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OPERATIONAL HISTORY OF FERMILAB'S 1500 W REFRIGERATOR USED FOR ENERGY SAVER MAGNET PRODUCTION TESTING*

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ABSTRACT

The 1500 W helium refrigerator system utilizes two oil-injected screw compressors staged to feed a liquid nitrogen pre-cooled cold box. Refrigeration is provided by two Sulzer TGL-22 magnetic/gas bearing turbines. The refrigerator feeds six magnet test stands via a 10,000 L dewar and subcooler equipped distribution box. The design of the controls has permitted the system to be routinely operated 24 hours/day, seven days/week with only five operators. It has operated approximately 90% of the 4 1/2 years prior to shutting down in 1984 for a period of one year to move the compressor skid. Scheduled maintenance, failures, repairs and holidays are about equal to the 10% off time. The equipment described was used to test approximately 1200 superconducting magnets for the Fermilab accelerator ring. The seven year operating experience is presented as an equipment and technique review. Compressor hours currently exceed 42,000 and turbine hours exceed 39,000 each. Failure rates, causes, preventive maintenance, monitoring practices and equipment, and modifications are examined along with notes on some of the more successful applications of technique and equipment.

INTRODUCTION

The Magnet Development and Test Facility's 1500 W Helium Refrigerator System consists of the following subsystems: compressor skid, cold box, 10,000 L dewar, distribution box, magnet test stands (6), quench tanks, purifiers, buffer tank (113.2 cu meters), low pressure helium recovery system, LN_2 trailers (2), and support utilities, including: vacuum equipment, cooling towers (3), compressed air system, and turbine water chiller system.

The refrigerator was commissioned in October 1977. It was initially connected directly to a single test stand. Magnet cooling was difficult to control until a 10,000 L dewar was added between the refrigerator and the magnet test system. The dewar minimizes the load changes which the refrigerator sees. By July of 1978, the distribution box was added, equipped with both helium and nitrogen subcoolers. It had provisions for feeding cryogens to six test stands which were added shortly thereafter.

While this enabled cooling other magnets for test, actual tests were limited to a single stand at a time until mid-1981, when a second power supply and measuring apparatus doubled this potential.

1979 brought two quench tanks (3.8 cu meters each) to absorb the sudden bursts of boil-off helium generated by large superconducting magnets going "normal" at their current limits. By this time, the testing operations had become a round-the-clock, seven-day-week effort; the tanks served to aid recovery time, reduce helium losses, and lessen the risk of surge-induced compressor shutdowns.

By 1981, the cryogenic operating crew for the 1500 W had grown to five operators who covered the three shifts. During this period, magnet throughput had increased greatly from one or two per week to a peak of more than twenty. During the final three years of high production, refrigerator downtime, including holidays and maintenance, accounted for about 10% of the total. Typical training time for operating and maintanence skills ranged from four to six months to achieve independent operating capability.

After a check run in April of 1984, following heat exchanger repairs, the refrigerator remained down for a year. During this time the entire skid, including the concrete floor pad, was raised and moved to a new location. At this writing, operations have resumed with total compressor hours exceeding 42,000 on each stage, and total turbine hours well over 40,000 and 39,000 on first and second turbine positions, respectively.

COMPRESSOR SKID

The skid was originally designed as an outdoor unit but two oil pumps and six shear pin failures due to cold oil, and a November change of a failed motor quickly convinced us that an enclosure would be beneficial. After a year under a tent, the skid received its own permanent shed late in 1978.

The skid holds two Sullair oil-injected C25L screw compressors of 2905 cu meter/hr. displacement, in a high and low stage configuration with 3.7:1 and 2.6:1 compression ratios, respectively. There have been two compressor failures, both on the high stage. One, in August 1980, was caused by incorrect assembly of the flex coupling to the motor. This prevented the coupling from flexing properly, causing the drive rotor to be pulled into the compressor casting wall, destroying the unit. The second failure was strictly a bearing failure, discovered during a shaft seal change, and was not permitted to run to catastrophic failure.

The compressors are driven by 480 V.A.C three phase motors of 746 kW and 149.2 kW ratings, high and low stages respectively. Motor-compressor couplings consist of a floating hub, interfaced on both sides to driving and driven units by stacked leaf packages which take up starting shock and misalignment. When properly assembled, they have proven quite reliable, despite the fact that the motors have no "soft" start arrangement.

The majority of motor failures have been bearing oriented, with perhaps one being related to overheating of windings. The first bearing failures are believed to be due to improper lubrication; later ones are believed to be connected with fit tolerances between replacement bearing and motor end shields. The six motor failures are evenly divided between the high and low stages. The last occurred in December of 1980. We have logged some 26,000 hours since then with no motor problems.

A major concern with the skid has been progressive vibration induced damage. Concrete was poured between the skid framing members in an effort to reduce vibration, but helped less than expected. More success was obtained by regular monitoring of vibrations, and adjusting compressor operating points to minimize vibrations. Several potentially severe failures were detected in the rotating components at an early enough stage to permit replacement before additional components were damaged.

Early monitoring was done with a probe type accelerometer which required time consuming r.p.m. synchronization with a stobe unit. An improvement on this was the vibration signature recorder, which is easier and quicker as it requires no synchronization. It also produces a trace on a paper card of vibration levels across a wide frequency range. Taking sets of readings regularly at critical locations produces not only a picture of the rate of deterioration, but also after analysis gives a fair idea of the nature of the failure. This gives time to order parts and schedule maintenance into the test program. A continuous monitoring system was later purchased with sensors for each of the critical points. However, the nature of the system necessitated mounting the amplifier cans on parts of the skid. Heat and vibration caused deterioration, and false signals began to trigger alarms often enough to require that the device be disabled. From that point the signature recorder has been used exclusively.

Two oil coolers and an aftercooler exchange heat with an external closed circuit water/glycol system incorporating three air cooling towers. Obtained from surplus, these towers were designed for optimum performance at higher entry and exit temperatures than our compressor parameters permit. As a result, full compressor loading at the higher pressure ranges becomes impractical in the summer months, and operators plan maximum cooling loads for night and early morning, as much as possible.

The gas management valve manifolding is located after the final filter to avoid fouling the valve trim with oil and charcoal dust. It is electronically controlled and pneumatically operated, with I/P faces mounted inside the skid instrument cabinet.

CONTAMINATION MANAGEMENT

Oil removal on the skid is achieved with a combination of a bulk oil separator after each stage, a mist separator, two demisters, three in-line high pressure filters, a charcoal filter, and a final filter. The in-line filters and modifications to demisters and piping are not original, and were added to solve an oil carryover problem which contributed to early cold-box damage. These modifications and their effects are more fully described in a paper entitled Oil Removal from Helium at the Fermilab 1500 W Refrigerator.[1]

Several methods of oil detection have been tried. One which we have found most satisfactory involves exposing a coated slide to a jet of process gas in an apparatus which mounts at any of several sample points on the compressor. Slides are compared to a standard under an ultraviolet light to yield an approximate oil contamination level. Although the method has limited accuracy, it has proven suitable for our purpose and the equipment is easy to use. In an attempt to dispense with rounds of sample taking and subjective comparisons, continuous sampling aerosol monitors were installed in the piping at two positions. Initial operation was very good, but within four months, the system began to fail. After some attempts at servicing, the heads were completely removed by mid-1982, and the slides were back in use.

Water contamination has been successfully monitored with a rack-mounted hygrometer unit which reads any of six heads installed at selected locations. Although requiring the use of a nomograph to convert to p.p.m., the unit has performed reliably with a minimum of attention.

Gaseous contaminants, for our purposes, divide themselves into two categories: gases removable in a nitrogen bath purifier, i.e. the major constituents of air, and gases which penetrate to some colder parts of the machine before condensing out, primarily neon and hydrogen.

Monitoring is done with a spectrographic detector developed by R. Walker.[2] The device is essentially a bulb with two electrodes with high voltage between them, through which the sample gas is run. The resulting arc spectra are viewed by a monochromator tuned to a particular wavelength, and the signal is fed into a chart recorder. This device is in continuous use whenever the compressors are on. It is typically tuned for nitrogen to detect air contamination, but can quickly be dialed to other frequencies to check for other gases such as neon or hydrogen. A multi-valved switching manifold is used to sample various points in the system, as well as two calibration gas sources. The detector is easy to use and requires minimal maintenance, but is sensitive mechanically and should be protected. It is most stable when run continuously and should be calibrated at least once a day.

Two liquid nitrogen bath purifiers are piped to a switching manifold which enables them to be run independently, in parallel, or in series with each other, as well as selecting output and source points, to and from the system. All makeup helium is now "scrubbed" through purifiers to the process system, regardless of sampled purity.

Gases with normal boiling points below 77 K are not trapped in the purifiers. Neon, and sometimes hydrogen build up in colder (7-14 K) sections of the machine, most notably the second turbine. This slows the turbine speed with a corresponding loss of efficiency. This condition can be reversed with no noticeable damage to the turbine by shutting down and isolating the turbine, and allowing it to warm. The trapped gas is then vented. Monitoring usually reveals this gas to be rich in neon (sometimes > 1000 p.p.m.). The turbine is repressurized with clean gas and bled again. The cycle is repeated until gas comes out clean, then the turbine is restarted. Performance differences of 600-700 r.p.s. are not uncommon.[3]

COLD BOX

The cold box consists of a train of five brazed aluminum, plate and fin type heat exchangers, two Sulzer TGL-22 magnetic/gas bearing turbo-expanders, a 190 L internal dewar, turbine inlet filter vessels, and internal valves & piping enclosed in a superinsulated carbon-steel vacuum vessel. Initial vacuum is established by a 15 cm diffusion pump and improves quickly with cryopumping to about 10^{-5} Pa.

Turbines and heat exchangers are arranged in a dual return pressure, pre-cooled Collins cycle with return pressures of 2.6 atm. and 1.05 atm.

High pressure helium at 10 to 15 atm. enters HX-1, a four stream exchanger, giving up heat to both helium return streams as well as receiving LN_2 precooling from the fourth stream. Additional LN_2 precooling occurs in a two stream exchanger, HX-RC. HX-RC was originally piped as an auxiliary cooldown circuit. In June 1978, the piping was modified so that HX-RC is in series with high pressure and LN_2 passes of HX-1. This was done to compensate for surface area lost in HX-1 when damaged passes were repaired. HX-2 and HX-3 are three stream helium exchangers containing the return stream from the larger first turbine. HX-4 and HX-5 are two steam exchangers with only the high and low pressure streams. Joule-Thompson valves are positioned after HX-5; one discharges into the 10,000 L dewar, the other to the low pressure return stream.

Refrigeration rate is largely regulated by compressor discharge pressure and the first turbine inlet pressure. The second turbine inlet valve is normally run fully open. First turbine temperature is regulated by a bypass around turbine 2. LN_2 precooling is now regulated by HX-1 medium pressure exit temperature; earlier attempts to regulate by the LN_2 exhaust temperatures lacked stability.

The cold box repair history centers mainly on HX-1 and HX-RC heat exchanger failures and turbine cartridge failures.

Early in 1978, a bad vacuum in the cold box was discovered to have been caused by gas escaping through a cracked end parting plate of HX-1. Inspection revealed additional passes to have been damaged, but only the LN_2 and high pressure helium passes were involved. The repair required isolating damaged passes at headers by welding them closed and venting the isolated passages by drilling to a low pressure pass. (In some cases this was the low pressure return helium; in others, the LN_2 pass.) The cold box manufacturer considered this damage critical enough to perform the rerouting of the HX-RC piping mentioned earlier, in June 1978.

The cause of the failure was believed to have been expanding gas trapped between two ice plugs in the passes. HX-1 sees entering gas first, and therefore becomes a condenser trap for impurities in the process stream which are condensible at 77 K. Unlike the other LN_2 cooled exchanger HX-RC, it also sees cold helium return streams. Under certain error conditions, return helium streams can unbalance the exchanger so that N_2 could solidify in the LN_2 passes. The nature of the plugs is a bit unclear, as water, oil, and later freon have been removed from that area. In August 1978, an N_2 alarm was added to the spectrographic detector. Freon was used to wash out oil, discovered in November 1979, but proved nearly as hard to remove completely as the oil, possibly contributing to a later failure. Although the oil removal problem on the compressor skid has been solved, some evidence exists that there are traces of oil, freon and water still in the box. Startup procedures allow for this, requiring that contaminants be thermally immobilized before allowing flow through the process stream.

During the November 1979 maintenance, HX-RC support bars were found to be starting cracks from incorrect mounting. This was repaired and mounting was corrected. Drain lines were installed at low points in the high pressure piping beneath HX-1 and HX-RC; HX-2 was fitted for a similar tap which was capped. Drilling at these points released, respectively: 3 L of oil/water/freon mix, 2 L oil, and nothing from beneath HX-2.

In February 1982, a test stand plumbing error introduced massive N_2 contamination to the system, resulting in an HX-1 blockage but no apparent damage. A similar error in August produced the same result except that drain lines could not cleared until the box was warmed to nearly room temperature. Significant amounts of water were drained when the passages cleared. By late October 1982, helium detected in LN_2 exhaust vent samples suggested that there was some additional HX-1 damage. It was decided that the size of the leak did not merit a teardown at that point, as we had entered a high production period. To reduce losses and prevent further damage, compressor discharge was held low (around 10 atm.). An interlocked N_2 exhaust vent valve was added to prevent backflow of contaminants, particularly water, during shutdowns.

In March 1984, the cold box was opened and HX-1 repairs similar to those of 1978 were performed. The heat exchanger manufacturer made the recommendation that the rate of cooldown be slowed on startups to lessen the chance of failure due to contraction differences. This recommendation was incorporated into operational procedures. Test runs in April that year and shakedown runs in 1985 show the leaks to have been fixed with little noticeable loss in efficiency.

TURBINES

Turbines originally supplied with the cold box were designed to be supplied with startup bearing gas. In March 1979, the machine and interlock program were modified and the turbine cartridges converted to a new model featuring a magnetically preloaded startup bearing requiring no externally suppied bearing gas. After some initial problems with preload adjustment, the new style cartridge performed well.

Turbines are protected from backpressure reversing by check valves at the exits. Turbine warmup circuits are orificed to prevent unintentional spinning. Additional protection is supplied by sequencer interlocks which will not grant a "permit" to the turbine inlet valve unless a proper configuration of interlocked conditions is satisfied. Violation of these conditions while running will shut down the turbine.

Inlet valve plugs for both turbines were modified to improve metering but the second turbine inlet valve might have better been sized about 13 mm instead of 25 mm as originally installed.

In our experience, there appear to be four main causes for a turbine failure: sudden pressure changes, overspeed, operation outside turbine pressure/temperature parameters, and contamination.

Sudden pressure changes on upstream, downstream or brake circuit can unbalance the thrust bearing loads, cause the bearing to touch at high speed (~ 3000 r.p.s.), and destruct. Turbine brake circuits operate on process gas which enters along the shaft. Pressure change rates exceeding that entry rate can result in imbalancing the thrust bearing to the point at which it sustains damage, often accompanied by journal bearing damage as well. It is believed that the majority of our turbine failures are from this cause. Turbine starting procedures require brake valves to be restricted to allow the brake circuit to respond to process pressure increases more quickly.

Overspeed exceeds the limits of dynamic balance accuracy, causing instability and resultant high speed wall collision damage. The first of our turbine failures was from this cause, due to a speed sensor defect. Starting procedure was changed to guard against this.

Operating outside pressure/temperature limits puts forces on the turbine that the density of the bearing gas will not support, resulting in bearing damage.

Contamination damage depends on the form the contaminant takes on entry to the turbine. Condensate plating of surfaces in moderate amounts slows a turbine down without noticeable damage, and can be reversed by warming and purging. Neon has been observed to have this effect on our second turbine.[3] Operating procedures for the refrigerator call for turbines to be shut down when nitrogen contamination exceeds 3 p.p.m. on a cold refrigerator for more than 30 min., so our knowledge of actual nitrogen-produced turbine damage is limited to hearsay. It has been suggested that when frozen nitrogen takes the form of loose crystals or flakes, the damage produced on turbine blades may be similar to a sandblasting effect. To date, we have observed no such damage on our own units.

The typical bearing failure pattern begins with difficult starting requiring extra tries (a single try involves opening the inlet valve enough for the turbine pressure to rise and observing the speed indicator; if no speed registers, the valve is closed). Starting becomes progressively harder, until the turbine finally refuses to start at all. Post mortems by the manufacturer usually reveal a damaged thrust bearing and on at least one occasion, journal bearing and blade damage was also found.

One unusual failure was observed during the shakedown run on a new turbine cartridge. The turbine would start and run normally until cooled nearly to operating temperature, then stop dead, with a distinctly audible squeaking sound. After warming, the turbine restarted with similar results. It was suggested, but not confirmed, that contraction tolerances might have been inadequate on that particular unit.

THE 10,000 L DEWAR

The dewar is used as a storage and interface device. Cold box J.T. valving causes the downstream flow to vary. The dewar absorbs this, controlling its own pressure by returning excess pressure from vapor space back to the cold box return. This allows precisely controlled feed pressure from the dewar to the distribution box and magnets. Early procedures for shutdown called for depressurizing cold box piping. Backflow through a leaking J.T. valve caused ice buildup and, on two occasions, solid plugging. Removal of the plug was accomplished once with a little extra pressure, but a more stubborn case required rigging a "gas hammer" out of a helium pressure source, a 3-way solenoid valve, and a switching circuit to cycle and vent the solenoid. Operating procedures were changed to keep pressure in the cold box piping and the problem has not recurred. A second problem was a vacuum leak which caused the dewar to empty itself over a weekend in January 1979. The leak was repaired by welding; the dewar was pumped down again and made operational.

DISTRIBUTION BOX

The distribution box is vacuum insulated and fitted with subcoolers for both helium and nitrogen. It serves as the cryogenic switchyard of the system, feeding cryogens to each of five (formerly six) superconducting magnet test stands. Each stand requires three transfer lines: supply and return helium and LN_2 supply. Accordingly, the box is constructed with valved bayonet insertions for eighteen transfer lines.

Two phase helium return flow feeds the bath subcooling the one phase liquid helium supply. Early efforts to obtain more cooling for the dual testing system were hampered by rising pressure over the bath caused by the increased return flow. In September 1981, the addition of a dual return transfer line accommodated the extra flow and dropped the pressure over the bath to required levels.

Bursts of pressure caused by magnet "quenching" disturbed the subcooler seriously in early operations. Two solutions were attempted. The supply valves were interlocked to quench sensing electronics and tripped shut when the magnet quenched. An alternative solution placed check valves in the supply transfer lines. The first was largely ineffective due to the slow response time of the pneumatic valve actuator; the second one worked fairly well. Due to the normal direction of flow in the return line, little could be easily done to help there. Having a second magnet stand on line was found to aid subcooler recovery significantly.

QUENCH/RECOVERY SYSTEM

Magnet quench pressure surges are vented through high flow, quick acting valves to two 3.8 cu meter tanks acting as an intermediate volume to protect the first stage compressor from tripping off on intake surges. Return flow is restricted through a 13 mm line.

These tanks also serve as a collection point for vented boil-off from the 10,000 L dewar during shutdowns. A small compressor pushes this gas through a purifier and stores it in the large (113.2 cu meter) system buffer/storage tank. The gas recovery compressor is interlocked to trip off as the buffer reaches 10 atm. Typical shutdown pressure in the buffer is about 5 atm. The recovery system will boost this to the trip point of 10 atm. over about three day's time. Further boil-off is lost through reliefs.

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