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LOW-COST TANKAGE PROVIDED FOR RECENT DISCOVERY MISSIONS

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ABSTRACT

Several recent and up-coming planetary missions all have one thing in common, the use of low-cost tankage provided by Pressure Systems, Inc. (PSI). The missions include Near Earth Asteroid Rendezvous (NEAR), Lunar Prospector, Mars Surveyor ’98, and Mars Pathfinder. These missions all have absolute cost ceilings and short development periods. Therefore, the use of flight qualified hardware was essential to achieve schedule and cost goals. However, unlike instruments and other components, spacecraft tankage is under further constraints such as performance and weight which make customization necessary. This paper focused on PSI’s approach in developing customized but low-cost tankage without sacrificing quality and reliability to meet the requirements for these programs.

INTRODUCTION

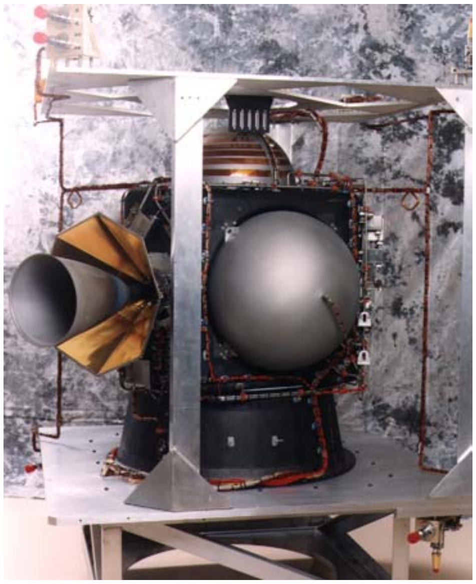
The recent emphasis on “faster, better, and cheaper” NASA missions provided significant challenges for the spacecraft integrators as well as component manufacturers. In the case of spacecraft tankage, designing a tank to meet a new mission requirement demands several design iterations for stress and fracture mechanics analyses, several design reviews, a complete set of engineering drawings and supporting documentation, a complete set of tooling, an additional tank (or more) built for qualification testing, acceptance and qualification test procedures, a qualification testing program, and a qualification test report. Needless to say, the development process is both costly and time consuming.

To achieve the goal of “faster, better, and cheaper”, the use of off-the-shelf hardware with proven flight heritage becomes absolutely essential to the success of these low-cost, fast-pace missions. PSI has a vast inventory of over 400 tank designs with flight-proven heritage on over 600 programs. The many existing designs allowed PSI customers to select a tank that best meets the specific program requirements. Occasionally, minor modifications were necessary to customize the tank for the mission, but the changes were not significant enough to affect the qualification status. It is this unique position that enabled PSI to contribute to many low-cost planetary missions, including NEAR, Lunar Prospector, Mars Surveyor ’98, and Mars Pathfinder.

NEAR

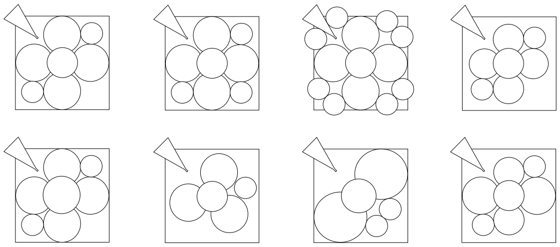
NEAR was the first spacecraft launched under the Discovery Program. The spacecraft was launched on 17 February 1996, and is now heading toward the asteroid EROS. The spacecraft bi-propellant propulsion system was designed for attitude control and ΔV maneuvers. The propulsion system has already been fired successfully in July 1997 to bring the spacecraft back to Earth for a gravity assist. PSI provided both the fuel and oxidizer tanks for the NEAR propulsion system, shown below in Figure 1. A fuel tank can be seen installed on the side of the spacecraft structure, and an oxidizer tank is visible on top of the structure.

Figure 1: NEAR Propulsion System



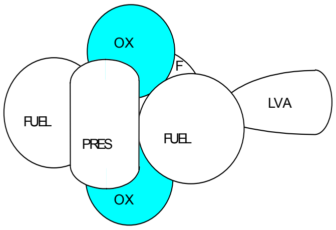
The NEAR mission requires 499 lbm of hydrazine fuel and 234 lbm of nitrogen tetroxide oxidizer. The propulsion engineers, working with PSI, were able to search through an extensive list of qualified, flight proven tanks to select the most desirable tank design and determine the system configuration. The search took into consideration size, weight, propellant volume, tank capacity, expulsion capability, mounting feature, quantity, and orientation. A trade study was also conducted to identify the optimal tank orientation within the spacecraft structure. Some of the tank orientations considered are shown below in Figure 2.

Figure 2: NEAR Tank Orientations Considered



The final propulsion system tank orientation includes 3 identical hydrazine fuel tanks and 2 identical oxidizer tanks, as shown in Figure 3. The fuel tanks are located radially along the Large Velocity Adjust (LVA) thruster plane, 120° apart. The oxidizer tanks are located on the launch vehicle spin axis. This configuration was selected to allow for system balance and stability.[1]

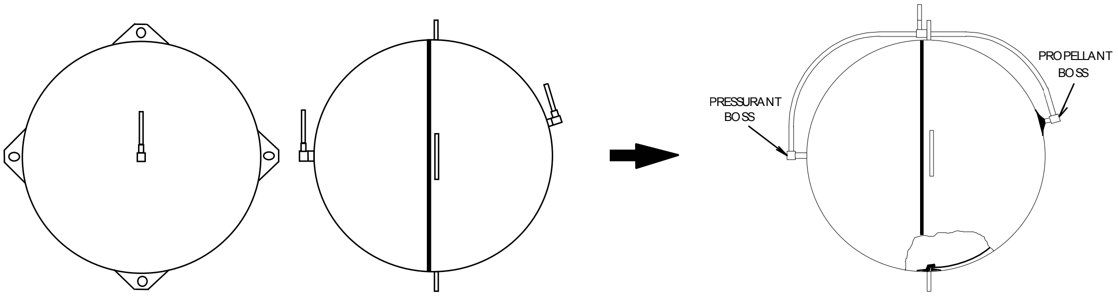
Figure 3: NEAR Tank Orientation



FUEL TANK. The NEAR fuel tank is a positive expulsion diaphragm tank. The diaphragm actively manages the hydrazine fuel. The tank is a modification of the 22-inch diameter TOMS-EP propellant tank, which itself is a modification of the DSCS III propellant tank. Both tanks have flight heritage and are currently in operation.

The modification to the TOMS-EP tank design was limited to the mounting tabs, propellant tube, and pressurant tube only. The changes are shown below in Figure 4. The tank shell and internal features were not changed. Stress and fracture mechanics analyses were conducted to verify the new tank design under the new operational requirements. The new design met all program requirements with positive safety margins. Tank qualification was based on similarity. Qualification testing was not conducted. Existing tooling was used to fabricate the new tank. The manufacturing period of performance, including design, analysis, and fabrication, was less than 1 year.

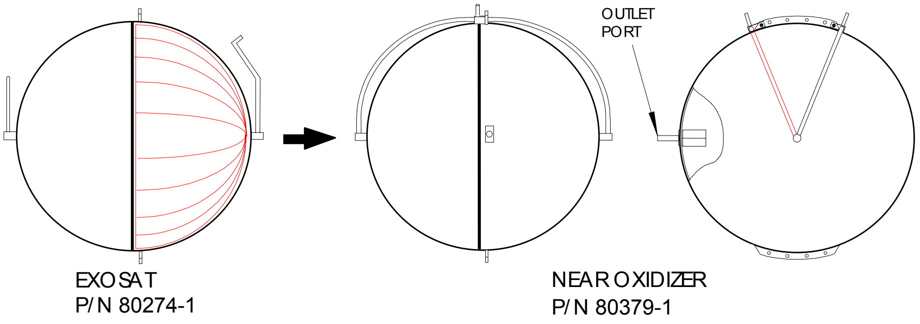
Figure 4: NEAR Fuel Tank, Design Heritage



TOMS-EP
P/N 80362-1

NEAR FUEL
P/N 80378-1

Figure 5: NEAR Oxidizer Tank, Design Heritage



OXIDIZER TANK. The NEAR oxidizer tank is based on the EXOSAT 19-inch diaphragm tank. The modification to the basic design was more extensive than the fuel tank. The changes included the elimination of the elastomeric diaphragm, removal of the mechined-in diaphragm retaining feature on the diaphragm support ring and the propellant hemisphere, addition of an outlet tube near the tank equator, modification of the pressurant and propellant tube configurations and tube supports, and the addition of a vortex suppressor.[2] The changes are presented in Figure 5 above. Reference 2 provides a complete description of the tank development process for the NEAR oxidizer tank.

Stress and fracture mechanics analyses were conducted to verify the new tank design under the new operational requirements. The tank met all the mission requirements with positive safety margins. Existing tooling was used to make the tank shell. A few simple tools were built to resistance spot weld the vortex suppressor. Qualification was based on similarity, since all the above changes did not affect the tank shell nor the girth weld.

NEAR SPACECRAFT TANK MOUNTING AND PROPELLANT MANAGEMENT. The diaphragm in the fuel tank actively manages the hydrazine fuel. It is capable of expelling fuel in any orientation and under any adverse conditions such as spin or tumble[3]. Therefore the fuel tanks could be mounted in any orientation without affecting the expulsion performance.

The oxidizer tanks are mounted such that the tank outlets are parallel to the spacecraft thrust vector. Prior to the main engine burn, the oxidizer is settled at the tank outlets using the 5 lbf thrusters which accelerate the vehicle along the spacecraft thrust vector. Once the oxidizer is settled, the main engine is ready for a long duration burn. During the main engine operation, the oxidizer is forced to the tank outlet and continues to remain settled throughout the engine firing. A vortex suppressor is used to prevent the formation of a vortex at the oxidizer outlet port.[2] No other propellant management devices are used. The design of the simple four vane cruciform vortex suppressor was established by the Southwest Research Institute[4] and adapted by engineers to use on NEAR.

LUNAR PROSPECTOR

With the January 6th Lunar Prospector launch from Cape Canaveral Complex 46 on a Lockheed Martin Missiles & Space Athena II booster, NASA returned to the moon for the first time in 25 years. Apollo 17 was the last mission to conduct basic lunar research. For a period of at least one year, the Lunar Prospector Spacecraft, shown in Figure 6, will perform low altitude mapping of surface composition, magnetic fields, gravity fields, & gas release. On January 11th the spacecraft was inserted into its lunar orbit by firing its 22 Newton hydrazine thrusters. All of the spacecraft thrusters are provided hydrazine propellant from the PSI-provided fuel tanks. Three tanks, each containing 101 pounds of hydrazine, are installed equidistant around the central spin axis of the spacecraft propulsion bus as pictured schematically in Figure 7.

Figure 6: Lunar Prospector Spacecraft

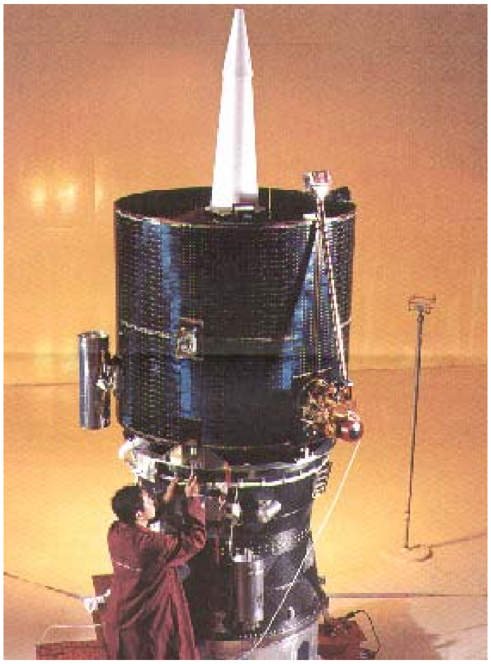


Figure 7: The Lunar Prospector Propulsion Tank Orientation

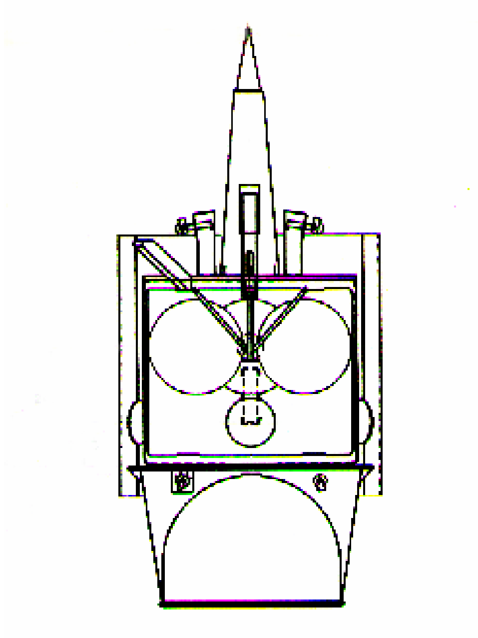


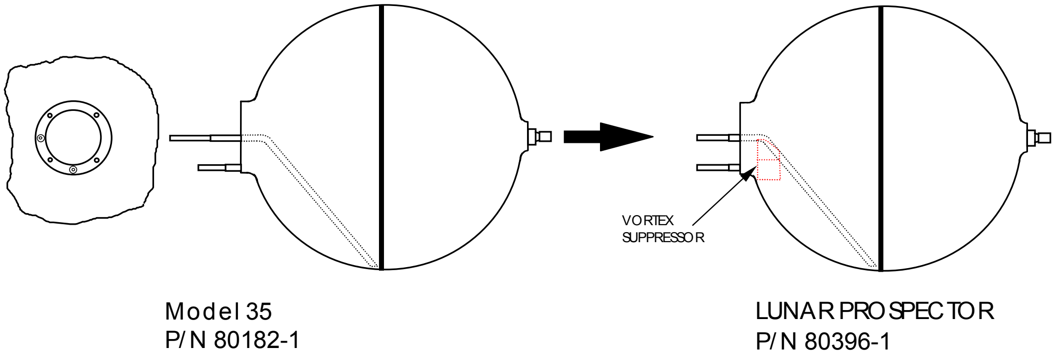
Figure 8: Lunar Prospector Propellant Tank

PROPELLANT TANK. The basic tank design selected for this mission was originally test & flight qualified for the TRW Model 35 Program in the early 1970's. A completed tank is shown in Figure 8. The simple mounting arrangement includes a threaded boss at one end and a four-bolt pattern at the other end. The solution treated and aged 6AL-4V titanium alloy shell, machined from forgings, was completely stress & fracture mechanics analyzed to the new mission requirements. No design changes were required and these analyses further validated the selection. Manufacturing tooling and the forging die were available from the earlier program. The tank incorporates two ¼ diameter tubes, one drain tube and one propellant outlet tube. Each tube ends in a a 304L CRES-to-6AL-4V titanium alloy transition tube for Astro-arc welding into the spacecraft fluid system.

A slosh analysis was performed to establish the propellant location in the tanks during the separation, spin-up, & pitch over maneuvers. This resulted in the only design change to the original tank configuration. The vortex suppressor, designed for the NEAR mission oxidizer tank, was modified to attach to the internal drain tube & to be positioned over the propellant outlet. Figure 9 depicts the tank configuration and change.

Because of the successful flight history, previous qualification status, and validating analyses, no qualification or protoflight tests

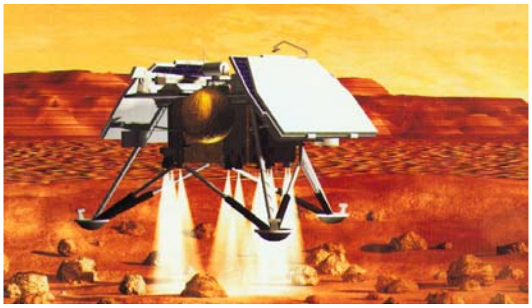
Figure 9: Lunar Prospector Hydrazine Tank, Design Heritage



MARS '98

The Mars '98 program consists of two spacecrafts: an orbiter and a lander. The objective of the Lander mission is to soft land a 23 kg science payload on the surface of Mars. This Lander is a three-axis stabilized platform and uses a monopropellant attitude control system for ΔV maneuvers and rotational control. The Lander spacecraft is depicted in Figure 10.

Figure 10: The Mars '98 Lander

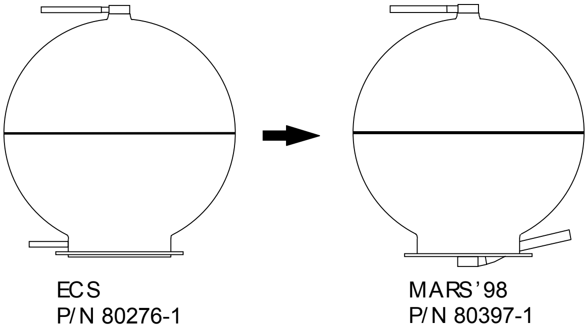


PSI provides the two 16.5-inch diameter spherical diaphragm tanks for use in the Mars Lander propulsion system. The tanks are mounted in the landing stage on the aeroshell and are used during cruise and power descent. At final descent the two tanks must provide hydrazine for the 12 descent engines to achieve a 2.4 m/s constant velocity descent to the surface of Mars.

The Mars '98 Lander propellant tank is a re-design of the ECS propellant tank. Similar to the NEAR fuel tank program, the modification to the ECS tank is limited to the tank mounting feature, the propellant tube, and the pressurant tube. The most significant change was to enlarge the outlet tube from .250" OD to .750" OD to accommodate the high propellant flow rate at final descent. A pictorial representation of the changes is shown in Figure 11.

The tank qualification was based on similarity to the ECS flight tank. Qualification testing was not performed. However, a protoflight acceleration test was performed on one tank. Existing tooling was utilized to fabricate the tanks. The period of performance, including re-design and fabrication, was 12 months.

Figure 11: The Mars'98 Lander Propellant Tank, Design Heritage



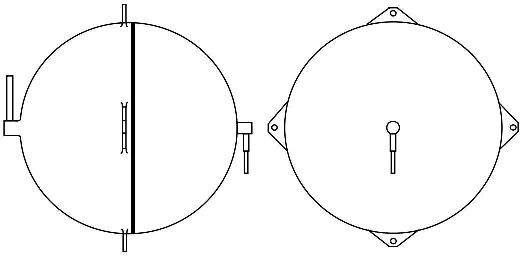
MARS PATHFINDER

The Mars Pathfinder was the second spacecraft launched under the Discovery program and the first to complete its mission. The Pathfinder lander successfully landed on Mars on July 4, 1997. The spacecraft, shown below in Figure 12, included a cruise stage and an aeroshell. The lander and the Sojourner rover were stowed inside the aeroshell. One of the PSI propellant tanks is shown in the foreground under its micrometeorite protective cover.

Figure 12: The Mars Pathfinder Spacecraft

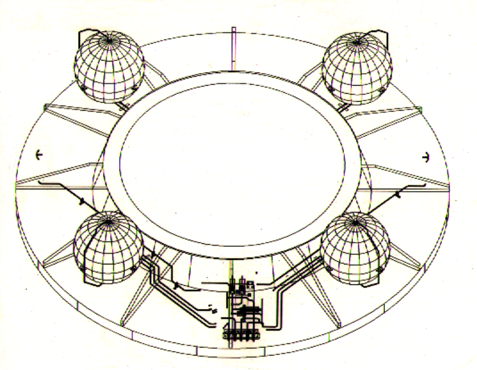
Unlike the NEAR, Lunar Prospector, and Mars '98 Lander programs, which developed new tankage, the Pathfinder program was even more frugal. An off-the-shelf tank design was furnished without any modifications. The tank is a 16.5-inch diameter spherical diaphragm tank. Heritage on this tank included flights on the Space Shuttle as well as on some classified programs. PSI manufactured three tanks for the Pathfinder program. In addition, JPL returned 2 previously delivered tanks to PSI for refurbishment and re-test. A sketch of the tank is shown below in Figure 13.

Figure 13: The Pathfinder Tank



Four tanks were installed on the Pathfinder spacecraft. These tanks were mounted on the cruise stage as shown below in Figure 14. The hydrazine fuel was used for de-spin, mid-course maneuver, positioning for re-entry, and de-orbit burn. The fuel was not used during landing because Pathfinder Lander used airbags to cushion its fall upon landing.

Figure14: The Mars Pathfinder Tanks Mounted on the Cruise Stage



There was no non-recurring cost to the program. Existing tooling was used to build and test the tanks. Program period of performance was less than 1 year.

The spare fifth tank was allocated to the New Millennium Deep Space 1 program at the conclusion of the Pathfinder program.

SUMMARY

Table 1 summarizes the major characteristics of the propellant tanks presented above.

Table 1: Tank Summary

PROGRAM	NEAR Fuel	NEAR Oxidizer	Lunar Prospector	Mars Surveyor ’98	Mars Pathfinder
Fuel	Hydrazine	N_2O_4 Oxidizer	Hydrazine	Hydrazine	Hydrazine
Size	22.14-inch ID, ∅	19.06-inch ID, ∅	19.23-inch ID, ∅	16.5-inch ID, ∅	16.5-inch ID, ∅
Total Volume	5555 in^3	3660 in^3	3775 in^3	2300 in^3	2300 in^3
Propellant Weight	166 lbm	117 lbm	101 lbm	70.5 lbm	35 lbm
Propellant Management	Diaphragm	Vortex Suppressor	Vortex Suppressor	Diaphragm	Diaphragm
Operating Pressure	280 psi	280 psi	450 psi	450 psi	435 psi
Proof Pressure	420 psi	420 psi	1100 psi	495 psi	653 psi
Burst Pressure	560 psi	560 psi	1200 psi	675 psi	1740 psi
Operating Temperature	44 to 122 °F	44 to 122 °F	40 to 120 °F	3 to 40 °c	45 to 160 °F
Tank Weight	16.2 lbm	10.7 lbm	11.5 lbm	10.0 lbm	17 lbm
Expulsion Efficiency	≥ 99%	≥ 99%	≥ 99%	≥ 99%	≥ 99%
External Leakage	1 x 10^{-6} scc/sec He	1 x 10^{-6} scc/sec He	1 x 10^{-7} scc/sec He	1 x 10^{-6} scc/sec He	1 x 10^{-6} scc/sec He
Tank Material	Ti-6AL-4V	Ti-6AL-4V	Ti-6AL-4V	Ti-6AL-4V	Ti-6AL-4V
Minimum Wall	0.027 in	0.023 in	0.040 in	0.020 in	0.043 in
Acceptance Tests	Volume capacity Proof pressure Volume capacity Internal leakage External leakage X-Ray Penetrant Mass Clean	Volume capacity Proof pressure Volume capacity External leakage X-ray Penetrant Mass Clean	Volume capacity Proof pressure Volume capacity External leak X-ray Penetrant Mass Clean	Volume capacity Proof pressure Volume capacity Internal leakage External leakage X-ray Penetrant Mass Clean	Volume capacity Proof pressure Volume capacity Internal leakage External leakage X-ray Penetrant Mass Clean
Qualification Tests	None	None	None	None Protoflight test on one tank	None
Flight Heritage	TOMS, DSCS	EXOSAT	MODEL 35	ECS	Space Shuttle, P80
Modifications	Modify mounting lugs, Modify in/outlet tubes	Remove diaphragm, Remove diaphragm Retaining features, Add outlet port, Modify mounting lugs, Modify in/outlet tubes Add vortex suppressor	Modify tubes Add vortex suppressor	Modify mounting, Modify tubes	None
Non-recurring Activities	Stress & fracture mechanics analyses, Some drawings, Mfg readiness review	Stress & fracture mechanics analyses, Some drawings Mfg readiness review, Some tooling	Stress & fracture mechanics analysis, Slosh analysis, Some drawings, Some tooling	Some drawings, Some tooling	None
Qualification	By Similarity	By Similarity	By Similarity	By Similarity	Not required

CONCLUSION

The current environment in the aerospace industry demands a more frugal approach to access space. However, the move to attain low-cost hardware for a fast-pace program does not have to come at the expense of quality and reliability. The Government and the industry have expended millions of dollars developing a vast inventory of qualified flight hardware. As this paper demonstrates, making use of these existing flight-qualified hardware not only makes good business sense, but it is absolutely critical to meeting the objectives of the mission.

ACKNOWLEDGMENT

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