Titanium Sublimation Pumping Considerations for High-Power Electric Propulsion Testing

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Titanium sublimation pumps (TSPs) are a proven and effective high vacuum pumping scheme for chemically reactive gases such as those containing hydrogen, nitrogen, oxygen, and carbon. This work outlines the requirements and considerations for TSP adoption for high-power molecular-propellant electric propulsion (EP) testing. The results presented here indicate that the conventional approach of employing hot filaments to sublimate the titanium does not scale effectively for the high pumping speeds required for EP test facilities. As an alternative, this work describes two prototype systems designed to achieve effective pump speeds greater than 1 million liters per second for alternative gases including combustion products, air constituents, and notably hydrogen gas. This pumping speed is targeted to support testing of next-generation EP thrusters operating at flow rates near= two standard liters per second on alternative propellants.

I. Introduction

Electric propulsion (EP) systems predominantly flown use noble gas propellants such as xenon and krypton due to their ease of ionization and non-reactivity, therefore the vast majority of research on and facilities for EP have focused on systems that operate on these gasses.[1–3] However, there is a sizable and growing interest in alternative propellants for next-generation EP systems. Alternative propellant choices are primarily driven by the need for both "multi-mode" propulsion[4–6] where energetic propellant from a chemical rocket system or it's byproducts are fed to an EP system, and air-breathing propulsion where atmospheric gasses are collected in-situ for drag makeup in very low earth orbit.[7,8] As a result, the relevant gas species are typically compounds of hydrogen, carbon, oxygen, and nitrogen including H_2, O_2, N_2, N, O, CO_2, and CO. This shift presents a significant technical challenge: the development of testing infrastructure capable of simulating a space-like environment for thrusters operating on these new propellants.

Modern EP test facilities mainly employ cryogenic pump systems which have been optimized for the traditional propellants, which are heavier, exhibit lower vapor pressures at higher temperatures, and are therefore easier to pump. With alternative propellants these existing pumping systems may not achieve adequate pumping speeds. To address this problem, the number or surface area of pumps could be increased, albeit this can become prohibitive with limited area within vacuum facilities. Yet beyond this concern, prevailing pumping strategies may be unable to safely evacuate more reactive species like oxygen or may be entirely ineffective on certain light propellants like hydrogen. While facilities exist that can adequately process alternative propellants, they are limited in either the types of gases they can process or their effective pumping speeds.

One successful technique to achieve the required vacuum level for testing EP systems using alternative propellants is the titanium sublimation pump (TSP). TSPs produce a clean film of titanium which actively pumps gases through chemical sequestration and absoprtion (gettering). As a result, these systems have

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not been employed in EP testing—to our knowledge—in large part because they cannot pump non-reactive noble gasses. However, TSPs have a proven history as a pumping scheme for ultra-high vacuum systems ($< 10^{-11}$ Torr),[9,10] particularly where out-gassed hydrogen poses a significant challenge for other pump systems. In fact, these systems are commercially available and have been scaled up for use high energy density plasma research and space simulators.[10–12] Despite their effectiveness however, even large existing TSPs are incapable of processing the gas loads demanded by next-generation electric propulsion systems, which can reach up to two standard liters per minute (slm). Consequently, novel approaches are therefore required to adapt TSPs for use in high-power EP testing.

Given the growing necessity for research facilities which can test molecular-propellant electric thrusters and the inadequacy of existing vacuum pumping systems, this work aims to capture the requirements and considerations for the use of TSPs in high-power EP testing. Furthermore, we outline two prototype systems designed to achieve effective pumping speeds greater than one million liters per second (ML/s) for alternative gases. To this end, this paper is organized as follows: Section II discusses the challenges associated with pumping alternative propellants and further motivates the pursuit of high-throughput TSPs. Section III provides a primer on the principles of titanium sublimation pumping and a review of existing concepts. Section IV presents a scaling analysis to highlight the challenges of employing existing techniques for EP testing. Section V details the designs of our two sub-scale prototype systems, which we anticipate will effectively scale to meet our overall needs. Finally, Section VI summarizes our findings.

II. Challenges for Pumping Alternative Propellants

We focus in this section on the challenges associated with testing propulsion systems that employ alternative propellants. We first discuss the need for high pumping speeds for EP testing and the resulting requirements for testing facilities. We then discuss issues with existing pumping techniques and show the present capability gaps in test facilities for alternative gases.

A. Overview of pumping speed requirements for EP testing

EP testing must be conducted under sufficiently high vacuum conditions to ensure the tests accurately represent space-like environments in terms of thruster performance.[13] Typically, this is achieved by operating thrusters in large-scale (> 3 m) test facilities equipped with active pumping systems. However, realizing true space-like vacuum levels (10^{-12} Torr) is not practically feasible, resulting in a finite background pressure within test chambers. This residual pressure can affect test results by altering plasma discharge locations within thrusters, permitting neutral ingestion that artificially increases the propellant flow rate, and increasing the prevalence of charge exchange reactions that can lead to errors in plasma diagnostic measurements (see Refs. 14–19). While quantifying the impacts of these facility effects and predicting thruster performance in orbit are active areas of research, according to a recent NASA specification, representative EP testing requires a vacuum level of less than 10^{-5} Torr. In this paper, we adopt this specification as a baseline standard to enforce requirements for various pumping systems.

In practice, the key challenge for all EP test facilities is to maintain this standard during thruster operation by removing the injected thruster propellant with sufficient pumping speed. Under the assumptions that the thruster flow rate dominates over any leak-rate or out-gassing, and that the operating pressure is much larger than the base pressure of the chamber, we can express the operating pressure in a vacuum facility as

$$p[\mathrm{Torr}] = (1.27 \times 10^{-2}) \frac{Q}{S_{\mathrm{pump}}}, \tag{1}$$

where Q is the propellant flow rate to the thruster in standard cubic centimeters per minute (sccm), and S_{pump} is the volumetric speed of the pump in liters per second (l/s).[13] From this relation it is clear that as the pumping speed is increased the ambient pressure in the facility is decreased.

To this point, Fig. 1 shows facility pressures for standard (100-200 sccm) and anticipated next-generation (2000 sccm or 2 slm) flow rates for EP thrusters as a function of pumping speed. We also show on this graph the 10^{-5} Torr standard as a horizontal line. As can be seen from this result, facility pumping speeds must exceed 250 kl/s to maintain this pressure standard at flow rates of 200 sccm. For next-generation systems, pumping speeds may need to be well above 2 Ml/s.

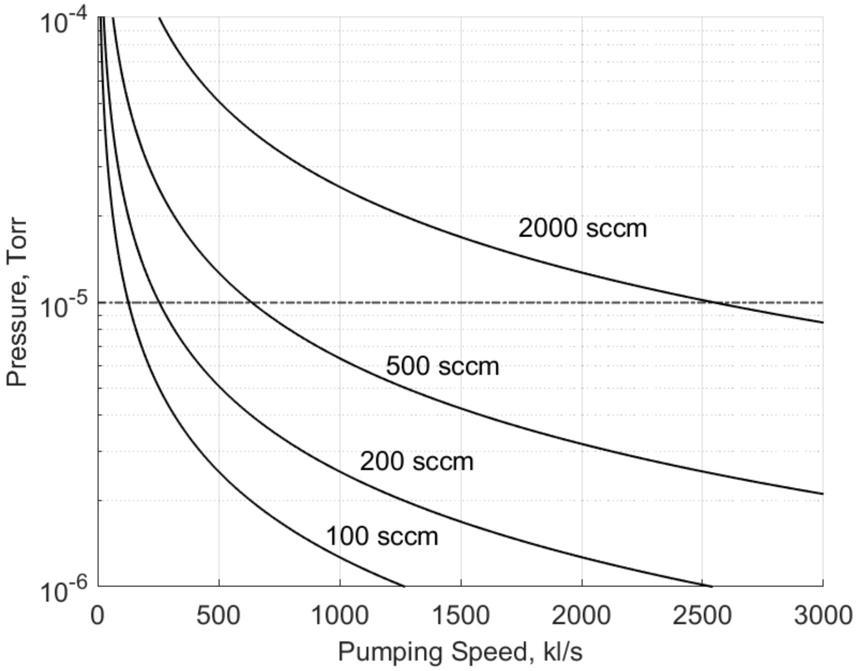

Figure 1: Background pressure as function of pumping speed for different thruster flow rates. Horizontal line indicates the 10^{-5} Torr standard for testing to be representative of space.

B. Limitations of existing pumping systems for alternative propellants

The major technical obstacle to achieve acceptable background pressures for EP testing is that the gases exist in the molecular limit. Positive displacement pumping schemes do not work, and it instead is necessary to employ alternative high-vacuum pumping strategies.[20] To this end, most of the EP facility development in the past 25 years has focused on optimizing pumping on the traditional EP propellants of xenon and krypton. This has led to the widespread adoption in the field of cryopumping at soft cryogenic temperatures (∼40 K). The most capable government and industry facilities with cryopumps[21–29] subsequently have achieved pumping speeds on xenon ranging from 200 kl/s – 2 Ml/s while the most powerful academic chambers have demonstrated 300-600 kl/s. With that said, cryopumps optimized for xenon do not function on most of the lighter species produced by thrusters operated on alternative gases—H_2, O_2, N_2, N, O, CO_2, and CO—because they exhibit substantial vapor pressures at soft cryogenic temperatures.[30] As a result, some of the most powerful EP facilities are not capable of supporting testing on these propellants.

As an alternative, there are some pumping schemes in the EP field aside from pure cryopumping that can process alternative propellants. However, a common limiting factor for these strategies is the size and/or number of pumps to achieve acceptable background pressures. To highlight this, we show in Table 1 representative specifications for the three most common methods used in EP that can process alternative propellants: hard cryogenic temperature cryopumps (< 20 K) with cryoadsorbing traps, diffusion pumps, and turbopumps. To compare these methods, we list three performance metrics: the typical dimensions of each pump type, the area-specific pumping capacity (pumping speed divided by the area of the pump facing the chamber), and the number of pumps required to maintain 10^{-5} Torr while pumping on 200 sccm of H_2 and N_2 respectively (neglecting conductance losses).

As can be seen from this comparison, the overall pumping speed—typically 1-2 kl/s—for individual turbopumps is small when contrasted to the other two pumping systems. The number of pumps required to achieve 250 kl/s is thus impractical for a real system. On the other hand, while both the cryopump and diffusion pumps have higher pumping speeds per device, the systems have larger footprints—on the order of 1 m^3. For most moderately sized facilities, there is insufficient space to accommodate the number of pumps necessary to achieve acceptable background pressures.

We show in Table 2 the pumping performance of several test facilities where we were able to infer

Table 1: Typical performance metrics for common EP vacuum pumping methods

Pump Type	Example	Dimensions	Pumping Speed (kl/s)		Area Specific Pumping Speed (l/s/cm^2)		Pumps to achieve 10^{-5} Torr on 200 sccm	
			H_2	N_2	H_2	N_2	H_2	N_2
Cryopump with trap	PHPK TM1200i	1.3 m × 1.3 m × 1 m	33	75	1.8	4.1	11	5
Diffusion	Agilent NHS 323	0.6 m (OD) × 1.8 m	35	28	4.4	3.5	10	13
Large Turbopump	Shimazdu TMP-V2304LM	0.5 m (OD) × 0.5 m	1.1	1.1	2.8	2.8	180	180

measured (as opposed to theoretical) pumping speeds from reported tests on alternative propellants. As a result of volumetric-limitations of the number of pumps, even the most powerful of these facilities is only marginally capable of testing thrusters at 150 sccm at an acceptable pressure level (Fig. 1). This facility, LVTF at Michigan, can achieve this speed by virtue of its size. With a 6 m × 9 m internal volume, it houses 13 TM1200i pumps—cryopumps with activated charcoal traps that can pump lighter gases. Even with this number of pumps, however, LVTF is still limited in the flow rates it can accommodate. In practice, most non-government EP test facilities are smaller than 6 m × 9 m and thus are not able to support the large number of conventional high-vacuum pumps required necessary for sufficient pumping on alternative gases.

Table 2: Demonstrated pumping capabilities on alternative gases for non-government facilities reported or inferred from published data or personal correspondence.

Facility	Pumping Scheme	Pumping Speed
Stanford Plasma Physics Lab.[31]	Cryopumps	6.7 kl/s on N_2
Busek Co. Inc.[32]	Cryo and diffusion	10-40 kl/s on N_2
University of Michigan's LVTF	Cryopumps with charcoal getters	200 kl/s on H_2, 350 kl/s on N_2
Georgia Tech's VTF-1 [a]	Diffusion pump	127 kl/s on N_2

This problem of volumetric constraint is further exacerbated at higher flow rates. Indeed, to achieve the targeted pumping speeds for next generation systems (∼2 Ml/s) with conventional pumping schemes, it would be necessary to employ up to 60 diffusion or cryopumps. Procuring this number of pumps and building facilities to accommodate them would be prohibitively expensive in time and resources. This ultimately invites the question as to whether there are alternative pumping strategies that may yield higher pumping yields with limited volume/surface area. We discuss our proposed solution to this problem in the next section.

III. Explanation of Titanium Pumping

The previous section illustrated that conventional methods for pumping standard EP gases are not effective for alternative propellants. The dimensions and capacity of pumps are significant constraints. Nevertheless, the reactivity of the products of alternative propellants opens up new possibilities for pumping techniques. There are well-known methods for removing reactive gases, particularly titanium sublimation pumps (TSPs), which have been extensively used in areas where pumping reactive gases is prevalent (see Refs. 11,12). Examples of such applications include materials processing, high energy density plasma experiments, and large-scale space simulators exceeding six meters.[10] In this section we describe both the principles of

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[a] Personal correspondence from Dr. D. Lev of Georgia Tech

operation for the TSP and the implementation of contemporary TSP systems.

A. Principles of Operation

We show in Fig. 2 the principle operating mechanism of TSPs. In this system a layer of clean titanium is deposited on a (typically cooled) metallic substrate. Once deposited on the substrate the titanium begins to chemically interact with any reactive species within the facility. For the most reactive species such as O_2, N_2, CO, and CO_2 the incident molecules readily react with the titanium surface and form titanium oxides, nitrites, and carbides thus sequestering the gases. On the other hand, hydrogen does not directly form compounds with the titanium surface. Instead, H_2 dissociates on the surface and diffuses into the titanium layer. This process is similar for the hydrogen in H_2O as well, however in this case the oxygen is removed to chemically form TiO on the surface.

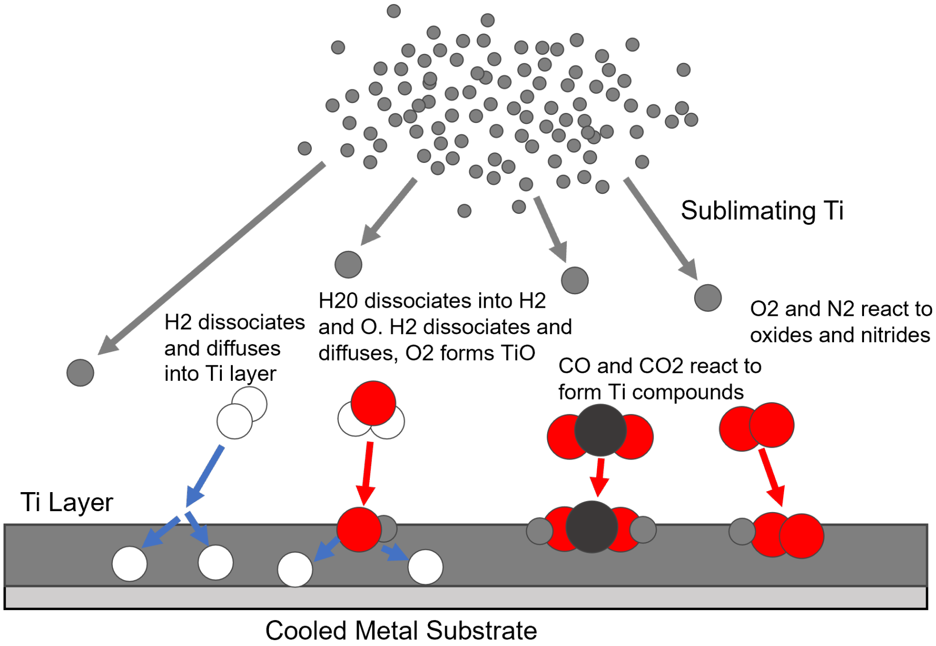

Figure 2: Principle of operation for TSP. Noble gases and methane are not pumped as they do not react with the surface. Figure adapted from tutorial provided by Gamma Vacuum.[b]

For this scheme to be effective, titanium must be deposited under initial vacuum conditions otherwise the titanium flux will react with the high partial pressures of reactive ambient gases during its transit to the pumping substrate, thus reducing its effectiveness. Consequently, TSPs must be paired with other high vacuum pumping systems such as turbo molecular, ion getter, diffusion, or cryogenic pumps to achieve initial vacuum conditions. Once operational, a TSP can provide significantly higher pumping speeds for reactive species compared to these other high vacuum systems as a result of the chemical processes central to their operation. However, because TSPs function chemically, they are ineffective on non-reactive gasses such as the noble gases typically = used for EP systems and also notably methane which can form when free hydrogen and carbon are both present in a vacuum system.

We show in Table 3 both the area specific pumping speeds for TSPs in addition to experimentally measured sticking coefficients for various gases for both room temperature (300 K) and liquid nitrogen temperatures (77 K).[33,34] This table highlights two key trends. The first is that this pumping scheme is highly dependent on temperature, yielding substantial improvements when cooled with liquid nitrogen (LN_2). The second trend is that the area specific pumping speed on the most problematic gas to pump, H_2, is four times higher than diffusion pumps and an order of magnitude higher than cryopumps (See Table 1). This advantage in specific pumping speed is combined with the fact that practically any surface in the vacuum chamber can be coated with titanium. Thus, it is possible to make large effective pumping areas in the

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[b] https://www.youtube.com/watch?v=9vJedaxRsxI

chamber. A similar principle has been applied in the testing of condensable propellants, e.g. liquid metals, in EP systems to date and has yielded in some cases overall pumping speeds in excess of 1 Ml/s.[35]

Indeed, we believe that with a TSP, we can achieve pumping speeds approaching 1 Ml/s for most alternative propellants of interest in a moderately-sized chamber (< 3 m diameter). The major limitation with TSPs is that the titanium surface is consumed overtime by reactions with the propellants and must be replenished. While this consumption means that new titanium must be supplied periodically, we estimate the total cost titanium will not be prohibitive——only 10% of our current expense of using LN_2 in LVTF at the University of Michigan.

Gas	Sticking Coefficient		Max Specific Pumping Speed, L/s/cm^2	
	300 K	77 K	300 K	77 K
H_2	0.06	0.4	2.6	17
CO	0.7	0.95	8.2	11
N_2	0.3	0.7	3.5	8.2
O_2	0.8	1.0	8.7	11
CO_2	0.5	1.0	4.7	9.3

Table 3: Surface pumping speeds and sticking coefficients for titanium sublimation pumps at room and liquid nitrogen temperatures.[33,34]

In summary, TSPs are a proven and highly effective on reactive gases. Given the shifting paradigm toward alternative propellants, TSPs thus appear to be an ideally suited approach for achieving rapid improvements in pumping capacity for EP applications.

B. Review of Existing Systems

Here, we review and describe the design and operation of existing TSP systems both those which are commercially available and bespoke high pumping capacity systems. The implementation of these systems revolves around the use of hot filaments to sublimate titanium atoms which subsequently condense on cooled pumping surfaces. The sublimation typically occurs at a process temperature of 1300° C (1600 K) which is generated ohmically by electric current passed through the filaments.

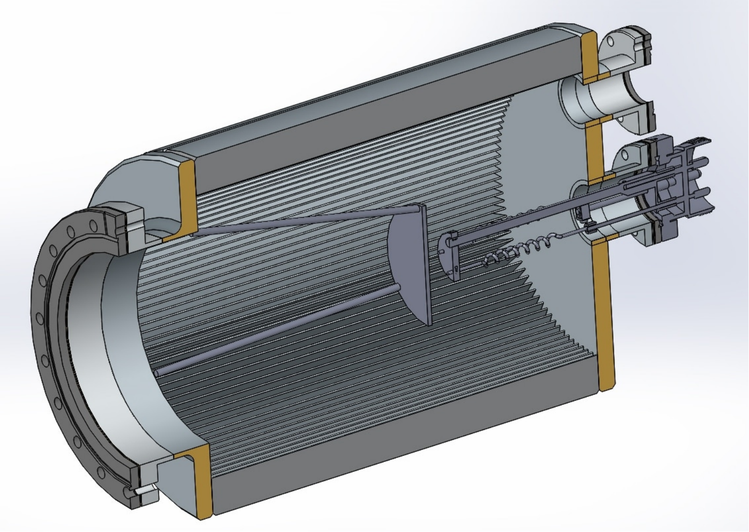

Figure 3: TSP system shroud from Atlas Technologies[c] and TSP element from Gamma Vacuum.[e]

Pure titanium filaments exhibit embrittlement and tend to fail structurally (and therefore electrically) prior to a significant deposition of the available titanium. To circumvent this problem, research was conducted by McCracken[36], McCracken and Pashley[37], and Lawson and Woodward[38] on the reliability of molybdenum titanium alloys as sublimation filament materials. The addition of molybdenum was found to significantly increase the overall lifetime and total deposition of titanium from the filaments as the molybdenum does not sublimate at the process temperature and maintains an additional degree of structural integrity. Indeed, present commercial systems typically employ coiled 85% Ti – 15% Mo filaments which exhibit a high degree of reliability, although several Ti filaments are typically installed within vacuum systems for additional Ti output and redundancy. We show in Fig. 3 a cross section of a commercially available TSP.[c] This figure shows the three centrally mounted titanium filaments which are surrounded by a cooled corrugated housing that acts as the pumping surface. A similar system (not shown) manufactured by Agilent reports an H_2 pumping speed of 4 kL/s at 3.1 L/s/cm^2.[d]

Additionally, there has been development work on large scale (∼1-4 m) TSPs developed for neutral beam injection studies and space simulators.[10–12] We show in Fig. 4 an example of one of these larger systems. In this setup, several long filaments are hung in each of a series of corrugated pumping alcoves. Instead of Ti–Mo alloy used in commercial systems the sublimation filaments are constructed from two 99% pure 0.8 mm diameter titanium wires wound around a 2 mm tantalum core in alternating layers with a molybdenum wire with a 0.6 mm diameter as shown in Fig. 4b. The latter provides structural support and enhances the heating of the titanium wires. We believe the choice to use pure titanium (over Ti–Mo) for this system is driven by the increased cost of the alloyed material at this scale. The reference length provided in Ref. 12 for a filament of this type is approximately 4 m, which in turn has ∼200 g of Ti available for sublimation. The pumping speed quoted for a system of nine of these alcoves is 700 kL/s on H_2 at a frontal area of 1.5 m × 4 m (11.7 L/s/cm^2) which agrees with the area specific pumping speeds shown Table 3, albeit the actual coated Ti surface area is not reported.

The reported pumping speeds for the existing TSP systems described here agree with what we have presented in Table 3, and the large neutral beam injection systems demonstrate scalability up to our target pumping speed range of 1 Ml/s on H_2. Although these architectures achieve target area specific pumping speeds, we argue using a scaling analysis in the following section that they are not suitable for the needs of high-power alternative-propellant EP testing, and indeed novel solutions are therefore required.

IV. Scaling Analysis

The primary limitations in regards to EP testing with TSPs are the available Ti throughput and the rate of Ti sublimation. Because these pumps operate on chemical interactions between the Ti and the propellant gas fed to the thruster, one needs to tailor the Ti sublimation rate in response to the thruster gas flow rate. In this way, EP applications of TSPs are contrary to the applications of the systems mentioned in Sec. III where the objective is to remove residual gasses prior to some ultra-high-vacuum process.

We can write an expression for the pumping speed of a TSP as

$$S_{\text{pump}}\,[\text{l/s}] = (\alpha A C)/(1 + Q/Q_{\text{Ti}}), \tag{2}$$

where α is the gas-dependent sticking coefficient (see Table 3), A is the pump area, $C\,[\text{L/s/cm}^2] = 3.64 \times \sqrt{T/M}$ is the conductance of a gas of molecular mass M [AMU] to the surface at temperature T [K], Q is the injected thruster flow rate, and Q_{Ti} is the Ti evaporation/deposition rate.[34] Combining this expression with Eq. 1 and recalling our target pressure of under 10^{-5} Torr, we arrive at the constraint

$$7.874 \times 10^{-4}\,[\text{sccm/(l/s)}] \geq \frac{Q(1 + Q/Q_{\text{Ti}})}{\alpha A C}. \tag{3}$$

For a TSP system, this is the inequality that must be satisfied for a chamber pressure of less than 10^{-5} Torr. If we now focus on H_2 as our target gas—as it is the most challenging for conventional EP pumping systems to process—we can substitute in for α from Table 3 at 77 K, and C from the expression under Eq. 2 to arrive at

$$140\,[\text{sccm/m}^2] \geq \frac{Q(1 + Q/Q_{\text{Ti}})}{A}. \tag{4}$$

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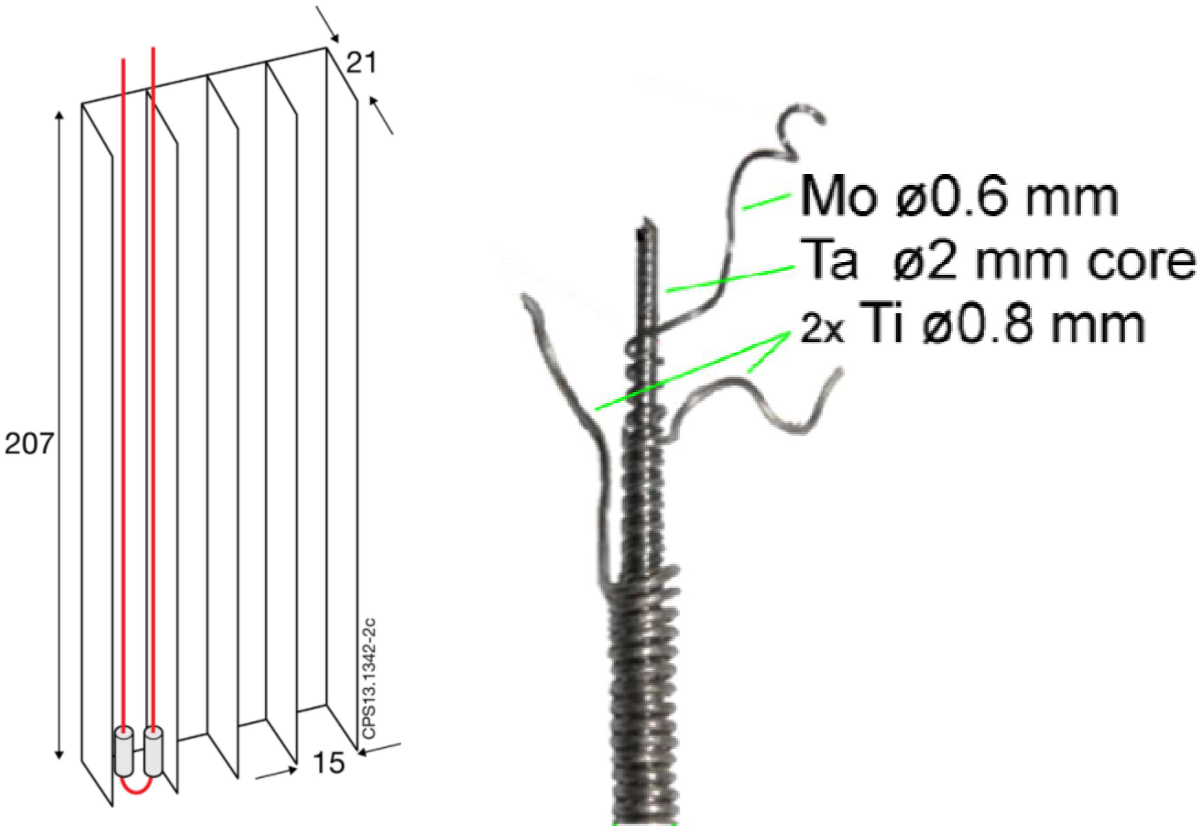
[c] Atlas Technologies, TSP Pumps and Shrouds, https://www.atlasuhv.com/products/tsp-pumps-shrouds/

[d] Agilent, Titanium Sublimation Combination Ion Pumps, https://www.agilent.com/en/product/vacuum-technologies/ion-pumps-controllers/titanium-sublimation-combination-ion-pumps-tsp

[e] Gamma Vacuum, Titanium Sublimation, https://www.gammavacuum.com/products/titanium-sublimation-tsp/



(a) Schematic of TSP layout adapted from Ref.[11].

(b) Ti sublimator wire used from Ref.[12].

Figure 4: TSP from neutral beam injection facility. Figures from Ref.[11] and Ref.[12].

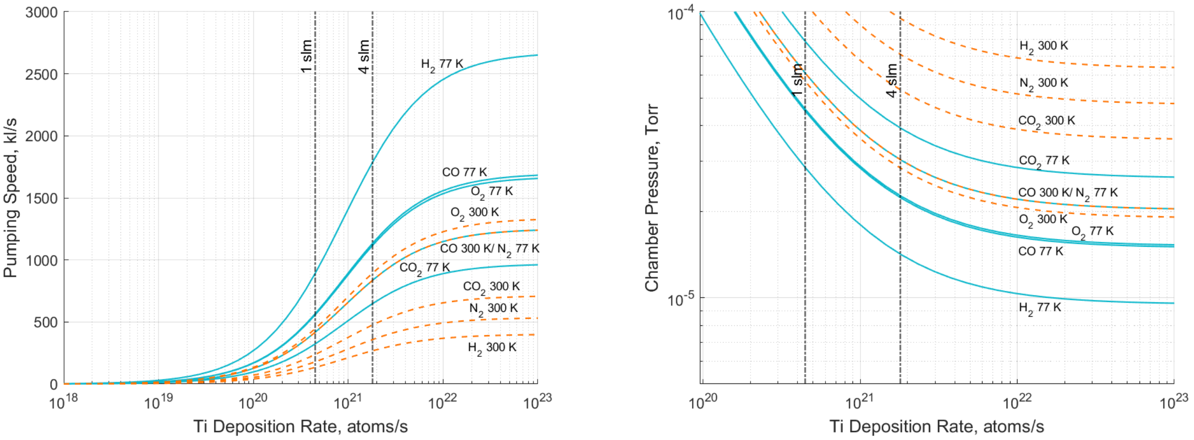
This equation shows that to achieve our target chamber pressure, we must scale both the Ti deposition surface area and the sublimation rate with the injected thruster flow rate. For next-generation thruster flow rates of 2 slm, Eq. 4 dictates a surface area of at least 14.3 m^2 with a Ti evaporation rate on the order of—or greater than—the thruster flow rate.

To further illustrate the scaling of Eq. 2, we show in Fig. 5 the resulting operating chamber pressure for the different gases in Table 3 as a function of Ti evaporation rate for 2 slm thruster flow on a pump with a surface area of 15 m^2. We assume here an injected gas temperature of 300 K. These figures indicate that a large Ti sublimation rate (with respect to the thruster flow rate) is required for high pumping speeds and low operating pressures. In fact, we expect that a minimum ratio of 2:1 continuous Ti evaporation rate to thruster gas flow rate is required for TSPs to be effectively used in EP testing. This is a notable departure from the typical operation of TSPs, where the pump surface is initially deposited with a layer of Ti and is allowed to pump for some time before being replenished[10,11,37].

Based on Fig. 5, a TSP that achieves our target metrics needs to support a Ti deposition rate on the order of 1.8e21 atoms/sec or 142 mg/s. This rate is factor of 17 higher than what we estimate of the large filaments from Ref. 12 (8.4 mg/s) and must be sustained for as long as the thruster is firing which could be up to several hours even for typical short-duration EP tests. Given this high sublimation rate, we anticipate that the power and hot surface area of a filament system will be prohibitively large for a practical system to be built.

Indeed, we can calculate the required power and the hot surface area required to achieve a Ti sublimation rate of 1.8e21 atoms/sec as a function of the process temperature. We calculate the Ti flux using the Langmuir flux density expression[39]

$$J = \frac{p_v}{\sqrt{2\pi k_b T m}}, \tag{5}$$



(a) Pumping Speed vs Titanium Rate

(b) Chamber Pressure vs Titanium Rate

Figure 5: Effect of titanium deposition Rate on pump performance for 1 slm gas flow and pump area of 15 m^2

where J is given in atoms per second per unit area, p_v is the vapor pressure as a function of temperature[40], T is the process temperature at the emitting surface, k_b the Boltzmann constant, and m is the atomic mass of the evaporating atom (in our case Ti). Given this flux density we can calculate the required surface area to achieve our target Ti deposition rate. Given this, we can also assess the power required to achieve this flux due to to black body radiation, the heat capacity of the titanium, the heat of sublimation, and the heat of fusion (where needed).[40]

We show in Fig. 6 the results of these calculations where we have included the melting point of Ti for reference (1943 K). Note, that Ti filaments are typically operated at 1750 K and no higher than 1900 K. Furthermore, the powers and areas reflected in Fig. 6 are in general agreement with the specific values published in Ref. 37.

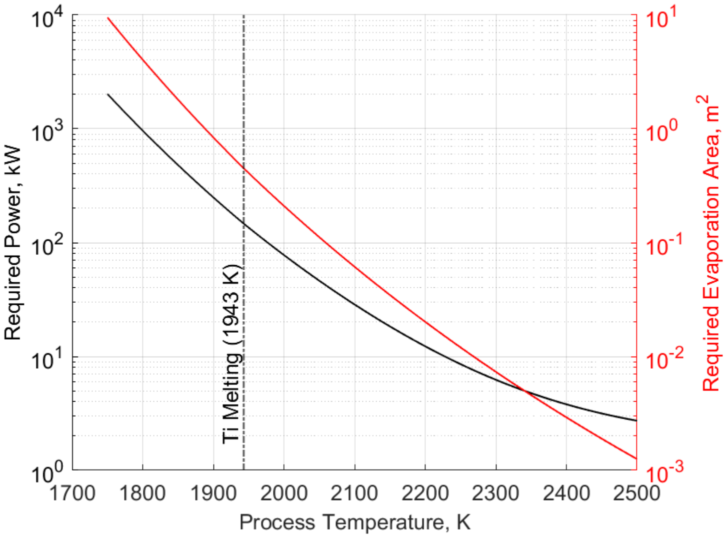


Figure 6: Titanium evaporation power and surface area to accommodate 2 slm of H_2 flow

The overall conclusion from these plots is that to sublimate the required rate of titanium from a solid Ti wire to pump a thruster flow of 2 slm would require a power of 276 kW, and a surface area of .85 m^2 at a sublimation temperature of 1900 K. This is a problematic amount of power, as existing large EP test facilities have difficultly managing the heat produced by thrusters operating between 50-100 kW. As an additional point of reference, one hour of operation of this pump would consume more than 5000 l of LN_2 which recall is critical for its operation.

Alternatively, if instead we adopt an architecture that does not require the Ti to remain solid (i.e. no wire filaments) and allow the process temperature to increase to 2500 K, we can get away with a required power of 2.7 kW and a hot area of 13 cm^2. Indeed, as the process temperature increases the required power approaches the minimum required for sublimation (1.3 kW). In this case, the 5000 l of LN_2 mentioned above would cool this load for over 80 hours.

As a result of this analysis, hot-wire sublimation filaments appear to be infeasible for the purposes of high-power EP testing on alternative propellants. Although they are a simple and convenient method to implement a TSP, they are ultimately unwieldy at the scale at hand. We turn in the next section to describing two design solutions to attain the Ti flux required with minimal power consumption for a thruster operating at 2 slm.

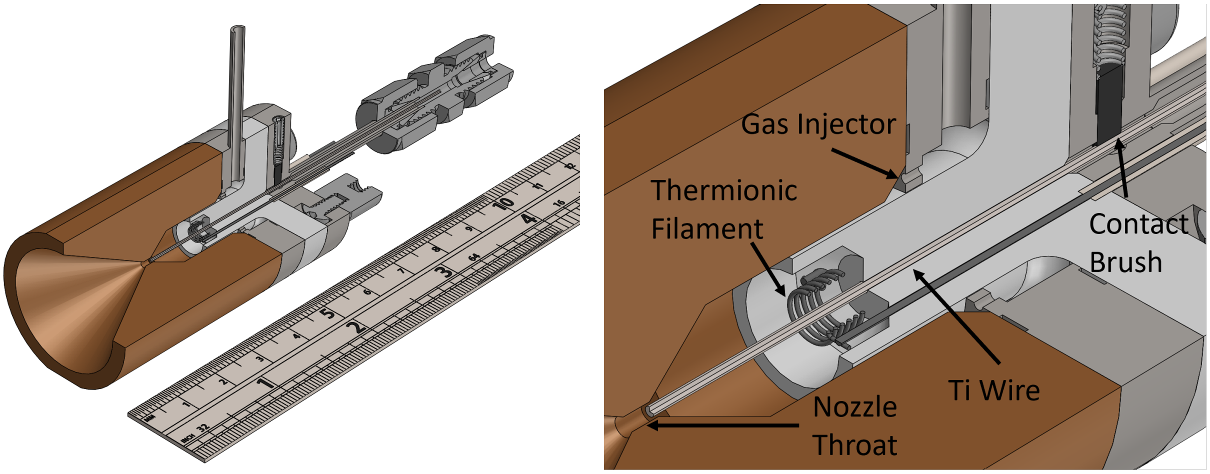
V. Design Concepts

In this section we describe two conceptual architectures to achieve the Ti flux required by the analysis in the previous section at a reduced power from what would be required for a hot-filament sublimation system.

A. Wire-fed Arc Spray

We show in Fig. 7 a render of our first design concept. This unit is inspired from both research conducted on vacuum arc thrusters (VAT)[41,42] and commercial metal thermal arc sprayers.[43] The proposed concept is to initiate an arc discharge between the body of the unit and a Ti wire which is continuously fed into the device. The power in the arc is intended to vaporize the Ti within a small diameter spot (~0.5 mm) to minimize radiative losses. Once vaporized, the Ti exits the nozzle body due to both thermal and magnetic pressure from the arc.

We intend for this unit to operate exclusively from the Ti vapor produced by the arc; however we anticipate difficulties in initiating the arc discharge. To this end, we have integrated both a thermionic tungsten filament to provide free electrons to assist with the electrical breakdown and a gas injector to provide a initial gaseous medium. These elements are labeled in Fig. 7 (b) for clarity.



(a) Full system with ruler for scale.

(b) Close up of Ti arc sprayer internal components.

Figure 7: Titanium arc sprayer CAD concept

This unit is roughly 5 cm long and and 4 cm in diameter, and for the full titanium evaporation rate as discussed in Sec. IV, this unit needs to dissipate on the order of 5 kW. This high power density may result in failure of the unit due to overheating and melting of components. To circumvent this, the desired Ti flux may need to be distributed across several units or water-cooling will need to be added to them. As a precautionary measure, we have selected an alloy of 75% W – 25% Cu as the nozzle material which is commonly used for high temperature electrical discharge machining and arc welding electrodes. This material exhibits similar properties to pure tungsten with enhanced thermal and electrical conductivity as a result of the copper content.

We anticipate the successful operation of this design will be a precarious balance of wire feed rate and arc power. And indeed, this concept may be too unreliable to incorporate as a fixed piece of vacuum infrastructure. However, if successful, this concept has the potential to deliver high titanium fluxes in a small volume with minimal wasted power. Furthermore, this unit can be operated from a spool of titanium wire which has no inherent size restriction, thus enabling long-duration testing of EP systems.

B. Induction Crucible

The second design concept we propose in this work is an inductively heated crucible which we represnt in Fig. 8. Titanium has 20% of the electrical conductivity of iron, which makes it a good candidate for induction heating. In-fact, induction forging of titanium is commonly practiced.[44–46]

Induction heating works by producing a high frequency (10-100 kHz) electric current in a surrounding coil which produces mirror currents in the heated piece via Lenz's law. In a minimally conductive media these currents can effectively heat the material resistively. In this proposed system, a water-cooled copper coil is used as the induction heating element which is placed around a non-conductive crucible which is loaded with titanium pellets. Under vacuum, the Ti pellets are heated until they exceed their melting temperature and are allowed to thermally vaporize upwards onto a cooled pumping surface.

Induction heating is advantageous as it separates the heater from the crucible material—commonly not the case for thermal vapor deposition systems. This facet can result in increased melt purity by careful selection of the crucible material. In our case, aluminum-nitride is quoted in Ref. 44 as being a suitable crucible material for minimal contamination with molten Ti. Additionally, in induction heating systems the melt can exhibit magnetic levitation as a result of the eddy currents produced in the material. While we are not designing for this in our proposed system, this allows for cooled crucible walls where very little wall contamination can occur. This process is known as induction skull melting[46] in reference to the "skull" of slag material that forms on the sides of the crucible that insulates the melt from the crucible walls.

We anticipate that the induction system will be more robust than the wire-fed arc design. However, it may consume more power due to the exposed molten surface and be limited in run duration by the quantity of pre-loaded Ti pellets. Furthermore, it is yet to be confirmed how the Ti purity effects the pumping capabilities of a system such as we have proposed, however we anticipate that if contamination is a concern, the induction heating system will have worse performance than the wire-fed arc design.

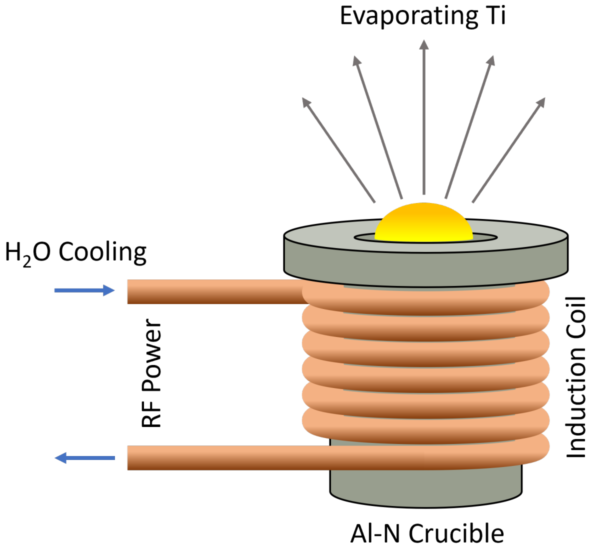


Figure 8: Schematic representation of induction heating Ti evaporator concept.

C. Facility Level System

With the design concepts presented in the preceding sections, we now turn to a depiction of how a full scale system may be integrated into a vacuum test facility. Here, we will take for reference the new alternative propellant test facility (APTF) at the University of Michigan (Shown in Fig. 9). This vacuum chamber measures approximately 2.7 m in diameter by 3.7 m long and will be the focus of the design study in this section.

Figure 9: Alternative propellant test facility (APTF) at the University of Michigan.

We show in Fig. 10 a schematic of the proposed vacuum pumping infrastructure for the APTF. The proposed system includes a conventional copper cryo-sail as the primary high vacuum pumping system for the facility. This pump will include a liquid nitrogen cooled shroud and activated charcoal traps, and make up the majority of the floor of the chamber with a pumping area of 5 m^2. We anticipate this cyro-sail will exhibit a pumping speed of 340 kl/s on H_2 alone.

Augmenting the cyro-sail will be the TSP tailored specifically for reactive alternative propellants. This system will sit beneath the bottom shroud of the cryo-sail, and evaporate Ti upwards onto the shroud to act as the pumping surface. Conductance to the TSP will occur though the gap along the edge of the cryo-sail as shown in Fig. 10. This configuration is desirable as the LN_2 shroud serves a double purpose. Both keeping the cryo-sail at cryogenic pumping temperatures (20-30 K), and acting as a cold surface for the titanium to deposit onto. Additionally, in this scheme the location of the TSP constrains the evaporate to the bottom of the chamber where is it less likely to impinge upon facility equipment and the device under test.

Notably, the area of this pump is only 5 m^2 whereas the minimum required pump area for our target flow rate of 2 slm H_2 is 14.3 m^2 as stated in Sec. IV. To address this, we intend to use a highly corrugated surface to deposit Ti onto. This is commonly done for TSP systems as it improves pumping speed at no additional size[11,47] (See also Fig. 3).

We show in Fig. 11 a rendering of our proposed pumping plate design. This panel is constructed of machined aluminum alloy—as Ti adheres well to Al[47]—, measures 30 × 30 cm, and consists of 289 square based pyramids. These pyramids are sized such that their side wall areas sum to a factor of three over the area of their bases. In so doing, the effective pump area will be also be a factor three larger at 15 m^2 which meets our target size. A series of these plates will be thermally mounted to the underside of the LN_2 shroud and will be removable for servicing. These panels will need to be cleaned periodically via grit blasting as Ti will build up on the Al surface and eventually slough off hindering pump performance.[47]

To evenly deposit Ti on to this corrugated pumping surface a (or set of) evaporation unit(s) will be placed on a linear motion stage that runs along the long axis of the chamber as shown in Fig. 10. This stage will be swept back and forth during evaporation to ensure an even distribution. The deposition area from a single evaporation unit is likely to be limited, although this remains to be characterized. This motion system is intended to allow for fewer units to cover a larger surface area.

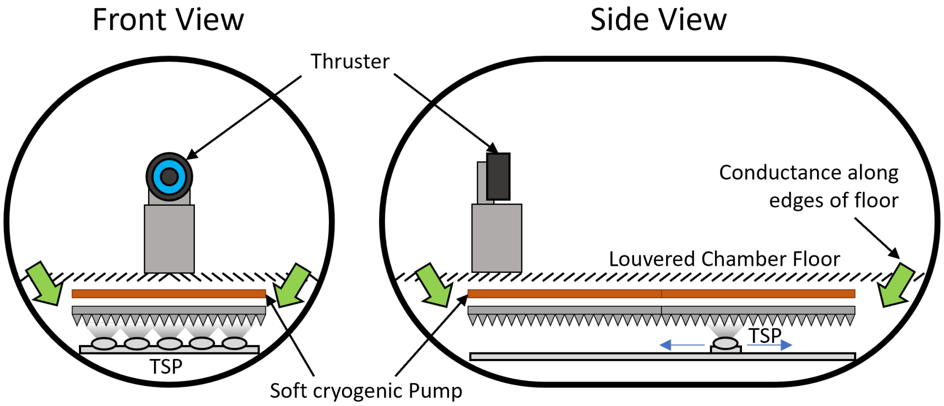


Figure 10: Schematic of facility level titanium sublimation pump infrastructure.

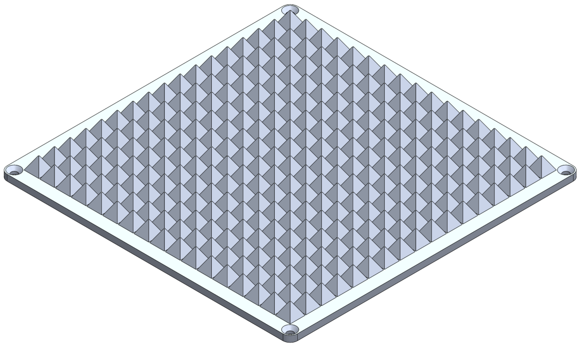


Figure 11: Highly corrugated cooled aluminum pumping surface for TSP operation.

VI. Conclusion

In this work we explore the titanium sublimation pump for use in electric propulsion testing as traditional cryogenic pump systems—optimized for noble gases such as xenon and krypton—fall short when tasked with handling lighter and more reactive gases like hydrogen and oxygen. TSPs offer a promising solution due to their ability to chemically sequester reactive gases at significantly increased specific pumping speeds. While TSPs have not traditionally been employed in EP testing due to their incompatibility with non-reactive noble gases, their effectiveness in handling reactive species makes them an attractive option for the emerging needs of high-power alternative-propellant EP systems.

The integration of TSPs into the field of electric propulsion however presents a formidable challenge, primarily revolving around the management of high titanium throughput and sublimation rates which we anticipate to be an order of magnitude higher than existing TSP systems. This necessitates a departure from the traditional TSP operational paradigm of hot sublimating wires.

This paper has outlined the requirements and considerations for employing TSPs in high-power EP testing, presenting two prototype designs capable of achieving effective pumping speeds exceeding 1 million liters per second for a variety of alternative gases. Through a comprehensive analysis and detailed design concepts, we have demonstrated the potential of these prototypes to address the current limitations in EP testing infrastructure. By refining these design concepts and integrating them into practical testing environments, we aim to enhance the capabilities of testing facilities for next-generation electric propulsion systems using alternative propellants.

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References

[1] Goebel, D. M., and Katz, I., *Fundamentals of Electric Propulsion: Ion and Hall Thrusters*, Jet Propulsion Laboratory, California Institute of Technology, 2008. https://doi.org/10.1002/9780470436448.

[2] Jorns, B., and Lafleur, T., "Foundations of plasmas as ion sources," *Plasma Sources Science and Technology*, Vol. 32, No. 1, 2023, p. 014001.

[3] Boeuf, J.-P., "Tutorial: Physics and modeling of Hall thrusters," *Journal of Applied Physics*, Vol. 121, No. 1, 2017.

[4] Rovey, J. L., Lyne, C. T., Mundahl, A. J., Rasmont, N., Glascock, M. S., Wainwright, M. J., and Berg, S. P., "Review of multimode space propulsion," *Progress in Aerospace Sciences*, Vol. 118, 2020, p. 100627. https://doi.org/10.1016/j.paerosci.2020.100627, URL https://doi.org/10.1016/j.paerosci.2020.100627.

[5] Pringle, H., Gregg, M., Phillps, S., and Sneden, J., "The Future of Propulsion," *AFA's Air, Space and Cyber Conference*, 2022.

[6] Dechert, J., and Koo, J., "Evolution of the AFRL In-space Propulsion Vision," *12th Space Propulsion Conference, JANNAF*, 2022.

[7] DARPA, "Defense Sciences Office: Project Daedalus Solicitation," 2022.

[8] DARPA, "Defense Sciences Office: Project Otter Solicitation," 2023.

[9] Halama, H. J., "Behavior of titanium sublimation and sputter-ion pumps in the 10^{-11} Torr range," *Journal of Vacuum Science and Technology*, Vol. 14, No. 1, 1977, pp. 524–528. https://doi.org/10.1116/1.569295, URL https://doi.org/10.1116/1.569295.

[10] Prevot, F., and Sledziewski, Z., "The Titanium Evaporation Pump, Its Application to Nuclear Fusion Experiments and Space Simulation," *Journal of Vacuum Science and Technology*, Vol. 9, No. 1, 1972, pp. 49–54. https://doi.org/10.1116/1.1316669, URL https://doi.org/10.1116/1.1316669.

[11] McAdams, R., "Control and calculation of the titanium sublimation pumping speed and re-ionisation in the MAST neutral beam injectors," *Fusion Engineering and Design*, Vol. 90, 2015, pp. 47–54. https://doi.org/https://doi.org/10.1016/j.fusengdes.2014.11.006, URL https://www.sciencedirect.com/science/article/pii/S0920379614006280.

[12] Orozco, G., Fröschle, M., Heinemann, B., Hopf, C., Nocentini, R., and Riedl, R., "Optimization of Large Titanium Sublimation Pumps for the Neutral Beam Injection System on AUG and W7-X," *IEEE Transactions on plasma science*, Vol. 44, No. 9, 2016, pp. 1553–1558.

[13] Dankanich, J. W., Walker, M. L. R., Swiatek, M. W., and Yim, J. T., "Recommended practice for pressure measurement and calculation of effective pumping speed in electric propulsion testing," *Journal of Propulsion and Power*, Vol. 33, 2017, pp. 668–680. https://doi.org/10.2514/1.B35478.

[14] Randolph, T., Kim, V., Kaufman, H., Kozubsky, K., Zhurin, V., and Day, M., "Facility effects on stationary plasma thruster testing," *23rd International Electric Propulsion Conference*, The Electric Rocket Propulsion Society Worthington, OH, 1993, pp. 13–16.

[15] Hofer, R. R., and Anderson, J. R., "Finite pressure effects in magnetically shielded Hall thrusters," *50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, 2014, p. 3709.

[16] Hargus, W., Tango, L., and Nakles, M. R., "Background pressure effects on krypton Hall effect thruster internal acceleration," *Proceedings of the 33rd International Electric Propulsion Conference*, 2013, pp. 2013–340.

[17] Huang, W., Kamhawi, H., and Haag, T., "Facility effect characterization test of NASA's HERMeS Hall thruster," *52nd AIAA/SAE/ASEE Joint Propulsion Conference*, 2016, p. 4828.

[18] Hargus, W., and Nakles, M. R., "Hall effect thruster ground testing challenges," *25th Aerospace Testing Seminar*, 2009.

[19] Walker, M. L. R., *Effects of facility backpressure on the performance and plume of a Hall thruster*, University of Michigan, 2005.

[20] Gessert, T. A., “Typical High-Vacuum Pumps Used in Vacuum Technology,” *Overview of Vacuum Technology*, AIP Publishing LLC Melville, New York, 2021, pp. 9–1.

[21] Garner, C., Polk, J., Brophy, J., and Goodfellow, K., “Methods for cryopumping xenon,” *32nd Joint Propulsion Conference and Exhibit*, 1996, p. 3206.

[22] Schoeffler, D., and Crofton, M. W., “Design of electric propulsion testing facility with custom cryopumping system,” *AIAA Scitech 2019 Forum*, 2019, p. 1244.

[23] Jovel, D. R., Walker, M. L., and Yang, V., “Research capability in combustion and propulsion at the Georgia Institute of Technology,” *53rd AIAA/SAE/ASEE Joint Propulsion Conference*, 2017, p. 4803.

[24] Viges, E. A., Jorns, B. A., Gallimore, A. D., and Sheehan, J., “University of Michigan’s upgraded large vacuum test facility,” *36th International Electric Propulsion Conference*, 2019, pp. 1–18.

[25] Chien, K., Hart, S. L., Tighe, W. G., DePano, M. K., Bond, T. A., and Spears, R., “L-3 communications ETI electric propulsion overview,” *29th International Electric Propulsion Conference. IEPC-2005-315. Princeton University. Oct*, Citeseer, 2005.

[26] 12V SPACE CHAMBER, ., *Arnold Air Force Base*, 2024. [Online]. Available: https://www.arnold.af.mil/About-Us/Fact-Sheets/Display/Article/409309/12v-space- chamber/.

[27] MacDonald, N. A., “Electric propulsion test and evaluation methodologies for plasma in the environments of space and testing (EP TEMPEST),” *AFOSR T&E Program Review*, 2016.

[28] Invigorito, M., Ricci, D., Battista, F., and Salvatore, V., “CIRA roadmap for the development of electric propulsion test facilities,” *Proc. of Space Propulsion*, 2016, pp. 2–6.

[29] Saverdi, M., Signori, M., Milaneschi, L., Cesari, U., and Biagioni, L., “The IV10 space simulator for high power electric propulsion testing: Performance improvements and operation status,” *Proc., 30th International Electric Propulsion Conference, IEPC-2007-321*, 2007.

[30] Gareis, P., and Hagenbach, G. F., “Cryosorption,” *Industrial & Engineering Chemistry*, Vol. 57, No. 5, 1965, pp. 27–32.

[31] Marchioni, F., and Cappelli, M. A., “Extended channel Hall thruster for air-breathing electric propulsion,” *Journal of Applied Physics*, Vol. 130, No. 5, 2021.

[32] Hruby, V., Hohman, K., and Szabo, J., “Air breathing Hall effect thruster design studies and experiments,” *37th International Electric Propulsion Conference, Boston, Massachusetts, IEPC-2022-446. https://www. electricrocket. org/index. php*, 2022.

[33] Bertolini, L., “Titanium sublimation pumping,” *US Particle Accelerator School*, 2002.

[34] Harra, D., “Predicting and Evaluating Titanium Sublimation Pump Performance,” *Japanese Journal of Applied Physics*, Vol. 13, No. S1, 1974, p. 41.

[35] Brophy, J. R., Polk, J. E., and Goebel, D. M., “Development of a 50,000-s, lithium-fueled, gridded ion thruster,” *Proceedings of the 35th International Electric Propulsion Conference, Atlanta, GA, USA*, 2017, pp. 8–12.

[36] McCracken, G., “The performance of a high speed getter pump using a cooled titanium film,” *Vacuum*, Vol. 15, No. 9, 1965, pp. 433–436.

[37] McCracken, G. M., and Pashley, N. A., “Titanium Filaments for Sublimation Pumps,” *Journal of Vacuum Science and Technology*, Vol. 3, No. 3, 1966, pp. 96–98. https://doi.org/10.1116/1.1492460, URL https://doi.org/10.1116/1.1492460.

[38] Lawson, R., and Woodward, J., “Properties of titanium-molybdenum alloy wire as a source of titanium for sublimation pumps,” *Vacuum*, Vol. 17, No. 4, 1967, pp. 205–209.

[39] Poullain, T., Bellot, J.-P., Jourdan, J., Crassous, I., and Jardy, A., “Vacuum evaporation and expansion of pure metals at high temperature: Application to titanium and zirconium,” *Vacuum*, Vol. 203, 2022, p. 111209. https://doi.org/https://doi.org/10.1016/j.vacuum.2022.111209, URL https://www.sciencedirect.com/science/article/pii/S0042207X22003359.

[40] Arblaster, J., “Thermodynamic Properties of Titanium,” *Journal of Phase Equilibria and Diffusion*, Vol. 44, No. 4, 2023, pp. 542–558.

[41] Polk, J. E., Sekerak, M., Ziemer, J. K., Schein, J., Qi, N., Binder, R., and Anders, A., “A theoretical analysis of vacuum arc thruster performance,” 2001.

[42] Aheieva, K., Toyoda, K., and Cho, M., “Vacuum arc thruster development and testing for micro and nano satellites,” *Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan*, Vol. 14, No. ists30, 2016, pp. Pb_91–Pb_97.

[43] Abd Malek, M. H., Saad, N. H., Abas, S. K., and Shah, N. M., “Thermal arc spray overview,” *IOP Conference Series: Materials Science and Engineering*, Vol. 46, IOP Publishing, 2013, p. 012028.

[44] Fashu, S., Lototskyy, M., Davids, M. W., Pickering, L., Linkov, V., Tai, S., Renheng, T., Fangming, X., Fursikov, P. V., and Tarasov, B. P., “A review on crucibles for induction melting of titanium alloys,” *Materials & Design*, Vol. 186, 2020, p. 108295.

[45] Lu, L., Zhang, S., Xu, J., He, H., and Zhao, X., “Numerical study of titanium melting by high frequency inductive heating,” *International journal of heat and mass transfer*, Vol. 108, 2017, pp. 2021–2028.

[46] Breig, P., and Scott, S., “Induction skull melting of titanium aluminides,” *MATERIAL AND MANUFACTURING PROCESS*, Vol. 4, No. 1, 1989, pp. 73–83.

[47] Feist, J.-H., Staebler, A., Ertl, W., Heinemann, B., and Speth, E., “Large scale titanium getter pumps for the ASDEX-Upgrade neutral beam injectors,” *Fusion Technology 1992*, Elsevier, 1993, pp. 262–266.