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# Report of operational Design Basis Accident case studies for a SMR with cogeneration

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## Summary

This deliverable presents the results of Task 4.3, which focuses on the simulation of relevant transient scenarios for the safety assessment of cogenerating Small Modular Reactors (SMRs). The impact of cogeneration on Design Basis Accidents (DBAs) is discussed to identify the relevant transient scenarios to be simulated. It is concluded that cogeneration is not expected to adversely affect the severity of any DBA, however, it may play a role in their prevention. In particular, cogeneration can reduce the risk of failing a load rejection procedure and incurring in a loss of offsite power scenario, which is a design basis transient that can also evolve into a DBA if it lasts for several hours. The load rejection and the loss of offsite power transients have been simulated with the modelling tools developed in other work packages of the TANDEM project to study the impact of cogeneration on them. Notably, a Nuclear Steam Supply System (NSSS) model, developed with the thermal-hydraulic system code CATHARE3, has been coupled with a Balance of Plant (BoP) model, developed using the ThermoPower library in the Modelica language. A set of Proportional-Integral-Derivative (PID) controllers have been also designed to adjust the main physical parameters of both the NSSS and BoP, aiming to simulate the response of the power plant automatic control systems during the load rejection. The results of the load rejection simulations show that the transient appears less severe when the plant is cogenerating compared to when it is generating only electricity. This is because the electrical load is initially lower and the heat extraction from the secondary circuit for thermal power generation helps to reduce the overheating in both the primary and secondary circuits. Therefore, the risk of failing the load rejection and incurring in a loss of offsite power scenario is lower for cogeneration conditions. Such beneficial impact of cogeneration cannot be generalized to all possible initiating events. In some instances, the thermal load may be lost together with the electrical load as soon as the load rejection begins, thereby preventing most of the beneficial effect from cogeneration. The results of the simulations for the loss of offsite power scenario are practically identical for the cogeneration and the full electricity cases, confirming that cogeneration does not have any significant impact on the accident severity. This is due to the fact that, once the loss of offsite power s...

Approval

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# D4.4 – Report of operational Design Basis Accident case studies for a SMR with cogeneration

## WP4 - Task 4.3

March 31st 2025 [M31]

**Paolo Olita (CEA), Guido Carlo Masotti (CIRTEN-POLIMI), Alessandro De Angelis (CIRTEN-UNIPI), Walter Ambrosini (CIRTEN-UNIPI), Nicolas Alpy (CEA)**

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# Abbreviations and Acronyms

| Acronym | Description |
|---|---|
| BoP | Balance of Plant |
| DBA | Design Basis Accident |
| DEC | Design Extension Condition |
| E-SMR | European Small Modular Reactor |
| HES | Hybrid Energy System |
| HP | High Pressure |
| IP | Intermediate Pressure |
| LP | Low Pressure |
| NSSS | Nuclear Steam Supply System |
| PID | Proportional-Integral-Derivative |
| SG | Steam Generator |
| SMR | Small Modular Reactor |
| WP | Work Package |

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# Executive Summary

This deliverable presents the results of Task 4.3, which focuses on the simulation of relevant transient scenarios for the safety assessment of cogenerating Small Modular Reactors (SMRs).

The impact of cogeneration on Design Basis Accidents (DBAs) is discussed to identify the relevant transient scenarios to be simulated. It is concluded that cogeneration is not expected to adversely affect the severity of any DBA, however, it may play a role in their prevention. In particular, cogeneration can reduce the risk of failing a load rejection procedure and incurring in a loss of offsite power scenario, which is a design basis transient that can also evolve into a DBA if it lasts for several hours.

The load rejection and the loss of offsite power transients have been simulated with the modelling tools developed in other work packages of the TANDEM project to study the impact of cogeneration on them. Notably, a Nuclear Steam Supply System (NSSS) model, developed with the thermal-hydraulic system code CATHARE3, has been coupled with a Balance of Plant (BoP) model, developed using the ThermoPower library in the Modelica language. A set of Proportional-Integral-Derivative (PID) controllers have been also designed to adjust the main physical parameters of both the NSSS and BoP, aiming to simulate the response of the power plant automatic control systems during the load rejection.

The results of the load rejection simulations show that the transient appears less severe when the plant is cogenerating compared to when it is generating only electricity. This is because the electrical load is initially lower and the heat extraction from the secondary circuit for thermal power generation helps to reduce the overheating in both the primary and secondary circuits. Therefore, the risk of failing the load rejection and incurring in a loss of offsite power scenario is lower for cogeneration conditions. Such beneficial impact of cogeneration cannot be generalized to all possible initiating events. In some instances, the thermal load may be lost together with the electrical load as soon as the load rejection begins, thereby preventing most of the beneficial effect from cogeneration.

The results of the simulations for the loss of offsite power scenario are practically identical for the cogeneration and the full electricity cases, confirming that cogeneration does not have any significant impact on the accident severity. This is due to the fact that, once the loss of offsite power scenario begins, the NSSS is isolated from the rest of the power plant by closing the valves on the main steam lines and feed water lines, thus preventing any interaction between the NSSS and the BoP, where the cogeneration takes place.

# Keywords

E-SMR, Coupling algorithm, FMU, ICoCo, Python, CATHARE, Modelica, ThermoPower

# 1 Introduction

Work Package 4 (WP4) of the TANDEM project is devoted to "*Safety analysis of SMRs integrated into the hybrid systems*". Its goal is to assess the potential constraints and risks of cogeneration, i.e., the generation of both heat and electricity, for Small Modular Reactors (SMR) integrated into Hybrid Energy Systems (HES). The WP is divided into three tasks:

- Task 4.1. Identification of the potentially impacted safety margins of a cogenerating SMR;
- Task 4.2. Definition of a set of relevant safety cases to assess the safety margins;
- Task 4.3. Simulation and analysis of the safety cases.

Tasks 4.1 and 4.2 have been carried out between 2022 and 2023 and their results are presented in deliverables D4.1 (Pucciarelli et al., 2023) and D4.2 (Miss et al., 2023), respectively. Based on these results, task 4.3 has been conducted in 2024 and its results are presented in two deliverables:

- D4.3, focusing on normal operation and design basis transients analysis.
- D4.4, i.e., the present deliverable, focusing on Design Basis Accidents (DBAs) analysis.

This document is structured as follows: Section 2 discusses the safety scenarios of interest emerging from task 4.2 and describes the power plant layout chosen to simulate such scenarios. Section 3 describes the power plant modelling strategies, most of which are inherited from WP2. Section 4 presents the results of the safety scenarios simulations. Section 5 draws the conclusions.

# 2 Safety scenarios definition

## 2.1 Scenarios impacted by cogeneration

As mentioned in deliverables D2.2 (Olita et al., 2023) and D4.2 (Miss et al., 2023), power plant states can be grouped in four categories according to their estimated frequency of occurrence:

1. Normal operation (also known as Design Basis Condition 1, or DBC-1)
2. Design basis transients (also known as DBC-2)
3. Design Basis Accidents (DBAs, which includes sub-categories DBC-3 and DBC-4)
4. Design Extension Conditions (DECs).

Following EDF definitions (Cerru F. et al., 2012), the frequency of occurrence of design basis transients is greater than $10^{-2}$ per reactor per year, while for DBAs it is comprised between $10^{-2}$

and $10^{-6}$ per reactor per year. A DBA can be sub-classified as DBC-3 or DBC-4, depending on whether its estimated frequency is comprised in the range of $10^{-2} - 10^{-4}$ or $10^{-4} - 10^{-6}$ per reactor per year, respectively. Frequency of DECs is often difficult to assess, but it is generally considered to be lower than $10^{-6}$ per reactor per year. As explained in deliverable D4.2 (Miss et al., 2023), DECs scenarios are of no interest for the WP4.

Therefore, to assess the safety aspects of cogeneration in SMRs, TANDEM partners of WP4 focused on DBC-2, DBC-3 and DBC-4, and tried to determine which transient scenarios of these three categories could be significantly impacted by cogeneration. All design basis transients and accidents can be grouped in seven macro-types (NUREG-800, 2007):

A. Increase in reactor heat removal
B. Decrease in reactor heat removal
C. Decrease in reactor coolant system flow rate
D. Reactivity and power distribution anomalies
E. Increase in reactor coolant inventory
F. Decrease in reactor coolant inventory
G. Release of radioactive material from a subsystem or component

Each of these macro-types has been analyzed in deliverable D4.2 (Miss et al., 2023), and types A and B emerge as the most relevant for the WP4 since they concern reactor heat removal. During normal operation, heat removal is indeed ensured by both the electricity and heat generation systems in the secondary circuit. A malfunction affecting either of these systems can therefore lead to type A or B transient scenarios. Table 1 presents the list of selected scenarios to be considered in planning the present analyses, developed under two assumptions:

- The SMR is mainly devoted to electricity generation, meaning that the heat-to-electricity output ratio of the power plant is typically no larger than 0.5. Under this assumption, the loss of the external electrical load is inevitably a more severe transient than the loss of the thermal load.
- All transient scenarios in the list are assumed to occur while the power plant is in normal operation at full power, with the maximum possible heat-to-electricity output ratio. This initial condition appears to be the most relevant one for the safety assessment of cogeneration. Other initial conditions (operation at reduced power, shutdown, maintenance, etc.) are not taken into account.

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**Table 1. Transient scenarios here considered for the safety assessment of cogeneration**

| | | Event type A: Increase in reactor heat removal | Event type B: Decrease in reactor heat removal |
|---|---|---|---|
| Design basis transients | DBC-2 | • Feed water system malfunction causing an increase in feed water flow<br>• Feed water system malfunction causing a reduction in feed water temperature<br>• Inadvertent opening of the turbine bypass line | • Loss of feed water flow<br>• Turbine trip<br>• Loss of condenser vacuum<br>• Loss of the external electrical load leading to a short term (<2hrs) loss of offsite power |
| Design Basis Accidents (DBAs) | DBC-3 | • Small steam piping failure (including break of connecting lines)<br>• Inadvertent opening of a relief valve on the main steam line | • Small feed water piping failure (including break of connecting lines)<br>• Inadvertent closure of one or multiple steam isolation valves<br>• Loss of the external electrical load leading to a long term (>2hrs) loss of offsite power |
| | DBC-4 | • Main steam line break | • Main feed water line break |

In relation to the events listed in Table 1, the following paragraphs summarize the assumptions retained for planning the subsequent analyses, basing on the present understanding about the structure of the reactor plant and of the BoP with the related control systems. A future probabilistic safety assessment relying on a more detailed plant description, which is out of the scope of the present work, may suggest possible refinements.

The DBC-2 events of type A listed in the table are initiated by a malfunction either in the feed water system or in the turbine bypass system. Since cogeneration does not directly affect any of these two systems, it is not expected to directly increase the frequency of occurrence nor the severity of such events. Among the DBC-2 events of type B, one involves a malfunction in the feed water system and therefore is supposed not to be relevant for cogeneration safety assessment. The other three events involve a sudden failure of the electric power generation, due to issues with the turbine, the condenser or the external load. In all of these scenarios, a reactor shutdown occurs in response to the power generation failure, followed by the activation of the decay heat removal systems. The most severe scenario among these three appears to be the loss of the external electrical load leading to a short-term loss of offsite power, since it is the only scenario where the primary pumps stop working and cannot contribute to decay heat removal. Indeed, this scenario is a combination of a type B and type C event, as mentioned in D4.2 (Miss et al., 2023). In all three scenarios, cogeneration stops as soon as the reactor is shut down and is not expected to play any role in decay heat removal. For this reason, cogeneration does not affect the scenario severity. On the other hand, it may have a beneficial impact in preventing at least one scenario: the loss of offsite power. Indeed, cogeneration may help to reduce the risk that a loss of the external electrical load turns into a loss of offsite power scenario, depending on the causes of the load loss. This will be further explained in section 4.1.

The loss of offsite power is reported in Table 1 not only among the design basis transients, but also among the DBAs. This transient may indeed evolve from a DBC-2 to a DBC-3 if it lasts for several hours. Regarding the other DBAs (DBC-3 and 4) reported in Table 1, only one appear to be negatively impacted by cogeneration in terms of accident prevention: the small steam piping failure. Since a cogeneration layout increases the number of steam lines in the secondary circuit, the risk of a pipe failure is likely to increase, even though the overall risk remains low. In terms of accident severity, none of the DBAs are affected by cogeneration. As explained in deliverable D4.2 (Miss et al, 2023), in case of a DBC-3 or a DBC-4 the reactor is immediately shut down and the Nuclear Steam Supply System (NSSS) is isolated from the rest of the power plant due to the closure of the valves on the main steam and feed water lines. The decay heat removal function is then assured by the safety classified systems contained in the NSSS. Since the cogeneration system of the power plant is located outside of the NSSS, it does not interact with the NSSS once the latter is isolated.

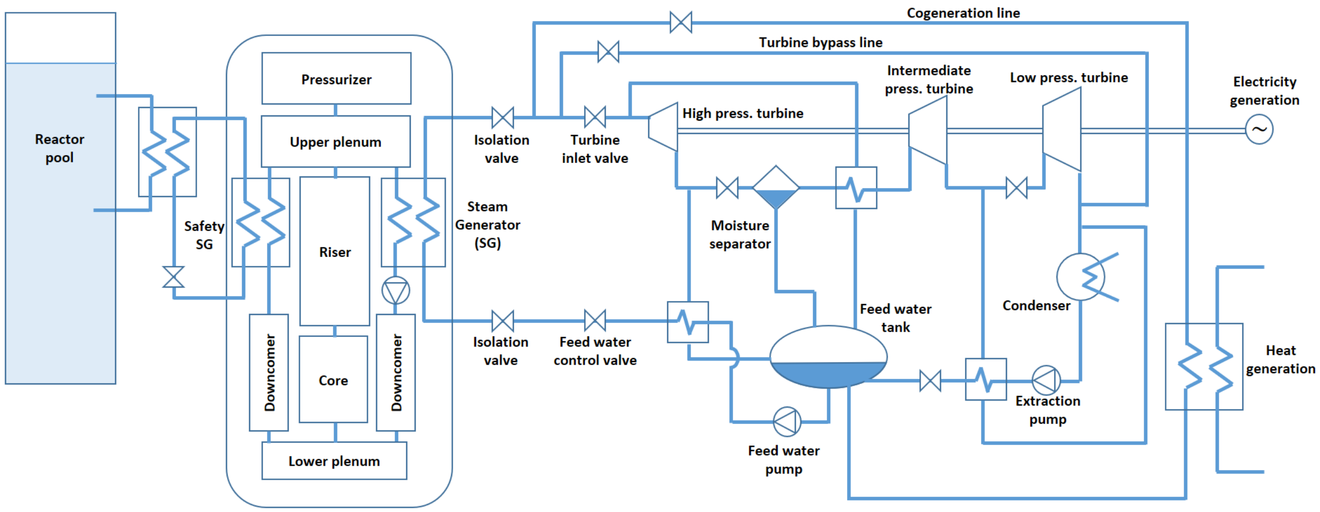
The outcomes of the qualitative transient scenario analysis performed on the basis of the above considerations are summarized in Table 2. We can postulate that the DBA most impacted by cogeneration is the loss of the external electrical load leading to a long-term (>2 hrs) loss of offsite power. For this reason, this accident sequence and the potential role of cogeneration in its prevention will be further analyzed in the following sections of this deliverable.

**Table 2. Impact of cogeneration on DBC-2, 3 and 4 events**

| Event | Possible impact of cogeneration | |
|---|---|---|
| | On prevention | On severity |
| Loss of the external electrical load leading to a short term (<2 hrs) loss of offsite power (DBC-2) | **Favorable** | None |
| Loss of the external electrical load leading to a long term (>2 hrs) loss of offsite power (DBC-3) | **Favorable** | None |
| Small steam piping failure (including break of connecting lines) (DBC-3) | **Unfavorable** | None |
| All the other DBC-2, 3 and 4 | None | None |

## 2.2 Power plant layout with cogeneration

The SMR power plant layout chosen to conduct the safety studies on cogeneration is presented in Figure 1. It is based on the European SMR (E-SMR) design, developed in the framework of the ELSMOR project between 2019 and 2023. The nominal core power is 540 MWth, and the maximum gross electric power output is 177 MWe. The main reactor parameters in nominal operation are reported in Table 3.



Nuclear Steam Supply System (NSSS) Balance of Plant (BoP)

Figure 1. Power plant layout

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The NSSS includes six Steam Generators (SGs) to transfer the core thermal power from the primary to the secondary circuit during normal operation. The coolant flow in the primary circuit is maintained by six pumps, each located at the SG outlet (one pump per each SG). The NSSS also includes two SGs, specifically designed for abnormal operation (DBC-2, 3 and 4). These two SGs, referred to as “safety SGs”, do not need pumps to operate. They can extract decay heat from the primary circuit and transfer it to a water pool by means of natural circulation. For readability purposes, Figure 1 shows a simplified layout with only one SG for normal operation instead of six, and one safety SG instead of two.

The Balance of Plant (BoP) includes a fairly standard power conversion cycle: the steam produced by the SGs (T=300°C, P=45 bar in nominal conditions) flows through a High-Pressure (HP) turbine, a steam dryer, a re-heater and then two other turbines (Intermediate-pressure IP and Low Pressure LP turbines) before arriving to the condenser. The fluid extracted from the condenser is pumped up to 7.15 bar, pre-heated and sent to a feed water tank. It is then pumped up to 49 bar, pre-heated again and sent to the SGs inlet. When the power plant is set up for cogeneration, a fraction of the steam produced by the SGs is diverted towards a heat exchanger instead of passing through the turbines. This steam condenses in the exchanger, releasing heat, and then flows to the feed water tank. The heat is extracted by a thermal oil that enters the heat exchanger at 200°C and exits at 250°C. This range of temperatures is sufficiently high for several industrial applications in the hybrid energy system, as explained in deliverable D2.5 (Amezcua et al., 2024). In case lower temperature ranges were desired for other applications, e.g., district heating, a different BoP layout could have been adopted: steam could have been extracted downstream of the HP and IP turbines, rather than at the SGs outlet (Simonini et al., 2024). This alternative layout would make heat and electricity generation more interdependent and would entail some constraints on the heat-to-electricity output ratio. A comparison between different BoP layouts for cogeneration – especially in terms of flexibility and safety – may be a research subject for future studies beyond the TANDEM project.

The BoP also includes a bypass line that allows dumping the steam directly into the condenser without passing through the turbines. This line is closed in nominal conditions, but can be opened in case the secondary circuit pressure rises too high or too fast to reduce the amount of steam accumulated in the circuit.

**Table 3. Main reactor parameters in nominal operation**

| Parameter | | Value |
|---|---|---|
| Primary circuit | Core power | 540 MWth |
| | Core inlet temperature | 300 °C |
| | Core outlet temperature | 324.5 °C |
| | Primary mass flow rate | 3700 kg/s |
| | Pressurizer pressure | 150 bar |
| Secondary circuit | Steam generator inlet temperature | 160 °C |
| | Steam generator inlet pressure | 49 bar |
| | Steam generator outlet temperature | 300 °C |
| | Steam generator outlet pressure | 45 bar |
| | Mass flow rate (x6 steam generators) | 40 x 6 kg/s |
| | IP turbine inlet pressure | 7.55 bar |
| | LP turbine inlet pressure | 0.8 bar |
| | Condenser pressure | 0.07 bar |
| | Feed water tank pressure | 7.15 bar |
| | Turbine rotational speed | 1500 rpm |

# 3 Power plant modelling

To conduct the safety studies on the E-SMR power plant, two models have been developed and then coupled together:

- an NSSS model developed with the CATHARE3 code;
- a BoP model developed with the Modelica language.

Both models have also been equipped with a set of Proportional-Integral-Derivative (PID) controllers simulating the action of the automatic control systems on the power plant. The following subsections will briefly describe the NSSS, the BoP, the PID controllers and the coupling algorithm.

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## 3.1 Nuclear Steam Supply System (NSSS)

The NSSS model has been developed with the thermal-hydraulic system code CATHARE3 (Prea et al., 2020), within the WP2 of the TANDEM project. All the hydraulic components of the NSSS are modelled as a set of 1-D and 0-D elements. The core component includes a 0-D reactor physics model (point kinetics) to compute the core power evolution during transients. The reactivity balance equation of the point kinetics model accounts not only for the fuel and moderator temperature effects but also for the control rod movement.

The reader can refer to deliverable D2.6 (Lombardo et al., 2024) for a general description of the model. Some small improvements have been implemented compared to the version presented in D2.6. In particular:

- a relief valve has been added to the pressurizer, allowing to extract steam from the primary circuit when its pressure becomes larger than 166 bar.
- check valves have been added to the safety SGs and the SGs bypass, to prevent any reverse flow in such elements.
- primary pumps have been placed on the same 1-D element representing the six SGs for normal operation. This ensures that, as long as the pumps are in operation, the primary flow rate will traverse only the six normal SGs and not the safety SGs.
- a liquid source and a sink have been added to the downcomer in the primary circuit; these elements allow simulating the action of the volume control system, which regulates the pressurizer level by adding or subtracting small amounts of liquid to or from the circuit.

The nodalization of the updated version of the CATHARE3 model is presented in Figure 2. Inlet and outlet boundary conditions are placed on the secondary side of the six SGs designed for normal operation. Liquid mass flow rate and enthalpy must be imposed at the inlet boundary condition, while the pressure must be imposed at the outlet. These boundary conditions allow coupling the NSSS model with the BoP model (cf. section 3.4).

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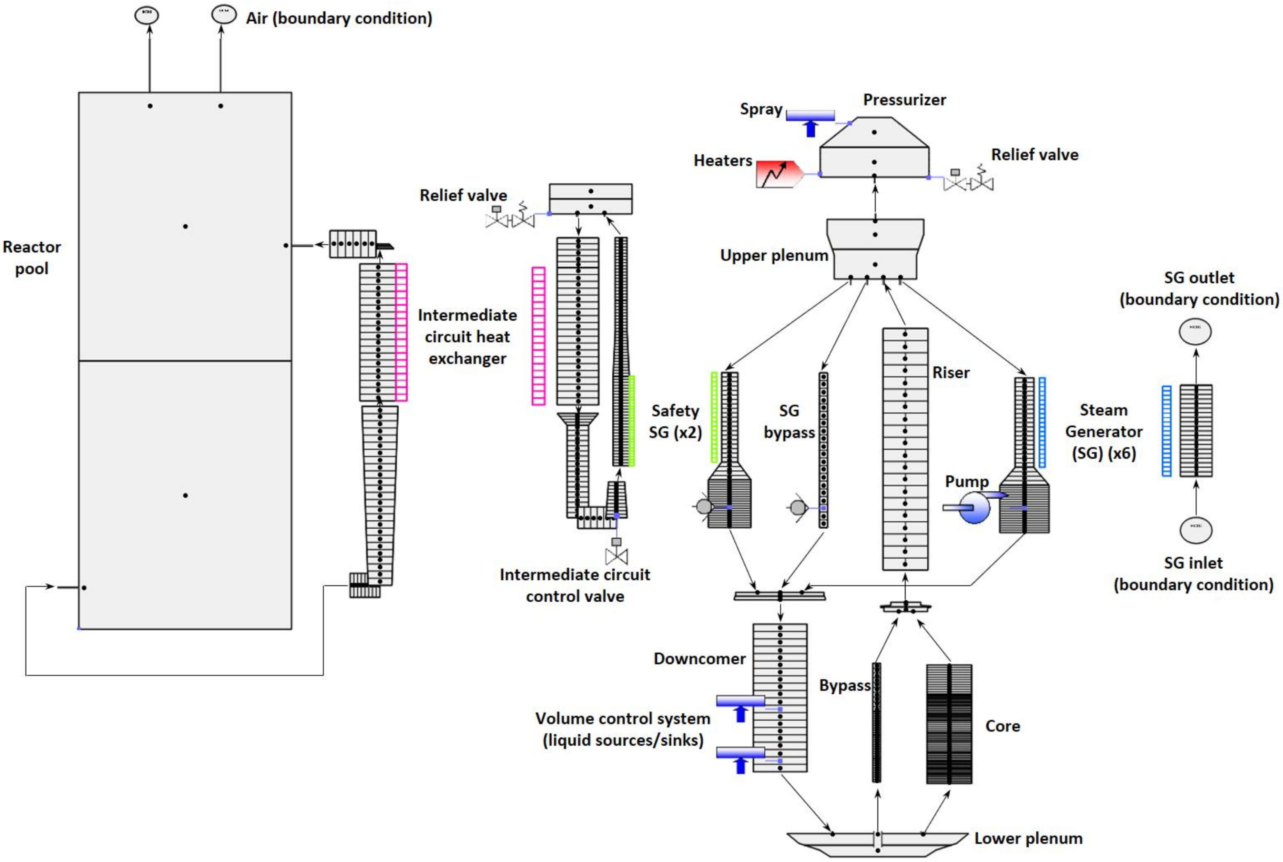

**Figure 2. CATHARE3 model of the Nuclear Steam Supply System**

## 3.2 Balance of Plant (BoP)

Three BoP models have been developed and are available in the TANDEM library (Simonini et al., 2024), using open-source Modelica libraries: two based on ThermoPower (Casella and Leva, 2006) and one on ThermoSysPro (El Hefni, 2019). The BoP model selected for this study is based on the ThermoPower library and is presented in Figure 3. This BoP model is designed to receive multiple inputs (blue triangles in Figure 3) to compute a time step, in particular:

- the opening positions of the control valves in the circuit; these positions must be provided by the PID controllers;
- the steam mass flow rate and enthalpy at the SGs outlet, and the feed water pressure at the SGs inlet; these values must be provided by the NSSS model;
- the electric power requested by the grid, the mass flow rate and the enthalpy of the thermal oil entering the heat exchanger for thermal power generation; these inputs must be provided directly by the user.

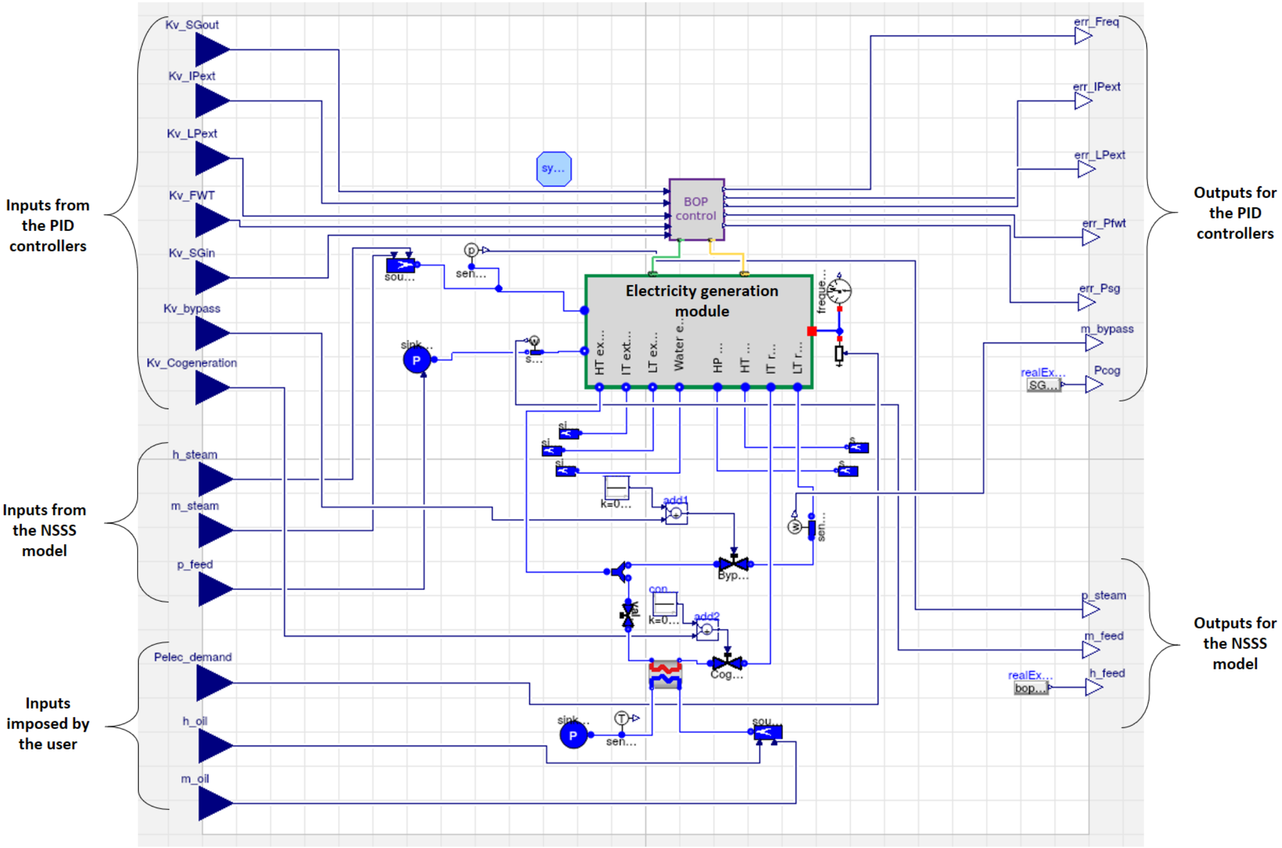

Figure 3. Modelica model of the Balance of Plant

After successfully computing one time step, the BoP model provides multiple outputs (white triangles in Figure 3), in particular:

- the errors on the controlled variables of the circuit (i.e. the differences between the set point values and the current values), which are then supplied to the PID controllers.
- the feed water enthalpy and mass flow rate at the SGs inlet, and the pressure at the SGs outlet, which are then supplied to the NSSS model.

The BoP is constituted by several components and modules, the largest of which is the electricity generation one, as shown in Figure 4. The reader can refer to deliverable D2.3 (Simonini et al., 2024) to have an overview of the basic assumptions and limitations of such module. The reader can also refer to deliverable D2.5 (Amezcua et al., 2024) to find an overview on the thermal power generation module based on thermal oil.

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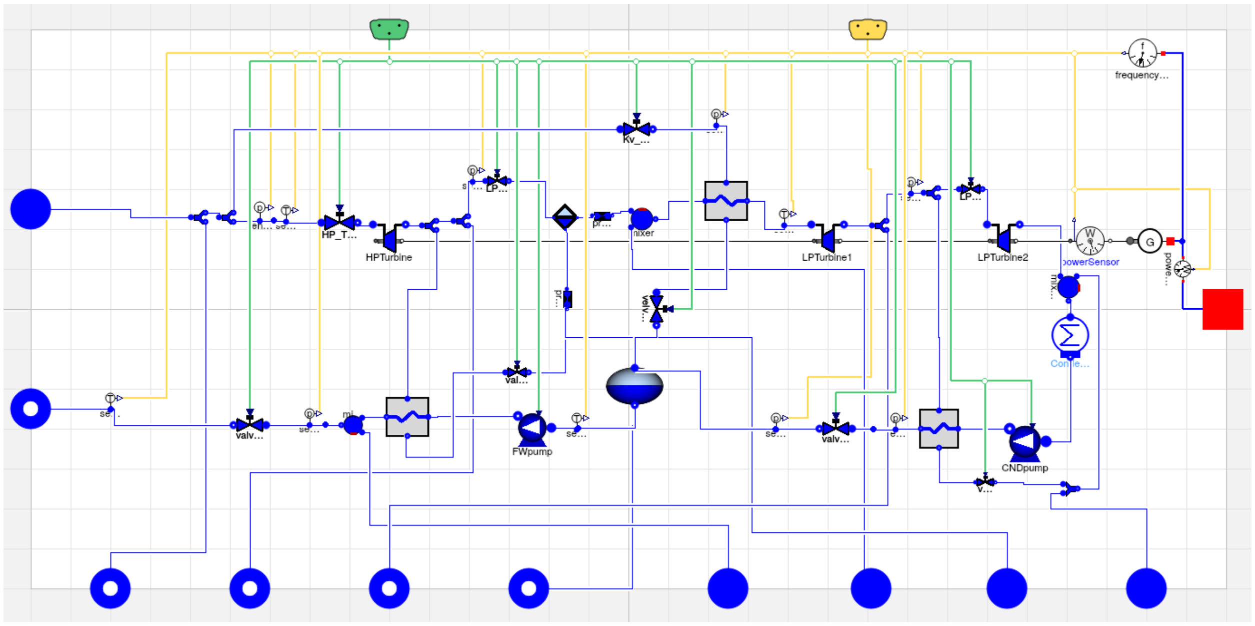

Figure 4. Electricity generation module

## 3.3 Control systems

Table 4 presents the PID controllers implemented for the NSSS and the BoP. They are all designed to maintain the controlled variables as close as possible to their set point values during normal operation. Most of these set point values are fixed as long as the power plant remains in DBC-1. For example, the set point value of the primary average temperature is maintained at 312.2 °C regardless of whether the power plant is in steady state at full power, at reduced power, or undergoing some normal operation transients. However, two specific set point values are designed to change:

- turbine bypass flow rate: Normally set to 0 kg/s, but it can evolve into other values depending on the power plant operating conditions; for example, during a load rejection transient, this set point value is increased to prompt the turbine bypass valve to open, allowing steam to be dumped into the condenser;
- steam flow rate in the cogeneration line: set to 0 kg/s when the power plant produces only electricity, but it may evolve in time depending on the thermal power demand.

All the PID controllers have been implemented in the Python language. Their parameters have been calibrated manually by performing DBC-1 transient scenarios like power ramps (cf. section 3.5). Figure 5 shows the location of all actuators in the power plant.

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**Table 4. PID controllers**

| Controlled variable | | Actuator |
|---|---|---|
| NSSS controls | Primary average temperature | Control rods |
| | Pressurizer pressure | Pressurizer spray and heaters |
| | Pressurizer level | Volume control system |
| BoP controls | Turbine frequency | Turbine inlet valve |
| | HP turbine inlet pressure | Feed water control valve |
| | IP turbine inlet pressure | Intermediate pressure valve |
| | LP turbine inlet pressure | Low pressure valve |
| | Feed water tank pressure | Feed water tank inlet valve |
| | Turbine bypass flow rate | Turbine bypass valve |
| | Steam flow rate for thermal power generation | Cogeneration control valve |

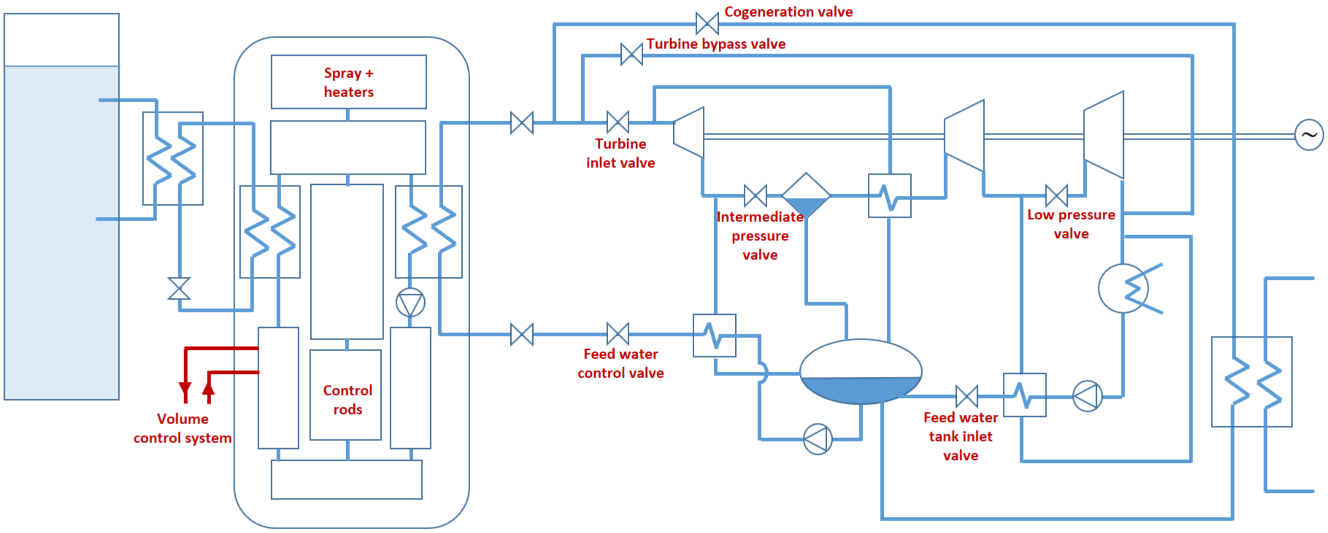

**Figure 5. Actuators of the PID controllers**

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## 3.4 Coupling algorithm

A Python supervisor script is used to implement the coupling between the NSSS, BoP and PID controllers. The following steps have been taken to set up the coupling environment:

- the CATHARE3 model of the NSSS was first compiled into a C++ dynamic library by means of an Application Programming Interface (API) named ICoCo (Interface for Code Coupling) (Deville and Perdu, 2012); it was then imported into Python via the SWIG software (Simplified Wrapper and Interface Generator) (Beazley, 1996);
- the Modelica BoP model has been compiled into a Functional Mock-up Unit (FMU) using the Dymola software (Dassault Systèmes, 2023), then imported into Python via the FMPy software (CATIA-Systems, 2023);
- the PID controllers, already implemented in Python, were imported directly into the supervisor script as standard Python modules.

The coupling algorithm contained in the supervisor script is presented in Figure 6. This algorithm is explicit, meaning that each time step is computed only once, without iterations between the models. Some small numerical oscillations have been observed during the analyses, but these have been effectively controlled by limiting the time step size: an upper bound of 0.1 seconds is adopted for all transient scenarios. Overall, the explicit algorithm has proven to be reliable enough as it did not lead to any significant numerical instability. The adoption of an implicit algorithm is not possible due to technical limitations, specifically because the FMU of the BoP does not support iterations within a time step.

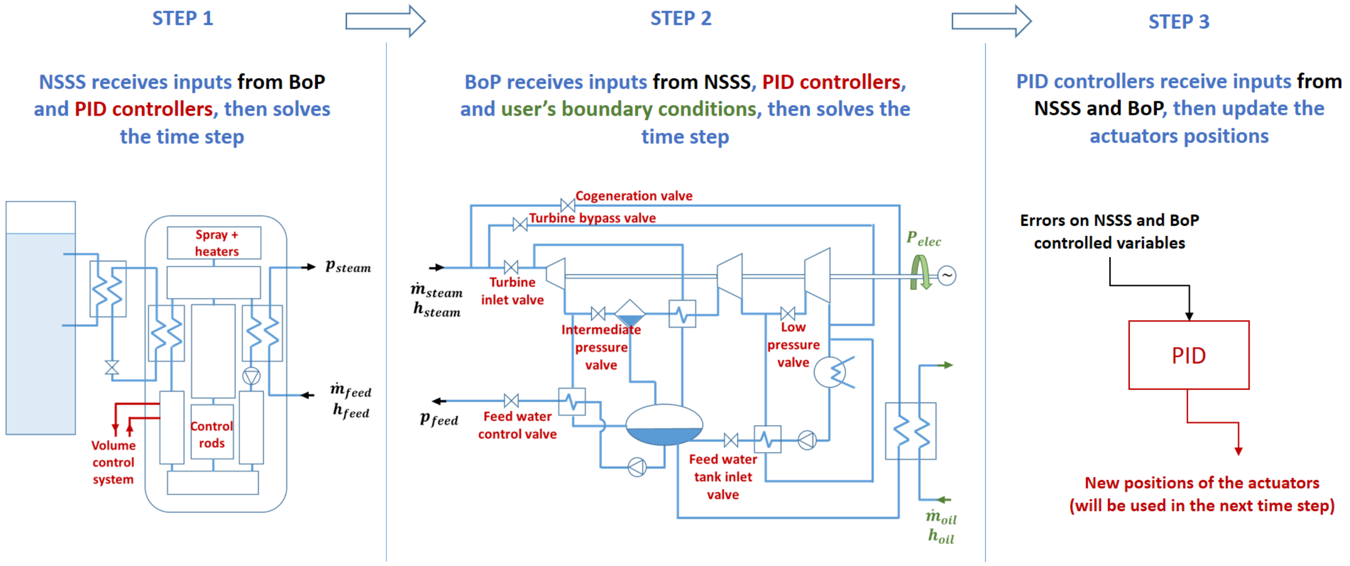

Figure 6. Coupling algorithm to solve a time step

## 3.5 Model testing in normal operation

Before dealing with the safety scenarios of interest for the WP4, some simpler scenarios have been simulated to assess the behavior of the power plant and calibrate the PID controllers.

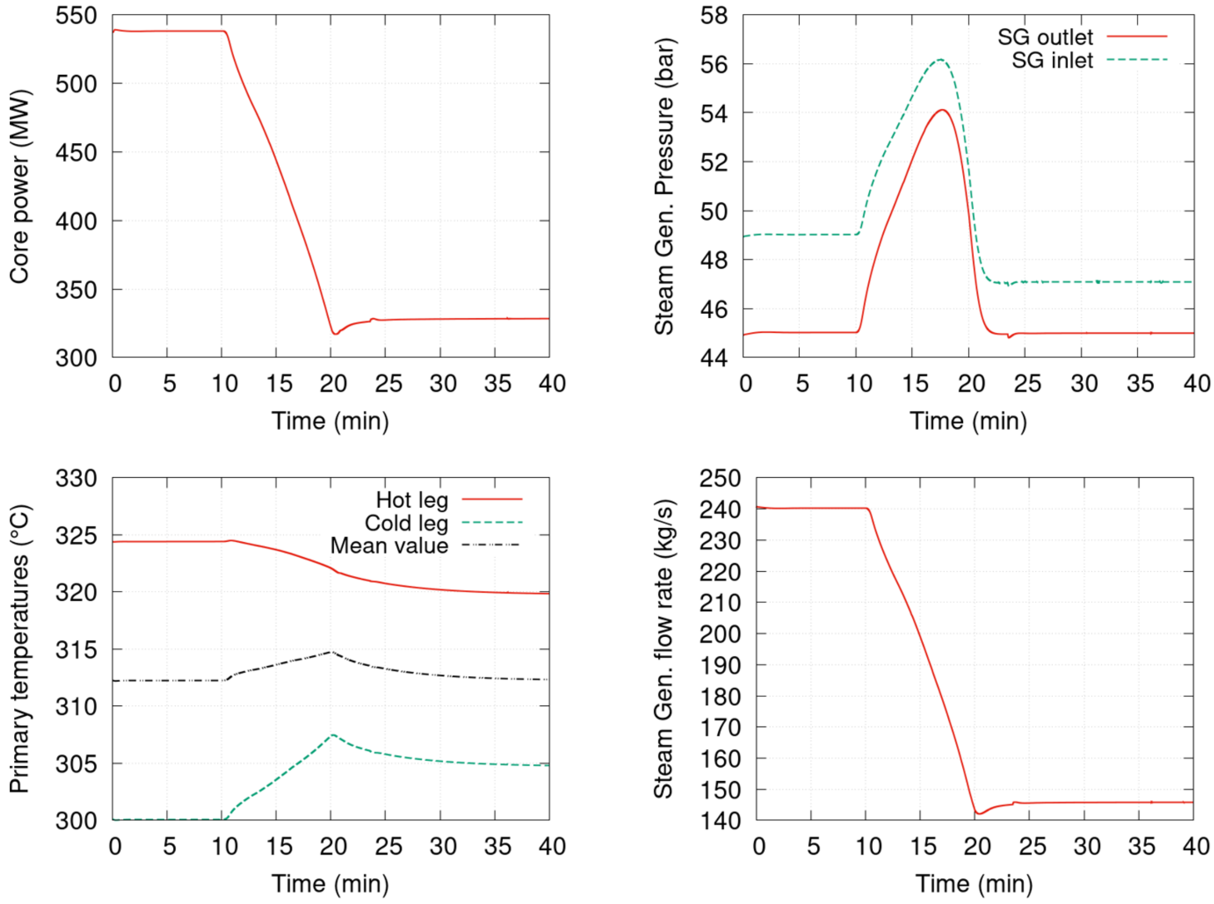

Figure 7. Electrical load reduction transient

As an example, Figure 7 shows the results of an electrical load reduction. The power plant is in a fully electric setup: the electrical output is initially at the nominal value (177 MWe) while the thermal output for cogeneration is 0 MWth. The electrical power demand is then decreased linearly from 100% to 50% of the nominal value on a 10-minute time span. This corresponds to a linear reduction of the resistive torque on the turbo-generator shaft; the turbine frequency control system immediately responds to this by partially closing the turbine inlet valve, and therefore reducing the mechanical torque produced by the turbine. As a result, steam accumulates in the secondary circuit, making its pressure rise. Since the secondary circuit is unable to extract all the thermal power produced by the core, part of this thermal power remains in the primary circuit and is absorbed by the reactor coolant. The average coolant temperature rises, and the core power immediately starts decreasing in response. This is due to the moderator temperature feedback, a reactor physics effect contributing to the reactor core inherent stability.

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The core power continues decreasing until a new balance is reached, where the power produced in the primary circuit equals the power absorbed by the secondary circuit. At this point, the core power stabilizes and the plant returns gradually to steady state conditions. The core power reduction is also aided by the action of the control rods, whose insertion is commanded by the primary average temperature controller. At the end of the transient, all the PID controllers implemented in both the NSSS and BoP successfully restore the controlled variables to their respective set point values, ensuring operational stability.

It is worth noting that, once the power plant has reached its new steady state, the electrical power output has been effectively decreased to 50% of its nominal value. However, the core power has been only decreased to 60% of its nominal value (330 MWth), leading to a reduction in thermodynamic efficiency from 32.8% under nominal conditions to 26.8%. The efficiency loss is usually expected in power plants when their operating conditions shift from the nominal ones, but in this case it is further accentuated by the simplified design of the PID controllers. As mentioned in section 3.3, the set point values for the pressures in the secondary circuit are kept constant independently of the operating point, leading to suboptimal performance of the HP, IP and LP turbines when the power level is reduced.

# 4 Simulation of selected safety scenarios

## 4.1 Load rejection

A disturbance on the main electrical grid, e.g., a storm damaging the transmission lines, may induce significant perturbations on the grid frequency and voltage. This poses a safety concern for a nuclear power plant, since its auxiliary systems, including the primary pumps that provide the core coolant flow, normally rely on the grid power to operate. To ensure the power plant safety and avoid the reactor shut down, a load rejection procedure (or islanding) is automatically launched by the plant control systems when strong grid anomalies are detected. This procedure can be summarized with a list of events reported below.

- The load rejection starts with the trip of the circuit breaker connecting the generator to the grid. The power plant is abruptly disconnected from the grid, leading to a complete loss of the external electrical load.
- Once the plant is disconnected, its electrical power output is immediately redirected towards its auxiliary systems to keep them in operation. Since the only resistive torque on the turbo-generator is now due to the reactor auxiliary systems, the generator shaft accelerates.

- The primary pumps are now directly powered by the generator, so their rotation also accelerates. This leads to an increase in the coolant flow rate, and a slight decrease of the moderator temperature in the core. Due to the moderator temperature feedback, the core power rises and attains a peak.
- The turbine frequency control system responds to the turbo-generator acceleration by partially closing the turbine inlet valves. The heat produced by the core starts accumulating in both the primary and secondary circuits, increasing their temperatures and pressures. This behavior is similar to the simple load reduction scenario described in section 3.5, but in this case the pressure in the secondary circuit rises fast enough to trigger the turbine bypass valve to open. As a result, part of the steam accumulated in the secondary circuit is dumped into the condenser.
- The primary average temperature controller commands the control rods insertion to reduce the core power, while the turbine bypass system contributes to cool down both the primary and secondary circuits.

If the load rejection is successful, the plant will be able to stabilize at a reduced power level in which the core power and the steam flow rate produced by the SGs are roughly 30% of their nominal values. Part of the steam flow rate will be sent to the turbines to generate the electricity needed for the auxiliary systems, while the rest will be used for heat generation and/or discharged into the condenser. This 30% power level serves as a stand-by point from which the power plant is able to get back to 100% in a relatively short time, once the grid anomalies are eliminated.

The load rejection is the most severe transient that the power plant can withstand while still remaining in DBC-1. The power plant control systems must provide a fast and synergistic response during the transient to reduce the risk of exceeding one or more safety thresholds and incurring in an automatic reactor shutdown. Among the most common causes for a reactor shutdown during a load rejection, the following may be cited: primary circuit overpressure, secondary circuit overpressure and too fast rate of change of the neutron flux. If the reactor is shut down, the plant becomes unable to supply electricity to its own auxiliary systems, and must be connected to the auxiliary electrical grid via the auxiliary transformer. However, if the auxiliary grid is also unavailable – potentially due to the same initiating event that made the main grid unavailable in the first place – then the power plant incurs in a loss of offsite power scenario. Figure 8 shows the event tree relating such scenarios.

The simulations conducted in the framework of task 4.3 aim to ascertain if cogeneration may have a beneficial or detrimental impact on the power plant response to a load rejection event, making failure more or less likely and thereby affecting the probability of a loss of offsite power scenario.

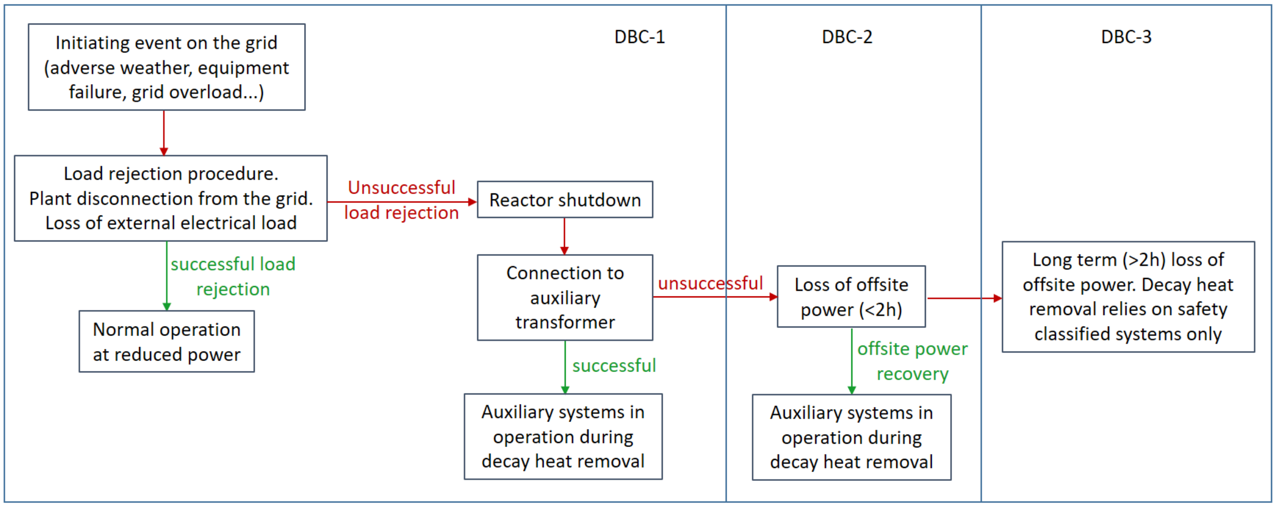

**Figure 8. Event tree leading to a loss of offsite power scenario**

Figure 9 presents a comparison between two simulations of successful load rejection performed on the E-SMR: one where the power plant initially generates only electricity (177 MWe), and another where the power plant generates both electricity and heat (164 MWe + 25 MWth). For both setups, the core is initially at full power (540 MWth). The simulation results show that the cogeneration setup is more favorable than the fully electric one in terms of safety. Specifically, the pressures attained in the pressurizer and in the steam generators are lower, and the core power peak following the pumps acceleration is also lower. As a result, the risk of exceeding one or more safety thresholds during a load rejection and incurring in a reactor shutdown is expected to be lower in the cogeneration setup. These results can be attributed to the following factors:

- In the fully electric setup, the E-SMR relies only on the turbine bypass system to extract the excess heat and avoid the circuits overheating. In contrast, in the cogeneration setup, the E-SMR can also transfer heat to an external thermal load, providing an additional heat sink.
- In the fully electric setup, the initial electrical load is higher, meaning that the sudden loss of the load leads to a larger turbo-generator acceleration, a larger pumps acceleration and a higher power peak in the core.

Towards the end of the transient, when the core power is stabilized at approximately 30% of its nominal value, the steam flow rate to the turbine bypass is lower in the cogeneration setup than in the fully electric one. This indicates that cogeneration helps to absorb part of the heat produced by the core, reducing the amount of wasted heat dissipated in the condenser.

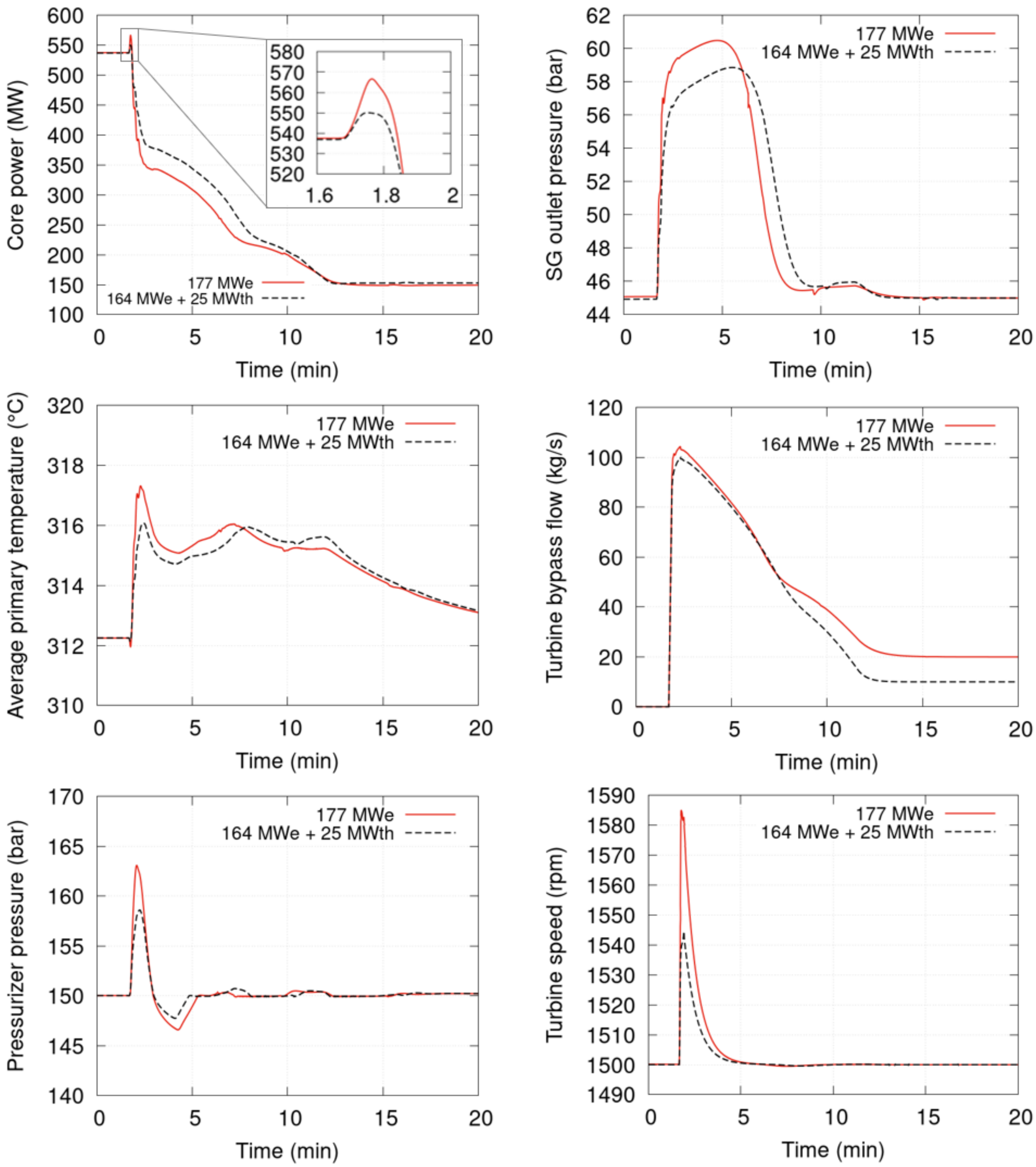

**Figure 9. Load rejection transient. Comparison between fully electric and cogeneration setup**

It is important to point out that these results, showing the beneficial impact of cogeneration during a load rejection, cannot be generalized to all possible initiating events. As highlighted in deliverable D4.2 (Miss et al., 2023), some initiating events may lead to the loss of both the electrical and thermal loads. In such cases, the primary and secondary pressure peaks attained during a load rejection will not differ in any significant way between the cogenerating setup and

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the fully electric one. In addition, some other initiating events may lead the power plant directly to the shutdown, excluding the possibility of a load rejection and making cogeneration irrelevant for the scenario. For example, if an earthquake occurs in proximity of the power plant, disrupting both the main and auxiliary grids, the safety systems of the power plant will not attempt a load rejection, but will shut down the reactor immediately as they receive a signal from the seismic detectors.

In conclusion, it can be stated that, depending on the postulated initiating events, cogeneration may have a favorable impact in preventing a loss of offsite power scenario or, at the very least, should not introduce any adverse effect.

## 4.2 Unsuccessful load rejection. Loss of Offsite Power transient

The long term (> 2hrs) loss of offsite power transient has been simulated for both the fully electric and the cogeneration setups, to inquire if the cogeneration setup has any significant impact on the accident severity. For both setups, the simulations started as load rejection transients with the core initially at full power, as was done for the case in section 4.1. Sixty seconds after the beginning of the load rejection, it is postulated that one of the safety thresholds monitored by the reactor control systems is exceeded, leading to a reactor shutdown. Additionally, it is assumed that the auxiliary grid is unavailable and remains as such for several hours. As a result, the plant loses all external sources of energy and the primary pumps stop operating. In response to this, the isolation valves on the main steam line and on the main feed water line are closed, leading to the isolation of the NSSS from the BoP. Concurrently, the valves on the intermediate circuits are opened, allowing the safety SGs to extract the decay heat from the primary circuit and deliver it to the reactor pool, as shown in Figure 10. As explained in section 2.1, once the NSSS is isolated, the setup of the BoP will not have any impact on the transient. Therefore, any differences between the results obtained with the two setups can only arise during the first minute of the transient scenario, before the isolation valves are closed. In practice, no significant differences between the results have been observed beyond the first minute, confirming that the accident severity is independent of the BoP setup.

Figure 11 shows the results of the long-term loss of offsite power simulation, obtained with either of the two setups. The core decay power is initially larger than the power extracted by the safety SGs, leading to an increase of the temperature and pressure in the primary circuit. When the pressurizer pressure becomes higher than 166 bar, the relief valve is opened, allowing to extract some thermal energy from the primary circuit due to the steam bleeding. Once the core decay power becomes smaller than the power extracted by the safety SGs, the primary circuit starts to cool down. Meanwhile, the decay heat accumulates in the reactor pool, making its temperature

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rise. The volume of the reactor pool has been designed to provide a passive cooling for several days.

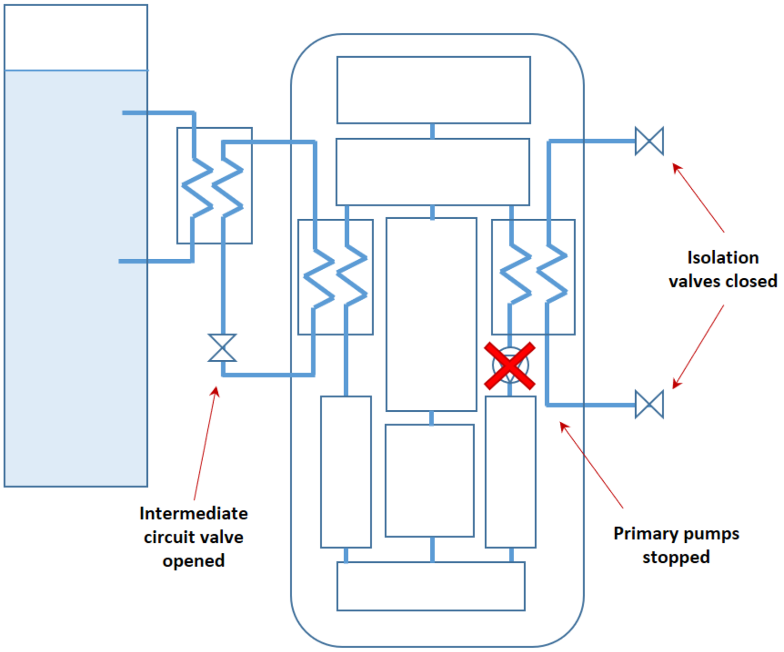

Figure 10. NSSS isolated from the BoP during a loss of offsite power transient (60 s after the initiating event)

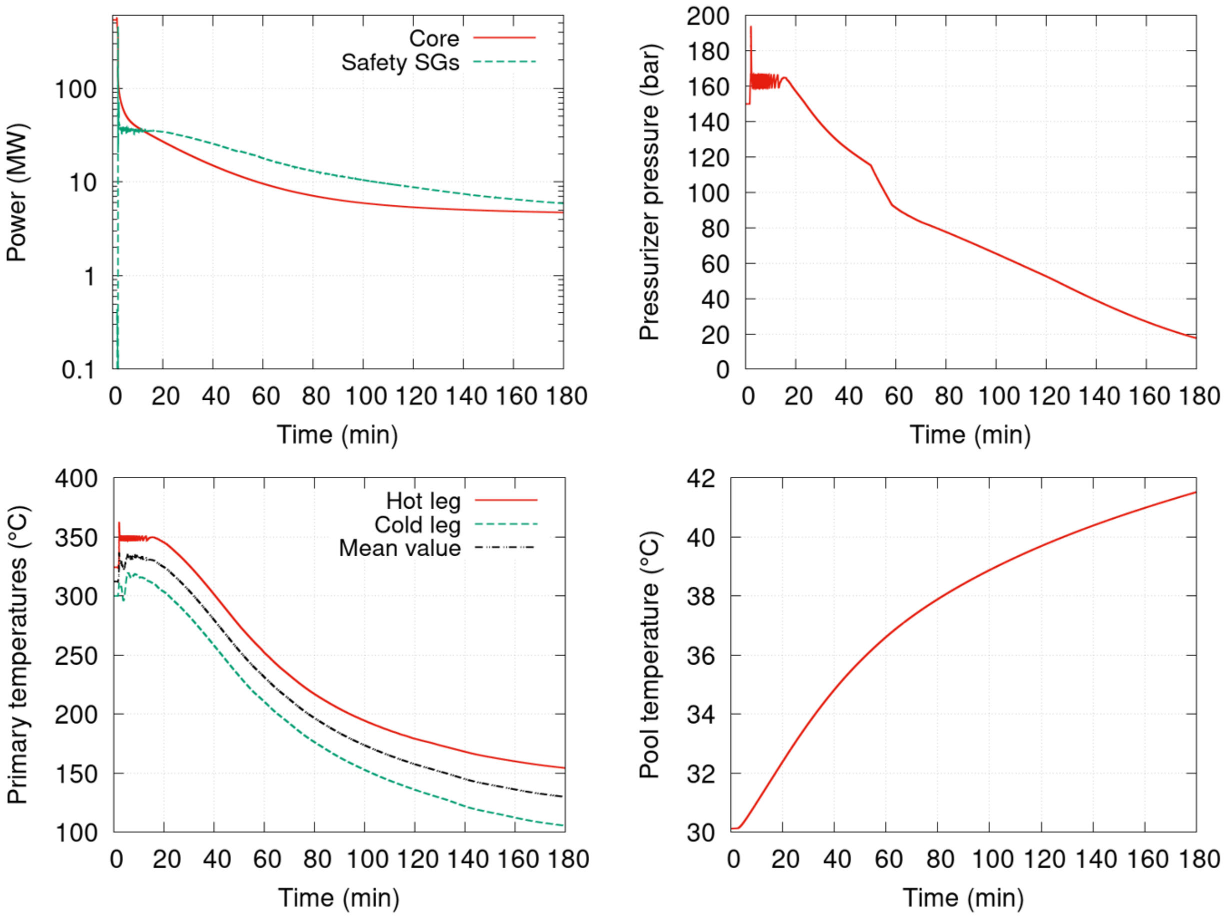

**Figure 11. Loss of offsite power transient results**

# 5 Conclusions

This deliverable presents the results of Task 4.3, concerning the simulation of some relevant transient scenarios for the safety assessment of cogenerating Small Modular Reactors (SMRs).

First, the impact of cogeneration on Design Basis Accidents (DBAs) was discussed to identify the relevant transient scenarios to be simulated. It is concluded that cogeneration is not expected to adversely affect the severity of any DBA, however, it may play a role in their prevention. In particular:

- cogeneration can reduce the risk of failing a load rejection procedure and incurring in a loss of offsite power scenario, which is a design basis transient that can also evolve into a DBA if it lasts for several hours; the actual impact of cogeneration in preventing the loss of offsite power depends on the initiating event that causes the load rejection;

- cogeneration is expected to (slightly) increase the risk of a small steam piping failure, which is a commonly considered DBA, as such not addressed specifically herein as it belongs to the class of accidents normally considered in safety analyses; the increase in risk is in fact just due to the increased number of steam lines in the secondary circuit for heat generation.

Following such preliminary discussion, the load rejection and the loss of offsite power transients have been simulated with the modelling tools developed in other work packages of the TANDEM project to study the impact of cogeneration on them. Notably, a Nuclear Steam Supply System (NSSS) model, developed with the thermal-hydraulic system code CATHARE3, has been coupled with a Balance of Plant (BoP) model, developed using the ThermoPower library in the Modelica language. A set of Proportional-Integral-Derivative (PID) controllers have been also designed to adjust the main physical parameters of both the NSSS and the BoP, aiming to simulate the response of the power plant automatic control systems during the load rejection.

The results of the load rejection simulations show that the transient appears less severe when the plant is cogenerating compared to when it is generating only electricity. This is because the initial level of electrical power produced by the reactor is lower (i.e., the electrical load is initially lower) and the heat extraction from the secondary circuit for thermal power generation helps to reduce overheating in both the primary and secondary circuits. Therefore, the risk of failing the load rejection and incurring in a loss of offsite power scenario is lower for cogeneration conditions. However, as previously mentioned, such beneficial impact of cogeneration cannot be generalized to all possible initiating events. In some instances, the thermal load may be also lost together with the electrical load as soon as the load rejection begins, thereby preventing most of the beneficial effect from cogeneration.

On the other hand, the results of the simulations for the loss of offsite power scenario are practically identical for the cogeneration and the full electricity cases, confirming that cogeneration does not have any significant impact on the accident severity. This is due to the fact that, once the loss of offsite power scenario begins, the NSSS is isolated from the rest of the power plant by closing the valves on the main steam lines and feed water lines, thus preventing any interaction between the NSSS and the BoP, where the cogeneration takes place.

Basing on these first analyses, the NSSS and BoP models developed so far within the TANDEM project can be useful for future studies involving the safety and the flexibility of cogenerating SMRs. The coupling between the NSSS and BoP models, whose functionality is demonstrated both in this deliverable and in D4.3, is well suited to analyze a wide variety of normal and abnormal operation transients.

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