EVALUATION OF DRY, ROUGH VACUUM PUMPS

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EXECUTIVE SUMMARY

This document provides information on the testing and evaluation of thirteen dry rough vacuum pumps of various designs and from various manufacturers.

Several types of rough vacuum pumps were evaluated, including scroll, roots, and diaphragm pumps. Tests included long term testing, speed curve generation, voltage variance, vibrations emissions and susceptibility, electromagnetic interference emissions and susceptibility, static leak rate, exhaust restriction, response/recovery time tests, and a contamination analysis for scroll pumps. Parameters were found for operation with helium, which often is not provided from the manufacturer.

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ABBREVIATIONS AND ACRONYMS

AC	alternating current
Ar	argon
c.	circa
CE	conducted emissions
ccm	cubic centimeter per minute
CDR	cleaning and decontamination request
CM	capacitance manometer
CS	conducted susceptibility
dBμV	decibel microvolt
DC	direct current
DVM	digital volt meter
G	acceleration, relative to Earth's acceleration due to gravity
G_{rms}	root mean square acceleration, relative to Earth's acceleration due to gravity
H_2	hydrogen
He	helium
Hz	Hertz
ID	inside diameter
LPM	liters per minute
MFM	mass flow meter
MHz	megahertz
min	minute
mTorr	milliTorr
NASA	National Aeronautics and Space Administration
N_2	nitrogen
N/A	not applicabale
N/T	not tested
NVR	non-volatile residue
O_2	oxygen
OD	outside diameter

RE	radiated emissions
RGA	residual gas analyzer
RS	radiated susceptiblility
sccm	standard cubic centimeter per minute
SDS	sample delivery system
sLpm	standard liters per minute
TNTC	too numerous to count
V	volt

1. OVERVIEW

Rough vacuum pumps are an integral part of vacuum systems in gas analysis systems. They are used to transport gas samples from the test article to the analyzer, move the gas sample throughout the analyzer, rough the high vacuum chamber of the analyzer, and back the turbo molecular pump used to generate high vacuum. The performance and reliability of these pumps strongly influences the performance and reliability of the system as a whole.

1.1 TYPES OF PUMPS

Rough vacuum pumps can be categorized as one of two varieties: oil-sealed and dry. Oil-sealed pumps are positive-displacement with one or more stages whose clearances (leak paths) are sealed with a low vapor pressure oil. As the pumping mechanism moves, the oil flows into new positions to seal against gas returning back through the pump. Oil pumps are highly reliable, but produce oil backstreaming that affects sensitive instrumentation. Also, pump oil is an oxygen hazard, a hazardous waste, and can be expensive. Dry pumps use various methods other than oil to seal the pumping mechanism. By eliminating the sealing oil, they attempt to produce no backstreaming, or hazardous waste stream. Because of the highly sensitive nature of analytical instrumentation used, the hazardous waste produced by oil pumps, and the oxygen hazard posed by the pump oil, dry pumps are desirable.

Several different types of dry pumps exist, but the three types evaluated here are scroll pumps, diaphragm pumps, and roots pumps. Scroll pumps use two or more concentric spirals, one inside the other, to move crescent shaped pockets of gas towards the outlet, which lies at the center of the spiral. Each of these crescent shaped pockets acts as a stage, compressing the gas as it moves towards the center until it is discharged from the outlet. Scroll pumps often have low ultimate pressures, and can also have high pumping speeds. Scroll pumps require a tip seal, which seals the spiral faces together. This restricts gas from traveling through any path other than through the spiral. Unfortunately, this material is prone to wearing, producing particles which can contaminate the vacuum system, plug exhaust lines, and cause failure of system components. The friction of the orbiting tip seal also generates substantial heat.

Diaphragm pumps use the reciprocating action of an elastomer diaphragm and valves to remove the gas in a system. As the diaphragm moves away from the head, gas flows through the intake valve to fill the void. When the diaphragm moves towards the head, the intake valve closes and the exhaust valve opens. The diaphragm then displaces the gas and the cycle repeats. Diaphragm pumps often have multiple pumping heads, referred to as stages. These stages can be arranged in parallel or in series depending on the application of the pump. Multiple stages in series help the diaphragm pump achieve low ultimate pressure but with the same pumping speed as a single head. Multiple stages in parallel provide higher pumping speed but no improvement in ultimate pressure. Often, the heads on a diaphragm pump can be arranged as required by the user, allowing for flexibility. Diaphragm pumps have very low contamination, but usually have higher ultimate pressures and lower flow rates than other types of dry pumps. In addition, the flow of gas through them often pulsates with the movement of the diaphragms, which can affect the stability of an instrument.

Roots pumps use two rotating, figure-eight shaped lobes that are always 90 degrees out of phase with one another. In current designs, there are no seals between the two lobes, so multiple stages must be used to achieve reasonable vacuum. Roots pumps are characterized by high flow rates and low ultimate pressure, but often do not function as well in helium environments than in nitrogen or air environments. Historically, roots pumps have not been able to start at atmospheric pressure, although recently such models have become commercially available.

1.2 PUMP FUNCTIONS

In many gas analysis applications, rough vacuum pumps are categorized by three distinct functions. These functions are referred to as transport, sample, and backing. Transport pumps are intended to quickly flow large amounts of gas long distances from the test article to the system. These pumps require high flow rates at higher pressures (60 – 150 sLpm at 250 – 500 torr). High flow rates ensure a quick system response time because it reduces the residence time of the sample in the transport line. To effectively transport the sample to the analyzer, higher pressures are often used.

Sample pumps move a small amount of gas from the transport pump stream throughout the system, ultimately leading to the analyzer. The sample pump requires neither high flow rates nor low ultimate pressure, but a balance of the two, typically 10 -20 sLpm at 50 - 500 torr.

Backing pumps rough the high vacuum chamber and provide the high vacuum pump with rough vacuum. Backing pumps require low ultimate pressure (<5 torr, but desire < 100 mTorr) to assist the compression of the turbo molecular pump and only small flow rates (<1 sLpm).

1.3 ABOUT THE TESTS

Thirteen dry, rough pumps from various manufacturers and of various designs were evaluated in this study. Table 1 outlines the various pumps, their possible uses, and some manufacturer specifications. Tests include long term testing, speed curve generation, voltage variance, vibrations emission and susceptibility, electromagnetic interference emission and susceptibility, static pressure test to determine leak rate, an exhaust restriction test, and response/recovery time test.

The long term test attempts to asses the long term reliability of pumps, their steady state power requirements, and heat generation. Scroll pumps also were tested for particulate generation, which could contaminate the system causing performance issues or failure.

The speed test generated pumping speed curves. These curves describe how the effective pumping speed changes with inlet pressure. This function is never constant, often changes with the gas being pumped, and is sometimes highly non-linear. Although manufacturers supply this curve for nitrogen and air, it is rarely provided for helium. Because helium is commonly used by NASA, the helium pumping speed curve is desirable. Additionally, the current required at each operating pressure was determined.

The voltage variance test determined how the current demand and inlet pressure of the pump changed with input voltage. In addition, this test determined the minimum voltage to sustain operation once the pump was running. In a brown-out condition, this voltage determines when the pump, and therefore the system, fails. Current vs. voltage curves are often highly varied from pump to pump and can be non-linear. Inlet pressure vs. voltage curves are typically non-linear, and pressure rises exponentially as voltage drops.

Many pumps generate substantial vibration while in operation. This vibration emission can fatigue components, and impact sensitive analytical instruments. The translational acceleration associated with pump operation was measured both at the pump inlet and at a surface the pump was sitting on.

When a pump is turned off, gas leaks back through it from the high pressure exhaust side to the low pressure vacuum. This gas leakage can bring contamination into the vacuum chamber. The faster the pump leaks back to atmospheric pressure, the more likely the contaminant will be pneumatically conveyed into the vacuum chamber. Static leak rates on the pumps were measured, and leak rates varied widely, even among pumps of the same type.

Rough vacuum pumps are typically designed to exhaust at atmospheric pressure or slightly above. Tubing and fittings attached to the exhaust of the vacuum pump can easily cause exhaust pressure to rise above the manufacturer's exhaust pressure specification. A test was performed to quantify the effects of exhaust restriction.

1.4 PUMP DESCRIPTIONS

Table 1 contains some manufacturer specified data about the candidate rough pumps. Photographs of the pumps used in this study are provided in Figures 1 – 13.

Table 1 – Candidate Rough Pumps with some Manufacturer Data

Pump	Type	Possible Function	Maximum Speed (LPM)*	Ultimate Pressure (mTorr)*	Hour Meter	Other Features or Notes
Adixen ACP 28	Roots	Transport	450	23	Yes	RS 232
Vacuubrand ME 16	Diaphragm	Transport	215	60 Torr	No	Start under Vacuum
Iwata ISP 250	Scroll	Transport, Sample	300	12	Yes	Gas Ballast
Edwards XDS 10	Scroll	Transport, Sample	185	50	Yes	Gas Ballast
Varian Triscroll 300	Scroll	Transport, Sample	250	10	No	
Vacuubrand MD 4 Vario	Diaphragm	Sample	63	1.1 Torr	No	Variable Speed, RS 232
Vacuubrand MZ 2D	Diaphragm	Sample, Backing	32	3.5 Torr	No	Start under Vacuum
Iwata ISP 90	Scroll	Sample, Backing	108	38	Yes	Gas Ballast
Edwards XDS 5	Scroll	Sample, Backing	100	50	Yes	Gas Ballast
Varian SH 100	Scroll	Sample, Backing	100	50	Yes	Solenoid Inlet Valve
Edwards XDD1	Diaphragm	Backing	25	<1.5 Torr	No	Private Label Vacuubrand MD1, Start Under Vacuum
KNF Neuberger 84.4	Diaphragm	Backing	4.8	1.5 Torr	No	Compact Size, 24 VDC
Vacuubrand MD 1 Vario	Diaphragm	Backing	27	1.1 Torr	No	Variable Speed, RS 232, Start under Vacuum, 24VDC

* Manufacturer's Claim

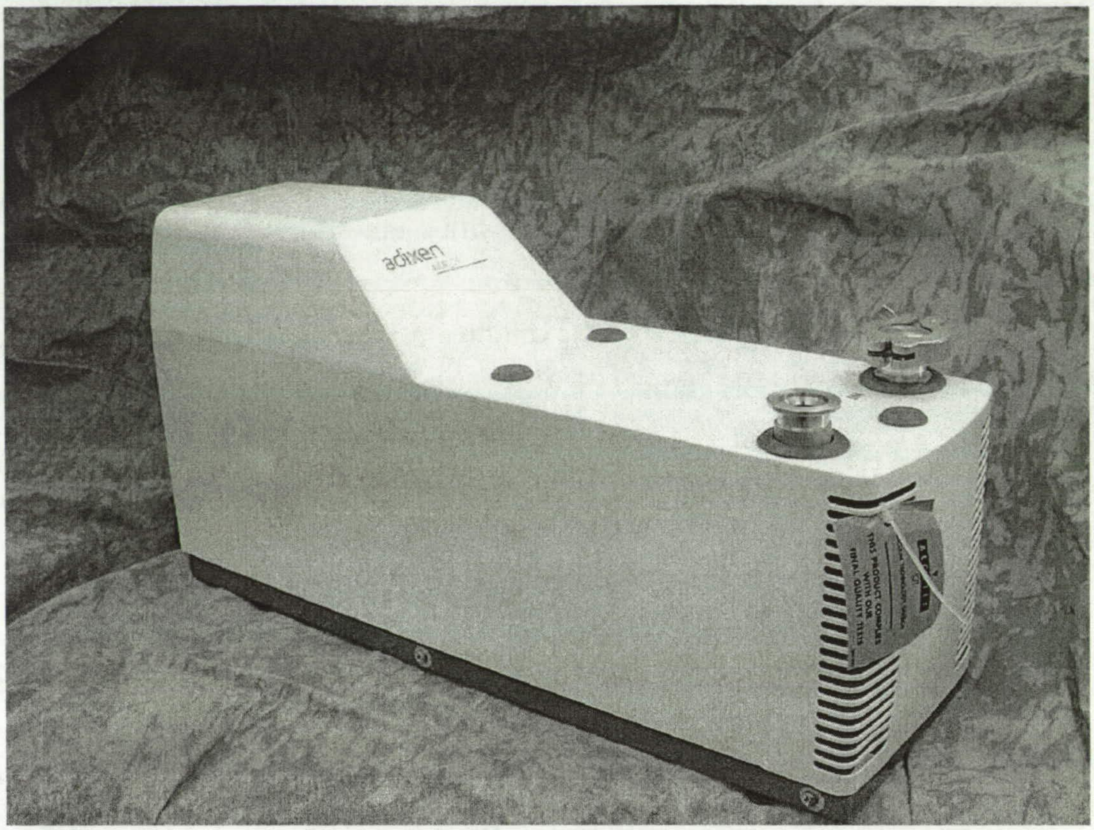

Figure 1 – Adixen ACP 28 Roots Pump

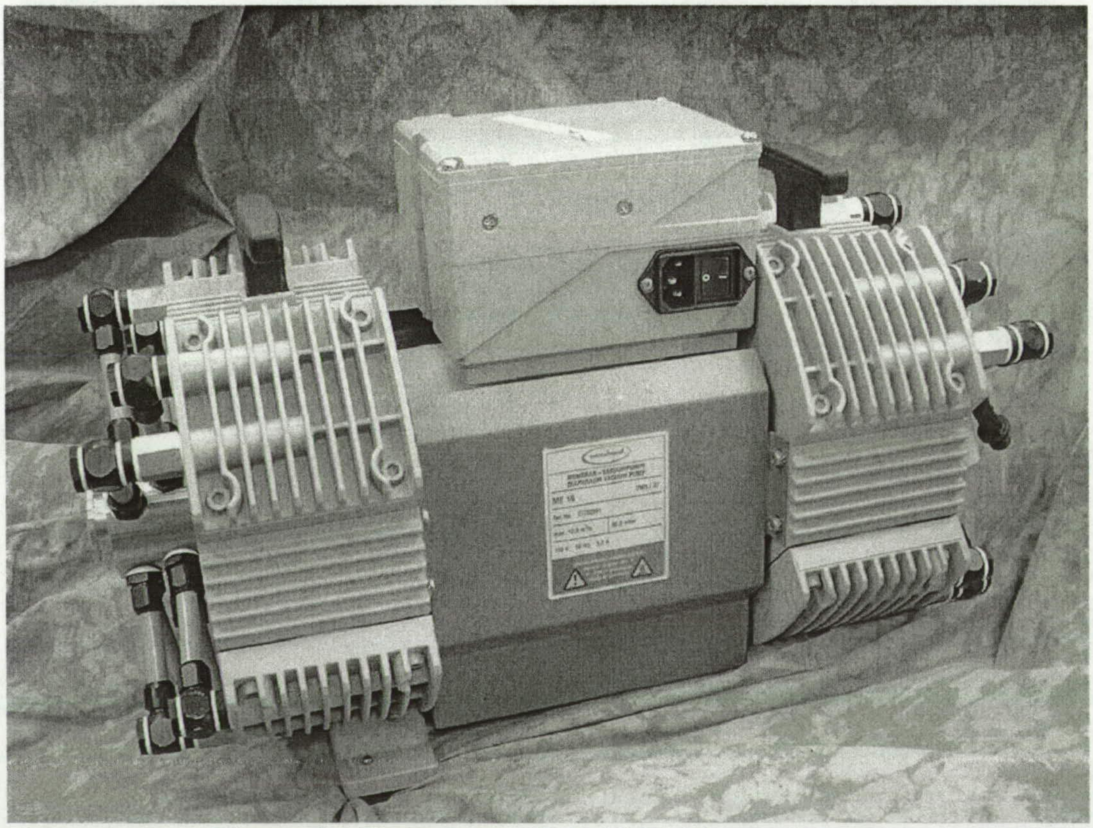

Figure 2 – Vacuubrand ME 16 Diaphragm Pump

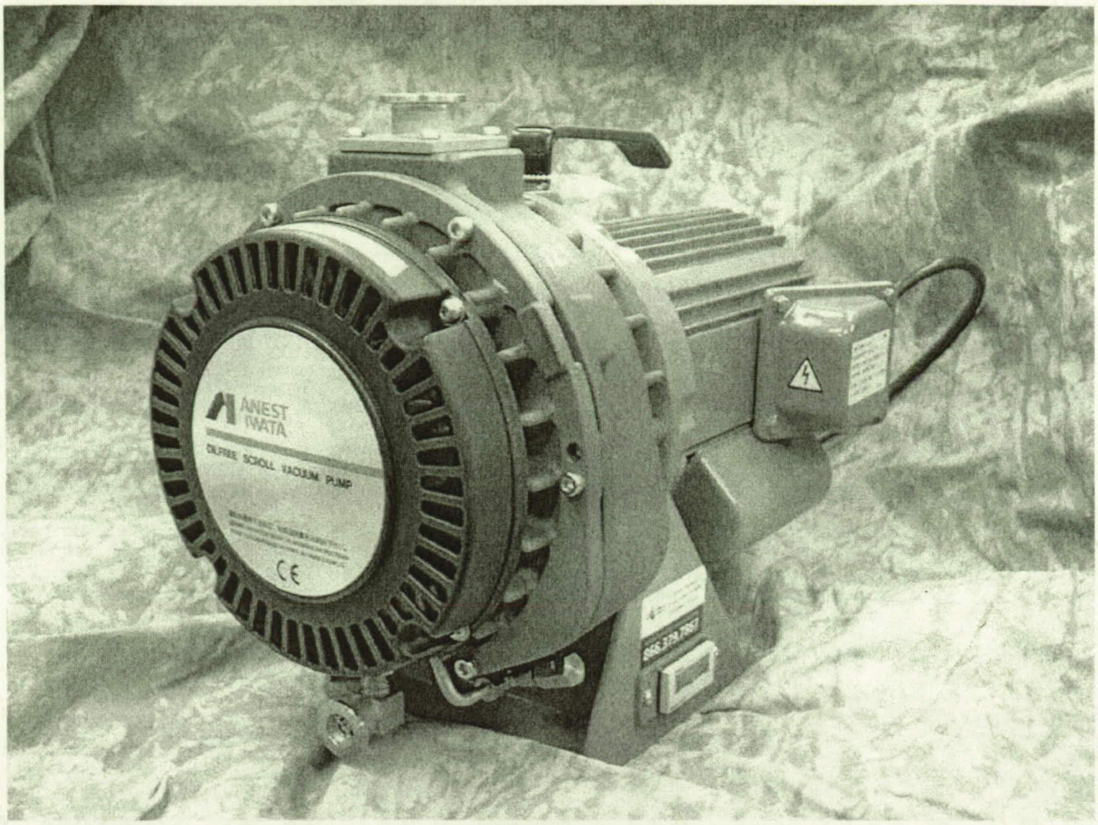

Figure 3 – Iwata ISP 250 Scroll Pump

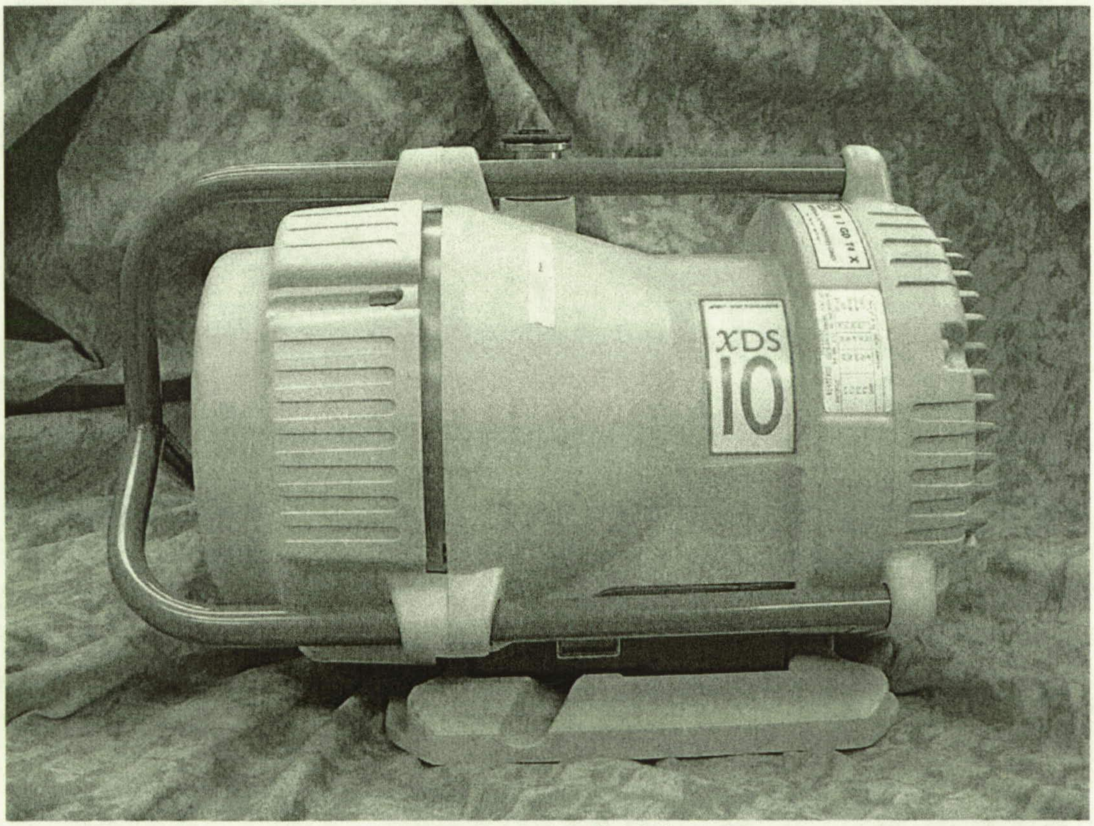

Figure 4 – Edwards XDS 10 Scroll Pump

Figure 5 – Varian TriScroll 300 Scroll Pump

Figure 6 – Vacuubrand MD 4 Vario Diaphragm Pump

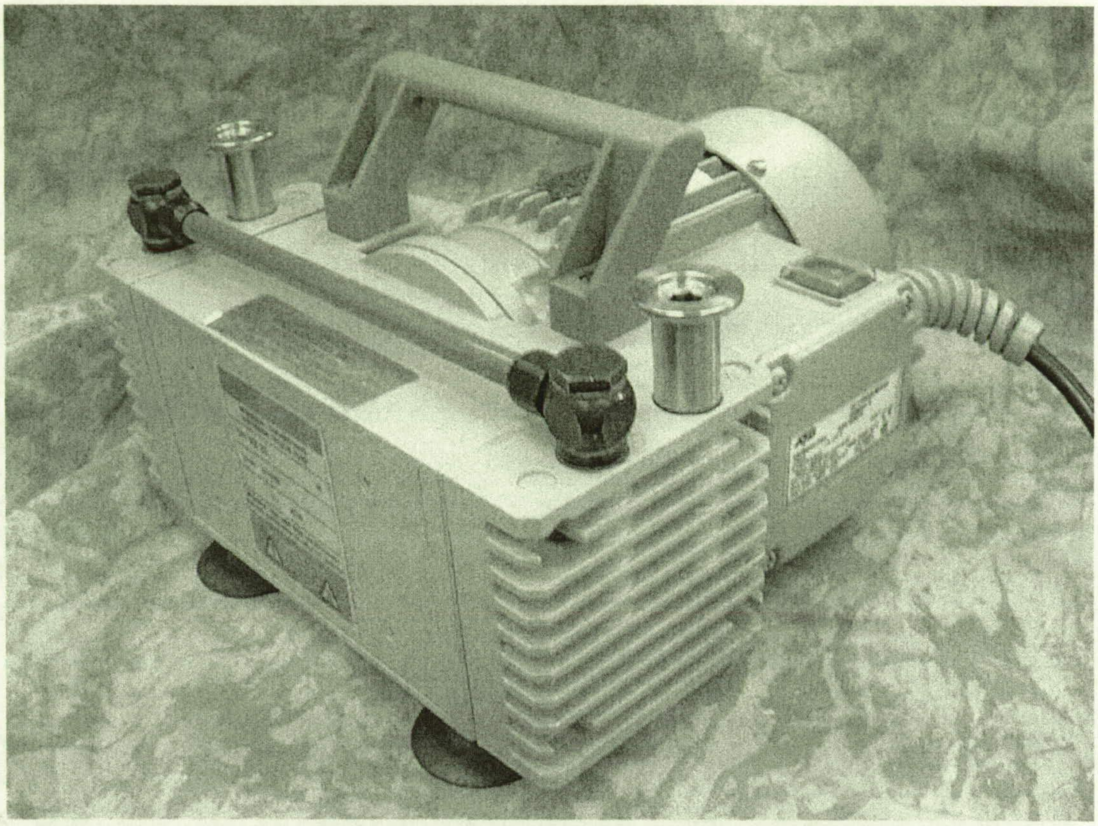

Figure 7 – Vacuubrand MZ 2D Diaphragm Pump

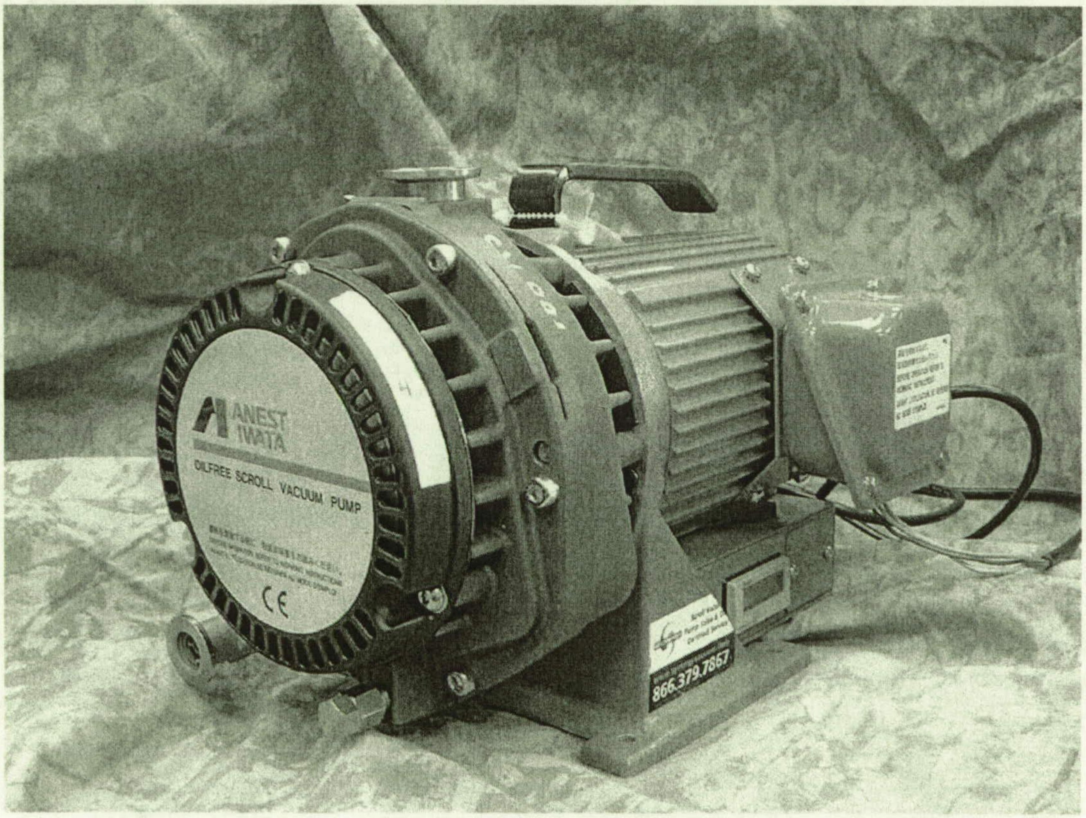

Figure 8 – Iwata ISP 90 Scroll Pump

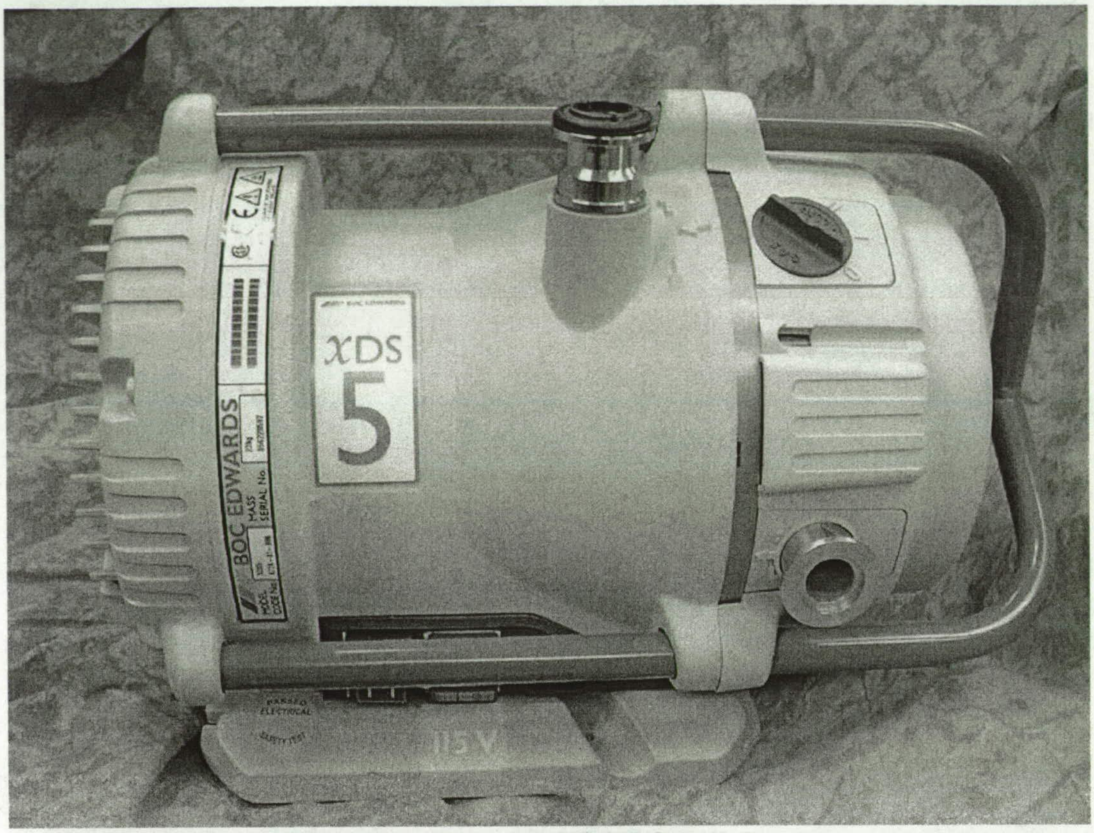

Figure 9 – Edwards XDS 5 Scroll Pump

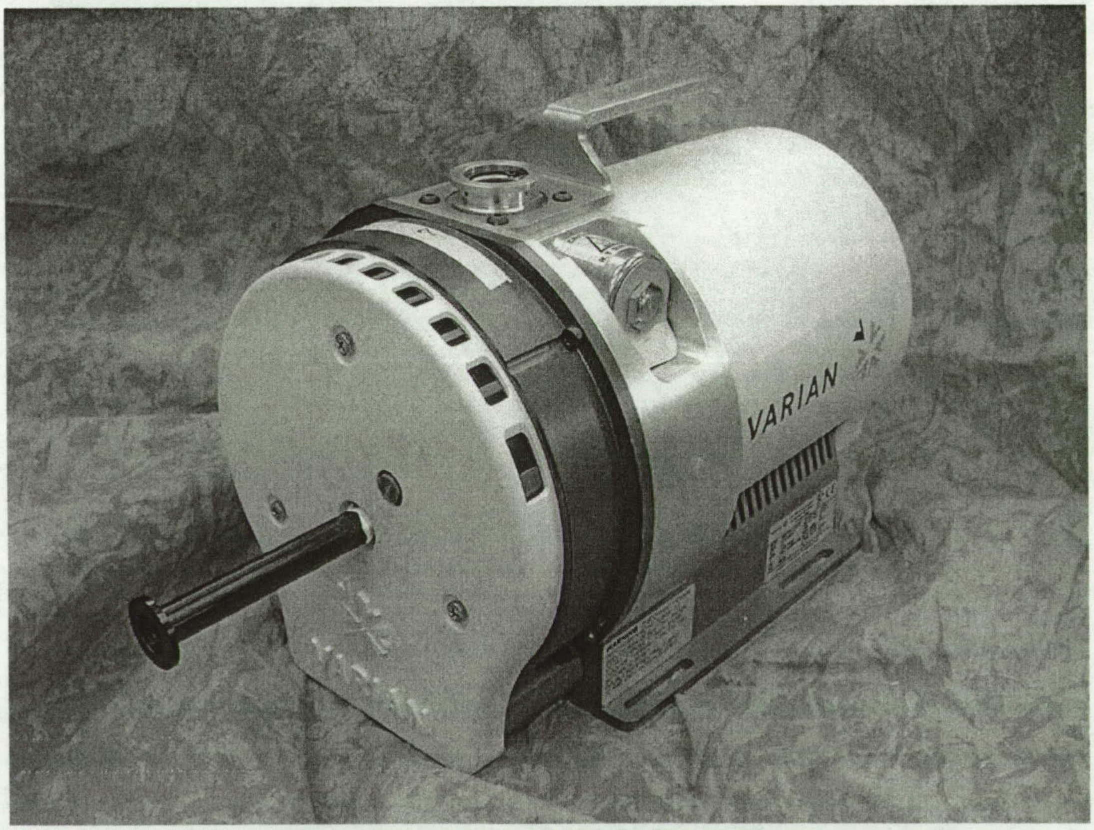

Figure 10 – Varian SH 100 Scroll Pump

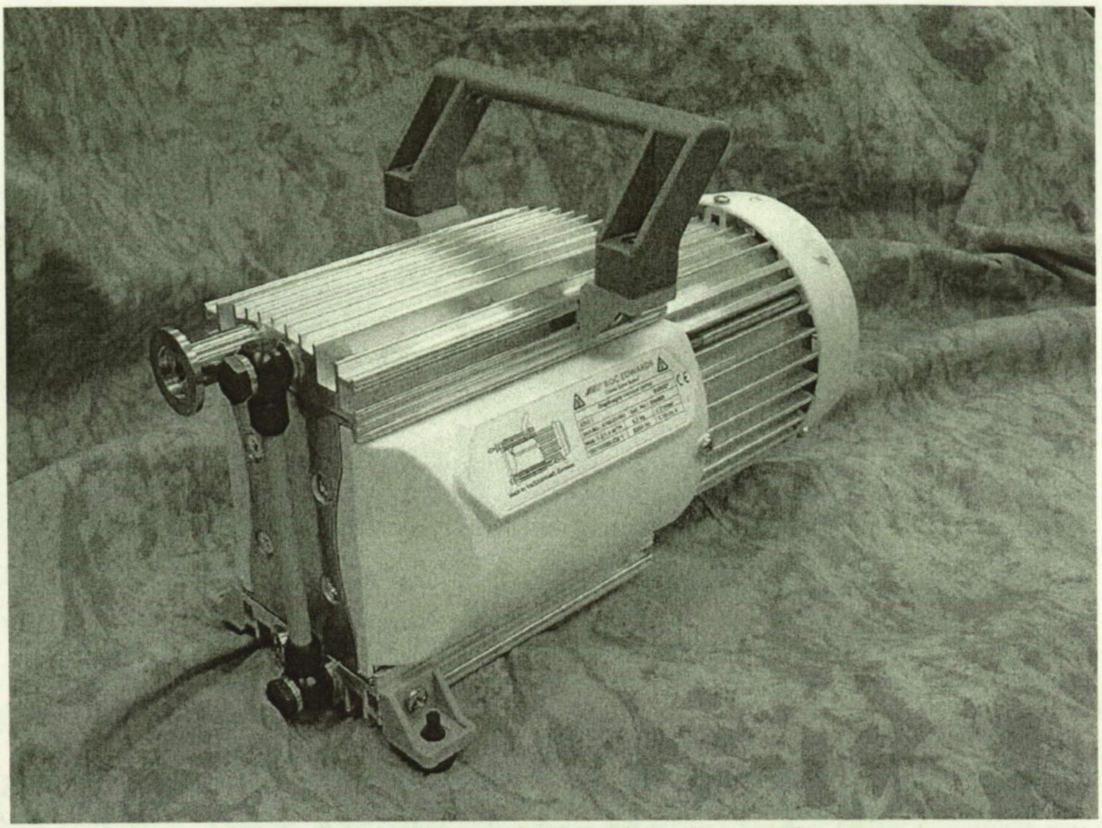

Figure 11 – Edwards XDD1 Diaphragm Pump

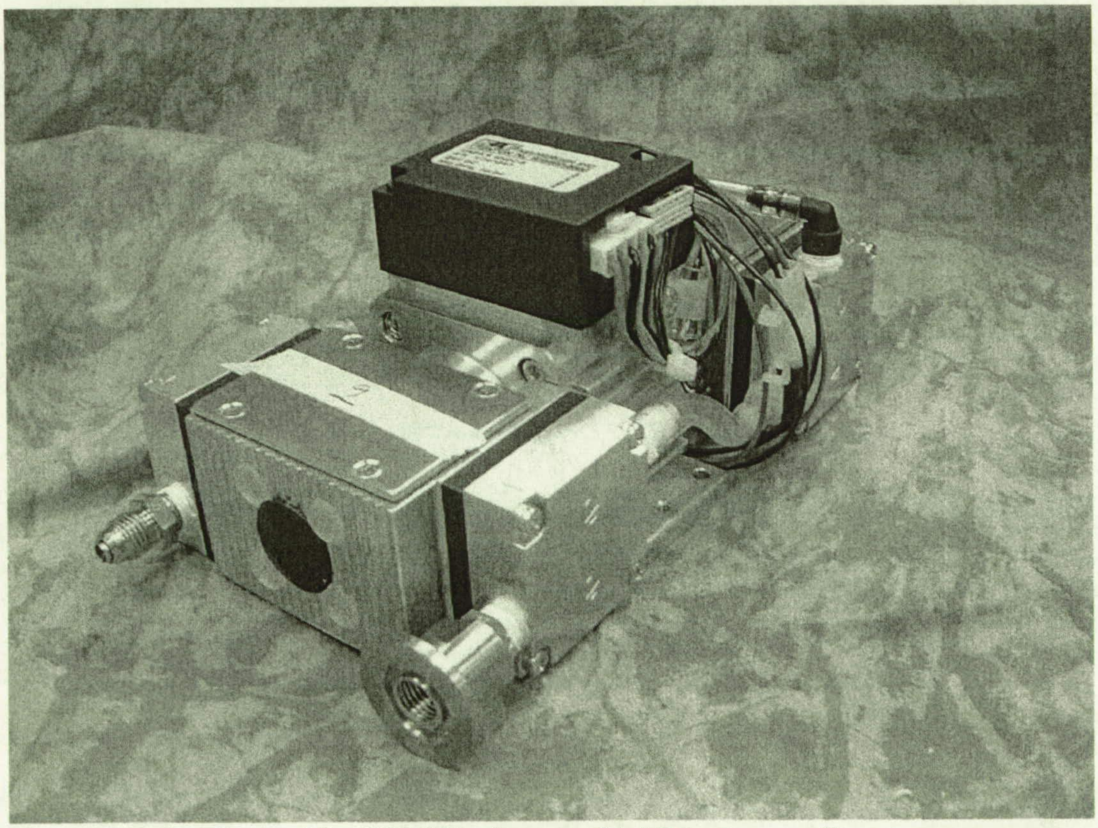

Figure 12 – KNF Neuberger 84.4 Diaphragm Pump

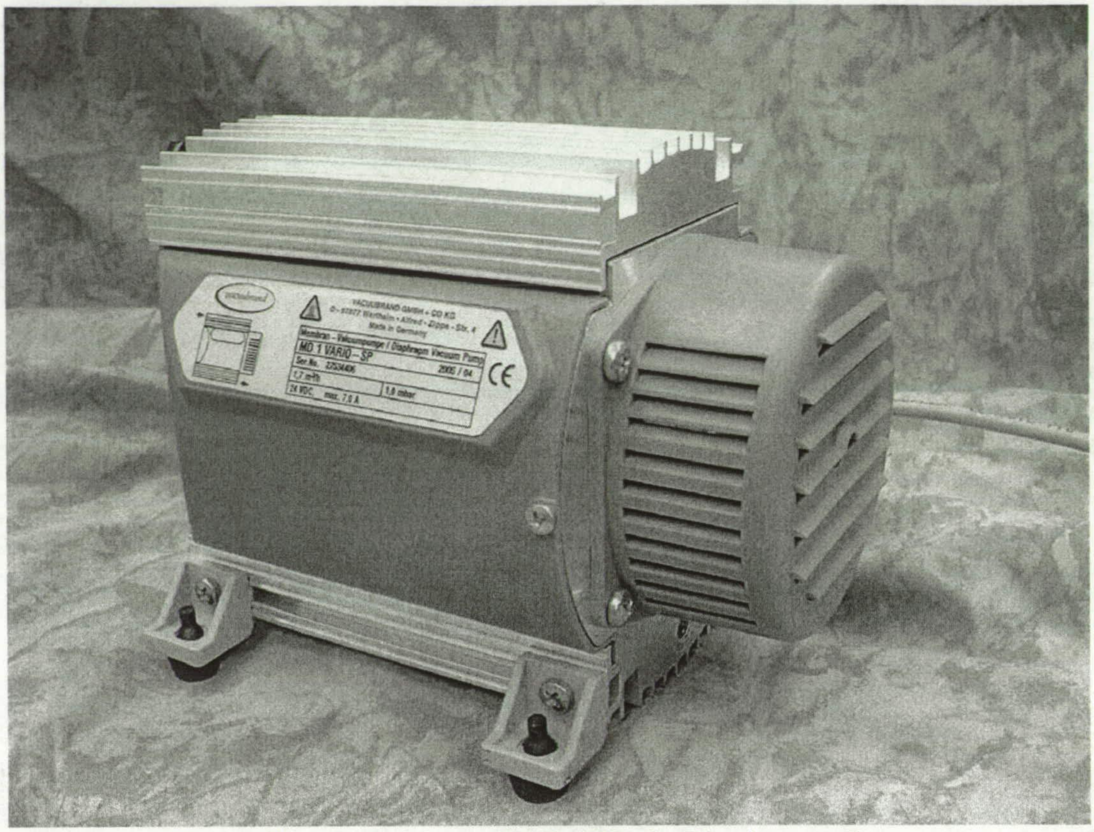

Figure 13 – Vacuubrand MD 1 Vario Diaphragm Pump

2. LONG TERM TEST

The long term test assessed long term functionality and reliability of pumps, as well as steady state power requirements of pumps. It also assessed the particulate generated by scroll pumps during long term use. With a few exceptions, the test duration was approximately 30 days. Transport and sample pumps were run at 300 torr, and turbo backing pumps were run at ultimate pressure. Scroll pumps had their exhaust filtered with a 100 micrometer filter to collect particulate generated during operation. The 100 micrometer filter is of a size that is efficient at capturing particles, but still allows the exhaust to flow relatively freely. Diaphragm pumps and the roots pump did not have the exhaust filtered because past experience has shown these pumps to have minimal contamination.

Current, exhaust temperature, and housing temperature were measured approximately once per day on turbo backing pumps. For transport and sample delivery pumps, current, housing temperature, flow rate, and pressure were also measured daily. Any deviations from normal operation were noted. Significant changes in current, flow rate, and housing temperature often are indicators of impending failure. Increases in current or decreases in flow rate may indicate increased power demand due to increased friction and/or reduced efficiency. Increases in temperature at steady ambient temperature and flow rate suggest increases in friction within the pump. Most measurements were expected to have approximately 10% deviation from day to day. Beyond this, an anomaly was noted. Pump temperature, however, was expected to vary by more than 10% because ambient temperature varied substantially.

At the conclusion of this test, rinse analysis was performed on the filters of scroll pumps to quantify the amount and size distribution of the particulate produced. In addition, non-volatile residue (NVR) analysis was performed to quantify the amount of grease and oil captured in the filters. Dry pumps are not oil sealed, and NVR signatures were expected to be low; only grease and oils that migrate through seals should be found in the filters. To help verify the results of the rinse analysis, and better understand or predict failure mechanisms, the scroll pump housings were removed and visually inspected for particulate generation and overall condition.

2.1 TRANSPORT PUMPS

Transport pumps are expected to quickly flow large amounts of gas long distances from the test article to the system. These pumps require high flow rates at higher pressures (60 – 150 sLpm at 250 – 500 torr). High flow rates ensure a quick system response time because it reduces the residence time of the sample in the transport line. Higher pressures are required so that the sample delivery system can effectively deliver the sample to the analyzer. All transport pumps were run for approximately 30 days near 300 torr. Scroll pumps had their exhaust filtered with a 100 micrometer in-line filter.

2.1.1 EDWARDS XDS 10

The Edwards XDS 10 scroll pump was run at approximately 300 torr for 34 days as a transport pump. The exhaust was filtered with a 100 micrometer in-line filter to collect particulate generated. During the test, temperature, flow rate, and current remained within the expected 10% deviation. Housing temperature averaged 55°C and exhaust temperature averaged 52°C, while ambient temperature averaged 19°C. The XDS 10 required approximately 5.5 amps steady state current.

After testing, the housing of the pump was removed and the scroll surfaces examined. The surfaces are shown in Figures 14 and 15. A light dusting of particulate was noted on the orbiting scroll, with slightly higher amounts of particulate noted on the fixed scroll. The particulate material was brown in color and seemed to adhere to surfaces with moderate strength. Tip seals appeared to be worn uniformly and evenly.

The filter contents were analyzed for particulate count as well as size distribution. Results indicate that the Edwards XDS 10 discharges the least amount of particulate of any scroll pump tested. The majority of the particles recovered were less than 50 micrometers in size. Only 0.5 mg of NVR was recovered from the filter, less than any other pump. See section 2.4 for a detailed contamination analysis.

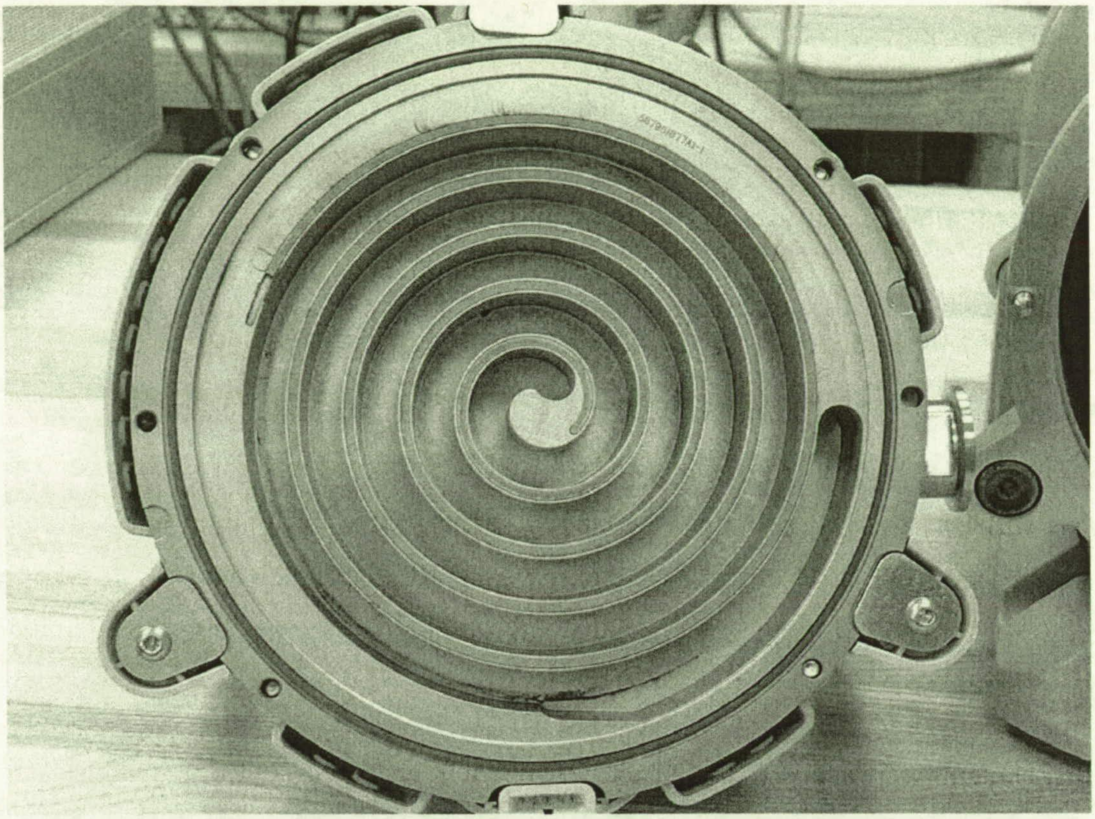

Figure 14 – Edwards XDS 10 Fixed Scroll Showing Particulate and Wear

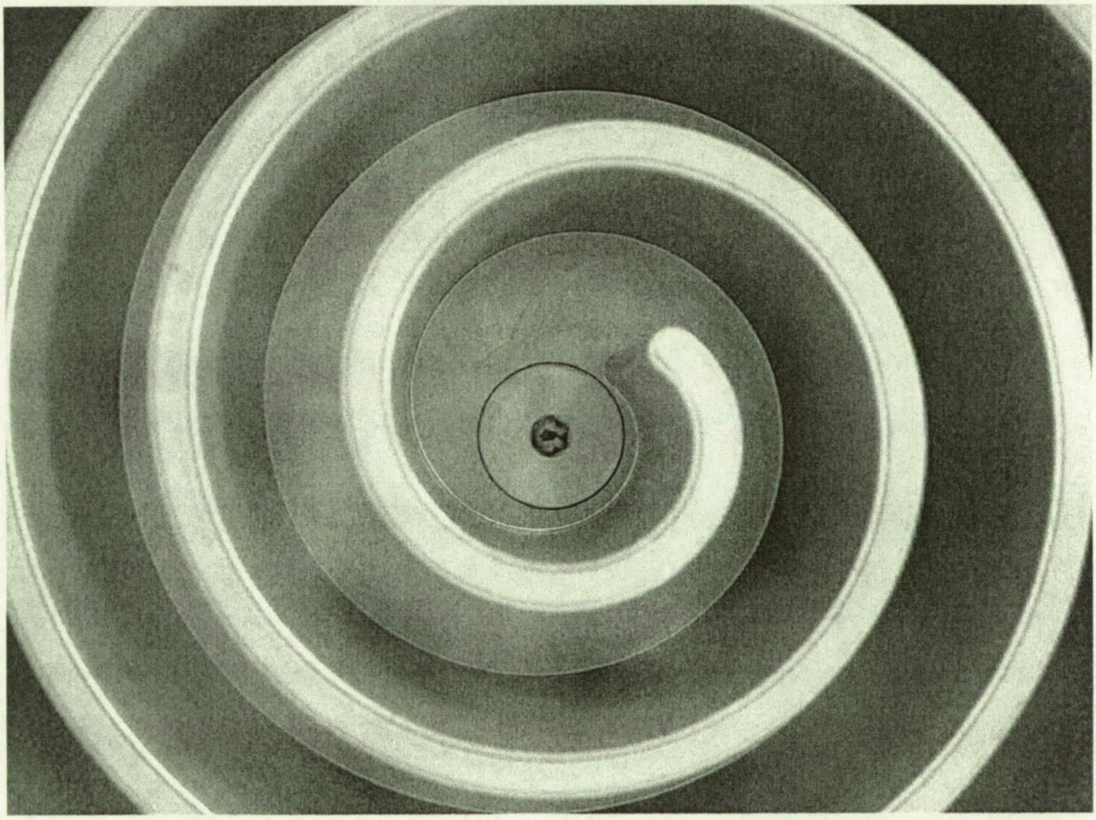

Figure 15 – Close up of Edwards XDS 10 Orbiting Scroll Showing Particulate

2.1.2 IWATA ISP 250

The Iwata ISP 250 scroll pump was run at approximately 300 torr for 30 days as a transport pump. The exhaust was filtered with a 100 micrometer in-line filter to collect particulate generated. During the test, current, flow rate, and temperature remained remarkably stable. Housing temperature averaged 50°C and exhaust temperature averaged 61°C while ambient temperature averaged 28°C. The ISP 250 required approximately 3.7 amps steady state current.

After testing, the housing of the pump was removed and the scroll surfaces examined. Some particulate was noted on both the orbiting and fixed scrolls. The particulate material was dark and tended to adhere to surfaces relatively strongly. The tip seals appeared to be worn in a non-uniform way on the orbiting scroll. White wear marks were observed with greater frequency towards the center of the scrolls. The fixed scroll appeared to be worn uniformly. The surfaces are shown in Figures 16 and 17.

The filter contents were analyzed for particle size distribution and NVR. Results show that there are large numbers of particles less than 50 micrometers generated. Compared to the other scroll pumps, the second highest amount of NVR was recovered from the filter, 4.08 mg. The o-ring which seals the fixed and orbiting scroll was covered in what appeared to be fluorinated grease, and the presence of a front bearing on the ISP pumps is likely responsible for the higher NVR signature. See section 2.4 for a detailed contamination analysis.

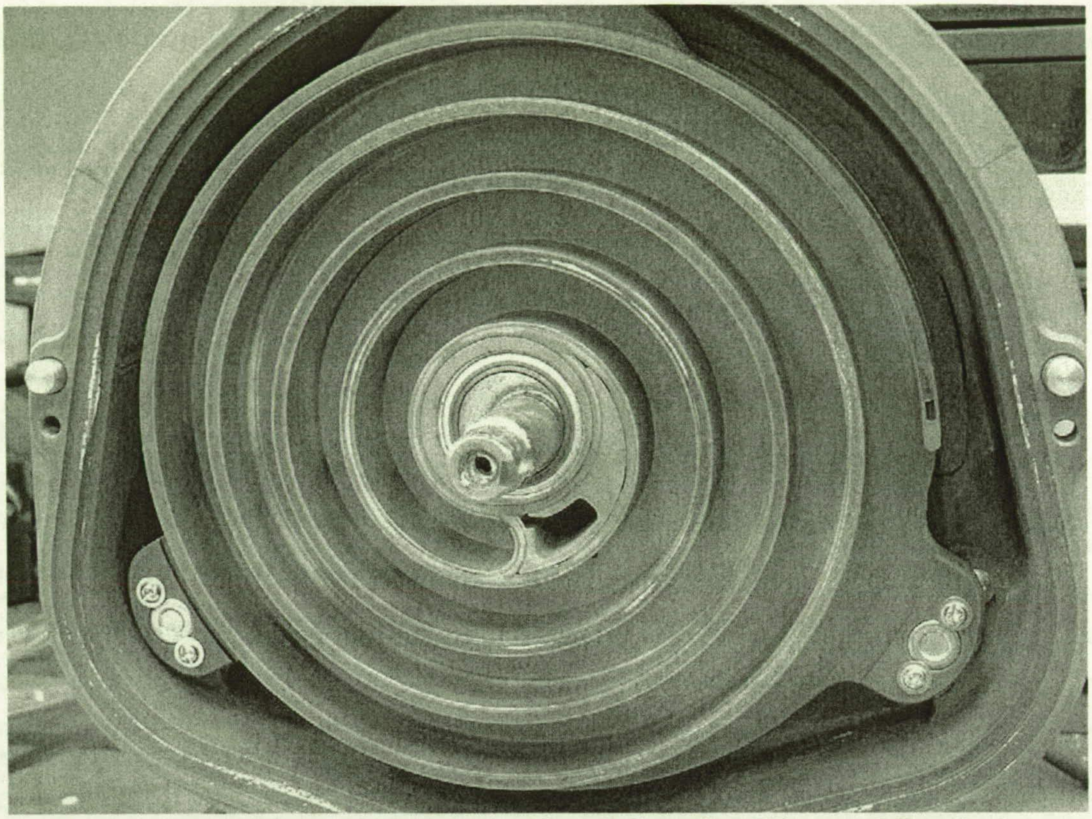

Figure 16 – Iwata ISP 250 Orbiting Scroll Showing Wear and Particulate

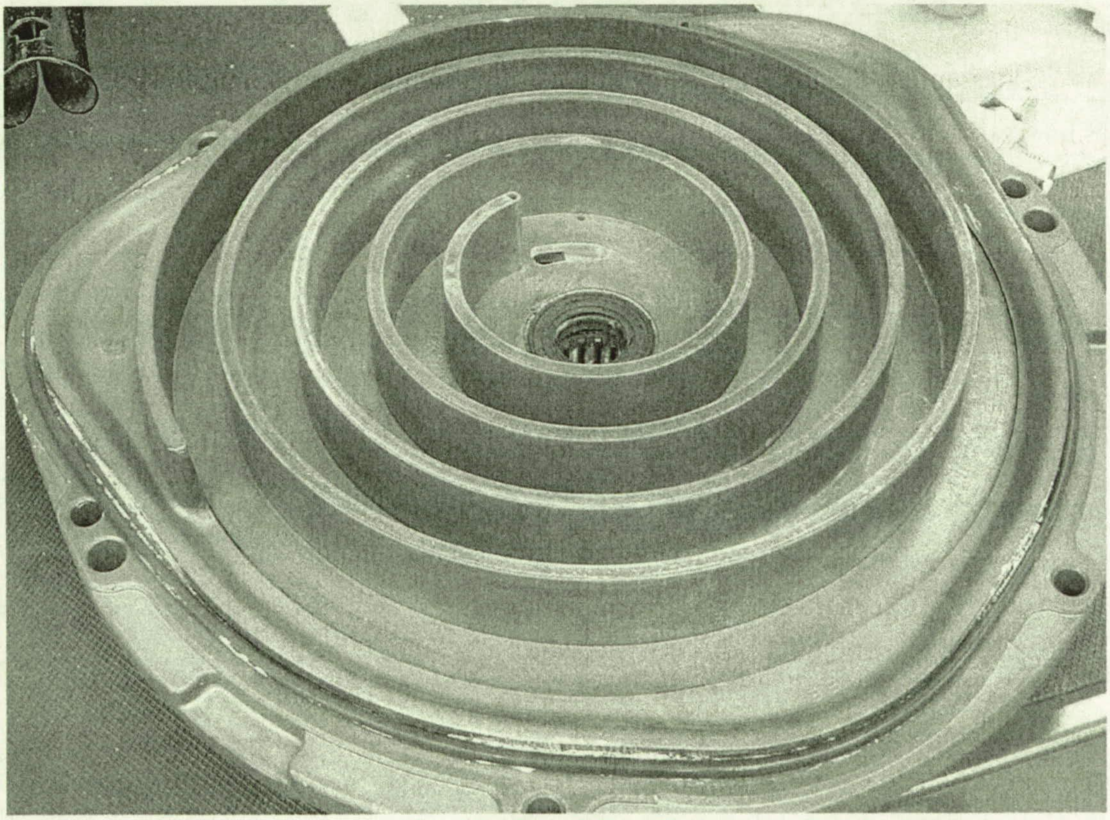

Figure 17 –Iwata ISP 250 Fixed Scroll showing Particulate

2.1.3 VARIAN TRISCROLL 300

The Varian TriScroll 300 scroll pump was run at approximately 300 torr for 30 days. The exhaust was filtered with a 100 micrometer in-line filter to collect particulates generated. After 11 days, the pump experienced significantly higher current draw while flow rate decreased 33% from 71 sLpm to 48 sLpm. Soon after, the pump tripped the circuit breaker. The cause of this problem was determined to be a clogged exhaust filter. The filter was replaced with another 100 micrometer filter and after 11 more days the filter was again clogged. It was replaced a third time, which lasted the remaining 8 days until the long term test was concluded. Also, a loud squeaking sound began 28 days into the test.

During the test, the highest recorded housing temperature was a staggering 104°C, and the highest recorded exhaust temperature was 69°C. Ambient temperature during these measurements was 30°C and 35°C, respectively. Current draw nearly doubled from approximately 7 amps to 12.6 amps while filter was clogged. Due to the wide variation of temperatures and currents, averages are not presented.

After testing was complete, the pump housing was removed and the scroll surfaces examined, which are shown in Figures 18 and 19. Large amounts of particulate were found in two forms. In one form, the particulate material is quite dense and adheres very strongly to the metal of the scroll. It was observed on the flat spaces between the spiral grooves, but not in the filter. It is likely caused by the tip seal being "smashed" against the opposing scroll. The second form of particulate is sawdust-like, being light and with little adherence to metal surfaces. This form was observed both inside the pump housing and in the filter.

The three filters were analyzed for particle size distribution and NVR. Particles in all size ranges and from all filters were too numerous to count, indicating large amounts of particulate. The TriScroll 300 had more particulate than any other pump tested. In addition, the TriScroll 300 had the highest NVR signature at 36.7 mg. The origin of this grease is unclear. See section 2.4 for a detailed contamination analysis.

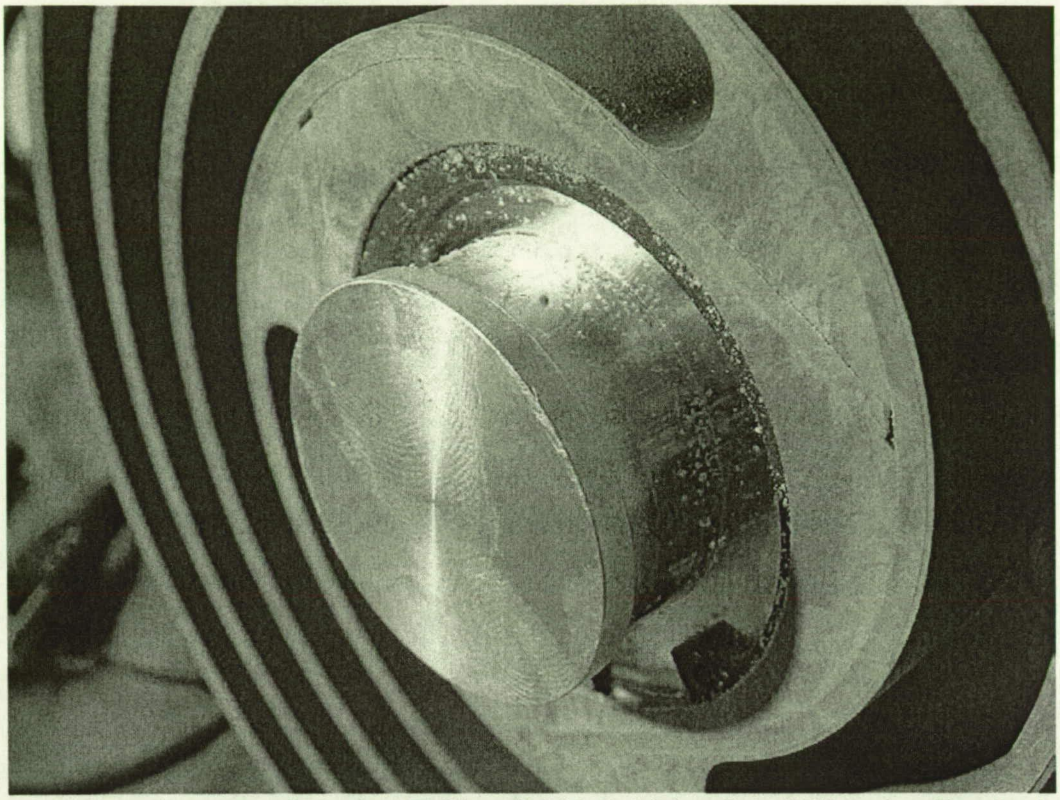
Figure 18 – Close up of Varian TriScroll 300 Orbiting Scroll Showing Particulate

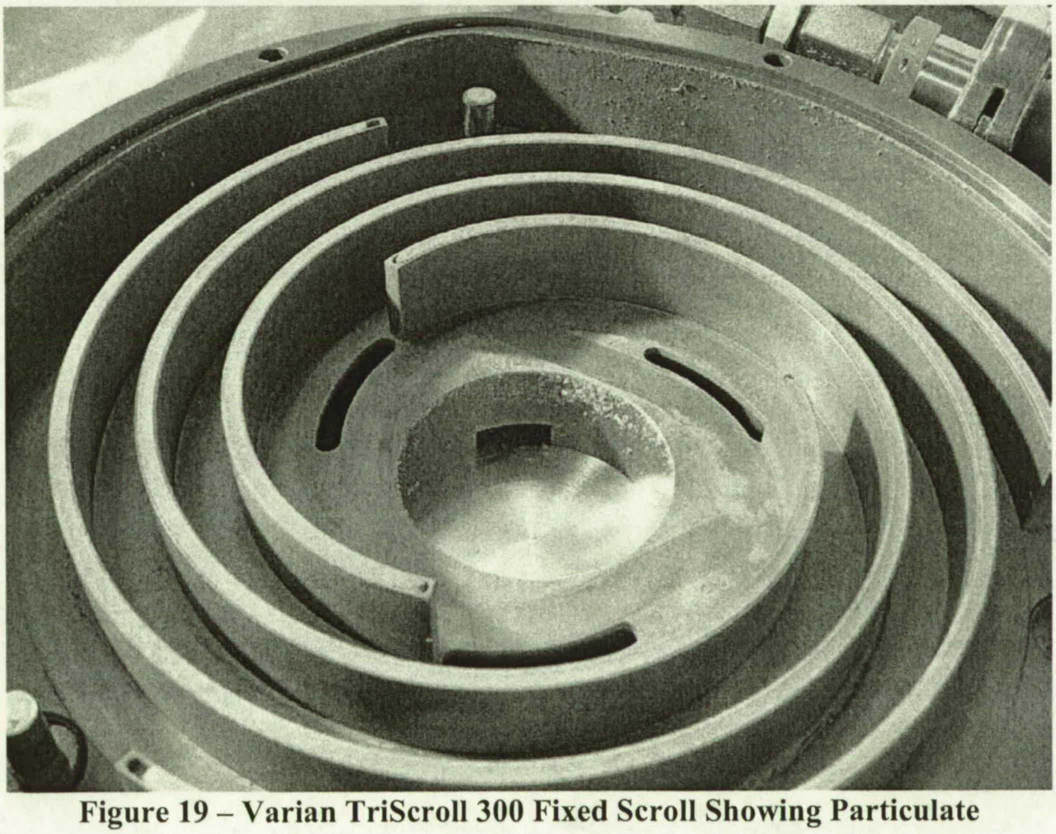
Figure 19 – Varian TriScroll 300 Fixed Scroll Showing Particulate

2.1.4 ADIXEN ACP 28

The Adixen ACP 28 roots pump was run at 300 torr for 30 days as a transport pump. Since the pumping mechanism is non-contacting, no filtering was done on this pump as contamination was not expected. No material or oils were noticed on the exhaust or inlet fitting of the pump after the conclusion of the test.

During the test, the pump shut down several times. Failure was determined to be caused by overheating and activation of the internal thermal protection circuit. The problem was reduced by placing an auxiliary fan near the cooling air intake, although the thermal protection was activated once after the auxiliary fan was installed. This experience suggests that the ACP 28 pump is likely to overheat when placed near thermal sources, such as other pumps in enclosed spaces. The ACP 28 required approximately 9 amps steady state current. Exhaust temperature averaged 66°C and rose as high as 71°C, while ambient temperature averaged 28°C.

2.1.5 VACUUBRAND ME 16

The Vacuubrand ME 16 diaphragm pump was run at 300 torr for 30 days as a transport pump. No filtering was done on this pump as contamination was not expected from diaphragm pumps. Housing and exhaust temperature averaged 47°C, while ambient temperature averaged 28°C. The ME 16 required approximately 4.5 amps steady state current.

During the test, current and temperature remained within deviation limits. However, large variation in measured flow rate was observed. This can be attributed to the restriction of the flow meter and associated tubing. Indeed, even slightly bending the flexible tubing connecting pump exhaust to the flow meter could reduce the indicated flow rate. Refer to section 7 for a more detailed analysis of the exhaust characteristics.

2.2 SAMPLE PUMPS

Sample pumps move a small amount of gas from the transport pump stream throughout the system, ultimately leading to the analyzer. The sample pump requires neither high flow rates nor low ultimate pressure, but a balance of the two, typically 10 -20 sLpm at 50 - 500 torr.
Sample pumps were run for 30 days near 300 torr. Scroll pumps had their exhaust filtered with a 100 micrometer in-line filter.

2.2.1 EDWARDS XDS 10

The Edwards XDS 10 is a candidate sample pump, but was tested as a transport pump. It had the lowest amount of ejected particulate recovered from its exhaust filter, as well as the lowest NVR signature. A more detailed description of the long term test is provided in section 2.1.1.

2.2.2 EDWARDS XDS 5

The Edwards XDS 5 scroll pump was run at 300 torr for 34 days as a sample pump. The exhaust was filtered with a 100 micrometer in-line filter to collect particulate generated. During the test, temperature, flow rate, and current remained within deviation limits. Housing temperature averaged 51°C and exhaust temperature averaged 40°C, while ambient temperature averaged 19°C. The XDS 5 required approximately 4.7 amps steady state current.

After testing, the pump housing was removed and the scroll surfaces examined (Figures 20 and 21). Significantly more particulate was observed than inside the XDS 10. This observation is surprising, given that the XDS 5 and XDS 10 are the same general design and use the same tip seal material. The particulate material was brown in color and seemed adhered to surfaces with moderate strength. Tip seals were worn in a uniform manner.

The filter contents were analyzed for relative particulate count as well as size distribution. Significantly more exhausted particulate was found in the filter of the Edwards XDS 5 than the Edwards XDS 10. NVR results show 2.4 mg of recoverable grease and oil. A detailed contamination analysis can be found in section 2.4.

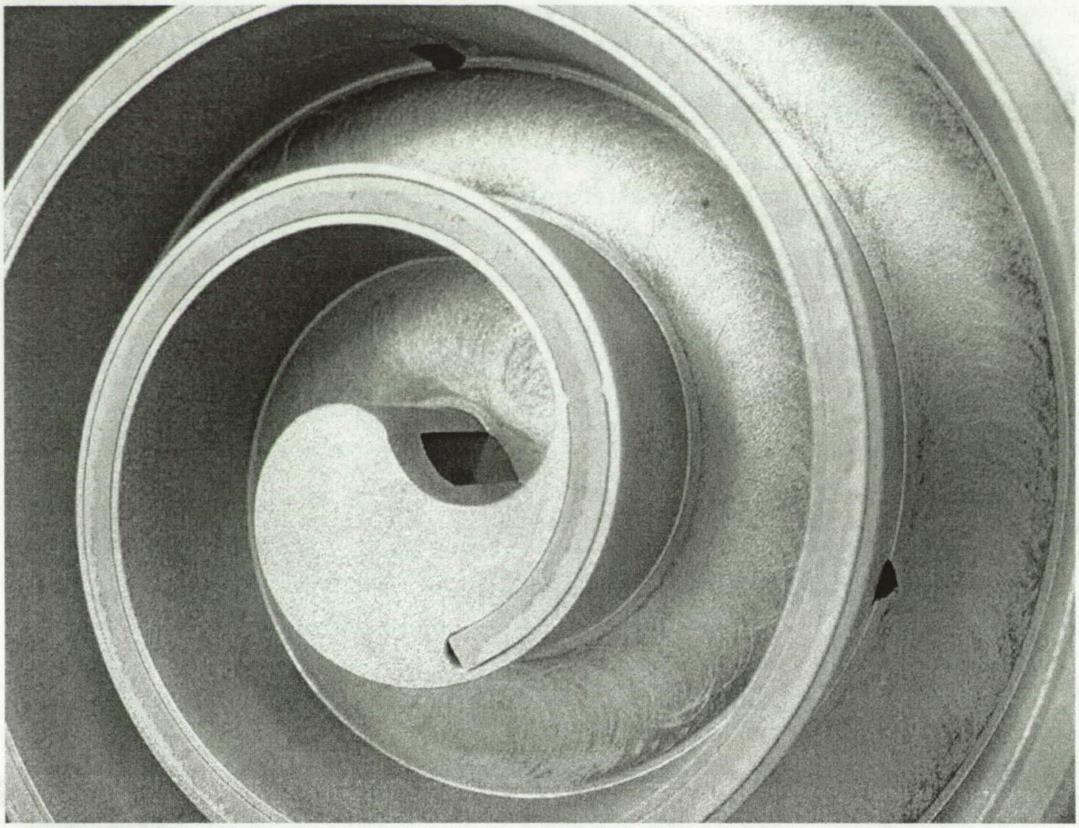

Figure 20 – Close up of Edwards XDS 5 Fixed Scroll Showing Particulate

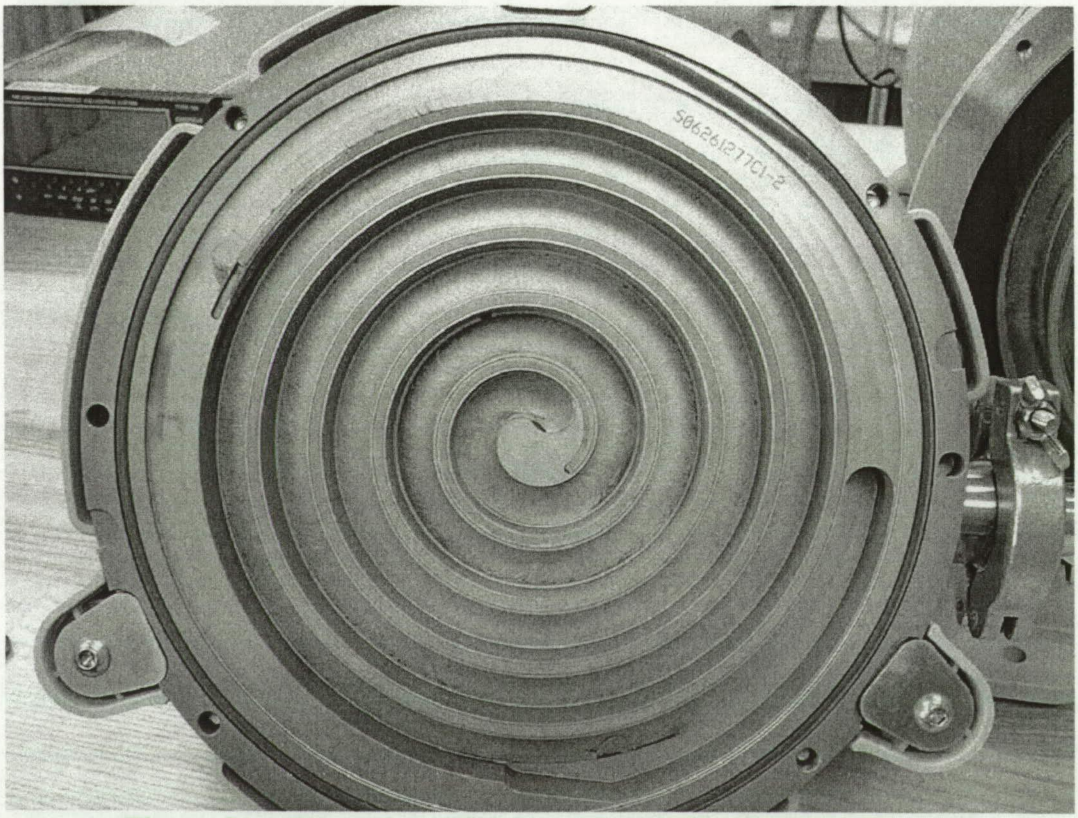

Figure 21 – Edwards XDS 5 Fixed Scroll Showing Particulate

2.2.3 IWATA ISP 250

The Iwata ISP 250 is a candidate sample pump, but was tested as a transport pump. Flow rate, temperature, and current were remarkably stable during the test. Section 2.1.2 provides a more detailed description of the long term test performed.

2.2.4 IWATA ISP 90

The Iwata ISP 90 is a candidate sample pump, but was tested as a backing pump. Temperature and current were remarkably stable during the test. See section 2.4.1 for a more detailed description of the long term test performed.

2.2.5 VACUUBRAND MD 4 Vario

The Vacuubrand MD 4 Vario diaphragm pump was run at 300 torr for 30 days as a candidate sample pump. No filtering was done on this pump as contamination was not expected from diaphragm pumps. Housing temperature averaged 55°C with a maximum of 65°C. Exhaust temperature averaged 80°C with a maximum of 91°C. Ambient temperature averaged 28°C.

During the test, flow rate, temperature, and current remained within deviation limits. A slight "ticking" sound could be heard from inside the pump, but was attributed to shipping damage because the package the pump arrived in was heavily damaged. It did not seem to affect the performance of the pump because the pump met all manufacturer specifications. The MD 4 Vario required approximately 2.2 amps steady state current.

2.2.6 VACUUBRAND MZ 2D

The Vacuubrand MZ 2D diaphragm pump was run at 300 torr for 30 days as a sample pump. No filtering was done on this pump as contamination was not expected from the diaphragm pumps. Housing temperature averaged 68°C and exhaust temperature averaged 94°C, while ambient temperature averaged 28°C. During the test, flow rate, temperature, and current remained within deviation limits. The MZ 2D required approximately 1.9 amps steady state current.

2.2.7 VARIAN TRISCROLL 300

Although the Varian TriScroll 300 is a candidate sample pump, it was tested as a transport pump. By far, this pump produced and ejected the largest amount of particulate of any pump evaluated, as well as the greatest NVR signature. It filled 3 separate exhaust filters and tripped the circuit breaker twice. A more detailed description of this test is provided in section 2.1.3.

2.2.8 VARIAN SH 100

The Varian SH 100 is a candidate sample pump, but was tested as a backing pump. Measurements were within deviation limits during the test period. Some particulate was noted, especially inside the pump housing. A more detailed description of this test is provided in section 2.3.3.

2.3 BACKING PUMPS

Backing pumps rough the high vacuum chamber and provide the high vacuum pump, such as a turbo molecular pump, with the rough vacuum. Backing pumps require low ultimate pressure to assist the compression of the turbo molecular pump and only small flow rates (<1 sLpm). All backing pumps were tested at their ultimate pressure for approximately 30 days. Scroll pumps had their exhaust filtered with a 100 micrometer in-line filter.

2.3.1 VACUUBRAND MD1 VARIO

The Vacuubrand MD1 Vario diaphragm pump was run at ultimate pressure (~ 1 torr) for 30 days. No filtering was done on this pump as contamination was not expected. Housing temperature averaged 41°C while ambient temperature averaged 28°C.

During the test, no anomalies were reported. Note that the pump was run at 20VDC rather than 24VDC during the course of this test because a 24VDC power supply with sufficient current capacity could not be secured for the entire 30 day period. With the Vario technology, power demand was low at approximately 0.75 amps steady state current.

2.3.2 VACUUBRAND MZ 2D

The Vacuubrand MZ 2D is a candidate backing pump, but was tested as a sample pump. Flow rate, pressure, and temperature all were within deviation limits, although the pump ran hotter than other pumps. See section 2.2.6 for a more detailed description of the long term test performed.

2.3.3 KNF 84.4

The KNF Neuberger 84.4 24 VDC diaphragm pump was run at ultimate pressure (<0.5 torr) for 30 days. No filtering was done on this pump as contamination was not expected from diaphragm pumps. Housing temperature averaged 41°C while ambient temperature averaged 28°C. During the test, no significant anomalies were reported. The KNF 84.4 required approximately 0.5 amps DC steady state current.

2.3.4 VARIAN SH 100

The Varian SH 100 scroll pump was run at ultimate pressure (~50 mTorr) for 30 days as a backing pump. The exhaust was filtered with a 100 micrometer in-line filter to collect particulate generated. Current and temperature remained within deviation limits throughout the test. Housing temperature averaged 51°C while ambient temperature averaged 28°C. The SH 100 required approximately 3.5 amps steady state.

After testing was complete, the housing of the pump was removed and the scroll surfaces examined. These surfaces are shown in Figures 22, 23, and 24. Two forms of particulate material were observed. In one form, the particulate material was quite dense and adhered very strongly to the metal of the scroll. It is most commonly observed on the flat spaces between the spiral grooves, and was not observed in the filter. It is likely caused by the tip seal being "smashed" against the opposing scroll. The second form of particulate is sawdust-like. It is light and has little adherence to metal surfaces. This form was observed both in the filter and inside the pump housing. Tip seals were worn unevenly. On both scrolls, the material looks burnt or scorched near the outside of the scroll wrap, but relatively unscathed near the center.

The filter was analyzed to determine particle size distribution and NVR. Some particulate was collected, the majority of which is less than 250 micrometer. NVR showed 1.97 mg of recoverable grease and oil. A detailed contamination analysis is provided in section 2.4.

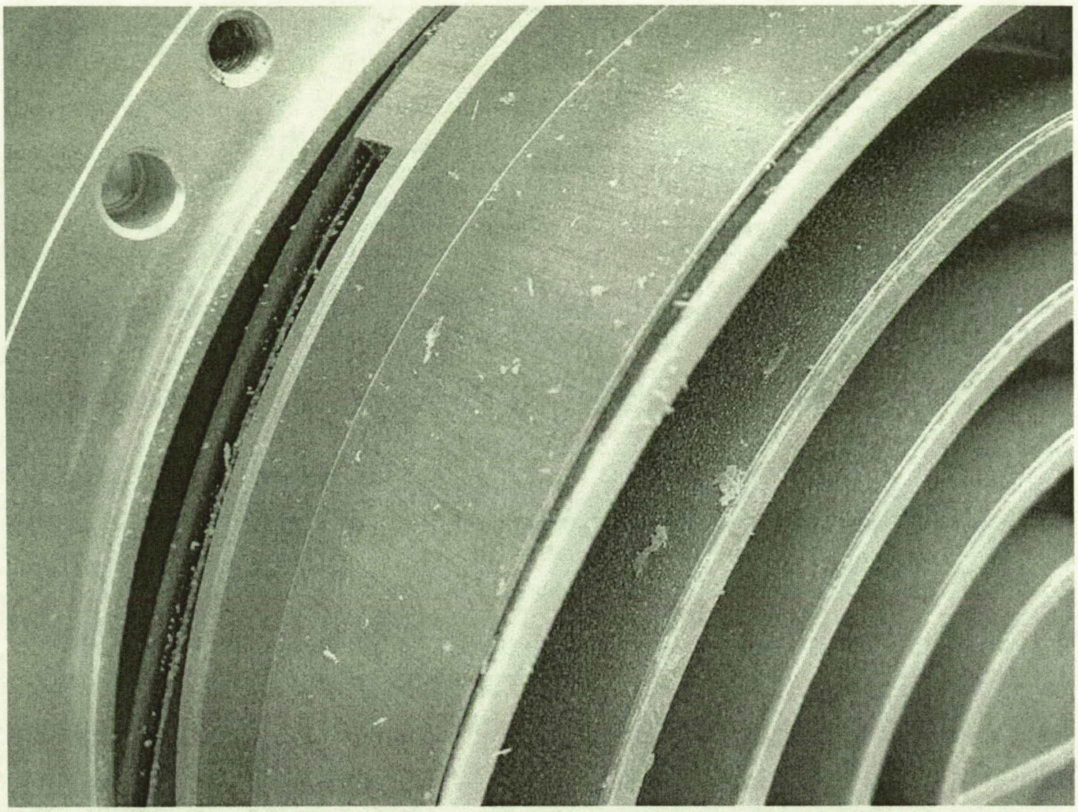

Figure 22 – Close up of Varian SH 100 Orbiting Scroll Showing Particulate

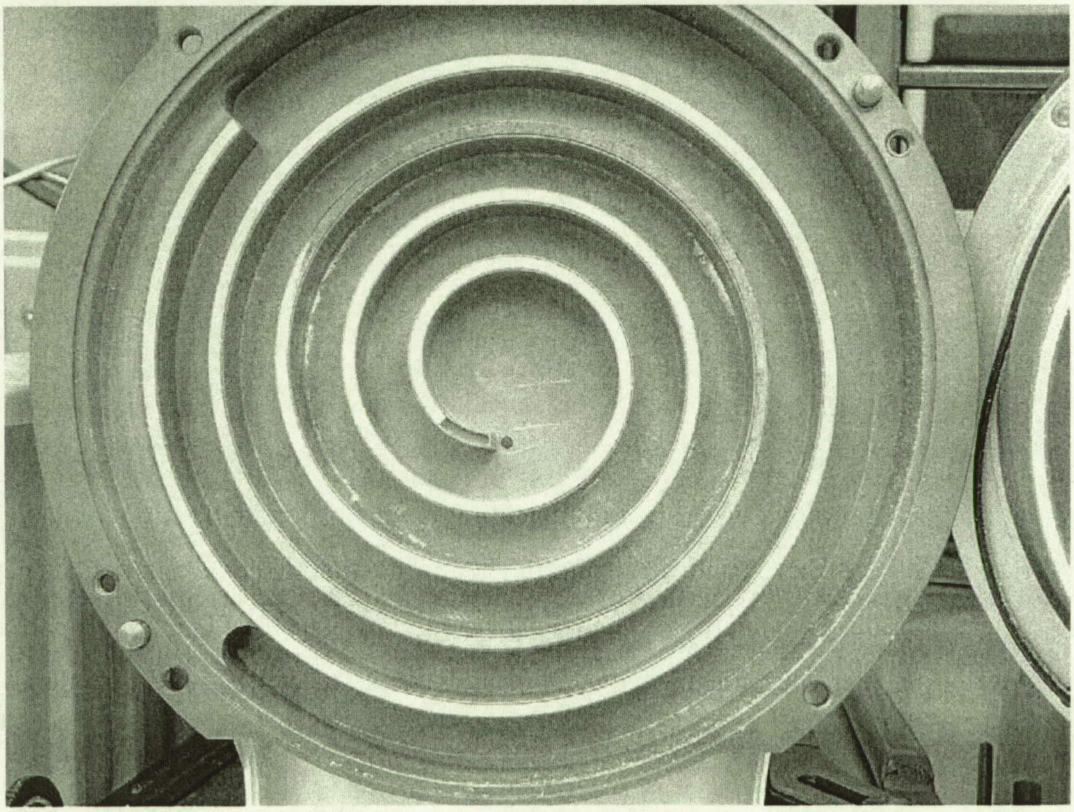

Figure 23 – Varian SH100 Fixed Scroll showing Particulate and Uneven Wear

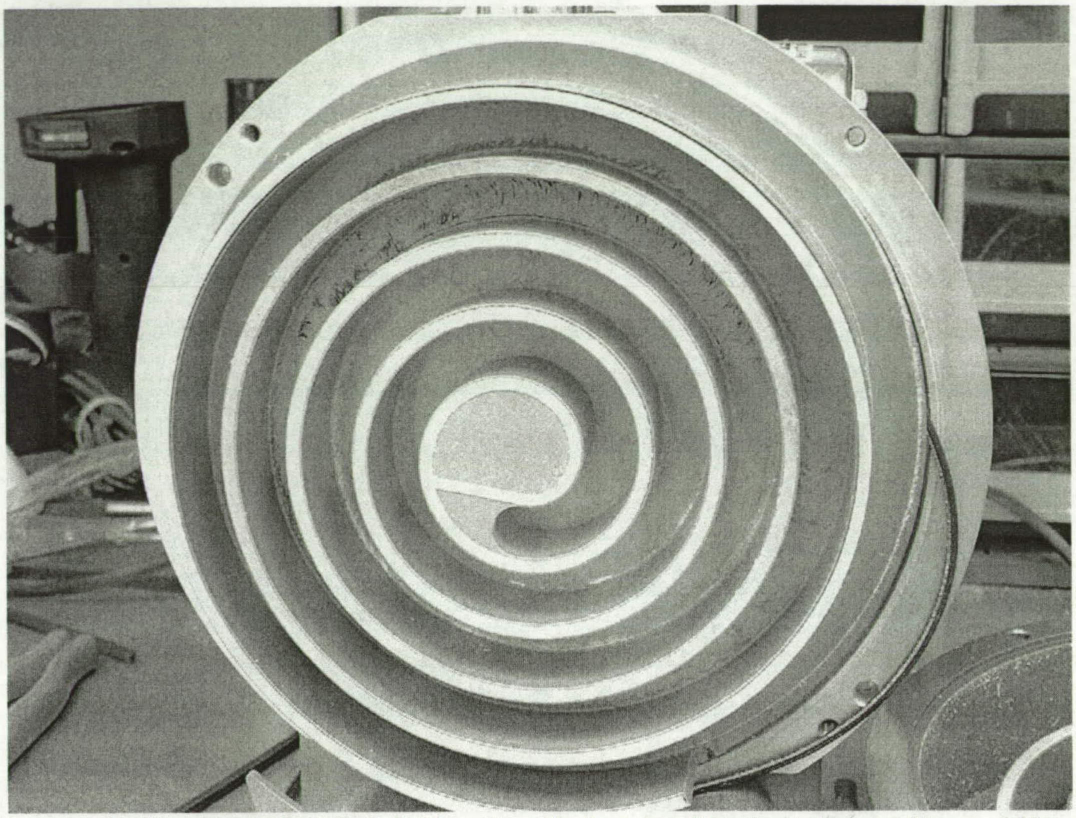

Figure 24 – Varian SH 100 Orbiting Scroll showing Particulate and Uneven Wear

2.3.4 EDWARDS XDD1

The Edwards XDD1 diaphragm pump was run at ultimate pressure (<1 torr) for 30 days as a backing pump. No filtering was done on this pump as contamination was not expected from diaphragm pumps. During the test, current and housing temperature remained within deviation limits. The XDD1 required approximately 1.1 amps. Housing temperature averaged 42°C while ambient temperature averaged 21°C.

2.3.5 IWATA ISP 90

The Iwata ISP 90 scroll pump was run at ultimate pressure (<60 mTorr) for 30 days as a backing pump. The exhaust was filtered with a 100 micrometer in-line filter to collect particulate generated. During the test, current and temperature were remarkably stable. The ISP 90 required approximately 1.7 amps steady state current. Housing temperature averaged 50°C while ambient temperature averaged 28°C.

After testing, the housing of the pump was removed and the scroll surfaces examined. Some build-up of particulate was noted, primarily on the orbiting scroll. The particulate material is dark and tends to adhere to surfaces relatively strongly. The tip seals appear to be worn in a non-uniform way. White wear marks were observed with greater frequency towards the center of the scrolls. Surfaces are shown in Figures 25 and 26. A detailed contamination analysis is provided in section 2.4.

Corrosion was noted on the exhaust fitting, shown in Figure 27. The stainless steel NW 16 centering ring was tarnished, and the coating on the NW 16 exhaust fitting was corroding.

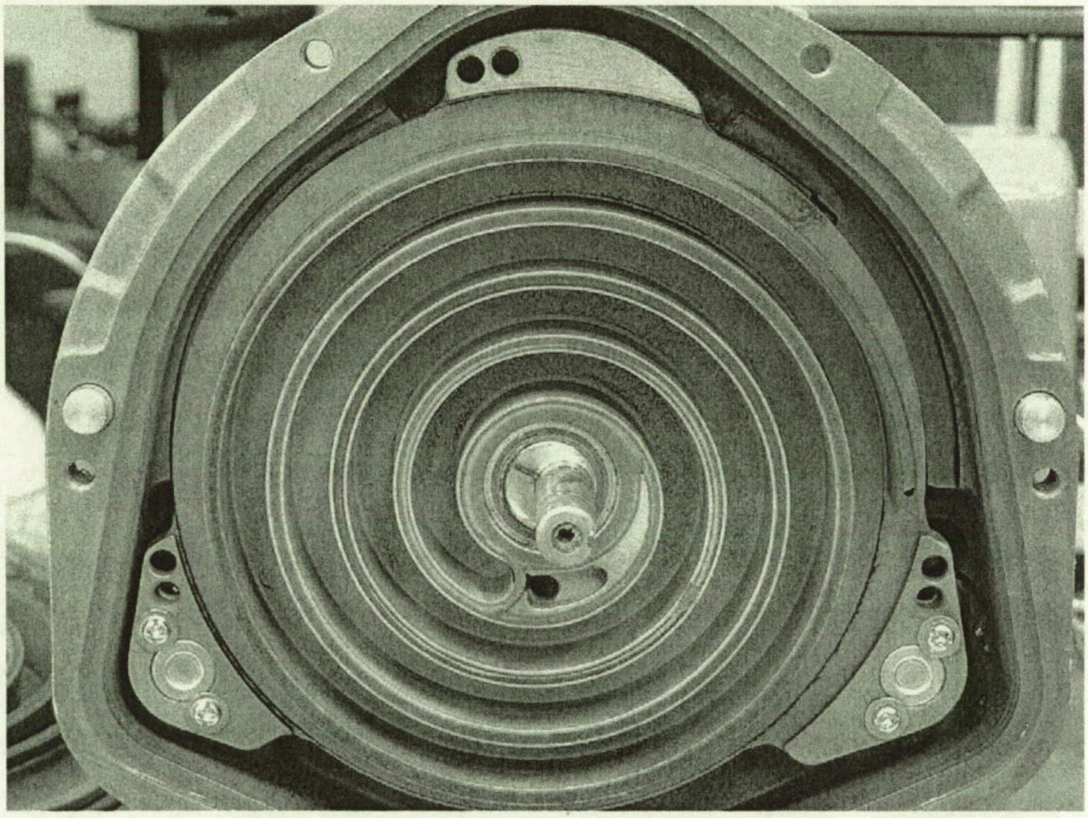

Figure 25 – Iwata ISP 90 Orbiting Scroll showing Particulate

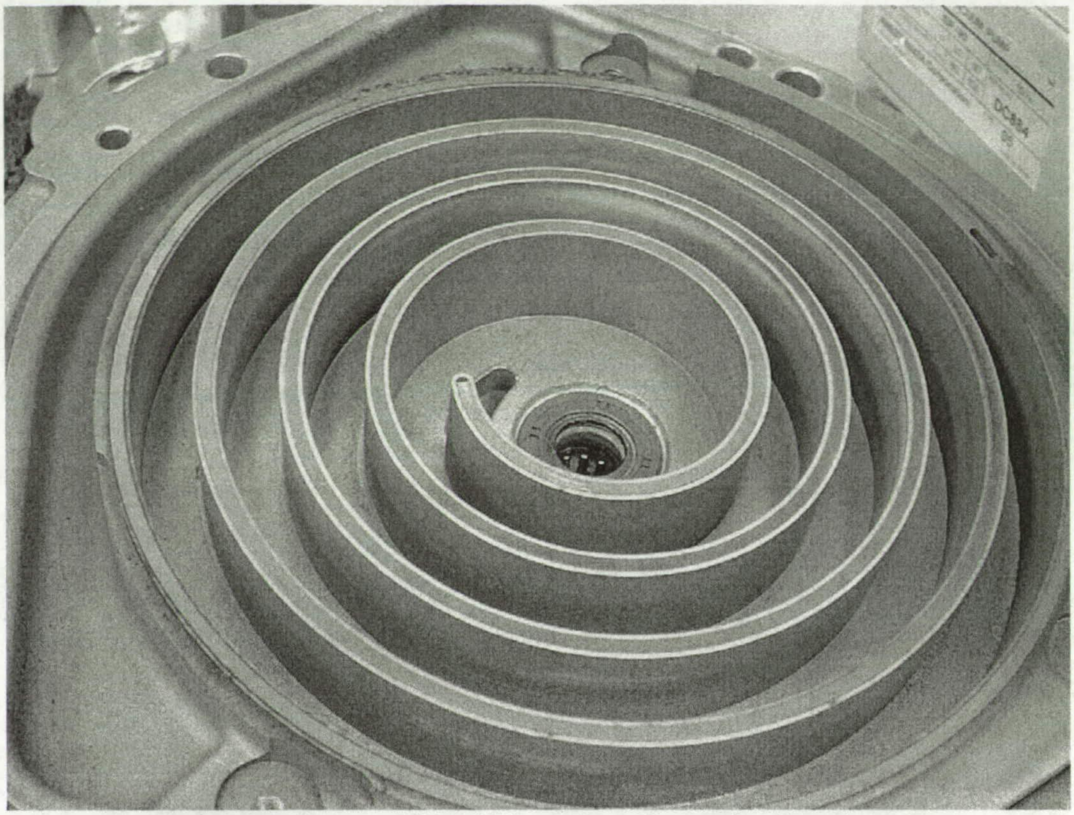

Figure 26 – Iwata ISP 90 Fixed Scroll showing Particulate

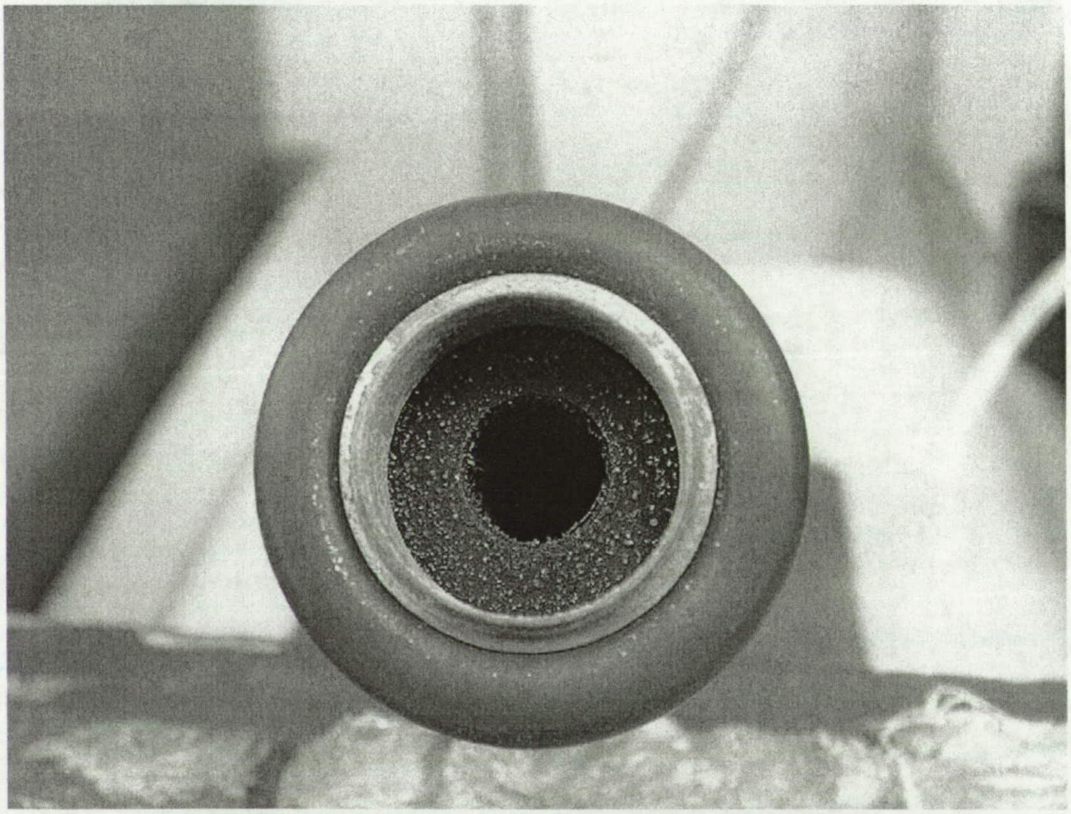

Figure 27 – Iwata ISP 90 Filter Inlet Showing Corrosion

2.4 SCROLL PUMP CONTAMINATION ANALYSIS

The largest downside of using scroll pumps is the particulate generated as the tip seal wears. This particulate can contaminate sensitive instrumentation present in the system, clog orifices and capillaries, or interfere with sensors in the sample delivery system. Any one of these events can cause performance issues or failure of the system. Filter contents collected during the long term test were analyzed for size distribution and NVR. Particulate results are presented based on the number of particles of a certain size range of the recovered particulate emissions.

Filters removed from the pump exhaust were analyzed at a chemical analysis laboratory. A rinse analysis in both the forward and reverse direction was performed, as well as a non-volatile residue analysis. Analysis could only be performed on the particles that were ejected from the pump, embedded in the filter, and were then removed from the filters. The analysis pads were sometimes silted with particles too numerous to count. This is represented with bars labeled "TNTC" in Figure 28. Nevertheless, the results are useful for qualitative comparisons when used in conjunction with other observations, such as visual inspection of the scroll surfaces.

Comparison of particulate count from pumps run at ultimate pressure (turbo backing) with those run at higher pressures is not a fair comparison. Higher gas flow rates transfer a higher percentage of the particles generated to the filter, causing them to appear to make more particulate. This also applies to the amount of NVR transferred to the filters.

Results of testing on transport and sample pumps indicate that the Edwards XDS 10 produced the least amount of recoverable particulate, followed by the Iwata ISP 250. The Edwards XDS 5 produced a significant amount of particulate. This is unexpected because it uses the same tip seal material as the XDS 10, however visual inspection of the exhausts shows significantly more particulate within the exhaust fittings of the XDS 5, confirming the result. The TriScroll 300, by far, produces the largest amount of particulate.

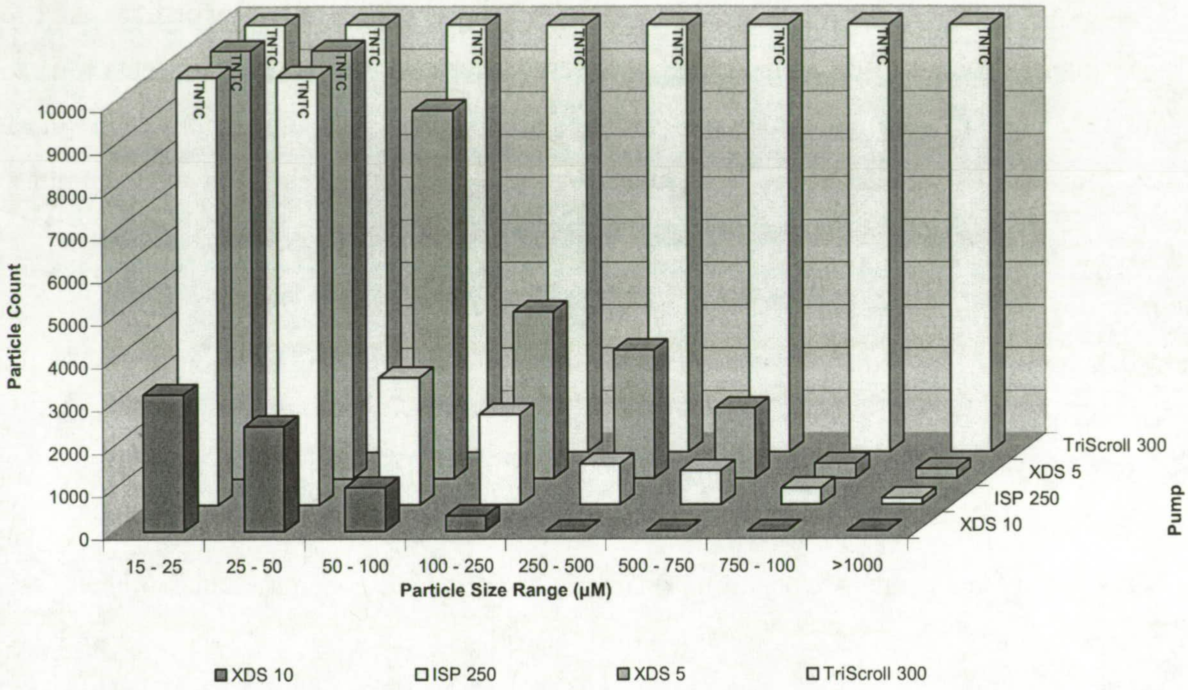

Figure 28 – Particulate Generation of Candidate Transport and Sample Scroll Pumps

Figure 29 shows the results of particulate testing on scroll pumps for backing duty. The SH 100 had less particulate in the filter than the ISP 90. As previously mentioned, this does not necessarily mean that the ISP 90 produces more net particulate, only that more was found in its filter. Due to the low gas flow rates of the backing pumps, only a small amount of the particulate generated inside the pumps actually made it to the filter. Therefore, it is possible that the ISP 90 produces less particulate than the SH-100, but a higher percentage was transferred. A visual inspection of scroll surfaces supports this.

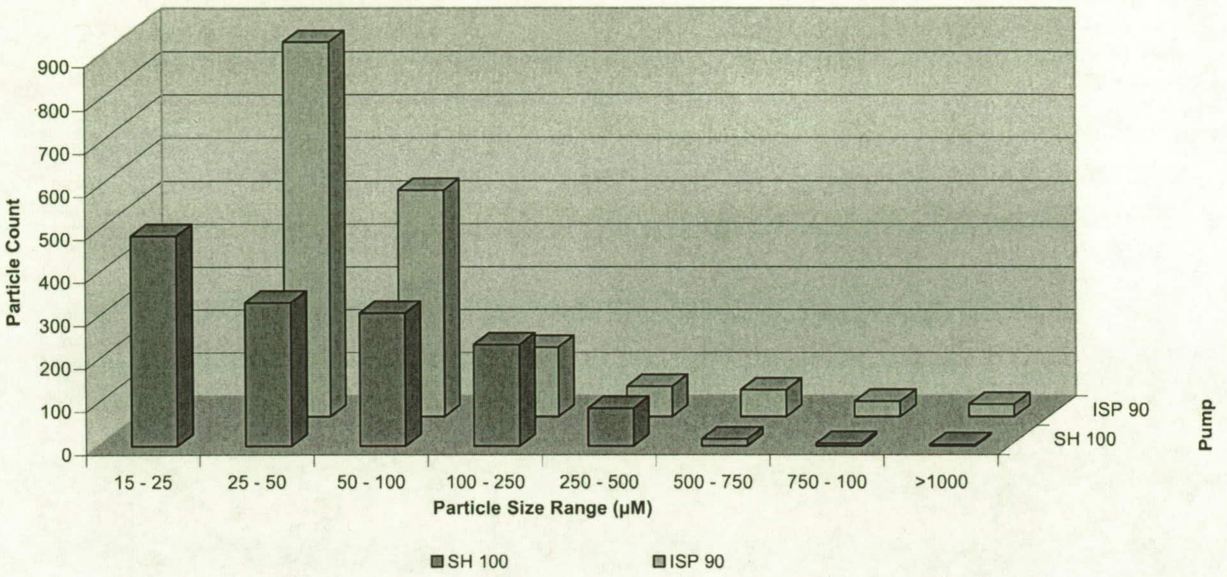

Figure 29 – Particulate Generation of Candidate Backing Scroll Pumps

Filters were also analyzed for NVR, which consists of deposits of greases and oils. Figure 30 shows the results of the analysis. Results are presented as mg of NVR per 100 mL of solvent. Since all filters were washed with 100 mL of solvent, results can be directly compared.

All filters had some level of contamination. Because they were run near ultimate pressure, the low flow rates of the ISP 90 and SH 100 probably did not carry much NVR into the filters. Therefore they are a good idea of the baseline contamination of the filters, indicating that 0-2 mg can be regarded as a baseline contamination level.

The Varian TriScroll 300 had much greater NVR signatures than the other scroll pumps. This partly could be because it required three separate exhaust filters, tripling the amount of contamination, but this cannot fully explain the extremely high readings.

The Iwata ISP 250 had significant NVR signature, indicating that some grease was recovered. In this pump, the scrolls are sealed with an o-ring covered in fluorinated grease, and the pump has one more bearing than usual for the fan. This is likely responsible for its higher NVR signature.

The Edwards XDS 10 had the least amount of NVR of any pump at 0.5 mg, although it cannot be said with certainty that the XDS 10 produces less NVR than the SH 100 or ISP 90 or XDS 5.

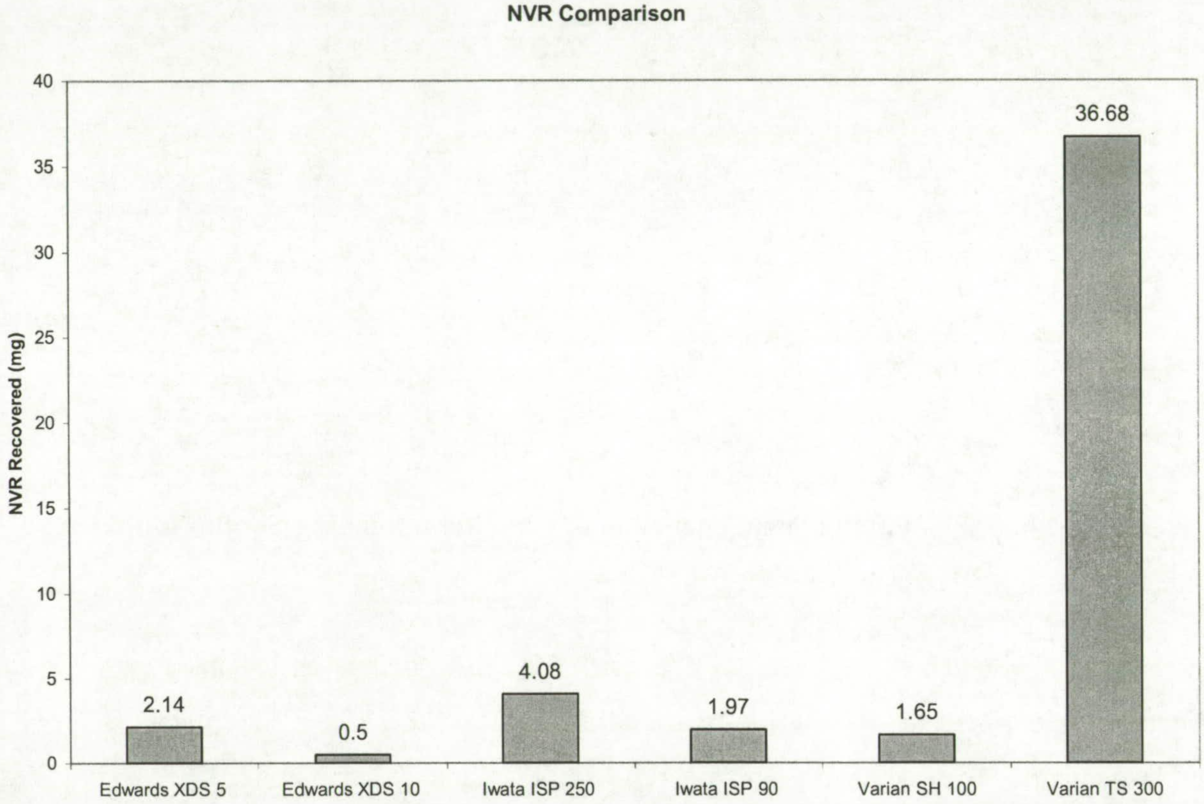

Figure 30 – NVR Recovered from Scroll Pump Filters

2.5 LONG TERM TEST DISCUSSION

Long term testing of scroll pumps reiterates that all scroll pumps create particulate. The quantity and qualities of the particulate material vary by pump and manufacturer. The TriScroll 300 produced the largest amount of particulate. The Edwards XDS 10 was found to eject the least amount of particulate, and comparatively little was observed within the pump. The Iwata ISP 250 also produced little particulate compared to the Varian TriScroll 300. Scroll pumps produce moderate amounts of heat, and are moderately power efficient, in terms of pumping speed per unit power.

All diaphragm pumps performed as expected, with no significant anomalies. They typically have low or moderate power demands, although they are less efficient than scroll pumps in terms of pumping speed. As a whole, they are clean and dry pumps with reliable, consistent performance.

The Adixen ACP 28 roots pump has high pumping speed but large power requirements and produces large amounts of heat. In enclosed spaces and near other pumps, heat generation may cause the thermal protection circuit to trip, shutting the pump off for at least several minutes, causing temporary failure of a pumping system.

3. PUMP SPEED TEST

The purpose of the pump speed test is to determine and/or verify the pump speed curves provided by the pump manufacturer. Curves were also determined for helium, which are usually not provided by the manufacturer. Helium speed curves are essential because of the large number of applications which use helium. Additionally, the current drawn by the pump at each pressure was determined. This information is useful when determining breaker and power requirements of pumps and the systems that use them.

The data was generated using 3 mass flow meters, a 1000 torr pressure transducer, and throttling valves. Flow meters were of the 300, 10, and 1 sLpm ranges. Throttling valves were sized appropriately to the meter being used. The pressure transducer was connected to the inlet of the pump via 3-way tee. The test gas was attached to the inlet of each flow meter. By opening the valve, and observing both the mass flow and pressure, it was possible to generate pumping speed curves. When the flow meter was out of range, the valve was closed and next largest flow meter was then used. For every point, the current was measured with an inductive ammeter.

Dividing the mass flow rate in torr-L/min by the inlet pressure in torr yields the pumping speed in L/min at that pressure. Graphs of inlet pressure vs. pumping speed and inlet pressure vs. current were then developed. Pumping speed and current demand at notable pressures are listed in Tables 2, 3, and 4. Curves themselves are presented in Figures 36 – 55 in Appendix A. Note that curves for air and nitrogen are similar. This is because air is comprised mostly of nitrogen and oxygen, another diatomic gas with molecular weight similar to nitrogen.

Error in measurement becomes much greater near the ultimate pressure of any pump. This is due to many factors which influence the ultimate pressure of the pumping system, such as chamber cleanliness and preparation, commodity moisture content, error in measurement devices, and extra gas load due to small leaks.

Some helium speed curves exhibit strange behavior, such as rising exponentially at higher pressures when it is expected to remain constant. This occurs due a systematic error in measurement with thermal flow meters. Unlike nitrogen, which most thermal flow meters are calibrated for, helium has a negative Joule-Thompson coefficient at standard temperatures. This means that the temperature of helium increases as it expands (drops pressure). In this case, helium is flowing from a high pressure cylinder, through a throttling valve, through a flow meter, and into a vacuum pump, so expansion is dramatic. The pressure profile is such that significant expansion occurs within the flow meter, increasing temperature of the gas. This is registered by the flow meter as an increase in gas flow rate. This phenomenon occurs much more strongly at high flow rates than low flow rates. Therefore more error is seen at the higher pressure end of pumping speed curves.

Another error is a disjointed curve when switching between two different flow meters. The MZ 2D speed curve shows this behavior. This error is caused when two flow meters do not have the same zero, or one flow meter has large error relative to the other. In this case, a 300 sLpm with 1.5% full scale error was used with a 10 sLpm with 1.0% full scale error. The acceptable error for the largest flow meter is 4.5 sLpm, a full 45% of the full range of the 10 sLpm flow meter. This difference accounts for the disjointed nature seen in some graphs.

3.1 TRANSPORT PUMP SPEED TEST RESULTS AND DISCUSSION

Effective transport pumps transfer high flow rates at a few hundred torr. High flow rates ensure a quick system response time because it reduces the residence time of the sample in the transport line. Higher pressures are required so that the sample delivery system can effectively deliver the sample to the analyzer. The ideal transport pump has low power demand, a very high pumping speed, and pumps helium at the same rate as air or nitrogen. Table 2 shows the speed and current at a typical transport pressure for nitrogen and helium.

Table 2 – Speed and Power Consumption of Candidate Transport Pumps at 350 torr

Transport Pump Comparison: Speed (Lpm) at 350 Torr				
Pump	**N_2**	**He**	**N_2 Current (Amps)**	**He Current (Amps)**
Edwards XDS 10	220	195	6.8†	5.1
Iwata ISP 250	250	230	3.2	3.1
Adixen ACP 28	290	220	8.8†	6.5
Vacuubrand ME 16	205	225	5.0	4.4
Varian TriScroll 300	145	125	4.4	3.6

† Nitrogen current unavailable. Value is air current at 350 torr.

Scroll pumps typically have constant pumping speeds from approximately 1 torr to atmospheric pressure. They pump helium at a rate slightly less than that of nitrogen or air, and the helium speed curve is similar in shape to the nitrogen and air speed curve. Below 1 torr pumping speed drops dramatically until it reaches zero at ultimate pressure. All Edwards and Iwata scroll pumps follow this trend. The exception is the Varian TriScroll 300, shown in Figure 51. It has a highly non-linear pumping speed curve which peaks with a speed of 225 Lpm at approximately 10 torr. Below 10 torr the pumping speed falls off rapidly. There is a substantial drop in pumping speed between 100 and 600 torr, reaching less than 150 Lpm near 350 torr. The pumping speed rises again to near 200 Lpm at atmospheric pressure.

The roots pump also exhibited highly non-linear pumping speed curves. When operating in air or nitrogen, the Adixen ACP 28 has peak pumping speed near 425 Lpm between 1 and 10 torr. This curve is shown in Figure 36. Above 10 torr the pumping speed gradually falls off until it reaches 275 Lpm at atmospheric pressure. The helium speed curve for the ACP 28, however, has a very different shape. Pumping speed for helium is always significantly less than for air or nitrogen, and is essentially constant at 220 Lpm from atmosphere to approximately 10 torr. Below 10 torr, the pumping speed falls off rapidly until it reaches zero at an ultimate pressure of ~1 torr. The significantly lower helium pumping speed is attributed to the clearances between non-contacting lobes, which allow fast moving helium atoms to travel backwards through the pump.

The Vacuubrand ME 16 exhibited a typical diaphragm pump speed curve, shown in Figure 47. Helium is pumped at a rate similar to that of air and nitrogen. Pumping speed is relatively constant at 230 Lpm above 500 torr, and begins to decline slowly, reaching 205 Lpm at 350 torr. Pumping speed drops off very rapidly near the ultimate pressure of 60 torr. The helium flow rate curve shows the helium pumping speed surpassing that of air and nitrogen at pressures above 200 torr. This is attributed to measurement error. Helium pumping probably occurs at a rate slightly less than that of nitrogen and air, as seen in the lower pressure end of the curve.

At transport pressures, current demand varied widely between pumps and amongst gases. Helium typically requires less current at a given pressure than nitrogen or air does, and the shape of the current curve is rarely similar to that of nitrogen or air. Most pumps have a smaller helium flow rate at a given pressure, and this may account for some of the difference. The Iwata ISP 250 requires the least current of all candidate transport pumps, requiring slightly above 3 amps for both nitrogen and helium. The Adixen ACP 28 requires the most at 8.8 amps for nitrogen/air and 6.5 amps for helium. Note from Figure 52 that the TriScroll 300 had rather scattered current curves.

3.2 SAMPLE PUMP SPEED TEST RESULTS AND DISCUSSION

Sample pumps move a small amount of gas from the transport pump stream throughout the system, ultimately leading to the analyzer. The sample pump requires neither high flow rates nor low ultimate pressure, but a balance of the two. The ideal sample transport pump has a moderate flow rate at 1 to 10 torr, low power demand, pumps helium, nitrogen, and air at the same speed, and has a very smooth gas flow. Table 3 shows the speed and power consumption of candidate sample pumps at a typically sample delivery pressure.

Table 3 – Speed and Power Consumption of Candidate Sample Pumps at 10 torr

Sample Pump Comparison: Speed (Lpm) at 10 Torr				
Pump	**N_2**	**He**	**N_2 Current (Amps)**	**He Current (Amps)**
Edwards XDS 5	95	90	4.8	4.6
Edwards XDS 10	200	190	5.5	4.7
Iwata ISP 90	85	80	1.7	1.8
Vacuubrand MD4 Vario	15	15	0.5	0.5
Vacuubrand MZ 2D	15	20*	1.5	1.5
Varian TriScroll 300	225	225	3.4	3.4
Varian SH 100	115	115	3.8	3.9

* Value high due to error in flow meter.

The scroll pumps evaluated here typically have constant pumping speeds from approximately 1 torr to atmospheric pressure. They pump helium at a rate slightly less than that of nitrogen or air, and the helium speed curve is similar in shape to the nitrogen and air speed curve. Below 1 torr, pumping speed drops dramatically until it reaches zero at ultimate pressure. All Edwards and Iwata scroll pumps follow this trend. The exception is the Varian TriScroll 300, which has a highly non-linear pumping speed curve which peaks with a speed of 225 Lpm at approximately 10 torr. Below 10 torr the pumping speed falls off rapidly. There is a substantial drop in pumping speed between 100 and 600 torr, reaching less than 150 Lpm near 350 torr. The pumping speed rises again to near 200 Lpm at atmospheric pressure. The Varian SH 100 does not have the shape of the TriScroll; its curves are similar to that of the Iwata and Edwards scroll pumps, which remain roughly constant from 1 torr to atmosphere.

For the Vacuubrand MD4 and MZ 2D, pumping speed is relatively constant at higher pressures, and begins a gradual decline which accelerates rapidly as ultimate pressure is approached. Near 10 torr, the speed for both is approximately 15 Lpm. Some flow meter error was experienced in generating the helium flow rate curve, showing helium pumping speed surpassing that of air and nitrogen.

At sample pressures, current demand varied greatly amongst pumps, but not amongst gases. Helium required only slightly less current than nitrogen or air. This is because the gas flow rates at this pressure are small, and therefore the difference in flow rates between nitrogen/air and helium are also small. The power required to compress the gas is less significant compared to the power required for mechanical operation of the pump itself. This statement becomes less true for pumps with larger flow rates, such as the Edwards XDS 10.

Vario is a variable speed technology developed by Vacuubrand. Near ultimate pressure, the pump slows down in speed to reduce wear and power consumption. The Vario technology reduced current demand of the MD4 Vario to only 0.5 amps, one-third of the current required by the MZ 2D. However, note the large variation in current demand from the MD 4 Vario, shown in Figure 49.

3.3 BACKING PUMP SPEED TEST RESULTS AND DISCUSSION

Backing pumps rough the high vacuum chamber and provide the high vacuum pump, often a turbo molecular pump in gas analysis applications, with rough vacuum. Backing pumps require low ultimate pressure to assist the compression of the turbo molecular pump and small flow rates. The ideal backing pump has low ultimate pressure, pumps helium at a rate similar to that of air or nitrogen, a modest pumping speed which rises rapidly with inlet pressure, and low power demand.

Table 4 shows the speed, power consumption, and ultimate pressure of candidate backing pumps at a maximum acceptable backing pressure.

Table 4 – Speed and Power Consumption of Candidate Backing Pumps at 5 torr

Backing Pump Comparison: Ultimate Pressure and Speed (Lpm) at 5 Torr					
Pump	**N_2**	**He**	**N_2 Current (Amps)**	**He Current (Amps)**	**Ultimate Pressure (Torr)***
Edwards XDS 5	90	90	4.9	4.6	0.031
Edwards XDD1	13	10	1.1	1.1	0.945
Iwata ISP 90	80	80	1.7	1.7	0.060
Vacuubrand MZ 2D	4	5	1.5	1.5	3.00
Vacuubrand MD 1 Vario	11	10	1.8 (DC)	1.6 (DC)	1.08
KNF 84.4	2	2	0.88 (DC)	1.00 (DC)	0.25
Varian SH 100	110	110	3.8	3.9	0.058

* Represents lowest pressure measured during testing. Actual ultimate pressure may be lower, and vary with wear.

All pumping speed curves decrease near the ultimate pressure of the pump. A steeper pumping speed curve is desirable, given a certain ultimate pressure. This steeper curve indicates a rapid increase in pumping speed as pressure rises, and if a small leak were to occur, a pump with a steeper curve will maintain a lower pressure.

The Edwards XDS 5, Varian SH 100 and Iwata ISP 90 have similar speed curves, with the XDS 5 having slightly higher pumping speed. Helium, air, and nitrogen are pumped at similar speeds. Although they have the lowest ultimate pressure and highest pumping speeds, scroll pumps also require the most power, and are often physically larger.

Diaphragm pumps have higher ultimate pressures, lower pumping speeds, and less steep pumping speed curves. Pumping speeds range from 13 Lpm for the Edwards XDD1 to 2 Lpm for the KNF 84.4. The diaphragm pumps tested, however, require less power than scroll pumps. The Vario technology from Vacuubrand reduces the power required by the MD1 Vario to 43 Watts at 5 torr. The KNF 84.4, a significantly smaller pump, requires only 21 Watts.

4. VOLTAGE VARIANCE TEST

The purpose of the voltage variance test is to quantify the effects input voltage variation has on the pump during nominal operating conditions. In a brown-out condition, pumps could increase current demand to the point where breakers are tripped or shutdown occurs. Excessively high voltage could damage the pump motor or electronics. This test attempts to quantify the results of voltage variance.

Pumps were operated at 300 torr or ultimate pressure, and voltage was varied with a transformer or adjustable DC power supply to voltages both above and below the nominal operating voltage of the pump. Current and pressure was measured at each voltage. In addition, the minimum voltage required to sustain operation was determined.

Pumps were tested to determine current and pressure variations as input voltage was varied. In addition, the minimum input voltage required to sustain operation is listed in Table 5. This voltage is not the minimum input voltage required to start the pump, rather to maintain operation. Curves presented in Figures 57 – 62 in Appendix B show the variation of inlet pressure and current with voltage.

Edwards scroll pumps require the highest voltage to sustain operation, while Varian scroll pumps require the least voltage to sustain their operation. The Edwards XDD1 required the least amount of voltage of diaphragm pumps tested.

Table 5 – Minimum Voltage Required for Sustained Operation

Pump	Function	Minimum Voltage Required for Sustained Operation
Adixen ACP 28	Transport	83 VAC
Vacuubrand ME 16	Transport	95 VAC
Iwata ISP 250	Transport, Sample	78 VAC
Edwards XDS 10	Transport, Sample	100 VAC
Varian Triscroll 300	Transport, Sample	58 VAC
Vacuubrand MD 4 Vario	Sample	72 VAC
Vacuubrand MZ 2D	Sample, Backing	72 VAC
Iwata ISP 90	Sample, Backing	64 VAC
Edwards XDS 5	Sample, Backing	90 VAC
Varian SH 100	Sample, Backing	57 VAC
Edwards XDD1	Backing	47 VAC
KNF Neuberger 84.4	Backing	14.5 VDC*
Vacuubrand MD 1 Vario	Backing	14.8 VDC*

* Tested at Ultimate Pressure

5. VIBRATION TESTING

Vibration is the motion of a body about an equilibrium position. The motion can be the result of motors or rotating equipment inside of the machine that is vibrating, or induced on a body by an outside force. Both emissions from operation and susceptibility to induced vibration are investigated. All motion can be described in one of six ways: X, Y, and Z directions, as well as 3 possible spherical rotations between these axes. For purposes of this test, only motion in the Cartesian X, Y, and Z directions are considered. The X-axis is defined as the axis of rotation of the pump motor; Y is defined as the axis perpendicular to the pump motor axis and parallel to the mounting surface, and the Z axis orthogonal to both the pump motor axis and mounting surface.

Vibration emissions can affect the precision instrumentation associated with gas analysis systems, as well as accelerate wear on turbo molecular pumps rotating at high speed. Emissions are measured using accelerometers, which measure the acceleration a pump undergoes as it vibrates in all 3 directions. This vibration was measured both on the pump itself and on a tabletop the pump was resting on. By doing this, it is possible to determine the vibration that can travel along hoses and electrical connectors, as well as the vibration transmitted to the mounting surface. For this test, no extra vibration isolation was added.

The results of vibration emissions testing are usually presented in root mean square acceleration, abbreviated G_{rms}. By taking the root mean square of the acceleration, negative accelerations become positive and contribute to the overall acceleration experienced by the body. Otherwise, the average acceleration would be zero because the body is vibrating around an equilibrium position. As the abbreviation implies, G_{rms} is related to the acceleration due to gravity on the earth, but is different because it accounts for the oscillatory nature of vibrations, while the acceleration due to gravity occurs only in one direction. Vibration emissions data are presented in Figures 31, 32, and 33.

Pumps not only generate vibration while in operation, they can be susceptible to vibration induced by outside factors. Pumps were shaken to launch vibration spectra. Pumps were bolted to a ¼" aluminum plate in a half-size 24" rack using mounting points already existing on the pump. Turbo backing pumps were run at ultimate pressure while shaken, transport and sample pumps were run at approximately 300 torr. Pass/fail criteria was based on whether or not the pump continued to function after being shaken. Note that rubber feet were sometimes removed to provide mounting points.

5.1 VIBRATION EMISSIONS

The vibration of pumps depends on the inlet pressure they are operated at. To facilitate easier testing by the vibration lab, pumps were tested at both ambient pressure and ultimate pressure. Transport pump vibration data is presented from data collected at ambient pressure. Sample pump and backing pump vibration data is presented from data collected at ultimate pressure.

Each graph shows the root mean square acceleration at both the inlet and tabletop. Relative comparisons can be made between vibration at pump inlets and between the vibrations transferred to the tabletop. Low vibration is desirable, although some vibration is tolerable. Pumps having high relative vibrations will require third party vibration isolation systems if used.

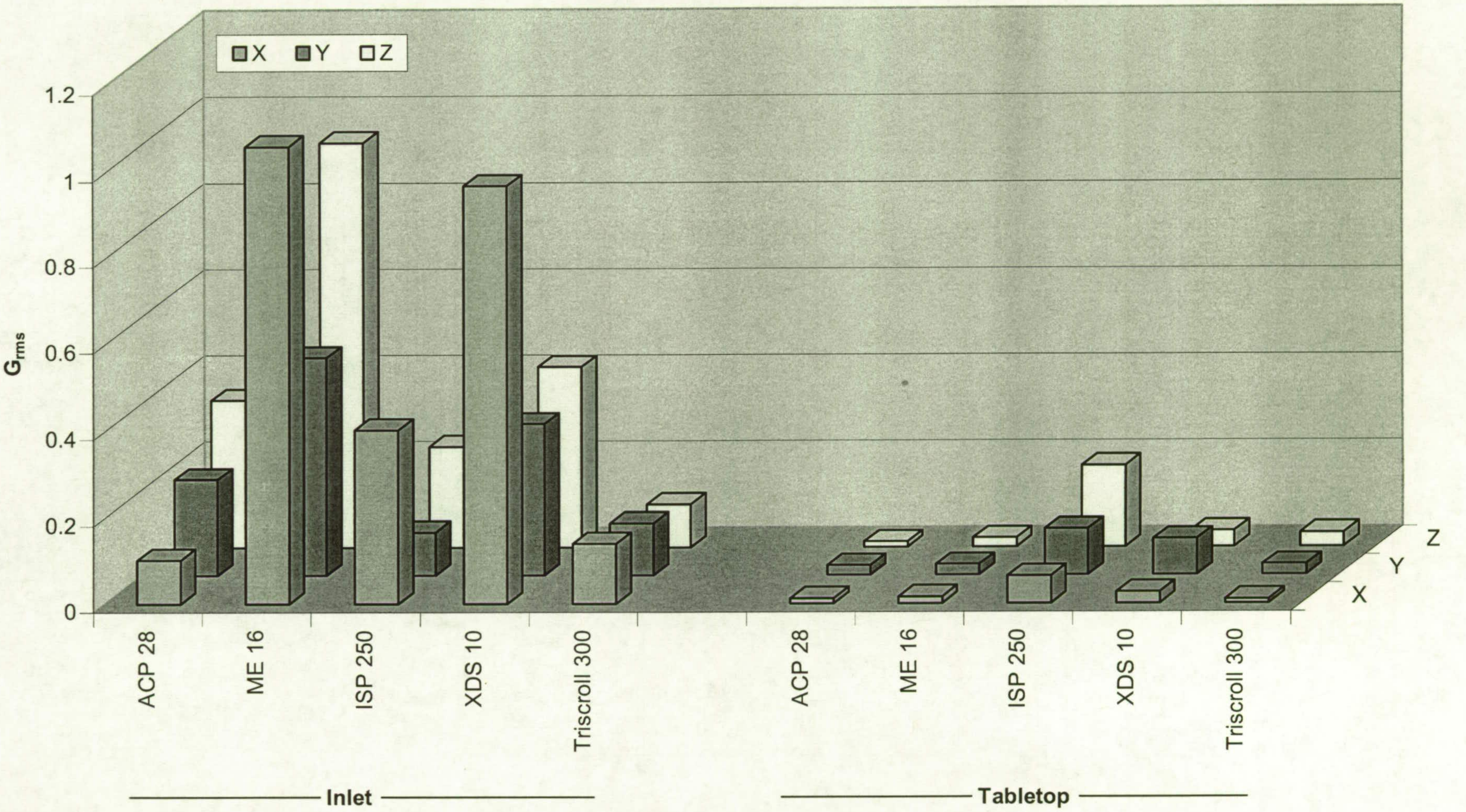

Figure 31 – Vibration at Pump Inlet and Tabletop for Transport Pumps

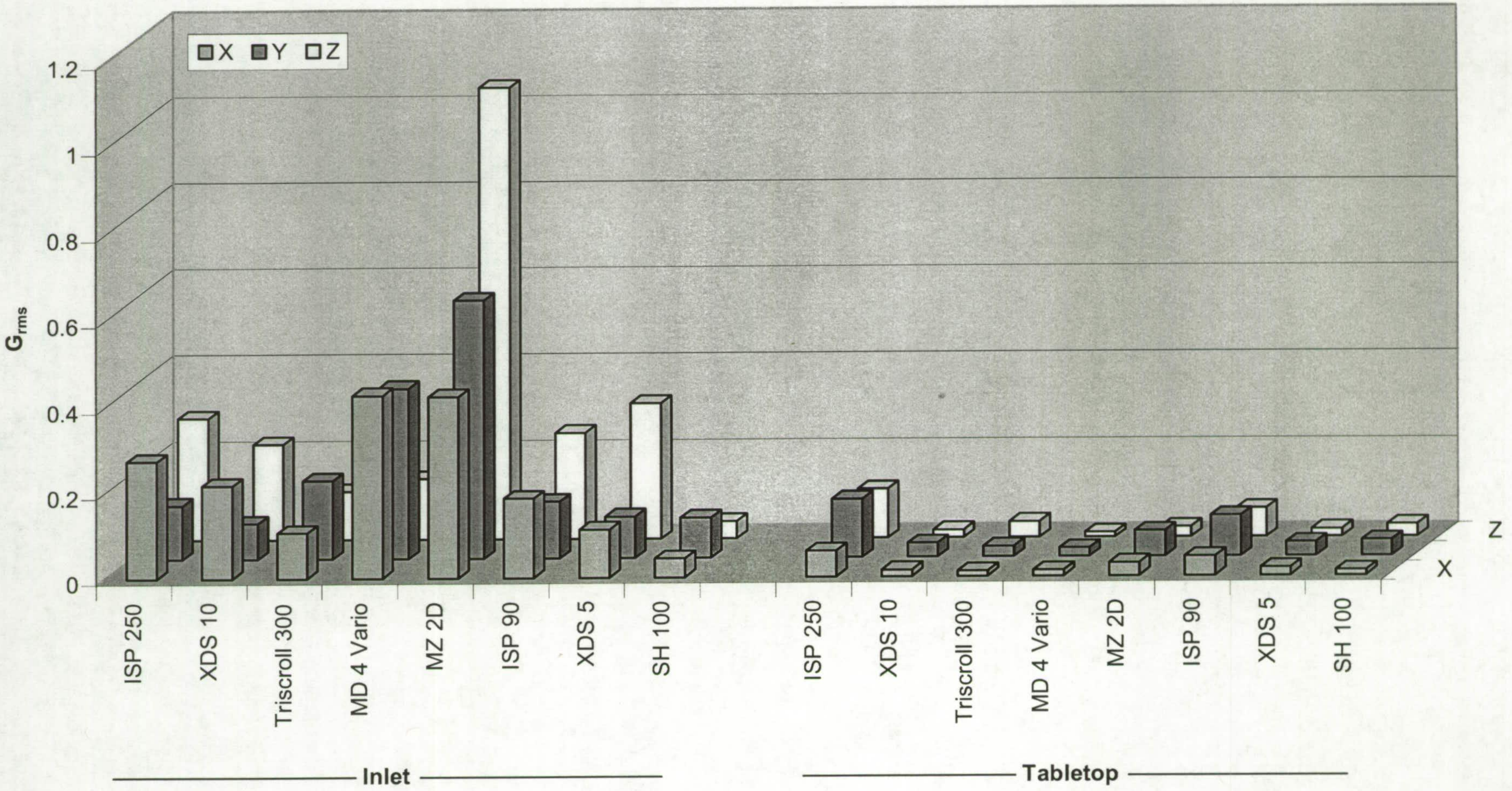

Figure 32 – Vibration at Pump Inlet Tabletop for Sample Pumps

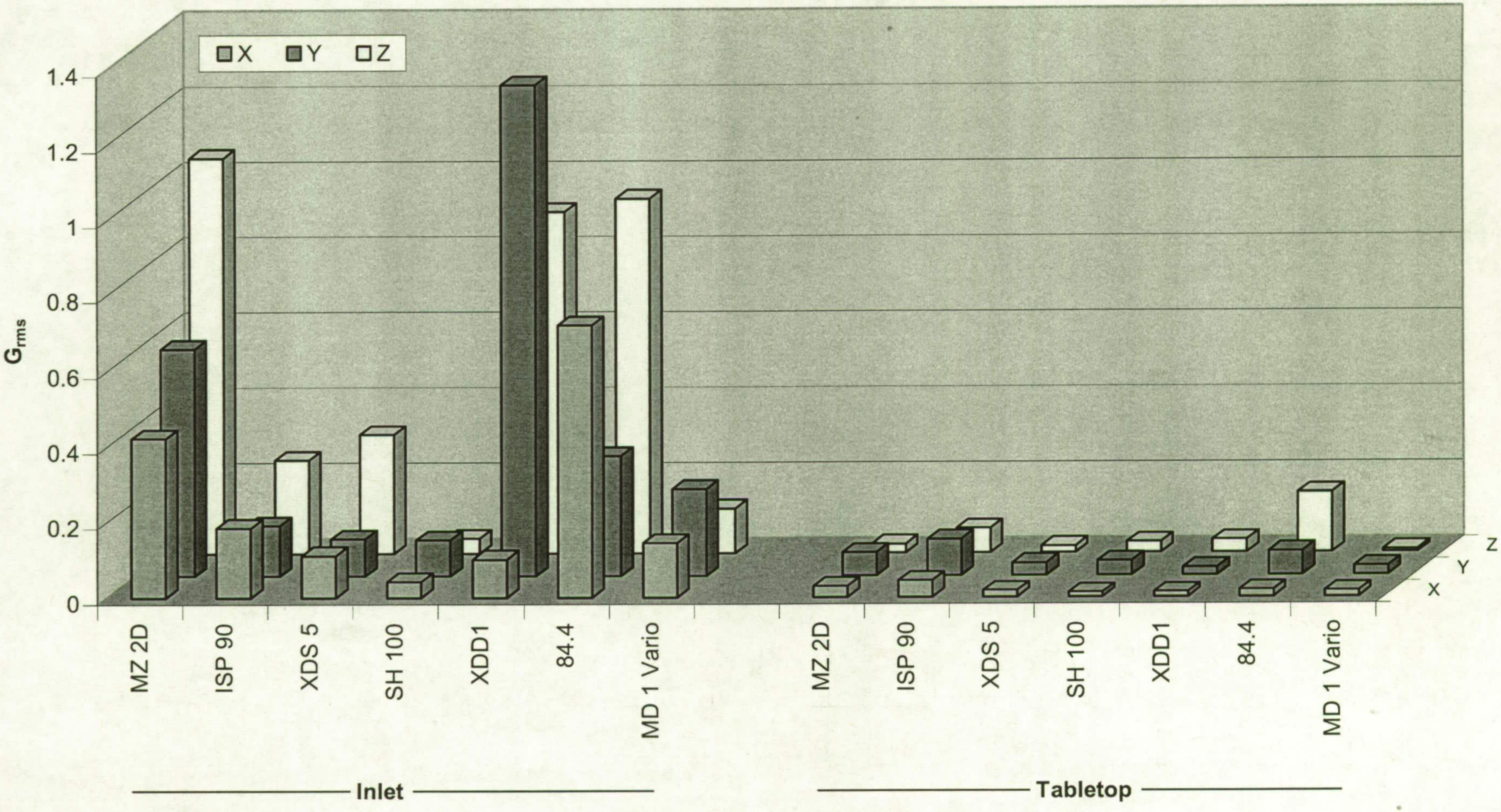

Figure 33 – Vibration at Pump Inlet and Tabletop for Backing Pumps

5.1.1 TRANSPORT PUMP EMISSIONS DISCUSSION

Transport pumps are often large, heavy, and have high flow rates. Because of the amount of power involved with these pumps, they can have substantial vibration associated with their operation. At the pump inlet, the Varian TriScroll 300 produces the least amount of vibration overall, with accelerations well under 0.2 G_{rms} in all axes. The Adixen ACP 28 and Iwata ISP 250 also have comparatively low vibrations. The Vacuubrand ME 16 and Edwards XDS 10 produce the most amount of vibration at the pump inlet, with the ME 16 having the most vibration associated with it. The ME 16 reaches over 1 G_{rms} in the X axis and nearly 1 G_{rms} in the Z axis.

The amount of vibration a transport pump transfers to a mounting surface, or in this case a tabletop it was resting on, is highly dependent on the way the two surfaces are mated. The acceleration of the tabletop quantifies the amount of vibration transferred. Vibration absorbing rubber feet drastically reduce the transfer, as the ME 16 shows. Although it had the highest vibration at the pump inlet, it causes very low acceleration at the tabletop. Conversely, the ISP 250 had comparatively mild vibration at the pump inlet, but transfers the more vibration to the tabletop than any other transport pump. This is because the ISP 250 has a large metal base with no rubber feet. The TriScroll 300 had the lowest vibration at the pump inlet, but because of its large metal base does not have the lowest acceleration at the tabletop. The ACP 28 has both low vibration and rubber feet, and therefore transfers the least amount of vibration of any pump. Although the XDS 10 has rubber feet, they are of a configuration that absorbs a smaller percentage of the vibration than feet on other pumps. This, coupled with the significant vibration of the XDS 10 at the inlet, leads to significant acceleration at the tabletop. A more complete description and results of the vibration emissions test may be provided upon request.

5.1.2 SAMPLE PUMP EMISSIONS DISCUSSION

Sample pumps are often the same pumps as transport pumps, but run at much lower pressure. This can cause significant changes in pump acceleration. Some pumps experience higher vibration while operating at low pressures, and other pumps experience lower vibration while operating at low pressures. The XDS 10 shows a lowering behavior; although pump acceleration with an open inlet was near 1 G_{rms} in the X axis, with a closed inlet it dropped to approximately 0.2 G_{rms}. Conversely, the

TriScroll 300 acceleration rose slightly when the inlet was closed, especially in the Y axis. The acceleration of the ISP 250 stayed essentially the same.

Other scroll pumps that were not candidates for transport duty were candidates for sample duty. These include the Iwata ISP 90, Edwards XDS 5, and Varian SH 100. All three of these pumps had mild vibration, with the Varian SH 100 having the lowest vibration at the pump inlet of any pump tested at 0.1 G_{rms} in the Y axis and less than half of that in the X and Z axis.

Two diaphragm pumps were tested as candidates for sample duty. The Vacuubrand MD 4 Vario had moderate vibration, with acceleration in the X and Y axes approaching 0.4 G_{rms}. The Vacuubrand MZ 2D had the highest vibration of any pump tested, with acceleration in the Z axis over 1 G_{rms}. Acceleration of the MZ 2D in other axes are also substantial. Both the MZ 2D and MD 4 Vario share the same pumping heads and are similar in many ways, although the MD 4 had lower vibration. The variable speed technology of the MD 4 Vario slows down as ultimate pressure is reached, which helps reduce vibration. In addition, the MD 4 Vario has 4 pumping heads, while the MZ 2D has only two. This helps balance the MD 4 Vario more effectively.

The amount of vibration the sample pumps transferred to the mounting surface is highly dependent on the way the two surfaces are mated. The acceleration of the tabletop quantifies the amount of vibration transferred. Vibration absorbing rubber feet drastically reduce the transfer. While diaphragm pumps produce far more vibration at their inlets than scroll pumps do, they transfer a similar amount or less vibration to the tabletop than scroll pumps. This is because diaphragm pumps are generally equipped with rubber feet and scroll pumps are not. The Iwata ISP 250 and ISP 90 transfer the most vibration to the tabletop because of their large metal bases. All other pumps transfer similar amounts of vibration to the tabletop, although the MZ 2D transfers slightly more in the Y axis than average.

5.1.3 BACKING PUMP EMISSIONS DISCUSSION

Like sample pumps, backing pumps were run at ultimate pressure while their vibration emissions were taken. As expected, diaphragm backing pumps had the highest acceleration at the pump inlet. The Edwards XDD1 had the highest acceleration in any single axis, over 1.2 G_{rms} in the Y axis. The Vacuubrand MZ 2D and KNF 84.4 also had large vibration. The Vacuubrand MD1 Vario, however, showed similar acceleration to scroll pumps. This is because the Vario technology slows the pump down near ultimate pressure, reducing the vibration.

At the pump inlet, all scroll pumps had vibration less than 0.3 G_{rms} in all axes. The Varian SH 100 had the least amount of vibration of any pump tested. The Iwata ISP 90 and Edwards XDS 5 had similar vibration output in all axes.

The amount of vibration the backing pumps transferred to the mounting surface is highly dependent on the way the two surfaces are mated. The acceleration of the tabletop quantifies the amount of vibration transferred. Vibration absorbing rubber feet drastically reduce the amount of vibration transferred. The KNF 84.4 accelerates the tabletop most strongly in the Z axis, with almost 0.2 G_{rms}. This is because it has high acceleration at the pump inlet, and no rubber feet to isolate this vibration from the mounting surface. Scroll pumps can transfer more vibration to the tabletop than diaphragm pumps because they often lack of rubber feet. The Iwata ISP 90 produces the most vibration in the X and Y axes because of its large metal base, which transfers vibration easily.

5.2 VIBRATION SUSCEPTIBILITY TESTING

The purpose of the vibration susceptibility test is to determine if pumps are able to withstand the vibrations experienced during certain NASA applications. All pumps must withstand essentially the same vibration, regardless of their function. Pumps were shaken for 30 seconds to the vibration spectrum, shown in Tables 6 and 7.

Table 6 – Power Spectral Density for Vibration Susceptibility Testing: X and Y axes

Frequency	Power Spectral Density (G^2/Hz)
10 Hz	0.01×10^{-3}
20 – 30 Hz	2.75×10^{-3}
45 – 400 Hz	1×10^{-3}
800 Hz	3.5×10^{-3}
850-1200 Hz	2.5×10^{-3}
1400 Hz	0.01×10^{-3}
Composite: 1.28 G_{rms}	

Table 7 – Power Spectral Density for Vibration Susceptibility Testing: Z axis

Frequency	Power Spectral Density (G^2/Hz)
3 Hz	0.01×10^{-3}
5.5 – 10 Hz	32×10^{-3}
20 Hz	27×10^{-3}
45 – 400 Hz	0.1×10^{-3}
800 Hz	3.5×10^{-3}
850 – 1200 Hz	2.5×10^{-3}
1400 Hz	0.01×10^{-3}
Composite: 1.37 G_{rms}	

Pumps were bolted to a ¼" aluminum plate in a half-size 24" rack using mounting points already existing on the pump. Turbo backing pumps were run at ultimate pressure while shaken. Transport and sample pumps were run at approximately 300 torr. Pass/fail criteria was based on whether or not the pump continued to function after being shaken.

No pump failures were noted during vibration testing. Therefore all pumps tested passed the vibration susceptibility test in the X, Y, and Z axes. However, two minor pump anomalies were observed. The BSP-threaded inlet fitting of the Edwards XDD1 became loose, and an M6 thread on a metal foot of the Vacuubrand ME 16 was stripped. It is unclear if the thread became stripped due to vibration or simply from excessive use, as the metal feet of the ME 16 are rather soft, and the M6 thread has only a 1 mm pitch. It should be noted that these threads are designed only to hold the rubber feet of the ME 16, not necessarily to provide mounting points. A coarser, larger thread would provide more resistance to stripping. A steel nut and bolt through the mounting plate would provide more resistance to stripping as well as strength. The loosened inlet fitting of the XDD1 could potentially be solved with thread sealant, although some chemical compatibility and contamination issues may exist with using this product in vacuum systems.

Because of the very small clearances between the pumping lobes, the Adixen ACP 28 was thought to be likely to fail the susceptibility test. However, the pump body is apparently mounted on a suspension within the pump case. During the test, high speed cameras showed large amounts of displacement on the pump inlet and exhaust relative to the case. This suspension is likely responsible for the durability of this pump during high vibrations.

The Varian TriScroll 300, Varian SH 100, and Vacuubrand MZ 2D were not tested here, but have passed under actual use in NASA applications. The MZ 2D, however, had third party vibration isolation in place.

6. STATIC LEAK TEST

When a vacuum pump is turned off, gas will leak back through the pump and into the vacuum system at a certain rate. The purpose of this test is to quantify the rate at which this flow occurs. This backwards gas flow can contaminate the vacuum system with particulate and/or oil in the pump or exhaust system. The amount of oil and particulate entrained in the gas stream is related to the velocity of gas traveling back through the pump. However, results are traditionally presented in units of mass flow rate, not volumetric flow rate or velocity. Although mass flow rate is constant through the pump while choked (vacuum system is at approximately 350 torr or less), the velocity changes with the cross sectional areas encountered as the gas travels back through the pump, with the highest velocity occurring at the smallest cross-sectional area (the choke point). The cross sectional areas and the resultant velocities in sections of the pump must be considered when interpreting results for the mitigation of contamination.

Reasons other than contamination are important when considering static leak rate of pumps. Some systems assume the pump is leak tight, such as a vacuum chamber being vented with a gas. Consider a chamber being evacuated with a vacuum pump to remove oxygen and then filled with a flammable gas at sub-ambient pressure. If the pump is assumed to be leak tight, no flammable condition could occur. However, air leaking back through the pump provides oxygen and could possibly create a flammable condition over time. Turbo molecular pumps also require a small gas load to spin down properly. In systems without a vent valve, this job can fall to the backing pump, although this can cause other issues. Too high of a leak rate can damage the turbo pump by "crashing" it or contaminating the system with particles, and too small of a gas load will not allow the turbo to spin down in a reasonable period of time.

Leak tightness of pumps was determined by pumping down a pressure vessel equipped with a Granville-Philips 275 Mini-Convectron gauge. With this gauge, the vessel had no detectable leak (<0.1 torr) over a 1 hour period (< 0.02 sccm). Pumps were allowed to reach their ultimate pressure for several minutes and then were turned off. Pressure values were recorded at 15 seconds, 30 seconds, 1 minute, 5 minutes, 10 minutes, 15 minutes, and 30 minutes. Graphs of the data quickly became linear for all pumps. The slope of the linear portion of the line represents the leak rate in torr/min. When multiplied by the vessel volume, the slope is the leak rate in torr-L/min.

All leak rates are shown for air. If a pump has been pumping helium into an exhaust plenum or manifold, the helium remaining in the manifold will travel backwards through the pump at a rate far exceeding the value for air.

Table 8 shows the leak rate in air for various pumps. The leak rate exhibited by the pump is influenced by several factors. The number of effective pumping stages, especially for diaphragm pumps, is one indicator of how leak tight a pump will be. Valve size also affects the leak rate. The larger the valves in a diaphragm pump, the higher the leak rate will be because of the greater area for leakage to occur. For scroll pumps, the leak rate varies widely, even within manufacturers. The primary source for leakage likely occurs at small gaps between the orbiting and fixed scrolls, where there is no sealing material to prevent it. Roots pumps exhibit poor leak-tightness for this very reason. There are no contacting parts, which means there are gaps between the individual stages where gas can leak back through.

The Iwata ISP 250 has a surprising trend which appears approximately 10 minutes after the pump is shut off. The indicated pressure inside the vessel actually decreased with time. This test was repeated a second time, and data was consistent with the previous run. One possible explanation for this is thermal adsorption coupled with a very low leak rate. As the pump body cools, water vapor, which makes up a significant gas load, adsorbs to the surface which reduces pressure. If this occurs at a rate higher than air leaking back through the pump, the pressure trend will be negative. Further investigation would be necessary to test this hypothesis, such as running the test for a longer period of time.

The Varian SH 100 is equipped with a solenoid inlet valve that seals the chamber from the pump when power is lost. This is responsible for the very low leak rate observed, although this can increase turbo spin down times. The TriScroll 300 seals poorly. It is unclear if this is because the pump has poor clearances, tip seal leakage, or if it is an inherent result of its design.

Table 8 – Leak Tightness of Various Pumps in Air

Pump	Type	Use	Leak Rate (Torr-L/Min)	Leak Rate (sccm)
Adixen ACP 28	Roots	Transport	2.23	2.93
Vacuubrand ME 16	Diaphragm	Transport	–	–
Iwata ISP 250	Scroll	Transport, Sample	-0.12	-0.16
Edwards XDS 10	Scroll	Transport, Sample	0.11	0.15
Varian Triscroll 300	Scroll	Transport, Sample	2850	3750
Vacuubrand MD 4 Vario	Diaphragm	Sample	0.34	0.45
Vacuubrand MZ 2D	Diaphragm	Sample, Backing	0.46	0.61
Iwata ISP 90	Scroll	Sample, Backing	1.77	2.33
Edwards XDS 5	Scroll	Sample, Backing	0.18	0.24
Varian SH 100	Scroll	Sample, Backing	0.07	0.09
Edwards XDD1	Diaphragm	Backing	0.13	0.17
KNF Neuberger 84.4	Diaphragm	Backing	0.29	0.38
Vacuubrand MD 1 Vario	Diaphragm	Backing	0.17	0.22

The ME 16 arrived with inlet flange damage it received during shipping. Although the pump did reach specified ultimate pressure, it was felt that this damage could contribute to an artificially high leak rate, and this test was not performed.

7. EXHAUST RESTRICTION TEST

Tubing and fittings used to route the exhaust of the pump away from personnel and equipment can have a significant resistance to flow. Often, this exhaust plumbing can be quite long. The maximum permissible exhaust pressure for a vacuum pump is typically only slightly above atmospheric pressure. With high flow rates and long tubing and fittings on the exhaust it is easy to exceed the maximum exhaust pressure specification. For example, 40 sLpm of nitrogen through a ¼" line, 130 feet long, and exhausting to atmosphere requires 2000 torr of pressure, more than twice the exhaust pressure specification for most vacuum pumps.

This test attempts to quantify the effect exhaust pressure (exhaust restriction) has on the pump. A throttling valve was installed on the exhaust of pumps operating in air at 300 torr. By partially closing this throttling valve, the exhaust pressure could be increased and the inlet pressure and current demand recorded. A graph of inlet pressure vs. outlet pressure was developed, and all graphs were linear. Figure 34 shows a typical graph. The slope of this line (dP_{in}/dP_{out}) is the sensitivity to exhaust restriction. A pump with a sensitivity of 0.300, for example, will have an inlet pressure rise of 0.300 torr for every torr the outlet pressure increases above atmospheric pressure.

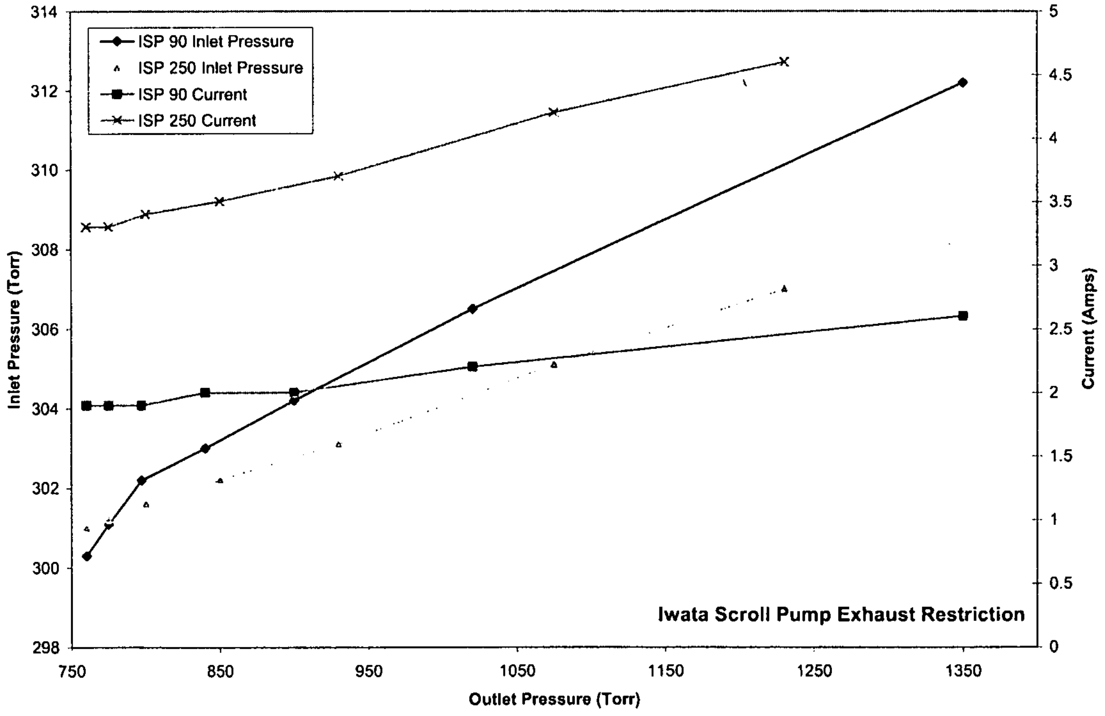

Figure 34 – Typical Exhaust Restriction Curves

All graphs presented are for air. Pumps showing a high sensitivity to air will likely have a much higher sensitivity to helium. This is important to remember when designing exhaust plumbing for systems operating in helium. One advantage to helium, however, is that it requires less pressure differential for a given flow rate than air or nitrogen does. This makes exhaust pressure less at a given flow rate compared to air or nitrogen, even though sensitivity will increase. Pumps had exhaust restriction tests performed on them while operating in air at 300 torr. Table 9 shows the sensitivity to exhaust restriction, the type, and candidate uses for various pumps.

Table 9 – Sensitivity to Exhaust Restriction in Air for Various Pumps

Pump	Type	Use	Sensitivity at 300 torr: dP_{in}/dP_{out}
Adixen ACP 28	Roots	Transport	0.270
Vacuubrand ME 16	Diaphragm	Transport	0.300
Iwata ISP 250	Scroll	Transport, Sample	0.013
Edwards XDS 10	Scroll	Transport, Sample	0.062
Varian Triscroll 300	Scroll	Transport, Sample	0.026
Vacuubrand MD 4 Vario	Diaphragm	Sample	ANOMALY
Vacuubrand MZ 2D	Diaphragm	Sample, Backing	ANOMALY
Iwata ISP 90	Scroll	Sample, Backing	0.019
Edwards XDS 5	Scroll	Sample, Backing	0.025
Varian SH 100	Scroll	Sample, Backing	0.049
Edwards XDD1	Diaphragm	Backing	N/A
KNF Neuberger 84.4	Diaphragm	Backing	0.004
Vacuubrand MD 1 Vario	Diaphragm	Backing	N/A

The number of effective stages has a strong effect on the sensitivity to exhaust restriction. Single stage diaphragm pumps, such as the ME 16, were most susceptible to exhaust restriction. The KNF

84.4 four stage diaphragm pump showed the least amount of sensitivity. Scroll pumps have a large number of effective stages due to their concentric design, and are not very sensitive. Although the ACP 28 has five stages, it is quite sensitive to exhaust restriction due to the clearance between the pumping lobes. In addition, the current demand of the pump became very unstable above an outlet pressure of 850 torr. This could indicate imminent pump failure, although exhaust pressures as high as 1150 torr were reached without damage to the unit.

Pumps typically require higher current as the exhaust pressure increases. This is because the pump must compress the gas at the inlet side to higher pressures, requiring more work to be done on the gas. There are exceptions, however. The Vacuubrand ME 16 has significant drop in current demand from atmosphere to 850 torr. Above 850 torr, the current rises until it surpasses the current demand at atmospheric pressure at approximately 1000 torr. A similar curve was observed with the XDS 5. No attempt was made to reproduce these results.

The Edwards XDD1 and Vacuubrand MD 1 Vario were not tested for exhaust restriction due to the 3/8"-19 BSP exhaust fitting, which had no replacement available. However, their three stage diaphragm design and low flow rate indicate that smaller diameter exhaust lines should be sufficient for backing duty.

The Vacuubrand MZ 2D and MD 4 Vario showed anomalous behavior during the test. Other pumps quickly reached a steady state as the exhaust throttling valve was closed, but the exhaust pressure of the MZ 2D and MD 4 Vario pumps oscillated with time in a sinusoidal manner. The inlet pressure also varied proportional to the exhaust pressure during these oscillations. The period and amplitude of these oscillations were constant with time. The cause of these oscillations remains unknown.

It must be noted that the sensitivity alone does not fully describe how the operation of the pump will be affected by specific exhaust plumbing. The exhaust pressure that will occur depends on the conductance of the exhaust plumbing and the flow rate the pump is operating at. Both flow rate and sensitivity indicate the degree of caution that must be taken when designing exhaust plumbing. For example, both the Vacuubrand ME 16 and Adixen ACP 28 have a high sensitivity to exhaust restriction as well as large flow rates at the pressures they will be operated at. This indicates that large diameter exhaust lines are necessary to ensure the proper operation of these pumps. Table 10 shows some flow vs. pressure data for both ¼" and ½" line. This information is represented graphically in

Figure 35, along with curve fits of the data. Fittings other than tubing, as well as bends and valves, will raise exhaust pressures beyond those figures given in Table 10 and Figure 35.

Using a combination of the pump speed curve, flow curve, and exhaust restriction curves is an appropriate way to design exhaust plumbing. First, the user should determine the maximum operational pressure of the vacuum pump. The resulting speed can then be read from the pump speed curve, and converted into mass flow rate rather than volumetric flow rate. Next, determine the exhaust pressure required at this mass flow rate. Table 8 and Figure 35 can be used for ¼" and ½" lines near 134 and 91 feet in length, respectively. Once the exhaust pressure is found, the exhaust restriction curve will yield the actual inlet pressure and current demand. An iterative process may be required for high exhaust pressures and sensitivities. The user should be cautioned that exhaust restriction curves are provided only around 300 torr, appropriate transport pressures. Sample and backing pumps generally have flow rates that low, and often ¼" line is assumed to be all that is necessary.

Table 10 – Pressure/Flow Relationships for Various Tubing

<table>
<tr><td colspan="4">Line: ¼” OD, 0.170” ID Dekaron Plastic Tubing, 134 Feet</td></tr>
<tr><td colspan="2">Nitrogen</td><td colspan="2">Helium</td></tr>
<tr><td>Δ Pressure (Torr)</td><td>Flow (SLPM)</td><td>Δ Pressure (Torr)</td><td>Flow (SLPM)</td></tr>
<tr><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>35</td><td>4</td><td>20</td><td>4</td></tr>
<tr><td>94</td><td>8</td><td>72</td><td>8</td></tr>
<tr><td>272</td><td>13</td><td>135</td><td>13</td></tr>
<tr><td>525</td><td>19</td><td>264</td><td>22</td></tr>
<tr><td>960</td><td>29</td><td>804</td><td>53</td></tr>
<tr><td>1344</td><td>39</td><td>1458</td><td>72</td></tr>
<tr><td colspan="4">Line: 1/2” OD, 3/8” ID Tygon Tubing, 91 Feet</td></tr>
<tr><td colspan="2">Nitrogen</td><td colspan="2">Helium</td></tr>
<tr><td>Δ Pressure (Torr)</td><td>Flow (SLPM)</td><td>Δ Pressure (Torr)</td><td>Flow (SLPM)</td></tr>
<tr><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>1</td><td>5</td><td>1</td><td>3</td></tr>
<tr><td>4</td><td>8</td><td>3</td><td>10</td></tr>
<tr><td>11</td><td>19</td><td>5</td><td>18</td></tr>
<tr><td>30</td><td>31</td><td>15</td><td>39</td></tr>
<tr><td>62</td><td>52</td><td>27</td><td>65</td></tr>
<tr><td>111</td><td>83</td><td>55</td><td>95</td></tr>
<tr><td>186</td><td>119</td><td>120</td><td>134</td></tr>
<tr><td>189</td><td>123</td><td>220</td><td>194</td></tr>
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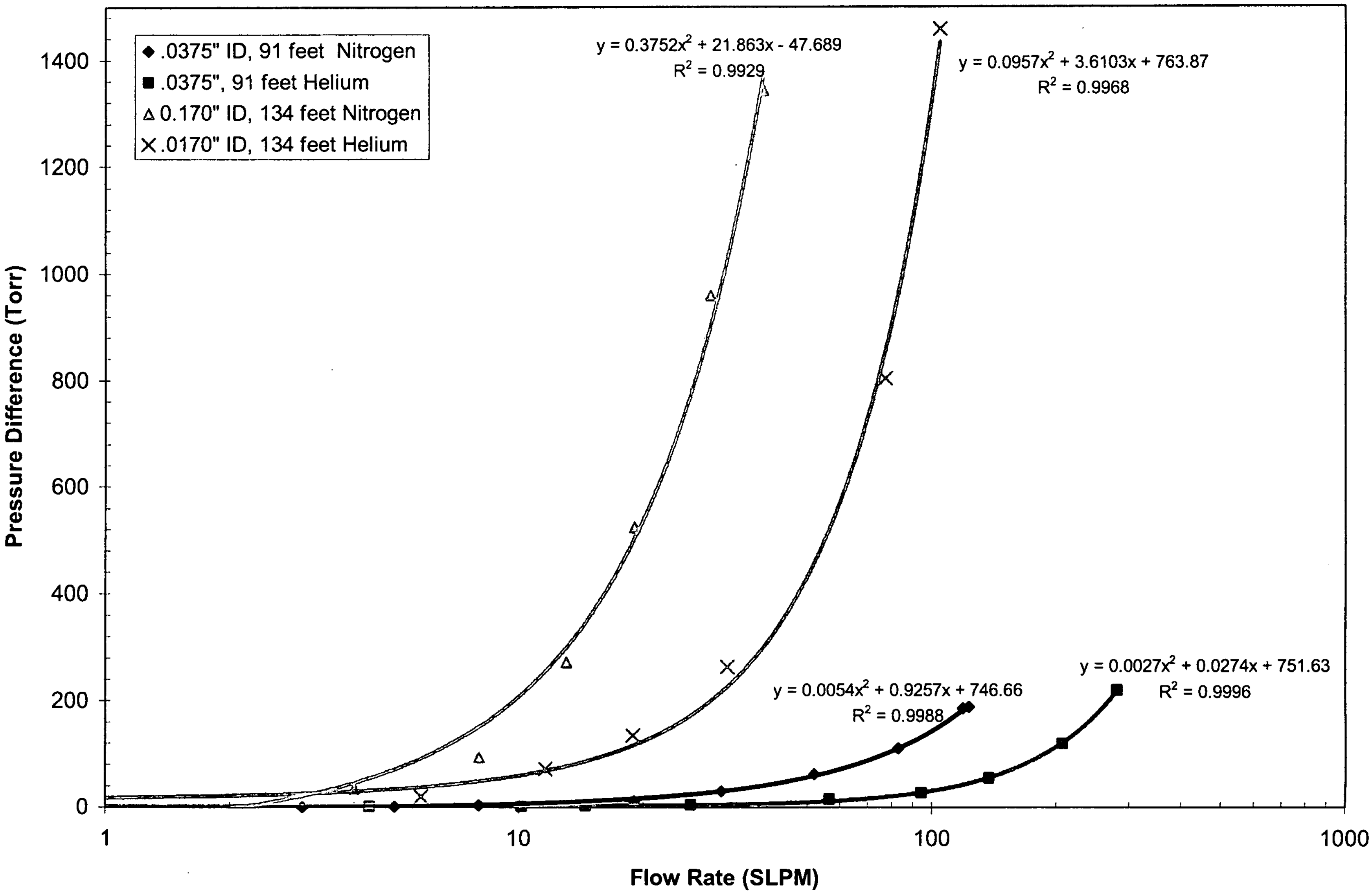

Figure 35 – Pressure/Flow Relationships for Various Tubing and Gases

8. ELECTROMAGNETIC INTEFERENCE TESTING

Electromagnetic emissions, both conducted and radiated, arise from changes in current. The change in current induces magnetic fields which induce unwanted currents in nearby conductors. If these emissions originate from the vacuum pump, they could interfere with other instruments operating nearby. Conversely, emissions caused by other devices may interfere with the normal operation of the vacuum pump.

High susceptibility to electromagnetic interference could potentially cause failure of the pump during operation. Such a situation could have dire consequences in a launch scenario. To prevent this, SL E-0002 Book 3 (Space Shuttle Specification Electromagnetic Interference Characteristics, Requirements for Equipment Book 3, New or Modified Equipment) specifies the allowable EMI emissions, as well as susceptibility. Compliance is determined by a series of tests contained within the specification.

Several pumps were tested for compliance to SL-E-0002 Book 3 RE102, and CE102. These are tests for radiated and conducted emissions, respectively. In addition, some pumps which might have been recommended as replacements were tested to RS103, CS101, and CS114 as well. These are electromagnetic interference susceptibility test. These tests required pass/fail criteria, which was based on inlet pressure measurements. After the pump stabilized, the pressure was read with a 1000 torr capacitance manometer and associated controller. The pump failed the test if the indicated pressure deviated by more than 1 torr.

8.1 EMI EMISSIONS – RESULTS AND DISCUSSION

Table 11 shows the results of RE102 and CE102 testing on various vacuum pumps. Electromagnetic emissions, both conducted and radiated, arise from changes in current. The change in current induces magnetic fields which induce unwanted currents in nearby conductors. Frequency generators, in particular, are prone to EMI emission because they involve rapid changes in current that occur at regular intervals. Both the Adixen ACP 28 and KNF 84.4 have frequency generators. This is likely the reason they failed RE102 and CE102, while all other pumps passed.

Table 11 – Radiated and Conducted Emissions Results

Pump	RE102	CE102
Adixen ACP-28	Fail	Fail
KNF 84.4	Fail	Fail
Iwata ISP-90	Pass	Pass
Edwards XDD1	Pass	Pass
Edwards XDS 10	Pass	Pass
Iwata ISP-250	Pass	Pass
Varian TriScroll 300	Pass	Pass
Varian SH 100	Pass	Pass
Vacuubrand ME-16	Pass	Pass

8.2 EMI SUSCEPTIBILITY – RESULTS AND DISCUSSION

Table 12 shows the results of EMI susceptibility testing on two vacuum pumps. Originally, all 9 pumps were to be tested, but because of time and funding constraints, only two rough pumps were tested before the cutoff date.

Table 12 – Radiated and Conducted Susceptibility Results

Pump	RS103	CS101	CS114
Edwards XDD1	Pass	Pass	Pass
Vacuubrand ME 16	Pass	Pass	Fail

The Edwards XDD1 passed all susceptibility tests, while the Vacuubrand ME 16 was found to fail the CS 114 power bundle test. This test simulates having noise introduced in all power leads at the same time, rather than just one lead. This scenario could occur, for instance, if a noisy line were wrapped around the power bundle to the vacuum pump. Pass/Fail criteria was based on change in inlet pressure while operating at 300 torr. If the inlet pressure deviated by more than 1 torr while testing, the pump failed the test. Although inlet pressure measurements are usually quite stable in the short term, over several hours they can be expected to drift slightly. CS 114 takes several hours to complete, so it is possible that drift is responsible for the failure of the test. It is suggested to make the pass/fail criteria for susceptibility testing of vacuum pumps an inlet pressure deviation of more than 5 torr.

A. PUMPING SPEED AND CURRENT CURVES

The following figures contain pumping speed and current curves discussed in Section 3. They show how the pumping speed and current demand change with inlet pressure. Curves are presented for nitrogen, air, and helium.

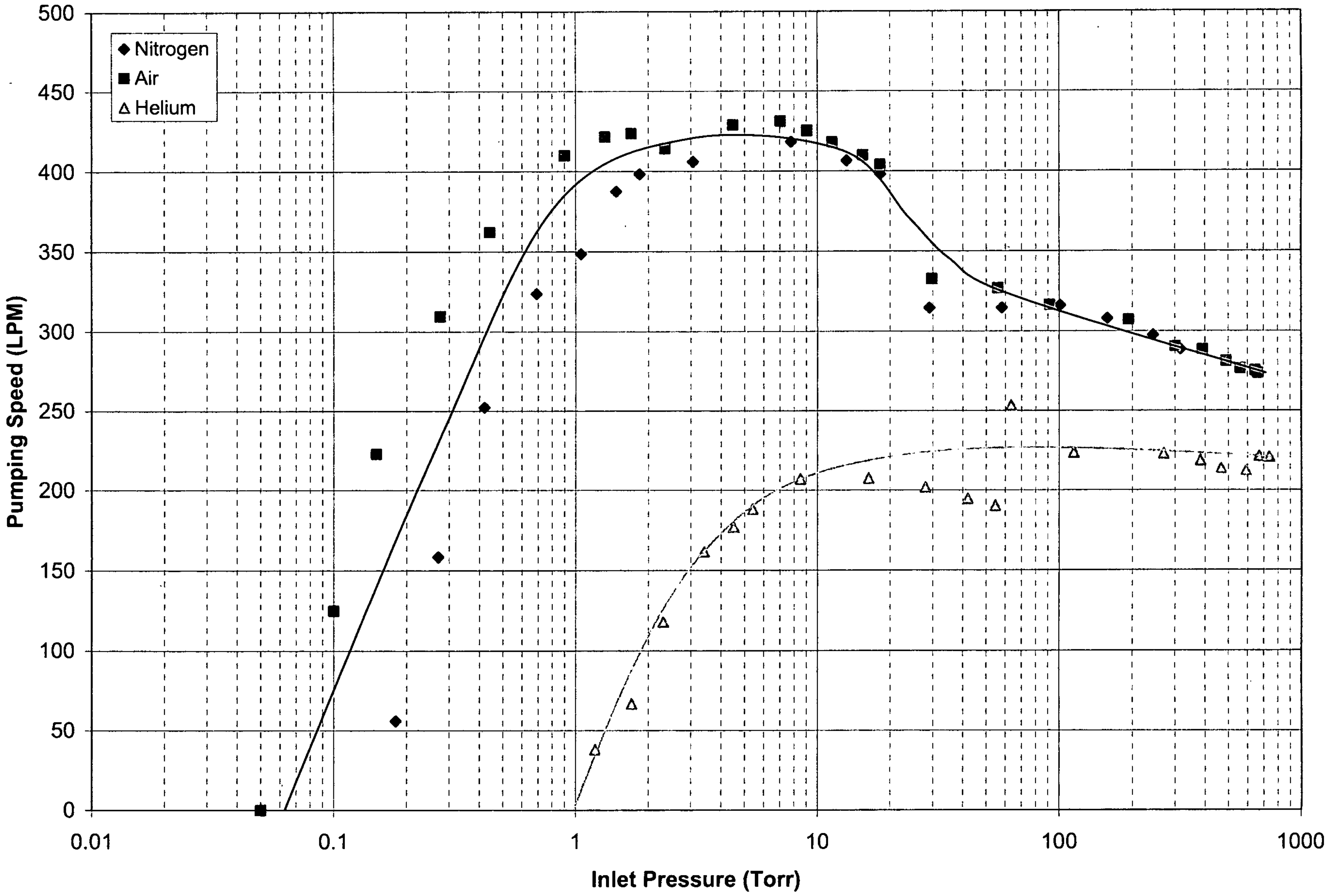

Figure 36 – Adixen ACP 28 Pumping Speed Curves

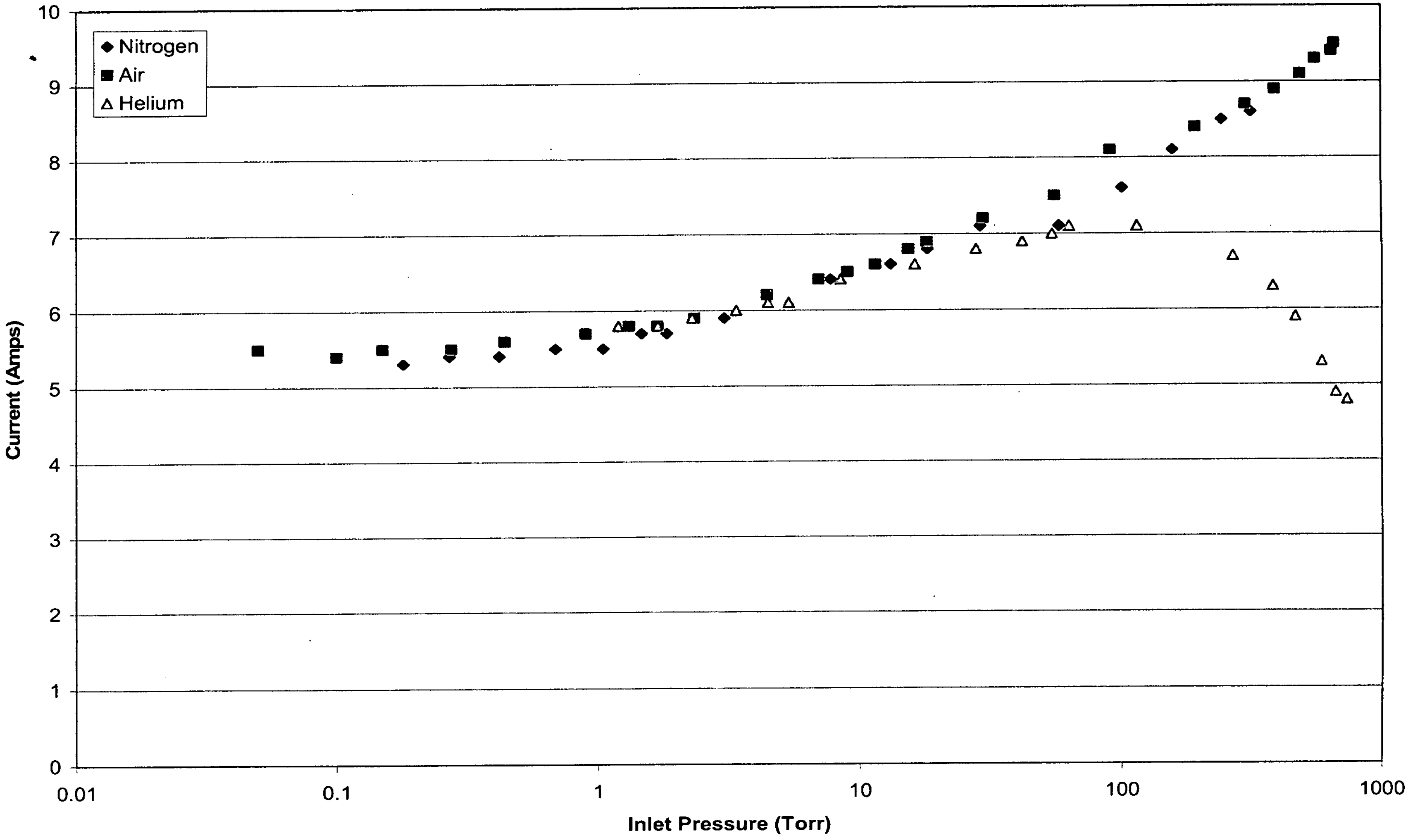

Figure 37 – Adixen ACP 28 Current Curves

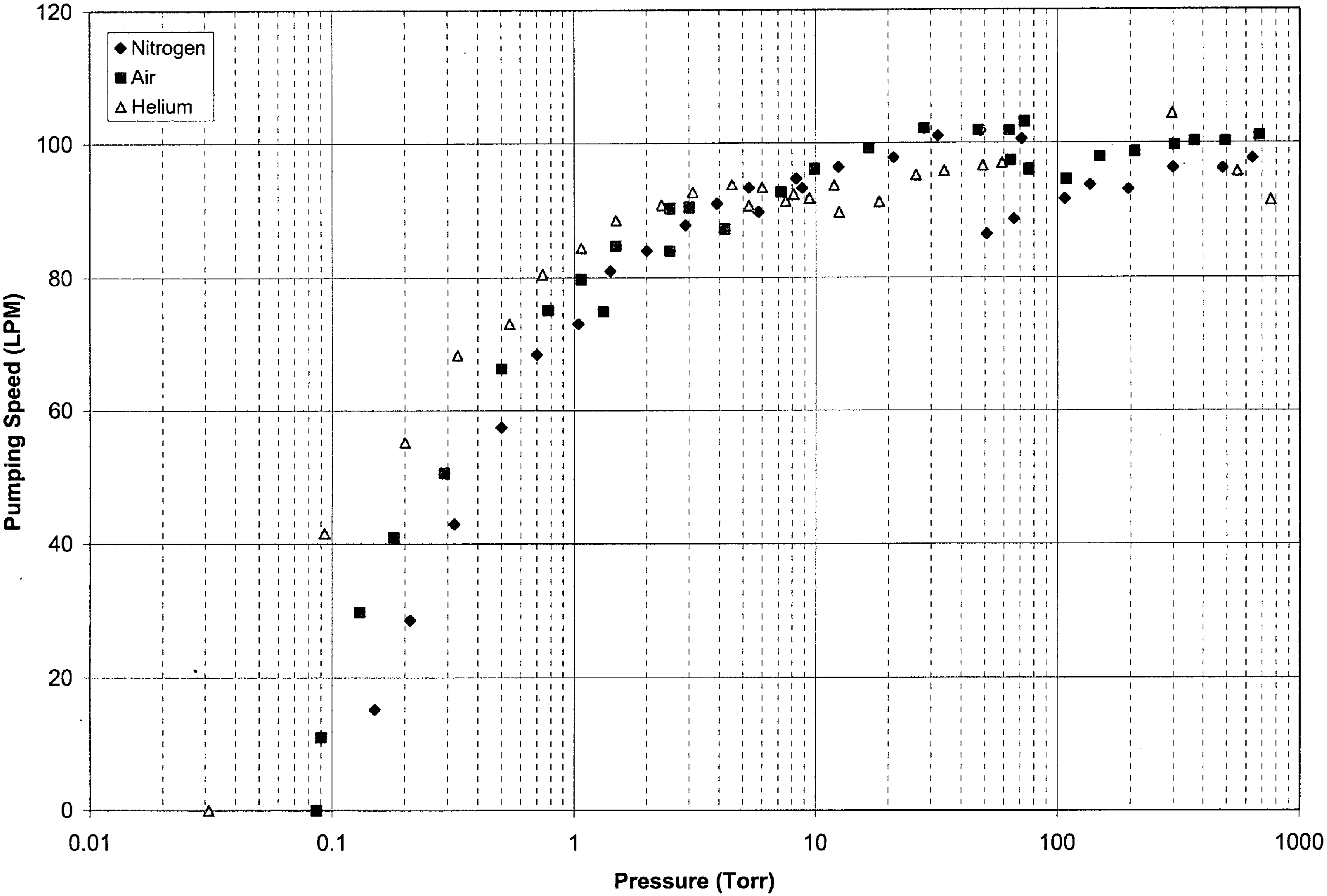

Figure 38 – Edwards XDS 5 Pumping Speed Curves

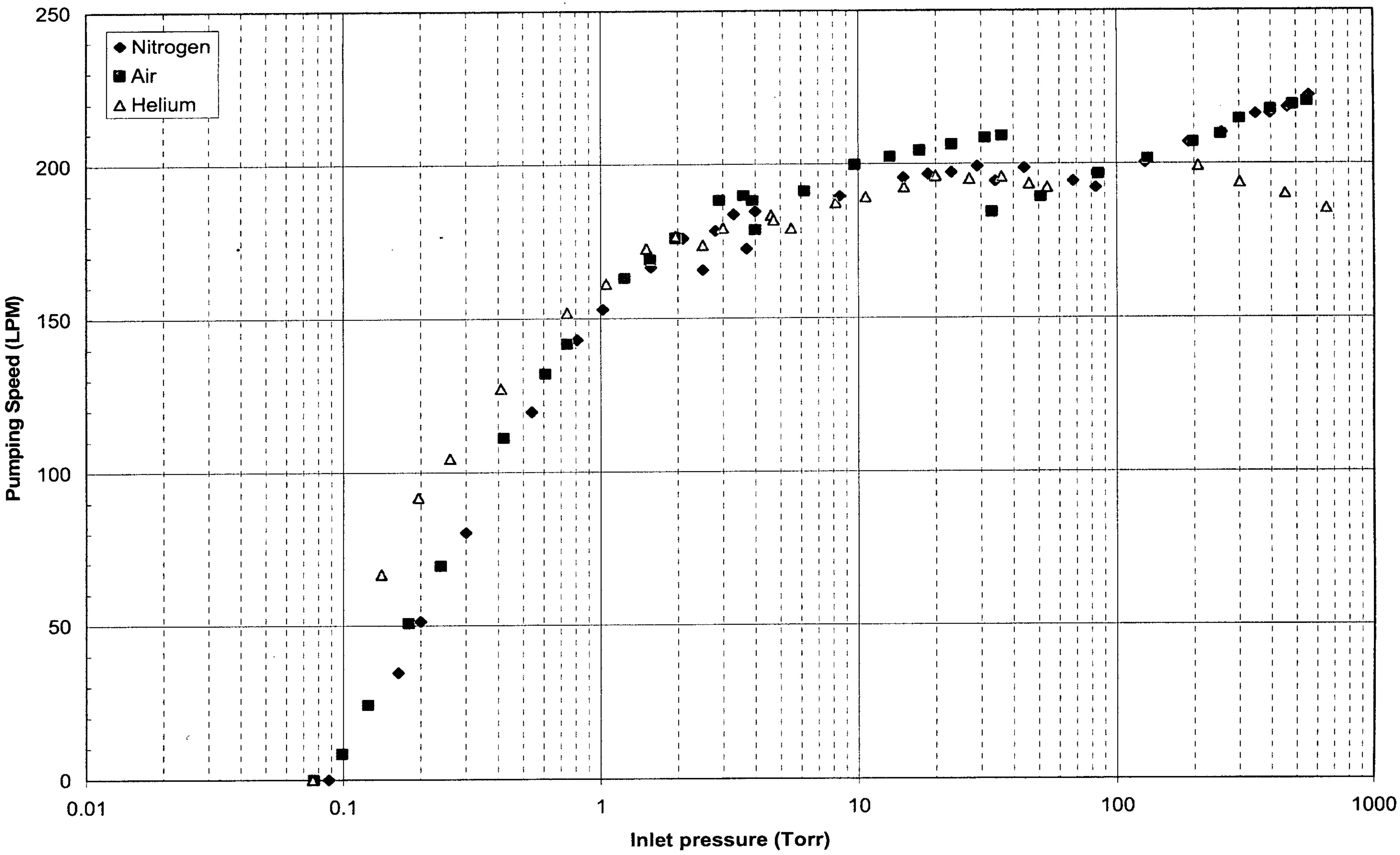

Figure 39 – Edwards XDS 10 Pumping Speed Curves

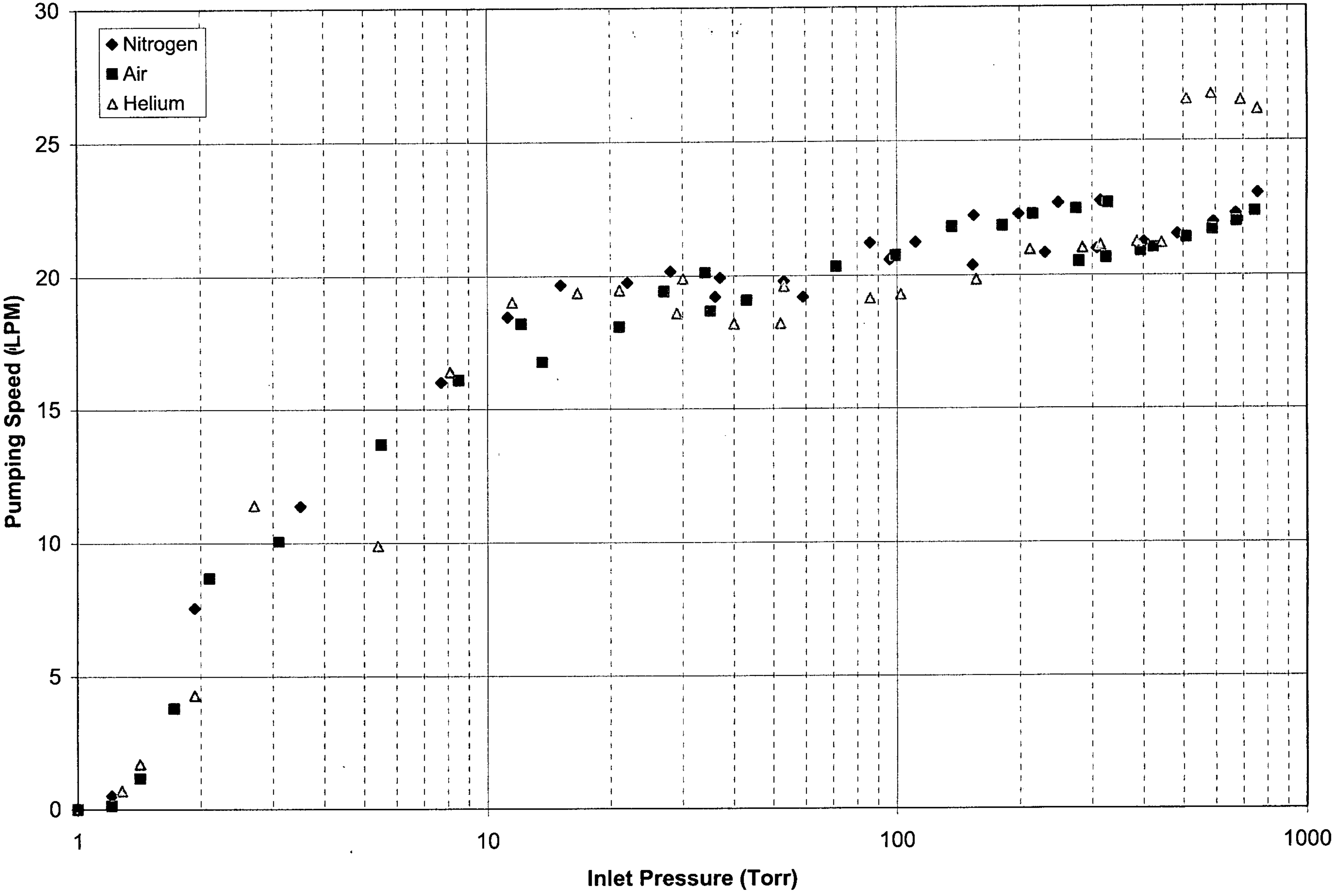

Figure 40 – Edwards XDD1/Vacuubrand MD1 Pumping Speed Curves

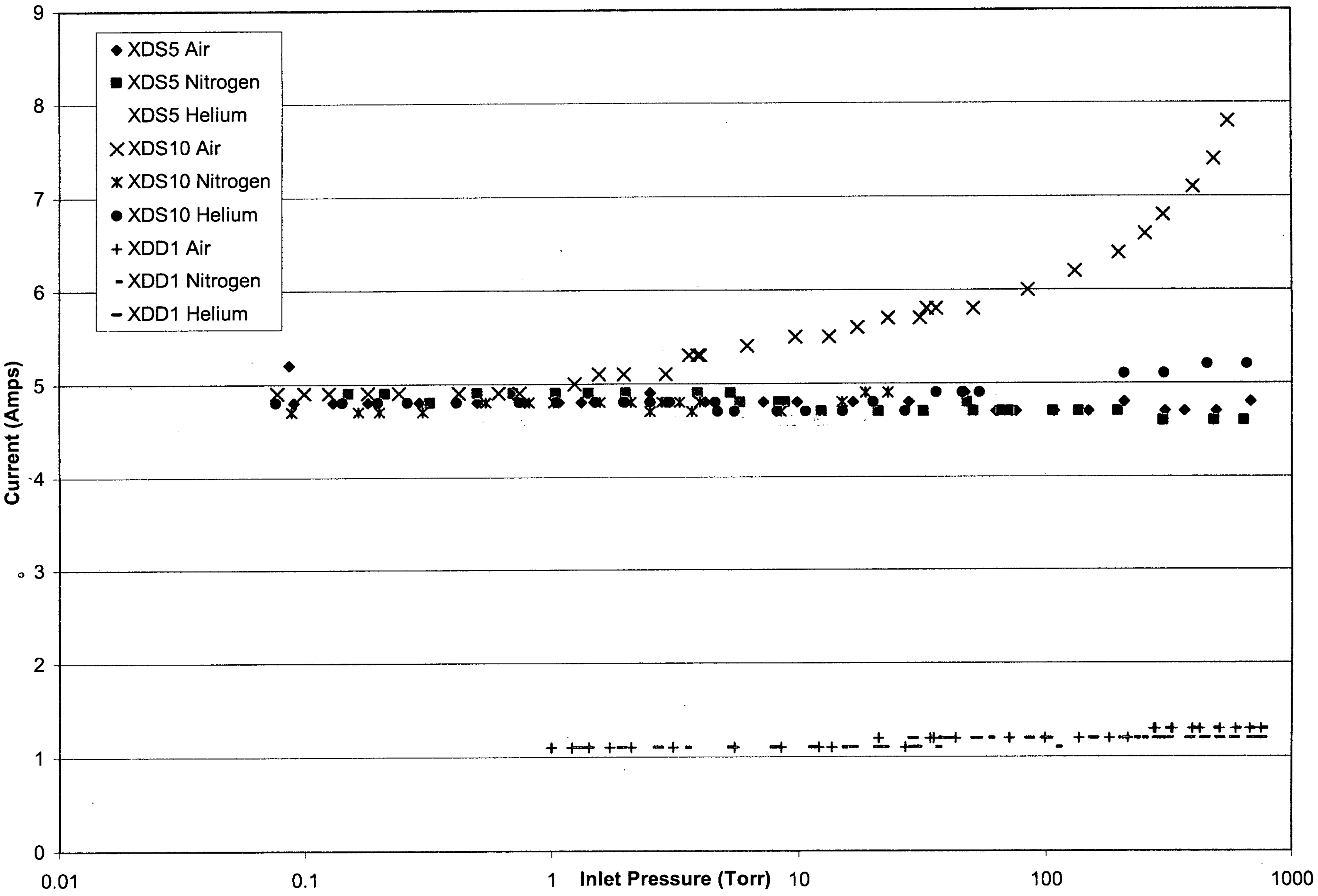

Figure 41 – Edwards Pump Current Curves

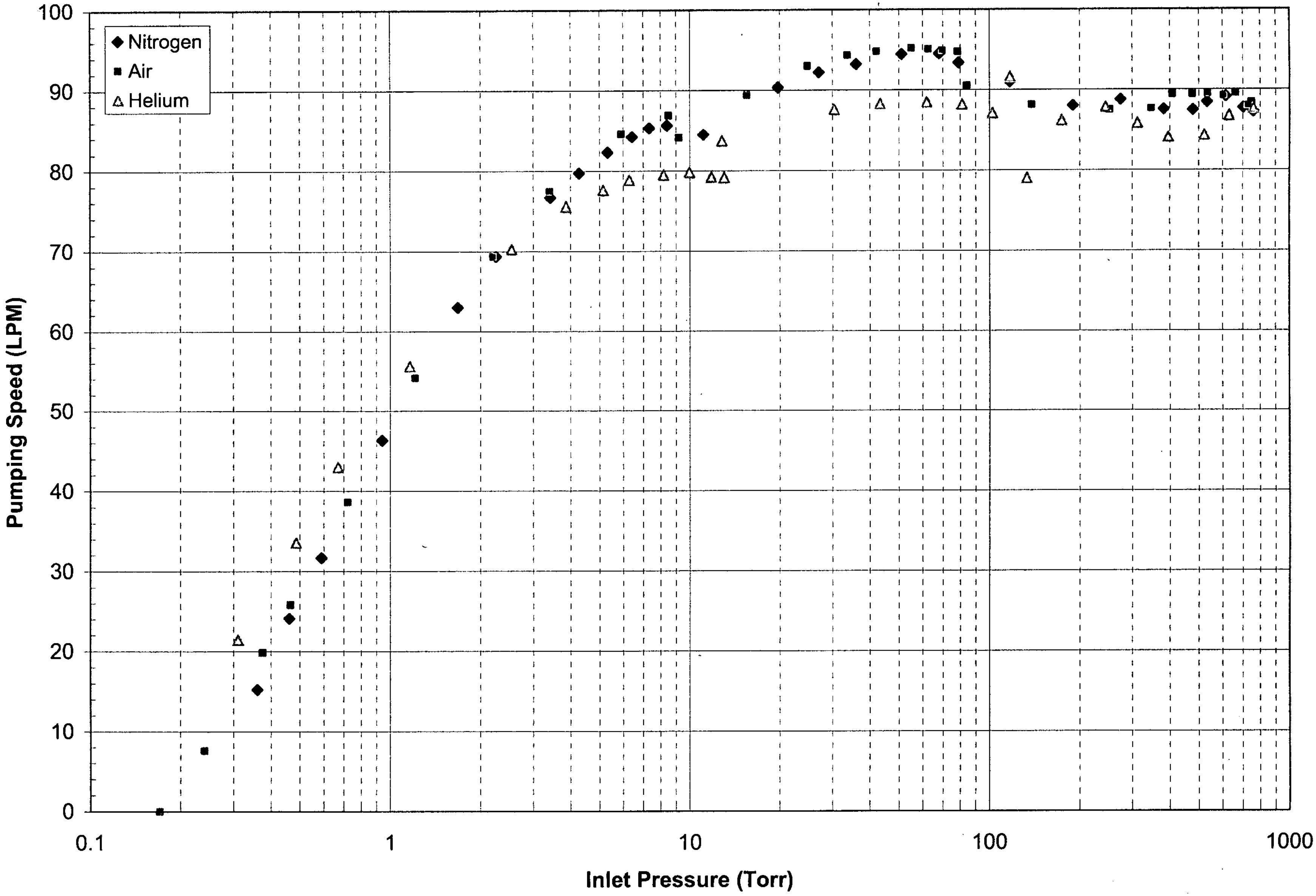

Figure 42 – Iwata ISP 90 Pumping Speed Curves

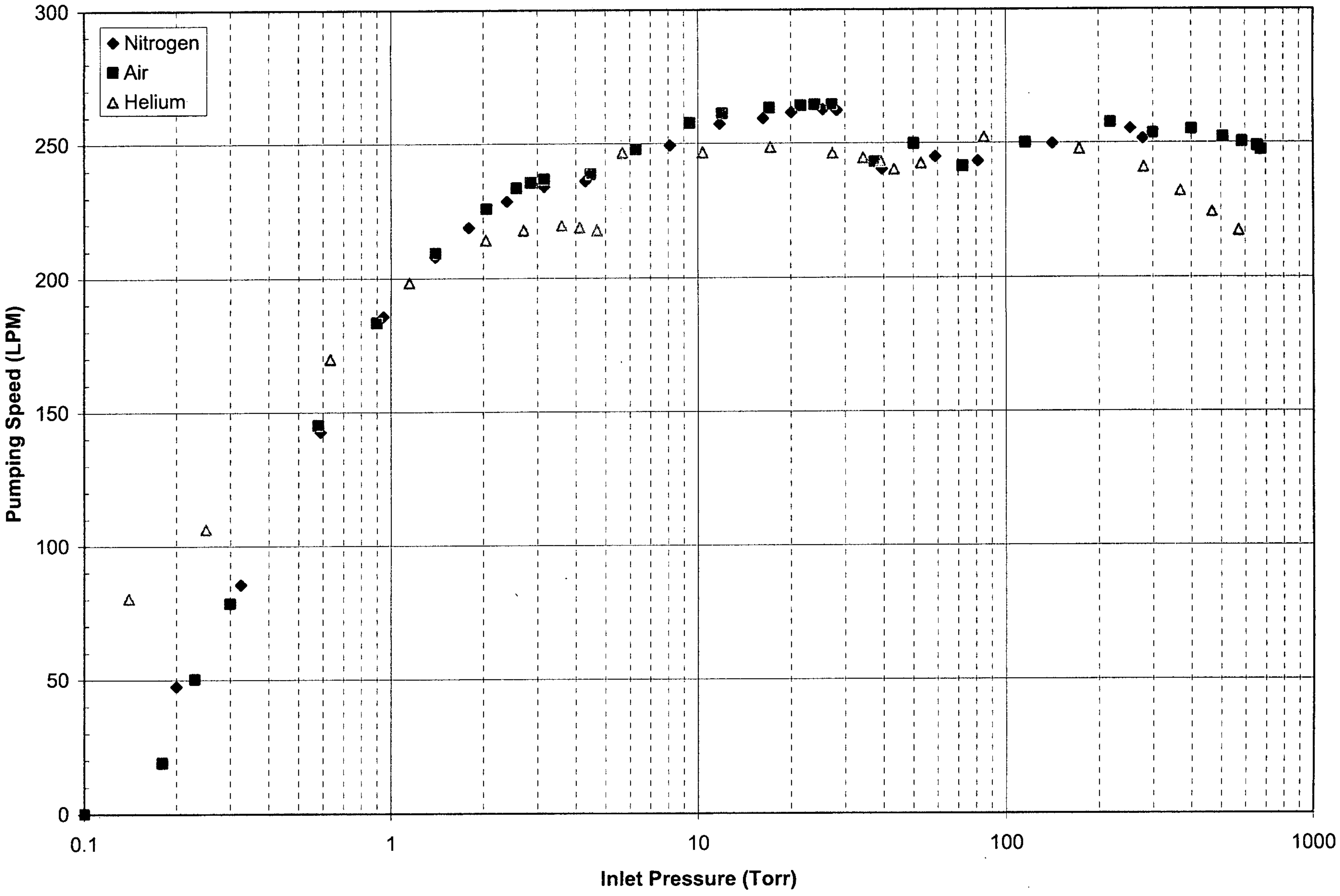

Figure 43 – Iwata ISP 250 Pumping Speed Curves

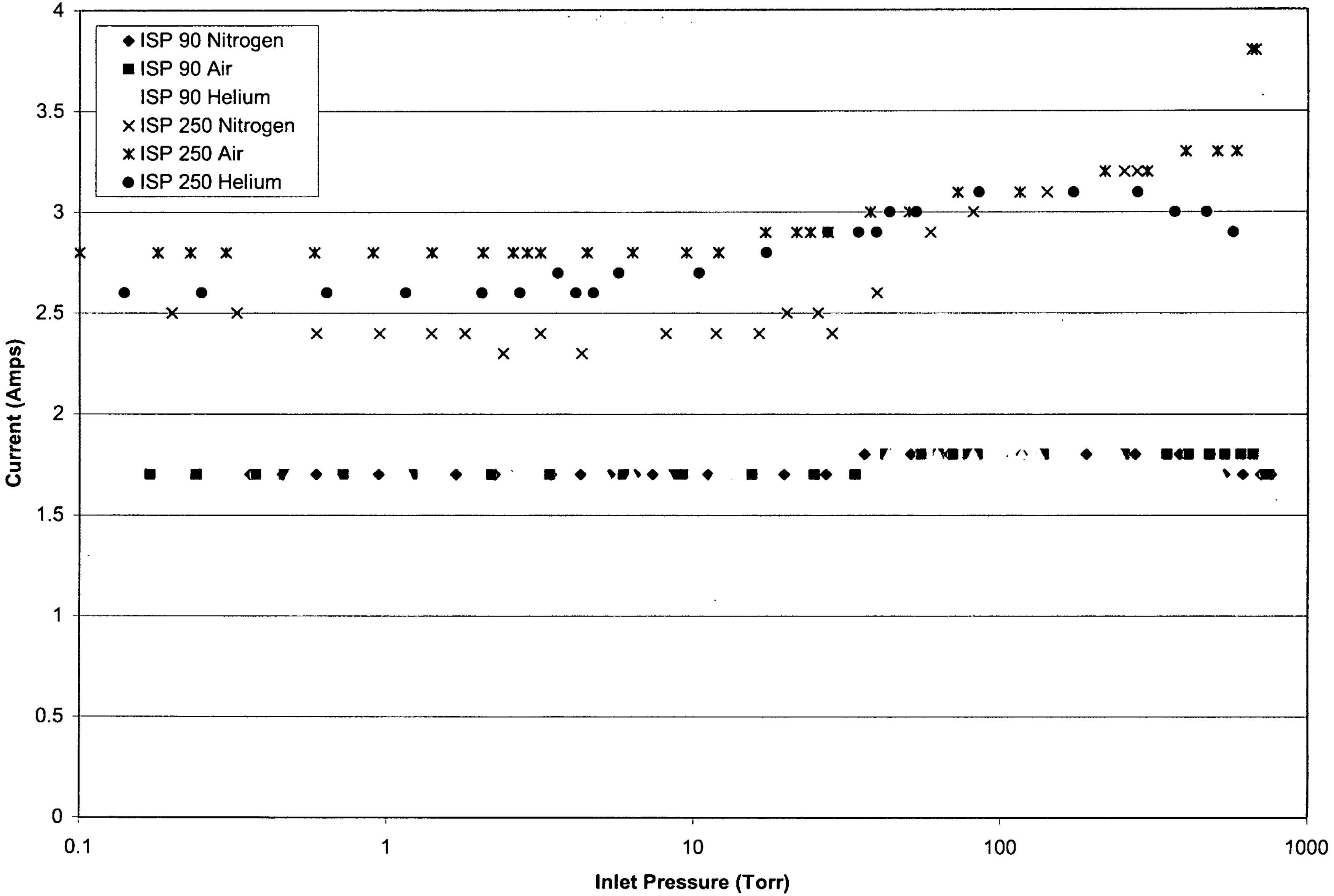

Figure 44 – Iwata Scroll Pump Current Curves

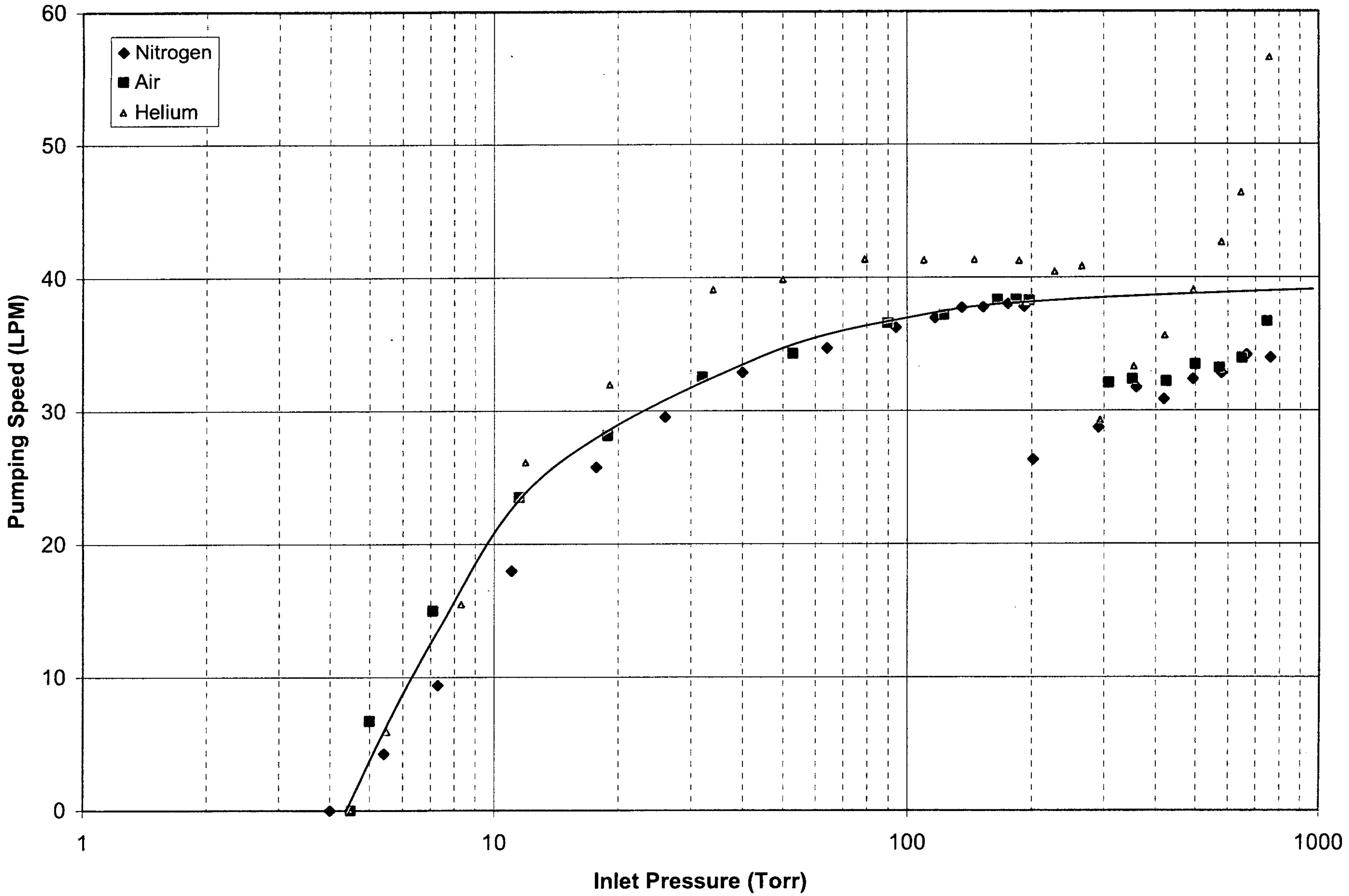

Figure 45 – Vacuubrand MZ 2D Pumping Speed Curves

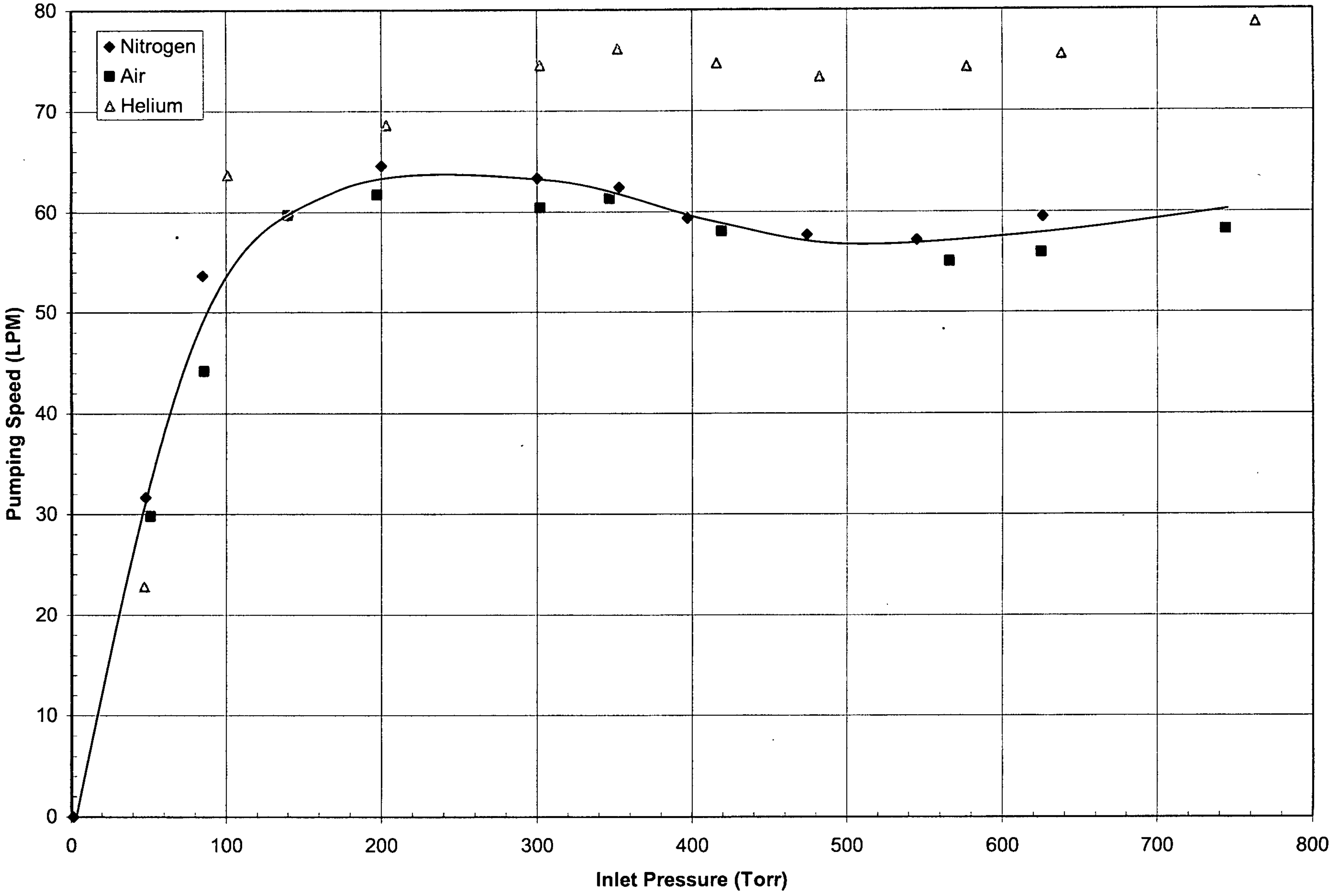

Figure 46 – Vacuubrand MD 4 Vario Pumping Speed Curves

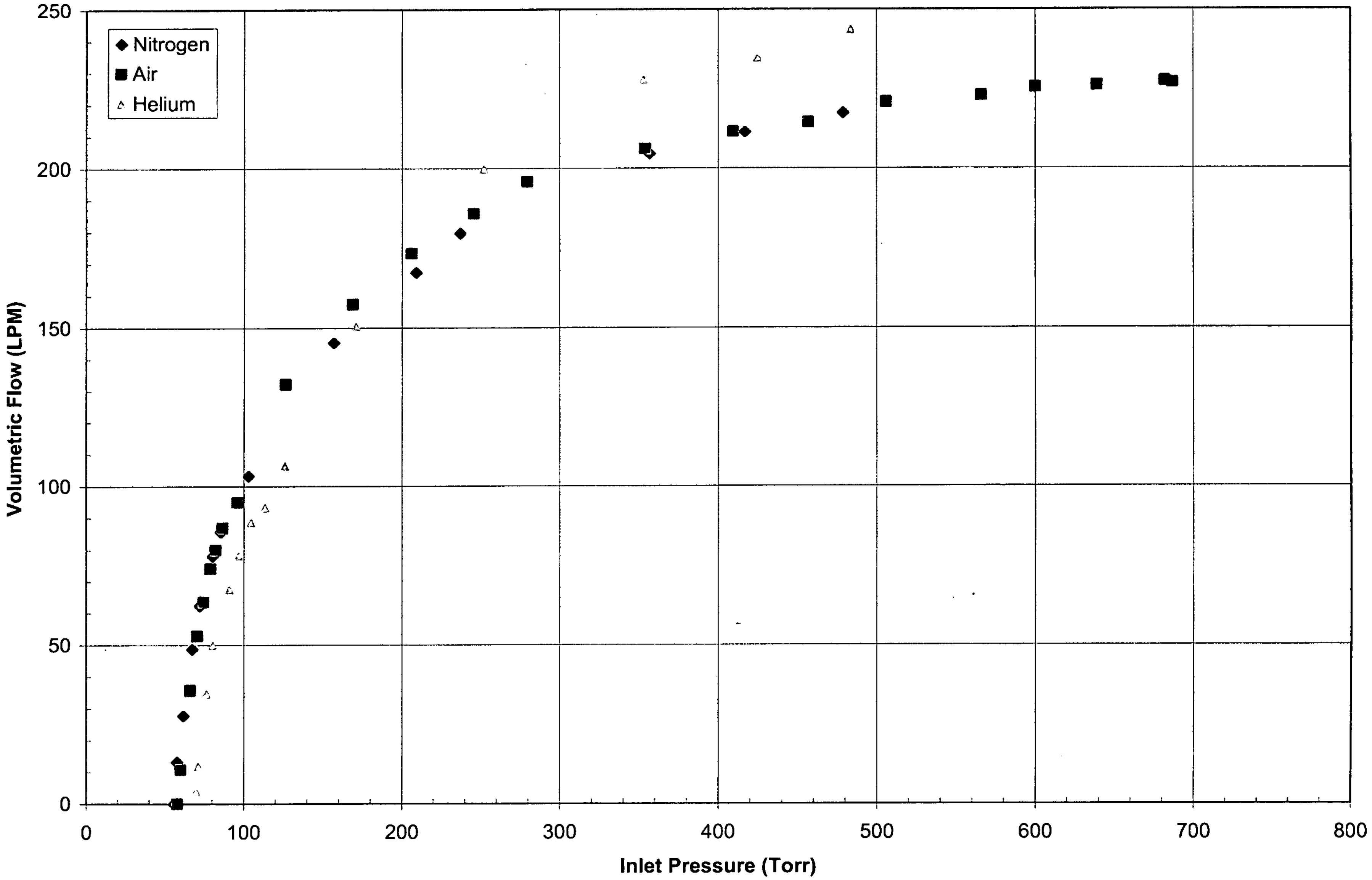

Figure 47 – Vacuubrand ME 16 Pumping Speed Curves

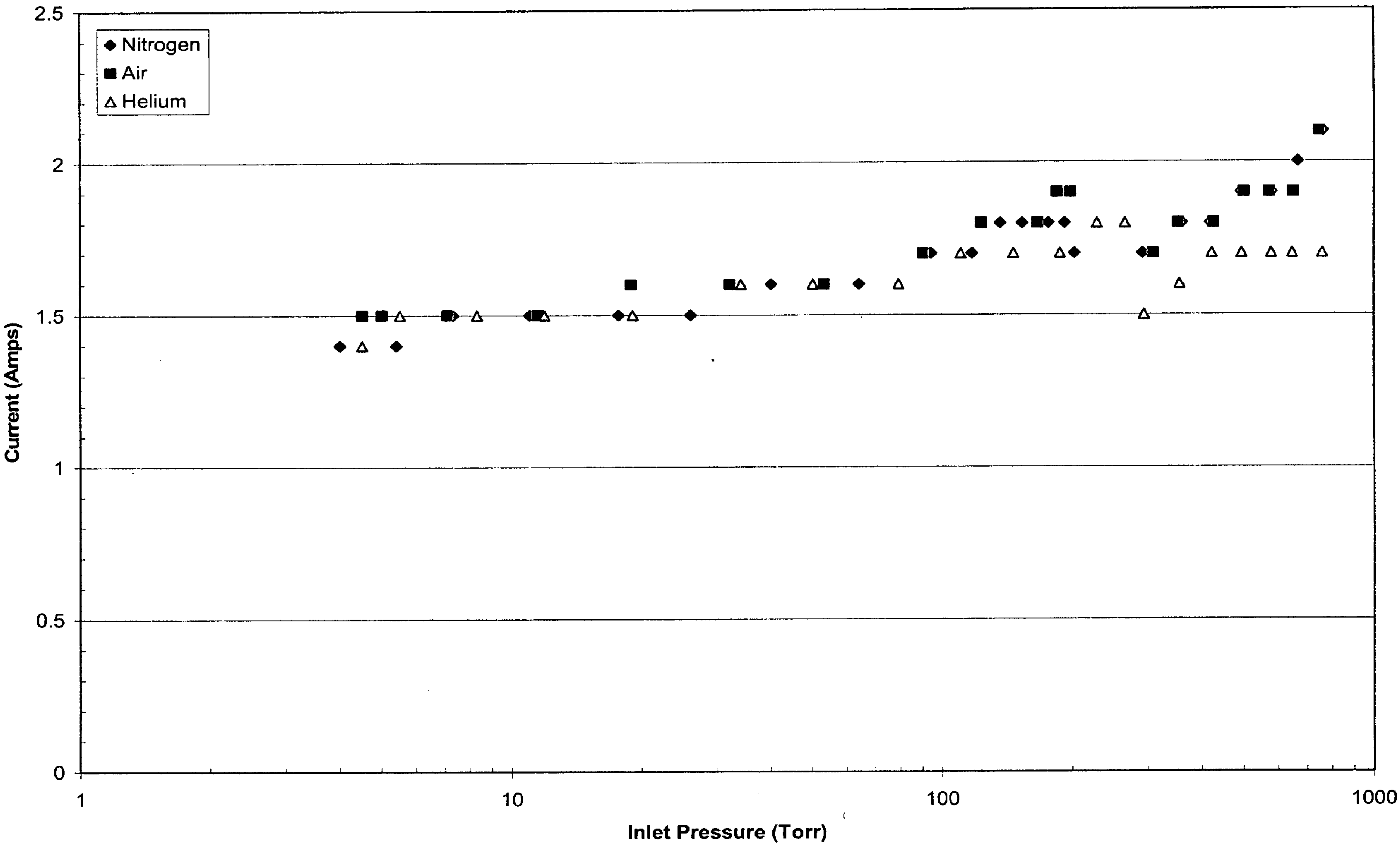

Figure 48 – Vacuubrand MZ 2D Current Curves

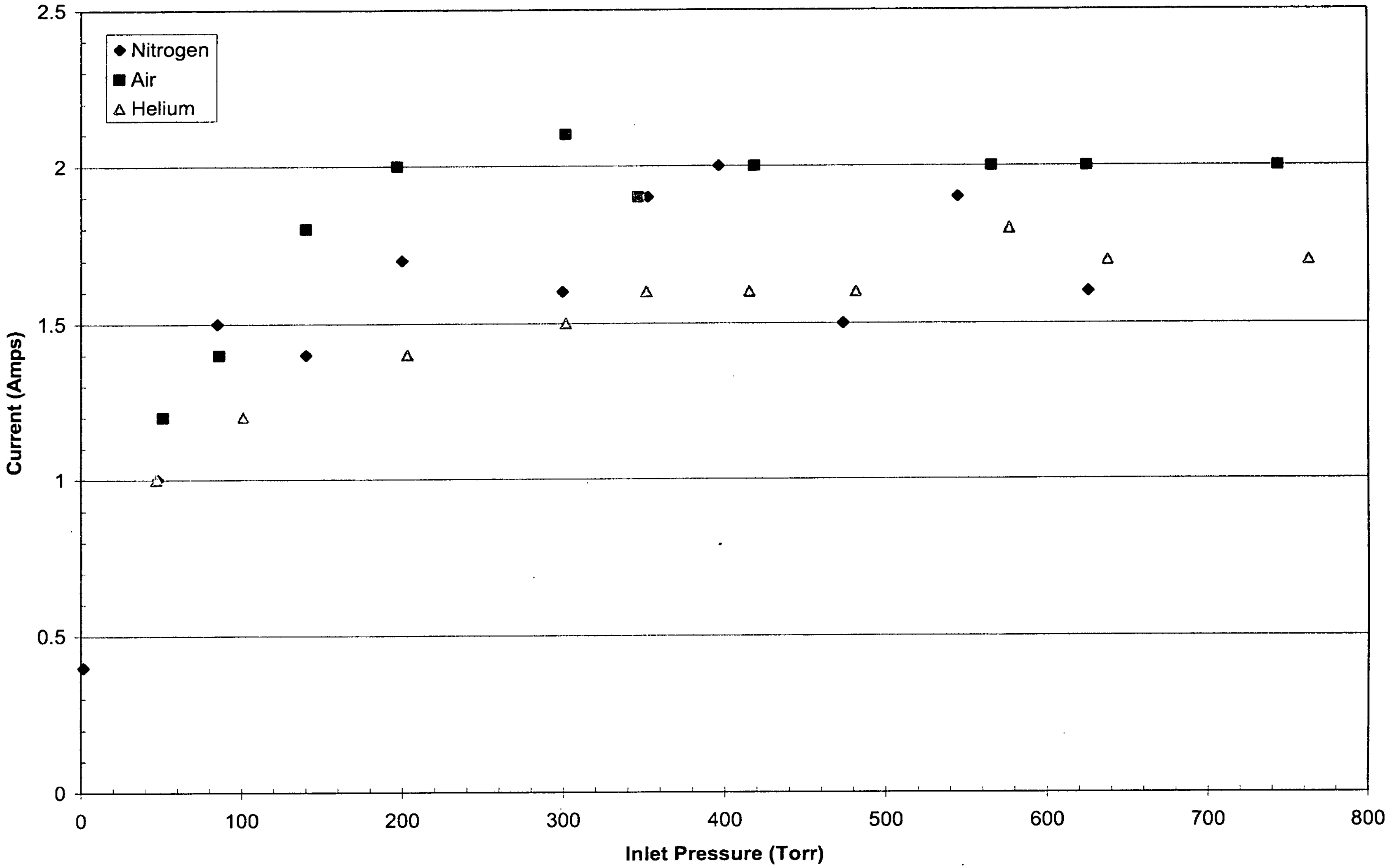

Figure 49 – Vacuubrand MD 4 Vario with Controller Current Curves

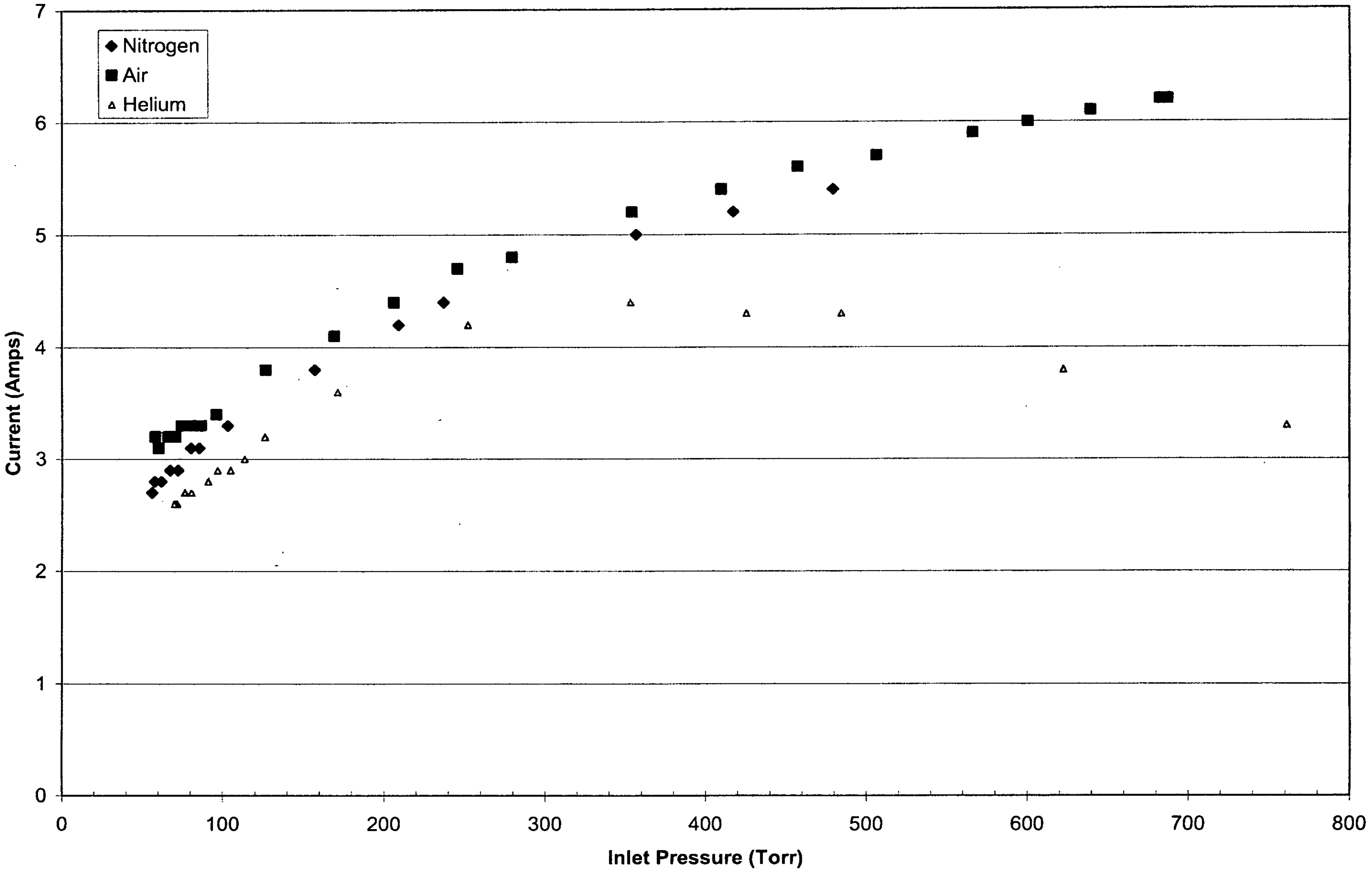

Figure 50 – Vacuubrand ME 16 Current Curves

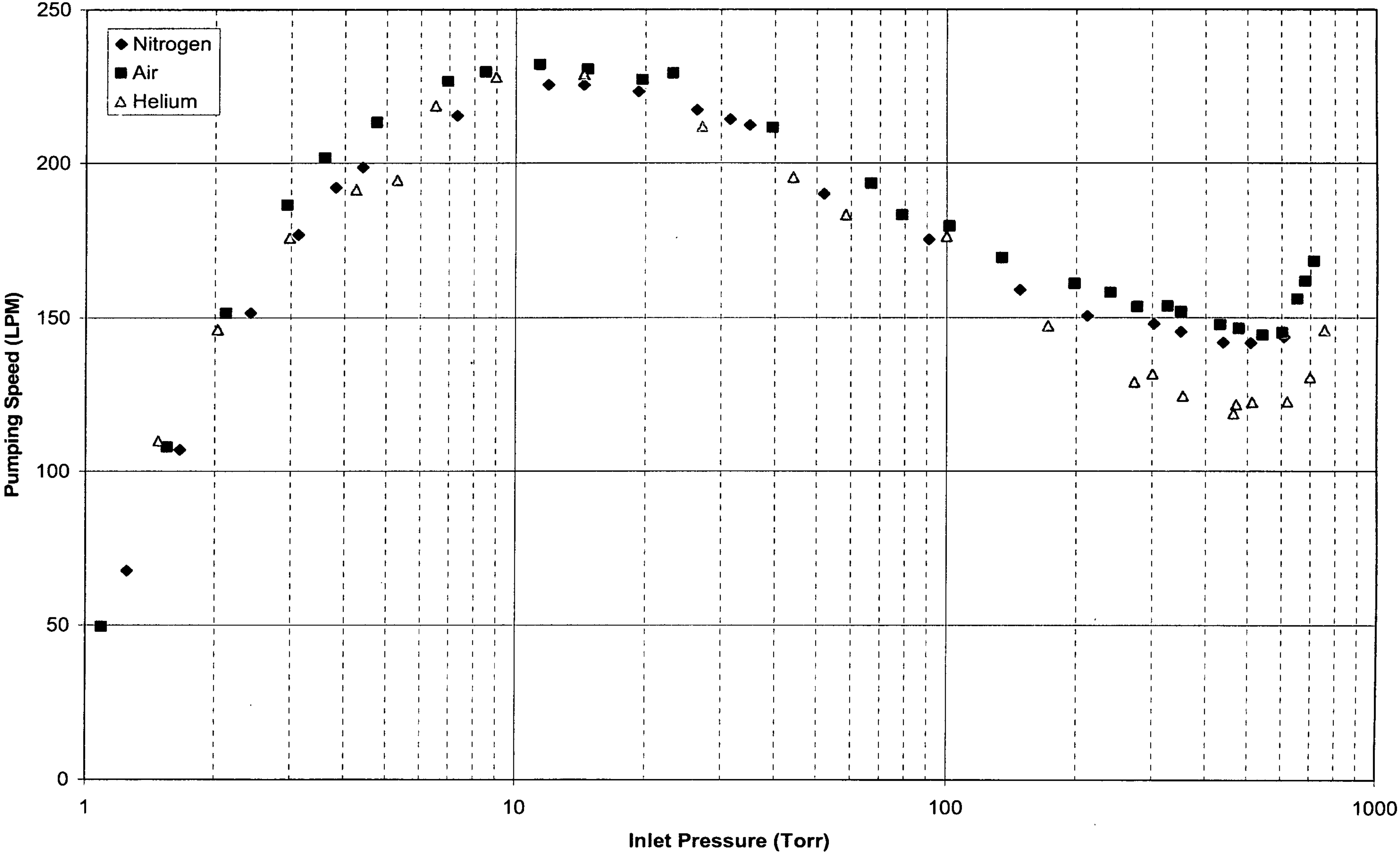

Figure 51 – Varian TriScroll 300 Pumping Speed Curves

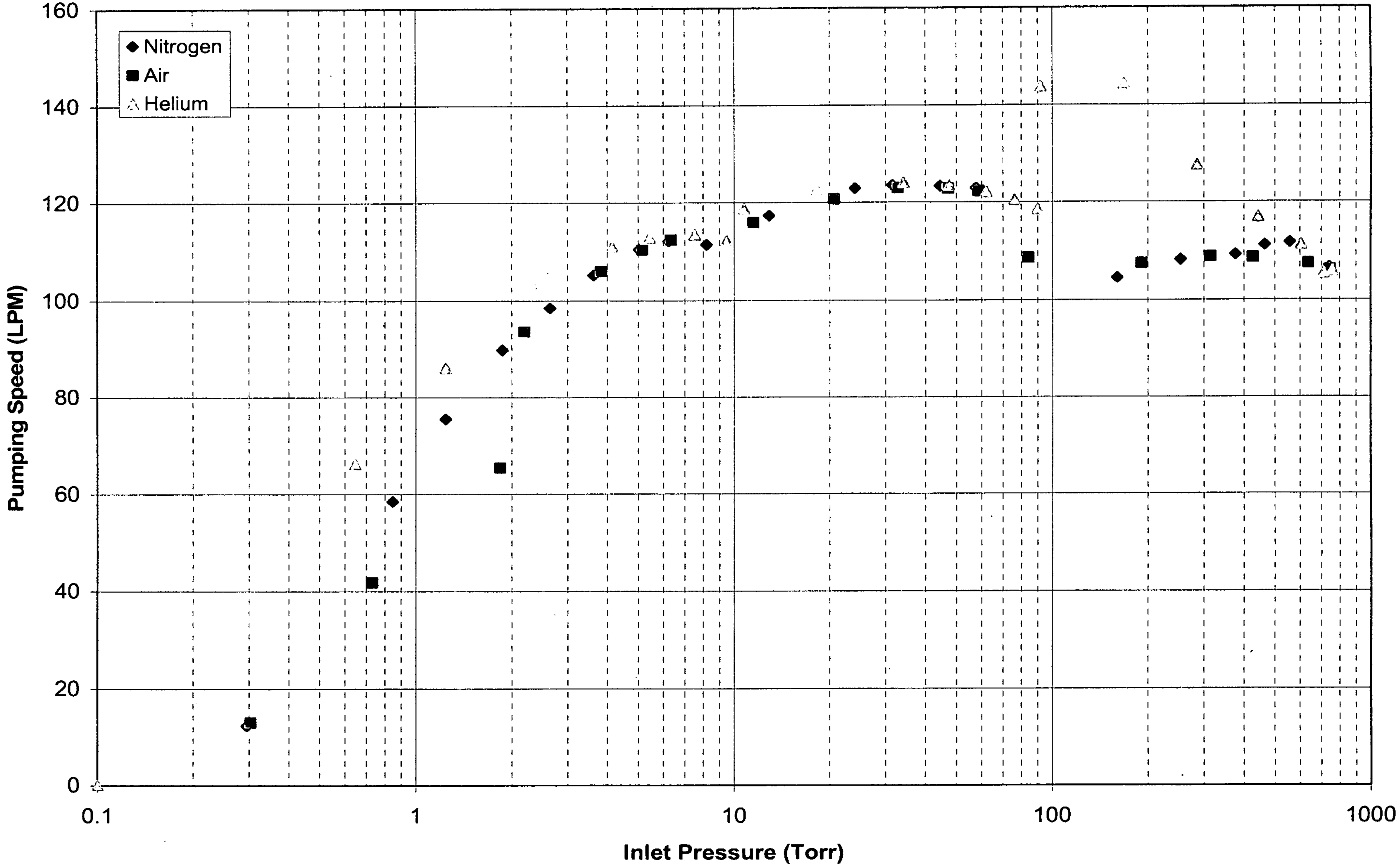

Figure 52 – Varian SH 100 Pumping Speed Curves

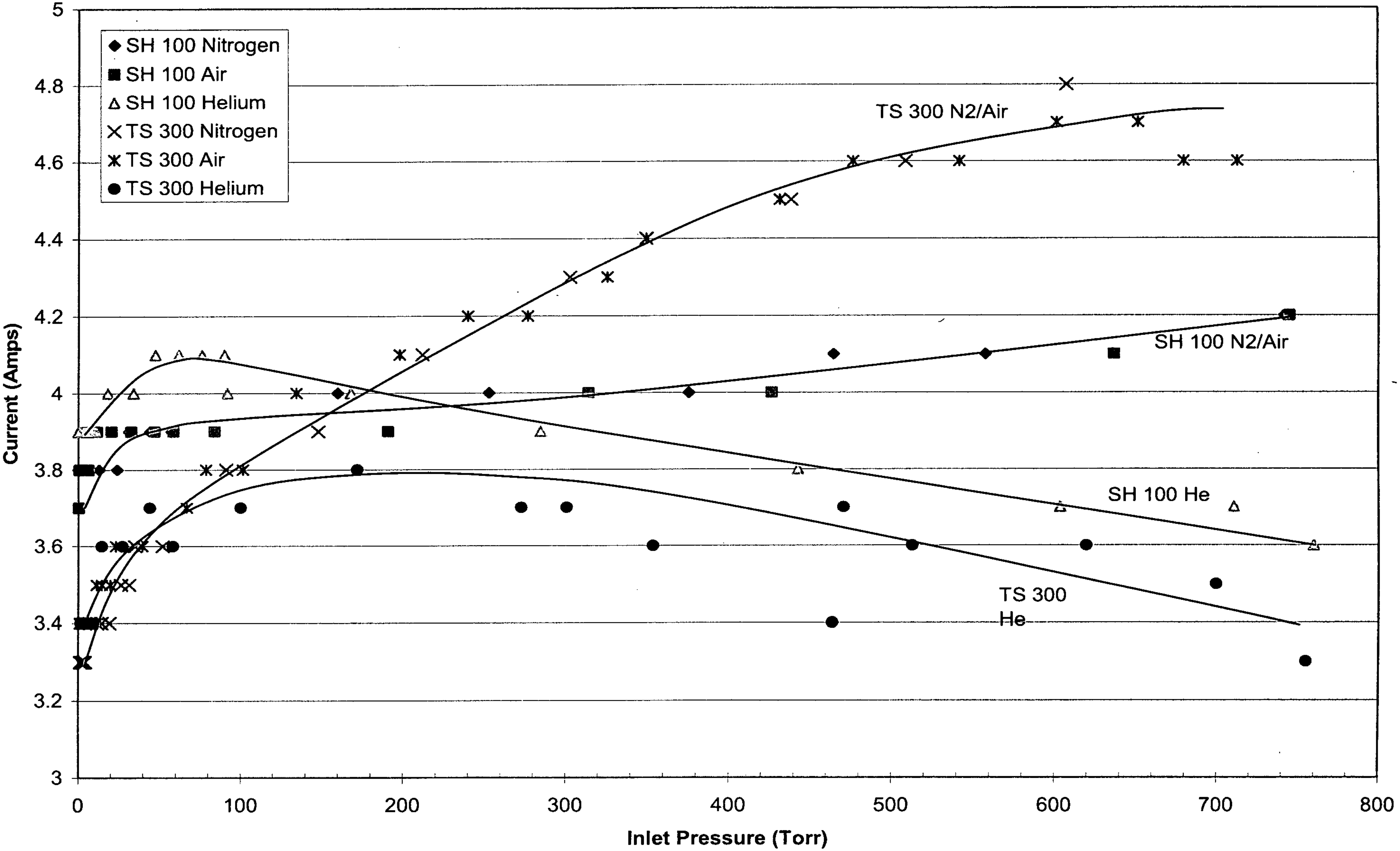

Figure 53 – Varian Scroll Pump Current Curves

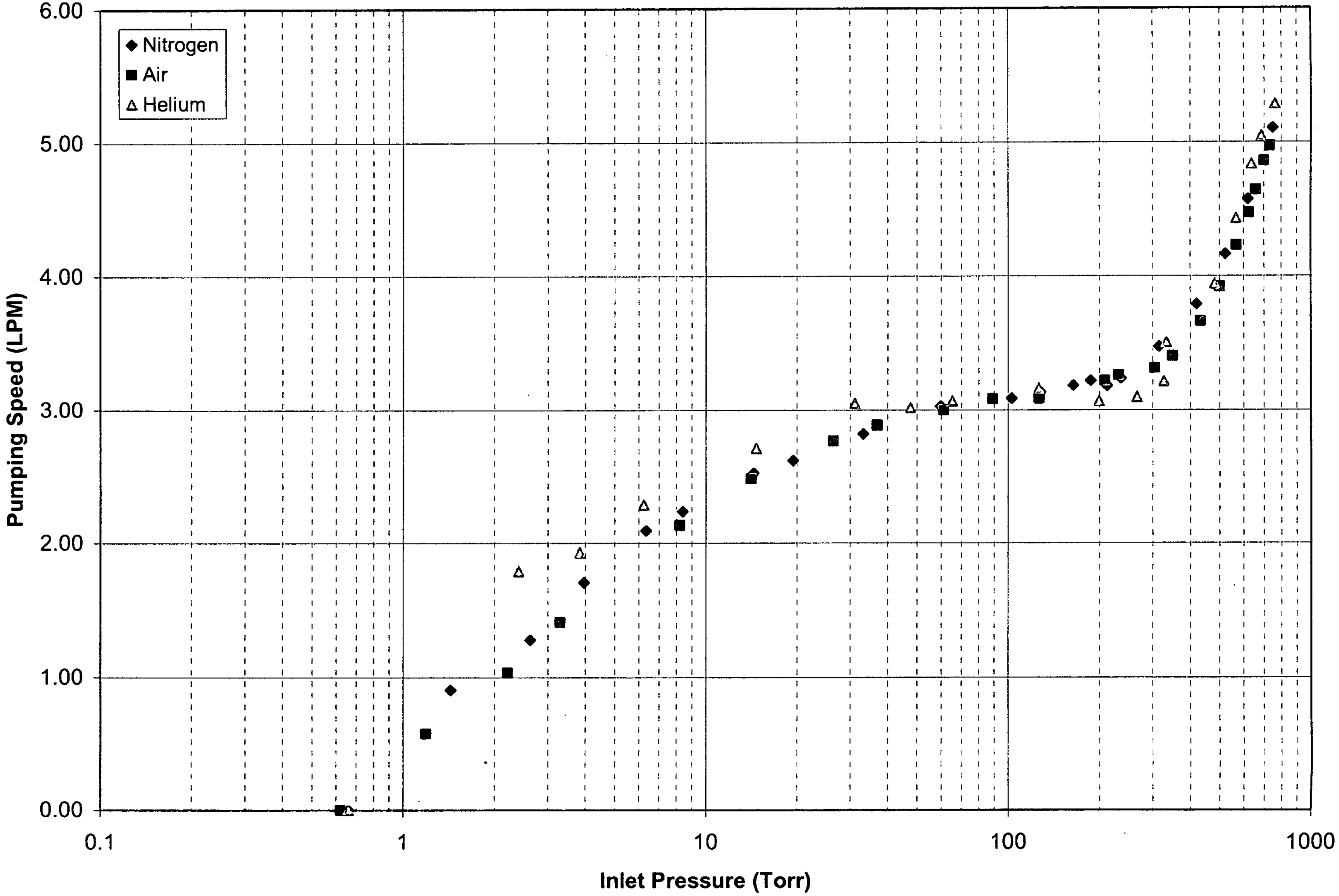

Figure 54 – KNF 84.4 Pumping Speed Curve

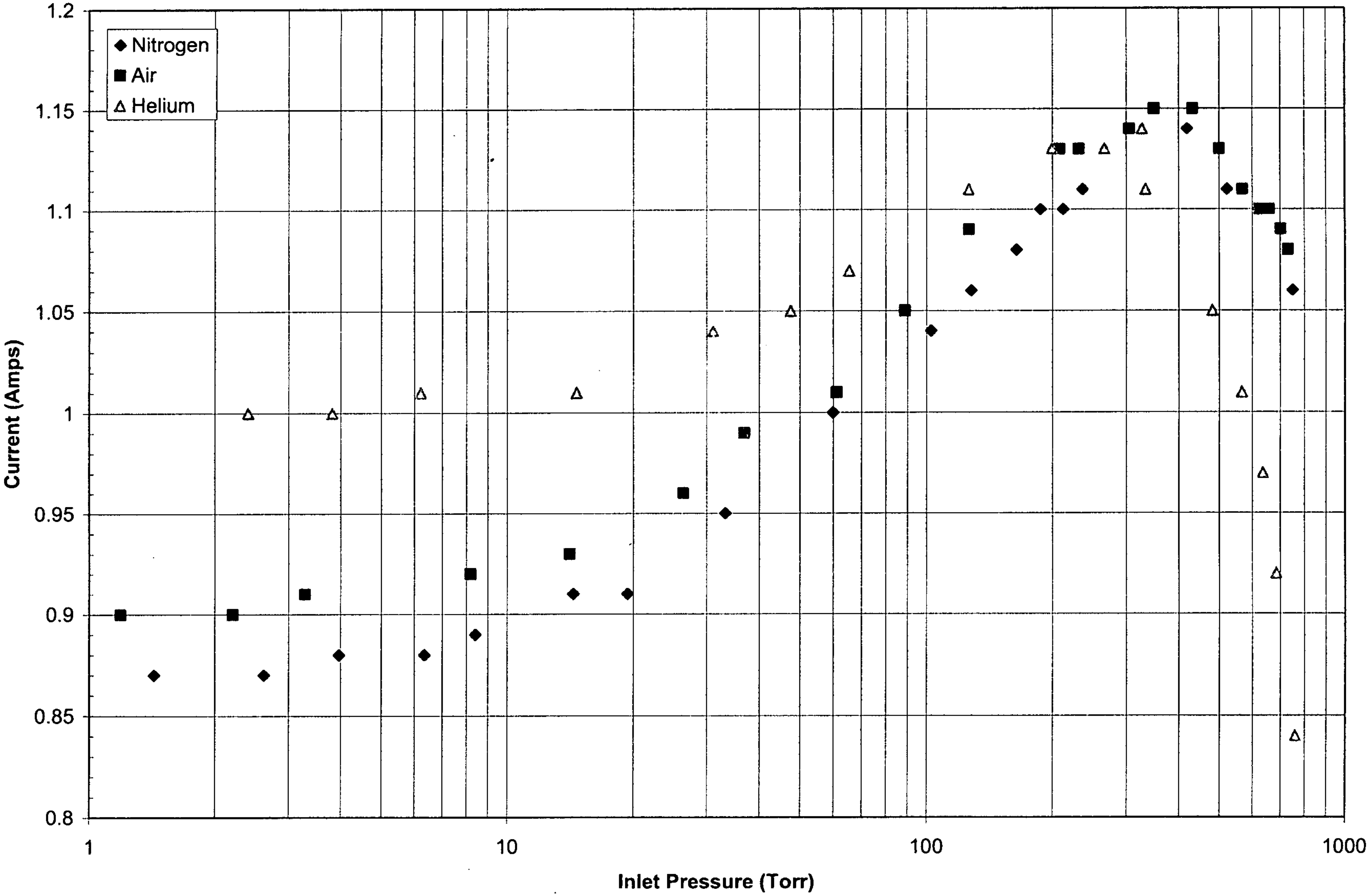

Figure 55 – KNF 84.4 Current Curves

B. VOLTAGE VARIANCE CURVES

The following figures contain voltage variance curves discussed in Section 4. They show how the inlet pressure and current demand vary as a function of input voltage while operating at 300 torr or ultimate pressure.

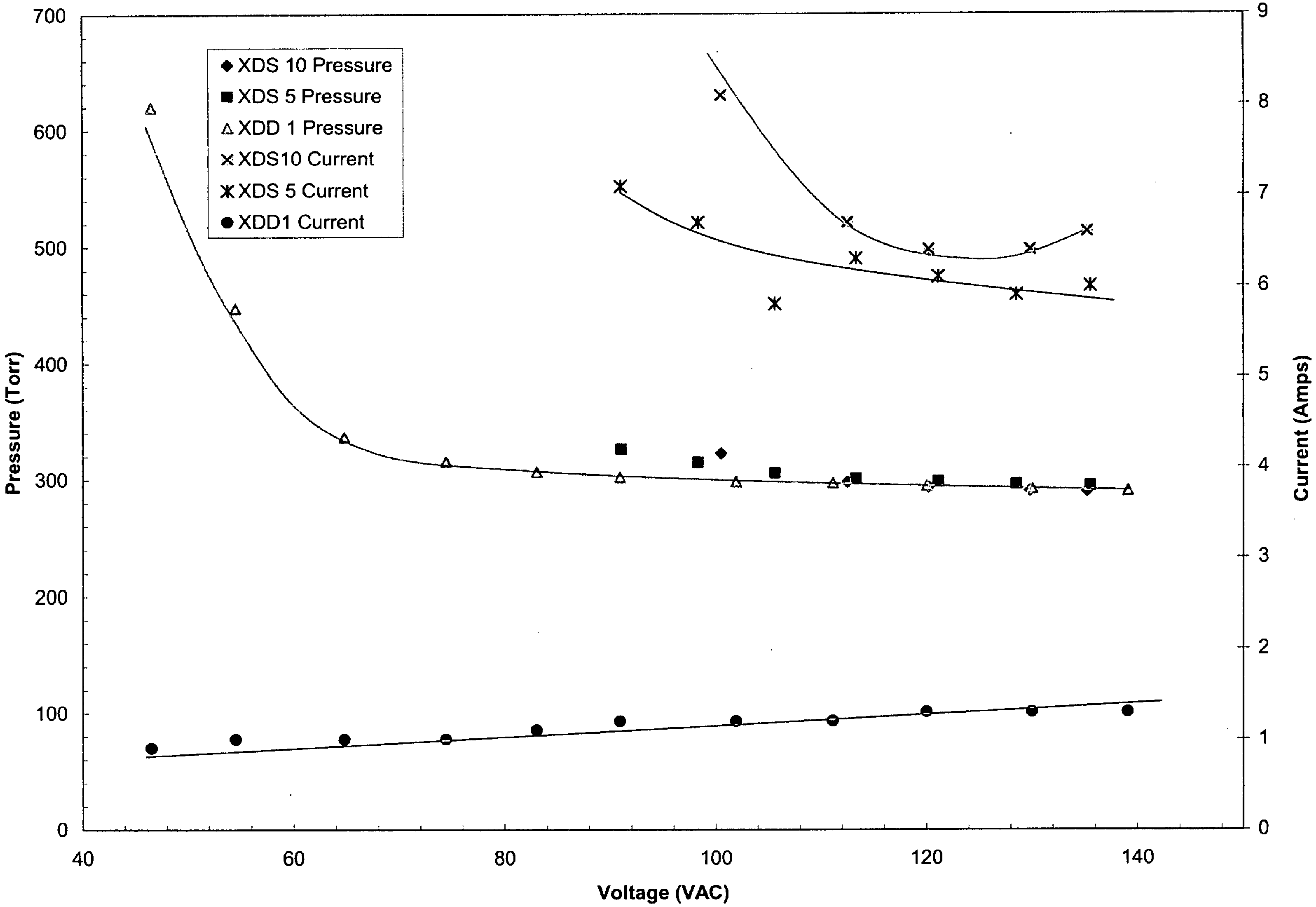

Figure 56 – Voltage Variance Curves for Edwards Pumps

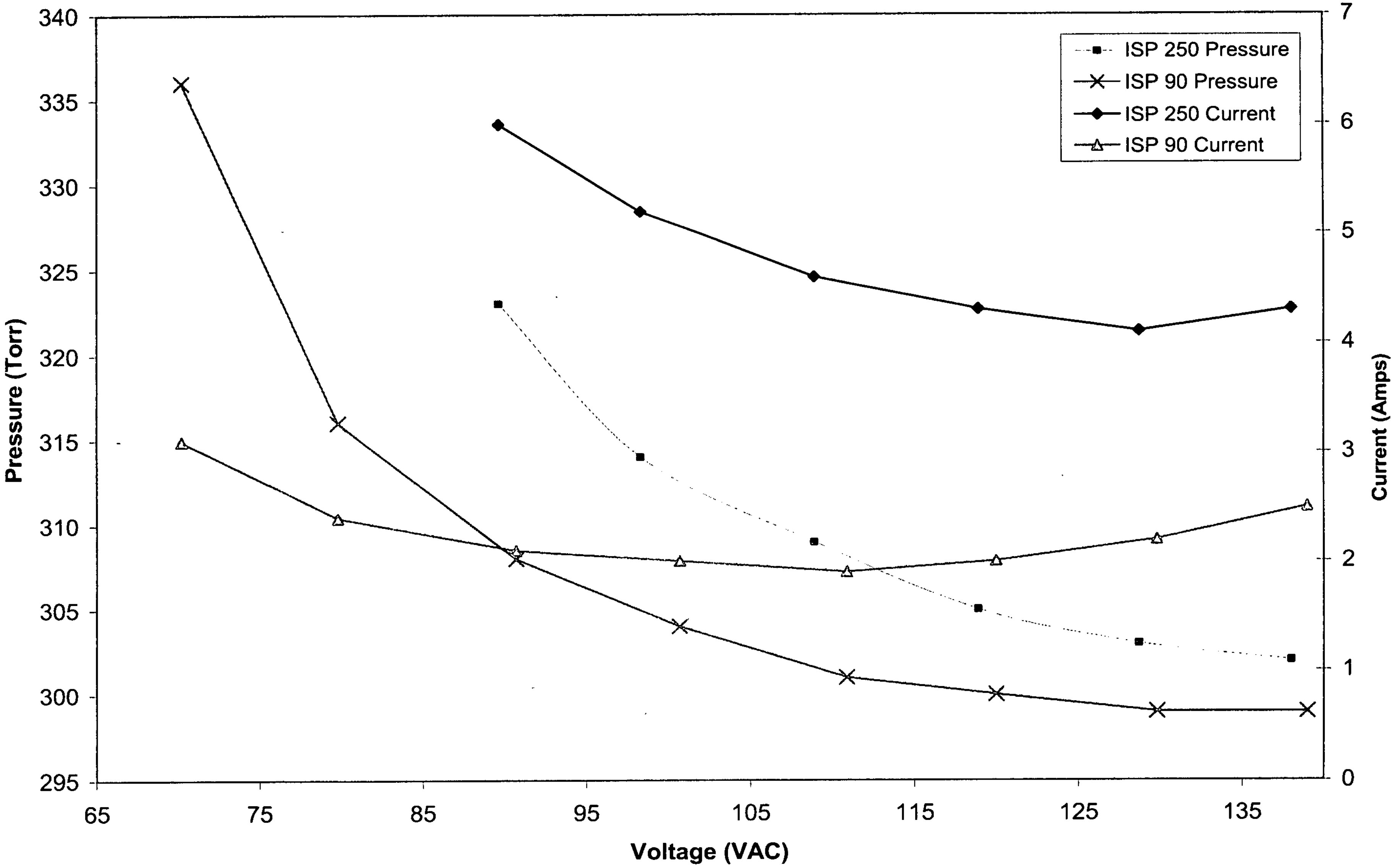

Figure 57 – Voltage Variance Curves for Iwata Scroll Pumps

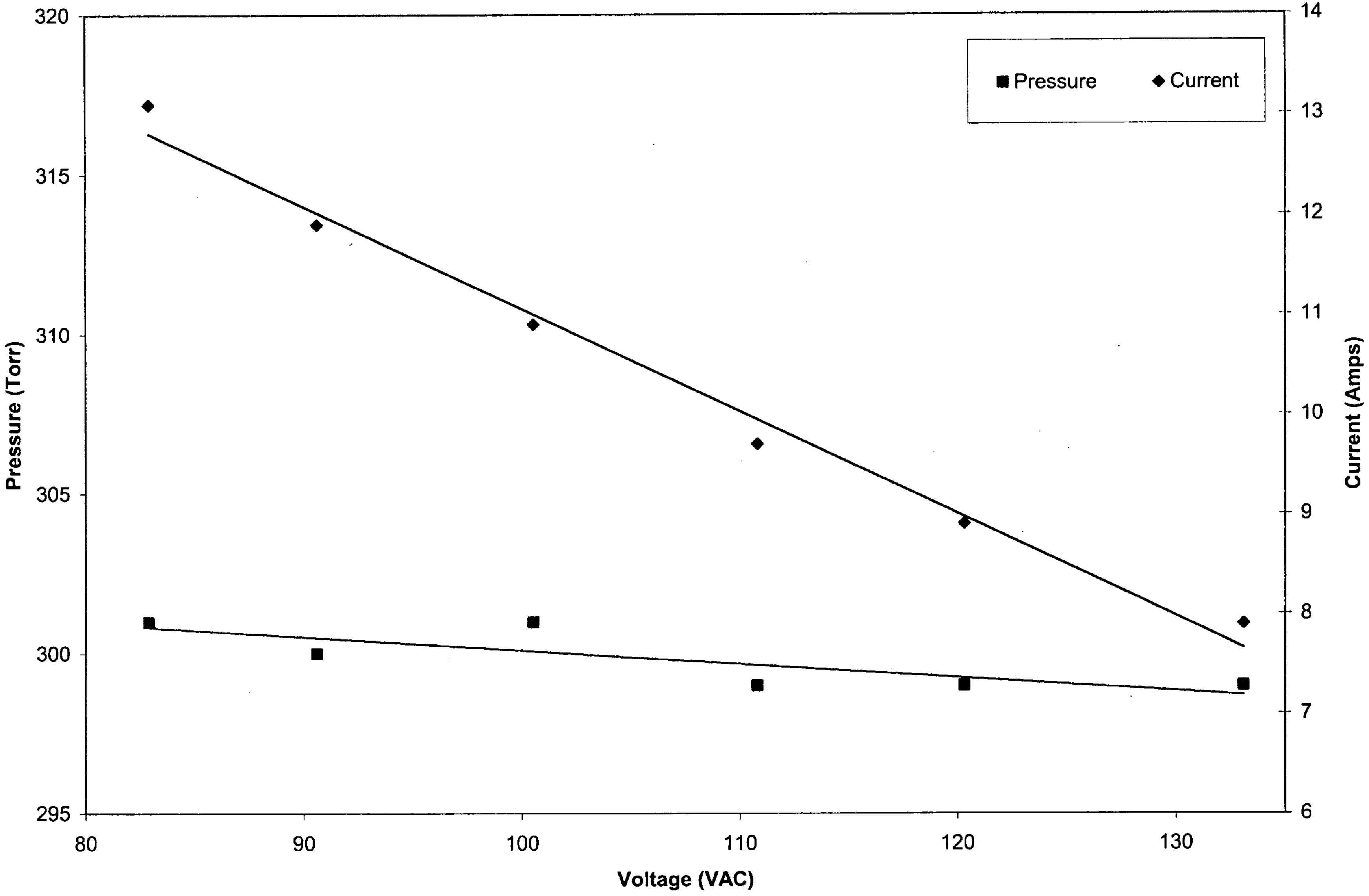

Figure 58 – Voltage Variance Curves for Adixen ACP 28

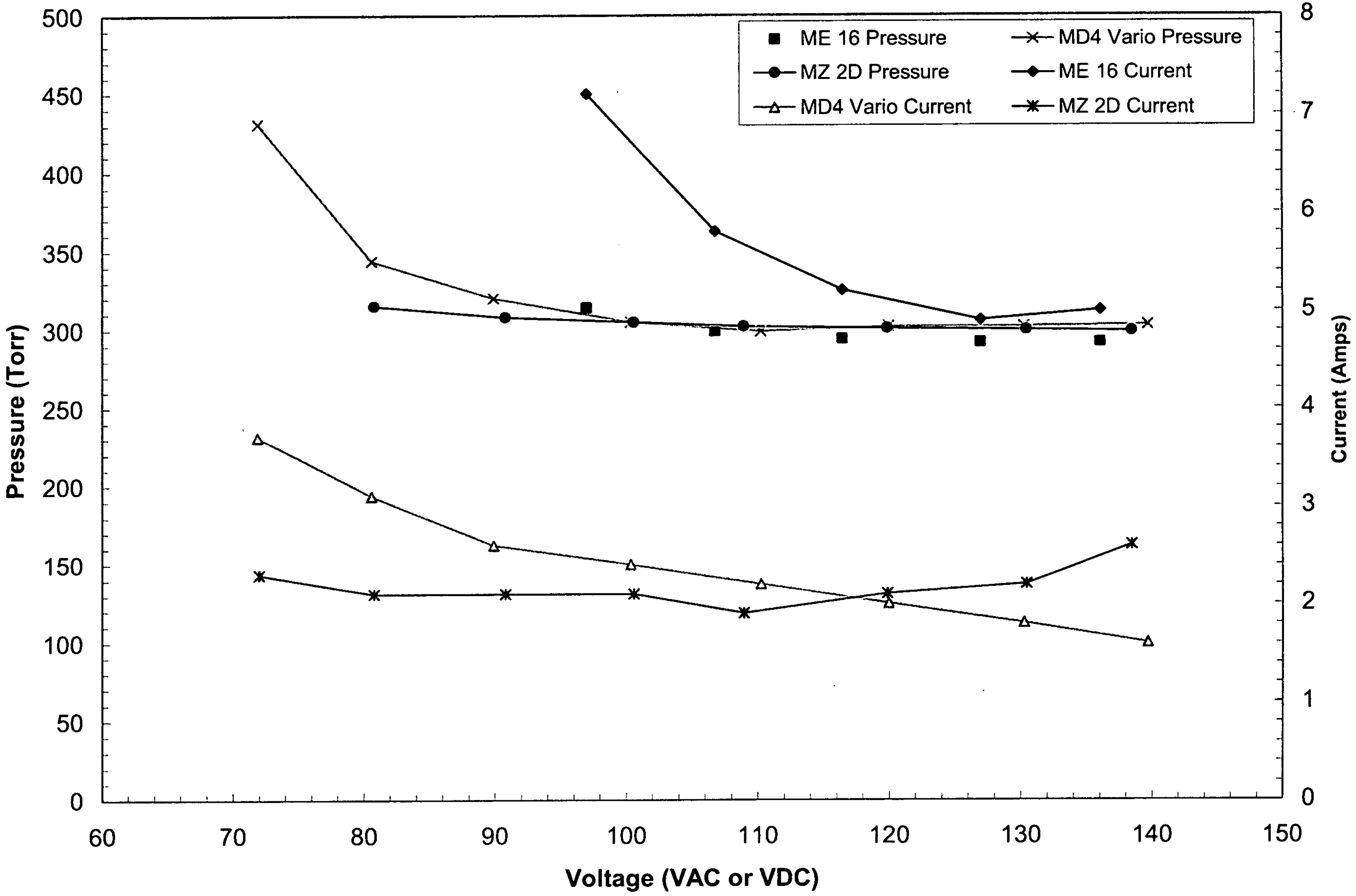

Figure 59 – Voltage Variance Curves for Vacuubrand Pumps

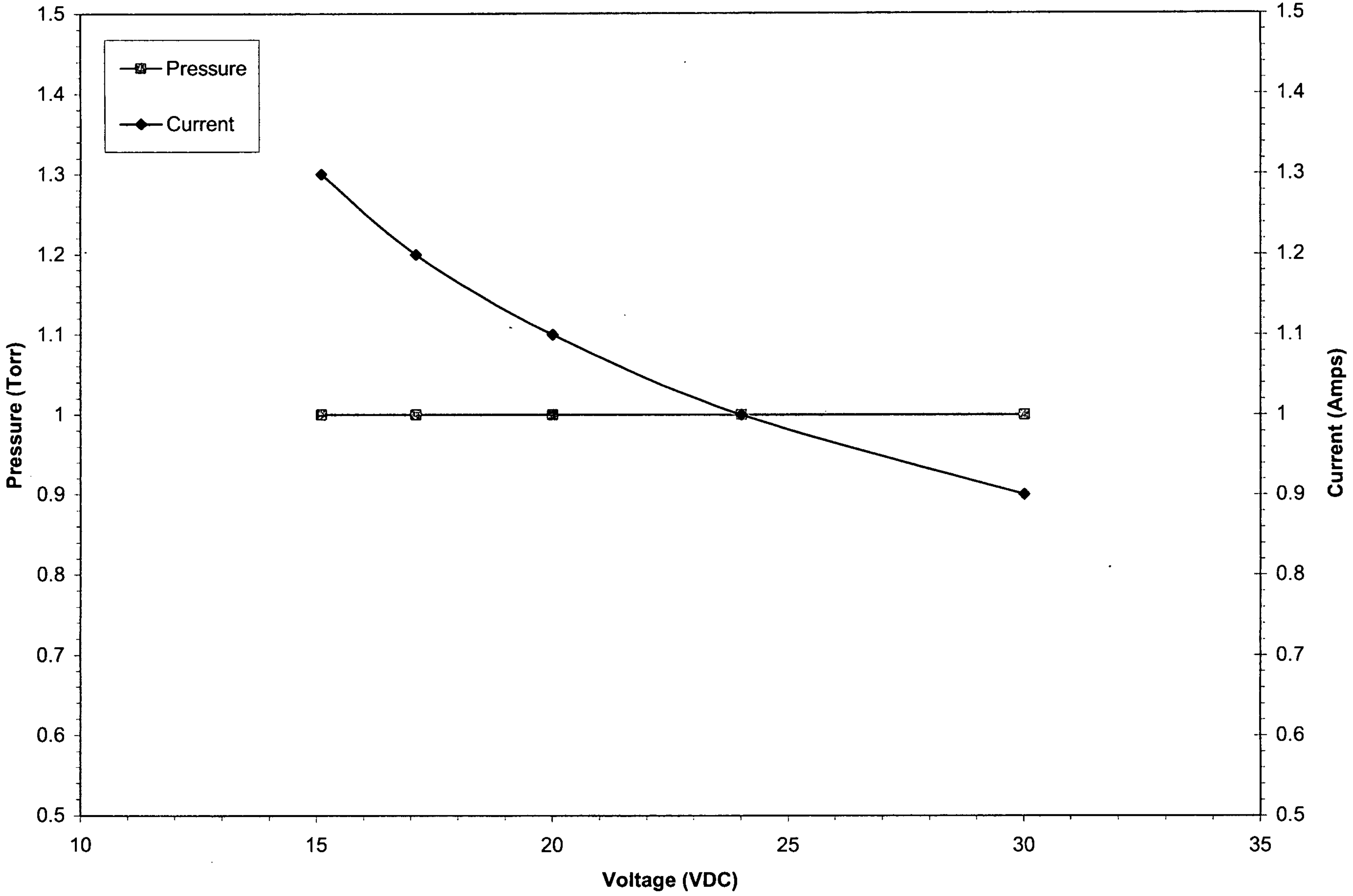

Figure 60 – Voltage Variance Curves for Vacuubrand MD 1 Vario

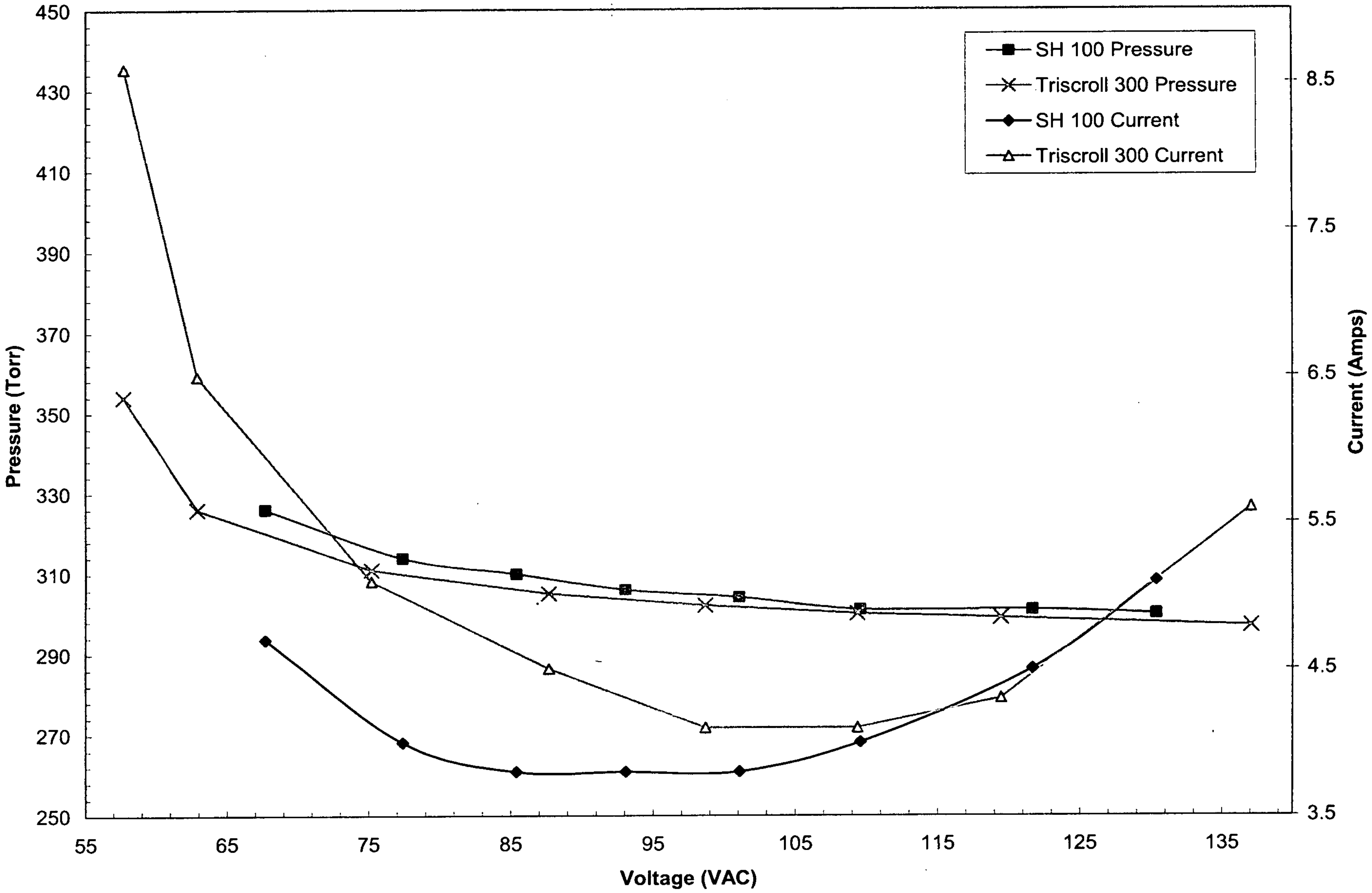

Figure 61 – Voltage Variance Curves for Varian Scroll Pumps

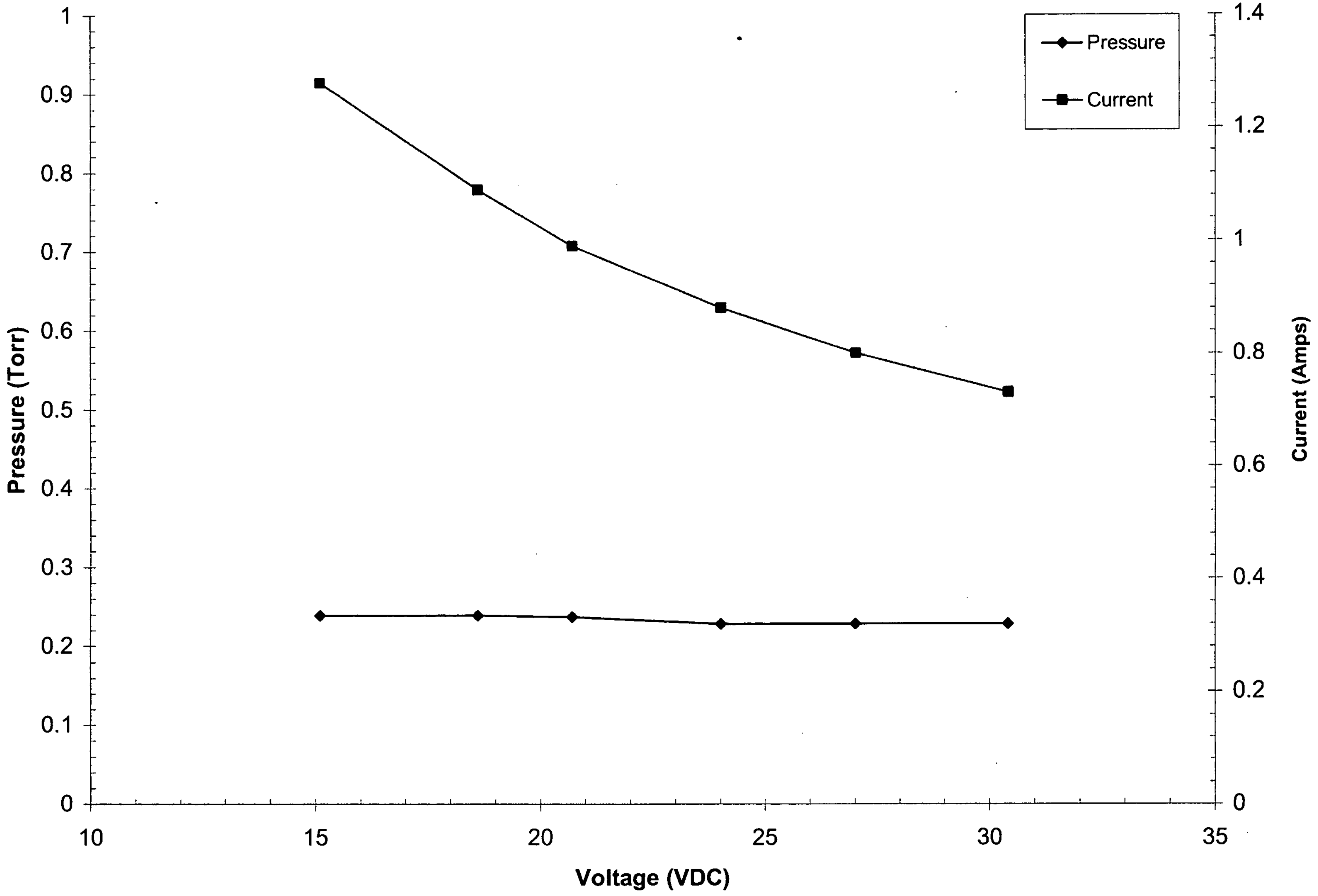

Figure 62 – Voltage Variance Curve for KNF 84.4

C. EXHAUST RESTRICTION CURVES

The following figures contain exhaust restriction curves discussed in Section 7. They describe how the inlet pressure and current varies with the outlet pressure. The outlet pressure that will occur depends on the length and diameter of the exhaust plumbing, as well as the type of gas being pumped.

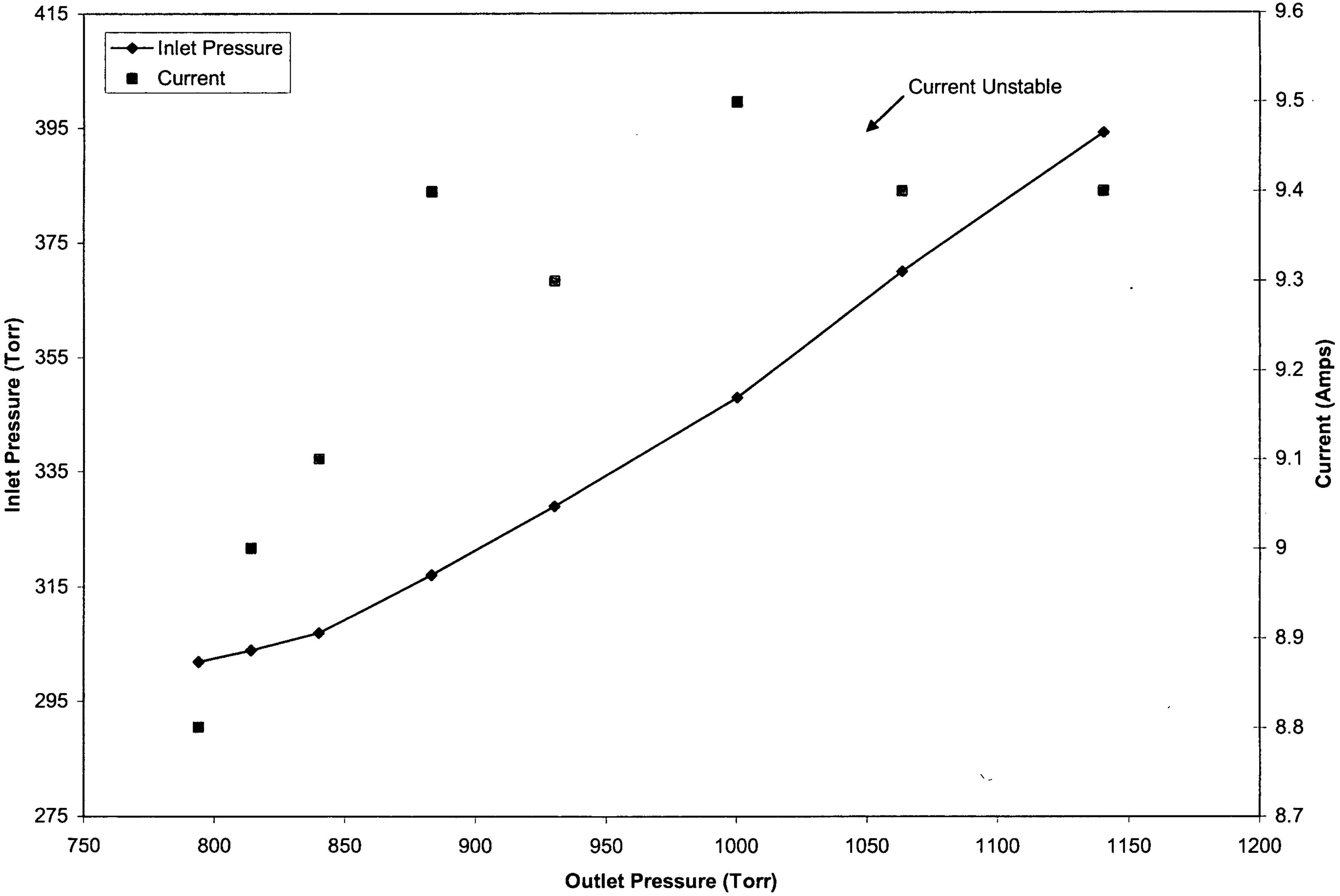

Figure 63 – Exhaust Restriction Curve for Adixen ACP 28

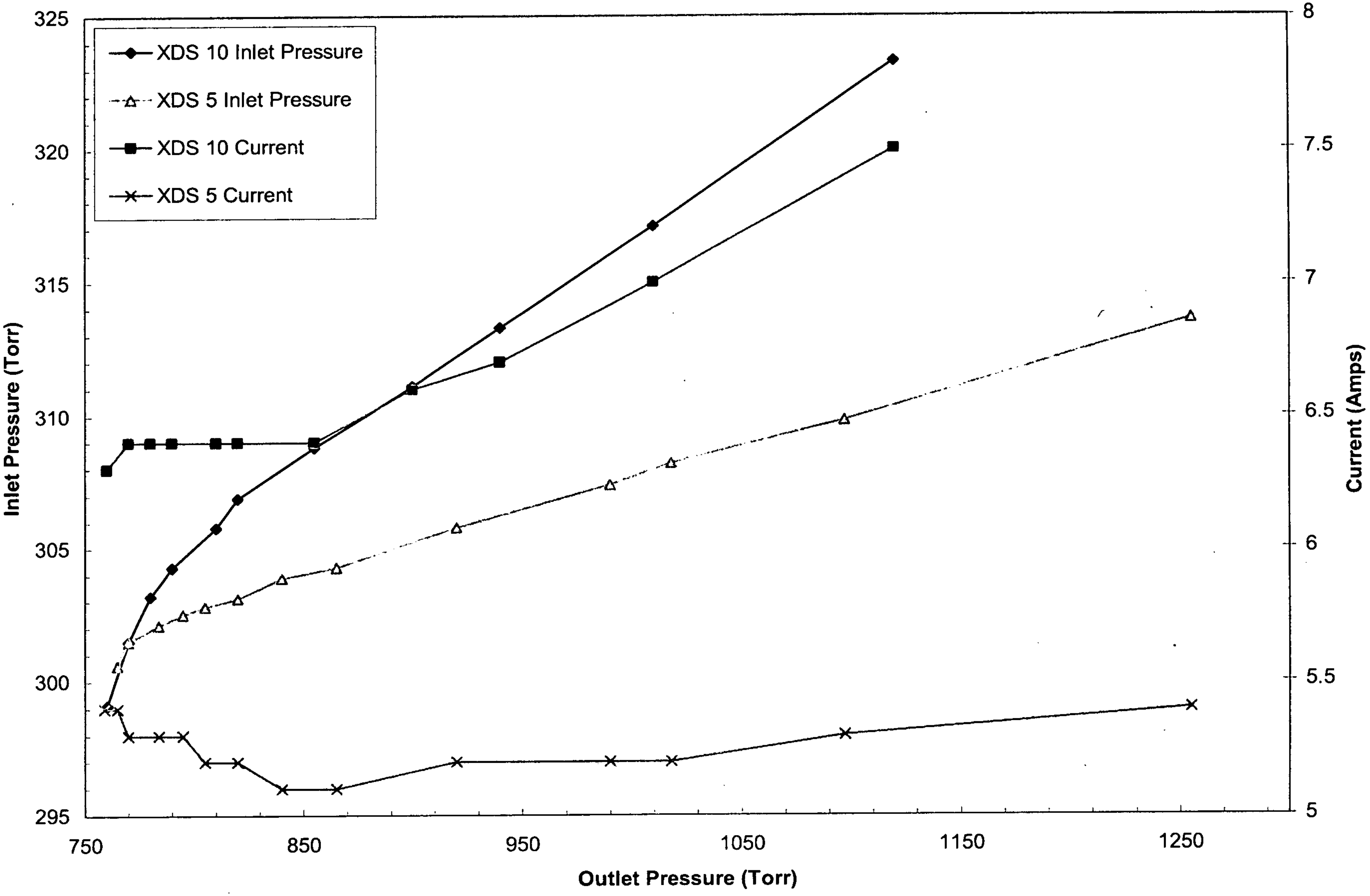

Figure 64 – Exhaust Restriction Curves for Edwards XDS 5 and XDS 10

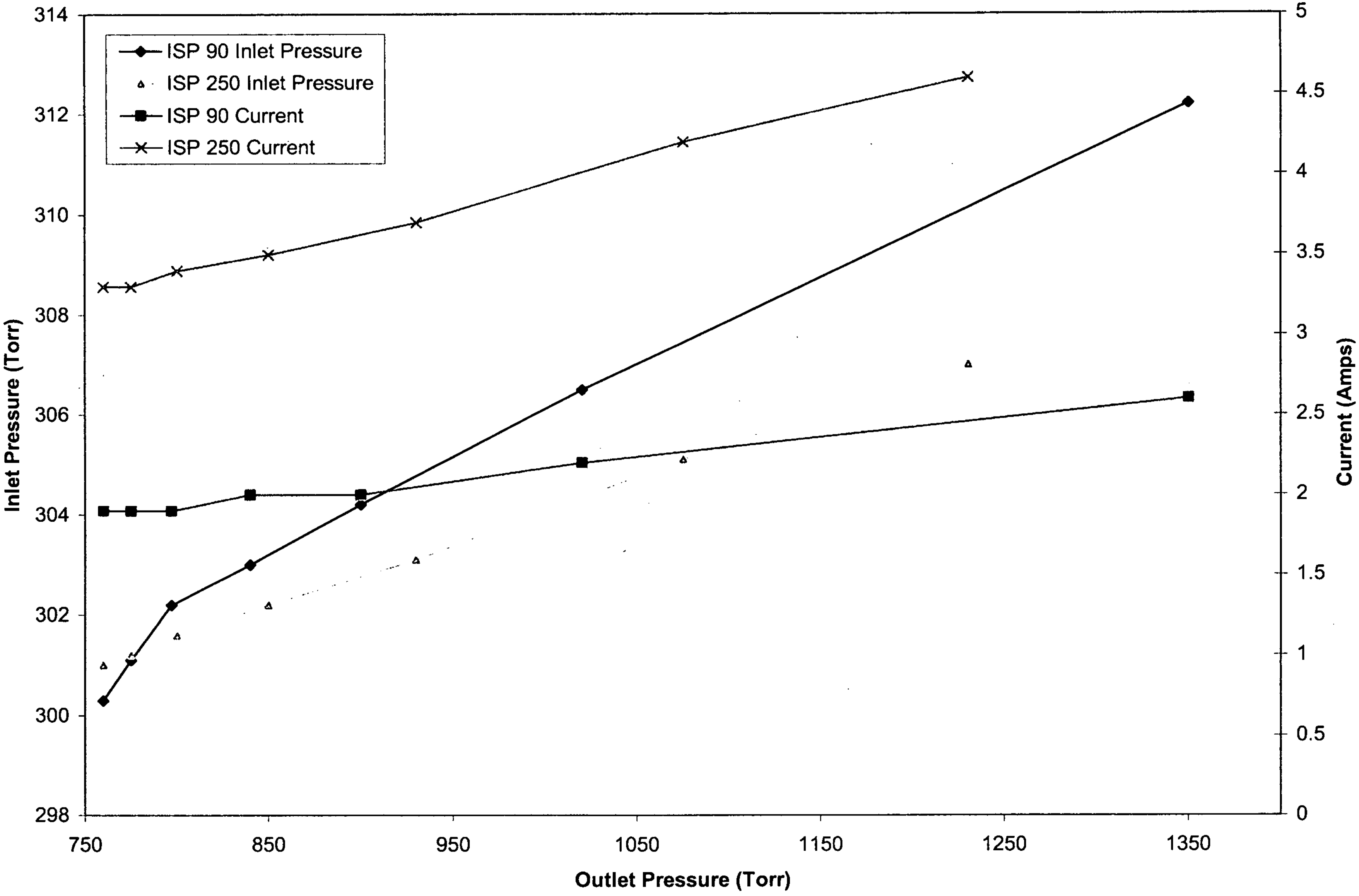

Figure 65 – Exhaust Restriction Curves for Iwata Scroll Pumps

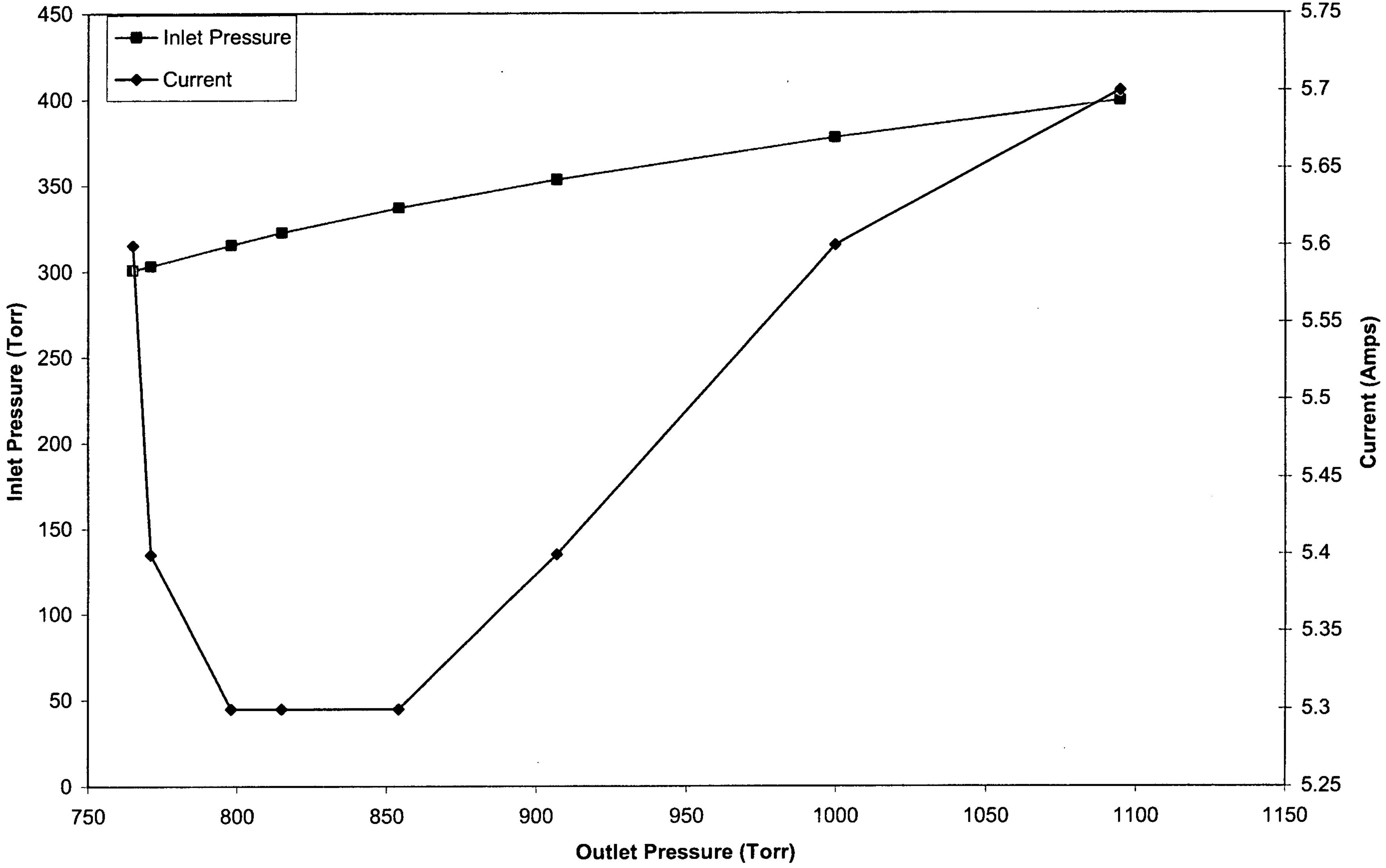

Figure 66 – Exhaust Restriction Curve for Vacuubrand ME 16

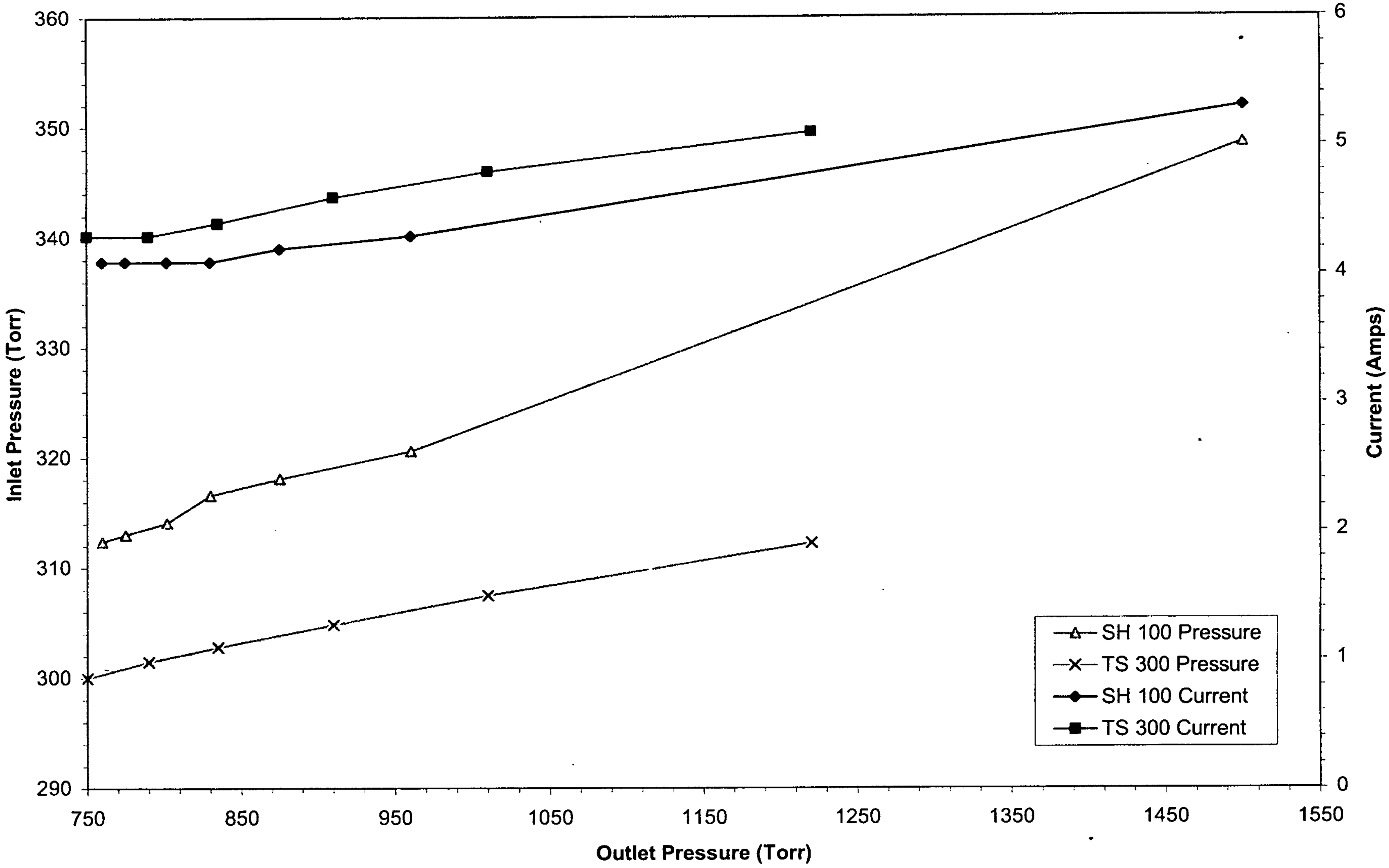

Figure 67 – Exhaust Restriction Curves for Varian Scroll Pumps

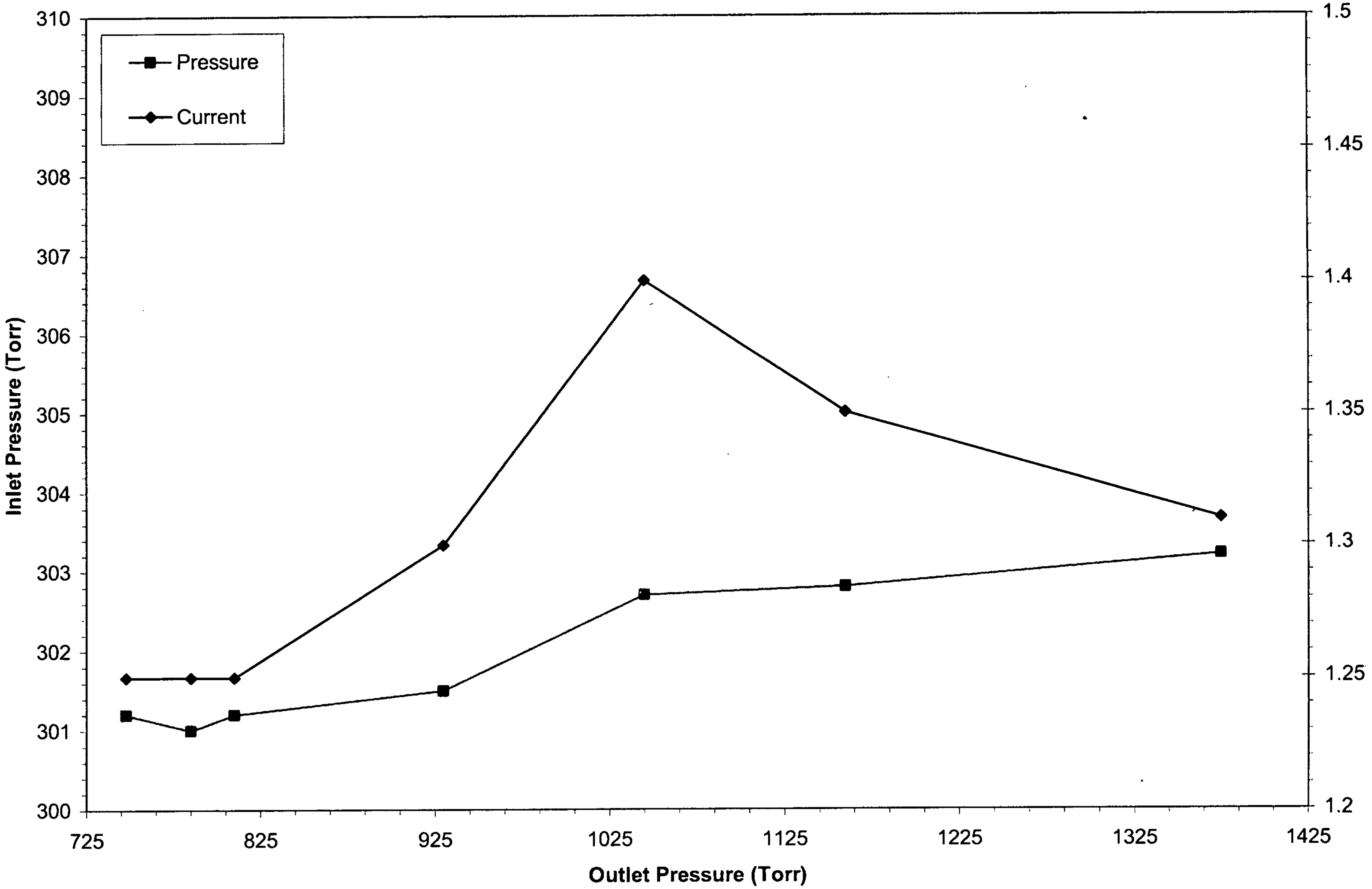

Figure 68 – Exhaust Restriction Curves for KNF 84.4

D. STATIC LEAK RATE CURVES

The following curves are discussed in Section 6. When pumps are turned off, gas leaks back through them and into the vacuum system. These curves show how the pressure of an 8.07 L chamber increases with time for various pumps. The Varian TriScroll 300 is presented separately, since its leak rate is drastically higher than any other pump.

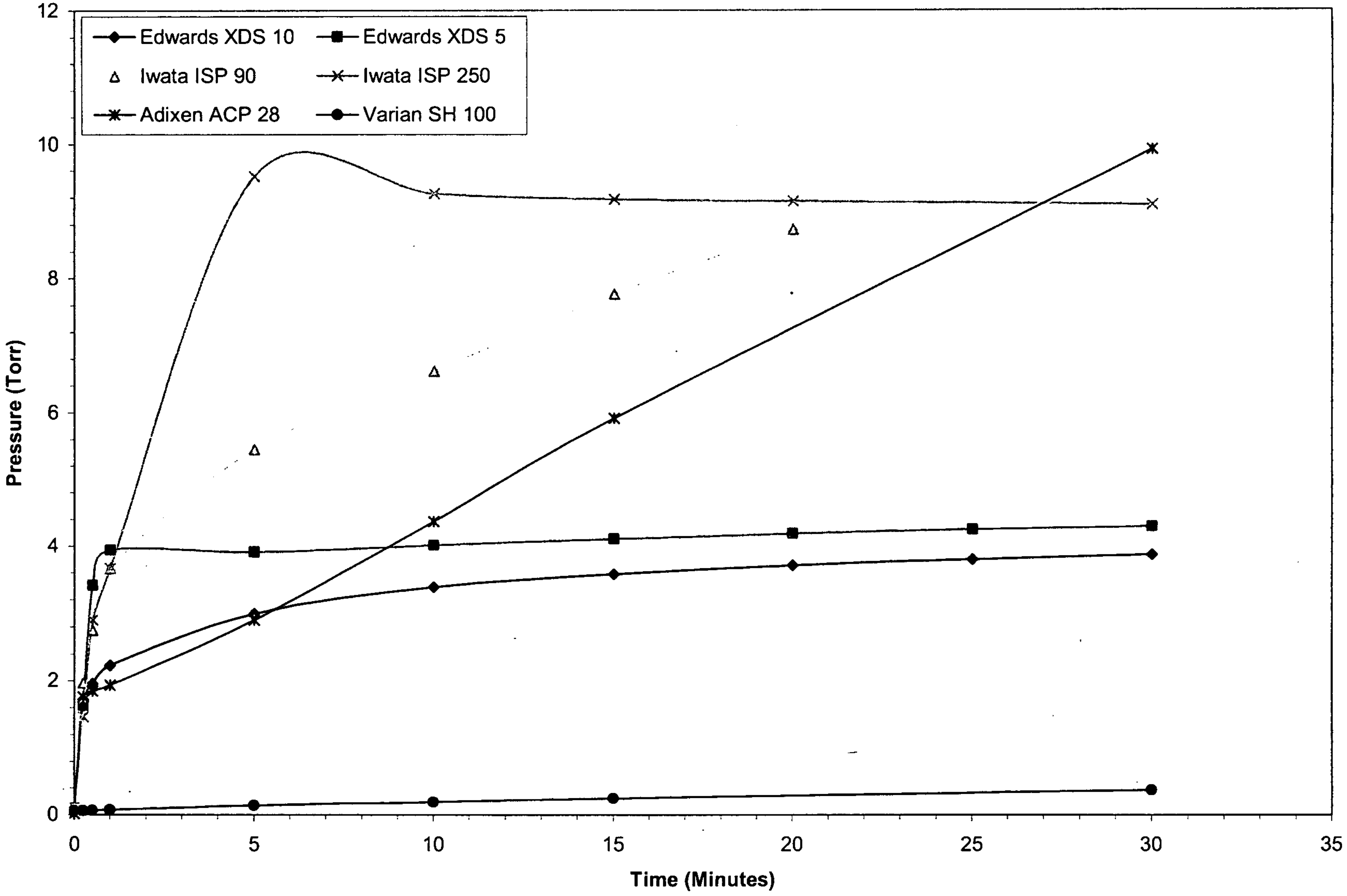

Figure 69 – Static Leak Rate Curves for Scroll Pumps and Adixen ACP 28

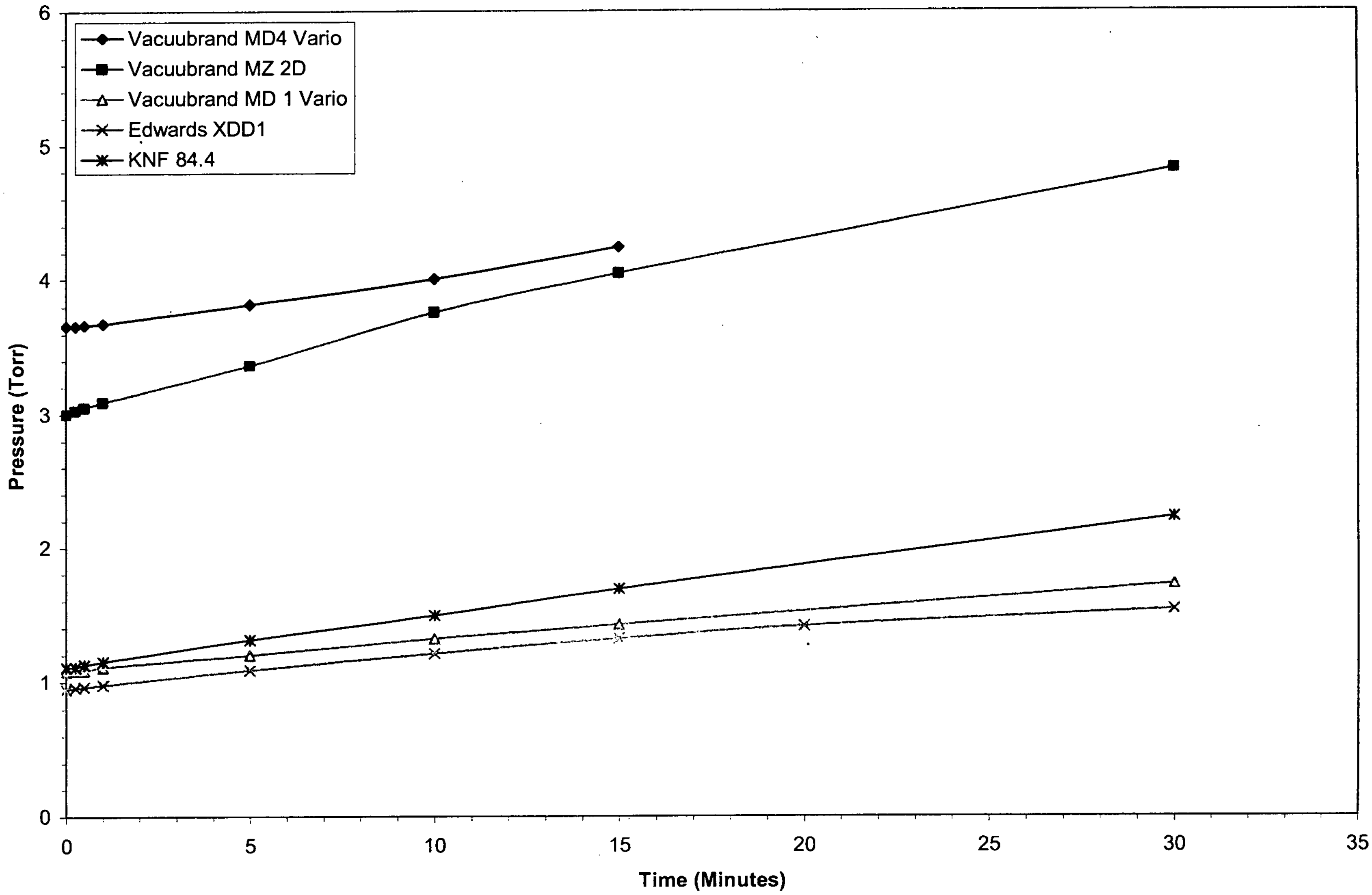

Figure 70 – Static Leak Rate Curve for Diaphragm Pumps

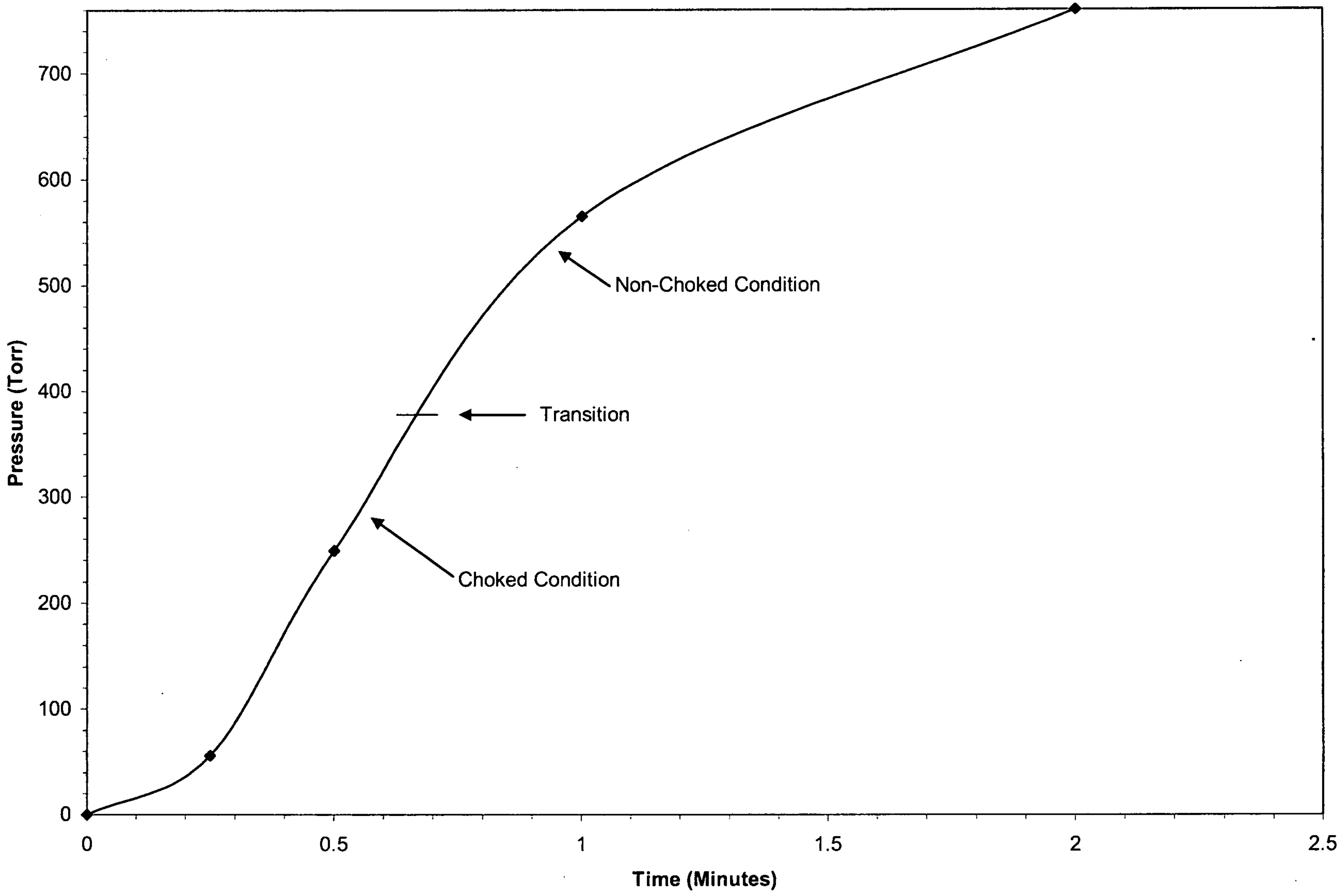

Figure 71 – Static Leak Rate Curve for Varian TriScroll 300

E. TEST PROCEDURES

This appendix contains the test procedures used in developing the data presented in this report.

1-00 LONG TERM TEST

This test has several purposes. One is to quantify the amount of particulate contaminant generated via long term use. The second is to characterize the start-up and steady state power requirements of the pump. The final purpose is to assess overall pump reliability over long term operation.

TEST SETUP:

1-01 Start with blank Test Data Sheet 1 and record pump manufacturer and model, serial number, and hours (if available).

1-02 Refer to Figure 72 for test set up of transport and sample pumps. All lines and valves must be at least ½" in diameter to minimize pressure drop between transducer and pump intake.

1-03 For backing pumps, put a flange blank on the inlet so that the pump receives no gas load, and skip steps 1-04 and 1-05.

1-04 On the plenum intake, connect a throttling valve and pressure transducer.

1-05 On the pump exhaust, connect a frit style filter on scroll pumps (100 micrometer), and fittings to connect a 300 sLpm flow meter.

1-06 Attach the appropriate tubing for noise reduction and gas exhaust. Be certain the exhaust is vented safely.

1-07 For AC current measurements, install the break-out test harness between pump power cable and AC outlet. Clamp the inductive current probe around the line wire (usually black).

TEST:

1-08 After setting up test, turn the pump on. Do not turn the pump off during the course of this test.

1-09 Adjust throttling valve so that the plenum is maintained at the following pressures:

- 300 Torr for Transport Pumps
- 300 Torr for Delivery Pumps
- Ultimate Pressure for Backing Pumps

1-10 Once or twice daily, note the date, plenum pressure, exhaust flow rate, pump housing temperature, ambient temperature, steady-state current, and any anomalies and record on Test Data Sheet 1.

1-11 Repeat the sequence for approximately 30 days.

1-12 After 30 days, remove the filters and note any observations on Test Data Sheet 1. Be careful not to disturb particles that may be embedded within the filter.

1-13 Place each filter in a container, noting on it whether it was the exhaust or intake filter, and which pump it came from. This information should also be recorded on Data Sheet 1.

1-14 For scroll pumps, remove the pump housing and examine the internals for particulate buildup. Note any observations on Test Data Sheet 1.

<u>ANALYSIS:</u>

1-16 Submit the filter contents for particle size distribution and NVR analysis.

1-17 Determine the cause of any anomalies noted during the operation of the test.

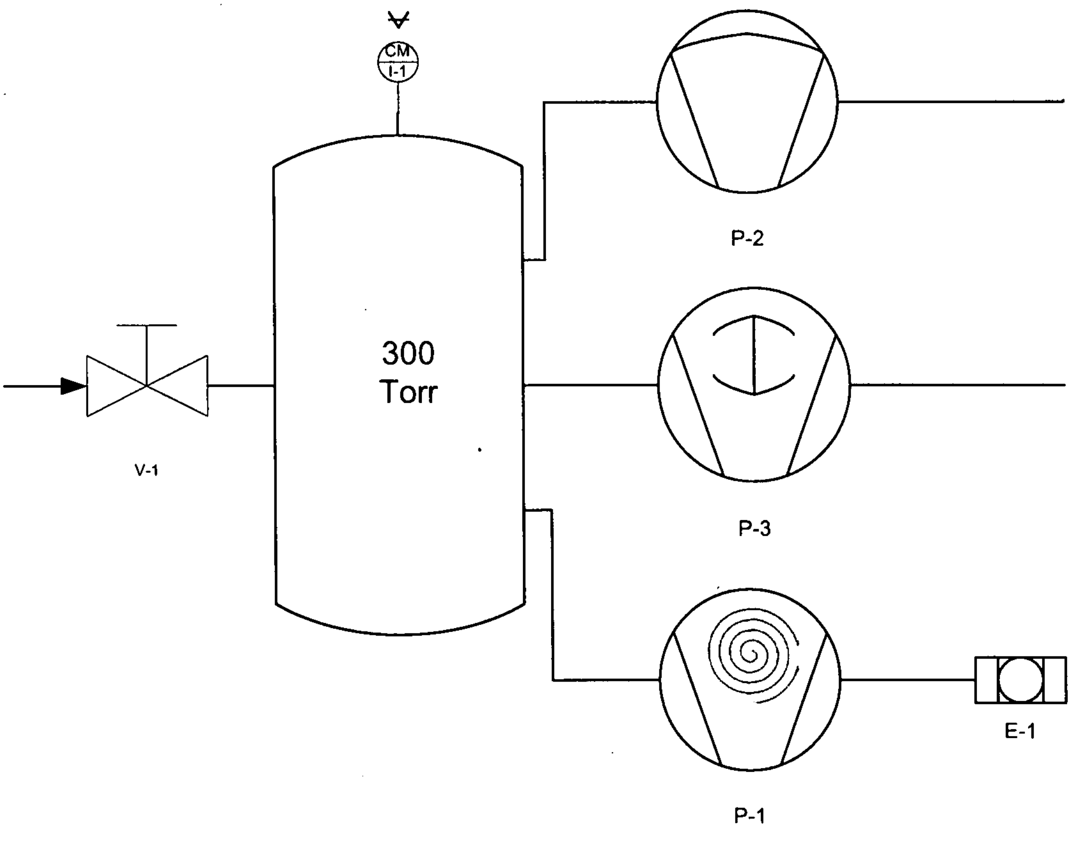

Figure 72 – Long Term Test Setup for Transport/ and Sample Pumps

2-00 PUMP SPEED TEST

The purpose of this test is to identify and/or verify the pump specifications for various gases. Collect and review all pump specs and technical information from manufacturer for comparison with test data. This can also include current measurements for the pressure and flow envelope of operation.

TEST SETUP:

2-01 Record pump manufacturer and model on Data Sheet 2.

2-02 Obtain pure helium, nitrogen, and breathing air cylinders.

2-03 Refer to Figure 73 for test set up.

TEST:

2-04 Place the He cylinder on the inlet of the flow meter. Open the hand valve on the regulator.

2-05 Open the high flow test apparatus inlet valve until test apparatus pressure reaches atmospheric pressure or maximum attainable pressure, whichever is less.

2-06 Note the gas type, reported flow, pressure and steady-state current. Record on Test Data Sheet 2.

2-07 Partially close the inlet valve so as to reduce flow rate by approximately 10% of the active flow meter full scale range.

2-08 Allow to stabilize and again note the gas type, reported flow, pressure, and steady-state current. Record on Test Data Sheet 2.

2-09 When flow rate reaches approximately 10 sLpm, close the high flow inlet valve, install gas hose on medium flow inlet valve, and open medium flow inlet valve.

2-10 Allow to stabilize and again note the gas type, reported flow, pressure, and steady-state current. Record on Test Data Sheet 2.

2-11 Partially close the inlet valve so as to reduce flow rate by approximately 10% of the active flow meter full scale range.

2-12 When flow rate reaches approximately 1 sLpm, close the medium flow inlet valve, install gas hose on low flow inlet valve, and open low flow inlet valve.

2-13 Allow to stabilize and again note the gas type, reported flow, pressure, and steady-state current. Record on Test Data Sheet 2.

2-14 Partially close the inlet valve so as to reduce flow rate by approximately 10% of the active flow meter full scale range.

2-15 When flow reaches zero/ultimate pressure, stop recording data points.

2-16 Repeat steps 2-04 to 2-12 for nitrogen and breathing air.

ANALYSIS:

2-17 Four columns of data should be written down on Test Data Sheet 2, the gas type, reported mass flow (RMF), current, and pressure (P). The volumetric flow (VF) is then calculated using the equation below:

$$VF = (760 \text{ torr}/P)\ MF$$

IMPORTANT: If the flow meter was calibrated with nitrogen, apply the appropriate correction factor for breathing air and helium! (MF = α RMF)

α(Nitrogen) =1	α(Helium) =1.4151	α(Air) =1.006

2-17 Graph volumetric flow vs. pressure.

2-18 Graph mass flow vs. pressure.

2-19 Graph steady-state AC current as a function of inlet pressure.

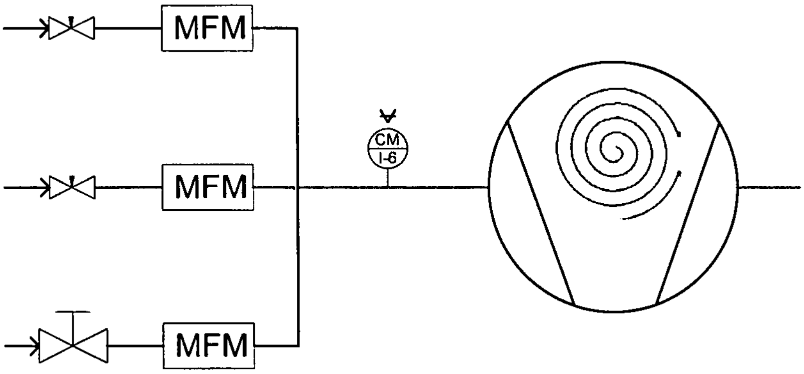

Figure 73 – Pump Speed Test Setup

3-00 VOLTAGE VARIANCE TEST

The purpose of this test is to observe the effects that input voltage variations may have on the pump at nominal operating flow and pressure.

TEST SETUP:

3-01 Record pump manufacturer and model on Data Sheet 4.

3-02 Refer to Figure 74 for test set up. On the pump intake, connect a valve, flow meter, and a pressure transducer, in that order.

3-03 On the pump exhaust, connect appropriate tubing for noise reduction and gas exhaust.

3-04 Connect pump wiring to a Variac AC transformer, or similar, with rated load capability. If the pump to be tested is equipped with a DC operated motor, connect to a variable DC power supply of sufficient capacity.

3-05 Install inductive ammeter on pump power line for steady-state AC current measurements. Install the break-out test harness between pump power cable and AC outlet. Clamp the inductive current probe around the line wire (usually black). Connect the output of the current probe to the DVM with banana jumpers.

3-06 Install a volt meter between line and neutral wires.

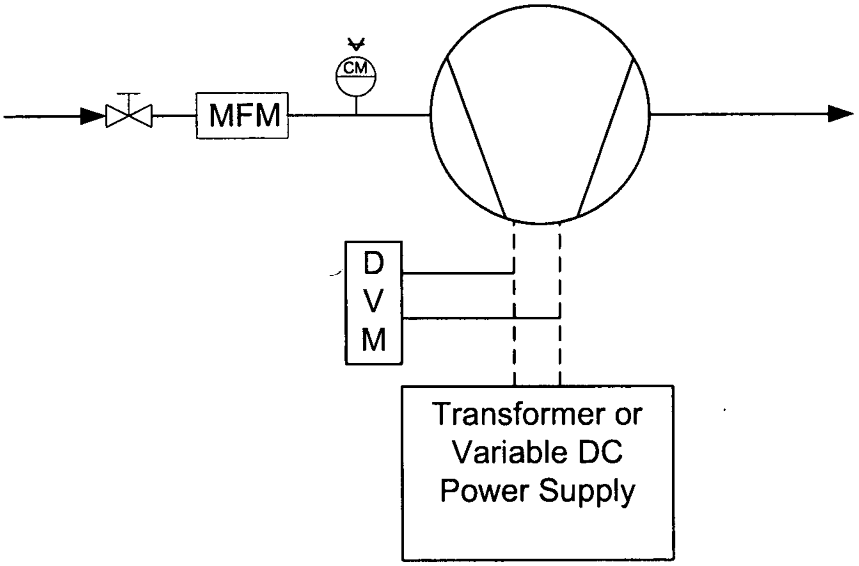

Figure 74 – Voltage Variance Test Setup

TEST:

3-07 Connect pump to electrical power and power on through Variac, setting it for nominal 115 VAC.

3-08 Adjust flow valve to attain pressure for pump application as specified in Test Setup Table 1.

3-09 Note pressure and flow rate indicated and record on Test Data Sheet 4. Note steady-state current and record on Test Data Sheet 5.

3-10 Adjust Variac to various AC voltages, both above and below 115VAC, and record new voltage on Test Data Sheet 4.

3-11 Again note pressure, flow rate and steady-state current and record on Test Data Sheet 4.

3-12 Determine the minimum voltage required to sustain operation. Decrease the voltage until the pump motor fails to turn. Record this on Test Data Sheet 4.

ANALYSIS:

3-13 Plot inlet pressure and current vs. voltage.

4-00 VIBRATION EMISSIONS AND SUSCEPTIBILITY TEST

The purpose of this test is to determine the extent of vibration emissions created by the operation of the pump as well as the susceptibility of the pump to induced vibrations.

TEST SETUP:

4-01 The vibration profile for the vibration susceptibility test should match expected vibration profiles the system will encounter during its operation.

4-02 The vibration emissions shall be measured with accelerometers placed on the pump mounting surface as well as the pump inlet.

EMISSIONS TEST:

4-02 Turn the pump on. Wait approximately 5 minutes.

4-03 Obtain the vibration emission spectrum on both the mounting surface and the pump inlet in all 3 axes for each pump.

SUSCEPTIBIILTY TEST:

4-04 Pumps shall be bolted into a rack and shaken in all 3 axes to the vibration spectra.

ANALYSIS:

4-05 Graph the X, Y, and Z axis vibration at the inlet and mounting surface for each pump.

4-06 Susceptibility testing shall be analyzed using a pass or fail criteria.

5-00 STATIC PRESSURE TEST

The purpose of this test is to determine the leak rate through the pump at shutdown, or if power failure occurs.

TEST SETUP:

5-01 Set up test apparatus as per figure 75

5-02 Use a graduated cylinder and water to measure the internal volume of the vacuum chamber, if necessary.

5-03 Install a pressure transducer on a vacuum chamber of between 5 and 10 L volume.

5-04 Perform a leak check on the pressure vessel. Seal the vacuum chamber with a valve and perform leak check. The tank should leak less than 1 torr in 1 hour. If this leak rate is not satisfied, check fittings and attempt again.

5-05 Connect the pump to the vacuum chamber. Use a minimum amount of fittings to reduce leakage and systematic error in the test.

5-06 Close all gas ballast and air flush ports and gas ballast valves.

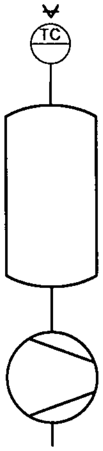

Figure 75 – Static Pressure Test Setup

TEST:

5-07 Connect pump to electrical power and turn on the pump.

5-08 Allow the pump to pump down the vacuum chamber until pressure increase is less than 0.1 torr over a 1 hour period.

5-09 Turn off pump and immediately record pressure at 15 seconds, 30 seconds, 1 minute, 5 minutes, 10 minutes, 15 minutes, and 30 minutes.

ANALYSIS:

5-10 Generate plots of pressure vs. time.

5-11 The slope of the linear portion of the graph represents leak rate in torr/second.

5-12 Multiply the slope of the linear portion of the graph by the chamber volume to determine leak rate.

6-00 EXHAUST RESTRICTION TEST

TEST SETUP:

6-01 Refer to Figure 76 for test setup. Minimize the amount of pressure dropping fittings in the path to the pressure transducer.

6-02 Record pump manufacturer and model on Test Data Sheet 9.

TEST:

6-03 Use the inlet valve to regulate the inlet pressure at 300 torr.

6-04 Turn the pump on.

6-05 Note the reported mass flow, exhaust pressure, and steady-state current. Record on Test Data Sheet 9. Also make any relevant observations.

6-06 Partially close the exhaust valve approximately 1/10th of full rotation to increase pressure drop.

6-07 Repeat step 4.

6-08 Repeat steps 4 and 5 until zero flow rate is achieved or pump failure is imminent.

ANALYSIS:

6-09 Graph inlet pressure vs. outlet pressure, and a graph of outlet pressure vs. current.

6-10 The slope of the linear portion of the inlet pressure vs. outlet pressure is the exhaust sensitivity of the pump.

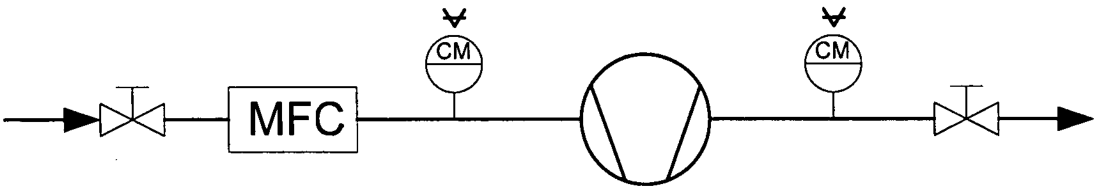

Figure 76 – Exhaust Restriction Test Setup

7-00 EMI TESTING

The purpose of this test is to identify any EMI emissions and susceptibility. This test will be performed on a limited number of pumps.

TEST:

7-01 Perform SL-E-0002 Book 3 CE102 and RE102.

7-02 Perform SL-E-0002 Book 3 RS103, CS101, and CS114 on selected pumps.

ANALYSIS:

7-03 Performed by electromagnetics testing team.