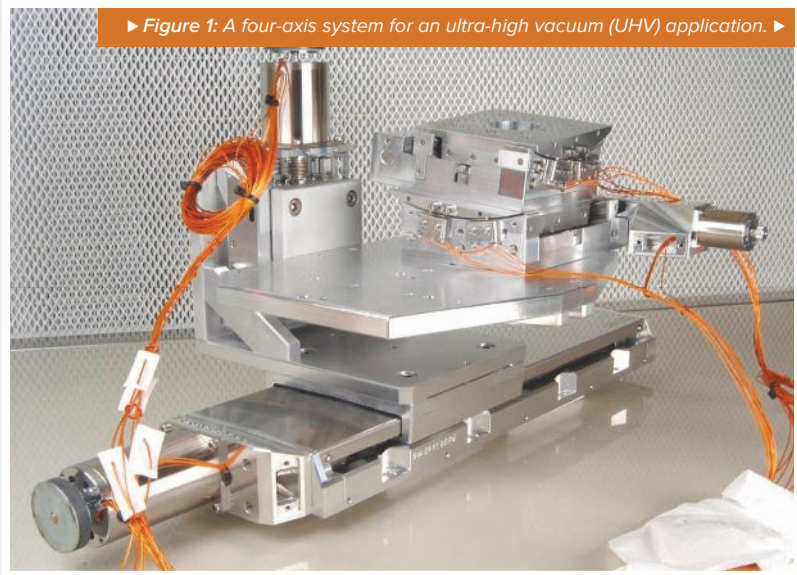


Design of motion control and precision positioning equipment for high and ultra-high vacuum applications

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Applications in scientific research and industrial production often require motion and positioning in a vacuum. Several factors influence the quality of the vacuum environment. One of the main challenges is outgassing of the components used. Manufacturers, such as Physik Instrumente (PI), address this by providing standardised vacuum-ready or customised products that meet the requirements of high vacuum (HV) and ultra-high vacuum (UHV) applications. A team of experts provide support to select and configure products to specific vacuum applications.

This article focusses on motorised positioners for vacuum applications and describes how they are designed, manufactured and tested according



► Figure 1: A four-axis system for an ultra-high vacuum (UHV) application. ►

to their specific requirements. It also homes in on the permissible materials for different vacuum levels and quality control (QC) measurements that can be performed.

Vacuum applications

Vacuum applications are becoming increasingly important because of new technologies that can only be used in a vacuum. Lens optics are coated in a vacuum, and fibre and laser optics as well as sensitive detectors are manufactured in a vacuum. In the production of microelectronic circuits, a vacuum ensures safe handling of sensitive components. The aerospace and automotive industries use electron beam processes in a vacuum to minimise angular distortion and transverse shrinkage during

welding of microcomponents or thick-shelled workpieces. Surface and material analysis, conducted using scanning electron microscopy (SEM), transmission electron microscopy (TEM) or X-ray tomography equipment, must be carried out in a vacuum. Nanocharacterisation and nanostructuring is also dependent on a vacuum environment due to the methods used, such as ion-beam focusing. The semiconductor industry uses extreme ultraviolet (EUV) lithography to further reduce feature sizes, necessitating very clean conditions and therefore an UHV.

Both scientific research and industry require different vacuum classes for all of the aforementioned and many other applications, and the appropriate equipment must be provided.

There are clearly defined challenges for operating positioning systems, such as limited installation space, particle contamination of the vacuum chamber by abrasion or outgassing, and excessive heat input.

Manufacturers of motion control and precision positioning equipment that are experienced in vacuum applications and technology, such as Physik Instrumente (PI), can offer standard and customer-specific drive technologies that are precisely tailored to the requirements of the vacuum application, as shown in figure 1. This includes motorised positioners that have specially designed direct current (DC) or stepper motors to allow large travel ranges.

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It is important to analyse the demands of a specific application to select the required vacuum class. In addition to the final pressure, the outgassing rate is relevant because it determines the partial pressure of specific residual components. For example, hydrocarbons (HCs) may be introduced into the vacuum chambers unintentionally due to the use of grease or plastic components not compatible for use in a vacuum. HCs are fragmented by strong UV light or X-rays, and therefore, they are especially critical in laser applications in the UV range and in beamline applications. HC fragments deposited on optic surfaces pollute or can even damage the in-vacuum optics or the test sample.

Vacuum classes

As per the standards document *DIN 28400-1: Vacuum technology; terms and definitions; general terms*, vacuum is defined as pressure lower than normal atmospheric air pressure and is measured in either hectopascal (hPa), millibar (mbar) or torr (Torr). Different levels of vacuum classes are defined: fine, high, ultra-high and extreme. While high and ultra-high are commonly applied, extremely high vacuum is rarely necessary. Table 1 shows that to determine the required vacuum class, it is necessary to know the pressure range required by the application.

Outgassing rate

The outgassing rate is the next relevant specification because it represents the partial pressure of specific residual components. Outgassing is the detachment of volatile molecules that are absorbed or adsorbed on the surface, or in the volume of a material.

As the rate of outgassing defines the pressure in the system (together with the capacity of the vacuum pump), outgassing prohibits fast achievement of low-pressure values. In addition, the outgassing compounds deposit on surfaces of optical elements or other sensitive devices and can obscure or damage them.

Overall, motorised positioners with low outgassing are required. Furthermore, the residual gas must contain very little or no HCs and no metals that have high vapour pressure such as zinc, lead or cadmium.

► **Table 1:** Definition of vacuum classes based on pressure ranges. ►

Vacuum class	Abbr.	Pressure range hPa	PI class
Fine vacuum	FV	1 to 10^{-3}	Standard
High vacuum	HV	10^{-3} to 10^{-7}	V6, V7
Ultra-high vacuum	UHV	10^{-7} to 10^{-12}	V9
Extreme high vac.	XHV	< 10^{-12}	n/a

Vacuum-ready motorised positioners

Since outgassing is a challenge for creating and maintaining clean high-vacuum environments, the right choice of materials and treatments is compulsory in the design and production of vacuum systems. To achieve a HV or an UHV vacuum-compatible motorised positioner, four main issues must be considered, namely material selection, design and manufacturing and commissioning processes. Manufacturers, such as PI,

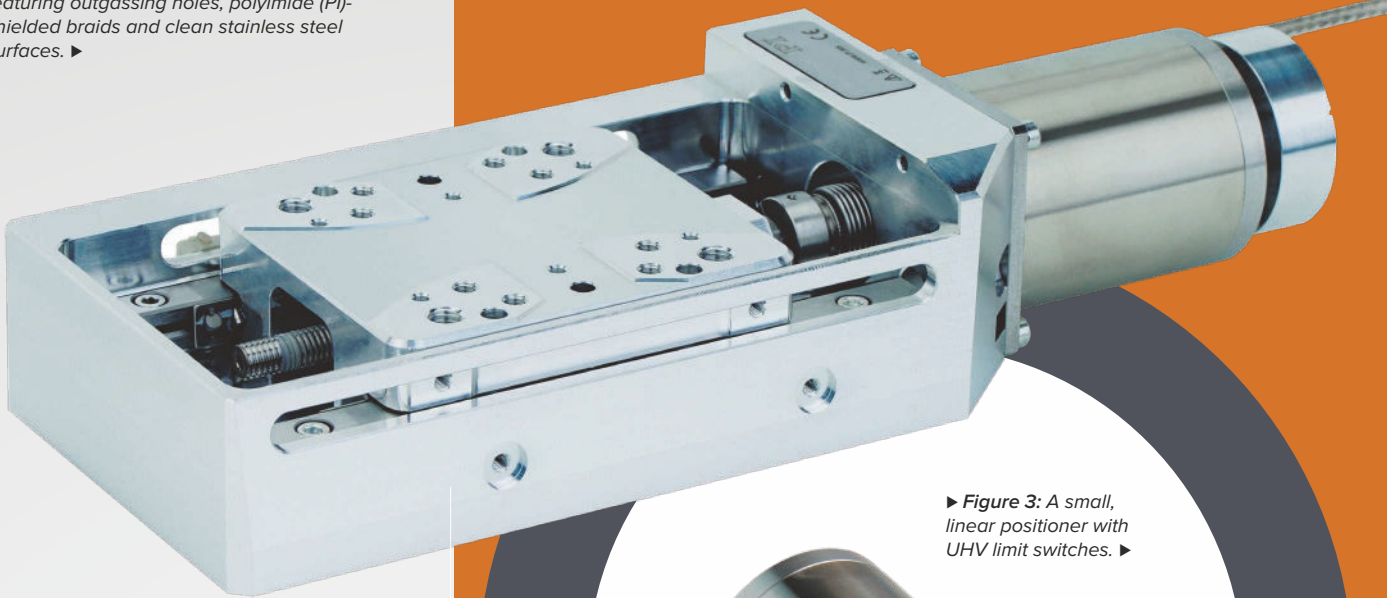
offer specific vacuum-ready catalogue items for selected product series that are already compatible for HV or UHV, or can be modified on request for use in a vacuum.

There are three specific standard vacuum classes of motorised positioners available from PI, namely V6 for high vacuum specifications, V7 for higher cleanliness/pressure demands and V9 for ultra-high vacuum requirements. Table 2 shows the different measures taken to achieve the corresponding vacuum class.

► **Table 2:** Different measures to achieve corresponding vacuum classes. ►

HV - V6	HV - V7	UHV - V9
Greased motor	Special HV motor	Special UHV motor with temperature sensor
Standard measuring system	HV measuring system	UHV measuring system
2 m PTFE cable with standard connector	2 m PI or PTFE cable with UHV connector	2 m PI cable with UHV connector
Standard limit switch	Vacuum limit switch	Vacuum limit switch
Anodized aluminum components	Aluminum, blank	Aluminum, blank
Partly with cannulated screws	Cannulated screws	Cannulated screws
Guides and spindles with vacuum grease	Guide and spindle made of stainless steel with vacuum grease	Guide and spindle made of stainless steel with vacuum grease
Brass allowed	Brass allowed	Brass not allowed
Plastics allowed	Selected plastics	No plastic except PEEK or polyimide
No vented holes	Vented holes	Vented holes
Bakeout temperature max. 80 °C	Bakeout temperature max. 80 °C	Bakeout max. temperature 120 °C with/150 °C without measuring system

► **Figure 2:** Typical motors for UHV applications, featuring outgassing holes, polyimide (PI)-shielded braids and clean stainless steel surfaces. ►



Vacuum-ready materials

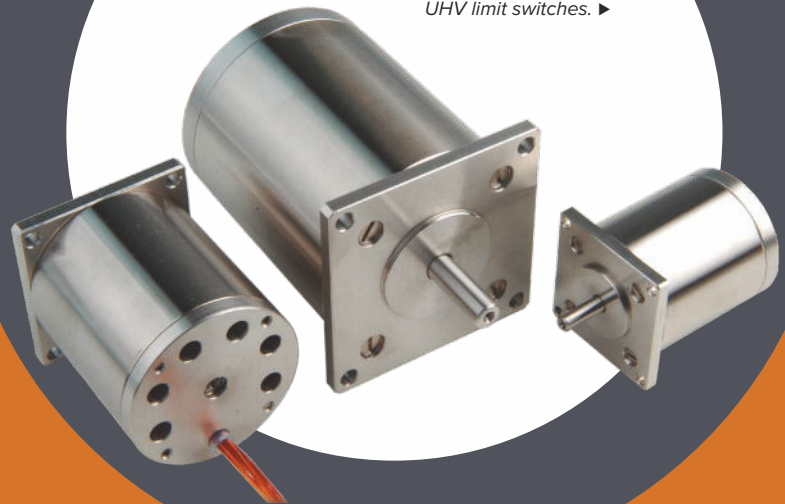
Common electrical and electronic equipment contains components that either do not suit vacuum applications or only limitedly. These comprise cables, motors, scaling systems, connectors, limit switches and others. Common cables are usually shielded with polyvinyl chloride (PVC) insulation, the outgassing of which negatively affects the vacuum level and production process; common motors are lubricated with grease or oil, which have high vapour pressure containing HCs; and common electronic parts are embedded in plastics, which have high outgassing rates. Specific product features should be implemented to avoid outgassing from these components.

Replacing PVC cables with polytetrafluoroethylene (PTFE)- or polyimide (PI)-shielded braids is technically simple but expensive. PI, in particular, has the necessary cleanliness for use in a vacuum, but it absorbs considerable water molecules, which increases the pump-down period drastically. Therefore, only the number of braids necessary should be used for operating the positioning system. The braids should be as short as possible and, ideally, the vacuum chamber should be designed for short cables.

Motors modified for vacuum, as shown in figure 2, have several holes for venting and PI-shielded motor coils that ideally have a temperature sensor installed in the motor. Temperature control is important for two reasons. Firstly, the motor should be operated at a point below excessive heat generation, meaning that slow driving is recommended. Secondly, a temperature-controlled bakeout process must be performed by applying current to the motor, at least for UHV systems.

Therefore, all components for UHV positioners must be able to sustain heat up to a certain temperature. Physik Instrumente, for example, typically sets this temperature to 120 °C for positioners with a scaling

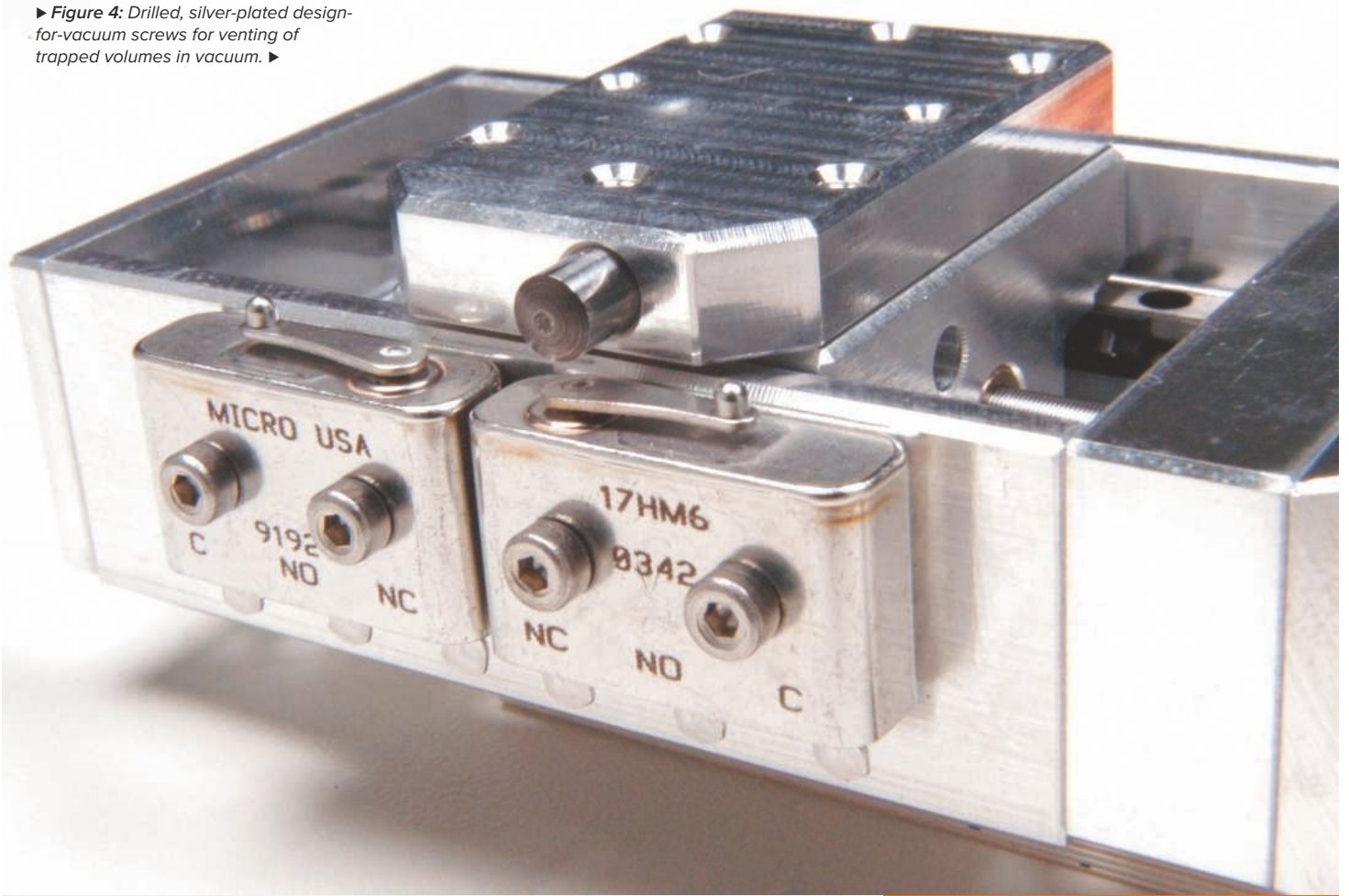
► **Figure 3:** A small, linear positioner with UHV limit switches. ►



system and to 150 °C for positioners without. Due to the huge number of windings of the motor coils, the amount of PI is very high, and therefore, a large amount of adsorbed water must be baked out. Specially designed, two-phase stepper motors are used in UHV products.

Common connectors and limit switches cannot be used in vacuum beyond 10^{-6} hPa due to their high-outgassing plastic components. These are replaced with components made of low-outgassing plastics for HV or ceramic, metal or polyether ether ketone (PEEK) for UHV, as shown in figure 3. The pins of the connectors and the contacts of the limit switches are not soldered but clamped, crimped or laser welded.

► **Figure 4:** Drilled, silver-plated design-for-vacuum screws for venting of trapped volumes in vacuum. ►



The selection of materials for the chassis of the positioner is limited, for example, copper-zinc alloys should not be used in vacuum systems. Such materials are replaced by bronze if possible. Other standard plastic components are replaced with ceramic, metal or PEEK components for UHV.

"Substitution of standard materials for vacuum-compatible materials is a strict requirement of vacuum positioner design."

Design-for-vacuum positioners

Substitution of standard materials for vacuum-compatible materials, as described above, is a strict requirement of vacuum positioner design. Another requirement is the reduction and minimisation of the surface of the vacuum positioner. The surface of its uncoated body is not sandblasted. Covers for protection against contamination are usually not required. Protective shields for limit switch electronics are not necessary in the case of mechanical limit switches.

The third and very important requirement in vacuum positioner design is the prevention of virtual leaks. A virtual leak is a trapped volume connected to the vacuum side of a chamber. The gas in this trapped volume cannot be pumped out easily due to only narrow paths connecting to the vacuum chamber. This results in slow outgassing and appears as a leak in the vacuum system. Poor design is the major

cause of virtual leaks, not only for positioners but for vacuum chambers and vacuum equipment in general.

Trapped volumes are usually caused by unvented or poorly vented blind tapped holes. These are either at the tip of a screw or under the rim of the screw head. Furthermore, holes that are covered, either when mounting the positioner on a base plate or fixing a sample on the positioner, often cause virtual leaks.

In the case of virtual leaks caused by screws, use of vented screws, as shown in Figure 4, is recommended. Vented screws have a hole down the length of the screw to avoid trapped volumes. In this way, the trapped volume can be vented. Furthermore, the head of the screw has a groove to ensure venting of the cavity under the screw head. If the hole is covered by the positioning unit, which then causes a virtual leak, it must have either a perforation or an air vent groove.

Vacuum-enabled manufacturing and commissioning processes

Before a vacuum positioner is assembled, all pure metal parts undergo a cleaning process in an ultrasonic bath. Electrical and electronic units are wipe-cleaned. Standard lubricated components such as bearings and guides are degreased, cleaned and lubricated with special vacuum grease. Ultrasonic-cleaned components are dried in a climate chamber.

Assembling of a positioner is carried out in a cleanroom or in a laminar flow system. After assembling, the positioner must pass a performance test in a clean environment. Vacuum tests are performed for each type of positioner and when vacuum-critical changes are made to the product.

After assembling, the system is packed in vacuum-sealed bags,

protected against dirt, air and humidity. First, the positioner undergoes a baking process in a climate chamber. After packing and sealing in an inner vacuum bag, the positioner is then put into a second outer vacuum bag that is then vacuum sealed completely.

Vacuum-ready product accessories

Accessories used in the vacuum environment can also be provided in vacuum versions, such as suitable feedthroughs and cable adaptors. Further accessories such as flanges or connectors are available for vacuum-ready products. However, it is recommended that electronic devices, such as controllers and amplifiers, are used outside the vacuum environment.

Test and quality control

Vacuum-ready products undergo standard testing. Following are

examples of how these products are tested by Physik Instrumente (PI).

For testing single components or for testing small positioners, a chamber is available with a volume of approximately 10 l. The small vacuum chamber is equipped with a pump stand consisting of a 400 l/s (N₂) turbomolecular pump and a pressure sensor for continuous pressure sensing, which means that pressures below 10⁻¹⁰ hPa can be reached. A heating facility allows bakeout temperatures up to 200 °C.

The large chamber shown in figure 5 has a volume of 260 l and is designed for large positioners up to a length of 800 mm, hexapods and multi-axis systems. A pump stand with a 700 l/s (N₂) turbomolecular pump and a pressure sensor allow testing down to 10⁻⁹ hPa. Bakeout temperatures up to 150 °C are possible with the integrated heating system.



► Figure 5: A large vacuum chamber. ►

"PI classifies and verifies the vacuum products by vacuum pressure measurements and RGA in the vacuum chambers."

For in-vacuum operation, tests on positioners and flanges of different sizes are available for motor current, linear encoder, limit switches, temperature sensors etc. with various feedthroughs. If interferometric measurements are required or visual observation of processes is necessary, both chambers can be equipped with inspection windows. A quadrupole mass spectrometer is available for real-time residual gas analysis (RGA) between 1 amu to 200 amu, which can be attached to both chambers.

PI classifies and verifies the vacuum products by vacuum pressure measurements and RGA in the vacuum chambers. Depending on which vacuum level needs to be reached, the chambers and positioners are baked out accordingly.

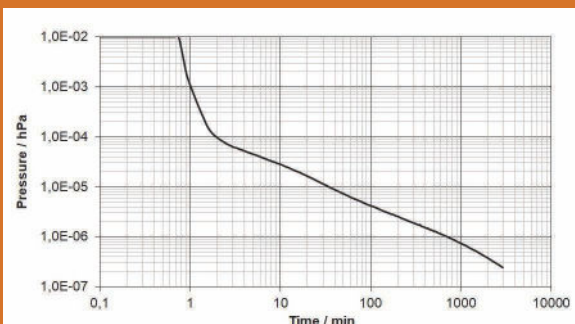
► **Figure 6:** The L-509 HV linear positioner. ►



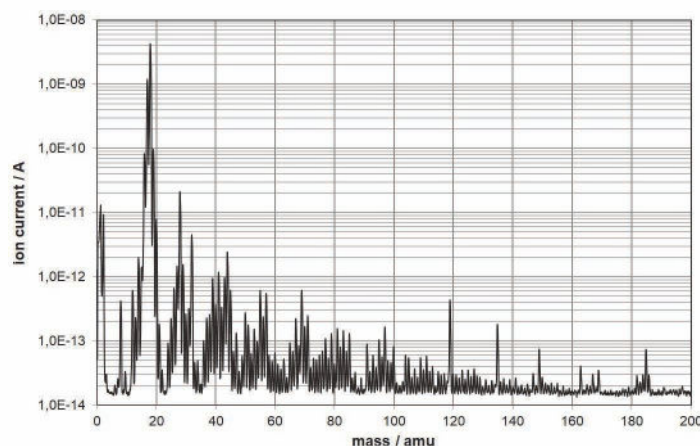
Parallel to pressure measurements, RGA scans are performed at important points during the vacuum test. Residual ionised molecules in the chamber are separated in the mass filter of the spectrometer. A downstream Faraday cup with secondary electron multiplier allows measuring with low pressure detection limits. Not only can outgassing of water, HCs or other impurities be determined but desorption processes can be traced and (virtual) leaks detected.

Standard HV test

PI's L-509 HV linear positioner, shown in figure 6, was tested inside a vacuum chamber. The results are shown in figures 7 and 8. A pump-down pressure curve for the positioner was recorded using the small chamber (10 l, 400 l/s pump). After pumping down for two days, a final pressure in the order of 10^{-7} hPa was reached.



► **Figure 7:** A pump-down pressure curve of the L-509 HV linear positioner. After pumping for two days, a final pressure in the order of 10^{-7} hPa was reached. ►



► **Figure 8:** A residual gas analysis (RGA) scan of the L-509 HV linear positioner. In addition to the strong water peak at 18 amu, a considerable contribution of HCs was observed. ►

A RGA scan was produced after 48 hours pumping time and showed a spectrum that was dominated by the water peaks (16 amu to 18 amu), followed by the nitrogen signal (28 amu). All other contributions are in an order of less than 1 percent of the water peak. Nevertheless, HC contributions were observed over the full range of measured masses and summed up to a considerable HC partial pressure.

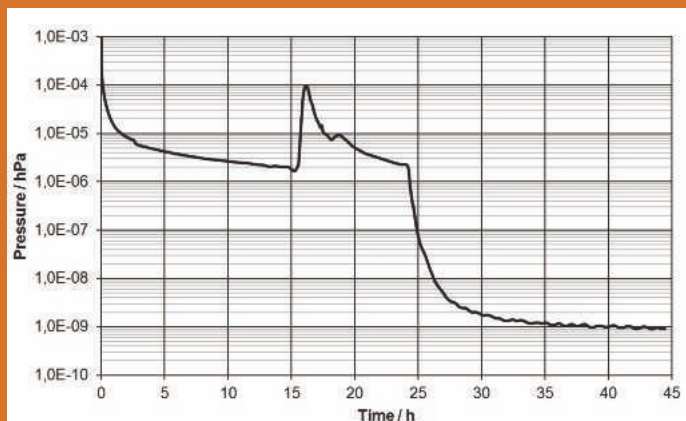
Standard UHV test

For UHV positioners, the pump-down period in the vacuum chamber is followed by a bakeout process of several hours or days, depending on the size of the positioner. The positioner is kept in thermal contact with the vacuum chamber, which is heated. The permitted bakeout temperature is between 80 and 150 °C, determined by the components the positioner is assembled from.

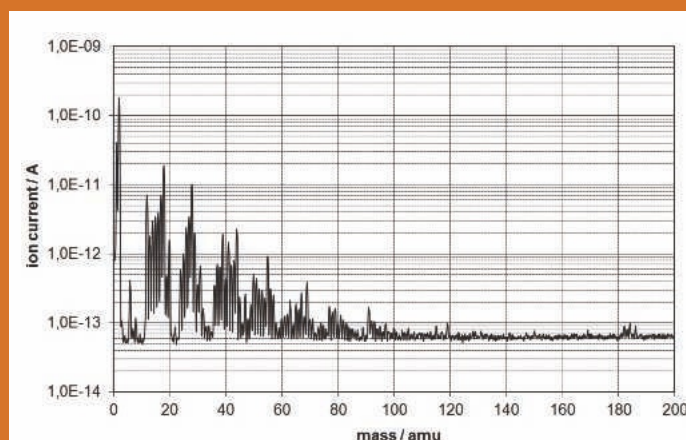
Additionally, because all vacuum motors outgas during operation and motor warmup, the motor of the positioner is heated by applying current to the motor coil in order to outgas most of the residual volatile compounds. The motor temperature should be about 40 to 50 K above the overall bakeout temperature and controlled via an integrated temperature sensor. Furthermore, the motor should be moved slowly during the whole bakeout process. In this way, homogeneous heating of the motor and therefore continuous bakeout of the volatile compounds is ensured.

PI's PLS 85 UHV linear positioner was tested in the same chamber as previously mentioned (10 l, pump 400 l/s). The results are shown in figures 9 and 10. After a pump-down sequence of 15 hours, the positioner was heated to 150 °C for eight hours.

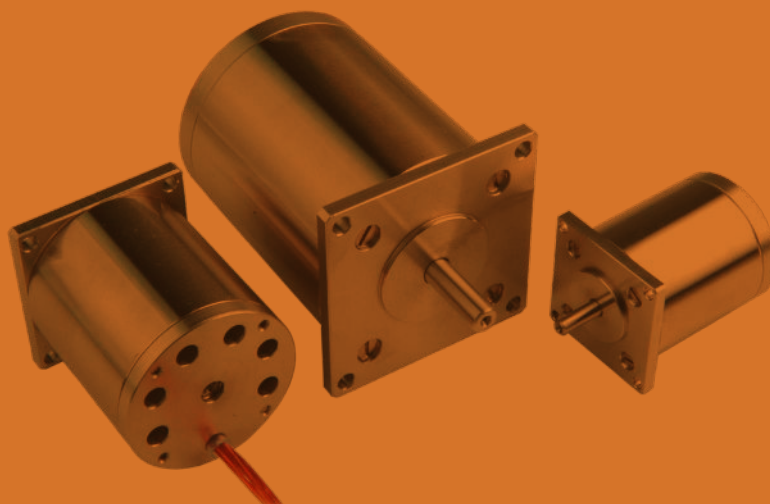
When switching the heater on, the pressure in the vacuum chamber increased by almost two orders of magnitude, and it slowly decreased during the heat-out period. After switching the heater off, the effect of bakeout could be observed. The pressure in the vacuum chamber decreased by more than three orders of magnitude, reaching pressures below 10^{-9} hPa at room temperature.



► Figure 9: A pump-down pressure curve of the PLS 85 UHV linear positioner. ►



► Figure 10: A RGA scan of the PLS 85 UHV linear positioner. Contributions of HCs above 91 amu can be neglected. The water peak at 18 amu is comparable to other contributions. ►



A RGA scan was produced after the cool-down period and showed that hydrogen (1 amu to 2 amu) dominated, which is hard for a turbo pump to remove. All other signals were at least 10 times smaller. Hydrogen is the exception and water is still the largest part of the residual gas. However, it exceeded other contributions by a factor of two instead of fifty as in the example for HV. HCs were strongly reduced but above 91 amu, and there were practically no significant values in the spectrum.

Initial startup and operation

Prior to moving the positioner into the clean area and unpacking it, the outer bag must be wiped clean and removed. Then, cleanroom gloves must be worn when opening the inner bag in the clean area where the product should be kept.

Before the desired vacuum level is reached, conditioning of the positioner in a vacuum environment must be performed depending on the vacuum class of the positioner. In the case of HV positioners, it is usually sufficient to pump for several hours or days to reach the HV vacuum level, depending on the size of the positioner and the pumping capacity of the vacuum pump. Motor bakeout, by running the motor, supports the outgassing process. HV positioners are designed for temperatures up to a maximum of 80 °C.

For UHV positioners, the pump-down period should be accompanied by heating of the positioner and the vacuum chamber, as well as additional bakeout of the motor by current feed. For temperature control of the motor, the UHV motors are equipped with a temperature sensor. During heating, the temperature of the motor should be 40 to 50 K above the positioner temperature. The heat-out process of several hours or days also depends on the size of the positioner and the capacity of the pump. A good thermal contact to the heated vacuum

"Hydrogen is the exception and water is still the largest part of the residual gas. However, it exceeded other contributions by a factor of two instead of fifty as in the example for HV."

chamber is essential for a fine bakeout result. After the vacuum-chamber has cooled down, the desired vacuum level is reached.

Conclusion

As many parameters for vacuum applications must be considered prior to selection, a thorough review of technical requirements should be performed to determine the best fitting solution.

Grease and/or oil lubrication is present in all positioners, apart from oil-free UHV-conditioned ones. Oil-free UHV vacuum conditioning is available for a selection of positioner models. Most positioners can be equipped with optional linear encoders (angular encoders for rotary positioners). Initially, a standard vacuum positioning system is selected to meet the application requirements. If this is not satisfactory, alternative products can be custom designed. ●

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