubes, then void.

Starting from a material composition reported in table 2.17, analyses results are reported in tables 2.18 to 2.20.

In all cases a negative trend can be seen. In particular, case A1 shows a significant increase in Tritium production from Lithium 7 since the neutron flux encounters considerably fewer targets to interact with. This solution also leads to major problems related to shielding to the outside of the reactor. Cases A2 and A3, on the other hand, again demonstrate the advantage in using a moderator such as ZrH₂ to allow greater utilization of the first ≈ 40 cm of BZ and potentially think about reducing the overall radial size of the reactor.

Table 2.17: *Group 4 slices material composition (BSS not considered)*

		Eurofer	H ₂ O	Zr ₅ Pb ₃	ACB	Void	ZrH ₂	W	Vol [cm ³]
Ref	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	46.96%	37.90%	0.00%	0.00%	0.00%	7.432E+04
G4A1	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	0.00%	37.90%	46.96%	0.00%	0.00%	7.432E+04
G4A2	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	0.00%	37.90%	0.00%	46.96%	0.00%	7.432E+04

Table 2.17 continued from previous page

		Eurofer	H ₂ O	Zr ₅ Pb ₃	ACB	Void	ZrH ₂	W	Vol [cm ³]
G4A3	FW	82.84%	13.18%	0.00%	0.00%	0.00%	0.00%	3.98%	5.711E+03
	BZ	12.39%	2.75%	0.00%	37.90%	26.69%	20.27%	0.00%	7.432E+04

Table 2.18: Group 4 slices TBR due to Li6 reactions

Row	Vol [cm ³]	Ref	A1	A2	A3
1	8.022E+02	6.995E-02	-29.09%	86.62%	87.16%
2	8.867E+02	7.700E-02	-33.92%	62.83%	62.02%
3	1.325E+03	8.087E-02	-27.54%	8.73%	8.05%
4	1.325E+03	6.156E-02	-25.07%	-23.46%	-23.89%
5	2.864E+03	6.898E-02	0.79%	-54.10%	-53.69%
6	2.864E+03	4.609E-02	6.84%	-67.35%	-71.13%
7	4.496E+03	3.275E-02	57.40%	-67.92%	-73.41%
8	4.496E+03	1.449E-02	130.36%	-77.01%	-75.18%
9	4.496E+03	6.635E-03	241.63%	-80.81%	-63.01%
10	4.496E+03	3.141E-03	471.76%	-83.80%	-34.32%
Total	2.805E+04	4.615E-01	-2.59%	-1.77%	-2.05%

Table 2.19: Group 4 slices TBR due to Li7 reactions

Row	Vol [cm ³]	Ref	A1	A2	A3
1	8.022E+02	3.070E-04	24.21%	-0.29%	0.35%
2	8.867E+02	2.516E-04	40.82%	-0.74%	-0.72%
3	1.325E+03	1.878E-04	121.35%	-1.66%	-2.12%
4	1.325E+03	1.226E-04	162.26%	-2.91%	-3.67%
5	2.864E+03	1.220E-04	323.90%	-5.59%	-6.36%
6	2.864E+03	8.020E-05	366.12%	-7.01%	-7.11%
7	4.496E+03	4.434E-05	755.82%	-11.63%	35.09%
8	4.496E+03	1.716E-05	1228.99%	-15.37%	112.76%
9	4.496E+03	6.617E-06	1956.07%	-19.34%	231.49%
10	4.496E+03	2.534E-06	3077.61%	-21.77%	413.29%
Total	2.805E+04	1.142E-03	179.19%	-2.76%	3.33%

Table 2.20: Group 4 total slices TBR

Row	Vol [cm ³]	Ref	A1	A2	A3
1	8.022E+02	7.026E-02	-28.86%	86.24%	86.78%
2	8.867E+02	7.726E-02	-33.68%	62.63%	61.82%
3	1.325E+03	8.106E-02	-27.19%	8.71%	8.03%
4	1.325E+03	6.168E-02	-24.70%	-23.42%	-23.85%

Table 2.20 continued from previous page

Row	Vol [cm ³]	Ref	A1	A2	A3
5	2.864E+03	6.910E-02	1.36%	-54.02%	-53.61%
6	2.864E+03	4.617E-02	7.47%	-67.24%	-71.02%
7	4.496E+03	3.279E-02	58.34%	-67.84%	-73.26%
8	4.496E+03	1.451E-02	131.66%	-76.93%	-74.96%
9	4.496E+03	6.641E-03	243.34%	-80.75%	-62.72%
10	4.496E+03	3.143E-03	473.86%	-83.75%	-33.95%
Total	2.805E+04	4.626E-01	-2.14%	-1.77%	-2.04%

Chapter 3

Automation of the HELIAS 5B breeding blanket design procedure

3.1 Introduction

Within the framework of the EUROfusion Work Package (WP) Prospective Research and Development – Stellarator Power Plant Studies (PRD-SPPS) activities, in parallel to the DEMO tokamak, a fusion reactor concept based on the stellarator-type geometry named HELIAS 5B is being studied [41, 42, 43, 44]. It is a direct extrapolation of the W7-X located at the Max Planck Institute for Plasma Physics in Greifswald, Germany, and represents the next step in the study of stellarator-type machines.

Because of the stellarator geometry complexity, the manual CAD model handling and the set-up of the proper numerical models for the thermal and structural assessments requires a remarkable time amount. Moreover, it is error prone because of the huge number of manual operations to be executed, as highlighted in the previous research activities [45, 46]. Hence, a semi-automatic procedure and parametric design tools have been developed.

As a first step in the study, a bibliographic review was carried out on the state of the art of multi-physics analysis software, in order to identify the most suitable and versatile for the intended purposes. Among those taken into consideration, attention was focused on the commercial ANSYS software, listed among the reference codes adopted from the international scientific community involved in the research on the nuclear fusion technology. Indeed, since its last releases, ANSYS has a stable version with a programming and operation automation module based on Python. Hence, following a study of the documentation provided [47], the great potential of the software emerged. In particular, it allows numerous operations to be carried out, even onerous in terms of work and calculation time, with just a few lines of code, with an intuitive syntax that is in any case well-detailed and explained

in the relevant guide, also considering the fact that Python is one of the easiest programming languages to learn and use at present [48].

What has been obtained is a functional, semi-automated workflow based on a series of multi-scale and multi-physics FEM analyses that can provide accurate results on the structural response of any part of the model, without losing the realism of the boundary conditions.

To be more clear in the description of the methodology developed, it is mandatory to chose a specific case study and describe first the geometry considered. In particular the DEMO Dual-Coolant Lithium-Lead (DCLL) [49] BB was chosen, adapting it to the HELIAS geometry [50]. It is important to say however that the already mentioned procedure can be easily implemented as the design solution changes, as already demonstrated in [51] and [52].

It is also important to reiterate that the goal was not to obtain accurate results for the analyses, but rather to outline a working semi-automatic procedure which was reliable, flexible and easy to use, in order to perform quick preliminary analyses to find the most promising design. The reported results have to be intended just as an exercise, properly carried out to verify the set-up procedure testing the scripts set-up.

3.2 Description of the geometries

Since the analysis procedure is based on a multi-scale approach, two 3D main models (at two different hierarchical levels) were considered for its application: an Homogeneous Model (HoM) and an Heterogeneous Model (HeM). The first one essentially represent the fundamental unit in which the reactor can be divided with very few structural details, while the second one is a small portion of the same model but with detailed components. Moreover, in principle, several HeMs can be simultaneously developed and assessed, as they stay all at the same hierarchical level in the procedure, each simulating a specific region of interest of the BB sector. Then, the obtained outcomes would be combined to allow a more detailed analysis of the HoM in view of the back-and-forth workflow characterizing the analysis procedure. For the sake of brevity and considering that the work herein reported in not intended to perform design studies, being rather oriented to the assessment of the analysis procedure flexibility and capabilities, only one HeM has been set-up.

3.2.1 The Homogeneous Model

The HoM consists of an entire 72° sector of the HELIAS 5B BB composed of homogeneous material blocks, divided into sixteen rings that are in turn divided into five segments for a total of 80 BB segments (figure 3.1a). In each segment

it is possible to distinguish the tungsten armor, the FW, the BZ and the BSS “dummy” components, namely full solids without any internal detail. Each ring in the toroidal direction and each segment in the poloidal direction are separated by 20 mm gaps. The VV, which is divided into inner, shield and outer part, is also defined [45, 46] using dummy (i. e. homogeneous) solid blocks (figure 3.1b). The “dummy” solids composing the HoM are therefore homogenized components characterized by equivalent properties, calculated on the basis of a given assumed material composition. In case of the HELIAS 5B machine here considered as exercise, the HoM represents 1/5 of the torus. More in general, whatever is the HELIAS shape taken into account, the HoM should represent the basic geometric entity that can be symmetrically reproduced to give the whole blanket shape.

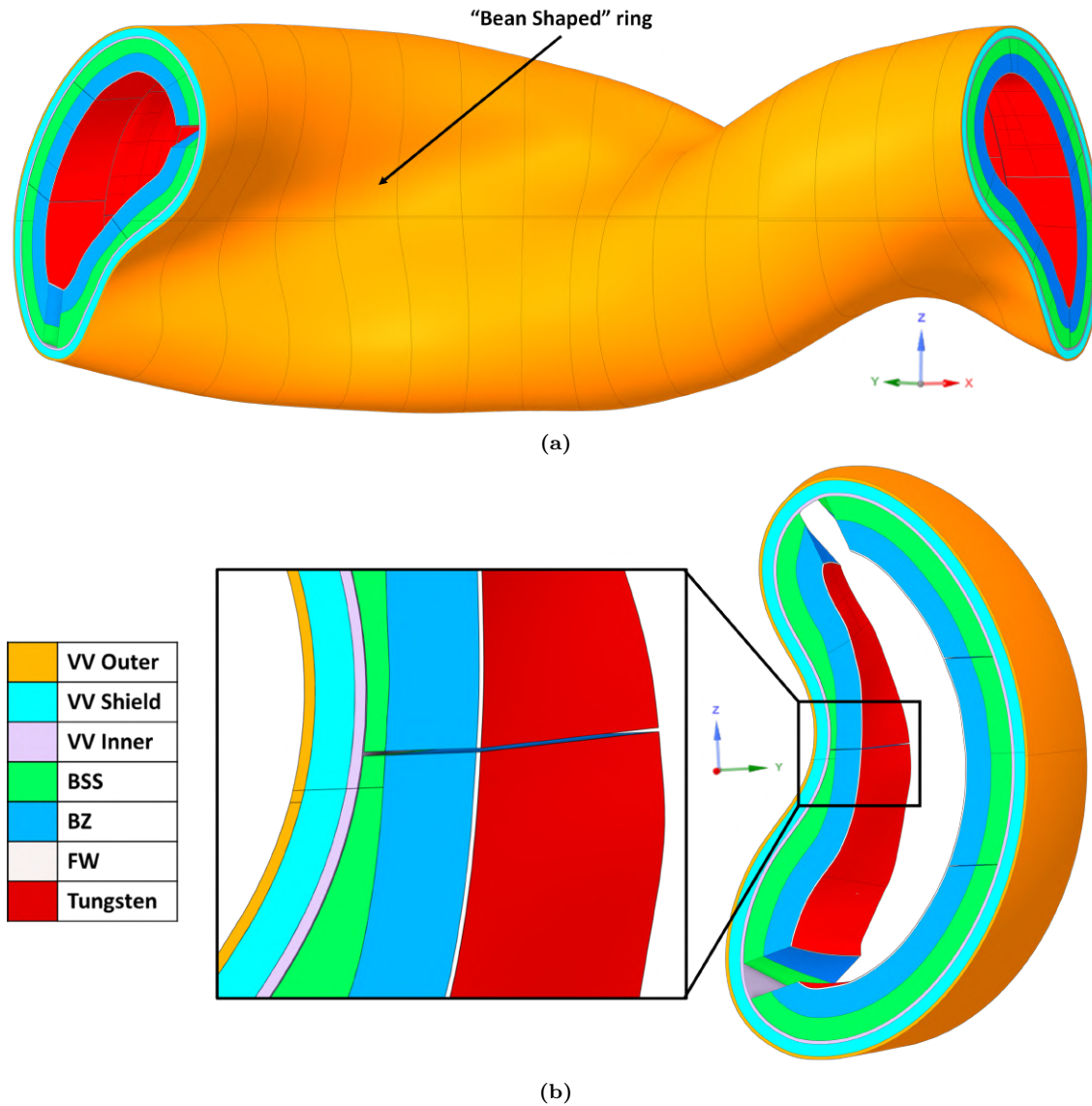


Figure 3.1: The homogeneous model (a) and “bean shaped” ring details (b)

3.2.2 The Heterogeneous Model

The HeM represents, in principle, an arbitrary local region of the HELIAS 5B BB sector that is the focus of the analysis. Practically, it reproduces in detail that region for which one wants performing the detailed design analysis in view of the prescribed code and standards criteria. Hence, it stays at the lowest hierarchical level of the procedure. In the present study, the selected HeM represents a localized region of the outboard side of the HELIAS 5B “bean shaped” BB ring (called in literature Segment 2, Ring 12, figure 3.2). Specifically, the space reservation of this BB region was taken from the neutronic analysis model used in [53], integrated in the HELIAS 5B BB (see figure 3.2) and properly modified to make it compliant for the thermomechanical analyses. In particular, only a relevant piece of the original neutronic model has been considered for the thermomechanical analysis (circled in red in figure 3.2). Then, the internal details have been added by means of a dedicated campaign of geometry editing, referring to the DEMO tokamak DCLL BB architecture described in [50]. It is important to underline that most of the geometry editing operations have to be done manually, representing a time-consuming part of the whole modelling activity.

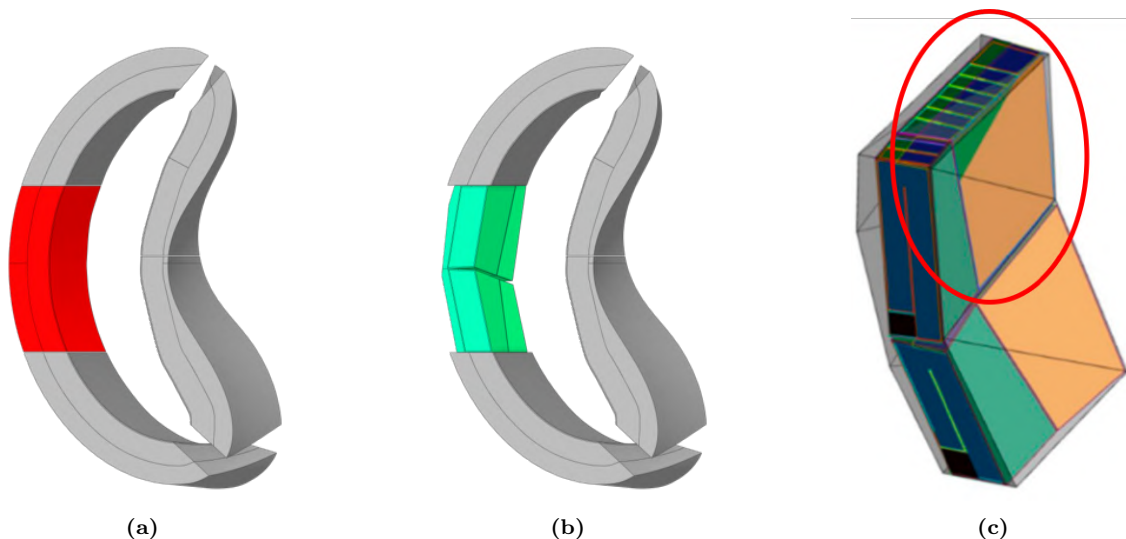


Figure 3.2: Homogeneous segment 2 of the “bean shaped” ring (a), detailed version of the same segment with a DEMO DCLL architecture (b) and representation of its neutronic model (c)

The HeM encompasses a Segment Box (SB) in which a total of 94 Helium cooling channels were designed, following the shape of the component in order to be uniformly distributed to guarantee a proper refrigeration. Hence, the size of the channels has an average value of $12.5 \times 12.5 \text{ mm}^2$ with a pitch between 7 and 9 mm, and the distance between the FW plasma-facing interface and the helium channels is 2 mm. A Top Cap (TC) and a Bottom Cap (BC) are also present to enclose the blanket and a total of 12 channels each were designed for the coolant with $\approx 12.5 \times 14 \text{ mm}^2$ area. Six radial-poloidal Cooling Stiffeners (CSs) are present

along with an “L” shaped toroidal-poloidal SP that also serves as a guide for the PbLi flow path as depicted in red in figure 3.3. Two bearings systems were modelled in the form of homogeneous blocks, one between the SB and the BSS and another one between the BSS and the VV in order to simulate the attachment systems in the mechanical analysis. Finally, a 2 mm tungsten armor is also present as plasma facing component.

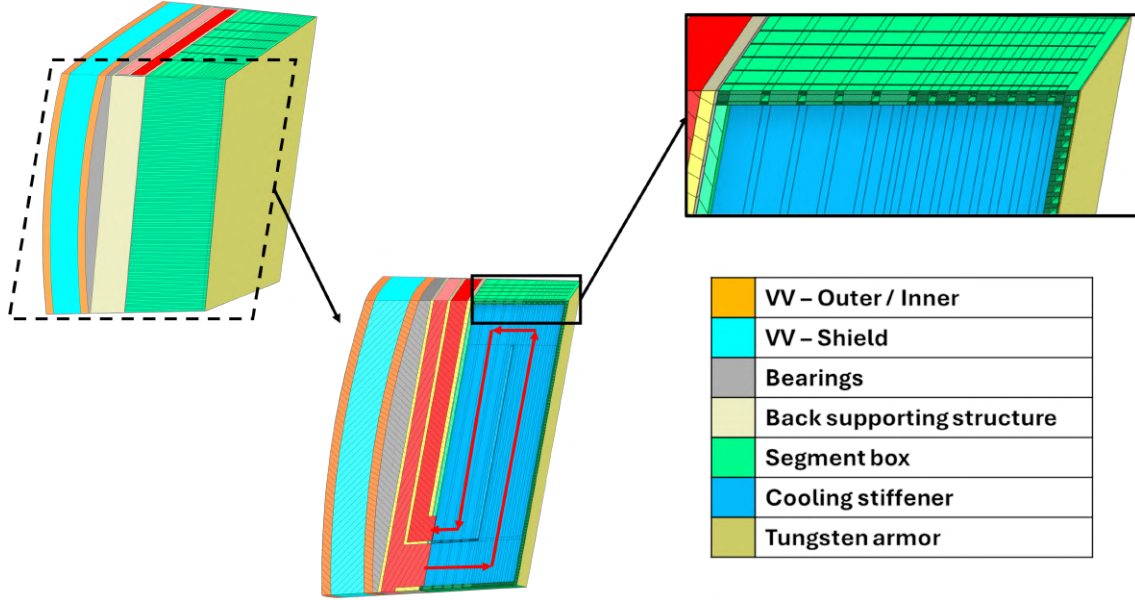


Figure 3.3: *The heterogeneous model in details*

3.3 Methodology and case study

The set-up procedure, schematically shown in figure 3.4, begins by considering any design solution whose structural response is wanted to be investigated, building some multi-scale models. In particular a global model with a very rough representation of the components characterizing the particular BB, i. e., HoM and two or more portion of the just mentioned global model that represent some areas that one want to analyze in detail, i. e., HeM(s).

It has to be underlined that the geometries must be provided externally, since the developed procedure is able to perform very few geometry editing operation. Once the geometric layout to be analyzed is chosen (i. e. provided), assumptions have to be made regarding the thermal loads the structure is subjected to, i. e., the thermal heat flux radiated from plasma and the neutronic and photonic thermal power density deposited within the bodies. For the purposes of this study, both geometry and thermal loads spatial distributions must be provided as input. Once determined the loads, the HeM thermal analysis is then performed, and the thermal field of the structure components is obtained. Starting from these results, temperatures to be imposed to the corresponding HoM components can be estimated. The simplest

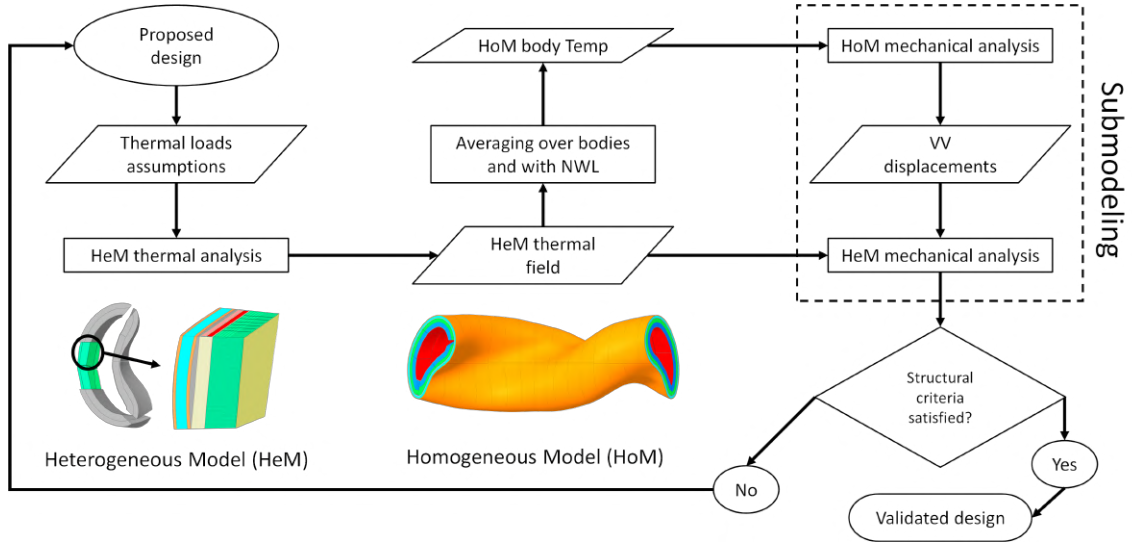


Figure 3.4: *Semi-automated procedure's flow chart*

way, as done in the exercise here reported, consists in calculating the average temperatures of the above said components of the HeM. At this point, if only one HeM is considered, such average temperatures can be assigned to all the components of the corresponding HoM area. Instead, if multiple HeMs are considered (in case different zones of the same components have to be studied in detail), several thermal fields for each component are available and, therefore, the calculated thermal fields can be combined in order to obtain more precise temperatures for the HoM. In principle, they can be either uniform values or space dependent functions. For the exercise here reported, uniform temperatures are assumed for the HoM components. Once determined the temperatures of the HeM components, using the relation

$$\bar{T}_{k,R_i S_j} = \bar{T}_{k,R_{ref} S_{ref}} \frac{\overline{NWL}_{k,R_i S_j}}{\overline{NWL}_{k,R_{ref} S_{ref}}} \quad (3.1)$$

a uniform temperature value for the k -th component located in the j -th BB segment of the i -th BB ring can be calculated starting from the same component of the reference segment and ring (namely the BB segment represented by the HeM) scaled by the corresponding average Neutron Wall Loading (NWL) ratio. In the case here reported as exercise, the average NWLs have been calculated starting from the NWL spatial distribution reported in [54] and the reference segment is the Segment 2 of the “bean shaped” BB ring. At this point each component of every BB segment represented in the HoM is characterized from the thermal point of view. Once these data are obtained and the boundary conditions are imposed, a submodeling phase begins with the HoM mechanical analysis. From this analysis, the displacements associated with the nodes that constitute the finite element model are obtained, which are used as boundary conditions for the subsequent mechanical analysis of HeM, along with the temperature values averaged over the bodies obtained earlier.

In particular, the displacement field calculated for the HoM at the border with the cut performed to derive the HeM are used as mechanical boundary conditions in the next HeM mechanical analysis. In this way, the structural behavior of the HeM can be assessed taking into account the effect of the rest of the BB sector.

Once the displacements and stresses spatial distributions have been obtained, it is then possible to apply the structural criteria verification procedure according to the RCC-MRx standards in order to determine whether they are fulfilled or not. Thus, a more accurate structural response can be obtained in this way, which is the result of more realistic assumptions and it considers the effect of the entire BB 72° sector.

In the next chapters the procedure will be applied to the DCLL case study and all the steps will be described in details.

3.4 Heterogeneous model thermal analysis

The first step of the procedure is represented by the HeM thermal analysis. In order to characterize the problem, first it is necessary to understand how the considered blanket architecture is supposed to work and to be refrigerated. In the following paragraphs the fluids flow path, the thermal loads and the boundary conditions imposed will be described and the results in terms of the temperature 3D spatial distributions will be shown.

3.4.1 The finite element model

Concerning the materials used in the simulations, the temperature dependent physics properties of the Eurofer (the structural steel), the PbLi (the circulating breeder), the Tungsten (the plasma facing materials) and the Helium (the main coolant) were taken from [50]. A mesh composed by a total of $\approx 2\text{M}$ nodes connected into $\approx 3\text{M}$ linear elements was generated and some of its details are shown in figure 3.5.

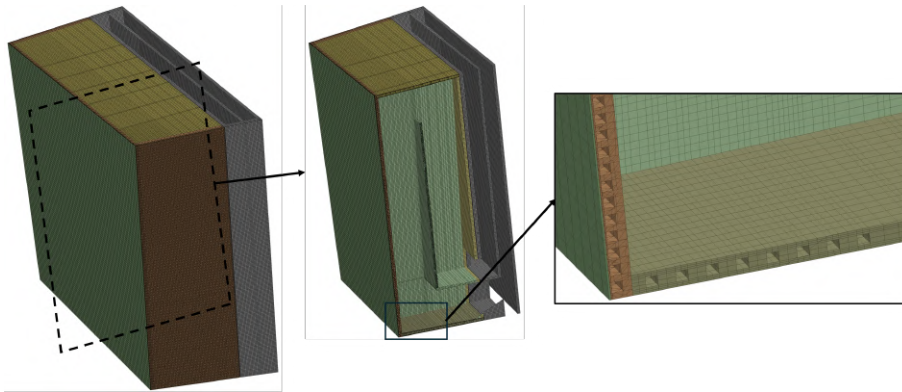


Figure 3.5: *Heterogeneous model thermal analysis mesh details*

The VV and the bearings were not simulated in the thermal analysis, but they have taken into account with proper radiative boundary conditions as described in the next paragraphs.

3.4.2 Helium and PbLi flow path

The DCLL BB concept works with Helium as main coolant fluid, foreseeing a circulating PbLi acting as breeder, neutron multiplier and tritium carrier while removing a non-negligible heat power. In order to simulate the cooling effect of the flowing Helium, a proper 1D FEM approach has been adopted. Assuming the flow velocity field as “frozen”, the Helium can be modelled as a group of 1D solids exploiting the “thermal fluids” capability of ANSYS mechanical. In figure 3.6 the Helium flow scheme of the original DCLL BB architecture and the one adapted to this case study are shown.

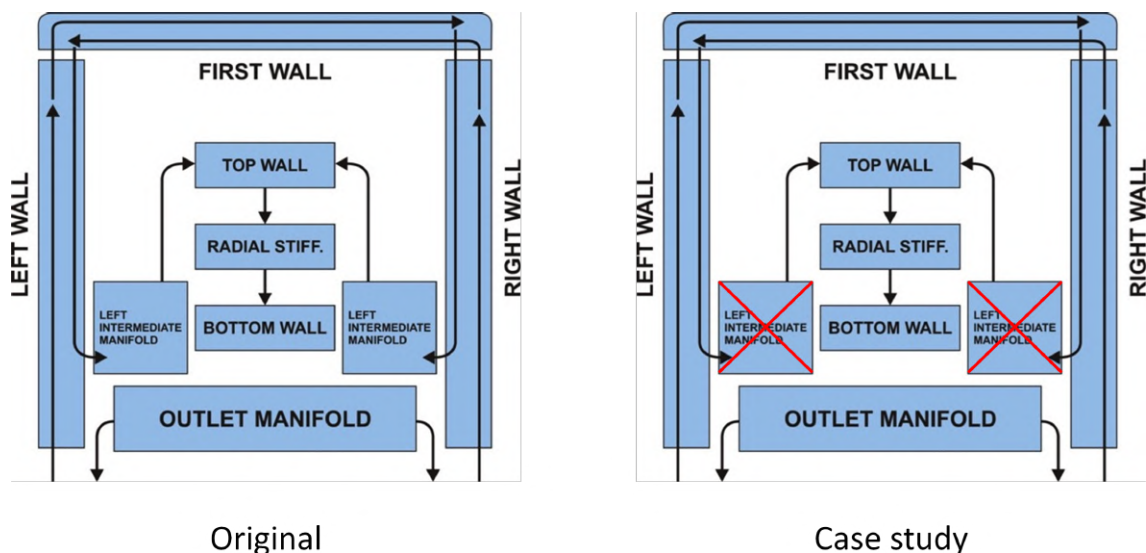


Figure 3.6: *Helium flow scheme*

In particular, compared to the original flow scheme [50], in this case study the left and right intermediate manifolds were not simulated. However, their presence has been considered assuming that the temperature of the Helium entering the TC was equal to the average of the temperatures of the Helium leaving the SWs channels, so simulating somehow the Helium mixing expected in the intermediate manifolds. Specifically, the Helium enters from the right or left SW in counter current, flows throughout the FW and exits from the opposite SW. Then it enters in sequence the TC (counter current), the CSs (co-current) and the BC (counter current). Finally, it exits the system through the manifolds located in the BSS. Hence, for the simulation, were created:

- 94 thermal fluids for the FW;

- 12 thermal fluids for the TC;
- 72 thermal fluids for the CSs;
- 12 thermal fluids for the BC.

To link the thermal fluids and properly characterize the flow path considering the mixing effects occurring at the exit of every component, almost 3k lines of APDL code were automatically written by means of a specifically conceived Python script [cite script in appendix B] to impose the following conditions:

For the i -th TC thermal fluid inlet node, with i from 1 to 12:

$$T_i^{TC,in} = \frac{1}{94} \sum_{k=1}^{94} T_k^{FW,out} \quad (3.2)$$

For the i -th CS thermal fluid inlet node, with i from 1 to 72:

$$T_i^{CS,in} = \frac{1}{12} \sum_{k=1}^{12} T_k^{TC,out} \quad (3.3)$$

For the i -th BC thermal fluid inlet node, with i from 1 to 12:

$$T_i^{BC,in} = \frac{1}{72} \sum_{k=1}^{72} T_k^{CS,out} \quad (3.4)$$

This saved a considerable amount of time and allowed to avoid any kind of human mistake.

Similarly to what has been described for the Helium, also the PbLi was modelled as a group of 7 thermal fluids. In this case there was no need to impose equations to link the nodes since every thermal fluid connects the inlet to the outlet of the PbLi system (figure 3.3).

3.4.3 Loads, boundary conditions and iterative procedure

A series of loads and boundary conditions were imposed to characterize the problem from the thermal standpoint as follows:

- the heat flux radiated from the plasma;
- the volumetric density of heat power deposited inside every component by neutrons and photons;
- a radiative condition between the SB and the BSS;
- a radiative condition between the BSS and the VV;
- a Dirichlet boundary condition to impose the temperature to the BSS manifold surfaces;
- a convective condition for the Helium cooling system;
- a convective condition for the PbLi flowing system.

Starting from a fusion-generated power of 3000 MW [5] and considering that the fraction associated with alpha particles (≈ 600 MW) is entirely transferred to the plasma and from it radiated toward the tungsten armor, which is approximately 2400 m^2 [46], an average (yet conservative) heat flux value of 0.247 MW/m^2 was obtained as the ratio of the latter two values. In this exercise, power radiated toward the divertor and residual alpha particles energy are not considered.

The radial profiles of the deposited nuclear volumetric power densities were provided by [43] and are shown in figure 3.7. For the Tungsten a uniform value of 9 W/cm^3 was considered.

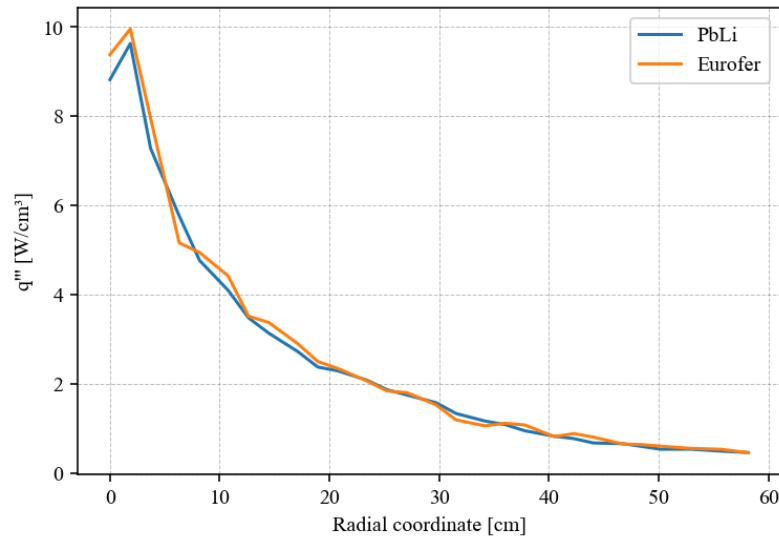


Figure 3.7: Power densities per material with radial origin on the FW surface

Since that the SB and the BSS as well as the BSS and the VV are supposed to be connected by means of a discrete attachment system (like a pin o key-based system), in order to take into account the radiative phenomenon within the cavities originated by the connected surfaces, two radiative boundary conditions were imposed. The one between the SB and the BSS has a “surface to surface” correlation (corresponding to assume the mutual radiative heat transfer in between the surfaces, with the corresponding view factor matrix calculated by the code) with an emissivity equal to 0.3 [55] whereas the one between the BSS and the VV has a “to ambient” correlation (corresponding to assume the VV, not physically represented in the model, as a black body at uniform temperature with a radiation view factor of 1.0) with an emissivity equal to 0.3 and an ambient temperature equal to 90°C which is the temperature considered for the inner VV.

Three Dirichlet conditions, taken from [50], were imposed onto the BSS manifold wetted surfaces as follows:

- 300°C to all the surfaces wetted by the inlet PbLi;
- 538°C to all the surfaces wetted by the outlet PbLi;

- 375 °C to all the surfaces wetted by the Helium;

In order to impose the convective boundary conditions, the iterative calculation loop (consisting in phase A and phase B) depicted in figure 3.8 has been followed, whereas in table 3.1 and table 3.2 the geometric characteristics of the channels and the assumptions on the inlet and outlet temperature of the fluids are shown. In the latter table, the yellow values mean that imposed (i. e. target) data is reported and, moreover, the hydraulic diameter D_h is reported, calculated as the ratio in between the channel cross section area A and the channel cross section wetted perimeter WP .

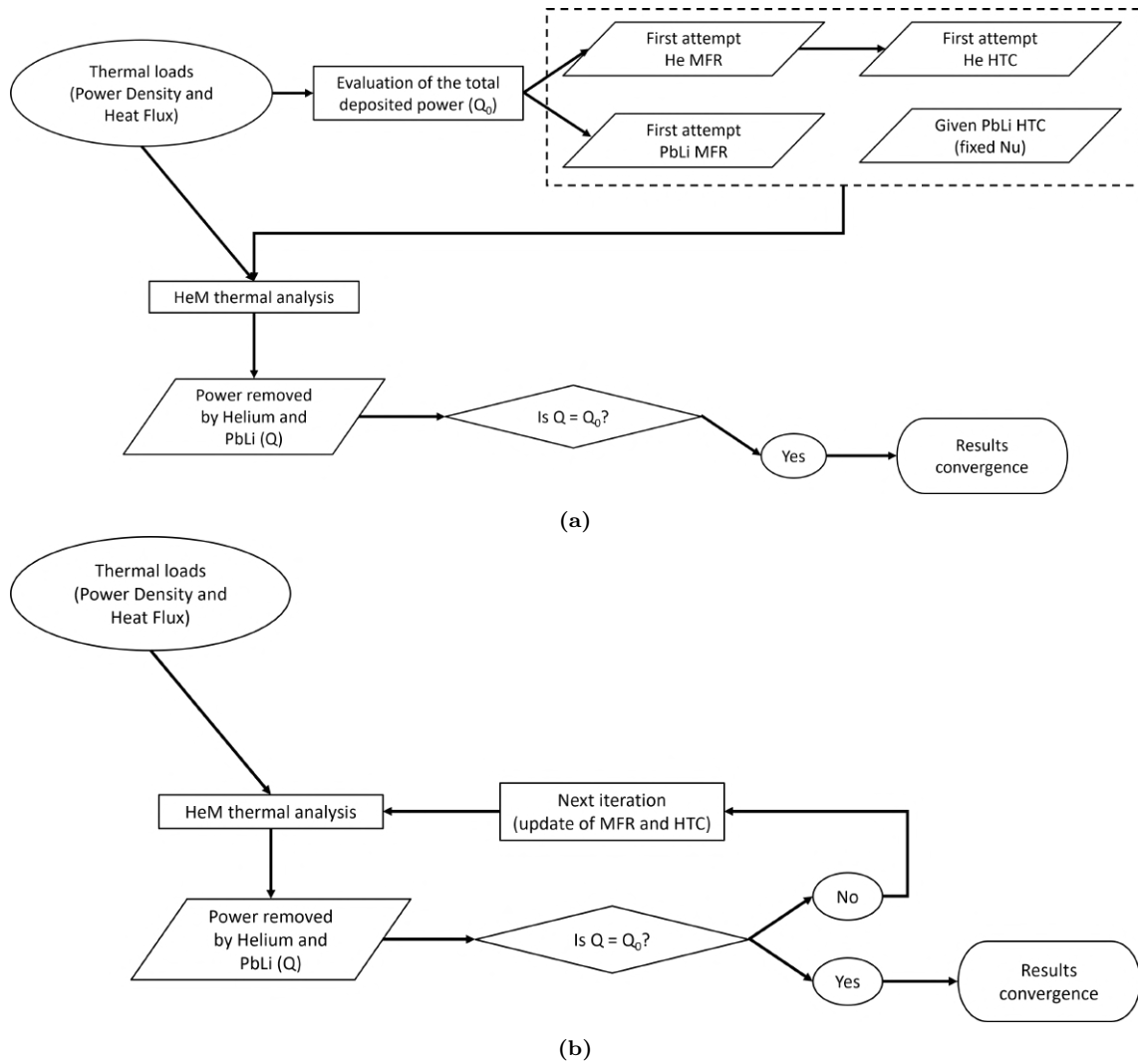


Figure 3.8: Phase A (a) and B (b) of the iterative procedure

In the “A” phase, using the power density and the heat flux already defined, it was possible to evaluate the total deposited power in the system, Q_0 . Then using this value, a first attempt Helium and PbLi total Mass Flow Rate (MFR) were calculated using:

$$\text{MFR}_0 = \frac{Q_0}{c_p(T_{ave})\Delta T} \quad (3.5)$$

Table 3.1: Geometric characteristics of the channels

Data	B [m]	H [m]	A [m ²]	WP [m]	Dh [m]	n _{ch}
FW	1.25E-02	1.25E-02	1.56E-04	5.00E-02	1.25E-02	94
TC	1.40E-02	1.25E-02	1.75E-04	5.30E-02	1.32E-02	12
CPs	1.40E-02	6.00E-03	8.40E-05	4.00E-02	8.40E-03	72
BC	1.40E-02	1.25E-02	1.75E-04	5.30E-02	1.32E-02	12
PbLi	1.75E-01	2.82E-01	4.94E-02	9.14E-01	2.16E-01	7

Table 3.2: Assumptions for the convective conditions

Data	T _{in} [°C]	ΔT [°C]	T _{ave} [°C]	ρ(T _{ave}) [kg/m ³]	c _p (T _{ave}) [J/(kgK)]	k(T _{ave}) [W/(mK)]	μ(T _{ave}) [kg/(ms)]	Pr(T _{ave})
He [8 Pa]	3.00E+02	1.50E+02	3.75E+02	5.85E+00	5.19E+03	2.69E-01	3.32E-05	6.40E-01
PbLi	3.00E+02	2.38E+02	4.19E+02	9.70E+03	1.89E+02	2.27E+01	1.58E-03	/

being the fluid average temperature T_{ave} known since T_{in} and ΔT are imposed as target values. Once calculated the total MFR, it is then possible to obtain the MFR per channel for every component. Regarding the Helium, the Gnielinsky correlation [56] was used to calculate the first attempt heat transfer coefficient as a function of MFR_0 , whereas for the PbLi, some assumptions must be made. In fact, finding a suitable correlation for the heat transfer coefficient is not an easy task. The main reason is that due to the heat volumetric source, the temperature boundary layers cannot be well approximated by a linear formula. Therefore, the concept of heat transfer coefficient is not really applicable. This problem arises in every liquid metal blanket but it is particularly important for a DCLL since the breeder is self-cooled. That said, due to the preliminary nature of these analyses an heat transfer coefficient can be used taking in mind that there is an important uncertainty on this kind of calculations, no matter the correlation or value is chosen.

It is possible to rely on mix-convection experiments under transverse magnetic field. From the experience of Gardner and Lykoudis [57] and posterior numerical analyses [58] it is shown that the turbulence suppression caused by the B-field will decrease the heat transfer. However, in the laminar regime the B-field increases Nusselt by narrowing of the velocity boundary layers. In laminar conditions Nusselt reaches an asymptotic value for Hartmann $\gg 1$ of around 5 [59].

However, the mentioned works are for insulated walls in circular pipes, not really relevant for this case. Nevertheless, the qualitative behavior should be maintained for conducting channels as well as seen in [60].

In this case, due to the orientation of the segments, the Hartmann is not as big as in tokamaks (between 1000-4000) while Reynolds is estimated to be of the order of 10^5 . This means that the field should not be able to completely suppress turbulence. According with [60], for this case study a range of values between 10 and 30 can be considered.

At this point the problem is fully set, and a first tentative thermal analysis can

be performed. As a result, a value Q of the power actually removed by the Helium and the PbLi can be calculated and compared to Q_0 . If the two values match, then the convergence is already reached and the results obtained can be considered valid. Otherwise, the procedure enters in the “B” phase. In particular, with this Q value, new MFRs for both Helium and PbLi and an heat transfer coefficient for the Helium can be calculated, whereas for the PbLi this value remains fixed due to the imposed Nusselt number. It is then possible to iterate the procedure until the power convergence is reached and the outlet temperature of the Helium and PbLi is respectively 450 °C and 538 °C.

3.4.4 Results

The convergence of the results has been reached in three iterations (figure 3.9), considering the PbLi Nusselt number equal to 30 (other values could have been set, allowing the automatic procedure to repeat the iterative loop). In table 3.3 the final MFRs and heat transfer coefficients are reported (highlighted in yellow).

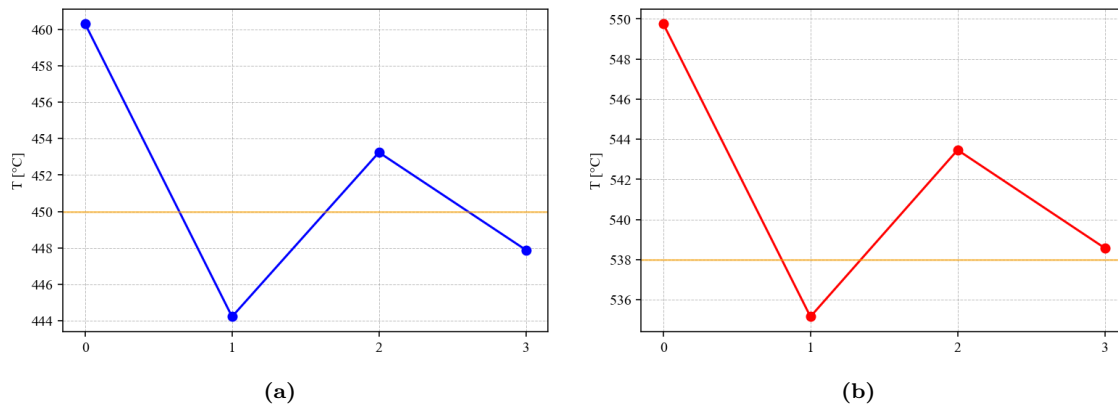


Figure 3.9: Helium (a) and PbLi (b) outlet temperatures convergence

Table 3.3: Final MFR and HTC values

Per channel	MFR [kg/s]	u [m/s]	Re	f	Nu	HTC [W/m ² K]
FW	4.467E-02	4.884E+01	1.077E+05	1.771E-02	1.787E+02	3.844E+03
TC	3.499E-01	3.416E+02	7.960E+05	1.209E-02	8.810E+02	1.793E+04
CSs	5.832E-02	1.186E+02	1.758E+05	1.602E-02	2.624E+02	8.398E+03
BC	3.499E-01	3.416E+02	7.960E+05	1.209E-02	8.810E+02	1.793E+04
PbLi	4.874E+00	/	/	/	3.000E+01	3.158E+03

The results of the thermal analysis in terms of 3D thermal field are shown in figure 3.10, where the only Eurofer domain is depicted. The highest temperatures (≈ 610 °C) are reached in proximity of the back plate of the SB due to the poor cooling of that region. In general, the internal plates experiences quite high

temperatures. On the other side, a good thermal behavior is globally predicted for the SB and the caps under the considered assumptions.

Nonetheless, since the purpose of the activity is not to optimize the geometric layout (that is, actually, not fully HELIAS relevant but adapted starting from a DCLL BB architecture conceived for tokamak DEMO) but to verify the robustness of the procedure, these results can be of high interest for the following phases of the research activity, possibly helping in designing fully HELIAS relevant BB architectures. Indeed, a promising behavior can be predicted for this DCLL BB architecture, even though it was conceived for DEMO and adapted to HELIAS geometry and, mainly, the semi-automatic analysis procedure has allowed predicting the thermal behavior of the selected region with a limited number of adjustments.

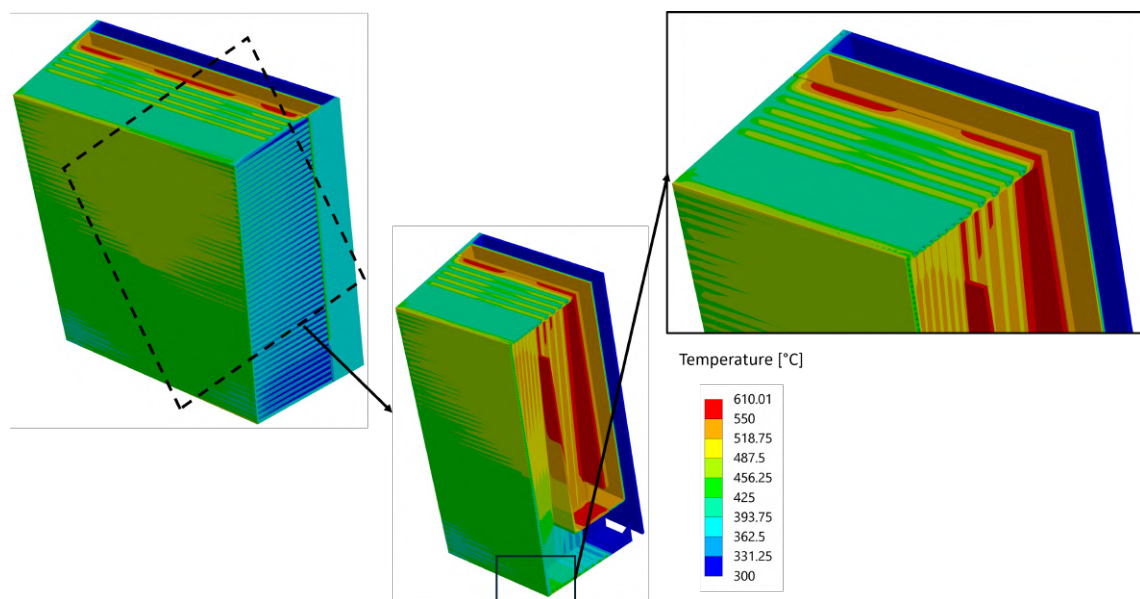


Figure 3.10: *Heterogeneous model thermal field*

With these results is then possible to average the temperature for every component and, in particular the values reported below were obtained:

- 402 °C for the BSS;
- 473 °C for the BZ;
- 439 °C for the FW;
- 449 °C for the Tungsten.

3.5 Homogeneous model mechanical analysis

The second step of the procedure is represented by the HoM mechanical analysis and a mesh consisting of ≈ 1.5 M nodes and ≈ 4 M tetrahedral linear elements was generated.

Once that the thermal field of the HeM is calculated, it is necessary to properly scale it to obtain a 3D temperature distribution for the whole BB sector in order to impose the loads for the HoM mechanical analysis. To this purpose, the averaged NWL spatial distribution calculated in [54] and reported in table 3.4 (in which the reference NWL is highlighted in yellow) were used with equation (3.1) along with the averaged temperature calculated in the HeM thermal analysis to obtain 79 temperatures for each component for a total of 316 values. The calculation and assignment of temperatures to the various components was automated using Python scripts.

Table 3.4: *Homogeneous model average NWLs*

	S1	S2	S3	S4	S5
R1	9.5642E-01	6.5739E-01	1.0976E+00	6.7315E-01	1.2868E+00
R2	1.0585E+00	1.1079E+00	1.0127E+00	9.6797E-01	7.1192E-01
R3	6.9013E-01	1.1843E+00	1.0449E+00	1.2356E+00	7.6515E-01
R4	6.9292E-01	7.3365E-01	1.2203E+00	1.2670E+00	6.9754E-01
R5	6.9292E-01	6.9754E-01	1.2670E+00	1.2203E+00	7.3365E-01
R6	6.9013E-01	7.6515E-01	1.2356E+00	1.0449E+00	1.1843E+00
R7	1.0585E+00	7.1192E-01	9.6797E-01	1.0127E+00	1.1079E+00
R8	9.5642E-01	1.2868E+00	6.7315E-01	1.0976E+00	6.5739E-01
R9	8.8995E-01	1.6188E+00	7.1314E-01	8.5714E-01	7.4940E-01
R10	8.3192E-01	1.5852E+00	6.5152E-01	8.0757E-01	6.4046E-01
R11	6.1809E-01	1.6874E+00	7.5634E-01	7.4319E-01	5.6425E-01
R12	5.6968E-01	1.6402E+00	8.1494E-01	7.0486E-01	4.6012E-01
R13	8.1494E-01	1.6402E+00	5.6968E-01	4.6012E-01	7.0486E-01
R14	7.5634E-01	1.6874E+00	6.1809E-01	5.6425E-01	7.4319E-01
R15	6.5152E-01	1.5852E+00	8.3192E-01	6.4046E-01	8.0757E-01
R16	7.1314E-01	1.6188E+00	8.8995E-01	7.4940E-01	8.5714E-01

The complete set of the obtained components temperature values is reported in tables 3.5 to 3.8.

Table 3.5: *Homogeneous model BSS temperatures [°C]*

	S1	S2	S3	S4	S5
R1	2.35E+02	1.61E+02	2.69E+02	1.65E+02	3.16E+02
R2	2.60E+02	2.72E+02	2.48E+02	2.37E+02	1.75E+02
R3	1.69E+02	2.90E+02	2.56E+02	3.03E+02	1.88E+02
R4	1.70E+02	1.80E+02	2.99E+02	3.11E+02	1.71E+02
R5	1.70E+02	1.71E+02	3.11E+02	2.99E+02	1.80E+02
R6	1.69E+02	1.88E+02	3.03E+02	2.56E+02	2.90E+02
R7	2.60E+02	1.75E+02	2.37E+02	2.48E+02	2.72E+02

Table 3.5 continued from previous page

	S1	S2	S3	S4	S5
R8	2.35E+02	3.16E+02	1.65E+02	2.69E+02	1.61E+02
R9	2.18E+02	3.97E+02	1.75E+02	2.10E+02	1.84E+02
R10	2.04E+02	3.89E+02	1.60E+02	1.98E+02	1.57E+02
R11	1.52E+02	4.14E+02	1.86E+02	1.82E+02	1.38E+02
R12	1.40E+02	4.02E+02	2.00E+02	1.73E+02	1.13E+02
R13	2.00E+02	4.02E+02	1.40E+02	1.13E+02	1.73E+02
R14	1.86E+02	4.14E+02	1.52E+02	1.38E+02	1.82E+02
R15	1.60E+02	3.89E+02	2.04E+02	1.57E+02	1.98E+02
R16	1.75E+02	3.97E+02	2.18E+02	1.84E+02	2.10E+02

Table 3.6: Homogeneous model BZ temperatures [$^{\circ}\text{C}$]

	S1	S2	S3	S4	S5
R1	2.76E+02	1.89E+02	3.16E+02	1.94E+02	3.71E+02
R2	3.05E+02	3.19E+02	2.92E+02	2.79E+02	2.05E+02
R3	1.99E+02	3.41E+02	3.01E+02	3.56E+02	2.20E+02
R4	2.00E+02	2.11E+02	3.52E+02	3.65E+02	2.01E+02
R5	2.00E+02	2.01E+02	3.65E+02	3.52E+02	2.11E+02
R6	1.99E+02	2.20E+02	3.56E+02	3.01E+02	3.41E+02
R7	3.05E+02	2.05E+02	2.79E+02	2.92E+02	3.19E+02
R8	2.76E+02	3.71E+02	1.94E+02	3.16E+02	1.89E+02
R9	2.56E+02	4.66E+02	2.05E+02	2.47E+02	2.16E+02
R10	2.40E+02	4.57E+02	1.88E+02	2.33E+02	1.85E+02
R11	1.78E+02	4.86E+02	2.18E+02	2.14E+02	1.63E+02
R12	1.64E+02	4.73E+02	2.35E+02	2.03E+02	1.33E+02
R13	2.35E+02	4.73E+02	1.64E+02	1.33E+02	2.03E+02
R14	2.18E+02	4.86E+02	1.78E+02	1.63E+02	2.14E+02
R15	1.88E+02	4.57E+02	2.40E+02	1.85E+02	2.33E+02
R16	2.05E+02	4.66E+02	2.56E+02	2.16E+02	2.47E+02

Table 3.7: Homogeneous model FW temperatures [$^{\circ}\text{C}$]

	S1	S2	S3	S4	S5
R1	2.56E+02	1.76E+02	2.94E+02	1.80E+02	3.44E+02
R2	2.83E+02	2.96E+02	2.71E+02	2.59E+02	1.90E+02
R3	1.85E+02	3.17E+02	2.79E+02	3.30E+02	2.05E+02
R4	1.85E+02	1.96E+02	3.26E+02	3.39E+02	1.87E+02
R5	1.85E+02	1.87E+02	3.39E+02	3.26E+02	1.96E+02
R6	1.85E+02	2.05E+02	3.30E+02	2.79E+02	3.17E+02
R7	2.83E+02	1.90E+02	2.59E+02	2.71E+02	2.96E+02

Table 3.7 continued from previous page

	S1	S2	S3	S4	S5
R8	2.56E+02	3.44E+02	1.80E+02	2.94E+02	1.76E+02
R9	2.38E+02	4.33E+02	1.91E+02	2.29E+02	2.00E+02
R10	2.22E+02	4.24E+02	1.74E+02	2.16E+02	1.71E+02
R11	1.65E+02	4.51E+02	2.02E+02	1.99E+02	1.51E+02
R12	1.52E+02	4.39E+02	2.18E+02	1.89E+02	1.23E+02
R13	2.18E+02	4.39E+02	1.52E+02	1.23E+02	1.89E+02
R14	2.02E+02	4.51E+02	1.65E+02	1.51E+02	1.99E+02
R15	1.74E+02	4.24E+02	2.22E+02	1.71E+02	2.16E+02
R16	1.91E+02	4.33E+02	2.38E+02	2.00E+02	2.29E+02

Table 3.8: Homogeneous model Tungsten temperatures [$^{\circ}\text{C}$]

	S1	S2	S3	S4	S5
R1	2.62E+02	1.80E+02	3.01E+02	1.84E+02	3.52E+02
R2	2.90E+02	3.03E+02	2.77E+02	2.65E+02	1.95E+02
R3	1.89E+02	3.24E+02	2.86E+02	3.38E+02	2.10E+02
R4	1.90E+02	2.01E+02	3.34E+02	3.47E+02	1.91E+02
R5	1.90E+02	1.91E+02	3.47E+02	3.34E+02	2.01E+02
R6	1.89E+02	2.10E+02	3.38E+02	2.86E+02	3.24E+02
R7	2.90E+02	1.95E+02	2.65E+02	2.77E+02	3.03E+02
R8	2.62E+02	3.52E+02	1.84E+02	3.01E+02	1.80E+02
R9	2.44E+02	4.43E+02	1.95E+02	2.35E+02	2.05E+02
R10	2.28E+02	4.34E+02	1.78E+02	2.21E+02	1.75E+02
R11	1.69E+02	4.62E+02	2.07E+02	2.04E+02	1.55E+02
R12	1.56E+02	4.49E+02	2.23E+02	1.93E+02	1.26E+02
R13	2.23E+02	4.49E+02	1.56E+02	1.26E+02	1.93E+02
R14	2.07E+02	4.62E+02	1.69E+02	1.55E+02	2.04E+02
R15	1.78E+02	4.34E+02	2.28E+02	1.75E+02	2.21E+02
R16	1.95E+02	4.43E+02	2.44E+02	2.05E+02	2.35E+02

Lastly as boundary conditions, nodes laying onto the far end VV lateral faces have been constrained along the local toroidal direction (planar skating condition) and the displacement along the vertical direction has been prevented to nodes laying on the central edges of the VV (figure 3.11). Gravity load has been imposed along the global Z direction.

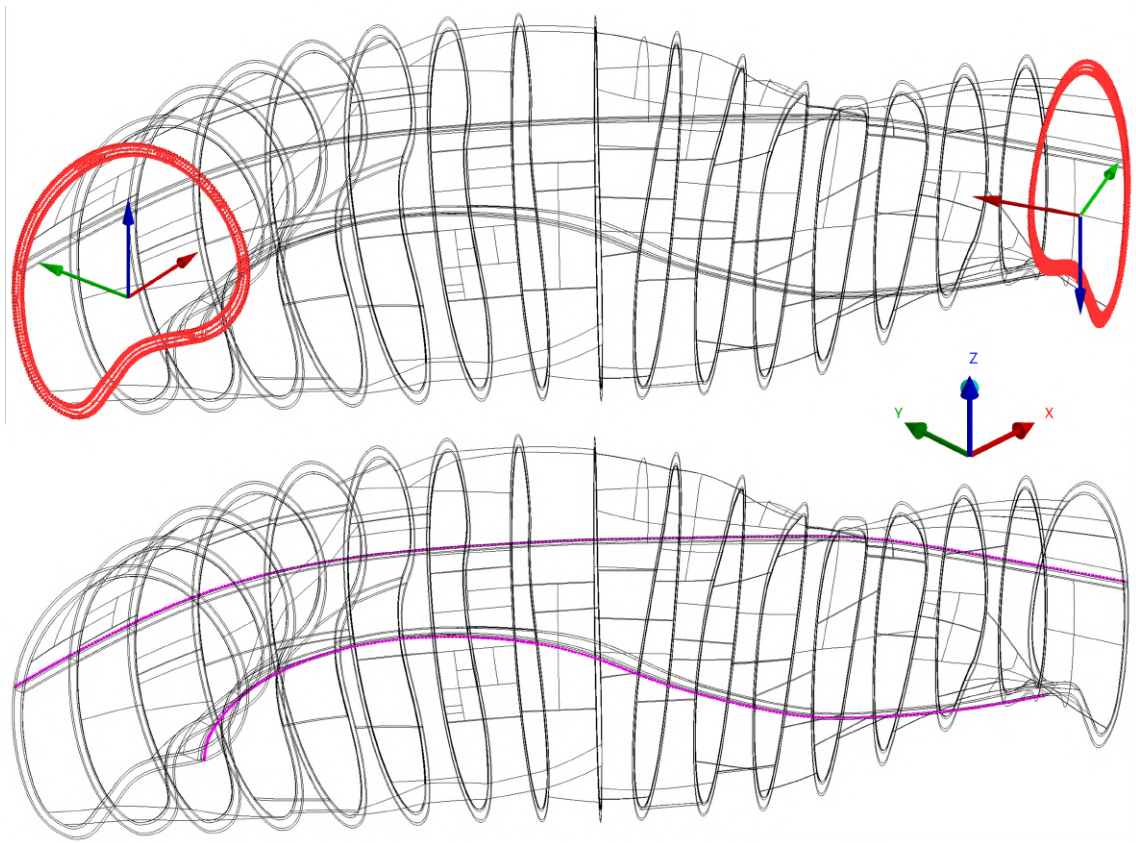


Figure 3.11: *Homogeneous model mechanical analysis boundary conditions*

Then, structural analysis has been launched to obtain the displacement field of the HoM. The results in terms of displacements of the whole 72° sector are shown in figure 3.12 (VV not shown), whereas in figure 3.13 only the ones referred to the “bean shaped” ring (including the proper portion of the VV), used to provide the HeM structural analysis with the necessary mechanical boundary conditions, are reported.

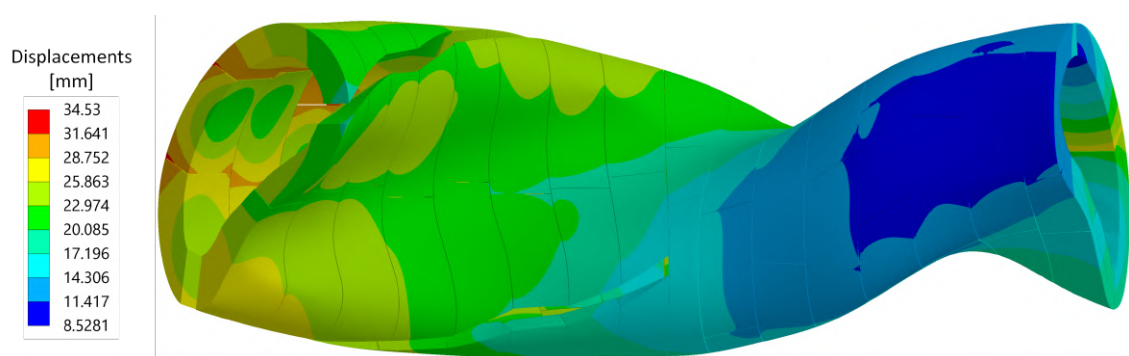


Figure 3.12: *Homogeneous model displacements of the BB rings*

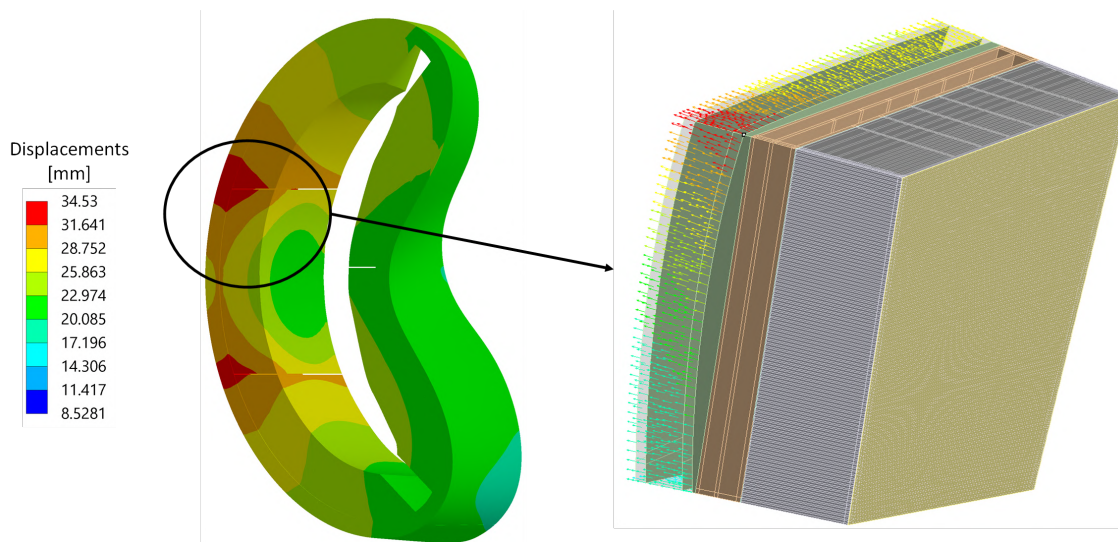


Figure 3.13: “Bean shaped” ring displacements with the pertinent VV portion and mapping onto the heterogeneous model boundaries

In particular, it can be seen how the displacements related to the VV boundary surfaces were taken in order to be imposed as the submodeling condition for the subsequent HeM mechanical analysis.

3.6 Heterogeneous model mechanical analysis

The third and most important step of the procedure in the submodeling phase, is represented by the HeM mechanical analysis, following the back-and-forth logic on the basis of the analysis loop. Indeed, this is the phase in which the particular BB architecture is effectively tested, performing the verification of the structural criteria prescribed by the RCC-MRx code. To this purpose, a new finite element model was generated. In particular it has a total of ≈ 2.5 M nodes connected in ≈ 2.5 M linear elements. In this case the bearings were also taken into account as homogeneous blocks, and their mechanical behavior has been parameterized in terms of the effective Young modulus to simulate the presence of the attachment system, which could be represented by pins and/or springs. In particular three cases were considered:

- Case A: 20% of the temperature-dependent Eurofer Young modulus;
- Case B: 60% of the temperature-dependent Eurofer Young modulus;
- Case C: 100% of the temperature-dependent Eurofer Young modulus.

All the other materials are the same considered for the HeM thermal analysis. The VV portion was also considered and directly taken from the HoM analysis so to avoid approximations in the displacement mapping.

To properly set the mechanical problem, the following boundary conditions were imposed [50]:

- the gravity load;
- a pressure equal to 8.0 MPa to all the Helium wetted surfaces;
- a pressure equal to 0.5 MPa to all the PbLi wetted surfaces;
- the outer, shield and inner VV temperatures were set to, 40, 65 and 90 °C respectively [46];
- the temperatures of the bearing that connects the SB and the BSS and the one that connects the BSS and the VV were set to 565.5 °C and 195 °C respectively, using mean temperatures taken from the HeM thermal analysis;
- the thermal field of all the remaining components was mapped from the HeM thermal analysis;
- the submodeling conditions on the displacements of the VV, namely the 3D spatial distributions of displacement along x, y and z directions mapped from HoM mechanical analysis.

As a result of the mechanical analyses, the equivalent Von Mises stresses and the displacements fields were calculated. As an example only the ones related to the Case A will be shown in figure 3.14 and figure 3.15 (only reporting the Eurofer domain).

As stated above, the scope of this study is not to be design relevant but showing the capabilities of the analysis procedure set-up. However, in order to give useful indications for the development of HELIAS relevant BB architectures, the SWs seem to suffer because of the high stress, probably due to the absence of internal reinforcements on the radial-toroidal plane. Lastly, the quite high displacement seems to indicate that a stiffer attachment should be considered to reduce the blanket deformation, minimizing the probability to hit adjacent segments. In any case, it has to be underlined that, as for thermal analysis, this structural assessment has been possible by using the semi-automatic analysis procedure with a quite limited number of adjustments.

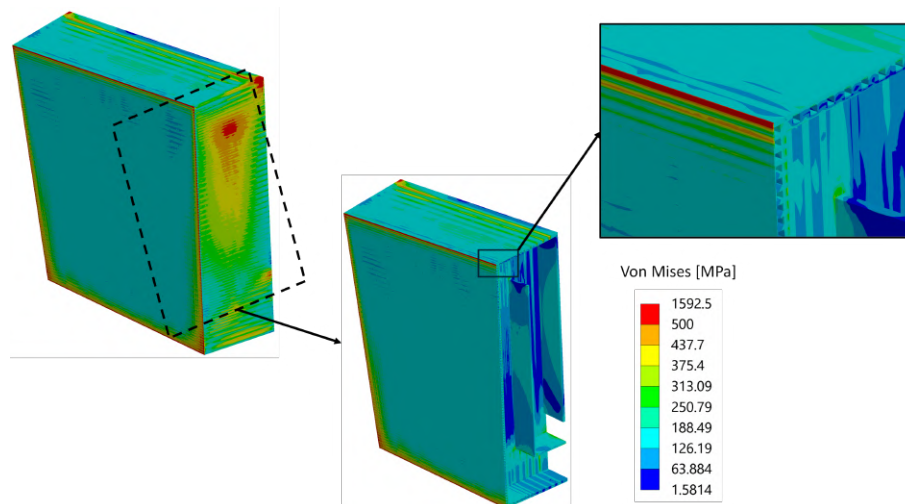


Figure 3.14: Case A equivalent Von Mises stress in the SB

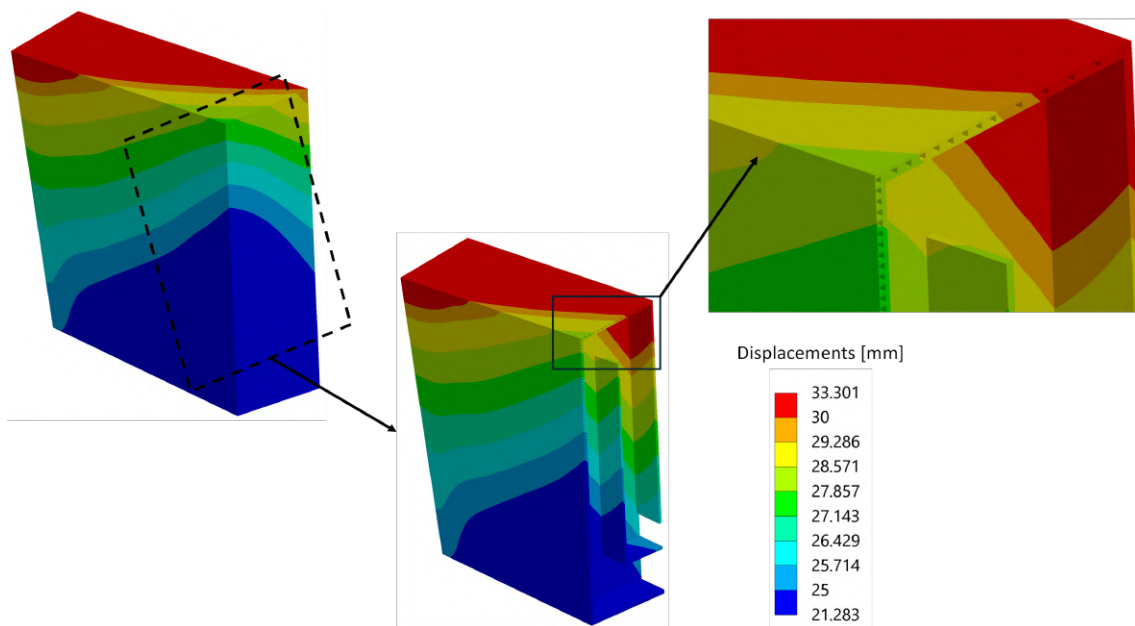


Figure 3.15: Case A displacement field in the SB

With these results it was possible to select some paths (figure 3.16) in order to perform the stress linearization procedure and apply a script that automates the verification of the RCC-MRx structural criteria [codes B.1 to B.3]. In table 3.9 the results obtained for the present cases are reported, highlighting the total fulfillment of the rules in location shown as an example. Specifically, the Von Mises over Sm field is generated and plotted to identify the most critical regions where building the paths. It is a semi-qualitative criterion implemented in the procedure, in order to highlight the most stressed regions. Again, it is necessary to stress that the automatic scripts already developed for a different BB concept have been straightforwardly used in this case study with practically no need of modifications [51]. At present, the most time-consuming and error prone part is the path construction, that has to be done almost totally by hand.

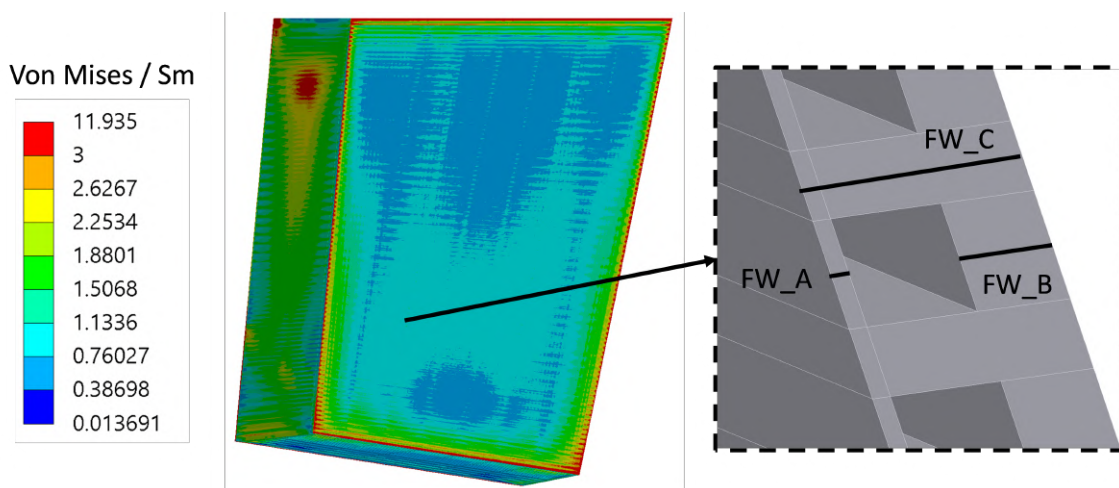


Figure 3.16: Path used for the stress linearization procedure

Table 3.9: *RCC-MRx criteria verification*

Rule	E	FW_A	FW_B	FW_C
$\frac{P_m}{S_m}$	20%	1.51E-01	1.23E-01	4.45E-02
	60%	1.51E-01	1.23E-01	4.41E-02
	100%	1.50E-01	1.23E-01	4.39E-02
$\frac{P_m + P_b}{K_{eff}S_m}$	20%	1.21E-01	1.00E-01	4.13E-02
	60%	1.20E-01	9.98E-02	4.10E-02
	100%	1.20E-01	9.96E-02	4.09E-02
$\frac{P_m + Q_m}{S_{em}}$	20%	4.85E-01	4.33E-01	3.58E-01
	60%	4.89E-01	4.36E-01	3.60E-01
	100%	4.90E-01	4.37E-01	3.60E-01
$\frac{P_m + P_b + Q + F}{S_{et}}$	20%	9.29E-02	1.01E-01	9.47E-02
	60%	9.35E-02	1.00E-01	9.51E-02
	100%	9.36E-02	1.00E-01	9.52E-02

3.7 Strength of the methodology and open issues

The strength of the methodology relies on the fact that many laborious and complex tasks can be automated, allowing a considerable time saving. For example, considering the definition of the thermal fluid dynamics viewed in the HeM thermal analysis section, in order to tell the code how to simulate the flow path a lot of equations must be written to connect temperatures across different nodes. This operation is practically impossible to perform manually without errors and/or in a short time, as normally the nodes involved are in the range of thousands. On the other hand, using the scripts saves a lot of time and thus allows to make more realistic simulations.

Another big advantage is the fact that the scripts rely on the nomenclature of the bodies involved, untying their application from the geometry. Hence any kind of configuration could potentially be studied, with few adjustments to the code. To this purpose, all the methodology was built with the scope to be accessible to as many users as possible, isolating the editable parts and making some support files in order to explain the steps to do in order to make it work.

As described in the previous chapters, although the core of the methodology is functional in many aspects, it still has several limitations given by the inherent geometric complexity of the HELIAS machine. The main problem is certainly related to the lack of tools that allow the automation of the mesh validation procedure, however, it cannot be ruled out that new, more detailed functions will be added in subsequent ANSYS releases, since the scripting-related module is still relatively new. Moreover, the moment the shared topology procedure proves to be complicated to manage during the mesh creation, it will be necessary to manually define the contacts between the parts of the structure, a process which greatly slows down the analytical procedure. Lastly, regarding what could be explored more in detail, the focus could

be on the automation of the geometric operations to be performed on the models prior to the actual analysis, and moreover, an attempt could be made to generalize the scripts as much as possible so that they can be used and understood even by operators totally unfamiliar with the use of the Python language. In addition, other BB concepts could be considered to enlarge the field of application of the procedure. As the DCLL BB concept is currently studied too for a possible application to HELIAS, the focus could be put on it in the close future. Lastly, a summary listing the main automated and non-automated operations is reported below in table 3.10:

Table 3.10: *Automated and non-automated operations*

Automated operations	Non-automated operations
Assign the materials	Geometry operations
Contact generation	Mesh validation
Apply loads	Path creation
Set the simplified fluid dynamics of the coolant	
Extract and evaluate results	

Conclusions

One of the fundamental components of a nuclear fusion reactor is undoubtedly the breeding blanket. In fact, it is responsible for shielding functions, removal of the power produced by the plasma and Tritium production. The dynamics involved during the deployment of this component are complex and interconnected, bringing numerous complications in its design phase. Therefore, in this PhD thesis work, two methodologies have been developed to enable this process to be addressed in a semi-automatic, multi-scale and multiphysics way.

In particular, the first of the two methodologies is based on a submodeling approach through which, starting from a radial power density profile and the source from which it was derived, a local geometry composed of tubular and/or plate structures is generated that allows a blanket architecture to be defined from scratch. The procedure, at first, was explained in detail in each of its steps, starting from the generation of a first attempt geometry through a simplified approach developed in MATLAB and then verified with APDL, to its neutron analysis, using the code MCNP with use of unstructured mesh. Being as mentioned a submodeling study, it was also necessary to sample the local neutron and photon sources from a global BB model. Once the definition of the procedure and its validation had been completed, it was then decided to apply it to a particular BB architecture, namely the WLCB, which is a hybrid of WCLL and HCPB designed to address the possible issues that emerged during the development of these two variants. The results validated the methodology and made it possible to exploit one of the generated geometries for a parametric study on the influence of the blanket material composition with respect to the TBR. A total of nineteen models were studied with the same neutron boundary conditions by varying the composition first of the FW then of the BZ allowing noteworthy results to be obtained. In fact, it has been shown how, the use of materials with moderating qualities, such as ZrH_2 can lead to a greater exploitation of tritium breeding reaction from Lithium 6 in the first 40 cm of BZ and to a greater overall TBR of the local model, allowing a possible reduction of the radial BB thickness.

The second methodology, on the other hand, aims to validate from a structural point of view a local and detailed model of any typical HELIAS 5B BB architecture, but more generally of any type of stellarator reactor. In fact, these devices, being

composed of high complexity geometries, must necessarily be studied through the submodeling approach, so that local behaviors can be analyzed without losing information about global boundary conditions. In particular, the procedure follows a back-and-forth flow in which, starting from local thermal analyses, thermal fields are derived, which are then averaged to obtain effective temperatures to be associated with the components of a less detailed global model in order to study it at the structural level while maintaining the actual boundary conditions of the system. Once the results of this analysis are derived in terms of displacements, they are then applied as boundary conditions for the local model's mechanical analysis. Lastly, it is validated from a mechanical point of view through the application of RCC-MRx code rules. The methodology, previously employed for other activities carried out during the three years of the PhD course, was applied to a DEMO DCLL BB architecture adapted to the HELIAS 5B geometry, which was examined for this study. The results, which are not relevant from a design point of view since that is not the main objective, however, showed how the procedure is highly versatile and functional, making it a viable alternative for future studies in the field of stellarator-type reactors.

The methodologies have proven to be flexible and robust enough to deal with preliminary design calculations in order to skim the most promising breeding blanket variants. However, they still need to be improved to generalize some aspects of the mesh generation for their large-scale implementation on general geometries.

Both activities were developed through the use of codes written with different programming languages, Python being the main one, and some of the most important have been listed and explained in the appendix.

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Appendix A

Codes mentioned in Chapter 2

In this chapter, the Python scripts used in the activity related to the design procedure presented in chapter 2 will be discussed in detail.

The first of these codes was written with the goal of automating the local neutron source sampling procedure for the submodel analysis starting from the global analysis results in the “mctal” format. Specifically, the code is divided into two sections. From line 6 to 32 the input data, i. e., the F1 tally number used in the global analysis and the path in which it is located, the total number of cosine and energy bins, also specifying the latter in MeV should be entered. From line 38 onward, instead, a series of operations listed below are performed:

- Lines 38 – 57: creation of a function to extract from the results file “mctal” a specific portion of text that corresponds to the F1 tally results;
- Lines 61 – 96: manipulation of the results and application of the methodology described in section 2.2.2.1;
- Rows 101 – 149: screen printout of the local source ready to be copied into the neutron analysis input for the submodeling.

In the case that the script is to be reused on a submodel located in a different part of the reactor, it will also be necessary to modify the data contained in lines 110 – 114.

The script to obtain the photon source sampling is formally identical to this one with appropriate modifications to the input data and will not be reported for brevity.

Code A.1: *Local neutron source sampling*

```
1  """
2  Campionamento della sorgente neutronica a partire da un mctal
3  """
4
5  # ===== #
6  # SEZIONE EDITABILE
7  # ===== #
8
9  # Inserisci il numero della tally
```

```

10 n_tally = 11
11
12 # Inserisci il numero di bin di energia
13 n_en_bin = 99
14
15 # Inserisci il numero di bin di coseni
16 n_cos_bin = 10
17
18 # Inserisci il percorso del mctal
19 file_path = 'C:\\Analisi\\*NOME*.mctal'
20
21 E_bin_neutrons = [
22 0.00E+00, 1.11E-01, 1.17E-01, 1.23E-01, 1.29E-01, 1.36E-01, 1.43E-01, 1.50E-01,
23 1.58E-01, 1.66E-01, 1.74E-01, 1.83E-01, 1.93E-01, 2.02E-01, 2.13E-01, 2.24E-01,
24 2.35E-01, 2.47E-01, 2.73E-01, 2.87E-01, 2.95E-01, 2.97E-01, 2.98E-01, 3.02E-01,
25 3.34E-01, 3.69E-01, 3.88E-01, 4.08E-01, 4.50E-01, 4.98E-01, 5.23E-01, 5.50E-01,
26 5.78E-01, 6.08E-01, 6.39E-01, 6.72E-01, 7.07E-01, 7.43E-01, 7.81E-01, 8.21E-01,
27 8.63E-01, 9.07E-01, 9.62E-01, 1.00E+00, 1.11E+00, 1.16E+00, 1.22E+00, 1.29E+00,
28 1.35E+00, 1.42E+00, 1.50E+00, 1.57E+00, 1.65E+00, 1.74E+00, 1.83E+00, 1.92E+00,
29 2.02E+00, 2.12E+00, 2.23E+00, 2.31E+00, 2.35E+00, 2.37E+00, 2.39E+00, 2.47E+00,
30 2.59E+00, 2.73E+00, 2.87E+00, 3.01E+00, 3.17E+00, 3.33E+00, 3.68E+00, 4.07E+00,
31 4.49E+00, 4.72E+00, 4.97E+00, 5.22E+00, 5.49E+00, 5.77E+00, 6.07E+00, 6.38E+00,
32 6.59E+00, 6.70E+00, 7.05E+00, 7.41E+00, 7.79E+00, 8.19E+00, 8.61E+00, 9.05E+00,
33 9.51E+00, 1.00E+01, 1.05E+01, 1.11E+01, 1.16E+01, 1.22E+01, 1.25E+01, 1.28E+01,
34 1.35E+01, 1.38E+01, 1.42E+01, 2.00E+01
35 ]
36
37 # ===== #
38 # SEZIONE DA NON TOCCARE
39 # ===== #
40
41 def estrai_testo(file_path, parola_inizio, parola_fine):
42     with open(file_path, 'r', encoding='utf-8') as file:
43         testo = file.read()
44
45         inizio = testo.find(parola_inizio)
46         fine = testo.find(parola_fine, inizio)
47
48         if inizio != -1 and fine != -1:
49             return testo[inizio + len(parola_inizio):fine]
50         else:
51             return "Parole chiave non trovate nel testo."
52
53 estratto = estrai_testo(file_path, "tally "+str(n_tally), "tfc")
54
55 def filtra_contenuto(testo, parola_chiave):
56     posizione = testo.find(parola_chiave)
57
58     if posizione != -1:
59         return testo[posizione + len(parola_chiave):]
60     else:
61         return "Parola chiave non trovata nel testo."
62
63 contenuto_filtrato = filtra_contenuto(estratto, "vals")
64
65 # ===== #
66
67 contenuto_filtrato = contenuto_filtrato.replace("\n", "").strip().split(" ")
68 skip = (n_en_bin+1)*(n_cos_bin+1)
69 val_fin = contenuto_filtrato[-skip:]
70

```

```

71 listone = []
72 for jj in val_fin:
73     listone.append(float(jj.split()[0]))
74
75 def dividi_lista(lista, n_sott):
76     l_sott = len(lista) // n_sott
77     sottoliste = [lista[i * l_sott:(i + 1) * l_sott] for i in range(n_sott)]
78     return sottoliste
79
80 sottoliste = dividi_lista(listone, n_cos_bin+1)
81 del sottoliste[0]
82
83 somma_ultimi_valori = sum(ii[-1] for ii in sottoliste)
84 lista_somme = []
85 for ii in sottoliste:
86     lista_somme.append(ii[-1]/somma_ultimi_valori)
87 lista_somme.insert(0, 0.0)
88 lista_somme = [f"{numero:.5e}" for numero in lista_somme]
89
90 cos_bin_pr = []
91 for xx in lista_somme:
92     cos_bin_pr.append(float(xx))
93
94 E_bin_pr = [[bb / kk[-1] for bb in kk] for kk in sottoliste]
95 E_bin_pr = [cc[:-1] for cc in E_bin_pr]
96 for vv in E_bin_pr:
97     vv.insert(0, 0.0)
98
99 # ===== #
100
101 # Funzione per stampare i numeri con la formattazione richiesta
102 def stampa_con_formattazione(lista, primo_rigo):
103     print(primo_rigo, end="") # Aggiungi "SI1 " all'inizio del primo rigo
104     for i, numero in enumerate(lista):
105         if i % 5 == 0 and i != 0:
106             print("\n", end="") # A capo e aggiungi 7 spazi
107             print(f"{numero:.5e}", end=" " if (i + 1) % 5 != 0 else "")
108     print() # Aggiungi un a capo finale
109
110 print(
111     ""SDEF      POS=0 0 0  X=1204.45 Y=D1 Z=D2  PAR=1  VEC=1 0 0  DIR=D3  ERG FDIR D4
112     SI1      -0.05          74.25
113     SP1       0.0           1.0
114     SI2     -6.845          6.845
115     SP2       0.0           1.0
116     c
117     c -----
118     c Cosine bin
119     c -----
120     c
121     SI3    0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00
122     c
123     c -----
124     c Cosine bin probability
125     c -----
126     c "")
127 stampa_con_formattazione(cos_bin_pr, "SP3 ")
128 print("c
129 DS4 S 5 6 7 8 9 10 11 12 13 14
130 c ")
131 stampa_con_formattazione(E_bin_neutrons, "SI5 ")

```

```

132 stampa_con_formattazione(E_bin_pr[0], "SP5  ")
133 stampa_con_formattazione(E_bin_neutrons, "SI6  ")
134 stampa_con_formattazione(E_bin_pr[1], "SP6  ")
135 stampa_con_formattazione(E_bin_neutrons, "SI7  ")
136 stampa_con_formattazione(E_bin_pr[2], "SP7  ")
137 stampa_con_formattazione(E_bin_neutrons, "SI8  ")
138 stampa_con_formattazione(E_bin_pr[3], "SP8  ")
139 stampa_con_formattazione(E_bin_neutrons, "SI9  ")
140 stampa_con_formattazione(E_bin_pr[4], "SP9  ")
141 stampa_con_formattazione(E_bin_neutrons, "SI10 ")
142 stampa_con_formattazione(E_bin_pr[5], "SP10 ")
143 stampa_con_formattazione(E_bin_neutrons, "SI11 ")
144 stampa_con_formattazione(E_bin_pr[6], "SP11 ")
145 stampa_con_formattazione(E_bin_neutrons, "SI12 ")
146 stampa_con_formattazione(E_bin_pr[7], "SP12 ")
147 stampa_con_formattazione(E_bin_neutrons, "SI13 ")
148 stampa_con_formattazione(E_bin_pr[8], "SP13 ")
149 stampa_con_formattazione(E_bin_neutrons, "SI14 ")
150 stampa_con_formattazione(E_bin_pr[9], "SP14 ")

```

The second proposed script is the one used to evaluate the TBR of the analyzed slices from the “wse” files obtainable as the MCNP output (code A.2).

This script is also divided into an editable part that runs from lines 13 to 38 and a non-editable part that includes lines 5-6 and 45 to 177.

In the editable part it is necessary to indicate the directory in which to find the “wse” files, the case number considered (n), the number of the material associated with the breeder, the Lithium 6 and Lithium 7 atomic densities expressed in $\text{b}^{-1}\text{cm}^{-1}$ and the respective numbers of the “edits” corresponding to the “wse” files (m). Moreover, the name of the particular analysis should be written as “*analysis_n-ed.m.wse*”. Finally, the extremal coordinates in cm identifying radially the ACB tube rows in the particular slice should be given: for example, if the model contains four ACB tube rows and a cassette, it will be necessary to indicate four pairs of values in the form made explicit in the script. For the first pair, it will be sufficient to indicate only the coordinate at greater radius, while for the last pair it will be necessary to indicate only the one at lesser radius.

The non-editable part allows data-frames to be created from the tables reported in the “wse” files and the data to be manipulated. Specifically, the EMBEEn4 results are expressed in part/cm^2 which are then multiplied by the respective atomic densities of the Lithium isotopes in order to obtain the values in part/cm^3 . These values are per incident neutron, so they already represent the TBR/cm^3 measurement. The script also multiplies each value obtained by the volume of the mesh element in whose centroid it was calculated, obtaining the TBR of the element. By summing all elements TBRs subdivided by ACB tube rows, an average radial TBR trend in the slice can be obtained.

Finally, the script generates summary figures with the newly calculated values and a spreadsheet containing all the data-frames created.

Code A.2: Slice TBR evaluation

```

1 # ===== #
2 # LIBRARIES IMPORT
3 # ===== #
4
5 import pandas as pd
6 import matplotlib.pyplot as plt
7
8 # ===== #
9 # EDITABLE SECTION
10 # ===== #
11
12 # Directory of the wse files
13 directory = "C:\\Analisi\\"
14
15 # Case number
16 Slice_n = 37
17
18 # Breeder material number
19 ACB_n = 5
20
21 # Lithium 6 atomic density [b-1 cm-1]
22 rhoa_Li6 = 2.88776E-02
23
24 # Lithium 7 atomic density [b-1 cm-1]
25 rhoa_Li7 = 2.75025E-03
26
27 # Lithium 6 edit number
28 edit_Li6 = 6
29
30 # Lithium 7 edit number
31 edit_Li7 = 7
32
33 # Radial extremal coordinates of ACB tube rows [cm]
34 R_coords = [(None, 1211.54),
35             (1215.87, 1218.95),
36             (1223.79, 1227.69),
37             (1233.26, 1238.66),
38             (1238.66, None)]
39
40 # ===== #
41 # NON-EDITABLE SECTION
42 # ===== #
43
44 # Lithium 6 wse name
45 wse_Li6 = "analysis_"+str(Slice_n)+"_ed_"+str(edit_Li6)+".wse"
46
47 # Lithium 7 wse name
48 wse_Li7 = "analysis_"+str(Slice_n)+"_ed_"+str(edit_Li7)+".wse"
49
50 # Dynamic footer generation
51 with open(directory+wse_Li6) as t:
52     Ist_n = t.readlines()
53     Ist_n = Ist_n[16].strip().split()
54     Ist_n = int(Ist_n[3])
55 Footer = 6*Ist_n+6
56
57 # Lithium 6 dataframe creation
58 dfLi6 = pd.read_table(directory+wse_Li6,
59                       skiprows=36,
60                       skipfooter=Footer,

```

```

61         sep="\s+",
62         names=["Element","Type","Material","Density [g/cm^3]",
63               "Volume [cm^3]","X [cm]","Y [cm]","Z [cm]",
64               "Res Li6 [part/cm^2]","Err% Li6"],
65         engine="python")
66 dfLi6 = dfLi6.drop(dfLi6.columns[1],axis=1)
67 dfLi6 = dfLi6.drop(dfLi6[dfLi6['Material'] != ACB_n].index)
68 dfLi6["Res Li6 [part/cm^3]"] = dfLi6["Res Li6 [part/cm^2]"]*rhoa_Li6
69 dfLi6["Res Li6 [part]"] = dfLi6["Res Li6 [part/cm^3]"]*dfLi6["Volume [cm^3]"]
70 dfLi6["Err% Li6"] *= 100
71 dfLi6 = dfLi6[["Element","Material","Density [g/cm^3]",
72               "Volume [cm^3]","X [cm]","Y [cm]","Z [cm]",
73               "Res Li6 [part/cm^2]","Res Li6 [part/cm^3]",
74               "Res Li6 [part]","Err% Li6"]]
75
76 # Lithium 7 dataframe creation
77 dfLi7 = pd.read_table(directory+wse_Li7,
78                       skiprows=36,
79                       skipfooter=Footer,
80                       sep="\s+",
81                       names=["Element","Type","Material","Density [g/cm^3]",
82                             "Volume [cm^3]","X [cm]","Y [cm]","Z [cm]",
83                             "Res Li7 [part/cm^2]","Err% Li7"],
84                       engine="python")
85 dfLi7 = dfLi7.drop(dfLi7.columns[1],axis=1)
86 dfLi7 = dfLi7.drop(dfLi7[dfLi7['Material'] != ACB_n].index)
87 dfLi7["Res Li7 [part/cm^3]"] = dfLi7["Res Li7 [part/cm^2]"]*rhoa_Li7
88 dfLi7["Res Li7 [part]"] = dfLi7["Res Li7 [part/cm^3]"]*dfLi7["Volume [cm^3]"]
89 dfLi7["Err% Li7"] *= 100
90 dfLi7 = dfLi7[["Element","Material","Density [g/cm^3]",
91               "Volume [cm^3]","X [cm]","Y [cm]","Z [cm]",
92               "Res Li7 [part/cm^2]","Res Li7 [part/cm^3]",
93               "Res Li7 [part]","Err% Li7"]]
94
95 # Total dataframe creation
96 dfT = pd.concat([dfLi6,dfLi7["Res Li7 [part/cm^2]"],dfLi7["Res Li7 [part/cm^3]"],
97                 dfLi7["Res Li7 [part]"],dfLi7["Err% Li7"]],axis=1)
98 dfT["Res Li all [part]"] = dfT["Res Li6 [part]"]+dfT["Res Li7 [part]"]
99
100 # ===== #
101 # dfSum CREATION
102 # ===== #
103
104 # Empty list initialization
105 volumes = []
106 res_li6 = []
107 res_li7 = []
108 res_li_all = []
109 res_li6_part = []
110 res_li7_part = []
111 res_li_all_part = []
112
113 # Iterations through the R coordinates
114 for i, (start, end) in enumerate(R_coords):
115     if start is None:
116         dfTR = dfT.loc[dfT['X [cm]'] <= end]
117     elif end is None:
118         dfTR = dfT.loc[dfT['X [cm]'] >= start]
119     else:
120         dfTR = dfT.loc[(dfT['X [cm]'] >= start) & (dfT['X [cm]'] <= end)]
121

```

```

122     volume = dfTR["Volume [cm^3]"].sum()
123     volumes.append(volume)
124
125     res_li6.append(dfTR["Res Li6 [part]"].sum() / volume)
126     res_li7.append(dfTR["Res Li7 [part]"].sum() / volume)
127     res_li_all.append(dfTR["Res Li all [part]"].sum() / volume)
128
129     res_li6_part.append(dfTR["Res Li6 [part]"].sum())
130     res_li7_part.append(dfTR["Res Li7 [part]"].sum())
131     res_li_all_part.append(dfTR["Res Li all [part]"].sum())
132
133 # Final dataframe creation
134 DataT = {"ACB radial row": list(range(1, len(R_coords) + 1)),
135          "Row volume [cm^3]": volumes,
136          "Res Li6 [part/cm^3]": res_li6,
137          "Res Li7 [part/cm^3]": res_li7,
138          "Res Li all [part/cm^3]": res_li_all,
139          "Res Li6 [part]": res_li6_part,
140          "Res Li7 [part]": res_li7_part,
141          "Res Li all [part]": res_li_all_part}
142 dfSum = pd.DataFrame(DataT)
143
144 # ===== #
145 # FIGURES PRINTING
146 # ===== #
147
148 # List of the figure columns and titles
149 columns = [("Res Li all [part/cm^3]", "TBR/cm^3 (from all Li)", "Tpercm3_tot.png"),
150            ("Res Li6 [part/cm^3]", "TBR/cm^3 (from Li6)", "Tpercm3_Li6.png"),
151            ("Res Li7 [part/cm^3]", "TBR/cm^3 (from Li7)", "Tpercm3_Li7.png"),
152            ("Res Li all [part]", "TBR (from all Li)", "TBR_total.png"),
153            ("Res Li6 [part]", "TBR (from Li6)", "TBR_Li6.png"),
154            ("Res Li7 [part]", "TBR (from Li7)", "TBR_Li7.png")]
155
156 # Figure creation
157 for col, title, filename in columns:
158     plt.figure()
159     plt.bar(dfSum['ACB radial row'], dfSum[col])
160     plt.ticklabel_format(axis="y", style='sci', scilimits=(0,0))
161     plt.xlabel('ACB radial row')
162     plt.ylabel('')
163     plt.xticks(dfSum['ACB radial row'])
164     plt.title(title)
165     plt.savefig(directory + filename, format="png", dpi=400, bbox_inches="tight")
166     plt.show()
167     plt.close()
168
169 # ===== #
170 # SPREADSHEET FILE CREATION
171 # ===== #
172
173 with pd.ExcelWriter(directory + "analysis_" + str(Slice_n) + "_TP.xlsx") as writer:
174     dfT.to_excel(writer, sheet_name='Res table', index=False)
175     dfSum.to_excel(writer, sheet_name='Res sum', index=False)
176
177 print("Script eseguito correttamente")

```

Appendix B

Codes mentioned in Chapter 3

This section contains some of the codes developed for everything related to verifying the structural criteria imposed by the RCC-MRx standard. In particular, the three codes should be performed in a certain order and setting up the analysis in a specific way. First it is necessary to perform the mechanical analysis considering both primary (P) and secondary (Q) loads renaming the instance “ $P + Q$ ”. After that it is sufficient to duplicate the analysis just performed eliminating all primary loads in order to perform an analysis under secondary loads only, renaming it “ Q ”. Finally through the “solution combination” command it is necessary to perform the linear combination of the $P + Q$ analysis results with the Q analysis ($P + Q - Q$) in order to obtain the results for the analysis at the primary loads only, which must be called “ P ”. At this point the paths in the zones of interest should be defined as shown in section 3.6, and code B.1 can be executed. In particular, it allows the automatic generation of x “stress linearization” commands with x ranging from 1 to the total number of paths, for each analysis considered (in this case 3) and simultaneously generates y command, ranging from 1 to the total number of paths, to calculate path temperatures.

Code B.1: *Stress linearization and path T_{ave} creation*

```
1  mdl = ExtAPI.DataModel.Project.Model
2  geom = mdl.Geometry
3  mat = mdl.Materials
4  cosys = mdl.CoordinateSystems
5  conn = mdl.Connections
6  msh = mdl.Mesh
7  ns = mdl.NamedSelections
8  mdl.AddConstructionGeometry()
9  anl = mdl.Analyses
10 gobi = DataModel.GetObjectById
11 gobn = DataModel.GetObjectsByName
12 gobt = DataModel.GetObjectsByType
13
14 # ===== #
15
16 sol_pq = anl[0].Solution # P+Q solution
17 sol_q = anl[1].Solution # Q solution
```

```

18 sol_p = gobt(DataModelObjectCategory.SolutionCombination)[0] # P solution
19
20 L_Sol = []
21 L_Sol.append(sol_pq)
22 L_Sol.append(sol_q)
23 L_Sol.append(sol_p)
24
25 path = gobt(DataModelObjectCategory.Path)
26
27 # ===== #
28
29 with Transaction(True):
30     for ii in path:
31         for yy in L_Sol:
32             SL = yy.AddLinearizedEquivalentStress()
33             SL.Location = ii
34             SL.Name = "SL_"+ii.Name
35             T_path = sol_pq.AddUserDefinedResult()
36             T_path.Expression = r'BFE'
37             T_path.Location = ii
38             T_path.Name = "T_"+ii.Name
39
40 print("Script eseguito!")

```

Once code B.1 has been executed, code B.2 must be copied into the folder indicated in line 4. Note that it may vary depending on the operating system and ANSYS version. The code initially defines a Python class called “Materiale” which is followed by instances of the various materials used in the analyses. The class attributes are the material name and the time-dependent stress limits given in the RCC-MRx standard while the methods are linear interpolation and plotting functions, useful for the subsequent codes.

Code B.2: *Materials library*

```

1 # ===== #
2 # READ ME
3 # If you use ANSYS 2023 R2 copy this file in
4 # C:/Program Files/ANSYS Inc/v232/aisol/Bin/winx64
5 # Otherwise "RCC-MRx_P-type_Level_A_criteria_verification.py" won't work
6 # ===== #
7
8 # ===== #
9 # "Materiale" class definition
10 # ===== #
11
12 from scipy.interpolate import interp1d
13 import matplotlib.pyplot as plt
14
15 class Materiale:
16     def __init__(self, Nome, SmA, SmD, SemA, SemD, TSm, TSem):
17         self.Nome = Nome
18         self.SmA = SmA
19         self.SmD = SmD
20         self.SemA = SemA
21         self.SemD = SemD
22         self.TSm = TSm
23         self.TSem = TSem
24

```

```

25     def SmA_eval(self, T):
26         f = interp1d(self.TSm, self.SmA, fill_value="extrapolate")
27         return f(T)
28
29     def SmA_plot(self):
30         plt.plot(self.TSm, self.SmA)
31         plt.xlabel('TSm [C]')
32         plt.ylabel('SmA [MPa]')
33         plt.show()
34
35     def SmD_eval(self, T):
36         f = interp1d(self.TSm, self.SmD, fill_value="extrapolate")
37         return f(T)
38
39     def SmD_plot(self):
40         plt.plot(self.TSm, self.SmD)
41         plt.xlabel('TSm [C]')
42         plt.ylabel('SmD [MPa]')
43         plt.show()
44
45     def SemA_eval(self, T):
46         f = interp1d(self.TSem, self.SemA, fill_value="extrapolate")
47         return f(T)
48
49     def SemA_plot(self):
50         plt.plot(self.TSem, self.SemA)
51         plt.xlabel('TSem [C]')
52         plt.ylabel('SemA [MPa]')
53         plt.show()
54
55     def SemD_eval(self, T):
56         f = interp1d(self.TSem, self.SemD, fill_value="extrapolate")
57         return f(T)
58
59     def SemD_plot(self):
60         plt.plot(self.TSem, self.SemD)
61         plt.xlabel('TSem [C]')
62         plt.ylabel('SemD [MPa]')
63         plt.show()
64
65 # ===== #
66 # Materials library.
67 # Add below Eurofer other materials to create a database.
68 # The values are taken from RCC-MRx
69 # ===== #
70
71 Eurofer = Materiale(Nome="Eurofer",
72                     SmA=[212,212,212,212,206,199,192,183,173,161,145,126,102,
73                         74,40],
74                     SmD=[445.9,433.3,416.5,401.1,388.5,375.9,361.9,346.5,
75                         327.6,303.8,274.4,238,193.9,140,74.9],
76                     SemA=[313,313,313,313,313,313,313,319.1,325.2,
77                         331.3,260,171.3,262.5,322.5],
78                     SemD=[506,506,506,506,506,506,506,515.8613419,525.7226837,
79                         535.5840256,420.3194888,276.9258786,424.3610224,
80                         521.3578275],
81                     TSm=[20,50,100,150,200,250,300,350,400,450,500,550,600,650,700],
82                     TSem=[20,100,150,200,250,300,350,400,450,500,550,600,650,700])

```

The last code here reported (code B.3) is the one that performs the actual verification of the structural criteria, i. e., immediate excessive deformation, immediate plastic instability, immediate plastic flow localization, and immediate fracture due to exhaustion, as established for the P-type Level A criteria of the RCC-MRx. Other scripts have also been developed for different load scenarios but are not listed here for brevity.

Before launching the code it will be necessary to:

- Set CPython as the interpreter of the ANSYS mechanical scripting module;
- Change the material name in lines 7 and 8 (in this case Eurofer) according to the material traversed by the considered paths;
- Modify the values of K_{eff} and K_t if necessary.

as a result the code will print a detailed report containing all the information about the path location, average and maximum temperature, values of membrane, bending and peak stresses, values of stress limits at those specific temperatures and verification of the above criteria. A table formatted in such a way that it can be easily copied to any spreadsheet software will also be printed in the queue.

Code B.3: *RCC-MRx P-type Level A criteria verification*

```

1  # ===== #
2  # Change the name of the material (in this case Eurofer) in the next two lines
3  # with the name of the considered material (check that the properties are also
4  # in the Materials.py file)
5  # ===== #
6
7  from Materiali import Eurofer
8  Mat = Eurofer
9
10 # ===== #
11 # Set K values
12 # ===== #
13
14 Keff = 1.5
15 Kt = 1/0.66
16
17 # ===== #
18 # Import scipy function for linear interpolation. This requires to use CPhyton
19 # in ANSYS mechanical otherwise the script doesn't work
20 # ===== #
21
22 from scipy.interpolate import interp1d
23
24 # ===== #
25 # Set less verbose ANSYS commands
26 # ===== #
27
28 mdl = ExtAPI.DataModel.Project.Model
29 geom = mdl.Geometry
30 mat = mdl.Materials
31 cosys = mdl.CoordinateSystems
32 conn = mdl.Connections
33 msh = mdl.Mesh

```

```

34 ns = mdl.NamedSelections
35 mdl.AddConstructionGeometry()
36 anl = mdl.Analyses
37 gobi = DataModel.GetObjectById
38 gobn = DataModel.GetObjectsByName
39 gobt = DataModel.GetObjectsByType
40
41 # ===== #
42 # Set unit to mm and MPa
43 # ===== #
44
45 ExtAPI.Application.ActiveUnitSystem = MechanicalUnitSystem.StandardNMM
46
47 # ===== #
48 # Set - G. Zhou (20 DPA) T [C] S [MPa]
49 # ===== #
50
51 TSet = [20,100,150,200,250,300,350,400,450,500,550,600,650,700]
52 DSetA = [1309,1309,1309,1309,1309,1309,1309,1603.65,1898.315,2193,2193,2193,
53          2193,2193]
54 DSetD = [1767,1767,1767,1767,1767,1767,1767,2397.5,3028.15,3659,3659,3659,
55          3659,3659]
56
57 SetA = interp1d(TSet, DSetA, fill_value="extrapolate")
58 SetD = interp1d(TSet, DSetD, fill_value="extrapolate")
59
60 # ===== #
61 # St - RCC-MRx T [C] S [MPa]
62 # ===== #
63
64 TSt = [375,425,450,475,500,525,550,575,600,625,650]
65 DSt = [284.130304,218.6881119,190.5263403,164.353613,139.6827506,
66        116.2671329,94.10069933,73.41794871,54.69393933,38.64428897,
67        26.22517484]
68
69 St = interp1d(TSt, DSt, fill_value="extrapolate")
70
71 # ===== #
72 # Create Linearized Stress and path temperature lists
73 # ===== #
74
75 SL_PQ = []
76 SL_Q = []
77 SL_P = []
78 T_path = []
79
80 SL = gobt(DataModelObjectCategory.LinearizedEquivalentStress)
81
82 for ii in SL:
83     if ii.Parent.Parent.Name == "P+Q":
84         SL_PQ.append(ii)
85     if ii.Parent.Parent.Name == "Q":
86         SL_Q.append(ii)
87     if ii.Parent.Name == "P":
88         SL_P.append(ii)
89
90 UDR = gobt(DataModelObjectCategory.UserDefinedResult)
91
92 for cc in UDR:
93     if cc.Expression == "BFE":
94         T_path.append(cc)

```

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95
96 L_print = [{"Path", "Pm/Sm", "(Pm+Pb)/(Keff*Sm)",
97             "(Pm+Qm)/Sem", "(Pm+Pb+Q+F)/Set",
98             "Pm/St", "(Pm+Pb/Kt)/St"}]
99
100 path = gobt(DataModelObjectCategory.Path)
101
102 for yy in range (0,len(path),1):
103 # ===== #
104 # Prints path description
105 # ===== #
106     print("# ===== #")
107     path_n = path[yy].Name
108     print("Path "+path_n)
109     L_sub = []
110     L_sub.append(path_n)
111     print("")
112     print("S (" +str(path[yy].StartXCoordinate.Value/1000)+
113           ", " +str(path[yy].StartYCoordinate.Value/1000)+
114           ", " +str(path[yy].StartZCoordinate.Value/1000)+") [m]")
115     print("E (" +str(path[yy].EndXCoordinate.Value/1000)+
116           ", " +str(path[yy].EndYCoordinate.Value/1000)+
117           ", " +str(path[yy].EndZCoordinate.Value/1000)+") [m]")
118     print("Discretization Points = "+str(path[yy].DiscretizationPoints))
119 # ===== #
120 # Prints temperatures and stresses info
121 # ===== #
122     Ta = T_path[yy].Average.Value
123     print("T ave = "+str(Ta)+" [C]")
124     Tm = T_path[yy].Maximum.Value
125     print("T max = "+str(Tm)+" [C]")
126     print("")
127     print("Loading data:")
128     pm = SL_P[yy].Membrane.Value
129     print("Pm = "+str(pm)+" [MPa]")
130     pm_pb = max(SL_P[yy].MembraneBendingOutside,SL_P[yy].MembraneBendingInside).Value
131     print("Pm + Pb = "+str(pm_pb)+" [MPa]")
132     pm_qm = SL_PQ[yy].Membrane.Value
133     print("Pm + Qm = "+str(pm_qm)+" [MPa]")
134     p_q_f = max(SL_PQ[yy].TotalInside,SL_PQ[yy].TotalOutside).Value
135     print("P + Q + F = "+str(p_q_f)+" [MPa]")
136     print("")
137 # ===== #
138 # Prints stress limits calculated at path Tave
139 # ===== #
140     print("Allowable data:")
141     print("Sm("+str(Ta)+") = "+str(Mat.SmA_eval(Ta))+" [MPa]")
142     print("Sem("+str(Ta)+") = "+str(Mat.SemA_eval(Ta))+" [MPa]")
143     print("Set("+str(Ta)+") = "+str(SetA(Ta))+" [MPa]")
144     print("St("+str(Ta)+") = "+str(St(Ta))+" [MPa]")
145     print("")
146 # ===== #
147 # Prints low temperature rules verification
148 # ===== #
149     print("Low Temperature rules:")
150 # ===== #
151     print("Pm/Sm = "+str(pm/Mat.SmA_eval(Ta)))
152     if pm/Mat.SmA_eval(Ta) > 1:
153         print("Pm/Sm > 1")
154         print("Immediate Excessive Deformation criterion not verified")
155     elif pm/Mat.SmA_eval(Ta) >= 0.8 and pm/Mat.SmA_eval(Ta) <= 1:

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156     print("0.8 <= Pm/Sm <= 1")
157     print("Immediate Excessive Deformation criterion to be attentioned")
158     else:
159         print("Pm/Sm < 0.8")
160         print("Immediate Excessive Deformation criterion verified")
161     L_sub.append(str(round(pm/Mat.SmA_eval(Ta),2)))
162     print("")
163 # ===== #
164     print("(Pm+Pb)/(Sm*Keff) = "+str(pm_pb/(Mat.SmA_eval(Ta)*Keff)))
165     if pm_pb/(Mat.SmA_eval(Ta)*Keff) > 1:
166         print("(Pm+Pb)/(Sm*Keff) > 1")
167         print("Immediate Plastic Instability criterion not verified")
168     elif pm_pb/(Mat.SmA_eval(Ta)*Keff) >= 0.8 and pm_pb/(Mat.SmA_eval(Ta)*Keff) <= 1:
169         print("0.8 <= (Pm+Pb)/(Sm*Keff) <= 1")
170         print("Immediate Plastic Instability criterion to be attentioned")
171     else:
172         print("(Pm+Pb)/(Sm*Keff) < 0.8")
173         print("Immediate Plastic Instability criterion verified")
174     L_sub.append(str(round(pm_pb/(Mat.SmA_eval(Ta)*Keff),2)))
175     print("")
176 # ===== #
177     print("(Pm+Qm)/Sem = "+str(pm_qm/Mat.SmA_eval(Ta)))
178     if pm_qm/Mat.SmA_eval(Ta) > 1:
179         print("(Pm+Qm)/Sem > 1")
180         print("Immediate Plastic Flow Localization criterion not verified")
181     elif pm_qm/Mat.SmA_eval(Ta) >= 0.8 and pm_qm/Mat.SmA_eval(Ta) <= 1:
182         print("0.8 <= (Pm+Qm)/Sem <= 1")
183         print("Immediate Plastic Flow Localization criterion to be verified")
184     else:
185         print("(Pm+Qm)/Sem < 0.8")
186         print("Immediate Plastic Flow Localization criterion verified")
187     L_sub.append(str(round(pm_qm/Mat.SmA_eval(Ta),2)))
188     print("")
189 # ===== #
190     if p_q_f > SetA(Ta):
191         print("P + Q + F > Set")
192         print("(P + Q + F) / Set = "+str(p_q_f/SetA(Ta)))
193         print("Imm. Fracture due to Exhaustion of Ductility criteria not verified")
194     else:
195         print("P + Q + F <= Set")
196         print("(P + Q + F) / Set = "+str(p_q_f/SetA(Ta)))
197         print("Imm. Fracture due to Exhaustion of Ductility criteria verified")
198     L_sub.append(str(round(p_q_f/SetA(Ta),2)))
199     print("")
200     if Ta >= 400:
201         print("High Temperature rules:")
202         if pm > St(Ta):
203             print("Pm > St")
204             print("Pm / St = "+str(pm/St(Ta)))
205             print("NOME DEL CRITERIO criteria not verified")
206             L_sub.append(str(pm/St(Ta)))
207         else:
208             print("Pm <= St")
209             print("Pm / St = "+str(pm/St(Ta)))
210             print("NOME DEL CRITERIO criteria verified")
211             L_sub.append(str(pm/St(Ta)))
212         print("Secondo criterio non ancora implementato")
213         L_sub.append("Not impl")
214     else:
215         print("T average < 400 --> High Temperature rules not calculated")
216         L_sub.append("NA")

```

```

217         L_sub.append("NA")
218     L_print.append(L_sub)
219     print("# ===== #")
220 print("")
221 # ===== #
222 # Prints a summary table with all the results that can be pasted into Excel
223 # ===== #
224 for ii in L_print:
225     print(ii[0]+"\\t"+ii[1]+"\\t"+ii[2]+"\\t"+ii[3]+"\\t"+ii[4]+"\\t"+ii[5]+"\\t"+ii[6])#

```