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Selection of Cold Compressors for the Fermilab Tevatron

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SELECTION OF COLD COMPRESSORS

FOR THE FERMILAB TEVATRON

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ABSTRACT

This paper discusses performance of a final prototype cold compressor and the specification and purchase of production units for the Fermilab Tevatron. Cold helium vapor compressors will be added to the satellite refrigeration system in order to operate the accelerator at higher beam energy. A final machine specification emerged from extensive prototype testing in actual Tevatron refrigerators. These tests resulted in a decision to use high speed turbomachines instead of reciprocating units. The choice was based on performance, size, maintenance requirements, and reliability. IHI Co., Ltd. was selected to provide a final prototype centrifugal machine. Thermodynamic as well as mechanical performance of this unit is described.

Satisfactory performance of our final prototype enabled us to solicit bids for the full 27 unit order. Cryostat details differ from the prototype although the performance specification is identical. IHI received the order and has delivered all machines. A brief description of the design, purchase, and acceptance testing of these units is given.

INTRODUCTION

The Tevatron low temperature/high energy upgrade consists primarily of replacement of the refrigerator controls system and the addition of cold compressors to reduce the operating pressure of the magnet strings[1,2]. This pressure reduction takes place in the two phase flow passages, causing a corresponding reduction in temperature. Lower operating temperatures allow the superconducting magnets to carry higher currents without quenching. This generates higher magnetic fields which are capable of directing higher energy particle beams. A pressure reduction in the two phase circuits from the current

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operating value of about 135 kPa (slightly above atmospheric) to about 50 kPa (1/2 atmosphere) should allow a maximum increase in beam energy of about 22%.

Prototype tests[3,4] helped to define our performance specification, outlined in Table 1. With a firm specification in hand, we prepared for the purchase of two final prototypes. A contract for a high speed centrifugal machine was competitively awarded to IHI Co., Ltd. of Japan while a two cylinder reciprocating machine was fabricated in-house using components purchased from CCI Cryogenics. The design and performance of the reciprocating unit is described elsewhere.[5] This paper will discuss performance of the IHI prototype and the rationale for selecting centrifugal compressors over reciprocating machines. The latter issue is developed by an exploration of several determining criteria including size, maintenance, and reliability. Chief among these is size, since our refrigerator buildings allow very little room for additional equipment. For this reason a small package is required to maintain a safe working environment which provides adequate access and escape routs in the event of cryogenic or other emergencies. The reciprocating unit was physically too big for the buildings. Additional concerns include a recip's regular maintenance requirements (compared to a turbomachine's essentially nonexistent mechanical needs), the projected likelihood of breakdown, and the relative ease of replacement in the event of a compressor failure.

IHI Co., Ltd. was competitively awarded a contract to supply 27 centrifugal cold compressors (24 installed units plus three spares) with performance specifications equal to the prototype. The production units differ from the prototype in several peripheral areas including cryostat design, motor cooling, and controls. Certain details of these production units are presented later.

DESIGN

The IHI cold helium vapor compressor is a high speed, gas bearing turbomachine. Table 1 shows the operating specification while Figure 1 shows the unit as installed. Inlet and outlet conditions as well as flow rate were specified by Fermilab. IHI designed the unit around a high speed induction motor housed in a barrel type, water cooled stainless steel

Table 1. Specification for Fermilab Tevatron Cold Helium Vapor Compressors

	Normal Operation	Off-Design Operation	Standby
Inlet Condition			
Pressure	50.7 kPa (0.5 atm)	40.5–81.1 kPa (0.4–0.8 atm)	141.9 kPa (1.4 atm)
Temperature	sat. vap. (3.56 K)	sat. vap. (3.38–3.99 K)	sat. vap. (4.60 K)
Outlet Condition			
Pressure	141.9 kPa (1.4 atm)	141.9 kPa (1.4 atm)	
Flow Rate	60 g/s	40–70 g/s	55 g/s
Rated Speed (approximate)	80,000 rpm	40,000 rpm min. 95,000 rpm max.	0 rpm
Minimum Efficiency	60%	60%	

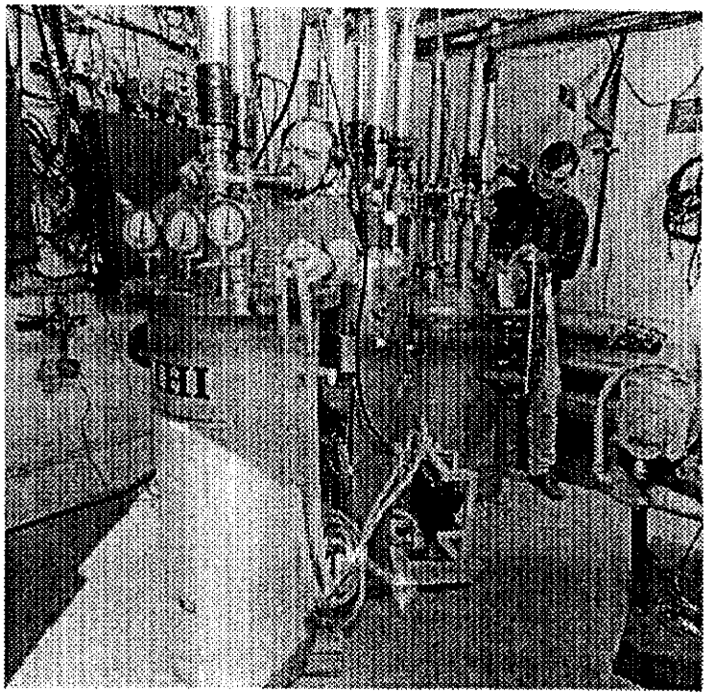

Figure 1: Installation of the prototype IHI cold helium vapor compressor in a Fermi test refrigerator. The compressor is in the foreground, with the phase separator dewar and associated plumbing in the background. The cooling water pump is visible on the floor.

casing. The overhung impeller is shroudless and fabricated as an aluminum precision casting. Journal and thrust bearings are foil–type self acting (dynamic) gas bearings. Foil bearings were developed and patented by Hamilton Standard for use in air cycle machines on aircraft.[6] The IHI foils do not establish a lubricating gas film until the shaft reaches an appropriate speed. IHI therefore specifies a minimum operating speed of 40 krpm; there is shaft–to–foil contact during startup and shutdown. This characteristic is also described in reference [6], together with reliability data. The Hamilton Standard information strengthens our confidence in the foil bearing concept. We expect similar reliability from the IHI foils since the design is similar. IHI predicts high reliability, although they do not have performance data to support this prediction.

The vacuum cryostat is a free standing, stainless steel design with an O–ring sealed top flange supporting the compressor and piping. Inlet and outlet bayonet connections were supplied by Fermilab. The compressor is relieved at 686 kPa (85 psig). Instrumentation consists of inlet and outlet pressure taps and carbon resistor thermometers as well as an inlet vapor pressure thermometer. Motor cooling is supplied by a 10 L/min circulating water pump.

The controller contains a Toshiba variable frequency inverter which powers the induction motor. Local and remote start/stop/reset is available, as is a local/remote switch and an hour meter. Remote operation takes place via the Fermilab ACNET control system, which monitors and controls all Tevatron functions including refrigerator operations. Remote readbacks are provided for local/remote status, trip status, and speed. Speed is derived from inverter frequency and does not represent actual shaft revolution. This implies a slight mismatch between reported speed (inverter frequency) and actual speed due to the slip inherent in the drive. However, this error is small and consistent so there is no interference with speed settings or automatic loop control. The compressor is expected to regulate its speed based on its intake pressure. This control is carried out by a PID control loop resident in the ACNET control system. The controller can regulate compressor speeds to an accuracy of 1% of full speed.

PERFORMANCE

Figure 2 plots isentropic efficiency against mass flow rate while Figure 3 plots efficiency against compressor pressure ratio. In both cases the efficiency includes the effect of static heat leak, measured to be 28 watts. Efficiencies in the 60 to mid–70% range are shown. Notice also the relatively flat curve over a wide flow rate range. This demonstrates good turn–down capability and provides us with acceptable compressor efficiency even at low flow rate, off–design conditions. We were unable to achieve the highest pressure ratios required by our design criteria due to an unusually high discharge pressure in our test refrigerator which threatened to open a relief valve in the compressor discharge line. However, at required flow rates, the unit achieved the highest obtainable pressure ratios

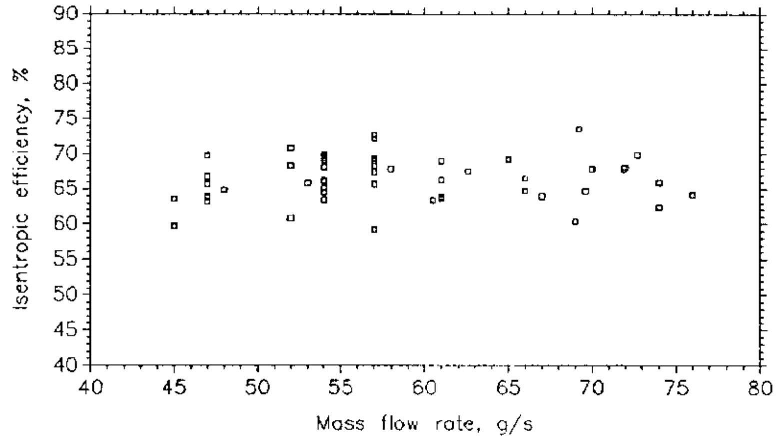

Figure 2: IHI efficiency data plotted against compressor mass flow rate. Efficiency calculation includes the impact of static heat leak, measured at 28 watts. Pressure ratios range from 1.3 to 2.9, with compressor speeds ranging from 40 to 90 krpm.

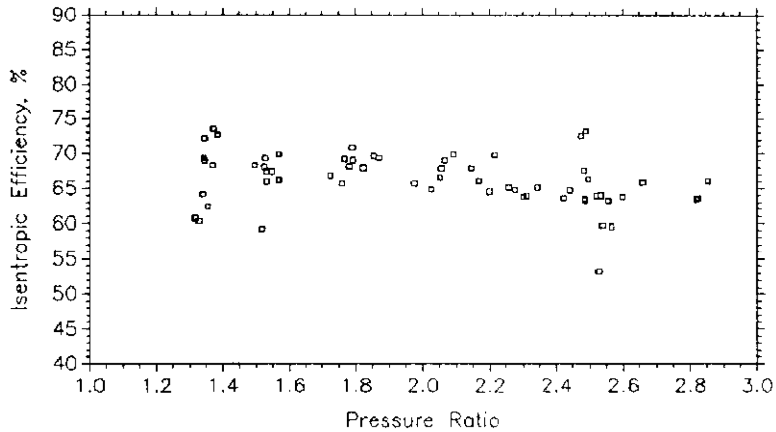

Figure 3: IHI efficiency data plotted against compressor pressure ratio. Efficiency data includes the impact of static heat leak, measured at 28 watts. Mass flow rates range from 45 to 75 g/s, with compressor speeds ranging from 40 to 90 krpm.

without reaching maximum speed. Thus higher ratios would have been achievable had our test setup permitted them.

This prototype compressor was supplied to Fermilab at the end of December, 1990. It was operated without incident for about 2000 hours between then and October, 1991. During this time several operational modes were tried, including bypass mode (unit off and helium vapor flowing through the unit) and calibration mode (unit off and two-phase helium flowing through the unit to calibrate the thermometry). The unit was observed during surge on one occasion. Surge is the condition where a centrifugal compressor passes insufficient mass flow to maintain a given pressure ratio. The result is a periodic backstreaming of flow through the unit accompanied by a drop in discharge pressure and a rise in suction pressure. After the back flow, the unit attempts to re-establish the pressure ratio until surge again takes place. The unit was observed in surge for several cycles before conditions were altered to eliminate the phenomenon. No damage or adverse impact on performance was recorded.

The compressor is designed to pump saturated or superheated vapor. Inhalation of liquid or two phase flow is to be avoided – the shock of liquid impinging on the impeller can overburden the journal and thrust bearings and destroy the machine. This IHI unit has proven remarkably resilient to liquid ingestion, having been hit with liquid on at least a dozen occasions over approximately 2000 hours of service. These events occur when the phase separator dewar upstream of the compressor overflows due to a controls or instrumentation failure. In each case the unit trips off on "inverter fault." This indicates that the motor drew unacceptably high current, probably due to the increased torque required to turn the rotor/impeller in the presence of liquid. The unit was able to be restarted on every occasion. We are impressed with the durability of the IHI compressor and attribute this quality to the foil bearings.

In mid-October 1991 we were unable to restart the compressor after it had tripped off due to liquid ingestion. On the first attempt at restart, the unit accelerated up to 20 krpm, at which time a loud percussive sound was heard followed by a periodic scraping noise accompanied by high current draw. The unit was shut down and IHI was contacted. At their suggestion several additional restarts were attempted, some of which were successful, some of which mimicked the initial event. Upon shutdown after the successful restarts, however, loud percussive noises were heard as the unit decelerated. The compressor was taken out of service and returned to IHI. During disassembly of the unit, IHI technicians found a 1 cm long metal chip in the exhaust volute. Failure was attributed to the ingestion of this chip rather than ingestion of liquid. The impeller shroud needed to be re-polished and all bearings required replacement. The chip was determined to have come from the IHI compressor cryostat itself. After repair, the unit was returned to Fermilab where it once again functioned normally and with performance equal to that originally seen. No other failures have been recorded.

PRODUCTION MODELS

We were sufficiently satisfied with the IHI prototype centrifugal compressor that a decision was made to solicit bids for a ring's worth of centrifugal units. This amounts to one compressor for each of 24 Tevatron satellite refrigerators, plus three spare units and spare parts. Our decision to select centrifugal machines was influenced by the satisfactory performance of the IHI unit combined with it's small size and relatively low maintenance characteristic. We ultimately decided that the satellite refrigerator buildings were too small to house a reciprocating compressor along with the equipment already installed. Therefore, installation of recips would have meant prohibitively expensive building modifications given the centrifugal alternative. Bids for 27 centrifugal cold compressors plus spare parts (ten sets of bearings, two rotor/shafts, and two impellers) were solicited, with IHI receiving the contract.

The production compressor is shown in Figure 4. The operating specification is identical to the prototype. Differences include fan forced air cooling instead of water cooling and a different vacuum cryostat. While the prototype was free standing, the production models are housed in a small pod with bayonet connections extending out of the bottom. The compressors will mount directly on top of the satellite refrigerator's valve box (the component that houses the phase separator and joins the refrigerator to the magnets below ground). Production controllers are similar in function to the prototype controller although they are physically smaller and utilize programmable logic control in instead of relay logic.

All production units have been delivered, inspected, checked out, and accepted. Acceptance was based on visual inspection as well as trial operation on ambient temperature air. Each unit and controller was powered and run for several hours to verify operation and control function. Thermodynamic and vibration measurements were taken to allow us to recognize any potential problems. All machines exhibited roughly the same thermodynamic performance, although a few units showed somewhat higher vibration than "normal." We will watch these units carefully when operations commence. IHI has not expressed concerns over these vibration signatures.

CONCLUSION

Fermilab purchased and tested a prototype centrifugal cold helium vapor compressor. The unit was supplied by IHI Co., Ltd. of Japan. The unit is designed to pump 60 g/s of 3.6 K saturated helium vapor at a pressure ratio of 2.8, with off–design range requirements of

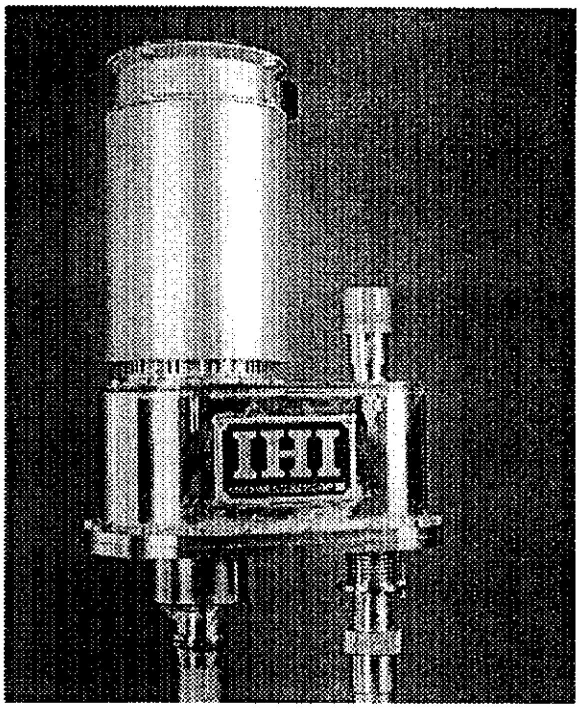

Figure 4: IHI cold helium vapor compressor – production model.

40–70 g/s and pressure ratios between 1.75 and 3.5. The prototype was able to meet these criteria while maintaining an isentropic efficiency above our required value of 60%, including static heat leak. The unit utilizes foil–type self acting gas bearings, a shroudless aluminum cast impeller, and a high speed induction motor powered by a variable frequency inverter drive. Operating speeds are between 40 and 95 krpm, with a speed of 80 krpm at the design point. The prototype logged over 2000 hours of successful operation, during which time several episodes of liquid inhalation were experienced with no observable damage. Failure occurred after the unit ingested a metal chip, most likely debris from cryostat fabrication. IHI repaired the unit and returned it to Fermilab where it performed per specification once again.

Based on our positive experience with the IHI prototype centrifugal compressor, a purchase of 27 centrifugal machines was concluded. Performance specifications are identical to the prototype although the production units are air cooled and reside in compact cryostats which will mount directly to existing refrigerator hardware. All production units have been delivered, inspected, and accepted. Installation in the Tevatron is scheduled for the fall/winter of 1993, at the conclusion of our current shut down period.

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