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TANK TRADE STUDIES – AN OVERVIEW

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ABSTRACT

After nearly 5 decades of space flight, the tank industry has accumulated a large amount of valuable resources such as qualified forgings, tooling, and qualified tank designs that may provide significant contribution to new programs. To a propulsion engineer seeking a flight tank on a new mission, we always recommend an initial trade between utilization of available assets versus development of custom-designed hardware. Because the multiple options and the economic, programmatic, and technical implications would complicate the tank selection process, trade studies are often employed to investigate all options and select the optimal tank solution. Similar trade studies are also conducted during tank design to evaluate the many available design options, with the same goal of providing the optimal value to the customer.

The demand for both formal and informal tank trade studies have increased significantly in recent years due to their effectiveness in the tank selection process. We have supported many programs where informal and formal trades may last years before a tank solution is defined. This paper provides some examples of the various trade studies we have conducted in recent years. When used properly, tank trade studies can be valuable tools that deliver exceptional value to their users.

INTRODUCTION

A pressure vessel is an important component of a space flight mission requiring propulsion. In an ideal world with unlimited budget and no schedule constraints, an optimal tank can be custom-designed specifically for a mission. Unfortunately, rarely do these ideal programs exist. Satellite manufacturers and propulsion system integrators are usually faced with many pre-existing conditions such as tight schedule, inadequate budget, insufficient space or limiting envelope, tight mass target, or some other constraints. All these limiting factors must be considered during tank selection.

A spacecraft propulsion engineer in need of a pressure vessel usually faces several options:

(A) **Qualifying a new, custom-designed tank:** This process includes design, analysis, engineering, tooling, component qualification, tank qualification, and tank fabrication. The effort demands considerable expertise and consumes significant amount of resources, and requires the commitment to an extended program schedule. There are also risks associated with the commitment of time and resources to such an endeavor. Above all, it is always the highest price option. The advantage of this approach, obviously, is that it provides the optimal tank solution. This may be the best use of available envelope, the most favorable mounting scheme, the highest performance, the lowest mass, the lowest risk, or the best overall value. It is not unusual for customers to select this option if there are no other available options or the non-recurring costs can be amortized over a large number of recurring units, such as commercial satellite applications. On average, ATK Commerce develops three or four new tanks of various sizes each year for customers requiring custom-designed solutions.

(B) **Qualifying a new tank by adapting element or elements of an existing tank:** There are varying degrees of adaptation. One may choose to use an existing forging only, but design all other features free of restrictions. The available forging tooling and the elimination of the forging qualification program provide the program savings, which are not insignificant on a large diameter tank. More cost savings can be realized if an existing mandrel for finish machine is baselined, with added benefit of additional savings from weld tooling and perhaps some engineering drawings. However, this also places further restrictions of fixed dimensions and fixed inside contour due to the use of this available machining mandrel. Even more cost savings can be realized when all the elements of an existing tank are retained while new components are added to the new tank. Adding a cylinder section between two domes to increase tank volume is a perfect example of this approach. However, as more pre-existing features are utilized in favor of reduced cost, more limitations or constraints are placed on the new tank design, making it progressively less optimal.

(C) **Adapting an existing tank:** This option usually involves modification of an existing tank without affecting the tank shell qualification status. Some simple modifications include changing the size (diameter) of inlet or outlet tubes, welding a reducer to existing interface tubing, or rotating the inlet or outlet interface tubes. More complex modification involves designing a new Propellant Management Device (PMD) and adapting it to the existing tank shell. These modifications usually do not require qualification if the mission environment is enveloped by the qualified environment. Cost savings are usually very significant when the customer need not pay for a qualification tank and run a qualification program. Tank qualification is usually by analysis, by protoflight testing, or both.

(D) **Using a qualified tank as is:** This is usually the least expensive approach. Non-recurring efforts may vary from a simple qualification-by-similarity (QBS) report to a full stress and fracture analysis plus some protoflight testing. Many qualified diaphragm tanks are selected for new programs under this option.

TANK TRADE STUDIES

The process of determining the tank configuration usually comes after the mission is defined, a propulsion system (bi-propellant, monopropellant, or dual mode) approach is chosen, a launch vehicle is selected, and the available envelope for tankage is determined. These information are needed for tank definition, including tank diameter and height, tank volume, propellant volume, pressure rating, flow rate, mounting requirements, launch environment, etc. The process can be made simple if these requirements were fixed and tank fabrication can proceed immediately. Unfortunately, a large inventory of qualified hardware developed after decades of spaceflight has made the task of finalizing the tank configuration more difficult. Due to the large expense and extended time commitment associated with developing and qualifying new space hardware, it is always prudent for a propulsion engineer to identify available hardware for adaptation. Thus the process of defining a tank solution has evolved into an iterative effort involving economic and programmatic considerations as well as technical decisions.

The exercise of tank definition and selection is far from an exact science. Because there are always multiple options when deciding a tank solution, and sometimes the optimal solution may not be readily apparent, it is often worthwhile to conduct a tank trade study to weight the available options. The trade studies can be conducted at different stages of tank definition, selection, and development, and for various purposes. These include:

1. Search available hardware,
2. Define and iterate specification requirements,
3. Evaluate economic and programmatic impacts,
4. Facilitate technical decisions,
5. Define quantity and configuration,
6. Assess risks and benefits, and
7. Evaluate overall value.

Tank trade studies can be conducted before or after the issuance of the tank specification for different objectives. They can be performed as part of the tank selection process, or as a part of the tank design. They are conducted for external customers, or for internal customers such as Engineering and Manufacturing to facilitate the design and manufacture of the tank. In actuality, each tank design and engineering effort is nothing more than a series of trades that culminates in a final tank design.

The following pages provide some examples of tank trade studies we have conducted in recent years.

COPV Liner Material Selection Trade Study

This example of a pressurant tank trade study was previously presented in AIAA 96–2751 [(1)]. The trade study was initiated after a contract was received to design and manufacture a high pressure composite overwrapped pressure vessel (COPV), and therefore was an integral part of the tank design effort. The study compared various liner material candidates and facilitated the selection of the most optimal liner material. See Table 1. In this example, it was determined that CP titanium was more suitable than aluminum for the intended COPV application. Data collected for the trade study was also used for subsequent tank analysis.

Table 1: COPV Liner Selection Trade Study

TABLE 1. MATERIAL TRADE STUDY - TANK LINER

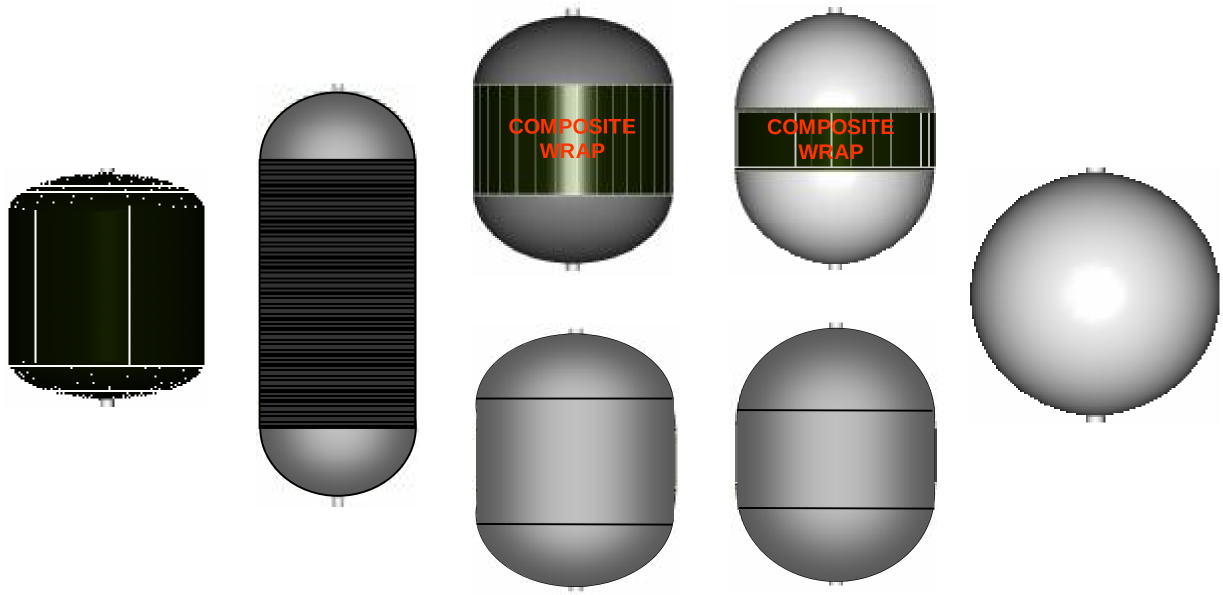
	ALUMINUM 6061-T6	CP TITANIUM CP-3	CP TITANIUM CP-70
MATERIAL PROPERTIES			
YIELD STRENGTH - KSI	41.5	40.0	70.0
ULTIMATE STRENGTH - KSI	47.0	50.0	80.0
ELASTIC MODULUS - MSI	10.0	15.5	15.5
PLASTIC MODULUS - MSI	0.076	0.178	0.188
MIN ELONGATION - e_p - % *	10	20	15
MIN REDUCTION OF AREA - RA - % *	24	38	30
MIN FRACTURE STRAIN - ε_F - % *	27	48	36
MEMBRANE STRAINS - NOMINAL			
ε_{HOOP} - PROOF PRESS - %	1.35	1.34	1.32
ε_{LONG} - PROOF PRESS - %	0.86	0.85	0.83
ε_{HOOP} - ZERO PRESS - %	0.03	0.03	0.05
ε_{LONG} - ZERO PRESS - %	0.03	0.03	0.05
ε_{HOOP} - OPER PRESS - %	1.07	1.06	1.04
ε_{LONG} - OPER PRESS - %	0.68	0.66	0.65
LINER PLASTIC STRAIN MAGNITUDE - NOMINAL			
ε^{PEQ} - PROOF PRESS - %	1.69	1.85	1.54
ε^{PEQ} - ZERO PRESS - %	0.61	0.41	0.70
ε^{PEQ} - OPER PRESS - %	1.22	1.40	1.09
LINER Δ PLASTIC STRAIN MAGNITUDE - NOMINAL			
$\Delta\varepsilon^{PEQ}$ - 0 to PROOF PRESS - NOMINAL - %	1.08	1.44	0.84
$\Delta\varepsilon^{PEQ}$ - 0 to OPER PRESS - NOMINAL - %	0.61	0.99	0.39
LINER Δ PLASTIC STRAIN MAGNITUDE - PEAK			
$\Delta\varepsilon^{PEQ}$ - 0 to PROOF PRESS - PEAK - %	2.91	3.15	1.93
$\Delta\varepsilon^{PEQ}$ - 0 to OPER PRESS - PEAK - %	1.90	2.20	1.06
PREDICTED LINER CYCLES - NOMINAL STRAINS			
0 to PROOF PRESS	156	278	459
0 to OPER PRESS	490	588	2130
PREDICTED LINER CYCLES - PEAK STRAINS			
0 to PROOF PRESS	22	58	87
0 to OPER PRESS	50	119	288
* Specimen thickness 0.02 to .25 inch			

However, it is necessary to state here that all trade studies are unique. Results and conclusions derived for one trade study, although valuable, should not be universally applied.

Tank Shell Configuration Trade Study

Tank shell selection is a key decision process for a new tank develop program. For a given propellant volume, there can be many tank configurations: spherical, hemispheroid heads with various diameters and a central cylinder, and ellipsoidal heads of various diameters and a central cylinder. Tank construction is also part of the trade space, including all-metal, hybrid construction with metal heads and composite overwrapped cylinder section, and fully overwrapped tanks. The various possible configurations are shown in Figure 1 below.

Figure 1: Tank Shell Trade Study



The following parameters are often traded when making tank shell decisions:

- Tank Diameter
- Shape of tank domes
- Construction of the cylinder section
- Resonant frequency
- Tank shell transition
- Types of tank mounts (flange, tabs, lugs, bosses)
- Location of mounting points
- Size (length, width & thickness) of mounting tabs
- Overall tank configuration
- Mass
- Risk
- Schedule
- Cost
- Available design data

There are no absolute ground rules for tank shell selection. Depending upon the limiting factors, such as available envelope (diameter and height), mass budget, cost, frequency requirement, material availability, many different tank solutions can be reached. Although technical requirements often drive tank configuration decisions, other non-technical factors are frequently considered, such as schedule, handling, available space, availability of material, and pre-existing hardware. One example of this is our tank Part Number 80342-1. This tank was designed to prevent accidental damage of the elastomeric diaphragm during ground testing. The tank contains an ellipsoidal pressurant head which enables a fully reversed diaphragm to rest against the tank shell in order to prevent damage to the diaphragm during ground testing. See Figure 2 below. Another example is our Part Number 80386-1, which was designed to fit within a conical envelope[(2)]. See Figure 3. Both are examples of tank configuration dictated by non-technical factors.

Figure 2: Our Part Number 80342

Figure 3: Our Part Number 80386

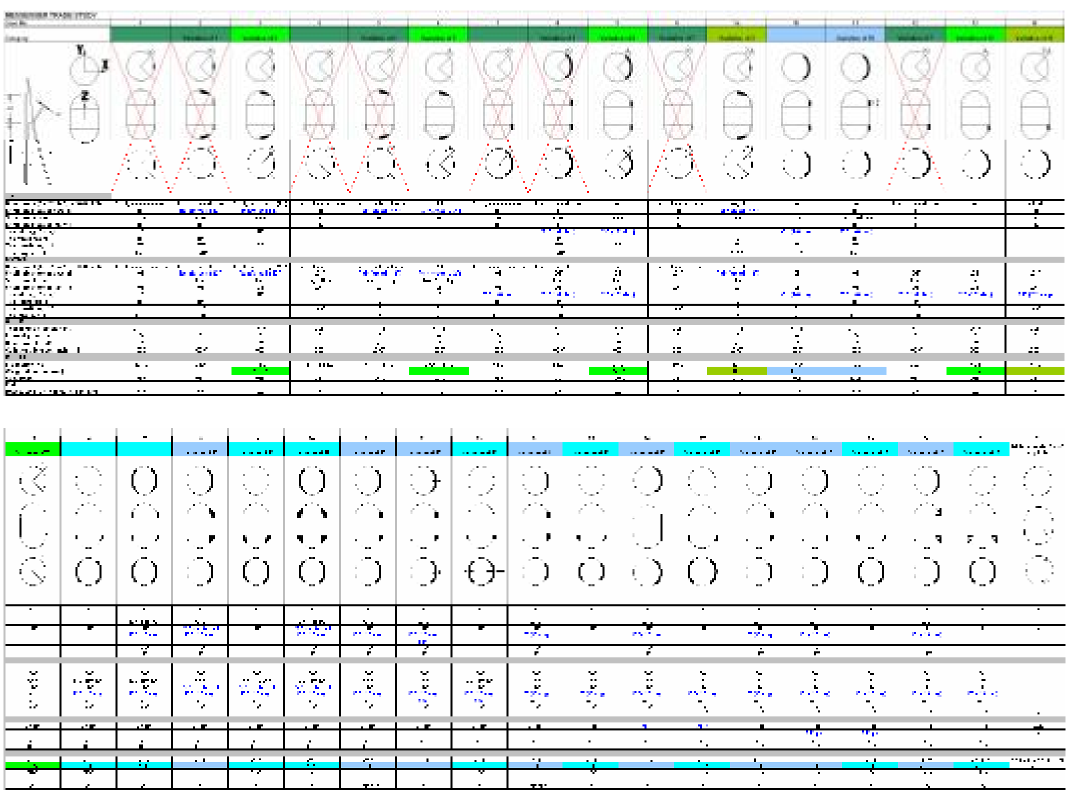
MESSENGER Propellant Tank Mass Minimization Trade Study

The design and manufacture of the MESSENGER propellant tank is described in AIAA 2002–4139 [(3)]. The tank design was based on utilizing existing forgings, but all other parameters were open for the new tank design effort. This decision was a wise one because ATK Commerce possesses several forgings near or at the ideal tank diameter.

The primary concern of the MESSENGER tank development program was mass, and a mission-enabling mass target must be achieved. To develop the final tank configuration, a comprehensive and year-long trade study was conducted. The focus of the trade study was to generate the most effective tank mount and achieve the most mass-efficient tank configuration. The trade study analyzed over 50 combinations of tank mounts. Trade space included tank diameter, resonant frequency, tank shell thickness, tank shell transition, types of tank mounts (flange, tabs, struts), location of tank mounts, size (length, width and thickness) of mounting tabs, risk, and cost. See Table 2.

The trade study favored a strut-mounted tank configuration. Lightweight mounting struts were designed and analyzed as part of the tank design package, and the tank qualification testing included the qualification testing of the tank as well as the struts. The delivered tank, with a mass of 19 lbm (8.6 kg), is 5 lbm less than the mass budget allocated by the equipment specification. The highly successful tank development program met and exceeded all the program objectives.

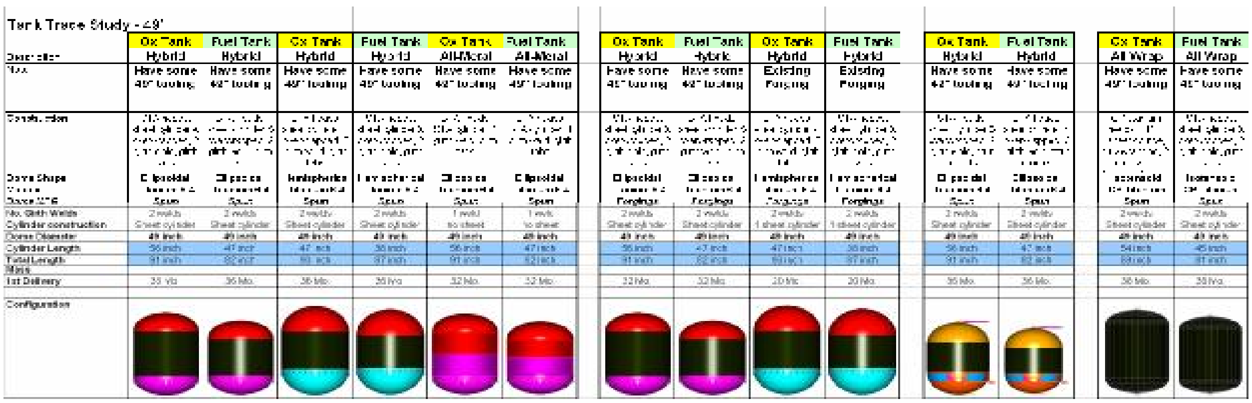
Table 2: MESSENGER Propellant Tank Configuration Trade Study



Large Propellant Tank Shell Configuration Trade Study

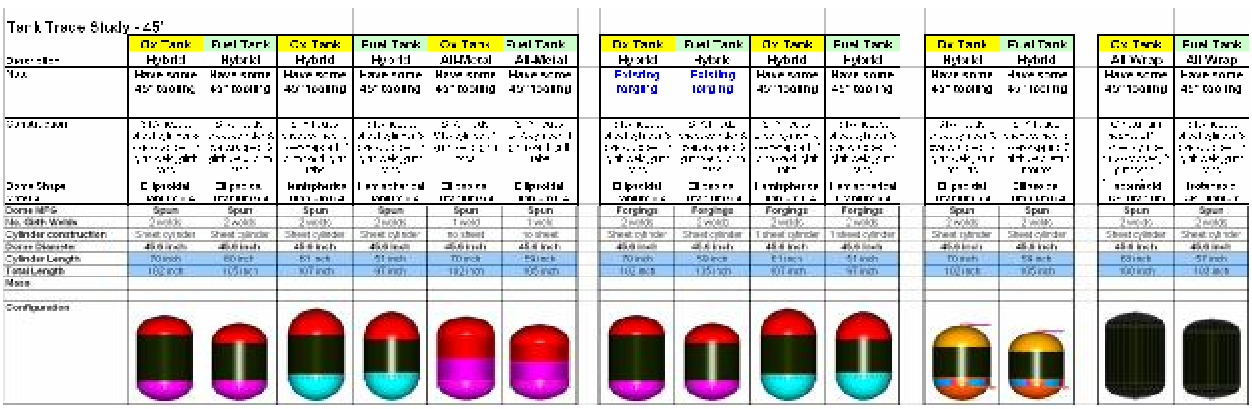
The non-recurring expenditures on a new large diameter propellant tank is comparatively high. It is therefore prudent to examine the possible use of existing tooling whenever a large diameter tank is contemplated. Table 3 compared two large diameter tanks based on utilizing existing tooling for 45" diameter and 49" diameter tanks. Trade space included hemispheroid heads vs. ellipsoidal heads, forged domes vs. spun domes, all-titanium construction vs. hybrid construction vs. full wrap, skirt mount vs. boss mount vs. tab/pin mount, cost, and schedule.

Table 3: Large Diameter Propellant Tank Trade Study



Tank Trade Study - 49"

	Ox Tank	Fuel Tank	Ox Tank	Fuel Tank	Ox Tank	Fuel Tank	Ox Tank	Fuel Tank	Ox Tank	Fuel Tank	Ox Tank	Fuel Tank	Ox Tank	Fuel Tank
Description	Hybrid	Hybrid	Hybrid	Hybrid	All-Metal	All-Metal	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	All Wrap	All Wrap
[illegible]	Have some 49" tooling	Have some 49" tooling	Have some 49" tooling	Have some 49" tooling	Have some 49" tooling	Have some 49" tooling	Have some 49" tooling	Have some 49" tooling	Existing Forging	Existing Forging	Have some 49" tooling	Have some 49" tooling	Have some 49" tooling	Have some 49" tooling
Construction	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Dome Shape	Ellipsoidal	Ellipsoidal	Hemispherical	Hemispherical	Ellipsoidal	Ellipsoidal	Ellipsoidal	Ellipsoidal	Hemispherical	Hemispherical	Ellipsoidal	Ellipsoidal	Isotensoid	Isotensoid
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Dome MFG	Spun	Spun	Spun	Spun	Spun	Spun	Forgings	Forgings	Forgings	Forgings	Spun	Spun	Spun	Spun
No. Girth Welds	2 welds	2 welds	2 welds	2 welds	1 weld	1 weld	2 welds	2 welds	2 welds	2 welds	2 welds	2 welds	2 welds	2 welds
Cylinder construction	Sheet cylinder	Sheet cylinder	Sheet cylinder	Sheet cylinder	no sheet	no sheet	Sheet cylinder	Sheet cylinder	1 sheet cylinder	1 sheet cylinder	Sheet cylinder	Sheet cylinder	Sheet cylinder	Sheet cylinder
Dome Diameter	49 inch	49 inch	49 inch	49 inch	49 inch	49 inch	49 inch	49 inch	49 inch	49 inch	49 inch	49 inch	49 inch	49 inch
Cylinder Length	56 inch	47 inch	47 inch	36 inch	56 inch	47 inch	56 inch	47 inch	47 inch	36 inch	56 inch	47 inch	54 inch	45 inch
Total Length	91 inch	82 inch	93 inch	87 inch	91 inch	82 inch	91 inch	82 inch	93 inch	87 inch	91 inch	82 inch	89 inch	81 inch
Mass														
1st Delivery	33 Mo.	36 Mo.	36 Mo.	36 Mo.	32 Mo.	32 Mo.	32 Mo.	32 Mo.	20 Mo.	20 Mo.	36 Mo.	36 Mo.	38 Mo.	38 Mo.
Configuration														



Tank Trade Study - 45"

	Ox Tank	Fuel Tank	Ox Tank	Fuel Tank	Ox Tank	Fuel Tank	Ox Tank	Fuel Tank	Ox Tank	Fuel Tank	Ox Tank	Fuel Tank	Ox Tank	Fuel Tank
Description	Hybrid	Hybrid	Hybrid	Hybrid	All-Metal	All-Metal	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	All Wrap	All Wrap
[illegible]	Have some 45" tooling	Have some 45" tooling	Have some 45" tooling	Have some 45" tooling	Have some 45" tooling	Have some 45" tooling	Existing forging	Existing forging	Have some 45" tooling	Have some 45" tooling	Have some 45" tooling	Have some 45" tooling	Have some 45" tooling	Have some 45" tooling
Construction	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Dome Shape	Ellipsoidal	Ellipsoidal	Hemispherical	Hemispherical	Ellipsoidal	Ellipsoidal	Ellipsoidal	Ellipsoidal	Hemispherical	Hemispherical	Ellipsoidal	Ellipsoidal	Isotensoid	Isotensoid
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Dome MFG	Spun	Spun	Spun	Spun	Spun	Spun	Forgings	Forgings	Forgings	Forgings	Spun	Spun	Spun	Spun
No. Girth Welds	2 welds	2 welds	2 welds	2 welds	1 weld	1 weld	2 welds	2 welds	2 welds	2 welds	2 welds	2 welds	2 welds	2 welds
Cylinder construction	Sheet cylinder	Sheet cylinder	Sheet cylinder	Sheet cylinder	no sheet	no sheet	Sheet cylinder	Sheet cylinder	1 sheet cylinder	1 sheet cylinder	Sheet cylinder	Sheet cylinder	Sheet cylinder	Sheet cylinder
Dome Diameter	45.6 inch	45.6 inch	45.6 inch	45.6 inch	45.6 inch	45.6 inch	45.6 inch	45.6 inch	45.6 inch	45.6 inch	45.6 inch	45.6 inch	45.6 inch	45.6 inch
Cylinder Length	70 inch	60 inch	61 inch	51 inch	70 inch	59 inch	70 inch	59 inch	61 inch	51 inch	70 inch	59 inch	68 inch	57 inch
Total Length	102 inch	105 inch	107 inch	97 inch	102 inch	105 inch	102 inch	105 inch	107 inch	97 inch	102 inch	105 inch	100 inch	102 inch
Mass														
Configuration														

This trade study revealed that the development of a large propellant tank has its own unique set of circumstances that must be considered when making the final tank shell selection. Several observations were made upon completion of this trade study:

1. Due to the exceedingly high titanium prices at the time of the trade study, the unit price of the all-metal tank is noticeably higher than the hybrid tank. However, this condition is subject to changing economic conditions and is not entirely dependent upon the tank design.

2. The cost of tooling increases exponentially as tank diameter becomes larger. The first flight delivery also takes longer, due to the extended lead time required to procure the tooling material.

3. As tank diameter increases, it becomes increasingly difficult to secure the titanium plates needed for spun domes, as the larger plate sizes are approaching the mill's capability limit.

4. As tank diameter increases, a forged dome becomes thicker due to process constraints, and progressively more expensive.

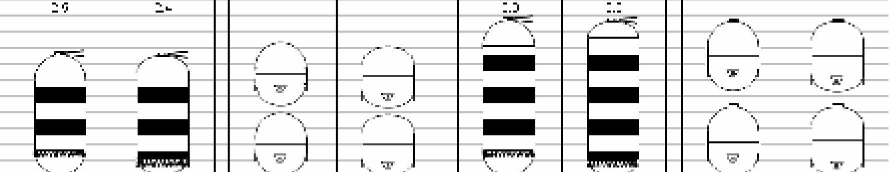
This trade study showed that for large diameter tanks, securing a supplier capable of providing high quality domes with consistent delivery performance will be one of the keys to program success. Such programmatic and economic issues brought forth by the trade study will provide all the participants in the design effort the facts necessary to make the appropriate decisions on the final tank configuration.

Propellant Tank Sizing and Risk Mitigation Trade Study

This trade study was conducted with only one constraint: the available envelope. The trade space included use of existing hardware and tooling vs. all new design, hemispheroid heads vs. ellipsoidal heads, single tank vs. multiple tanks, all-metal shell vs. hybrid shell, skirt mount vs. tab mount, PMD vs. diaphragm, cost, risk, and schedule. See Table 4. Part of the trade also examined the upper limit of our in-house capability to manufacture elastomeric diaphragms.

Table 4: Propellant Tank Trade Study

	FIXED LOAD Single Tank Configuration		FIXED LOAD Dual Tank Configuration		FIXED LENGTH Single Tank Configuration		FIXED LENGTH Dual Tank Configuration	
	PMD Tank Spherical Heads	PMD Tank Elliptical Heads	Diaphragm Tank Spherical Heads	Diaphragm Tank Elliptical Heads	PMD Tank Spherical Heads	PMD Tank Elliptical Heads	Diaphragm Tank Spherical Heads	Diaphragm Tank Elliptical Heads
MEOP	400 psi	400 psi	400 psi	400 psi	400 psi	400 psi	400 psi	400 psi
Total Hydrazine Load (kg)	500	500	500	500	[illegible]	695	[illegible]	[illegible]
Each Tank (kg)	500	500	250	250	[illegible]	695	[illegible]	[illegible]
Each Tank (lbm)	1100	1100	550	550	1470.4	1529	615	663
Hydrazine Volume (cubic inches)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Propellant Fraction	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total tank volume	37,745	37,745	18,873	18,873	50,730	52,406	21,103	22,750
Reference P/N	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Tank Radius (inches)	14	14	14	14	14	14	14	14
Cylinder Length (in)	40.0	40.0	10.4	7.9	54.0	72.0	5.0	24.0
Dome height (in)	20	19.0	20	9.0	20	9.0	20	7.0
Each Tank Length	71.0	59.0	40.4	27.7	80.0	72.0	44.0	44.0
Clearance top and bottom	4.0	4.0	0.0	0.0	4.0	4.0	0.0	0.0
Overall Tank Length	75.0	72.0	80.8	60.4	96.0	96.0	96.0	95.0
Max Structure Length	[illegible]	[illegible]	[illegible]	90	[illegible]	90	90	[illegible]
L/D ratio	2.6	2.4			3.0	3.0		

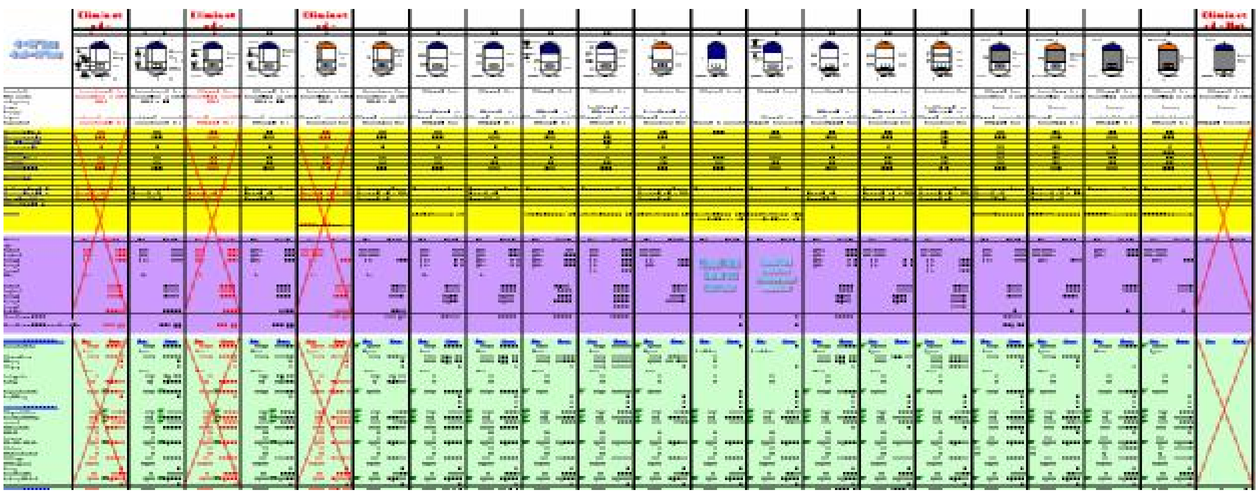


The trade study results were provided to the customer to generate specification requirements that allowed us to fabricate a key component of the propellant tank in-house. In other words, the trade study led to a tank program that minimizes the overall risk to both the customer and ATK Commerce. There were also other key findings, including the confirmation that the most economical tank packaging would include the least number of tanks.

Propellant Tank Design Optimization Trade Study

This effort is similar to the MESSENGER trade study. The trade was conducted after a contract was issued, and became an integral part of the tank design process that led to the Preliminary Design Review (PDR). The primary purpose of this design trade was to evaluate the available options and determine an optimal tank configuration for a large diameter tank. Essentially every item was traded, including hemispheroid dome vs. ellipsoidal dome, forged dome vs. spun dome, metal cylinder vs. composite wrapped cylinder, integrally machined tank mount vs. bonded tank mount, sectional cylinder vs. single-piece cylinder, optimal location of the mounting features, cost, risk, and schedule. See Table 5.

Table 5: Propellant Tank Trade Study



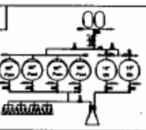
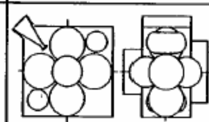
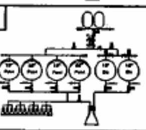
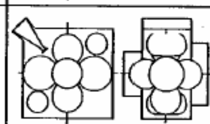
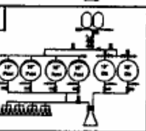
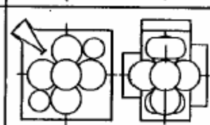
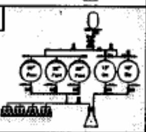
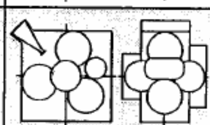
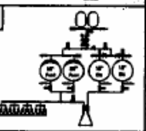
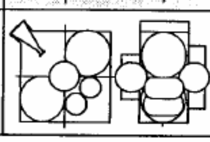
At the conclusion of the tank trade, our customer did not select the lowest price option, but wisely chose the optimal tank solution that provided the best overall value.

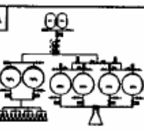
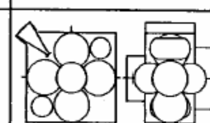
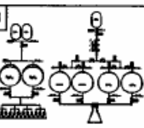
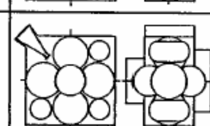
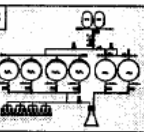
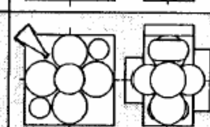
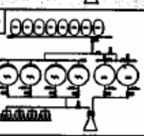
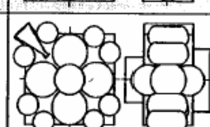
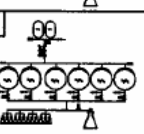
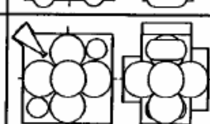
NEAR Propellant Tank Packaging Trade Study

The NEAR program utilized two oxidizer tanks [(4)] and three fuel tanks [(5)]. Both tanks were adaptation to existing, qualified tanks. However, prior to finalizing the two tank designs, a system packaging trade study was conducted to assist tank selection and lay out the propulsion system. The trade space included various combinations of fuel, oxidizer, and pressurant tanks, tanks of various diameters, various system layouts, tank orientation, diaphragm vs. PMD for propellant management, cost, risk, and schedule. The trade study is summarized in Table 6**.**

The NEAR mission was extremely successful. The spacecraft orbited the Asteroid Eros and concluded its science missions. At the end of the mission, there was sufficient fuel left for additional maneuvers, and the NEAR spacecraft conducted a de-orbit mission and descended onto the surface of the asteroid to collect additional science data. This final maneuver was made possible by the excellent performance of these propellant tanks.

Table 6: NEAR Propellant Packaging Tank Trade Study

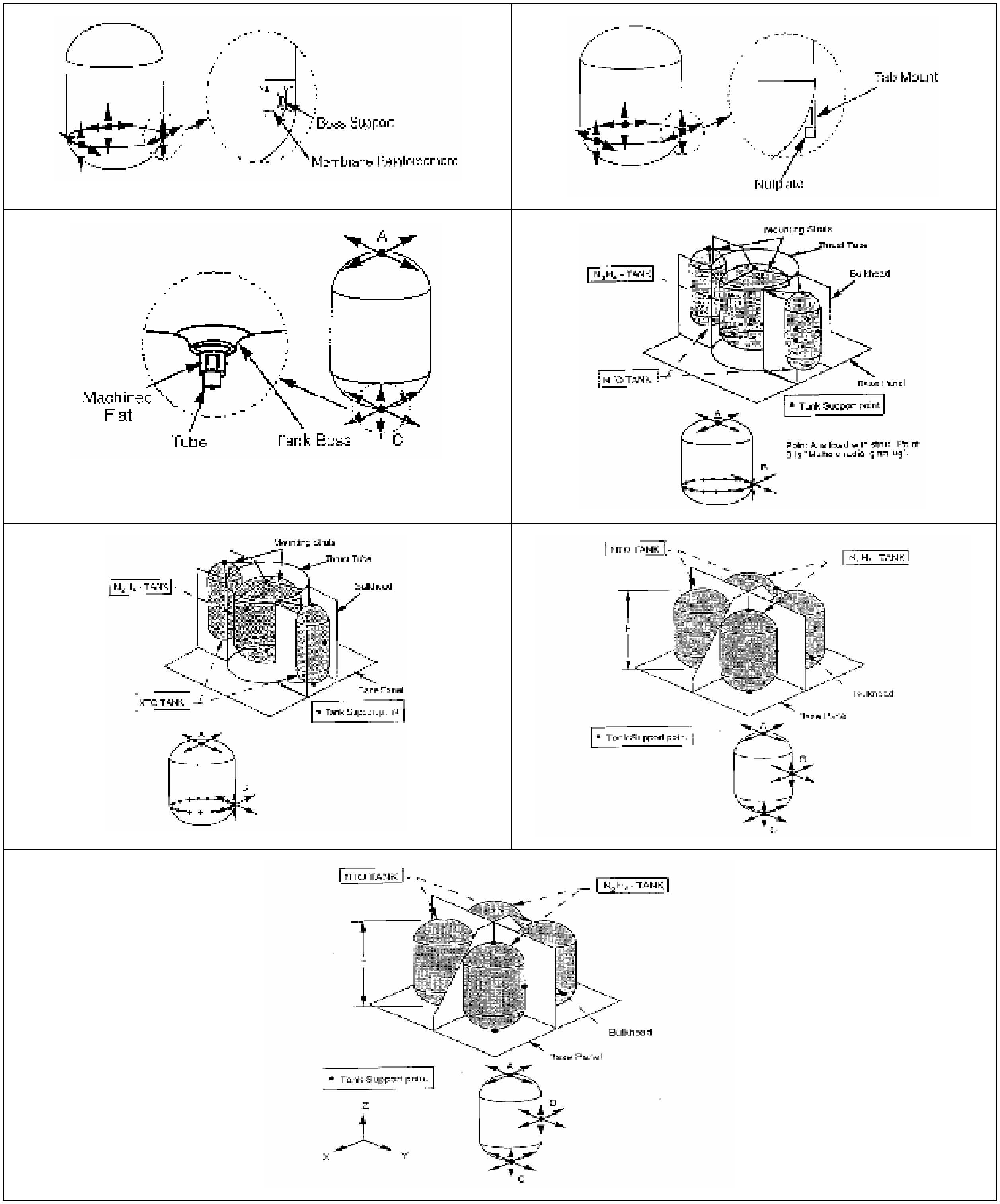
System	Description	Total PS Mass Kg (lbm)	Additional FVC Thruster Fuel Capability	Envelope	Advantages	Disadvantages
1 	• **Baseline from Propellent and Pressurization Study** • 2-19" dia Passive PMD Ox Tanks • 4-22" dia Active PMD Fuel Tanks • 2 Helium Tanks	413.5 (911.7)	48%		• Equal size fuel tanks	• Excess additional FVC thruster fuel capability • Non optimum fuel volume
2 	• 2-19" dia Passive PMD Ox Tanks • 2-19" dia Active PMD Fuel Tanks • 2-22" dia Active PMD Fuel Tanks • 2 Helium Tanks	409.2 (902.1)	18%		• Lighter System • Better use of existing tanks	• Excess additional FVC thruster fuel capability • System requires 3 different tanks • Complicates Spacecraft fueling
3 	• 2-19" dia Passive PMD Ox Tanks • 4-19" dia Active PMD Fuel Tanks • 2 Helium Tanks	404.3 (891.3)	-19%		• Equal size fuel tanks	• Required fuel quantity does not package
4 	• 2-19" dia Passive PMD Ox Tanks • 3-22" dia Active PMD Fuel Tanks • 1 Helium Tank	398.3 (878.0)	10%		• Selected, lightest NEAR PS • Optimum fuel quantity • Requires 1 less helium tank	• Approx. 3 mm COM due to Pressurant
5 	• 2-19" dia Passive PMD Ox Tanks • 2-28" dia Active PMD Fuel Tanks • 2 Helium Tanks	424.9 (936.7)	103%		• Least number of tanks • Simple system	• Tanks will not fit into NEAR PS envelope • COM problem with helium tanks

System	Description	Total PS Mass Kg (lbm)	Additional FVC Thruster Fuel Capability	Envelope	Advantages	Disadvantages
A 	• MMH/NTO LVA Thruster • N2H4 FVC Thrusters • Regulated Pressurization • 2 LVA Passive PMD Fuel Tanks • 2 LVA Passive PMD Ox Tanks • 2 FVC Active Fuel Tanks • 2 Helium Tanks	414.4 (913.7)	50%		• Light System • Uses lighter Passive PMD tanks for LVA Thruster	• Can not use LVA thruster residual for FVC thruster operation • Carbon in LVA thruster plume
B 	• MMH/NTO LVA Thruster • N2H4 FVC Thrusters • Regulated LVA Pressurization • Blowdown FVC Pressurization • 2 LVA Passive PMD Fuel Tanks • 2 LVA Passive PMD Ox Tanks • 2 FVC Active Fuel Tanks • 2 Helium Tanks	423.4 (933.4)	50%		• Separate LVA and FVC thruster pressurization	• More complex system • Heavy system • COM problem with helium tanks
C 	• N2H4/NTO LVA Thruster • N2H4 FVC Thrusters • Regulated Pressurization • 4 Active Fuel Tanks • 2 Passive Ox Tanks • 2 Helium Tanks	413.5 (911.7)	48%		• Lightest propellant and pressurization concept • All fuel on-board spacecraft can be used • No carbon in plume	• Selected tanks create excess FVC thruster fuel volume capability (optimized in tank trade study)
D 	• N2H4/NTO LVA Thruster • N2H4 FVC Thrusters • Blowdown Pressurization • 4 Active Fuel Tanks • 2 Passive Ox Tanks • 8 Helium Tanks	475.5 (1048.2)	48%		• Simple system	• Heavy system • Helium tanks will not package
E 	• N2H4 LVA Thruster • N2H4 FVC Thrusters • Regulated Pressurization • 6 Active Fuel Tanks • 2 Helium Tanks	462.7 (1020.0)	34%		• Simple system • LVA fuel could be run through FVC thrusters if required	• Heavy system • Low performing LVA thruster (monoprop)

Propulsion Module Packaging Trade Study

Trade studies can be conducted to specifically evaluate tank packaging options, as shown in Figure 4.

Figure 4: A Trade Study on Tank Packaging



Trade space on packaging trades can include:

- Various tank diameters
- Tank location and orientation
- Resonant frequency
- Types of tank mounts
- Location of tank mounts
- Risk
- Cost

Packaging trades are usually part of the higher-level, system-wide trades. Multiple iterations with customers are often required to optimize the trade results. Successful trades provide benefits to many areas within the spacecraft, including structure and plumbing.

Propellant Tank Trade Study for Proposal Support

This trade study was conducted to support a proposal effort. The equipment specification accompanying the Request for Information (RFI) was very loose and only provided enveloping requirements. To select an optimal tank design, a trade study was conducted to trade various options, including adapting existing hardware vs. developing new hardware, PMD vs. diaphragm for propellant management, various tank mounts, mass, and cost. See Table 7. The tank trade provided the customer sufficient information to finalize its equipment specification for the procurement Request for Proposal (RFP).

Table 7: Propellant Tank Trade Study

	PROPELLANT TANK					
	Requirement	Basic	Option 1	Option 2	Option 3	Option 4
		Diaphragm Tank	Diaphragm Tank	Diaphragm Tank	PMD Tank	PMD Tank
Ref PSI P/N		New	80290	80342	80491	80491
Scope		Custom build tank to meet all customer requirements	Use 80290 tank internal features, but thicken tank wall to meet pressure rating. Savings on tooling.	Use 80342 tank internal features, but thicken tank wall to meet pressure rating. Savings on tooling.	Use existing PMD and operate within the capabilities (TBD) of this PMD	New custom designed tank with new PMD
Total Hydrazine Load (ci)	854	854	854	882	854	854
Total Tank Volume (ci)	1098	1098	1080	920	1232	1232
Total Tank Volume (liter)	18	18				
Propellant Fill Fraction	78%	78%	79%	96%	69%	69%
Inside Diameter (inch)	12.8	12.8	12.8	22.1	13.33	13.33
Cylinder length (inch)						
Overall Size (diameter x length)	12.8 ID Sphere	12.8 ID Sphere	12.8 ID Sphere	22.1 ID Sphere	13.3 ID Sphere	13.3 ID Sphere
MEOP	534 psi (37 bar)	534 psi (37 bar)	396 psi --> 534 psi	480 psi --> 534 psi	300 psi --> 534 psi	300 psi --> 534 psi
Proof	812 psi (56 bar)	812 psi (56 bar)	594 psi --> 812 psi	720 psi --> 812 psi	450 psi --> 812 psi	450 psi --> 812 psi
Burst	1073 psi (74 bar)	1073 psi (74 bar)	792 psi --> 1073 psi	960 psi --> 1073 psi	620 psi --> 1073 psi	620 psi --> 1073 psi
Note						
						
Mounting	Not specified	Boss Mounted	Boss Mount	Pedestal Mount	Boss Mount	Boss Mount
Mass Each Tank (lbm)	6.6	5.0	6.6	6.5	5.0	5.5
Mass Each Tank (kg)	3.0	2.3	3.0	3.0	2.3	2.5
ROM COST		1 Q + 2F	1 Q + 2F	1 Q + 2F	1 Q + 2F	1 Q + 2F

System Packaging Trade Study

This trade study was conducted to support a system-level trade. The primary objective of the trade study was to examine a variety of tank packaging options for a launch vehicle propulsion system. Trade space included various diameters, blowdown vs. pressure regulated operation, 2-tank system vs. 4-tank system, cost, risk, tank mount, and schedule. See Table 8. This trade study helped the customer understand the cost and schedule impact of various packaging options, and assisted in the final selection of system package. During the tank analysis, it was also discovered that the mounting bracket design (provided by the customer) must be refined to withstand the dynamic loads. The finding again proved the usefulness of such trade studies.

Table 8: Propellant Tank Trade Study

	BLOWDOWN 4 Tank Configuration			PRESSURE REGULATED 4 Tank Configuration			BLOWDOWN 2 Tank Configuration			PRESSURE REGULATED 2 Tank Configuration		
	Diaphragm Tank	Diaphragm Tank	Diaphragm Tank	Diaphragm Tank	Diaphragm Tank	Diaphragm Tank	Diaphragm Tank	Diaphragm Tank	Diaphragm Tank	Diaphragm Tank	Diaphragm Tank	Diaphragm Tank
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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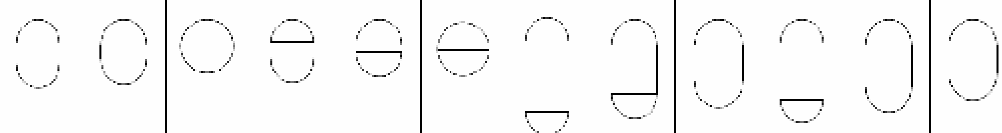
[illegible]	[illegible]	[illegible]	[illegible] Sphere	[illegible]	[illegible]	[illegible] Sphere	[illegible]	[illegible] baseline	[illegible]	[illegible]	[illegible] baseline	[illegible]

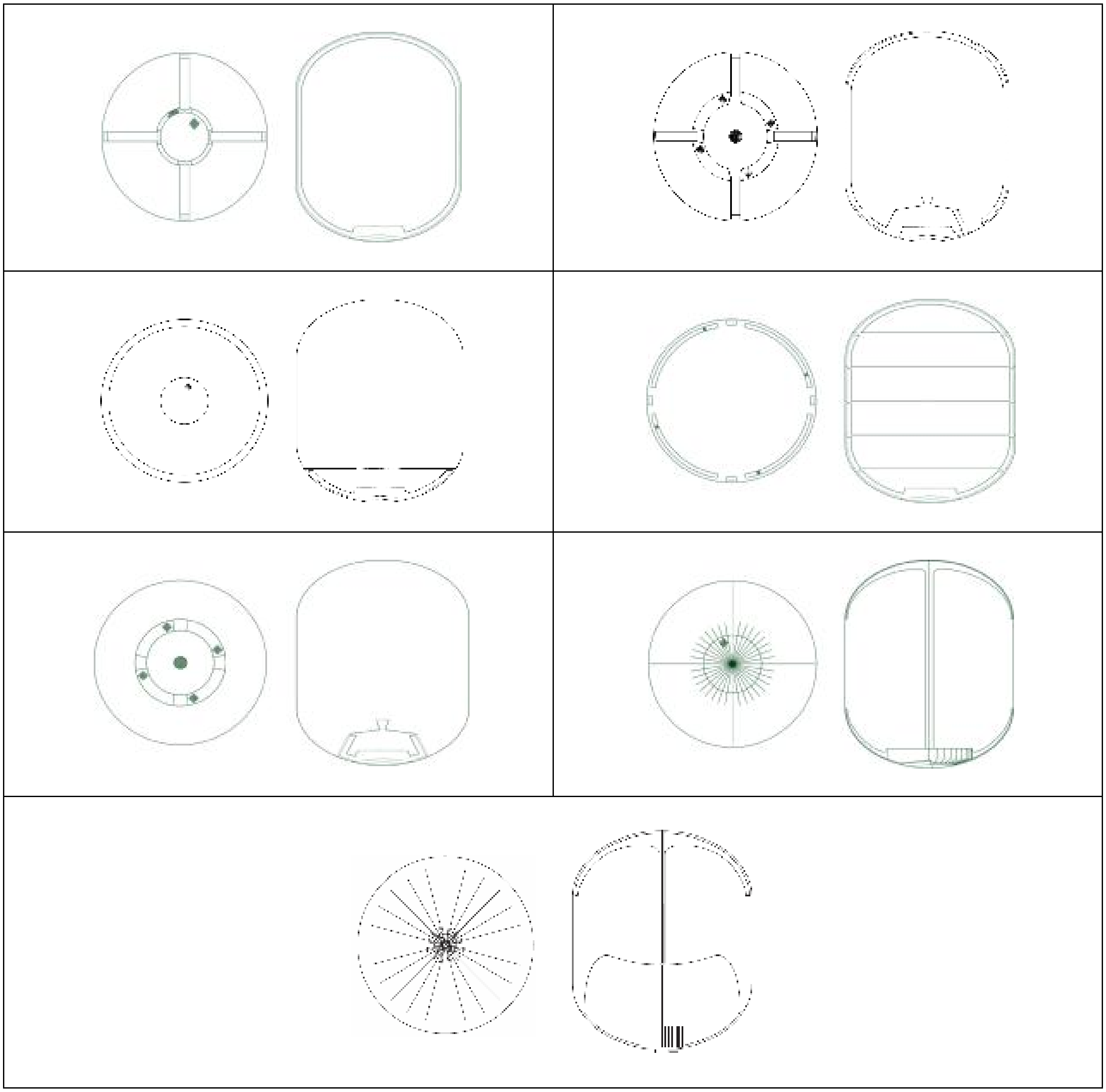


PMD Tank Trade Study

Not all trade studies are conducted for tank shells. Trade studies to determine the appropriate Propellant Management Device (PMD) configuration is very common and extremely useful. PMD trades serve the same function and purpose as the tank shell trades - to find the optimal PMD solution for a given mission. PMD trades often compliment a tank shell trade, and are always an integral part of the tank design process. Similar to tank shell trade studies, PMD trades can be conducted before or after an Equipment Specification is finalized. Many PMD trades were conducted as a service to the customer for the purposes of optimizing the PMD design and finalizing the equipment specification. Just as many PMD trades have been conducted as an integral part of the tank and PMD design process to optimize both the tank shell and the PMD design.

As in the case of tank shell trades, there can be multiple PMD solutions for a given mission. Figure 5 shows the various classical PMD elements, including vanes (6), sponges (7), traps and troughs (8), and galleries (9). Each PMD element fills a functional niche, and it is not unusual that a combination of various PMD elements is employed to meet the mission requirements. Some examples are sponge and vanes PMD (10), and trap, sponge, pickup tubes, and slosh control device PMD (11).

Figure 5: Propellant Management Device Trade Study for a Propellant Tank



The design of a PMD is usually a function of the tank shell configuration. The PMD trade is therefore an iterative process involving the tank shell and PMD designs. The tank shell must provide mounting feature or features for the installation of the PMD, and the PMD design must consider the internal features of the tank shell, such as dome contour and cylinder length. The sequence of PMD installation in the overall tank construction as well as tooling for PMD construction and installation must all be an integral part of the overall tank design. Above all, the design iterations must maintain the goal of optimizing the overall design to achieve the best overall value for the customer.

Very often PMDs must be designed to allow installation into an existing qualified tank shell. Under these circumstances the PMD must be designed with pre-existing constraints. Appropriate PMD trades can evaluate the proper PMD solution taking into consideration these pre-existing constraints to offer the optimal tank solution.

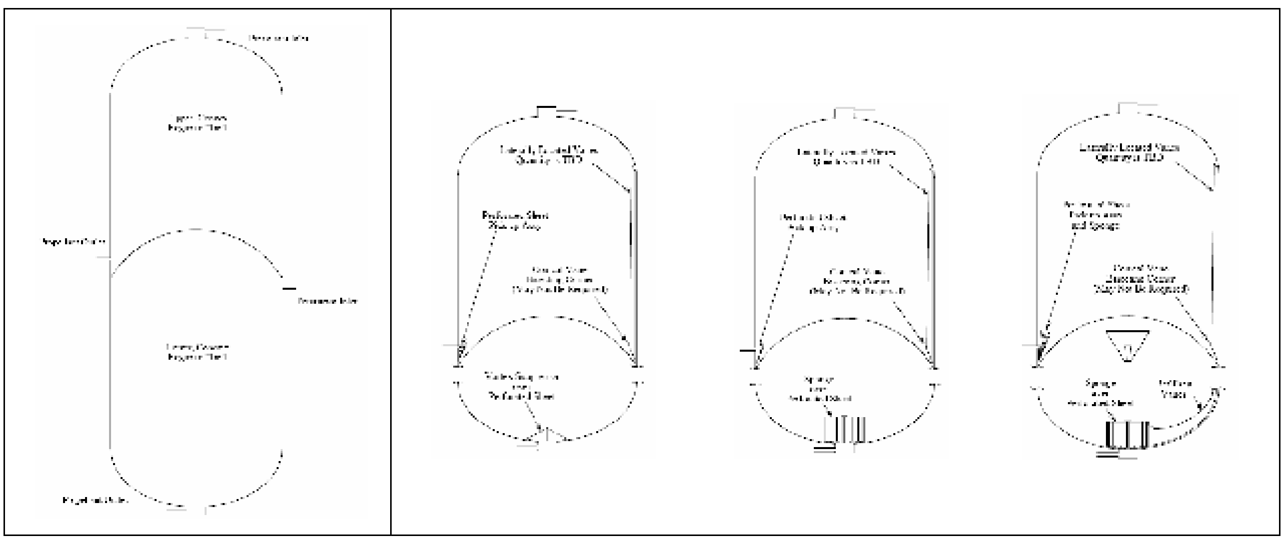
PMD design is also closely associated with spacecraft operations, and PMD trades may provide alternative operational sequences to find the optimal solution for the spacecraft. It is not unusual for a customer to accept recommendations on a slightly modified operational sequence with no impact to the overall mission but with significant improvements in the tank solution, such as lower mass, risk, and cost.

PMD trades are conducted with various objectives, such as:

1. PMD feasibility
2. PMD capabilities vs. mass, cost, or risk
3. PMD functionalities vs. mass, cost or risk

An example of a PMD feasibility trade study is a PMD trade conducted on a common bulkhead tank, as shown in Figure 6, with the various PMD options.

Figure 6: PMD Trade Study for a Common Bulkhead Tank



Unconventional Tanks Packaging Trade Study

Common bulkhead tanks and nested tanks are needed when the available envelope for tank is severely restricted [12]. Figure 7 shows examples of common bulkhead tanks, and Figure 8 provides examples of nested tanks.

Figure 7: Common Bulkhead Tanks

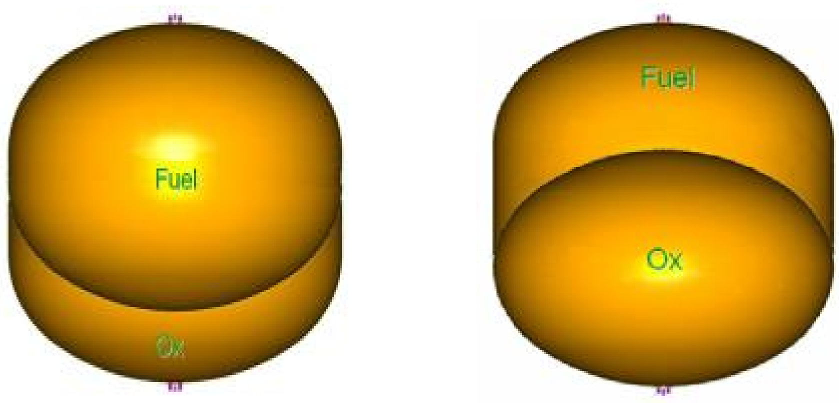
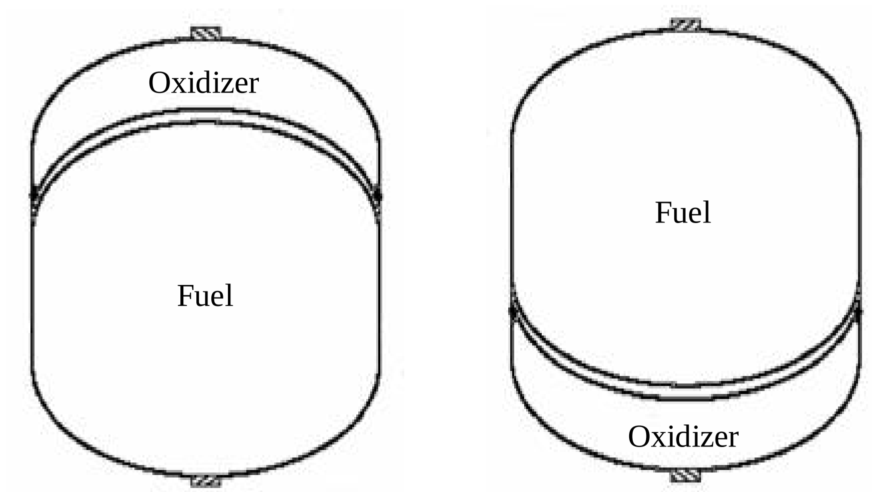


Figure 8: Nested Tanks



The design and manufacture of common bulkhead and nested tanks face similar challenges. On tank packages such as these, the optimal solution is never readily apparent and the many possible tank and PMD options must be carefully evaluated to ensure that not only the tanks are well designed, but their contributions to the spacecraft design and operations are equally optimized.

Trade space for common bulkhead and nested tanks can include:

- Dome configuration (ellipsoidal or hemispheroid)
- Bulkhead configuration (ellipsoidal or hemispheroid)
- Contour of ellipsoidal domes
- Relative location of fuel and oxidizer compartments/tanks
- Location of inlet and outlet ports for each compartment/tank
- Various PMD configurations within the two compartments/tanks
- Ground handling and ground drain feasibility
- Mounting method
- Location of tank mounts
- Construction of the common bulkhead or concave shell
- Mass and mass reduction efforts
- Propellant residuals
- Risk
- Cost

The propulsion community has great interest in, as well as great fear against, common bulkhead tanks. To make a case for or against common bulkhead tanks based on judgment and without scientific study is not sound engineering practice. It is through a properly conducted trade study that one can accurately perform technical and economic evaluations of a common bulkhead tank.

CONCLUSION

Tank trade studies are critically important in today's environment where multiple options are available for the propulsion system tank solution. While one option may offer the best tank price, and another the lowest tank mass, the optimal tank solution – the best overall value for the spacecraft – can only be found through a systematic review of all available options. A comprehensive review also provides opportunities to examine other factors, such as risk, schedule, and benefits such as launch vehicle savings. More often than not, a single-minded focus on lowest price always result in a less-than optimal tank solution for the spacecraft system. The impact of such a decision is often magnified to far greater extent than merely the cost of the tank for the satellite integrator.

Trade studies also serve another critical function – to facilitate communication between customers and tank designers. While Equipment Specification should be respected as a governing document with a collection of all requirements, the intent of these requirements are best communicated through technical and programmatic interchanges. The opportunity for such interchanges offered by the trade studies can be tremendously valuable. We have concluded many trade studies by recommending minor changes to the Equipment Specification which resulted in significant improvements on mass, schedule, risk, recurring and non-recurring prices, or best overall value. It is through these trade studies that one can learn to look beyond the requirements of a single component and focus on a system-level approach to find the best value for the satellite system.

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Mr. Don Jaekle, Jr. is the President of PMD Technology, North Andover, Massachusetts

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