Technical Information

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System Design Considerations

INTRODUCTION

This section should be helpful as a general guide to help the system user better understand the requirements needed for normal system operation and pump selection. A vacuum system is a system designed to achieve and maintain a vacuum. One key element in any vacuum system is the vacuum pump. A good vacuum pump is essential to the performance of any vacuum system. In addition the performance characteristics of the vacuum pump should be well matched to the demands of the system. The ultimate pressure that must be attained, pumpdown time constraint, and gases to be pumped must all be carefully considered. To meet these needs a wide range of high quality Sargent-Welch vacuum pumps are available.

The primary component of the system is the pump or pumps which generate and maintain the vacuum. The other components consist of the **tubing** used to conduct the gas through the system; the **seals** used to minimize leaks between the system and the outside environment; **valves** to maintain and control the vacuum; **pressure gauges** and instruments used to monitor and help control the vacuum level and process; **traps** and **baffles** to minimize backstreaming and vapors present within the system.

CONDUCTANCE

The purpose of all vacuum pumps is to remove gases either temporarily or permanently from a chamber. The selection of the pumping capacity and pump type will be determined by the requirements for the process to be performed within the vacuum system.

All vacuum pumps are characterized by their ability to maintain a base pressure for a given gas throughput. Pumping speed and throughput are related by:

Throughput =
Pumping Speed × Suction Pressure of Pump

In order to properly size a pump for the system, the flow of gases through the components must be taken into account. The first step is to determine the flow conductance that exists in the system tubing. The use of nomographs (see next page) allows the user to quickly calculate the conductances of the tubing components. The conductance is a measure of the resistance to the flow caused by the component (tubing, etc).

Conductance (Z) =
Throughput/Pressure Drop Across Component

Components with a high flow resistance will have a smaller conductance than those with a low flow resistance. In practice the components should have a length as short as possible with the greatest inside diameter possible to minimize flow losses. When the conductances for the various components have been determined, the total conductance can be calculated as follows:

For N components in series:

$$1/Z = 1/Z(1)+1/Z(2)+1/Z(3)+ \cdots +1/Z(N)$$

For N components in parallel:

$$Z = Z(1)+Z(2)+Z(3)+ \cdots +Z(N)$$

To determine the effective pumping speed at the point where the tubing connects the pump with the system, use the following relation:

$$1/S_{eff} = 1/S+1/Z$$

Where:

- S_{eff} is effective pumping speed
- S is pumping speed of pump at pressure at inlet of pump
- Z is total conductance of components between pump and system entrance

PRESSURE GAUGES

In order to know whether the vacuum system is functioning correctly, it is necessary to measure the pressure at points within the system with a high level of accuracy. To do this the proper type of pressure gauge must be selected based on the range of pressures to be measured and the type of gases used. Some of the types of gauges and their approximate operating ranges are as follows.

Bourdon Tube	760 - 10 Torr
Liquid Manometer	760 - 1 Torr
Force Balance Gauge	760 - 1 Torr
Mechanical Diaphragm	760 - 0.01 Torr
Capacitance Manometer	760 - 0.001 Torr
Thermocouple (Pirani)	1 - 0.0001 Torr
McLeod Gauge	50 - 0.00001 Torr

It should be remembered that each type of gauge has its own operating and accuracy limitations.

LEAK RATE

Successful system operation must also consider the presence of leaks into the system and establish what leak rates are acceptable. To determine whether a leak rate is acceptable, the effect on pumping capacity and the system process must be considered. To find the leak rate several different detection methods are available, each with its own range of use and leak rate sensitivity.

PUMPING WATER VAPOR OR CONDENSABLE GASES

Water vapor or some condensable gases are present in many vacuum processes. When gases or vapors condense in the vacuum pump, contamination of the vacuum pump oil occurs. The oil contamination cannot be completely prevented but could be considerably reduced.

The following are ways to minimize pump contamination:

1. Use of gas ballast.
2. Purging with inert gas.
3. Use of intake cold traps.
4. Frequent oil changes.

The frequency of oil changes depends on the process media and the way the condensation is being prevented. There is no rule on how often this should be done. It should be determined by observing vacuum deterioration of the vacuum system.

BACKSTREAMING

The backstreaming in rotary vane vacuum pumps is the migration of oil molecules in the direction opposite to air flow; i.e., towards the vacuum chamber. Oil condensation is observed along the walls of the piping connecting the pump to the vacuum system.

Backstreaming can be reduced in the following ways:

1. By introducing a few elbows or bends between pump intake and the vacuum system.
2. Use of a foreline sorption trap.
3. Use of an intake cold trap.

OUTGASSING

Outgassing is the evolution of gas and vapor from the walls of a vacuum system. The outgassing rate refers to the amount of gas and vapor evaporated per unit of time.

Outgassing depends on several factors:

1. Venting procedure at end of previous pumpdown.
2. Type of materials used in system design.
3. The ultimate pressure reached in the system.

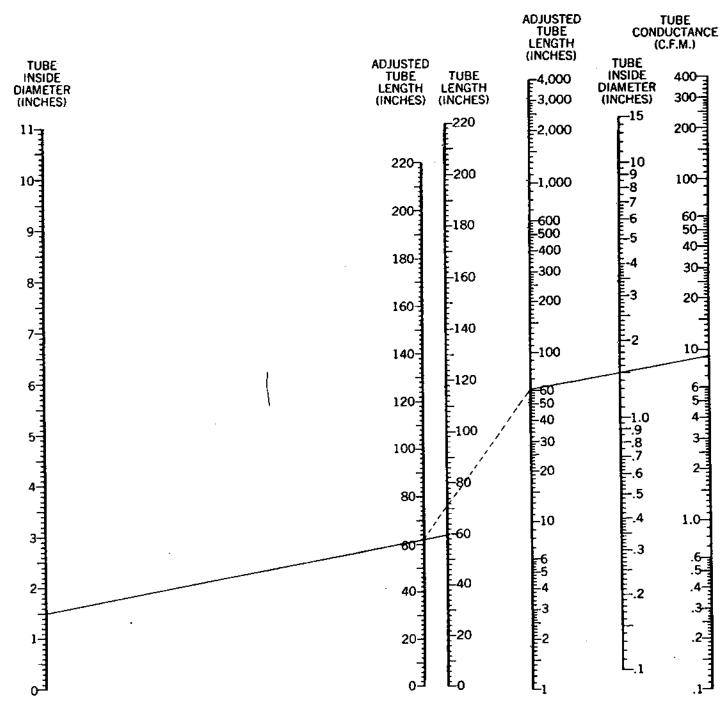
The outgassing rate will have a significant impact on pumpdown time for systems operating in the high or ultra-high regions. To reduce the outgassing rate, the components of the system must be kept clean. The heating (baking) of the system may accelerate the outgassing process.

SUMMARY

This has been meant as a brief overview of vacuum system design considerations. A few of the important points to consider are as follows:

a. Type of process
b. Type of pumping systems and fluids
c. System monitoring and control
d. Air leakage and detection methods
e. Flow of gases through system components
f. Type of gases and vapors present in process
g. Pressure measurement
h. Seals and system materials
i. Reliability and maintenance
j. Contamination of process from backstreaming and improper venting
k. Cost (purchase, installation and operating)

TUBE CONDUCTANCE NOMOGRAM



This nomogram can be used to determine the conductance of connecting tubing to insure that the system is not conductance limited.

Example: Consider a system where the connecting tubing is 60 inches long and has an inside diameter of 1.5 inches. The tube conductance in CFM is required.

The solution is:

1. Draw a line from 1.5 on the tube ID line to 60 on the tube length line. The point where this line intercepts the intervening line is the adjusted tube length, or 62 inches.
2. On the adjusted tube length line (to the right of the tube length line), draw a line from 62 through 1.5 on the tube ID line and extend it to the tube conductance line.
3. The tube conductance is 9 CFM.

Generating A Vacuum With A Mechanical Vacuum Pump

Vacuum Pumping

The essential purpose of a vacuum pump is to reduce the pressure in a given vessel or enclosed system. The degree of reduction in pressure is dependent upon the requirements of the application, the type of vacuum pump employed, and the design of the pump. Mechanical, rotary, oil-sealed pumps which are capable of attaining pressures in the low millitorr region will be discussed in this section. Reduction in pressure is accomplished by steadily and consistently removing a portion of the original volume of a gas contained in an enclosed vessel. Removal is performed by the action of the rotating elements of the pump which cause a given space to be successively enlarged and diminished.

Figure 1 illustrates a section through a typical pump stage. The action of the pump creates an increasingly enlarged, hollow, vacuum-tight space (1), into which gas is drawn by virtue of the difference in pressure between the space created and the inlet connection (4), to the space. The volume of gas is trapped by action of the vanes (2) and (3) and is ultimately compressed out of the stage into the exhaust port (5) by action of vane (3) as the space is gradually diminished. This expansion and contraction constitutes one complete cycle of operation. This cycle is repeated as vane (2) passes and closes the intake port. Thus, for each revolution of the pump two cycles of evacuation are performed.

Production of Low Pressures

With the completion of each evacuation cycle, the quantity of gas contained in the vessel (6) is reduced. The quantity of gas remaining in the vessel must necessarily expand to fill the vessel and consequently with each cycle the pressure in the vessel is reduced. This action is a manifestation of Boyle's law which states that the volume of a body of gas is inversely proportional to its pressure, provided the temperature remains constant; i.e., if the volume is enlarged the pressure must be reduced. As the original amount of gas in the vessel is steadily diminished, its pressure is correspondingly reduced. The action of the pump must therefore compress a successively smaller quantity of gas with each cycle to something greater than atmospheric pressure in order to expel it from the pump.

At the beginning of an evacuation sequence, the compression ratio is very small. In the first cycle of operation the pump draws in a volume of gas at atmospheric pressure and expels it at approximately atmospheric pressure. At blankoff pressure, on the other hand, the pump will draw in a volume of gas at, say, one millitorr and compress this volume to a pressure of 760,000 millitorr, or atmospheric pressure, in order that it may be expelled. Since the exhaust valve is generally spring-loaded to provide a good seal, a pressure somewhat greater than atmospheric pressure is required to open it. Therefore at a guaranteed blankoff pressure of 10^{-4} Torr, the compression ratio performed by the pump is in the order of 10,000,000 to one.

The Ultimate Pressure

With each cycle of the pump, as mentioned earlier, a quantity of gas is removed from the vessel being evacuated. With the completion of each cycle, the remaining gas in the vessel will expand to a newly reduced pressure. Since the pump can remove only a small portion of the remaining amount in the vessel at one time with each cycle, it is obvious that this method of evacuation can never completely remove all the gas in the vessel. In addition to this, the components of the system, including the vacuum pump, the vessel being evacuated and the necessary connections, each contain minute sources of leakage which are impossible to seal completely against atmospheric pressure. Outgassing of materials within the system provide additional sources of gas evolution.

Thus, after prolonged pumping, a state of equilibrium is reached in which the summation of all the leakage sources is balanced by the ability of the pump to maintain a steady pressure within the system. This steady state of equilibrium is referred to as the blankoff pressure or ultimate pressure of the pump and the particular system. No matter how much additional time is provided for the pump to continue its evacuation of the system, no further reduction in pressure can be accomplished by mechanical action.

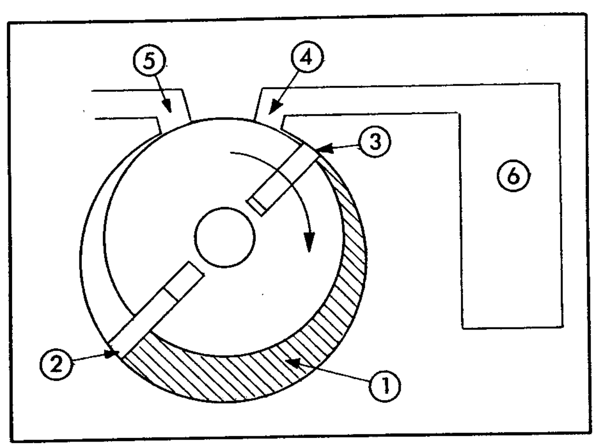


Figure 1. Cut-away schematic of a rotary vane pump connected to a chamber.

DESIGN FEATURES OF MECHANICAL VACUUM PUMPS

Function of the Gas Ballast

Condensation takes place particularly in the compression stroke of the backing or second stage of a two-stage pump. The compression stroke is that portion of the cycle during which the gas drawn from the intake port is compressed to the pressure necessary to expel it past the exhaust valve. Condensation takes place when the ratio between the initial pressure and the end pressure of the compression is high, that is, when the mixture of vapor and gas drawn from the intake port is compressed from a low pressure to a high pressure. By adding air through the gas ballast valve to the mixture of vapor and gas being compressed, the pressure required for delivery past the valve is reached with a considerably smaller reduction of the volume of the mixture; thus, depending upon the amount of air added, condensation of the vapor is either entirely avoided or substantially reduced.

Some degree of variation in ballast flow may be obtained by the amount of opening applied to the gas ballast valve. Two or more turns of the valve are sufficient to open it wide. With the valve open, the sound of the exhaust is similar to that of a pump operating against a large leak. Because of the increased pressure introduced into the compression stroke, the pump must work a little harder to function, thus resulting in an increased operating temperature over a prolonged period of time.

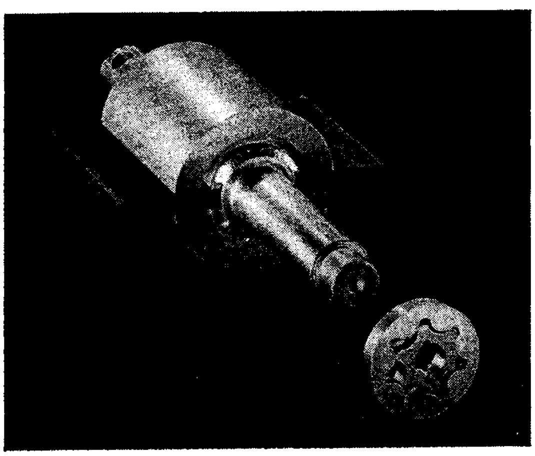


Figure 2. Rotary Vane Motor and Gerotor

Rotary Vane Vacuum Pump

Rotary vane pumps consist of a rotor with radially slidable vanes which are in continuous contact with an eccentrically located surface of the stator. Figure 2 shows a rotor with two vanes. Vanes are typically spring loaded. These vanes slide along the walls of the stator and move the air drawn in at the pump inlet which is then finally compressed out of the stage through the exhaust port.

Oil serves as the lubricating, cooling and sealing medium. For DuoSeal® Vacuum Pumps, a pressure differential between the oil reservoir and the stator provides lubrication inside the pump. Inherent to the DirecTorr® II Vacuum Pump line is the positive pressure oil lubrication system. Constant internal oil lubrication is maintained by a small gerotor-type pump incorporated in the direct drive design. Lammert® Vacuum Pumps use a pressurized gravity oil and force feed oiling system.

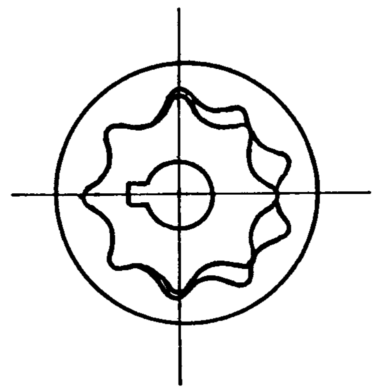


Figure 3. Schematic of Gerotor Chamber

Gerotor Vacuum Pump

Sargent-Welch has developed a patented technology employing a gerotor to pump gases. The gerotor mechanism consists of inner and outer toothed elements with one tooth differential, the inner element having fewer teeth. The tooth profiles generated provide continuous fluid-tight contact during pumping. Figure 3 shows a inner and outer rotor from a Gerotor Vacuum Pump.

The teeth of the inner rotor are in continuous contact with the surface of the outer rotor which define the pumping chamber between each pair of teeth. The chamber expands and contracts as the rotors turn. This produces pumping action when connected to properly shaped inlet and outlet ports. The relative velocity between the inner and outer rotor is very low, resulting in minimal wear of the rotating parts.

For lubricating as well as sealing between relative moving parts of the rotor assembly, oil is introduced into the pumping chamber by using differential pressures created by the rotation of the pump itself. The small quantity of oil metered through a narrow opening into the pump stage is sufficient to lubricate and seal the moving parts, permitting the pumping of relatively low pressure levels.

Mechanical Pump Selection

Drive for Vacuum Pump

Vacuum pumps are driven by a pulley and belt arrangement, or are connected directly to the motor through flexible coupling. Space, size, service life and budget will be the factors that will help you decide which pump is right for you.

Belt-Driven Pumps

The distinguishing features of Sargent-Welch belt-driven pumps are:

* Low rpm assures a long service life
* Proven dependability
* Ease of pump serviceability
* Low ultimate pressure

Because belt-driven pumps operate at a lower rpm, they run cooler and reach a lower ultimate pressure with less oil backstreaming. Lower rpm means lower frictional wear, resulting in a longer service life.

Direct-Drive Pumps

The distinguishing features of the direct-drive pumps are:

* Compact
* Lightweight
* Positive Pressure Oil Lubrication
* Quiet Operation

A direct-drive pump is smaller and lighter than a belt-drive pump of the same free air displacement. Inherent in the design, direct-drive pumps are quieter than belt-driven pumps. A steady oil pressure is maintained in the DirectorTorr® II pumps through the use of the highly reliable gerotor oil pump.

Motor

Sargent-Welch offers a variety of different motors to meet your particular electrical and environmental requirements.

Open, Drip-Proof Motors

Pumps using these motors are designed for use at locations that are reasonably dry, clean and well ventilated, usually indoors. If installed outdoors, the motor must be protected with a cover that will not interfere with motor cooling.

Totally Enclosed Fan Cooled Motors (TEFC)

Pumps using these motors are suitable for use where exposed to dirt or moisture is expected. However they are not suitable for hazardous locations. This motor is standard on most DirecTorr® II Vacuum Pumps.

Explosion-Proof Motors

These motors meet National Electrical Code Standards for use in hazardous locations. These motors go on pumps that will be in locations where the atmosphere does or may contain gas, vapor or dust in explosive quantities. The National Electrical Code divides these locations into Classes and Groups based on the explosive agent which may be present. Consult the factory for the Class and Group availability of a particular motor.

General

Once you have decided whether a belt-driven or a direct-drive pump best meets your application needs, it is important to select the right size to match your evacuation speed requirements. The selection of a vacuum pump too small will result in inadequate operation, and the pump will probably overheat.

You must choose not only the right size pump, but also one designed for the pressure region you are operating in. DirecTorr® II and DuoSeal® Vacuum Pumps are designed for continuous use in the medium and high vacuum region (5 to 0.0001 Torr). Sarvac® Vacuum Pumps are for intermittent use in the medium and high vacuum region. Lammert® Vacuum Pumps are designed for continuous use in the low vacuum region (760 to 20 Torr).

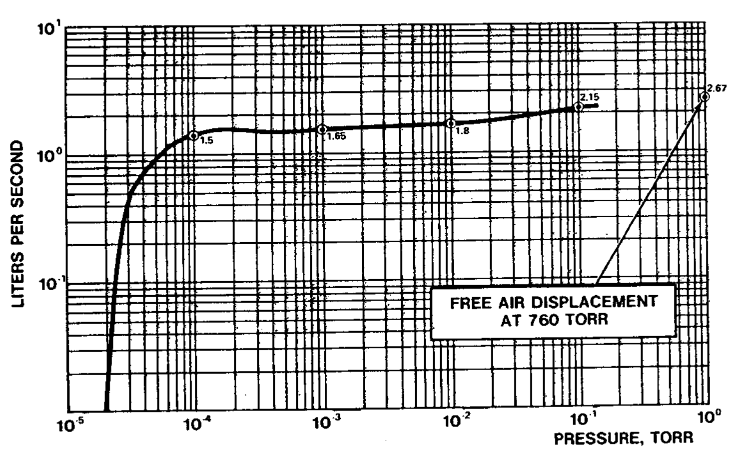


Figure 4. Pumping Speed Curve

Speed of Evacuation

The selection of the size of vacuum pump you need is determined by the time desired for evacuating a given chamber volume to a particular pressure. Variable factors make it almost impossible to determine a highly accurate mathematical solution. By establishing certain basic assumptions and eliminating any attempts at refinement, a simple and direct approach is possible. The following formula can be used to estimate the pump size needed to lower the chamber pressure from atmospheric (760 Torr). The following formula can be used to estimate the pumping speed needed to evacuate a given volume in a given time, from atmospheric pressure to process pressure. The formula does NOT account for any additional gas or vapor entering chamber.

$$S = \frac{V \times F}{t}$$

S = Pumping speed (liters per minute)
V = Chamber volume (liters)
t = Time of evacuation desired (minute)
F = Pump-Down Factor
= 2.3 x log (760/Desired Chamber Pressure in Torr)

	Desired Chamber Pressure in Torr						
	100	10	1	0.1	0.01	0.001	0.0001
F	2.03	4.33	6.62	8.93	11.2	13.5	15.8

As an example, a chamber of 50 liters must be evacuated to 0.01 Torr in ten minutes. What is the effective pumping speed needed?

$$S = \frac{50 \text{ liters} \times 6.62}{10 \text{ minutes}} \cong 33 \text{ liters/minute}$$

The effective pumping speed will increase significantly if long length tubing, traps, valves or small diameter tubing are used. Hence, it is very important to keep vacuum lines short and of adequate diameter. See page 136 for formulas to calculate effective pumping speeds for situations where the pump is not directly coupled to the chamber, or the gas is introduced into the chamber during evacuation.

Use of the Pumping Speed Curve

Once you have estimated the effective pumping speed (S) needed for your application, you can examine pumping speed curves of pumps with free air displacements close to S. Figure 4 shows a typical pumping speed curve. The pumping speed of a pump is not constant over its entire operating pressure range.

The implication of the pumping speed changing with inlet pressure is that a pump should not be selected simply by looking at its free air displacement. A better choice is made by using the average pumping speed over the pressure range in question. For example, the average pumping speed over the pressure range from 760 to 0.01 Torr using the pumping curve in Figure 4 is:

$$S = \frac{1.8 + 2.7}{2} = 2.2 \text{ liters/minute}$$

PUMP NOMOGRAM

Instead of using the method described above, it is sometimes possible to use a nomograph to determine the desired pumping information. This method can be used for systems which are reasonably clean.

Example: Consider a system volume of 1 cubic foot, an operating pressure of 0.01 Torr, and a desired pumping speed of 8 minutes. The pump speed and selection of appropriate pump is required.

The solution is:

1. Draw a line from the system volume to 0.01 on the pressure line.
2. Draw a line from the intercept of this line with the index line through the 8 point on the time line and extend it to the pump capacity line.
3. The required pump speed is 2.1 CFM and the Model 1405, or its direct-drive equivalent, is the appropriate pump to select.

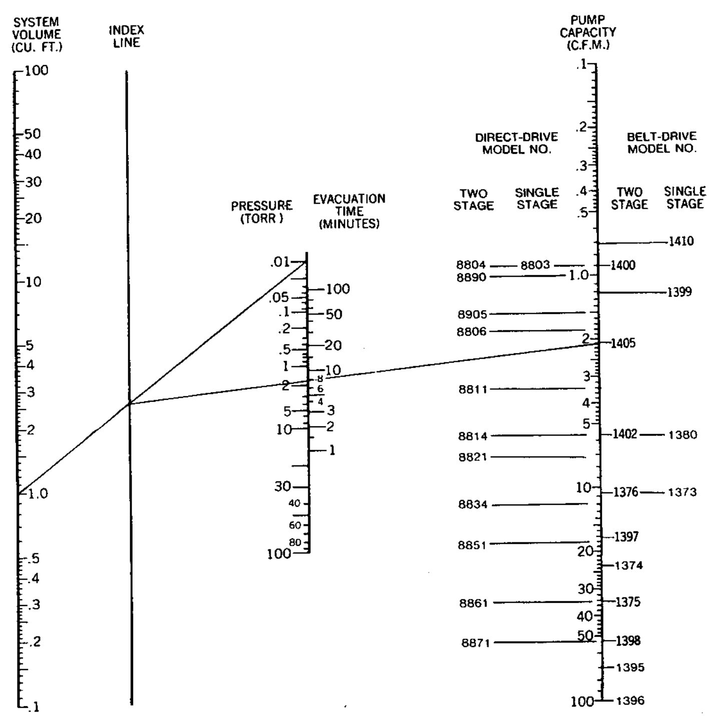


Figure 5.
Pump Nomogram

Mechanical Pump Selection

Use of the Pumpdown Curves

If a particular DirecTorr® II or a DuoSeal® vacuum pump model has been chosen for the application, the pumpdown curve can be used as an approximate check that the correct pump size has been chosen. The curve for a Model 8834 is shown here:

Here is an example of how to check your work using the pumpdown curve below. Evacuate a 200 liter chamber to a pressure of 10^{-1} Torr in 10 minutes.

(1) From the curve, a 100 liter chamber will be pumped down to 10^{-1} Torr in 4½ minutes.
(2) Based on a 200 liter chamber, it will take 9 minutes to pump down to 10^{-1} Torr using a Model 8834.
(3) It is recommended that you select the next larger pump since anything you add to your vacuum system will reduce pumping speed.

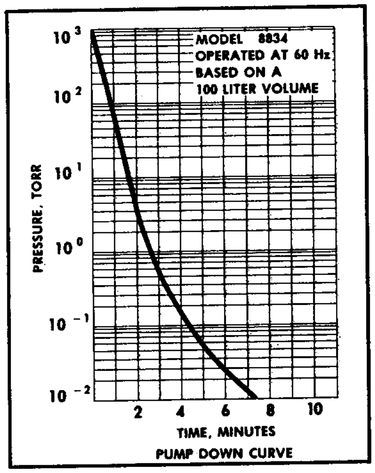


Figure 6.
Pumpdown Curve
for Model 8834

BASIC RULES FOR THE USE OF MECHANICAL VACUUM PUMPS

RULE 1 Always check motor nameplate for specified electrical requirements.

The power source should match the specified voltage, frequency and phase on the motor nameplate. Damage to the motor will result if it is plugged into the wrong power source.

RULE 2 Insure that the pump is rated for the pressure region it will be operating in.

Pumps designed for operation in the medium vacuum range should not be run continuously above their maximum operating pressure. The pump will overheat and ultimately fail if operated out of its specified maximum operating pressure.

RULE 3 NEVER operate with the exhaust port blocked or restricted.

Sargent-Welch pumps are designed for a maximum back pressure of 1.5 atmospheres. If the exhaust port is plugged, the pump WILL rapidly build up pressure internally, and then fail. Failure can mean metal fragments flying in all directions. We recommend that the diameter of the exhaust discharge line not be smaller than that of the inlet line.

RULE 4 The MAIN FACTOR affecting the service life of a pump is MAINTENANCE OF THE OIL.

Upon receipt of a new pump, the user should drain the oil that is in the pump and give it a fresh charge prior to using the pump. This is a simple precautionary measure. Overfilling the pump with oil will result in the pump blowing out excessive oil mist and liquid oil being expelled from the exhaust port.

Once the pump has been operated, the user should look for changes in color or consistency of oil which are an indication of contamination, overheating and/or unusual wear. Regular inspection of oil level and condition can spotlight a minor problem before it becomes major. Oil changes should be made based on oil condition, not operating time. Numerous chemical compounds accelerate the degradation of pump oil.

RULE 5 Do NOT allow the pump to ingest liquids and solids.

Ingestion of liquids or solids can damage the moving parts of the pump and will shorten the pump service life. An inlet cold trap will minimize the ingestion of liquids. A particulate trap will reduce the ingestion of solids.

RULE 6 Pump placement should be as close as possible to the vacuum system.

Long, narrow tubing WILL reduce the observed pumping speed, particularly at lower operating pressures. Tubing should be at least the size of the inner diameter of the intake port. It's strongly recommend using vacuum tubing as short as possible and of inner diameter as large as possible. Vacuum lines should be kept as clean as possible. Dirty vacuum lines, in particular rubber vacuum hose, can produce considerable outgassing. High levels of outgassing can slow pumping speed.

RULE 7 Operate the pump with the gas ballast valve open if the pump is ingesting condensible vapors.

Vacuum systems which contain undesirable vapors cause difficulty both from the standpoint of attaining desirable ultimate pressures as well as contamination of the pump oil. Opening the gas ballast valve two or more turns reduces this problem. If the gas ballast is not used, a high dilution of the pump oil by condensed or dissolved vapors will degrade pump performance and may damage the pump.

RULE 8 Operate pumps with the appropriate foreline trap with systems that introduce condensible or reactive vapors.

If a reactive or condensible vapor is not ingested by a pump, it will not cause pump problems. This is particularly important when organic solvents are pumped. Solvents with high vapor pressure at room temperature may not even be expelled from the pump if a gas ballast is used. These solvents will degrade a pump performance and impact its service life.

SIMPLE TROUBLESHOOTING OF MECHANICAL VACUUM PUMPS

CONDITION	PROBABLE CAUSE	RECOMMENDED CORRECTIVE ACTION
Pump will not start.	1. Power off.	Check switches and fuses.
	2. Belt/Pulley or coupling damaged. Pulley or coupling setscrew loose.	Check V-belt/pulley or coupling.
	3. Room is too cold.	Drain and refill pump with warm fluid. Try to start with intake open to atmosphere.
	4. Pump mechanism is seized.	Pump to be repaired.
Pump does not reach ultimate pressure.	1. Pump oil is contaminated.	Flush and change pump oil. Use a foreline trap and/or gas ballast valve in future.
	2. Pump is not filled with oil, or has low oil level.	Add recommended pump oil.
	3. Pump has wrong oil in it.	Flush and refill with recommended oil.
	4. Leak in vacuum system.	Locate and eliminate leak source.
	5. Dirty foreline trap.	Clean out cold traps and replacement elements in coaxial and molecular sieve traps.
	6. Gas ballast valve open.	Close valve if condensible vapors are not a problem.
Excessively noisy pump.	1. Intake or exhaust lines are restricted.	Clear and straighten out lines.
	2. V-belt or coupling damaged.	Examine V-belt or coupling and replace.
	3. Slapping noise at ultimate pressure is typical for some pumps.	Gas ballast slightly open will eliminate this noise.
	4. Inside mechanism damaged.	Pump to be repaired.
Pump generates excessive smoke or oil mist from exhaust port.	1. Pump overfilled with oil.	Drain excess pump oil.
	2. Pump operating continuously above its maximum operating pressure.	Use a larger capacity pump or modify your vacuum system.
	3. Gas ballast valve wide open.	Close valve or install a heavy duty exhaust filter.
Pump oil is unusual color - dark and dirty.	1. Pump oil contaminated by process gases, dirt, or other foreign material ingested by pump.	Flush and change pump oil. Use a foreline trap and/or gas ballast valve in future. Consider using an oil filtration system or inert pump oils.
	2. Pump oil has degraded.	Pump was run too low on oil. The recommended oil was not used. Pump is running continuously above its maximum operating pressure.
	3. Gas ballast valve is plugged.	Clean gas ballast valve. Flush and change pump oil.
Pump does not achieve its rated pumping speed.	1. Pump is running too cold.	Allow pump to run for at least an hour until it warms up to its operating temperature.
	2. Exhaust or intake line is too narrow.	Install larger inner diameter tubing.
	3. Pump oil is contaminated.	Flush and change pump oil. Use a foreline trap and/or gas ballast valve in future.
	4. Very dirty trap or intake line.	Clean out cold traps and replacement elements in coaxial and molecular sieve traps. Clean or replace vacuum piping.

Principles of Operation

INTRODUCTION

The turbomolecular vacuum pump was first introduced by Becker in 1958 and consisted of a bladed rotary disk mounted above a diffusion pump. In 1968 Sargent-Welch became the first US company to begin to manufacture turbomolecular pumps in the United States. These pumps were of the horizontal, double-ended design. Today turbomolecular pumps are available in either vertical or horizontal configurations and can be distinguished by a bladed rotor and stator assembly with running clearances in the millimeter range.

Sargent-Welch vertical turbomolecular pumps are characterized by a high speed rotor consisting of 8 axial flow bladed disks of Shapiro type (US Pat. No. 3,1644,051) and an electric motor rotor. The pump disks and electric motor rotor are assembled into a rigid body supported on a vertical ball thrust bearing and centered by a journal or "sleeve" bearing. Interleaved between the rotor disk are stator disks which have blade angles opposite to the adjacent rotor disks. Thus, the turbo is an axial flow cascade of 16 stages, 8 moving and 8 stationary. The top speed of the rotor disks is 1,473 ft/second or 1004 mph. The rotor assembly has a vertical axis of rotation.

TURBOMOLECULAR vs. DIFFUSION PUMP COMPARISON

Sargent-Welch oil lubricated vertical turbomolecular pumps incorporate a two bearing design with the bearings being lubricated either by a centrifugal pump or by an external oil pump. Turbomolecular pumps are free of oil backstreaming compared to Diffusion Pumps because they operate on purely mechanical principles. The bearing area is under vacuum provided by a roughing pump, and the pressure difference created by the compression stages of the blade assembly prevents oil migration, and correspondingly, hydrocarbon contamination.

An axial cascade type of blade design coupled with a high rotational speed gives the turbomolecular vacuum pump several added advantages over diffusion pumps. 1) Speed - many turbomolecular pumps can accelerate from rest to operational speed in approximately 3 minutes. 2) Size - the increased performance provided by the Shapiro type blades allows the turbo design to remain compact (See Figure 1). Turbomolecular vacuum pumps can be used on almost any system requiring sustained pressures between 10^{-1} and 10^{-9} Torr.

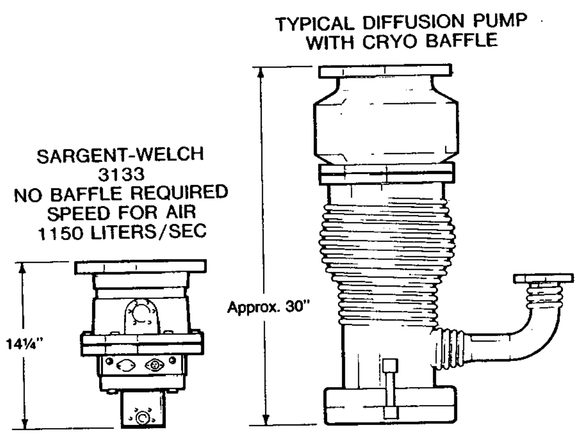
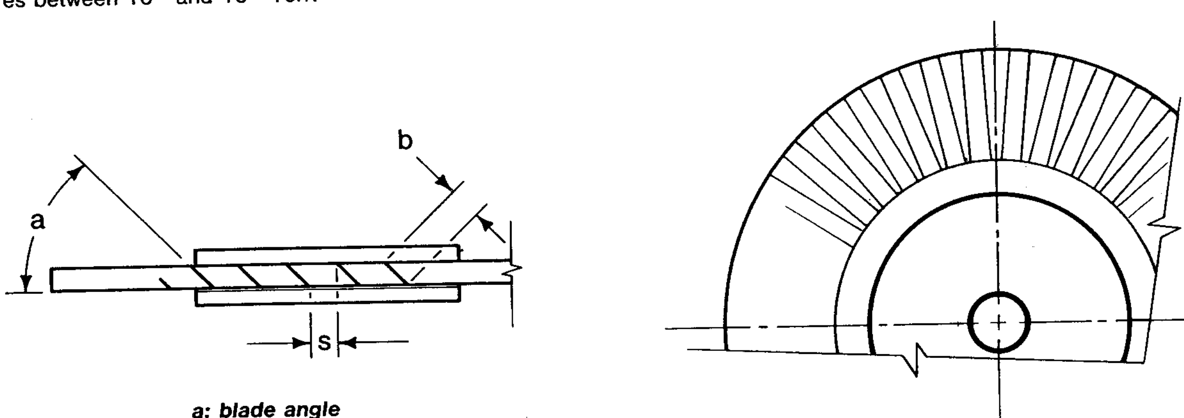


Figure 1. Size Comparison of a Sargent-Welch Vertical Turbomolecular Pump with Comparable Oil Diffusion Pump with Baffle



a: blade angle
s/b: gives spacing/cord ratio

Figure 2. Turbomolecular Pump Blade Design

BLADE DESCRIPTION

The turbo blade assembly contains two types of disks, rotor disks and stator disks. Both the rotor and the stator disks are further subdivided into inlet and outlet stages. Inlet stages are generally designed to have a high pumping speed and a low compression ratio. They have a larger radial span and a larger blade angle than do the outlet stages in order to "catch" as many molecules as possible. Once the molecules are captured, they are transferred to the outlet stages which have a relatively small radial span and a reduced blade angle. (See Figure 3). The outlet stages are designed to have a high compression ratio and low pumping speed.

Molecules of air, water vapor, or other gases randomly enter the pump. Some of them rebound axialy, pass through, or are struck by the first rotor disk blades. The molecules tend to rebound in a favorable axial direction and enter the blade passages of the first stator disk. The molecules again rebound in such a direction as to increase the probability of their being favorably impelled by the second rotor disk. This process is repeated through all the stages of the pump. The series of impacts statistically favoring motion toward the discharge end constitutes a pumping action with a very high compression ratio. Maximum compression ratio is attained when the gas in all stages is in the molecular flow range.

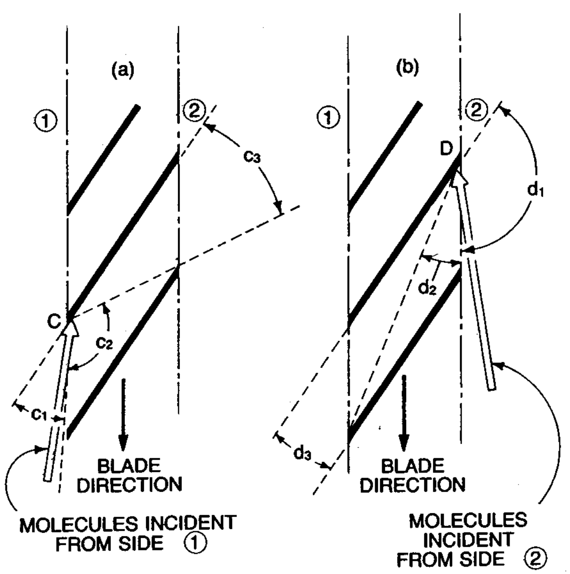


Figure 3. Turbomolecular Blade Diagram

Figure 3 illustrates the probability of transmission of molecules through turbine blade rows when blade speed is large compared with molecular speed. Two conditions are given:

(a) Blade row transmission angles in forward direction.

(b) Blade row transmission angles in backward direction

Variables C1, C2, C3 and d_1, d_2, d_3 refer to the angle of molecular emission. For a complete explanation of turbomolecular pump blade theory, see Methods of Experimental Physics, Volume 14, Chapter 5.5.

ADVANTAGES OF JOURNAL BEARING

In a turbomolecular pump using a two ball bearing design, the life of the pump is dependant upon the life of the larger upper bearing. When the larger upper bearing is replaced with a journal (or sometimes referred to as a sleeve) bearing, the life of the pump becomes dependent upon the much smaller lower bearing. Thus, the life of the turbomolecular pump will be substantially increased.

Turbomolecular pumps using a journal bearing also have low levels of vibration compared to those using a two ball bearing design. Ball bearings have substantial contact forces which cause noise, vibration, heat, and wear. These contact forces are not present within the journal bearing because no mechanical contact is being made.

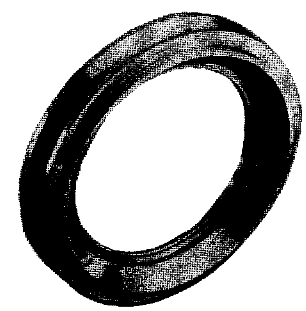


Figure 4. Journal Bearing

During acceleration (assuming no lateral forces), the rotor shaft seeks the center of the journal bearing; however, an unstable condition exists which causes the rotor to begin to "whirl" within the bearing. At critical speed (V_{CR}) the whirl becomes symmetrical and sufficient pressure develops in the oil film to maintain separation of bearing surfaces (See Figure 5).

In summary, a turbomolecular pump using the journal bearing design has longer life, increased reliability, and better vibration characteristics than a turbomolecular pump using the two ball bearing design.

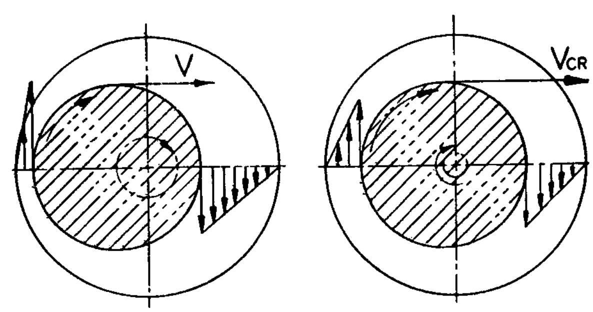


FIG. 1. FIG. 2.

Figure 5. Schematic Diagram of Hydrodynamic Oil Field

Figure 5 shows that at slow speeds, the oil velocity and pressure are not uniform, creating an unstable state (left). The hydrodynamic oil field develops at critical velocity V_{CR} when oil velocity and pressure become more uniform (right).

Turbomolecular Pump Selection

INTRODUCTION

Turbomolecular Pumps have been designed for a variety of applications and system requirements over the years. As a result a wide variety of pump models are now available. This section describes the various model configurations available, and how they differ from each other. This information will be helpful to select the right pump for your specific requirements. The key elements to consider when making a selection are the following:

1) Type of rotor mounting; double-ended horizontal, or single-ended vertical.
2) Bearing lubrication; oil or grease lubrication.
3) Inlet flange type; ASA, AVS, CONFLAT®, ISO.
4) Pump Housing Material; aluminum or stainless steel.
5) Power supply types.
6) Vibration characteristics
7) Pumping Speed; from 160 liter/second to 3400 liter/second available from Sargent-Welch.

Horizontal and Vertical Turbomolecular Pumps

The Models 3106 and 3120 turbomolecular pumps are both double ended pumps with a horizontal axis of rotation. This is helpful in that any objects which enter the center section of the pump can fall harmlessly to the bottom of the pump rather than enter the blade cascade. Both pumps have three inlets which are available simultaneously or one at a time for ease of operation.

Vertically mounted turbomolecular pumps such as the Models 3133, 3134, and 3137 contain two bearings; a lower ball bearing which supports the rotor down weight and provides up-thrust resistance, and an upper journal bearing. The pump lubrication system creates an oil film between the moving rotor shaft and the stationary journal. Since no metallic contact is being made unlimited life should be possible. This journal type bearing has very small internal forces and can tolerate much more misalignment than a ball bearing without increase of wear, noise, or fatigue damage. The journal bearing also has better heat transmission capabilities than typical ball bearings and makes possible a further extension of the turbomolecular pump's application into the blower range.

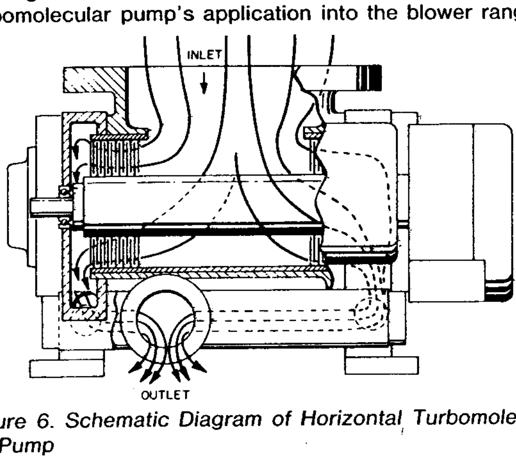


Figure 6. Schematic Diagram of Horizontal Turbomolecular Pump

Bearing Lubrication

The Models 3106 and 3120 turbomolecular pumps use a specially formulated grease to lubricate the bearing surfaces.

The single-ended Model 3131 Turbomolecular Pump also uses grease to lubricate both upper and lower bearings. Because the grease is held in place against the bearing, this pump can be mounted in any orientation. The design of the pump and its power supply permit regreasing without interrupting the operation of the pump.

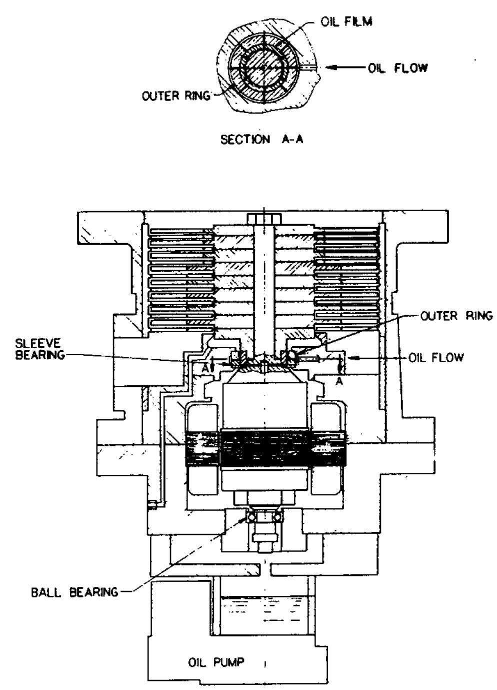


Figure 7. Schematic Diagram of Model 3133 Oil Lubrication System

The Model 3133 uses an external oil pump to lubricate the upper journal bearing. Oil is pumped up through the passages in the housing to the upper bearing plane. The oil then travels through passages in the journal bearing to create an oil film between the bearing and the rotating journal. (See Figure 7, Section AA).

The Model 3134 uses a centrifugal oil pump to lubricate the upper journal bearing. The nozzle tip is submerged in oil from the reservoir and as the rotor shaft rotates, oil is impelled up through a passage inside the rotor to the upper bearing plane where an oil film is created between the rotating journal and the stationary journal (sleeve) bearing.

In both the Models 3133 and 3134 a dynamic seal is created between the thrust disc and the upper bearing housing which helps to keep the ultra-high vacuum side of the pump free from contamination. Also, as excess oil is "thrown" from the bearing plane, it begins to accumulate in the upper bearing housing and is recycled through the lower bearing plane back to the reservoir.

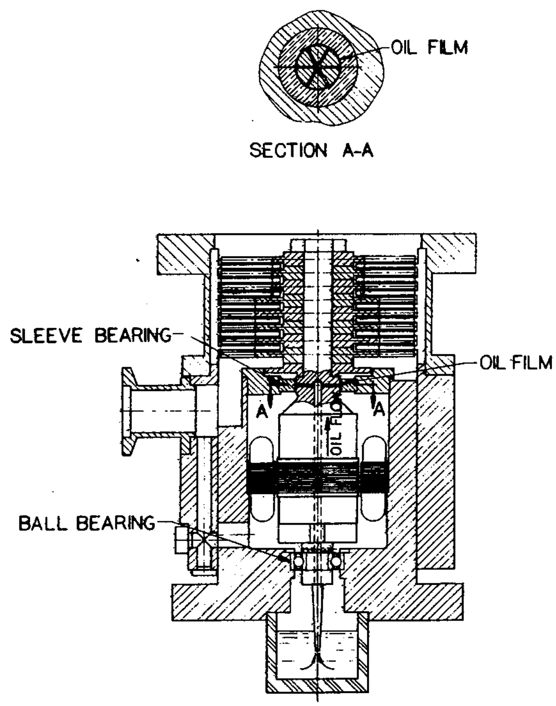


Figure 8. Schematic Diagram of Model 3134 Oil Lubrication System

Inlet Flanges

A variety of inlet flanges are available. The ASA (American Standards Association)-type flange It is flat-faced and uses bolts to connect mating surfaces. The AVS flange was developed from standards issued by the American Vacuum Society. It is a flat-faced flange using bolts to connect mating surfaces. The CONFLAT® flange, developed by Varian, is made of stainless steel so that it can be baked at a high temperature. It uses a copper seal with a special knife edge on the flange face to provide excellent sealing at ultra-high vacuum levels. It uses bolts to connect matching surfaces. The bolt pattern of the AVS and the CONFLAT® match; however, the CONFLAT® uses twice as many bolt holes as the AVS. The ISO (International Standards Organization) flange is a clamp flange without bolt holes. It uses claw clamps, and is very easy to install and disconnect.

Pump Housings

Sargent-Welch turbomolecular pumps can be baked out to 100°C if the body is made of aluminum or 150°C if the body is made of stainless steel. By increasing the temperature of the housing, degassing of surfaces occurs much quicker and hydrocarbon contaminants are decomposed into readily pumped gases.

Power Supplies

The Model 3134 is driven by a solid state power supply capable of auto restart on power failure, *Interrupted* signal for connected systems, *Run Mode* contacts for connected systems, and Electronics Protection *Interrupt*.

The Models 3131, 3133, and 3137 are each driven by a solid-state power supply capable of auto restart on power failure; overcurrent protection with auto by-pass for acceleration, and latchout and Indicator Lights for various problem conditions:

The Models 3120 and 3106 do not require power supplies. They operate directly from a 3-phase power source.

Vibration Analysis

The vibration levels for an oil lubricated pump with a journal bearing are considerably lower than for a pump with two ball bearings. A typical vibration scan for the Model 3134 vertically mounted turbomolecular vacuum pump is represented below. Units of measurement are revolutions per minute (rpm) along the x-axis and nanometers along the y-axis. During normal operation the pump is virtually vibration free between 120 Hz and its operating frequency. Vibration peaks are predominant on the low frequency end of the scan. These peaks are generally present at 30 Hz, 40 Hz, 60 Hz, and 120 Hz.

The peaks at 30 and 60 Hz can be attributed to the operation of the mechanical roughing pump, while the peak at 40 Hz is due to the operation of the refrigeration unit. The peak present at 120 Hz is caused by equipment operating at line voltage. In this particular scan vibration peaks are also present between 150 Hz and 250 Hz. A peak is also present at 1500 Hz, the operating frequency of the pump. These vibration levels are extremely low. For the Model 3134, vibration levels are less than 0.3 μm.

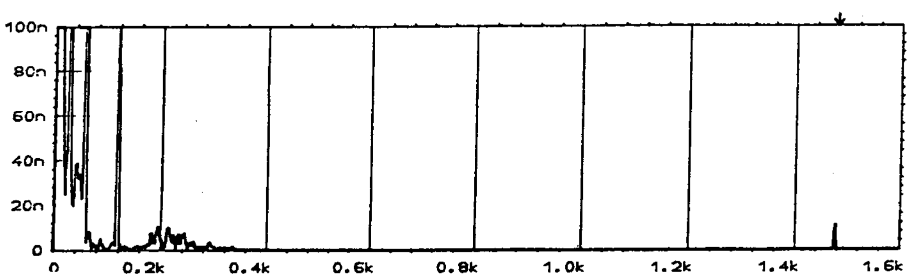


Figure 9. Vibration Analysis Graph for Model 3134 Pump

Practical Considerations

Pumping Speed

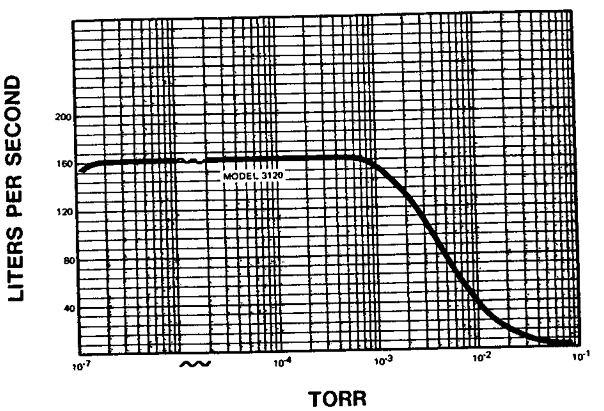


Figure 8. Pumping Speed Curve for Model 3120

Once the proper configuration of turbomolecular pump has been determined, a pump with adequate pumping speed for the application can be selected. See page 136 for a sample calculation of pumping speed and refer to the Bibliography for other text material for properly sizing a pump to a particular system. Once the throughput and speed requirements have been established, use the pumping speed curve to make your final selection.

Pumping speed curves can generally be broken down into three separate regions: Low pressure roll-off (1), plateau (2), and high pressure roll-off (3). As explained earlier, the maximum compression ratio is attained when the gas in all stages is in the molecular flow range. This is called the "plateau" region because pumping speed and molecular flow conductance do not vary with pressure, and because blade velocity is constant. The low pressure "roll-off" area of the curve represents the region where the compression ratio created by the pump design approaches its zero flow ratio capability. This is a slight "roll-off" in most instances, and this area of the curve is not represented in standard Sargent-Welch literature. Low pressure "roll-off" is most visible for hydrogen, and is a key factor in determining the pumps blank-off pressure of the pump. The high pressure "roll-off" region illustrates a drastic decrease in performance at high inlet pressures.

Using Turbomolecular Pumps

INTRODUCTION

The following section is intended as a general guide for operating, maintaining, and troubleshooting Sargent-Welch Turbomolecular Pumps. An overview is presented here. The instruction manual provided with the pump should be consulted for specific and more detailed information.

Generalized Start-up Procedure for Sargent-Welch Turbomolecular Vacuum Pumps

1) Close pump to atmosphere.
2) Check the alignment of Models 3133, 3134 and 3137. These models must be vertically aligned to ±1°.
3) Turn on the roughing pump and allow the turbomolecular pump to be pumped down to 100 microns or below. The oil in the reservoir will begin to bubble as dissolved air and water are extracted.
4) Check the oil reservoir to be sure that the outgassing process is complete. Add oil if necessary.
5) Start the turbomolecular vacuum pump. A high pitched "whine" is normal during acceleration, and its "tone" may change as the pump accelerates through several critical speeds, corresponding to the harmonic frequencies of the pump.
6) Once the turbomolecular vacuum pump reaches running speed, turn on the refrigeration unit. (Note: Model 3131 does not require cooling, and the Model 3134 has a fan cooling option which, if implemented, should be started simultaneously with the turbomolecular pump).

Generalized Shutdown Procedure for Sargent-Welch Turbomolecular Vacuum Pumps

1) Shut down turbomolecular vacuum pump.
2) If gate valves (or any other valve type) are being used, the turbomolecular pump should be isolated from the chamber before the chamber is vented. If no valves are being used, allow the turbomolecular pump to spin down completely before venting the chamber.
3) Shut down the roughing pump as soon as the turbomolecular vacuum pump completes spinning down. The turbomolecular pump can now be vented to atmosphere.

MAINTENANCE SCHEDULE

Oil Lubricated Turbomolecular Pumps

Vertical: Model 3133, Model 3134, Model 3137

Oil should be added as necessary in order to maintain an appropriate oil level in the reservoir. The turbomolecular pump should be "flushed" and the oil supply replaced only if signs of oil breakdown or oil contamination are evident.

While the ball bearings used in turbomolecular pumps are capable of operating effectively for much longer than twelve months, a one year bearing replacement maintenance schedule is recommended in order to insure high turbomolecular pump reliability.

Grease Lubricated Turbomolecular Pumps

Horizontal (Double Ended): Model 3106, Model 3120
Vertical (Single Ended): Model 3131

A steady increase in current at operating frequency is an indication that the bearings need to be regreased. The regreasing process should be carried out as needed. A syringe is available for inserting the grease into a channel to lubricate the bearings.

TROUBLESHOOTING

Sudden Pressure Change ("Air Inrush")

If the turbomolecular pumped vacuum system will be characterized by sudden changes in pressure, it is necessary to design in protection for the turbomolecular pump. In the worst cases a gate valve may be necessary to isolate the pump from the high pressure gas. However, most systems can operate effectively over relatively wide pressure ranges by changing the pressure in the system gradually instead of suddenly. A vent valve or venting system may be utilized. Double ended horizontal turbomolecular pumps are relatively less sensitive to pressure changes than high speed vertical turbomolecular pumps.

Vibration Considerations

1) Make sure the roughing pump is as isolated as possible from the turbomolecular pump. (Flexible bellows are the preferred outlet connection for vibration dampening purposes).
2) The refrigeration unit should also be isolated if possible. Model 3134 has a fan cooled option and this fan may produce a vibration peak at approximately 40 Hz.
3) Minimize any vibration which can be transmitted through the floor to the turbomolecular pump.

If vibration levels begin to increase while the pump is at operating frequency, this may be an indication of:

A) Bearing Failure
B) Leak in System
C) Misalignment - make sure that the Models 3133, 3134, or 3137 are vertically aligned to within $\pm 1°$.

Oil Discoloration

Amber Color - Indicates oil breakdown most probably caused by an increase in temperature.

Black - Indicates failure of the upper journal bearing.

Oil Backstreaming

Avoid the situation where the turbomolecular pump is stopped and the roughing pump is still running and is open to the turbomolecular pump outlet. Oil and other vapors will condense in the turbomolecular pump.

Typical Causes of Turbomolecular Vacuum Pump Crashes

1) Air Inrush - the running turbomolecular pump has been vented directly to atmosphere creating excessive reverse loading to the lower ball bearing leading to its failure. Air inrushes can also cause excessive blade damage.
2) Contamination of Oil Supply - A foreign object enters the pumps oil supply and is passed through the bearing plane. This can create a "glitch" in the bearing which drastically reduces bearing life.
3) Lack of Lubrication - without proper lubrication, bearings will quickly deteriorate. Lubrication failure generally occurs due to:
   A) A foreign object blocking an oil passage and thus preventing the bearing from being lubricated.
   B) Lack of oil in the reservoir. (NOTE: Models 3134 and 3137 have a centrifugal oil pump and the oil level must remain above the nozzle tip (red line on the oil reservoir) to insure proper bearing lubrication.
   C) Grease has begun to separate and can no longer provide an adequate lubrication film to the bearing.
4) If the turbomolecular pump inlet is exposed, an object may fall into the blade cascade causing a crash.
5) Bearing Failure - due primarily to factors described above:
   A) Air Inrush
   B) Contamination of Oil Supply
   C) Lack of Lubrication

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Glossary Of Terms

The following is a partial list of Vacuum Technology terms used in this catalog.

Absolute Pressure, a term used in engineering literature to indicate pressure above the absolute zero value corresponding to empty space, or the absolute zero of temperature as distinguished from gauge pressure. In vacuum technology pressure always corresponds to absolute pressure and not to gauge pressure; therefore, the term absolute pressure is not required.

Antisuckback Valve, a valve or other device that retards the migration of oil from a vacuum pump into a vacuum system, when the pump stops while the system is under vacuum.

Atmospheric Pressure, the pressure of the atmosphere at a specified place and time. The normal atmosphere has been defined as the pressure exerted by a mercury column 760 mm in height at 0°C under standard acceleration of gravity of 980.665 cm/sec^2.

Belt-drive Pump, a pump with the motor drive force supplied by a belt. A pulley is attached to the pump shaft. The ratios of the diameters of the pump and motor pulleys defines the rotational speed of the pump.

Compression Ratio, the ratio between the outlet pressure and the inlet pressure of a pump for a specific gas.

Conductance, is a quantity describing the flow of gas in a channel. Conductance in a vacuum system can be limited by the diameter and geometry of vacuum lines.

Corrosion Resistant, constructed of materials resistant to attack by aggressive gases or chemicals in liquid or particulate form.

Degassing, the deliberate removal of gas from a material, usually by application of heat under high vacuum.

Diffusion Pump, an ultra-high vacuum pump which transports gas molecules on collision with a high speed vapor stream.

Direct-drive Pump, a pump with the motor drive force supplied by a direct coupling to the pump rotor shaft. The rotational speed of the motor defines the rotational speed of the pump.

Foreline, vacuum line connecting to the inlet of a vacuum pump.

Fore Pump, the pump which produces the necessary fore vacuum for a pump which is incapable of discharging gases at atmopheric pressure. Sometimes called the backing pump.

Free Air Displacement, the volume of air passed per unit of time through a mechanical pump when the pressure on the intake and exhaust sides is equal to atmospheric pressure. Also called displacement and free air capacity.

Gas, gas is defined as the state of matter in which the molecules are practically unrestricted by intermolecular forces so that the molecules are free to occupy any space within an enclosure. In vacuum technology the word "gas" has been loosely applied to both the non condensable gas and the vapor within a vacuum system.

Gas Ballast, the venting of the compression chamber of a mechanical pump to the atmosphere to prevent condensation of condensable vapor within the pump. Sometimes called vented exhaust.

Gas Flow, within a vacuum system, the passage of gas through a duct. Gas flow behavior varies with pressure range as Viscous Flow from atmospheric pressure to 10^{-3} Torr, and Molecular Flow below 10^{-3} Torr, as well as with system design.

Gerotor Pump, gear type pump with multilobed inner rotor rotating within multilobed outer rotor to produce a flow of liquid or gas. Commonly used in lubrication systems as an oil pump. Can also be used as a vacuum pump.

High Vacuum, vacuum range from 10^{-2} to 10^{-6} Torr.

Isolation Valve, device that seals off a vacuum system from its vacuum pump when the pump is not operating. Designed to maintain a vacuum for a period of time.

Leak, opening in the wall, joint, or seal of a vacuum system that allows passage of gas from the higher to lower pressure space.

Leakage Rate, the rate of flow of a gas through a leak.

Low Vacuum, vacuum range from atmospheric pressure to 1 Torr (760 mm Hg to 1 mm Hg).

McLeod Gauge, a liquid level vacuum gauge in which a known volume of the gas, at the pressure to be measured, is compressed by the movement of a liquid column to a much smaller known volume, at which the resulting higher pressure is measured. Particular designs are named after the inventors or by various trade names.

Micron, unit of pressure equal to 10^{-3} Torr.

Millimeter of Hg, unit of pressure equal to 1 Torr.

Molecular Flow, type of gas flow, which usually occurs at pressures below 10^{-3} Torr. In molecular flow gas molecules travel randomly, virtually without interaction.

Outgassing, the desorption of gas from materials within a vacuum system. In ultra-high vacuum systems outgassing can be a limiting factor on the lowest ultimate pressure that can be achieved.

Oxygen Service, evacuation of oxygen by a vacuum pump at partial pressures above that of oxygen in atmosphere. Vacuum pumps for oxygen service must use a non-hydrocarbon vacuum fluid.

Oil Diffusion Pump, see Diffusion Pump.

Partial Pressure, pressure due to a gas or vapor component of a gaseous mixture.

Pumpdown Curve, a graph representing the relationship between pressure and time. Used to determine the time required to achieve the desired operating pressure in a system with a given pump.

Pumping Speed, the volume of gas per unit time which the vacuum pump is able to remove from the system. Pumping speed is often expressed in liters per minute (L/m), liters per second (L/s), or cubic feet per minute (CFM).

Rotary Vane Pump, type of vacuum pump producing a flow of gas by the action of vanes sweeping the inside of a cylindrical chamber.

Rough Vacuum, see Low Vacuum.

Roughing Pump, vacuum pump used to pump down a system to a desired vacuum range. Often used to quickly pump down the system from atmosphere to its operating range, or to the operating threshold of an ultra-high vacuum pump.

Stage, operating unit of a vacuum pump. By combining stages in series a higher compression ratio can be achieved. Most belt drive and direct drive high vacuum pumps are two-stage.

Thermocouple Gauge, electronic pressure gauge measuring pressure-dependent heat flow.

Torr, unit of pressure equal to 1 mm of mercury (1 atmosphere = 760 mm Hg).

Total Pressure, the sum of the partial pressures of all the components of a gaseous mixture.

Turbomolecular Pump, an ultra-high vacuum pump that transports gas molecules on impact with high speed rotating blades.

Ultimate Pressure, lowest attainable pressure in a vacuum system. In a vacuum pump, the lowest pressure that can be attained with that pump. Ultimate pressure is limited by the pumping speed of the vacuum pump and the vapor pressure of the vacuum pump sealing fluid among other factors.

Ultra-High Vacuum, vacuum range with pressures of 10^{-6} Torr and below.

Vacuum, a space with gas pressure less than 1 atmosphere.

Vacuum System, a closed system for the achievement and maintenance of a vacuum. Consists of a vacuum pump or pumps, vacuum chamber, interconnecting piping, and a variety of other vacuum components.

Vapor, a substance in gas phase which is condensable at the ambient temperature.

Vapor Pressure, partial pressure of a vapor.

Vented Exhaust, see Gas Ballast.

Viscous Flow, type of gas flow which usually occurs at pressures from atmosphere to 10^{-3} Torr. In viscous flow, the preferred direction of gas molecules is in the direction of the streaming gas.

Basic Formulas

Pumpdown Time

The theoretical pumpdown time of vacuum chamber assuming no conductance between the pump and the chamber is given by:

$$T = \frac{V \times F}{S} \quad \text{(Eqn. 1)}$$

Where: S = Pumping Speed (Free Air Displacement CFM)
V = Volume of Vacuum Chamber cu ft

$$F = 2.3 \log \frac{P_o}{P} \quad \text{(Eqn. 2)}$$

Where: P_o = Atmospheric Pressure
P = Desired Pressure

Sample Calculation: Calculate the time required to evacuate a 10 cubic feet chamber to 10^{-2} Torr using a Model 8871 Vacuum Pump.

$$F = 2.3 \log \frac{P_o}{P} = 2.3 \log \frac{760 \text{ Torr}}{0.01 \text{ Torr}} = 11.2$$

$$T = \frac{V \times F}{S} = \frac{10 \text{ cu ft} \times 11.2}{50 \text{ CFM}} = 2.2 \text{ minutes}$$

Throughput

Throughput (Q) and Pumping Speed(s) are interelated and can be calculated as follows:

$$Q = \frac{P_o \times V}{T} \quad \text{(Eqn. 3)}$$

$$S = \frac{Q}{P} \quad \text{(Eqn. 4)}$$

Where: P_o = Atmospheric Pressure (Torr)
P = Equivalent Pressure (Torr) (Inlet Pressure - Base Inlet Pressure)
V = Volume of Gas (liters)
T = Time Taken for Gas to Flow Through Conductive Element (seconds)

Sample Calculation:

Given the following data, determine the throughput and pumping speed for a Model 3134 Turbomolecular Pump.

Atmospheric Pressure = 760 Torr
Inlet Pressure = 7.0×10^{-5} Torr
Base Inlet Pressure = 7.5×10^{-8} Torr
V = 1.0×10^{-3} liters
T = 36 seconds
P = $(7.0 \times 10^{-5}$ Torr) - $(7.5 \times 10^{-8}$ Torr)
P = 6.99×10^{-5} Torr

$$Q = \frac{P_o x V}{T} = \frac{(760 \text{ Torr})\,(1.0 \times 10^{-3} \text{ L})}{36 \text{ s}}$$

$$= 2.11 \times 10^{-2} \frac{\text{Torr L}}{\text{s}}$$

$$S = \frac{Q}{P} = \frac{2.11 \times 10^{-2} \text{ Torr L/s}}{6.99 \times 10^{-5} \text{ Torr}} = 302 \text{ L/s}$$

Pumping Speed of Vacuum System

The effective pumping speed of a vacuum system may be calculated as follows:

$$\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{Z} \quad \text{(Eqn. 5)}$$

Where S_{eff} = Effective Pumping Speed (CFM)
S = Pumping Speed (Free Air Displacement CFM)
Z = Conductance of Vacuum System (CFM)

Pumpdown Time (T) can be described as:

$$T = \frac{V \times F}{S_{eff}} \quad \text{(Eqn. 6)}$$

Sample Calculation:

Given the following data calculate the time to evacuate a 10 cubic feet chamber to 10^{-2} Torr pressure using a Model 8871 Vacuum Pump. The chamber is connected to the pump by 2 in. dia. piping, 3 feet long.

From the tube conductance nomogram (page 121)
Z = 35 CFM for 2 in. diameter piping, 3 feet long.
S = 50 CFM (8871)

$$\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{Z} = \frac{1}{50} + \frac{1}{35}$$

$$S_{eff} = 20.6 \text{ CFM}$$

The effective pumpdown time (T) of the system:

$$T = \frac{V \times F}{S_{eff}} = \frac{10 \text{ cu ft} \times 11.2}{20.6 \text{ CFM}} = 5.4 \text{ minutes}$$

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General Conversions*

atmosphere (atm)	=	760 mm Hg (0°C)
atm		14.696 lbs/in.^{2}
atm		29.921 in. Hg (32°F)
atm		33.899 ft H_2O (39.2°F)
atm		1033.2 g/cm^2
atm		1.0581 ton/ft^2
centimeter (cm)	=	0.3937 in.
cm^2		0.1550 in.^{2}
cm^3		3.5314×10^{-5} ft^3
cm^3		6.1024×10^{-2} in.^{3}
cm^3		0.99997 mL
cm^3/sec		2.1189×10^{-3} ft^3/min
foot (ft)	=	0.3048 m
ft H_2O		0.0295 atm (4°C)
ft H_2O		0.8826 in. Hg (32°F)
ft H_2O		0.4335 lbs/in.^{2} (4°C)
ft^3		28.316 liter
ft^3		7.480 gal (US Liq)
ft^3		0.02832 m^3
ft^3		2.832×10^4 cm^3
ft^3 H_2O		62.426 lbs (39.2°F)
ft^3/min		472.0 cm^3/sec
ft^3/min		0.472 liters/sec
ft^3/min		1.6990 m^3
ft^3/min		0.1247 gal/sec
ft^3/min		28.316 liters/min
gram (g)	=	15.432 grain
g		0.03527 avdp
inch (in.)	=	25.4 mm
in. Hg		13.55 in. H_2O
in. H_2O		0.074 in. Hg
in.^{2}		6.4516 cm^2
in.^{3}		16.387 cm^3

kilogram (kg)	=	2.2046 lbs avdp
liter	=	61.025 in.^{3}
liter		0.03532 ft^3
liter		0.26418 gal (US Liq)
liter		1.0567 qt (US Liq)
liters/sec		2.1189 ft^3/min
liters/sec		3,600 m^3/hr
lbs avdp		7000 grain
lbs avdp		453.59 g
lbs H_2O		0.01602 ft^3 (39.2°F)
lbs H_2O		0.11983 gal (US Liq)
meter (m)	=	39.37 in.
m		3.2808 ft
m		1.0936 yd
m^3		35.315 ft^3
m^3/hr		0.5886 ft^3/min
m^3/hr		16.666 liters/min
mm		0.03937 in.
mm Hg		1 Torr
mm Hg		1000 μ
mm Hg		0.00132 atm
mm Hg		0.01934 lbs/in.^{2}
micron (μ or mμ)	=	0.001 mm
μ		0.001 Torr
μliters/sec		1.27×10^2 μft^3/hr
oz avdp	=	28.349 g
pint (US Liq) (pt)	=	28.875 in.^{3}
quart (US Liq) (qt)	=	32 fl oz
qt		0.94633 liter
qt		946.353 cm^3
Torr	=	1 mm Hg

*From HANDBOOK OF CHEMISTRY AND PHYSICS

Pressure Conversions

ABSOLUTE PRESSURE (1)									GAGE PRESSURE (2)	
cm of Hg	Torr or mm of Hg	Micron	Atmosphere	lb/in²	ton/ft²	gram/cm²	ft of H_2O	in of Hg	lb/in²	in of Hg
76	760	760000	1.0	14.70	1.06	1033	33.9	29.9	0	0
70	700	700000	.921	13.53	.975	952	31.2	27.6	1.16	2.36
60	600	600000	.790	11.60	.835	816	26.8	23.6	3.10	6.30
50	500	500000	.659	9.67	.696	680	22.3	19.7	5.03	10.2
40	400	400000	.526	7.74	.557	545	17.8	15.7	6.97	14.2
30	300	300000	.395	5.80	.417	408	13.4	11.8	8.90	18.1
20	200	200000	.263	3.87	.278	272	8.92	7.87	10.8	22.0
10	100	100000	.132	1.94	.139	136	4.46	3.94	12.8	26.0
5	50	50000	.066	.967	.070	68.0	2.23	1.97	13.7	27.9
1	10	10000	.013	.194	.014	13.6	.446	.394	14.5	29.5
0.1	1	1000	.001	.019	.001	1.36	.045	.039	14.68	29.88
0	0	0	0	0	0	0	0	0	14.70	29.92

(1) Positive pressure measured from absolute zero.
(2) Negative pressure (or vacuum) measured from atmospheric pressure.

Pressure Equivalents

Millitorr or Micron		Torr or mm of Hg		
1000	=	1.0	=	10^0
100	=	0.1	=	10^{-1}
10	=	0.01	=	10^{-2}
1.0	=	0.001	=	10^{-3}
0.5	=	0.0005	=	5×10^{-4}
0.1	=	0.0001	=	1×10^{-4} or 10^{-4}
0.01	=	0.00001	=	10^{-5}
0.001	=	0.000001	=	10^{-6}

Pressure and Temperature Values for Various Altitudes

Based on U.S. Standard Atmosphere									From N.A.C.A. Report No. 538		
ALTITUDE	PRESSURE			TEMPERATURE		ALTITUDE	PRESSURE			TEMPERATURE	
(Feet)	in Hg	mm Hg	P.S.I.	°C	°F	(Feet)	in Hg	mm Hg	P.S.I.	°C	°F
-1,000	31.02	787.9	15.25	17.0	62.6	32,500	7.91	201.0	3.89	-49.4	-56.9
- 500	30.47	773.8	14.94	16.0	60.8	33,000	7.73	196.4	3.80	-50.4	-58.7
0	29.921	760.0	14.70	15.0	59.0	33,500	7.55	191.8	3.71	-51.4	-60.5
500	29.38	746.4	14.43	14.0	57.2	34,000	7.38	187.4	3.63	-52.4	-62.3
1,000	28.86	732.9	14.18	13.0	55.4	34,500	7.20	183.0	3.54	-53.4	-64.1
1,500	28.33	719.7	13.90	12.0	53.6	35,000	7.04	178.7	3.46	-54.3	-65.8
2,000	27.82	706.6	13.67	11.0	51.8	35,332	6.93	175.9	3.40	-55.0	-66.0
2,500	27.31	693.8	13.41	10.0	50.0	35,500	6.87	174.5	3.375	-55.0	-66.0
3,000	26.81	681.1	13.19	9.1	48.4	36,000	6.71	170.4	3.296	-55.0	-66.0
3,500	26.32	668.6	12.92	8.1	46.6	36,500	6.55	166.4	3.22	-55.0	-66.0
4,000	25.84	656.3	12.70	7.1	44.8	37,000	6.39	162.4	3.14	-55.0	-66.0
4,500	25.36	644.2	12.45	6.1	43.0	37,500	6.24	158.6	3.067	-55.0	-66.0
5,000	24.89	632.3	12.23	5.1	41.2	38,000	6.10	154.9	2.994	-55.0	-66.0
5,500	24.43	620.6	12.00	4.1	39.4	38,500	5.95	151.2	2.925	-55.0	-66.0
6,000	23.98	609.0	11.77	3.1	37.6	39,000	5.81	147.6	2.852	-55.0	-66.0
6,500	23.53	597.6	11.56	2.1	35.8	39,500	5.68	144.1	2.798	-55.0	-66.0
7,000	23.09	586.4	11.34	1.1	34.0	40,000	5.54	140.7	2.72	-55.0	-66.0
7,500	22.65	575.3	11.12	0.1	32.2	40,500	5.41	137.4	2.66	-55.0	-66.0
8,000	22.22	564.4	10.90	- 0.8	30.67	41,000	5.28	134.2	2.595	-55.0	-66.0
8,500	21.80	553.7	10.70	- 1.8	28.8	41,500	5.16	131.0	2.535	-55.0	-66.0
9,000	21.38	543.2	10.50	- 2.8	27.0	42,000	5.04	127.9	2.47	-55.0	-66.0
9,500	20.98	532.8	10.30	- 3.8	25.2	42,500	4.92	124.9	2.415	-55.0	-66.0
10,000	20.58	522.6	10.10	- 4.8	23.4	43,000	4.80	122.0	2.36	-55.0	-66.0
10,500	20.18	512.5	9.91	- 5.8	21.6	43,500	4.69	119.1	2.304	-55.0	-66.0
11,000	19.79	502.6	9.73	- 6.8	19.8	44,000	4.58	116.3	2.25	-55.0	-66.0
11,500	19.40	492.8	9.53	- 7.8	18.0	44,500	4.47	113.5	2.195	-55.0	-66.0
12,000	19.03	483.3	9.35	- 8.8	16.2	45,000	4.36	110.8	2.14	-55.0	-66.0
12,500	18.65	473.8	9.15	- 9.8	14.4	45,500	4.26	108.2	2.094	-55.0	-66.0
13,000	18.29	464.5	8.97	-10.8	12.6	46,000	4.16	105.7	2.042	-55.0	-66.0
13,500	17.93	455.4	8.81	-11.7	10.9	46,500	4.06	103.2	1.997	-55.0	-66.0
14,000	17.57	446.4	8.63	-12.7	9.1	47,000	3.97	100.7	1.948	-55.0	-66.0
14,500	17.22	437.5	8.46	-13.7	7.3	47,500	3.873	98.38	1.90	-55.0	-66.0
15,000	16.88	428.8	8.28	-14.7	5.5	48,000	3.781	96.05	1.858	-55.0	-66.0
15,500	16.54	420.2	8.13	-15.7	3.7	48,500	3.693	93.79	1.813	-55.0	-66.0
16,000	16.21	411.8	7.96	-16.7	1.9	49,000	3.605	91.57	1.772	-55.0	-66.0
16,500	15.89	403.5	7.81	-17.7	0.1	49,500	3.52	89.41	1.729	-55.0	-66.0
17,000	15.56	395.3	7.64	-18.7	- 1.7	50,000	3.436	87.30	1.689	-55.0	-66.0
17,500	15.25	387.3	7.49	-19.7	- 3.5	51,000	3.276	83.22	1.610	-55.0	-66.0
18,000	14.94	379.4	7.34	-20.7	- 5.3	52,000	3.124	79.34	1.533	-55.0	-66.0
18,500	14.63	371.7	7.19	-21.7	- 7.1	53,000	2.978	75.64	1.463	-55.0	-66.0
19,000	14.33	364.0	7.04	-22.6	- 8.7	54,000	2.839	72.12	1.395	-55.0	-66.0
19,500	14.04	356.5	6.90	-23.6	-10.5	55,000	2.707	68.76	1.33	-55.0	-66.0
20,000	13.75	349.1	6.75	-24.6	-12.3	56,000	2.581	65.55	1.269	-55.0	-66.0
20,500	13.46	341.9	6.61	-25.6	-14.1	57,000	2.460	62.49	1.208	-55.0	-66.0
21,000	13.18	334.7	6.48	-26.6	-15.9	58,000	2.346	59.58	1.152	-55.0	-66.0
21,500	12.90	327.7	6.34	-27.6	-17.7	59,000	2.236	56.80	1.098	-55.0	-66.0
22,000	12.63	320.8	6.21	-28.6	-19.5	60,000	2.132	54.15	1.048	-55.0	-66.0
22,500	12.36	314.1	6.08	-29.6	-21.3	61,000	2.033	51.63	1.000	-55.0	-66.0
23,000	12.10	307.4	5.94	-30.6	-23.1	62,000	1.938	49.22	0.952	-55.0	-66.0
23,500	11.84	300.9	5.82	-31.6	-24.9	63,000	1.847	46.92	0.906	-55.0	-66.0
24,000	11.59	294.4	5.70	-32.5	-26.5	64,000	1.761	44.73	0.865	-55.0	-66.0
24,500	11.34	288.1	5.58	-33.5	-28.3	65,000	1.679	42.65	0.825	-55.0	-66.0
25,000	11.10	281.9	5.45	-34.5	-30.1	66,000	1.601	40.66	0.786	-55.0	-66.0
25,500	10.86	275.8	5.33	-35.5	-31.9	67,000	1.526	38.76	0.748	-55.0	-66.0
26,000	10.62	269.8	5.22	-36.5	-33.7	68,000	1.455	36.95	0.714	-55.0	-66.0
26,500	10.39	263.9	5.11	-37.5	-35.5	69,000	1.387	35.23	0.681	-55.0	-66.0
27,000	10.16	258.1	4.99	-38.5	-37.3	70,000	1.322	33.59	0.649	-55.0	-66.0
27,500	9.94	252.5	4.88	-39.5	-39.1	71,000	1.261	32.02	0.619	-55.0	-66.0
28,000	9.72	246.9	4.78	-40.5	-40.9	72,000	1.202	30.53	0.590	-55.0	-66.0
28,500	9.50	241.4	4.67	-41.5	-42.7	73,000	1.146	29.10	0.562	-55.0	-66.0
29,000	9.29	236.0	4.56	-42.5	-44.5	74,000	1.093	27.75	0.536	-55.0	-66.0
29,500	9.08	230.7	4.46	-43.4	-46.1	75,000	1.041	26.45	0.512	-55.0	-66.0
30,000	8.88	225.6	4.36	-44.4	-47.9	76,000	0.993	25.22	0.488	-55.0	-66.0
30,500	8.68	220.5	4.27	-45.4	-49.7	77,000	0.946	24.04	0.465	-55.0	-66.0
31,000	8.48	215.5	4.17	-46.4	-51.5	78,000	0.902	22.92	0.443	-55.0	-66.0
31,500	8.29	210.6	4.07	-47.4	-53.3	79,000	0.860	21.85	0.423	-55.0	-66.0
32,000	8.10	205.8	3.98	-48.4	-55.1	80,000	0.820	20.83	0.403	-55.0	-66.0