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DESIGN AND DEVELOPMENT OF THE NEAR OXIDIZER TANK

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ABSTRACT

The Near Earth Asteroid Rendezvous (NEAR) oxidizer tank is developed based on adaptations to a flight-proven tank design. The modifications include removal of an elastomeric diaphragm and elimination of the diaphragm retaining features, addition of an outlet tube near the tank equator, addition of an internal vortex suppressor at the entrance of the outlet tube, and added bracketry to the external tube stubs. Qualification of this tank is based on similarity to the flight qualified tank and by analysis. The updated stress and fracture mechanics analyses showed large positive margins of safety for this tank.

INTRODUCTION

The NEAR program is one of the two Discovery science missions approved by NASA. The Discovery missions are designed to have a clear objective, proven instrumentation, a short development cycle, and an absolute cost ceiling. The last two items drove the development of the NEAR oxidizer tank.

Funding for NEAR was approved in early 1994 for a scheduled launch in February 1996. Since it is not feasible and not practical to analyze, design, qualify, fabricate, assemble and test a new tank due to the short development period and the limited budget, use of existing, flight proven hardware is critical to the success of the mission. An industry-wide search produced a flight-proven tank that, with some modifications, would meet the NEAR program requirements. Two flight oxidizer tanks are required for the program.

A comparison of the flight-proven tank versus the NEAR tank requirements is presented below:

Figure 1: Comparison Of The Existing Tank Design vs. NEAR Oxidizer Tank Requirements

REQUIREMENT	Existing Tank Design Requirement	"NEAR" Tank Design Requirement
Propellant	N_2H_4	N_2O_4
Liquid Mass	100 lbm	120 lbm
Propellant Volume	2000 in^3	2354 in^3
Total Tank Volume	3660 in^3	3660 in^3
Propellant Management	Elastomeric Diaphragm	Vortex Suppressor
Operating Pressure	377 psi	280 psi @ 120 °F
Proof Pressure	565 psi	420 psi @ 70 °F*
Burst Pressure	754 psi	560 psi @ 120 °F
Shell Leakage	$< 1 \times 10^{-8}$ std cc/sec He	$< 1 \times 10^{-6}$ std cc/sec He
Operating Temperature Range	41 to 122 °F	44 to 122 °F
Weight	14.7 lbm	10.7 lbm
Size	19.06 in ID	19.06 in ID
Expulsion Efficiency	≥ 98%	≥ 99%
Material of Construction	Ti-6AL-4V	Ti-6AL-4V
Shell Wall Thickness	0.026 in	0.026 in

*Acceptance tested at 525 psi

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CUSTOMIZATION OF EXISTING TANK DESIGN

The existing flight tank is a diaphragm tank developed nearly twenty years ago for the EXOSAT program. It is a 19.06 inch (in.) ID pressure vessel constructed of 6AL-4V Titanium, with an elastomeric diaphragm retained near the girth by a custom machined ring. The adaptation of this tank for the NEAR mission includes:

- Elimination of the elastomeric diaphragm;
- Removal of the machined-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
- Addition of a vortex suppressor.

The modifications were made within the framework of qualification-by-similarity principles in order to preclude the need for a qualification test program. The modified design is also supported by new stress and fracture mechanics analyses.

Figure 2 below shows the two tanks' external configurations:

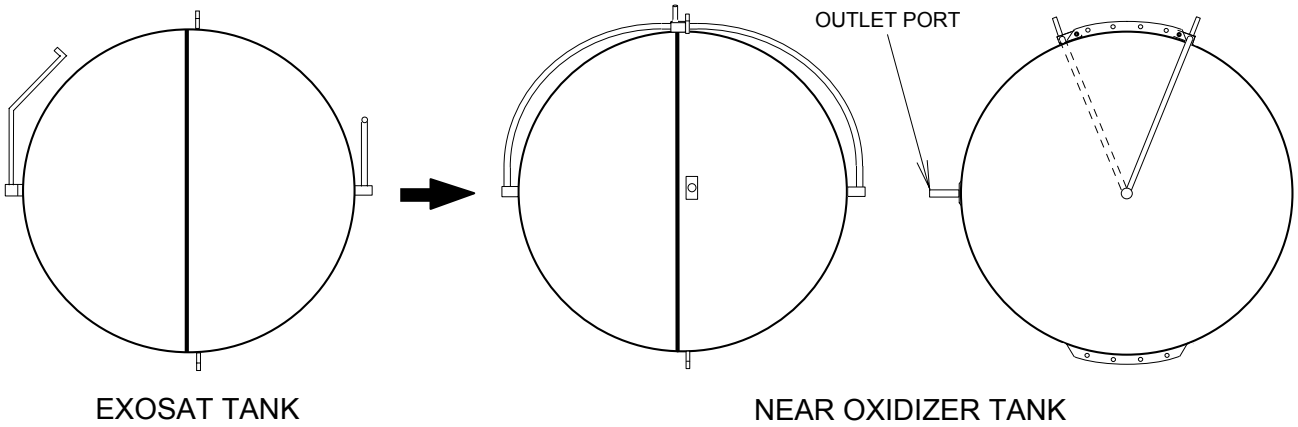
The NEAR oxidizer tank contains Nitrogen Tetroxide (NTO), hence the existing elastomeric diaphragm is removed due to its incompatibility. The diaphragm retaining features on the diaphragm retaining ring and the propellant hemisphere are removed to minimize machining time and to reduce weight. However, the diaphragm retaining ring cannot be totally removed because it is an integral feature of the qualified girth weld design. The removal of this ring would prevent the qualification of this tank by similarity. This ring is therefore redesigned to function as a backup ring.

An outlet tube is added near the equator. This tube is 0.375 OD x .028 wall, and the centerline of the tube is located 13/16 in. from the girth plane. The outlet tube and the boss region are integrally machined into the oxidizer tank.

The tube stubs on the tank were modified such that additional bracketry from the propulsion system structure would not be required to support the lines along the tank wall.

The vortex suppressor is added to prevent vortices from forming at the entrance of the outlet tube, thus maintaining a desired flowrate to the propulsion system thruster. The vortex suppressor is designed to withstand the fluid loads associated with spacecraft spin and de-spin maneuvers. The development of the vortex suppressor is presented in the following section.

Figure 2: Comparison Of External Configuration, EXOSAT And NEAR Oxidizer Tank



VORTEX SUPPRESSOR DEVELOPMENT

Typical spacecraft design generally requires a technique and/or equipment to effectively manage propellants in a zero gravity environment. Many spacecraft elect to use passive Propellant Management Devices (PMDs). However, these can be very costly and difficult to manufacture. The NEAR propulsion system utilizes a simplistic approach to managing propellants.

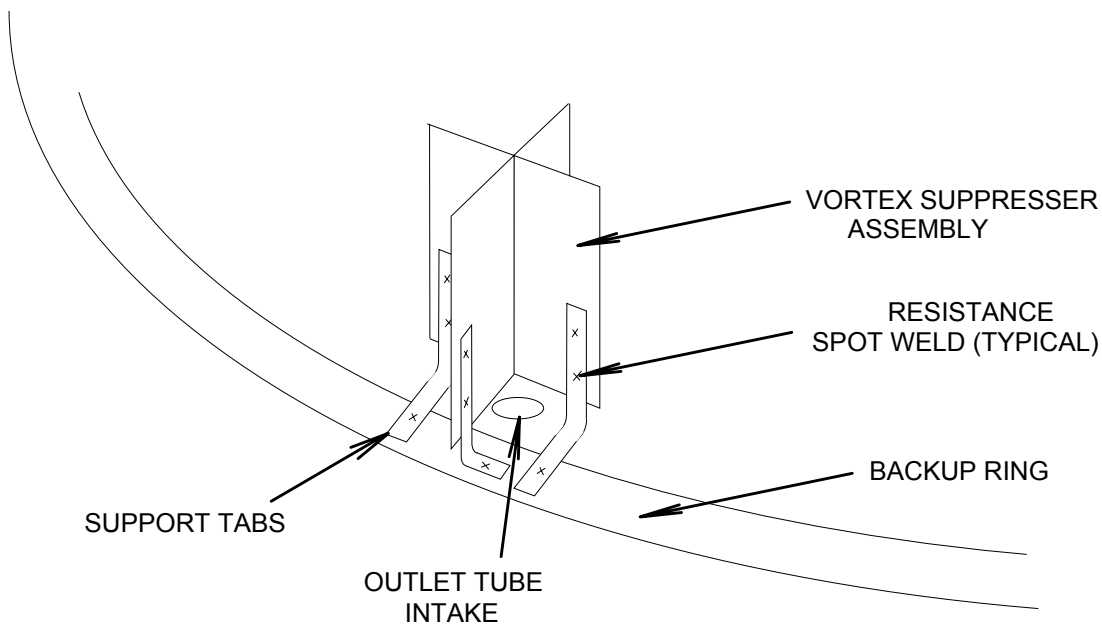
The NEAR propulsion system uses an elastomeric diaphragm tank to actively manage the hydrazine fuel. During thruster settling burns, an in-line filter external to the oxidizer tank and vortex suppressors inside each oxidizer tank passively manage the system's oxidizer prior to and during main engine firings.

Unlike the fuel tanks, the oxidizer tanks have no way of controlling the position of the fluid during a zero gravity coast. Surface tension behavior of the oxidizer adheres the liquid to the tank's wall. However, since these tanks are initially loaded with approximately 33% ullage (helium gas), the position of this bubble must be away from the outlet of the tank to prevent ingestion of a large bubble into the propellant feed system (and subsequently through the main engine). Utilizing the surface tension behavior of NTO, a 5 micron filter (nominal) was positioned external to the tank near the tank outlet to insure a liquid interface. The filter's screen holds oxidizer in the mesh during zero gravity conditions.

The propulsion system design positions the two oxidizer tanks such that the tank outlets are parallel to the spacecraft thrust vector. Prior to a main engine burn, the oxidizer is settled at the tank outlets using four 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 main engine operation, the oxidizer is forced to the tank outlet and continues to remain settled throughout the engine firing.

Although the in-line filter and the settling burn operations effectively manage the position of the oxidizer prior to main engine firing, the formation of a vortex can quickly occur at the tank outlet during main engine burns, thus greatly reducing the oxidizer flowrate. A simple four vane cruciform device, shown in Figure 3, is internally installed at the tank outlet to suppress the vortex and allow complete expulsion of the oxidizer without any reduction in propellant flowrate.

Figure 3: Vortex Suppressor For The NEAR Oxidizer Tank



This vortex suppressor device was conceptually designed by Southwest Research Institute. A four vane "cruciform" baffle placed over the outlet has been found in the past to be an effective anti-vortex device.[1] From this previous work, it was estimated that each of the four vanes of the baffle for a 19 in. diameter NTO tank should have a length of approximately 1.5 in. and a width of 0.75 in. The vanes must also be positioned close enough to the tank outlet (0.25 in. above the outlet) to maintain a tank expulsion efficiency of 99% or better.

Structurally, the imposed vortex suppressor loads are very low. Since the spacecraft is spin stabilized prior to its elliptical orbit insertion, the device is exposed to fluid loads resulting from a 70 rpm spin-up of the vehicle. The oxidizer tanks are located about the spin axis of the vehicle with the tank outlets at 9.5 in. off the spin axis. This results in fluid loads much less than 10 lbf.

VORTEX SUPPRESSOR TESTS

The vortex suppressor was tested at sea level conditions to verify its ability to suppress the formation of a vortex. A simple test approach utilized a 19 in. diameter Plexiglas hemisphere which enabled visual identification of any vortices. The test article configuration, shown in Figure 4, simulated the actual tank geometry with the vortex suppressor placed 0.25 in. above the .319 in. dia. outlet hole. Using Equation 1.0 provided by Southwest Research Institute, the flight conditions of the oxidizer tank in its low acceleration environment could be correlated to sea level test conditions. Subsequently, the test fluid velocities were obtained by establishing the proper head and orifice diameter. Finally, the kinematic viscosity of the test fluid was obtained by matching the oxidizer Reynolds Number of the flight conditions to the test fluid configuration. A mixture of 7% sugar (by weight) with water obtains the necessary test fluid viscosity.

Equation 1.0:

$$\left[\frac{V^2_{NTO}}{G_{act}\,D_{hole}}\right]_{flight} \propto \left[\frac{V^2_{water}}{G_{sea}\,D_{hole}}\right]_{sea\ level}$$

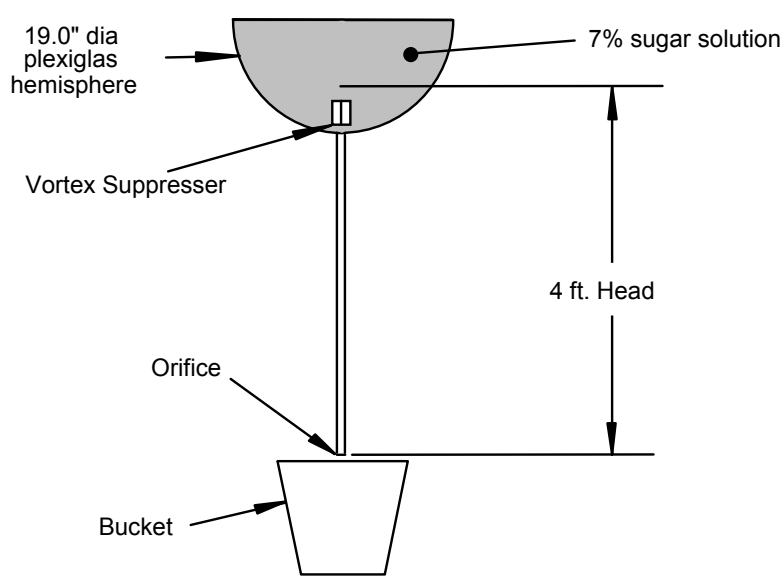
V = Fluid Velocity

G_{act} = 0.1 g's acceleration

D_{hole} = 0.319 in.

The objective of the tests was to qualitatively verify the effectiveness of the vortex suppressor. The test examined the presence of vortices both with and without the vortex suppressor installed in the test apparatus. The effects of fluid sloshing and swirling were also examined to determine if these conditions could cause a vortex to form.

Figure 4: Vortex Suppressor Test Apparatus



Test sequence 1 allowed the test fluid to flow through the test apparatus without an installed vortex suppressor. Immediately, a 9 in. diameter vortex formed at the outlet hole and the test fluid flowrate was reduced by a factor of 5. Next, the vortex suppressor was installed above the outlet hole. The effect of this unit prevented the formation of a vortex and subsequently allowed full expulsion of the test fluid without any reduction in flowrate. This test sequence 2 was repeated several times and achieved the same result.

Test sequence 3 evaluated the effects of fluid sloshing. Prior to flowing the test fluid, the test fluid was sloshed back and forth and continued to slosh during expulsion. Again, the presence of the vortex suppressor prevented the formation of a vortex and subsequently allowed full expulsion of the test fluid without a reduction in flowrate.

Test sequence 4 evaluated the effects of fluid swirling. Prior to flowing the test fluid, the sugar water was swirled rapidly and continued to swirl during expulsion. Once again, the vortex suppressor prevented the formation of a vortex and subsequently allowed full expulsion of the test fluid without a reduction in flowrate.

Test sequence 5 evaluated the combined effect of both fluid swirling and sloshing. Again, the presence of a vortex suppressor prevented the formation of a vortex and subsequently allowed full expulsion of the test fluid without a reduction in flowrate.

QUALIFICATION ANALYSES

Upgraded stress and fracture analyses were performed based on previous analyses completed on the EXOSAT tank, taking into consideration the new design changes.

The stress analysis showed large positive margins of safety, as summarized in Figure 5.

The Fracture Mechanics Analysis is performed using NASA/FLAGRO with minimum thicknesses as parameters. The result shows that this design satisfies all fracture mechanics requirements.

Qualification of the tank design is thus based on similarity to the flight qualified EXOSAT tank.

AREA	M.S.
Membrane, proof	.68
Membrane, burst	.37
Top/Bottom Boss, proof	.70
Top/Bottom Boss, burst	.32
Membrane, transition from weld, proof	.69
Membrane, transition from weld, burst	.31
Shell/lug, proof, yield	2.56
Shell/lug, burst, ult	2.10
Weld, proof, yield	.79
Weld, burst, ult	.67
Shell/lug, external load, yield	2.59
Shell/lug, external load, ult	1.55
Weld, external load, yield	1.06
Weld, external load, ult	.48
Tabs, yield	10.2
Tabs, ult	9.7
Bolts, yield	2.62
Bolts, ult	1.72
External tubes, yield	.51
External tubes, ult	.73

Figure 5: Summary of Margins of Safety

OXIDIZER TANK FABRICATION

The NEAR oxidizer tank shell is machined from two identical 6AL-4V Titanium alloy hemispherical forgings. Rough machined hemispheres are solution heat treated, quenched and partially aged. After aging the two hemispheres are machined to the final shell configurations.

The vortex suppressor components are fabricated from .025 in. thick 6AL-4V Titanium alloy sheets. Four identical vanes are resistance spot-welded into the four vane cruciform assembly. Three mounting tabs are also bent into the device to enable spot welding the assembly onto the backup ring to form the backup ring assembly, as shown in Figure 3.

The backup ring assembly is match machined to fit onto the finish machined propellant hemisphere to form the expulsion assembly. This expulsion assembly and the pressurant hemisphere are then automatic Tungsten Inert Gas (TIG) welded into the tank weldment. The girth weld is radiographic and dye penetrant inspected. The tank weldment is then post girth weld stress relieved and final machined. External tubes are then

custom fabricated and welded to the tank weldment to form the finished tank assembly. The propellant and pressurant ports are .250 OD x .028 wall 3AL-2.5V Titanium alloy tubes. The outlet port is a .375 OD x .028 wall 3AL-2.5V Titanium alloy tube.

The tank is mounted into the spacecraft structure by two lugs near the girth plane. These lugs are Electron Beam welded onto the hemispheres at the rough machined stage, and finish milled after tank shell final age. Four equally spaced holes are drilled into each lug after post weld stress relief and final machining.

ACCEPTANCE TESTING

The NEAR oxidizer tank assembly is subjected to the following sequence of acceptance tests prior to delivery:

- Preliminary visual examination
- Pre-proof volumetric capacity
- Ambient proof pressure test
- Post-proof volumetric capacity
- External leakage test
- Radiographic examination of girth weld
- Penetrant inspection
- Mass measurement
- Final examination
- Cleanliness

The ambient hydrostatic proof pressure test is conducted at 525 psig for a pressure hold period of 10 seconds. Post proof test volume growth cannot exceed 0.3%.

The external leak test is conducted to verify the integrity of the tank shell. The test specimen is placed in a chamber, which is evacuated to 0.2 microns of mercury or less, and helium pressurized to 280 psig for three minutes. The leakage cannot exceed 1 x 10^{-6} std cc/sec.

Post acceptance test radiographic examination on the girth weld and penetrant inspection on the entire external surface are conducted to verify that the tank is not damaged during acceptance testing.

The tank is cleaned to the cleanliness level specified in Figure 6:

Figure 6: NEAR Oxidizer Tank Cleanliness Requirement

Particle Size Range (Microns)	Maximum Allowed per 100 ml
15 Max	280
>15 to 25	75
>25 to 50	11
>50 to 100	1

Two NEAR oxidizer tanks successfully completed these acceptance tests.

CONCLUSION

The NEAR oxidizer tank was successfully developed and acceptance tested without failure or redesign. Two tanks were delivered for installation into the NEAR spacecraft propulsion system. The propulsion system is currently undergoing acceptance testing for a scheduled launch on 17 February, 1996. Rendezvous with asteroid EROS will be on 6 February 1999.

REFERENCE:

1. *H.N. Abramson, The Dynamic Behavior of Liquids in Moving Containers, Chapter 10. NASA SP-106, 1966 (Corrected and reprinted by Southwest Research Institute, 1982)*