Vacuum Pump-Down of the Annular Insulation Space for Large Field-Erected Liquid Hydrogen Storage Tanks

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Abstract. Insulation systems are critical to liquid hydrogen storage tank performance. Tanks in the capacity range of 100 to 1,000 m^3 are typically shop built and designed with high-vacuum (HV) multi-layer insulation (MLI), whereas storage vessels larger than 1,000 m^3 are typically field-erected and supplied with bulk fill insulation working at moderate vacuum (MV) levels (1-100 millitorr). For large, field-erected vessels, two types of bulk fill insulation typically used: perlite and hollow glass microspheres (glass bubbles). Selection of either material is driven by a tradeoff between CAPEX and OPEX, such as the material and construction cost versus operating thermal performance and maintenance. In either case, the vacuum level needed to achieve optimum performance is likely to drive the field testing and commissioning portion of the construction schedule. A primary goal of this paper is to present practical experience and data for warm vacuum pressure (WVP) and cold vacuum pressure (CVP) levels. Recommended WVP levels needed prior to cooldown consider both perlite powder and glass bubbles. Pumping time expected to achieve target vacuum levels, considering a variety of factors, is also discussed. Recommendations for a standard practice in vacuum-insulated tank commissioning are based on historical NASA data, and those collected during recent projects.

1. Introduction

Except for special cases, such as space launch vehicle flight tanks or one-off test apparatuses, all liquid hydrogen (LH_2) storage tanks, regardless of size, have been of double-walled construction and employed vacuum-insulation. This vacuum-insulation system (VIS) is necessary for two primary reasons: 1) To improve thermal performance, thereby reducing boiloff losses, and 2) To eliminate the liquefaction of air or purge gas that would take place at the 20 K inner tank surface in a non-vacuum configuration.

Choosing a particular VIS depends on a variety of factors, most notably the physical scale of the LH_2 storage tank, and has consequences not only on the ultimate thermal performance, but also on the commissioning of the vessel. Tanks within the range of 100 m^3 to 1,000 m^3 are typically shop built—meaning that the entire fabrication takes place under-roof, in a controllable environment—and are horizontal-cylindrical geometries, whereas tanks larger than 1,000 m^3 are generally spherical, and erected outdoors in the field. The impact of a shop-built versus field-erected LH_2 tank on VIS-related considerations is not insignificant, as the former allows for higher cleanliness levels during fabrication, as well as the ability to perform adequate bake-out procedures to drive moisture out of the annular space; both of which help to achieve high vacuum (HV) levels under 1 millitorr to improve VIS performance, and decrease the pumping time required. In field-erected applications, the large physical scales preclude tight control of surface cleanliness and bake-out, hence the operational vacuum levels are typically higher, in the 1-100 millitorr range, or moderate vacuum (MV). Additionally, the annular volume of field-erected tanks can be very large, which impacts the pump-down time required.

For shop-built tanks of cylindrical geometry achieving HV allows for the use of high-performance Multilayer Insulation (MLI); whereas for field-erected vessels bulk-fill insulations such as perlite or hollow glass microspheres (glass bubbles) operating at MV level are employed. High surface area bulk-fill materials present additional challenges related to vacuum pump-down and achieving the operational target due to their propensity to hold moisture, and the necessity for proper filtering.

In general, the pump-down is affected by numerous factors, including:

- Physical scale of the LH_2 tank
- Type of insulation material and bulk density
- Size, number, and location of vacuum pump-out ports
- Filtering scheme
- Initial commissioning or maintenance
- Annular space cleanliness
- Shop-built vs. field-erected
- Insulation installation procedure
- Vacuum pumping system(s)
- Environmental conditions (temperature)
- Annular vacuum plumbing layout
- Moisture content of insulation material
- Hermetic seal of inner and outer tank

Operational vacuum level is divided into two categories according to ASTM C1774: Warm Vacuum Pressure (WVP), which is the target/range when pumping down the annular space while the tank is warm (i.e. prior to introducing any LH_2 into the vessel), and Cold Vacuum Pressure (CVP), the value/range once the tank has been fully cooled down. The decrease from WVP to CVP is highly significant and provides an important VIS performance boost for LH_2 tanks. Therefore, proper conditioning to WVP targets is a crucial step in the commissioning process, especially for large, field-erected tanks.

At the time of this report, NASA Kennedy Space Center (KSC) in Florida owns and operates the largest field-erected LH_2 tanks in the world [1]. Located at launch pad 39B, and presented in figure 1, two LH_2 spheres are employed to support space launches: a perlite-insulated vessel with 3,200 m^3 usable capacity, built in the 1960s to support the Apollo moon program, and a recently completed 4,700 m^3 capacity, glass bubble-filled tank to support the Artemis program and Space Launch System (SLS).

Figure 1. LH_2 Spheres at Pad 39B at NASA: Apollo-Era (left), and New Construction (right)

Drawing from the 60+ years of operational experience with the 3,200 m^3 vessel at KSC, the design, construction, and initial vacuum pump-down of the new 4,700 m^3 tank, as well as other recent projects, this paper aims to establish a baseline understanding on the topic of VIS and vacuum pump-down for large, field-erected LH_2 storage tanks. Common vacuum-insulation materials will be discussed, as well as factors contributing to pump-down inefficiency and how to combat them, and expected timetables based on practical experience.

2. Vacuum Insulation System Materials

Two types of bulk fill insulation have been used in the evacuated annular space of large field-erected liquid hydrogen storage tanks in the United States: expanded perlite (~128 kg/m^3 bulk density) and glass bubbles (3M brand, K1 type). The former is the industry standard and has been used for over 60 years in over 100 liquid hydrogen storage tanks, whereas the latter has seen much development over the past 20 years [2,3], and has culminated in implementation into the new 4,700 m^3 sphere at KSC [4].

Perlite is typically expanded from a dense ore on-site using a large furnace and dried while still hot prior to placement in the annular space—helpful factors that combat moisture intrusion, which slows vacuum pump-down. Perlite is commonly used as insulation in other refrigerated gas storage such as double wall liquefied petroleum gas (LPG) and liquified natural gas (LNG) storage tanks, therefore the supply chain for ore and the construction equipment for installation are mature. Glass bubbles, conversely, require centralized production facilities, and must be shipped to the tank construction site. Once on-site, the product can be loaded directly into the annular space from the trucks if the product is dry, or through intermediate processing equipment if the product requires additional drying.

Either perlite or glass bubbles can be used to insulate field-erected LH_2 storage tanks, but tradeoffs must be considered carefully. The choice of insulation material impacts the storage tank construction schedule, the capital cost of storage, and the operating costs of storage through heat leak and long-term maintenance. All three cost components must be balanced to achieve the best project economics and storage performance. Perlite raw material has relatively low cost, the supply chain is mature, installation methods are proven, and straightforward procedures are developed for final annular space vacuum pumping. These advantages drive a faster construction schedule and lower capital cost of storage. The most significant advantage of glass bubbles is the higher thermal performance—proven to reduce LH_2 boiloff by 46% versus perlite in field testing [4]—which leads to lower, long term operating costs.

An additional advantage of glass bubbles over perlite is the relative flowability of the bulk product. Macroscopically, both materials are a white powder, however, at the microscopic level expanded perlite is highly porous, whereas glass bubbles are uniform, perfect spheres with an average diameter of 65 microns. Thus, when aerated, glass bubbles flow more like a liquid than a powdered product, which facilitates the complete filling of the annular space as the material conforms to/around complex geometries formed by structural supports, piping, etc. Preventing insulation voids in the annular space is of utmost importance, as the thermal performance of the VIS will be affected. This fact was born out on the 3,200 m^3 Apollo-era sphere at KSC, as a large perlite void was present on the upper part of the tank which led to excessively high boiloff. The void was repaired in 2010, resulting in a decrease in boiloff from roughly 3,800 L/day to 800 L/day [5,6].

2.1 Supply Chain and Logistics

As previously mentioned, perlite insulation arrives on the jobsite as a dense ore and then "popped" using large furnaces and blowers which simultaneously expand the perlite into a much less dense granular product and convey it into the pressure differential trailers prior to placement in the annular space There are many sources globally for this ore, the choice of which is usually driven by the location of the jobsite and shipping logistics. Glass bubbles on the other hand arrive at the jobsite via truck in their final low-density form. Therefore, the shipping volumes to the jobsite are much higher, and should be considered in logistics costs. Additionally, the global supply chain for glass bubbles is not as mature as perlite, hence, product availability needs to be considered depending on the jobsite location.

As a point of reference, the annular space of a 5,000 m^3 LH_2 storage sphere can take anywhere from a few days to 2 weeks to fill with perlite, and the new 4,700 m^3 sphere at KSC required 62 truckloads of glass bubbles over a 1-month period to fill the annular space.

3. Warm and Cold Vacuum Pressures

The choice of WVP target can have a significant impact on the overall vacuum pump-down timeline and construction schedule as the process becomes inefficient as the pressure decreases. For large, field-erected LH_2 storage tanks, a realistic WVP target is 50 millitorr. Upon cool down of the system, the vacuum pressure will steeply decrease to the steady-state, operational CVP. This decrease can be significant—up to an order of magnitude or more [3]—and provides a crucial VIS performance boost which can be expected to bring the vacuum levels to a range that allows high performance of the bulk fill insulation. Specifying a WVP target that is too low can result in unnecessarily long pump-down times that does not provide a significant performance improvement.

4. Key Factors Affecting Vacuum Pump-Down

4.1 Cleanliness/Dryness of the Annular Space

The cleanliness of the annular space is paramount in achieving the target WVP. Time to ensure a 'hydrogen clean' environment must be accounted for in the overall schedule. The inner surface of the carbon steel outer sphere, the outer surface of the stainless-steel inner sphere, and the outer surface of the annular space piping should be cleaned to ensure all surfaces are free of all dirt, debris and foreign matter including scale, flux, and weld splatter. Hydrocarbons should be removed from the surfaces using either a solvent or detergent. After cleaning is complete and prior to the initial vacuum pump-down, the annular space should be purged with dry nitrogen or dry air to ensure all moisture has been removed. If the annular space is not sufficiently clean and dry, the target vacuum level may never be reached during final pump-down because the contaminated surfaces will continue to off-gas which will increase the pressure in the annular space.

4.2 Insulation Moisture Content

Moisture inside the annular space is a primary impediment to vacuum pump-down, therefore insulation materials must be installed into a dry annular space with at least -40°C dew point. In the case of perlite, popping on-site and introduction into the drying trailer while hot helps reduce the required drying time. However, special jobsite drying operations should be planned in the event glass bubbles arrive with a dew point greater than -40°C. Jobsite drying operations using intermediate equipment between the trucks and tank were employed for filling the KSC sphere, which added significant schedule delays that would be avoidable if the glass bubbles were dried to -40°C dew point at the point of manufacturing and maintained during shipment and storage. If the glass bubbles are dried at site the average drying time is significantly longer than perlite because the glass bubbles are not hot at the time of delivery and installation. Since there may be long breaks between truck shipments, after the last trailer of the day has been installed the annular space should be back purged with dry nitrogen and then evacuated while waiting for the next shipment of glass bubbles.

4.3 Vacuum Plumbing Configuration

Design of the vacuum plumbing, both internal and external to the outer vessel, can play a key role in the pump-down process. Large, field-erected LH_2 tanks tend to employ a distributed vacuum manifold inside the annular space consisting of large diameter (i.e. >76 mm) piping with either sintered or perforated sections with wrapped filter blankets to allow gas to pass. This manifold generally terminates at a single pump-out port on the outer tank where the vacuum pumping system interfaces. The physical size/length of the internal manifold affects pump-down. Providing additional pump-out ports that access the manifold could reduce pump-down times, however this increases system complexity and additional leak points.

On the external pumping side, it is important to maintain at least the same physical flow diameter of the pump-out port when interfacing the pumping system, and to position the pump(s) as close to the port as possible. Adding long sections of hose between the port and pump(s) increases flow conductance, which negatively impacts pump-down times.

4.4 Vacuum Pumping Systems

In general, two different pumping regimes must be navigated to pump-down the annular space to the WVP target: Ambient to >500 mTorr, and <500 mTorr. The higher-pressure range can be handled using a variety of different pumping technologies, such as oil-filled rotary vane, roots-type, or dry scroll pumps, with large capacities (i.e. >1000 L/min). Multiple units placed in parallel can accelerate the process. As moisture can be a primary constituent of the exhausted gas >1 torr, if using an oil-filled pump regular changing of the oil will be necessary to prevent damage to the unit.

Once below 500 mTorr, turbomolecular pumps can be additionally employed to condition down to the WVP target. Again, multiple turbomolecular pumps in parallel can aid in accelerating the process, however, most of the overall pump-down time will likely be spent in the lower pressure regimen.

5. Case Studies

5.1 NASA Stennis Space Center 218 m^3 Sphere, Glass Bubbles

In 2008, a 218 m^3, perlite-insulated LH_2 sphere located at NASA Stennis Space Center (SSC) in Mississippi was retrofitted with glass bubbles as part of on-going research efforts into the use of the material for LH_2 applications [3]. The inner and outer diameters of the vessel are 7.3 m and 9.3 m respectively, giving an annular volume of roughly 200 m^3. The perlite was drained and replaced with four trailer loads of 3M type K1 glass bubbles, without any intermediate drying steps (i.e. raw glass bubbles were conveyed directly from the trailers into the annular space).

A single, Kinny brand KTC-60, oil-filled rotary vane vacuum pump (102 m^3/hr nominal pumping capacity) was used for pump-down. Active pumping took place during first shift, five days per week, with occasional downtimes related to external factors. Initial pump-down from ambient pressure to roughly 5 torr was rapid, achieved within the first week of pumping. Depressurization slowed thereafter due to the removal of significant quantities of moisture. The vacuum pump oil was changed regularly over the next month, which slowed operations, but ensured the vacuum pump would not be damaged due to water intrusion. Moisture removal significantly decreased <0.1 torr, and after roughly 42 days of active pumping, the average annular vacuum level, taken across the top and bottom sensors on the tank, was 200 millitorr. The WVP target was 50 millitorr, however, due to project scheduling, the decision was made to cease pumping and load the tank with LH_2. Upon cool down, the average pressure dropped a full order of magnitude, from 200 millitorr to roughly 10 millitorr. Figure 2 shows the SSC sphere during glass bubble fill, and the vacuum pump-down curve.

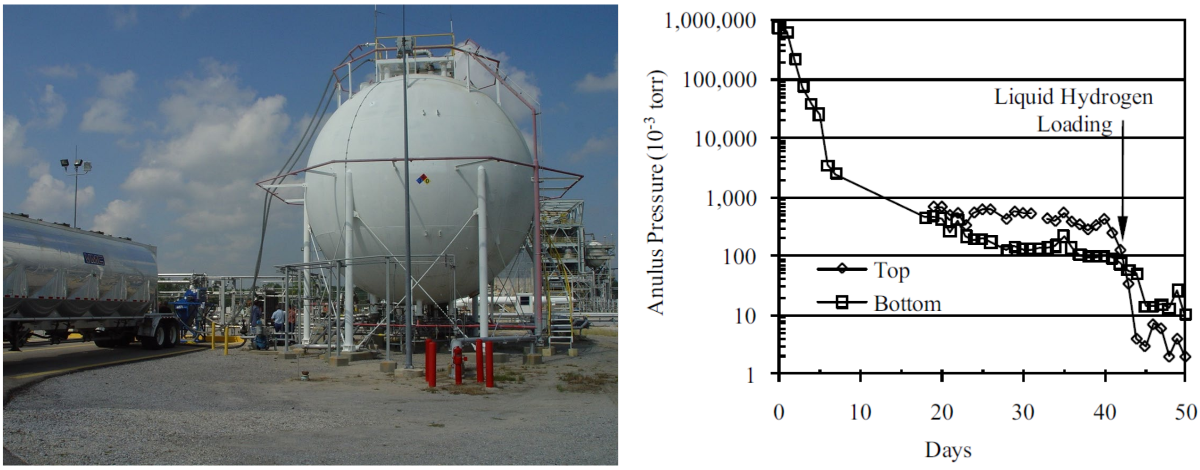

Figure 2. 218m^3 LH_2 Sphere at NASA-SSC During Glass Bubble Filling [3] (left); Vacuum Pump-Down Curves at the Top and Bottom Sensors for SSC Sphere [3] (right)

The case of the 218 m^3 SSC tank reveal two key facts: 1) maintaining dryness of the insulation material and annular space is extremely important, as vacuum pump-down was hindered by having to remove large amounts of moisture, and 2) the decrease from WVP to CVP is significant, even when starting from a relatively high WVP. The decision was made in advance to not perform any drying steps at all – to form experience for the worst-case situation.

5.2 NASA Kennedy Space Center 3,200 m^3 Sphere, Perlite

Due to the existence of a void in the perlite insulation of the 3,200 m^3 LH_2 sphere at Pad B at NASA-KSC, the vacuum was broken, and the void was fixed in 2010. The inner and outer diameters of the vessel are 18.7 m and 21.6 m respectively, with an annular volume of roughly 1,642 m^3, and high-density grade expanded perlite (~144 kg/m^3) was used as the insulation material.

As the repair was a maintenance-type operation, the cleanliness/dryness of the annular space and existing perlite was already established. Care was taken when breaking the vacuum (done with dry nitrogen), conveying the perlite (popped off-site and introduced into the annular space with dry air), and sealing the annular space to maintain dryness. Vacuum-pump-down began in 2014, continuing over the course of four months, at which point the tank was refilled with LH_2 and remains in operation today.

A variety of vacuum pumps/configurations were employed during pump-down of the tank—the details of which were previously reported [6]—including dry scroll and turbomolecular units, drawing from a single 20.32 cm diameter pump-out port connected to an internal manifold distributed throughout the annular space. The large scroll pumps brought the vacuum from ambient to an average of 245 millitorr, taken across three sensors located at the top, middle, and bottom of the tank, in 449.5 hours of active pumping time. A turbomolecular pump was then installed in parallel, and the vacuum was drawn down to 70 millitorr over an additional 132 hours of pumping. The scroll pump was swapped out with an additional turbomolecular unit, and the vacuum was decreased to a steady 45 millitorr over the course of 24 hours of pumping. The annular space was then sealed and monitored over two weeks, showing a decay of only 3-5 millitorr, at which point it was deemed ready for LH_2 fill, which took place in December 2017. The decrease from WVP to CVP was not captured during the operation; however, periodic readings are taken, and the operational pressure of the annular space is roughly 5 millitorr.

Figure 3 presents the 3,200 m^3 LH_2 sphere at KSC, and the pump-down curve, averaged across all three sensors, associated with the perlite void repair operation—the dotted part of the curve >1,000 millitorr are approximate values, as the pressure was outside the calibrated range of the vacuum reader.

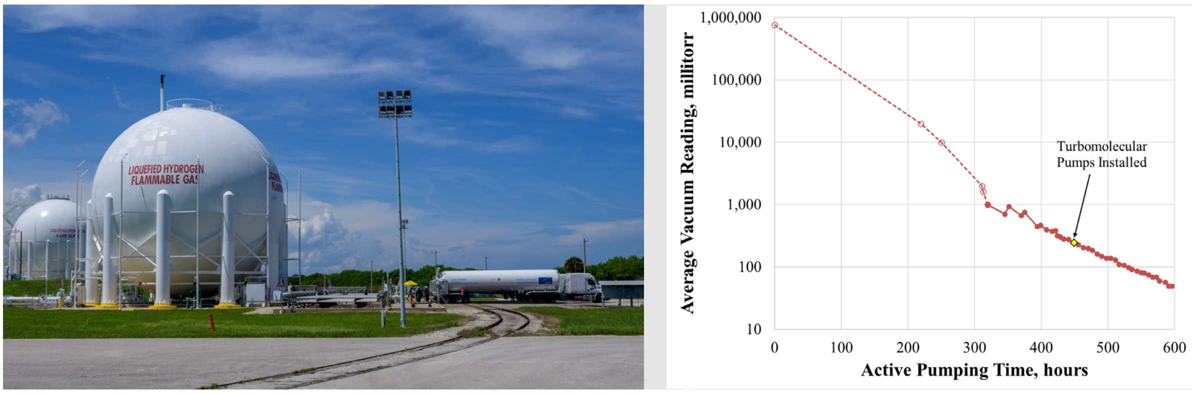

Figure 3. 3,200 m^3 LH_2 Sphere at NASA/KSC During LH_2 Fill Operations (left, foreground); Average Vacuum Pump-Down Curve Following Perlite Void Repair (right)

The impact of maintaining dryness within the annular space and insulation material is evident from the pump-down curve in figure 3, with no significant plateauing of the pressure around 1,000 millitorr due to moisture removal as was seen during evacuation the 218 m^3 tank at SSC.

5.3 NASA Kennedy Space Center 4,700 m^3 Sphere, Glass Bubbles

Construction of a new, 4,700 m^3 LH_2 sphere at Pad B at NASA/KSC began in 2019 and was completed in 2022. Seen in the right of figure 1, and in the background in figure 3, the new tank is located adject to the 3,200 m^3 sphere, and is the same general design expect for the insulation material, which is K1 type glass bubbles instead of perlite. The inner and outer diameters of the vessel are 21.9 m and 25.3 m respectively, with an annular volume of approximately 2,980 m^3.

As with the 218 m^3 tank at SSC, the glass bubbles were transported in tanker trucks to the construction site. However, instead of conveying the bulk product directly from the trucks into the annular space, the bubbles were first dispensed into a stationary tank, dried with nitrogen gas for 24-30 hours, and then conveyed to the storage tank. This operation was conducted as a batch process, at a rate of two trailers per day. Between shipments the annular space was pumped down to a soft vacuum (~100 torr) to help settle the bubbles, and aid in keeping the space clean and dry.

Initial vacuum pump-down began the first week of January 2022, with numerous down-times due to various Pad operations. Two roots-style pumps were configured in parallel, which brought the vacuum, averaged across sensors located at the top, equator, and bottom of the tank, to roughly 100 millitorr by the end of February. A single turbomolecular pump was then installed, which slowly began to bring the vacuum level to the original WVP target value of 15 millitorr. After an additional two months of operations the vacuum level had only decreased to roughly 65 millitorr, at which point three additional turbomolecular pumps were installed in parallel to accelerate the pump-down. This addition had little effect, as well as changing out a 101.6 mm vacuum gate valve due to suspicion of leaking and resulted in a plateauing of the pressure at 37.7 millitorr at the end of August 2022—8 months after initial pump-down began. Rotary vane pumps were then installed at each of the three vacuum sensor locations to supplement the four turbomolecular units, the combination of which were allowed to pump 24 hours per day. After roughly 10 days the average vacuum level only decreased to 37 millitorr, at which point it was decided to raise the WVP target to 50 millitorr and proceed with the required 7-day retention test. After 7 days the vacuum increased from 37 millitorr to 57 millitorr, which was accepted by NASA.

WVP was monitored over the course of 10 months, and showed signs of a small, systemic leak as vacuum pressure decayed up to 477 millitorr. Helium mass spectrometer (HMS) leak checking found small leaks at the vacuum lift plate—a pressure relief device that protects the annular space from pressurization—and a threaded sensor port. The leak at the lift plate was due to small amounts of dust on the O-ring that did not allow the O-ring to seal properly. The annular space vacuum was broken using dry nitrogen gas, and the O-ring and threaded sensor were repaired in the summer of 2023. The subsequent pump-down, using a large, roots-style pump, brought the vacuum down from ambient pressure to roughly 70 millitorr in around 16 days of continuous pumping. Initial cool down of the tank and LH_2 fill is scheduled for late 2023. This event highlights the effect that the cleanliness of the vessel and all sealing surfaces can have on the vacuum pump down of the vessel. In this case, the leak was small enough that it was not noticeable during the initial pump down and final vacuum retention test, and it was below the sensitivity range of established HMS leak testing performed in 2022.

5.4 Western New York 1800 m^3 Sphere, Perlite

Construction of a new 1800 m^3 sphere was recently completed in western New York in 2023. The sphere is a similar configuration to previous spheres with an evacuated perlite insulation system. The sphere has an annular space volume of 1,097 m^3. The perlite was expanded on site, dried, and conveyed to the sphere annular space over approximately a one-week period.

After the perlite was installed, pumping began for the final vacuum retention test. A combination of roughing pumps and turbomolecular pumps were used to bring the annular space vacuum pressure from 100 torr to 38 millitorr over a period of approximately 120 hours.

The impact of maintaining dryness within the annular space and insulation material is evident from the results of the final vacuum retention test. During the final vacuum retention test the annular space pressure increase approximately 10 millitorr with a final pressure of 48 millitorr.

6. Rough Estimates for Vacuum Pump-Down

Using the four case studies presented above, table 1 presents rough estimates for pump-down timelines as a function of annular space volume and insulation material, as well as WVP and CVP for each tank. Assumptions were active pumping only during a single work shift of 8 hours, and turbomolecular pump(s) installed around 100 millitorr. CVP values are not available for cases 3 and 4 at the time of this report due to the vessels awaiting initial cooldown and LH_2 fills. Case 3a and 3b refence the initial pump-down of the 4700-m^3 tank at KSC, and pump-down follow leak repairs respectively.

Table 1. Rough Estimates for Pump-Down Timelines

Case Study	Insulation Material	Dry	Annular Volume (m^3)	Active Pump Time vs. Annular Volume (hours/m^3) Ambient to 100 millitorr	Active Pump Time vs. Annular Volume (hours/m^3) 100 millitorr to 50 millitorr	WVP (millitorr)	CVP (millitorr)
1	Glass Bubbles	No	200	1.68	N/A	200	<10
2	Expanded Perlite	Yes	1642	0.27	0.09	45	~5
3a	Glass Bubbles	Yes	2980	0.13*	0.26*	37	---
3b	Glass Bubbles	Yes	2980	0.09	0.04†	66	---
4	Expanded Perlite	Yes	1097	0.04	0.06	48	---

* Initial pump-down, with a small leak discovered late in the operation
† Pump-down from 100 millitorr to 66 millitorr

5. Conclusion

Topics related to the vacuum insulation systems and pump-down of the annular space for large (>1,000 m^3), field-erected liquid hydrogen storage tanks were presented and discussed. Four different cases of existing spherical tanks were examined, ranging in scale from 4,700 m^3 to 218 m^3 usable LH_2 volume, with two different insulation materials: high density (~184 kg/m^3) expanded perlite and 3M K1 type glass bubbles. These cases were used to establish rough estimates for vacuum pump-down timelines to aid in planning for new and existing LH_2 storage tank projects. The data over multiple projects show it takes approximately 2 to 4 times longer to pump-down glass bubble filled annular space compared to perlite filled annular space, all other factors being equal. The data and practical field experience also demonstrate the critical importance of annular space cleanliness during construction, insulation material dryness, and well-designed and tested pumping arrangements and field procedures.

6. References

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