PERFORMANCE OF THE IFSMTF HELIUM REFRIGERATOR IN PARTIAL-ARRAY TESTS*

S. W. Schwenterly, W. A. Fietz, R. E. Stamps,

and J. F. Ellis

Oak Ridge National Laboratory
Oak Ridge, Tennessee

ABSTRACT

Performance of the International Fusion Superconducting Magnet Test Facility (IFSMTF) helium refrigerator in Partial Array Tests with three coils is described. The refrigerator was able to cool the coils and facility structure to 4.2 K in 20 days, with maximum temperature differentials of less than 50 K. Boiloff measurements were made for several components; only the lead dewars showed losses substantially higher than expected. Forced-flow cooling tests were also conducted. The coils and facility were warmed back to room temperature in 30 days. Several repairs and improvements were carried out. Results of another recent test on the refrigerator alone are reported.

INTRODUCTION

The International Fusion Superconducting Magnet Test Facility (IFSMTF) contains six large prototype fusion reactor coils which are being tested together in a toroidal array. Three coils, the Westinghouse (W), EURATOM (EU), and Swiss (CH), are cooled by 3.8-K forced-flow (FF) supercritical helium at 10-15 bar. The other three coils are cooled by 4.2-K pool-boiling liquid helium (PB LHe) at 1 bar and were produced by General Dynamics (GD), General Electric (GE), and Japan (JA). Cooling of the very large mass (360,000 kg) of the coils and associated support structure to LHe temperatures and maintaining these temperatures for long periods is the task of the facility helium refrigerator, which must produce 300 g/s of supercritical helium at 3.8 K and simultaneously provide sufficient 4.2-K refrigeration and liquefaction under varying heat load conditions. Because high reliability is required of this system, three major preliminary tests have been carried out in preparation for the testing with all six coils. An acceptance test of the refrigerator was carried out in 1983. In 1984, the GD, JA, and CH coils were cooled down in the Partial Array Test, and the GD and JA coils operated to full current.¹ Many repairs, modifications, and improvements were suggested by these tests, and so a third set of tests on the refrigerator alone were carried out during April-June 1985. This paper summarizes refrigerator performance during the Partial Array Test and the recent Refrigerator Test.

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Figure 1.
Elevation view of facility.

FACILITY DESCRIPTION

The heart of the facility is the test stand, depicted in Fig. 1. The D-shaped test coils have 2.5 by 3.5-m bore dimensions, masses between 34,000 and 40,000 kg, and produce a peak field of 8 T when operating at their design currents of 10 to 19 kA. The coils are mechanically supported by the central bucking post which sits on the hexagonal spider frame, and by torque rings which maintain the coils' azimuthal positions in the array. Both the bucking post and the torque rings run at or near LHe temperature. The test stand is thermally isolated by the vacuum in the surrounding 11-m-diam vessel, which is lined with super-insulated panels cooled by liquid nitrogen (LN). Each test coil can be subjected to a pulsed vertical field from a pair of LN-cooled pulse coils, which can be remotely moved on a circular track by a gaseous-helium-actuated drive mechanism.

The helium refrigerator² is the most complex ancillary system in the facility. A block diagram is shown in Fig. 2. Helium gas is compressed in two stages—from 0.5 bar to 3 bar at 100 g/s by a pair of 0.3-MW (400-hp) oil-lubricated screw compressors, and from 3 bar to 15-bar at 300 g/s by a similar pair of 0.75-MW (1000-hp) compressors. Filters and charcoal beds on the compressor skids remove all oil from the 15 bar stream, after which a LN-cooled full-flow purifier with charcoal and molecular sieve beds reduces all contaminants to levels below 5 ppm. A pair of buffer tanks with a total free volume of 1500 m receives excess

Figure 2.
Schematic of refrigerator system.
Pressures are shown in bar;
(L) signifies liquid helium.

high-pressure gas or supplies low-pressure makeup gas as needed. In the main cold box, the high-pressure gas is precooled with LN and is then cooled below 4.5 K in four three-pass heat exchangers. It then passes to the valve box, where a set of cryogenic valves on a branch line allows tapping off part of the stream for cooling or warming various parts of the facility structure. The main portion of the stream flows to a fifth exchanger immersed in 0.5-bar LHe in the auxiliary cold box (ACB) where it is cooled to 3.8 K. This exchanger is constructed in three parts to allow cooling of the supercritical stream to 3.8 K before it passes through each of the three FF coils. The ACB also contains a cluster of cryogenic valves which allows series or parallel connection of the FF coils, and bypassing of individual coils. After passing through the FF coils and expanding from 15 to 10 bar, the helium returns to the main cold box at 4.2 K. At this point the stream splits and 200 g/s is passed back up through the heat exchangers and turbine 1 (T1), while the remaining 100 g/s is liquefied in turbine 2 (T2) and the Joule-Thomson (JT) expansion valve. LHe is collected and stored in the 19,000-L and 2,000-L dewars and supplied automatically to the PB coils and bucking posts by control valves in the valve box. The vapor-cooled lead (VCL) dewars are separately supplied by a line from the 2000-L dewar. Liquid is also supplied to the cooling bath in the ACB, where it expands to 0.5 bar through the inlet valve and cools evaporatively to 3.5-K. Cold vapor from the ACB, all dewars, bucking post, and PB coils returns to the main cold box, is mixed by appropriate control valves, and returns at 0.5 bar to the compressors via the low-pressure paths in the heat exchangers. Warm gas from the VCLs returns directly to the compressors. All components at cryogenic temperatures are interconnected by vacuum-jacketed, liquid-nitrogen-traced (VJNT) transfer lines.

In the event of a quench that produces massive boiling in a PB coil, fast-acting valves open to vent the vapor through the dump tank to atmosphere. Simultaneously, valves in the return lines to the main cold-box close to minimize pressure transients and consequent risk of damage to the gas bearings in the turbines. If a quench occurs in a FF coil, its inlet and outlet valves close, and a bypass valve opens. Rising pressure is relieved by vent valves on the coil supply and return lines.

PARTIAL ARRAY TEST

For the Partial Array Test, the JA and GD coils were completely installed. The CH coil was piped into the helium system, but had no high current leads because installation of the lead ducts would have caused undue delay. In preparation for the test, the helium system was cleaned up by circulating warm helium gas from the purifier through all elements in a closed loop. It took about four days to bring all contaminant levels below 5 ppm. During this time, the coils were also hipot tested and leak checked, the instrumentation system was checked out, and the vacuum tank was pumped down. A helium leak of about 5×10^{-4} atm-cc/s remained on the GD coil. A cracked instrumentation feedthrough was suspected. Because the tank pumps could handle this leak even if it increased several orders of magnitude, cooldown commenced in early July 1984.

Figure 3 shows a plot of various temperatures in the coils and facility vs time in days. Ten-bar gas from the main coldbox was used to cool down the Swiss coil and facility structure. Part of this high-pressure stream was bled off and throttled to about 2 bar for cooling the PB coils. The total flow rate was 130 g/s, with approximately 15 g/s to each coil and the remainder to the facility structure. The inlet gas temperature to coils and facility was controlled by bypassing part of the flow of 10-bar gas from the compressors through an LN-cooled heat exchanger in the main coldbox. The maximum temperature differential was

Figure 3.
Facility temperatures vs time for Partial Array Test.

held to 50 K. This was quite easy to accomplish with only manual control of the system flow rates, because cold gas returning from the coils and facility through the main coldbox heat exchangers tended to reduce the inlet gas temperature at nearly the facility cooldown rate. Adjustments to the inlet temperature were generally needed only every 5 to 8 hours.

After six days, system temperatures were in the neighborhood of 220 K, and the coldwall was cooled down and filled with liquid nitrogen. Cooldown proceeded relatively smoothly, punctuated every other day or so by brief compressor shutdowns which were triggered either by faulty interlocks or by outages in power, instrument air or cooling water. Summer electrical storms were a major factor in these outages. By the twelfth day, the inlet helium temperature had been reduced to 86 K, and system temperatures had fallen into the range of 100-120³ K. At this point, the helium leak rate into the tank had risen to 8×10^{-3} scc/s. Total gas flow to the system had increased to 230 g/s.

Flow to the system was stopped, the coldbox turbines were started, and liquefaction into the storage dewars proceeded for about a day until about 18,000 liters of liquid helium were on hand. Flow to the coils and facility was then resumed, with turbine 1 supplying refrigeration for cooling below liquid nitrogen temperature. Cooldown continued smoothly until day 19, when temperatures had fallen to about 20 K. At this point, turbine 2 was started. After another two days, temperatures in the coils reached 10 K, and resistance measurements indicated that large portions of the windings had become superconducting. The ACB bath was filled with LHe, and liquid transfer was started to the pool-boiling coils, lead dewars, and facility structure for the final cooldown to 4.2 K.

No major increase in helium leakage occurred when the JA coil was filled. However, when the GD coil and bus ducts were filled with LHe, the tank pressure rose to about 5×10^{-4} torr. Leakage was too high to measure directly with the leak detector, but assuming 800 L/s pumping speed for the turbopump gives a helium leak rate of about 0.5 scc/s. Since these helium pressures were too high for acceptable heat loads to the coils and facility, the large oil diffusion pump was turned on. This was able to maintain tank vacuum at about 2×10^{-5} torr with all components full of liquid helium.

Late in the evening of day 24 of cooldown, all the coils were fully superconducting. However, about four days were spent checking the automatic helium refill system, measuring component boiloff rates, and

Table 1. 4.2-K Boiloff Heat Loads in Partial Array Test

Item	Boiloff Rate (L/h)/(W)		
GD Coil	53/38		
JA Coil	62/45		
CH Coil	n.a./40		
19,000-L Dewar	0.3/0.2		
2,000-L Dewar	1.5/1.0		
ACB	7/5		
Bucking Post	71/52		
JA Lead Dewars	Liquefaction (L/h) + Refrigeration (L/h)/(W)		
0.0 kA:			
Positive	10	+	48/35
Negative	10	+	48/35
10.0 kA:			
Positive	16	+	49/36
Negative	22	+	48/35

allowing all structures to reach their minimum temperatures before energizing the coils. The helium fill system worked well, although it was found necessary to build up pressure slightly in the 19,000-L dewar by closing its vent valve to achieve an adequate liquid transfer rate. A servo-controlled valve was later installed on the vent to allow more even pressure control in the dewar. Each PB coil was refilled roughly every three hours by transferring about 180 L of LHe in 30 minutes. The lead dewars were automatically refilled roughly every 45 minutes, with a 5 to 10 min fill time. The cryogenic valve to divert liquid flow from the bottom of the GD coil in cooldown to the top for refill froze shut, so that the coil had to be refilled from the bottom. This did not cause serious difficulty.

Table 1 shows boiloff heat loads measured for the various coils and facility components. Two types of loads are shown. Refrigeration loads are those for which the boiloff gas is returned to the refrigerator cold. In contrast, for liquefaction loads the gas is returned directly to the compressors at room temperature. Liquefaction loads use up much more of the refrigerator's capacity because the cooling effect of the return gas in the heat exchangers is lost. The warm gas flow from the VCLs is the major liquefaction load. All loads were close to expected values except for the lead dewars, each of which required up to ~50 L/h of refrigeration in addition to the liquefaction required by the VCL gas flow. Acceptance tests on the leads had originally shown that they would be self-sufficient (i.e., require no extra refrigeration) at a flow rate equivalent to about 20 L/h. In the zero-current case, about half the extra refrigeration requirement resulted from the fact that the lead flow was only 10 L/h and gave insufficient vapor cooling. However, a flow-independent background load of about 27 L/h (20 W) per lead dewar has not been explained. At 10 kA, the negative JA coil lead needed an extra 6 L/h of cooling gas which resulted from an overheated joint to the room temperature buswork. The GD lead dewars performed similarly, but consistent data could not be obtained because LHe leakage through the coil power feedthroughs from the lead dewars into the coil itself affected the results. Cryogenic tests performed by Lue³ on an isolated pair of lead dewars at full current did not show the extra refrigeration requirement. Hence, the extra load must be a heat leak to the bus ducts or coils, or perhaps thermal oscillations in the lead dewar vent lines.

Coil testing began with the introduction of 330 A to the GD coil. The coil was ramped up at 1 A/s and dumped without incident. Further tests on the following day were interrupted by a major failure in the cryogenic system. Due to a slight leak in its vapor-cooled shield piping, it was necessary to pump the vacuum jacket of the 19,000-L dewar continuously. A mechanical pump, in the system failed and vacuum in the jacket began to degrade. Because of the remote location of the dewar on the building roof, this condition was not noticed by the operators until the dewar boiloff exceeded compressor capacity and inlet pressure started rising. Unfortunately, the jacket could not be repumped quickly enough and all the liquid in the dewar was lost. Because large amounts of air and water had condensed inside the dewar jacket, five days were spent repairing the pumps, warming the dewar, and repumping it. During this time the coils and facility warmed up to 30-40 K and had to be cooled back down. This incident taught us the value of control room alarms for critical parameters on remotely-located equipment.

Compressor reliability continued to be a problem during recooling of the facility. Vibration caused further leaks to appear in various pressure lines, and the loading mechanism for one compressor eventually had to be replaced. However, two weeks after the dewar vacuum failure, the coils were again cold and ready for further testing. The automatic helium fill system again worked well except for a sticking cryogenic supply valve on the bucking post. Several relief valves began leaking continuously during coil tests, evidently due to freeze damage to the seats when the valves operated. The programmable logic controller which handled the refrigerator safety interlocks also began causing frequent compressor shutdowns, which were later traced to a defective memory chip. Nevertheless, coil tests were completed in good order. Results are reported in detail elsewhere⁴.

A final series of tests designed to demonstrate the forced-flow refrigeration capabilities of the system was attempted before the coils were warmed up. Results were not conclusive because one of the main coldbox heat exchangers plugged up shortly after one-half-atmosphere operation of the ACB began, so that long-term stable operation could not be obtained. Air contamination from a faulty ACB bath burst disc appeared to be the cause. Also, helium leakage had reduced liquid helium inventory to the point where cooling of all components could not be maintained. However, the CH coil was successfully cooled below 3.8 K with a helium mass flow of over 300 g/s and a forced-flow heat load of 250 W. When an additional 500 W was added to the 4.2-K system, compressor inlet pressures began to rise, and the tests had to be terminated. The tests showed that the ACB heat exchangers were adequate for cooling the FF coils, but it was clear that many repairs and improvements to the refrigerator were necessary before the six-coil tests could begin.

Warmup of the system took nearly four weeks, as shown in Fig. 3, and was carried out by circulating helium through the facility at a temperature 50 K warmer than the coils and structure. When temperatures neared 250 K, dry air was introduced in to the tank. However, warmup over the last 50 K was very slow because of the decreasing temperature differences as the system neared room temperature. A means of supplying hotter gas will be required for the Six-Coil Test. Leak tests conducted near room temperature showed a 1.6×10^{-4} scc/s leak on the positive JA bus duct and a very large leak on the GD negative duct.

When temperatures reached the 290 to 295-K range, the tank was opened to atmosphere and the lid removed. A visual inspection turned up little damage beyond a loose wall probe on the GD coil and several cracked heat-shrink sleeves on instrument lead cables.

Several repairs and improvements were made to the refrigerator system after the Partial Array Tests were concluded. The vacuum pumping system on the 19,000-L dewar was completely reworked for greatly improved reliability. Most of the hydraulic and pneumatic instrumentation tubing on the compressors was replaced with stainless tubing to eliminate a frequent source of leakage. Additional superinsulation was installed inside the main coldbox. Cold buffer volumes were added at the turbine inlets to protect the gas bearings by preventing an overly rapid pressure decay in the turbines after a sudden compressor shutdown. Several leaks in the cryopiping vacuum jackets were repaired. Many leaks in the room-temperature subatmospheric He piping were also eliminated. The leaking relief valves and burst discs were replaced with more reliable items. Instrumentation improvements included LHe vapor bulb thermometers on turbine T2, new mass flowmeters on the compressor low and medium pressure return lines, and new temperature sensors in the main cold box and ACB. Analysis of the refrigerator operating data also suggested some modified operating methods which promised to improve performance. In particular, minimizing the pressure drop across the FF coils during standby operation showed prospects for improved standby liquefaction rates. Calculations were carried out to determine the available coil testing time per week for various values of the LHe depletion rate during testing and recovery rate during standby. To assess the effects of all this work on the refrigerator system, another test of the refrigerator alone was carried out during April-June 1985.

Figure 4 is a simplified schematic diagram showing only the equipment included in the Refrigerator Test. The heat loads and pressure drops of the FF coils were respectively simulated by heaters H1, H2, and H3, and valves V1, V2, and V3 in the ACB circuits. Heater H4 in the 2000-L dewar simulated the refrigeration loads of the PB coils, 19,000-L dewar, and bucking post. A new piece of equipment, the VCL simulator, was added to simulate lead liquefaction loads. This was merely a large dewar continuously fed with 1-bar liquid from the 2000-L dewar. The liquid was boiled off by heater H5, and the cold gas passed through four parallel coils of copper tubing in a circulating water bath fed by water heater H6. The resulting warm gas was passed through a flowmeter to measure the liquefaction load and expanded through valve V5 into the 0.5-bar compressor inlet.

Figure 4. Schematic of refrigerator test.

The test procedure was set up to reflect operation of the actual facility in full six-coil tests. The system was cleaned up in the same way as for the Partial Array Test. The entire system was cooled to LHe temperature in less than two days, owing to the relatively small thermal mass involved. The 2000-L dewar, ACB, and VCL simulator were then filled approximately half full with LHe. Filling the ACB bath was simplified by temporarily removing the high-pressure flow (and its associated heat load) from the exchangers and bypassing it directly to the turbines via a valve in the main cold box. After the vessels were filled, liquid flow from the J-T valve was shifted completely to the 2000-L dewar. Flow was then gradually increased to 300 g/s in the FF circuits, the bath pressure in the ACB was slowly reduced, and power was gradually applied to the various heaters until the desired values were obtained. Finally, the level in the 2000-L dewar was stabilized by adjusting the inlet valve to the VCL simulator. Liquefaction rates were determined by converting the VCL simulator gas flow to an equivalent liquefaction rate and adding any residual level change rates in the 2000-L dewar and VCL simulator. For a given set of test conditions, roughly 4 h were required to attain stable operation, and the conditions were then maintained for roughly 8 h.

Table 2 summarizes the estimated refrigeration power and liquefaction rates required by the IFSMTF. Each of the coils has a certain estimated heat load in standby mode (zero current), background mode (90% current), and test mode (110% current with pulsed external field). During coil tests, one coil is in test mode and the other five in background. The total heat load during coil tests increases considerably due to joint dissipation and ac heating from the pulsed field. Liquefaction loads similarly increase during test due to the extra cooling required by the leads. Fixed heat loads from the various cryogenic vessels, transfer lines, and facility structure are also shown in Table 2. Finally, the extra lead dewar refrigeration load observed during the Partial Array Test must be considered. This load is entered in parentheses because it is not clear whether it will appear for all 12 dewars. In addition to the loads shown in Table 2, there is also a refrigeration load on the ACB of about 1000 W which is associated with the cooling and expansion of the 15-bar, 4.5-K stream to roughly 12 bar and 3.8 K before entering the final FF coil. This load was automatically included by setting the valves V1, V2, and V3 to give the required pressure drop through the ACB FF circuit.

The refrigerator test results are summarized in Table 3 and Fig. 5. The values for heater H4 include an additional 180 W to account for heat leaks in the 4.2-K vapor return lines, plus a deduction of 44 W to account for cryogenic lines which were already included in the test circuit. The liquefaction rates available under the various test loads ranged from 200

Table 2. Estimated IFSMTF Heat Loads

<u>Refrigeration:</u>		
Coils - Standby	-	300 W
Coils - Test	-	400-500 W
4.2 K Background	-	220 W
3.8 K Background	-	50 W
(Lead Dewars)	-	(300 W-400 W)
<u>Liquefaction:</u>		
VCL's - Standby	-	220 L/h
VCL's - Test	-	300 L/h
Total Load - Standby	-	220 L/h + 570 W
Total Load - Test	-	300 L/h + 770 W

Figure 5.

Measured refrigeration rate vs liquefaction rate.

L/h to 335 L/h. Tests 1 and 2 show that with similar refrigeration heat loads, T2 did not contribute very much to the liquefaction rate. The low efficiencies (40%) previously observed for T2 were confirmed by the vapor bulb thermometers. Comparison of tests 2 and 3 shows that performance is not very sensitive to whether the heat is added to the ACB via H1 and H2, or returned entirely to the turbines from H3. The large H4 load used in test 4 reflects the extra 400 W of refrigeration which might be required by the lead dewars. In this worst-case situation, the maximum liquefaction deficit would be 100 L/h, assuming the VCLs need 300 L/h during testing. On the other hand, tests 1-3 show that during standby, excess liquefaction of over 100 L/h should be available to reliquefy the helium boiled off during testing. Test 5 was a check on the ability of the system to meet its specified design loads. Under the applied refrigeration loads, the design liquefaction rate was 170 L/h, whereas the actual production was 255 L/h. The only major shortcoming in system performance was an excessive flow rate in the low-pressure return circuits which overloaded the low-pressure compressor stages and prevented reaching pressures below about 0.6 bar in the ACB bath. This would raise the FF supply temperature by 0.2 K and reduce the stability margin of the FF coils.

CONCLUSION

The foregoing tests give confidence that the basic design of the IFSMTF refrigerator is adequate for the requirements of the facility. However, several deficiencies in operation still need to be corrected. A booster compressor is being considered to achieve the desired 0.5 bar in the ACB bath. Problems were encountered with increasing pressure drop in the helium purifier which seem to result from oil carryover from the compressors. An extra oil demister is being added, and a larger purifier

Table 3. Refrigerator Test Results

Test	Description	H1(W)	H2(W)	H3(W)	H4(W)	Liq. Rate(L/h)
0	Refrigeration	425	425	210	425	-
1	Standby w/o T2			190	505	325
2	Standby w/ T2			190	495	335
3	Standby	75	70	65	505	315
3a	Standby	105	125	65	705	255
4	EU Test	105	125	65	930	200
5	Design Loads	55	180	60	505	255
6	CH Test	80	60	190	545	275
7	W Test, 3.8 K	130	35	115	545	260
7a	W Test, 4.2 K	130	35	115	545	270
8	PB Test	85	30	120	650	245
9	Low Refrigeration	55	55		210	345
9a	Liquefaction					365
9a'	Liquefaction					400

heat exchanger is under consideration. Two compressor shutdowns were caused by oil supply line breakage due to vibration, and more flexible lines with better supports are being installed. Several more automatic controls and interlocks are being added to simplify operation and increase protection. Finally, an additional 60 L/h laboratory liquefier system is being installed to supplement the output of the main refrigerator.

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