

Challenges of Cryopumping EP-Propellants in DLR's Electric Propulsion Test Facility

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Andreas Neumann¹, Klaus Hannemann²
DLR German Aerospace Center, 37073 Goettingen, Germany

Michaela Brchnelova³
Delft University of Technology, Delft, The Netherlands, and DLR, 37073 Goettingen, Germany

Abstract: The German Aerospace Center DLR operates in Goettingen the test facility STG-ET for electric space propulsion. This facility has been especially designed for electric propulsion testing with a large graphite target that reduces the impact of sputtering, and ion beam diagnostics for monitoring thruster operation. In the early times of electric space propulsion development mercury or caesium were typical propellants due to their easy cryopumping in vacuum chambers, simple handling and low ionization energies. Thruster erosion, metal deposition on chamber walls and on other devices inside chambers, and major health and safety issues forced a switch of propellant to safer noble gases. Electric space propulsion is on the rise over the last few decades, and the most common propellant for mN electric thrusters actually is the noble gas xenon. Therefore, at the STG-ET cryopumps with high pumping speed for xenon are installed. Xenon is the favorite propellant, but this gas is rare and expensive. The rapid market growth triggered activities for studying alternative propellants. This paper describes the pumping system of STG-ET and pumping speed measurements for xenon, krypton and argon. Another aspect of operation and pumping speed measurement is the usage of precise pressure transducers. These devices are often treated as robust and accurate, but hands-on experience often draws a different picture. We found a rather short lifetime if nominal accuracy is expected. Furthermore, one must be aware of gas composition dependence of measurements.

I. Nomenclature

<i>sccm</i>	=	Standard cubic centimeters per minute
<i>DLR</i>	=	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
ε	=	emissivity, here: optical property in the infrared
<i>EP</i>	=	electric space propulsion
$\dot{m}$	=	propellant flow rate, mbar l/s
p	=	pressure, mbar
p_n	=	pressure measured with sensor number n , mbar
S	=	pumping speed, l/s
<i>STG-ET</i>	=	Simulationsanlage Treibstrahlen Göttingen – Elektrische Triebwerke

¹ Head of Electric Propulsion Test Facility, Institute of Aerodynamics and Flow Technology, DLR, email: a.neumann@dlr.de

² Head of Spacecraft Department, Institute of Aerodynamics and Flow Technology, DLR, email: klaus.hannemann@dlr.de

³ Master student, Delft University of Technology, Delft, The Netherlands, and DLR, email: michaela.brchnelova@dlr.de

II. Introduction

In the early times of electric space propulsion mercury and caesium were typical propellants due to easy cryopumping in vacuum chambers, simple handling because of being liquid or solid, and quite low ionization energies. Thruster erosion, metal deposition on chamber walls and on other devices inside chambers with the issue of dangerous chamber venting and major health and safety issues forced a switch of propellant to less harmful



Figure 1. Open DLR STG-ET facility with view onto cryopumps and beam dump targets.

propellants, e.g. noble gases. As can be seen with the many satellites in production and in orbit, electric space propulsion is on the rise over the last decades¹. The majority of high specific impulse thrusters are Hall effect devices, and for these the most common propellant actually is xenon.

On-ground qualification of thrusters requires large vacuum chambers and long duration tests. The German Aerospace Center DLR operates the test facility STG-ET for electric space propulsion^{2 3} at its site in Goettingen, Germany. This facility has been especially

designed for electric space propulsion testing. A large graphite target reduces the impact of sputtering, and ion beam diagnostics is used for monitoring thruster operation. Its vacuum chamber measures 12.2 m in length and 5 m in diameter.

Figure 1 gives a view into the open chamber. Cryopumps and target are visible. Xenon is the standard propellant for satellites, and is mainly used in the STG-ET facility, but the rapid market growth triggered activities for studying alternative propellants⁴. This paper describes the pumping system of STG-ET, shows measurements of pumping speed, and lists a few challenges when xenon has to be pumped. Pumping speed measurements took also place for krypton and argon.



Figure 2. Single stage cryopump composed of cold head, vacuum chamber flange, and cold plate⁷.

III. Cryopumping Basics

Electric space propulsion applies to a power range from a few Watts up to several kilowatts, left aside the experimental thrusters going up to hundreds of kilowatts. This paper deals with thrusters in the kW range that use ions or plasma in order to achieve high specific impulse. For those ground testing needs to be done in vacuum chambers. The pumping system of such a facility must be able to cope with thruster gas flow in the order of 1-20mg/s for typical thrusters up to 5kW, depending on thruster technology (Hall effect, gridded ion thruster).

Nowadays, xenon is the preferred propellant for the mentioned thrusters. Under high vacuum conditions with molecular flow, pumping speed scales with pump aperture area, and the preferred way of trapping gas is to use cryo trapping on large cold surfaces⁵. The pumping speed for xenon is of the order of a few $l/(s \cdot cm^2)$ for cryopumps⁶, and this value is similar to

turbo molecular pumps. Concerning infrastructure cost and effort it is much simpler to build a large cold surface of m^2 size compared to a $1m^2$ entry area based on turbo pumps. This explains why cryopumps are usually the preferred way to go.

Commercially available cryopumps come in different configurations. The standard type has a two-stage head with baffles, and is contained in a vessel of standard diameters (e.g. up to 500mm). The pumps are meant primarily for air pumping (oxygen, nitrogen). The pumping speed of such a design is much lower for xenon than for air.

For EP application with xenon as propellant single stage cryo panel pumps are more common. In this configuration a copper plate is directly attached to the cold head, and this assembly protrudes into the vacuum chamber (see Figure 2). If the plate temperature is below 55-60K in the typical EP operating pressure range of 10^{-4} - 10^{-5} mbar (see phase diagram in Figure 3, adapted from Ref.⁷), xenon freezes at the plate surfaces and the pumping process takes place. It should be noted that if the plate temperature stays above approximately 35K the cryopump will not pump air constituents like oxygen, nitrogen, or argon. Carbon dioxide and water will of course be pumped. Especially condensing (cryopumping) water is an issue, as it starts to freeze out at temperatures below 200K. The main issue is the optical property of the ice, the absorption of thermal radiation or emissivity ϵ . The emissivity/absorptivity of icy water condensate is quite high, and close to unity. As a consequence the infrared radiation inside a vacuum chamber is well absorbed and the heat load on a water-ice covered pumping surface is high, leading to a rise in temperature. This effect may be reduced by taking all measures to lower the water vapor content in the residual atmosphere and adsorbed water on chamber walls.

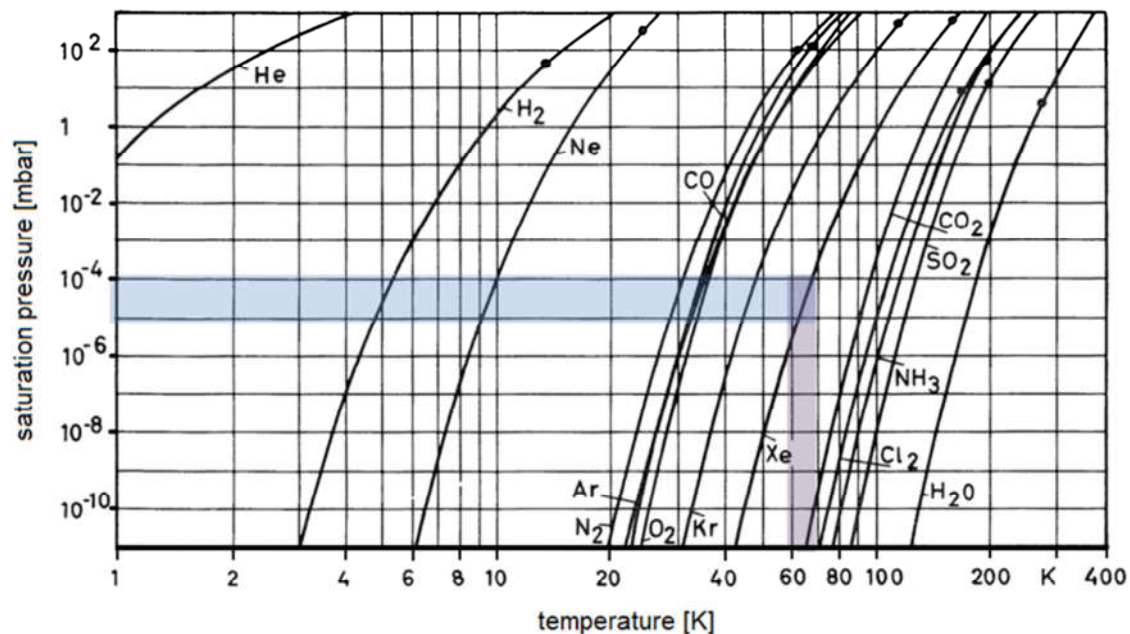


Figure 3. Saturation pressures of several gases important to vacuum technology and electric space propulsion (adapted from Ref⁶).

IV. DLR Electric Propulsion Test Facility

The STG-ET is one of the largest EP vacuum test chambers. Figure 4 shows a schematic of the pumping system of DLR's facility³. A dedicated roughing pump system (rotating vane and Roots pump No. 2) generates in the first place the necessary vacuum level for a switch-on of turbomolecular pumps. These turbopumps have their own backing pump stand (No. 1).

Under thruster operation up to 18 cryogenic pumps remove the xenon gas. As these pumps do not have cold plates of equal size, measurement of the pumping speed was mandatory. Such a determination implies accurate pressure measurement, and therefore the next section explains pumping speed determination in conjunction with pressure measurement. After that, results of pumping tests for xenon, krypton, and argon will be given.

V. Measuring Chamber Pressure

For measuring pressure in vacuum chambers different methods may be used, depending on pressure range (Piezoelectric, Pirani, cold cathode, hot cathode, etc.). In case of pressure measurement for EP thruster testing the boundary conditions can be listed as:

- Typical background pressure: $<10^{-6}$ mbar
- Typical thruster operation pressure: 10^{-4} - 10^{-5} mbar
- Directional ion and plasma beams inside vacuum chamber
- Thruster beam produces heavy sputtering, often chamber wall atoms plus carbon from protective cladding, and this interacts with delicate equipment
- Operational gas is commonly xenon for many thruster types

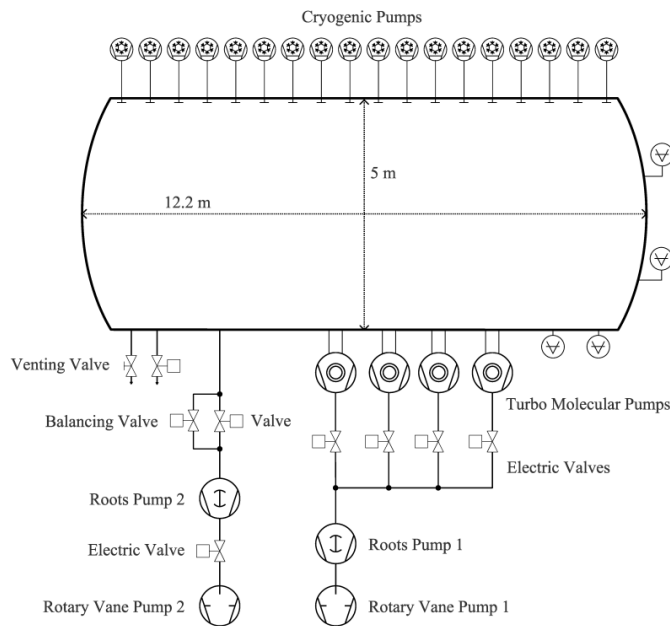


Figure 4. Schematic diagram of pumping systems at DLR STG-ET facility.

At the STG-ET we often use dual gauges, either Pirani/Bayard-Alpert or Pirani/cold cathode. It must be said that both types of instruments work in the above mentioned pressure ranges, but have their specific pros and cons. It should be noted that, depending on pressure measurement technology, calibration factors have to be used for conversion of pressure readings to true pressure, due to dependency on gas species. In Table 1 conversion factors are listed for several gases for Bayard-Alpert sensor technology which is calibrated for nitrogen. One can see that best practice literature (e.g. Ref. ⁹) differs from factors given by manufactures (e.g.

company Pfeiffer Vacuum, Asslar, Germany). In the following text the conversion factors of Ref. ⁹ are used.

Table 1

Gas	Pfeiffer Vacuum pressure transducer manual	Dankanich et al. ⁹
He	5.93	
H ₂	2.39	2.17
Ar	0.80	0.755
CO ₂	0.74	
Ne	3.50	
Kr	0.60	0.515
Xe	0.41	0.348

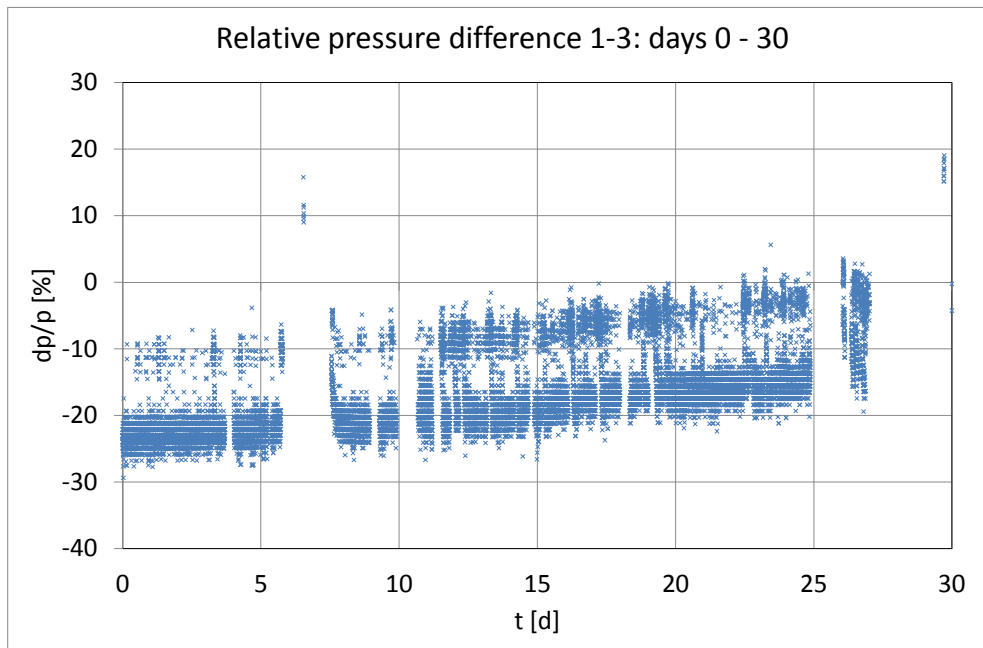


Figure 5. Development over time of pressure measurement in the STG-ET with different gauges (first period, see text).

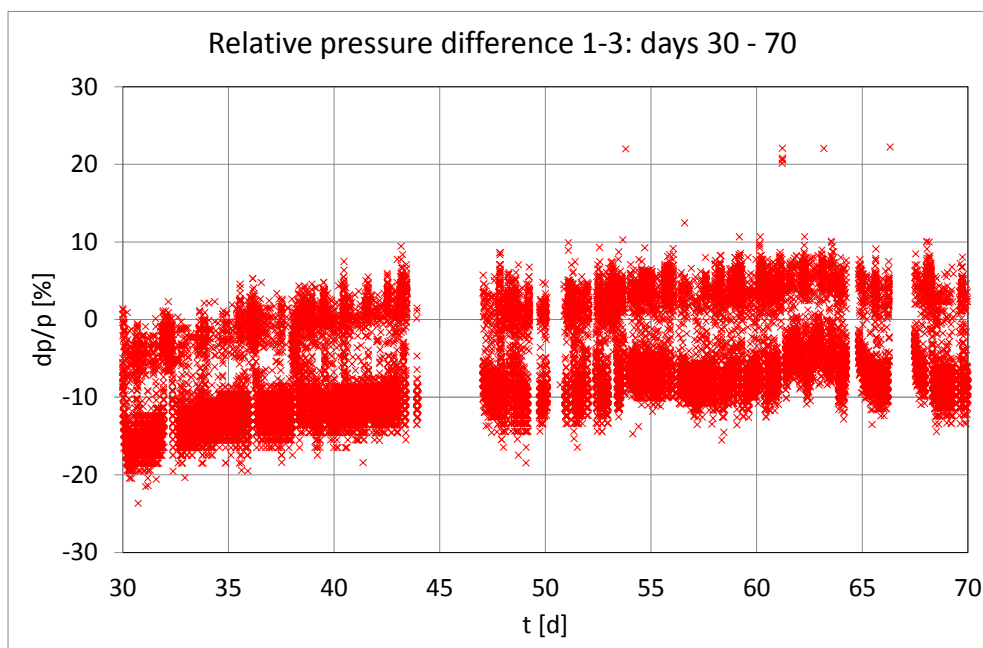


Figure 6. Development over time of pressure measurement in the STG-ET with different gauges (second period, see text).

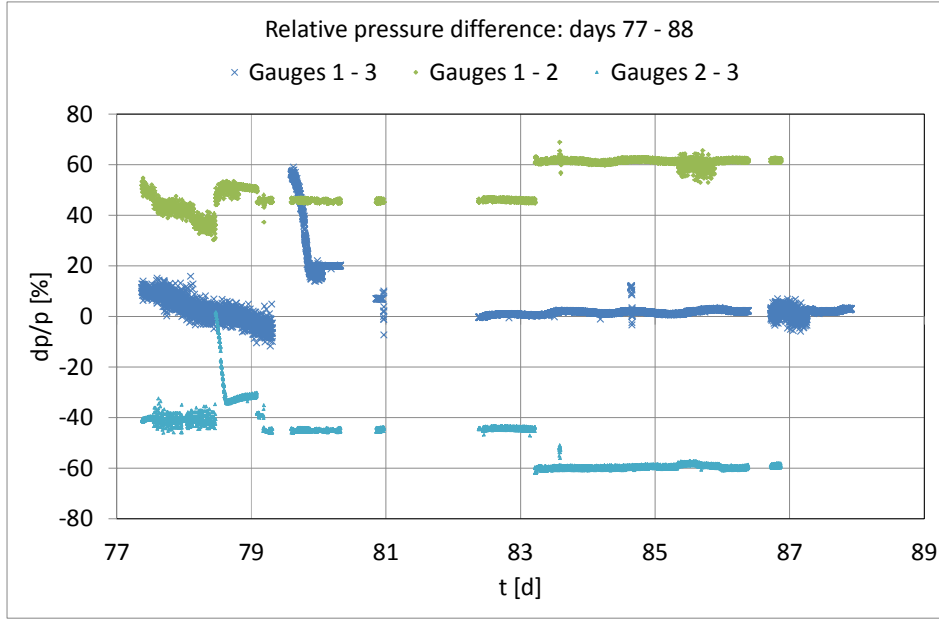


Figure 7. Development over time of pressure measurement in the STG-ET with different gauges (third period, see text).

In any case, the measurement accuracy decreases during EP testing on a timescale of weeks or months, depending on instrument mounting position and thruster beam geometry. We observed that the measurement accuracy of for example Bayard-Alpert instruments was off by easily by 10-50% compared to a reference instrument (reference instrument only operated in a quality calibration test stand, e.g. a Pfeiffer Vacuum HiCube). Such deterioration can happen after a few months in EP testing. Unfortunately an instrument off specs cannot be re-calibrated and often has to be dumped. Another observation is that different instruments show different error trends over time. This is illustrated in Figure 5, Figure 6, and Figure 7, which show the respective difference between two out of three sensors over a time interval of about 90 days. The relation used in the figures is:

$$\frac{dp}{p} = \frac{(p_n - p_m)}{\frac{1}{2}(p_n + p_m)} \quad (1)$$

In the first two plots sensor no.2 was not available. It can be seen that the difference between two sensors may easily change by 10% or more over a few tens of days.

VI. Determining Pumping Speed

Extracting pumping speed S from measurements requires accurate throughput measurement $\dot{m}$ (for compatibility we follow the not very common nomenclature from Ref. ⁹ for $\dot{m}$ not being kg/s but mbar-l/s) and pressure measurement p . The equation is (see Ref. ⁹):

$$S(\text{gas}, e. g. Xe) = \frac{\dot{m}}{p - p_{base}} \quad (2)$$

p_{base} is the background pressure without propellant flow. As stated in the preceding section pressure measurement is critical and easily off by tens of percent. Such errors propagate to determination of pumping speed.

Pumping tests were carried out with freshly regenerated clean cryopumps. Doing so, the cold plates could cool down to lowest possible temperatures that can be reached with those cold heads. The temperatures may go down into the range of 17-23K. At these temperatures trapping of krypton and argon is possible. If temperatures increase beyond about 30K, argon will not be trapped anymore, and the same applies to krypton above 40K (see Figure 3). This should be kept in mind when interpreting the pumping results shown in the next sections. As soon as gas is adsorbed, the plate emissivity will increase which leads to an increase in temperature.

The gas inlet for the pumping tests was a single pipe supplying cold gas into the vacuum chamber. Using a real EP thruster may give somewhat different results. One reason for that is the more directional flow, another is the use of an ionized gas for propulsion which may interfere with the pressure sensor that uses an ionization method.

VII. Pumping Speed for Noble Gases

As mentioned above, the most relevant gas for electric propulsion (Hall-effect, HEMPT, or gridded ion thrusters) nowadays is xenon. Therefore, the first pumping speed measurement presented here is the one for xenon.

Figure 8 shows the chamber pressure development for xenon cold gas flows of 10, 30, 50, and 100sccm. The pressure shown is for nitrogen pressure gauge calibration, i.e. not corrected for xenon. Additionally, one of the cryopump cold plate temperatures is shown in the diagram. During the measurement, its temperature stayed in the band of 18-19K. In order to get stable conditions the gas flow at each step was left on for about 30 minutes. The pumping speed was calculated using Eq. (2), and applying the calibration factor to the pressure measurement for time periods with gas flow switched on. The resulting xenon pumping speed is:

$$S(Xe) = 276000 \text{ l/s} \quad (3)$$

Figure 9 shows the pumping test with krypton cold gas feeding (flow: 10, 30, 50, and 100sccm). Using the same processing as shown above for xenon the krypton pumping speed is:

$$S(Kr) = 360000 \text{ l/s} \quad (4)$$

Argon has the lowest condensation temperature of the here mentioned gases, and the cryopumps are at their limit when pumping argon. Figure 10 shows the pumping test with argon cold gas feeding (flow: 10, 30, 50, and 100sccm). With the same processing as shown above for xenon, the argon pumping speed can be deduced as:

$$S(Ar) = 452000 \text{ l/s} \quad (5)$$

Of course, the lower the condensation temperature of a gas is, the shorter the time span with the given pumping speed will be. This is due to the fact that the pump will warm up during operation and condensation of the working gas will come to an end.

The physics of condensation processes at the cold plate surface is complex and depends on many parameters. The condensation happens with different gases at the same time, builds different ice structures, and may depend on the surface microstructure and cleanliness of the cold plate as well. The literature about this subject is also not very abundant, and designing a pump is not straightforward.

VIII. Cryopump Challenges

Based on the theoretical assumptions operating a cryopump should be quite simple. The cold plate should have a highly reflective coating for rejecting the infrared radiation originating from the environment, e.g. the vacuum chamber, and additionally some multilayer insulation for areas not supposed to act as gas pumping surfaces. The real picture is much more complex, especially in the field of electrical thruster testing (which is not done in ultrahigh vacuum). Condensed gases will remarkably change the optical properties.

For example, water is trapped as ice which has an infrared absorptivity of close to unity. Water ice should therefore be avoided, but this is often not possible due to leak gas flow from the environment or porous material like carbon sheets absorbing water. Condensates of other gases (noble gases for EP applications) are often not that critical, but may still increase the absorption factor up to 0.3-0.6. If the original cold plate surface is nickel-

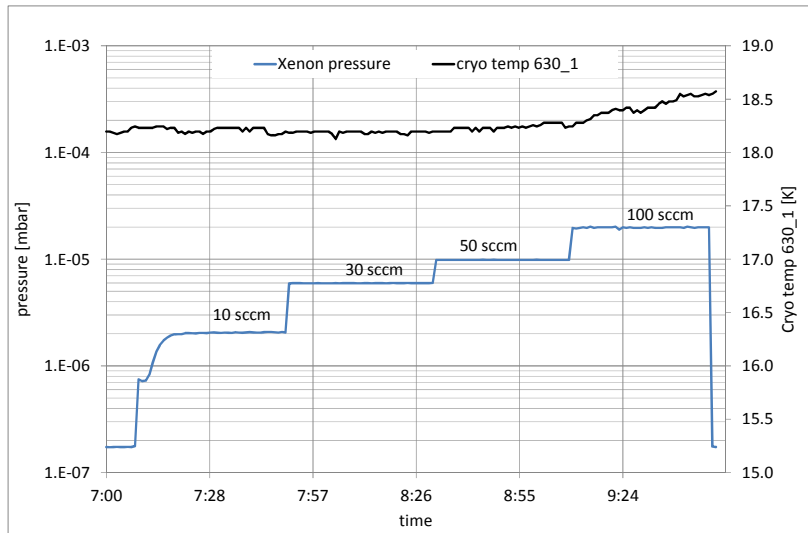


Figure 8. Cold gas pumping test on xenon. The pressure is nitrogen calibrated and not corrected for xenon.

plated, as it is often done, the genuine infrared absorptivity is well below 0.1.

Therefore, condensates will increase the heat load on a cold plate easily by factors of 2 to more than 10 compared to initial clean conditions. As the cryopump can only dump a certain amount of heat, its temperature will increase. As mentioned, this will be extreme in case of high water content, and the operation time before regeneration will be much shorter. The vacuum chamber pump down must therefore follow a procedure that reduces the residual water as much as possible (long pumping times with turbo molecular pumps, heating or baking components and walls, etc.).

Running electric space propulsion thrusters with ion beam in vacuum chambers will produce sputtering and deposition of many different materials onto components in the chamber, and also on the cryopump heads.

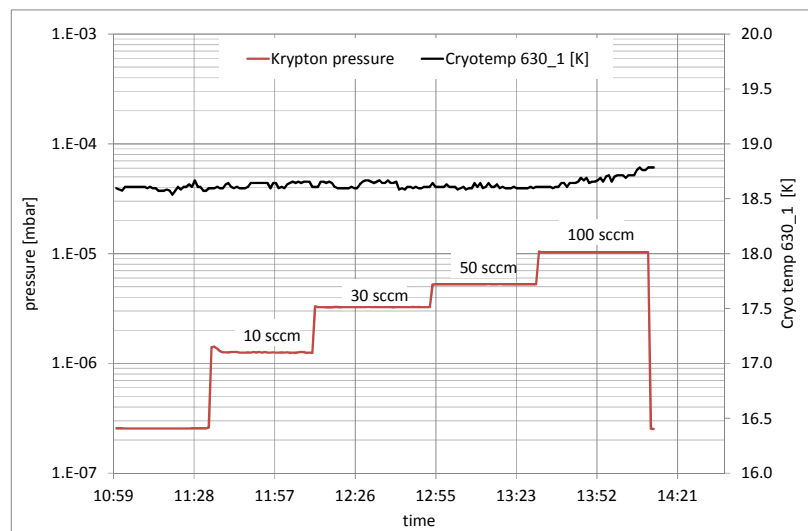


Figure 9. Cold gas pumping test on krypton.

These deposits can be solid and will not vanish during regeneration of cryopumps. As an example Figure 11 shows a cryopump cold plate after several weeks of thruster testing inside the vacuum chamber. Some of the shown

deposits can easily be removed by wiping off with a cloth or by suction with a vacuum cleaner. Off course, this action can only take place if the vacuum chamber is open, but opening is not an option during long-term testing. Sometimes the deposits on the cold plate cannot easily be removed and appear more as a surface coating. Such a feature can be seen in Figure 12.

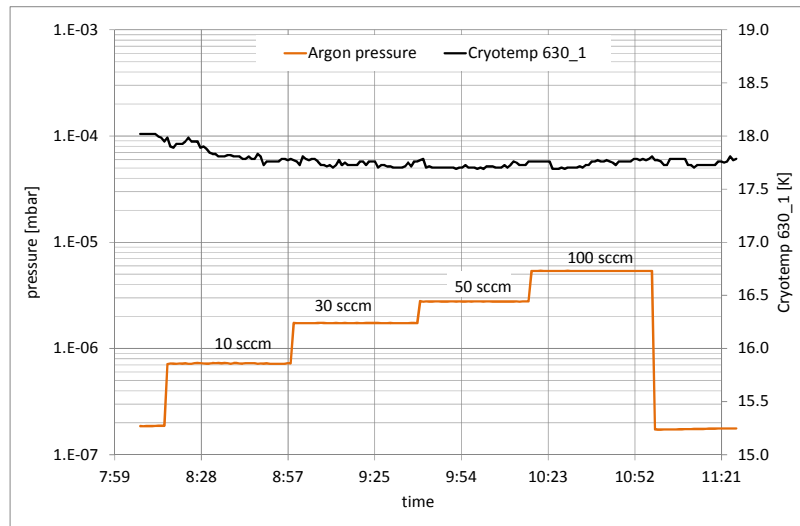


Figure 10. Cold gas pumping test on argon.

An optimization of a cryopump layout for EP testing must take into account the above mentioned effects. Very clean and low reflectivity cold plates will not last long. If a vacuum chamber must not be opened often, regeneration will not lead to a clean surface of cold plates because solid deposits remain sticking on them. The next cooling cycle will start with cold plates having a noticeably higher infrared absorption. Such a cycle may continue and performance will decrease.

Another issue is condensate detachment. If the gas condensate load on a cold plate has grown to a certain thickness and the bond onto the cold plate is poor, then it can happen that part of the condensate detaches and either slides from the plate or directly falls onto the warm chamber wall which typically is at room temperature. This triggers rapid evaporation and causes a peak in chamber pressure, and probably an interruption of an ongoing test. In order to give a rough number for DLR's facility STG-ET evacuated at 10^{-6} mbar, evaporating an ice sphere of 4mm radius may roughly double the chamber pressure. Ice detachment was seen a few times at the STG-ET, and also reported by other EP test facility staff. Unfortunately the observation is difficult as the view into an operating vacuum test facility is commonly poor, and the detachment process does not happen often and only sporadically. Furthermore, these processes are not investigated in the scientific literature. The ongoing R&D work at DLR's STG-ET will investigate these phenomena in more detail.



Figure 11. Cryopump cold plate after several weeks of thruster testing. Some of the deposits can easily be removed by wiping off with a cloth or with suction with a vacuum cleaner.

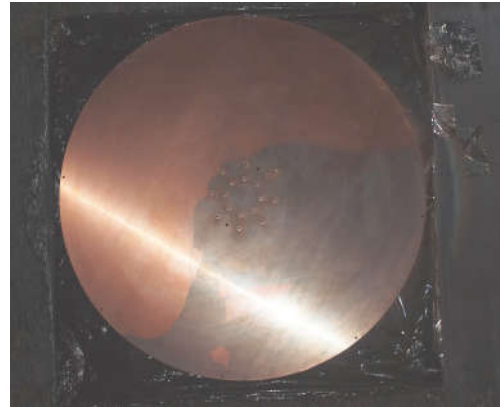


Figure 12. Cryopump cold plate after cleaning with a vacuum cleaner. Some permanent surface coating is still left on.

IX. Conclusion and Outlook

The STG-ET at DLR is a large electric propulsion test facility with special design features for mitigating challenges occurring during ion and plasma thruster testing. A high pumping speed is required, and chamber and insets have to be protected with a low sputtering coefficient material (e.g. carbon). In this paper we presented the pumping speed measurements for typical gases. At STG-ET four turbomolecular pumps and 18 cryopumps are installed.

The pumping speed measurements gave the following baseline values for noble gas propellants:

- 276,000 l/s for xenon
- 360,000 l/s for krypton
- 452,000 l/s for argon.

We have listed a few remarks when using cryopumps. It has been shown that pressure measurement is not straightforward, and has a big impact test boundary conditions and on pumping speed determination. Concerning accuracy of pressure measurement we have to face absolute errors of easily 10% or more, and a worsening over a timescale of months.

Within the frame of an optimization of pumping at the STG-ET we are developing numerical models of cryopumps to get a handle on several of the described effects and being able to check other advanced configurations or cold plate geometries for future hardware.

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