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Verification and optimization of cooldown operation mode for the ESS cryogenic moderator system during preliminary commissioning using helium

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Abstract. At the European Spallation Source (ESS), two hydrogen moderators, where the nuclear heating is estimated to be 6.7 kW at 5 MW proton beam power, are installed above a rotating target wheel. The cryogenic moderator system (CMS) circulates subcooled liquid hydrogen through the moderators. Dynamic and static heat loads are removed by a large-scale 20 K helium refrigeration system, the Target Moderator Cryoplant (TMCP), with a cooling capacity of 30.3 kW at 15 K. Installation of the CMS was completed in May 2024, and preliminary commissioning was subsequently conducted at 17 K using helium, prior to hydrogen operation and without connecting the moderators. In this study, the CMS cool-down process was examined to aid in the development of an automated operation control system, and the operational parameters were optimized.

1. Introduction

At the European Spallation Source (ESS), a 5 MW beam of 2.0 GeV proton with a nominal current of 62.5 mA driven by an accelerator strikes a tungsten wheel target at a repetition of 14 Hz and a pulse length of 2.86 ms. Spallation neutrons produced in the target are moderated to cold and thermal neutrons by the moderators. This system, consisting of a water pre-moderator and two liquid hydrogen cold moderators, has been optimized to achieve a high cold neutron brightness [1]. Initially, ESS will install two hydrogen moderators above the target wheel, with plans to expand to four moderators positioned above and below the target in the future. The nuclear heating is estimated to be 6.7 kW at a proton beam power of 5 MW, increasing to 17.2 kW for the four-moderator configuration [2].

A cryogenic moderator system (CMS) was designed to continuously supply subcooled liquid hydrogen at 17 K and 1.1 MPa with a parahydrogen fraction exceeding 99.5% to the two moderators as shown in Fig.1 [3]. An ortho-to-parahydrogen catalyst is incorporated to achieve the required parahydrogen fraction. The distribution lines to each moderator are arranged in a parallel to ensure consistent inlet temperatures. Each moderator requires a flow rate of 250 g/s to limit temperature rises to below 3 K, resulting in total circulation flow rates of 0.5 kg/s for the two-moderator configuration and 1.0 kg/s for the future four-moderator configuration. A fast-response heater is integrated downstream of one of the future moderator distribution lines to compensate for nuclear heating while proton beams are not injected [4]. Heat loads are removed via a heat exchanger (HX11) in the CMS cold box, which is cooled by a large-scale 20 K helium refrigeration system, the Target Moderator Cryoplant (TMCP), with a cooling capacity of 30.3 kW at 15 K [5]. The heater ensures that the heat load applied to the TMCP remains constant. All ESS

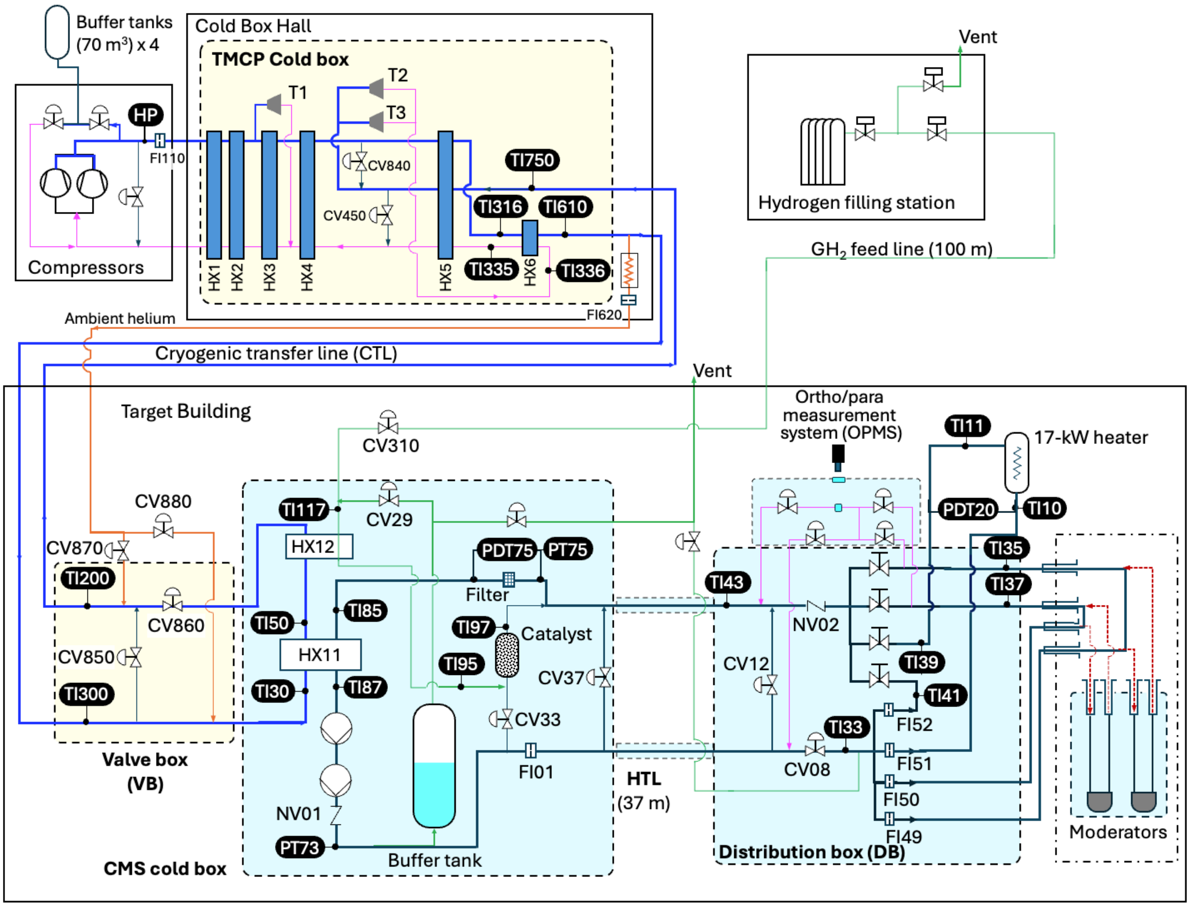

Figure 1. Overview of the ESS cryogenic moderator system (CMS).

helium cryoplants are co-located to facilitate maintenance and to share utilities such as the helium recovery system, external purifier, and helium buffer tanks with a volume of 70 m^3. A temperature controller regulates the helium supply temperature by operating two bypass valves for the two cold parallel turbines (T2 and T3) using a split range control strategy. A high-pressure helium stream (HP) at 15 K is transported to the CMS cold box via a 308-meter-long vacuum-insulated cryogenic transfer line (CTL) and a valve box (VB) adjacent to the CMS cold box in the Target building. A small fraction of the cooled HP stream, which is less than 25 g/s, is warmed up through an ambient heater (aluminum star fin tube vaporizer). The valve box adjusts both the helium supply temperature to the CMS cold box and the return temperature to the TMCP cold box using two mixing valves. In addition, the available cooling capacity for the CMS is regulated by adjusting the helium feed flow rate to the heat exchanger (HX11) using the return valve (CV860) and the bypass valve (CV850). The TMCP cooling capacity is controlled by the so-called floating pressure process [6], in which the discharge pressure (HP) is varied from 0.7 to 2.0 MPa while maintaining a compression ratio of 4.1. While the CMS was being installed, commissioning of the TMCP alone was carried out over five-month period until December 2022, confirming that the TMCP met the design requirements. Installation of the CMS was completed by May 2024. Subsequently, preliminary commissioning of the CMS was conducted using helium, without connecting the moderators, prior to hydrogen operation.

In this study, the cooldown process was investigated during the preliminary commissioning, based on the results of the TMCP commissioning [7] and simulations of the CMS cooldown process

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[8]. The CMS operational pressure was set to 0.6 MPa to match the helium density to that of gaseous hydrogen at the CMS hydrogen operational pressure of 1.2 MPa. Operational procedures for the cooldown process were established, and the associated parameters were optimized in preparation for the CMS commissioning with hydrogen, scheduled for Spring 2025.

2. Establishing and verifying the cooldown procedure

The CMS cooldown process was divided into three phases: Phase I (vapor state), Phase II (condensation state at supercritical pressure), and Phase III (liquid state). Tatsumoto et al. [8] developed a one-dimensional cooldown process simulation code and investigated methods and parameters for the cooldown process. During commissioning, the established cooldown procedure and its associated parameters were verified and optimized.

2.1 Starting the cooldown operation from room temperature

The TMCP commissioning confirmed that all three turbines, including the two parallel cold turbines (T2 and T3), must be operated to complete the cooldown within 30 hours [7]. Although the temperatures at the cold end of the heat exchangers (HX5 and HX6) rapidly decrease once the turbines are started, the return flow entering the heat exchangers (HX5) remains at room temperature for an extended period due to the 300-meter-long CTLs. During this transient period, it is crucial to carefully manage the heat exchangers to avoid exceeding the allowable temperature difference of 40 K at both the cold and warm ends. Figure 2 shows the behaviors of the TMCP and CMS at the beginning of the cooldown operation when the turbines were started. The two compressors were already in operation, with their high discharge pressures (HP) set to 1.1 MPa. The compression ratio (R_c) was temporary decreased from 4.1 to 3.6, to indirectly lower the

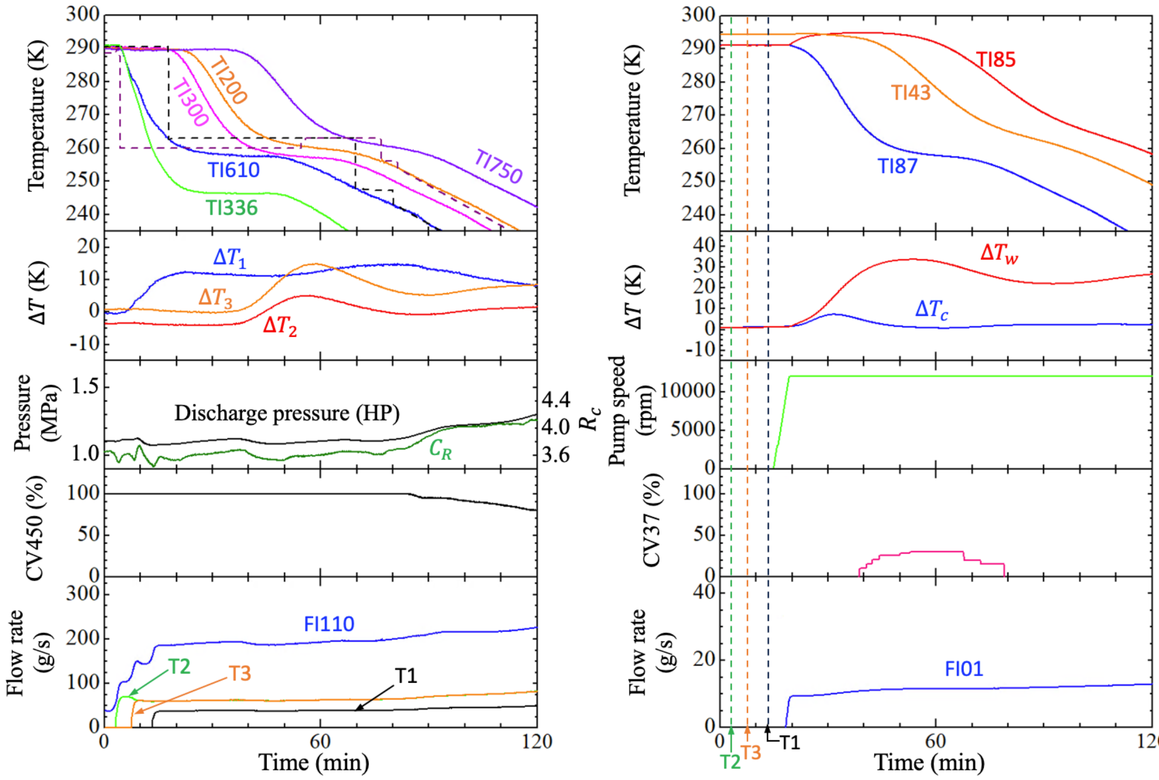


Figure 2. Behaviors of the TMCP and CMS at the beginning of the cooldown.

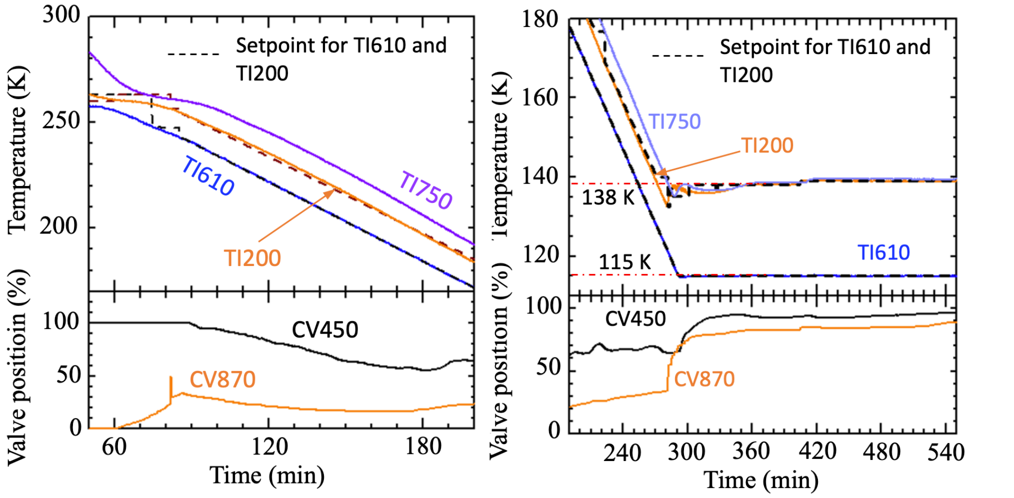
expansion ratio of the cold turbines. Additionally, the setpoint for the feed helium temperature (TI610) was set to 258 K. The cold turbines were started first, followed by the startup of the warm turbine (T1). Upon startup, the feed temperature (TI610) was rapidly decreased to 258 K, falling below the setpoint because the CV450 valve for the TI610 controller had already been fully opened at 100%. This indicates that the TMCP provided excessive cooling power, exceeding the control range of the TI610 controller. The temperature at the valve box (TI300) began to decrease after 15 minutes, while the return temperature at the HX5 (TI750) began to decrease after 32 minutes. As expected, the temperature differences at the end of the heat exchangers, ($\Delta T_1 = \text{TI610} - \text{TI336}$, $\Delta T_2 = \text{TI750} - \text{TI316}$, and $\Delta T_3 = \text{TI750} - \text{TI335}$) were successfully maintained below the allowable limit of 40 K.

Meanwhile, the CMS was cooled down at a pressure of 0.6 MPa to align the helium density with that of gaseous hydrogen at the operational pressure of 1.2 MPa. Initially, the pressure was set slightly higher, at 0.65 MPa, to prevent the supply valve from opening during the transient phase at startup. Once the warm turbine (T1) reached its nominal operating condition, both hydrogen pumps ramped up simultaneously to 12,000 rpm (S_p). The temperature at the cold end of HX11 (TI87) began to decrease as the temperature at TI300 started to drop, whereas the return temperature entering HX11 (TI85) remained near room temperature for an additional 30 minutes. Although the setpoint for the TI610 temperature controller was 258 K, TI610 began to decrease only after the return temperature (TI750), which was nearly equivalent to the turbine inlet temperature, started to drop. This is due to CV450 still being fully opened at 100%. Consequently, the feed helium temperature to HX11 (TI300) also began to decrease. This led to a significant increase in the temperature difference at the warm end of HX11 (ΔT_w), while the temperature difference at the cold end (ΔT_c) was maintained at approximately 2 K. To mitigate the rise in ΔT_w, the return temperature (T85) in the CMS was intentionally reduced by mixing a colder flow from the supply side through the cold box bypass valve (CV37). The temperature difference (ΔT_w) remained below the allowable limit, although it increased to 33 K. Based on these results, it was determined that CV37 should initially be opened to 35% at the start of cooldown and closed once TI85 decreases by 10 K. When TI85 decreased by 5 K from the initial temperature of 291 K, the TI610 and TI200 temperature controllers were activated, initiating ramp-downs at rates of 0.62 K/min and 0.60 K/min, respectively.

2.2 Phase I: Cooldown to 120 K

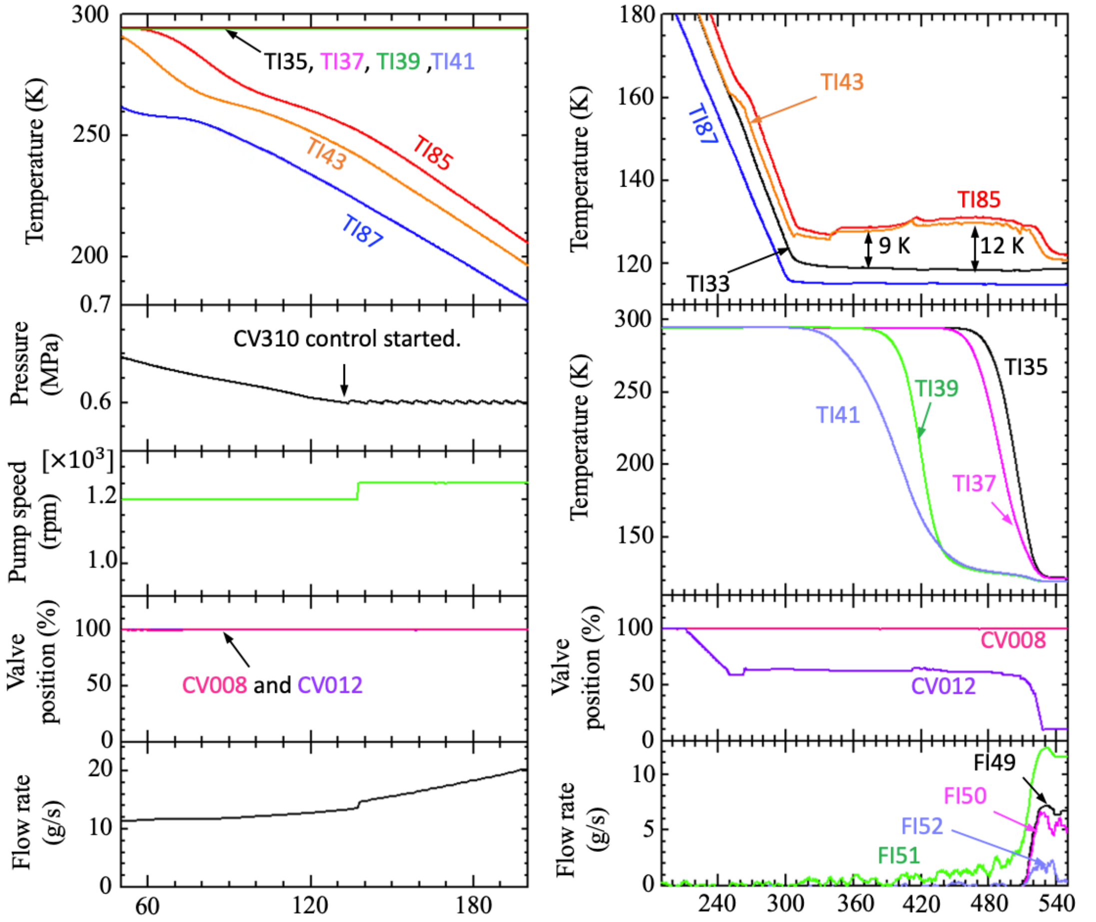
Figures 3 and 4 show the behaviors of the TMCP and CMS during the cooldown process to 120 K in Phase I, respectively. The feed helium temperature (TI610) and return temperature (TI200) followed their setpoints at the ramp-down rates of 0.62 K/min and 0.6 K/min, reaching their target temperatures of 115 K and 138 K without any significant disturbances. While maintaining the target temperatures, the control valves (CV450 and CV870) remained stable at approximately 95% and 85%, respectively.

On the other hand, due to the combined cracking pressures of 4.8 kPa from the two check valves (NV01 in the CMS cold box and NV02 in the distribution box), helium at 0.65 MPa and room temperature was unable to flow through the moderator distribution lines, as there was insufficient pump head [8]. Consequently, all helium was circulated through the bypass valve (CV12) in the distribution box, despite the moderator supply valve (CV08) being fully open. When TI87 reached 175 K, CV12 began to close, initiating the precooling of the moderator distribution lines. Once CV12 reached 61%, a rise in the return temperature (ΔT_D), measured as TI43−TI33, was observed. While maintaining the target temperatures for TI610 and TI200, the precooling was conducted with ΔT_D kept below 20 K. Through this test, a ΔT_D of 12 K shows no thermal disturbance on TI200 and TI87.



(a) After starting each temperature controller (b) Upon approaching the target temperatures

Figure 3. Behaviors of the TMCP during the cooldown process to 120 K in Phase I.



(a) Cooldown process to target temperature (b) Precooling of the moderator distribution lines

Figure 4. Behaviors of the CMS during the cooldown process to 120 K in Phase I.

2.3 Phase I: Cooldown from 120 K to 40 K

Figure 5 shows the results of the cooldown test from 120 K to 40 K conducted in Phase I. Following the completion of precooling of the moderator distribution lines, the TI200 controller was reactivated to decrease TI200 at a ramp-down rate of 0.6 K/min, followed by the activation of the TI610 controller at a ramp-down rate of 0.62 K/min. Both TI610 and TI200 were cooled to their respective target temperatures of 30.5 K and 38 K. The positions of control valves CV450 and CV870 remained below 100%, and the other split control valve associated with the TI610 controller (CV840) was not engaged. In the final phase of this process, the ramp-down rates for both the controllers were reduced to 0.2 K/min to avoid thermal disturbances as TI610 and TI200 approached their target values. The CMS supply temperature (TI85) was maintained at 36 K, which was above the hydrogen critical temperature of 33 K, by mixing room-temperature helium gas using CV880 in the valve box. This approach ensured that TI87 could be precisely regulated by CV880 during Phase II, while hydrogen condensation occurred, to prevent any thermal and pressure fluctuations. As expected, TI87 was successfully maintained at 36 K under the control of CV880, as shown in Fig. 5. However, prior to reaching the 36 K setpoint, CV880 momentarily opened to 80% due to an initial misconfiguration upon activation of the CV880 PID controller, causing disturbances in the CMS temperatures (TI87, TI43 and TI85). Nevertheless, the resulting pressure rise was limited to approximately 0.02 MPa.

Finally, the feed helium temperature (TI610) reached 30.1 K, slightly lower than its target temperature of 30.5 K, because CV450 for the TI610 controller was fully opened to 100%. To

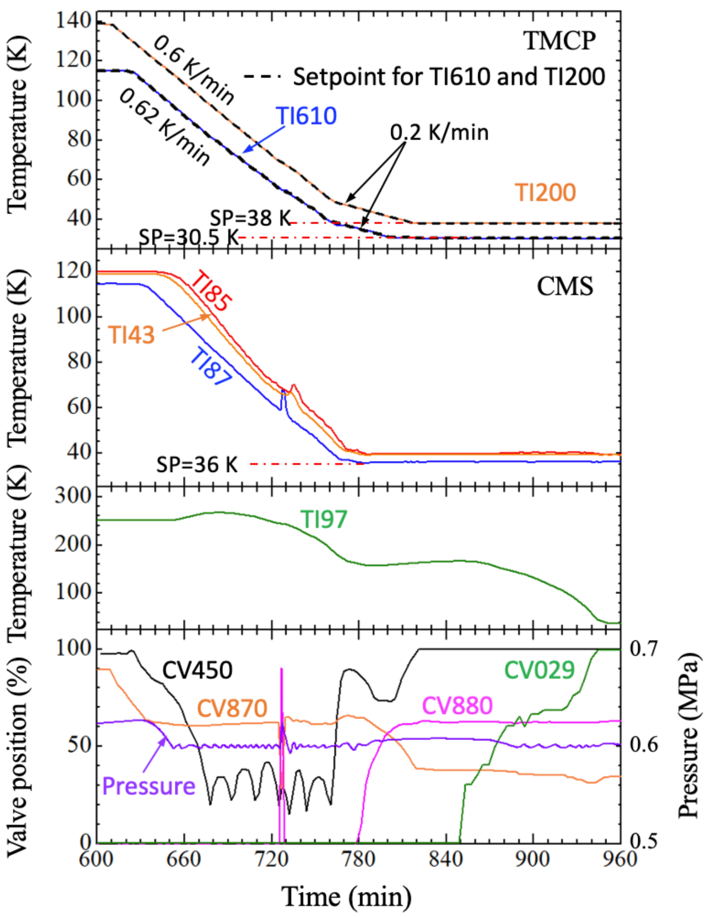


Figure 5. Behaviors of the TMCP and CMS during the cooldown from 120 K to 30 K in Phase I.

improve this situation, the target temperature for TI200 should be increased from its current value of 38 K.

On the other hand, room-temperature helium gas from the filling station was supplied to the CMS loop via CV310 and precooled through HX12. Before being delivered to the CMS process line, it passed through the catalyst vessel, which was not filled with ortho-to-parahydrogen catalyst during commissioning. The vessel was cooled down to 158 K only by the precooled helium gas. Once all the target temperatures were reached, the precooling of the PCB tank and the catalyst vessel was conducted by opening CV29, prior to starting Phase II.

2.4 Phase II: Cooldown from 40 K to 30 K

In Phase II, where hydrogen condensation occurs, the feed helium temperature (TI610) and return temperature (TI200) are maintained at approximately 30 K and 38 K, respectively. The TI87 temperature controller, operated via CV880, is then activated to fine-tune TI87 at slow ramp-down rates between 0.008 K/min and 0.012 K/min [8], to prevent thermal and pressure fluctuations during condensation process.

Figure 6 illustrates the results of the cooldown test from 38 K to 30 K in Phase II. The ramp-down rates ranged from 0.008 K/min to 0.23 K/min. As TI870 decreased, the CV880 position also decreased, while the CV870 position increased to maintain TI200 at its target temperature of 38 K. When TI87 reached 30 K, CV880 was fully closed, and the CV870 was opened to 62%. Therefore, the TI200 target temperature can be increased until the CV870 position reaches 90% to address the issue of TI610 being lower than its target temperature, as described in Section 2.3.

The helium gas supplied to the CMS loop via CV310 was precooled by mixing with the bypass flow through CV29, which was fully opened to 100%. As shown in Fig. 6, temperature fluctuations were observed at the inlet of HX12 (TI117). However, downstream of HX12, these fluctuations disappeared, and the supply temperature was cooled to approximately 1 K above TI87.

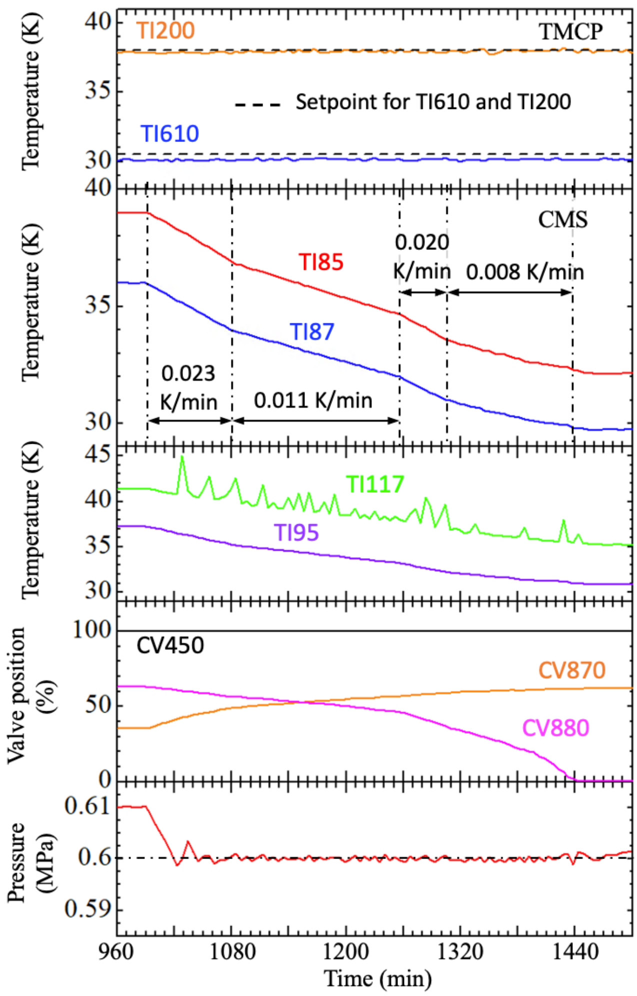


Figure 6 Cooldown process in Phase II.

2.5 Phase III: Cooldown from 30 K to 17 K

Figure 7 illustrates the results of the cooldown test from 30 K to 17 K in Phase III. TI200 was decreased to 21.2 K at a ramp-down rate of 0.06 K/min, while TI610 was reduced to 16.0 K at 0.04 K/min. Initially, TI610 did not follow its controller setpoints because CV450 remained fully open at 100%. To prevent this issue, the TI610 controller should be activated first at the beginning of Phase III, with the activation of the TI200 controller delayed until the CV450 position drops below

90%. During this commissioning, the TI200 controller was temporarily suspended until the CV450 position dropped below 94%. Following this, both TI610 and TI200 followed their respective setpoints. The CV450 position remained above 90% throughout the helium-based Phase III test, which had a lower heat capacity than hydrogen, indicating that the TMCP provided sufficient cooling capacity. The simulation results for the CMS cooldown process using hydrogen concluded that the maximum TMCP cooling capacity required during Phase III was 7 kW [8]. The TMCP commissioning results confirmed that the cooling capacity was 20 kW at 16 K [7] under the same operational conditions. Therefore, the available TMCP cooling capacity is expected to be sufficient for Phase III hydrogen operation. For the future hydrogen cool-down operations in Phase III, potential fluctuations in the return temperature (T85) will be addressed by lowering the ramp-down rate if necessary.

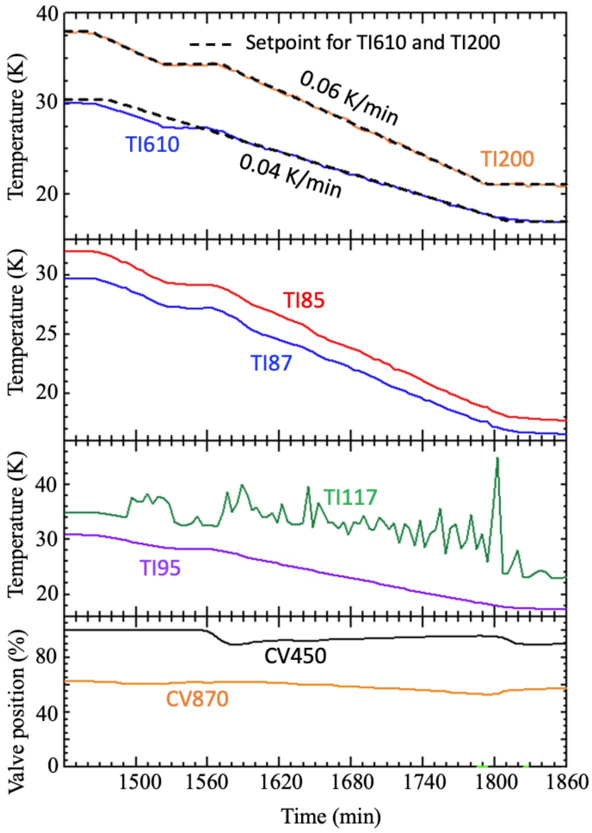


Figure 7 Cooldown process in Phase III.

3. Conclusions

The cooldown process was investigated during preliminary commissioning using helium to support the development of an automated operation control system. The CMS operational pressure was set to 0.6 MPa to match the helium density to that of gaseous hydrogen at the CMS hydrogen cooldown pressure of 1.2 MPa. During commissioning, the established procedures for cooldown process from Phase I to III were tested to verify their effectiveness and confirm that the system functioned as intended. Based on the test results, the associated operational parameters were optimized and fine-tuned to achieve reliable and stable cooldown operation.

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