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Cryogenic testing of HL-LHC Q1/Q3 cryo-assemblies at Fermilab

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Abstract. Fermilab is conducting horizontal cryogenic testing of Q1/Q3 cryo-assemblies for the high-luminosity LHC upgrade (HL-LHC). Cryo-assemblies are installed on the upgraded Fermilab horizontal test stand previously used for testing the LHC inner triplet quadrupoles. The cryogenic process requirements of these tests include controlled cool-down and warm-up with a 100 K maximum temperature differential between the two ends of the cold mass, operation of a 1.3 bar, 1.9 K bath of subcooled superfluid helium during power testing and magnetic measurements, and operation at pressure up to 18 bar with full helium recovery after a quench. This paper presents the operational experience gained from the first tests as well as improvement for subsequent tests.

1. Introduction

The U.S. is contributing new Nb_3Sn-based superconducting interaction region quadrupole magnets to the CERN High-Luminosity Large Hadron Collider (HL-LHC) upgrade. Each HL-LHC cryo-assembly, consisting of two magnets integrated into a cold mass and installed in a vacuum vessel, will be horizontally tested at the Fermilab Industrial Building 1 test facility in 1.9 K, 1.3 bar(a) helium II at currents up to nearly 17 kA.

The upgraded horizontal test stand, previously described [1], is now in full operation to support testing of HL-LHC cryo-assemblies. Figure 1 shows the test stand with the first installed cryo-assembly.

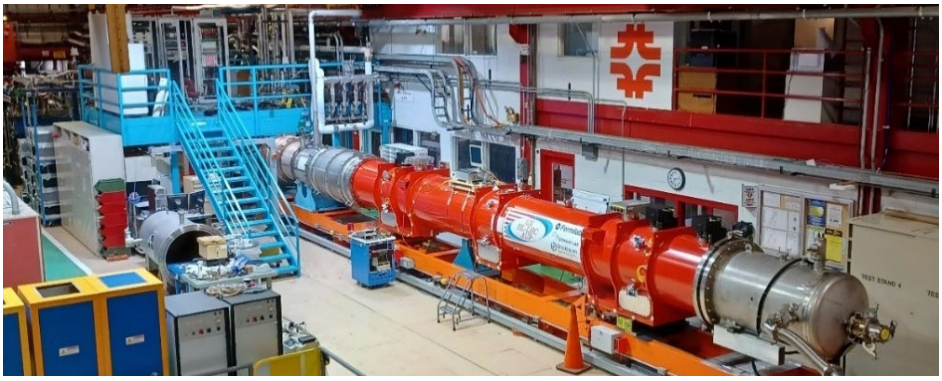

Figure 1. The first HL-LHC cryo-assembly installed on the Fermilab horizontal test stand.

2. Interconnect

The interconnect piping provides the process connections between the test stand and the cryo-assembly, and it accommodates thermal motion that occurs during cooldown. This thermal motion is defined by the system fixed points, which are at the test stand Adapter Box and the longitudinal midpoint of the cold mass. The Adapter Box is the interface between the existing test stand feed box and the new cryo-assemblies.

Flexible hose loops, consisting of three individual flexible hoses assembled in a U-shaped pattern, are used on process lines where there are no requirements for straight piping. One such flexible hose loop can be seen to the left of center in the left picture of figure 2. This flexible hose loop is installed on the cooldown return line. It can accommodate a combined longitudinal and lateral motion of up to 0.80 in and a vertical motion of up to 0.40 in.

There are some process lines where flexible hose loops cannot be used. The pipe carrying the electrical bus cannot be configured in such a shape, and it must have provisions for making the bus splice between the cryo-assembly and the test stand. Similarly, the heat exchanger pipes have a small internal line for supplying helium to the heat exchangers. For these process pipes, externally pressurized (e-p) expansion joints are used to accommodate the longitudinal motion. These are commercially available units rated to 300 psi, and because of the externally pressurized design they are not susceptible to squirming. The bus line uses two of these e-p expansion joints in series. Each of them can expand by 0.625 inches and contract by 4 in, providing 8 in of available length for making the bus splice. The heat exchanger lines each have a similar e-p expansion joint that can expand by 2 in and contract by 6 in. In addition, a tied universal expansion joint is used on each of these pipes to accommodate up to 0.5 in of combined vertical and lateral motion.

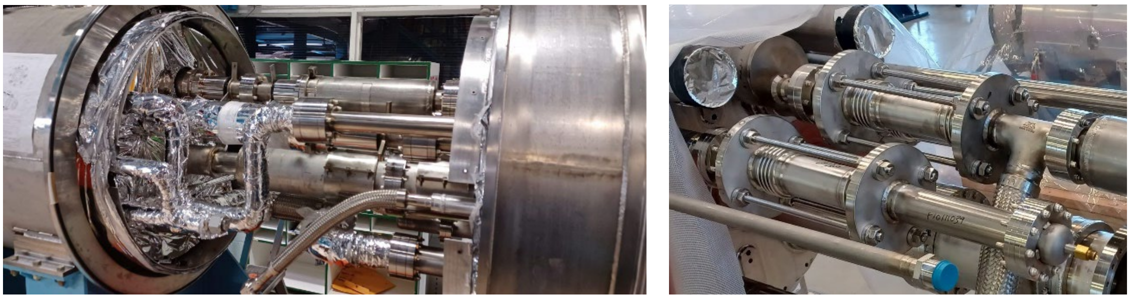

Figure 2. The left photo shows the interconnect between the horizontal test stand (to the left) and the HL-LHC cryo-assembly (to the right). The flexible hose loop on the cooldown return line is seen to the left of center and wrapped in MLI. The e-p expansion joints on the bus line are seen at the top middle. The right photo shows the tied universal expansion joints used on the bus pipe and the two heat exchanger pipes.

3. Return end

Two liquid helium reservoirs are attached to the return end of the cold mass in preparation for horizontal testing. Each reservoir contains an instrumentation assembly consisting of temperature sensors and superconducting liquid level probes. One reservoir attaches to the two heat exchanger pipes and allows for monitoring and control of the liquid helium level in the horizontal heat exchanger pipes to ensure 1.9 K cool-downs progress steadily. The second reservoir attaches to the cold mass and allows monitoring and control of the liquid helium level in the cold mass during 4.5 K filling. Both reservoirs are shown in figure 3.

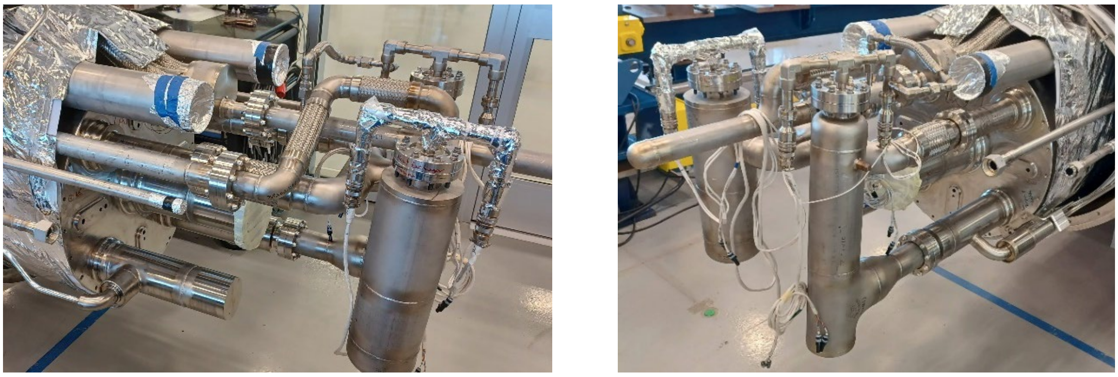

Figure 3. The left photo shows the heat exchangers reservoir. The right photo shows the cold mass reservoir in the foreground.

4. Cool-down and warm-up: 300 – 4.5 K

To protect the brittle Nb_3Sn superconductor used in the magnets, during cool-down or warm-up the temperature difference across the cold mass cannot exceed 100 K. At the test stand, a maximum operating temperature difference of 80 K across the cold mass is used. This is accomplished using a PLC script to automatically control the temperature of the helium supplied to the test stand. Helium at three temperature levels is available to the test stand: 300 K gas, 80 K gas, and 4.5 K liquid.

In 'high temperature mode', 300 K helium gas and 80 K helium gas are mixed to achieve helium supply temperatures of 80 K and above. The 80 K helium gas is provided by a set of two 'cold' mass flow controllers which provide 300 K helium gas from compressor discharge at a flow rate specified by energy balance calculations to an 80 K liquid nitrogen bath heat exchanger. This liquid nitrogen bath heat exchanger is a repurposed Fermilab Tevatron subcooler. A second set of two 'warm' mass flow controllers provide 300 K helium gas from compressor discharge at a flow rate specified by PID control loop operation to achieve the desired supply temperature to the test stand after the two flow streams are mixed. A typical flow rate supplied to the test stand in this high temperature mode is 18 g/s.

In 'low temperature mode', 80 K helium gas and 4.5 K liquid helium are mixed to achieve helium supply temperatures below 80 K. The 4.5 K liquid is supplied from a 10,000 gallon liquid helium storage dewar with a flow rate limited by the dewar operating pressure. The 80 K helium gas is provided by the two 'cold' mass flow controllers in a manner similar to high temperature mode but operated by a PID control loop. A typical flow rate supplied to the test stand in this low temperature mode is 12 g/s.

To date, there have been five cryo-assembly thermal cycles on the test stand: two thermal cycles for the first cryo-assembly CA-01, two thermal cycles for the second cryo-assembly CA-02, and one thermal cycle for the third cryo-assembly CA-03. Cooldown time is 2 weeks, and warmup time is just over 1 week. Figure 4 is a plot of temperature data from the warmup at the end of the first thermal cycle and the cooldown at the beginning of the second thermal cycle of CA-01. Fermilab placed platinum temperature sensors on the iron pads at the lead end (Magnet B) and return end (Magnet A) of the cold mass. The lead end of the cold mass is closer to the test stand feed box and therefore sees the warmup and cooldown flows first. The intermediate temperatures seen in figure 3 are Cernox sensors measuring the fluid temperature near the outer periphery at the longitudinal midpoint of the two individual magnets that comprise a cold mass.

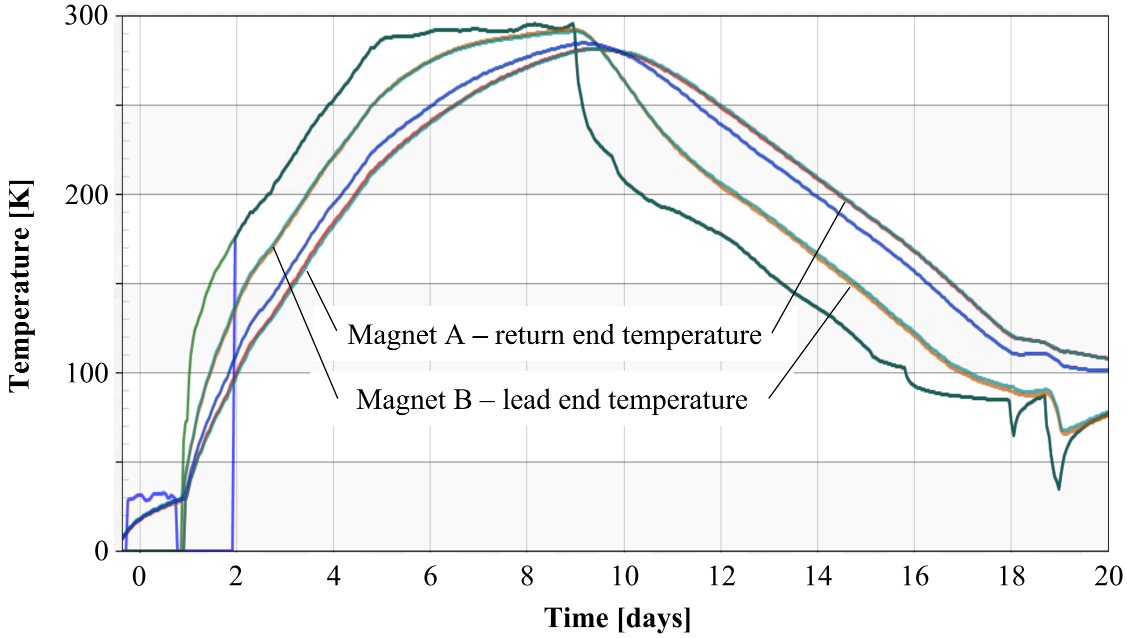

Figure 4. Cold mass temperature data from warm-up at the end of the first thermal cycle and cool-down at the beginning of the second thermal cycle of cryo-assembly CA-01.

As described, on the first cryo-assembly CA-01 there were temperature sensors measuring the temperature at both ends of the cold mass, not across each individual magnet. To estimate the temperature difference over the length of one magnet, the average temperature of each individual magnet was calculated using the measured resistance of the coils. Cernox sensors are mounted on the inboard ends of each magnet for subsequent cryo-assemblies so that the temperature difference across the individual magnets can be directly calculated and assured that it does not exceed 50 K.

Figure 5 shows the end temperature and average temperature of each magnet during the first cooldown of CA-01 in March 2023. For Magnet B, the lead end temperature diverged from the average temperature as the lead end was immediately exposed to the helium supply flow. Conversely, for Magnet A, the return end temperature converged with the average temperature as there was a smaller temperature difference between this downstream magnet and the helium flow which allowed for longitudinal equalization. At the ~230 hr mark, the end temperature and average temperature of each magnet converged as each magnet thermally equalized during a pause in the cooldown.

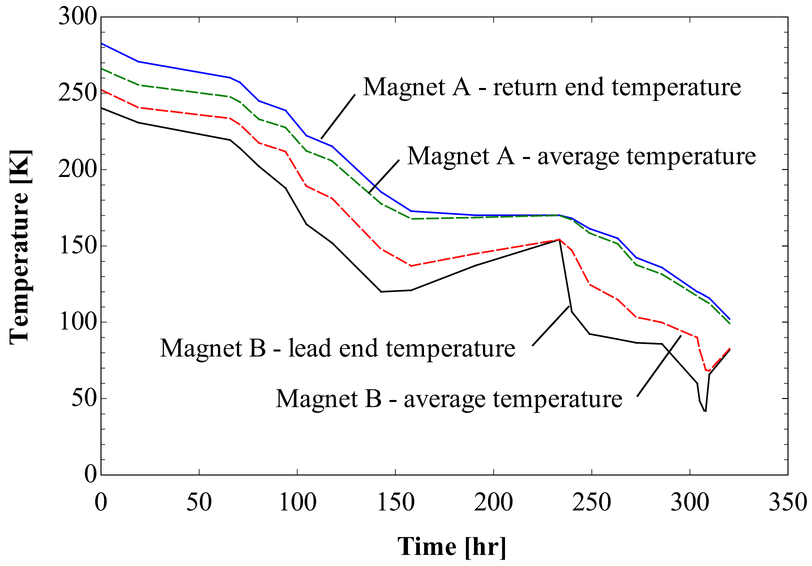

Figure 5. Cold mass temperature data from warmup at the end of the first thermal cycle and cooldown at the beginning of the second thermal cycle.

5. Cool-down to 1.9 K

Superfluid heat transfer for cool-down from 4.5 K to 1.9 K (both at 1.3 bar) is performed with two bayonet heat exchangers placed internally along the 10.5 m length of the cold mass. Pumping is provided by two subatmospheric warm pumping skids [2] consisting of Roots blowers backed by liquid ring pumps. Each pump skid has a pumping capacity of 2.5 g/s of helium at 16 mbar.

Figure 6 shows temperature data for a cryo-assembly CA-01 1.9 K cool-down, which required 3 hours. Subsequent procedural improvements combined with operator experience has allowed recent 1.9 K cool-downs of cryo-assembly CA-03 to require only 2 hours.

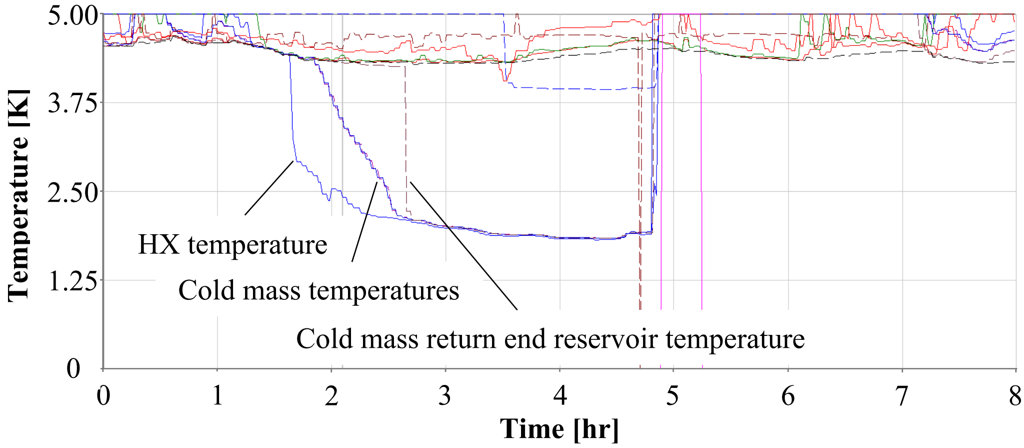

Figure 6. Temperature data for a 1.9 K cool-down.

Cryo-assembly CA-01 reached a minimum temperature of 1.69 K. A detailed analysis of the test stand and pumping line result in a calculated 43 W heat load to the superfluid. The heat load varies, depending on the recent operational history of the warm finger (or anti-cryostat, used for magnetic measurements). If the warm finger had been recently used for magnetic measurements, it would still be relatively warm and the measured heat load would be higher. On the day when 1.69 K was reached, the system heat load was low because the warm finger had been under vacuum for many days and had reached temperatures of 88-104 K.

6. Heat load to 4.5 K

The static heat load to the 4.5 K test stand feed box due to radiation and conduction down the vessel wall from the 80 K thermal intercept is 38 W. Each of the three 15 kA vapor-cooled current leads provides an additional 15 W of zero-current static heat load. These calculated heat loads are based on measured rates of liquid level change after the liquid helium supply to the feed box is turned off.

The dynamic heat load to 4.5 K was much greater than expected during testing of cryo-assembly CA-01. Increasing the current from 6 kA to 16.23 kA saw an accompanying 200 W increase in heat load. The problem was traced to a high-resistance mechanical joint at the current lead bottom flag, as shown in figure 7. Figure 7 shows this joint, as well as the new copper fixture with soldered joints that was designed, fabricated, and tested before installation. Sectioning of soldered practice pieces showed all joints were of high-quality and expected to have low resistance.

Figure 7. The left photo shows the original configuration, where a copper splice block containing the superconducting bus was bolted to the current lead bottom flag. The middle photo shows the new two-piece copper fixture with a current lead dummy flag used for testing. The right photo shows the copper fixture after being soldered onto the in-service current lead.

After installation on the one current lead, dynamic heat load measurements were taken during powering of cryo-assembly CA-02. The dynamic heat load was reduced from 100 W to 12.6 W. A further reduction in heat load will be realized when new fixtures are installed on the two remaining current leads.

7. Heat load to 1.9 K

The heat load to 1.9 K was calculated using the estimated combined 465 l superfluid volume of the cryo-assembly and the measured rate of temperature rise of the 1.9 K liquid helium after pumping was stopped. The calculated heat load at this time was 53.5 W. In table 1, heat loads of individual test stand components are provided. The heat load of the warm finger was calculated based on its measured cooling rate while it was maintained under vacuum. The Adapter Box conduction is the result of a finite element analysis of its G-10CR pipe support spiders. The quench line heat load is the calculated conduction from the 300 K vacuum break to the superfluid check valve. The radiation heat load to the 1.9 K portions of the test stand were calculated assuming a radiation heat flux of 0.1 W/m^2 over the surface areas of multilayer insulation blankets and individually wrapped helium pipes. Subtracting these test stand heat loads from the overall 1.9 K heat load resulted in a calculated cryo-assembly 1.9 K heat load of 14.6 W.

The expected cryo-assembly heat load to 1.9 K in table 1 is based on CERN heat load analyses. The support posts present a conduction heat load with a thermal intercept at the thermal shield temperature. The support post heat load at the Fermilab test stand were scaled with the temperature differential between the 1.9 K cold mass, the CERN 60 K intercept, and the Fermilab test stand 85 K intercept. The radiation heat load uses the same 0.1 W/m^2 heat flux as described previously. The CLIQ (Coupling Loss Induced Quench), KMOD (K-Modulation), and IFS (Instrumentation Feedthrough System) capillary systems and the FSI (Frequency Scanning Interferometry cold mass position monitoring system) ports do not interface with the thermal shield, so the CERN analysis results are used directly. The heat loads of components not installed at the Fermilab test stand, such as beam screens, beam position monitors, and CERN-specific interconnect piping, are not included. The expected cryo-assembly heat load to 1.9 K on the Fermilab test stand is 16.2 W.

The calculated 1.9 K heat load of a cryo-assembly is in good agreement with the expected heat load. This provides a first measure of confidence that the Q1/Q3 cryo-assemblies will thermally perform as expected when installed in the HL-LHC.

Table 1. Summary of heat loads to 1.9 K. The calculated cryo-assembly heat load based on the overall system heat load is very close to the expected cryo-assembly heat load based on its construction.

Fermilab analysis/data	1.9 K heat load (W)	CERN analysis	1.9 K heat load (W)
Measured total	**53.5**		
Test stand component		Cryo-Assembly component	
Warm finger (anti-cryostat)	28.8	Support posts	5.0
Adapter Box conduction	5.1	CLIQ capillary systems	3.3
Quench line conduction	4.2	KMOD capillary system	2.4
Radiation	0.8	KMOD capillary system	2.3
		IFS capillary systems	1.8
		FSI ports	1.4
Cryo-assembly, calculated	**14.6**	**Cryo-assembly, expected**	**16.2**

8. Quench and quench recovery

Figure 8 is the cryo-assembly pressure after a 16,237 A system trip during CA-01 testing. This pressure was measured at the inlet to the quench recovery line, not directly at the cold mass. Within 2 seconds, the pressure rises from just above atmospheric pressure to a maximum pressure of 278 psia (19.2 bar(a)).

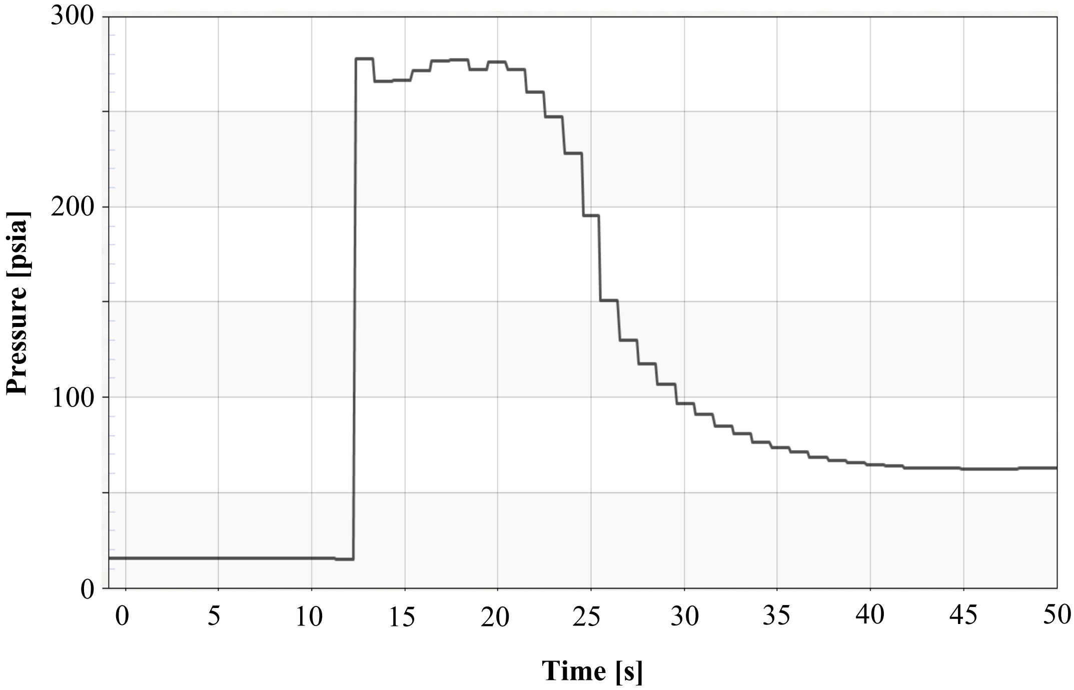

Figure 8. Pressure increase in the quench recovery line near the test stand following a 16,237 A system trip.

The upgraded test stand includes capabilities for helium recovery in the event of a magnet quench or a system trip. A valve is opened as soon as possible after the quench or trip, connecting the test stand to a 114 m^3 gas storage tank. A measured 3 psi/s rate of pressure rise in the gas storage tank corresponds to a quench flow rate of 4 kg/s.

9. Conclusion

The upgraded Fermilab horizontal test stand has been brought into full operation to test HL-LHC cryo-assemblies. The first installation of a cryo-assembly on the test stand has proven the interconnect design to be sound. Controlled cooldown and warmup have been successfully demonstrated, and the required temperature of 1.9 K has been achieved. Finally, quench pressures of just over 19 bar(a) have been successfully handled in conjunction with recovery of a 4 kg/s quench flow rate.

10. References

[1] Rabehl R, Al Atassi O, Chlachidze G, Feher S, Koshelev S and Ranpariya S *2022 IOP Conf. Ser.: Mater. Sci. Eng.* **1240** 012078

[2] Rabehl R, Carcagno R, Huang Y, Norris B and Sylvester C *2010 AIP Conference Proceedings* **1218** 18-25

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