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RELAP5/Mod3.3 thermal-hydraulics characterization of the steam generator mock-up during operational transients in STEAM facility in support of the design of the DEMO WCLL BoP

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ABSTRACT

The Water Cooled Lithium Lead Breeding Blanket (WCLL BB) is a key candidate for the driver blanket of the European DEMO reactor, progressing toward its Conceptual phase by the end of 2027. To assess different water and lithium-lead technologies for the WCLL BB and Balance of Plant (BoP) systems, the Water-thermal-HYDRAulic (W-HYDRA) experimental platform is under development at the ENEA Brasimone Research Centre. Among the facilities constituting the new W-HYDRA multipurpose infrastructure, STEAM is going to experimentally investigate the DEMO WCLL BoP thermal-hydraulics, focusing on the Steam Generator (SG) of the Primary Heat Transfer Systems (PHTS), to qualify its performances and suitability under its unconventional operation. The paper aims at supporting the thermal-hydraulic characterization of the Steam Generator mock-up during the sudden power variations typical of a pulsed fusion reactor. The analyzed selected scenario is the operational transient dwell-pulse-dwell, which determines high thermal cycling and correspondent high thermo-mechanical stresses on the primary side components. Two control logics with their relative drawbacks have been analyzed with a RELAP5/Mod3.3 1-D model, the first regulating the primary side average temperature, the second monitoring the minimum one. The comparison of the two systems highlighted that neither approach leads to hazardous conditions for the facility. However, while the average temperature controller is characterized by reduced thermal stresses on the components, the minimum temperature controller is characterized by higher thermal gradients for the primary loop. Both methodologies will be tested in the dedicated experimental campaign, aiming at yielding insights and evaluations concerning control strategies applicable to the DEMO reactor.

1. Introduction

The European Research Roadmap of Fusion Energy sets ambitious objectives aimed at advancing the development of sustainable and clean energy, with the goal of achieving net electricity production from nuclear fusion by the mid-21st century. DEMO [1], as the upcoming commercial-scale prototype magnetic confinement fusion reactor following ITER [2], is a milestone in the journey towards harnessing fusion energy. Building upon the ITER achievements, DEMO represents the critical next step in realizing the practical exploitation of fusion energy, serving as a bridge between experimental research and commercial fusion power generation. However, DEMO also faces distinct physics, material, and engineering challenges that demand innovative solutions to unlock the full fusion potential.

DEMO operates according to a pulsed regime, characterized by 2-hour pulse and 600-second dwell time. Within each pulse cycle, the PHTSs must efficiently manage the removal of approximately 2 GW_{th} of thermal power. During the dwell, instead, plasma is inactive, and the power retained within this structure approaches approximately 1 % of the nominal value [3]. With an envisioned frequency of eleven pulses

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per day, this unique operational pattern presents challenges and concerns related to the unconventional operation of DEMO Balance of Plant (BoP) system [4]. Since traditional power plants, whether fossil fuel or nuclear fission-based, are design to maintain constant power output, the adoption of BoP configurations employed in conventional power plants in fusion reactors requires careful consideration and thorough experimentation.

To address this need for comprehensive testing under pulsed operating conditions, ENEA is actively working at the construction of a new experimental infrastructure, named W-HYDRA, composed by STEAM [5], Water Loop (WL) [6] and LIthium FUSion 5 Mod 4 (LIFUS5/Mod4) [7]. STEAM and WL are water facilities designed to test and characterize the Steam Generator (SG) to be installed in the DEMO BB primary cooling system [8,9] and to investigate the WCLL Test Blanket Module phenomena and components [10], respectively. LIFUS5/Mod4 is a PbLi loop aiming at reproducing the corresponding systems to be used in the ITER and DEMO reactors, considering their operative conditions and characterizing their behavior during an in-box Loss of Coolant Accident (LOCA).

This paper aims at supporting the thermal-hydraulic characterization of the STEAM SG mock-up [11] during the sudden power variations through the use of RELAP5/Mod3.3 code [12]. Two control logics have been tested on the developed numerical model and their relative impact on the transient evolution has been examined and compared, providing outcomes relevant for the experimental campaign.

2. STEAM facility

STEAM [13] is a 3.1 MW water facility conceived to investigate the impact of the rapid load variations typical of fusion tokamaks on the steam generator design envisioned for DEMO. The experimental setup will host two loops thermally coupled by the DEMO SG mock-up. They will reproduce the thermal hydraulic conditions of pressure and temperatures characterizing the DEMO BB primary cooling system and Power Conversion System.

The primary loop (15.5 MPa) includes the Steam Generator tube-side, where the fluid cools down from 328 °C to 295 °C delivering power to the secondary side (SS), a filter, a pump, an electrical heater, which heats the fluid from 295 °C to 328 °C, and a pressurizer to keep the pressure set-point. The secondary loop is divided into a high-pressure part and a low-pressure part, to prevent the propagation towards the test section (i.e., the SG) of eventual instabilities occurring in the heat sink. The high-pressure part (6.4 MPa) is composed by the pumping system, an electrical heater that heats up the fluid from 210 °C to 238 °C and the shell-side of the SG, where fluid exchanges power with the primary loop and heats up from 238 °C to 300 °C. The low-pressure part (2.5 MPa) comprehends a lamination valve to perform the pressure reduction, air coolers serving as heat sink, a condensate tank acting as a pressurizer and a filter.

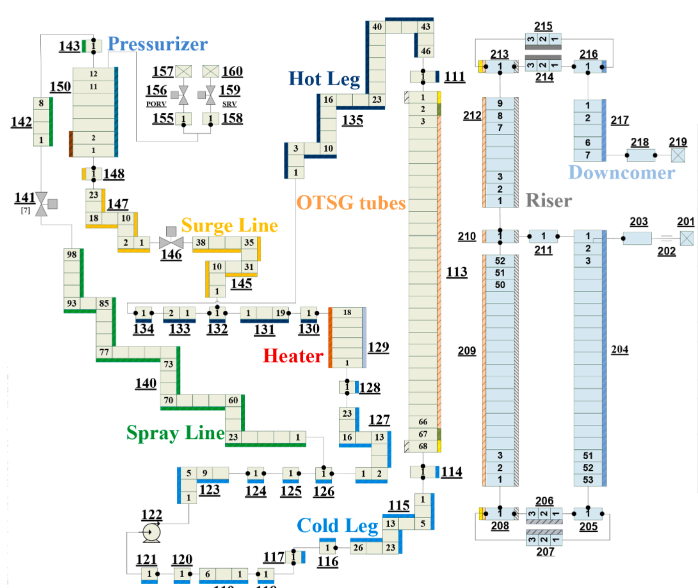
3. RELAP5/Mod3.3 1-D model

Thermal hydraulic simulations have been performed using the RELAP5/Mod3.3 code, enabling the 1-D reproduction of the facility, by discretizing the loops in hydrodynamic components connected through junctions. The analysis primarily focuses on the impact of pulsed operation on the primary loop components, specifically on the test section. The model replicates the entire primary loop and exclusively the SG section of the secondary loop. The nodalization adopted for the analysis is reported in Fig. 1. Concerning the Primary Side (PS), SG plena and tubes are modelled through pipe 113. The cold leg (CL) is realized with components from 114 to 128, with branch 117 serving as the filter and number 122 as the pump. The electrical heater is represented by pipe 129 and the Hot Leg (HL) is simulated by components from 130 to 135. The pressurizer system, comprising the surge line, spray line, main tank and valve relief system located at the component top (Pilot Operated Relief Valve and Safety Relief Valve), is represented by components from 140 to 160. Regarding the SG Secondary Side (SS), components 203 to 205 model the FeedWater (FW) downcomer,while pipes 206 and 207 simulate the tubes connecting the riser with the external downcomer Components from 208 to 213 model the riser, and pipes 214 and 215 reproduce the tubes connecting riser and downcomer. Components from 214 to 218 represent the steam downcomer.

4. RELAP5 steady state characterization

The thermal hydraulic behavior of the STEAM facility has been investigated in steady-state conditions using the RELAP5/Mod3.3 code. Boundary conditions have been imposed in correspondence of the SG secondary side inlet and outlet: time-dependent volumes (TDV) 201 fixes the inlet temperature, and TDV 218 sets the outlet pressure.

Control systems have been set to regulate the main nominal parameters. The PS electrical heater power is regulated to obtain the SG inlet required temperature and the PS pump velocity is adjusted to



#	HS	Symbols	Description
1	113 - 1		OTSG primary side tube
2	113 - 2		Inside tube sheets
3	113 - 3		Tube sheets
4	113 - 4		OTSG plena
5	310 - 1		Shell thickness
6	312 - 1		Downcomer insulation
7	312 - 2		Little steam line insulation (2 ½")
8	312 - 3		Little FW DC insulation (1 ½")
9	129 - 1		PS Electric heater heating elements
10	129 - 2		PS Electric heater insulation
11	150 - 1		Prz heating elements
12	150 - 2		Prz insulation
13	130 - 1		PS Hot Leg insulation (5" Sc.160)
14	114 – 1 123 – 1		PS Cold Leg insulation (5" Sc.160)
15	140 – 1 142 – 1		PS Spray Line insulation (2" Sc.160)
16	145 – 1		PS Surge Line insulation (2" Sc.160)

Fig. 1. RELAP5/Mod3.3 nodalization of whole the primary loop and SG secondary side.

maintain the nominal mass flow rate. A further control system is associated with the time-dependent junction (TDJ) 203, tuning the SG feedwater mass flow to achieve the nominal PS outlet temperature. steady-state conditions are attained after a "null transient" period of 200 s. The simulation extended for 3000 s to demonstrate the stability of parameters trends, ensuring compliance with the design values. The inherent drift associated with all parameters is < 1 % / 100 s. Table 1 collects and compares the steady state conditions computed by the code with the design data, emphasizing the SG mock-up. The discrepancy in SS mass flow rate between RELAP5 (R5) and the design value is a direct result of the control system that varies the feedwater to obtain the PS SG outlet temperature.

5. Pulse-dwell-pulse scenario

The full power – low power – full power transition represents a significant operational scenario, that demands to be addressed by numerical analyses and experimental campaigns. The primary concern associated with the pulsed operation of a burning plasma is the thermo-mechanical stress induced on the materials during abrupt power fluctuations. These stresses are induced by the temperature variation within the system, which must be managed to mitigate sudden temperature spikes that could potentially harm the structural integrity.

The RELAP5 numerical replication of the transient behavior in STEAM is achieved by modulating the facility power source (i.e., the electrical heater) to match the plasma power profile. Starting from the steady state conditions described in Sect. 4, at the Start of Transient (SoT), occurring after 4000 s of steady-state conditions, the electrical heater power, which remains constant until SoT, is characterized by:

- 150 s of constant power (100 %);
- 150 s of linear ramp down from 100 % to 1 % of the constant value, according to the power profile of [14];
- 600 s of constant power (1 %);
- 150 s of ramp-up from 1 % to 100 %, with a power peak reaching 115 %, according with [15].

The overall power profile adopted for transient calculations is shown in Fig. 2.

5.1. RELAP5 implemented control logics

The capability of STEAM to simulate such behavior is challenging and requires the design of an adequate control system to ensure acceptable dynamic performances of the facility. Two different Proportional-Integral (PI) controllers, both foreseeing the regulation of the FW mass flow, have been tested. The regulation of the feedwater mass flow aims at keeping constant the PS average temperature (control system 1, referred to as "T average"), or the PS minimum temperature (control system 2, referred to as "T minimum"). In both cases, during the overall transient evolution, the PS mass flow is maintained at the nominal value.

Table 1
Steady state characterization of the STEAM primary loop connected with the SG section of the secondary loop.

Quantity	Unit	Design	R5	±ε[a]
SG power	MW	3.1	3.1	0.0 %
PS SG outlet pressure	MPa	15.5	15.56	+0.4 %
SS SG outlet pressure[b]	MPa	64.1	64.1	–
P S SG inlet temperature	°C	328.0	328.0	0.0 °C
P S SG outlet temperature	°C	295.0	295.0	0.0 °C
S S SG inlet temperature[b]	°C	238.0	238.0	–
PS mass flow rate	kg/s	16.05	16.05	0.0 %
SS mass flow rate	kg/s	1.69	1.66	0.0 %

[a] Defined as the ratio |R5 - design|/design.
[b] Boundary condition.

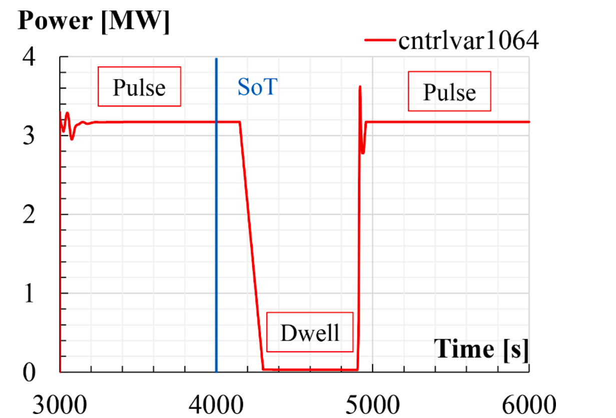


Fig. 2. Power provided to the electrical heater during the pulse-dwell-pulse transition.

Both two controllers base their operation on minimizing the error between the measured variable and the set point. In the "T average" (see Fig. 3), the measured variable is the PS average temperature, calculated as the media between the hot leg (i.e., SG inlet) and the cold leg (i.e.; SG outlet) temperatures. The set point is the SG PS average temperature during pulse (i.e., 311.5 °C, see Table 1). In the "T minimum" (see Fig. 4), the measured variable is the SG PS outlet temperature, and the set point is the SG PS outlet design temperature (see Table 1).

The operation principle is common to both control systems. If a negative error occurs (measured value lower than the set point), it indicates an excess of exchange power. To reduce it, the feedwater mass flow has to be lowered. The main difference between the two control systems lies in the thermal cycling amplitude experienced by the primary side components. The "T average" control system foresees an even thermal cycling amplitude for both hot and cold legs (ΔT=16.5 °C). On the other hand, the "T minimum" controller is characterized by a thermal cycling amplitude of 33 °C (i.e., the total nominal pulse phase ΔT) for the hot leg components, while the cold leg experiences no thermal cycling since its temperature is kept constant.

5.2. RELAP5 results

The thermal-hydraulic response of the facility to the pulse-dwell-pulse operational transient has been analyzed and the comparison between the "T average" and "T minimum" controller has been conducted. To achieve this, sensitivities analyses have been performed to tune the proportional and integral parameters and determine their impact on the thermal-hydraulic performances of the system (i.e., test section, primary system pressurizer, etc.). Reference values for both Proportional (P) and Integral (I) parameters have been selected based on engineering judgment. The performed sensitivities, the adopted P and I parameters and the main results are listed in Table 2.

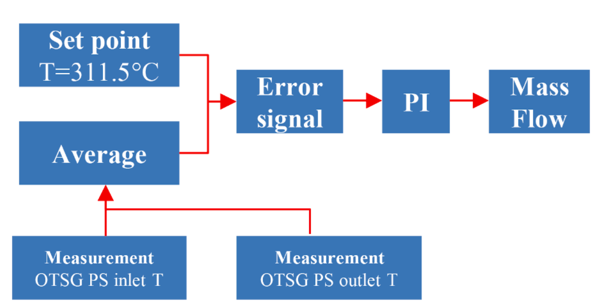


Fig. 3. FW mass flow regulation controlling PS average temperature.

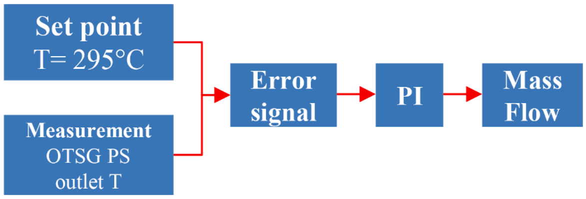


Fig. 4. FW mass flow regulation controlling PS minimum temperature.

5.2.1. *Transient evolution with the "T average" control*

Transient evolution analyses with the feedwater regulated by the "T average" control system have been initially conducted. In particular, preliminary sensitivities with first-guess parameters (cases #1 and #2 in Table 2) revealed that the PI controller accumulates an error that grows during the dwell, resulting is a significant delay in the response following the sudden power increment typical of the ramp-up. To improve the system responsiveness, the "Error resetting" technique has been implemented, which involves resetting the error calculation after the dwell.

A sensitivity analysis on the proportional and integral parameters (cases #3 to #8 in Table 2) led to the selection of a reference configuration for the controller (case #6), minimizing distortions in the transient evolution. While this combination of parameters ensures a proper system operation, it is worth noting that the hot and cold leg average temperature does not reach the set point temperature during the dwell; instead, it remains about 1 °C below it (Fig. 5). This is due to the steepness of the feedwater mass flow (Fig. 6), which is influenced by the proportional parameter whose increment is in turn limited by occurrence of oscillations. The HL over-temperature of approximately 2 °C in correspondence of the ramp up is a direct consequence of the higher temperature imposed by the controller during the dwell phase. However, this temperature spike is quite reduced and considered acceptable for the STEAM PS operation.

Furthermore, the feedwater regulation capability during the dwell ceases as soon as the mass flow reaches zero, meaning that temperature can only rise during the low-power phase. Consequently, the primary side average temperature experiences a gradual positive drift that persists until the following pulse (Fig. 5) without causing any significant concern. The trend of the pressurizer level during the overall transient evolution (Fig. 7) qualitatively reproduces the one of the PS hot leg temperature, as expected. Pressure goes down and up following the density (i.e., temperature) variations experienced in the primary loop section where this component is installed.

5.2.2. *Transient evolution with the "T minimum" control*

Being the "T minimum" logic simpler (as it is based on the monitoring of a single parameter), this controller does not require error resetting at the end of the dwell phase, as it deals with errors of lower entity. Proportional and integral parameters tuning has been performed (cases #9 to #14 in Table 2) and a reference configuration has been selected on the basis of the transient evolution (case #14). Fig. 8 shows a cold leg temperature peak of 5 °C above the nominal value in correspondence of the ramp up, consequence of the fact that the error has not been reset. Indeed, the error accumulated during the dwell determines a delay of approximately 30 s in the feedwater response to the power pulse (Fig. 9). The variation in pressurizer level during pulsed operation is depicted in Fig. 10, showing a significant level shrinking during the dwell phase. At the pulse beginning, the decrease in cold leg density, due to the temperature peak mentioned above, produces a delay in the restore of the nominal pressurizer level (compare in Fig. 10 the first and the second pulse phases).

5.2.3. *Comparison of analyzed control logics*

The comparison of the two analyzed control logics has led to the following results:

Table 2
Performed analyses test matrix.

#	Kind of control	Parameters		Error reset	Description	Main results
		P	I			
1	Average	1	0.01	✘	First guess parameters	Low system responsity, high temperature peaks. Higher P parameter reduces the delay in the FW regulation.
2	Average	5	0.01	✘		
3	Average	1	0.01	✔	Sensitivity on the P parameter	• Resetting the error at the dwell phase end enhances the system responsivity. • Higher P parameter reduces the delay in the FW regulation. • Too high P parameter leads to the insurgence of oscillations.
4	Average	5	0.01	✔		
5	Average	10	0.01	✔		
6	**Average**	**5**	**0.1**	✔	Sensitivity on the I parameter	• I parameter has smaller influence on the results with respect to the P one. • For I parameters lower than 0.1 temperature set-point is not reached during the dwell (low responsivity).
7	Average	5	0.01	✔		
8	Average	5	10^{-10}	✔		
9	Minimum	1	0.01	✘	Sensitivity on the P parameter	• Sufficient responsivity also without resetting the error at the dwell phase. • P coefficient variability is limited by insurgence of big oscillations. • CL temperature peak of 5 °C do not jeopardize the system. No peaks detected for the HL temperature.
10	Minimum	0.1	0.01	✘		
11	Minimum	0.05	0.01	✘		
12	Minimum	0.1	10^{-10}	✘	Sensitivity on the I parameter	• The I parameter can be wider varied (below 0.01) without oscillations. • Higher I parameter determines higher system responsivity and a better control of the set-point temperature.
13	Minimum	0.1	10^{-4}	✘		
14	**Minimum**	**0.1**	**0.01**	✘		

- imposing the average temperature reduces the maximum thermal cycling amplitude that the primary loop components has to withstand and reduces the pressurizer level swelling;

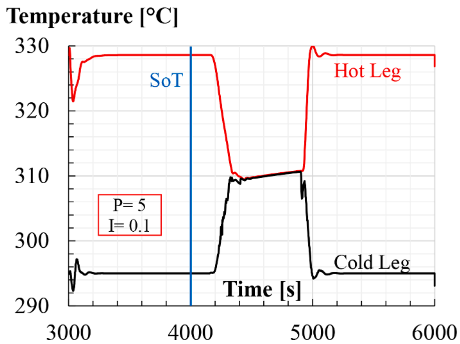


Fig. 5. CL and HL temperatures variation during pulse-dwell-pulse transition with the "T average" PI reference controller.

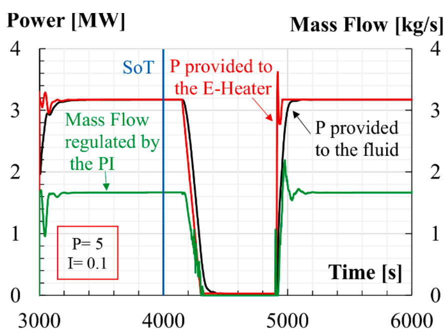


Fig. 6. Power variation during pulse-dwell-pulse transition with the "T average" PI reference controller.

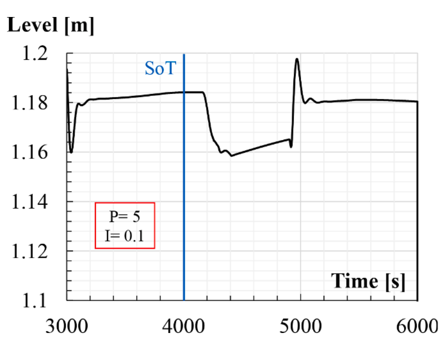


Fig. 7. Pressurizer level variation during pulse-dwell-pulse transition with the "T average" PI reference controller.

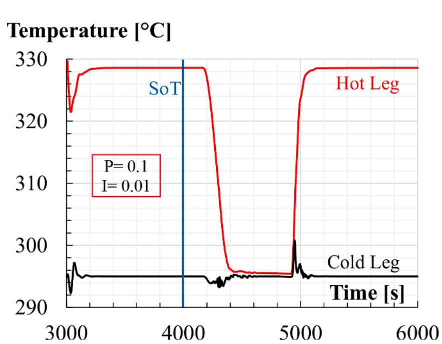


Fig. 8. Primary side temperatures variation during pulse-dwell-pulse transition with the "T minimum" PI reference controller.

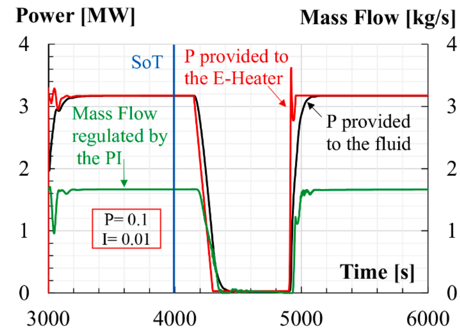


Fig. 9. Power variation during pulse-dwell-pulse transition with the "T minimum" PI reference controller.

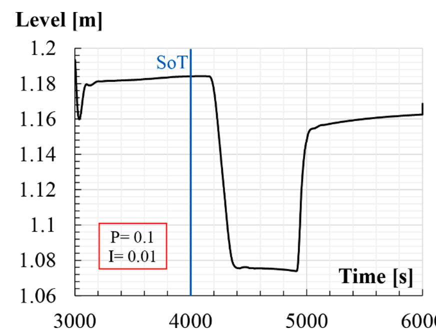


Fig. 10. Pressurizer level variation during pulse-dwell-pulse transition with the "T minimum" PI reference controller.

- the minimum temperature control system is easier to realize since it controls a single temperature in a single point, therefore the variable to be controlled does not need elaboration before being used;
- during the ramp-up, the minimum temperature control avoids the occurrence of a temperature peak in the PS hot leg;
- to allow the system that controls the average temperature to perform without jeopardizing the circuit, the controller error has to be reset to 0 at the end of the dwell phase, in order to speed up the system response.

6. Conclusions

STEAM facility, as part of the novel infrastructure named W-HYDRA to be built at ENEA Brasimone R.C., will be in charge of the experimental investigation of the DEMO Steam Generator mock-up both in steady-state and pulsed operation. Thermal-hydraulic analyses have been performed with the system code RELAP5/Mod3.3, aiming at providing preliminary feedbacks on the regulation strategy to be adopted for the SG control.

The pulse-dwell-pulse transient evolution have been numerically investigated adopting two different control logics to regulate the feed-water mass flow with the aim of keeping a fixed set-point (primary side average temperature for the first controller and minimum temperature for the second). Sensitivity analyses have also been performed for the controller P and I parameters tuning and reference combinations of them have been selected based on the transient evolution.

The analysis of the transient evolution conducted with the implementation of both control logics, has demonstrated that neither approach leads to hazardous conditions for the facility. As a result, both control strategies will be further tested within the STEAM facility during the upcoming experimental campaign. These tests aim to provide valuable insights and assessments regarding control strategies for the DEMO reactor, ensuring the safe and efficient operation of the Steam Generator mock-up in both steady-state and pulsed operation scenarios.

CRediT authorship contribution statement

Alessandra Vannoni: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marica Eboli:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Pierdomenico Lorusso:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Cristiano Ciurluini:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fabio Giannetti:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Amelia Tincani:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alessandro Del Nevo:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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