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MASTER'S DEGREE PROGRAMME IN ENERGY ENGINEERING

DEVELOPMENT OF DYNAMIC MODELS FOR PWR NUCLEAR POWER PLANT SIMULATION IN THE MODELICA ENVIRONMENT

Master's Degree Thesis in Nuclear Plants

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Abstract

This thesis presents the development of a dynamic Pressurized Water Reactor (PWR) model, starting with a simplified basic model and progressively increasing its level of detail in both the neutronic and thermal-hydraulic domains within the open-source OpenModelica environment.

The secondary thermal-hydraulic circuit is progressively extended from a single-turbine layout to a two-stage turbine configuration and, finally, to a fully regenerative cycle with high-pressure steam extraction and a direct-contact spray condenser. The increased model complexity requires a dedicated initialization strategy based on previously generated `.mat` simulation state files.

From a neutronic standpoint, the original point-kinetics formulation is extended to a two-region axial core model that couples the neutron population and precursor concentration in the upper and lower regions via a diffusive term. A control rod model based on insertion depth is also developed and shown to reproduce the point-kinetics response exactly.

The resulting Modelica configurations: Control Rods, Two-Zone, and Spray-Condenser are compared with the IAEA *Advanced PWR Simulator* at nominal and partial-load steady-state conditions. A steady-state comparison is adopted because the permanent Xenon-135 dynamics implemented in the reference simulator prevent a direct transient comparison. The models closely reproduce the reference thermal-hydraulic behavior, while the remaining discrepancies are attributed to identified structural differences between the models. The results demonstrate the consistency of the developed neutronic and thermal-hydraulic formulations and provide a basis for future extension of the modeling framework to Small Modular Reactor systems.

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Chapter 1

Introduction

Interest in nuclear energy has increased significantly in recent years, driven by the growing demand for low-carbon energy sources to support the decarbonization of the energy sector while ensuring a reliable, continuous supply of electricity. In this context, Pressurized Water Reactors (PWRs) remain particularly relevant, as they are the most widely used nuclear reactor technology worldwide. At the same time, increasing attention is being devoted to advanced reactor concepts and to applications in which nuclear energy can contribute not only to electricity generation, but also to district heating, hydrogen production, and the supply of process heat for industrial applications.

The analysis and development of such systems require simulation tools capable of representing the interaction between different physical domains, including neutronics and thermal hydraulics. Dynamic simulation models provide a flexible framework for investigating the behavior of nuclear power plants under different operating conditions and for progressively increasing the level of detail of the plant representation. In this context, the Modelica language, together with the open-source OpenModelica environment, provides a suitable framework for the integrated development of coupled neutronic and thermal-hydraulic models.

The present thesis builds upon the work carried out during the author's curricular internship and focuses on the development and improvement of a coupled neutronic and thermal-hydraulic dynamic model of a PWR nuclear power plant. The work is intended to provide a basis for continuing the modeling activities in a subsequent Ph.D. research project, in which the framework will be further extended to Small Modular Reactor (SMR) systems. The PWR is therefore adopted as a representative, well-established reference configuration for the development and assessment of the modeling approach.

The main developments concern both the reactor neutronics and the thermal-hydraulic system. The original point-kinetics formulation is extended to a two-region axial representation of the reactor core, together with a control rod model based on insertion depth. In parallel, the secondary-side system is progressively developed from the original single-turbine configuration towards a more detailed thermodynamic cycle, including a second turbine stage, high-pressure steam extraction, and a direct-contact spray condenser for feedwater regeneration. The increased model complexity also motivates the development of dedicated initialization procedures for the resulting configurations.

The developed models are assessed through comparison with the *Advanced PWR Simulator* distributed by the International Atomic Energy Agency (IAEA). The comparison considers nominal and partial-load steady-state conditions and is used to evaluate the consistency of the developed neutronic and thermal-hydraulic formulations with the corresponding reference results.

The thesis is organized as follows.

Chapter 2 presents the state of the art relevant to the development of the present work, including the current energy context, the role of nuclear energy and PWRs, the development of Small Modular Reactors, and the modeling framework adopted in the thesis.

Chapter 3 presents a basic dynamic PWR model, describing its thermal-hydraulic layout, point kinetics neutronics model, coupling strategy, main assumptions, and limitations.

Chapter 4 describes the main developments introduced with respect to the basic model, focusing on the two-region neutron kinetics formulation, the control rod model, and the upgrade of the secondary loop.

Chapter 5 presents the development of the final thermodynamic-cycle configuration and the associated initialization strategies, together with the comparison of the plant configurations developed throughout the thesis.

Chapter 6 is devoted to the assessment of the developed models against the *Advanced PWR Simulator* distributed by the IAEA, presenting the comparison of the three Modelica configurations under nominal and partial-load steady-state conditions.

Finally, Chapter 7 summarizes the main outcomes of the thesis and discusses possible directions for future work.

Chapter 2

State of the Art

This chapter provides the background and context for the work presented in this thesis about the development of models for the dynamic simulation of Pressurized Water Reactors (PWRs). It first discusses the current energy context and the role of low-carbon energy sources, then focuses on PWRs and the modeling framework used to simulate them.

2.1 Energy Context and Role of Low-Carbon Energy Sources

The development of future energy systems is strongly influenced by the need to meet growing energy demand while progressively reducing the environmental impact associated with energy production. In this context, low-carbon energy sources are expected to play an increasingly important role in the transition towards more sustainable energy systems. Nuclear energy is of particular interest because it can provide continuous electricity production with low direct carbon emissions, thereby complementing variable renewable energy sources. Understanding the role that nuclear energy may play in future energy systems is consequently relevant to assessing the need for the development, optimization, and safe operation of nuclear power plants, and to studying suitable simulation tools to represent their behavior.

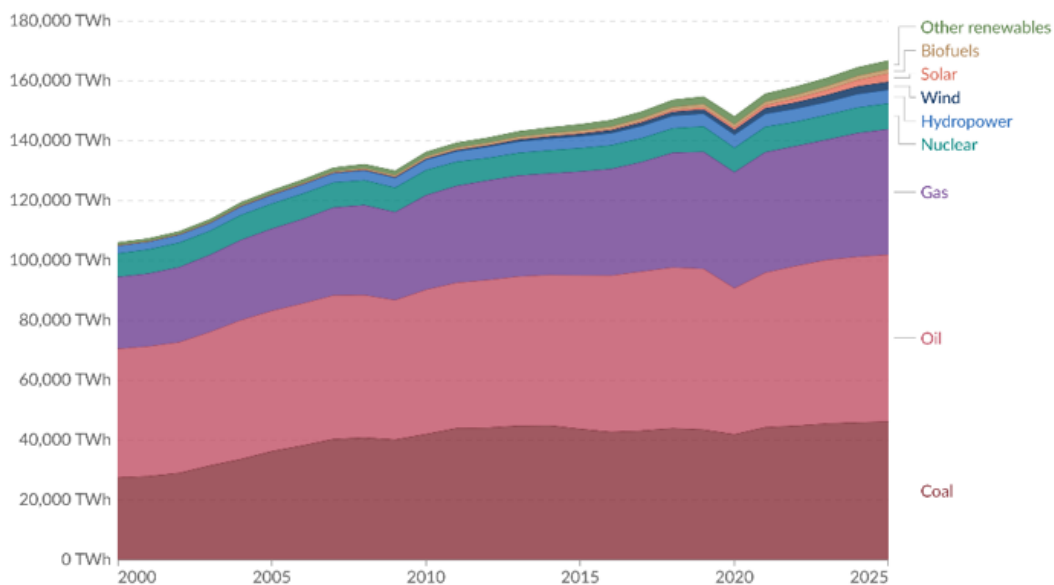


Figure 2.1: Primary energy use by source worldwide, 2000–2025. [1].

The evolution of energy consumption provides a first indication of the different challenges faced at the global and European levels. Figure 2.1 shows the evolution of primary energy consumption worldwide over the last 25 years (2000–2025). At the global level, primary energy consumption has been increasing, reaching values above 160,000 TWh in recent years. This evolution reflects the increasing energy requirements of a growing world population and, in particular, the continued growth in energy demand associated with developing and emerging economies. The energy mix remains predominantly fossil-based, with coal, oil, and natural gas still accounting for the largest share of global primary energy consumption. The data reported by Our World in Data are based on the Energy Institute Statistical Review of World Energy [1].

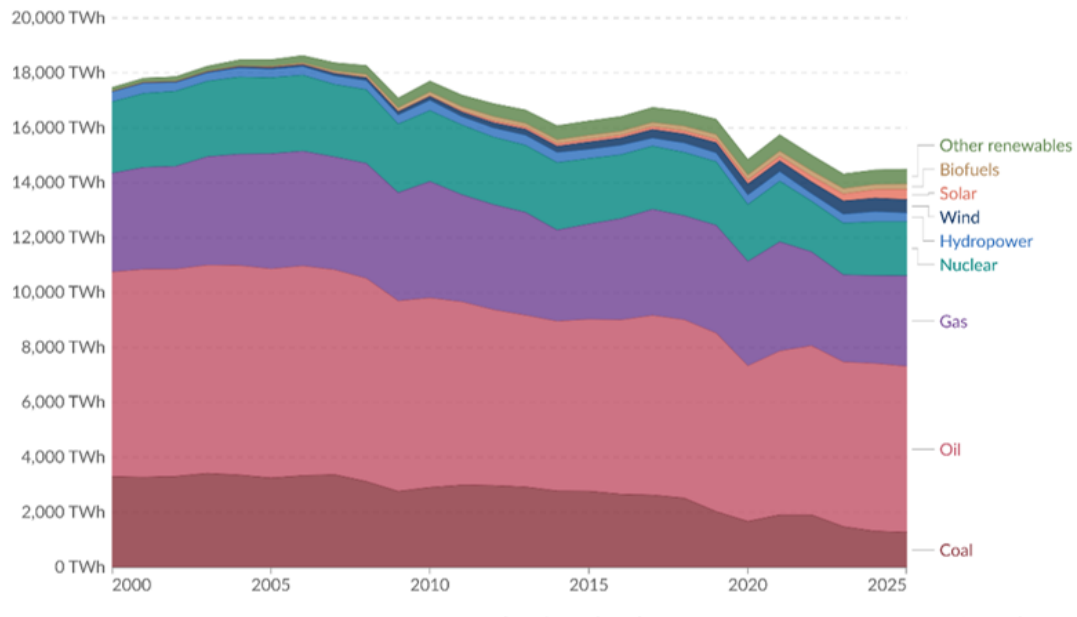


Figure 2.2: Primary energy use by source in the European Union, 2000–2025. [1].

A substantially different trend can be observed in the European Union (Figure 2.2). Over the same period, total primary energy consumption shows an overall decreasing trend, falling from approximately 17,500–18,000 TWh in the early 2000s to values below 15,000 TWh in recent years. This reduction is particularly associated with the progressive decline in the use of coal and oil, which have contributed significantly to the decrease in total energy consumption. At the same time, the contribution of low-carbon energy sources has progressively increased, as discussed below. The European energy context, therefore, differs from the global one, where the overall increase in energy demand remains the dominant trend [1].

Figure 2.3 shows the evolution of the share of primary energy derived from low-carbon energy sources in the European Union. In the classification adopted by Our World in Data, low-carbon sources include nuclear energy and renewable energy sources, the latter comprising hydropower, wind, solar, bioenergy, geothermal energy, wave energy, and tidal energy [1]. Despite these differing trends in total primary energy consumption, both contexts show a growing contribution from low-carbon sources, as discussed below.

In the European Union, the share of primary energy derived from low-carbon sources increases over the period considered, rising from approximately 18% in 2000 to 26.80% in 2025. This evolution indicates a progressive increase in the contribution of nuclear and renewable energy sources to the European primary energy supply, despite the overall reduction in primary energy consumption.

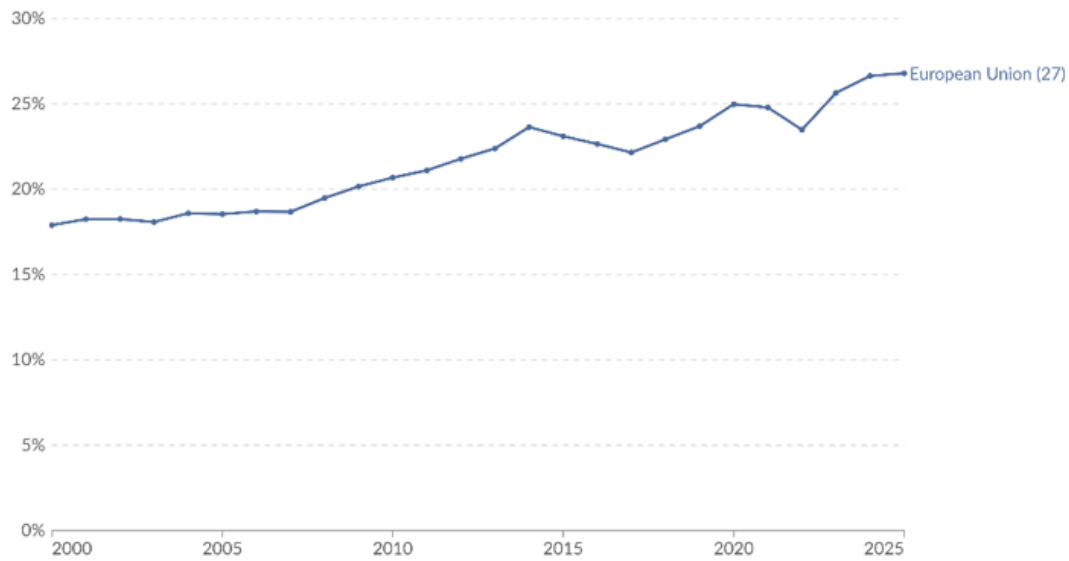


Figure 2.3: Share of primary energy derived from low-carbon sources in the European Union, 2000–2025. [1].

A similar, though less pronounced, trend can be observed globally. Figure 2.4 shows the evolution of the share of primary energy derived from low-carbon sources worldwide between 2000 and 2025. The share increases from approximately 11% in 2000 to almost 14% in 2025, indicating a gradual increase in the contribution of nuclear and renewable energy sources to the global energy mix [1].

The increasing contribution of low-carbon energy sources occurs within an energy system in which nuclear power already represents a significant source of electricity generation. According to the International Atomic Energy Agency (IAEA), nuclear energy accounted for approximately 9% of global electricity production in 2024, making it the second-largest low-carbon source of electricity after hydropower. In the same year, coal and natural gas remained the largest and second-largest sources of global electricity production, respectively. At the same time, the combined contribution of wind and solar energy reached almost 15% [2].

Projections from the IAEA further highlight the future role of nuclear energy. Starting from a global operational nuclear capacity of approximately 377 GW(e) at the end of 2024, the low-case scenario projects an increase of approximately 50%, reaching 561 GW(e) by 2050. In the high-case scenario, operational nuclear capacity is projected to reach 992 GW(e), corresponding to approximately 2.6 times the 2024 value. These projections include both the construction of new nuclear capacity and increases in the power output of existing plants [2].

The contribution of Small Modular Reactors (SMRs) is also explicitly considered in the IAEA projections. In the high-case scenario, SMRs are expected to account for approximately 24% of the 676 GW(e) of new nuclear capacity added by 2050, while their contribution in the low-case scenario is estimated at approximately 5% of the 320 GW(e) of new capacity added. The IAEA projections therefore indicate not only a substantial expansion of nuclear generating capacity, but also a possible increasing role of modular reactor technologies in the future nuclear fleet [2].

Looking towards 2050, the IAEA also projects a substantial change in the global energy system, with electricity production expected to approximately double compared with 2024 levels, while global final energy consumption is projected to decrease by approximately 3% [2]. Although such projections depend on technological, economic, and policy developments, they

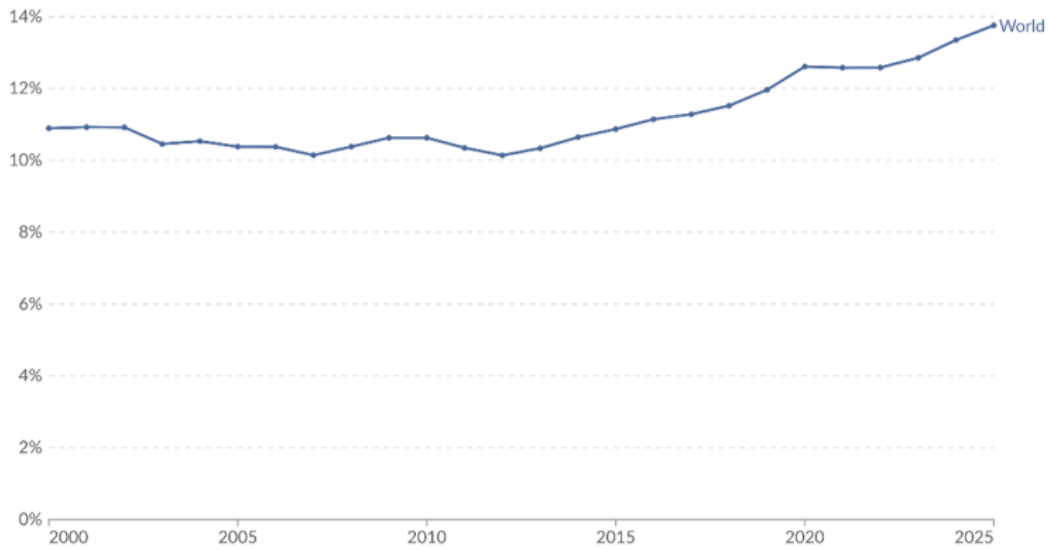


Figure 2.4: Share of primary energy derived from low-carbon sources worldwide, 2000–2025. [1].

indicate a scenario in which electricity is expected to play an increasingly central role in the energy system and in which additional nuclear capacity may help meet this demand while limiting carbon emissions.

Overall, the data considered in this section highlight the relevance of nuclear energy within the ongoing transformation of the energy system. Global energy demand continues to increase, while the contribution of low-carbon sources is progressively expanding both globally and in Europe. At the same time, the IAEA projections indicate that global nuclear capacity could increase by at least approximately 50% by 2050, with a potentially substantial contribution from SMRs. These trends reinforce the importance of developing reliable, sufficiently detailed tools for analyzing and simulating nuclear power plants to support assessments of their performance, operation, and safety. Within this context, the following section focuses on Pressurized Water Reactors, which represent the dominant technology in the current nuclear fleet and an important technological basis for several future reactor concepts.

2.2 Pressurized Water Reactors

As discussed in the previous section, the expected increase in nuclear energy’s contribution to the future energy system motivates continued development of reliable tools for analyzing and simulating nuclear power plants. Among reactor technologies, Pressurized Water Reactors (PWRs) are particularly relevant because of their dominant role in the current nuclear fleet and their continued presence in new reactor designs, including Small Modular Reactors (SMRs). For these reasons, PWR technology is adopted as the reference configuration for the present work. It serves as the basis for the subsequent development of the modeling framework towards other reactor configurations.

The prevalence of PWR technology is clearly illustrated by data from the International Atomic Energy Agency (IAEA)’s Power Reactor Information System (PRIS). In 2025, 420 nuclear reactors were reported as being in operation worldwide, of which 310 were classified as Pressurized Light-Water Moderated and Cooled Reactors, corresponding to approximately 74% of the total number of operating reactors (Figure 2.5). In terms of net electrical capacity,

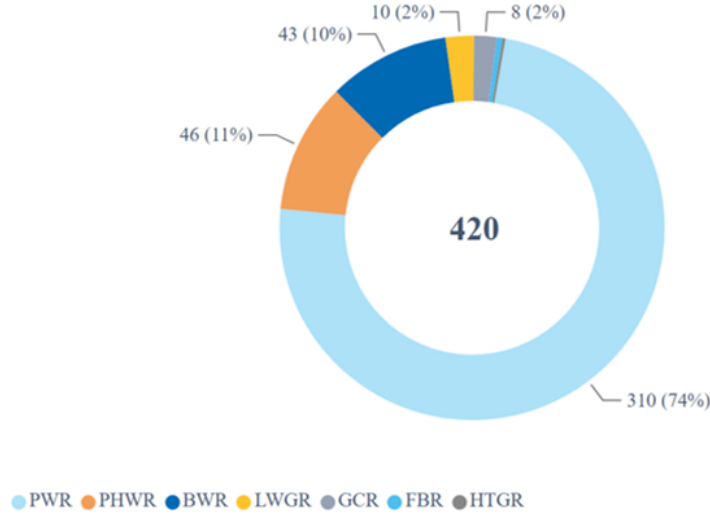


Figure 2.5: Distribution of operable nuclear reactors worldwide by reactor type (2025). [3].

PWRs accounted for approximately 297.7 GWe out of a total of 379.7 GWe, corresponding to approximately 78% of the total operating nuclear capacity, as shown in Figure 2.6. Furthermore, as illustrated in Figure 2.7, PWRs accounted for approximately 78% of the 2635 TWh of nuclear electricity generated worldwide in 2025 [3].

The prevalence of PWR technology is even more evident when considering reactors currently under construction. Of the 72 reactors reported by PRIS, 65 are PWRs, corresponding to approximately 90% of the total (Figure 2.8). In terms of net electrical capacity, PWRs account for approximately 72 GWe out of a total of 77.7 GWe, corresponding to approximately 92.7% of the capacity currently under construction [4].

The relevance of pressurized water technology also extends to the development of Small Modular Reactors. The International Atomic Energy Agency (IAEA) catalog of Small Modular Reactor technologies includes several water-cooled designs based on PWR technology, including integral-PWR, compact-PWR, and loop-PWR configurations. The 2024 edition of the catalog identifies several PWR-based concepts, including CAREM, NuScale Power Module, NUWARD, SMART, RITM-200N, i-SMR, and Rolls-Royce SMR. For example, NUWARD is classified as an integral PWR with a configuration consisting of two 170 MWe modules. In contrast, NuScale Power Module, SMART, i-SMR, and Rolls-Royce SMR are also classified as PWRs [5]. This continuity between the established PWR technology and several SMR concepts is particularly relevant to the longer-term development of the modeling framework considered in this work.

Having established the relevance of PWR technology, a simplified representation of the plant is introduced to describe its main operating principles and the configuration considered in the present work. PWRs are characterized by an indirect thermodynamic cycle in which heat produced in the reactor core is transferred from the primary circuit to the secondary circuit via the steam generator, without mass exchange between the two circuits. The primary circuit, therefore, has the function of removing the heat generated in the reactor and transferring it to the secondary circuit. To maintain the coolant under predominantly single-phase operating conditions, the primary circuit is maintained at high pressure by the pressurizer. The primary coolant acts simultaneously as coolant and moderator and is maintained at sufficiently high pressure to prevent significant boiling in the reactor core under normal operating conditions. In the secondary circuit, on the other hand, the fluid undergoes a phase change: water is heated

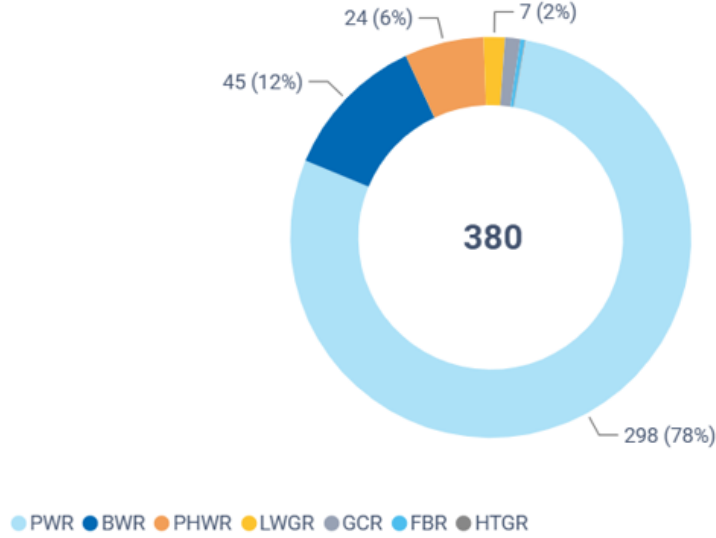


Figure 2.6: Net electrical capacity of nuclear reactors in operation in 2025, by reactor type [GWe]. [3].

and vaporized in the steam generator, after which the steam is supplied to the turbine to convert thermal energy into mechanical and, subsequently, electrical energy. The steam leaving the turbine is finally condensed and returned towards the steam generator through the feedwater system [6].

The primary circuit is maintained at a pressure of approximately 154 bar by the pressurizer. This high pressure raises the coolant's saturation temperature and prevents significant boiling in the reactor core under normal operating conditions. The secondary circuit operates at a substantially lower pressure, reaching approximately 70 bar in the steam generation region before progressively decreasing towards the condenser. The resulting pressure difference between the two circuits allows the secondary-side water to undergo phase change while the primary coolant remains in the liquid phase.

A schematic representation of the system considered in the present work is shown in Figure 2.9. The configuration comprises the main components of the primary and secondary circuits and provides the basis for subsequent modeling.

From a thermal-hydraulic perspective, the primary coolant enters the reactor core at approximately 292 °C and leaves at approximately 326 °C. The corresponding coolant mass flow rate is of the order of 1.7×10^4 kg/s. Maintaining the primary coolant below the saturation condition is essential for the normal operation of the reactor. In particular, Departure from Nucleate Boiling (DNB) represents an important thermal-hydraulic limit, since excessive degradation of heat transfer between the fuel and coolant must be avoided. The pressure-temperature conditions considered for the PWR are represented in Figure 2.10.

The general configuration of a PWR therefore comprises the primary circuit, consisting of the reactor, steam generators, primary pumps, and pressurizer, and the secondary circuit, which includes the energy conversion system, turbines, condenser, and feedwater systems. The separation between the two circuits is one of the main characteristics that distinguishes PWRs from BWRs. In a BWR, the water flowing through the reactor core is allowed to boil, and the resulting steam is directed directly towards the turbine through the steam line. In a PWR, instead, boiling is confined to the secondary circuit, while the primary coolant remains separated from the turbine system by the steam generator [6].

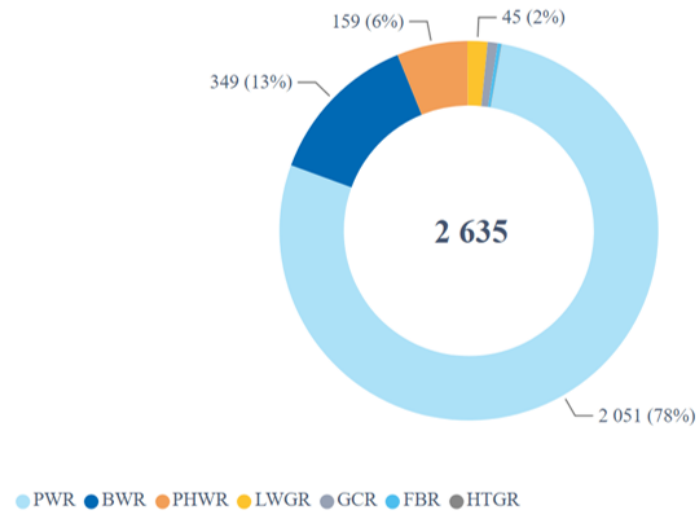


Figure 2.7: Global nuclear electricity generation by reactor type in 2025 (TWh). [3].

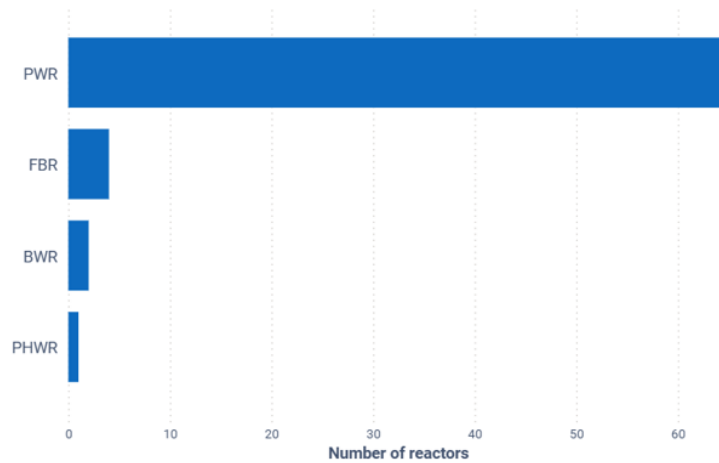


Figure 2.8: Number of nuclear reactors under construction in 2025, by reactor type. [4].

This configuration provides a physical separation between the primary coolant and the secondary-side steam supplied to the turbine, limiting the transfer of radioactive material towards the turbine system. The presence of a separate secondary circuit also provides a clear interface between the nuclear heat source and the conventional power conversion system [6]. From a modeling perspective, this separation allows the nuclear heat source, the reactor coolant system, and the power conversion system to be represented as interconnected but physically distinct subsystems.

PWR technology is also present across different generations of nuclear reactors. Generation II reactors, developed and constructed mainly from the 1970s onwards, still constitute a significant part of the current commercial nuclear fleet and are predominantly characterized by the presence of active safety systems. Generation III reactors, and in particular Generation III+ (Gen III+) reactors, introduce additional safety features, including passive heat removal systems and measures to reduce the risks associated with severe accidents. Large-scale PWR projects of this generation include the EPR, developed by Framatome and EDF (such as the Flamanville 3 unit shown in Figure 2.11), as well as the AP1000, developed by Westinghouse, and the VVER-1200.

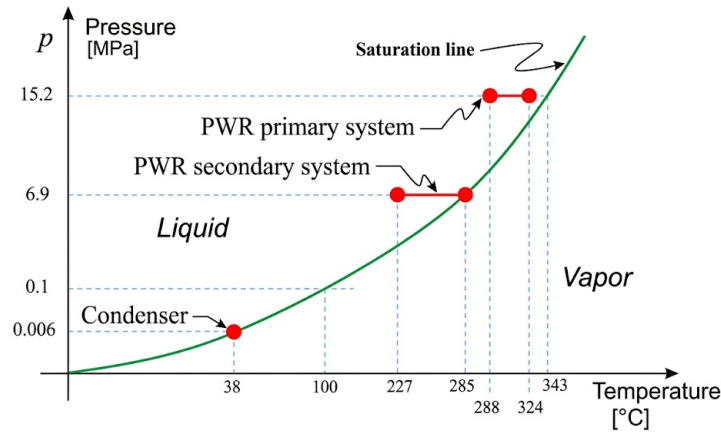


Figure 2.10: Pressure-temperature representation of the primary and secondary systems of the PWR, adapted from Buongiorno [6].



Figure 2.11: Overview of the Flamanville 3 EPR nuclear power plant unit upon completion of construction [7].

The development of object-oriented and multi-physics dynamic modeling languages led to the definition of Modelica, introduced in 1997 as the result of an international effort to define an object-oriented language for modeling general physical systems using algebraic and differential equations. The language is open-source and has been applied to several engineering fields, including automotive systems, robotics, thermal-hydraulics, and mechatronics [8].

One of the fundamental features of Modelica is its acausal modeling paradigm, which allows the equations of individual models to be defined independently of the actual boundary conditions, without specifying in advance which variables should be considered inputs or outputs. The model's causality is automatically determined by the interpreter or compiler when the individual components are assembled into the overall system representation. This approach facilitates the development, documentation, and reuse of models, leaving the determination of the computational sequence required for the simulation to the compiler [8].

Another relevant feature is model transparency, since the equations defined in Modelica maintain a form closely related to their physical formulation, making them easier to understand, modify, and extend. Components are also connected through interfaces, or *connectors*, which represent their physical interactions with the surrounding system. Components with compatible interfaces can therefore be interconnected independently of their internal structure, allowing a

component to be replaced by a more detailed or simplified version without modifying the rest of the model [8].

The structure of the language also allows models to be organized hierarchically through mechanisms such as encapsulation, inheritance, and reusability, supporting the development of libraries of reusable components. The general nature of the language also makes it possible to represent systems involving the interaction of different physical domains. This feature is particularly relevant for nuclear power plants, where the overall behavior results from the interaction between thermal-hydraulic, nuclear, and control systems [8].

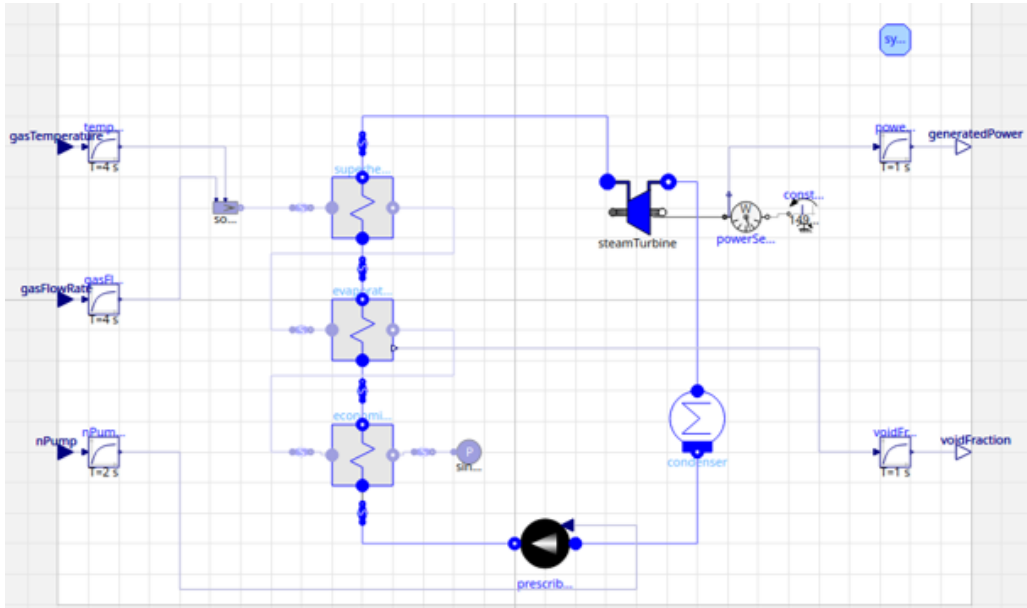


Figure 2.12: Example of a simple Rankine cycle included in the ThermoPower library and visualized in the OpenModelica environment.

It is also important to note that variables declared inside a connector fall into two categories that determine the equations generated when components are connected. *Potential* variables, such as pressure or temperature, are set equal in all the connectors joined at a connection point. *Flow* variables, declared with the prefix *flow*, such as mass flow rate or heat flow rate, are instead subject to a balance: their sum at the connection point is zero, with the convention that a flow is positive when entering a component. In this way, every *connect* statement automatically generates the equality of potentials and the conservation law of the flow quantities over an infinitesimal control volume [9].

In the present thesis, Modelica is therefore adopted as the modeling language for developing the dynamic PWR plant model. At the same time, simulations are performed using OpenModelica, an open-source environment for compiling and executing Modelica models. Using this framework, the plant can be represented as a set of interconnected components. It enables the exploitation of models already available in specialized libraries, reducing the development effort to the components that require specific modeling.

In this context, the present thesis makes extensive use, in addition to the Modelica Standard Library (MSL) [9], of the ThermoPower library [10], developed at the Politecnico di Milano as an open-source library for the system-level modeling of thermal power plants and for supporting the design and analysis of control systems [8]. The library was developed according to principles consistent with system-level modeling: the models are derived, whenever possible, from the fundamental conservation equations of mass, momentum, and energy, or from established

empirical correlations; the level of detail is kept compatible with the requirements of system-level simulation; and the component interfaces are designed to be as independent as possible from the modeling assumptions adopted internally. This allows a component to be replaced with a version with a different level of detail without modifying the overall structure of the model [8].

An additional advantage of the ThermoPower library is the availability of examples that facilitate familiarization with and understanding of the library and, more generally, of the Modelica language. Figure 2.12 shows an example of a Rankine cycle included in the library and visualized in the OpenModelica environment.

In the present work, the ThermoPower library therefore provides the modeling framework underlying the thermal-hydraulic models developed during the curricular internship and further extended in this thesis. The models presented in the following chapters build upon this existing implementation, introducing the modifications and extensions required for the objectives of the present work.

Chapter 3

Basic Models

The work initially focused on developing a first dynamic model of a Pressurized Water Reactor (PWR) nuclear power plant, implemented in the Modelica environment and integrating a lumped-parameter thermal-hydraulic model of the primary and secondary circuits with a point-kinetic neutronic model. The thermal-hydraulic model combines lumped-parameter components with one-dimensional flow models for the pipes and heat exchangers, while the turbine behavior is described using the Stodola law. This basic model represents the starting point for the further developments presented in the subsequent chapters.

3.1 Development of the Thermal-Hydraulic System

The development of the thermal-hydraulic model began with the implementation of simplified configurations of the thermodynamic cycle. This initial activity was carried out using the Modelica graphical interface, adopting a drag-and-drop approach to assemble components from the Modelica Standard Library (MSL) and the ThermoPower library. This first implementation provided an opportunity to become familiar with the modeling environment and, in particular, to address some of the main issues associated with the initialization of Modelica systems and parameters. These issues subsequently became increasingly relevant as the complexity of the model increased.

As a first reference configuration, an ideal Rankine cycle was reproduced based on the thermodynamic cycle presented in *Sistemi energetici e macchine a fluido, Vol. 1* by Negri di Montenegro, Bianchi, and Peretto [11]. The purpose of this first model was not to reproduce a specific nuclear power plant, but rather to provide a simple reference case for testing the behavior and initialization of the components available in the MSL and ThermoPower libraries.

The first step towards increasing the model's complexity was to replace the ideal steam generator, represented by an ideal Modelica component, with two gas-to-water heat exchangers available in the ThermoPower library. The two components were used to represent the sensible heating and evaporation processes separately. In this configuration, the first heat exchanger served as the economizer, where the secondary fluid remained in the liquid phase. In contrast, the second served as the evaporator, where the secondary fluid underwent a phase change. The resulting configuration was based on the corresponding representation of the Rankine cycle described in the aforementioned reference [11]. This model is illustrated in Figure 3.1.

This configuration provided the first relevant test of the initialization of a system involving multiple components with thermal and fluid-dynamic storage and a phase change. In particular, it enabled verification of the consistent initialization of the thermodynamic variables, the use of a fixed-state pressure condition in the condenser, and the model's ability to reach operating

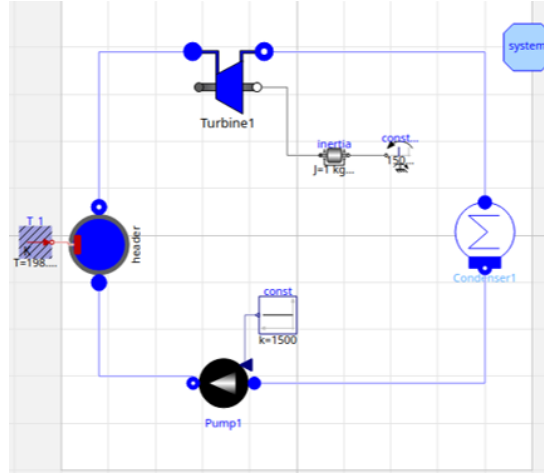


Figure 3.1: Ideal Rankine cycle described in the basic model.

conditions close to the expected values. The interaction between components characterized by energy and mass accumulation, together with the occurrence of phase change, introduced additional nonlinearities and made the initialization substantially more demanding than in the preceding ideal-cycle configuration.

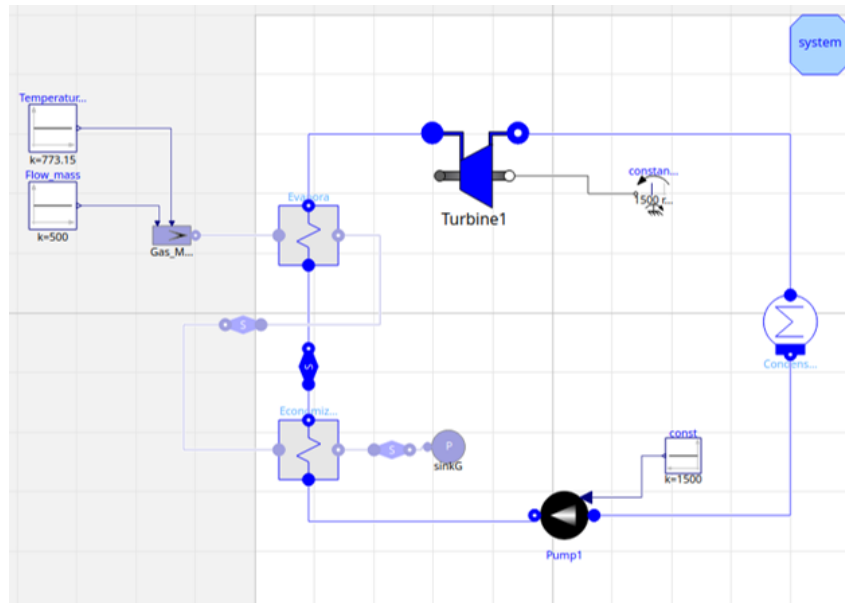


Figure 3.2: Rankine cycle with gas-to-water heat exchangers.

After this preliminary phase, the gas-to-water heat exchangers were replaced with dedicated water-to-water components to reproduce the thermal-hydraulic configuration of a PWR secondary circuit. Before proceeding to develop these components, a dedicated icon was created for the heat exchanger models. This made it possible to distinguish the economizer and evaporator directly from the graphical representation of the components in the Modelica icon view, facilitating their identification when assembling the complete system.

The development of water-to-water heat exchangers marked the first implementation carried out directly in the Modelica text view, where component equations and connections can be defined explicitly in Modelica code. Two different heat exchanger models were developed, distinguishing the economizer from the evaporator according to the thermodynamic regime of

the secondary-side flow. The `Economizzatore_Water` component was designed for single-phase heat transfer on both sides and therefore employs two `Flow1DFV` components, one for each fluid side. Conversely, the `Evaporator_Water` component was designed to represent heat transfer between a single-phase primary flow and a two-phase secondary flow. For this reason, it combines a `Flow1DFV` component on the primary side with a `Flow1DFV2ph` component on the secondary side. Both components were developed starting from the structure of the corresponding gas-to-water heat exchangers available in the ThermoPower library, adapting their geometry, thermal connections, and constitutive equations to the water-to-water configuration.

The complete source code for the two components developed for this model is reported in Appendix A, in Sections A.1 and A.2.

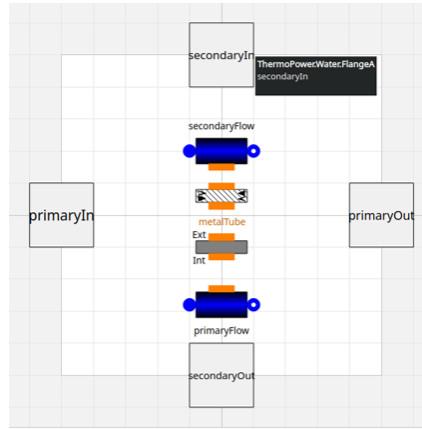


Figure 3.3: Economizer developed in the graphical interface.

Once the behavior of the individual components had been verified, the complete secondary-side Rankine cycle was implemented. The sizing and verification of the system behavior were carried out using the *Passive_PWR* plant simulator, which was used to obtain a configuration consistent with the case under consideration. The characteristics of the simulator and the procedure adopted for the subsequent comparison are described in Chapter 6.

To complete the secondary-side configuration, a feedwater preheater was also introduced. The preheater did not require the development of a new component: the previously developed `Evaporator_Water` model was reused in the reverse thermal configuration. In this case, the two-phase flow acts as the hot fluid, transferring heat to the single-phase feedwater flow and thereby performing the preheating function. The configuration of the secondary circuit also required the introduction and sizing of two valves to regulate the flow rate directed to the preheater and the flow rate supplied to the turbine.

To ensure proper sizing of the economizer, evaporator, and preheater, the energy balance between the primary and secondary sides was explicitly considered. The exchanged thermal power was evaluated from the mass flow rate and the specific enthalpy variation according to

$$\dot{Q} = \dot{m} \Delta h, \quad (3.1)$$

where $\dot{Q}$ is the exchanged thermal power, $\dot{m}$ is the mass flow rate, and Δh is the specific enthalpy variation of the fluid. Accordingly, for each heat exchanger, the energy exchanged between the primary and secondary sides was required to be consistent. Neglecting heat losses to the surroundings, this condition can be expressed as

$$\dot{m}_{\text{primary}} (h_{\text{in}} - h_{\text{out}}) = \dot{m}_{\text{secondary}} (h_{\text{out}} - h_{\text{in}}). \quad (3.2)$$

This approach ensured that the primary and secondary sides exchanged the same amount of thermal power and was used to determine the appropriate combination of mass flow rates, thermodynamic conditions, and heat exchanger characteristics. The consistency of these energy balances was particularly important for the initialization of the complete Modelica system. An inconsistent thermal power exchange between the two sides would introduce an energy imbalance into the initial conditions, increasing the difficulty of obtaining a physically consistent steady-state solution and potentially affecting the convergence of the initialization procedure.

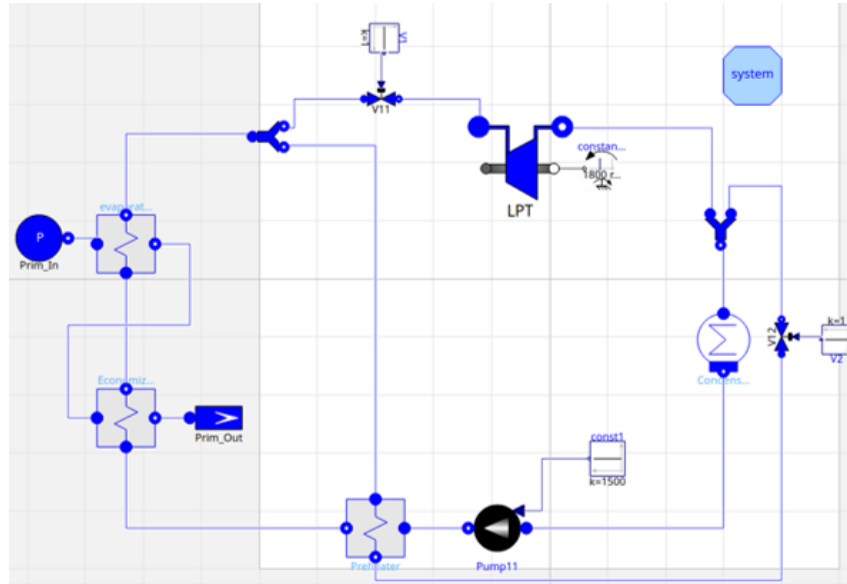


Figure 3.4: Water-to-water Rankine cycle.

After these stages of development and verification of the secondary circuit, the primary circuit was modeled using a pressurizer, a pump, and a pipe from the ThermoPower library to represent the primary coolant loop and single-phase heat transfer in the reactor core.

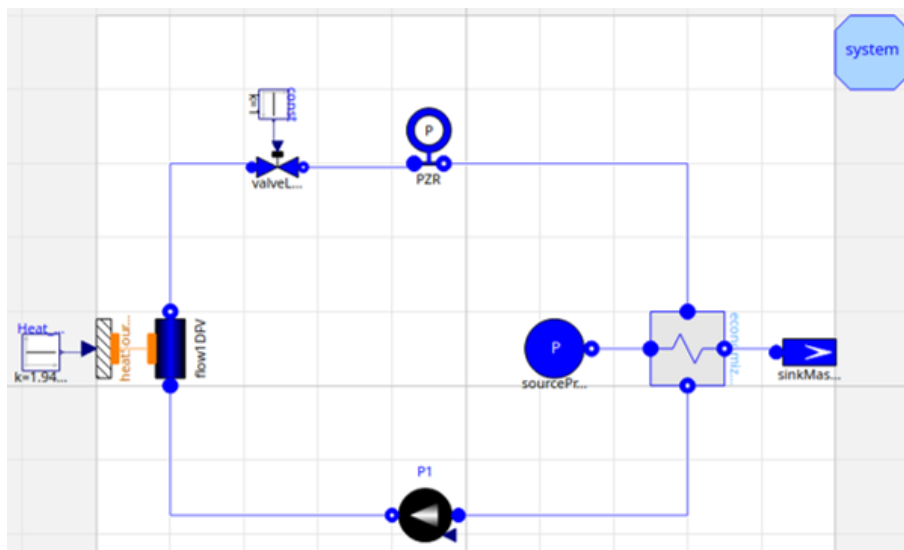


Figure 3.5: Primary circuit.

The resulting thermal-hydraulic model, obtained by integrating the primary and secondary circuits, therefore describes a simplified yet complete PWR cycle. The turbine, pressurizer,

pumps, and condenser were modeled using components from the ThermoPower library. Modelica Standard Library components were used for system inputs, such as pump rotational speed, the ideal heat source, and valve openings. One-dimensional flow models are used to represent fluid dynamics and heat transfer in pipes and heat exchangers. At the same time, the remaining components are described using lumped-parameter formulations. The turbine behavior is instead represented through the Stodola law. The model, therefore, includes both the standard components available in the MSL and ThermoPower libraries and the two original water-to-water heat exchanger components developed for the basic model.

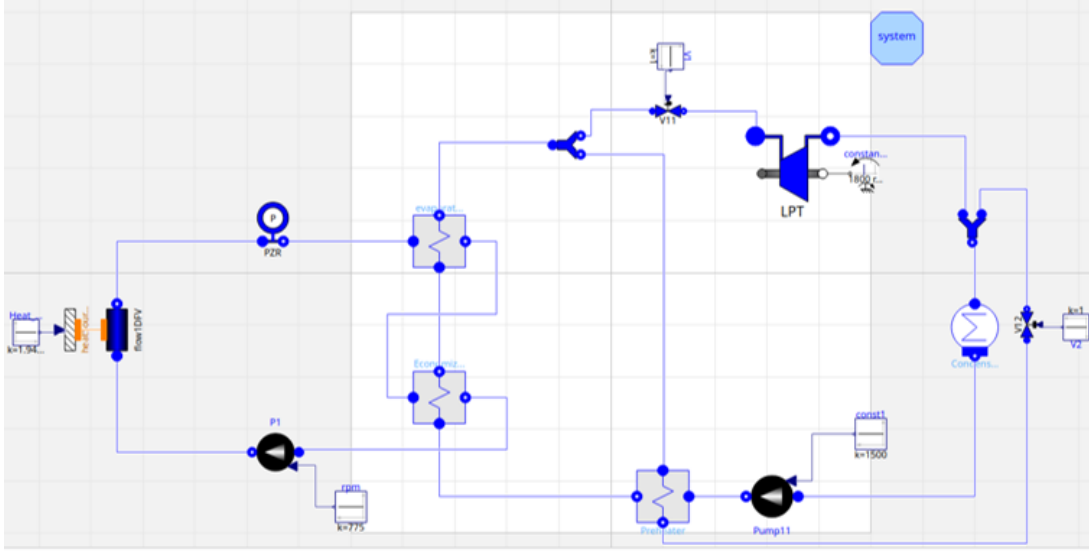


Figure 3.6: Complete PWR model with an ideal heat source.

3.2 Development of the Neutronic Model and Integration

Once a functioning thermal-hydraulic configuration had been obtained, the activity focused on introducing the reactor's neutronic dynamics. Since the libraries used did not provide a model suitable for the project's requirements, a dedicated component was developed directly in the Modelica environment, based on point-kinetic equations with a single group of delayed-neutron precursors.

The implemented equations are reported below:

$$\begin{aligned}\frac{dn(t)}{dt} &= \frac{\rho - \beta}{l} n(t) + \lambda C(t), \\ \frac{dC(t)}{dt} &= \frac{\beta}{l} n(t) - \lambda C(t).\end{aligned}\tag{3.3}$$

The model describes the time evolution of the normalized neutron population and the concentration of delayed-neutron precursors. A simplified thermal feedback model was added to this description through the moderator reactivity feedback coefficient, thereby coupling the neutronic dynamics with the temperature calculated by the thermal-hydraulic model. The thermal power generated by the reactor core was then expressed through a linear relationship with the neutron population:

$$P(t) = P_0 n(t)\tag{3.4}$$

where P_0 represents the nominal thermal power of the reactor.

```

1 model Point_Model "One Point-Kinetic Model"
2
3 // Model Function if we start from rho_tot = 0. So for example, if we use an fixed temperature Tm, we need to say in rho_1 input = -alfa_Tm*(Tm0 - Tm_rif);
4
5 parameter Real beta = 0.0065 "Delayed neutron fraction";
6 parameter Real lambda = 0.405 "Decay constant [1/s]";
7 parameter Real l = 2e-5 "Prompt neutron generation time [s]";
8 parameter Real alfa_Tm = -4e-4 "Moderator conerreactivity coefficient";
9 parameter Real Tm_rif = 579.32 "Moderator nominal temperature";
10 parameter Real P0 = 1.949e9 "[wth] Nominal thermal power";
11
12 Real n(start = 1, fixed = true) "Normalized neutron density";
13 Real C "Precursor concentration";
14 Real rho_Tm "Moderator Reactivity";
15 Real rho "Total Reactivity";
16
17 Modelica.Blocks.Interfaces.RealInput rho_1 "Reactivity perturbation"
18 annotation (Placement(transformation(extent = {{-70, 40}, {-50, 20}}), iconTransformation(origin = {0, -50}, extent = {{-70, 40}, {-50, 20}})));
19
20 Modelica.Blocks.Interfaces.RealInput Tm "Moderator Temperature"
21 annotation (Placement(transformation(extent = {{-70, -40}, {-50, -20}}), iconTransformation(origin = {0, 60}, extent = {{70, -40}, {50, -20}})));
22
23 Modelica.Blocks.Interfaces.RealOutput P "Thermal power [wth]"
24 annotation (Placement(transformation(extent = {{50, -10}, {70, 10}}), iconTransformation(origin = {0, -30}, extent = {{50, -10}, {70, 10}})));
25
26 // -----
27 initial equation
28 der(n) = 0;
29 der(C) = 0;
30
31 equation
32 rho_Tm = alfa_Tm * (Tm - Tm_rif);
33 rho = rho_1 + rho_Tm;
34
35 der(n) = ((rho - beta)/l)*n + lambda*C;
36 der(C) = (beta/l)*n - lambda*C;
37
38 P = P0*n;
39
40 annotation(
41   iconTransformation(
42     origin = {0, 0},
43     extent = {{-10, -10}, {10, 10}}
44   )
45 end Point_Model;

```

Figure 3.7: Point kinetics model for the neutronic system implemented in Text View.

The point kinetics model requires a set of numerical parameters that are assumed constant throughout the simulations. The selected values are reported in Table 3.1. These parameters are also used in the more advanced *Two Zones* (Section 4.2) and *Control Rods* (Section 4.3) models. Therefore, in order to avoid unnecessary repetition, the same values are not reported again in the corresponding sections.

Table 3.1: Numerical parameters adopted for the point kinetics model.

Parameter	Symbol	Value	Unit	Description
Delayed neutron fraction	β	0.0067	–	Fraction of delayed neutrons
Decay constant, averaged over six groups	λ	0.405	s^{-1}	Effective decay constant averaged over the six delayed-neutron precursor groups
Moderator reactivity coefficient	α_{T_m}	-4×10^{-4}	K^{-1}	Moderator temperature reactivity coefficient
Prompt generation time	l	2×10^{-5}	s	Prompt neutron generation time
Reference moderator temperature	$T_{m,ref}$	579.32	K	Reference temperature used for the moderator temperature feedback
Nominal thermal power	P_0	1.949×10^9	W	Reference thermal power of the reactor

The delayed-neutron parameters are obtained from literature data for Uranium-235 and thermal neutrons. In particular, the delayed neutron fraction β and the decay constants associated with the six precursor groups are taken from the reference data reported by Stacey [12]. The value of λ reported in Table 3.1 corresponds to an effective decay constant obtained by averaging the six group-specific decay constants.

The adopted prompt generation time is also consistent with the typical values reported in the literature for thermal reactor systems [13, Chapter 7].

The moderator temperature coefficient α_{T_m} is assumed to be negative, consistent with the negative moderator temperature feedback characteristic of pressurized water reactors. Its numerical value is selected within the range reported for PWR applications [14]. The actual moderator

temperature coefficient depends on several reactor parameters, including fuel burnup and the soluble boron concentration. The selected value is therefore a representative constant coefficient for the dynamic simulations, rather than a value calculated for a specific reactor core state.

In the final configuration, the neutronic model is connected to the thermal-hydraulic system through two inputs and one output. The external reactivity input is used to introduce reactivity perturbations, including those associated with control rod movements. In contrast, the moderator temperature input provides the feedback variable required by the neutronic model. The resulting reactor thermal power is provided as an output and used as the heat source for the primary thermal-hydraulic system.

Figure 3.8: Icon developed for the point kinetics model with its two inputs and single output.

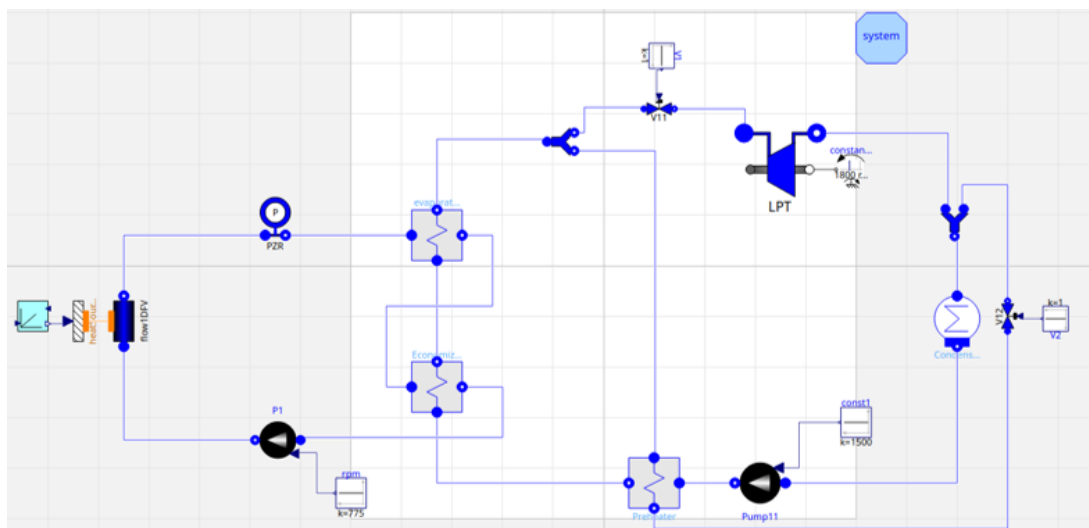


Figure 3.9: Complete plant model.

The neutronic model was subsequently integrated with the thermal-hydraulic system. In particular, the ideal heat source previously used to represent the core power was replaced by the point kinetics model. The thermal power supplied to the primary circuit is therefore no

longer externally imposed; instead, it is dynamically determined by the evolution of the neutron population and the feedback mechanisms introduced in the model. The integration of the two subsystems resulted in the first coupled neutronic–thermal-hydraulic dynamic model of the PWR plant.

During the verification phase of the integrated model, simulations were conducted to assess the system’s numerical stability and the consistency of its dynamic response. In particular, it was observed that after initialization, the average moderator temperature calculated by the thermal-hydraulic model did not exactly match the reference temperature used in the neutronic model. This difference introduced an initial variation in reactivity and, consequently, a transient before the system reached equilibrium conditions.

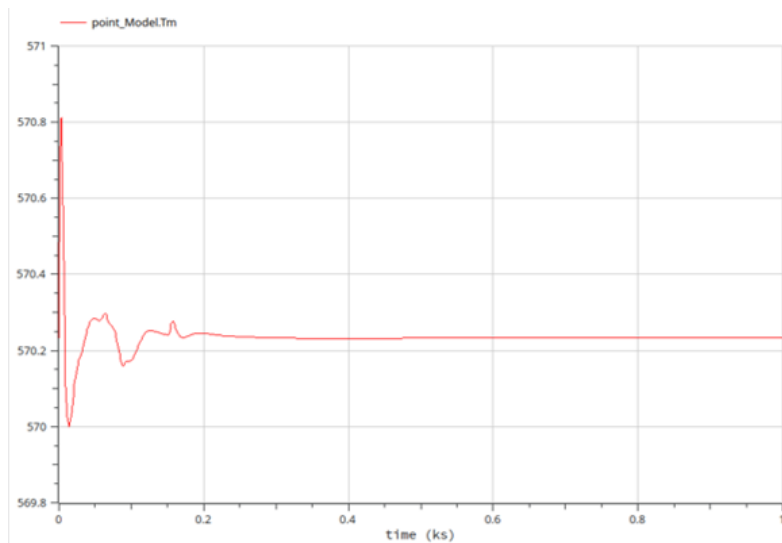


Figure 3.10: Moderator temperature transient.

For this reason, the initial phase of the simulation was analyzed until a stable steady-state condition was reached. Subsequently, perturbation simulations were performed, including the introduction of a negative reactivity step to represent the effect of control rod insertion. The perturbation was applied after the initial transient had decayed, resulting in a reduction in thermal power followed by the establishment of a new equilibrium condition at a lower power level.

The verification activity also led to a more detailed investigation of the initialization procedures available in OpenModelica. In particular, the possibility of using the results of a previous simulation as initial conditions for subsequent simulations was analyzed using result files in `.mat` format. This procedure enables initialization of the system close to an established steady-state condition, avoiding the need to repeat the entire initial transient in each simulation. The initialization procedure developed from this activity was subsequently revisited and further developed during the present thesis. The corresponding method and its application to the model are therefore described in a dedicated chapter.

3.3 Basic Model and Its Limitations

The basic model underpins subsequent development activities, but it has limitations due to the numerous simplifying assumptions it employs.

From a neutronic point of view, the reactor core is represented as a single homogeneous volume using a point-kinetic model. This approach does not allow the local effects associated

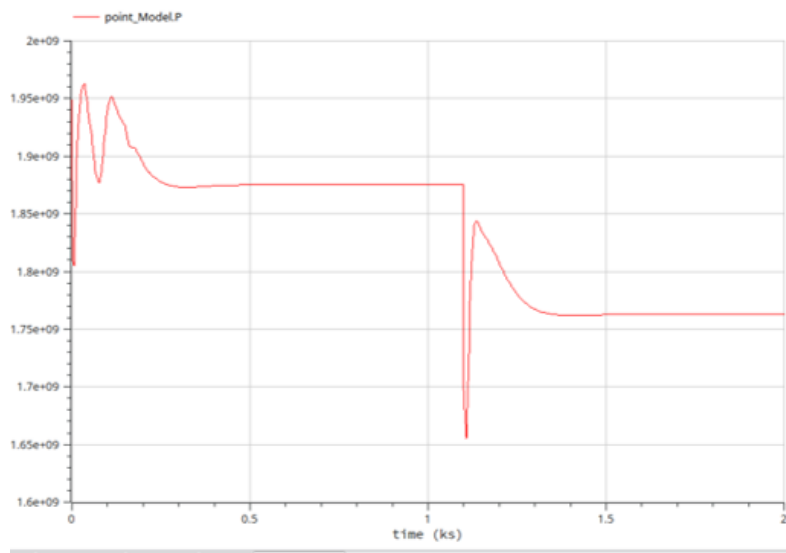


Figure 3.11: Thermal power following a negative reactivity step.

with the differential insertion of control rods or local variations in moderator temperature to be represented. It therefore prevents the spatial distribution of the neutron flux from being described.

The thermal-hydraulic system also presents some simplifications and numerical issues. From a layout perspective, the secondary circuit features a single turbine. From a computational point of view, the system exhibits a high degree of numerical stiffness. Although the simulation converges, the nonlinear solver reports that the maximum number of iterations has been reached, particularly when solving the system using the Newton method and homotopy. The robustness of such a model is therefore quite limited. This behavior is mainly attributed to the complex thermal-hydraulic interconnections among critical components, such as the economizer, evaporator, and preheater. The series coupling of heat exchangers involving two-phase flow introduces strong nonlinearities and discontinuities in the derivatives of thermodynamic properties, particularly near phase transitions and when evaluating density and enthalpy within the discretized volumes. The simultaneous solution of mass and energy balances across multiple interdependent two-phase components, therefore, results in a highly stiff differential-algebraic system, increasing the computational burden and pushing numerical solvers towards their convergence limits.

Nevertheless, these limitations do not detract from the relevance and importance of this basic model. In addition to providing a first complete configuration of the plant, the work led to the development and organization of a set of dedicated components for the modeling of nuclear systems, designed to be selected and reused in subsequent configurations. In particular, three original components were developed during the activity: the economizer, the evaporator, and the dedicated neutronic model. Moreover, the availability not only of individual components but also of complete plant configurations, such as the configuration based on the ideal heat source, makes it possible to use already functioning models as test platforms for introducing and verifying new components. In this sense, the work described in this chapter contributed to the development of a modular modeling framework in which components with different levels of detail can be progressively developed, verified, and integrated into increasingly complex configurations. The limitations identified above, therefore, represent not only aspects to be addressed, but also the starting point for the developments introduced in the present thesis, aimed at increasing the level of detail of both the neutronic modeling and the thermal-hydraulic system.

Chapter 4

Development of Modelica Models

This chapter describes the improvements and extensions to the thermo-hydraulic layout and the neutronic model relative to the basic model described in the previous chapter, focusing on three aspects: the upgrade of the secondary loop with a second turbine stage, a two-region neutron kinetics model, and a new control rod model.

4.1 Improvements to the Thermo-Hydraulic System

During the thesis activity, a significant portion of the work was devoted to optimizing and ensuring the completeness of features in the secondary loop thermo-hydraulic layout. The main objective was to move beyond the simplified single-turbine configuration and adopt a more realistic two-stage turbine layout comprising a High-Pressure Turbine (HPT) and a Low-Pressure Turbine (LPT). This configuration more accurately reproduces the design used in industrial Pressurized Water Reactor (PWR) power plants, accounting for fundamental design choices that shape the actual thermodynamic behavior of these systems.

It is worth emphasizing that the starting point for this activity is the plant configuration developed in Chapter 3, in which the secondary circuit featured a single turbine stage and a point-kinetics model supplied the reactor's thermal power. At this stage of the work, the neutronic model had not yet been modified: the two-region kinetics formulation described in Section 4.2 was introduced only later and integrated into the plant layout independently of the turbine upgrade discussed here.

The two turbine stages are represented using the `SteamTurbineStodola` component available in the *ThermoPower* library [16]: the turbine model itself, including the implementation of the Stodola law and the calculation of the isentropic enthalpy drop, is therefore not an original development of this thesis. The original contribution of the present work consists of the sizing and parametrization of the two stages (Stodola coefficient K_t , nominal flow and pressure conditions, isentropic efficiency) and in their integration within the two-stage layout, as detailed below. The upgrade of the secondary-side model, however, introduces additional complexity due to the thermo-hydraulic coupling between the two expansion stages and the heat-transfer components involved in the regenerative cycle.

The main numerical issues in this configuration concern the definition of suitable initial conditions for the system's steady-state initialization. The outlet of the High Pressure Turbine (HPT) is directly connected to the preheater. From a physical standpoint, the preheater receives steam extracted from the turbine to raise the feedwater temperature before it enters the economizer, thereby improving the overall thermodynamic efficiency of the cycle. As in the basic model, the economizer, evaporator, and preheater components are sized according to the energy-balance

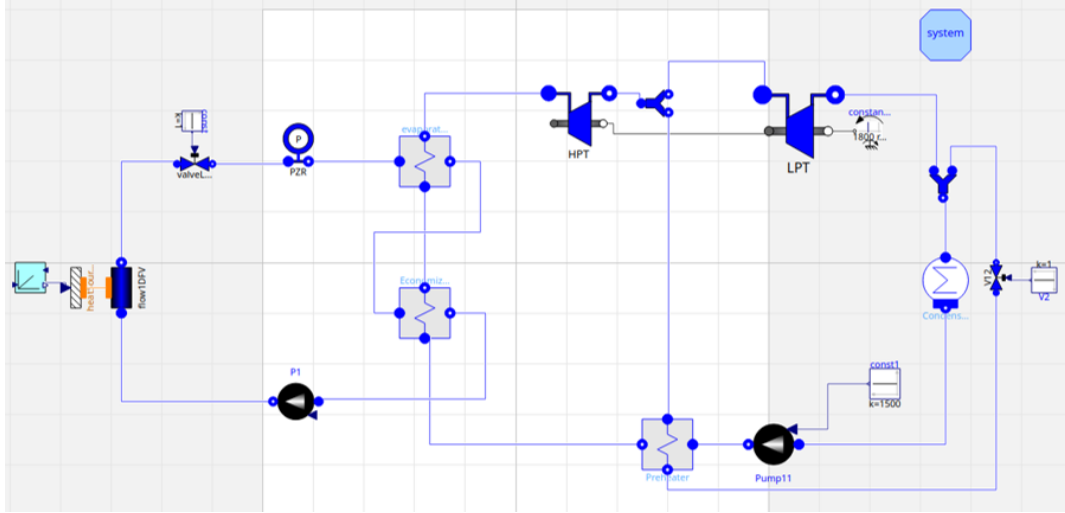


Figure 4.1: PWR layout with two turbine stages.

approach already described in Chapter 3, Section 3.1, which ensures consistency between the thermal power exchanged on the primary and secondary sides of each heat exchanger. During the initialization phase performed by the OpenModelica solver, deviations of pressure, enthalpy, or mass flow rate at the connection points between the HPT and the preheater from their physically consistent values may lead to severe numerical instabilities. To overcome this issue, a preliminary analytical sizing procedure was carried out for the turbine parameters to provide consistent initial conditions and constrain the solver's convergence.

Each turbine stage was modeled and sized according to the Stodola ellipse law for compressible flows:

$$w = K_t \theta \sqrt{p_{in} \rho} \sqrt{1 - \left(\frac{p_{out}}{p_{in}} \right)^2} \quad (4.1)$$

where:

- w is the steam mass flow rate [kg/s];
- K_t is the characteristic Stodola turbine coefficient [m²];
- $\theta \in [0, 1]$ is the valve opening degree;
- p_{in} is the inlet steam pressure [Pa];
- ρ is the steam density at turbine inlet [kg/m³];
- p_{out} is the outlet steam pressure [Pa].

As noted above, the turbine component itself is part of the *ThermoPower* library; the activity described in the remainder of this section concerns the definition of the parameters entering Eq. (4.1) and (4.2) (K_t , η_{iso} , and the nominal operating conditions), which were derived to obtain a physically consistent and numerically robust configuration.

The nominal values w_{nom} , $p_{in,nom}$, $p_{out,nom}$, and ρ_{nom} were derived from the steady-state thermal balance of the reference PWR plant. Once the Stodola coefficient K_t is treated as a constant model parameter, the turbine can automatically calculate the mass flow rate during off-design transients based on the instantaneous upstream and downstream pressure conditions.

The mechanical power produced by each turbine stage is calculated by coupling the mass flow rate w with the actual enthalpy drop experienced by the fluid. The *ThermoPower* turbine model assumes a constant isentropic efficiency (η_{iso}). Therefore, the real outlet enthalpy (h_{out}), which is subsequently supplied to the downstream component, is calculated as:

$$h_{out} = h_{in} - \eta_{iso} (h_{in} - h_{out,is}) \quad (4.2)$$

where $h_{out,is}$ represents the ideal isentropic outlet enthalpy.

To improve the robustness of the initialization procedure, the turbine model makes extensive use of the homotopy operator. The homotopy technique modifies the original numerical problem by introducing an artificial parameter $\gamma \in [0, 1]$, thereby allowing a continuous transition from a simplified problem to the actual nonlinear system.

At the initial step ($\gamma = 0$), OpenModelica solves a simplified model in which the turbine mass flow rate varies linearly with the inlet pressure:

$$w = \theta \frac{w_{nom}}{p_{nom}} p_{in} \quad (4.3)$$

After convergence of this simplified problem is achieved, the solver progressively increases γ up to 1, continuously updating the numerical solution towards the real nonlinear formulation based on the Stodola law.

The condenser continues to play an important role in defining the pressure boundary condition of the secondary circuit, as in the basic configuration, also in the resulting two-turbine layout. Thanks to the correct turbine sizing, the secondary-side valves are no longer required and have therefore been removed from the model.

To assess the stability and response of the coupled system, including both neutronic and thermo-hydraulic behavior, a reactivity-insertion transient was simulated. Starting from a steady-state operating condition, at $t = 1100$ s, a negative external reactivity ramp was introduced and held for 2 s to simulate the virtual movement of the control rods. The dynamic response of the system and the evolution towards a new equilibrium condition were then analyzed.

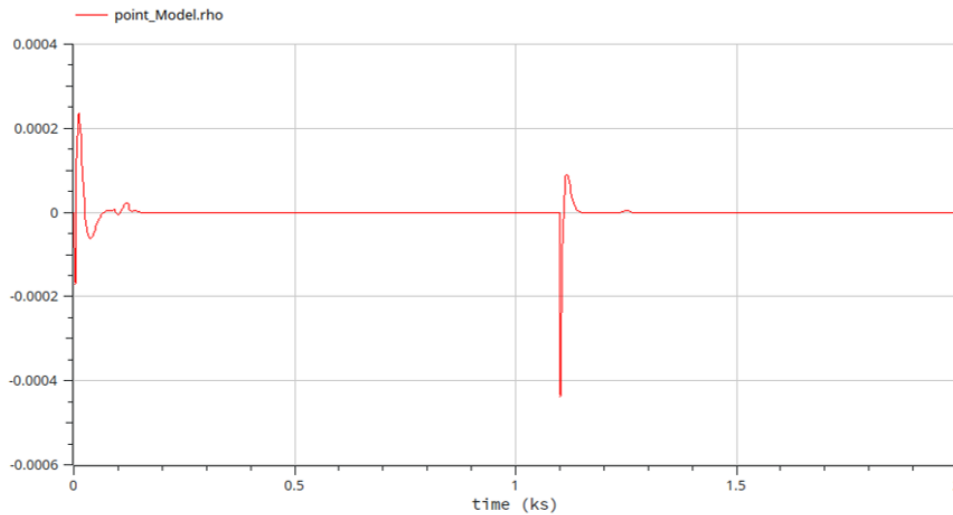


Figure 4.2: Total reactivity variation during the simulated transient.

Consistent with the point-kinetics equations, the insertion of the negative-reactivity step causes a sharp, rapid decrease in the neutron population. Consequently, the thermal power

generated by the reactor core undergoes a significant reduction. The system therefore departs from its initial equilibrium and enters a transient strongly governed by the thermal feedback coefficients.

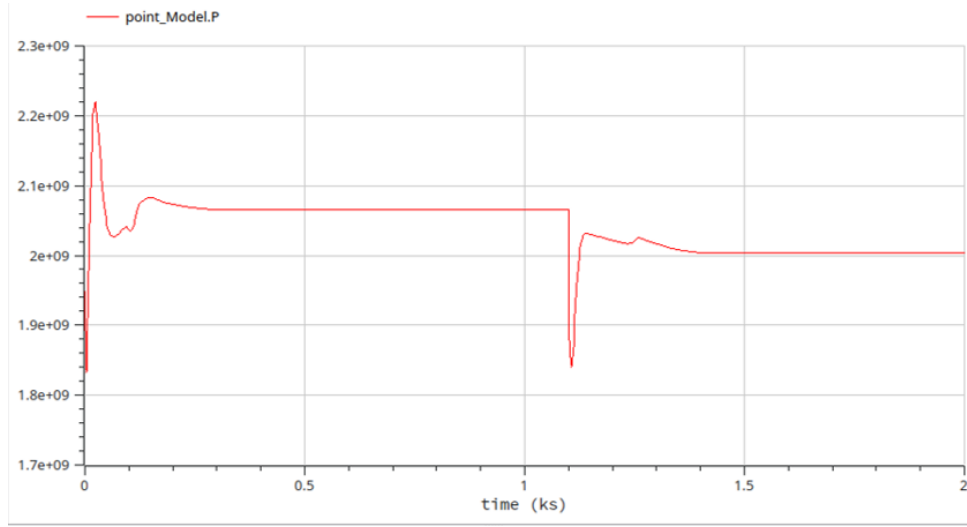


Figure 4.3: Thermal power variation at the reactor core outlet.

In the point-kinetics model considered here, the main feedback mechanism is associated with the moderator temperature. The decrease in power generated in the core reduces heat transfer to the primary coolant. Consequently, the average moderator temperature T_m decreases.

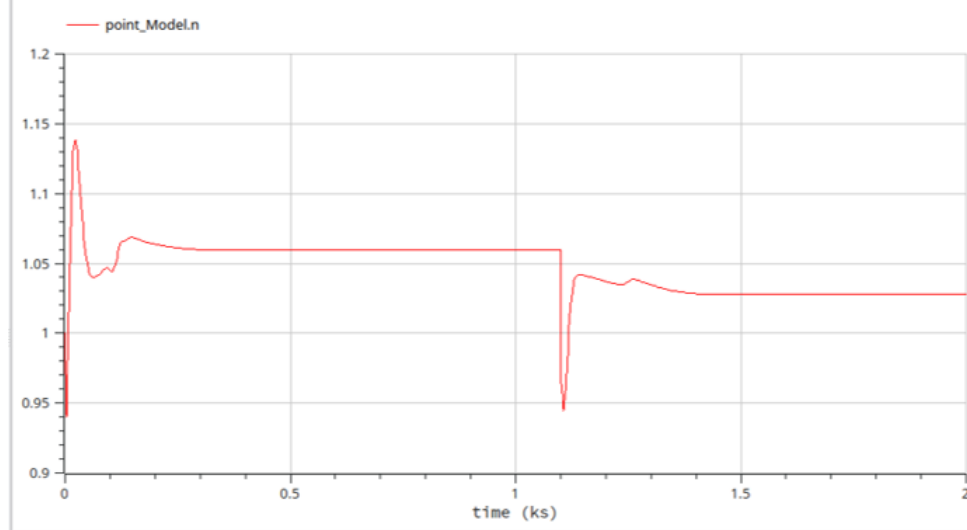


Figure 4.4: Neutron density variation during the reactivity insertion transient.

As is typical of Pressurized Water Reactors (PWRs) designed with inherent negative reactivity feedbacks, the reactor exhibits a strictly negative Moderator Temperature Coefficient (MTC), $\alpha_{T_m} < 0$. The cooling of the moderator therefore introduces positive reactivity ($\rho_{fb} > 0$). The dynamic evolution continues until this positive feedback reactivity exactly compensates for the initially inserted negative reactivity. The criticality condition for the new asymptotic regime, therefore, requires the total reactivity to be zero:

$$\rho_{\text{tot}} = \rho_{\text{ext}} + \rho_{\text{fb}} = 0 \implies \rho_{\text{fb}} = -\rho_{\text{ext}} \quad (4.4)$$

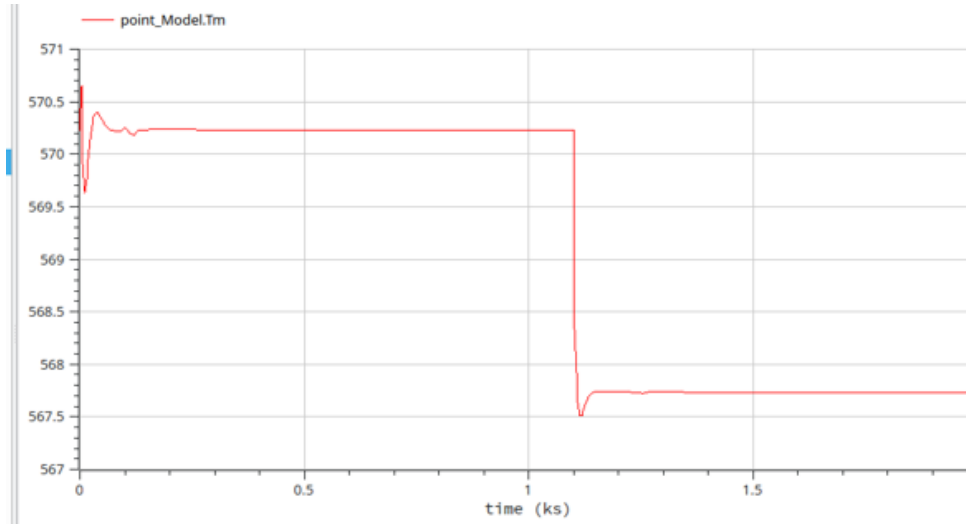


Figure 4.5: Moderator temperature variation during the transient.

For the system to maintain a positive ρ_{fb} capable of compensating for the negative control-rod insertion, the moderator temperature must physically stabilize at a value strictly lower than the original reference temperature, as shown in Figure 4.5, where T_m settles at a lower level.

The core of the analysis lies in the overall thermal balance. To sustain a permanently lower average moderator temperature at steady state while maintaining the same heat-removal logic on the secondary side, the thermal power supplied by the reactor core must be reduced. If the power were to return to 100% of its initial value, the coolant would heat up again, bringing the moderator temperature back towards its nominal value. This would remove the positive feedback and drive the reactor back into a subcritical condition. Therefore, in reactors characterized by negative temperature feedback, the insertion of negative reactivity does not simply cause the reactor to remain shut down in the long term; rather, it forces the system to operate at a reduced power level, which is the only condition capable of sustaining a sufficiently low coolant temperature to balance the control-rod insertion.

Once the correct coupled neutronic and thermo-hydraulic behavior had been verified, the analysis was extended to the thermo-hydraulic response of both the primary and secondary circuits. In the current configuration, the primary-circuit pump is allowed to adjust its rotational speed to track the target mass flow rate. The decrease in thermal power generated by the reactor core, along with the resulting temperature reduction, results in a lower enthalpy of the primary fluid supplied to the steam generator.

On the secondary side, the reduced thermal input from the primary circuit results in the production of steam with a lower enthalpy content. Under saturated conditions, the decrease in enthalpy is accompanied by a simultaneous reduction in pressure of approximately 1 bar for the point and the control rods model while 0.24 bar for the two zones model, reflecting the new thermodynamic equilibrium state of the steam generator.

A particularly interesting and initially counterintuitive thermo-hydraulic behavior can be observed by examining the secondary-side mass flow rate. Despite decreases in both steam enthalpy and pressure, the mass flow rate processed by the system increases to approximately 1090 kg/s in the new equilibrium condition, up from approximately 1065 kg/s. The explanation for this behavior lies in the circuit topology rather than in the turbine model itself. It must be stressed that the only quantity actually imposed from the outside on the turbo-generator group is the rotational speed of the HPT-LPT shaft, fixed at 1800 rpm (60 Hz) through the

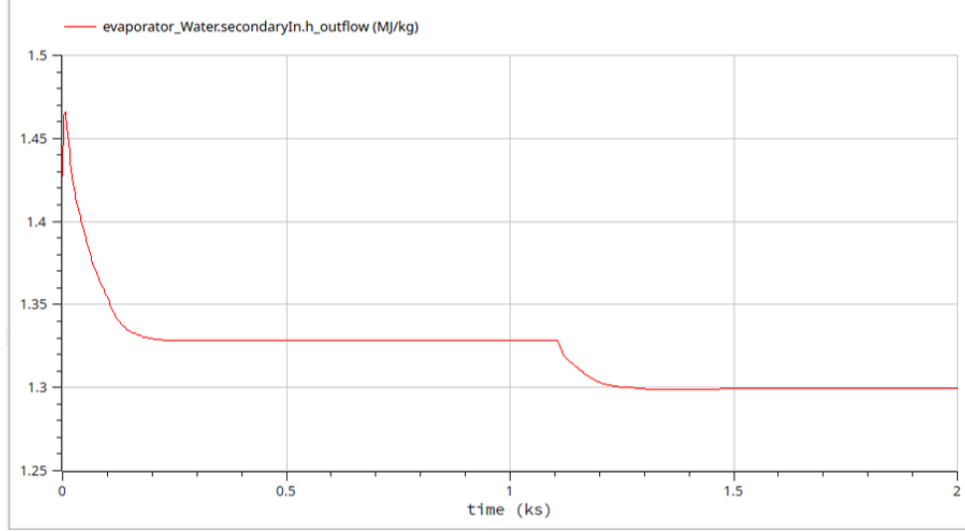


Figure 4.6: Variation of the secondary-side outlet enthalpy from the steam generator.

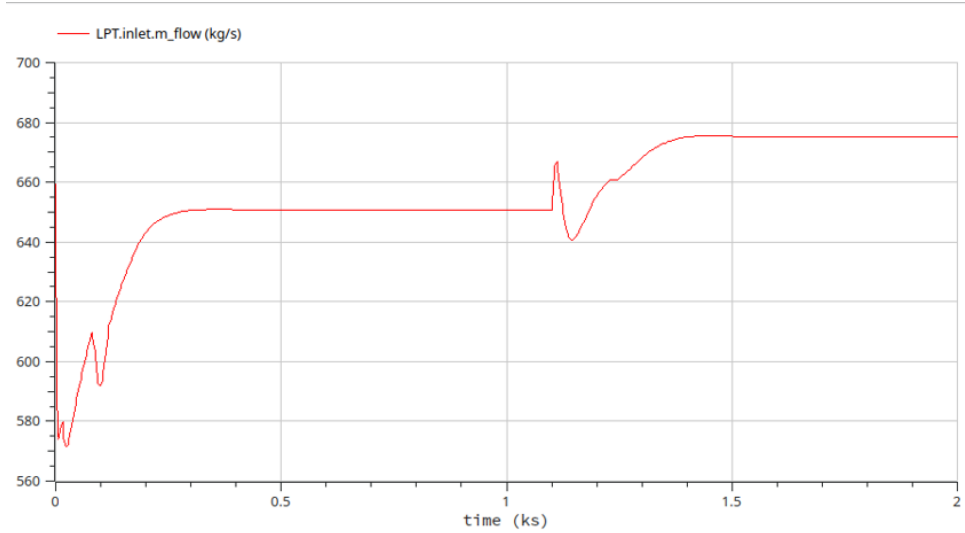


Figure 4.7: LPT mass flow rate during the transient.

ConstantSpeed component, the Modelica equivalent of a synchronous generator coupled to an infinite electrical grid, where it is the grid frequency that is imposed, not the delivered power. This component enforces the purely kinematic constraint $\omega = \text{const}$, used only to convert the mechanical power produced by the turbines into shaft torque ($\tau = P/\omega$); it does not enter the mass flow rate calculation of either stage, which is governed exclusively by the Stodola ellipse law (Eq. 4.1) as a function of the local inlet pressure, inlet density, and pressure ratio. The power delivered by the turbines is therefore not an externally imposed boundary condition; it is a consequence of the thermodynamic state reached by the coupled neutronic and thermo-hydraulic system, and it decreases together with the reactivity insertion (see Table 4.5), rather than remaining constant.

The observed increase in the secondary-side mass flow rate must instead be explained by the response of the feedwater pump (Pump11), which is likewise operated at a fixed rotational speed (PrescribedSpeedPump, $n_{\text{pump}} = 1500$ rpm). At fixed speed, a centrifugal pump operates along its characteristic head–flow curve, along which the delivered head decreases as the processed flow rate increases. Since the reduction in reactor thermal power lowers the

saturation pressure of the steam generated in the evaporator by approximately 1 bar, the head that the feedwater pump must supply to reach the steam generator, now operating at a lower pressure, decreases correspondingly. The pump operating point therefore shifts along its fixed-speed characteristic curve towards a higher flow rate, matching the reduced hydraulic resistance of the loop. This higher feedwater flow rate propagates through the closed secondary loop (preheater, economizer, evaporator) to the turbine inlet, where it is expanded according to the Stodola law under the new, lower-pressure and lower-density conditions. The increase in mass flow rate shown in Figure 4.7 is therefore not a direct consequence of the turbine speed constraint, but the result of the fixed-speed feedwater pump re-establishing equilibrium with a secondary loop operating at a reduced pressure level.

A significant improvement over the basic model is achieved with the present configuration. While the basic model reached a stable steady-state solution but still generated numerical warnings, the present model converges to the steady-state solution without such problems. In particular, the solver no longer reaches the maximum number of nonlinear iterations, indicating a more robust convergence of the complete thermo-hydraulic system. This improvement is mainly due to the introduction of the turbine between the two phase-change components and the appropriate sizing of its parameters, which provide better control of the mass flow rate and ensure a stable coupling between the different components of the secondary circuit. The complete Modelica source code of the layout is reported in Appendix B.1.

4.2 Two-Region Neutron Kinetic Model

The component responsible for estimating the thermal power generated within the reactor core is based on the direct proportionality between reactor thermal power and neutron population. The model was developed in textual mode (`TextView`) by extending the point-kinetics component previously implemented in the basic model.

The physical parameters β , λ , l , and α_{Tm} adopted in this model are the same as those already reported in Table 3.1 for the point-kinetics model in the basic model.

In the original model, the point-kinetics equations with one equivalent delayed neutron precursor group were expressed in their classical form:

$$\begin{cases} \frac{dn(t)}{dt} = \frac{\rho - \beta}{l} n(t) + \lambda C(t) \\ \frac{dC(t)}{dt} = \frac{\beta}{l} n(t) - \lambda C(t) \end{cases} \quad (4.5)$$

where:

- $n(t)$ is the normalized neutron population;
- $C(t)$ is the delayed neutron precursor concentration;
- ρ is the reactor reactivity;
- β is the total delayed neutron fraction;
- λ is the delayed neutron precursor decay constant, averaged over the six physical delayed neutron groups [s^{-1}];
- l is the prompt neutron lifetime [s].

The thermal power generated in the reactor core is assumed to be directly proportional to the neutron population according to:

$$P = P_0 n \quad (4.6)$$

where P_0 denotes the nominal reactor thermal power [W].

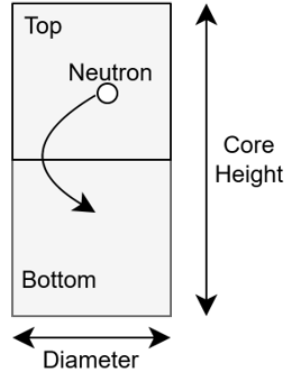


Figure 4.8: Conceptual scheme of the axial subdivision of the reactor core into two regions.

To overcome the intrinsic limitations of point kinetics and provide a first representation of spatial effects along the reactor axis, the reactor core was divided axially into two regions: an upper region (TOP) and a lower region (BOTTOM). Each region is described by its own set of neutron-kinetics equations and is coupled to the adjacent region through a diffusive neutron exchange term. This approach makes it possible to account separately for local variables, such as the moderator temperature in each region or the partial insertion of the control rods, which initially affects only the upper part of the core, while simultaneously representing the mutual neutron interaction between the two regions.

The equations implemented for the upper region (TOP) are:

$$\begin{cases} \frac{dn_1(t)}{dt} = \frac{\rho_1 - \beta}{l} n_1(t) + \lambda C_1(t) + \frac{D}{l(1 - \beta) + \beta/\lambda} (n_2 - n_1) \\ \frac{dC_1(t)}{dt} = \frac{\beta}{l} n_1(t) - \lambda C_1(t) \end{cases} \quad (4.7)$$

whereas the equations governing the lower region (BOTTOM) become:

$$\begin{cases} \frac{dn_2(t)}{dt} = \frac{\rho_2 - \beta}{l} n_2(t) + \lambda C_2(t) + \frac{D}{l(1 - \beta) + \beta/\lambda} (n_1 - n_2) \\ \frac{dC_2(t)}{dt} = \frac{\beta}{l} n_2(t) - \lambda C_2(t) \end{cases} \quad (4.8)$$

The coupling between the two regions is controlled by the dimensionless coefficient D , which is scaled by the effective reactor time constant:

$$\tau_{\text{eff}} = l(1 - \beta) + \frac{\beta}{\lambda} \quad (4.9)$$

Introducing the delayed neutron decay constant into the definition of the effective time scale accounts for the characteristic time associated with delayed neutron dynamics and avoids unrealistically fast exchange dynamics, resulting in a smoother interaction between the two regions. From a physical point of view, two limiting cases can be identified:

- $D \rightarrow 0$: the two regions become completely decoupled from the neutron-kinetic point of view, since the direct neutron exchange term vanishes;
- $D \rightarrow \infty$: the coupling becomes increasingly strong, forcing the neutron populations to converge towards the same value and approaching a spatially homogeneous point-kinetics behavior.

These two limiting cases provide useful reference conditions for assessing the physical behavior of the proposed two-region formulation. In particular, the intermediate values of D determine the extent to which a localized perturbation can be redistributed along the axial direction of the core.

The reactivity of each region is affected by external perturbations and by moderator temperature feedback:

$$\rho_{Tm,1} = \alpha_{Tm} (T_{m,1} - T_m^{\text{ref}}) \quad (4.10)$$

$$\rho_{Tm,2} = \alpha_{Tm} (T_{m,2} - T_m^{\text{ref}}) \quad (4.11)$$

where α_{Tm} denotes the moderator temperature reactivity coefficient, $T_{m,1}$ and $T_{m,2}$ are the local moderator temperatures of the TOP and BOTTOM regions, and T_m^{ref} is a single reference temperature, common to both regions and equal to the value already reported in Table 3.1. Only the local temperatures $T_{m,1}$ and $T_{m,2}$, and consequently the resulting feedback reactivities $\rho_{Tm,1}$ and $\rho_{Tm,2}$, differ between the two regions; the reference temperature itself does not. External reactivity perturbations, on the other hand, are in general applied independently to the two regions and are not required to be equal. This makes it possible, in particular, to reproduce the effect of control rods inserted from the top of the core, as in commercial PWRs, by applying the perturbation exclusively to the TOP region while leaving the BOTTOM region unperturbed, as will be done in the transient analysis presented later in this section.

The total neutron population is obtained by summing the contributions of the two regions:

$$n = n_1 + n_2 \quad (4.12)$$

and the total thermal power is consequently calculated as:

$$P = P_0 n \quad (4.13)$$

The initialization phase requires particular attention to ensure the solver's numerical stability at the start of the simulation. The model is initialized under steady-state (critical equilibrium) conditions by imposing:

$$\frac{dn_1}{dt} = 0, \quad \frac{dC_1}{dt} = 0, \quad \frac{dn_2}{dt} = 0, \quad \frac{dC_2}{dt} = 0 \quad (4.14)$$

Assuming that the total initial neutron population is normalized to unity, the solver starts from the initial condition:

$$n_1 = n_2 = 0.5 \quad (4.15)$$

To facilitate the graphical integration of the model within OpenModelica block diagrams, a dedicated graphical interface (Icon View) was also developed.

The blue arrows represent the model input connectors, while the white arrow represents the output connector. The complete Modelica source code of the `Two_Zones_Kinetic` component is reported in Appendix A.4. The upper input ports receive the reactivity perturbation and



Figure 4.9: Icon of the two-region neutron-kinetics model.

the moderator temperature of the upper region, whereas the lower input ports receive the corresponding quantities for the lower region. The output port provides the total reactor thermal power, which is transmitted to the thermo-hydraulic model.

The verification process for the two-region neutron-kinetics model was structured into two sequential phases: a preliminary standalone check using a simplified test model, followed by the integration of the component into the plant's complete thermo-hydraulic layout.

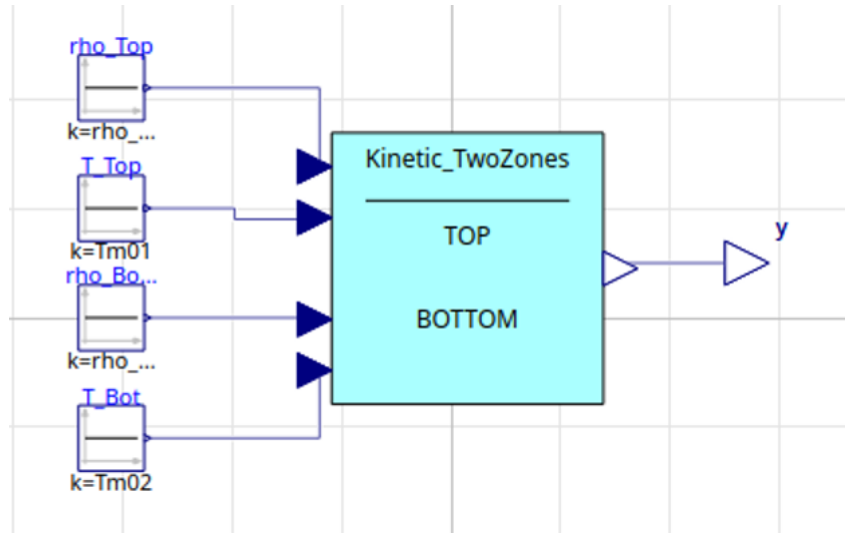


Figure 4.10: Standalone test layout for the two-region neutron-kinetics model.

The preliminary test was carried out by implementing a model dedicated exclusively to the neutron balance. In this configuration, the input signals required by the system, namely the external reactivity perturbations and moderator temperatures, were provided using constant signal generators from the Modelica Standard Library (MSL). The primary objective of this simulation was twofold: to check the numerical convergence of the model equations and to verify the sign and magnitude of the thermal feedback coefficients.

Specifically, the following constant boundary conditions were imposed:

- mean moderator temperature of the upper region (T_{m1}): 590 K;
- mean moderator temperature of the lower region (T_{m2}): 570 K;
- reference moderator temperature (T_m^{ref}): 579.32 K.

Since strict steady-state conditions were required at $t = 0$ s, the bias reactivity perturbations (ρ_{p1} and ρ_{p2}) were not arbitrarily prescribed: they were determined by the solver during the

initialization phase to compensate for the thermal feedback introduced by the deviation of the local temperatures from T_m^{ref} . Because the reactivity induced by the imposed temperatures was fully compensated, the system's dynamic response showed no net perturbation. Consequently, as expected, the normalized total neutron population remained constant at its initial value ($n = 1$).

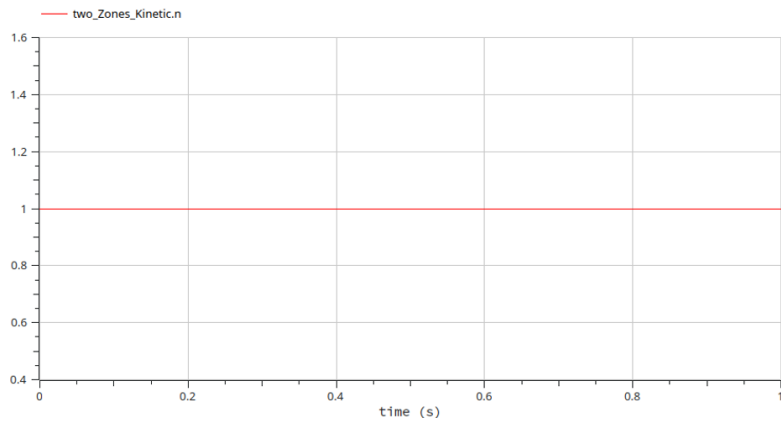


Figure 4.11: Normalized neutron density evolution during the standalone test.

The results of this isolated test confirm the physical consistency of the implemented model. In particular, in the upper region, the moderator temperature is higher than the reference temperature (590 K > 579.32 K). Since $\alpha_{Tm} < 0$, this temperature increase produces a negative reactivity contribution. Conversely, in the lower region, the lower moderator temperature produces a positive reactivity contribution. This behavior, consistent with the moderator temperature feedback expected in a PWR, is confirmed by the feedback curves generated by the simulation.

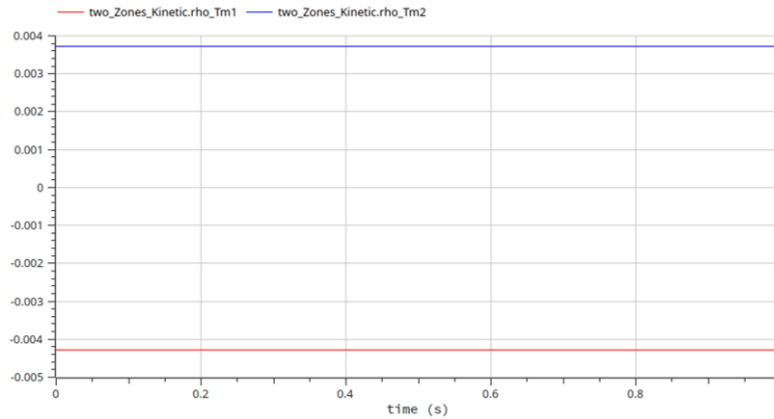


Figure 4.12: Moderator temperature feedback reactivity for the TOP and BOTTOM regions during the standalone test.

Having verified the numerical stability of the model and confirmed that the nominal output thermal power matched the target plant value of 1.94×10^9 W, the two-region neutron-kinetics model was integrated into the complete thermo-hydraulic layout, which features two turbine stages, replacing the previous point-kinetics component.

The integration of the two-region model required defining a spatially consistent interface between the neutron kinetics and the one-dimensional thermo-hydraulic channel representing the reactor core (Flow1DFV). Since the coolant channel is axially discretized into 10 finite-volume nodes, the moderator temperatures supplied to the two neutron regions were calculated using a spatial arithmetic mean:

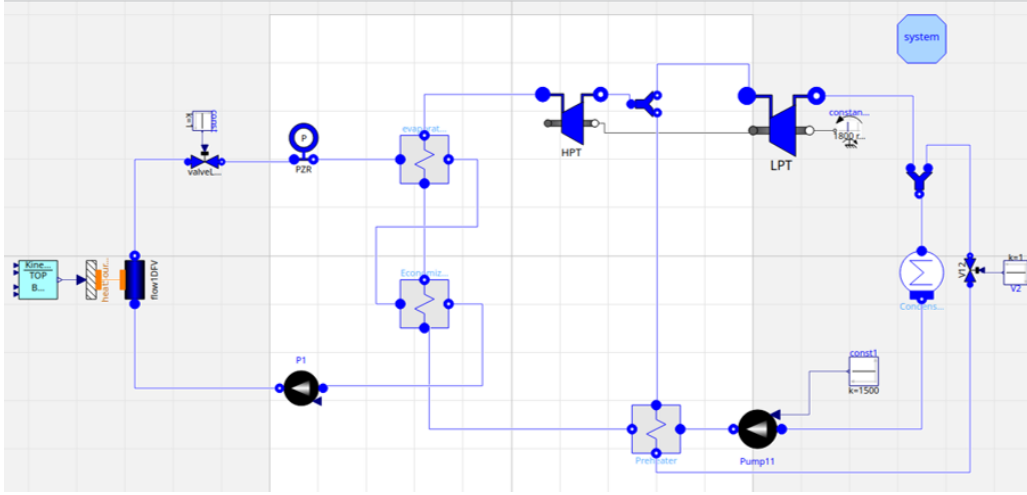


Figure 4.13: Complete PWR plant layout incorporating the two-region neutron-kinetics model.

- the moderator temperature for the upper region ($T_{m,Top}$) is computed as the average of the fluid temperatures of the five upper nodes, from node 6 to node 10;
- the moderator temperature for the lower region ($T_{m,Bottom}$) is computed as the average of the fluid temperatures of the five lower nodes, from node 1 to node 5.

To ensure a transient-free initialization of the coupled system, the time derivatives of the neutron densities and precursor concentrations were set to zero:

$$\frac{dn_1}{dt} = \frac{dC_1}{dt} = \frac{dn_2}{dt} = \frac{dC_2}{dt} = 0. \quad (4.16)$$

The algebraic solver autonomously determines the equilibrium initial values of the bias reactivity variables ρ_{p1} and ρ_{p2} required to maintain criticality. During the subsequent dynamic simulation, these variables are kept constant according to:

$$\frac{d\rho_{p1}}{dt} = 0, \quad \frac{d\rho_{p2}}{dt} = 0, \quad (4.17)$$

physically representing a critical reactor operating with fixed control rods.

At $t = 0$, the model sets $n_1 = n_2 = 0.5$. Because the two initial normalized populations are identical, the diffusive coupling term $D(n_2 - n_1)$ vanishes completely regardless of D . At this exact instant, the two regions behave as mathematically isolated point-kinetics systems, forcing the total local reactivities to be zero ($\rho_1(0) = \rho_2(0) = 0$), which yields an initial total neutron density of exactly $n(0) = 1$ and a thermal power perfectly equal to P_0 . However, this balance is built on the initial moderator temperatures $T_{m,Top}(0)$ and $T_{m,Bottom}(0)$, which are not fully relaxed at steady state. As the thermo-hydraulic system relaxes toward its self-consistent operating point during the first approximately 300 s, the actual moderator temperatures drift from their initial values. Because the bias reactivities ρ_{p1} and ρ_{p2} remain frozen at their $t = 0$ values, this temperature drift reintroduces non-zero net local reactivities.

Unlike single-point kinetics, where overall reactivity must remain strictly zero, the two-region model can reach a dynamic equilibrium with non-zero local reactivities. By setting $dn_1/dt = 0$ and $dC_1/dt = 0$ in Eq. (4.7), the local steady-state reactivity for the TOP region becomes:

$$\rho_1 = -l \frac{D}{\tau_{eff}} \frac{n_2 - n_1}{n_1} \quad (4.18)$$

This indicates that local reactivity stabilizes at the precise value needed to compensate for net neutron leakage exchanged with the adjacent region. Because the temperature drift affects the upper and lower core asymmetrically, the system settles into a new equilibrium where $n_1 \neq n_2$. Consequently, total neutron density does not return to unity, and total thermal power stabilizes at a self-consistent physical equilibrium of approximately 2.069×10^9 W.

From this stable initial state, the system response can be investigated by imposing external input signals, such as ramps or steps, on the regional reactivity to simulate control rod movement. To test the robustness and thermo-neutronic response of the complete coupled system, a negative reactivity insertion was simulated using a ramp with an amplitude of $-10^{-3} \Delta k/k$ and a duration of 2 s. The perturbation was initiated at $t = 1100$ s to ensure the system was operating under perfectly stable conditions after the initial thermo-hydraulic settling phase. The ramp is applied exclusively to the upper core region, representing the partial insertion of control rods from the top of the core, consistent with the typical kinematics of commercial PWRs.

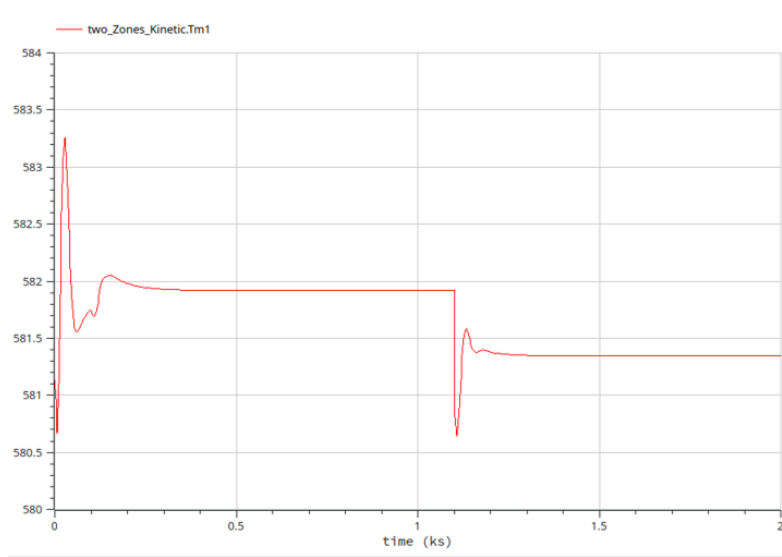


Figure 4.14: Moderator temperature evolution in the upper core region (T_{m1}).

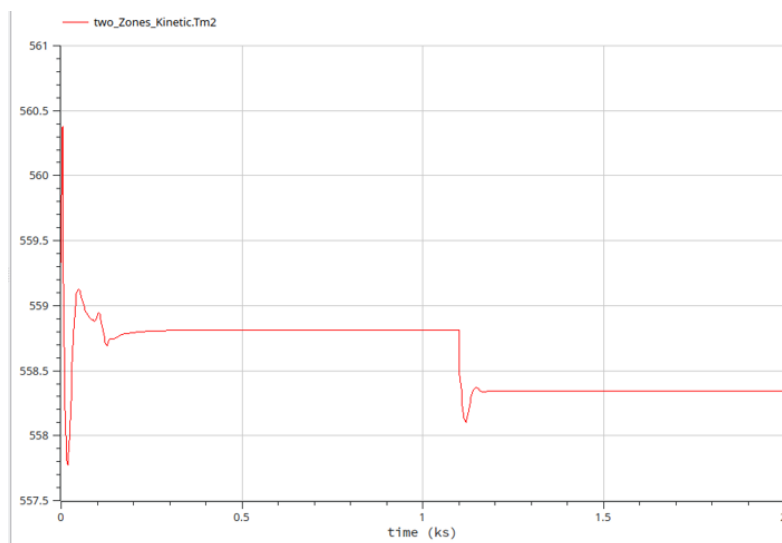


Figure 4.15: Moderator temperature evolution in the lower core region (T_{m2}).

The insertion of negative reactivity into the upper region causes an immediate decrease in the local neutron population n_1 . The resulting reduction in the heat flux transferred to the coolant leads to a decrease in the moderator temperature in both axial regions:

- **TOP region:** the average temperature T_{m1} decreases from an initial steady value of approximately 581.9 K to a new equilibrium value of about 581.3 K;
- **BOTTOM region:** the average temperature T_{m2} undergoes a similar reduction, decreasing from approximately 558.8 K to about 558.3 K.

Consistent with the negative moderator temperature coefficient discussed above, this cooling induces a positive feedback reactivity contribution in both axial regions.

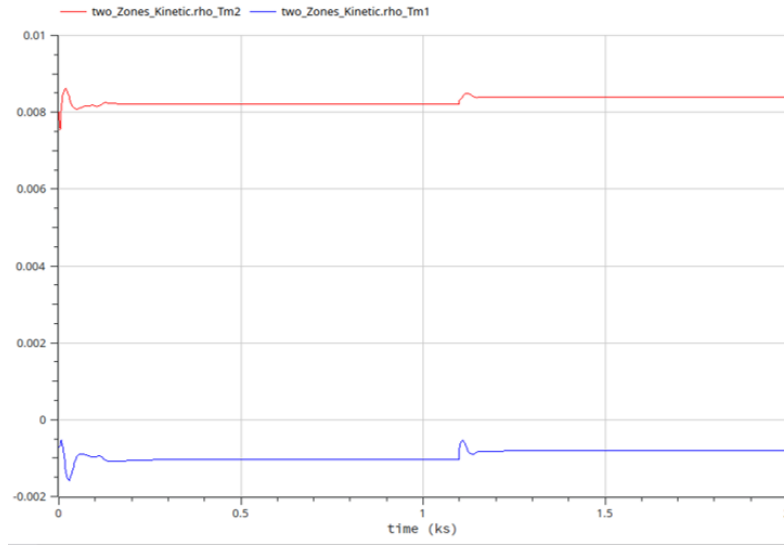


Figure 4.16: Moderator temperature feedback reactivity components for the TOP (ρ_{Tm1}) and BOTTOM (ρ_{Tm2}) regions.

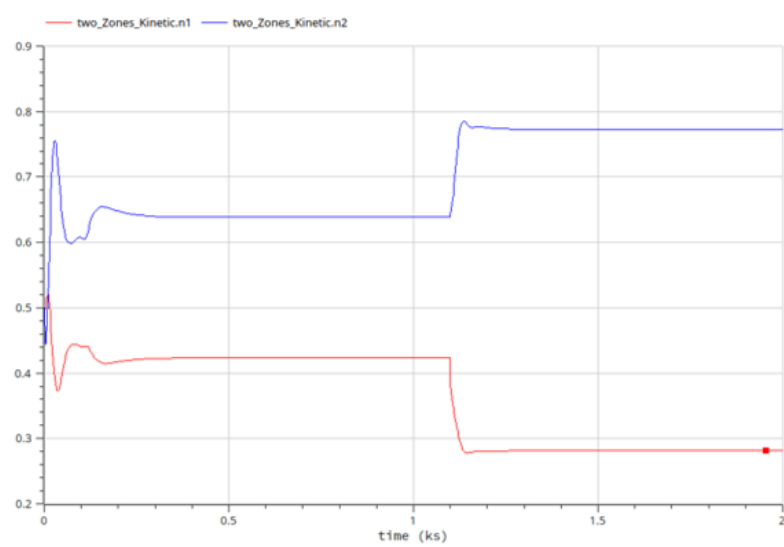


Figure 4.17: Neutron density variations in the TOP (n_1) and BOTTOM (n_2) core regions.

As shown by the feedback reactivity curves, following the temperature decrease at $t = 1100$ s, both ρ_{Tm1} and ρ_{Tm2} increase, becoming less negative or more positive. This increase in the

feedback component partially offsets the negative external reactivity insertion and thus serves as a self-regulating mechanism that mitigates the overall reduction in reactor power. The combined effect of the localized external perturbation and the regional reactivity balance induces a pronounced spatial redistribution of the neutron population:

- **TOP region (n_1):** the external negative reactivity insertion dominates over the local thermal feedback, resulting in a sharp decrease in neutron density, from approximately 0.425 to an asymptotic value of about 0.28;
- **BOTTOM region (n_2):** although no direct external reactivity perturbation is applied to this region, the reduction in moderator temperature produces a positive feedback contribution. In addition, neutron exchange with the upper region modifies its local neutron balance. As a result, the neutron density increases from approximately 0.64 to about 0.77.

This behavior results in a marked *axial power tilt* towards the lower part of the reactor core, illustrating the spatial redistribution produced by a localized reactivity insertion in the two-region model.

Overall, the integrated response of the two regions leads to a moderate reduction in the total thermal power generated by the reactor, which decreases from the initial equilibrium value of 2.069×10^9 W (2069 MWt) to a new equilibrium level of approximately 2.054×10^9 W (2054 MWt). The coupled model demonstrates stable numerical behavior and reaches the new equilibrium without unphysical oscillations.

4.2.1 Effect of the Neutron Coupling Coefficient

The effect of the neutron coupling coefficient D was subsequently investigated through a parametric analysis considering three representative cases: $D = 0$, corresponding to the absence of direct neutron exchange between the two regions; $D = 0.5$, representing a moderate coupling; and $D = 200$, representing the strong-coupling limit.

At this stage, to optimize the extraction of simulation data, the Python interface of the DyMat package is used. OpenModelica generates output files in the standard `.mat` format; however, these files do not contain simple text tables, but rather use a specific variable structure optimized to reduce data redundancy. In Modelica models, the connections between components often lead to multiple variables sharing the same values. Simulators can therefore store such time series only once, associating multiple variable names with the same data. Programmatic access to this structure is provided in Python through the `DyMatFile` class, which allows direct access to `.mat` files without requiring MATLAB, automating data retrieval and reducing manual transcription errors [17].

The comparison was performed at two different simulation times, $t = 500$ s and $t = 1600$ s. The first time instant precedes the application of the external negative reactivity perturbation, whereas the second corresponds to the post-perturbation regime. At $t = 500$ s, before the application of the external perturbation, the three cases already exhibit markedly different axial neutron distributions. For $D = 0$, this isolation is not limited to the initial instant considered above: since the diffusive coupling term vanishes identically for every t (regardless of whether $n_1 = n_2$), the BOTTOM region behaves as a fully isolated point-kinetics system throughout the entire simulation. Its total local reactivity must therefore equal zero at *any* true steady state for which $n_2 \neq 0$, not only at $t = 0$ but also at $t = 500$ s, once the thermo-hydraulic settling transient has been completed. This is confirmed to high numerical precision in Table 4.1: the moderator feedback reactivity, $\rho_{Tm2} = 8.010294 \times 10^{-3}$, is compensated almost exactly by the frozen

Table 4.1: Neutronic and thermal comparison at $t = 500.0$ s for different values of D .

Parameter / Variable	$D = 0$	$D = 0.5$	$D = 200$
Normalized Neutron Density			
TOP (n_1)	0.000000	0.418855	0.531341
BOTTOM (n_2)	1.073002	0.646596	0.531922
Total (n)	1.073002	1.065450	1.063263
Precursor Concentration			
TOP (C_1)	0.0000	336.1182	426.3844
BOTTOM (C_2)	861.0510	518.8726	426.8511
Total ($C_1 + C_2$)	861.0511	854.9908	853.2356
Moderator Temperature ($^{\circ}\text{C}$)			
TOP (T_{m1})	309.34	308.69	308.53
BOTTOM (T_{m2})	286.14	285.60	285.46
Core Average	297.74	297.14	297.00
Reactivity Components			
ρ_{Tm1}	-1.268974×10^{-3}	-1.008901×10^{-3}	-9.429891×10^{-4}
ρ_{Tm2}	8.010294×10^{-3}	8.229485×10^{-3}	8.282458×10^{-3}
ρ_{p1}	6.705325×10^{-4}	6.705325×10^{-4}	6.705325×10^{-4}
ρ_{p2}	-8.010293×10^{-3}	-8.010293×10^{-3}	-8.010293×10^{-3}

bias reactivity, $\rho_{p2} = -8.010293 \times 10^{-3}$, so that the total local reactivity vanishes within the numerical precision of the solver, consistent with the fully decoupled, quasi-critical equilibrium reached at $n_2 \simeq 1.073$.

The moderate-coupling case, $D = 0.5$, exhibits substantially different behavior. The exchange term continuously transfers neutrons from the region of higher neutron density to the region of lower neutron density. Consequently, although the TOP region remains affected by a negative local reactivity balance, its neutron population is sustained at a finite value of approximately 0.419. At the same time, the BOTTOM region retains the largest fraction of the neutron population, with $n_2 \simeq 0.647$, establishing a pronounced axial asymmetry. For $D = 200$, the neutron exchange term becomes sufficiently strong to redistribute the neutron population rapidly. The neutron densities become almost identical already at $t = 500$ s, with $n_1 = 0.531341$ and $n_2 = 0.531922$, representing the strong-coupling limit towards a spatially homogeneous point-kinetics behavior.

In the strong-coupling case, no significant axial power tilt is observed. This behavior results from the dominance of the coupling term, whose magnitude increases with the coupling parameter D . For sufficiently large values of D , the coupling becomes strong enough to enforce an almost uniform neutron population between the two axial regions, thereby approaching the behavior expected in the infinite-coupling limit.

The effect of the external perturbation is then evaluated by comparing the same three cases at $t = 1600$ s. This comparison confirms the trends observed prior to the perturbation and highlights the additional effect of the localized negative-reactivity insertion. For $D = 0$, the TOP region remains completely shut down, while the BOTTOM region continues to sustain almost the entire neutron population. The negative reactivity perturbation applied to the TOP region does not cause the shutdown, since the region was already subcritical prior to $t = 1100$ s. The absence of neutron exchange is the sole fundamental mechanism keeping the two regions

Table 4.2: Neutronic and thermal comparison at $t = 1600.0$ s for different values of D .

Parameter / Variable	$D = 0$	$D = 0.5$	$D = 200$
Normalized Neutron Density			
TOP (n_1)	0.000000	0.279074	0.522517
BOTTOM (n_2)	1.073003	0.779044	0.524040
Total (n)	1.073003	1.058118	1.046556
Precursor Concentration			
TOP (C_1)	0.0000	223.9484	419.3037
BOTTOM (C_2)	861.0521	625.1584	420.5256
Total ($C_1 + C_2$)	861.0521	849.1069	839.8293
Moderator Temperature ($^{\circ}\text{C}$)			
TOP (T_{m1})	309.34	308.13	307.16
BOTTOM (T_{m2})	286.14	285.15	284.34
Core Average	297.74	296.64	295.75
Reactivity Components			
ρ_{Tm1}	-1.268985×10^{-3}	-7.854124×10^{-4}	-3.959115×10^{-4}
ρ_{Tm2}	8.010293×10^{-3}	8.409673×10^{-3}	8.733564×10^{-3}
ρ_{p1}	-3.294675×10^{-4}	-3.294675×10^{-4}	-3.294675×10^{-4}
ρ_{p2}	-8.010293×10^{-3}	-8.010293×10^{-3}	-8.010293×10^{-3}

completely independent.

For $D = 0.5$, the TOP neutron population decreases from 0.419 to approximately 0.279 due to the negative reactivity insertion. However, unlike the $D = 0$ case, the upper region does not shut down completely because neutron exchange continuously supplies a fraction of the population. Simultaneously, the BOTTOM neutron population increases to 0.779, yielding a persistent but finite axial asymmetry.

In the strong-coupling case, $D = 200$, the effect of the localized perturbation is rapidly distributed between the two regions. The neutron densities at $t = 1600$ s are $n_1 = 0.522517$ and $n_2 = 0.524040$, corresponding to a relative difference of approximately 0.29%. The two regions, therefore, remain very close to a spatially uniform neutron distribution even though the external perturbation is applied only to the TOP region. The strong neutron exchange effectively prevents the formation of a significant axial neutron-density gradient.

The influence of the coupling coefficient on the thermo-neutronic response can also be interpreted through its effect on the moderator temperature feedback, already introduced in Eqs. (4.10)–(4.11): the different values of D modify the spatial distribution of neutron power and therefore alter the thermal response of the two regions, and these temperature variations subsequently modify the local moderator feedback reactivities, establishing a thermo-neutronic feedback loop between the neutron distribution and the thermal-hydraulic state of the core. As the coupling coefficient increases, this local constraint is progressively relaxed: for $D = 200$, the exchange is sufficiently strong to redistribute the neutron population almost completely between the two regions, so that the localized perturbation produces only a very small axial distortion.

Overall, the parametric analysis demonstrates that the coupling coefficient D directly controls the degree of spatial redistribution of the neutron population and, through the resulting power distribution and moderator temperature variations, indirectly affects the thermo-neutronic response of the core. The three cases therefore reproduce the expected limiting behaviors of

the proposed two-region formulation: complete neutron decoupling for $D = 0$, a finite axial power tilt for moderate coupling, and an almost spatially homogeneous neutron distribution in the strong-coupling limit.

The results consequently confirm that the proposed coupling formulation provides a physically consistent transition between two neutronic independent regions and a behavior that approaches the spatially homogeneous point-kinetics approximation.

4.2.2 Comparison between the Decoupled Case and the Point Kinetics Model

This subsection is dedicated to explaining the peculiar difference in behavior observed between the two models: while the single-zone point-kinetics model always settles at a new, reduced but non-zero power level following a negative reactivity insertion, the two-region model with $D = 0$ allows the TOP region to shut down completely. The reason for this qualitative difference is examined below by working directly with the steady-state form of the kinetic equations.

At any true steady state, both the neutron density and the precursor concentration are stationary, i.e. $\dot{n} = \dot{C} = 0$. Imposing $\dot{C} = 0$ in the precursor balance of Eq. (4.5) gives $C = \beta n / (\lambda l)$; substituting this expression into the neutron balance $\dot{n} = 0$ eliminates the precursor term entirely, yielding the compact steady-state condition

$$\frac{\rho n}{l} = 0. \quad (4.19)$$

In the single-zone point-kinetics model, n represents the total core power and cannot vanish while the reactor is operating, so Eq. (4.19) can only be satisfied by $\rho = 0$. Since T_m is a single-valued function of the total generated power, all the heat produced by the core feeds the same control volume from which T_m is evaluated for the feedback law. Since T_m is free to decrease without bound as n decreases, generating an arbitrarily large positive feedback reactivity, a value of T_m that exactly cancels any (physically reasonable) negative external perturbation can always be found. The criticality condition, therefore, always admits a solution with $n > 0$: the reactor settles at a lower power level rather than shutting down. This is confirmed by the isolated test of Section 4.3, where, with T_m externally fixed and the self-regulating loop consequently removed, Eq. (4.19) can no longer be balanced by $\rho \rightarrow 0$, and the neutron population instead decays asymptotically to zero under the permanently negative reactivity.

In the two-region model, the same manipulation applied to the TOP-region balance, Eq. (4.7), yields the analogous condition

$$\frac{\rho_1 n_1}{l} = \frac{-D}{\tau_{\text{eff}}} (n_2 - n_1), \quad (4.20)$$

which is consistent with the steady-state expression for ρ_1 already derived in Eq. (4.18). For $D = 0$, the right-hand side vanishes identically, and Eq. (4.20) reduces exactly to $\frac{\rho_1 n_1}{l} = 0$. This is the same condition obtained for the single-zone model, but now applied independently to each region. Unlike the single-zone case, however, this condition can be satisfied not only by $\rho_1 = 0$ but also, trivially, by $n_1 = 0$. Whether the former or the latter solution is realized depends on whether a physically admissible value of $T_{m,\text{Top}}$ exists that cancels ρ_1 . This is where the thermo-hydraulic coupling becomes decisive: although the two regions are neutronicly decoupled for $D = 0$, they are not thermally independent, since they share the same one-dimensional flow channel (flow1DFV, discretized into 10 axial nodes). $T_{m,\text{Top}}$ is evaluated as the average temperature of the five upper nodes (6–10), downstream of the five lower nodes (1–5) used for $T_{m,\text{Bottom}}$; since the coolant enters at the bottom of the core and flows upward, $T_{m,\text{Top}}$ is not a

function of the locally generated power n_1 alone, but also depends on the heat already absorbed by the fluid while crossing the BOTTOM region. This breaks the self-contained feedback loop that holds in the single-zone model: if the value of $T_{m,Top}$ required to satisfy $\rho_1 = 0$ is thermally unreachable because the fluid entering TOP is constrained by the heat already released upstream in BOTTOM, then no admissible steady state with $n_1 > 0$ exists, and Eq. (4.20) can only be satisfied by $n_1 = 0$. In this limit, the governing equation for the TOP region reduces exactly to an isolated point-kinetics system evolving under permanently negative reactivity, formally identical to the isolated test case of Section 4.3, and n_1 decays to zero for the same reason.

Any $D > 0$, however small, reintroduces a non-zero right-hand side in Eq. (4.20): a diffusive supply of neutrons from the BOTTOM region which retains ample positive reactivity, since it operates at a comparatively lower moderator temperature, becomes available to balance a persistently negative local reactivity ρ_1 , sustaining a finite equilibrium value of n_1 . The local reactivity deficit in the TOP region is thus compensated by diffusive neutron import rather than by an otherwise unreachable local temperature, exactly as observed in the parametric analysis presented before.

4.2.3 Effect of the Axial Distribution of Reactivity Insertion

A further comparison, again performed at $D = 0.5$, investigates how the same reactivity ramp is distributed between the two axial regions. In the case discussed above, the entire negative reactivity step was applied to the TOP region only, to reproduce the effect of control rods inserted from the top of the core. The effect of control rod insertion impacts, more realistically, both regions of the reactor with different intensities. Here, the same reactivity step is therefore split between the TOP and BOTTOM regions in different proportions: 100%/0%, 75%/25%, 50%/50%, 25%/75%, and 0%/100%. Table 4.3 reports the neutronic state of the two regions before the perturbation ($t = 500$ s, identical for all cases since the insertion has not yet occurred at this time) and after the perturbation ($t = 1600$ s) for each of the five splits. As in the previous comparison, only the neutronic and some thermal quantities are reported, since the thermo-hydraulic response follows directly from the neutronic behavior of the core.

As the fraction of the reactivity step applied to the BOTTOM region increases, the resulting axial power tilt becomes progressively less pronounced. This trend is not perfectly monotonic, however: in the 25%/75% case, the TOP and BOTTOM neutron densities are nearly equal ($n_1 = 0.534074$, $n_2 = 0.512470$), even though three quarters of the perturbation are applied to the BOTTOM region. This behavior is explained by the different moderator feedback shown by the two regions: since the TOP region operates at a higher temperature, the corresponding feedback reactivity ρ_{Tm1} has a much smaller magnitude than ρ_{Tm2} in the BOTTOM region (for the 25%/75% split, $\rho_{Tm1} = -3.95 \times 10^{-4}$ against $\rho_{Tm2} = 8.73 \times 10^{-3}$). As a result, a comparable reactivity insertion produces a proportionally larger effect on the TOP region than on the BOTTOM region, partially compensating for the fact that most of the external perturbation is applied to the latter, and leading to the nearly symmetric neutron distribution observed in this case.

When the reactivity step is instead applied entirely to the BOTTOM region (0%/100%), the TOP neutron density becomes markedly higher than the BOTTOM one ($n_1 = 0.633484$ against $n_2 = 0.414574$, a difference of approximately 0.22), reproducing an axial tilt smaller and in opposite direction to the one observed for a fully top-inserted perturbation.

It should be noted that these bottom-inserted configurations do not correspond to a physically realistic control-rod movement, since control rods in a PWR are inserted from the top of the core. Nevertheless, they provide a useful numerical verification of the correct response of

Table 4.3: Neutronic and thermal comparison at $t = 1600.0$ s, after the reactivity insertion, and initial state ($t = 500.0$ s), for different TOP/BOTTOM insertion splits ($D = 0.5$). Column headers indicate the fraction of the $-10^{-3} \Delta k/k$ step applied to the TOP and BOTTOM regions, respectively.

Parameter / Variable	Initial State	100%/0%	75%/25%	50%/50%	25%/75%	0%/100%
Normalized Neutron Density						
TOP (n_1)	0.418855	0.279074	0.344205	0.431275	0.534074	0.633484
BOTTOM (n_2)	0.646596	0.779044	0.707369	0.616307	0.512470	0.414574
Total (n)	1.065450	1.058118	1.051574	1.047582	1.046544	1.048058
Precursor Concentration						
TOP (C_1)	336.1182	223.9484	276.2137	346.0845	428.5775	508.3513
BOTTOM (C_2)	518.8726	625.1584	567.6419	494.5674	411.2417	332.6825
Total ($C_1 + C_2$)	854.9908	849.1069	843.8556	840.6519	839.8192	841.0338
Moderator Temperature ($^{\circ}\text{C}$)						
TOP (T_{m1})	308.69	308.13	307.61	307.26	307.16	307.31
BOTTOM (T_{m2})	285.60	285.15	284.72	284.43	284.33	284.47
Core Average	297.14	296.64	296.17	295.85	295.75	295.89
Reactivity Components						
ρ_{Tm1}	-1.008901×10^{-3}	-7.854124×10^{-4}	-5.771170×10^{-4}	-4.375223×10^{-4}	-3.953588×10^{-4}	-4.554852×10^{-4}
ρ_{Tm2}	8.229485×10^{-3}	8.409673×10^{-3}	8.579786×10^{-3}	8.697124×10^{-3}	8.734057×10^{-3}	8.681693×10^{-3}
ρ_{p1}	6.705325×10^{-4}	-3.294675×10^{-4}	-7.946747×10^{-5}	1.705325×10^{-4}	4.205325×10^{-4}	6.705325×10^{-4}
ρ_{p2}	-8.010293×10^{-3}	-8.010293×10^{-3}	-8.260293×10^{-3}	-8.510293×10^{-3}	-8.760293×10^{-3}	-9.010293×10^{-3}

the two-region model, and confirm that an insertion from the bottom of the core produces a systematically less pronounced axial tilt than the equivalent insertion from the top, as a direct consequence of the reduced moderator feedback available in the hotter TOP region.

Taken together, the parametric analysis on the coupling coefficient D and the present analysis on the spatial distribution of the reactivity insertion confirm that the axial power tilt following a localized perturbation depends on two distinct and independent factors: the strength of the neutron exchange between the two regions, controlled by D , and the location where the perturbation is applied relative to the axial temperature profile of the core.

4.3 New Control Rod Model

The control rod model was developed starting from the previous point-kinetic neutron model, keeping the governing equations describing the evolution of the neutron population and delayed-neutron precursors unchanged. To avoid redundancy, foundational equations and parameters β , λ , and l , already detailed in the point-kinetics model, are not repeated here. The main modification concerns the formulation of the total reactor reactivity.

In the model developed in the previous part, the reactivity was obtained as the sum of the contribution due to the moderator temperature and an external perturbation arbitrarily imposed by the user. In the model developed in the present section, the total reactivity is instead expressed as the sum of two physical contributions:

$$\rho = \rho_{Tm} + \rho_{CR}, \quad (4.21)$$

where ρ_{Tm} represents the reactivity due to variations in moderator temperature, while ρ_{CR} denotes the reactivity introduced by the control rod system. The moderator contribution is still described by the linear relationship

$$\rho_{Tm} = \alpha_{Tm} (T_m - T_{m,ref}), \quad (4.22)$$

whereas the reactivity associated with the control rods is assumed to be proportional to their insertion depth into the reactor core according to

$$\rho_{CR} = \rho_0 (z_{eff} - z_{ref}), \quad (4.23)$$

where z_{eff} represents the effective and normalized control rod position, ρ_0 is the proportionality coefficient between rod position and reactivity, and z_{ref} is the reference position at which the control rod contribution is zero.

The control rod position is normalized over the interval from 0 to 1, where:

- $z = 0$ corresponds to the control rods being fully inserted;
- $z = 1$ corresponds to the control rods being fully withdrawn.

The mid-plane of the reactor core was selected as the reference position:

$$z_{ref} = 0.5, \quad (4.24)$$

as illustrated in Figure 4.18. In this way, the model can represent both control rod insertion and withdrawal relative to a reference configuration, allowing both positive and negative reactivity variations to be compensated.

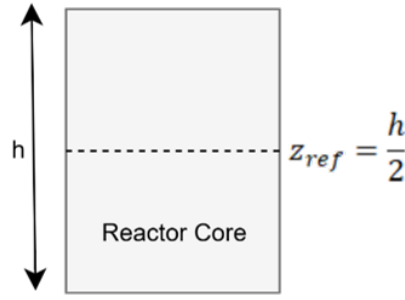


Figure 4.18: Reference control rod position located at the core mid-plane.

Under the selected linear proportionality law, the control rod contribution varies within:

$$-\frac{\rho_0}{2} \leq \rho_{CR} \leq \frac{\rho_0}{2}. \quad (4.25)$$

In particular:

$$z = 0 \quad \Rightarrow \quad \rho_{CR} = -\frac{\rho_0}{2}, \quad (4.26)$$

whereas:

$$z = 1 \quad \Rightarrow \quad \rho_{CR} = +\frac{\rho_0}{2}. \quad (4.27)$$

Since control rods in commercial PWRs are inserted from the top of the reactor core, a decrease in the normalized position z corresponds to a deeper rod insertion and therefore to a reduction in reactor reactivity. Conversely, increasing z progressively withdraws the control rods, thereby increasing reactivity.

For the definition of the parameter ρ_0 , reference was made to the actual worth of the fine-regulating control rod bank (Gray Rods, GRODS), obtained from the reference PWR plant simulator, which is approximately 15.54 mk (1554 pcm or 0.01554 $\Delta k/k$). Applying the corresponding proportionality according to the percentage of bank insertion and considering the full range of the normalized position, the following value was assigned to the parameter:

$$\rho_0 = 0.01682 \quad (1682 \text{ pcm}). \quad (4.28)$$

This choice is motivated by the fact that the objective of the developed model is not to simulate extreme accident conditions or rapid reactor shutdown events (scram or reactor trip), which would involve activating the entire shutdown rod system (Shutdown Rods, SDRODS) with significantly higher reactivity worths. Instead, the model is intended to accurately represent normal operational control and load-following maneuvers under standard operating conditions.

To ensure that the model reproduces physically consistent behavior, the position used in the governing equations is not directly equal to the input signal: it is replaced by an effective position defined as

$$z_{\text{eff}} = \min(\max(z, 0), 1). \quad (4.29)$$

In this way, values below 0 or above 1 are automatically saturated, ensuring that the control rods affect reactivity only while they are within the active core region. Any displacement beyond the physical stroke limits, therefore, produces no further variation in reactivity, consistently with the actual mechanical behavior.

Finally, by imposing the steady-state criticality condition during initialization,

$$\rho = 0, \quad (4.30)$$

and the code automatically calculates the initial control rod position z_0 to compensate for the moderator feedback exactly:

$$z_0 = z_{\text{ref}} - \frac{\rho_{Tm}(T_{m,0})}{\rho_0}, \quad (4.31)$$

with:

$$\rho_{Tm}(T_{m,0}) = \alpha_{Tm} (T_{m,0} - T_{m,\text{ref}}). \quad (4.32)$$

This expression ensures that, at the initial moderator temperature, the control rod contribution exactly compensates for the thermal reactivity, allowing the simulation to start under correct steady-state conditions.

For completeness, the customized Modelica icon developed for the control rod model is shown in Figure 4.19. The icon facilitates the identification of the component within the graphical layout of the complete system. The complete Modelica source code of the `Control_Rod_Model` component is reported in Appendix A.5.

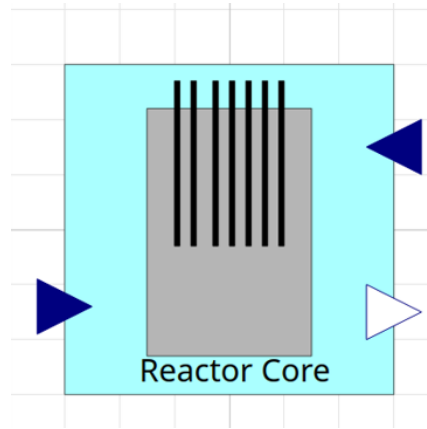


Figure 4.19: Icon of the point kinetics model including the control rod implementation.

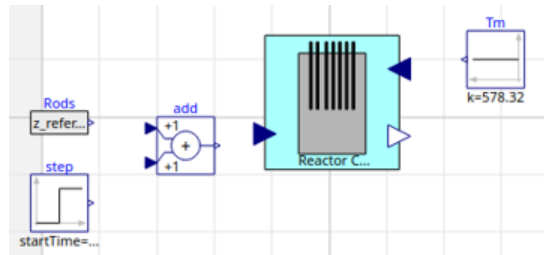


Figure 4.20: Test layout adopted for the verification of the control rod model.

To assess the numerical stability and dynamic response of the component before its integration into the complete plant model, an isolated test circuit was developed. In the test circuit, the moderator temperature T_m is maintained constant by means of a constant signal source from the Modelica Standard Library ($T_m = 578.32$ K). At the initial time $t = 0$ s, the solver automatically determines the equilibrium position $z_0 \approx 0.4762$, resulting in zero total reactivity. At $t = 10$ s, a negative step in the control rod position of $\Delta z = -0.01$ is applied, simulating an additional 1% insertion of the total control rod stroke. As shown by the reactivity profile in Figure 4.21, the downward displacement of the control rods introduces an immediate negative reactivity step equal to:

$$\Delta\rho = \rho_0 \cdot \Delta z = 0.01682 \cdot (-0.01) = -1.682 \times 10^{-4} \quad (-16.82 \text{ pcm}). \quad (4.33)$$

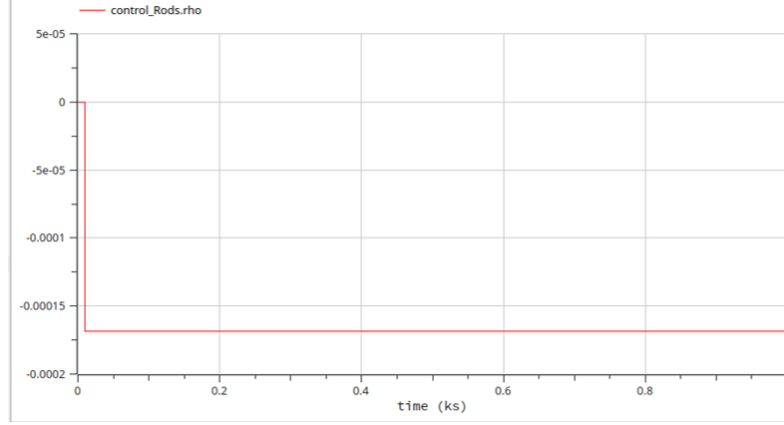


Figure 4.21: Total reactor reactivity following the step change in control rod position.

Since the moderator temperature is imposed as a constant boundary condition, the coolant-induced thermal feedback mechanism is disabled. Consequently, the total reactivity remains permanently fixed at the negative value of -1.682×10^{-4} for the entire duration of the simulation.

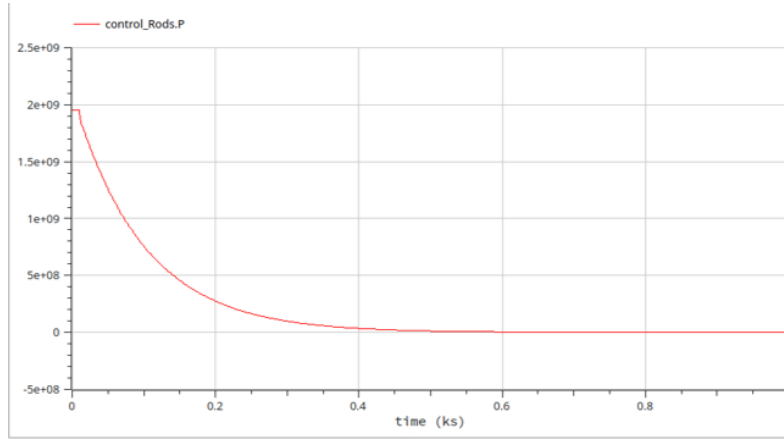


Figure 4.22: Neutron density and thermal power following the step change in control rod position.

The persistence of a total negative reactivity ($\rho < 0$) induces a condition of permanent subcriticality. The normalized neutron density n (and consequently the thermal power output P_{th}) responds with a transient decay damped by the presence of delayed neutrons, progressively and asymptotically approaching zero. This behavior, although lacking the stabilizing effect of thermal feedback that will be observed in the integrated plant layout, confirms the physical correctness of the implemented point-kinetics equations and demonstrates the absence of numerical instabilities or drift in the solver.

We now proceed with the integration of the neutronic model into the overall thermo-hydraulic layout. The thermo-hydraulic layout remains exactly the same as in the previous cases. Consequently, the analysis focuses on the coupling parameters between the neutronic component and the core. In particular, to ensure a consistent comparison with the previously analyzed cases, a negative-reactivity insertion is simulated starting at t_0 with a ramp of duration Δt . In this model, the perturbation is applied by directly moving the control rods; solving the relation $\rho(z)$, the displacement z by which the rod must be translated is derived to obtain a reactivity insertion exactly equal to $\Delta\rho$ (i.e., $\rho = -\Delta\rho$) used as a reference in the other tests.

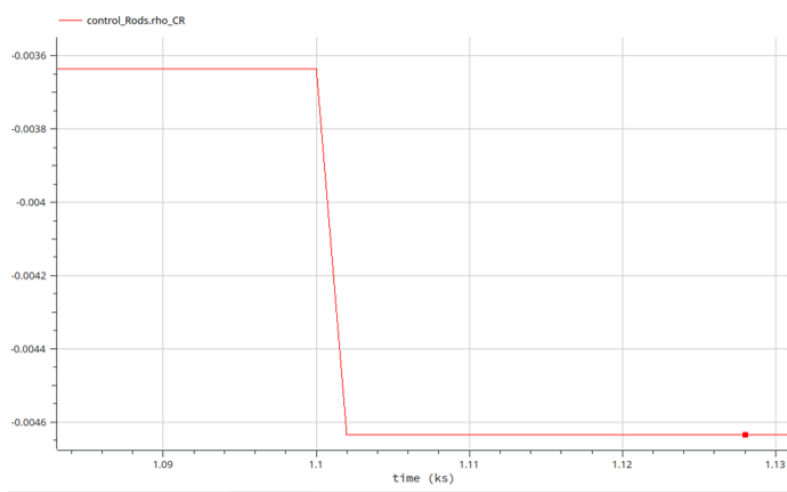


Figure 4.25: Control rod reactivity.

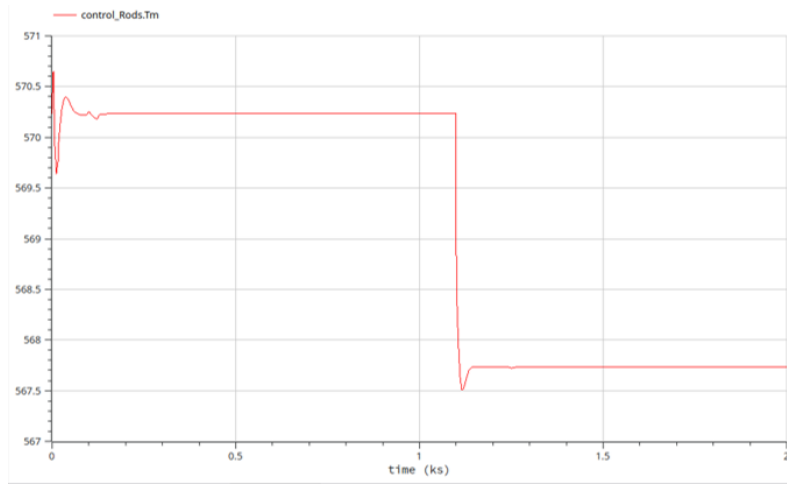


Figure 4.26: Moderator temperature evolution.

4.4 Short-Term Neutronic Response

While the transient analyses presented above focus primarily on the overall response of the reactor system, the behavior immediately following a reactivity perturbation deserves a more detailed examination. In particular, the short-term evolution of the neutron population and the delayed-neutron precursor concentration allow the different time scales governing the neutronic response to be clearly identified. This provides a direct interpretation of the prompt response of the neutron population and the subsequent, slower evolution of the delayed-neutron precursors. To avoid repeating essentially identical plots for the different configurations, only the case corresponding to the control rod model is reported here. The same qualitative behavior is obtained for the other configurations because the same point-kinetics balance equations govern the neutron population and precursor concentration. The difference between the models concerns how the reactivity perturbation is introduced, rather than the structure of the precursor balance itself.

The comparison between the short-term responses of the normalized neutron density n and the precursor concentration C following a reactivity perturbation illustrates the physical inertia introduced by delayed-neutron kinetics. Upon inserting negative reactivity at $t = 1.1$ ks, the

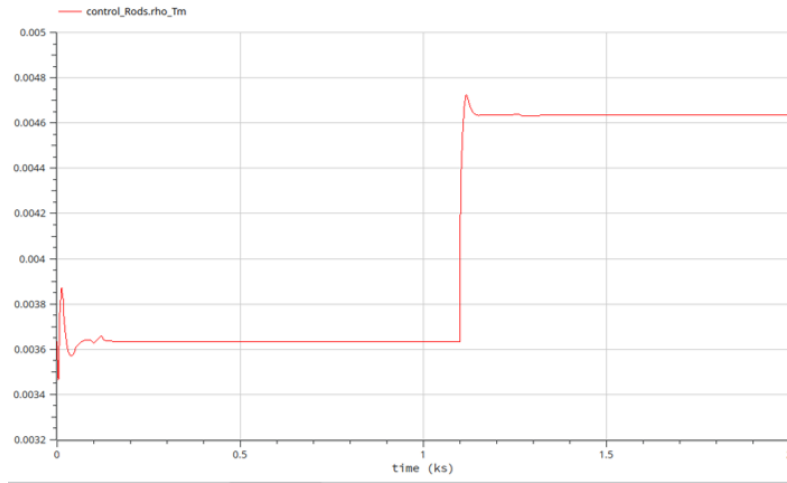


Figure 4.27: Moderator reactivity feedback.

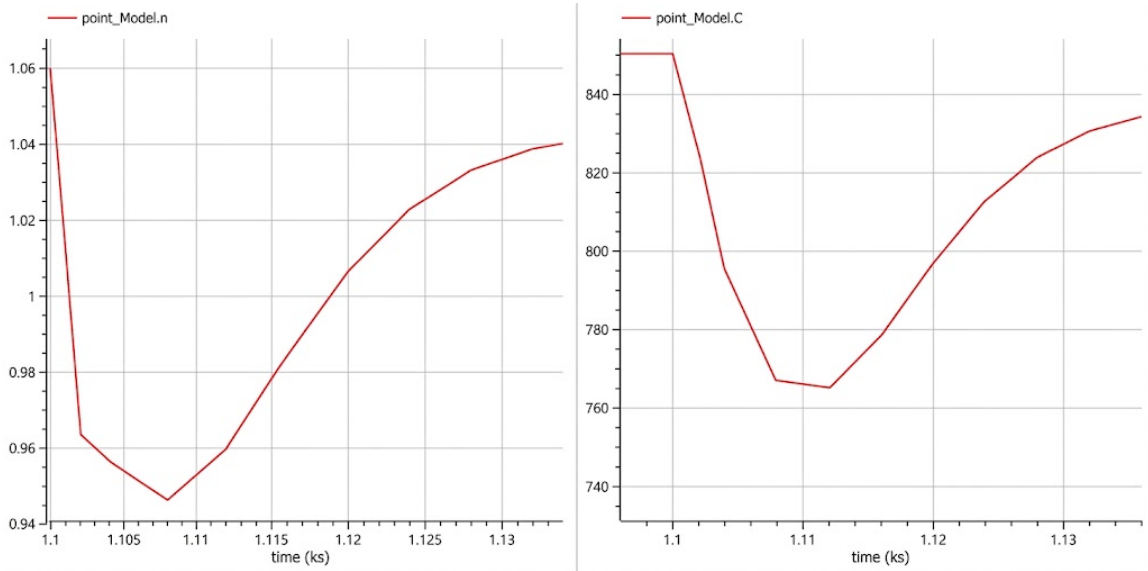


Figure 4.28: Short-term evolution of the normalized neutron density and precursor concentration following the insertion of negative reactivity in the control rod model.

normalized neutron density n exhibits an immediate step-like variation, characteristic of the prompt jump (or drop) phenomenon dictated by the prompt neutron generation time, here given by $l = 2 \times 10^{-5}$ s. In contrast, the precursor concentration C does not experience a discontinuous drop. Instead, its rate of change $\frac{dC}{dt}$ transitions smoothly from zero to a negative value in accordance with the balance equation

$$\frac{dC}{dt} = \frac{\beta}{l}n - \lambda C. \quad (4.34)$$

Because precursor production is directly tied to the neutron population, the sudden reduction in n immediately reduces the production term $\frac{\beta}{l}n$. The decay term λC , however, depends on the precursor population already present and therefore does not undergo a corresponding instantaneous reduction. Consequently, following the negative reactivity insertion, the decay rate temporarily exceeds the production rate, leading to a progressive decrease in precursor concentration.

The precursor concentration, therefore, does not exhibit the prompt discontinuity observed in the neutron population. Instead, its evolution remains smoother, with its slope determined by the balance between precursor production and radioactive decay. This behavior is a direct consequence of the distinct characteristic time scales of prompt-neutron kinetics and delayed-neutron precursor dynamics. The same mechanism applies when the neutron population increases. In this case, the production term $\frac{\beta}{\ell}n$ increases immediately, while the existing precursor population continues to decay according to λC . The resulting imbalance causes the precursor concentration to increase progressively.

4.5 Comparison between the Three Models

The comparative tables in this section enable direct comparison of the three modeling approaches developed in this work. As discussed previously, in the Point Model and Two Zones Model, the reactor perturbation is introduced directly as a variation in reactivity. In the CR Model, instead, an equivalent control-rod displacement is imposed, corresponding to the same net reactivity variation. In all three cases, the thermo-hydraulic system layout remains unchanged, so the differences observed in the results can be attributed exclusively to the adopted neutronic modeling approach. Table 4.4 reports the main system parameters and steady-state quantities evaluated after the initial transient has been completed ($t = 1000$ s), immediately before the insertion of the negative reactivity step. Table 4.5 reports the corresponding quantities after the second transient ($t = 2000$ s), following the insertion of the negative reactivity step.

A first important result is the excellent agreement between the Point Model and the CR Model. As shown in Tables 4.4 and 4.5, the two approaches provide highly consistent results for the main thermohydraulic quantities, both in the initial steady state and after the negative reactivity perturbation. Thermal power, moderator temperature, primary mass flow rate, steam production, enthalpies, and pressures are essentially identical between the two models. The neutron density also shows an identical behavior, with a value of 1.051 in both models before the perturbation and 1.017 in both models after the perturbation.

This agreement confirms the consistency of the control-rod implementation developed in the present work. In particular, imposing a direct variation in reactivity or reproducing the same net reactivity variation through an equivalent mechanical displacement of the control rods yields the same reactor response within the point-kinetics formulation. The small differences observed in the precursor concentration after the perturbation do not affect the system's overall thermo-hydraulic response.

The Two Zones Model, on the other hand, exhibits significant differences from the single-zone approximation, highlighting the effects of spatial discretization in the reactor core. A first difference is already evident in the initial steady-state thermal power. Before the perturbation, the Two Zones Model predicts a thermal power of 2.041×10^9 W_{th}, compared with 2.039×10^9 W_{th} obtained with both the Point Model and the CR Model. Although the difference is relatively small, the origin of this deviation is physically significant. The Two Zones Model explicitly accounts for the axial distribution of moderator temperature, with the Bottom region operating at a significantly lower temperature than the Top region, namely 558.8 K and 581.9 K, respectively.

Due to the negative moderator temperature reactivity coefficient, a lower temperature in the Bottom region corresponds to a more favorable local moderating condition and therefore to a higher local neutron density. As a consequence, the spatially resolved model predicts a slightly higher overall power than the single-zone models, in which the thermo-hydraulic feedback is represented through a single average moderator temperature. The differences become considerably more pronounced following the insertion of the negative reactivity step. In the

Table 4.4: System parameters and steady-state values after the initial transient ($t = 1000$ s), prior to the negative reactivity step insertion.

Parameter / Quantity	Point Model	2 Zones Model	CR Model
Thermal Power (W_{th})	2.039×10^9	2.041×10^9	2.039×10^9
Moderator Temperature (K)	570.2	581.9 (Top) 558.8 (Bottom)	570.2
Neutron Density	1.051	1.052 (Total) 0.419 (Top) 0.633 (Bottom)	1.051
Precursor Concentration	843.4	844.2 (Total) 336.1 (Top) 508.1 (Bottom)	843.4
Primary Flow in SG (kg/s)	9206	9206	9206
Primary SG Inlet Enthalpy (kJ/kg)	1436	1437	1436
Primary SG Outlet Enthalpy (kJ/kg)	1211	1211	1211
Secondary SG Inlet Enthalpy (kJ/kg)	920.0	920.6	920.0
Secondary Steam Production (kg/s)	1076	1075	1076
Secondary Steam SG Outlet Enthalpy (kJ/kg)	2864	2871	2864
Mass Flow in HPT (kg/s)	1076	1075	1076
HPT Inlet Enthalpy (kJ/kg)	2864	2871	2864
HPT Outlet Enthalpy (kJ/kg)	2792	2799	2792
Mass Flow in LPT (kg/s)	661.0	660.0	661.0
LPT Inlet Enthalpy (kJ/kg)	2792	2799	2792
LPT Outlet Enthalpy (kJ/kg)	1922	1926	1922
Pressure Before HPT (bar)	56.98	57.02	56.98
Pressure After LPT (bar)	0.05	0.05	0.05

Point Model and CR Model, the thermal power decreases from approximately $2.039 \times 10^9 W_{th}$ to $1.972 \times 10^9 W_{th}$, corresponding to a reduction of approximately 67 MW. In the Two Zones Model, instead, the power decreases from $2.041 \times 10^9 W_{th}$ to $2.029 \times 10^9 W_{th}$, corresponding to a reduction of approximately 12 MW.

The substantially smaller power excursion predicted by the Two Zones Model indicates a stronger capability of the spatially resolved system to counteract the imposed negative reactivity perturbation through local feedback mechanisms. This behavior can be interpreted by examining the evolution of the neutron density in the two axial regions. Before the perturbation, the neutron density is 0.419 in the Top region and 0.633 in the Bottom region. Following the negative reactivity insertion, these values become 0.279 and 0.767, respectively. Thus, while the neutron population decreases significantly in the upper region, the lower region experiences an increase in neutron density. The resulting redistribution of the neutron population allows the total neutron density to remain close to its initial value, decreasing only from 1.052 to 1.046.

This behavior is a direct consequence of the local thermo-hydraulic feedback. Following the initial reduction in reactor power, the moderator temperature decreases, introducing positive reactivity through the negative moderator temperature coefficient. This feedback is particularly effective in the Bottom region, which is already characterized by a lower moderator temperature and, therefore, a stronger moderating effect. The resulting increase in local reactivity promotes neutron production in this region and partially compensates for the negative perturbation imposed on the reactor.

A further important mechanism is represented by the neutron coupling between the two

Table 4.5: System parameters and steady-state values after the second transient ($t = 2000$ s), following the negative reactivity step insertion.

Parameter / Quantity	Point Model	2 Zones Model	CR Model
Thermal Power (W_{th})	1.972×10^9	2.029×10^9	1.972×10^9
Moderator Temperature (K)	567.7	581.3 (Top) 558.3 (Bottom)	567.7
Neutron Density	1.017	1.046 (Total) 0.279 (Top) 0.767 (Bottom)	1.017
Precursor Concentration	815.8	839.5 (Total) 223.9 (Top) 615.6 (Bottom)	815.8
Primary Flow in SG (kg/s)	9206	9206	9206
Primary SG Inlet Enthalpy (kJ/kg)	1419	1433	1419
Primary SG Outlet Enthalpy (kJ/kg)	1201	1209	1201
Secondary SG Inlet Enthalpy (kJ/kg)	892.7	918.2	892.7
Secondary Steam Production (kg/s)	1097	1081	1097
Secondary Steam SG Outlet Enthalpy (kJ/kg)	2736	2843	2736
Mass Flow in HPT (kg/s)	1097	1081	1097
HPT Inlet Enthalpy (kJ/kg)	2736	2843	2736
HPT Outlet Enthalpy (kJ/kg)	2674	2774	2674
Mass Flow in LPT (kg/s)	683.0	665.5	683.0
LPT Inlet Enthalpy (kJ/kg)	2674	2774	2674
LPT Outlet Enthalpy (kJ/kg)	1849	1911	1849
Pressure Before HPT (bar)	56.16	56.79	56.16
Pressure After LPT (bar)	0.05	0.05	0.05

axial regions. The non-zero coupling parameter allows a continuous exchange of neutron population between the two nodes. During the transient, the Bottom region remains relatively more reactive and can therefore sustain, through neutron diffusion, the neutron population in the more strongly depressed Top region. The resulting redistribution of the neutron population significantly reduces the overall power excursion compared with the single-zone models, in which the thermo-hydraulic feedback is averaged over the entire reactor core.

The strength of this spatial coupling is directly related to the value of the coupling parameter. By varying this parameter, the degree of neutron exchange between the two axial regions can be adjusted, thereby affecting the extent of interaction between the regions during the transient. This represents one of the main differences between the spatially resolved model and the point-kinetics approximation: the former can reproduce local interactions between neutron kinetics and thermo-hydraulic feedback that are intrinsically absent when the entire reactor core is represented as a single homogeneous region.

The precursor concentration follows the redistribution of the neutron population according to the same balance equations introduced in Section 4.2. In particular, the local precursor production rate is proportional to the local neutron population, whereas the existing precursors continue to decay according to the decay constant λ . Therefore, a reduction in neutron density decreases the local precursor production rate and, as the existing precursors progressively decay, leads to a gradual decrease in the local precursor concentration. Conversely, an increase in neutron density enhances precursor production, thereby increasing precursor concentration.

This behavior is clearly reflected in the two-region results. Following the negative reactivity

perturbation, the neutron density in the Top region decreases from 0.419 to 0.279, while the corresponding precursor concentration decreases from 336.1 to 223.9. In the Bottom region, the neutron density increases from 0.633 to 0.767, while the precursor concentration increases from 508.1 to 615.6. These trends are consistent with the local precursor balance and demonstrate the temporal inertia associated with delayed neutron kinetics.

The Point Model and the CR Model, which employ the same point-kinetics equations, show the same overall behavior. The precursor concentration in the final state is 815.8 for both models, confirming the consistency between the two implementations.

Taken together, the developments presented in this chapter, i.e., the two-stage turbine layout, the two-region neutron kinetics formulation, and the insertion-depth-based control rod model, provide an increasingly detailed and physically consistent representation of both the thermal-hydraulic and neutronic behavior of the plant, establishing the basis for the further refinement of the thermodynamic cycle presented in the following chapter.

Chapter 5

Modeling of a Complex Thermodynamic Cycle

In this chapter, the most advanced and representative configuration developed in the present thesis is analyzed. The model is characterized by the integration of the two-region axial neutron kinetics model within a complete regenerative secondary circuit. The high non-linearity of the constitutive equations and the strong coupling between the state variables required the adoption of specific numerical strategies to obtain a consistent initial steady-state solution. In particular, an initialization procedure based on result files in .mat format was employed. The working principle of this procedure is discussed, along with two alternative strategies for initializing the complete thermo-hydraulic layout with the embedded two-region kinetic model. The two strategies differ specifically in how the two neutronic bias reactivities, $\rho_{\text{bias},1}$ and $\rho_{\text{bias},2}$, are determined during the initialization of the coupled system. Their effects on the resulting steady-state configuration and transient response are compared.

5.1 Introduction to the Initialization Procedure

The dynamic simulation of thermal-hydraulic and nuclear power systems using the Modelica language leads to the solution of a system of differential-algebraic equations (DAEs), which can be expressed in the general form

$$F(\dot{x}, x, z, u, t) = 0, \quad (5.1)$$

where x represents the vector of state variables, z the vector of algebraic variables, and u the system inputs. The determination of the initial steady-state condition, corresponding to

$$\dot{x} = 0, \quad (5.2)$$

requires the solution of a strongly non-linear algebraic system.

As the complexity of the model increases due to the simultaneous presence of two-phase flows, heat exchangers, control loops, and strongly coupled circuits, manually defining the initial values of numerous state variables becomes increasingly demanding and may adversely affect the convergence of the initialization problem.

To overcome this limitation, OpenModelica provides a procedure that allows a model to be initialized using the results of a previously performed simulation stored in an output file with .mat extension. During this process, the values of the variables stored in the file can be assigned to the corresponding variables of the new model, provided that the relevant variable identifiers are shared. In this way, the solver can start from an initial state that is already

close to the operating condition of interest, reducing the numerical difficulty associated with the initialization problem.

A particularly useful feature of this procedure is the ability to initialize a complex model using results from a simpler, structurally analogous configuration. In the present work, a secondary circuit with the final thermal-hydraulic layout and an ideal heat source was first used to obtain a stable operating condition. The resulting state was then imported into the complete model, which included the two-region neutron-kinetics description of the reactor core.

Using a previously computed state provides two main advantages. First, starting from values already close to the operating condition improves the robustness of the initialization procedure. Second, it avoids repeating the long thermal-hydraulic settling transient for every new simulation, allowing the analysis to focus on the transient phenomenon of interest.

Within the OpenModelica environment, the initialization settings are available through the *Simulation Setup* interface, where the result file and the time instant from which the stored variables are imported can be specified. The treatment of variables not present in the imported file is particularly relevant to the two-region neutronic model and is discussed in the following sections.

For completeness, the graphical interface used to configure the initialization from a previously generated result file is shown in Figure 5.1.

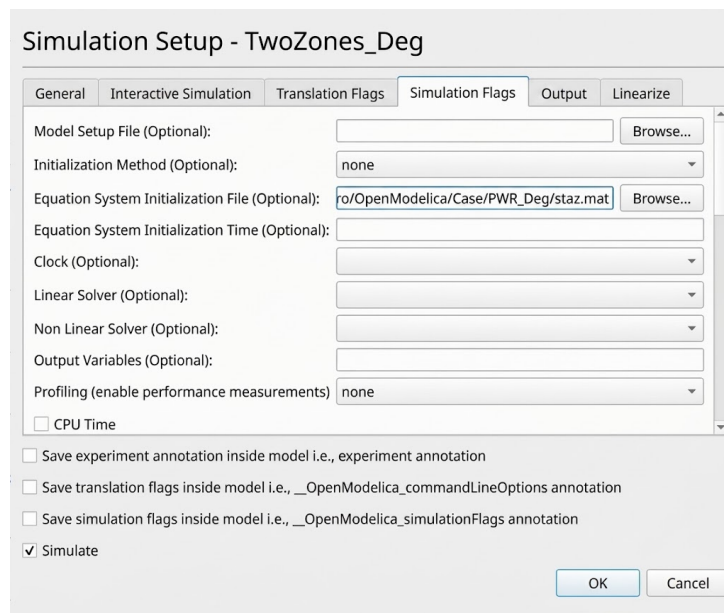


Figure 5.1: OpenModelica interface used to configure initialization from a previously generated result file.

5.2 Final Thermodynamic Cycle and Initialization Procedure

The final plant configuration, shown in Figure 5.2, integrates the two-region axial neutron kinetics model within a secondary circuit that is significantly more extensive than the configurations developed during the preliminary stages of the work. The main objective of this evolution is to increase the thermodynamic representativeness of the cycle and to obtain a configuration closer to that of a complete PWR.

The most relevant modification consists of the introduction of a steam extraction upstream of the high-pressure turbine. To obtain suitable feedwater conditions at the economizer inlet, a

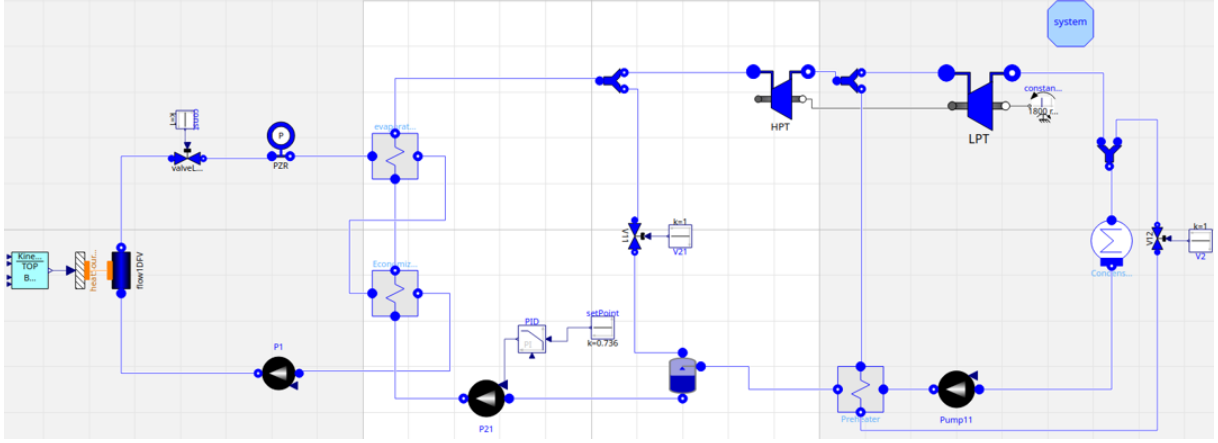


Figure 5.2: Complete plant layout with the integrated two-region neutron kinetics model.

direct-contact condenser, or open feedwater heater, was introduced. This component, modeled with the `ThermoPower.Water.SprayCondenser` component of the ThermoPower library [16], performs the preheating of the feedwater through direct mixing between the extracted steam and the feedwater flow.

The direct mixing of streams under conditions close to saturation introduces strong nonlinearities in the mass and energy balances, making the numerical stability of the component particularly challenging. To maintain the liquid inventory in the condenser and avoid complete emptying or flooding, the rotational speed of the second feedwater pump, P21, is regulated by a feedback control system.

The liquid level in the spray condenser is regulated by a Proportional-Integral controller, implemented using the standard `Modelica.Blocks.Continuous.LimPID` block of the Modelica Standard Library [9]; the block itself is therefore not an original development of this thesis. The controller compares the measured liquid-level fraction, taken directly from the `sprayCondenser.y` output, against a fixed setpoint of 0.736 – the same value used to initialize the level of the component ($y_0 = y_{\text{start}} = 0.736$), so that the regulator starts from a condition of zero initial error. The controller is configured in pure PI form, with integral time $T_i = 10$ s and no derivative action, in order to avoid introducing additional sensitivity to rapid numerical fluctuations while still eliminating the steady-state level error. The proportional gain is negative ($k = -2000$): since an increase in the pump rotational speed increases the liquid outflow and therefore reduces the level, a rise of the measured level above the setpoint must produce an increase, rather than a decrease, in the controller output, which is achieved precisely by a negative gain acting on the error $u_s - u_m$. The controller output directly sets the rotational speed of pump P21 and is saturated between $y_{\min} = 0$ and $y_{\max} = 3000$ rpm, reflecting the physical operating range of the pump, and is initialized at $y_{\text{start}} = 1500$ rpm, consistent with the nominal speed n_0 of P21.

The controller modifies the pump rotational speed and, consequently, the feedwater flow rate supplied to the secondary circuit. This regulation was found to be particularly important for obtaining a stable operating condition of the complete system. The complete Modelica source code of the thermo-hydraulic layout, including the two-region kinetic model, is reported in Appendix B.2.

Even with the control system, the initialization of the complete model remained more demanding than initializing the simplified configurations. Therefore, a sequential initialization procedure was adopted. In the first stage, a model with the same secondary-circuit layout

as the final configuration, but using an ideal heat source instead of the neutronic model, was simulated. This configuration provided a numerically more robust way of obtaining a stable thermal-hydraulic condition. The resulting state was stored in the `staz.mat` result file.

In the second stage, the `staz.mat` file was used to initialize the complete model, including the two-region neutron kinetics model. The variables shared by the two configurations were imported from the results file. In contrast, the treatment of variables exclusive to the neutronic model depended on the adopted initialization strategy, as discussed in Section 5.3. The layout of the model with the ideal heat source used during this procedure is reported in Figure 5.3.

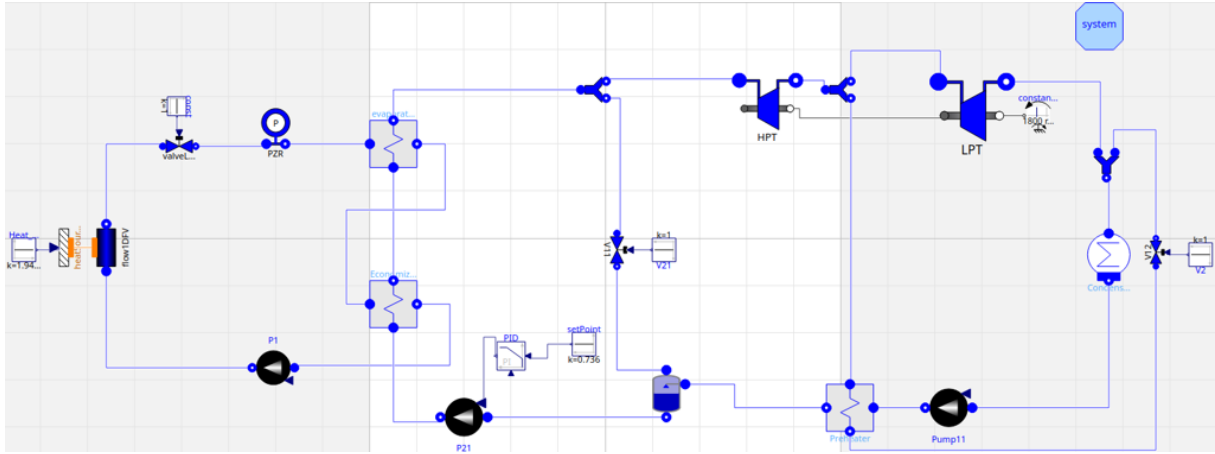


Figure 5.3: Complete plant layout with an ideal heat source used for the initialization procedure.

The ideal-heat-source simulation was run for 5000 s. As shown in Figures 5.4 and 5.5, the liquid and vapor volumes of the spray condenser, selected for this analysis because of its sensitivity to the coupled thermal-hydraulic conditions of the secondary circuit, and directly affected by the PI level-control loop described above, exhibit a damped oscillation that is already exhausted well before 1 ks, after which both quantities remain constant for the rest of the simulated interval, settling at 83.98 m^3 and 11.02 m^3 , respectively. Based on this evidence, the state of the system at $t = 2 \text{ ks}$ was selected, as a conservative choice, as the reference steady-state condition to be stored in the `staz.mat` result file and subsequently used to initialize the complete model.

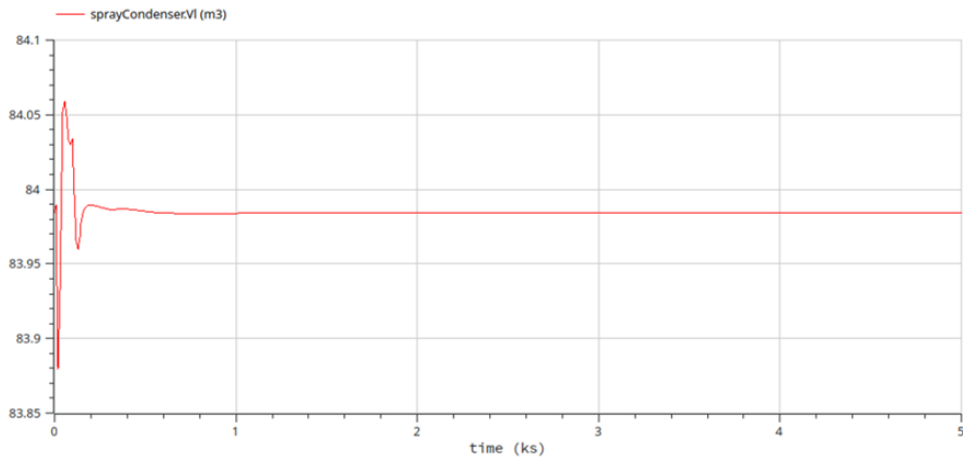


Figure 5.4: Liquid volume in the spray condenser during the ideal-heat-source settling simulation.

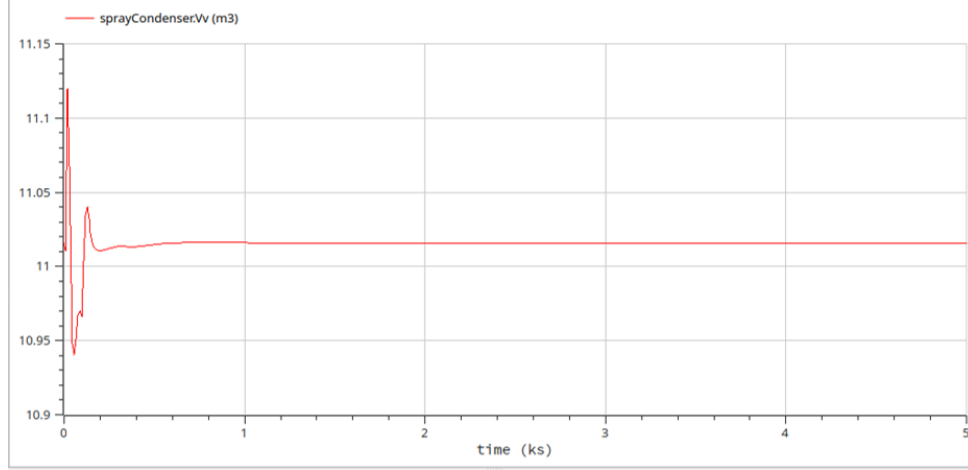


Figure 5.5: Vapor volume in the spray condenser during the ideal-heat-source settling simulation.

5.3 Initialization Strategies for the Two-Region Model

Two different approaches were investigated for initializing the complete coupled model, differing specifically in how the two bias reactivities of the two-region kinetic model are handled during initialization of the full thermo-hydraulic layout. The first approach was designed primarily to obtain a numerically stable initial configuration and to facilitate the convergence of the complete system. The two bias reactivities, $\rho_{\text{bias},1}$ and $\rho_{\text{bias},2}$, were calculated manually prior to the simulation. The mean moderator temperatures of the two axial regions, $T_{m,\text{Top}}(0)$ and $T_{m,\text{Bottom}}(0)$, were first extracted from the steady-state result of the ideal-heat-source simulation described in Section 5.2 (the same simulation used to generate `staz.mat`). Using the known moderator feedback coefficient α_{Tm} , each bias reactivity was then set to the value that exactly cancels the local moderator feedback evaluated at that temperature:

$$\rho_{\text{bias},i} = -\alpha_{Tm} (T_{m,i}(0) - T_{m,\text{ref}}), \quad i \in \{\text{Top}, \text{Bottom}\}, \quad (5.3)$$

so that, by construction, $\rho_i(0) = \rho_{\text{bias},i} + \rho_{Tm,i}(0) = 0$ for both regions independently. The definition of the bias reactivities and their role in obtaining the critical initial condition are otherwise identical to those already described in Chapter 4 and are not repeated here.

In this first approach, the previously generated `staz.mat` file was used to import the thermal-hydraulic variables. For the variables not present in the result file, namely n_1 , n_2 , C_1 , C_2 , and the two bias reactivities, none of which exist in the ideal-heat-source configuration, the none initialization option was selected in the *Simulation Setup*. As a consequence, these variables retain the initial conditions declared in the `Two_Zones_Kinetic` component itself, in particular $n_1(0) = n_2(0) = 0.5$ (declared as `start=0.5`, `fixed=true`), while $\rho_{\text{bias},1}$ and $\rho_{\text{bias},2}$ are fixed at the values calculated according to Eq. (5.3).

Although $T_{m,\text{Top}}(0)$ and $T_{m,\text{Bottom}}(0)$ are generally different, this procedure produces an initial state in which both regions are individually critical ($\rho_1(0) = \rho_2(0) = 0$) and carry the same neutron population ($n_1(0) = n_2(0) = 0.5$), and this near-symmetric configuration is found to persist throughout the entire first transient, resulting in the essentially identical values reported in Table 5.1 ($n_{\text{Top}} = n_{\text{Bottom}} = 0.5046$). The reason lies in how power is deposited in the reactor channel: the neutronic model outputs a single total power, $P = P_0(n_1 + n_2)$, connected to the heat source (`heatSource1DFV`), which distributes it uniformly along the channel independently of the internal split between n_1 and n_2 . The Top/Bottom temperature difference, $\Delta T_m(t) = T_{m,\text{Top}}(t) - T_{m,\text{Bottom}}(t)$, is therefore governed primarily by the total power

and by the fixed axial position of the two groups of nodes along the flow direction, rather than by which region nominally produced the power. Since the bias reactivities were calibrated to cancel exactly the initial value of this temperature difference, the local reactivity difference at any later time can be written as

$$\rho_1(t) - \rho_2(t) = \alpha_{T_m} [\Delta T_m(t) - \Delta T_m(0)]. \quad (5.4)$$

As long as the total power does not vary significantly during the settling transient, consistent with the total neutron density remaining close to its nominal value in both initialization strategies, $\Delta T_m(t)$ remains close to $\Delta T_m(0)$, and Eq. (5.4) implies $\rho_1(t) \approx \rho_2(t)$ for the whole transient. Combined with identical kinetic parameters and identical initial conditions for the two regions, this makes the governing equations for n_1 and n_2 effectively indistinguishable, so that $n_1(t) \approx n_2(t)$ is preserved throughout the first transient. The symmetric outcome obtained with this initialization strategy is therefore not a physical property of the reactor, but a consequence of forcing $n_1(0) = n_2(0)$ together with the absence of any axial resolution in the power deposition model.

A second approach was subsequently investigated to leave the determination of the initial-bias reactivities to the solver and to remove the artificial symmetry constraint identified above. In this case, the two bias reactivities were introduced as `Real` variables and their time derivatives were constrained to zero in the `equation` section:

$$\frac{d\rho_{\text{bias},1}}{dt} = 0, \quad \frac{d\rho_{\text{bias},2}}{dt} = 0. \quad (5.5)$$

For this strategy, the `none` option was *not* selected for the variables absent from `staz.mat`. As a result, the `fixed=true` attribute declared for n_1, n_2, C_1, C_2 in the `Two_Zones_Kinetic` component is no longer enforced: these variables, together with $\rho_{\text{bias},1}$ and $\rho_{\text{bias},2}$, are determined simultaneously by the solver as the self-consistent solution of

$$\dot{n}_1 = \dot{C}_1 = \dot{n}_2 = \dot{C}_2 = 0, \quad \frac{d\rho_{\text{bias},1}}{dt} = \frac{d\rho_{\text{bias},2}}{dt} = 0, \quad (5.6)$$

evaluated at the imported temperatures $T_{m,\text{Top}}(0)$ and $T_{m,\text{Bottom}}(0)$. Since n_1 and n_2 are no longer constrained to a common fixed value, the solver is free to find an initial equilibrium in which the two regions are unevenly populated already at $t = 0$, consistently with the local steady-state mechanism already discussed in Section 4.2. This is confirmed by Table 5.2, where the axial tilt is already present at the end of the first transient ($n_{\text{Top}} = 0.4892$, $n_{\text{Bottom}} = 0.5194$), rather than emerging only after the reactivity ramp.

Table 5.1 reports selected quantities obtained with the first strategy based on the pre-calculated ρ_{bias} values, whereas Table 5.2 reports the corresponding results obtained with the automated initialization procedure. The main difference between the two approaches therefore, concerns the neutronic distribution: the manual approach imposes an artificial axial symmetry through the combination of a fixed common starting value for n_1, n_2 and locally-zeroed bias reactivities, whereas the automated approach lets the solver determine a self-consistent, non-symmetric distribution directly from the imported moderator temperatures, consistent with the mechanism already discussed in Section 4.2. After the reactivity ramp is applied to the TOP region, both approaches converge to the same final state, with the neutron density decreasing to 0.3192 in the Top region and increasing to 0.6819 in the Bottom region, and the precursor concentrations following the same redistribution (256.1 and 547.2, respectively). This demonstrates that once the external perturbation dominates the local reactivity balance, the two initialization strategies become equivalent from the plant response perspective.

Table 5.1: Main system quantities at the end of the first and second transients using pre-calculated bias reactivities.

Quantity	End of First Transient	End of Second Transient
Thermal Power (W)	1.957×10^9	1.941×10^9
Neutron Density	1.009	1.001
Neutron Density (Top)	0.5046	0.3192
Neutron Density (Bottom)	0.5046	0.6819
Precursor Concentration (Total)	807.4	803.3
Precursor Concentration (Top)	403.7	256.1
Precursor Concentration (Bottom)	403.7	547.2
Moderator Temperature (Top) (K)	581.2	580.4
Moderator Temperature (Bottom) (K)	559.2	558.5
Liquid Volume in Spray Condenser (m ³)	83.98	83.98
Vapour Volume in Spray Condenser (m ³)	11.02	11.02
HPT Inlet Mass Flow (kg/s)	901.73	901.73
HPT Inlet Enthalpy (kJ/kg)	2802	2786
HPT Inlet Pressure (bar)	57.40	56.91
LPT Outlet Mass Flow (kg/s)	676.0	676.5
LPT Outlet Enthalpy (kJ/kg)	1864	1871
LPT Outlet Pressure (bar)	0.05	0.05

As established in Chapter 4 (Section 4.1), the secondary-side operating point is governed by only two externally imposed boundary conditions, i.e., the fixed rotational speed of the turbo-generator group (1800 rpm) and the fixed condensation pressure at the main condenser, with every other thermodynamic quantity following as a consequence of the reactor power delivered by the neutronic model; the underlying mechanisms are not repeated here. Under this framework, the close agreement between the two initialization strategies on every reported thermal-hydraulic quantity follows directly from the fact that both converge to essentially the same total reactor power, both before (1.966×10^9 W) and after (1.951×10^9 W, a reduction of approximately 15 MW) the reactivity insertion – the total power being set primarily by $n = n_1 + n_2$, which, as discussed above, is largely insensitive to how power is apportioned between the two axial regions. Consequently, the moderator temperatures, the spray-condenser liquid and vapor inventories, and the HPT/LPT inlet and outlet conditions are identical, within the reported numerical precision, in Tables 5.1 and 5.2.

The magnitude of the power reduction, approximately 0.8% of the nominal value, is considerably smaller than the corresponding excursion observed in the single-region models discussed in Chapter 4, and is consistent with the moderate power reduction already found for the two-region model in that chapter. As a result, the associated thermal-hydraulic response is comparatively small: the HPT inlet pressure decreases only marginally, from 57.40 bar to 56.91 bar, and the inlet enthalpy from 2802 kJ/kg to 2786 kJ/kg, while the HPT inlet mass flow rate remains unchanged at 901.73 kg/s. Unlike the single-region configurations of Chapter 4, where a larger power excursion required a comparatively larger adjustment of the mass flow rate along the fixed-speed pump characteristic, the smaller power variation obtained here with the two-region model produces only a slight increase in the LPT outlet mass flow rate, from 676.0 to 676.5 kg/s.

The liquid and vapor inventories of the spray condenser remain unchanged at 83.98 m³ and 11.02 m³, respectively, confirming that the PI-based level-control loop on pump P21, described in Section 5.2, effectively absorbs the perturbation without any lasting drift of the condenser inventory, despite the additional numerical sensitivity associated with the direct-contact mixing

Table 5.2: Main system quantities at the end of the first and second transients using the automated initialization procedure.

Quantity	End of First Transient	End of Second Transient
Thermal Power (W)	1.957×10^9	1.941×10^9
Neutron Density	1.009	1.001
Neutron Density (Top)	0.4892	0.3192
Neutron Density (Bottom)	0.5194	0.6819
Precursor Concentration (Total)	809.4	803.3
Precursor Concentration (Top)	392.6	256.1
Precursor Concentration (Bottom)	416.8	547.2
Moderator Temperature (Top) (K)	581.2	580.4
Moderator Temperature (Bottom) (K)	559.2	558.5
Liquid Volume in Spray Condenser (m ³)	83.98	83.98
Vapour Volume in Spray Condenser (m ³)	11.02	11.02
HPT Inlet Mass Flow (kg/s)	901.73	901.73
HPT Inlet Enthalpy (kJ/kg)	2802	2786
HPT Inlet Pressure (bar)	57.40	56.91
LPT Outlet Mass Flow (kg/s)	676.0	676.5
LPT Outlet Enthalpy (kJ/kg)	1864	1871
LPT Outlet Pressure (bar)	0.05	0.05

process. Therefore, the combination of the initialization procedure and the active control systems allows the complete model to maintain a stable operating condition. At the same time, the neutronic perturbation is introduced and propagated through the coupled plant model.

5.4 Comparative Performance Across Model Variants

To evaluate the progression of the modelling framework as a whole, a comparative synthesis was conducted across the three main plant configurations developed in this thesis: the *Control Rods Model* and the *Two-Zone Model*, both introduced in Chapter 4 with the two-turbine secondary layout, and the complete *Spray-Condenser Model* presented in this chapter, which additionally features the high-pressure steam extraction and the direct-contact spray condenser. While the first two configurations share an identical secondary-side layout and differ only in the neutronic representation of the core, the Spray-Condenser Model introduces a genuinely regenerative feedwater-heating scheme; comparing all three therefore makes it possible to separate the effect of the neutronic modeling choice from that of the thermodynamic cycle refinement. As in the two-region model already discussed, the neutronic behavior of the Spray-Condenser Model is governed by the coupling coefficient $D = 0.5$. The comparison covers both the baseline steady-state regime and the post-transient equilibrium following the same negative reactivity insertion of $-1 \times 10^{-3} \Delta k/k$ (-1 mk), introduced as a 2 s ramp, already used throughout Chapter 4. In both tables, all percentage power variables are normalized with respect to the same reference nominal thermal power, 1.94×10^9 W (1940 MW_{th}).

Table 5.3 reports the unperturbed operating condition of the three configurations. The core inlet and outlet temperatures are essentially unchanged across all three models, confirming that the primary side and the reactor core are unaffected by the secondary-circuit modifications. The main difference introduced by the Spray-Condenser Model lies in the feedwater conditions: the direct-contact regeneration raises the secondary-generator inlet temperature to 229.38 °C,

Table 5.3: Steady-state results prior to the negative reactivity insertion. The system is operating at 100% nominal power, and the transients have fully exhausted.

Parameter	Control Rods	Two-Zone	Spray-Condenser
	Model	Model	Model
Reactor Thermal Power (%)	105.10	105.22	101.25
Reactor Neutron Power (%)	105.10	105.22	101.25
Core Inlet Temperature (°C)	275.98	276.06	276.77
Core Outlet Temperature (°C)	316.95	317.06	316.25
Core Mean Temperature (°C)	297.00	297.09	297.00
Core Pressure (bar)	157.78	157.78	157.78
SG Primary Inlet Temperature (°C)	316.87	316.98	316.18
SG Primary Outlet Temperature (°C)	280.88	280.95	276.65
SG Primary Pressure (bar)	157.78	157.78	155
SG Primary Inlet Flow Rate (kg/s)	9206	9206	9206
Produced Steam Flow Rate (kg/s)	1076.19	1075.12	1086.15
Steam Production Pressure (bar)	56.98	57.02	57.35
SG Secondary Outlet Temperature (°C)	277.96	279.12	275.52
SG Secondary Inlet Temperature (°C)	213.47	213.61	229.38
Condensation Pressure (bar)	0.05	0.05	0.05
Steam to Turbine Flow Rate (kg/s)	1076.19	1075.12	901.73
Turbine Speed (rpm)	1800	1800	1800
Turbine Electricity Production (MW)	622.73	623.31	692.41
Thermodynamic Efficiency (%)	30.54	30.54	35.25

against approximately 213.5–213.6 °C in the two simpler configurations, at the cost of routing part of the produced steam to the extraction line rather than to the turbine (the flow rate reaching the turbine drops from about 1075–1076 kg/s to 901.73 kg/s, even though the total steam production is comparable). This trade-off, typical of a regenerative Rankine cycle, is reflected in a marked increase in the overall thermodynamic efficiency, from approximately 30.54% in the Control Rods and Two-Zone Models to 35.25% in the Spray-Condenser Model. The difference in equilibrium thermal power between the three configurations (from 101.25% to 105.22% of nominal) is a consequence of the same bias-reactivity mechanism discussed in Section 4.2, and depends on the specific initial temperature distribution obtained in each thermal-hydraulic layout; it is not repeated here.

Table 5.4 reports the corresponding asymptotic state after the reactivity ramp. In all three cases, the intrinsic moderator feedback is sufficient to bring the system smoothly to a new stable equilibrium, without oscillations or convergence issues. Consistently with the discussion in Chapter 4, the single-region Control Rods Model exhibits the largest power reduction (from 105.10% to 101.66%, i.e. about 3.44 percentage points), whereas both two-region-based configurations – the Two-Zone Model (from 105.22% to 104.61%, i.e. about 0.61 percentage points) and the Spray-Condenser Model (from 101.25% to 100.49%, i.e. about 0.76 percentage points) – show a substantially smaller excursion (about 0.6–0.8 percentage points), reflecting the

Table 5.4: Steady-state results following the negative reactivity insertion. The perturbation was introduced as a ramp with a duration of 2 s and an amplitude of -1×10^{-3} ; the data were extracted after the transients had fully decayed.

Parameter	Control Rods Model	Two-Zone Model	Spray-Condenser Model
Reactor Thermal Power (%)	101.66	104.61	100.49
Reactor Neutron Power (%)	101.66	104.61	100.49
Core Inlet Temperature (°C)	273.99	275.59	276.10
Core Outlet Temperature (°C)	314.05	316.45	315.42
Core Mean Temperature (°C)	294.50	296.54	296.24
Core Pressure (bar)	157.78	157.78	157.78
SG Primary Inlet Temperature (°C)	313.98	316.38	315.42
SG Primary Outlet Temperature (°C)	279.27	280.55	276.10
SG Primary Pressure (bar)	157.78	157.78	155
SG Primary Inlet Flow Rate (kg/s)	9206	9206	9206
Produced Steam Flow Rate (kg/s)	1097.07	1081.08	1085.82
Steam Production Pressure (bar)	56.16	56.79	56.88
SG Secondary Outlet Temperature (°C)	271.31	272.91	272.12
SG Secondary Inlet Temperature (°C)	207.43	212.58	228.56
Condensation Pressure (bar)	0.05	0.05	0.05
Steam to Turbine Flow Rate (kg/s)	1097.07	1081.08	901.73
Turbine Speed (rpm)	1800	1800	1800
Turbine Electricity Production (MW)	605.05	620.16	686.65
Thermodynamic Efficiency (%)	30.68	30.56	35.22

self-regulating capability of the axial neutron redistribution already highlighted in Section 4.2. Because the power variation is small in all three cases, the associated thermal-hydraulic response is limited: the steam production pressure decreases only slightly in every configuration, and the thermodynamic efficiency of the Spray-Condenser Model remains essentially unchanged, from 35.25% to 35.22%, confirming that the regenerative benefit introduced by the spray condenser is preserved under transient conditions and is not undermined by the reactivity perturbation.

The results of this final comparison confirm that the modeling framework developed throughout this thesis can accurately represent, within a single coherent Modelica environment, plant configurations of increasing physical detail, from the point-kinetics single-turbine model of the basic model to the two-region, regenerative-cycle configuration presented in this chapter. The advanced models preserve numerical robustness and a consistent thermo-neutronic response across all levels of complexity.

Chapter 6

Comparison with the Passive_PWR Plant Simulator from IAEA

This chapter is dedicated to the verification and comparison of the models developed in the preceding chapters. For this purpose, numerical results obtained from the Modelica implementation are benchmarked against those provided by the Advanced PWR Simulator, distributed by the International Atomic Energy Agency (IAEA) under its PC-based Nuclear Power Plant Simulators program [15].

The comparative evaluation is limited to steady-state operating conditions. No time-domain reactivity-insertion transient is reproduced in this comparison. As discussed in Section 6.3, this choice reflects a fundamental modeling divergence concerning Xenon-135, as well as the difficulty of obtaining a well-defined comparison point from quantities that are still rapidly evolving in time. As an alternative, two distinct steady-state operating points are compared instead: the nominal, 100% power condition (Section 6.2), and a partial-load condition at approximately 90% of the nominal thermal power (Section 6.4), reached through different means on the reference simulator and on the Modelica models but compared, in both cases, once every transient has fully decayed.

Specifically, for the steady-state benchmarking, three Modelica configurations are considered: the **Control Rods Model** and the **Two-Zone Model**, both based on the dual-turbine thermal-hydraulic layout without a spray condenser (reported in Appendix B.1), and the **Spray-Condenser Model**, based on the more complex layout incorporating the direct-contact spray condenser already described in Chapter 5 (reported in Appendix B.2). The single-point kinetics model was excluded from the comparison because its nominal steady-state response proved virtually identical to that of the Control Rods Model under the conditions investigated in this work.

In the following sections, the Two-Zone Model is used to describe the neutronic formulation adopted in the Modelica implementation, as it represents the more sophisticated of the two configurations and shares the layout without the spray condenser.

6.1 The Advanced PWR Simulator

The Advanced PWR Simulator is part of the suite of PC-based Nuclear Power Plant Simulators promoted by the IAEA for educational and training purposes [15]. Developed by Cassiopeia Technologies Inc. (CTI), the software models an advanced 600 MWe Pressurized Water Reactor equipped with passive safety systems, drawing its architectural layout from the Westinghouse AP600 design [15]. The simulator features an interactive graphical user interface (GUI) that

displays the primary and secondary loop topologies, enabling real-time monitoring of key process parameters and the execution of operational transients [15]. It is used as a reference for the comparative assessment of the Modelica framework due to its system-level representation and the availability of internal variables for analyzing both neutronic and thermal-hydraulic phenomena.

Calibration and parameter extraction were performed using several specific operational screens within the GUI:

- **PWR Plant Overview (Figure 6.1):** Illustrates the overall plant layout, including the two-loop primary architecture, pressurizer, steam generators, feedwater line, and turbine system. This schematic forms the topological baseline for the Modelica implementation.
- **Control/SD Rods & Reactivity (Figure 6.2):** Enables single-row and bank-level control rod management. It provides quantitative reactivity insertion data and spatial flux distribution maps within the core [15].
- **Reactor Power Control (Figure 6.3):** Allows power setpoint adjustments, selection of reactivity control modes (soluble boron vs. gray/dark control rod banks), and observation of automatic control logic responses [15]. Combined with Figure 6.2, this interface yielded the reactivity parameters and calibration curves used in the Modelica models.
- **PWR Trend Screen (Figure 6.4):** Serves as the primary data acquisition tool for time-series extraction (coolant/fuel temperatures, pressures, and steam flow rates), used to extract the steady-state operating points considered in the comparison.

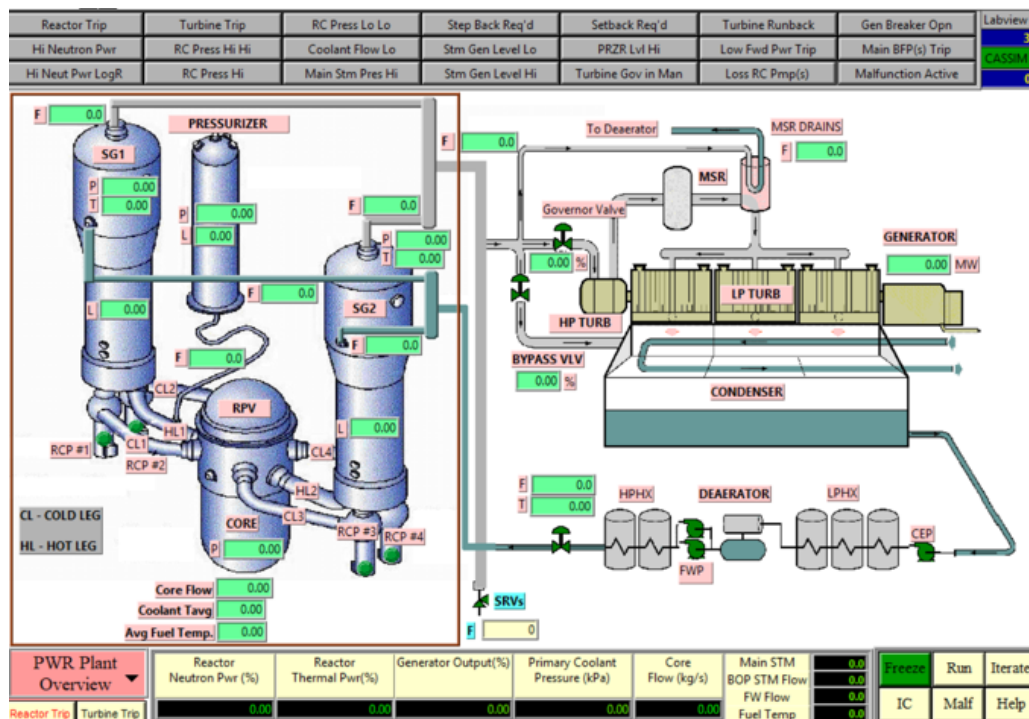


Figure 6.1: Advanced PWR Simulator: Plant Overview layout [15].

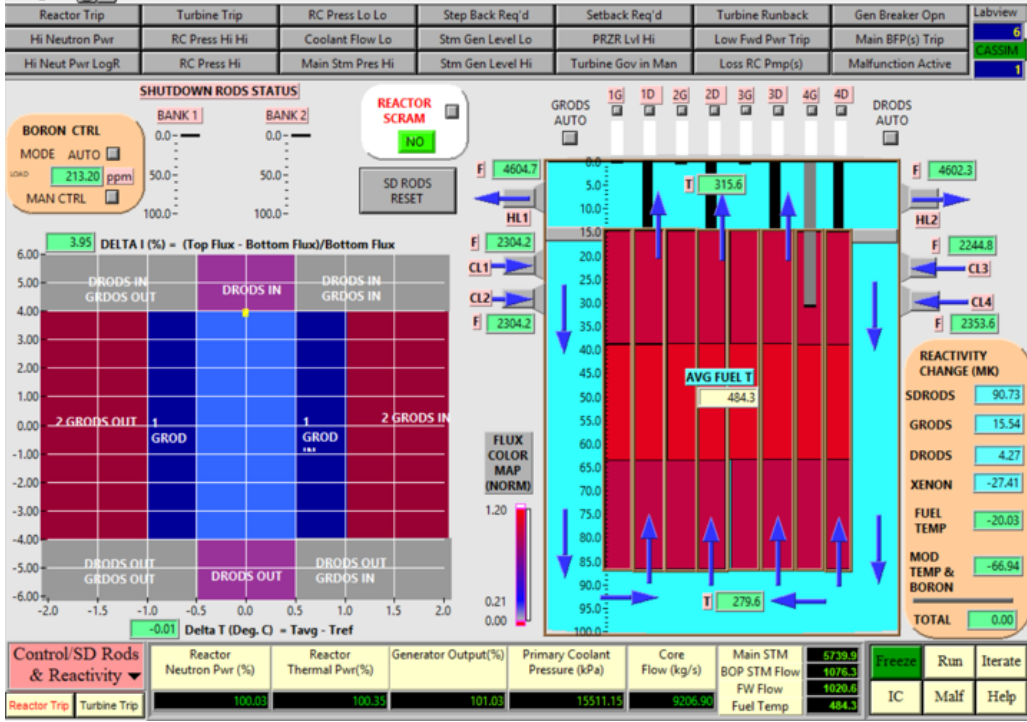


Figure 6.2: Advanced PWR Simulator: Control Rods and Reactivity interface [15].

6.1.1 Nodal Neutronics and Zone Reactivity

The simulator adopts a spatial kinetics approach grounded in Avery's coupled region kinetics theory [15]. The core is discretized into 12 nodes (zones) distributed over three axial levels (Upper, Middle, and Lower), with four nodes per level corresponding to the cross-sectional quadrants [15].

The neutronic dynamics of each node i ($i = 1, \dots, 12$) are governed by a coupled point-kinetics system with six delayed neutron precursor groups [15]:

$$\frac{dN_i(t)}{dt} = \frac{(K_i - \beta)N_i(t)}{T_{\text{NEUTRON}}} + \sum_{m=1}^6 \lambda_m C_{mi}(t) \quad (6.1)$$

$$\frac{dC_{mi}(t)}{dt} = \frac{\beta_m N_i(t)}{T_{\text{NEUTRON}}} - \lambda_m C_{mi}(t) \quad \text{for } m = 1, \dots, 6 \quad (6.2)$$

where the total delayed neutron fraction β is defined as the sum over all precursor groups [15]:

$$\beta = \sum_{m=1}^6 \beta_m \quad (6.3)$$

The parameter K_i is formally defined in the manual as the *zone multiplication* factor via [15]:

$$K_i = \frac{K_{ii} - 1}{K_{ii}} \quad (6.4)$$

where K_{ii} is the internal coupling coefficient of zone i [15]. Because this expression mirrors the classical reactivity definition, $\rho = (k - 1)/k$, and all feedback increments (K_{FUEL} , K_M , K_B , etc.)

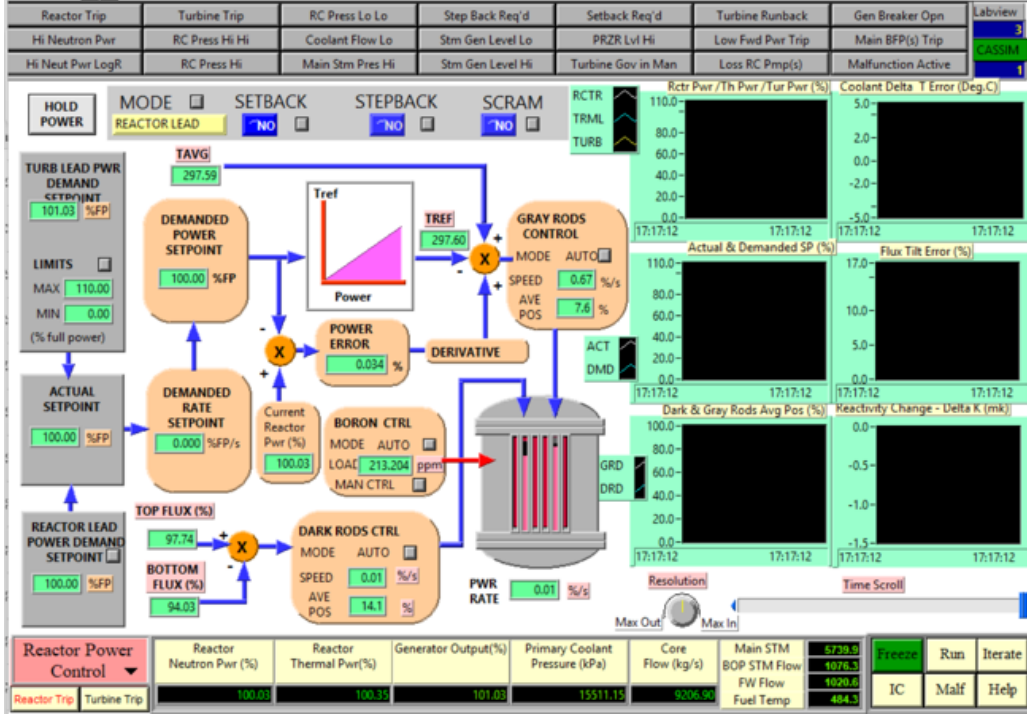


Figure 6.3: Advanced PWR Simulator: Power Setpoint and Control interface [15].

are expressed in milli-k (mk, where 1 mk = 0.001), K_i acts operationally as the net reactivity of node i [15]:

$$K_i = K_{C,i} + K_{M,i} + K_{B,i} + K_{XE,i} + K_{SDS,i} + K_{FUEL,i} + K_{DIFF,i} \quad (6.5)$$

The specific reactivity components are evaluated as follows [15]:

- **Doppler Effect:** Modeled via a quadratic temperature dependence in the fuel:

$$K_{FUEL,i} = a_1 \Delta T_{f,i} + a_2 (\Delta T_{f,i})^2 \quad (6.6)$$

- **Moderator Temperature ($K_{M,i}$) and Boron Concentration ($K_{B,i}$):** Evaluated as two separate contributions to the zone reactivity, combined for display purposes into the single “Moderator Temperature & Boron” reactivity indicator shown on the reactivity-change interface (Figure 6.2).
- **Xenon Poisoning:** Distributed uniformly across nodes using the empirical expression:

$$K_{XE,i} = 0.001 \times \frac{27.93 - C_{XE,i}}{12} \quad (6.7)$$

- **Control Systems ($K_{C,i}$):** Superimposes the absorption of gray and dark rod banks:

$$K_{C,i} = K_{GRAY,i} + K_{DARK,i} \quad (6.8)$$

- **Spatial Coupling ($K_{DIFF,i}$):** Accounts for mutual inter-node leakage using nominal coupling coefficients K_{ij}^0 and normalized gradients K_{ijk} .

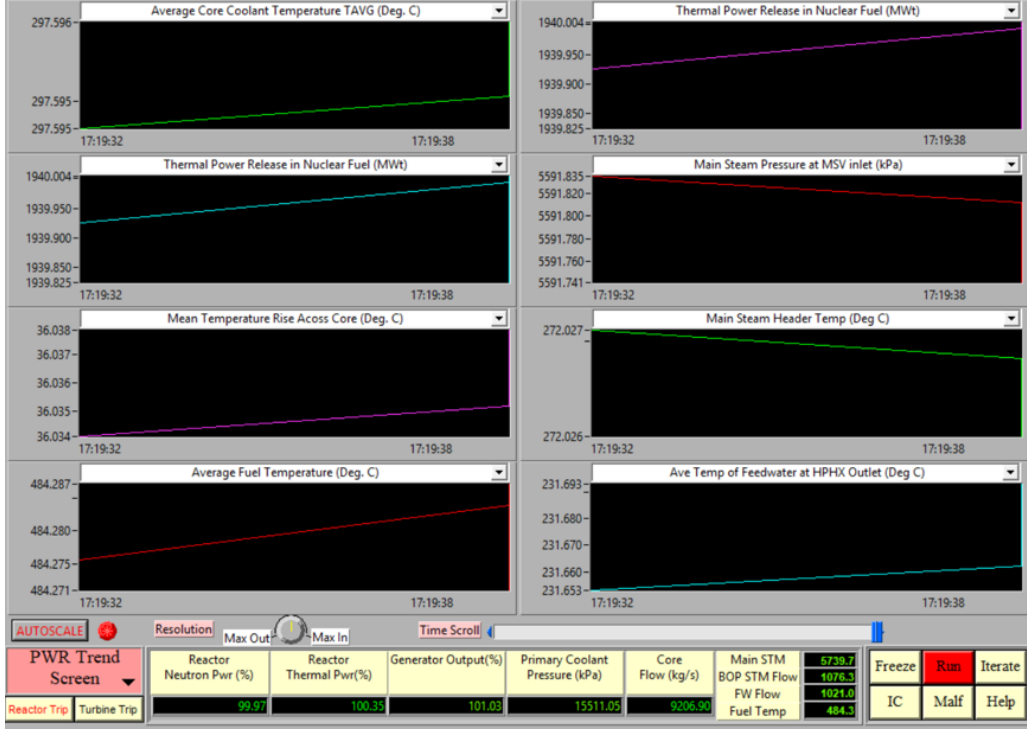


Figure 6.4: Advanced PWR Simulator: Trend Screen for dynamic data logging [15].

6.1.2 Primary Hydraulics, RCPs, and Secondary Circuit

The core thermal-hydraulics in the simulator are based on a lumped-parameter formulation structured as a *Nodal Flow Network* with four parallel channels [15]. Mass balance at pressure nodes,

$$C_N \frac{dP_N}{dt} = W_{IN} - W_{OUT}, \quad (6.9)$$

and momentum conservation in connections,

$$W = K \sqrt{\Delta P + P_{DYH}}, \quad (6.10)$$

are solved simultaneously with fuel rod heat conduction (UO_2) [15].

The fuel heat transfer is described by the following lumped equations:

$$C_1 \frac{dT_{1,i}}{dt} = Q_{n,i} - \frac{T_{1,i} - T_{2,i}}{R_{1,i}} \quad (6.11)$$

$$C_2 \frac{dT_{2,i}}{dt} = \frac{T_{1,i} - T_{2,i}}{R_{1,i}} - \frac{T_{2,i} - T_{c,i}}{R_{2,i}} \quad (6.12)$$

As depicted in Figure 6.5, coolant returning from the steam generators (SG1, SG2) is driven by four Reactor Coolant Pumps (RCPs) through cold legs (from CL1 to CL4) into the lower plenum. The flow splits into four parallel core channels (from Channel 1 to Channel 4), each divided axially into three hydraulic zones (*Lower, Middle, Upper*) matching the 12-node neutronic grid, before rejoining in the upper plenum towards the hot legs (HL1, HL2) [15]. The auxiliary plant dynamics within the simulator rely on the following formulations [15]:

- **Reactor Coolant Pumps (RCP):** Shaft angular momentum is resolved via:

$$I \frac{d\omega}{dt} \frac{2\pi}{60} = T_M - T_h - T_f \quad (6.13)$$

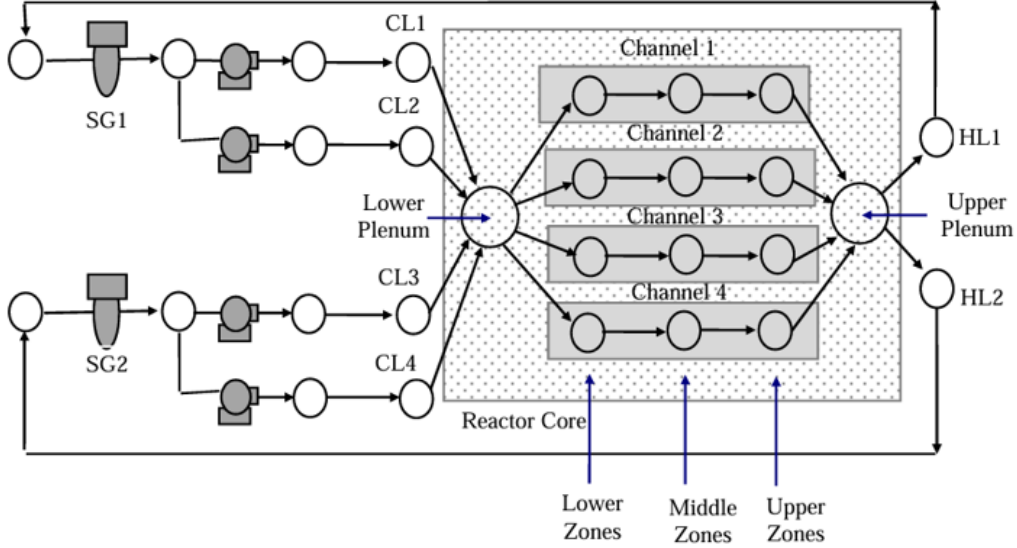


Figure 6.5: Coolant flow hydraulic network topology showing primary loops, core channels, and axial zoning [15].

where I is rotational inertia, ω is speed in RPM, T_M is motor torque, T_h is hydraulic load, and T_f is friction torque [15]. Hydraulic head and torque are computed using high-order polynomial fits of Stepanoff homologous curves [15].

- **Turbine Generator:** The simulator assumes direct proportionality between steam mass flow rate and generated electrical/mechanical power [15]. Steam flow through governor valves is calculated under choked flow conditions, governed by speeder gear settings and turbine governor control logics [15].

6.1.3 Comparison between the IAEA Simulator and the Modelica Implementation

The Modelica implementation replaces the 12-node 3D kinetics with an axial two-zone formulation (Upper n_1 , Lower n_2) using a single equivalent precursor group (β, λ) coupled spatially by:

$$\pm \frac{D}{l(1 - \beta) + \beta/\lambda} (n_2 - n_1) \quad (6.14)$$

This term represents a linear, symmetric approximation derived from finite-difference discretization of the 1D neutron diffusion equation.

The Two-Zone Model is used here as the reference Modelica configuration for the neutronic model, since it is the more spatially resolved of the two Modelica configurations included in the steady-state comparison. The Control Rods Model, also considered in Section 6.2, instead adopts a single-region, point-kinetics representation of the whole core: the reactivity associated with control rod motion is expressed as a function of a single, core-averaged rod position z (Section 4.3), rather than through the axial two-zone structure described above.

Starting from Avery's 12-node 3D coupled core model, asymmetric coupling matrices ($K_{ij} \neq K_{ji}$), and 6 delayed neutron groups, the reference simulator captures complex 3D-like localized phenomena, including axial and radial flux tilts resulting from asymmetric rod insertion [15]. Among the Modelica configurations, only the Two-Zone Model provides any

spatial resolution at all, and, due to its two-zone axial geometry, it is, in any case, restricted to purely axial flux redistribution (1D power tilts along the core height); it cannot resolve azimuthal or radial flux asymmetries. The Control Rods Model, being a single-region point-kinetic representation, does not resolve spatial flux distributions.

A comparable trade-off appears at the thermal-hydraulic level. The simulator provides a broader plant-level loop topology (a multi-loop primary circuit, four parallel core channels, and extensive control networks). However, it relies on lumped-parameter hydraulics and empirical component relations, such as linear proportionality of turbine power and the Stepanoff empirical curves used for the RCPs [15]. The Modelica implementation, conversely, adopts a simplified single-loop primary structure (a single equivalent steam generator and a reduced number of extraction-line stages) but represents the individual components through first-principles physical models. The core channel is modeled as a 1D distributed-parameter system, discretized using a finite-volume scheme that captures continuous axial temperature and density gradients, rather than the simulator's lumped nodal network. The turbine system is implemented via the `ThermoPower.Water.SteamTurbineStodola` component of the `ThermoPower` library [16], based on Stodola's ellipse law for multi-stage vapor expansion, in place of the linear flow-power scaling adopted by the simulator. The primary pumps are implemented via the `ThermoPower.Water.Pump` component of the same library [16], which models centrifugal pumps operating at an ideally controlled rotational speed ($n = n_{\text{int}}$), set either by a fixed parameter (n_{const}) or by an external speed signal (`in_n`); this bypasses the need to solve pump shaft torque balances and empirical homologous tables, at the cost of not representing the pump dynamics captured by the Stepanoff curves.

In summary, while the IAEA/CTI simulator prioritizes 3D neutronic spatial resolution and a multi-loop plant topology, coupled with lumped-parameter thermal-hydraulics, the Modelica framework emphasizes first-principles physical modeling of individual thermal-hydraulic components, with spatial resolution of neutronic behavior available only in the Two-Zone Model along the axial direction.

6.2 Steady-State Benchmarking at Nominal Power

The comparison of the steady-state results across the reference IAEA/CTI `Passive_PWR` simulator and the three Modelica model configurations at 100% nominal power is presented in Table 6.1. The core thermal-hydraulic quantities show close agreement between the simulator and all three Modelica configurations. The core mean temperature, in particular, differs by less than 1 °C in every case (297.6 °C in the simulator against 297.00–297.09 °C in the Modelica models), and the core outlet temperatures agree within approximately 1.5 °C. The core inlet temperature is systematically lower in the Modelica models by approximately 11–12 °C, which is consistent with the correspondingly larger inlet-to-outlet temperature rise. This discrepancy, however, does not affect the core-averaged condition, confirming that the same amount of thermal energy is removed from the core in both implementations. The primary-side steam generator pressure and mass flow rate are essentially identical between the simulator and every Modelica configuration (155.00–157.78 bar and 9206–9210.2 kg/s, respectively), as is the steam production pressure at the secondary-side outlet of the steam generator (56.98–57.35 bar against 57.40 bar), confirming that the steam generator sizing adopted throughout this thesis reproduces the reference operating point closely. The turbine rotational speed is identical in all four cases (1800 rpm), reflecting the same 60 Hz grid-frequency constraint discussed in Chapter 4 for the Modelica models, and evidently adopted as a fixed boundary condition in the reference simulator as well.

Table 6.1: Steady-state results at nominal power for the reference Passive_PWR simulator and the three Modelica model configurations. A dash indicates a quantity not extracted from the reference simulator.

Parameter	Simulator Passive_PWR	Control Rods Model	Two-Zone Model	Spray-Condenser Model
Reactor Thermal Power (%)	100.35	105.10	105.22	101.25
Reactor Neutron Power (%)	100.00	105.10	105.22	101.25
Core Inlet Temperature (°C)	287.6	275.98	276.06	276.77
Core Outlet Temperature (°C)	315.6	316.95	317.06	316.25
Core Mean Temperature (°C)	297.6	297.00	297.09	297.00
Core Pressure (bar)	155.01	157.78	157.78	157.78
SG Primary Inlet Temperature (°C)	315.6	316.87	316.98	316.18
SG Primary Outlet Temperature (°C)	287.6	280.88	280.95	276.65
SG Primary Pressure (bar)	155.10	157.78	157.78	155.00
SG Primary Inlet Flow Rate (kg/s)	9210.2	9206.00	9206.00	9206.00
Produced Steam Flow Rate (kg/s)	1075.2	1076.19	1075.12	1086.15
Steam Production Pressure (bar)	57.40	56.98	57.02	57.35
SG Secondary Outlet Temperature (°C)	272.0	277.96	279.12	275.52
SG Secondary Inlet Temperature (°C)	231.8	213.47	213.61	229.38
HPT Steam Flow Rate (kg/s)	1021.6	1076.19	1075.12	901.73
HPT Outlet Pressure (bar)	–	39.41	39.40	5.90
LPT Steam Flow Rate (kg/s)	–	660.96	659.98	675.94
Condensation Pressure (bar)	0.091	0.050	0.050	0.050
Turbine Speed (rpm)	1800	1800	1800	1800
HPT Power Production (MW)	–	73.76	74.49	327.55
LPT Power Production (MW)	–	548.97	548.82	364.85
Turbine Electricity Production (MW)	625.70	622.73	623.31	692.41
Thermodynamic Efficiency (%)	32.25	30.54	30.54	35.25

The remaining discrepancies can be traced to two structural differences between the simulator and the Modelica layouts. First, the condensation pressure is prescribed as a fixed boundary condition in the Modelica models at 0.05 bar via the `PrescribedPressureCondenser` component. In contrast, the simulator uses a higher fixed value of 0.091 bar [15]. The Spray-Condenser Model, based on the layout with the direct-contact spray condenser described in Chapter 5, reaches a feedwater temperature of 229.38 °C, closely matching the simulator’s 231.8 °C, at the cost of diverting part of the produced steam away from the turbines: the flow rate reaching the turbine drops to 901.73 kg/s, well below both the simulator’s 1021.6 kg/s and the values obtained with the non-regenerative Modelica layout. With the lower condensation pressure now combined with a feedwater temperature comparable to that of the reference simulator, the Spray-Condenser Model achieves the highest thermodynamic efficiency of the four cases (35.25%, against 32.25% for the simulator), along with the highest electrical power output (692.41 MW, against 625.70 MW).

The extracted HPT/LPT breakdown makes it possible to identify why the higher electrical

output is achieved despite the Spray-Condenser Model processing markedly less steam overall (901.73 kg/s at the HPT inlet, compared with 1076.19–1075.12 kg/s for the other two Modelica configurations). The HPT outlet pressure is substantially lower in the Spray-Condenser Model (5.90 bar, compared with 39.40–39.41 bar for the Control Rods and Two-Zone Models), resulting in a much larger enthalpy drop across the high-pressure stage. Consequently, the HPT alone produces 327.55 MW in the Spray-Condenser Model, compared with 73.76–74.49 MW in the other two configurations, despite handling a comparable or smaller mass flow rate. This difference is related to HPT sizing and, more importantly, to the different secondary-side layouts adopted in the two configurations, as reflected in the corresponding component parameters reported in Appendices B.1 and B.2. The HPT initial pressure ratio is $PR_{start} = 1.425$ in the layout without the spray condenser, compared with $PR_{start} = 9.676$ in the layout with the spray condenser. The latter configuration can therefore accommodate a much larger fraction of the overall expansion within the HPT because the feedwater preheating is not entirely dependent on the conditions at the HPT outlet. In the Spray-Condenser Model, the presence of an extraction line upstream of the turbine provides an additional steam source for feedwater preheating, allowing the HPT to expand the remaining steam to a substantially lower outlet pressure without requiring the HPT exhaust to provide the entire preheating duty. The resulting specific work extracted in the HPT is therefore roughly five times higher in the Spray-Condenser Model (approximately 0.363 MJ/kg, compared with 0.069–0.070 MJ/kg), which more than compensates for the reduced total mass flow rate and explains the higher overall electrical output. This behavior is consistent with the regenerative-cycle rationale discussed in Chapter 5.

Finally, the reactor thermal and neutron power levels obtained with the three Modelica configurations (from 101.25% to 105.22% of nominal, against 100.35% for the simulator) reflect the specific initial temperature distribution obtained in each thermal-hydraulic layout and the corresponding bias-reactivity mechanism already discussed in Section 4.2, rather than a discrepancy in the reactor physics itself; the same mechanism is responsible for the analogous power differences already discussed among the Modelica configurations in Chapter 5.

6.3 Rationale for a Steady-State, Rather than Transient, Comparison

As an alternative to the steady-state comparisons presented in this chapter, a time-domain comparison could in principle have been pursued, reproducing a reactivity-insertion transient on the reference simulator, i.e., a step or ramp insertion on one of the Gray or Dark Rod banks, and then comparing the resulting time evolution directly against the corresponding Modelica simulation. This possibility was considered, but ultimately not pursued, for two related reasons.

First, a fundamental modeling divergence concerning Xenon-135 poisoning would affect any such comparison. In the reference simulator, the dynamics of Iodine-135 and Xenon-135 are intrinsic and permanently hardcoded in FORTRAN for each of the 12 core nodes, with no possibility of deactivation [15]; in the Modelica models, this phenomenon is not implemented. Following any reactivity perturbation that reduces thermal power and neutron flux (ϕ), the resulting drop in the Xenon burnup removal channel ($-\sigma_X X \phi$) in the reference simulator is not matched by an equivalent drop in Xenon production, since the Iodine-135 accumulated during prior full-power operation continues to decay ($\lambda_I I$) with its own, much slower time constant of several hours [15]. This imbalance leads to a progressive accumulation of Xenon (C_{XE}), introducing an additional, slowly time-varying negative reactivity (K_{XE}) into the core of the reference simulator [15] that has no counterpart in the Modelica models. Any transient

comparison would therefore, over a sufficiently long time frame, be affected by a divergence between the two implementations that is unrelated to the neutron kinetics and thermal-hydraulic feedbacks that are actually of interest.

Second, independently of the Xenon issue, most process variables of interest, starting from core and steam generator temperatures, flow rates, and up to pressures, vary continuously, and often rapidly, for a significant portion of any such transient, in both the reference simulator and the Modelica models. A comparison based on a value extracted at some specific instant during this evolution would primarily reflect the essentially arbitrary choice of sampling time, rather than a genuine, reproducible difference between the two implementations. The comparison would therefore be of little significance and would not constitute a robust benchmark.

For these two reasons, a genuine steady-state comparison at two distinct operating points was adopted instead: the nominal, 100% power condition already discussed in Section 6.2, and a partial-load condition at approximately 90% of the nominal thermal power, presented in the following section. In both cases, the comparison is performed only once every transient in both simulators has fully decayed to a new steady state, so that the quantities being compared are well-defined and free from any ambiguity related to the sampling instant.

6.4 Partial-Load Comparison at 90% Nominal Power

As an alternative to a time-domain transient comparison, which was not pursued for the reasons discussed in Section 6.3, a finite-duration transient bringing the reactor to approximately 90% of the nominal thermal power was instead performed on both the reference simulator and the three Modelica configurations, and the two resulting steady states are compared.

This partial-load comparison was carried out with every automatic control system of the reference simulator left fully engaged. The reactor was operated in *Reactor Lead* mode, and the power setpoint of the Reactor Power Control (RPC) was reduced from 100% to 90%; the simulator's own control logic (soluble boron concentration, gray and dark rod banks, and the turbine governor) then autonomously drove the plant to the corresponding equilibrium. Because every control loop, including boron and rod compensation, remained active throughout, the simulator was allowed to run until the transient had fully decayed and a genuine steady state was reached, in which the Xenon-135 concentration had settled to its equilibrium value and was already compensated for by the automatic reactivity controls. At this steady state, the neutron power oscillates slightly around the 90% setpoint, settling between approximately 89.97% and 90.03%; the simulator values reported below were extracted at the instant corresponding to 90.03%, purely to ensure a consistent basis for data extraction, with no material effect on the comparison.

Since none of the Modelica configurations implements an automatic reactivity control loop, unlike the reference simulator, whose control architecture is described above, the same target was instead approached by manually inserting a negative reactivity step (or a combination of independent step insertions, in the two-zone-based configurations) directly into the neutronic component, and letting the moderator temperature feedback settle the system to a new equilibrium point close to 90% of the nominal thermal power. Specifically:

- For the **Control Rods Model**, a ramp reactivity insertion of amplitude -1 (in the normalized rod-position variable z , corresponding to a full-stroke withdrawal from the reference rod position z_0) was applied at $t = 1100$ s;
- For the **Two-Zone Model**, two independent ramp insertions of amplitude -2×10^{-2} and

-0.43×10^{-2} were applied to the upper- and lower-zone reactivity biases, respectively, at $t = 1100$ s;

- For the **Spray-Condenser Model**, the same two-zone strategy was adopted, with ramp amplitudes of -2×10^{-2} and -0.25×10^{-2} applied at $t = 5000$ s.

In all three cases, the amplitude of the inserted reactivity was tuned by trial and adjustment rather than derived analytically, since, unlike the reference simulator, where the RPC computes the exact compensation required, the Modelica models have no automatic mechanism relating a given reactivity insertion to the resulting steady-state power level; the final power level is instead the result of the balance between the imposed reactivity step and the self-limiting effect of the moderator temperature feedback.

Table 6.2: Comparison at approximately 90% of nominal thermal power for the reference Passive_PWR simulator and the three Modelica model configurations. A dash indicates a quantity not extracted from the reference simulator.

Parameter	Simulator Passive_PWR	Control Rods Model	Two-Zone Model	Spray-Condenser Model
Reactor Thermal Power (%)	90.65	91.41	90.33	90.44
Reactor Neutron Power (%)	90.03	91.41	90.33	90.44
Core Inlet Temperature (°C)	278.3	266.15	265.36	269.95
Core Outlet Temperature (°C)	310.9	303.46	302.35	306.44
Core Mean Temperature (°C)	294.62	285.14	284.19	288.54
Core Pressure (bar)	155.11	157.78	157.78	157.78
SG Primary Inlet Temperature (°C)	310.9	303.41	302.31	306.38
SG Primary Outlet Temperature (°C)	286.2	266.05	265.26	269.84
SG Primary Pressure (bar)	155.10	155.00	155.00	155.00
SG Primary Inlet Flow Rate (kg/s)	9205.4	9205.99	9205.99	9206.00
Produced Steam Flow Rate (kg/s)	961.0	1163.03	1170.61	1088.41
Steam Production Pressure (bar)	56.22	53.43	53.10	52.96
SG Secondary Outlet Temperature (°C)	273.30	268.13	267.73	267.57
SG Secondary Inlet Temperature (°C)	227.8	184.31	181.96	219.17
HPT Steam Flow Rate (kg/s)	961.2	1163.03	1170.61	901.73
HPT Outlet Pressure (bar)	–	38.41	38.29	5.65
LPT Steam Flow Rate (kg/s)	–	758.12	766.97	685.65
Condensation Pressure (bar)	0.091	0.05	0.05	0.05
Turbine Speed (rpm)	1800	1800	1800	1800
HPT Power Production (MW)	–	48.39	46.82	282.26
LPT Power Production (MW)	–	497.40	492.62	332.76
Turbine Electricity Production (MW)	568.28	545.79	539.43	615.02
Thermodynamic Efficiency (%)	32.31	30.78	30.78	35.06

Table 6.2 reports the resulting operating point for the reference simulator and for the three Modelica configurations, alongside the corresponding nominal-power values already presented in Table 6.1. All four models reach a thermal power level within approximately one percentage

point of the 90% target (90.33–91.41% against the simulator’s 90.65%), confirming that the manually tuned reactivity insertions adopted for the Modelica configurations were an adequate substitute for the closed-loop power setpoint reduction performed on the reference simulator. All three Modelica configurations report identical thermal and neutron power values at both the nominal and partial-load operating points (Tables 6.1 and 6.2), consistent with the direct proportionality $P = P_0 n$ adopted in the neutron kinetics formulation, regardless of whether a single-region or two-region representation is used.

As expected from the reduction in core power at an essentially unchanged primary mass flow rate (9205–9206 kg/s in all four cases), the core temperature rise decreases in every configuration, and the resulting core mean temperatures remain close to one another across the three Modelica models (284.19–288.54 °C), while running systematically below the simulator value (294.62 °C) by an amount consistent with the offset already observed at nominal power. The condensation pressure in the reference simulator is unchanged from its nominal-power value (0.091 bar in both cases), which further supports treating it as a fixed boundary condition in the simulator rather than a quantity actively recalculated with the operating point.

A structural difference already noted at nominal power is amplified at partial load. In the Control Rods and Two-Zone Models, the produced steam flow rate *increases* with respect to the corresponding nominal-power case (1066.00 → 1163.03 kg/s and 1064.26 → 1170.61 kg/s, respectively), despite the reduction in thermal power. This is a direct consequence of the fixed-speed feedwater pump (Pump11, operated at a constant 1500 rpm via `const1`) and of the fully open extraction valve (V12, permanently commanded to 1 via V2) in this layout: with no feedwater flow control responding to the reduced heat input, the feedwater temperature entering the steam generator drops markedly with respect to the nominal-power case (184.31 °C and 181.96 °C at partial load, against 214.53 °C and 214.68 °C at nominal power, for the Control Rods and Two-Zone Models respectively), and the secondary-side outlet temperature of the steam generator correspondingly drops close to saturation at the reduced production pressure (268.13 °C and 267.73 °C, against 289.69–291.85 °C at nominal power); a larger mass flow rate of nearly-saturated steam is thus required to carry the reduced thermal power, rather than a lower flow rate of superheated steam as in a load-following scheme. The Spray-Condenser Model exhibits the same qualitative feedwater-temperature drop, but far more contained (229.38 → 219.17 °C), since part of its feedwater heating comes from the controlled steam extraction to the spray condenser rather than from the fixed-speed pump alone; consistently, the flow rate of steam reaching the turbines remains identical between the nominal and 90%-power cases (901.73 kg/s in both), since the extraction flow rate to the spray condenser preheater (`Preheater.primaryFlow.w`) is itself fixed in the model equations, and the reduction in thermal power is instead absorbed through a lower steam production pressure (52.96 bar, against 57.35 bar at nominal power) and a correspondingly lower turbine electrical output (615.02 MW, against 692.41 MW). In all three configurations, the underlying cause is the absence, in the present Modelica implementation, of a feedwater or extraction control system capable of adjusting flow rates in response to a change in reactor power. This is a limitation of the current control architecture rather than of the underlying thermal-hydraulic modeling, and a natural candidate for improvement in the subsequent development of the model library.

Similarly to the nominal power case, the HPT/LPT breakdown clarifies the origin of the difference in electrical output between the configurations at partial load. The Spray-Condenser Model retains a markedly lower HPT outlet pressure (5.65 bar, against 38.29–38.41 bar for the other two configurations), so that, despite processing the smallest HPT steam flow rate (901.73 kg/s, against 1163.03–1170.61 kg/s), it produces by far the largest share of power in the high-pressure stage alone (282.26 MW, against 46.82–48.39 MW), for the same structural reason

already identified at nominal power (Section 6.2). This confirms that the higher thermodynamic efficiency of the Spray-Condenser Model and the associated difference in electrical output relative to the other two Modelica configurations are consistently preserved from nominal down to partial-load operation.

Finally, the electrical power output decreases in every Modelica configuration relative to its own nominal-power case (e.g. $628.54 \rightarrow 545.79$ MW for the Control Rods Model), consistent with the reduced steam production pressure and, in the Spray-Condenser Model, the reduced turbine flow rate; the same downward trend is observed in the reference simulator ($625.70 \rightarrow 568.28$ MW). This confirms that, notwithstanding the absence of an automatic control system in the Modelica models, the combination of a manually inserted reactivity step and the intrinsic moderator temperature feedback is sufficient to reproduce a physically consistent partial-load operating point qualitatively comparable to that obtained by the reference simulator through its closed-loop Reactor Lead control.

Chapter 7

Conclusions

The work carried out in this thesis resulted in a first set of reusable Modelica components and plant layouts for the dynamic simulation of Pressurized Water Reactor (PWR) systems. Building on the initial coupled neutronic and thermal-hydraulic model, the activity progressively expanded both the physical representation and the range of reusable components, providing a basis for further developments in the author's doctoral research.

From the neutronic standpoint, the extension from the original point-kinetics formulation to a two-zone axial model provided a simple means of investigating the effect of spatial coupling within the reactor core. The parametric analysis showed the expected transition from distinct neutron populations under weak coupling towards a progressively more uniform distribution as the coupling coefficient increased. The subsequent inclusion of control rod dynamics extended the model to account for a spatially dependent reactivity contribution based on rod insertion depth. The consistency of this formulation was verified by comparing its response with that of the point-kinetics model under equivalent variations in net reactivity.

The thermal-hydraulic development resulted in progressively more detailed representations of the secondary-side system. The resulting layouts ranged from simpler single-turbine configurations to systems including two turbine stages, steam extraction, feedwater preheating, and a direct-contact spray condenser. The comparison of these configurations showed that the inclusion of regeneration modifies the energy distribution within the cycle, leading to higher thermodynamic efficiency and electrical output. In particular, the Spray-Condenser Model achieved higher performance despite processing a lower overall steam flow rate, with the turbine analysis indicating that this behavior is primarily attributable to the larger enthalpy drop across its high-pressure turbine stage.

The increasingly complex models also required suitable initialization procedures. The use of previously generated .mat simulation states provided a practical method for transferring consistent operating conditions between configurations and facilitating convergence towards the desired steady states. The two initialization strategies investigated for the bias reactivities of the two-zone model converged to the same post-transient equilibrium, although they produced different initial axial neutron distributions.

The comparison with the *Advanced PWR Simulator* distributed by the International Atomic Energy Agency (IAEA) served as the primary assessment of the developed configurations. At nominal power, the three Modelica configurations showed close agreement with the reference values for the reactor thermal power and for the principal thermal-hydraulic quantities, including core temperatures, primary-side pressure, and steam-generator mass flow rate. The remaining differences in efficiency and feedwater temperature were consistent with identifiable differences in plant layout, particularly the presence or absence of feedwater regeneration and the different

treatment of condenser pressure.

The partial-load comparison further showed that the models remain physically consistent away from the nominal operating point. All three configurations were brought to a power level within approximately one percentage point of the 90% target through manually tuned reactivity insertions, despite the absence of an automatic reactivity control system in the Modelica models. The comparison also highlighted a limitation that becomes particularly relevant under load-following conditions. In the non-regenerative configurations, the fixed-speed feedwater pump maintains an approximately unchanged volumetric flow rate when reactor power is reduced, resulting in an increase in the produced steam flow rate rather than the expected reduction. The effect is considerably less pronounced in the Spray-Condenser Model due to controlled steam extraction to the spray condenser. This behavior identifies feedwater and extraction-flow control as a key area for further development.

Overall, the activity undertaken during the thesis established a first reusable modeling framework rather than a single plant-specific model. The developed components include the `Evaporator_Water` and `Economizzatore_Water` on the thermal-hydraulics side, and `Single_Point_Kinetics_Model` and `Two_Zone_Kinetics_Model` on the neutronics side, and `Control_Rod_Kinetics_Model` for reactivity control. These components can be combined with standard ThermoPower and Modelica Standard Library components to construct plant layouts of different levels of complexity. Together with the system-level configurations developed throughout the work, they constitute a foundational basis for a dedicated, progressively extensible library for the dynamic simulation of nuclear energy systems.

The benchmark also highlighted the main limitations of the current framework. In particular, the absence of Iodine-135/Xenon-135 dynamics prevents a fully consistent time-domain comparison with the reference simulator for transients in which xenon effects are relevant. At the same time, the limited load-dependent control of feedwater and steam-extraction flows constrains the present load-following capability. Addressing these aspects represents the main direction for future development. The introduction of Iodine-135 and Xenon-135 dynamics will allow more complete transient comparisons, while improved feedwater and extraction-flow control will provide a more realistic response under variable-load conditions. Building on the framework established through the thesis, these developments will support the subsequent extension towards Small Modular Reactor configurations and the consolidation of a reusable Modelica library for nuclear energy systems.

Appendix A

Modelica Source Codes

This appendix reports the Modelica source code of the main thermal-hydraulic and neutronic components developed during the internship and thesis activities. These components form the basis of the Modelica library developed in this work.

A.1 Evaporator Water-to-Water

The following code implements the `Evaporator_Water` component, which models heat transfer between a single-phase primary flow and a two-phase secondary flow. The same component can also be used as a preheater.

```
1  model Evaporator_Water "Evaporator Water-Water"
2
3  import SI = Modelica.Units.SI;
4  import ThermoPower.Choices;
5
6  // Fluidi
7  replaceable package PrimaryMedium =
8    ThermoPower.Water.StandardWater
9    constrainedby Modelica.Media.Interfaces.PartialPureSubstance
10    "Primary side fluid";
11
12  replaceable package SecondaryMedium =
13    ThermoPower.Water.StandardWater
14    constrainedby Modelica.Media.Interfaces.PartialPureSubstance
15    "Secondary side fluid";
16
17  parameter Integer N_primary = 8 "Number of node of the primary side";
18  parameter Integer N_secondary = 8 "Number of node of the secondary side";
19
20  // Nominal parameters
21  parameter SI.MassFlowRate primaryNomFlowRate "Nominal flow rate through the
    primary side";
22  parameter SI.MassFlowRate secondaryNomFlowRate "Nominal flow rate through the
    secondary side";
23  parameter SI.Pressure primaryNomPressure "Nominal pressure in the primary side
    inlet";
24  parameter SI.Pressure secondaryNomPressure "Nominal pressure in the secondary
    side inlet";
25
26  // Physical parameters
```

```

27 parameter SI.Area exchSurface_primary "Exchange surface between primary - metal
    tube (Inside)";
28 parameter SI.Area exchSurface_secondary "Exchange surface between metal tube -
    secondary (Outside)";
29 parameter SI.Area extSurfaceTub "Total external surface of the tubes";
30 parameter SI.Volume primaryVol "Primary volume (Inside tubes)";
31 parameter SI.Volume secondaryVol "Secondary volume (Shell/Outside)";
32
33 // Metal Wall
34 parameter SI.Volume metalVol "Volume of the metal part in the tubes";
35 parameter Real rhomcm "Metal heat capacity per unit volume [J/m^3.K]";
36 parameter SI.ThermalConductivity lambda "Thermal conductivity of the metal";
37
38 // Start values
39 parameter SI.SpecificEnthalpy hstart_primary "Primary side start enthalpy"
    annotation(Dialog(tab="Initialization"));
40 parameter SI.SpecificEnthalpy hstart_secondary "Secondary side start enthalpy"
    annotation(Dialog(tab="Initialization"));
41 parameter SI.SpecificEnthalpy hstartout_primary "Primary side start out
    enthalpy" annotation(Dialog(tab="Initialization"));
42 parameter SI.SpecificEnthalpy hstartout_secondary "Secondary side start out
    enthalpy" annotation(Dialog(tab="Initialization"));
43
44 parameter SI.Temperature Tstart_M "Average metal wall temperature start value"
    annotation(Dialog(tab = "Initialization"));
45
46 parameter Choices.FluidPhase.FluidPhases PrimaryPhaseStart = Choices.FluidPhase
    .FluidPhases.Liquid "Initialization fluid phase for primary" annotation(Dialog
    (tab="Initialization"));
47 parameter Choices.FluidPhase.FluidPhases SecondaryPhaseStart = Choices.
    FluidPhase.FluidPhases.TwoPhases "Initialization fluid phase for secondary"
    annotation(Dialog(tab="Initialization"));
48
49 parameter Choices.Init.Options initOptPrimary = Choices.Init.Options.
    steadyState "Initialization Option Primary";
50 parameter Choices.Init.Options initOptSecondary = Choices.Init.Options.
    steadyState "Initialization Option Secondary";
51
52 // Heat Transfer
53 parameter SI.CoefficientOfHeatTransfer gamma_primary "Constant heat transfer
    coefficient in the primary side";
54 parameter SI.CoefficientOfHeatTransfer gamma_nom_liq "Constant heat transfer
    coefficient secondary (Liquid)";
55 parameter SI.CoefficientOfHeatTransfer gamma_nom_2ph "Constant heat transfer
    coefficient secondary (2Ph)";
56 parameter SI.CoefficientOfHeatTransfer gamma_nom_vap "Constant heat transfer
    coefficient secondary (Vapor)";
57
58 // Friction
59 parameter Choices.Flow1D.FFtypes FFtype_primary = Choices.Flow1D.FFtypes.
    NoFriction "Friction Factor Type, primary side";
60 parameter Real Kfnom_primary = 0 "Nominal hydraulic resistance coefficient,
    primary side";
61 parameter SI.PressureDifference dpnom_primary = 0 "Nominal pressure drop,
    primary side (friction term only!)";
62 parameter SI.Density rhonom_primary = 0 "Nominal inlet density, primary side";
63 parameter Real Cfnom_primary = 0 "Nominal Fanning friction factor, primary side
    ";

```

```

64 parameter Choices.Flow1D.HCtypes Hctype_primary = Choices.Flow1D.HCtypes.
    Downstream "Location of the hydraulic capacitance, primary side";
65
66 parameter Choices.Flow1D.FFtypes FFtype_secondary = Choices.Flow1D.FFtypes.
    NoFriction "Friction Factor Type, secondary side";
67 parameter Real Kfnom_secondary = 0 "Nominal hydraulic resistance coefficient,
    secondary side";
68 parameter SI.PressureDifference dpnom_secondary = 0 "Nominal pressure drop,
    secondary side (friction term only!)" ;
69 parameter SI.Density rhonom_secondary = 0 "Nominal inlet density, secondary
    side";
70 parameter Real Cfnom_secondary = 0 "Nominal Fanning friction factor, secondary
    side";
71
72 parameter Boolean counterCurrent = true "Counter-current flow";
73 constant Real pi = Modelica.Constants.pi;
74
75 final parameter SI.Distance L = 1 "Reference Length (Dummy, geometry is
    volumetrically scaled)";
76
77 // Flanges
78 ThermoPower.Water.FlangeA primaryIn(redeclare package Medium = PrimaryMedium)
    annotation(Placement(transformation(extent = {{-120, -20}, {-80, 20}})));
79 ThermoPower.Water.FlangeB primaryOut(redeclare package Medium = PrimaryMedium)
    annotation(Placement(transformation(extent = {{80, -20}, {120, 20}})));
80 ThermoPower.Water.FlangeA secondaryIn(redeclare package Medium =
    SecondaryMedium) annotation(Placement(transformation(extent = {{-20, 80}, {20,
    120}})));
81 ThermoPower.Water.FlangeB secondaryOut(redeclare package Medium =
    SecondaryMedium) annotation(Placement(transformation(extent = {{-20, -120},
    {20, -80}})));
82
83 // --- FLOW COMPONENTS ---
84
85 // Primary Flow (Inside Tubes)
86 ThermoPower.Water.Flow1DFV primaryFlow(
87     Nt = 1,
88     N = N_primary,
89     wnom = primaryNomFlowRate,
90     redeclare package Medium = PrimaryMedium,
91     L = exchSurface_primary^2/(primaryVol*pi*4),
92     A = (primaryVol*4/exchSurface_primary)^2/4*pi,
93     omega = primaryVol*4/exchSurface_primary*pi,
94     Dhyd = primaryVol*4/exchSurface_primary,
95     FFtype = FFtype_primary,
96     dpnom = dpnom_primary,
97     rhonom = rhonom_primary,
98     HydraulicCapacitance = Hctype_primary,
99     Kfnom = Kfnom_primary,
100     Cfnom = Cfnom_primary,
101     FluidPhaseStart = PrimaryPhaseStart,
102     pstart = primaryNomPressure,
103     hstartin = hstart_primary,
104     hstartout = hstartout_primary,
105     initOpt = initOptPrimary,
106     redeclare model HeatTransfer = ThermoPower.Thermal.HeatTransferFV.
    ConstantHeatTransferCoefficient(gamma = gamma_primary)) annotation(Placement(
    transformation(extent = {{-20, -76}, {20, -36}})));

```

```

107
108 // Metal Tube (The Wall)
109 ThermoPower.Thermal.MetalTubeFV metalTube(
110     rhomcm = rhomcm,
111     lambda = lambda,
112     L = exchSurface_primary^2/(primaryVol*pi*4),
113     rint = primaryVol*4/exchSurface_primary/2,
114     WallRes = false,
115     rext = (metalVol + primaryVol)*4/extSurfaceTub/2,
116     Tstartbar = Tstart_M,
117     Nw = N_primary - 1) annotation(Placement(transformation(extent = {{-20, 0},
118     {20, -40}})));
118
119 // Secondary Flow (Outside Tubes - Shell side) - Two Phase Model
120 ThermoPower.Water.Flow1DFV2ph secondaryFlow(
121     Nt = 1,
122     N = N_secondary,
123     wnom = secondaryNomFlowRate,
124     redeclare package Medium = SecondaryMedium,
125     L = L,
126     A = secondaryVol/L,
127     omega = exchSurface_secondary/L,
128     Dhyd = 1,
129     FFtype = FFtype_secondary,
130     dpnom = dpnom_secondary,
131     rhonom = rhonom_secondary,
132     Kfnom = Kfnom_secondary,
133     Cfnom = Cfnom_secondary,
134     FluidPhaseStart = SecondaryPhaseStart,
135     pstart = secondaryNomPressure,
136     hstartin = hstart_secondary,
137     hstartout = hstartout_secondary,
138     initOpt = initOptSecondary,
139     redeclare model HeatTransfer = ThermoPower.Thermal.HeatTransferFV.
    FlowDependentHeatTransferCoefficient2ph(
140         gamma_nom_liq = gamma_nom_liq,
141         gamma_nom_2ph = gamma_nom_2ph,
142         gamma_nom_vap = gamma_nom_vap,
143         wnom_ht = secondaryNomFlowRate)) annotation(Placement(transformation(extent
    = {{-20, 60}, {20, 20}})));
144
145 // Counter Current Bridge
146 ThermoPower.Thermal.CounterCurrentFV cC(Nw = N_primary - 1) annotation(
    Placement(transformation(extent = {{-20, -8}, {20, 32}})));
147
148 equation
149     connect(secondaryFlow.infl, secondaryIn);
150     connect(secondaryFlow.outfl, secondaryOut);
151     connect(primaryFlow.outfl, primaryOut);
152     connect(primaryFlow.infl, primaryIn);
153
154 // Thermal Connections
155     connect(metalTube.ext, cC.side2);
156     connect(metalTube.int, primaryFlow.wall);
157     connect(secondaryFlow.wall, cC.side1);
158
159 annotation(
160     Diagram(coordinateSystem(preserveAspectRatio = false, extent = {{-100, -100},

```

```

    {100, 100}})),
161   Icon(graphics = {Rectangle(extent = {{-100, 100}, {100, -100}}, lineColor =
    {0, 0, 255}, fillColor = {230, 230, 230}, fillPattern = FillPattern.Solid),
    Line(points = {{0, -80}, {0, -40}, {40, -20}, {-40, 20}, {0, 40}, {0, 80}},
    color = {0, 0, 255}), Text(extent = {{-100, -115}, {100, -145}}, lineColor =
    {85, 170, 255}, textString = "%name"))},
162   Documentation(revisions = "<html><ul><li><i>Updated</i>: Volumetric Geometry
    adaptation for Water-Water.</li></ul></html>", info = "<html></html>"));
163 end Evaporator_Water;

```

A.2 Economizer Water-to-Water

The following code implements the Economizzatore_Water component, which models heat transfer between single-phase flows on the primary and secondary sides.

```

1  model Economizzatore_Water "Economizzatore Water-Water (1-Phase Both Sides)"
2
3  import SI = Modelica.Units.SI;
4  import ThermoPower.Choices;
5
6  // Fluidi
7  replaceable package PrimaryMedium = ThermoPower.Water.StandardWater
    constrainedby Modelica.Media.Interfaces.PartialPureSubstance "Primary side
    fluid";
8  replaceable package SecondaryMedium = ThermoPower.Water.StandardWater
    constrainedby Modelica.Media.Interfaces.PartialPureSubstance "Secondary side
    fluid";
9
10 parameter Integer N_primary = 2 "Number of node of the primary side";
11 parameter Integer N_secondary = 2 "Number of node of the secondary side";
12
13 // Nominal parameters
14 parameter SI.MassFlowRate primaryNomFlowRate "Nominal flow rate through the
    primary side";
15 parameter SI.MassFlowRate secondaryNomFlowRate "Nominal flow rate through the
    secondary side";
16 parameter SI.Pressure primaryNomPressure "Nominal pressure in the primary side
    inlet";
17 parameter SI.Pressure secondaryNomPressure "Nominal pressure in the secondary
    side inlet";
18
19 // Physical parameters
20 parameter SI.Area exchSurface_primary "Exchange surface between primary - metal
    tube (Inside)";
21 parameter SI.Area exchSurface_secondary "Exchange surface between metal tube -
    secondary (Outside)";
22 parameter SI.Area extSurfaceTub "Total external surface of the tubes";
23 parameter SI.Volume primaryVol "Primary volume (Inside tubes)";
24 parameter SI.Volume secondaryVol "Secondary volume (Shell/Outside)";
25
26 // Metal Wall
27 parameter SI.Volume metalVol "Volume of the metal part in the tubes";
28 parameter Real rhomcm "Metal heat capacity per unit volume [J/m^3.K]";
29 parameter SI.ThermalConductivity lambda "Thermal conductivity of the metal";
30

```

```

31 // Start values
32 parameter SI.SpecificEnthalpy hstart_primary "Primary side start enthalpy"
   annotation(Dialog(tab="Initialization"));
33 parameter SI.SpecificEnthalpy hstart_secondary "Secondary side start enthalpy"
   annotation(Dialog(tab="Initialization"));
34 parameter SI.SpecificEnthalpy hstartout_primary "Primary side start out
   enthalpy" annotation(Dialog(tab="Initialization"));
35 parameter SI.SpecificEnthalpy hstartout_secondary "Secondary side start out
   enthalpy" annotation(Dialog(tab="Initialization"));
36
37 parameter SI.Temperature Tstart_M "Average metal wall temperature start value"
   annotation(Dialog(tab = "Initialization"));
38
39 parameter Choices.FluidPhase.FluidPhases PrimaryPhaseStart = Choices.FluidPhase
   .FluidPhases.Liquid "Initialization fluid phase for primary" annotation(Dialog
   (tab="Initialization"));
40 parameter Choices.FluidPhase.FluidPhases SecondaryPhaseStart = Choices.
   FluidPhase.FluidPhases.Liquid "Initialization fluid phase for secondary"
   annotation(Dialog(tab="Initialization"));
41
42 parameter Choices.Init.Options initOptPrimary = Choices.Init.Options.
   steadyState "Initialization Option Primary";
43 parameter Choices.Init.Options initOptSecondary = Choices.Init.Options.
   steadyState "Initialization Option Secondary";
44
45 // Heat Transfer (Constant for both sides in an economizer)
46 parameter SI.CoefficientOfHeatTransfer gamma_primary "Constant heat transfer
   coefficient in the primary side";
47 parameter SI.CoefficientOfHeatTransfer gamma_secondary "Constant heat transfer
   coefficient in the secondary side";
48
49 // Friction
50 parameter Choices.Flow1D.FFtypes FFtype_primary = Choices.Flow1D.FFtypes.
   NoFriction "Friction Factor Type, primary side";
51 parameter Real Kfnom_primary = 0 "Nominal hydraulic resistance coefficient,
   primary side";
52 parameter SI.PressureDifference dpnom_primary = 0 "Nominal pressure drop,
   primary side (friction term only!)" ;
53 parameter SI.Density rhonom_primary = 0 "Nominal inlet density, primary side";
54 parameter Real Cfnom_primary = 0 "Nominal Fanning friction factor, primary side
   ";
55 parameter Choices.Flow1D.HCtypes HCtype_primary = Choices.Flow1D.HCtypes.
   Downstream "Location of the hydraulic capacitance, primary side";
56
57 parameter Choices.Flow1D.FFtypes FFtype_secondary = Choices.Flow1D.FFtypes.
   NoFriction "Friction Factor Type, secondary side";
58 parameter Real Kfnom_secondary = 0 "Nominal hydraulic resistance coefficient,
   secondary side";
59 parameter SI.PressureDifference dpnom_secondary = 0 "Nominal pressure drop,
   secondary side (friction term only!)" ;
60 parameter SI.Density rhonom_secondary = 0 "Nominal inlet density, secondary
   side";
61 parameter Real Cfnom_secondary = 0 "Nominal Fanning friction factor, secondary
   side";
62 parameter Choices.Flow1D.HCtypes HCtype_secondary = Choices.Flow1D.HCtypes.
   Downstream "Location of the hydraulic capacitance, secondary side";
63
64 parameter Boolean counterCurrent = true "Counter-current flow";

```

```

65  constant Real pi = Modelica.Constants.pi;
66
67  final parameter SI.Distance L = 1 "Reference Length (Dummy, geometry is
    volumetrically scaled)";
68
69  // Flanges
70  ThermoPower.Water.FlangeA primaryIn(redeclare package Medium = PrimaryMedium)
    annotation(Placement(transformation(extent = {{-120, -20}, {-80, 20}})));
71  ThermoPower.Water.FlangeB primaryOut(redeclare package Medium = PrimaryMedium)
    annotation(Placement(transformation(extent = {{80, -20}, {120, 20}})));
72  ThermoPower.Water.FlangeA secondaryIn(redeclare package Medium =
    SecondaryMedium) annotation(Placement(transformation(extent = {{-20, 80}, {20,
    120}})));
73  ThermoPower.Water.FlangeB secondaryOut(redeclare package Medium =
    SecondaryMedium) annotation(Placement(transformation(extent = {{-20, -120},
    {20, -80}})));
74
75  // --- FLOW COMPONENTS ---
76
77  // Primary Flow (Inside Tubes - 1-Phase Liquid)
78  ThermoPower.Water.Flow1DFV primaryFlow(
79      Nt = 1,
80      N = N_primary,
81      wnom = primaryNomFlowRate,
82      redeclare package Medium = PrimaryMedium,
83      L = exchSurface_primary^2/(primaryVol*pi*4),
84      A = (primaryVol*4/exchSurface_primary)^2/4*pi,
85      omega = primaryVol*4/exchSurface_primary*pi,
86      Dhyd = primaryVol*4/exchSurface_primary,
87      FFtype = FFtype_primary,
88      dpnom = dpnom_primary,
89      rhonom = rhonom_primary,
90      HydraulicCapacitance = Hctype_primary,
91      Kfnom = Kfnom_primary,
92      Cfnom = Cfnom_primary,
93      FluidPhaseStart = PrimaryPhaseStart,
94      pstart = primaryNomPressure,
95      hstartin = hstart_primary,
96      hstartout = hstartout_primary,
97      initOpt = initOptPrimary,
98      redeclare model HeatTransfer = ThermoPower.Thermal.HeatTransferFV.
    ConstantHeatTransferCoefficient(gamma = gamma_primary)) annotation(Placement(
    transformation(extent = {{-20, -76}, {20, -36}})));
99
100 // Metal Tube (The Wall)
101 ThermoPower.Thermal.MetalTubeFV metalTube(
102     rhomcm = rhomcm,
103     lambda = lambda,
104     L = exchSurface_primary^2/(primaryVol*pi*4),
105     rint = primaryVol*4/exchSurface_primary/2,
106     WallRes = false,
107     rext = (metalVol + primaryVol)*4/extSurfaceTub/2,
108     Tstartbar = Tstart_M,
109     Nw = N_primary - 1) annotation(Placement(transformation(extent = {{-20, 0},
    {20, -40}})));
110
111 // Secondary Flow (Outside Tubes/Shell - 1-Phase Liquid)
112 ThermoPower.Water.Flow1DFV secondaryFlow(

```

```

113     Nt = 1,
114     N = N_secondary,
115     wnom = secondaryNomFlowRate,
116     redeclare package Medium = SecondaryMedium,
117     L = L,
118     A = secondaryVol/L,
119     omega = exchSurface_secondary/L,
120     Dhyd = 1,
121     FFtype = FFtype_secondary,
122     dpnom = dpnom_secondary,
123     rhonom = rhonom_secondary,
124     HydraulicCapacitance = Hctype_secondary,
125     Kfnom = Kfnom_secondary,
126     Cfnom = Cfnom_secondary,
127     FluidPhaseStart = SecondaryPhaseStart,
128     pstart = secondaryNomPressure,
129     hstartin = hstart_secondary,
130     hstartout = hstartout_secondary,
131     initOpt = initOptSecondary,
132     redeclare model HeatTransfer = ThermoPower.Thermal.HeatTransferFV.
        ConstantHeatTransferCoefficient(gamma = gamma_secondary)) annotation(Placement
        (transformation(extent = {{-20, 60}, {20, 20}})));
133
134     // Counter Current Bridge
135     ThermoPower.Thermal.CounterCurrentFV cC(Nw = N_primary - 1) annotation(
        Placement(transformation(extent = {{-20, -8}, {20, 32}})));
136
137     equation
138     connect(secondaryFlow.infl, secondaryIn);
139     connect(secondaryFlow.outfl, secondaryOut);
140     connect(primaryFlow.outfl, primaryOut);
141     connect(primaryFlow.infl, primaryIn);
142
143     // Thermal Connections
144     connect(metalTube.ext, cC.side2);
145     connect(metalTube.int, primaryFlow.wall);
146     connect(secondaryFlow.wall, cC.side1);
147
148     annotation(
149         Diagram(coordinateSystem(preserveAspectRatio = false, extent = {{-100, -100},
            {100, 100}})),
150         Icon(graphics = {Rectangle(extent = {{-100, 100}, {100, -100}}, lineColor =
            {0, 0, 255}, fillColor = {230, 230, 230}, fillPattern = FillPattern.Solid),
            Line(points = {{0, -80}, {0, -40}, {40, -20}, {-40, 20}, {0, 40}, {0, 80}},
            color = {0, 0, 255}), Text(extent = {{-100, -115}, {100, -145}}, lineColor =
            {85, 170, 255}, textString = "%name"))},
151         Documentation(revisions = "<html><ul><li><i>Updated</i>: Volumetric Geometry
            adaptation for Water-Water, 1-Phase both sides.</li></ul></html>", info = "<
            html></html>"));
152     end Economizzatore_Water;

```

A.3 Point-Kinetics Model

The following code implements the single-point neutron kinetics model with moderator temperature feedback; this componet is used to simulate the reactor thermal power.

```

1  model Point_Model "One Point-Kinetic Model"
2
3  parameter Real beta = 0.0065 "Delayed neutron fraction";
4  parameter Real lambda = 0.405 "Decay constant [1/s]";
5  parameter Real l = 2e-5 "Prompt neutron generation time [s]";
6  parameter Real alfa_Tm = -4e-4 " Moderator conterreactivity coefficient";
7  parameter Real Tm_rif = 579.32 "Moderator nominal temperature";
8  parameter Real P0 = 1.94e9 "[wth] Nominal thermal power";
9
10 Real n(start = 1, fixed = true) "Normalized neutron density";
11 Real C "Precursor concentration";
12 Real rho_Tm "Moderator Reactivity";
13 Real rho "Total Reacitivity";
14
15 Modelica.Blocks.Interfaces.RealInput rho_1 "Reactivity perturbation"
16   annotation (Placement(transformation(extent = {{-70, 40}, {-50, 20}}),
17     iconTransformation(origin = {0, -58}, extent = {{-70, 40}, {-50, 20}})));
18
19 Modelica.Blocks.Interfaces.RealInput Tm "Moderator Temperature"
20   annotation (Placement(transformation(extent = {{-70, -40}, {-50, -20}}),
21     iconTransformation(origin = {0, 60}, extent = {{70, -40}, {50, -20}})));
22
23 Modelica.Blocks.Interfaces.RealOutput P "Thermal power [wth]"
24   annotation (Placement(transformation(extent = {{50, -10}, {70, 10}}),
25     iconTransformation(origin = {0, -30}, extent = {{50, -10}, {70, 10}})));
26
27 initial equation
28   der(n) = 0;
29   der(C) = 0;
30
31 equation
32   rho_Tm = alfa_Tm * (Tm - Tm_rif);
33
34   rho = rho_1 + rho_Tm;
35
36   der(n) = ((rho - beta)/l)*n + lambda*C;
37   der(C) = (beta/l)*n - lambda*C;
38
39   P = P0*n;
40
41 annotation(
42   Icon(graphics = {Rectangle(fillColor = {170, 255, 255}, fillPattern =
43     FillPattern.Solid, extent = {{-60, 60}, {60, -60}}), Text(origin = {31, 55},
44     extent = {{-27, 27}, {27, -27}}, textString = "Kinetic_OnePoint"), Line(origin
45     = {-6, -7}, points = {{-42, 37}, {-42, -37}, {42, -37}, {42, -37}}), Text(
46     origin = {22, -48}, extent = {{-20, 4}, {20, -4}}, textString = "Neutron
47     Density"), Text(origin = {-31, 36}, extent = {{-25, 2}, {25, -2}}, textString
48     = "Thermal Power(wth)"), Line(origin = {-18, -18}, points = {{-30, -26}, {30,
49     26}, {30, 26}})}));
50 end Point_Model;

```

A.4 Two-Zones Kinetic Model

The following code implements the coupled two-zone neutron kinetics model, representing the axial separation of the reactor core into top and bottom regions.

```
1  model Two_Zones_Kinetic "Two Zones Kinetic Model"
2
3  // Shared Parameters
4  parameter Real beta = 0.0065 "Delayed neutron fraction";
5  parameter Real lambda = 0.405 "Decay constant [1/s]";
6  parameter Real l = 2e-5 "Prompt neutron generation time [s]";
7  parameter Real alfa_Tm = -4e-4 "Moderator conterreactivity coefficient";
8  parameter Real P0 = 1.94e9 "[wth] Nominal thermal power";
9  parameter Real D = 0.5 "Coupling Coefficient Between Zones (Dimensionless)";
10
11 // Variables Top Zone
12 parameter Real Tm1_rif = 579.32 "Moderator nominal temperature Top";
13 Real n1(start = 0.5, fixed = true) "Normalized neutron density Top";
14 Real C1 "Precursor concentration Top";
15 Real rho_Tm1 "Moderator Reactivity Top";
16 Real rho1 "Total Reacitivity Top";
17
18 // Variables Bottom Zone
19 parameter Real Tm2_rif = 579.32 "Moderator nominal temperature Bottom";
20 Real n2(start = 0.5, fixed = true) "Normalized neutron density Bottom";
21 Real C2 "Precursor concentration Bottom";
22 Real rho_Tm2 "Moderator Reactivity Bottom";
23 Real rho2 "Total Reacitivity Bottom";
24
25 // Global variables
26 Real n "Total normalized neutron density";
27
28 // Connectors
29 Modelica.Blocks.Interfaces.RealInput rho_p1 "Reactivity perturbation Top"
30   annotation (Placement(transformation(extent = {{-100, 50}, {-80, 70}})));
31 Modelica.Blocks.Interfaces.RealInput Tm1 "Moderator Temperature Top"
32   annotation (Placement(transformation(extent = {{-100, 20}, {-80, 40}})));
33
34 Modelica.Blocks.Interfaces.RealInput rho_p2 "Reactivity perturbation Bottom"
35   annotation (Placement(transformation(extent = {{-100, -40}, {-80, -20}})));
36 Modelica.Blocks.Interfaces.RealInput Tm2 "Moderator Temperature Bottom"
37   annotation (Placement(transformation(extent = {{-100, -70}, {-80, -50}})));
38
39 Modelica.Blocks.Interfaces.RealOutput P "Thermal power [wth]"
40   annotation (Placement(transformation(extent = {{80, -10}, {100, 10}})));
41
42 initial equation
43   der(n1) = 0;
44   der(C1) = 0;
45   der(n2) = 0;
46   der(C2) = 0;
47
48 equation
49   // Reactivity Calculations
50   rho_Tm1 = alfa_Tm * (Tm1 - Tm1_rif);
51   rho_Tm2 = alfa_Tm * (Tm2 - Tm2_rif);
52
53   rho1 = rho_p1 + rho_Tm1;
```

```

54 rho2 = rho_p2 + rho_Tm2;
55
56 // Top Zone Kinetics (with Coupling)
57 der(n1) = ((rho1 - beta)/l)*n1 + lambda*C1 + (D/(l*(1 - beta) + (1/lambda) *
    beta))*(n2 - n1);
58 der(C1) = (beta/l)*n1 - lambda*C1;
59
60 // Bottom Zone Kinetics (with Coupling)
61 der(n2) = ((rho2 - beta)/l)*n2 + lambda*C2 + (D/(l*(1 - beta) + (1/lambda) *
    beta))*(n1 - n2);
62 der(C2) = (beta/l)*n2 - lambda*C2;
63
64 // Total Outputs
65 n = n1 + n2;
66 P = P0 * n;
67
68 annotation(Icon(graphics={
69     Rectangle(fillColor={170,255,255},fillPattern=FillPattern.Solid,extent
    ={{-80,80},{80,-80}}}),
70     Text(origin={0,65},extent={{-60,10},{60,-10}},textString="
    Kinetic_TwoZones"),
71     Line(points={{-60,40},{60,40}},color={0,0,0},thickness=0.5,smooth=Smooth.
    None),
72     Text(origin={0,20},extent={{-40,10},{40,-10}},textString="TOP"),
73     Text(origin={0,-30},extent={{-40,10},{40,-10}},textString="BOTTOM"))));
74 end Two_Zones_Kinetic;

```

A.5 Control Rods Kinetics Model

The following code implements the point kinetics model with control rod reactivity, with the rod contribution defined as a function of the normalized insertion position.

```

1  model Control_Rods
2    "Point kinetic model with linear control rod reactivity feedback"
3
4    parameter Real beta = 0.0065
5      "Delayed neutron fraction";
6    parameter Real lambda = 0.405
7      "Delayed neutron precursor decay constant [1/s]";
8    parameter Real l = 2e-5
9      "Prompt neutron generation time [s]";
10   parameter Real alfa_Tm = -4e-4
11     "Moderator temperature reactivity coefficient";
12   parameter Real Tm_rif = 579.32
13     "Reference moderator temperature [K]";
14   parameter Real rho_0 = 1
15     "Linear control rod reactivity coefficient";
16   parameter Real z_max = 1
17     "Maximum normalized rod position (fully withdrawn)";
18   parameter Real z_reference = 0.5
19     "Reference rod position corresponding to zero control rod reactivity";
20   parameter Real P0 = 1.94e9
21     "Nominal thermal power [Wth]";
22
23   Real n(start = 1, fixed = true)

```

```

24     "Normalized neutron density";
25 Real C
26     "Delayed neutron precursor concentration";
27 Real rho_Tm
28     "Moderator temperature reactivity";
29 Real rho_CR
30     "Control rod reactivity";
31 Real rho
32     "Total reactor reactivity";
33 Real z_eff
34     "Normalized rod position limited to [0, z_max]";
35
36 Modelica.Blocks.Interfaces.RealInput z
37     "Normalized control rod position"
38     annotation (Placement(transformation(extent = {{-70,40},{-50,20}}),
39         iconTransformation(origin = {0,-58},
40             extent = {{-70,40},{-50,20}})));
41
42 Modelica.Blocks.Interfaces.RealInput Tm
43     "Moderator temperature [K]"
44     annotation (Placement(transformation(extent = {{-70,-40},{-50,-20}}),
45         iconTransformation(origin = {0,60},
46             extent = {{70,-40},{50,-20}})));
47
48 Modelica.Blocks.Interfaces.RealOutput P
49     "Thermal power [Wth]"
50     annotation (Placement(transformation(extent = {{50,-10},{70,10}}),
51         iconTransformation(origin = {0,-30},
52             extent = {{50,-10},{70,10}})));
53
54 initial equation
55     der(n) = 0;
56     der(C) = 0;
57
58 equation
59     // Limit the effective rod position to the physical operating range
60     z_eff = min(max(z, 0), z_max);
61
62     // Reactivity contributions
63     rho_Tm = alfa_Tm*(Tm - Tm_rif);
64     rho_CR = rho_0*(z_eff - z_reference);
65
66     // Total reactivity
67     rho = rho_CR + rho_Tm;
68
69     // Point kinetics equations
70     der(n) = ((rho - beta)/l)*n + lambda*C;
71     der(C) = (beta/l)*n - lambda*C;
72
73     // Thermal power
74     P = P0*n;
75
76 annotation(
77     Icon(graphics = {Rectangle(fillColor = {170, 255, 255}, fillPattern =
78         FillPattern.Solid, extent = {{-60, 60}, {60, -60}}), Text(origin = {2, -51},
79         extent = {{-34, 9}, {34, -9}}, textString = "Reactor Core"), Rectangle(origin
80         = {0, -1}, fillColor = {181, 181, 181}, fillPattern = FillPattern.Solid,
81         extent = {{-30, 45}, {30, -45}}), Rectangle(origin = {-19, 24}, fillPattern =

```

```

FillPattern.Solid, extent = {{-1, 30}, {1, -30}}), Rectangle(origin = {-5,
24}, fillPattern = FillPattern.Solid, extent = {{-1, 30}, {1, -30}}),
Rectangle(origin = {-13, 24}, fillPattern = FillPattern.Solid, extent = {{-1,
30}, {1, -30}}), Rectangle(origin = {19, 24}, fillPattern = FillPattern.Solid,
extent = {{-1, 30}, {1, -30}}), Rectangle(origin = {13, 24}, fillPattern =
FillPattern.Solid, extent = {{-1, 30}, {1, -30}}), Rectangle(origin = {7, 24},
fillPattern = FillPattern.Solid, extent = {{-1, 30}, {1, -30}}), Rectangle(
origin = {1, 24}, fillPattern = FillPattern.Solid, extent = {{-1, 30}, {1,
-30}})),
78   Diagram(graphics));
79   end Control_Rods;

```

Appendix B

Thermo-Hydraulic Layouts

This appendix reports the two most complete system-level thermo-hydraulic layouts developed and extensively used throughout the present work for the simulation of the PWR plant. The layouts integrate the thermo-hydraulic and neutronic models developed during the internship and subsequently extended in the thesis with standard components from both the ThermoPower library and the Modelica Standard Library (MSL), providing the complete plant configurations used for the main simulation activities.

During the development of the models, several preliminary and less complete configurations were also implemented. These were progressively replaced by more comprehensive versions as the model development proceeded. The two configurations reported here were selected as they represent the most complete and extensively used plant layouts adopted for the simulations presented in the thesis. Other variants, mainly corresponding to earlier development stages or to different neutronic representations, are therefore omitted to avoid unnecessary repetition.

B.1 PWR Layout with Steam Extraction

The following code reports the PWR600_Spillamento system-level model, including the main primary and secondary circuits and the steam extraction line with the associated preheater and flow-control components. The layout was used with the different reactor neutronic representations described in the thesis.

```
1 model PWR600_Spillamento
2   import ThermoPower;
3   replaceable package Water = ThermoPower.Water.StandardWater constrainedby
      Modelica.Media.Interfaces.PartialPureSubstance "Fluid model";
4   //-----Temperature e reattività bias moderatore
5   Real Tm_Bottom "Temperatura media zona inferiore";
6   Real Tm_Top "Temperatura media zona superiore";
7   Real rho_bias1 "Reattività zona top iniziale";
8   Real rho_bias2 "Reattività zona bottom iniziale";
9   Real pump_speed(start = 1000, unit = "1/min") "Velocità adattiva della pompa";
10  //-----Parameters
11  parameter Real alfa_Tm = -4e-4 "Moderator conterreactivity coefficient";
12  parameter Real Tm_rif = 579.32 "Moderator nominal mean temperature Top";
13  inner ThermoPower.System system(fnom = 60) annotation(
14    Placement(transformation(origin = {170, 90}, extent = {{-10, -10}, {10, 10}})
15  ));
16  Evaporator_Water evaporator_Water(redeclare package PrimaryMedium = Water,
      redeclare package SecondaryMedium = Water, Tstart_M = 546.45,
```

```

    exchSurface_primary = 33500, exchSurface_secondary = 36900, extSurfaceTub =
    36900, gamma_nom_2ph = 20000, gamma_nom_liq = 2500, gamma_nom_vap = 2000,
    gamma_primary = 2500, hstart_primary = 1426e3, hstart_secondary = 1200e3,
    hstartout_primary = 1240e3, hstartout_secondary = 2790e3, lambda = 20,
    metalVol = 54.7, primaryNomFlowRate = 9206, primaryNomPressure = 1.55e7,
    primaryVol = 100, rhomcm = 7900*500, secondaryNomFlowRate = 1076.3,
    secondaryNomPressure = 5.7e6, secondaryVol = 150, initOptPrimary = ThermoPower
    .Choices.Init.Options.fixedState, initOptSecondary = ThermoPower.Choices.Init.
    Options.noInit) annotation(
16   Placement(transformation(origin = {-36, 40}, extent = {{-10, 10}, {10, -10}})
    ));
17   Economizzatore_Water Economizzatore(redeclare package PrimaryMedium = Water,
    redeclare package SecondaryMedium = Water, Tstart_M = 546.45,
    exchSurface_primary = 6800, exchSurface_secondary = 7544, extSurfaceTub =
    7544, gamma_primary = 2500, gamma_secondary = 2500, hstart_primary = 1240e3,
    hstart_secondary = 1000e3, hstartout_primary = 1217e3, hstartout_secondary =
    1200e3, initOptPrimary = ThermoPower.Choices.Init.Options.noInit,
    initOptSecondary = ThermoPower.Choices.Init.Options.steadyState, lambda = 20,
    metalVol = 9.33, primaryNomFlowRate = 9206, primaryNomPressure = 1.55e7,
    primaryVol = 25, rhomcm = 7900*500, secondaryNomFlowRate = 1076.3,
    secondaryNomPressure = 5.7e6, secondaryVol = 40) annotation(
18   Placement(transformation(origin = {-36, -20}, extent = {{-10, 10}, {10,
    -10}}))));
19   ThermoPower.Water.SteamTurbineStodola LPT(Kt = 0.0737, redeclare package Medium
    = Water, PRstart = 800, explicitIsentropicEnthalpy = true, phi(start = 0),
    pnom = 4e6, pout(displayUnit = "Pa"), wnom = 663.96, wstart = 663.96)
    annotation(
20   Placement(transformation(origin = {112, 52}, extent = {{-18, -18}, {18, 18}})
    ));
21   Modelica.Mechanics.Rotational.Sources.ConstantSpeed constantSpeed(w_fixed(
    displayUnit = "rpm") = 188.4955592153876) annotation(
22   Placement(transformation(origin = {140, 52}, extent = {{6, -6}, {-6, 6}})));
23   ThermoPower.Examples.RankineCycle.Models.PrescribedPressureCondenser Condenser1
    (redeclare package Medium = Water, Vlstart = 1000, Vtot = 2000, initOpt =
    ThermoPower.Choices.Init.Options.fixedState, p(displayUnit = "bar") = 5000)
    annotation(
24   Placement(transformation(origin = {170, -8}, extent = {{-10, -10}, {10, 10}})
    ));
25   ThermoPower.Examples.RankineCycle.Models.PrescribedSpeedPump Pump11(redeclare
    package FluidMedium = Water, SSInit = true, head_nom = {702, 583.59, 0},
    hstart = 137e3, n0 = 1500, nominalInletPressure = 5000, nominalMassFlowRate =
    1076.3, nominalOutletPressure = 5.7e6, q_nom = {0, 1.08197, 2.00164}, rho0(
    displayUnit = "kg/m3") = 994.76) annotation(
26   Placement(transformation(origin = {102, -72}, extent = {{10, -10}, {-10,
    10}})));
27   Modelica.Blocks.Sources.Constant const1(k = 1500) annotation(
28   Placement(transformation(origin = {146, -48}, extent = {{6, -6}, {-6, 6}})));
29   Evaporator_Water Preheater(redeclare package PrimaryMedium = Water, redeclare
    package SecondaryMedium = Water, Tstart_M = 546.45, exchSurface_primary =
    3800, exchSurface_secondary = 4143, extSurfaceTub = 4143, gamma_nom_2ph =
    20000, gamma_nom_liq = 2500, gamma_nom_vap = 2000, gamma_primary = 2500,
    hstart_primary = 142e3, hstart_secondary = 2726.52e3, hstartout_primary = 995
    e3, hstartout_secondary = 500e3, initOptPrimary = ThermoPower.Choices.Init.
    Options.steadyState, initOptSecondary = ThermoPower.Choices.Init.Options.
    steadyState, lambda = 20, metalVol = 4.1, primaryNomFlowRate = 1076.3,
    primaryNomPressure = 5.7e6, primaryVol = 15, rhomcm = 7900*500,
    secondaryNomFlowRate = 412.34, secondaryNomPressure = 4e6, secondaryVol = 30)
    annotation(

```

```

30     Placement(transformation(origin = {60, -72}, extent = {{-10, 10}, {10, -10}},
    rotation = 180)));
31 ThermoPower.Water.FlowSplit flowSplit(redeclare package Medium = Water,
    allowFlowReversal = false, rev_in1 = false, rev_out1 = false, rev_out2 = false
    , checkFlowDirection = true) annotation(
32     Placement(transformation(origin = {55, 63}, extent = {{-9, -9}, {9, 9}})));
33 ThermoPower.Water.FlowJoin flowJoin(redeclare package Medium = Water,
    allowFlowReversal = false, rev_in1 = false, rev_in2 = false, rev_out = false,
    checkFlowDirection = true) annotation(
34     Placement(transformation(origin = {169, 31}, extent = {{-9, -9}, {9, 9}},
    rotation = -90)));
35 Modelica.Blocks.Sources.Constant V2(k = 1) annotation(
36     Placement(transformation(origin = {209, -7}, extent = {{-5, -5}, {5, 5}},
    rotation = 180)));
37 ThermoPower.Water.ValveLin V12(redeclare package Medium = Water, Kv = 1.055e-4,
    allowFlowReversal = false) annotation(
38     Placement(transformation(origin = {190, -6}, extent = {{-6, 6}, {6, -6}},
    rotation = 90)));
39 ThermoPower.Water.SteamTurbineStodola HPT(redeclare package Medium = Water,
    PRstart = 1.425, wnom = 1076.3, pnom = 5.7e6, Kt = 0.1173, wstart = 1076.3,
    explicitIsentropicEnthalpy = true, eta_iso_nom = 0.92) annotation(
40     Placement(transformation(origin = {25, 55}, extent = {{-15, -15}, {15, 15}}))
    );
41 ThermoPower.Examples.RankineCycle.Models.PrescribedSpeedPump P1(redeclare
    package FluidMedium = Water, SSInit = true, head_nom = {47.76, 39.8, 0},
    hstart = 1.27e6, n0 = 1000, nominalInletPressure = 1.55e7, nominalMassFlowRate
    = 9206, nominalOutletPressure = 1.58e7, q_nom = {0, 11.961, 21.53}, rho0(
    displayUnit = "kg/m3") = 769.68) annotation(
42     Placement(transformation(origin = {-87, -55}, extent = {{-9, -9}, {9, 9}},
    rotation = 180)));
43 ThermoPower.Thermal.HeatSource1DFV heatSource1DFV(Nw = 9) annotation(
44     Placement(transformation(origin = {-174, -10}, extent = {{-10, -10}, {10,
    10}}, rotation = 90)));
45 ThermoPower.Water.Flow1DFV flow1DFV(A = 3.99, Dhyd = 0.014, FluidPhaseStart =
    ThermoPower.Choices.FluidPhase.FluidPhases.Liquid, H = 3.7, L = 3.7, redeclare
    package Medium = Water, N = 10, allowFlowReversal = false, dpnom = 0,
    hstartin = 1.27e6, hstartout = 1.426e6, initOpt = ThermoPower.Choices.Init.
    Options.steadyState, omega = 1142, pstart = 1.58e7, wnom = 9206) annotation(
46     Placement(transformation(origin = {-156, -10}, extent = {{-10, -10}, {10,
    10}}, rotation = 90)));
47 ThermoPower.Water.ExpansionTankIdeal PZR(redeclare package Medium = Water,
    allowFlowReversal = false, pf = 1.55e7) annotation(
48     Placement(transformation(origin = {-86, 46}, extent = {{-10, -10}, {10, 10}})
    ));
49 ThermoPower.Water.ValveLin valveLin(Kv = 0.0331, redeclare package Medium =
    Water) annotation(
50     Placement(transformation(origin = {-127, 39}, extent = {{-7, -7}, {7, 7}})));
51 Modelica.Blocks.Sources.Constant const(k = 1) annotation(
52     Placement(transformation(origin = {-128, 56}, extent = {{-4, -4}, {4, 4}},
    rotation = -90)));
53 Two_Zones_Kinetic two_Zones_Kinetic annotation(
54     Placement(transformation(origin = {-196, -10}, extent = {{-10, -10}, {10,
    10}})));
55 Modelica.Blocks.Sources.Ramp Rods_Ramp(height = -1e-3, duration = 2, startTime
    = 1100);
56 equation
57 P1.nPump = pump_speed;
58 flow1DFV.w = 9206;

```

```

59  der(rho_bias1) = 0;
60  der(rho_bias2) = 0;
61  Tm_Top = (flow1DFV.T[6] + flow1DFV.T[7] + flow1DFV.T[8] + flow1DFV.T[9] +
        flow1DFV.T[10])/5;
62  Tm_Bottom = (flow1DFV.T[1] + flow1DFV.T[2] + flow1DFV.T[3] + flow1DFV.T[4] +
        flow1DFV.T[5])/5;
63  two_Zones_Kinetic.Tm1 = Tm_Top;
64  two_Zones_Kinetic.Tm2 = Tm_Bottom;
65  two_Zones_Kinetic.rho_p1 = rho_bias1 + Rods_Ramp.y;
66  two_Zones_Kinetic.rho_p2 = rho_bias2;
67  connect(Economizzatore.secondaryOut, evaporator_Water.secondaryIn) annotation(
68      Line(points = {{-36, -10}, {-36, 30}}, color = {0, 0, 255}));
69  connect(evaporator_Water.primaryOut, Economizzatore.primaryIn) annotation(
70      Line(points = {{-26, 40}, {-14, 40}, {-14, 12}, {-56, 12}, {-56, -20}, {-46,
        -20}}, color = {0, 0, 255}));
71  connect(LPT.shaft_b, constantSpeed.flange) annotation(
72      Line(points = {{123.52, 52}, {133.52, 52}}));
73  connect(const1.y, Pump11.nPump) annotation(
74      Line(points = {{139.4, -48}, {123.4, -48}, {123.4, -66}, {109, -66}}, color =
        {0, 0, 127}));
75  connect(Condenser1.waterOut, Pump11.inlet) annotation(
76      Line(points = {{170, -18}, {170, -72}, {112, -72}}, color = {0, 0, 255}));
77  connect(Pump11.outlet, Preheater.primaryIn) annotation(
78      Line(points = {{92, -72}, {70, -72}}, color = {0, 0, 255}));
79  connect(Preheater.primaryOut, Economizzatore.secondaryIn) annotation(
80      Line(points = {{50, -72}, {-34, -72}, {-34, -30}, {-36, -30}}, color = {0, 0,
        255}));
81  connect(flowJoin.out, Condenser1.steamIn) annotation(
82      Line(points = {{169, 25.6}, {170, 25.6}, {170, 1.6}}, color = {0, 0, 255}));
83  connect(V2.y, V12.cmd) annotation(
84      Line(points = {{203.5, -7}, {194.5, -7}}, color = {0, 0, 127}));
85  connect(Preheater.secondaryOut, V12.inlet) annotation(
86      Line(points = {{60, -82}, {60, -90}, {190, -90}, {190, -12}}, color = {0, 0,
        255}));
87  connect(V12.outlet, flowJoin.in1) annotation(
88      Line(points = {{190, 0}, {190, 46}, {172, 46}, {172, 36}}, color = {0, 0,
        255}));
89  connect(evaporator_Water.secondaryOut, HPT.inlet) annotation(
90      Line(points = {{-36, 50}, {-36, 67}, {13, 67}}, color = {0, 0, 255}));
91  connect(LPT.outlet, flowJoin.in2) annotation(
92      Line(points = {{126.4, 66.4}, {166.4, 66.4}, {166.4, 36.4}}, color = {0, 0,
        255}));
93  connect(HPT.shaft_b, LPT.shaft_a) annotation(
94      Line(points = {{34.6, 55}, {38.6, 55}, {38.6, 51}, {100.6, 51}}));
95  connect(HPT.outlet, flowSplit.in1) annotation(
96      Line(points = {{37, 67}, {49, 67}, {49, 62}}, color = {0, 0, 255}));
97  connect(flowSplit.out1, LPT.inlet) annotation(
98      Line(points = {{60.4, 66.6}, {60.4, 79.6}, {98.4, 79.6}, {98.4, 65.6}}, color
        = {0, 0, 255}));
99  connect(flowSplit.out2, Preheater.secondaryIn) annotation(
100     Line(points = {{60.4, 59.4}, {60.4, -61.6}}, color = {0, 0, 255}));
101  connect(P1.outlet, flow1DFV.infl) annotation(
102     Line(points = {{-96, -55}, {-156, -55}, {-156, -20}}, color = {0, 0, 255}));
103  connect(heatSource1DFV.wall, flow1DFV.wall) annotation(
104     Line(points = {{-171, -10}, {-161, -10}}, color = {255, 127, 0}));
105  connect(const.y, valveLin.cmd) annotation(
106     Line(points = {{-128, 51.6}, {-128, 44.6}, {-127, 44.6}}, color = {0, 0,
        127}));

```

```

107 connect(valveLin.outlet, PZR.WaterInfl) annotation(
108   Line(points = {{-120, 39}, {-90, 39}, {-90, 40}}, color = {0, 0, 255}));
109 connect(flow1DFV.outfl, valveLin.inlet) annotation(
110   Line(points = {{-156, 0}, {-156, 40}, {-134, 40}}, color = {0, 0, 255}));
111 connect(PZR.WaterOutfl, evaporator_Water.primaryIn) annotation(
112   Line(points = {{-82, 40}, {-46, 40}}, color = {0, 0, 255}));
113 connect(Economizzatore.primaryOut, P1.inlet) annotation(
114   Line(points = {{-26, -20}, {-12, -20}, {-12, -54}, {-78, -54}}, color = {0,
0, 255}));
115 connect(two_Zones_Kinetic.P, heatSource1DFV.power) annotation(
116   Line(points = {{-187, -10}, {-179, -10}}, color = {0, 0, 127}));
117 annotation(
118   Placement(transformation(origin = {-214, 20}, extent = {{-10, -10}, {10,
10}})));
119 annotation(
120   uses(ThermoPower(version = "3.1"), Modelica(version = "4.1.0")));
121 end PWR600_Spillamento;

```

B.2 PWR Layout with Spray Condenser

The following code reports the TwoZones_Deg system-level model, which includes the spray condenser and the associated feedwater and control components. The layout was used with the two-zone kinetic model and the ideal heat-source representation.

```

1 model TwoZones_Deg
2   import ThermoPower;
3   replaceable package Water = ThermoPower.Water.StandardWater constrainedby
4     Modelica.Media.Interfaces.PartialPureSubstance "Fluid model";
5   //-----Temperature e reattività bias moderatore
6   Real Tm_Bottom "Temperatura media zona inferiore";
7   Real Tm_Top "Temperatura media zona superiore";
8   Real pump_speed(start = 1000, unit = "1/min") "Velocità adattiva della pompa";
9   Real pump11_speed(start = 1500, unit = "1/min") "Velocità adattiva della pompa"
10  ;
11  //-----Parameters
12  parameter Real alfa_Tm = -4e-4 "Moderator counterreactivity coefficient";
13  parameter Real Tm_rif = 579.32 "Moderator nominal mean temperature Top";
14  Real rho_bias1 "Reattività zona top iniziale";
15  Real rho_bias2 "Reattività zona bottom iniziale";
16  inner ThermoPower.System system(fnom = 60) annotation(
17    Placement(transformation(origin = {210, 90}, extent = {{-10, -10}, {10, 10}})
18    ));
19  Evaporator_Water evaporator_Water(redeclare package PrimaryMedium = Water,
20    redeclare package SecondaryMedium = Water, Tstart_M = 546.45,
21    exchSurface_primary = 33500, exchSurface_secondary = 36900, extSurfaceTub =
22    36900, gamma_nom_2ph = 20000, gamma_nom_liq = 2500, gamma_nom_vap = 2000,
23    gamma_primary = 2500, hstart_primary = 1426e3, hstart_secondary = 1200e3,
24    hstartout_primary = 1240e3, hstartout_secondary = 2790e3, initOptPrimary =
25    ThermoPower.Choices.Init.Options.fixedState, initOptSecondary = ThermoPower.
26    Choices.Init.Options.noInit, lambda = 20, metalVol = 54.7, primaryNomFlowRate
27    = 9206, primaryNomPressure = 1.55e7, primaryVol = 100, rhomcm = 7900*500,
28    secondaryNomFlowRate = 1076.3, secondaryNomPressure = 5.7e6, secondaryVol =
29    150) annotation(
30    Placement(transformation(origin = {-86, 32}, extent = {{-10, 10}, {10, -10}})
31    ));

```

```

18 Economizzatore_Water Economizzatore(redeclare package PrimaryMedium = Water,
    redeclare package SecondaryMedium = Water, Tstart_M = 546.45,
    exchSurface_primary = 6800, exchSurface_secondary = 7544, extSurfaceTub =
    7544, gamma_primary = 2500, gamma_secondary = 2500, hstart_primary = 1240e3,
    hstart_secondary = 1000e3, hstartout_primary = 1217e3, hstartout_secondary =
    1200e3, initOptPrimary = ThermoPower.Choices.Init.Options.noInit,
    initOptSecondary = ThermoPower.Choices.Init.Options.steadyState, lambda = 20,
    metalVol = 9.33, primaryNomFlowRate = 9206, primaryNomPressure = 1.55e7,
    primaryVol = 25, rhomcm = 7900*500, secondaryNomFlowRate = 1076.3,
    secondaryNomPressure = 5.7e6, secondaryVol = 40) annotation(
19   Placement(transformation(origin = {-86, -28}, extent = {{-10, 10}, {10,
    -10}})));
20 ThermoPower.Examples.RankineCycle.Models.PrescribedSpeedPump P1(redeclare
    package FluidMedium = Water, SSInit = true, head_nom = {47.76, 39.8, 0},
    hstart = 1.27e6, n0 = 1000, nominalInletPressure = 1.55e7, nominalMassFlowRate
    = 9206, nominalOutletPressure = 1.58e7, q_nom = {0, 11.961, 21.53}, rho0(
    displayUnit = "kg/m3") = 769.68) annotation(
21   Placement(transformation(origin = {-137, -63}, extent = {{-9, -9}, {9, 9}},
    rotation = 180)));
22 ThermoPower.Thermal.HeatSource1DFV heatSource1DFV(Nw = 9) annotation(
23   Placement(transformation(origin = {-224, -18}, extent = {{-10, -10}, {10,
    10}}, rotation = 90)));
24 ThermoPower.Water.Flow1DFV flow1DFV(A = 3.99, Dhyd = 0.014, FluidPhaseStart =
    ThermoPower.Choices.FluidPhase.FluidPhases.Liquid, H = 3.7, L = 3.7, redeclare
    package Medium = Water, N = 10, allowFlowReversal = false, dpnom = 0,
    hstartin = 1.27e6, hstartout = 1.426e6, initOpt = ThermoPower.Choices.Init.
    Options.steadyState, omega = 1142, pstart = 1.58e7, wnom = 9206) annotation(
25   Placement(transformation(origin = {-206, -18}, extent = {{-10, -10}, {10,
    10}}, rotation = 90)));
26 ThermoPower.Water.ExpansionTankIdeal PZR(redeclare package Medium = Water,
    allowFlowReversal = false, pf = 1.55e7) annotation(
27   Placement(transformation(origin = {-136, 38}, extent = {{-10, -10}, {10,
    10}})));
28 ThermoPower.Water.ValveLin valveLin(Kv = 0.0331, redeclare package Medium =
    Water) annotation(
29   Placement(transformation(origin = {-177, 31}, extent = {{-7, -7}, {7, 7}})));
30 Modelica.Blocks.Sources.Constant const(k = 1) annotation(
31   Placement(transformation(origin = {-178, 48}, extent = {{-4, -4}, {4, 4}},
    rotation = -90)));
32 Two_Zones_Kinetic two_Zones_Kinetic annotation(
33   Placement(transformation(origin = {-246, -18}, extent = {{-10, -10}, {10,
    10}})));
34 Modelica.Blocks.Sources.Ramp Rods_Ramp(height = -1e-3, duration = 2, startTime
    = 5000);
35 ThermoPower.Water.SteamTurbineStodola LPT(Kt = 0.4579, redeclare package Medium
    = Water, PRstart = 117.82, explicitIsentropicEnthalpy = true, phi(start = 0),
    pnom = 589100, pout(displayUnit = "Pa"), wnom = 676.3, wstart = 676.3)
    annotation(
36   Placement(transformation(origin = {170, 54}, extent = {{-18, -18}, {18, 18}})
    ));
37 Modelica.Mechanics.Rotational.Sources.ConstantSpeed constantSpeed(w_fixed(
    displayUnit = "rpm") = 188.4955592153876) annotation(
38   Placement(transformation(origin = {198, 54}, extent = {{6, -6}, {-6, 6}})));
39 ThermoPower.Examples.RankineCycle.Models.PrescribedPressureCondenser Condenser1
    (redeclare package Medium = Water, Vlstart = 1000, Vtot = 2000, initOpt =
    ThermoPower.Choices.Init.Options.fixedState, p(displayUnit = "bar") = 5000)
    annotation(
40   Placement(transformation(origin = {228, -6}, extent = {{-10, -10}, {10, 10}})
    ));

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));
41 ThermoPower.Examples.RankineCycle.Models.PrescribedSpeedPump Pump11(redeclare
package FluidMedium = Water, SSInit = true, head_nom = {351.0, 291.5, 0},
hstart = 137e3, n0 = 1500, nominalInletPressure = 5000, nominalMassFlowRate =
901.73, nominalOutletPressure = 2.85e6, q_nom = {0, 0.906, 1.8}, rho0(
displayUnit = "kg/m3") = 994.76) annotation(
42 Placement(transformation(origin = {160, -70}, extent = {{10, -10}, {-10,
10}})));
43 Evaporator_Water Preheater(redeclare package PrimaryMedium = Water, redeclare
package SecondaryMedium = Water, Tstart_M = 420.15, exchSurface_primary =
3800, exchSurface_secondary = 4143, extSurfaceTub = 4143, gamma_nom_2ph =
20000, gamma_nom_liq = 2500, gamma_nom_vap = 2000, gamma_primary = 2500,
hstart_primary = 142e3, hstart_secondary = 2422e3, hstartout_primary = 647.50
e3, hstartout_secondary = 400e3, initOptPrimary = ThermoPower.Choices.Init.
Options.steadyState, initOptSecondary = ThermoPower.Choices.Init.Options.
steadyState, lambda = 20, metalVol = 4.1, primaryNomFlowRate = 901.73,
primaryNomPressure = 2.85e6, primaryVol = 15, rhomcm = 7900*500,
secondaryNomFlowRate = 225.43, secondaryNomPressure = 589100, secondaryVol =
60) annotation(
44 Placement(transformation(origin = {118, -70}, extent = {{-10, 10}, {10,
-10}}, rotation = 180)));
45 ThermoPower.Water.FlowSplit flowSplit(redeclare package Medium = Water,
allowFlowReversal = false, checkFlowDirection = true, rev_in1 = false,
rev_out1 = false, rev_out2 = false) annotation(
46 Placement(transformation(origin = {113, 65}, extent = {{-9, -9}, {9, 9}})));
47 ThermoPower.Water.FlowJoin flowJoin(redeclare package Medium = Water,
allowFlowReversal = false, checkFlowDirection = true, rev_in1 = false, rev_in2
= false, rev_out = false) annotation(
48 Placement(transformation(origin = {227, 33}, extent = {{-9, -9}, {9, 9}},
rotation = -90)));
49 Modelica.Blocks.Sources.Constant V2(k = 1) annotation(
50 Placement(transformation(origin = {267, -5}, extent = {{-5, -5}, {5, 5}},
rotation = 180)));
51 ThermoPower.Water.ValveLin V12(Kv = 3.859e-4, redeclare package Medium = Water,
allowFlowReversal = false) annotation(
52 Placement(transformation(origin = {248, -4}, extent = {{-6, 6}, {6, -6}},
rotation = 90)));
53 ThermoPower.Water.SteamTurbineStodola HPT(Kt = 0.0704, redeclare package Medium
= Water, PRstart = 9.676, eta_iso_nom = 0.92, explicitIsentropicEnthalpy =
true, pnom = 5.7e6, wnom = 901.73, wstart = 901.73) annotation(
54 Placement(transformation(origin = {83, 57}, extent = {{-15, -15}, {15, 15}}))
);
55 ThermoPower.Water.FlowSplit flowSplit1(redeclare package Medium = Water,
allowFlowReversal = false, checkFlowDirection = true, rev_in1 = false,
rev_out1 = false, rev_out2 = false) annotation(
56 Placement(transformation(origin = {9, 65}, extent = {{-9, -9}, {9, 9}})));
57 ThermoPower.Water.ValveLin V11(Kv = 6.125e-5, redeclare package Medium = Water,
allowFlowReversal = false) annotation(
58 Placement(transformation(origin = {19, -3}, extent = {{-7, -7}, {7, 7}},
rotation = -90)));
59 Modelica.Blocks.Sources.Constant V21(k = 1) annotation(
60 Placement(transformation(origin = {39, -3}, extent = {{-5, -5}, {5, 5}},
rotation = 180)));
61 ThermoPower.Examples.RankineCycle.Models.PrescribedSpeedPump P21(redeclare
package FluidMedium = Water, SSInit = true, head_nom = {422.0, 351.8, 0},
hstart = 995e3, n0 = 1500, nominalInletPressure = 2.885e6, nominalMassFlowRate
= 1076.3, nominalOutletPressure = 5.7e6, q_nom = {0, 1.303, 2.5}, rho0(
displayUnit = "kg/m3") = 825.783) annotation(

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62     Placement(transformation(origin = {-46, -74}, extent = {{10, -10}, {-10,
63         10}})));
64 ThermoPower.Water.SprayCondenser sprayCondenser(A = 19, redeclare package
    Medium = Water, V0 = 70, Vt = 95, initOpt = ThermoPower.Choices.Init.Options.
    fixedState, pstart = 2.85e6, y0 = 0.736, ystart = 0.736) annotation(
65     Placement(transformation(origin = {40, -64}, extent = {{10, -10}, {-10, 10}})
    ));
66 Modelica.Blocks.Continuous.LimPID PID(Ti = 10, controllerType = Modelica.Blocks
    .Types.SimpleController.PI, initType = Modelica.Blocks.Types.Init.
    InitialOutput, k = -2000, yMax = 3000, yMin = 0, y_start = 1500) annotation(
67     Placement(transformation(origin = {-26, -48}, extent = {{6, -6}, {-6, 6}})));
68 Modelica.Blocks.Sources.Constant setPoint(k = 0.736) annotation(
69     Placement(transformation(origin = {5, -43}, extent = {{5, -5}, {-5, 5}})));
70 equation
71     der(rho_bias1) = 0;
72     der(rho_bias2) = 0;
73     P1.nPump = pump_speed;
74     flow1DFV.w = 9206;
75     Pump11.nPump = pump11_speed;
76     Preheater.primaryFlow.w = 901.73;
77     Tm_Top = (flow1DFV.T[6] + flow1DFV.T[7] + flow1DFV.T[8] + flow1DFV.T[9] +
        flow1DFV.T[10])/5;
78     Tm_Bottom = (flow1DFV.T[1] + flow1DFV.T[2] + flow1DFV.T[3] + flow1DFV.T[4] +
        flow1DFV.T[5])/5;
79     two_Zones_Kinetic.Tm1 = Tm_Top;
80     two_Zones_Kinetic.Tm2 = Tm_Bottom;
81     two_Zones_Kinetic.rho_p1 = rho_bias1 + Rods_Ramp.y;
82     two_Zones_Kinetic.rho_p2 = rho_bias2;
83     PID.u_m = sprayCondenser.y;
84     connect(Economizzatore.secondaryOut, evaporator_Water.secondaryIn) annotation(
85         Line(points = {{-86, -18}, {-86, 22}}, color = {0, 0, 255}));
86     connect(evaporator_Water.primaryOut, Economizzatore.primaryIn) annotation(
87         Line(points = {{-76, 32}, {-64, 32}, {-64, 4}, {-106, 4}, {-106, -28}, {-96,
88             -28}}, color = {0, 0, 255}));
89     connect(P1.outlet, flow1DFV.infl) annotation(
90         Line(points = {{-146, -63}, {-206, -63}, {-206, -28}}, color = {0, 0, 255}));
91     connect(heatSource1DFV.wall, flow1DFV.wall) annotation(
92         Line(points = {{-221, -18}, {-211, -18}}, color = {255, 127, 0}));
93     connect(const.y, valveLin.cmd) annotation(
94         Line(points = {{-178, 43.6}, {-178, 36.6}, {-177, 36.6}}, color = {0, 0,
95             127}));
96     connect(valveLin.outlet, PZR.WaterInfl) annotation(
97         Line(points = {{-170, 31}, {-140, 31}, {-140, 32}}, color = {0, 0, 255}));
98     connect(flow1DFV.outfl, valveLin.inlet) annotation(
99         Line(points = {{-206, -8}, {-206, 32}, {-184, 32}}, color = {0, 0, 255}));
100     connect(PZR.WaterOutfl, evaporator_Water.primaryIn) annotation(
101         Line(points = {{-132, 32}, {-96, 32}}, color = {0, 0, 255}));
102     connect(Economizzatore.primaryOut, P1.inlet) annotation(
103         Line(points = {{-76, -28}, {-62, -28}, {-62, -62}, {-128, -62}}, color = {0,
104             0, 255}));
105     connect(two_Zones_Kinetic.P, heatSource1DFV.power) annotation(
106         Line(points = {{-237, -18}, {-229, -18}}, color = {0, 0, 127}));
107     connect(LPT.shaft_b, constantSpeed.flange) annotation(
108         Line(points = {{181.52, 54}, {191.52, 54}}));
109     connect(Condenser1.waterOut, Pump11.inlet) annotation(
110         Line(points = {{228, -16}, {228, -70}, {170, -70}}, color = {0, 0, 255}));
111     connect(Pump11.outlet, Preheater.primaryIn) annotation(
112         Line(points = {{150, -70}, {128, -70}}, color = {0, 0, 255}));

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109 connect(flowJoin.out, Condenser1.steamIn) annotation(
110     Line(points = {{227, 27.6}, {228, 27.6}, {228, 3.6}}, color = {0, 0, 255}));
111 connect(V2.y, V12.cmd) annotation(
112     Line(points = {{261.5, -5}, {252.5, -5}}, color = {0, 0, 127}));
113 connect(Preheater.secondaryOut, V12.inlet) annotation(
114     Line(points = {{118, -80}, {118, -88}, {248, -88}, {248, -10}}, color = {0,
0, 255}));
115 connect(V12.outlet, flowJoin.in1) annotation(
116     Line(points = {{248, 2}, {248, 48}, {230, 48}, {230, 38}}, color = {0, 0,
255}));
117 connect(LPT.outlet, flowJoin.in2) annotation(
118     Line(points = {{184.4, 68.4}, {224.4, 68.4}, {224.4, 38.4}}, color = {0, 0,
255}));
119 connect(HPT.shaft_b, LPT.shaft_a) annotation(
120     Line(points = {{92.6, 57}, {96.6, 57}, {96.6, 53}, {158.6, 53}}));
121 connect(HPT.outlet, flowSplit.in1) annotation(
122     Line(points = {{95, 69}, {107, 69}, {107, 64}}, color = {0, 0, 255}));
123 connect(flowSplit.out2, Preheater.secondaryIn) annotation(
124     Line(points = {{118.4, 61.4}, {118.4, -59.6}}, color = {0, 0, 255}));
125 connect(flowSplit1.out2, V11.inlet) annotation(
126     Line(points = {{14.4, 61.4}, {20.4, 61.4}, {20.4, 3.4}}, color = {0, 0, 255}
));
127 connect(V21.y, V11.cmd) annotation(
128     Line(points = {{33.5, -3}, {23.5, -3}}, color = {0, 0, 127}));
129 connect(Preheater.primaryOut, sprayCondenser.coolingWater) annotation(
130     Line(points = {{108, -70}, {69, -70}, {69, -60}, {48, -60}}, color = {0, 0,
255}));
131 connect(V11.outlet, sprayCondenser.condensingSteam) annotation(
132     Line(points = {{19, -10}, {19, -54}, {39, -54}}, color = {0, 0, 255}));
133 connect(setPoint.y, PID.u_s) annotation(
134     Line(points = {{-0.5, -43}, {-10.5, -43}, {-10.5, -49}, {-18.5, -49}}, color
= {0, 0, 127}));
135 connect(sprayCondenser.liquidOutlet, P21.inlet) annotation(
136     Line(points = {{40, -74}, {-36, -74}}, color = {0, 0, 255}));
137 connect(P21.outlet, Economizzatore.secondaryIn) annotation(
138     Line(points = {{-56, -74}, {-86, -74}, {-86, -38}}, color = {0, 0, 255}));
139 connect(evaporator_Water.secondaryOut, flowSplit1.in1) annotation(
140     Line(points = {{-86, 42}, {-86, 66}, {4, 66}}, color = {0, 0, 255}));
141 connect(flowSplit1.out1, HPT.inlet) annotation(
142     Line(points = {{14.4, 68.6}, {72.4, 68.6}, {72.4, 70.6}}, color = {0, 0,
255}));
143 connect(flowSplit.out1, LPT.inlet) annotation(
144     Line(points = {{118.4, 68.6}, {156.4, 68.6}}, color = {0, 0, 255}));
145 connect(PID.y, P21.nPump) annotation(
146     Line(points = {{-32, -48}, {-38, -48}, {-38, -68}}, color = {0, 0, 127}));
147 annotation(
148     uses(ThermoPower(version = "3.1"), Modelica(version = "4.1.0"));
149 end TwoZones_Deg;

```

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