National Space Simulation Facility Concept Design

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Walter A Rodriguez[1]
University of Houston, Houston, Texas, 77004

John Dankanich[2]
NASA Marshall Space Flight Center, MSFC, Huntsville, Alabama, 35812

Current Electric Propulsion test facilities have limitations impacting the accuracy of testing and understanding of Electric Propulsion systems. This study is to support a potential partnership between the Army and Air Force with the Space and Missile Defense Command (SMDC) hosting a national capability in support of future Space and Mission Systems Center (SMC) missions. Presented is a preliminary design of a large scale chamber to be used for Electric Propulsion testing that addresses several of the current issues faced by high powered electric propulsion test facilities. The chamber was designed taking into account conductance limitations and the latest vacuum chamber technology advancements. The chamber was designed to be significantly more cost effective and higher performing, by an order of magnitude, over the current state of the art civilian testing facilities. The chamber was modeled in Creo and analyzed using Ansys to determine the structural integrity of the design. The chamber was also modeled using the Air Force developed Hypersonic Aerothermodynamics Particle code to estimate the performance of the facility and complete several trade studies to determine the ideal dimensions and arrangement of the facility. Presented as well is a sensitivity trade comparing various pressures and pumping speeds achievable compared to chamber size, cryopanel density and facility costs.

Nomenclature

a = Clausing Transmission coefficient
A = Cross-sectional area of a pipe, cm^2
C_M = Molecular Conductance
I_s = Molecular Impacts with a Surface, atoms/ cm^2-s
p = pressure, Torr
P = pressure, Pascal's
R = Universal Gas Constant, Torr L/Kmol
M = molar mass, grams / mole
T = Temperature, K
V = Volumetric Flow Rate, L/cm^2-s

I. Introduction

CURRENT electric propulsion test facilities have limitations that impact the prediction of system performance in the space environment. Limitations include performance and lifetime measurements, plume and potential spacecraft interaction assessments, and facility backsputter contamination. These limitations are well documented and

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[1] Student, University of Houston, walter.rodriguez12@gmail.com.

[2] Project Manager, Technology Development and Transfer, ZP30, john.dankanich@nasa.gov.

have been a topic of research. The power level, flow rates, and lifetimes of thrusters are all increasing from state-of-the-art. The need for a large scale electric propulsion test facility has been well documented as current testing of electric propulsion systems require the addition of large margins or the completion of expensive testing with known unknowns; hindering the development and research of electric propulsion technology.[1]

The effective pumping speed of several current state of the art chambers is severely limited due to conductance limitations imposed by the radius, size and design of the chamber.[2] These conductance limitations lead to a facility backpressure presence that has been documented to effect thruster performance[3] and has led to inconsistencies between ground testing and flight performance. Backsputtering issues during electric propulsion testing have also been well documented[4,5] and must be taken into account for the design of any new space simulation chambers looking to be useful for current and future electric propulsion systems. A direct relation with the size and shape of the chamber has shown that many current chambers are too small for current and future long duration qualification tests. An example includes the results of the long duration NSTAR qualification test that were compromised due to excessive amounts of backsputtered facility material deposition onto the thruster.[6]

These varying limitations with the current state-of-the-art reinforce the notion that a large scale space simulation chamber is needed to ensure the accurate and reliable testing of current and future electric propulsion systems. The design of this large scale facility is detailed below with the ultimate goal of a magnitude of order improvement over the representative state-of-the-art of Vacuum Facility 5 (VF5) at NASA Glenn Research Center[7]. Along with significant improvements performance, the facility design is planned to leverage regenerative Liquid Nitrogen system, similar to that of Georgia Tech's space simulation chamber[8], in order to significantly lower the operations cost of the facility over current methods.

The facility design was modeled using Creo Parametric software and Ansys for structural analysis, the Air Force developed Hypersonic Aerothermodynamics Particle (HAP) code for background pressure performance and modified legacy tools[9] for backsputter estimates. Along with the design of a large scale facility, a trade study was performed using the Air Force HAP code to more accurately define and understand the relationships between facility dimensions and configuration to effective pumping speeds and achieved pressures assess the "best value" pumping speed to dollars spent. The costs assessments included the sensitivity to Liquid Nitrogen and electricity costs justify recommendations between capital investments versus operational costs. Last, testing was performed to validate performance predictions.

II. Facility Design Objectives and Approach

A challenge with facility designs or modifications to existing facilities is the determination of near-term and final configuration performance requirements. There is insufficient data and on-going research to determine what facility performance is sufficient to address concerns of all potential stakeholders and meet the needs of future system testing. An arbitrary goal was established for a case study: demonstrate a facility performance improvement of an order of magnitude over NASA GRC's Vacuum Facility 5 while attempting to simultaneously reduce the operating costs. VF5 was chosen both because it represents state-of-the-art, and because facility models are well documented.[10] During the assessment, additional questions arose regarding where the relevant performance requirements should be measured (e.g. a 10x improvement at the exit plane of the thruster 1 cm or 1 thruster diameter from the outer diameter or near the facility chamber wall.) Approaching a perfect vacuum will show diminishing returns of absolute pressure benefits at the thruster, yet near-field effects are critical to characterize.

The baseline requirement was an order of magnitude improvement over effective pumping speed of VF-5. A thin slice of the chamber was taken at various distances relative to the exit plane of the thruster for conductance calculations to determine effective pumping speeds. The size and quantity of cryopanels were driven by HAP analyses. The cryopanel effecting pumping speeds was initially estimated using the VF-5 data sheet[7] and the approximate area sizes of the cooled surfaces.

After a modest distance from the thruster, the length of the facility no longer became a driving factor for effecting pumping speed performance. As example, HAP analyses found that the 20 meter long chamber effective pumping speed around the thruster exit plane is approximately the same as the 15 meter long chamber. The recommended lengths of chamber options were determined through backs sputter limitations with a goal of facility application to long duration and life qualification testing.

The other major criteria for the facility is a reduction is operating costs and known sensitivities to operations, utility and consumables are understood. The baseline assumption is that a closed loop system to cool the radiation shrouds of the cryopanels would result in lower overall operations costs over boiling off the Liquid Nitrogen. Multiple Cost estimations were completed on the chamber to compare a liquid nitrogen regenerative system to a boil off system.

III. Preliminary Design Methodology and Validation

The primary expectation is that by significantly increasing the facility diameter with commensurate pumping surfaces, higher performance is achieved. This is primarily due to conductance limitations, but the HAP modeling clearly shows that pure conductance is not the only factor to consider including strategic locations of the pumping surfaces. Before performing detailing HAP runs, an estimate of the maximum effective pumping speed of VF-5 was determined using basic conductance equations. As shown below in equations (1) and (2) the conductance of a cylindrical pipe is shown. The pipe was assumed to be an infinitely small thin slice in order to give the maximum conductance at the thruster exit plane. The equations shown below and further explanation of them and proper vacuum chamber calculations can be found in reference.[2]

A. Preliminary Design Methodology

As VF-5 is the main basis of comparison and the representative state of the art facility, it is important to model the chamber using the HAP code and determine what the limiting factor regarding pumping speed and pressures reached is. A molecular conductance equation was used to determine the conductance of the chamber as shown below. A further explanation is available in the literature.[2]

$$C = V * a * A \tag{1}$$

$$I_s = \frac{P * 3.5 * 10^{22}}{(M * T)^{\frac{1}{2}}} \tag{2}$$

$$P * V = n * R * T \tag{3}$$

$$V = \frac{\left(\frac{I_s}{6.022 * 10^{23}}\right) * R * T}{P} \tag{4}$$

Assuming a temperature, T, of 293K, a Molar mass, M, for xenon of 131.29 and the measured base pressure of $1*10^{-7}$ Torr. The clausing transmission coefficient, a, is assumed to be 1 as this is an infinitely thin slice. The cross sectional area of the pipe, A, is calculated to be 457 m^2. Equation 1-3 are combined into equation 4 which presents the effective pumping speed.

$$I_s(Xenon) = \frac{(1 * 10^{-7}) * 3.5 * 10^{22}}{(131.29 * 293)^{\frac{1}{2}}} = 1.7845 * 10^{13} \left[\frac{atoms}{cm^2 * s}\right] \tag{5}$$

$$V = \frac{\left(\frac{1.7845 * 10^{13}}{6.022 * 10^{23}}\right) * 62.363 * 293}{(1 * 10^{-7})} = 5.4147 \left[\frac{L}{cm^2 * s}\right] \tag{6}$$

$$C = 5.4147 * 1 * 457 = 888{,}167 \left[\frac{L}{s}\right] \tag{7}$$

The maximum predicted effective pumping speed of VF-5 at the thruster exit plane is calculated in equations 5-7 to be 888,167 [L/s]. This value was then compared the HAP code results.

The Hypersonic Aerothermodynamics Particle (HAP) code was used to model the facility pressure distributions of both VF-5 and the large scale chamber designs. The Hap code provides rapid simulation of rarefied gas flow problems using the direct simulation Monte Carlo (DSMC) method.[11] The gas source is modeled as an annular cold flow gas source and has been documented to be a good model of both cold and hot flow thruster use in a vacuum chamber. [11] The first step accomplished was to recreate the previous model of the HAP code performed by Yim and Herman[11] to establish a baseline to complete the design of the improved facility. Along with this run a larger diameter facility with the same cryopanel arrangement was run to test the conductance limitations of VF-5. Figure 1 and 2 display the VF5 run and the larger chamber. Figure 3 shows the effective pumping speed and pressure radially outward from the thruster along the thruster exit plane. The diameter of the facility was doubled in order to determine the conductance effects. The results clearly indicate that VF-5 is conductance limited and simply using a larger shell with the same pump configuration would yield a significant performance benefit as measured at the wall. The results also indicate that a capital investment in only a larger shell, should result in a performance increase without a large impact to recurring operations costs above baseline. However, performance near the thruster has minimal variance.

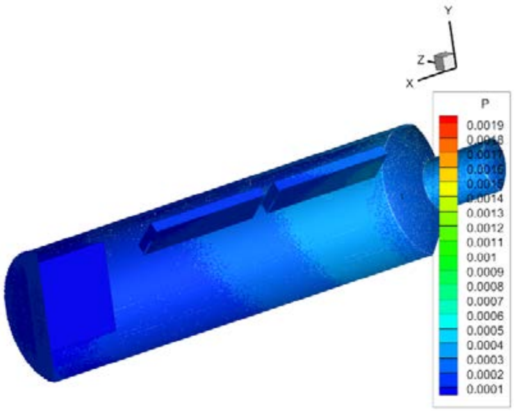


Figure 1: VF-5 HAP model results.

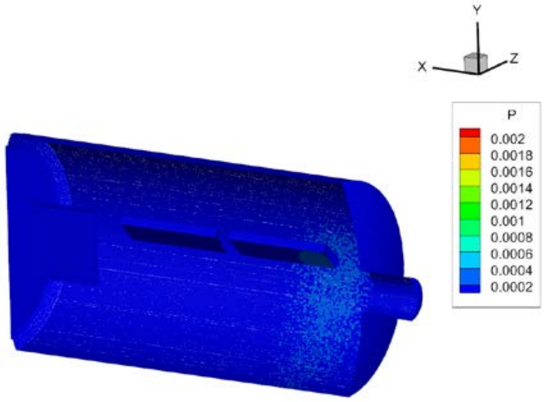


Figure 2: Larger diameter facility with VF-5 cryopanel arrangement.

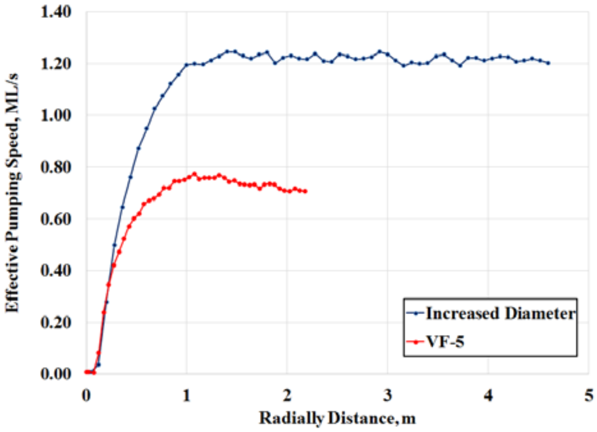


Figure 3: Effective pumping speed comparison between VF-5 and larger diameter chamber.

B. Sticking Coefficient

The HAP code is analytically defined with several user set variables. The sticking coefficient is one of the most important variables as it defines the probability that a particle will stick to the surface of the cryopump after it makes contact. The HAP code models the cryopumps as flat surfaces resulting in the sticking coefficient representing both the probability that a particle will pass through the radiation shroud and that the particle will then stick to the helium cooled panels. A sticking coefficient of .25 has been established before by Yim and Herman[11] who compare the HAP model with pressure data from VF-5 to determine an accurate sticking coefficient. It is hypothesized that this sticking coefficient could be accounting for other facility variables including outgassing, leaks, and conductance limitations. This hypotheses would lead to the conclusion that the sticking coefficient is not transportable between facilities or configurations.

IV. Trade Studies

With general expectations understood, a series of trades studies were completed with a range of facilities sizes and configurations. Unless notes, analyses were completed using an XR-5 thruster as the baseline with a flow rate of 12.9 mg/s and pumping speeds are provided for Xenon. Some runs were initially completed to address exit velocity sensitivity, but it was previously determined unnecessary for performance trends while impacting computer demand.[12] The HAP code measurements are presented thruster exit plane. Pressure calculations at this location have been previously recommended for facility backpressure effects on the thruster and was chosen here to represent the independent variable to be optimized.[2] The trade studies shown were used to drive the final recommended design and cryopanel arrangement of the facility. Several hundred configurations were compared throughout the study and only a small subset of cases is provided to indicate overall trends.

A. Panel Density

The first trade study compares the cryopanel arrangement and density in a 15 meter diameter chamber. Several runs were completed modeling a 15 m diameter by 15 m length facility using the HAP code to predict pressures achieved. As shown in figures 4-6 the number of cryopanels was varied from 36 to 72. Figure 7 depict the pressures and pumping speed along the thruster exit plane radially outward from the thruster centerline. The fidelity of the model is .10 meters accounting for the large changes in pressure near the thruster. As expected, the performance of the facility increases as the number of cryopanels increases.

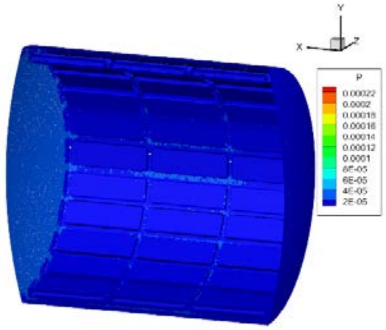


Figure 4: 72 cryopanels in 3 rings of 24.

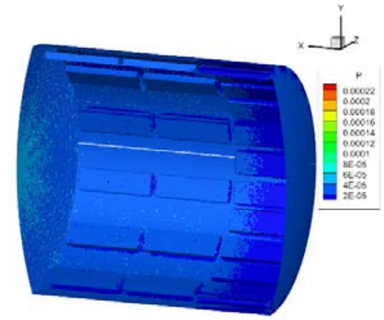


Figure 5: 48 cryopanels arrange in 1 ring of 24 and 2 rings of 12.

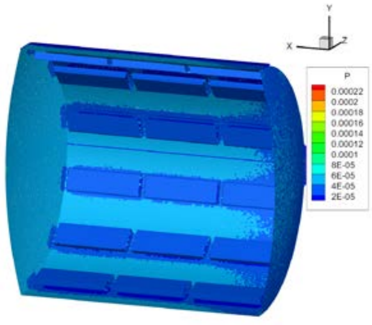


Figure 6: 36 cryopanels arranged in 3 rings of 12.

For the panel arrangement and density trades, the performance increased as additional cryopanels were increased. The facility was not conductance limited, rather limited by pumping capability. These trades were completed for a range of facility diameters. A 100% surface coverage of cryo-pumps provides the highest pumping performance for any given facility diameter.

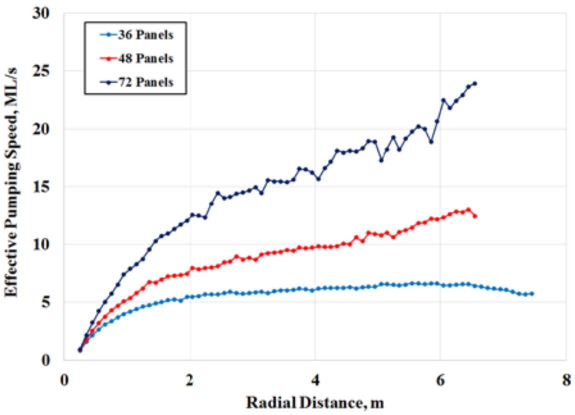
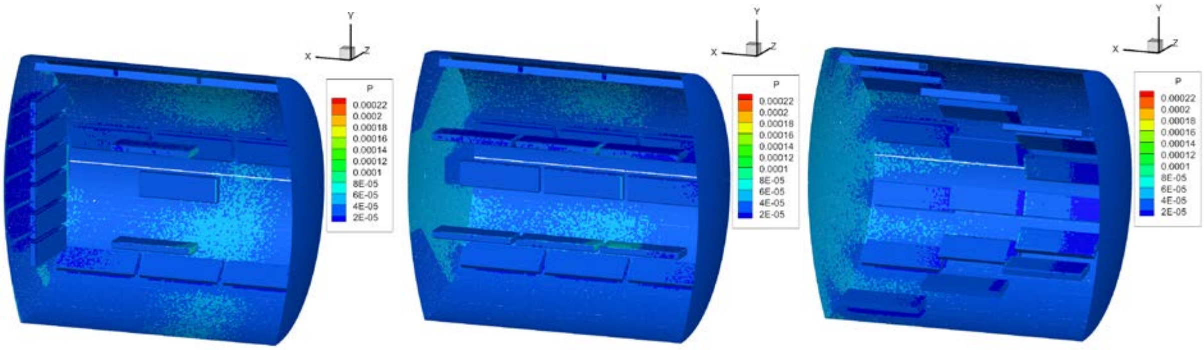


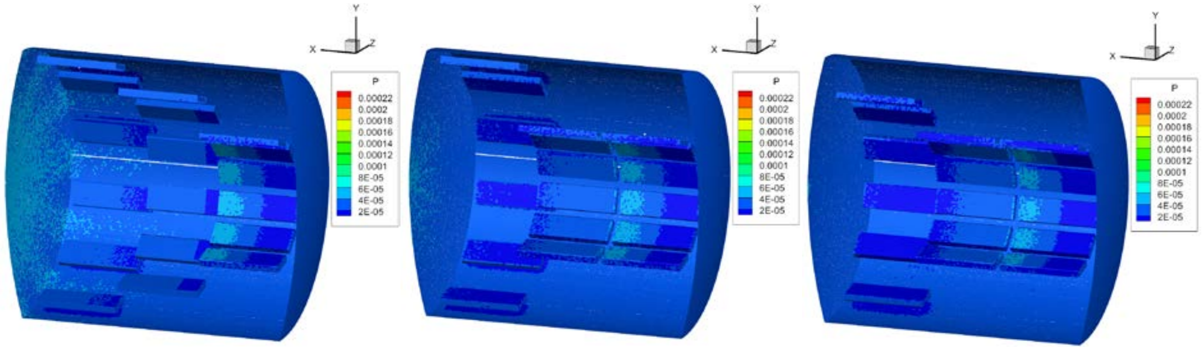
Figure 7: Effective pumping speed from varying amount of cryopanels.

B. Internal Panel Configuration

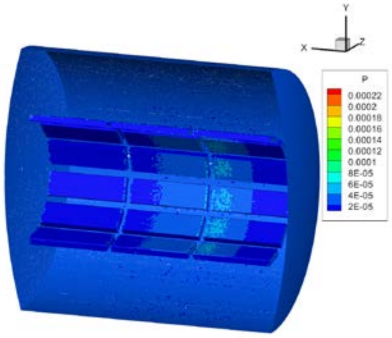
Another trade study was completed to assess sensitivity to internal configuration. This was uses to understand trends on benefits of placing pumping surfaces closer to the gas flow. For these trades, the same 36 cryopanels are using with only changing positions. All of the panel configuration cases were modeling using a sticking coefficient of 0.4 in the presented results. The configurations of the facility are shown in figure 8 with the results provided in figure 9.



(a) – Arrangement 1 (b) – Arrangement 2 (c) – Arrangement 3



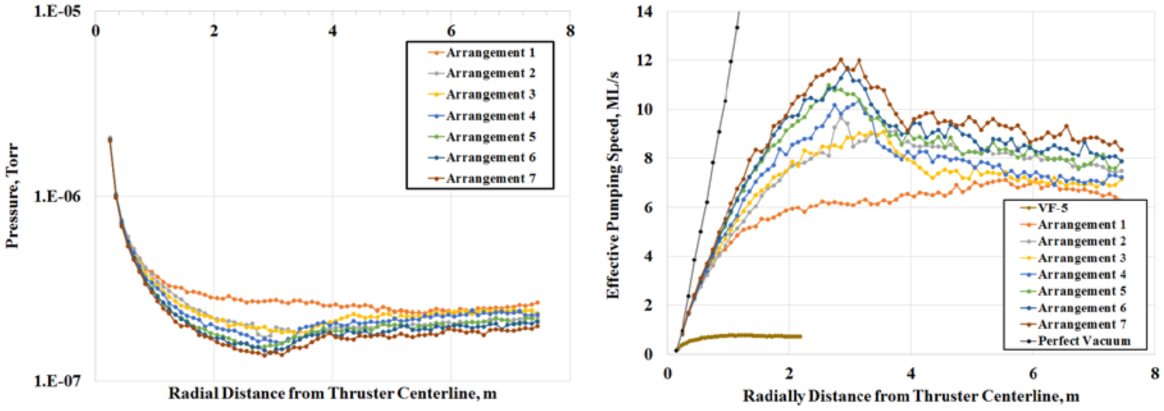
(d) – Arrangement 4 (e) – Arrangement 5 (f) – Arrangement 6



(g) – Arrangement 7

Figure 8: 36 panel arrangements for configuration comparison.

The results from the configuration trade illustrate that the highest performance for a fixed set of panels is the maximum density layout. Figure 9 (b) also includes performance comparison to both the existing VF-5 and a pure vacuum.



(a) (b)

Figure 9: Results from panel configuration trade analyses with pressure (a) and effective pumping speed (b) versus radial distance.

Cost

Costing trends was also determined for the facilities. To develop a facility cost model, a combination of estimates and quotes were obtained from industry for the manufacturing costs of the shells, helium and liquid nitrogen regenerative systems, cryogenic panels, etc. It's noteworthy that the bids for manufacturing the large shells did not indicate any appreciable cost benefit or penalty for scaling the system. However, some provided had concerns with shipping components for on-site assembly without knowing the specific route (i.e. overpass height constraints, etc.) that may increase cost. Also, it should be noted that vendors said it is highly probable that lower prices could be negotiated for bulk purchases of liquid nitrogen systems. A price for sets of units was used for analyses to represent a conservative cost to the larger scale options. Individual shell options and pump configurations were costed for a series of point costs and plotted to develop the trend lines shown in figure 10. The two lines represent sticking coefficients of 0.25 and 0.4. Note, the two top right data points are identical facility configurations, but with the variable sticking coefficients; resulting in a 12ML/s variance.

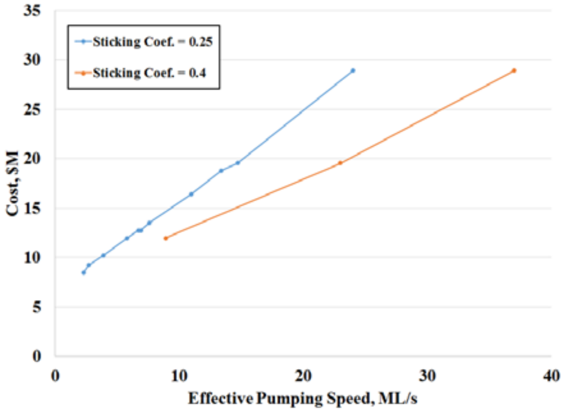


Figure 10: Capital investment cost versus facility capability trends.

C. Facility Length

Facility length recommendations are provided based on calculations of backsputter deposition rates. The objective was to determine a practical length with consideration to long duration test effects.[9] The predicted backsputter for electric propulsion thrusters improves as facility length increases and as the length to diameter ratio approaches 1. An objective was set to achieve a backsputter rate of 0.02 µm/khr·beam ampere. Figure 11 is the generated curve of backsputter rates for preliminary facility designs. Increasing facility length without simultaneously increasing pumping capability is a non-optimal pumping performance solution, but allows for a minimal cost approach to achieve a backsputter requirement after pumping requirements have been satisfied. The cost difference to improve backsputter performance is shown in figure 12. Increasing facility length alone did not indicate any appreciable improvement in pumping performance in length ranges from 15-30m; as shown in figure 13.

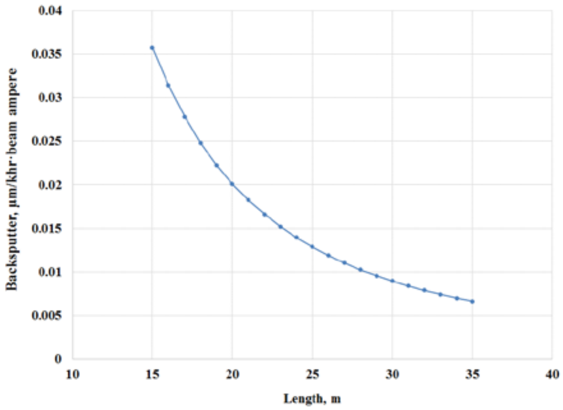


Figure 11: Facility length versus backsputter performance for a 15m diameter facility.

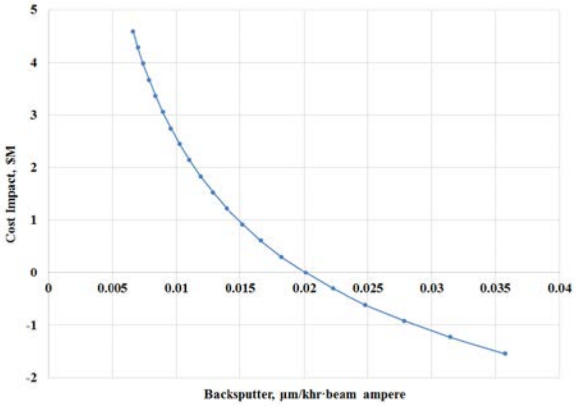


Figure 12: Delta costs to improve backsputter performance without impacting pumping.

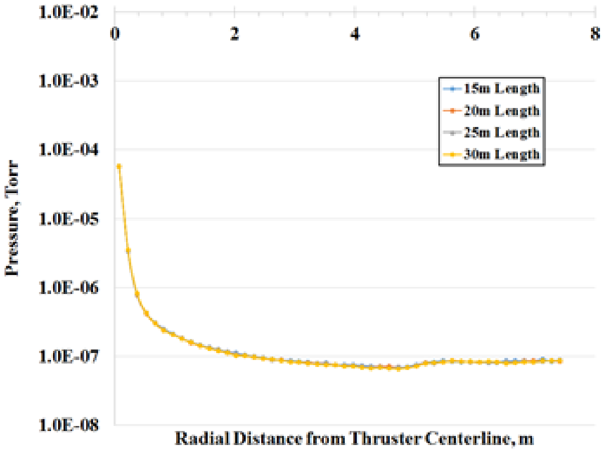


Figure 13: Pressure performance as a function of facility length.

V. Recommended Baseline Design for New Facility

After completing hundreds of point design to understand system performance sensitivities, a recommended facility point design was assessed for more detailed cost and performance assessment. From the preliminary trades, a recommendation is for a 15m diameter chamber and a 20m length. The facility would be populated with an array of 300,000 L/s sized cryopanels. The panels would be configured to along the walls with 3 rings of 16 panels for a total of 48. The system would be fully regenerative for working fluids. High fidelity cases were modeled using the HAP tool as a 0.05m resolution using the NASA MSFC computer cluster. The recommended HAP model configuration is shown in figure 14.

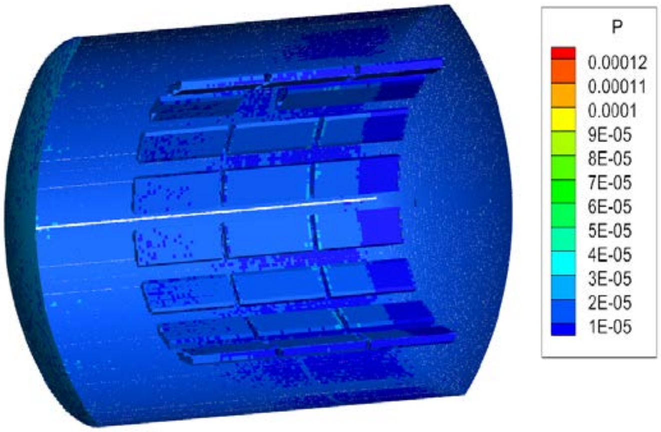


Figure 14: Recommended design HAP model.

A. Performance

1) Effective Pumping Speeds

The original cost was to achieve a performance improvement in effective pumping speed as measured at the chamber wall by an order of magnitude. Figure 15 illustrates the recommended facility performance in the radial distance from the thruster centerline in the first meter from the thruster. The figure also includes the performance for a perfect vacuum at the chamber wall (modeled with a sticking coefficient of 1.0). To optimize cost and performance, an improvement significantly beyond 10x is achieved at the chamber wall. However, as noted previously, the performance near the thruster is of high interest. Even the perfect vacuum scenario has relatively high pressure near the thruster. A comparison of the recommended facility design to capability of VF-5 as a function of distance from the thruster was calculated. The results are shown in figure 16. The results indicate that the recommended facility only has twice the performance of VF-5 near the thruster and does not achieve a 10x improvement in near-field pressures until a distance of approximately 1 meter from the thruster. Figure 17 shows the comparison of performance between the recommended facility design and a perfect vacuum. The recommended design is calculated to have 93% of the performance of the expected space environment.

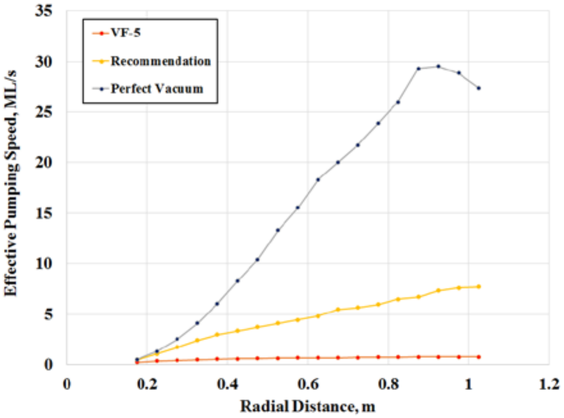


Figure 15: Recommended design HAP performance comparison.

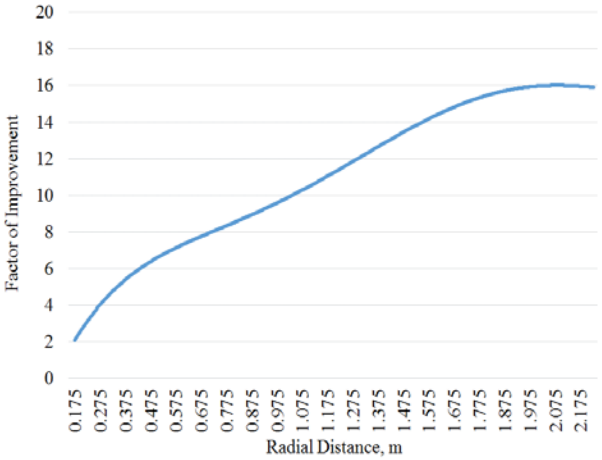


Figure 16: Recommended facility improvement over VF-5.

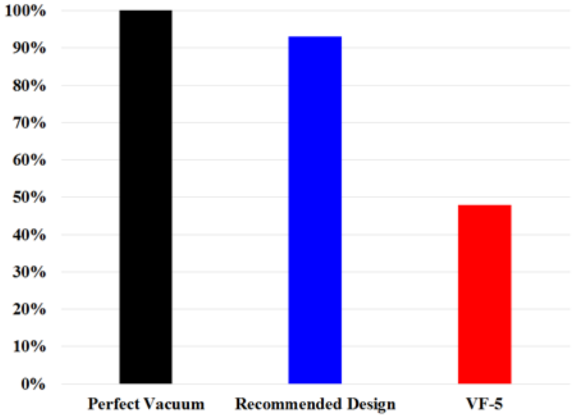


Figure 17: Comparison 10cm from the thruster.

2) Backsputter

The recommended facility length is 20 meters. This is approximately 50% of the backsputter rate calculated for VF-5 at 0.02 μm/khr·beam ampere. Results are consistent with all previous studies that longer the facility and wider the diameter the better backsputter effects can be mitigated.[9,13]

B. Operations

The operations logistics was also an area of concern for facility of this magnitude. Logistical challenges were uncovered with mounting the thruster near the center of such a large chamber. Several animations and computer aided drawings were generated to develop an operational flow. An overhead crane is recommended and included in the final configuration. The crane is used for a completely removable door solution modeled after the NASA X-Ray and Cryogenic Facility (XRCF) operations experience. A system of rails is employed to allow thruster preparation outside the chamber and insertion for test. A rendering of the recommended configuration is shown in figure 18.

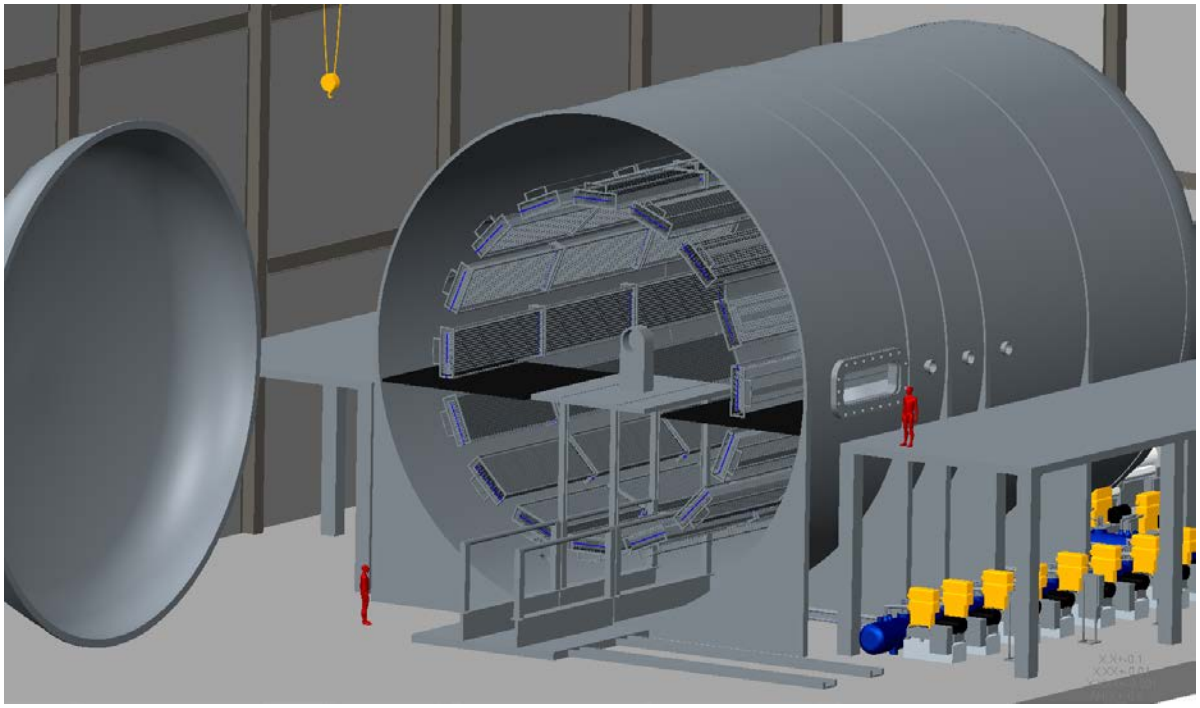


Figure 18: Rendering of recommended configuration.

C. Costs

After selection of a recommended design, industry inputs were solicited for all-inclusive facility costs (the building for the chamber, the shell, cryopanels, regenerative systems, a suite of model power supplies, data acquisition systems, over-head crane, etc. The goal was to minimal full life cycle costs. The life cycle costs are dominated by operational costs of power and manpower.

1) Operational Costs

Operations costs are provided assuming steady-state 24/7 operation. Operational costs do not included personal spikes estimated for facility preparation and setup. The estimates also assume using the maximum capability of the facility, which is the higher power demand case. Assumptions include an electricity and labor costs associated with the Tennessee Valley. Additional trades studies were performed with higher labor and electricity costs associated with California and Cleveland. Early assessment were also performed to compare a regenerative versus consumable coolant option. As has been seen in other current facilities the use of regenerative system can provide significant savings. For the recommended facility, the use of a regenerative capability paid for the cost of regenerative system in approximately 1 year and would result in savings in excess of the total capital investment of the entire facility in less than 5 years. The recommended facility all inclusive operations costs with a 200kW thruster and maximum pumping capabilities is approximately \$30,000 a week or ~\$1.5M per year if operating a stead state long duration test. Operations costs would be significantly lower if much lower pumping speeds are required for individual tests.

2) Capital Investment

Costs were determined individually for the shell, the door as a separate line item, the helium and liquid nitrogen engines, shrouds, vacuum jacketed lines throughout, a beam dump sized for 200kW operation, an initial suite of diagnostics, facility checkout and calibration all within the initial capital investment. Note the facility costs are without reserves or costs of land purchase. The recommended facility initial capital investment is approximately \$24.7M.

VI. Conclusions and Summary

A study was performed to understand sensitivities and provided a recommendation for a new space simulation facility. A series of trades were completed using the HAP modeling tool with an objective to improve performance over the state of the art civilian test facility. Analyses indicate that maximum pumping performance for a given diameter chamber is achieved with a maximum density of pumping surface. The use of a regenerative cryogenic system will pay for itself in only one year of operation. Operations costs are driven by electricity and labor.

A recommended chamber design is provided with a diameter of 15 meters and a length of 20 meters. The recommended facility includes 48 cryopanels, each measuring 4.6 meters in length and 1.6 meters in width with approximately 5m^2 of helium cooled surface reaching the desired pumping temperatures. While operating thrusters state-of-the-art thrusters, the facility has potential achieve 10^{-7} Torr at the chamber wall and achieve pressures an order of magnitude lower than NASA GRC's State of the Art VF-5 facility at a distance of 1 meter from the thruster. Without reserves, the capital investment for the recommended facility is approximately $25M with an operating cost of approximately $1.5M per year.

Acknowledgments

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