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CATHARE SMR model description

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Summary

Description of developpment and test of the model with the CATHARE code to be used in the analysis

Approval

Date	By
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2024-07-05 20:03:18	Dr. Claire VAGLIO-GAUDARD (CEA)

D2.6 – CATHARE SMR model description

WP2 - Task 2.4

June 24th 2024 [M22]

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History

Date	Version	Submitted by	Reviewed by	Comments
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Abbreviations and Acronyms

Acronym	Description
BoP	Balance of Plant
E-SMR	European Small Modular Reactor
ME	Model Exchange
SG	Steam Generator
SMR	Small Modular Reactor
WP	Work Package

Executive Summary

The TANDEM project aims to provide assessments and tools to facilitate the safe, secure and efficient integration of light water SMRs into smart low-carbon hybrid energy systems. One of the objectives of the TANDEM WP2 is the development of SMR models with both CATHARE and ATHLET safety codes to perform the safety analysis considering the integration of SMRs into hybrid energy systems (related to the Task 2.4). The present deliverable is devoted to describe the CATHARE3 model of the E-SMR concept; this model is used in Task 4.3 for the simulation of the safety transients identified in Task 4.2.

In particular in this deliverable are reported:

- ✓ a description of the E-SMR (selected as the SMR use-case in TANDEM)
- ✓ a detailed description of the CATHARE model
- ✓ the steady state analysis of the E-SMR
- ✓ the CATHARE/MODELICA coupling procedure

Keywords

SMRs, Hybrid Energy Systems, Modelling, Coupling algorithm, CATHARE

1. Introduction

Work Package 2 (WP2) in the TANDEM project is devoted to *"Modelling for the simulation of the hybrid system behaviour"*. In particular, the specific objectives of the work package are:

- *"the identification of the modelling approach and the requirements needed by the simulation tools to be employed in SMRs safety analyses (WP4), as well as in techno-economics assessment (WP3);*
- *the development of an Open-Source "TANDEM" model library aimed at simulating the behaviour of power plants, systems and components, including SMRs, and needed to analyse the hybrid systems;*
- *the development of SMR models with both CATHARE and ATHLET safety codes to perform the safety analysis considering the integration of SMRs into a hybrid energy system;*
- *the delivery of a hybrid system simulator to develop a coupling with the SMR CATHARE and ATHLET models in WP2 and techno-economics tools in WP3."* (from the TANDEM Grant Agreement).

In particular, the activities related to the Task 2.4, entitled "*Development of SMR detailed models for safety analysis"*, is devoted to the development of the E-SMR detailed model for the system thermal-hydraulics safety studies (identified in Task 4.2). CEA and CIRTEN-UNIPI, with support of CIRTEN-POLIMI and ENEA, have developed and tested the CATHARE model to be used in the analyses defined in WP4.

2. E-SMR data set

The SMR data used in this deliverable have been provided by the ELSMOR (Towards European Licencing of Small Modular Reactors) [1] consortium. ELSMOR was a EU-funded project aimed at designing methods and tools for stakeholders to assess and verify Light Water SMRs' safety when installed across Europe.

In the framework of the activity related to the WP5 of the ELSMOR project, the need to have a congruent set of data pushed the ELSMOR partners to develop the design of this academic concept at the system scale, and to collect its data in a spreadsheet containing geometrical description of all parts of the E-SMR. The E-SMR data set is made open and available by ELSMOR partners at the following address: https://etsin.fairdata.fi/dataset/00b62da2-7b96-4e70-82ef-1e8afaa0ecb1/data.

This data set has been used to prepare the CATHARE input deck in the WP2 of the TANDEM project.

3. E-SMR description

Table 1 shows the main parameters of the E-SMR implemented as the SMR use-case in the TANDEM project.

Table 1: Main E-SMR parameters.

Parameter	Value	Unit
Core thermal power	540	MWt
Electrical output	170	MWe
Nominal coolant flow rate (primary)	3700	kg/s
Nominal coolant flow rate (secondary)	240	kg/s
Core inlet temperature	300	°C
Core outlet temperature	324.5	°C
Primary pressure	15	MPa
Secondary pressure	4.5	MPa

The E-SMR input deck is constituted by primary and secondary circuits and by safety systems.

3.1 Primary circuit

The primary circuit of the E-SMR is composed by the following components:

- Downcomer
- Lower Plenum
- Core
- Riser
- Upper plenum
- Pressurizer
- Annular plenum (steam generators by-pass)
- Steam Generators (SGs)
- Pumps

3.1.1 Downcomer

The geometrical data of the downcomer are reported in Table 2.

Table 2: Downcomer data.

Parameter	Value	Unit
Height (H_{dc})	5.2	m
Annulus inner diameter $(D_{in,ann})$	2.45	m
Annulus outer diameter $(D_{out,ann})$	3.65	m
Flow area (A_{dc})	5.7491	m^2
Volume (V_{dc})	29.8953	m^3

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Hydraulic diameter $(D_{h,dc})$	1.2	m

3.1.2 Lower plenum

The geometrical data of the lower plenum are reported in Table 3.

Table 3: Lower plenum data.

Parameter	Value	Unit
Height (H_{lp})	0.5	m
Ellipse major (and semi minor) axis (a_{lp})	3.65 (0.5)	m
Flow area (A_{lp})	5.7491	m^2
Volume (V_{lp})	3.488	m^3
Hydraulic diameter $(D_{h,lp})$	1.2	m

3.1.3 Core

The parameters for the core description are reported in Table 4.

Table 4: Core parameters.

Parameter	Value	Unit
Core Geometry		
Active fuel length (H_a)	2	m
Active core diameter $(D_{in,core})$	2.3556	m
No. of assemblies (N_A)	76	
Core volume (V_{core})	11.2771	m^3
Volumetric power density	47.8844	MW/m^3
Heat Flux		
Core average heat flux	451	kW/m^2
Hot assembly average heat flux	586	kW/m^2
Hot pin average heat flux	645	kW/m^2
Peak Factors		
Axial power peaking factor	1.45	
Hot assembly peaking factor	1.3	
Hot pin peaking factor	1.1	
Core peaking factor	2.0735	
Fuel Geometry		
Fuel rod length	2.159	m
Fuel pellet outer diameter	8.11e-3	m
Diametral gap	1.65e-4	m
Cladding inner diameter	8.28e-3	m
Cladding outer diameter	9.49e-3	m
Cladding thickness	6.09e-4	m
Guide tube outer diameter	1.22e-2	m

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Instrument tube outer diameter	1.22e-2	m
Fuel rod pitch	1.25e-2	m
Fuel assembly envelope side length	0.214	m
Fuel assembly pitch (P_{fa})	0.215	m
No. of fuel rods per assembly (N_{fr})	264	
No. of guide tubes per assembly (N_{gt})	24	
No. of instrument tubes per assembly (N_{ins})	1	
Spacer grids per assembly	5	
Overall fuel assembly length (H_{core})	2.6	m
Core Flow Area Quantities		
Assembly area (A_{ass})	4.62e-2	m^2
Fuel rod area per assembly (A_{fr})	1.87e-2	m^2
Guide thimble area per assembly (A_{gt})	2.82e-3	m^2
Instrumentation area per assembly (A_{ins})	1.17e-4	m^2
Assembly flow area $(A_{ass,flow})$	2.45e-2	m^2
Core flow area (A_{core})	1.8686	m^2
Core Barrel Geometry		
Barrel inner diameter	2.35	m
Barrel thickness (t_{barr})	0.05	m
Barrel outer diameter	2.45	m
Baffle Assembly Sides	40 (Fuel assembly sides)	
Hydraulic Diameter		
Core hydraulic diameter $(D_{h,core})$	1.09e-2	m
Assembly hydraulic diameter	1.11e-2	m

3.1.4 Riser

The data for the riser are given below in Table 5.

Table 5: Riser data.

Parameter		**Value**	**Unit**
	Riser Geometry		
Riser height (H_{riser})		5.6	m
Internal diameter $(D_{in,core})$		2.3556	m
Flow area (A_{riser})		0.79	m^2
Volume (V_{riser})		4.41	m^3
Hydraulic diameter $(D_{h,riser})$		4.19e-2	m

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3.1.5 Upper plenum

The data for the upper plenum are reported in Table 6.

Table 6: Upper plenum data.

Parameter	Value	Unit
Height (H_{up})	1.8	m
Internal diameter ($D_{in,RPV}$)	3.65	m
Flow area (A_{up})	10.46	m^2
Volume (V_{up})	18.8342	m^3
Hydraulic diameter ($D_{h,up}$)	3.65	m

3.1.6 Pressurizer

The parameters related to the pressurizer are reported in Table 7

Table 7: Pressurizer data.

Parameter	Value	Units
Geometry		
Height (H_{pr})	2	m
Inner diameter (base) ($D_{in,pr}$)	3.65	m
Separator plate hole (surge orifice) diameter (D_{so})	0.05	m
No. of surge orifices (N_{so})	8	
Base Flow area (A_{pr})	0.0157	m^2
Volume (V_{pr})	14.4866	m^3
Hydraulic diameter ($D_{h,pr}$)	0.4	m
Levels		
Initial water level	0.8	m
Initial water volume	10.4634	m^3
Initial steam height	1.2	m
Initial steam volume	4.0232	m^3
Physical parameters		
Pressure	15	MPa
Initial Temperature	553.15	K

3.1.7 Annular plenum

The details of the plenum are given in the Table 8.

Table 8: Annular plenum data.

Parameter	Value	Unit
Height (H_{ap})	2.5	m
Inner diameter ($D_{in,ap}$)	2.4556	m

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Outer diameter $(D_{out,ap})$	3.65	m
Steam generator occupied area $(A_{occ,SG})$	2.86	m^2
Flow area (A_{ap})	2.89	m^2
Volume (V_{ap})	7.2227	m^3
Hydraulic diameter $(D_{h,ap})$	0.41	m

3.1.8 Steam Generators

The data for the steam generators (six for nominal operations) are reported in Table 9.

Table 9: Steam generators data.

Parameter	**Value**	**Units**
Primary flow rate	3700	kg/s
Secondary flow rate	294.6	kg/s
Channel		
Channel length	4.0e-3	m
Channel width	2.0e-3	m
Channel perimeter	1.2e-2	m
Channel flow area	8.0e-6	m^2
No. of channels	28818	
Heat Exchanger		
Thermal power per HX	90.53	MW/m^3
Active height	2	m
Flow area	0.1152	m^2
Heated area	345.816	m^2
No. of heat exchangers	6	
Total power	540	MW
Total HX flow area	0.6916	m^2
Hydraulic Diameter		
Channel hydraulic diameter	2.6667e-3	m
Channel heated diameter	2.6667e-3	m

3.1.9 Pumps

The pumps characteristics are reported in Table 10.

Table 10: Pumps characteristics.

Parameter	**Value**	**Units**
Flow rate	589	kg/s
Developed Head	23.90	m
Plenum height	0.5	m
Plenum Flow Area	5.791	m^2

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3.2 Secondary circuit

The data for the secondary circuit are given in the Table 11.

Table 11: Secondary side steam generator data

Parameter	Value	Units
Pressure	4.5	MPa
Saturation temperature	257.5	°C
Feedwater inlet temperature (initial)	164 (93.5°C subcooled heating)	°C
Steam outlet temperature (initial)	288 (30.5°C superheating)	°C
Secondary flow rate	245	kg/s
Feedwater inventory	2500	kg

3.3 Safety systems

The safety systems of the E-SMR consist in:

- A passive heat removal system designed to cool down the primary circuit in case of accident. It is constituted by two safety SGs, two condensers and a water pool which serves as a heat sink. The safety SGs can extract heat from the primary circuit and the condensers can transfer it to the water pool, by means of a natural circulation loop.
- Four identical accumulators connected laterally to the upper plenum.
- The containment.

3.3.1 Safety compact steam generators and pool

The data for the safety compact steam generators and the pool are reported in Table 12.

Table 12: Safety compact steam generators and pool data

Parameter	Value	Units
Temperature	50	°C
Saturation pressure	0.01235	MPa
Condenser height	2	m
No. of tubes	5	
Tube diameter	0.0508	m
Pool height	6	m
Pool flow area	0.833	m^2
Pool volume	5	m^3
Pool operating pressure	0.1	MPa

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3.3.2 Accumulator

The data for the accumulators are reported in Table 13.

Table 13: Data accumulators.

Parameter	Value	Units
Internal diameter	2.58	m
Height	5	m
Operating pressure	1.5	MPa
Wall thickness	0.01	m

3.3.3 Containment

The containment data are reported in Table 14.

Table 14: Containment data.

Parameter	Value	Units
Internal diameter	15	m
Height	16	m
Operating pressure	(Slightly lower than) 1	MPa
Wall thickness	1.75 / 0.0445 [1]	inch / m

4. CATHARE Model

4.2 CATHARE3 code

CATHARE-3 is the new version of the French thermal-hydraulic code for safety analysis of nuclear reactors. Its development has begun in 2006 as part of the NEPTUNE project launched by the CEA, EDF, AREVA-NP and IRSN in 2001 [2].

The major characteristics of CATHARE-3 in comparison to the current reference code for safety studies, CATHARE-2 are reported below:

1. CATHARE-3 is validated on more than one hundred Integral Effect Tests (IET) and Separate Effect Tests (SET) from the CATHARE-2 validation matrix that demonstrate the Non-Regression of CATHARE-3 against CATHARE-2. They confirm that the 6-equation 2-fluid model of CATHARE-3 is reliable, as most of the results superimpose with those of the CATHARE-2. These tests are included in Non-Regression reports delivered with the code.

2. CATHARE-3 has optional closure laws for sub-channel analysis (void fraction dispersion, temperature dispersion and diffusion, velocity diffusion), validated on various experiments.

3. Multi-field models of CATHARE-3 have been improved and their validation extended .

4. The 3D modelling abilities of CATHARE-3 have been improved.

The version of CATHARE used for the calculations presented in this deliverable is CATHARE3-V2.3.0.

4.3 Model Description

4.3.1 Primary side

The sketch of the primary side of the CATHARE nodalization is reported in Figure 1.

All parts of the primary circuit are modelled as 0-D or 1-D elements, as typically assumed in the nodalization of Nuclear Power Plants (NPPs). In the primary side of the plant, no phenomena for which a 3D representation strictly needs to be adopted are expected.

The primary side in constituted by a lower plenum (FONDCUVE), a core (ACORMOY) and core by pass (BPCOR). This last two elements are connected to the volume (VOLSOR) connected to the riser (RISER). At the outlet of the FONDCUVE there is a downcomer (DOWNCOME) connected to the volume in the lower part of the primary side of the steam generators. In such volume there is the connection of the turbopump (TUBPOMP1). The primary side of the steam generators are connected to a volume (PLENU) and this volume is connected to pressurizer (PRESSU).

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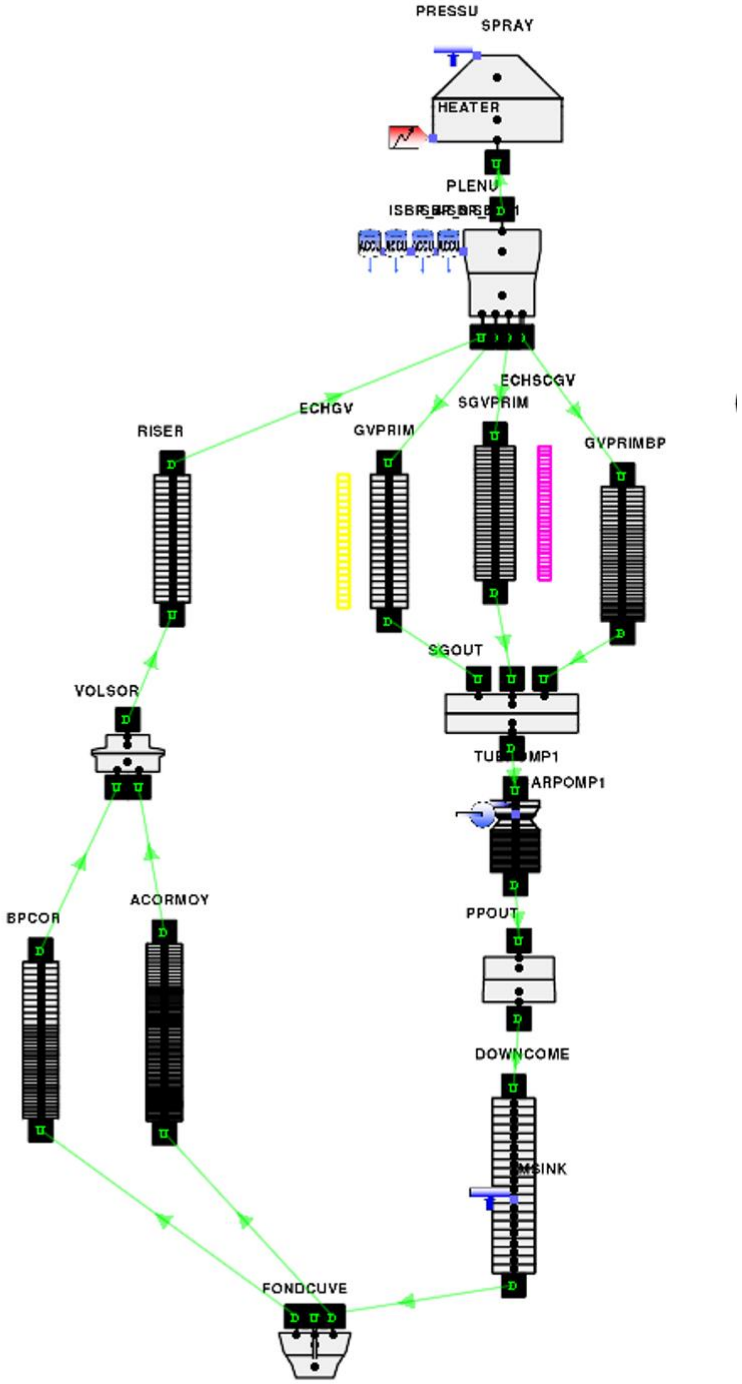

Figure 1: Primary side CATHARE nodalization.

4.3.2 Secondary side

In the reactor pressure vessel there are 8 Steam Generators (SG): 6 are used in normal operation and 2 for accidental conditions.

As shown in Figure 2, the 6 SG for normal operation are modelled by means of:

- An equivalent Pipe component that simulates the SG channels coupled to the primary side by means of a heat structure, which simulates the SG plates;
- Boundary conditions for the feedwater and the steam outlet respectively.

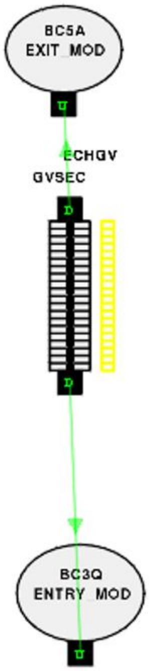

Figure 2: Secondary side nodalization.

4.3.3 Safety systems

The Safety systems are composed by the heat SG used in accidental conditions (safety heat exchangers), the containment, the pool side and the accumulators.

Figure 3 shows the nodalization of the secondary side of the SG used in accidental conditions (safety heat exchangers).

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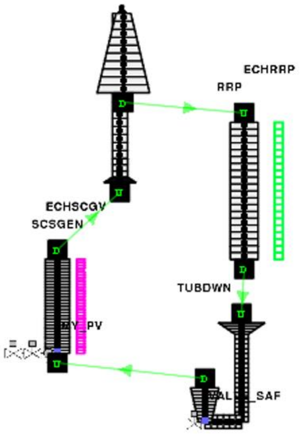

Figure 3: Nodalization for the secondary side of the safety heat exchangers.

The CATHARE nodalization of the containment is reported in Figure 4.

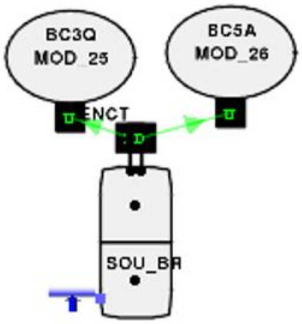

Figure 4: Containment nodalization.

The heat sink during accidental conditions is the tertiary system and its CATHARE nodalization is reported in Figure 5.

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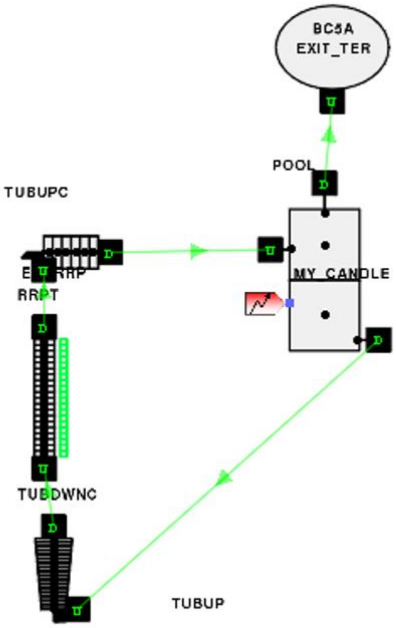

Figure 5: Pool nodalization.

The 4 accumulators have been simulated using the ACCU OPERATOR; each of the 4 accumulators was inserted in the upper part of the PLENU (see Figure 6).

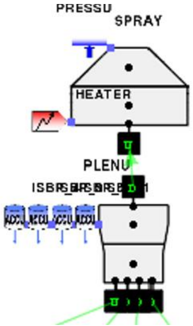

Figure 6: Accumulator nodalization.

4.4 Steady state

The Table 15 report the values of the steady state conditions.

Table 15: Steady state conditions.

Parameter	Target
Core power [MWth]	540
Primary pressure [MPa]	15
Primary flow rate [kg/s]	3700
Primary By pass flow rate [kg/s]	150
Secondary flow rate [kg/s]	240
Core inlet temperature [°C]	300
Core outlet temperature [°C]	324.5
Secondary pressure [MPa]	4.5
Accumulators’ total liquid inventory [t]	78
Accumulators’ water temperature [°C]	25
Accumulators’ initial pressure [MPa]	1.5

5. CATHARE-MODELICA coupling

Being the safety assessment of SMRs integrated into Hybrid Energy Systems one of the main goals of TANDEM, the present chapter gives a preliminary description of the coupling between CATHARE and MODELICA. As a matter of fact, the WP4 of TANDEM requires analyses also made through coupled calculations since “*the coupling between the reference nuclear system thermal-hydraulics codes and the Modelica-based simulator enables to take into account dynamically the physical interactions between the SMR and the rest of the hybrid system. The impact of the coupling will be quantified.*” At present time, the coupling, established by a joint work between CEA and University of Pisa, gave reasonably good results in terms of capabilities in dealing with simple transient scenarios, e.g., those involved in the changes in the thermal power demand requested by the cogeneration section of the Balance of Plant (BOP).

5.1 Adopted Coupling Tools

To perform the coupling, the Functional Mock-up Interface (FMI) is used [3]. Generally, FMIs are unified tools that embed dynamic models in standard objects, called Functional Mock-up Units (FMU), which can be imported in common simulation environments to perform co-simulations, i.e., a coupled analysis (see again [3] for a general overview). Co-simulations can be run by using an external supervisor which can be either a dedicated software (in this case Dymola [4]) or a coded interface making use of some common developed libraries, e.g., the python-based FMPy [5], [6]. In general, an FMU is an executable file generated by a dynamic model using a shared

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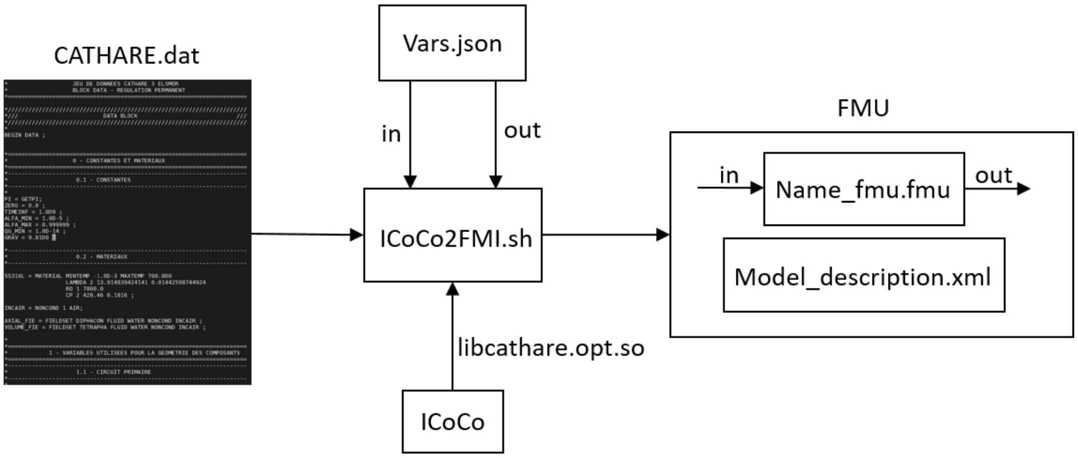
object (.so file extension) as input library. Regarding the FMU generation starting from a CATHARE input deck, a tool developed by CEA called ICoCo2FMI [7] is needed. In particular, ICoCo2FMI generates an FMU starting from an already-compiled shared library *libcathare.opt.so* belonging to the ICoCo interface [8], which is a common interface to perform coupling between ICoCo-compliant codes. To make the conversion in FMU, four inputs must be given to ICoCo2FMI:

- a CATHARE input data file;
- a .json file in which the input and output variables to be imposed on the FMU are listed;
- the *libcathare.opt.so* object (or its path).

The results of the procedure, depicted in Figure 7, is the generation of a Functional Mock-up Unit, embedding the CATHARE model metadata and having as input and output the variables defined in the .json file.



```
*                     JEU DE DONNEES CATHARE 3 ELSMOR
*                     BLOCK DATA - REGULATION PERMANENT
*=====================================================================

*/////////////////////////////////////////////////////////////////////
*///                            DATA BLOCK                         ///
*/////////////////////////////////////////////////////////////////////
*
BEGIN DATA ;


*=====================================================================
*                     0 - CONSTANTES ET MATERIAUX
*=====================================================================
*---------------------------------------------------------------------
*                      0.1 - CONSTANTES
*---------------------------------------------------------------------
*
PI = GETPI;
ZERO = 0.0 ;
TIMEINF = 1.0D9 ;
ALFA_MIN = 1.0D-5 ;
ALFA_MAX = 0.999999 ;
QG_MIN = 1.0D-14 ;
GRAV = 9.81D0 ;

*---------------------------------------------------------------------
*                      0.2 - MATERIAUX
*---------------------------------------------------------------------

SS316L = MATERIAL MINTEMP -1.0D-3 MAXTEMP 700.0D0
                  LAMBDA 2 13.914839424141 0.01442598744924
                  RO 1 7800.0
                  CP 2 428.46 0.1816 ;

INCAIR = NONCOND 1 AIR;

AXIAL_FIE = FIELDSET DIPHACON FLUID WATER NONCOND INCAIR ;
VOLUME_FIE = FIELDSET TETRAPHA FLUID WATER NONCOND INCAIR ;

*
*=====================================================================
*             1 - VARIABLES UTILISEES POUR LA GEOMETRIE DES COMPOSANTS
*=====================================================================
*---------------------------------------------------------------------
*                      1.1 - CIRCUIT PRIMAIRE
*---------------------------------------------------------------------
*
```

Figure 7: Schematization of the FMU generation starting from a CATHARE input deck.

5.2 Assessment of the FMU functionality

Before performing some preliminary coupling tests, the generated FMU from the CATHARE model of the E-SMR was numerically assessed by running a CATHARE stand-alone simulation and then comparing the results with those achieved from the related FMU. Being the selected coupling with the BOP a "fluid" one, i.e., with exchange of thermal hydraulic variables through the secondary side of the Steam Generator (see Figure 8), the generated FMU had as input and output three variables, namely mass flow rate, pressure and enthalpy. An important aspect to be pointed out is that the calculations were made by setting the core power constantly equal to its nominal value (i.e., 540 MW) and no core neutronics and fuel thermal-mechanics models were activated.

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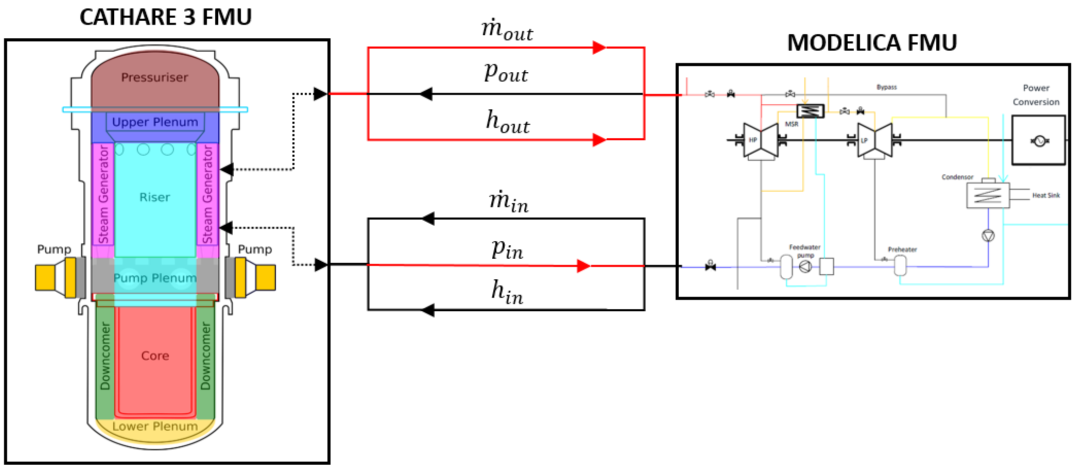

Figure 8: Schematization of the FMU coupling between E-SMR and BOP.

The adopted boundary conditions, imposed on the secondary side of the steam generator to run the two stand-alone calculations, are listed hereafter:

- Inlet mass flow rate constantly equal to 40 kg/s;
- Inlet Feed Water Specific enthalpy equal to $6.90704 \cdot 10^5$ J/kg;
- Outlet pressure equal to 45 MPa.

The FMU was run by using a python script adopting the FMPy library with a constant time-step of 0.1 s, whereas the CATHARE calculation was run by using the related solver which adjusts the time-step in accordance with its internal algorithms.

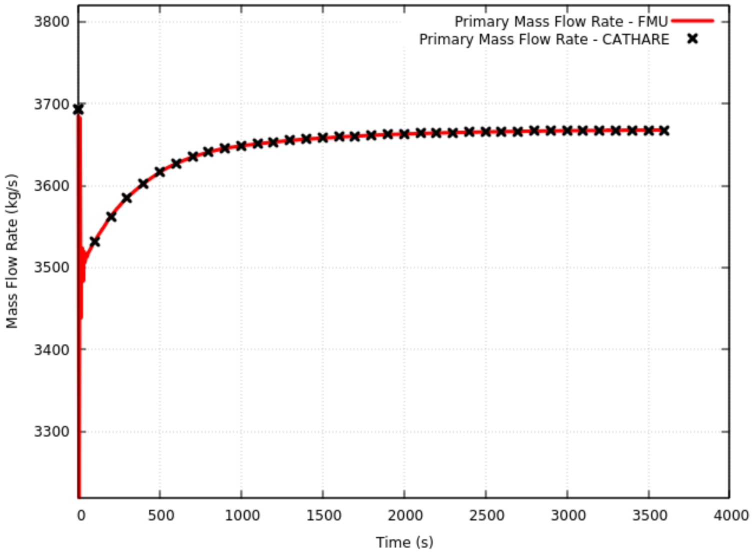

Figure 9: Riser Mass Flow Rate achieved by FMU and CATHARE stand-alone simulations.

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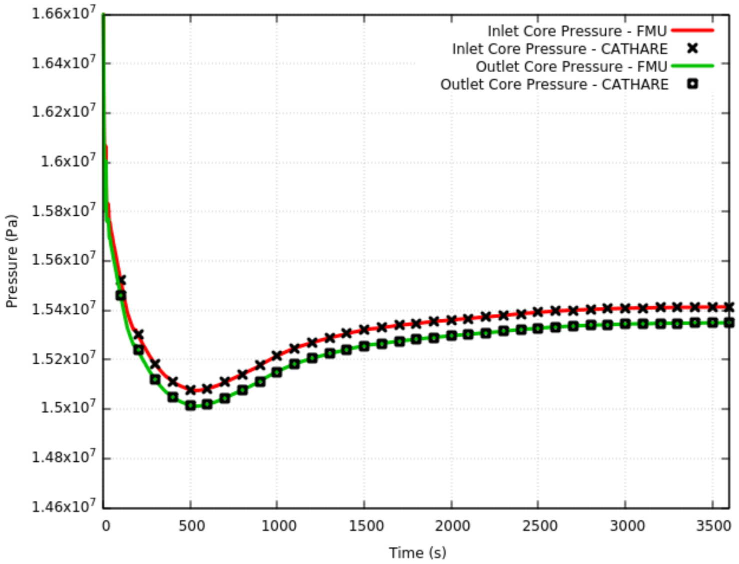

Figure 10: Inlet and Outlet Core Pressure achieved by FMU and CATHARE stand-alone simulations.

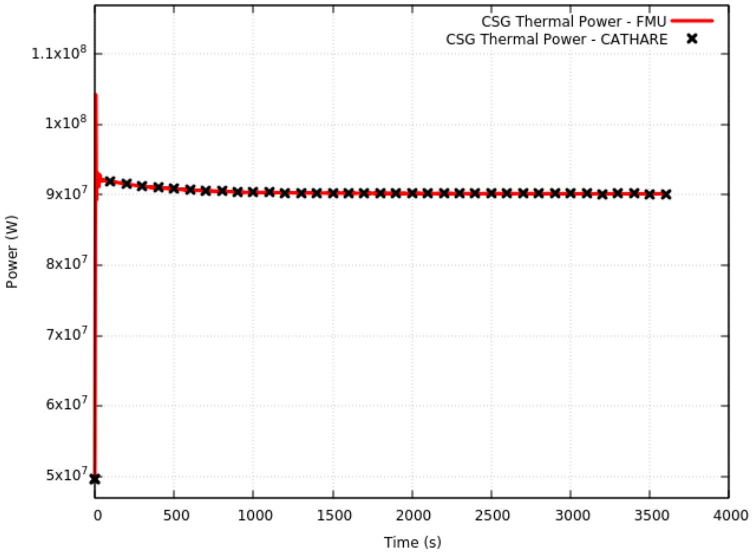

Figure 11: Thermal power exchanged through one Compact Steam Generator achieved by FMU and CATHARE stand-alone simulations.

Figure 9, Figure 10 and Figure 11 show the comparison between the behaviour of some parameters of the E-SMR primary circuit achieved by both stand-alone calculations. As it can be seen from the presented results, the generated FMU was capable of accurately reproducing the general behaviour of the CATHARE model, hence it can be considered ready to be used in performing the requested coupling with MODELICA.

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5.3 Preliminary coupling tests

After several preliminary co-simulations made by using a python-based interface to supervise them, the two FMUs were implemented in Dymola (version 24x) to assess the coupling on the latter environment. The usage of Dymola may allow the user to change the coupling algorithm with different time-advancing schemes without any need of implementing them in a scripted interface, thus resulting in a more time-saving procedure. To perform first coupling tests between the E-SMR and the BOP, the preliminary BOP model developed in TANDEM using the ThermoSysPro MODELICA library [9] was used. The considered BOP system is depicted in Figure 12, where the fluid connectors used during its translation into FMU are also represented.

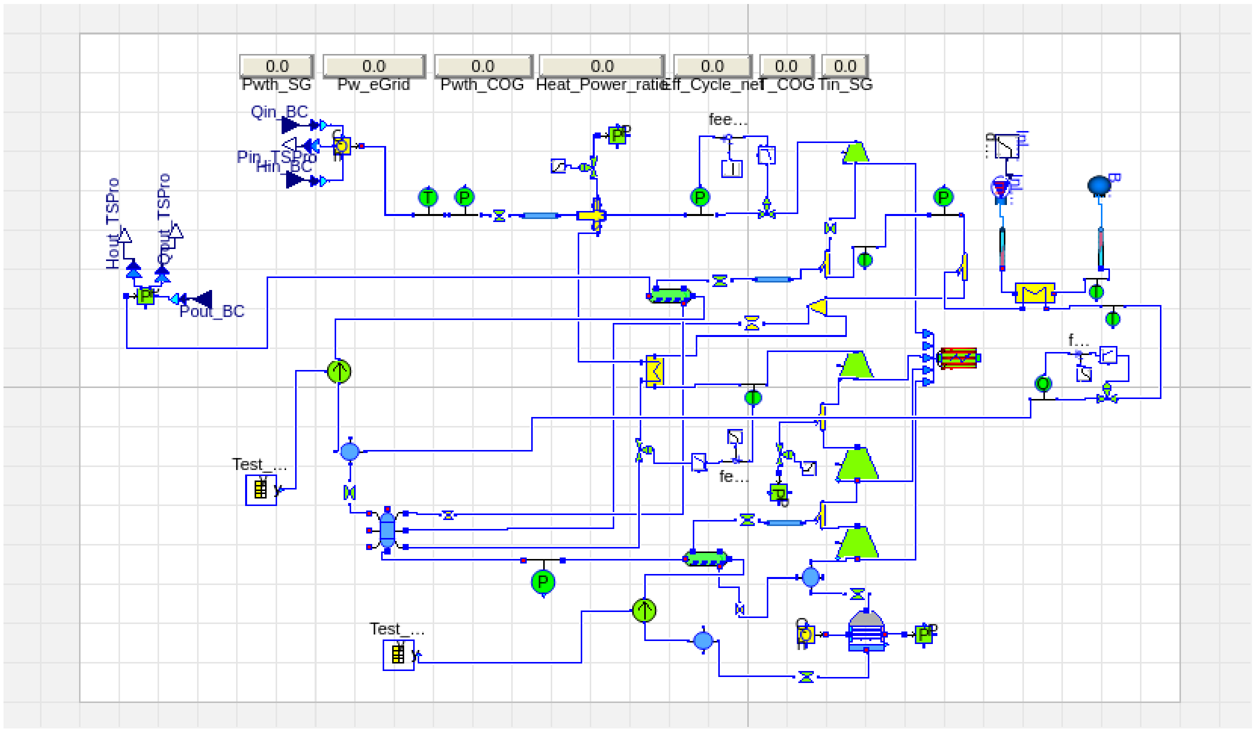

Figure 12: Schematization of the BOP used for preliminary coupling tests.

As it can be seen from the BOP representation of Figure 12, the present model conceives a steam bypass at the outlet of the High-Pressure Steam Turbine to be sent to the cogeneration section of the system. The opening coefficient of the cogeneration control valve is assigned by a table. The rotational speed of the main feed water pumps and of the condensate extraction pump are also assigned by tables. In the present calculations, the rotational speed is defined, so that the mass flow rate at the inlet of the steam generator is kept as constant as possible.

After the generation of the BOP FMU, performed by using Dymola, the logic circuit depicted in Figure 13 was built to obtain a staggered-in-time coupling. This choice was made since the primary circuit parameters evaluated by CATHARE at the beginning of the stabilized transient could experiment some initial high-amplitude oscillations due to the first numerical stabilization of the simulation. The latter oscillations could result in numerical instabilities in the coupling, hence, the two FMUs were run individually for 800 seconds after the coupling (i.e., after the start of the exchange of information between them). The latter circuit allows to impose constant boundary conditions to each FMU for a certain simulation time, while switching to the boundary conditions exchanged by the coupled FMUs after a certain time threshold.

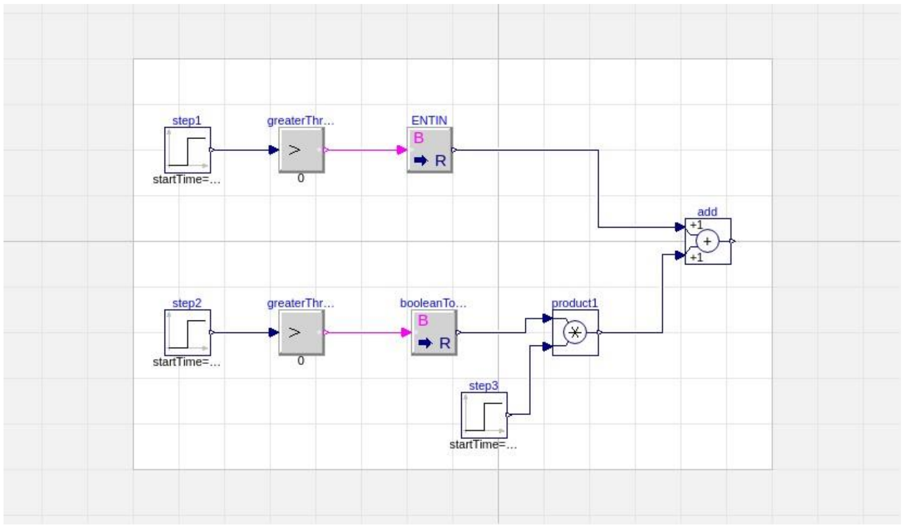

Figure 13: Logic circuit to perform coupling staggered in time.

The global coupling scheme is depicted in Figure 14 were all the channels for information exchange between the two FMUs are also represented.

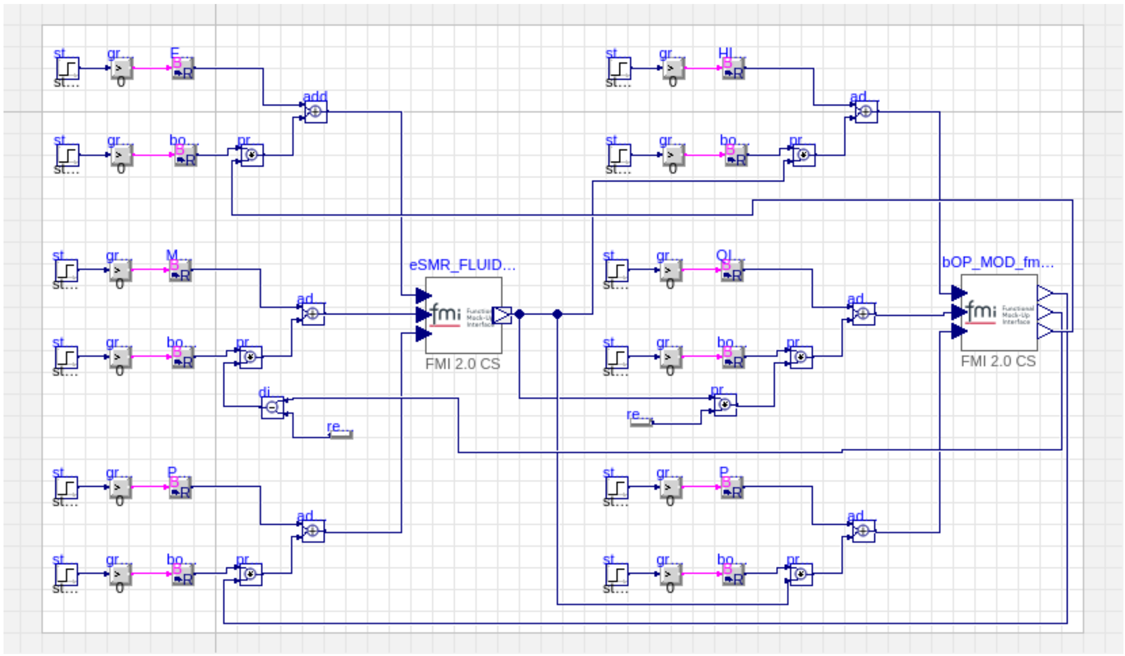

Figure 14: Coupling scheme achieved on Dymola24x.

5.3.1 Steady-state coupling

First, a steady-state coupling between the two FMUs was run. The simulation lasted 9000 s and the coupling occurred after 800 s (i.e., the two FMU were run individually for 800 seconds before the coupling occurrence). The co-simulation time-step was set constant equal to 0.1 seconds. The boundary conditions, indicated in Figure 8 and listed in Table 16, were imposed to the two FMUs for the stand-alone calculations.

Boundary Condition	E-SMR (Secondary Side of one CSG)	BOP
Inlet Mass Flow Rate (kg/s)	40.0	240.0
Inlet Specific Enthalpy (J/kg)	$6.909 \cdot 10^5$	$2.944 \cdot 10^6$
Outlet Pressure (MPa)	4.5	4.9

Table 16: Boundary Conditions imposed on the two FMUs during stand-alone calculations.

The obtained results are depicted in Figure 15 and Figure 16 for the primary side (i.e., from the CATHARE FMU) and in Figure 17 for the secondary side (i.e., the MODELICA FMU). As it can be seen in the figures, the coupling was found to be sufficiently stable, as the primary and secondary parameters experience a pretty constant behaviour after some time since the coupling.

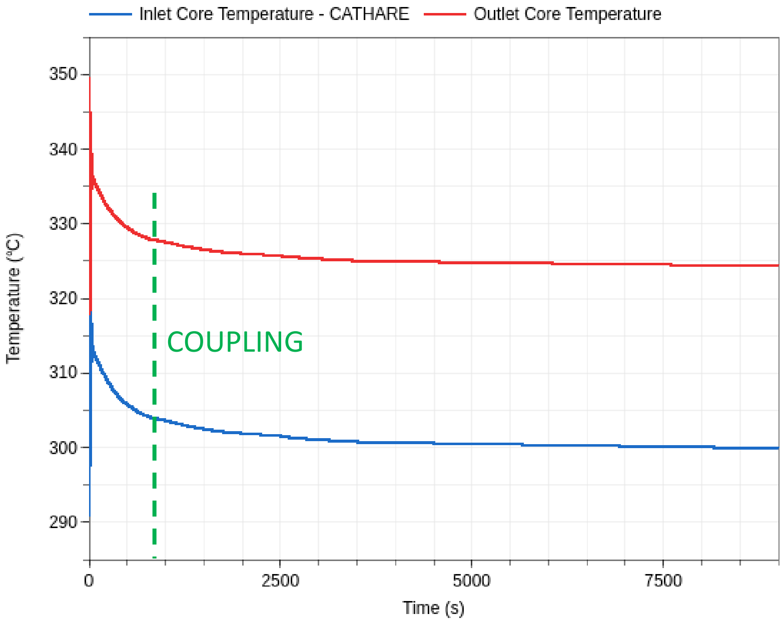

Figure 15: Inlet and Outlet Core Temperature achieved during the steady-state co-simulation.

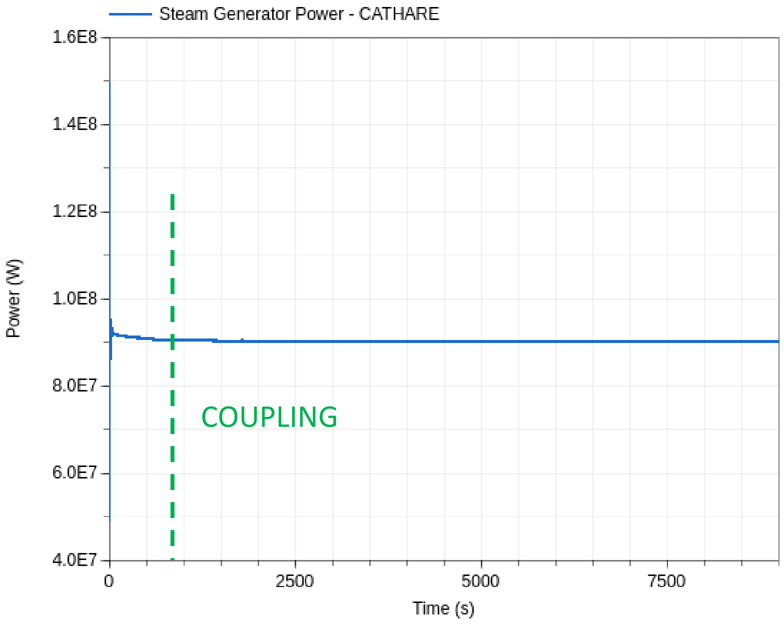

Figure 16: Thermal power of one Steam Generator during the steady-state co-simulation.

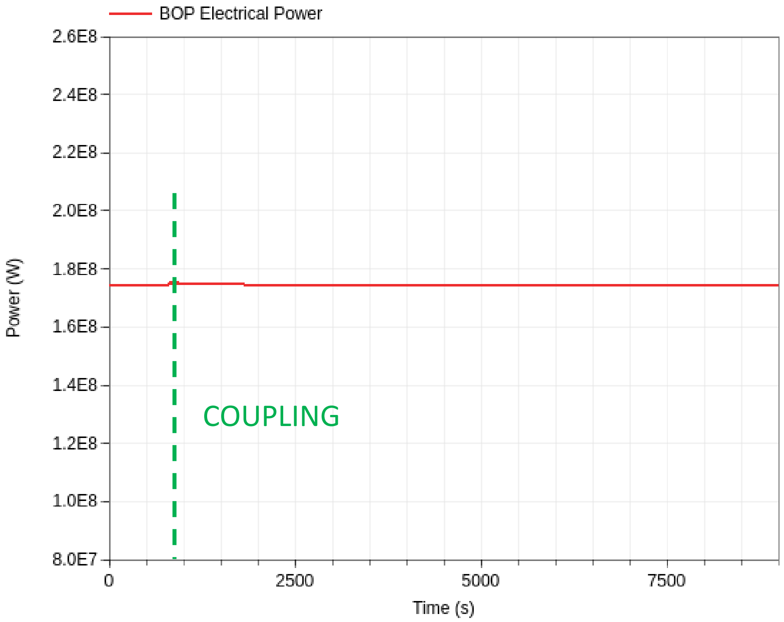

Figure 17: Electrical power produced by the BOP during the steady-state co-simulation.

Concerning the exchange of information between the two FMUs, Figure 18 and Figure 19 report the behaviour of the exchanged variables during the whole co-simulation, showing that the exchange of information between the two models was consistent after the coupling occurrence.

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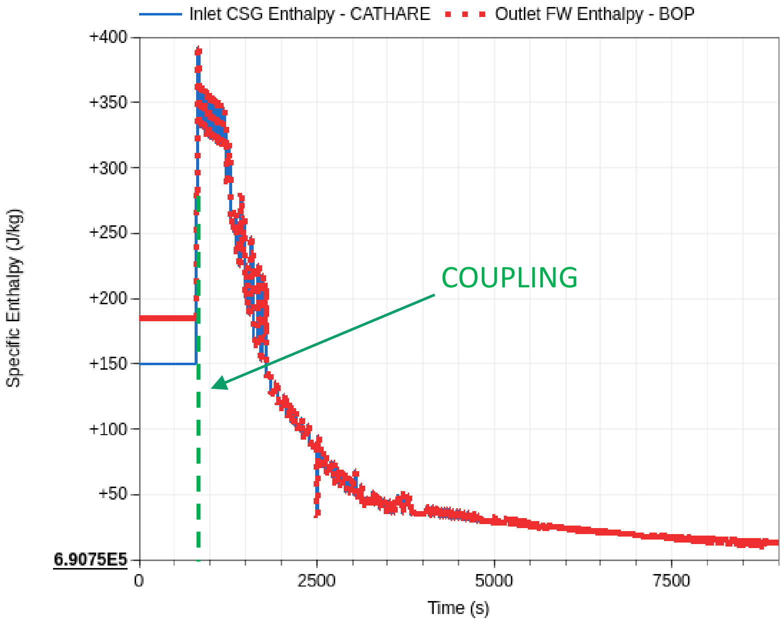

Figure 18: Inlet CSG Specific Enthalpy evaluated by the two FMUs during steady-state co-simulation.

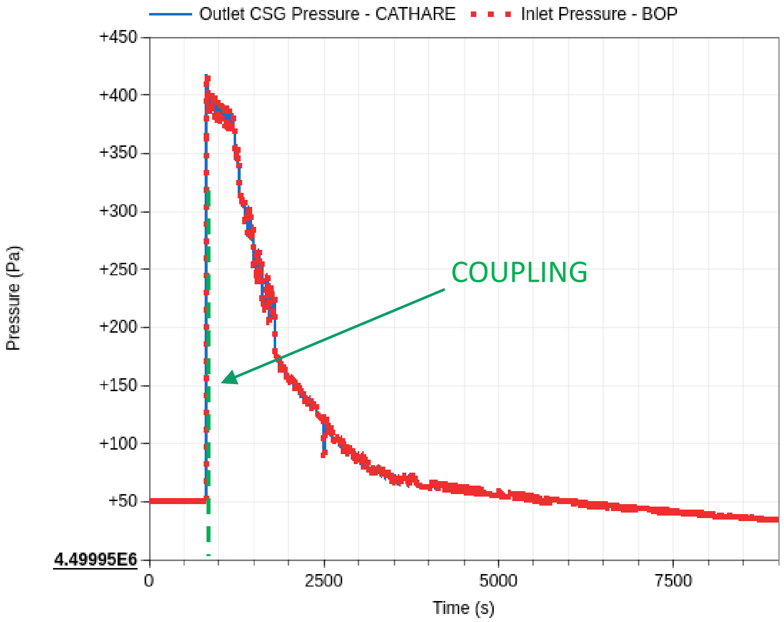

Figure 19: Outlet CSG Pressure evaluated by the two FMUs during steady-state co-simulation.

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5.3.2 Preliminary transient tests

After the steady-state test, first transient tests were performed to assess the capability of the coupling in dealing with simple dynamic transients of the system. To perform the test, different changes in the heat-to-power ratio were considered (from 10% to 50%), developed with a ramp that started after 5000 s and lasted 100 s. As it is shown in Figure 20, the different values of the heat-to-power ratio were achieved by changing the valve coefficient of the cogeneration section control valve resulting in a change of by-passed steam at the outlet of the High Pressure Steam Turbine. For the sake of clarity, it must be mentioned again that the calculations were run without neutronic feedback and neutronic controls (i.e., no control rod movement), hence the core thermal power was set equal to its nominal value of 540 MW. Introducing these effects is matter for the work to be done in a further phase.

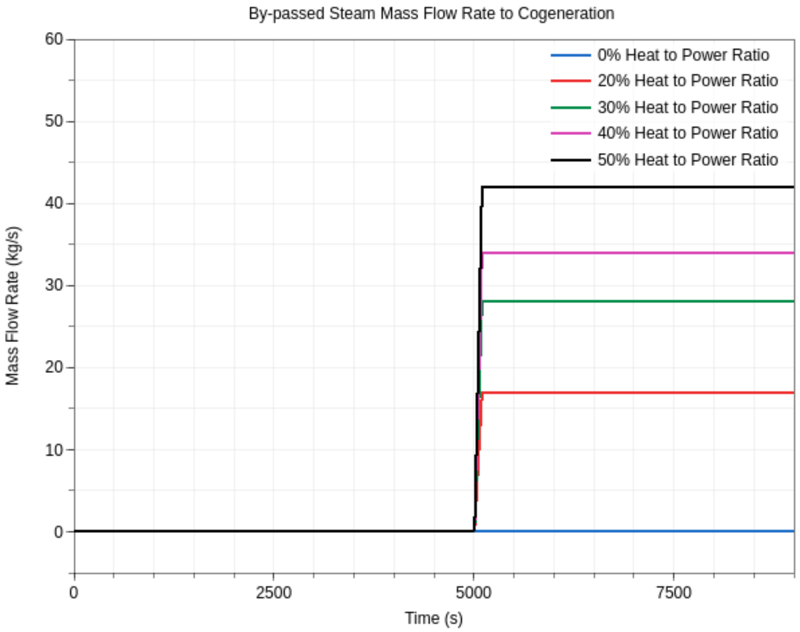

Figure 20: Behaviour of the by-passed mass flow rate for different heat-to-power ratios.

The by-passed mass flow rate from the steam turbine led to a decrease of the feed water specific enthalpy as shown in Figure 21. This result may be related to the adopted system architecture of the BOP, which leads to a decrease of the steam flow that is routed to the low-pressure stages of the turbine when cogeneration is activated and, consequently, of the steam that is tapped to be sent to the feed water pre-heaters. As a consequence of the decrease of the feed water temperature on the secondary side, the primary temperature decreases as it is shown in Figure 22. Being the reactor power constant, the decrease of the secondary temperature leads to a decrease in the secondary steam specific enthalpy (see Figure 23) that in turn contributes to the decrease of the electrical power generated by the BOP as shown in Figure 24, mainly caused by the lower steam flow through the lower pressure stages of the turbine.

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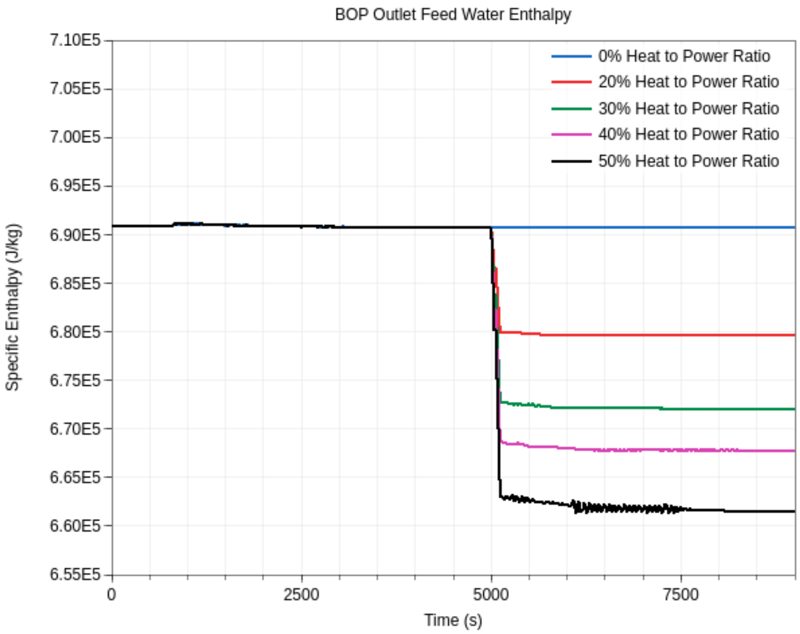

Figure 21: Inlet Steam Generator Specific Enthalpy achieved with the addressed transient scenarios.

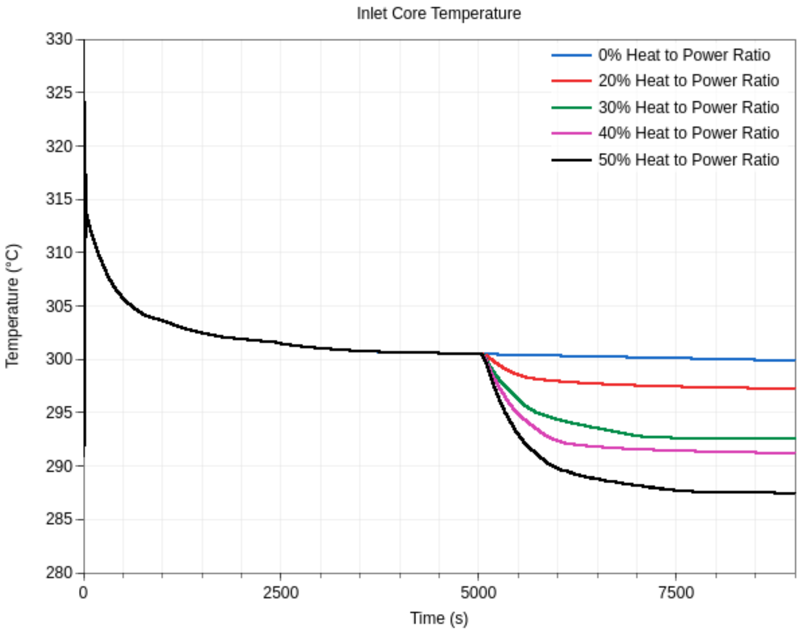

Figure 22: Inlet Core Temperature achieved with the addressed transient scenarios.

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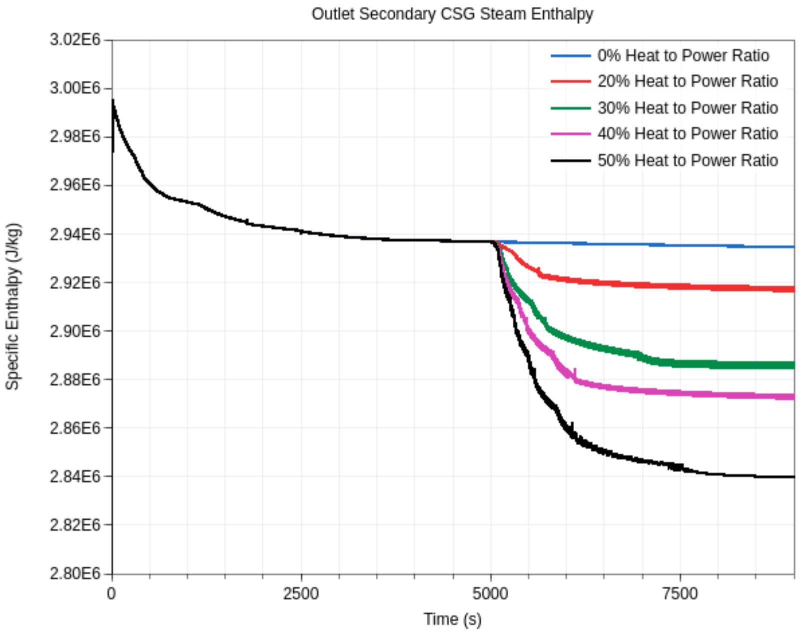

Figure 23: Steam Generator outlet Specific Enthalpy achieved with the addressed transient scenarios.

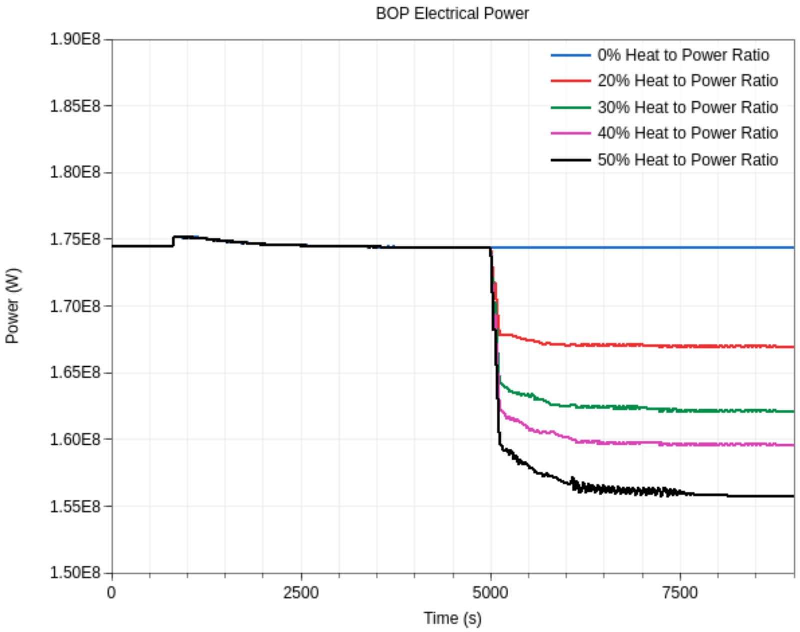

Figure 24: Electrical power generated by the BOP achieved with the addressed transient scenarios.

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In summary, the coupling between CATHARE and MODELICA, for the particular purpose of assessing the behaviour of the primary system when dealing with different levels of cogeneration, was found to be stable and consistent from the physical point of view, at least for heat-to-power ratios up to 50%. However, it must be reminded that the present results are only representative of the coupling capabilities of the two codes, deferring to a further phase of the work the analysis of the interaction of the NSSS and BOP in realistic transients. Therefore, also considering the achieved coherence of the information exchanged during the co-simulation by the two models, it is reasonable to assume that the set-up coupling is capable of handling transients which are of interest for the TANDEM project concerning, e.g., different AOOs or normal operating conditions of the system. In addition, it must be mentioned that, at present time, several tests are being made to implement in the E-SMR model the reactivity feedback and the reactivity control system (i.e., the control rods).

6. Conclusions

This deliverable presents the results of Task 2.4, concerning the *Development of SMR detailed models for safety analysis*. It contains the results of the activity devoted to the development of the E-SMR detailed model for the system thermal-hydraulics safety studies (identified in task 4.2). The CEA and CIRTEN-UNIPI, with support of CIRTEN-POLIMI, and ENEA, have developed and tested the CATHARE model to be used in the analysis of WP4.

A detailed description of the E-SMR (assumed as reference SMR) data set is presented together with the CATHARE model developed.

The steady state conditions are reached using the CATHARE model and the values of the main parameters are reported.

Finally, a detailed description has been reported about the strategy and the tools adopted for coupling the CATHARE reactor model with the representation of the BoP by MODELICA. Parametric tests at constant reactor power with different shares of cogeneration have shown a physically coherent behaviour, constituting a good basis for the ongoing analyses being performed after activating the reactivity feedback and the reactivity controls.

7. References

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