Helium Compressors for Closed-Cycle, 4.5-Kelvin Refrigerators

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An improved helium compressor for traveling-wave maser and closed-cycle refrigerator systems was developed and is currently being supplied to the DSN. This new 5-hp compressor package is designed to replace the current 3-hp DSN compressors. The new compressor package was designed to retrofit into the existing 3-hp compressor frame and reuse many of the same components, therefore saving the cost of documenting and fabricating these components when implementing a new 5-hp compressor.

I. Introduction

The DSN currently uses 30 1-W 4.5-K cryogenic systems to cool traveling-wave masers (TWM's). The systems use 3-hp reciprocating compressors to supply helium gas at the required pressures. The compressors exhibit a mean time between failure (MTBF) of approximately 5000 hours and require approximately 18 work hours to repair. Although this performance has been considered adequate, the DSN has desired that the design be upgraded to (1) reduce overhaul labor, (2) increase MTBF, and (3) increase helium mass flow to accommodate larger closed-cycle refrigerators (CCR's). Future maser systems will be based on a new 2-W capacity refrigerator that requires more mass flow than the current DSN compressor can deliver.

The improved DSN helium compressor (Fig. 1) is a 5-hp, two-stage, reciprocating, oil-lubricated unit, 58 in. long, 24 in. wide, 32.25 in. high, and 720 lb in weight. It is designed to supply high-pressure helium gas to 4.5-K Gifford–McMahon/Joule Thompson (GM/JT) CCR's. The compressor is a modified Dunham Bush model 50 PCF 5-hp unit with a free air displacement of 10.7 l/sec (22.6 standard ft^3/min). This increase in displacement over the current 3-hp DSN units of 4 l/sec (8 standard ft^3/min) allows the GM engine to operate at a higher pressure ratio (2.0 MPa supply, 0.5 MPa return) and a higher mass flow, resulting in a 40-percent average increase in maser/refrigerator third-stage (4.5-K stage) cooling capacity. In spite of this increase in mass flow, the new compressor operates at lower temperatures and requires no more AC input power than the 3-hp unit it is designed to replace. Improvements in the oiling system, heat exchanger, electrical system, and hardware are also designed to increase reliability and improve maintainability of the system. Table 1 shows a performance comparison between the 3-hp and 5-hp compressors. The operation of the 5-hp compressor will be described by presenting the flow diagram of a simple one-stage compressor, then a simple two-stage compressor, and finally a simplified flow diagram of the 5-hp compressor.

II. Description

A simplified block diagram of a typical single-stage compressor is shown in Fig. 2. The purpose of this is to compress gas from low pressure to high pressure while maintaining required purity. Oil injection to the compressor is required to lubricate and control temperatures of moving parts. The high-pressure gas and oil stream flows through a heat exchanger to remove the heat of compression. From the heat exchanger, the gas and oil stream flows through an oil separator assembly that returns the oil to the compressor and supplies the refrigerator with high-purity, high-pressure gas.

A two-stage compressor is required to operate a GM/JT system. A simplified block diagram of a two-stage compressor is shown in Fig. 3. A two-stage compressor cascades a single-stage compressor with another to provide two stages of compression. The first stage compresses gas from the low-pressure Joule-Thompson return circuit to an intermediate pressure that corresponds to the return pressure from the Gifford-McMahan expansion engine. Compression heat is removed in the first-stage heat exchanger. The oil and gas stream output from the first stage is combined with the gas returning from the expansion engine. Both streams are then recompressed in the second compressor stage to the required supply pressure. The heat of compression is then removed by the second-stage heat exchanger. Oil from both stages is removed by a common oil separator and returned to the compressor crankcase. High-pressure gas is routed to the supply (input) sides of both the GM expansion engine and the JT circuit in the closed-cycle refrigerator.

A schematic diagram of the 5-hp DSN two-stage compressor is shown in Fig. 4. Additional components have been added to the basic two-stage system discussed above to control and monitor system pressures, meter oil injection to both compressor stages, and improve compression heat removal. The compressor used for the DSN configuration is a Dunham Bush V-4, air-cooled, reciprocating, hermetic R-22 refrigeration unit. The unit is then modified at JPL for a two-stage helium closed-cycle application. Operating pressures are controlled by a low-pressure regulator, a high-pressure regulator, and a storage tank. The low-pressure regulator governs the pressure at the first-stage intake of the compressor. The high-pressure regulator governs the second-stage supply pressure by returning the gas not required by the CCR system to the storage tank. The storage tank contains a reserve supply of helium gas. Gas is withdrawn from the storage tank during refrigerator cooldown. The heat exchanger is a fan-cooled gas-to-air type with two sections, one for each compressor stage. System lubrication is supplied by an oil pump for the second stage and by crankcase pressure for the first stage. Metering orifices at both compressor stages govern the amount of oil injected.

III. Reliability and Maintainability

The new helium compressor design has evolved from the experience gained with past prototype and test compressors. The low MTBF (5000 hours) of current 3-hp compressors is primarily attributed to compressor component overheating and reed valve failure. A larger heat exchanger and the placement of internal oil-injection nozzles just above each reed valve have reduced operating temperatures in the compressor. Both first- and second-stage valve plates and reed valves have also been redesigned and have proven to be stronger than earlier designs.

Three major design changes were incorporated into the new model to improve compressor maintainability. The heat exchanger is mounted externally on the compressor frame and can be removed and repaired or replaced without interfering with other compressor components. All major electrical components are also externally mounted at the opposite end of the compressor frame in an electrical box. Grouping and relocating these electrical components have reduced maintenance time when troubleshooting and repairing the electrical system. The main compressor motor is now mounted to the compressor frame by means of a caster and rail system. A compressor motor handling fixture attaches to existing screw holes in the compressor frame and allows the compressor motor to be rolled out and back into the compressor frame without manual lifting or other handling apparatus. This new compressor motor handling system (Fig. 5) eliminates the necessity of removing other compressor components and helium piping to gain access for overhead hoisting systems.

IV. Performance

The 5-hp helium compressor significantly increases the 4.5-K cooling capacity of the existing DSN refrigerator. This increase is due to an increase in the GM engine pressure ratio and therefore the capacity of the refrigerator's first and second stages. The increase in the 4.5-K refrigerator capacity using the 5-hp compressor is even more substantial when the first stage of the refrigerator is loaded heavily due to large radiation shields and RF input lines, such as in the DSN Block V 2.3-GHz (S-Band) TWM/CCR, the DSN Block II A 8.4-GHz (X-Band) TWM, and the 23-GHz Maser/CCR.

Figure 6 shows a comparison of a standard DSN refrigerator 4.5-K-stage capacity when using a standard DSN 3-hp compressor or the new 5-hp compressor. The 5-hp compressor provides a 230-percent increase in 4.5-K capacity when an additional 20-W load is applied to the refrigerator first stage.

The additional JT mass flow available from the larger 5-hp compressor is shown in Fig. 7. The 3-hp compressor is capable of providing the refrigerator with a JT maximum mass flow of 3.5 standard ft^3/min, (at a maximum desired JT return pressure of 3.5 standard ft^3/min) while the 5-hp compressor can provide the refrigerator with a JT mass flow of 5.5 standard ft^3/min.

The first of these newly designed 5-hp compressors was built in 1990. This unit is being used for continuous-operation "life testing" and is completely disassembled and thoroughly inspected for signs of wear and deterioration at 5000-hour intervals. The compressor has accumulated over 20,000 hours of operation and has exhibited no failures or significant symptoms of wear or deterioration to date.

V. Conclusion

The new DSN 5-hp helium compressor, compared with the existing 3-hp design, improves the cooling capacity at all three stages of maser refrigerators. This results in an increase in the refrigerator's tolerance to first- and second-stage GM expander performance degradation and external heat loads (which have been increasing with the recent development of higher performance masers, some of which are incorporating cryogenic feed components). In addition, the increased helium mass flow that the new compressor can provide will be required for operation of future 2-W DSN refrigerators. This compressor has been designed to retrofit into the current 3-hp compressor frames and share many existing 3-hp compressor components, therefore saving the cost of documenting and fabricating these components when implementing a new 5-hp compressor.

The new compressor requires no more AC input power to operate and runs at lower operating temperatures than the 3-hp units. The design improvements to the heat exchanger, valve plates, and oil-injection system should result in an improvement in both DSN closed-cycle refrigerator and compressor MTBF. Packaging improvement has significantly reduced the labor required to repair and replace major components. The 5-hp life-test compressor has already surpassed 20,000 hours of operation with virtually no measurable signs of wear or failures.

Acknowledgments

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Table 1. Performance comparison of 3-hp and 5-hp compressors.

Specification	3-hp compressor	5-hp compressor
Bore, mm (in.)	48 (1 7/8)	56 (2 3/16)
Stroke, mm (in.)	35 (1 3/8)	38 (1 1/2)
Cycles	2	4
RPM	1750	1725
Amps	11.0	9.5
Compressor rating (air), l/sec (scfm[a])	3.6 (7.66)	10.7 (22.6)
Average motor temp., deg C (deg F)	119 (246)	59 (138)
Average compression temp., deg C (deg F)	77 (170)	72 (162)
Maximum JT mass flow (at 300 psig supply) l/sec (scfm)	1.4 (3)	2.6 (5.5)

[a] scfm = standard cubic feet per min.

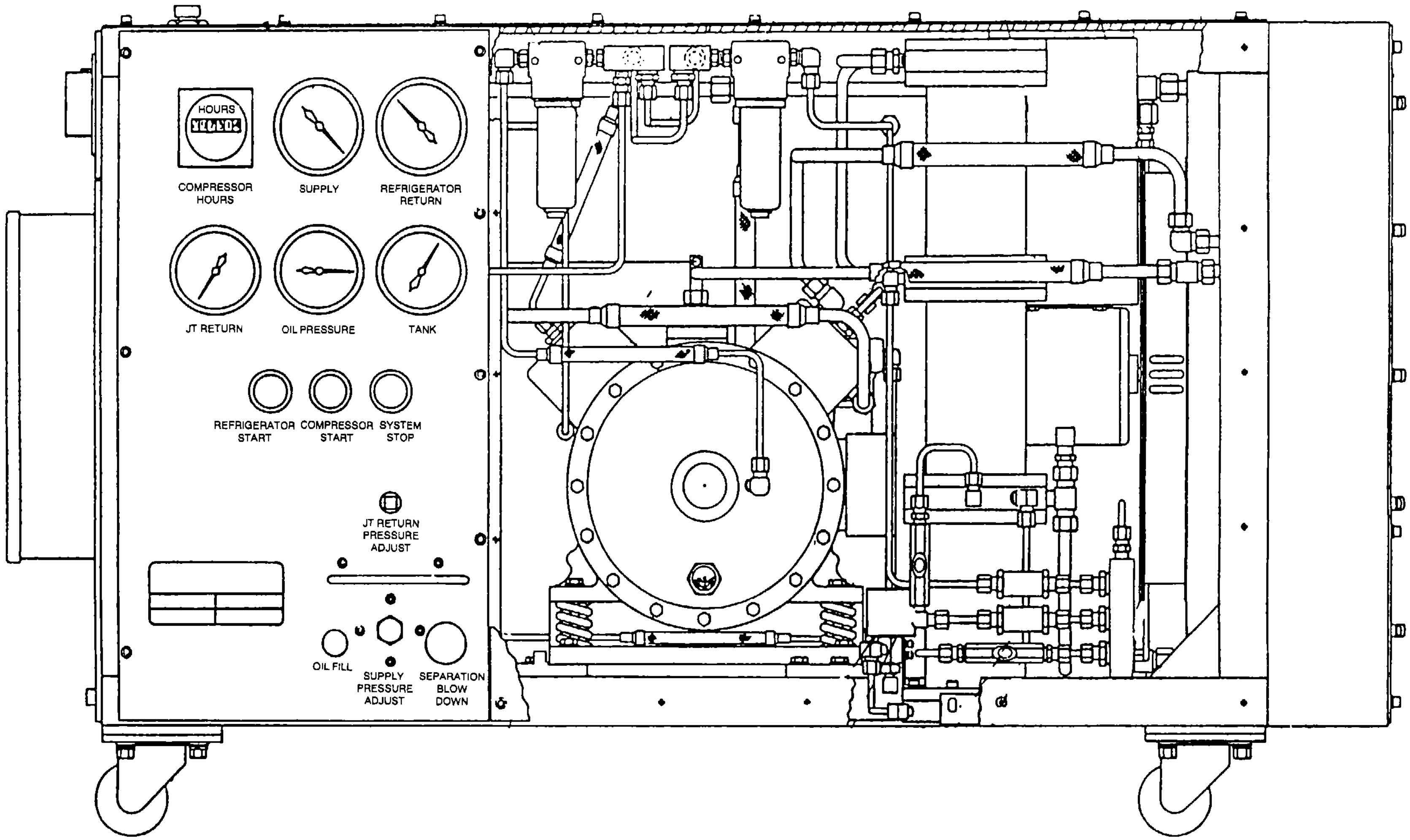

Fig. 1. 5-hp DSN helium compressor.

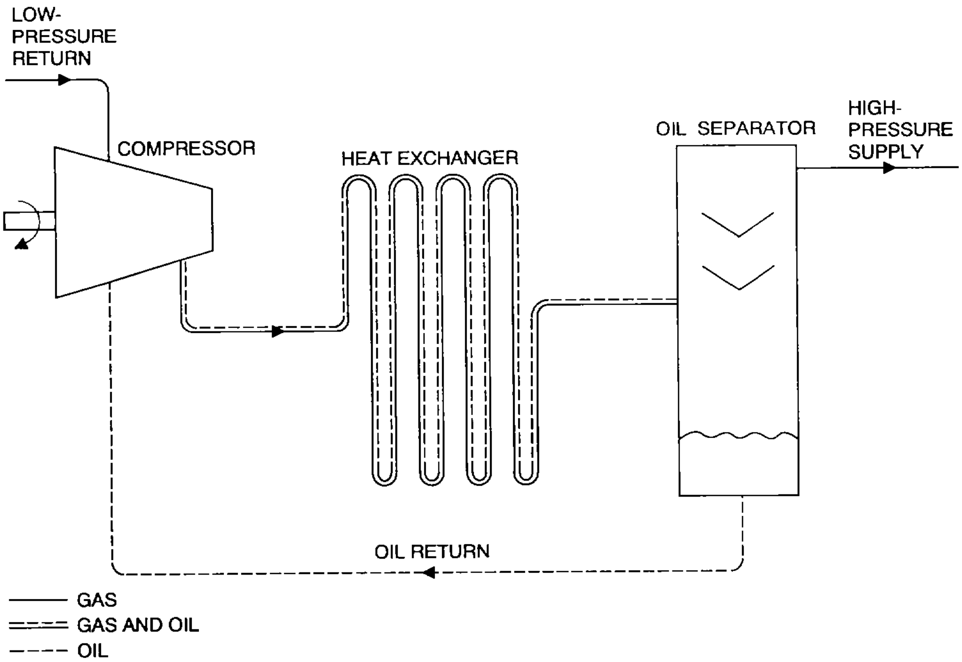

Fig. 2. Simplified single-stage compressor schematic.

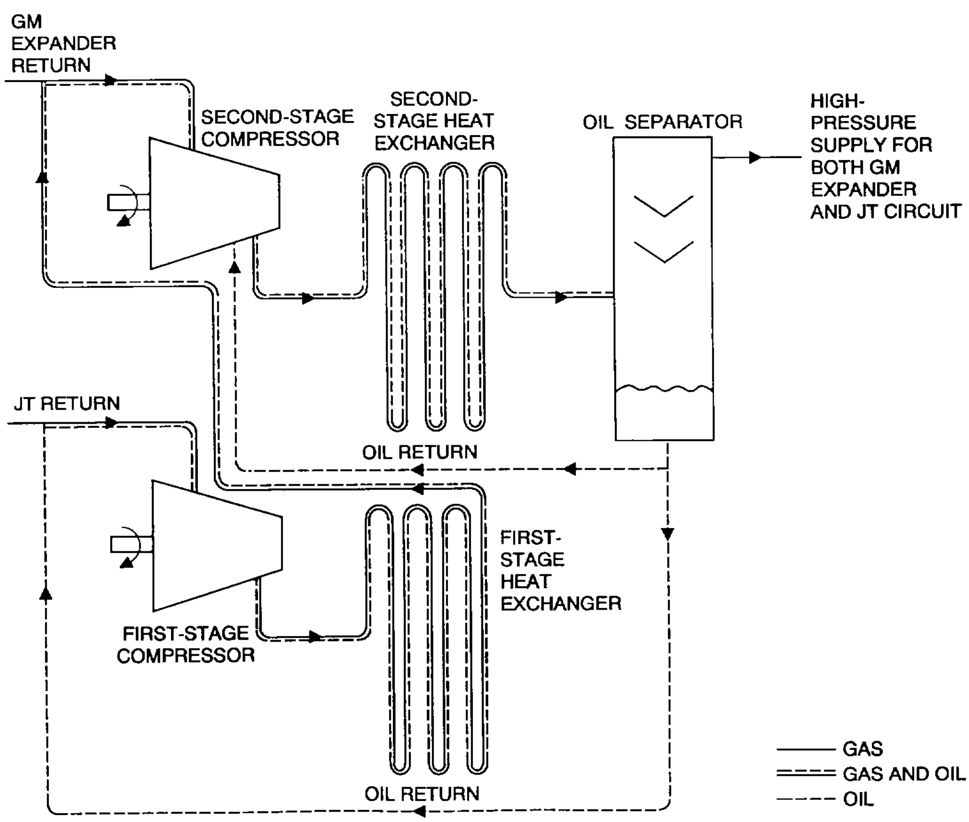

Fig. 3. Simplified two-stage compressor schematic.

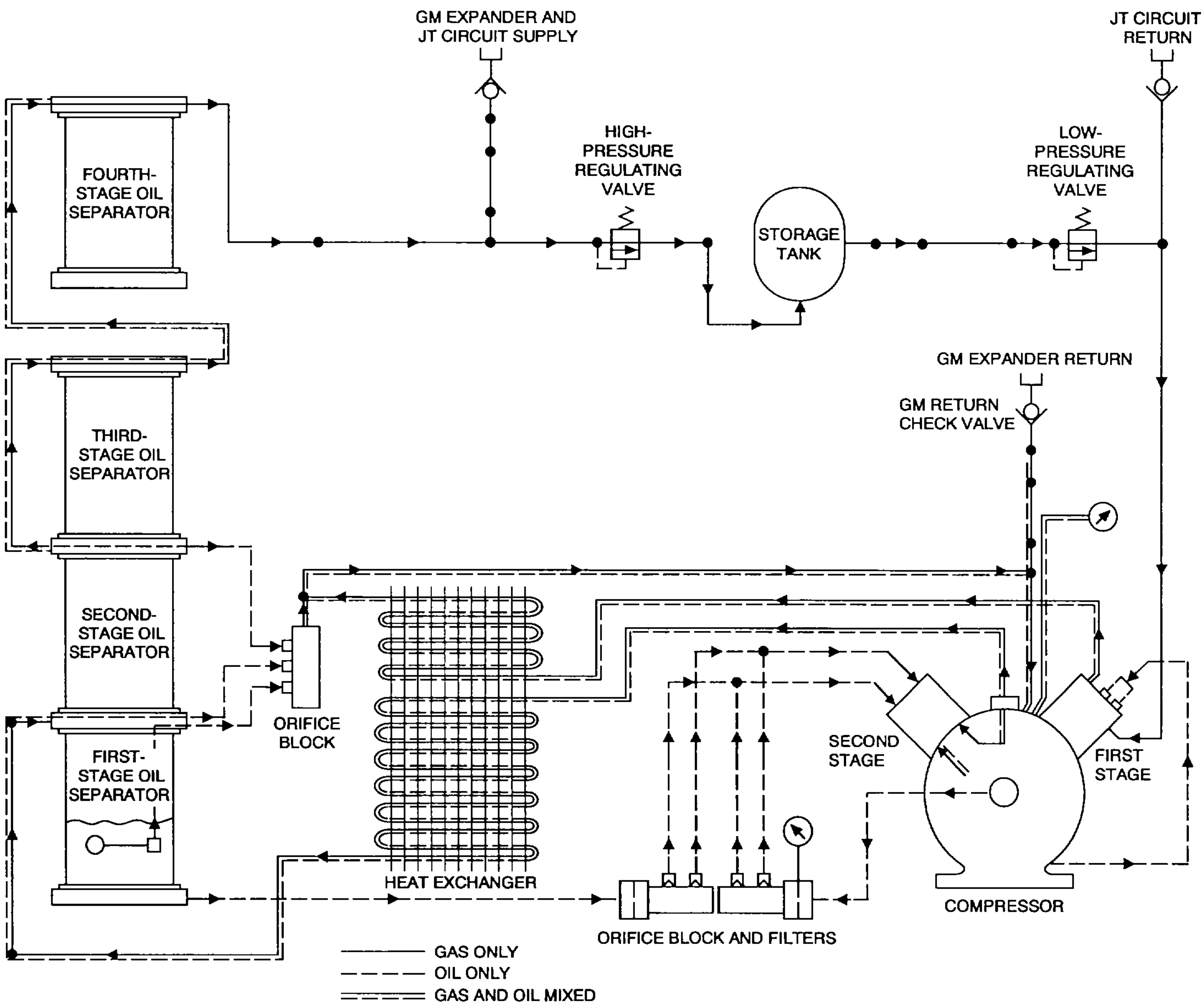

Fig. 4. Simplified 5-hp DSN two-stage compressor schematic.

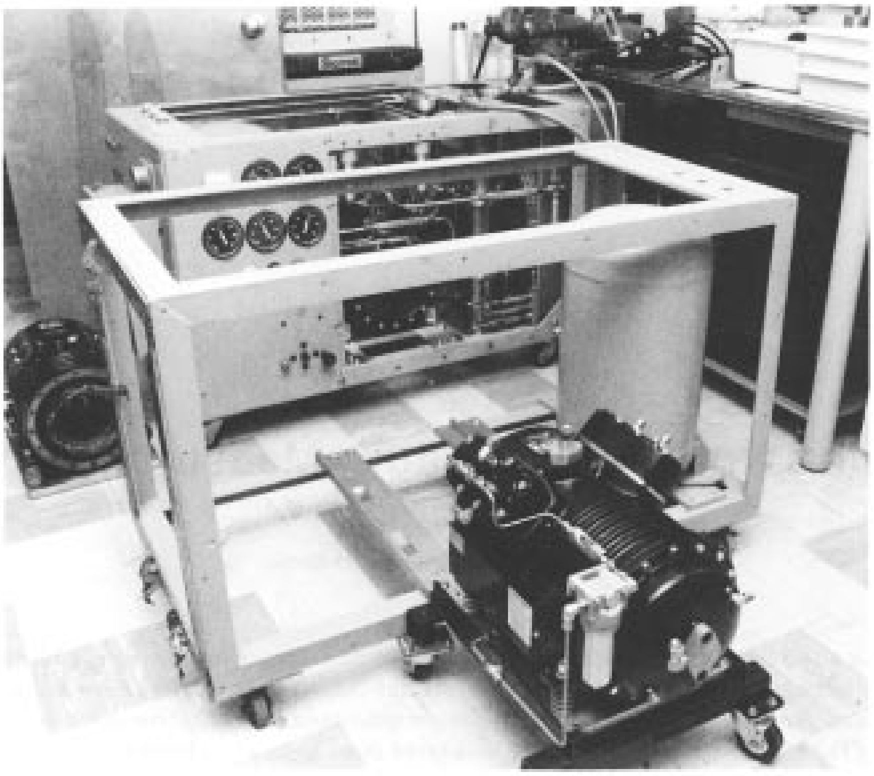

Fig. 5. The new compressor motor handling system.

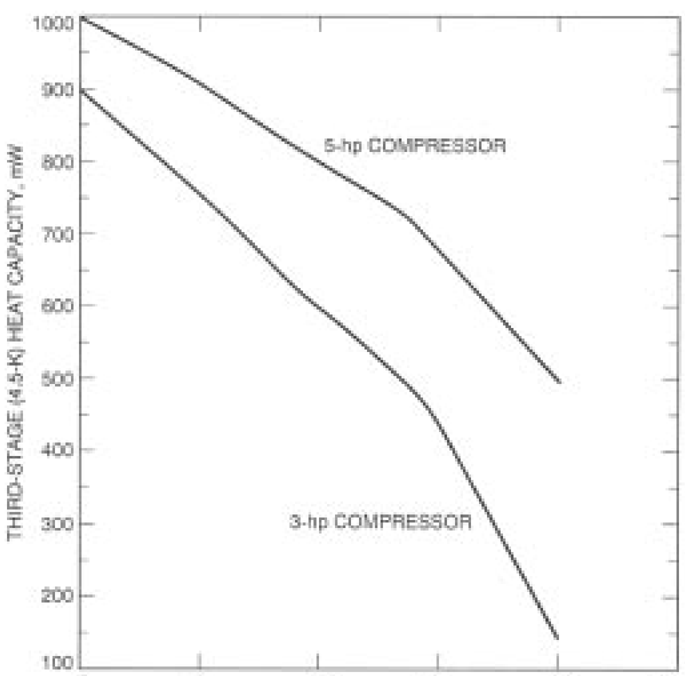

Fig. 6. DSN refrigerator third-stage (4.5-K) heat capacity with load applied to refrigerator first stage.

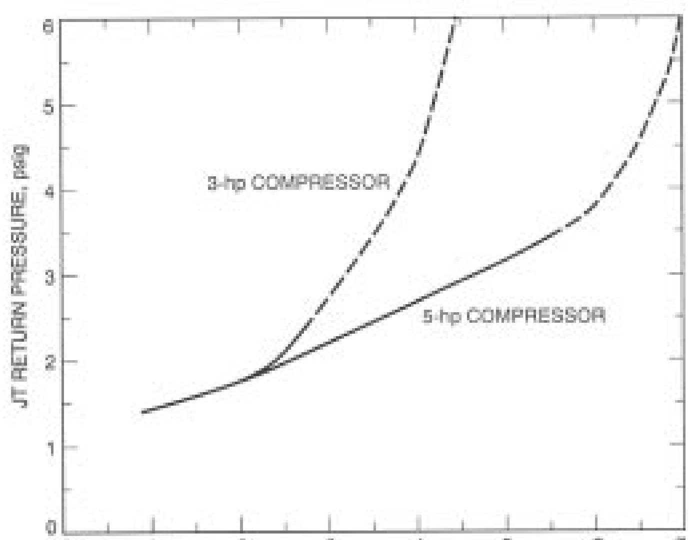

Fig. 7. Refrigerator JT return flow comparison.