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I. A. Ballinger, W. D. Lay, and W. H. Tam,
Pressure Systems, Inc.
Commerce, CA

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ABSTRACT

The elastomeric diaphragm tanks have been in use since the early stages of space flight, and Pressure Systems, Inc. (PSI) has been a long time participant in their application in the Aerospace Industry. This paper presents the history of the elastomeric diaphragm tanks at PSI, covering the program heritage, the evolution of diaphragm material, the tank design philosophy, the manufacturing process, and the testing heritage. Comparison of a diaphragm tank with a simple surface tension Propellant Management Device (PMD) is also made to illustrate the different approaches to their usage.

1.0 INTRODUCTION

The history of space flight is filled with many glorious innovations and fascinating technologies. Amid the rapid technological evolution that has accompanied space flight, a conceptually simple component, the elastomeric diaphragm tank remains virtually unchanged since its initiation during the earliest days of space exploration. The elastomeric diaphragm tank continues to be a steady workhorse and credit to it is long overdue. Just as remarkable is the fact that the majority of the flight history associated with this component has and continues to be produced by a single, small aerospace company. This paper presents the history of diaphragm tank design, manufacturing and test at Pressure Systems, Inc. (PSI).

Founded in 1963, PSI delivered its first elastomeric diaphragm tank in June of 1967 and continues to be at the forefront of elastomeric diaphragm tank production. This paper describes the history of positive expulsion technology, discusses issues relating to the design, fabrication and test of diaphragm tanks and describes the comprehensive family of diaphragm tanks that has made PSI the world leader in this field. The history and discussions relating to AF-E-332 diaphragm tanks are almost exclusively applicable to monopropellant propulsion systems.

PSI is a small privately owned business which specializes in the design, manufacture and test of spacecraft propellant and pressurant tankage. It is located in the City of Commerce in Southern California. Shipping over three thousand five hundred (3,500) tanks to date, PSI has grown to be the world's largest independent titanium tank producer. Over 700 of the propellant tanks shipped have employed positive expulsion diaphragm devices for fluid control and delivery. The majority of these tanks are for use in monopropellant hydrazine systems and use PSI's unique AF-E-332 elastomeric material and all-welded construction. Table 1 presents a summary of programs on which diaphragm tanks have or are to be used.

In this paper, the term positive expulsion describes the use of a pressure differential to expel propellant from its storage vessel. Positive expulsion devices include diaphragms, bladders, pistons or bellows based systems for fluid control and delivery. Two of the most practical types of spacecraft propulsion fluid control devices have proven to be diaphragms and bladders, which use elastomeric materials for an effective barrier between the pressurant gas and liquid propellant.

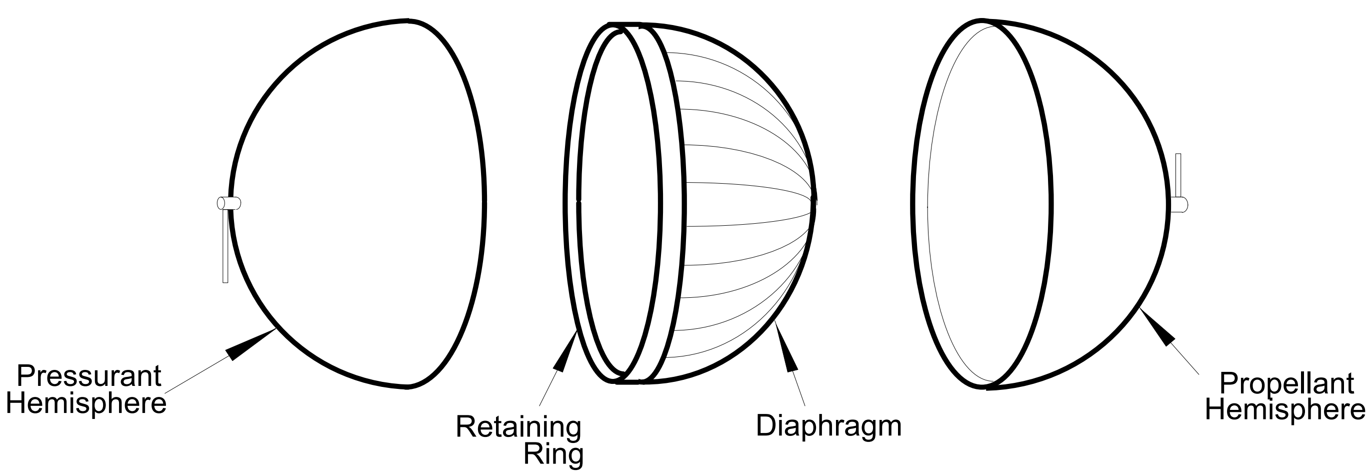
Table 1 : AF-E-332 Tank Program Summary

SIZE	QTY	PROGRAMS
9.4" Sphere	28	AEROS, IUS, HCMM, SCATHA, SHUTTLE
12.9" Sphere	94	CTS, OTS, GPS, APPLE, ITV, DMSP, (TIROS), GEOSAT, MSTI, (WORLDVIEW)
15.4" Sphere	11	OTS
16.5" Sphere	219	PIONEER, ATS, NOVA, BSE, SEASAT, MMS, TOPEX, P-80, ECS, TELECOM, GPS, SKYNET 4), NATO IV, CRRES, TOS, TITAN II, LANDSAT, MESUR PATHFINDER, (MUPS)
17.4 Sphere	9	ISPM, SAX
19" Sphere	3	EXOSAT
20.8" Sphere	53	IUS
22.1" Sphere	231	P-95, VIKING, HEAO, FLTSATCOM, DSCS, (CENTAUR), RADARSAT, (STEP), TOMS, NEAR
23.1" x 25.7" Long	8	EURECA
28" Sphere	54	VOYAGER, SHUTTLE, MMS-ATK, UARS, TOPEX, ERBS, VRM, TITAN III, CASSINI, (INDOSTAR)
36" x 47" Long	5	GRO
40" Oblate Spheroid	28	TDRSS, SOHO, P80, COBE, TRMM, EOS, (EST-VII)
TOTAL	**743**	

NOTE: Programs in parenthesis indicate tanks in production at time of writing

Diaphragm tanks are positive expulsion devices which form a membrane to separate the propellant compartment from the pressurant compartment. Figure 1 illustrates the typical embodiment of a diaphragm tank. In most cases the diaphragms are hemispherical or hemispherical with an integral cylindrical section and the outermost edge of the open end of the diaphragm is sealed against the pressure shell. In the PSI diaphragm design the sealing bead is retained by a metallic retaining ring which is welded to the tank shell during the weld closure of the exterior pressure shell. Alternative designs achieve diaphragm retention by a clamping device that is mechanically fastened to an intermediate cylinder or by mechanically trapping the diaphragm directly between the upper and lower pressure shells.

Figure 1 : A typical PSI elastomeric diaphragm tank assembly



Bladder tanks are balloon-like membranes, similar to that used in a soccer ball, which have a relatively small opening sealed at either the tank's inlet or outlet port depending on the tank's design principle. Typically, the propellant is inside the bladder and the pressurant gas is in the external cavity between the bladder and the pressure shell wall. However, the relative positions of the fluids may be reversed in some designs. In order to keep the bladder volume open (i.e prevent vertical collapse) until expulsion is nearly complete, a center post or support mast is usually required.

The main advantages of the diaphragm principle over the bladder principle are its easier manufacture and more repeatable, less severe folding pattern during operation, and lighter weight. The principle advantages of the bladder principle relative to diaphragm principle are its small sealing area and ability for easier installation, removal and replacement.

In monopropellant systems the fuel is typically hydrazine which is sprayed onto a catalyst bed which thermally decomposes the liquid to produce expanding and accelerating gases in a nozzle for thrust. Although positive expulsion devices have also been used in hypergolic bipropellant systems, typically using monomethylhydrazine (MMH) fuel and dinitrogen tetroxide (NTO) oxidizer, they have fallen into disuse due to high cost and limited life.

Monopropellant hydrazine systems are widely used on launch vehicle attitude control systems, interplanetary missions, the US Space Shuttle and numerous other on-board satellite propulsion systems for scientific, military and commercial payloads.

By definition all positive expulsion devices provide some degree of barrier between the pressurant gas and the propellant so as to provide gas-free propellant delivery to the engine(s). Furthermore, an ideal system will also provide the following features, as quoted from a 1966 Jet Propulsion Laboratory (JPL) report prepared by R. N. Porter and H. B. Stanford [1]:

- Eliminate chemical reactions between the pressurant gas and the liquid propellant,
- ### Eliminate absorption of the pressurant gas in the liquid propellant,
- ### Eliminate propellant loss due to vaporization,
- ### Eliminate corrosion of the tank and adjacent components of the pressurization system by completely containing the propellant and its vapor within the positive expulsion device. This could lead to the use of lighter materials,
- Eliminate propellant slosh and provide enhanced center of gravity control,
- ### Provide the capability for propellant gauging.

As with any ideal system "wish list", practical and commercial compromises are invariably required. The following paragraphs describe how the AF-E-332 diaphragm tank has evolved as the most effective positive expulsion solution for monopropellant hydrazine systems.

2.0 PROPELLANT MANAGEMENT FOR HYDRAZINE SYSTEMS

Today's hydrazine monopropellant propulsion systems almost exclusively use either AF-E-332 elastomeric diaphragms, surface tension devices or employ centripetal forces generated from spinning the spacecraft to provide gas-free expulsion.

For satellites using three axis control rather than dominant spin, the choice of a diaphragm or surface tension based propellant management device (PMD) is influenced by many inter-related technical and commercial considerations. Surface tension devices using vanes, galleries and liners are used in a number of hydrazine flexible demand systems. Flexible demand systems provide gas-free delivery during thrusting in any direction and for any duration under specified flow rate and acceleration limits. The simplest surface tension system is a vane-type system. Vanes have been extensively used in hydrazine systems because typically the flow rates, in the order of 0.025 lb./sec and acceleration levels in the range of $1x\ 10^{-4}$ g to 7×10^{-4} g are tolerable and hydrazine has favorable kinematic surface tension characteristics relative to typical bipropellants.

The following qualitative comparison is for equivalent tanks using an AF-E-332 elastomeric diaphragm and a vane surface tension PMD. PSI built and tested a number of hydrazine surface tension tanks and this comparison is based on observations made at PSI. The following primary criteria of reliability, size, expulsion efficiency, weight, material compatibility-flight heritage, slosh control, performance flexibility and cost are discussed.

Reliability

A diaphragm tank's functional design and operational reliability may be verified by qualification and acceptance ground testing. The common operational principle of all diaphragm tanks and the standardization of critical diaphragm parameters pertaining to the diaphragm and its sealing bead allow qualification by similarity for many designs which enhances system reliability.

Surface tension devices are passive devices i.e. no moving parts, which greatly enhances reliability. Functional reliability depends on analysis since ground testing is not possible. Each surface tension device is designed for a specific mission profile, expulsion efficiency and tank geometry.

It should be noted that a rigorous numerical analysis of propellant tanks cannot be generally performed since the sample size associated with any particular design is statistically inadequate. Reliability assessments are invariably limited to a qualitative assessment of the failure modes, effects and criticalities.

Size Limitation

PSI has produced diaphragm tanks up to 40 inches in diameter. PSI currently has press capability for a 48 inch diameter envelope. Long cylindrical tanks do present more severe problems with respect to the control of diaphragm folding as the diaphragm passes through the geometric center of the tank. PSI has produced diaphragms with length to diameter ratios approaching 2:1. At length to diameter ratios much above this a change to a bladder tank design is anticipated.

Surface tension device design is a function of the required flow rate, acceleration and tank geometry. The surface tension driving pressure is opposed by hydrostatic and viscous losses which both are effected by tank geometry. The addition of porous elements and/or sponges, traps or troughs may be used to overcome vane limitations.

Expulsion Efficiency

Expulsion efficiencies of 99.9% or greater can be readily achieved with diaphragm tanks.

Equivalence with surface tension devices is difficult since calculated expulsion efficiency is dependent on acceleration levels towards end of life and safety factor assumptions. Typical, conservative assessments provide expulsion efficiencies of around 99.7 % or greater.

Weight

The use of a simple vane device will be considerably lighter than an equivalent diaphragm. Although AF-E-332 material has a competitive relative density of approximately 1.1, the volume of diaphragm material required is relatively significant - approximating to the product of one-half the tank's internal surface area multiplied by a nominal diaphragm thickness of 0.060 inch (1.524 mm). Additional tank shell material is also required to facilitate the diaphragm mounting feature.

For a typical 28 inch diameter spherical diaphragm tank the diaphragm and retaining ring will weigh around 4.50 lbm.

Material Compatibility - Flight Heritage

AF-E-332 tanks have flight data up to 14 years in hydrazine systems. Considerable AF-E-332 material compatibility for duration of 10 years is also available. Further discussion on this aspect is provided in Section 8 of this paper.

Simple vane devices are all-titanium structures which have extensive flight heritage. Current design life for such devices is up to 20 years.

Slosh Control

The diaphragm tank provides inherently superior slosh control compared to a simple vane device. Selective placement of concentric reinforcement rings can be used to provide additional enhanced slosh control. Slosh control may be designed into a surface tension device through the provision of baffles, although this greatly complicates the fluid analysis and invariably reduces expulsion efficiency.

Performance Flexibility

Diaphragm devices can deliver gas-free expulsion under any practical combination of acceleration, orientation and flow rate. Ground testing can be used to demonstrate capability. For a given diaphragm design, performance data is applicable to any similar tank design regardless of mission profile.

`Vane devices are designed for each specific mission scenario and tank size. Flexible demand systems provide gas-free delivery during thrusting in any direction and for any duration under specified flow rate and acceleration limits. The flow rates and acceleration limits are related to one another and are dependent on the tank geometry, the type of vane structure and the allowable residual fluid quantities.

Comparative Cost

The design and analysis effort (i.e. structural and operational performance) required for diaphragm tanks is considerably less than that required for a surface tension device. However, a new diaphragm tank typically requires more expensive tooling - diaphragm mold - than a simple vane device.

The recurring cost for a simple vane device is typically less than that of an equivalent diaphragm tank.

For a new tank design comparison, the cost benefit is largely a function of tank quantity. The larger the tank quantity the greater the simple vane benefit.

Invariably, for any of the tank sizes listed in Table 1, PSI can utilize existing diaphragm tooling and design which yields considerable non-recurring cost savings compared to a new tank design. The ability to use similarity for diaphragm performance qualification avoids the need to re-analyze and redesign unlike surface tension tanks where each new mission scenario must be analytically reevaluated. The continually developing family makes diaphragm tanks extremely competitive, particularly for small tank quantities.

3.0 THE EARLY YEARS OF ELASTOMERIC POSITIVE EXPULSION DEVICES

Positive expulsion devices were first actively pursued in the Western world during the mid-1940's during the development of America's first sounding rocket, the WAC Corporal. The initial positive expulsion prototypes examined were bladder concepts. However material compatibility with red fuming nitric acid was a major problem. The initial bladder design for the oxidizer used a vinyl plastic reinforced with glass fibers without success. All of the WAC's were flown with an inert-gas pressurization system and without any positive expulsion devices.

Interest in the concept of reducing weight by substituting a gas generator for stored gas carried over to the full-scale Corporal program. The first attempt to convert the Corporal missile to gas generation used a number of floating piston devices to separate the pressurizing gas from the propellants. A number of explosions and fires as a consequence of propellant leakage past the piston and the inability to wipe the cylinder walls clean of propellant reinforced the desire to use a bladder design concept.

With the development of dual gas generator systems using monopropellant hydrazine, butyl rubber was identified as having some degree of suitable compatibility. In the mid 1950's, the Voit Rubber Corporation used a beach ball mold to make a 13.5 inch diameter butyl (Voit 1840 butyl) bladder tank. Compatibility and expulsion tests were successfully conducted at Edwards Test Station and this expulsion device was incorporated in the dual gas generator conversion of the Corporal missile. In late 1955 and early 1956 two Corporal missiles were converted and successfully flown. Further work on the Corporal was not attempted because its successor, the Sergeant missile was nearing the end of its development at JPL. As part of the Sergeant program a pump-fed monopropellant hydrazine auxiliary power unit (APU) was designed and built in 1956. As a weight reduction exercise a spherical spun tank incorporating a butyl rubber bladder was designed and fabricated. This tank was successfully tested, however, improvements in the Sergeant battery APU obviated the necessity for further development.

Following the Soviet Sputnik success in 1957 and the dawning of the space age, the challenges facing the future of positive expulsion devices shifted to space missions. At the forefront of much of the work was JPL. Much of the initial work was directed at using the more powerful nitrogen tetroxide. In 1959, JPL tested a number of bladders fabricated by alternately spraying TFE Teflon dispersion onto a mandrel and sintering the coating in an oven. Every item ultimately developed leaks during slosh testing.

In the early 1960's, JPL evaluated propellant management during the Advance Liquid Propulsion System (ALPS) program. The ALPS system was a bipropellant pressure-fed rocket where pressurizing gas was produced by monopropellant hydrazine gas generator. Bladder development started with an extensive search for a satisfactory material from which to fabricate bladders for hydrazine and nitrogen tetroxide. The ALPS system required that both propellants be stored in a single spherical vessel and as such permeation of the propellants through the material was a critical parameter. The results of the comprehensive ALPS evaluation[2] indicated that non-metallic devices were preferred over equivalent metallic devices and that the diaphragm concept was preferred over the bladder concept. As part of the development program three flight-type 6AL-4V titanium generant tanks were fabricated for testing in the ALPS pressurization subsystem. Coincidentally at the time of this work, PSI was developing expertise in the machining, processing and welding of titanium, particularly the 6AL-4V alloy. With this expertise PSI was chosen to conduct a series of tests to determine the necessary axial loads on the hemispheres for effecting a seal on the diaphragm lip. In addition, PSI conducted a test program to determine the optimum ratio of diaphragm thickness to outlet port diameter as a function of differential pressure so as to prevent diaphragm extrusion. These tests were conducted with an extensive list of materials which included butyl and ethylene propylene. At this time, these were the two most promising hydrazine-compatible materials. The butyl was preferred from a permeability resistance point of view while the EPR compounds were better from an overall compatibility point of view. The generant tank was designed in such a manner that either of the above elastomers would be satisfactory for effecting a seal at the diaphragm lip. For the flight version of the generant tank the EPR compound was chosen because of its greater compatibility with hydrazine. The initial fabrication of the flight tanks was carried out at the Electrada Corporation, Airite Division, Los Angeles, California. The fabrication of the flight hardware was later continued and completed by PSI. The production of flight standard hardware produced considerable data with respect to tooling (i.e. forging dies, molding dies, chill rings), welding parameters (i.e. welding speed, current, voltage, weld wire feed rate, back-up ring temperatures) and weld inspection (i.e. X-Ray, penetrant inspection and metallographic samples). Much of the knowledge developed by this program remains at the core of the operating procedures and practices still used today at PSI.

Prior to the development of AF-E-332, hydrazine monopropellant systems have used at least three other different basic rubber compounds with progressively improving compatibility. The earliest spacecraft flight devices built used a Fargo Rubber Company butyl rubber. Such butyl rubber bladders were used on the Ranger and Mariner spacecraft. The limited hydrazine compatibility was a catalyst for further investigation. AF-E-132 was used in the Titan missile with reported significant improvement and in 1969 under a JPL contract, a new material designated EPT-10 elastomer was developed and flown on Pioneer and Viking 75. This material has good mechanical properties and reasonable hydrazine propellant compatibility and processability.

PSI's first material specification for diaphragms was issued in October 1968 and was for an EPT-10 rubber. PSI supplied EPT-10 diaphragms for a number of programs including P95, MVM '73, CTS, Viking Deorbiter, AEROS, Pioneer F & G, ATS F& G, Viking '75, BSE, IUE and AEM. During the late 60's and early 1970's, PSI also established process specifications for Viton B and Buna-N diaphragm materials.

4.0 AF-E-332 MATERIAL DEVELOPMENT HISTORY

Recognizing the capability of bladder or diaphragm tank concepts and the disadvantages of the EPT-10 material, the Air Force Materials Laboratory (AFML) sought the development of an improved elastomeric material. The initial work of major significance in the development of the AF-E-332 diaphragm material was performed under USAF Contract F33615-69-C-1521 by the Applied Chemistry Department of TRW Systems Group, Redondo Beach, California. This work established the basic technology of co-reacting elastomers with low molecular 1,2-polybutadiene resin and was completed about June 1971. At the conclusion of this work a compound designated 332-6 was identified as the most promising candidate material for the use in hydrazine positive expulsion devices. While this material had favorable properties of processability, high tear strength and relatively low permeability, further improvements were required to meet the program goals. This work was continued by TRW Systems Group under USAF Contract F33615-71-C-1233. A number of derivative compounds were formulated and evaluated, and based on the test results, compound 332-11 was selected for extensive characterization. On the basis of the successful test results this composition was selected as the prime candidate material and was given the AFML designation AF-E-332.

Extensive testing was performed to demonstrate the suitability of the material. Key tests included multiple propellant expulsions at -40°F, +75°F and +160°F, over 257,000 hard fold cycles in hydrazine, and long term compatibility, permeability and compression set measurements. Full scale diaphragms and bladders were made from the new material and qualified for several programs including P-95 diaphragms, FLTSATCOM diaphragms, Mariner '69 bladders and Block 5-D bladders.

In addition to work under the AFML contract, other government agencies and commercial companies evaluated the material for specific applications. Some of the tests were performed with specimens produced from the contract in exchange for test data. Tests were performed by the Jet Propulsion Laboratory, Rocket Research Corporation, Sunstrand Aviation Company, Bell Aerospace Company, Rockwell International (Seal Beach), and the Titan Program (Martin Co., Denver). All of these evaluations showed positive results and the synonymous role of AF-E-332 and PSI in diaphragm hydrazine tanks was underway.

The original formulation of AF-E-332 was based on the use of DuPont Nordel 1040-an ethylenepropylene dienemodified (EPDM) terpolymer (EPT). A problem existed with this formulation in hydrazine propellant systems where low molecular weight materials were extracted from the polymer and left as non-volatile residue (NVR) that could plug small thrusters. In order to overcome this problem, prior to rubber compound mixing, the EPT was extracted by refluxing for 24 hours with methanol followed by an additional 24 hours refluxing with methylethyl ketone. This material was designated Type A rubber in the first PSI Material Specification, PSI No. 90-000072, issued in October 1972. Later DuPont began the commercial manufacture of a sister polymer Nordel 1635, similar to 1040 but without the low molecular weight oils. As a consequence this base EPT rubber could be used without preliminary processing which offered significant cost savings and environmental benefits. The material using Nordel 1635 was designated Type B rubber in PSI Material Specification 90-000072. As a consequence of its simplified processability Nordel 1635 became the base polymer for AF-E-332.

In mid 1988 DuPont ceased production of the 1635 gum stock and work was initiated to identify an alternative polymer. Evaluation of a number of candidates was made, including extracted 1040 as had originally been used, against control samples of 1635. Often a single type of Nordel will meet the requirements, as in the case of 1635 and extracted 1040, but on occasion a blend of types is needed to achieve similarity. A number of blends were included in the evaluation. The candidates were evaluated for mechanical strength, hydrazine compatibility and processability. Tensile properties and compression set of both virgin and hydrazine-aged compounds were performed. Cure characteristics were examined by oscillating disk rheometry (ODR) and hydrazine compatibility was assessed on pressure rise, volume swell and NVR results. Finally thin film IR spectroscopy and gel permeation chromatography (GPC) analyses were performed to study polymer structure and molecular weight distributions in each compound.

Based on the evaluation results a 50:50 Nordel 1440/2744 blend was deemed the best alternative to Nordel 1635. Test results indicated that this new blend meets all specification requirements. The blend provides superior processability characteristics, satisfactory properties and is readily available.

5.0 DIAPHRAGM TANK DESIGN

General

PSI's design approach to the expulsion diaphragm and its retention is of an empirical nature that has been evolved over the last 25 years. The emphasis has been in establishing a design which provides controlled installation and assembly - selective fit and dimensional control - with features to prevent over compression. Over compression of the lip seal will result in lip seal damage with potential uncontrolled leakage of the pressurant gas into the propellant and visa versa.

The original target mechanical properties of the material were selected on an arbitrary best judgment basis. Although it is recognized that for simple diaphragm designs with low duty cycles much lower mechanical properties could be tolerated, it has been PSI policy to standardize the basic diaphragm design parameters as much as possible so that the diaphragm has considerable margin for all applications and applicable heritage is maximized.

All of the PSI AF-E-332 diaphragm tanks built to date use 6AL-4V titanium material for the shell and diaphragm retaining ring. In order to provide high strength and premium quality material, titanium billet is forged into the basic shell components. These components are then rough machined to thicknesses for optimum heat treatment response. The rough machined components are then solution heat treated, quenched and aged to acquire the required mechanical properties. All of the pressure shells built to date have used a minimum internal burst pressure factor of two.

The molded and inspected diaphragm is inserted into the propellant hemisphere and mechanically retained with a titanium ring, so forming the expulsion assembly. The two hemispheres are then joined by tungsten-inert gas (TIG) welding. As a result of the closure weld the retaining ring becomes an integral part of the weld joint. The girth weld is inspected and accepted by a dye penetrant inspection and X-ray inspection. After closure the tank assembly is final machined, acceptance tested, cleaned and shipped to the customer.

As a consequence of the welding process considerable local heat is generated and considerable effort is taken to ensure that the rubber is not heated above its cure temperature. The development and efficient control of this process was a major factor in establishing PSI as the preferred manufacturing source during the early days of diaphragm development conducted by JPL. Indeed, this ability remains a major manufacturing attribute.

Although it is possible to measure the diaphragm temperature during welding for Qualification tanks by inserting intrusive thermocouples, it is not possible to readily verify the temperature for flight tanks. Therefore during weld development the priority is to establish a controlled and repeatable process.

After the tank closure weld, PSI employs neutron radiography as an enhanced inspection technique to verify the integrity of the AF-E-332 diaphragm. PSI has developed unique experience in interpreting these images. This inspection is conducted so as to provide final verification that the welding process has not caused unexpected shrinkage which could effect the performance of the sealing interface or there has been some other unforeseen variation during the diaphragm's thermal history which may have caused damage.

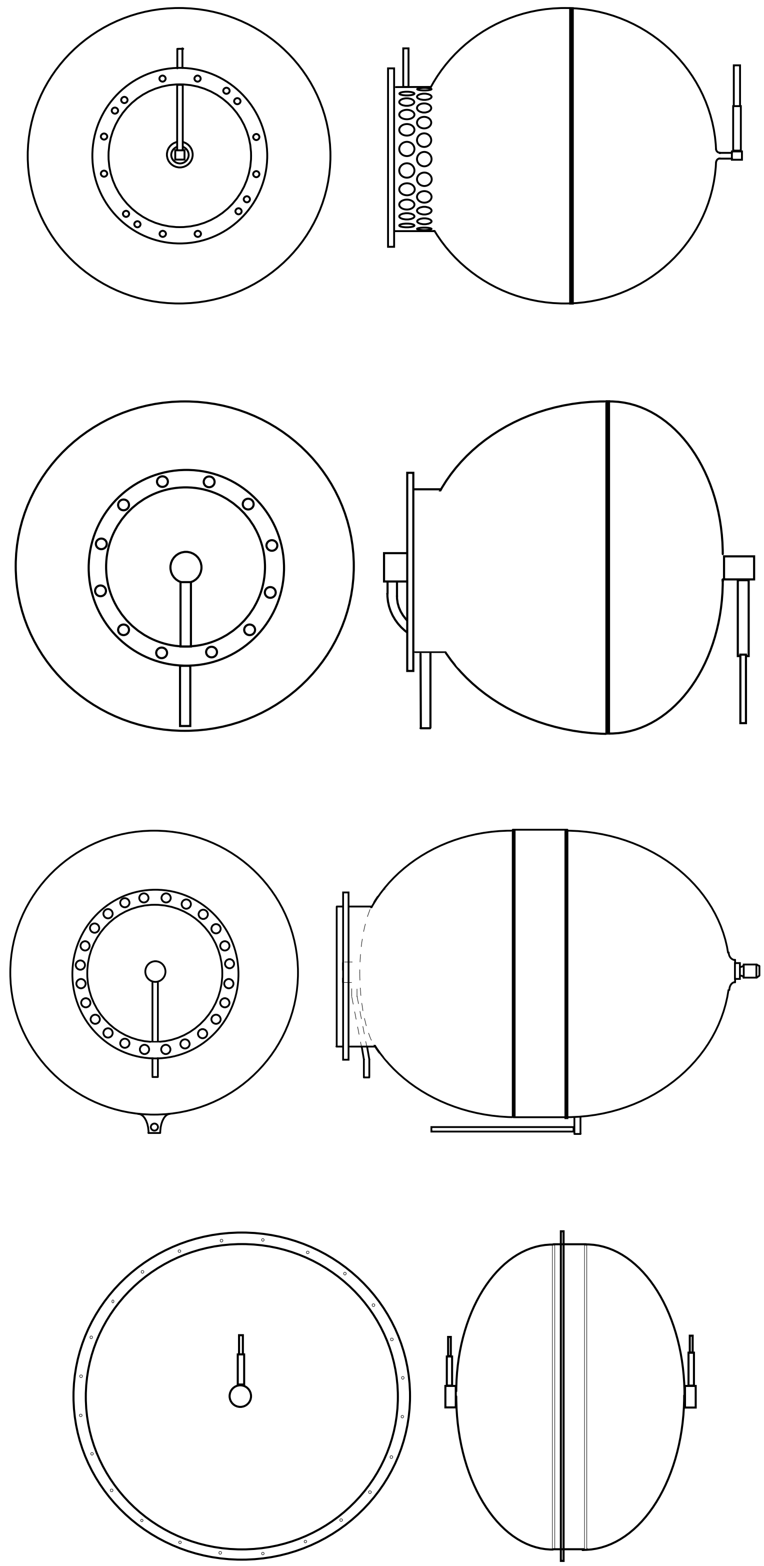
Tank Configurations

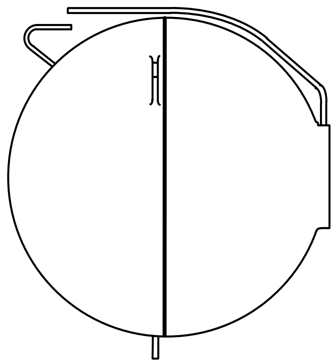
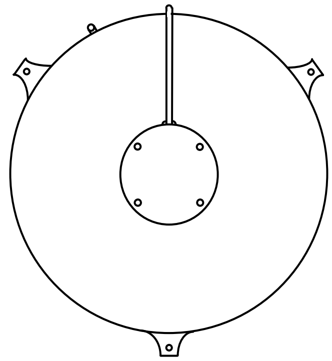
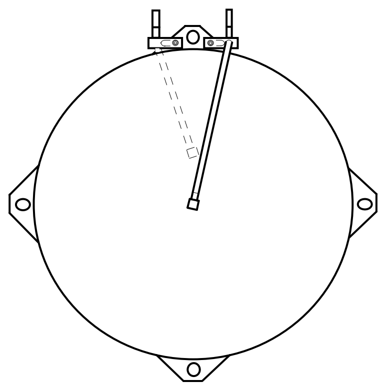
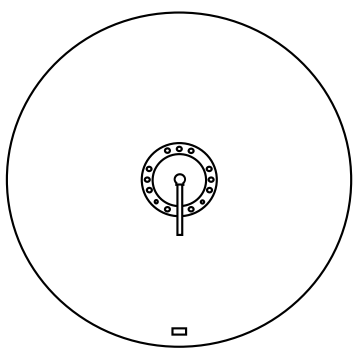
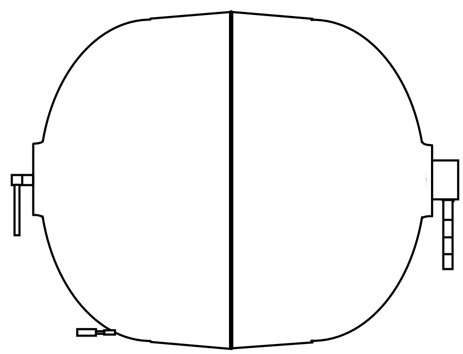
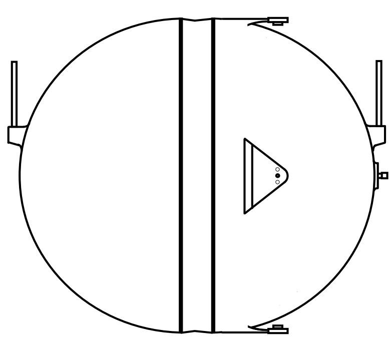
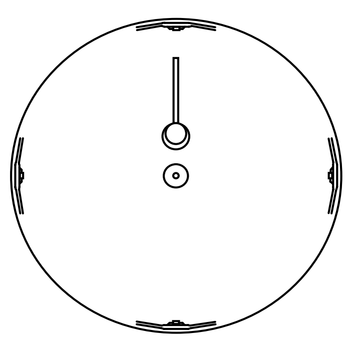
PSI has supplied propellant tanks which range from 415 cubic inches (6.8 liters) to 36,626 cubic inches (600.2 liters) in available internal volume, have membrane wall thicknesses as low as 0.014 inch (0.356 mm) and have been qualified for propellant capacities of up to 28,000 cubic inches (458.8 liters) of hydrazine. Appendix A shows an assortment of diaphragm configurations.

Tank mounting and porting configurations have been provided in a multitude of configurations. Mounting configurations have included simple boss mounts, skirt mounts, multiple radial girth lugs, boss and girth lug combinations, full girth flange mounts, girth tab mounts, strap mounts and off-axis mounts. Although most of the tank shells are spherical in the pursuit of expulsion efficiency, tanks have been produced which are a combination of ellipsoids, hemispherical heads with cylindrical center sections, ellipsoidal heads with cylindrical center sections and with tapered cylindrical sections. Diaphragm tanks have been supplied with off-axis propellant and pressurant ports and pressurant ports which enter the tank at the girth weld location. PSI has custom designed tanks with interface tubing, tube supports and integral fill and drain valves and pyrotechnic valves.

Figure 2 presents a collage of tank mounting, shell profiles and port arrangements, not to scale, which demonstrate the unique range of PSI-supplied tank configurations.

Figure 2 : Various Propellant Tank Configurations



Diaphragm Reversal & Loading

Diaphragms are sized to accommodate the propellant volume and conform to the tank shell internal profile at tank depletion without undue strain. For spherical tanks with single girth weld designs the positioning of the diaphragm is such that in the fully reversed unstressed position, the diaphragm will not be supported against the upper pressurant shell. Therefore, undue pressurization of the diaphragm in this position may induce biaxial strains large enough to tear the material. Pressure differentials in excess of approximately 0.1 psid may be sufficient to cause damage. In such tanks, care is taken during the loading procedure to prevent such an occurrence. The preferred loading mechanism is for vacuum evacuation of the propellant side with initial back-filling of the propellant against a supporting pressure in the pressurant hemisphere. Generally for spherical, single girth weld tanks, relocating the diaphragm flexure point on the internal spherical centerline will result in propellant weight and volume losses.

PSI has manufactured a number of tanks which allow full diaphragm reversal. This is usually accomplished by using a short intermediate cylindrical section which positions the diaphragm flexure point on the tank's central plane.

Diaphragm designs typically provide a relatively high expulsion cycle capability in excess of 100 cycles.

The diaphragm in the static position typically experiences the peak strains at start of life since the diaphragm is partly reversed causing the diaphragm to be folded around the clamping retainer. There have been situations where propellant tanks (4570 cubic inch volume) have been loaded with 3370 cubic inches of hydrazine pressurized to 405 psi ullage pressure and configured with gravity at 90 degrees to the expelled contour, for 3 years preflight. This unique occurrence happened due to a launch delay.

NASA research work conducted by JPL[3] described a method for predicting the long-term durability in hydrazine under dynamic stressing conditions. From the data it was estimated that AF-E-332 stressed to about 150 psi, as could be expected in the worst case of a hard bladder fold, would not creep to failure in less than about twenty years under ambient room temperature. The tests were conducted in air and hydrazine. It is informative to also recognize from this data that the test results for air and hydrazine are essentially superimposable, thus illustrating the basic inert nature of the material with hydrazine propellant.

Fracture Mechanics Issues

Pressure vessels with heat sensitive elastomeric diaphragms cannot be thermally stress relieved after girth weld closure, and as a consequence, the residual stresses present after welding cannot be effectively reduced.

The residual stresses in the weld are a function of materials, weld design, weld schedule, thermal history and stress history. As a result the residual stresses in a girth weld vary through the weld thickness and around the tank profile. It is generally agreed that residual stresses cannot be higher than the yield strength of the parent metal itself.

Currently the majority of pressure vessels used in military space systems are designed, analyzed and test qualified per MIL-STD-1522A, "Standard General Requirements for Safe Design and Operation of Pressurized Missiles and Space Systems". Furthermore, most civilian space programs including NASA Space Shuttle payloads and ESA programs have adopted this standard. For payloads using the National Space Transportation System, fracture control is required as detailed in NHB 8071.1. For propellant tanks containing hazardous fluids, these documents require that it be demonstrated by analysis or test, that the largest undetected flaw that could exist in the most critical area and orientation for that part will not grow to failure when subjected to the cyclic and sustained loads encountered in four (4) complete service lifetimes.

For all metallic propellant tanks the standard approach is to use linear fracture mechanics flaw growth models to theoretically analyze the proposed structure. In order to start the fracture mechanics analysis, some value for the smallest detectable initial flaw must be made. The first published limits of detectability that were established on a statistical basis for flaws over a wide range of lengths and depths are given in the Space Shuttle Orbiter Fracture Control Plan[4]. The initial flaw dimensions correspond to a 90 percent probability and 95 percent confidence level of inspection reliability. The minimum detectable initial flaw sizes for "Standard NDI" , that is a level of inspection governed by general NDI specifications such as MIL-STD-6866 for Dye Penetrant or MIL-STD-453C for Radiography, are documented by NASA and ESA and can be claimed industry-wide without employing special methods. The use of "Special NDI" techniques to justify initial flaw sizes smaller than those termed Standard require prior approval by the sponsoring agency. Indeed, PSI employs inspectors with Special Level certification for fluorescent penetrant and radiographic inspection as administered by Rockwell and documented in the above referenced Space Shuttle studies.

If residual stresses approaching the yield strength of the material must be considered in the analysis, there is currently no reliable way, in practical weld joint thicknesses, of detecting flaws of a size which could provide the theoretical cycle life.

The principle concern with respect to residual stresses is that of stress corrosion cracking over an extended period of time in the presence of contained fluids. Pressure cycle life and design safety factor are not affected and can be verified through conventional acceptance testing.

Given the extensive and successful history of the diaphragm tank concept, a compromise approach has been applied to all designs since 1987 which follows the fracture mechanics requirements of MIL-STD-1522A but does not include the magnitude of residual stresses. This approach for PSI tanks has received acceptance from NASA and ESA agencies. In summary, the highly successful experience of the PSI diaphragm tank basic design concept with non-stress relieved welds, the highly conservative design principles and safety factors, the unlikely event of high sustained internal residual stresses in direct combination with a crack-like flaw, the established compatibility of hydrazine with the shell material and the application of stringent fracture control policies throughout the process, all support the premise that there is minimal, if any, risk associated with a flaw-initiated failure.

Diaphragm Permeability

To serve as an effective barrier between the propellant and the pressurant gas a bladder or diaphragm must provide an adequate barrier to permeation so that under typical operating conditions a loss of available fuel will not occur and the propellant delivered does not become gassy.

The permeability of AF-E-332 to pressurant gases, helium and nitrogen has been measured at a number of temperatures. The initial testing was established to measure true permeability, that is, permeability from a high pressure source across the elastomer into a relatively large, low pressure volume. This measured rate is higher than will be found in a flight system where gas concentration will equilibrate across the elastomer. Back diffusion will equal forward diffusion at equilibrium with a net zero mass transfer.

The standard approach today is to test for a total helium leak rate from the pressurant side of the diaphragm to the propellant side under a one atmosphere differential. Typical leak rates requirements are 80 standard cubic centimeters per hour (scc/hour) of helium.

Helium test requirements with differential pressures of 100 psi typically allow leak rates up to 120 scc/hour.

Expulsion Efficiency

PSI diaphragm tanks can provide 99.9 % expulsion efficiency of the propellant initial load with differential pressures as low as 25 psig. Typically, expulsion efficiency is slightly higher with the propellant port aligned in the positive one g direction than in the negative one g direction (i.e. inverted), which in turn is typically more efficient than when the outlet port is aligned at 90 degrees to the gravity vector. This ability to provide high expulsion efficiencies under severe operational conditions is a primary advantage of an elastomeric diaphragm device.

For elastomeric diaphragms a ribbed propellant side surface is required to provide high expulsion efficiency. The segmented ribs increase expulsion efficiency by preventing a sealing action between the diaphragm and the smooth tank wall which could trap and isolate fluid away from the outlet. Trials have been made to determine the effect of rib design on expulsion efficiency. The test results verify that for correctly ribbed diaphragms increasing pressure differential provides higher expulsion efficiencies whereas for smooth diaphragms, higher differential pressures can merely serve to seal off regions of fluid from the outlet producing reduced expulsion efficiency.

Outlet Port Design

In order to prevent extrusion of the diaphragm through the outlet port PSI typically employs a standard support configuration at the propellant hemisphere outlet which can accommodate relatively high pressure differentials. The basis of this design feature was a test program where diaphragm samples were subjected to a number of pressure differentials for varying durations. The testing included test pressures of 300 psid for durations up to 60 minutes and 540 psid for up to 2 minutes. Although during actual in-flight conditions the diaphragm is only subjected to relatively high differential pressures at the end of fluid expulsion, typically 120 psid for a blowdown system, the over design is usually incorporated to facilitate ground acceptance testing and provide some margin against inadvertent overtest.

6.0 Processing and Manufacture of AF-E-332 Diaphragms

PSI has in-house clean room facilities which are dedicated to the manufacture of AF-E rubber. Typically when rubber is made a batch of material is formulated which will be used to manufacture a large number of diaphragms for a variety of programs. A batch of material is a quantity of rubber compound formulated at one time from a single lot of each ingredient. The rubber making process begins with the milling together of a number of the ingredients in controlled proportions. After milling the material is then processed in an extruder through several screens. The rubber is then re-milled and the balance of ingredients and the curing agent are added. The mixture is then milled and fabricated into uniform thickness sheets. This material is then stored in clean plastic bags under controlled conditions.

To ensure quality conformance a qualification test program is conducted for each batch of material produced. Qualification is conducted on molded slab samples which are press cured and post cured under standard conditions of temperature and time. Multiple samples undergo testing for ultimate tensile strength, elongation, modulus, tear strength, hardness, specific gravity and compression set. For acceptance the results must meet minimum acceptance criteria. In addition to the qualification testing of the material mix, acceptance tests are undertaken to ensure the quality of the product. Acceptance is based on visual examination of the molded sheets and slabs for uniformity and radiographic examination of the milled sheets for indication of any inclusions. Inclusions may be removed from the material, however, if excessive in number the material is rejected. The produced material is translucent which greatly aids inspection.

Following acceptance the amount of rubber required to make a single diaphragm is determined and the required material is cut into squares and placed into heat sealed bags. Each bag of material is then radiographically inspected in accordance with PSI Specification 90-000006 for inclusions. All unacceptable inclusions are removed and replacement material added to the bag as required. A final radiographic check is then made to ensure that material cleanliness is acceptable. While awaiting use the material is stored under controlled temperature conditions.

Throughout all stages of manufacture every effort is made to maintain the cleanliness of the raw rubber.

Prior to molding, a silica-free mold release compound is applied to the mating surfaces of the mold. The diaphragms are compression molded at the PSI facility in a 1700 ton hydraulic press dedicated to making rubber. For each diaphragm design a mold schedule is developed by producing a part that meets the process specification and the diaphragm engineering drawing. The mold schedule consists of the mold closing pressure, a cure time and temperature and a post cure time and temperature. One diaphragm from each continuous run of twelve hours or less is tested as a process control diaphragm. A minimum of one diaphragm from each batch of rubber is tested. A number of test specimens are removed from the process control diaphragm and subjected to tensile and tear testing. Failure of the process control diaphragm is cause for rejection of the process group.

Each part is visually examined for defects. In order to ensure correct sealing the weld bead region of the diaphragm is match machined to the dimensions of the diaphragm engineering drawing. After the finishing operations each diaphragm is leak tested by installing into a leak test fixture, pressurizing with gas and submerging into water. The surface of the diaphragm is carefully examined to ensure there are no observable leaks. Following drying the diaphragm is then cleaned and undergoes a bright light visual examination at magnification. Each diaphragm is inspected against the dimensional requirements and weighed.

The following paragraphs of this report discuss the practical limits and issues relating to the design, manufacture, test and operation of diaphragm tanks for monopropellant systems.

7.0 DIAPHRAGM TANK TESTING

Qualification & Development Testing

In the early years of diaphragm tank history, Qualification test programs tended to be extensive. As an example, consider the Qualification testing of PSI Part Number 80225, Qualification Test Report 56-000068, a 15.38 inch internal diameter tank. Tank testing included:

- Examination of product including dimensional measurement
- Pre-proof volume, proof pressure & post-proof pressure
- Acceptance level random vibration
- Internal leak test with high differential pressure
- Temperature cycles at 120°F (49°C) and 24°F (-4 °C) with expulsion efficiency verification
- Internal leak test with low differential pressure and high differential pressure
- Radiographic and dye penetrant inspections and weight and dimensional measurements
- Cleanliness verification
- Sinusoidal vibration at qualification level
- Random vibration at qualification level
- Internal leak test with high differential pressure
- Shock Test of 100 g's for 0.5 milliseconds in each of the three orthogonal axes
- Internal leak test with high differential pressure
- Acceleration testing in three orthogonal axes up to 18 g's
- Internal leak test with high differential pressure
- Spin expulsion, for 6 minutes, at 67.5 rpm at a radius of 25 inches (63.5 cm)
- Internal leak test with low differential pressure and high differential pressure
- Temperature cycle of 8 hours at -41°F (-40.5°C) followed by 8 hours at 150°F (65.6°C) followed by expulsion efficiency demonstration
- Life Cycle testing of 50 expulsion/refilling cycles at 12°F (-11.1°C) and 50 expulsion/refilling cycles at 130°F (54.4°C) followed by expulsion efficiency
- Internal leak test with low differential pressure and high differential pressure
- Tank shell external leak testing
- Cleanliness verification
- Burst Testing

Such comprehensive testing was typical of the early designs and has provided the PSI design concept with extensive heritage under environment combinations far more severe than can ever be expected in operation. This extensive test database is a primary reason why PSI has maintained the same basic diaphragm and sealing bead design principle on virtually all of the tanks produced to date. Although the present diaphragm designs are conservative and not mass optimized, it is generally recognized that to fully characterize the performance characteristics of an optimized diaphragm design for each application is not commercially viable or indeed always desirable for program reliability.

Other examples of unique test programs have included:

- sinusoidal vibration testing of 35 to 20 g's in the 49 Hz to 200 Hz frequency band, reference PSI Part No. 80156-1,
- expulsion testing at 200 rpm spin for 5 minutes, reference PSI Part No. 80156-1,
- 535 psi differential pressure across diaphragm in fully expelled position for 5 minutes, reference PSI Part No. 80157-1,
- seven day hydrazine soak followed by slosh testing at 0.8 Hz and 1.0 inch D.A. at 47 % fill level for 120 hours with hydrazine, reference PSI Part No. 80193-1,
- expulsion demonstration under adverse steady state accelerations of 10 g's, reference PSI Part No. 80273-1,
- 200 hydrazine expulsion cycles at various fluid loads and temperatures, reference PSI Part No. 80228-1,

- slosh testing in each of the lateral axes as follows, reference PSI Part No. 80228-1;

  - 90% load with 3.0 inches total amplitude, at 0.5 cps for 4,000 cycles
  - 50% load with 10.0 inches total amplitude, at 1.0 cps for 2,000 cycles
  - 50% load with 10.0 inches total amplitude, at 1.0 cps for 8,000 cycles

Appendix B shows a 40 inch (1016 mm) diameter ellipsoidal tank centrifuge test set-up.

Extensive Qualification testing is rarely required today since invariably the majority of standard requirements may be qualified by similarity in lieu of Qualification testing. Similarity is used when the proposed tank is similar or identical in areas of design, manufacturing processes and quality control to other tanks that have been qualified to equivalent or more stringent criteria.

A number of slosh tests have been performed on diaphragm tanks supplied by PSI. One of the most comprehensive programs was conducted by TRW Space and Technology Group for the Tracking and Data Relay Satellite (TDRS). Tests were conducted in a full size Plexiglas simulator. In the satellite configuration the tanks were configured such that the aft tank had a liquid over ullage configuration (i.e. gas side of tank was down and liquid was on top side of diaphragm) and the forward tank had a liquid under ullage configuration. The use of such a configuration limits the spacecraft center of gravity (C of G) control problems associated with using two large stacked tanks.

The beneficial control aspects associated with using diaphragm tanks during high spin transfer stages has been evaluated and utilized by a number of customers. The critical parameter for maintaining stable flight is the spin inertia ratio. The most conservative assumption is that the bladder effects are ignored and the fuel is assumed to shift to the outer areas of the tank away from the vehicle spin axis. In practice the actual location of the fuel C of G is somewhere between the no-diaphragm and stiff (i.e. baffle) model assumption. Customers using diaphragm tanks have conducted test programs to better determine the C of G location and thus its resultant effect on spin inertia ratio. Typically test results have been obtained by building full size transparent, Plexiglas tanks and performing optical measurement and triangulation techniques.

Surprisingly, in spite of the wealth of knowledge on propellant slosh in tanks of various designs[5], very little information has been documented on the effects of elastomeric diaphragms. All of the observed ground testing has demonstrated that the damping of liquid motions is almost entirely due to the diaphragm viscoelasticity with very little or no contribution by the liquid viscosity. Since it is not possible to vary the acceleration levels during ground testing, the preferred test approach is to approximate the effect by using liquids of different densities. Tests have verified that the shape of the diaphragm in a pressure supported configuration depends primarily on the volume of liquid under the bladder and that neither the bladder nor the liquid configuration will change when the liquid density changes provided the volume of liquid remains the same. Therefore, it can be shown that the mode shape obtained under 1-g ground testing is valid and the associated slosh mass will merely increase or decrease in proportion to the liquid density.

Acceptance Testing

A typical acceptance test program includes the following :

- Examination and dimensional check of product
- Pre-proof volume, proof pressure and post-proof volumetric capacity
- Expulsion efficiency and pressure drop measurement
- Internal diaphragm leakage
- External tank leakage
- Radiographic and dye-penetrant inspections
- Mass measurement
- Cleanliness verification

These tests are designed to verify the quality of the delivered product. For an all-welded diaphragm tank where there are no mechanical fasteners, acceptance vibration testing is invariably unwarranted since it is not an effective level method of screening workmanship and may only serve to consume some portion of the tank's useful life. The industry is beginning to concur with this view.

8.0 FLIGHT HERITAGE

Mission Applications

The ultimate illustration of a diaphragm tank's ability to deliver propellant independent of acceleration and orientation was provided when the TDRS Flight 1 satellite encountered operational difficulties and went into a one-half revolution per second tumbling spin. Since the diaphragm tank could reliably provide propellant throughout, mission control was able to regain control of the satellite and eventually retain the operating orbit. It is highly unlikely that a surface tension device or other acceleration dependent propellant control device could have provided controlled propellant to allow spacecraft recovery.

AF-E-332 diaphragm tanks have been used on interplanetary missions, Space Shuttle, transfer vehicle upper stages, launch vehicles, military applications, commercial communication satellites, earth observation and general scientific satellites. The following paragraphs describe a number of these applications.

Interplanetary Missions

The first major mission to utilize PSI diaphragm tanks was the JPL Pioneer program, for which PSI built and delivered eight 16.5-inch diameter diaphragm tanks. The Pioneer missions were a tremendous success, with Pioneer 10 heading out of the solar system carrying a PSI diaphragm tank-one of the few man-made objects ever to leave the solar system.

PSI diaphragm tanks have also left their mark on the planet Mars. Between 1972 and 1974, PSI built twelve 22-inch diameter diaphragm tanks for the Viking mission.

The next interplanetary mission, Mariner Jupiter/Saturn 1977, utilized an even larger diaphragm tank. Eight 28-inch diameter tanks were built for this JPL mission in 1975. The same size tanks were also built for a subsequent Venus Radar Mapper program (later renamed Magellan).

A recent mission to survey the moon's surface also utilized a PSI diaphragm tank. The Clementine program uses a single 12.8 inch diameter diaphragm tank.

Other interplanetary programs in progress which require diaphragm tanks include CASSINI (28-inch diameter), NEAR (22-inch diameter), and Mars Pathfinder (16.5-inch diameter).

Space Shuttle

Two diaphragm tank designs received manned flight rating when they were chosen for use on the Space Shuttle. Each Space Shuttle utilizes three 28-inch diameter tanks on its Auxiliary Power Unit (APU) and a small, 9.4-inch diameter tank for engine cooling. Some of the diaphragm tanks on the Space Shuttle are 14 years old. The success of the Space Shuttle program is a true testimony of the longevity and reliability of the AF-E-332 diaphragm tank.

Upper Stage

Several upper stages use PSI diaphragm tanks. TOS uses a 16.5 inch diameter tank, IUS utilizes a 21 inch diameter tank, while Centaur utilizes a 22 inch diameter tank.

Launch Vehicles

The Titan II Launch Vehicle utilizes 16.5 inch diameter diaphragm tanks, while the Titan III uses 28 inch diameter tanks.

Other Missions

Other missions applications that have used, or plan to use, diaphragm tanks include;

- GPS (14 inch & 16.5 inch ∅), DSCS (22 inch ∅), Fltsatcom (22 inch ∅), DMSP (12.9 inch ∅), STEP (22 inch ∅), GeoSat (12.9 inch ∅), MSTI (12.9 inch ∅), Skynet (16.5 inch ∅), and NATO IV (16.5 inch ∅) for military missions,
- Telecom (16.5 inch ∅), TDRSS (40 inch ∅) and ECS (16.5 inch ∅) for TV/Communications satellite,
- GRO (36 inch ∅), SOHO (40 inch ∅), OTS (12.9 inch ∅ & 15.4 inch ∅), ISPM (17.4 inch ∅) and EURECA (23 inch ∅) for scientific missions,
- UARS (28 inch ∅), TOPEX (16.5 inch ∅ & 28 inch ∅), LANDSAT (16.5 inch ∅), TIROS (12.9 inch ∅), and EOS (40 inch ∅) for Earth Observation satellites.

Material Compatibility

Programs such as Voyager and Space Shuttle have used AF-E-332 diaphragms in excess of 14 years.

PSI has performed a long-term material compatibility (PSI Report No. 65-000037) assessment which ran for a total of ten years. A total of 71 tensile samples were cut from a single diaphragm and immersed in approximately 10 gallons of MIL-P-26536B hydrazine on March 26th, 1973. The test site experienced a mean annual temperature of 65 degrees F with extremes of 30 to 110 degrees F. Samples were periodically removed from the hydrazine, water washed and physically checked (weight and length), and hardness and tensile tested. The test program ended on July 25th, 1983. The test results at the end of the period show close conformance with the virgin material requirements and illustrate no appreciable degradation of properties.

PSI knows of diaphragms that have been stored for periods of nine years before launch without reported problems. Indeed PSI has performed mechanical property tests on a diaphragm which had been stored unprotected in a shop environment for 5 years at PSI. Approximate storage environment was an atmosphere of Los Angeles smog with temperatures of 40 to 115 °F. No significant mechanical property change was noted. In view of the long term hydrazine service data it is suggested that under proper storage conditions where the diaphragm is contained and supported in an inert atmosphere, storage life in excess of 15 years should be possible.

It is interesting to note that while AF-E-332 was tailored specifically for hydrazine service it is equally compatible with hydrazine derivatives including ammonia.

Several unmanned spacecraft using AF-E-332 diaphragms have been evaluated for the effect of exposure to man-made nuclear radiation during orbital flight. An experimental study was performed by Rockwell International to assess the effect of gamma radiation on AF-E-332 and EPT-10 rubber while immersed in hydrazine. An equal number of test articles were immersed in hydrazine as control samples. Standard mechanical property testing, thermal mechanical analysis (TMA) and differential thermal analysis (DTA) were performed to evaluate any physical changes that may have occurred following radiation exposure. Radiation may produce either crosslinking or scission in polymers. The AF-E-332 did not show any detectable signs of modification or degradation.

Early testing during AF-E-332's development recognized that some minute amounts of silica do leach from the diaphragm. AF-E-332 elastomer does contain Aerosil R-972 silane treated silicon dioxide. This particular silicon dioxide is added to the elastomer to combine the strengthening effect of the very small particulate with the low hydrazine wetting potential of the organosilane coating. The primary chemical mechanism for removal of silicon is believed to be the direct solubility of the silicon dioxide particles which are not effectively reacted with an organosilane. For those particles which are not effectively coated it is postulated that the silicon is removed by hydrolysis and then neutralized with the excess hydrazine. Testing indicates that the greatest rate of silicon leaching is in the first 10-12 weeks of hydrazine immersion. Thereafter, the increase in silicon content falls to a much lower level. When accelerated laboratory data was normalized to flight diaphragm surface area to volume (A/V) ratios at 23°C (75°F), all of the reported values were less than 0.6 ppm. Dynamic testing with up to 100,000 cycles was also performed and shown to contribute to the initial rate of silica leaching. Considering the allowable level of inorganic contaminants in hydrazine, 50 ppm for monopropellant grade and 10 ppm for high purity grade, potential levels of diaphragm contamination appear to be insignificant. The overwhelming evidence of experience over the last 25 years would appear to validate this observation.

However, it has been reported in Europe that a number of thruster anomolies have been attributed to silica contamination. During the life of the European Space Agency (ESA) Orbital Test Satellite (OTS-2) a performance degradation in the 0.5 N catalyst thrusters was initially experienced when operated in the pulse mode after a shut off period of several days. Subsequently the performance progressively increased to the nominal design value. Initially the performance degradation was attributed to the presence of gas in the propellant. A further loss of the N-S station keeping yaw thrusters promoted a material compatibility assessment of the various component materials used in the reaction control system. The investigation concluded that the most likely cause of the OTS-2 thruster performance problem was the contamination of the thruster catalyst bed by silicon dioxide leached from the diaphragm.

During the decomposition of the hydrazine in the catalyst bed the temperatures are in the order of 1000 °C. It is postulated that at such temperatures the hydrazine-Aerosil compound will pyrolize and liquid silicon dioxide may be deposited on the catalyst grains, causing some inhibition of the catalyst. The ability of the silicon dioxide to deposit on the catalyst bed is a function of the thermal history in the injector head and the flow pattern which will effect the ability of the capillary and adhesion forces to deposit particles.

Investigation of all obtainable US flight mission data has not revealed any failure mechanisms associated with diaphragm-induced contamination. It is interesting to note that when examining thruster performance anomalies in the US a number of verified mechanisms associated with thermal, contamination and process irregularities have been identified. Many of these problems have occurred where there has been no diaphragm in the system. It is not clear whether European investigations examined other possible failure mechanisms.

What is further puzzling is that long-term data generated at ERNO, used to support the failure explanation, conflicts with recently compiled flight data assembled for the EURECA satellite. A test program with the EURECA qualification model tank showed very low generation rates. Tests performed at Royal Ordnance (RO) showed similar results[6]. Furthermore, after return of the six EURECA tanks by Space Shuttle after 450 days of hydrazine exposure, the average silica rate of this worst case period, was again found to be extremely small and consistently in the order of 1.1×10^{-5} milligrams per square centimeter per day (mg/sqcm/d)[7]. It is also noted that ERNO also tried to generate silica contaminated hydrazine for the SAX program and had a problem doing so because of the low rates observed[7].

It has been suggested [6] that a process change at PSI, to eliminate the use of a silica release agent, might be responsible for a decrease in silica generation in diaphragms post 1987. However, investigations at PSI have identified that the same silica-free mold release agent has been used at PSI since the late 1970's.

It is noted that a number of the data points which have generated higher than expected silica generation results have not come from tests using flight standard tanks. That is, some of the samples have simply been swatches of AF-E-332 material taken from reject diaphragms. The significance of this observation is that these samples have not been subjected to the standard flight inspection, cleaning and preparation cycles used on flight tanks. Flight tank diaphragms are cleaned at piece part and tank levels. Cleaning techniques and the use of correct cleaning fluids are critical so as to prevent possible diaphragm damage and possible chemical attack. It is suggested that if silica contamination is viewed as a potential problem, then only data pertaining to PSI flight standard tanks should be considered as reliable.

Space Shuttle Auxiliary Power Unit (APU) Diaphragm testing

The Space Shuttle Orbiters use three PSI-built diaphragm tanks termed Auxiliary Power Unit (APU) tanks. During major modification of the Columbia Shuttle (OV-102) one of the tanks was tested and examined to assess the diaphragm and shell for signs of degradation. At the time of investigation the three tanks had been in service for 11 years. The physical examination of the diaphragm and shell was conducted by NASA JSC White Sands Test Facility (WSTF).

The tank selected for evaluation, Tank Part No. A49198, was chosen since it had the highest number of service cycles.

Testing of the diaphragm was based on previous tests of materials immersed in hydrazine. Visual examination, microscopic analysis, thickness measurement, hardness testing, specific gravity, tensile testing, chemical analysis and thermal gravimetric analysis (TGA) were performed on the diaphragm and on samples of EPDM that had not been exposed to hydrazine. The test results were compared against PSI's material requirements and with the properties of the unexposed EPDM.

The tank shell samples underwent a complete visual examination, hardness testing, thickness measurement, metallographic analysis (conventional, scanning electron microscopy, (SEM)), and electron spectroscopy for chemical analysis (ESCA). Samples taken included both base metal and weld seam locations in addition to any areas where apparent anomalies were noted.

The conclusion of the test program was that no appreciable degradation of the EPDM which may effect its function in the APU tank was noted. A slight decrease in the tensile properties, 97.4 percent of the virgin material requirement and 86.5 percent of the elongation, was found but tensile failure is totally unlikely since the diaphragm is designed to be subjected to low tensile strains and indeed the shell constrains the diaphragm to elongations not more than a few percent. The metal shell showed no signs of surface corrosion.

9.0 Conclusions

PSI's unique and proprietary all-welded AF-E-332 diaphragm tanks have a demonstrated hydrazine compatibility in excess of 14 years and have flown on a minimum of 730 missions without failure. This considerable flight heritage and the associated ability to qualify many derivative diaphragm tank designs by similarity will continue to make diaphragm tanks the best commercial solution for many applications.

In addition, the ability to provide total propellant delivery flexibility and a high level of inherent slosh control are highly desirable performance characteristics for many mission scenarios.

It is suggested that future mass savings may be best achieved by employing a reduced internal pressure burst pressure factor of 1.5 rather than 2.0 as currently practiced on diaphragm tanks. The principle mass savings would be achieved in the shell membrane areas.

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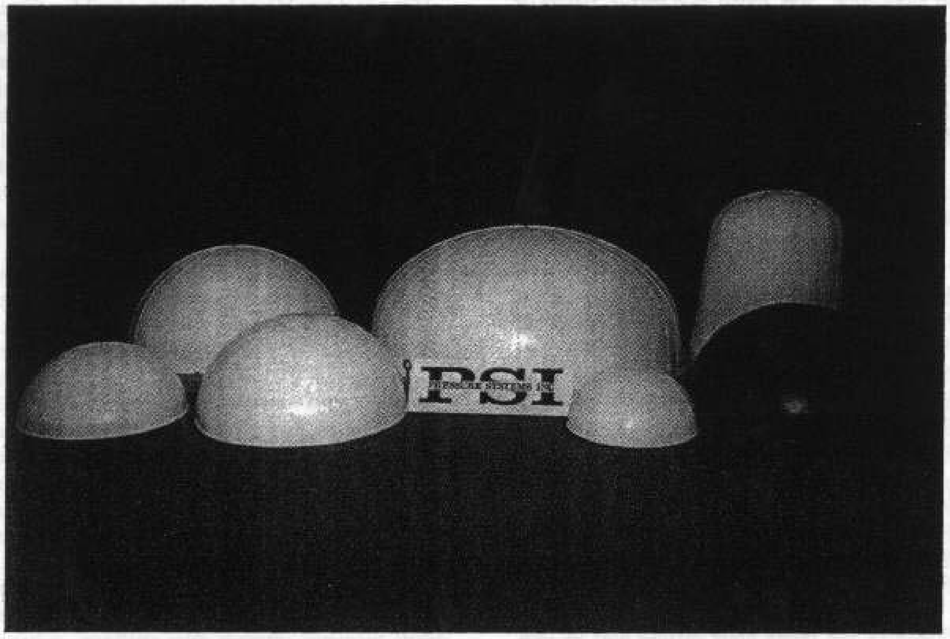
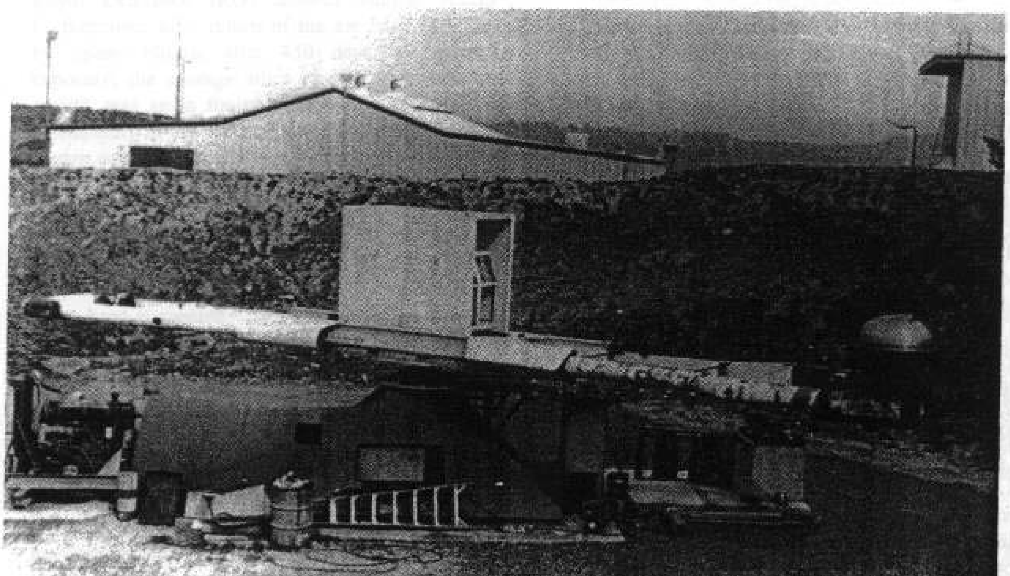
APPENDIX A: An Assortment of Diaphragms Produced by Pressure Systems, Inc.



APPENDIX B: Test Set-up Of A 40 inch Diameter Ellipsoidal Tank



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