Space Propulsion 2018

BARCELO RENACIMIENTO HOTEL, SEVILLE, SPAIN / 14 – 18 MAY 2018

Review of ATK Diaphragm Tanks – An Update

Walter Tam[(1)], Gary Kawahara[(2)], Kamil Wlodarczyk[(3)], Hector Gutierrez[(4)], and Daniel Kirk[(5)]

[(1)]ATK Space Systems, Inc., 6033 E. Bandini Blvd, Commerce, CA U.S.A 90040, walter.tam@orbitalatk.com
[(2)]ATK Space Systems, Inc., 6033 E. Bandini Blvd, Commerce, CA U.S.A 90040, gary.kawahara@orbitalatk.com
[(3)]ATK Space Systems, Inc., 6033 E. Bandini Blvd, Commerce, CA U.S.A 90040, kamil.wlodarczyk@orbitalatk.com
[(4)]Florida Institute of Technology, 150 West University Blvd, Melbourne, FL 32901, hgutier@fit.edu
[(5)]Florida Institute of Technology, 150 West University Blvd, Melbourne, FL 32901, dkirk@fit.edu

Keywords

Diaphragm, Diaphragm Tank, Positive Expulsion

Acronyms

AM = Additive Manufacturing
CFD = Computational Fluid Dynamics
DSCS = Defense Satellite Communications System
GEO = Geosynchronous
GPS = Global Positioning System
LEO = Low Earth Orbit
MEO = Medium Earth Orbit
MEOP = Maximum Expected Operating Pressure
PMD = Propellant Management Device
TDRS = Tracking and Data Relay Satellites

Abstract

Propellant tanks with elastomeric diaphragms to provide positive propellant expulsion have been the space propulsion workhorse from the mid-1960s. A diaphragm tank's simple construction and easy operation had always been attractive to space system developers and operators. Missions from low Earth orbit (LEO) satellites, medium Earth orbit (MEO) satellites, geostationary orbit (GEO) satellites, satellite constellations, space-based observatories, and planetary explorers had all incorporated diaphragm tanks to meet operational requirements. Over 1200 diaphragm tanks supported a multitude of space missions, and there are no signs of easing demand.

In this summary paper, we revisit the continued development of diaphragm tanks within the last two decades, provide useful information, dispel common misconceptions, fill the knowledge gap in the literature, and bring the readers up to date on recent research and innovations on diaphragm tanks. The paper has four sections. Section 1 is an introduction to diaphragm tanks. Section 2 contains diaphragm tank updates and useful information on incorporating diaphragm tanks into propulsion systems. In Section 3, we present research or development efforts to acquire diaphragm and diaphragm tank knowledge within the last decade, and introduce new tools and techniques to enhance product quality. In Section 4, we conclude with a discussion on the future direction of the diaphragm tank market.

1. Introduction

Propellant tanks with elastomeric diaphragms had been the space propulsion workhorse from the early days of the space age. ATK Space Systems Inc., a wholly owned subsidiary of Orbital ATK and previously known as PSI, TRW PSI, and ATK PSI Operations, started manufacturing diaphragm tanks in 1967. Famed Jet Propulsion Laboratory (JPL) solar system explorers such as Mercury, Pioneer, Viking, and Voyager all incorporated diaphragm tanks for propellant storage and expulsion. Diaphragm tanks' proven reliability led to their inclusion in other important government programs such as Global Positioning System (GPS) Block I and Block II, Tracking and Data Relay Satellites (TDRS), Defense Satellite Communications System (DSCS), and the Space Shuttle. For more than fifty years, ATK diaphragm tanks supported hundreds of space missions on board launch vehicles, upper stages, space platforms, and commercial, civil, and government spacecraft. As of April 2018, diaphragm tank delivery exceeded 1210 units. Our worldwide customer base includes organizations in North and South America, Asia, and Europe.

Despite their extensive usage, misconceptions regarding diaphragm tanks continue to exist. Several reasons contribute to these misconceptions. First, there are many possible diaphragm configurations, and it is not possible to identify a tank's internal configuration by examining the tank shell exterior. Second, there are few literature sources on diaphragm tank design and manufacture. Tank manufacturers are typically small organizations whose primary focus on operations often prevents them from engaging in publication activities. Third, academic studies on diaphragms often examine a single variable or assume idealized configurations, whereas diaphragm behavior is a function of multiple factors that interact with each other, thus making the task of characterization challenging.

In this paper, we take a holistic approach to examine the multiple variables that might affect diaphragm behavior. Our motivation for this diaphragm tank update came from years of answering questions about diaphragm tanks before, during, and after contract execution. We dispel many common misconceptions by summarizing the basic characteristics of diaphragm tanks. In addition, ATK funded several diaphragm characterization studies to further our understanding of diaphragm behavior and fill the knowledge gap. We use this forum to share our study results. Finally, as heritage is crucial to our customer base, we take this opportunity to update our diaphragm tank design and flight heritage.

As a provision, we limit the applicability of this paper's content to ATK diaphragm tanks only. We do not have detail knowledge of tanks designed by others. Many points we make might not be valid on tanks made by other manufacturers, and it is not appropriate to generalize our discussion for all diaphragm tanks.

1.1 Overview

Diaphragm tanks are pressure vessels for the storage of liquid propellant in space application. About 99% of diaphragm tanks delivered were for hydrazine storage. Other uses include storage of water, ammonia, and green propellants.

There are two compartments within a diaphragm tank: a propellant compartment and a pressurant compartment. The elastomeric diaphragm is the physical barrier separating the two compartments. Typically, we design diaphragm tanks for blowdown systems. Occasionally, some users might fill the entire tank with propellant and use a separate tank for pressurant storage. For such a case, we would design our diaphragm compartment capacity at approximately 99% of the total tank volume.

Diaphragm tanks have many advantages. First, they are easy to operate. Principally, the gaseous pressurant exerts pressure against the elastomeric diaphragm and expels liquid propellant through the outlet port. Second, diaphragm tanks are inherently reliable because of their operational simplicity. Third, unlike tanks containing surface tension propellant management devices (PMDs) that require extensive functional validation through analyses, there is no need to perform functional analysis for diaphragm tanks. For these reasons, diaphragm tanks are popular on many LEO, MEO, and exploration missions.

However, there are disadvantages to diaphragm tanks. First, as tank size grows in diameter or height, the diaphragm size must grow accordingly, and the mass increase might render the diaphragm tank option unattractive as compared to a PMD option. Second, there are size limitations. The current equipment produces diaphragms up to 1001 mm (39.4 in) in diameter and 613 mm (24.1 in) in height. Although it is possible to use a larger equipment to mold larger diaphragms, the mass penalty from the larger diaphragms usually does not favor this option.

Tank manufacturing is a small niche market within the larger space industry. There are few market players because the risk is high, the growth potential is small, the competition is fierce, and the organizational performance is often at the mercy of economic cycle and political climate. The conservative nature of end users and spacecraft integrators contribute to a cautious culture that is wary of change. Given this conservative environment, all our diaphragm tanks have similar or identical internal features because flight-proven design is an important contributor to a successful design review. There is little motivation to develop new diaphragm tanks unless there are no other alternatives. During pre-design trade studies, we always start by evaluating the applicability of flight proven designs for a new mission. Customers would only consider developing new tanks when all possibilities of using existing tanks were exhausted. Under these circumstances, most missions would fly derivate tanks from a pool of qualified tank designs. This conservatism is the reason behind the relatively small number of basic diaphragm tank designs. As of April 2017, we delivered 1211 diaphragm tanks in 55 years of operations while developing only 26 families of diaphragm tanks.

1.2 Tank Shell Material

A typical diaphragm tank consists of two key elements: a metal shell and an elastomeric diaphragm. Solution treated and aged (STA) 6Al-4V titanium is the most common tank shell material. Other tank shells include annealed 6Al-4V titanium made from forged domes or spun domes, and composite overwrap. Solution treating the Ti-6Al-4V alloy increases the mechanical strength of titanium alloy by about 30%, making it possible to produce thin shells and reduce mass. The same tank shell technology has been in use for over 50 years, and there is no evidence of any customer withdrawal from this heritage material. There had been attempts to revolutionize the satellite propellant tank market using alternative tank shell materials or manufacturing methods such as spun domes or composites. None had any impactful success. As an example, ATK developed a hybrid shell with annealed spun domes overwrapped with composite in 1999 [1]. The intent was to use low-cost elements to produce a low cost diaphragm tank. After 18 years in production, the end user finally authorized a qualification program to revert the tank shell back to the STA Ti-6Al-4V alloy. The decision to requalify a replacement tank was an economic one, but it underlined the quality, cost, and schedule concerns associated with using supposedly less expensive alternative materials.

The principal contributing factors for the enduring success of STA Ti-6Al-4V tank shells continue to be lowest mass, dependable processes, proven reliability, and unparalleled heritage. Our experience with using spun domes with annealed properties had led to a tank solution with higher mass, more quality issues, and ultimately increased cost. The higher tank mass might have additional impact to end users in the form of higher launch cost. We believe that spun domes bring value to products such as large diameter launch vehicle tanks, but not at the size range for traditional satellite tanks. Decades of organizational learning had convinced us that STA Ti-6Al-4V tank shells offer the highest value to the end users. The space industry's reliance on STA Ti-6Al-4V tank shells for spacecraft application is testimony to their higher value.

1.3 Tank Shapes and Implications

Diaphragm tanks can take on many shapes and sizes. We design the tank shells to meet user specification requirements such as pressure, volume, envelope, and mounting features. The diaphragm configuration is dependent upon the outlet dome configuration and the location of the diaphragm retaining weld. Figure 1 is a photo of diaphragms of various shapes and sizes, including diaphragms with hemispherical heads, ellipsoidal heads, ellipsoidal head with a cylinder extension, and ellipsoidal head with a frustum extension. These are typical shapes, and all diaphragms have custom-design features to enable propellant expulsion.

Figure 1: Various Shapes of Diaphragms

1.4 Characteristics of a Spherical Diaphragm Tank

The most common diaphragm tanks are all-metal spherical tanks made from two hemispherical domes. Figure 2 is a photo of a spherical diaphragm tank welded together with a single girth weld. The inclusion of an elastomeric diaphragm within the shell separates the total internal volume into two compartments: a propellant compartment and a pressurant compartment. The Gas Tungsten Arc Weld (GTAW), conducted within a weld chamber in an inert gas environment, is a proprietary process that retains the elastomeric diaphragm and seals the two compartments without damaging the rubber. This diaphragm sealing process has been in use from 1967 to the present day.

Figure 2: A Spherical Diaphragm Tank with a Single Closure Weld

A diaphragm within the spherical tank can take on limitless number of configurations during expulsion. However, the diaphragm's as-molded natural position is the same as its fully expelled position within a tank as depicted in Figure 3a. This is the diaphragm position immediately prior to propellant loading and the final position at the conclusion of a mission with all propellant expelled.

The introduction of fluid into the propellant compartment would reverse the diaphragm as depicted in Figure 3b. When the propellant compartment is full, or when the diaphragm fully reverses, the diaphragm in a spherical tank typically does not touch the pressurant compartment dome as depicted in Figure 3c. At this fully reversed diaphragm position, the typical propellant volume is about 75 to 90% of total tank volume. This capacity figure is tank design specific, and varies by a number of factors such as the tank diameter and the position of the diaphragm.

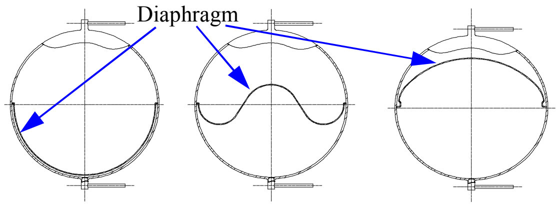


Figure 3a Figure 3b Figure 3c

Figure 3: The Various Diaphragm Positions within a Spherical Tank

1.5 Derivative Tanks with Diaphragm Support

The diaphragm position in Figure 3c is vital for blowdown. Most diaphragm tanks are blowdown tanks, and some gas volume in the pressurant compartment is necessary to enable blowdown. The Figure 3c tank design ensures minimal diaphragm mass while meeting all user specification requirements, including propellant volume. In this optimized design, tank mass is a major focus. On many missions, a low tank mass is critical. Some customers prefer or insist upon a minimal mass approach to tank design, especially given the large expenditures on a qualification program. Figure 4a is an example of a spherical tank designed for blowdown and minimal diaphragm mass. Figure 4b is the same tank with only the expulsion assembly shown. Note the diaphragm is unable to touch the pressurant dome in its fully reversed position.

Figure 4a

Figure 4b

Figure 4: An example of a Spherical Diaphragm Tank Designed for Blowdown

There is one drawback with a tank design having an unsupported diaphragm in its fully reversed position. It is possible that an operator might accidently overfill the propellant compartment and over stretch the diaphragm. While elastomers may have some elongation properties, overstretching the diaphragm beyond its elongation capability could cause damage. Inspection of returned tanks with overstretched diaphragms had revealed small crack-like features on diaphragm surfaces, and the diaphragms could not pass leak tests. Errors of this kind have been rare. Typically, propulsion engineers and technicians have a good understanding of the tank design prior to handling the hardware. Nevertheless, such a design has limited tolerance for operator errors.

Occasionally, some diaphragm tank users might prefer operational assurance over minimal mass. For example, the tank shown in Figure 5 has the same bottom hemispherical dome as the tank in Figure 4b, but it has an ellipsoidal pressurant dome to provide support for a fully reversed diaphragm. This tank shell configuration prevents the diaphragm from overstretching. Such a tank design is not optimal for several reasons. First, the ellipsoidal dome is thicker and heavier than a hemispherical dome with the same pressure rating, and such a tank design would take on a mass penalty. Second, the tank construction requires two different forging configurations. It is difficult to achieve economy of scale given the two different dome configurations, and the tank design would take on a cost penalty. Third, if an integrator uses the entire tank capacity for propellant, then a separate pressurant tank would be necessary for blowdown. The additional pressurant tank would add cost, mass, and complexity to the propulsion system. Nevertheless, other system-level considerations might justify the mass or cost penalties. One justification for such a design is for systems with tanks imbedded deeply into the center of a spacecraft. The cost of removing a damaged tank from deep within a spacecraft, along with the potentially severe schedule impact, might make this kind of tank design attractive. At the initial design trade study, we typically present all the different options for a configuration trade and allow users to make the configuration selection [2].

Figure 5: A Tank with a Conical Dome

There are other ways to support a fully reversed diaphragm. Figure 6 is a diaphragm tank with an internal metallic dome baffle. In essence, the diaphragm tank has three domes. Two of the domes are part of the structural membrane, and the third internal dome is functioning as an internal baffle. The purpose of the baffle is to hold the diaphragm in place during ground handling and launch to prevent unwanted diaphragm and propellant movement. After the spacecraft is on orbit and propellant consumption starts, the diaphragm would move away from the baffle, and the metallic baffle would no longer be functional. Nevertheless, perforations on the baffle continue to enable blowdown operations.

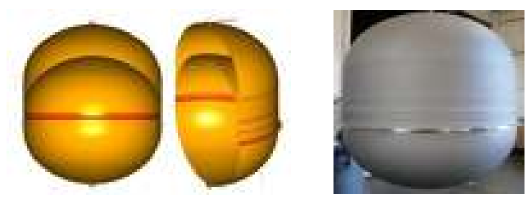


Figure 6: A Diaphragm Tank with an Internal Baffle

1.6 Characteristics of Diaphragm Tanks with a Cylinder Section

Another popular tank configuration is a tank with two hemispherical domes and a cylinder section. Figure 7 includes examples of tanks with a center cylinder and two girth welds. One of these welds is a diaphragm-retaining weld similar to the spherical tank closure weld in Figure 2. The second weld has a different weld configuration and does not include diaphragm-retaining features.

Figure 7: Diaphragm Tanks with Two Hemispherical Domes, a Center Cylinder, and Two Girth Welds

Both tanks in Figure 7 have the diaphragm closure weld on the upper girth weld or the weld furthest away from the propellant port. The diaphragms within these tanks have hemispherical domes with short cylinder extensions. When fully reversed, these diaphragms could touch the pressurant dome as depicted in Figure 8b. This configuration prevents operators from accidently stretching and damaging the diaphragm. It is possible to operate the tank in blowdown by not filling the propellant compartment completely full, thus allowing some pressurant volume for blowdown.

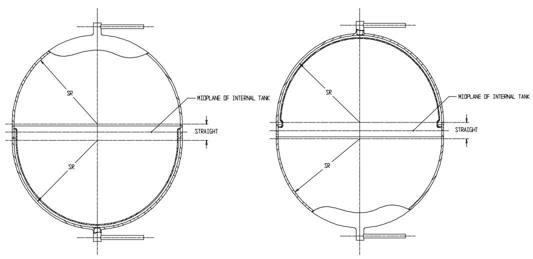


Figure 8a
Diaphragm in Fully Expelled Position

Figure 8b
Diaphragm in Fully Reversed Position

Figure 8: An Example of a Diaphragm Tank with a Cylinder Section

On elongated tanks with two welds, it is possible to have a second diaphragm configuration with the diaphragm closure weld on the lower girth weld or the girth weld closest to the propellant port. Such a diaphragm, when fully reversed, could not touch the pressurant dome. It is the lighter weight version of the two configurations, but it is inherently higher risk because an operator could accidentally stretch and damage the diaphragm during tank fill.

Occasionally, we incorporate a short cylinder extension to one or both domes to enable an elongated tank with a single girth weld. This approach reduces the number of shell components from three to two. The diaphragm tanks in Figures 9a and 9b are examples of one-weld tank construction. The taller dome is the propellant dome with a longer cylinder. The diaphragm configuration in this tank is similar to the one depicted in Figure 8. The low risk approach eliminates the potential for operator errors during tank fill.

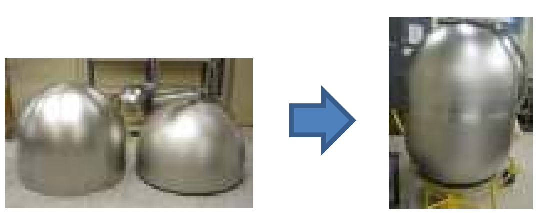


Figure 9a: A Diaphragm Tank Liner with Domes Having Cylinder Extensions and One Girth Weld

Figure 9b: A Diaphragm Tank with One Girth Weld

1.7 Characteristics of Large Diaphragm Tanks

Occasionally, a user might wish to maximize the use of an available envelope. Tanks designed for such a purpose often have ellipsoidal heads. Figure 10a and Figure 11 are examples of an elongated tank with ellipsoidal heads. In addition, the dome extensions have a noticeable conical shape. This is because as tanks grow longer in length, manufacturability considerations start to affect tank shell configuration. These conical domes are indications of this manufacturability constraint. As the diaphragm contour matches the propellant dome contour, both the tank shell and the diaphragm would have conical shapes.

The conical domes place the girth weld at the tank centerline. This physical constraint prevents a fully reversed diaphragm from touching the pressurant dome wall, as pictured in Figure 10b.

Figure 10a: An Example of a Diaphragm Tank Domes with Ellipsoidal Heads and Conical Bodies

Figure 10b: An Example of a Fully Reversed Diaphragm Not Touching the Pressurant Dome

Figure 11: A Liner with Ellipsoidal Domes and Conical Bodies

1.8 Diaphragm Material Status Update

The first-generation diaphragm tanks contained rubber diaphragms with a designation of EPT-10. PSI delivered 123 tanks with the EPT-10 diaphragms installed from 1967 through 1987. Customers using diaphragm tanks with EPT-10 diaphragms included Boeing, ERNO (now Airbus), Hamilton Standard, JPL, Lockheed, Martin Marietta, NASA, RCA, Rocket Research, Rockwell, and TRW.

The second-generation diaphragm has a product designation of AF-E-332 (Air Force Elastomer formulation number 332). Under an Air Force Material Laboratory contract, TRW developed the basic formulation for AF-E-332 in 1971. The rubber formulation underwent extensive characterization, and became the baseline for our diaphragm tanks. From 1972 through April 2018, ATK delivered 1061 tanks with AF-E-332 diaphragm installed. One of the longest flight histories of AF-E-332 is 30 years on the Space Shuttle program. Other programs such as TDRS and DSCS have over 26 years of flight heritage for their AF-E-332 diaphragms. JPL's Voyager probes, launched in 1977, contain diaphragm tanks with AF-E-332 diaphragms. The two Voyager spacecraft continue to find their way through the edge of our solar system after nearly 40 years of operation. The U.S. Air Force GPS I and GPS II satellites all incorporated AF-E-332 diaphragms, and so did the European Galileo satellites. ATK tanks with AF-E-332 diaphragms have been the propulsion workhorse of the space industry. A majority of diaphragm tanks in space use the AF-E-332 diaphragm in support of missions that include solar system exploration; civil, commercial, and military programs; as well as launch vehicle missions.

The AF-E-332 elastomer contains silica fillers to enhance stiffness and promote slosh damping. While most thrusters have robust designs to withstand silica deposits and complete their missions, some thrusters might be overly sensitive to the silica leached from the AF-E-332 rubber. This thruster concern led to the development of a silica-free rubber with a designation of SIFA. SIFA rubber development started in Europe in 1997. Additional funding from ESA through early 2000s solidified the rubber formulation with a rubber designation of SIFA-35. ATK funded additional compatibility and manufacturability studies from early 2000s until the mid-2010s. After extensive characterization that resolved compatibility and manufacturability issues, ATK formally introduced SIFA-35 at the 2006 Joint Propulsion Conference in Sacramento, California. We designed the SIFA-35 diaphragm as a drop-in replacement of AF-E-332 diaphragm. We use the same diaphragm mold to fabricate both AF-E-332 and SIFA-35 diaphragms, and all qualified diaphragm tank shells could accommodate either diaphragm material without affecting qualification status.

The literature contains publications on early SIFA-35 rubber development [3][4]. Table 1 is a summary table comparing the physical properties of AF-E-332 and SIFA-35. As part of a comprehensive material characterization study, ATK commissioned a 20-year rubber immersion program that included AF-E-332, SIFA-35, and other rubber formulations in various propellants such as hydrazine and green propellants. The intent of the 20-year immersion study is to validate new rubber formulations as well as continuing the characterization of existing rubber formulations in new propellants. As new green propellants gain popularity, we intend to publish the immersion study results and present our diaphragm solutions for the new propellants.

Diaphragm rubber development is a resource intensive and time-consuming endeavor. The new elastomer must meet requirements that include chemical compatibility, tensile strength, tear strength, elongation, leak rate, cycle life, stiffness, toughness, durability, dimensional stability, raw material availability, affordability, machinability, and manufacturability. Other characteristics to monitor include compression set, swell, rigidity, flexibility, docility, and malleability. It is a complex technical problem requiring multiple iterations to reach an optimized solution. After formulation development, an elastomer candidate must undergo long duration immersion tests to confirm long-term compatibility with the intended propellants. Financially, the consideration for a new elastomer formulation development must support the business goal of supplying propellant tanks, and the return on investment must justify the high expenses and long-term commitment. Lastly, market conditions must be suitable to support product introduction. In the space industry, this could mean years of positioning and waiting for all the market conditions to align before the product introduction.

Furthermore, market forces are introducing new uncertainties to the rubber development process. The banning of hydrazine in Europe, the introduction of new green propellants in Europe and the United States, and the growing small satellite market are changing market dynamics and affecting business models, including the course of new elastomer development. Our continued development of new elastomers must address the resource limitations, the time commitments, and the alignment with constantly changing market forces. While the technical challenge might be formidable, the process of navigating through the dynamic marketplace is often the greater challenge.

Table 1: A List of Physical Properties of AF-E-332 and SIFA-35.

	MIL-R-83412A	AFE-332	SIFA-35
Original physical value			
Tensile Strength, psi, min.	1650	2253	2893
Elongation, %, min.	260	372	492
Tensile Stress (modulus), psi at 100% elongation	1200 ± 250	1600	1080
Hardness , points	90 ± 5	90	90
Tear Strength, lb/in, min.	300	516	330
Temperature retraction, 10% (TR-10), °F, max	-30	Not performed	Not performed
Dry heat resistance, 70 hr @ 257 °F			
Tensile Strength Change, %, max.	-20	n/a	n/a
Elongation Change, %, max.	-30	n/a	n/a
Hardness Change, points, max.	+5	n/a	n/a
Fuel resistance, Hydrazine, 96 hours @ 160 °F			
Compatibility, Pressure Rise, psi, max	2	< 2 (2)	< 2
Tensile Strength Change, %, max.	-20	-10.9 (4)	-4
Elongation Change, %, max.	-20	-15.9 (4)	-21 (1)
Volume Change, %, max.	3	2.15	1.92 (1)
Compression set in hydrazine, %, max.	25	20.2 (3)	16.8 (3)

(1) Samples immersed for 192 hours
(2) Chromatographic evaluation
(3) Due to large quantity of hydrazine required, we performed this test in air for 22 hours @ 70˚C (158°F)
(4) Test performed using ASTM D1708-93 micro samples

1.9 Tank Manufacturing Tolerance and Tank Mass

ATK's tank shell manufacture follows the conventional machining methodology. However, we design and machine to tight tolerances in order to minimize tank shell mass. Ideally, customers would want us to machine shells from nominal to minimum wall, whereas our machinists typically machine to the upper end of the thickness range. Similarly, diaphragm fabrication adheres to a set of established tolerances, and we produce diaphragms at nominal thickness.

During tank design, we always generate a not-to-exceed mass, and this maximum tank mass appears on test procedures and data sheet. However, exceeding the maximum mass is not a violation of tank design. It merely signals that the tank is heavy. In practice, we rarely encounter such an issue. Typically, the actual tank mass is between 3 to 12% under the *maximum* or *not-to-exceed* mass. Incidentally, this condition is applicable to all ATK tank types, including PMD tanks.

1.10 Summary of Tank Families

Currently, ATK has 26 families of diaphragm tanks. Tank sizes range from ∅68 mm to ∅1021 mm (∅2.7 in to ∅40.2 in) in diameter and up to 622.7 liters (38,000 in^3) of total tank volume. Within each tank family, there might be multiple qualification programs to develop variants or derivatives. Table 2 is a summary of diaphragm tank sizes. We are currently under contract to develop a new tank size in the ∅762 mm (∅30 in) range, but we have no details to provide on this 27th tank family at the publication of this paper. All the diaphragm tanks use reversing diaphragms for functionality. Table 2 includes a column identifying whether a diaphragm, when fully reversed, could touch the pressurant dome.

A majority of diaphragm tanks manufactured are derivative tanks. Using derivative tanks is an effective way to reduce hardware acquisition cost. However, using derivative tanks has drawbacks. One major drawback is the potential for not obtaining an optimal tank solution as compared to custom designing a new tank to optimize fit and function. Another disadvantage is that the qualified environment might not envelop the new mission environment, and a proto-qualification test program might be necessary to supplement qualification analysis.

In Table 2, we further identify the estimated propellant compartment capacity and qualified propellant volume. On blowdown systems, diaphragm tank users would fill the propellant compartments partially to facilitate blowdown. It is possible to load more propellant than previously qualified, but it would affect the blowdown ratio and qualification status. To qualify a derivative tank for a new mission, a structural analysis is necessary as a minimum, and an accompanying protoflight vibration test might be necessary to complement qualification.

Table 2: ATK Diaphragm Tank Summary

No.	Size Description	Qualifying P/N	Derivative P/Ns	Qual Test Report	Total Tank Volume	Ref. Propellant Compartment Volume	Ref. Qualified Propellant Volume	Diaphragm Supported When Fully Reversed?
1	Ø67.6 mm ID x 80.5 mm Long, (Ø2.66" ID x 3.17" Long)	80575-1	None		0.2 liters (11 in^3)			No
2	Ø112.0 mm ID x 225.8 mm Long, (Ø4.4" ID x 8.89" Long), polar bosses	80588-1	None	56-000338	1.3 liters (80.5 in^3)			No
3	Ø235 mm ID x 414.3 mm Long (Ø9.17" ID x 16.31" long), polar bosses	80608-501	None		13.6 liters (830 in^3)	99%		Yes
4	Ø239.0 mm ID (Ø9.41" ID) sphere, bosses	80156-1		56-000044	6.8 liters (415 in^3)	85%	3.5 kg (7.8 lb_m)	No
	Ø239.0 mm ID (Ø9.41" ID) sphere, bosses	80222-1	80252-1, 80258-1, 80600-1	56-000066	6.8 liters (415 in^3)	85%	4.8 liters (290 in^3)	No
	Ø239.0 mm ID (Ø9.41" ID) sphere, bosses	80278-1		56-000092	6.8 liters (415 in^3)	85%	4.7 liters (285 in^3)	No
5	Ø327.2 mm ID (Ø12.88" ID) spheroid, pedestal	80342-1	80342-101, 80342-201, 80342-301, 80342-401, 80444-1, 80498-1, 80581-1	56-000140	15.1 liters (920 in^3)	99%	14.5 liters (882 in^3)	Yes
6	Ø327.2 mm ID (Ø12.88" ID) sphere, pedestal	80187-1	80208-1, 80266-1	56-000048	17.7 liters (1,080 in^3)	75%	12.5 kg (27.5 lb_m)	No
	Ø327.2 mm ID (Ø12.88" ID) sphere, pedestal	80216-1	80238-1, 80282-1	56-000071	17.7 liters (1,080 in^3)	75%	12.5 liters (760 in^3)	No
	Ø327.2 mm ID (Ø12.88" ID) sphere, lugs	80290-1		56-000086	17.7 liters (1,080 in^3)	75%	12.5 kg (27.5 lb_m)	No
7	Ø390.7 mm ID (Ø15.38" ID) sphere, pedestal	80225-1	80389-1, 80389-101, 80468-1, 80468-101	56-000068	30.6 liters (1,865 in^3)	80%	22.5 liters (1,375 in^3)	No
8	Ø419.1 mm ID (Ø16.50" ID) sphere, bosses	80081-1	80081-3, 80091-1		37.7 liters (2,300 in^3)	85%	-	No
	Ø419.1 mm ID (Ø16.50" ID) sphere, tabs	80157-1	80177-1, 80177-3, 80189-1, 80189-101, 80207-1, 80207-3	56-000039	37.7 liters (2,300 in^3)	85%	10.7 liters (650 in^3)	No
	Ø419.1 mm ID (Ø16.50" ID) sphere, lugs	80214-1 80214-3	80253-1	56-000065 56-000091	37.7 liters (2,300 in^3)	85%	24.5 kg (54 lb_m)	No
	Ø419.1 mm ID (Ø16.50" ID) sphere, lugs	80271-1	80271-3	56-000077	37.4 liters (2,280 in^3)	85%	24.9 liters (1,520 in^3)	No
	Ø419.1 mm ID (Ø16.50" ID) sphere, girth lugs	80275-1	80275-101, 80275-201, 80319-1, 80337-1	56-000079	37.7 liters (2,300 in^3)	85%	32.0 liters (1,955 in^3)	No
	Ø419.1 mm ID (Ø16.50" ID) sphere, pedestal	80276-1	80397-1	56-000081	37.7 liters (2,300 in^3)	85%	29.9 liters (1,827 in^3)	No
	Ø419.1 mm ID (Ø16.50" ID) sphere, lugs	80303-1	80316-1, 80358-1, 80384-1, 80384-101, 80573-1	56-000098	37.7 liters (2,300 in^3)	85%	32.2 liters (1,965 in^3)	No
9	Ø419.1 mm ID x 434.3 mm Long, (Ø16.50" ID x 17.10" Long) bosses	80552-1	80572-1, 80591-1	56-000284	39.2 liters (2,390 in^3)	99%	24.5 kg (54 lb_m)	Yes
	Ø419.1 mm ID x 434.3 mm Long (Ø16.50" ID x 17.10" Long)	80572-1		56-000330	37.7 liters (2,300 in^3)	99%	30.4 kg (67 lb_m)	Yes

No.	Size Description	Qualifying P/N	Derivative P/Ns	Qual Test Report	Total Tank Volume	Ref. Propellant Compartment Volume	Ref. Qualified Propellant Volume	Diaphragm Supported When Fully Reversed?
10	Ø419.1 mm ID x 506.0 mm Long (Ø16.50" ID x 19.92" Long) pedestal	80288-1	80526-1	56-000090	49.1 liters (2,996 in^3)	99%	35.2 kg hydrazine (77.6 lb_m hydrazine)	Yes
	Ø419.1 mm ID x 506.0 mm Long (Ø16.50" ID x 19.92" Long) pedestal	80308-1	80308-101, 80392-1, 80455-1, 80526-1, 80559-1, 80593-1	56-000108	49.1 liters (2,996 in^3)	99%	37.6 kg hydrazine (83 lb_m hydrazine)	Yes
11	Ø419.1 mm ID x 506.0 mm Long, (Ø16.50" ID x 19.92" Long) boss	80543-1		56-000291	49.1 liters (2,996 in^3)	99%	46.6 kg (102.7 lb_m)	Yes
12	Ø442.7 mm ID (Ø17.43 " ID) sphere, flange	80285-1	80401-1	56-000084	44.3 liters (2,705 in^3)	85%	36.6 liters (2,049 in^3)	No
	Ø442.7 mm ID (Ø17.43 " ID) sphere, lugs	80359-1		56-000143	44.0 liters (2,685 in^3)	85%	26 liters (1,585 in^3)	No
13	Ø484.1 mm ID (Ø19.06" ID) sphere, two families from two qualification programs	80274-1	80274-101, 80274-201, 80274-301, 80460-1, 80486-1, 80574-1, 80582-1, 80574-1, 80582-1	56-000078	60 liters (3,660 in^3)	91%	45.1 liters (2,748 in^3)	No
		80512-1		56-000246	60 liters (3,660 in^3)	91%	45.1 liters (2,748 in^3)	No
14	Ø529.1 mm ID (Ø20.83" ID) sphere, bosses	80273-1		56-000076	74.9 liters (4,570 in^3)	90%	55.2 liters (3,370 in^3)	No
15	Ø562.4 mm ID (Ø22.14" ID) sphere, lugs	80112-1	80112-5 80112-75, 80112-111, 80112-115, 80200-1	56-000030	91.4 liters (5,580 in^3)	85%	-	No
	Ø562.4 mm ID (Ø22.14" ID) sphere, lugs	80193-1		56-000053	91.2 liters (5,565 in^3)	85%	-	No
	Ø562.4 mm ID (Ø22.14" ID) sphere, lugs	80203-1	80226-1, 80241-1	56-000055	91.1 liters (5,555 in^3)	85%	60.8 kg hydrazine (134 lb_m hydrazine)	No
	Ø562.4 mm ID (Ø22.14" ID) sphere, lugs	80259-1 80259-101	80362-1, 80378-1, 80385-1, 80388-1, 80439-1, 80453-1, 80549-1	56-000073 56-000097	91.1 liters (5,555 in^3)	85%	68.3 liters (4,167 in^3)	No
	Ø562.4 mm ID (Ø22.14" ID) sphere, lugs	80298-1	80298-101, 80298-201, 80298-301, 80298-401, 80409-1, 80488-1, 80553-1, 80569-1	56-000099	91.1 liters (5,555 in^3)	85%	77.9 liters (4,754 in^3)	No
16	Ø562.4 mm ID x 907.0 mm Long, (Ø22.14" ID x 35.71" Long) Diaphragm up	80534-1		56-000280	175.3 liters (10,700 in^3)	99%	82.3 liters (5,022 in^3)	Yes
	Ø562.4 mm ID x 907.0 mm Long, (Ø22.14" ID x 35.71" Long) Diaphragm down	80547-1		56-000280	175.3 liters (10,700 in^3)	99%	82.3 liters (5,022 in^3)	Yes
17	Ø582.7 mm ID x 855.7 mm Long, (Ø22.94" ID x 33.69" Long)	80427-1	80489-1	56-000192	170.9 liters (10,431 in^3)	99%	152.4 kg hydrazine (337 lb_m hydrazine)	Yes
	Ø582.7 mm ID x 855.7 mm Long, (Ø22.94" ID x 33.69" Long)	80597-501		TBD	170.9 liters (10,431 in^3)	99%	Same internal design as 80427	Yes
	Ø582.7 mm ID x 855.7 mm Long (Ø22.94" ID x 33.69" Long)	80616		To be assigned	170.9 liters (10,431 in^3)	99%	Same internal design as 80427	Yes
18	Ø587.5 mm ID x 646.7 mm Long, (Ø23.13" ID x 25.46" Long)	80323-1	80428-1, 80447-1, 80450-1, 80469-1, 80524-1, 80531-1, 80555-1, 80562-1, 80578-1	56-000129	119 liters (7,261 in^3)	99%	113.5 kg hydrazine (250 lb_m hydrazine)	Yes

No.	Size Description	Qualifying P/N	Derivative P/Ns	Qual Test Report	Total Tank Volume	Ref. Propellant Compartment Volume	Ref. Qualified Propellant Volume	Diaphragm Supported When Fully Reversed?
19	Ø587.5 mm ID x 722.9 mm Long (Ø23.13" ID x 28.46" Long)	80505-1		56-000247	139.6 liters (8,521 in^3)	99%	133.8 liters (8,163 in^3)	Yes
20	Ø587.5 mm ID (Ø23.13" ID) Sphere	80583-1		56-000318	104.0 liters (6,348 in^3)	99%	83 kg hydrazine (182.9 lb_m hydrazine)	Yes
21	Ø635.0 mm ID x 1166.9 mm Long (Ø25.00" ID x 45.94" Long)	80514-1		50-000249	315.5 liters (19,250 in^3)	77%	245.8 liters (15,000 in^3)	No
22	Ø711.2 mm ID (Ø28.00" ID) sphere, lugs	80227-1			186.0 liters (11,350 in^3)	90%	-	No
	Ø711.2 mm ID (Ø28.00" ID) sphere, bosses	80228-1	80287-1, 80270-1, 80325-1, 80325-101, 80325-201, 80325-301, 80348-1, 80566-1, 80567-1	56-000070	186.0 liters (11,350 in^3)	90%	132.1 liters (8,060 in^3)	No
	Ø711.2 mm ID (Ø28.00" ID) sphere, bosses	80297-1		56-000096	186.0 liters (11,350 in^3)	90%	141.8 liters (8,648 in^3)	No
23	Ø870.0 mm ID x 1104.9 mm Long (Ø34.25" ID x 43.50" Long) flex plates	80557-1	80557-501	56-00276	480.8 liters (29,340 in^3)	99%	450 kg hydrazine) (992 lb_m hydrazine)	Yes
24	Ø915.4 mm ID x 1193.8 mm Long (Ø36.04" ID x 47.00" Long) bosses, lugs	80315-1		56-000119	600.2 liters (36,626 in^3)	99%	481.7 kg hydrazine (1062 lb_m hydrazine)	Yes
25	Ø1021.1 mm ID x 807.7 mm Long (Ø40.20" ID by 31.80" Long) Oblate Spheroid, flange mount	80263-1	80263-101, 80263-201, 80329-1, 80370-1, 80376-1, 80382-1, 80407-1, 80463-1, 80579-1, 80485-1, 80487-1, 80515-1	56-000075, 56-000082(S)	461.2 liters (28,144 in^3)	99%	446.3 kg hydrazine (984 lb_m hydrazine)	Yes
	Ø1021.1 mm ID x 807.7 mm Long (Ø40.20" ID by 31.80" Long) Oblate Spheroid, flange mount	80318-1		56-000114	461.2 liters (28,144 in^3)	99%	149.7 kg (330 lb_m)	Yes
26	Ø1021.1 mm ID x 1010.9 mm Long (Ø40.20" ID x 39.80" Long) Oblate Spheroid, flange mount	80451-1	80580-1, 80523-1, 80598-1, 80604-1	56-000205	622.7 liters (38,000 in^3)	71.5%	454 kg hydrazine (1000 lbm hydrazine)	Yes

2. Useful Information

In this section, we provide information updates on diaphragms or diaphragm tanks based on some frequently asked questions. One question we encountered most often is *why did we design a particular diaphragm tank in that particular way*? The nature of the questioning often bemoans that certain aspects of an available tank design does not provide the best fit for a potential customer. The answer to this question is that there is no standard way of designing a diaphragm tank. We custom design and qualify diaphragm tanks to specification requirements, with emphasis given to mass, cost, available envelope, schedule, tooling, manufacturability, and even heritage as dictated by the funding customers. Given that the qualified pool of diaphragm tanks is relatively small, diaphragm tank users seeking a derivative tank solution might not always find a perfect fit. Additionally, there are features in diaphragm tanks that a potential user might not have thorough knowledge. Our advice is to make an informed decision by conducting a trade study to understand the available options [2].

2.1 Nomenclature

The common terms for diaphragm tank components include:

Propellant dome: In a diaphragm tank, the propellant dome and the diaphragm form the propellant compartment. In daily conversations, the propellant side is the *wet* side.

Pressurant dome: In a diaphragm tank, the pressurant dome and the diaphragm form the pressurant compartment. In daily conversations, the pressurant side is the *dry* side or the *gas* side.

Diaphragm retaining ring**:** Every diaphragm tank has a retaining ring to retain the diaphragm [5]. Unless machined integral from the tank dome, the retaining ring is typically not part of the structural membrane.

The term ***fully reversible diaphragm*** has been in use for many years. However, all diaphragms are fully reversible, and all diaphragm tanks have reversing diaphragms to enable functionality. In daily conversations, a *fully reversible diaphragm* is a diaphragm that, when fully reversed, can touch the pressurant compartment dome. The use of the term is within the context of minimal operational risk because the pressurant dome prevents the diaphragm from overstretching and causing damage. In this paper, we refrain from using this term to avoid miscommunication. In practice, it is important to have clear definition of the term at the start of a conversation to prevent misunderstanding or miscommunication of requirements.

The term ***expulsion efficiency*** may have different meanings to different people. The most common definition of Expulsion Efficiency in daily use is:

$$\text{Expulsion Efficiency} = \frac{\text{Total Expelled Propellant Volume}}{\text{Total Loaded Propellant Volume}}$$

The term ***residual*** is the difference between total loaded propellant volume and total expelled propellant volume. There are other definitions of expulsion efficiency, one might include using the propellant compartment volume as the denominator in the above equation. Regardless of the definition, the residual propellant volume should be the same in all cases.

A diaphragm tank could have different expulsion performance based on initial load. For example, assuming a 100-liter tank with a propellant compartment capacity of 99 liters and a residual of 0.15 liter upon complete expulsion, with an initial propellant load of 99 liters, the Expulsion Efficiency would be:

$$\text{Expulsion Efficiency} = \frac{98.85\ liters}{99\ liters} = 99.85\%$$

In the above scenario, a separate pressurant tank is necessary for propellant expulsion.

It is also possible to use the same tank for blowdown. With an initial propellant load of 66 liters for a 3 to 1 blowdown, the expulsion efficiency would be:

$$\text{Expulsion Efficiency} = \frac{65.85\ liters}{66\ liters} = 99.77\%$$

However, if the initial propellant load were small, for example at 10 liters, then the expulsion efficiency would become:

$$\text{Expulsion Efficiency} = \frac{9.85\ liters}{10\ liters} = 98.5\%.$$

These examples demonstrate that the same tank design can have multiple expulsion efficiency values depending upon the initial propellant load. The lessons learned from past programs are that expulsion efficiency could be a function of tank size, diaphragm design, propellant load, and even operational constraints such as time between thruster firings. It is critically important to have a clear understanding of all the parameters involved when discussing expulsion efficiency at program start to avoid misinterpreting the requirement.

Regarding operational constraints mentioned above, past diaphragm tank users had noted that nearing end of life, given sufficient time between thruster firings, enough propellant would migrate to the tank outlet and support yet another thruster firing to raise the expulsion efficiency and prolong mission life well beyond the original expectation. This scenario is similar to ground expulsion testing, during which the longer the drain time, the more liquid would drain from the tank.

2.2 Common Misconception Regarding Trapped Propellant

A common misconception about diaphragm tanks circulating in academia is that it is possible to form a pocket of propellant when the diaphragm tank is in a horizontal orientation, thus preventing a pool of propellant from reaching the tank outlet. The ATK diaphragm design specifically prevents the isolation of a propellant pool by implementing ribs along the diaphragm wall to generate flow paths. The conventional design, introduced in 1967 by PSI and emulated by other diaphragm tank makers, has been an unchanging feature in diaphragm designs for over five decades. In Figure 12, the photo shows these ribs that enable high expulsion efficiency or low residual at any orientation, including upright, sideways, and upside down.

Figure 12: Diaphragm with Ribs to Direct Propellant Flow

2.3 Diaphragm Tank versus Bladder Tank

Another common misconception is that diaphragms are similar to bladders. There are major differences between the two propellant management approaches. The primary difference is that a diaphragm is an elastomeric dome that attaches to the tank girth as depicted in Figure 3, whereas a bladder is an elastomeric balloon with attachment at one of the tank bosses. In a diaphragm tank, a reversing diaphragm would force the propellant into the outlet port. In a bladder tank, the elastomeric balloon can either expand outwards or contract inwards to expel propellant [5]. There are very few bladder tanks in the space industry to enable a meaningful comparison. However, given that a diaphragm is only a dome but a bladder is a full balloon, diaphragm tanks can generally achieve higher expulsion efficiency and lower mass.

2.4 Diaphragm Extrusion

A third misconception about diaphragm tanks is that diaphragms could extrude through the opening at the tank outlet. This concern only applies to spacecraft using multiple diaphragm tanks when one tank depletes sooner than another does. To investigate the potential for diaphragm extrusion, ATK engineers conducted a series of experiments that pressed flat samples against ¼ inch or 1/16 inch holes at various pressures. Figures 13a and 13b are photographic summaries of test results. Note there were small imprints of the outlet hole, but extrusion did not take place.

Most diaphragm tanks are blowdown tanks. At depletion, the end of life pressure would be too low to cause extrusion of diaphragm through an opening. More importantly, the diaphragm does not lay flat on top of the propellant outlet at end of life. Typically, a diaphragm rib sits above the outlet, and the added thickness and reduced contact area make it impossible for diaphragm extrusion to occur. Figure 13c is the conclusive evidence to support this point. The absence of negative user feedback after end of life similarly supports this conclusion.

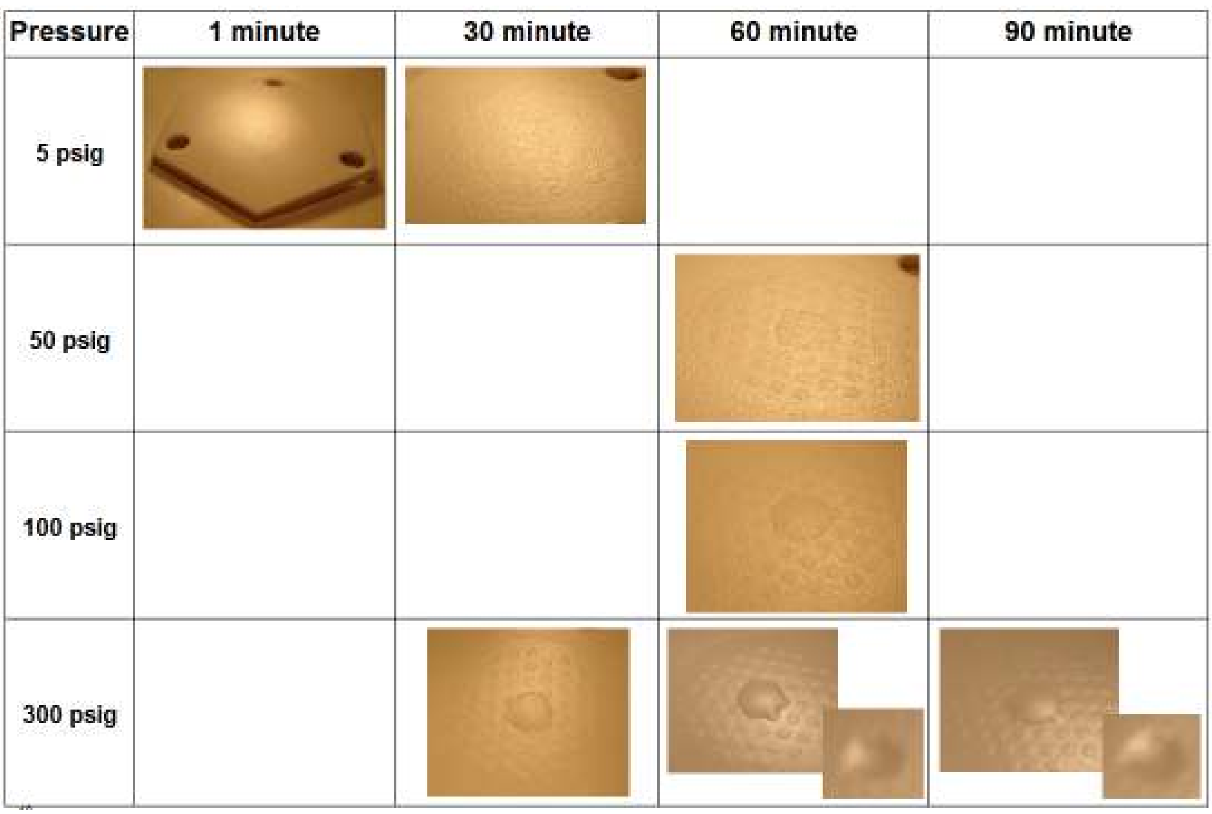


Figure 13a: Diaphragm Extrusion Test, ¼ inch Hole

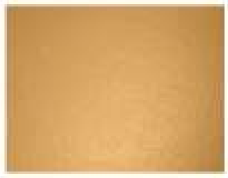
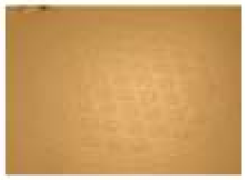
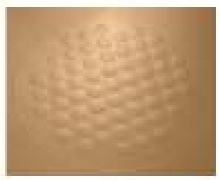
Pressure	1 minute	30 minute	60 minute	90 minute
5 psig				
50 psig				
100 psig				
300 psig				

Figure 13b: Diaphragm Extrusion Test, 1/16 in Hole

Figure 13c: Diaphragm Extrusion Test with Ribs Directly Above the Outlet and at 150 psig for 90 minutes

2.5 Vibration Testing

ATK has a long-standing position of not conducting acceptance vibration test on flight tanks, and especially on diaphragm tanks. To include a test in the acceptance test sequence, the test itself must add value. Acceptance vibration test is typically resource-intensive and not value added. Worst of all, vibration testing adds unnecessary risk to a piece of valuable hardware. Occasionally, some circumstances might warrant vibration testing on flight hardware, such as conducting a protoflight vibration test to augment analytical qualification. Nevertheless, unless specifically required by the customer and with valid reasons, we typically do not recommend vibration testing as a final acceptance check.

The rationale for not conducting acceptance vibration test on a flight diaphragm tank could include:

- Typically, the acceptance proof pressure testing induces more stress/strain on the tank shell than vibration testing. Analyses performed by ATK over the past 50 years supported this conclusion. Thus conducting vibration testing does not test the worst-case scenario and does not add value.
- During qualification vibration testing, we validate the structural integrity of the tank mounts. On flight tanks with metallic mounts, the structural validation is through dimensional inspection, process control, and validation of material properties throughout the manufacturing process. Acceptance level vibration testing at much lower level than qualification level vibration does not add value as a structural verification test.
- Vibration test is not useful as a workmanship test on a diaphragm tank. Vibration testing has no effect on a properly seated or improperly seated diaphragm. On diaphragm tanks, we conduct radiography examinations to validate proper diaphragm seating, appropriate gap, and alignment. The visual confirmation of proper diaphragm seating is the best validation method. The radiography methods are more effective, less expensive, and present less risk than vibration testing.
- Vibration testing is high risk. Vibration testing could cause damage or scrap by over testing. Mishandling and damaging hardware is also a constant concern during a vibration test campaign. The value of vibration testing as a screening test (as compared to proof pressure test) is low. Our position is that the lack of benefit from vibration testing is not worth the risk of potentially damaging valuable hardware that may take many months to replace.

Our experience base, accumulated over hundreds of structural analyses, indicate that tank shell stresses from proof pressure testing are significantly higher than stresses from vibration testing. In tank designs, pressure loads always dominate stress margins. On a stress plot, the vibration load stresses upon tank shells are almost negligible where it is more than a few centimeters away from the mounting interfaces. For tank shell validation, a proof pressure test is the worst-case and the enveloping test for the tank shell. A post-proof pressure helium leak test would be sufficient to validate the tank shell integrity. In general, this is true for all tank types, including PMD tanks and Composite Overwrapped Pressure Vessels (COPVs).

While our default position is no acceptance vibration testing, there might be cases that the tank analyses would result in a recommendation for protoflight vibration testing. For these cases, the purpose of the protoflight vibration testing is to supplement qualification. Such a purpose is significantly different from acceptance vibration testing.

One justification to continue conducting acceptance vibration testing that we frequently encounter is the sentiment that *it has always been done that way*! This statement has no scientific merit. It is a sentiment and not a valid technical justification. Worst of all, with space hardware becoming increasingly complex and expensive, it is fiscally irresponsible to conduct a high-risk test with little value. We present our recommendation based on scientific principles and sound engineering judgment, and make them in the interest of minimizing waste, exercising financial prudence, protecting program schedule, reducing program risk, and providing the best overall value.

2.6 Expulsion Cycles

Expulsion cycle testing is primarily a diaphragm durability test. Most diaphragm tanks must execute one expulsion cycle for the intended mission. The one notable exception is the Space Shuttle Auxiliary Power Unit diaphragm tank with repeated use. For typical one-time use missions, tank-level acceptance testing and system-level testing would add several fill and drain cycles. On most missions, the total number of expulsion cycles is below 10. For cycle life qualification, an adequate number of test cycles would be around 10x4 or 40 cycles. The logic for expulsion cycle qualification is to follow the same four times life cycle requirement as tank qualification. As a practice, we usually qualify diaphragms to 100 fill and drain cycles to leave no doubt that the diaphragms meet the expulsion cycle life requirement. Figure 14 are time-lapsed photos of expulsion testing in a simulator. For clarity, the liquid side is the top side in these photos.

Expulsion cycle test is only one aspect of the diaphragm screening. Other adverse conditions such as slosh cycles could affect diaphragms. In recent years, transportation slosh and launch pad slosh are becoming major qualification concerns. Qualifying diaphragm durability and survivability in slosh environments requires a different test setup than expulsion cycle life testing. More importantly, conducting a large number of expulsion cycles (such as >500 cycles) would not expose a diaphragm to transportation slosh or launch pad slosh environments. To ensure survivability, it might be necessary to conduct a slosh test to confirm that the diaphragm meets the worst-case transportation slosh or launch pad slosh environment.

Figure 14: Diaphragm Expulsion Test Performed on a Simulator (Liquid on Top of the Tank)

2.7 Proof Pressure and Burst Pressure Factors

During the early years of space industry, analysis techniques were under development and immature. It was common for system operators to require 1.5 x MEOP for proof pressure and 2.0 x MEOP for burst to compensate for inadequacies in analytical methodology and inexperience on the part of the analysts to reduce risk. Many ATK tanks designed during this period had the 2 to 1 burst factor requirement. By the 1990s, there had been a migration away from using the 2 to 1 burst factor to 1.5 to 1 burst factor. Several factors drove this change, including:

(1) The desire by the customer base to reduce mass,

(2) The advancements in analytical tools and techniques,

(3) The accumulation of analytical experience and knowledge,

(4) The improvements in computational power,

(5) The accumulation of test data validating the analytical approaches and techniques,

(6) The improvements in manufacturing processes and quality control, and

(7) The improvements in system operations and control.

With hundreds of tanks analyzed, tested, and flown without failure, there is abundant evidence that tank designs with 1.5 burst factor are suitable for space flight. Currently, the 1.5 to 1 burst factor is the industry norm. While it is the customer's prerogative to impose a conservative approach with a 2 to 1 burst requirement, there is a generally accepted lighter weight solution with proven success and minimal risk. Our heritage and performance record are more than sufficient to justify the 1.5 to 1 burst factor approach.

It is possible to take advantage of tanks previously qualified to 2 to 1 burst factor. For example, ATK P/N 80274 is a Ø483 mm (Ø19 in) spherical tank originally qualified in 1978 with a 26 bar (377 psi) MEOP and 52 bar (754 psi) burst pressure. In 2006, we requalified the same tank to a higher MEOP at 34.5 bar (500 psi) under a new P/N 80512. The goal of the P/N 80512 qualification was to take a tank design with a 2 to 1 burst factor and re-qualified the same shell to a higher MEOP but with a burst factor of 1.5 to 1. Both P/N 80274 and P/N 80512 have near identical burst pressure requirements by design, and both are lug-mounted tanks with near identical physical features. The higher MEOP of P/N 80512 enabled a more efficient use of the available tank design. The qualification was relatively low cost because there was no design effort and no new tooling to make.

2.8 Propellant Slosh within Diaphragm Tanks and Slosh Modeling

Unlikely PMD tank designs for which predictive modeling is highly advanced, there are no predictive models for assessing slosh behavior in a diaphragm tank. Propellant slosh characteristics within a diaphragm tank are functions of multiple factors including diaphragm diameter, diaphragm length, diaphragm thickness, diaphragm orientation, excitation amplitude, diaphragm stiffness, propellant fill fraction, and diaphragm design features. Below are some relevant discussions associated with diaphragm tank slosh:

Slosh Environments: There are many types of slosh environments: transportation slosh during upright or horizontal transport and handling, launch pad sway while the filled propellant tank is sitting atop the launch vehicle and subject to wind-induced oscillation, slosh during launch and ascent, slosh or swirl during spinning operations, and on orbit slosh during thruster operations. We frequently examine slosh environments individually and cumulatively. To support flight operations, customers typically require an examination of on-orbit slosh for mission assurance. However, in recent years, assessment of survivability in transportation slosh environments proved similarly important.

Durability and survivability: Increasingly, we are designing tanks that must survive transport and launch pad slosh for both PMD and diaphragm tanks. A lack of analytical assessment techniques for diaphragm tanks means slosh testing is necessary for tank qualification. Long duration slosh events such as launch vehicle transport and launch pad sway could induce diaphragm-to-diaphragm or diaphragm-to-tank wall rubbing. In ATK's diaphragm designs, we introduced sufficient thickness and durability to withstand slosh concerns. However, on missions with prolonged slosh events, it is prudent to conduct survivability tests in a simulator to examine a diaphragm's durability and survivability, and make design adjustments when necessary. Figure 15 is a photo of a slosh test setup with a diaphragm tank simulator. The Plexiglas dome enables visual observation and video recording while the test is in progress. Recommended test duration is 4 times the mission duration in accordance with industry standard. For example, if the requirement for transportation is 15 minutes at 1 Hz and 50 mm double amplitude, then the slosh testing is for 60 minutes at 1 Hz frequency and 50 mm double amplitude.

Figure 15: A Slosh Test Setup to Examine Diaphragm Behavior in a Slosh Environment

Propellant Fill Fraction: The criticality of propellant fill fraction is a function of the diaphragm design and configuration. In a best-case scenario in which the propellant fill corresponds to a fully reversed diaphragm, there would be no diaphragm folding and overlap, and thus minimal diaphragm membrane rubbing. The worst-case scenario is one in which the propellant compartment is partially filled, and folds and overlaps in the diaphragm would cause rubbing of the diaphragm during transport or launch pad slosh. Figure 16 includes photos of diaphragms at different fluid fill fractions. The severity of the folds varies at different fill fractions.

Figure 16: Diaphragm Configuration at Lower Fill Fraction and High Fill Fraction

On Orbit Slosh: In contrast to transportation slosh and pad sway, on orbit propellant slosh is relatively benign. As we start designing diaphragms to survive launch pad slosh environments, the diaphragm stiffness could envelop on orbit survivability. If an examination of the on orbit slosh characterization becomes necessary, we typically recommend using a 3D scanning technique to characterize diaphragm behavior [6]. Outputs that define slosh behavior include both qualitative data such as videos and quantitative data such as force measurements and charts. It is also possible to convert data into pendulum or spring mass models. Nevertheless, all must recognize that a test conducted in 1 g is not entirely representative of true conditions in zero g, and some qualitative assessments or engineering judgment might be necessary during the characterization process.

Diaphragm Modelling: Decades of witnessing diaphragm testing had given us the knowledge that a diaphragm shape is not repetitive during each fill event. This lack of repeatability prevents researchers from generating a predictive model, and characterization of diaphragm behavior is best through collecting qualitative and quantitative data using a tank simulator. Additionally, diaphragm endurance, or its ability to resist rubbing during slosh, is not predictable in a slosh model. We must address endurance concerns through testing using a diaphragm simulator. ATK, in cooperation with academia, has developed a 3D scanning technique to generate a 3D map of the diaphragm shape [6]. We use this technique to measure the propellant CoM for both static and dynamic cases.

Tank Diameter: In two stand-alone diaphragm tank studies, researchers noted significantly different slosh characteristics on two diaphragm tanks: a Ø1021 mm (Ø40.2 inch) diaphragm tank and a Ø419 mm (Ø16.5 inch) diaphragm tank. In both tanks, the diaphragm thickness was nearly identical at around 1.78 mm (0.070 inch), but the differences in diameter was an apparent contributor to the differences in relative stiffness [7].

One important finding from the two studies was that the stiffness of the diaphragm in the smaller diameter tank provided sufficient over-damping to prevent any observable diaphragm motion. In contrast, diaphragm in the larger tank was not sufficiently stiff, and diaphragm and propellant motion was observable. In other slosh tests, we noticed similar characteristics. Based on cumulative observations, it is possible to characterize diaphragms into two groups:

- Smaller diameter tank at or below Ø562 mm (Ø22.1 in) in diameter. There is minimal diaphragm movement based on current design. There is solid evidence that a combination of tight tank radius and diaphragm thickness is sufficient to keep the diaphragm stiff with little movement in all orientations: propellant on top, propellant on the side, and propellant at the bottom.

- Larger diameter tanks above Ø562 mm (Ø22.1 in) in diameter. There could be diaphragm movement using the typical diaphragm thickness. It might be necessary to conduct slosh simulation testing to ensure mission success, or incorporate a thicker diaphragm to enhance slosh damping.

The above observations applied to the typical diaphragms thickness of 1.65 to 1.78 mm (0.065 in to 0.070 in). Historically, diaphragm designs have the same thickness to maintaining heritage. The lessons learned indicate that it might be necessary to customizing diaphragm thickness based on tank diameter. In a recent large diaphragm tank development program, we implemented this new design approach to enable tank qualification. Nevertheless, continued research is necessary to refine the relationship between tank diameter and diaphragm thickness.

There is no generalized approach towards diaphragm modeling and evaluation. Diaphragm users must evaluate each mission scenario based on tank volume, fill fraction, tank design, diaphragm configuration, and mission requirements. The ideal scenario is no membrane rubbing during transport and launch pad slosh. However, some rubbing might be unavoidable. All ATK diaphragm tank designs can withstand some membrane-on-membrane rubbing based on our long history of flight successes. Nevertheless, on some severe environments, it would be prudent to examine slosh cases using a simulator to ensure mission success.

2.9 Diaphragm Tank Size Trends

From early 2000s to mid-2010s, new diaphragm tank developments were trending toward larger sizes, including ∅562 mm (∅22.1 in), ∅587 mm (∅23.1 in), ∅635 mm (∅25 in), and ∅870 mm (∅34.3 in). Figures 17a and 17b are photos of two larger diameter diaphragms.

Figure 17a: An Elongated Diaphragm for a ∅660 mm (∅25 in) Diaphragm Tank

Figure 17b: A Hemispherical Diaphragm for a ∅870 mm (∅34.3 in) Diaphragm Tank

However, the trend is reversing. In recent years, diaphragm tanks are becoming smaller. One probably cause is the developing demand for the New Space Small Sat market. Our new small diaphragms tanks include ∅68 mm (∅2.7 in), ∅112 mm (∅4.4 in), and ∅235 mm (∅9.3 in) diaphragm tanks. Figure 18 is a photo of some of the smaller diaphragms we developed, including a square diaphragm.

Figure 18: Small Diaphragms from ∅68 mm (∅2.7 in) to ∅239 mm (∅9.4 in)

2.10 Using Derivative Diaphragm Tanks for Green Propellants

Satellite integrators are beginning to use new green propellants such as AFM-315E [8] and LMP-103s [9]. It is possible to use diaphragm tanks previously qualified for hydrazine to store the green propellants. However, there are additional considerations as described below:

Cost competitiveness: It is always possible to custom design a new diaphragm tank for a new program intending to use green propellant. However, the current space industry infrastructure favors hydrazine systems. To overcome a high barrier to entry, using derivative diaphragm tanks for green propellants could be a cost competitive approach and a valid tank solution.

Tank Shell Compatibility: The legacy Ti-6Al-4V tank shell material is compatible with both AFM-315E and LMP-103s. Dozens of ATK PMD tanks with Ti-6Al-4V shells holding LMP-103s propellant are already on orbit. ATK also delivered a propellant tank with Ti-6Al-4V tank shell and an AF-E-332 diaphragm for the first flight of AFM-315E green propellant. The planned Green Propellant Infusion Mission (GPIM) launch is in 2018.

Structural Loads: The AFM-315E and LMP-103s green propellants have higher densities than hydrazine. Using a derivative tank qualified for hydrazine with a fixed structural load might reduce the volume of a green propellant that the tank could carry. This capacity constraint is a reality when using derivative tanks. Nevertheless, an existing tank design might have more capabilities than previously qualified, and a structural analysis could identify the optimal green propellant volume a previously qualified tank can carry.

Fracture Mechanics Analysis: Fracture data on both AFM-315E and LMP-103s are available. ATK completed fracture mechanics analyses for both propellants in Ti-6Al-4V shells in 2017. ATK contributed the material for test coupons on both fracture data development programs. The available fracture data correspond to ATK's manufacturing methods.

Diaphragm Material for LMP-103s: In 2015, ECAPS conducted an immersion test to determine the compatibility of SIFA-35 elastomer with ECAPS's LMP-103s green propellant. The test results indicate no contamination to the propellant from the SIFA-35 elastomer. In September 2016, ECAPS issued a technical memo validating the compatibility of SIFA-35 with LMP-103s. This technical memo is available to all users of LMP-103s upon request.

2.11 Diaphragm Height and Width Constraints

The current press for diaphragm fabrication has height and width constraints. During diaphragm design, we must incorporate these constraints when designing the diaphragm mold. Some of our larger diaphragms have the following dimensions:

- P/N 80263 is 448 mm (17.655 in) tall x 1001 mm (39.42 in) wide
- P/N 80315 is 613 mm (24.125 in) tall x 895 mm (35.2 in) wide
- P/N 80351 is 562 mm (22.115 in) tall x 460 mm (18.1 in) wide
- P/N 80514 is 560 mm (22.045 in) tall x 615 mm (24.2 in) wide
- P/N 80534 is 470 mm (18.515 in) tall x 543 mm (21.4 in) wide
- P/N 80557 is 562 mm (22.145 in) tall x 863 mm (34.0 in) wide

Based on the above heritage parts, the in-house press is capable of manufacturing diaphragms 613 mm tall x 1001 mm wide.

2.12 Diaphragm Tank Simulators

Simulators are valuable tools for the study of diaphragm behavior and tank testing. Engineers and researchers use simulators for a range of purposes, including:

- Conduct expulsion cycle test to examine functionality and endurance
- Characterize diaphragm behavior under external excitation
- Study coupled fluid/diaphragm motion
- Conduct slosh testing
- Evaluate diaphragm design features
- Measure Propellant Center of Mass (CoM) migration during tank drain

In recent years, some new diaphragm development programs had included stringent requirements on launch pad slosh and CoM control. There are no analytical validations for diaphragm endurance, and slosh testing using diaphragm simulators had become an essential part of new diaphragm tank qualification. Figure 19 are some examples of diaphragm tank simulators.

2.13 Diaphragm Shelf Life

ATK's standard process is to store diaphragms for no more than 10 years. In reality, the storage condition could affect the diaphragm shelf life. A diaphragm stored in a well-controlled environment could last well in excess of 10 years. Occasionally, if there were more than one diaphragm from the same production lot, we would dedicate one diaphragm for destructive testing. If the test results prove satisfactory, we would be able to extend the shelf life for the rest of the diaphragms.

2.14 Diaphragm Tank Shelf Life

A delivered diaphragm tank is a high-value space hardware and treated as such by our customers. Although some spare tanks might be in storage for many years, they are still flight worthy. NASA engineers have taken spare tanks out of storage and repurposed them for other missions. We also reworked a NASA X-38 diaphragm tank, originally delivered in 1999, for the L-CROSS program in 2007. The L-CORSS lunar mission concluded successfully in 2009.

Our most recent example is an ATK P/N 80308-1 originally delivered to UK in February 1997. As a program spare tank it sat in storage, un-opened, until Surrey Satellite Technology Ltd used it for a very rapid turn-around project. Surrey launched the spacecraft, based on the

SSTL-42 platform, in January 2018. The launch was nearly 21 years after the delivery of the diaphragm tank. The spacecraft operated its propulsion system heavily for the first 3 months in-orbit, and consumed 75% of the propellant. The tank performed flawlessly throughout the mission.

3. Experiments and Tests:

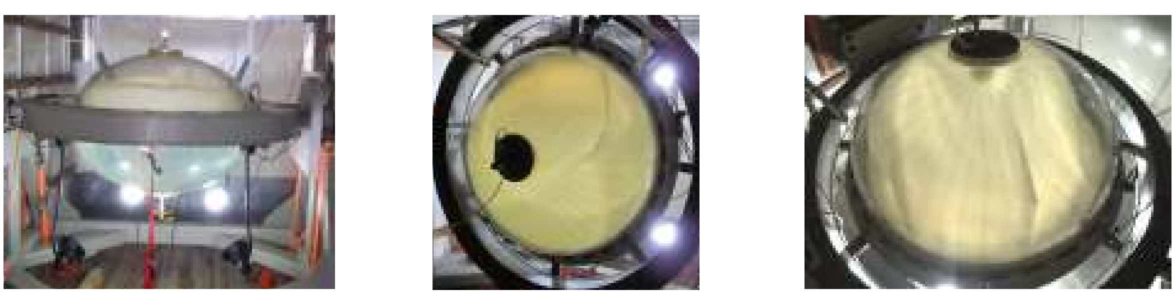
In this section, we describe diaphragm tank research or development efforts in the past fifteen years. With the customer base preferring derivative tanks, there had been few opportunities to develop new diaphragms and even fewer opportunities to study diaphragm behavior. In the past decade, we made a conscious decision to fund research efforts focusing on diaphragm characterization. The assembled diaphragm knowledge and diaphragm study results in this section fill an existing knowledge gap.

3.1 Transportation Experiment

The design and qualification of ATK's largest diameter diaphragm tank, P/N 80263 for the TDRS program, took place in 1977 before the introduction of launch vehicles requiring horizontal handling and transport. ATK delivered over 40 tanks from this tank family, and all of the tanks launched on upright handling launch vehicles. In 2013, an end user inquired about the effect of horizontal transport upon this tank. To generate a solution, ATK, NASA, and Florida Institute of Technology (FIT) reached a collaborative agreement to develop a slosh experiment using the TDRS simulator.

Researchers from FIT mounted the simulator to a handling fixture capable of 360° rotation, and positioned the experiment onboard a U-Haul truck. Lighting mounted on the fluid side of the test setup enabled video recording of diaphragm movement during the transport experiment. Sensors installed on the test setup recorded data that included displacement, frequency, and acceleration from the experiment. The U-Haul truck traveled back and forth on a long stretch of roadway along the FIT campus at the speed specified by the customer. In addition, a customer representative was present in the truck to observe the diaphragm movement. All the slosh cases during the test runs were benign. None of the slosh cases could cause damage to the diaphragm. Although some folds and overlaps were present at various fill levels, none caused concerns. The customer representative departed with satisfaction.

Figure 19: Diaphragm Tank Simulators of Various Sizes



Liquid on the bottom   Liquid on the side   Liquid on top

Figure 20: A Ground Transportation Experiment with the Ø1016 mm Diaphragm Tank

With the primary goal achieved, the research team took advantage of the test setup and performed a systematic examination of diaphragm behavior during transport at all three major orientations: upright, sideways, and upside down, and at several pre-selected fill fractions. Figure 20 includes photos of the three orientations with liquid on the bottom representing the typical upright handling, liquid on the side representing horizontal handling and transport, and liquid on top. The researchers published the test results at the Space Propulsion Conference 2016 in Rome [7].

An important benefit of the slosh experiment was the opportunity to collect both qualitative and quantitative data. Although the horizontal transport slosh cases were benign, the researchers also recognized the potential for damage if the observed folds and overlaps were under more severe slosh conditions such as launch pad oscillation at high frequency and long duration. Figures 21a and 21b are photos of some of the folds and overlaps formed in the simulator at various fill fractions. Interestingly, the folds and overlaps are more likely to occur during upright handling and not horizontal handling. When the tank was in horizontal condition (outlet at 3 o'clock position), there were fewer folds and no overlaps as shown in Figure 22. It is important to state here that the diaphragm configuration is specific to the tank design. Diaphragms in other tanks are likely to exhibit different behaviors.

Figure 21a: Folds and Overlaps Occurring at Low Fluid Fill Fraction

Figure 21b: Improved Diaphragm Configuration with Folds but no Overlap at Higher Fill Fraction

Figure 22: Diaphragm Configurations at Horizontal Handling and Transport

3.2 Horizontal Transport of a Ø419 mm (Ø16.5 in) Diaphragm Tank

At around the same time of the transport experiment, an overseas customer inquired about the ∅419 mm (∅16.5 in) diaphragm tank's capability to survive horizontal transport and launch. A simulator for the spherical tank was not available, but a simulator for an alternate size at ∅419 mm x 434 mm long (∅16.5 in x 17.1 in) was on site. See Figure 23. This simulator became the instrument for a new slosh experiment.

Figure 23: Simulator for a ∅419 mm (∅16.5 in) Diaphragm Tank Slosh Experiment

The FIT researchers constructed a test fixture to hold the simulator. After some preliminary test runs, it became apparent that the combination of small tank diameter and sufficient diaphragm thickness was keeping the diaphragm motion at a minimum [7]. The visual confirmation of the lack of diaphragm/fluid motion enabled the customer to proceed with the propulsion system architecture without reservation. The successful data collection effort, both qualitative and quantitative, provided a confirming data point on this tank family's ability to enable slosh damping. Photos and videos of the slosh test are available for review. It became possible to state with absolute certainty that there is visual confirmation of diaphragm stiffness and slosh damping capability in a slosh environment.

The researchers found the ratio of tank diameter (D) to diaphragm thickness (t) a useful tool for diaphragm stiffness characterization. In this experiment, the ratio of D/t is 16.5/0.065 or 254. We shall examine the D/t ratio of other diaphragm tanks in subsequent experiments.

3.3 Slosh Testing of ∅562 mm (∅22.1 in) Spherical Diaphragm Tank Simulator

In 2014, ATK conducted a long duration slosh test using a ∅561 mm (∅22.1 in) diaphragm tank simulator as part of the diaphragm durability validation. The test environment, replicating the launch pad slosh environment, included frequencies up to 1.1 Hz, displacement up to 64 mm (2.5 in), and duration up to 405 hours. There was no damage to the diaphragm at the conclusion of the slosh test.

Figure 24: Launch Pad Slosh Test Setup

The photographic and video recordings of the test run, along with a formal test report, are important data points on diaphragm tank capability and test history. The documents established the ∅562 mm (∅22.1 in) tank diameter as a lower bound for diaphragm damping capability under current design practice. This data point, along with other data points established on other research or production programs, would help researchers formulate recommendations on future programs when slosh damping could be a major concern.

The D/t ratio for this ∅562 mm (∅22.1 in) tank is 22.1/0.065 or 340.

3.4 Center of Mass (CoM) Migration Measurement

Space debris is becoming a sustainability concern for space system operators [10]. Simulations conducted by NASA scientists indicate that space systems will encounter increasing risk while operating in the overcrowded regions of LEO [11]. One important space debris mitigation measure is to deorbit a spacecraft upon mission completion [12]. Some space systems operators have already adopted deorbit as a spacecraft design requirement. Satellites must carry extra fuel to deorbit. On satellites with sensitive instruments, the propellant CoM shift throughout the mission might create disturbances that affect data collection. In 2013, an overseas customer requested a diaphragm characterization study to explore the implications of propellant CoM shift on a satellite mission. In response to the customer request, ATK commissioned a study to develop an accurate method of measuring CoM migration in the ∅1016 mm (∅40 in) diaphragm tank.

The quantitative study included an examination of concentric stiffening rings and their effect on CoM shift. Observations on hundreds of simulator fill and drain cycles had revealed that a uniform and symmetric diaphragm reversal is the best way to keep the propellant CoM near the tank central axis. In the transport experiment on the same tank described in Section 3.1, there was visual confirmation that diaphragms took on odd shapes during fill and drain as shown in Figures 21a and 21b. As fluid volume change, the diaphragm changed shape continuously throughout the expulsion process. We hypothesized that concentric rings placed strategically along the diaphragm interior wall could facilitate a uniform diaphragm reversal. In addition, the concentric rings could act as stiffeners for an otherwise floppy ∅1016 mm (∅40 in) diaphragm. The CoM shift study was the proper setting for the concentric ring assessment.

Developing a method to measure CoM migration had been a challenge from the earliest days of diaphragm tank application in space systems. Past CoM migration estimations had been to assume an idealized uniform shape for the diaphragm. However, this assumption is inconsistent with observed diaphragm behavior during fill and drain. The solution had eluded researchers for several decades until innovative ideas and the use of technology finally made it available. The FIT researchers developed a method of measuring propellant CoM using 3D scanners to establish a 3D map of the diaphragm surface. This information, combined with the known geometry of the propellant compartment, would enable the volume calculation of the 3D propellant body and its CoM. Figure 25 shows the scanner cluster setup and the data acquisition workstation for acquiring diaphragm configuration data in real time. The research team published the results of the CoM migration study, including the assessment of concentric rings, in the Space Propulsion Conference 2016 [6].

The 3D scanning technique enables the mapping of the diaphragm shape as a function of time or fill fraction with high accurately, thus providing empirical data on propellant CoM movement as propellant depletes. In a dynamic environment, high speed cameras mounted above the simulator could capture diaphragm movements and enable the calculation of CoM. The modeling technique is accurate, repeatable, and reliable. However, we can only conduct simulations in 1 g. Researchers still face the challenge of correlating test results at 1 g and actual diaphragm behavior in zero g.

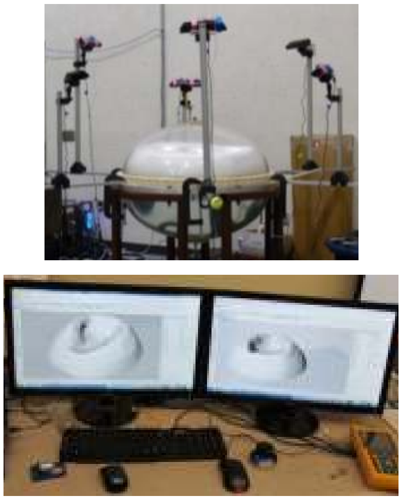


Figure 25: 3D Scanning Setup and Data Acquisition Station to Calculate the CoM Migration

3.5 Qualification Testing of a 26 inch Large Diameter Diaphragm Tank

The Ø660 mm x 1208 mm long (Ø26 in x 47.55 in long) diaphragm tank was ATK's first large diaphragm tank development program in over two decades. The custom designed tank must fit within a specified envelop with a goal of maximizing the overall propellant capacity. The design had an additional constraint on the diaphragm height imposed by the existing diaphragm press. The final tank configuration is as depicted in Figure 10a, with ellipsoidal heads and conical dome extensions.

With the two conical domes, the location of the single girth weld must be at the center of the tank. The length of the diaphragm is such that when the diaphragm fully reverses, it cannot touch the pressurant dome as shown in Figure 26.

Figure 26: The Diaphragm in a Fully Reversed Position

The qualification test sequence included a long-duration slosh test to simulate the launch pad slosh environment. We constructed a Plexiglas simulator for the test program as shown in Figure 10a. Figure 27 is the slosh test setup.

Figure 27: Slosh Test Setup

Unlike the smaller diameter tank tests, there were significant diaphragm motions during slosh testing. The oscillation was wave-like, with the diaphragm surface features changing constantly. There were rubbing of the diaphragm upon diaphragm, and to a lesser degree rubbing of the diaphragm with the Plexiglas wall. Figure 28 is a snapshot of the diaphragm during slosh testing. The D/t ratio of this tank is 26/0.065 or 400.

Figure 28 A Snapshot of the Diaphragm during the Slosh Test

In addition to tank diameter and diaphragm thickness, the new diaphragm design introduced a third variable that might affect slosh behavior. Unlike the hemispherical domes, the taller diaphragm has an ellipsoidal head and an integral frustum as shown in Figure 17a. The long frustum introduced another variable for increased floppiness. There were many valuable lessons learned from this tank development program, and one most important lesson was to always construct a simulator and conduct simulation testing to determine the adequacy of the diaphragm design with regard to slosh damping.

3.6 Qualification Testing of a 870 mm (34 inch) Large Diameter Diaphragm Tank

ATK's most recent large diaphragm tank is the Orbital ATK Cygnus fuel tank for the International Space Station Crew Resupply (CRS) missions. The internal dimensions of the CRS tank are ∅870 mm x 1105 mm long (∅34.25 in x 43.5 in long). Figure 17b is a photo of the large CRS tank diaphragm. The tank design enables the diaphragm to touch the pressurant dome at its fully reversed position.

Given lessons learned from past slosh tests, the stiffness of the large diameter CRS diaphragm was a major concern. Building upon the previous research findings (Section 3.4), ATK engineers explored the addition of concentric rings by modifying a diaphragm mold and molding a batch of diaphragms to assess manufacturability. Figure 29 is a photo of the diaphragms from the manufacturability experiment.

Figure 29: Adding Concentric Stiffening Rings to the diaphragm Interior Wall

In addition, design engineers increased the diaphragm thickness to 2.8 mm (0.110 in) to add overall stiffness. The D/t ratio is 34.25/0.11 or 311. The new combination of increased wall thickness and stiffener rings was sufficient to make the diaphragm stiff during slosh testing. Figure 30 are photos of the diaphragm during simulator testing. The stiffening rings are integral to the diaphragm design. This diaphragm tank is currently in service on CRS missions.

44.2% fill fraction

95.5% fill fraction

Figure 30: Diaphragm with Concentric Rings at Various Fill Fractions

3.7 New Small Diaphragm Tank Development Program

ATK's most recent diaphragm development program is for a ∅235 mm x 414 mm long (∅9.17 in x 16.3 in long) tank. The small diaphragm has a conventional design as shown in Figure 31. With available data, it became possible to predict that the diaphragm would remain stiff during slosh testing. Video evidence from the slosh test confirmed that there was little or no diaphragm movement during slosh testing. Figures 32 is the test setup for the small diaphragm tank slosh testing.

Figure 31: A small diaphragm for a ∅235 mm (∅9.17 in) Diaphragm Tank

Figure 32: Slosh Testing of a ∅235 mm (∅9.17 in) Diaphragm in a Simulator

3.8 Discussion of Diaphragm Slosh Damping

After more than 50 years of diaphragm tank manufacture, new information continues to emerge and challenge our perception of an optimal design. Diaphragm design has migrated from using a standard thickness to adjusting thicknesses based on diameter to maximize slosh damping. Additional data points are necessary to correlate diaphragm height into diaphragm design customization. Table 3 is a summary of stiffness coefficients D/t and Dh/t, and the observed diaphragm behavior during slosh testing.

It is possible to draw some preliminary conclusions even with the limited data. For appropriate stiffness, future diaphragm tanks could aim for a D/t ratio below 340 by adjusting diaphragm thickness. In addition, it might be appropriate to incorporate the diaphragm height into the quantitative and qualitative assessments as more data becomes available. This preliminary conclusion discounts environmental conditions such as slosh frequency and amplitude. As more data becomes available, we will enhance this general rule for diaphragm stiffness and slosh damping assessment.

Appreciably, this rule is not universally applicable. It applies to ATK's AF-E-332 diaphragms only, although preliminary data points to similar results for silica-free SIFA diaphragms. Diaphragms designed by others are likely to have completely different sets of characteristics. This is especially true for diaphragms without filler material to enhance diaphragm stiffness and promote slosh damping.

Table 3: Diaphragm Stiffness Data

Tank Internal Diameter (D)	Diaphragm Thickness (t)	Diaphragm Height (h)	D/t	Dh/t (mm, in)	Observations During Slosh Testing
∅235 mm (∅9.17 in)	1.65 mm (0.065 in)	216 mm (8.512 in)	142	30745, 1201	Little or no diaphragm movement
∅327 mm (∅12.9 in)	1.65 mm (0.065 in)	157 mm (6.185 in)	198	31096, 1226	Little or no diaphragm movement
∅419 mm (∅16.5 in)	1.65 mm (0.065 in)	224 mm (8.81 in)	254	56848, 2236	Little or no diaphragm movement
∅562 mm (∅22.1 in)	1.65 mm (0.065 in)	265 mm (10.45 in)	340	90206, 3553	Little or no diaphragm movement
∅660 mm (∅26.0 in)	1.65 mm (0.065 in)	560 mm (22.045 in)	400	223864, 8818	Appreciable diaphragm movement
∅870 mm (∅34.25 in)	1.65 mm (0.065 in)	562 mm (22.145 in)	527	299892, 11669	Appreciable diaphragm movement
∅870 mm (∅34.25 in)	2.79 mm (0.110 in)	562 mm (22.145 in)	311	174996, 6895	Little or no diaphragm movement
∅1016 mm (∅40 in)	1.78 mm (0.070 in)	448 mm (17.655 in)	571	256000, 10089	Appreciable diaphragm movement

3.9 Diaphragms in High Density Fluids

In 2015, ATK delivered the flight tank for the Green Propellant Infusion Mission (GPIM). The tank is a ∅327 mm (Ø 12.9 in) spheroid with a pedestal mount. Given the small diameter, diaphragm stiffness should not be a major concern. However, the intended green propellant, AF-M315E, has a higher density than hydrazine. There was no data on the effect of higher density fluid on the diaphragm behavior. To acquire slosh data, ATK commissioned a study using the ∅327 mm (Ø 12.9 in) tank simulator. The slosh test variables were:

- Two diaphragm materials (AF-E-332 and SIFA-35)
- Three different fluid densities (1.02, 1.24, and 1.30)
- Three different fill fractions (100%, 75%, 50%)
- Three different slosh environments (1 Hz @ 3 amplitudes, 5 Hz @ 3 amplitudes, and 10 Hz @ 3 amplitudes).

The research team collected both qualitative and quantitative data. As expected, both diaphragms exhibited little to no movement. However, researchers observed characteristics that indicate different rubber formulation contributes to different diaphragm behavior, and that fluid density does affect diaphragm behavior. The research team published the slosh test results at the Space Propulsion Conference 2016 [13]. The test results are the first set of slosh test data on high density fluids. As green propellant gain wider acceptance and usage, we expect additional opportunities to study the effect of higher density propellants on diaphragms.

3.10 Additive Manufactured Tank Shells

Additive manufactured components are appearing in many sectors of space industry. However, propellant tanks are pressurized vessels that often contain corrosive and explosive fluids operating within severe environmental conditions. While it is exciting to learn the many promising aspects of additive manufacturing (AM), we continue to take a cautious approach towards applying the technology on pressure vessels. Our research findings, based on exploratory trials, indicate that AM techniques are suitable for small diameter tanks. These small diameter tanks have greater than 4 to 1 burst factor of safety instead of the typical 1.5 to 1 burst factor on conventional and larger diameter tank designs. The high burst factor reduces uncertainties associated with the use of this new material on tank applications, and mitigates the perception of risk. Figure 33 is a photo of small diaphragm tank shells made by AM techniques.

Figure 33: A ∅68 mm (∅2.7 in) Tank Shell Made Using Additive Manufacturing Techniques

Figure 34 is a photo of a set of ∅112 mm (∅4.4 in) shells made by conventional machining process, and another set of shells made from AM techniques. Both shell sets underwent closure weld followed by pressure cycles and burst. The conventionally machine tank burst at 168.8 bar (2448 psi), and the AM tank burst at 255 bar (3699 psi). See Figure 35. Both tanks have >4 to 1 burst factor of safety based on 27.6 bar (400 psi) MEOP. The conventional machined tank mass is 0.57 kg (1.23 lb_m). The AM tank mass is 0.55 kg (1.22 lb_m). [14]

Figure 34: ∅112 mm (∅4.4 in) Domes Made From Machined Domes and AM Domes

Figure 35: ∅112 mm (∅4.4 in) Diaphragm Tanks after Burst Pressure Tests

The test results indicate that additive manufactured shells have excellent tensile strength for tank applications. Nevertheless, other issues persist, including the collection of A-basis and B-basis design allowables to support tank structural analysis, the collection of fracture data for fracture analysis, and the application of fracture critical non-destructive inspection techniques. In addition, engineers and designers need to understand the variability of data from AM machine to AM machine, and from AM technique to AM technique. We envisage many uses for non-pressurized additive manufactured components. For tank shell applications, we suggest additional research to resolve a long list of compliance issues.

3.11 Linear Stage for Slosh Testing

As propellant tanks grow in size and volume, it is becoming difficult to find existing facilities capable of conducting slosh testing for high capacity tanks at high frequency, high amplitude, and long duration. ATK, in collaboration with our research partner Florida Institute of Technology, had developed a high capacity linear stage to meet this need [15]. The linear stage is now on line. We have already concluded a long duration slosh test, and the equipment is available to meet future demands for slosh testing.

4. Conclusion

Diaphragm tanks had been an important contributor to space system operations for over fifty years. Their extensive presence on launch vehicles, satellites, and planetary explorers is testimony to diaphragm tanks' versatility and durability. With their many advantages such as heritage, simple construction, and ease of operation, the use of diaphragm tanks is likely to continue for many years to come.

In this summary paper, we provide an update to the literature to help users gain a more nuanced understanding of diaphragm tanks. It is evident from our presentation that a key research focus in the past decade had been on diaphragm characterization. Admittedly, even after fifty years of designing and fabricating diaphragm tanks, we still seek more data to optimize tank design in terms of mass, durability, and slosh damping capability. Given the customer preference for derivative tanks, and with an average rate of one qualification program per every two years, there will be few opportunities to gather new data. Conducting research on existing designs is another method of acquiring diaphragm tank knowledge to pursue optimization. ATK had been consistent in committing resources towards product and process research and development, along with continued contribution to the literature.

Internally, we are evaluating data to determine the need to update diaphragm design for larger diameter tanks. In the coming years as we gather more slosh data, we expect more and better understanding of the diaphragm slosh damping capabilities. In addition, we are developing new rubber formulations for existing propellants such as hydrazine, as well as for new propellants such as LMP-103s and AF-M315E. Externally, we expect continued use of diaphragm tanks in the traditional market space. We do not anticipate significant changes to the diaphragm tank market in terms of order quantity or tank size. As for the impact of the New Space, we are already noticing increasing demand for smaller diameter diaphragm tanks. However, there is insufficient data to confirm a definitive trend.

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Acknowledgment

We wish to recognize Mr. Henry Richardson for his efforts in compiling the diaphragm tank data. We acknowledge and thank the following individuals for their contributions during the compilation of this paper: Mr. Haroon Ali, Professor Steven Collicott, Ms. Debbie Gary, Mr. Dave Gibbon, Mr. Mathias Larsson, and Mr. Jim Reinholdt.