Oxygen Storage Tanks Are Feasible for Mars Transit

Harry W. Jones[1]
NASA Ames Research Center, Moffett Field, CA, 94035-0001

The Mars transit tanks will probably be titanium lined, composite overwrapped pressure vessels (COPVs) similar to those used in the space shuttle and International Space Station (ISS). Since the mass of a storage tank is proportional to the mass of the gas it contains, the required oxygen will use about the same mass of tanks regardless of the number and size of the tanks. Using existing relatively small COPVs is possible. Pressure vessels can fail due to rupture and leakage but no failures have occurred in space and the expected failure rates are very low. Since one or two spare tanks are required for reliability, using smaller tanks can reduce the total mass. For a Mars round trip, the mass of oxygen and tanks including spares is roughly equal to the mass of the ISS Oxygen Generation Assembly (OGA) and its spares. Since the OGA must orbit Mars and be returned to Earth, while half the storage tanks are emptied on the way to Mars and can be abandoned, storage tanks have a significant launch mass advantage over the OGA. Storage tanks are simpler, more reliable, and have fewer failure modes than an OGA. They would have smaller design and development costs and need less crew time and maintenance. Oxygen storage tanks are feasible for Mars transit and are attractive compared to the ISS OGA.

Nomenclature

AIK	=	Airlock Installation Kit
COPV	=	Composite Overwrapped Pressure Vessel
EFA	=	External Fill Assembly
GFA	=	Ground Fill Assembly
HPGT	=	High Pressure Gas Tank
IFA	=	Internal Fill Assembly
ISS	=	International Space Station
MDP	=	Maximum Design Pressure
MPQD	=	Medium Pressure QD
NORS	=	Nitrogen Oxygen Recharge System
OGA	=	Oxygen Generation Assembly
PCA	=	Pressure Control Assembly
Pr(LOC)	=	Probability of Loss of Crew
QD	=	Quick Disconnect
RTA	=	Recharge Tank Assembly
RVA	=	RTA Valve Assembly

Mathematical symbols

M	=	mass, kg
P	=	gauge pressure, Pa
Pa	=	Pascal, kg/m-s^2
R	=	radius, m
T	=	thickness, m
V	=	volume, m^3
W	=	width, m
ρ	=	density, kg/m^3
σ	=	stress, Pa

[1] Systems Engineer, Bioengineering Branch, Mail Stop N239-8.

I. Introduction

THIS paper describes the design of oxygen storage tank systems suitable for Mars transit. The oxygen storage tank is the major component of a complete oxygen storage system for Mars transit. Filters, valves, and sensors are also needed.

The design of gas pressure vessels is described. Pressure vessels are usually spheres or cylinders with rounded end caps. Traditionally they are made of welded steel, but for light weight space applications, composite fiber is wound around a titanium metal liner, forming a composite overwrapped pressure vessel (COPV). The mass of a pressure vessel decreases with the strength of its materials and increases proportionally to the mass of the gas it contains.

Pressure vessels are designed for safety reasons to "leak before burst." Proof testing at overpressure can be used to detect flaws. Close mechanical tolerances and pressure safety factors are used to reduce the failure probability. The usual failure probability is very low, 1 in 1,000 to 1 in 100,000 per year. To ensure a safe supply of oxygen, one or two spare oxygen tanks must be provided. Providing the total required oxygen in five or ten tanks rather than in one large one does not change the total launch mass and does not significantly increase development cost.

The design of pressure vessels has advanced in five steps, all-metal, metal with overwrap in the hoop direction only, metal liner with a composite fiber overwrap (a COPV), all-composite with a polymer liner and fiber overwrap, and all-composite linerless. NASA has developed an all-composite pressure vessel, but nearly all operational NASA pressure vessels are COPVs. The NASA space shuttle orbiter had twenty-four. They were somewhat overdesigned and their effective life was estimated by accelerated test at 350 years. The ISS has thirteen different types of on-board COPVs, some in multiple copies. Orbital ATK has produced 20 different COPVs for space use. None of the shuttle, ISS, or other space COPVs has ever failed.

The most recent NASA pressure vessel development is for the International Space Station (ISS) Nitrogen Oxygen Recharge System (NORS). The NORS system design provides guidance for the design of a Mars transit oxygen storage system, but more mass efficient COPVS similar to other recent Orbital AKT products would probably be used.

II. Pressure vessel design

This section describes the design of gas pressure vessels. It includes a description, mass estimate, scaling, and materials.

The mass of a pressure vessel is proportional to the mass of the gas it contains. "No matter what shape it takes, the minimum mass of a pressure vessel scales with the pressure and volume it contains and is inversely proportional to the strength to weight ratio of the construction material." (Wikipedia, Pressure vessel) Since, according to the Ideal Gas Law, the mass of the gas within a tank is proportional to its pressure times volume divided by temperature, this means that the minimum mass of a pressure vessel is proportional to the mass of the gas it contains. (Roylance, 2001)

A. Pressure vessel description – shape, material, safety features

Pressure vessels are designed to hold gases at much higher than ambient pressures, thousands of psi. Since they are intrinsically dangerous, commercial pressure vessels are built to code and inspected. Pressure vessels are usually spheres or cylinders. The most common design is a cylinder with end caps that are hemispherical or dish shaped. (Wikipedia, Pressure vessel) (Roylance, 2001)

Many pressure vessels are made of welded steel. The steel should have high impact resistance and, if needed, be composed for corrosion resistance. Some lightweight pressure vessels are made of composite materials, such as carbon fiber held in place with a polymer. The composite material may be wound around a metal liner, forming a COPV. (Wikipedia, Composite overwrapped pressure vessel) (McLaughlan et al., 2011) Composites save launch mass for space applications.

Pressure vessels are designed to "leak before burst," so that a crack will grow through the wall and allow the gas to escape and reduce pressure, before the vessel fractures and explodes. Pressure vessels are designed to a Maximum Design Pressure (MDP) and usually have a safety valve to ensure that the maximum pressure is not exceeded. (Wikipedia, Pressure vessel) (Megyesy, 2008)

B. Pressure vessel design – tank mass `

For any shape, the mass of a pressure vessel increases directly with the pressure and volume it contains and is inversely proportional to the strength to weight ratio of its construction material. For a cylinder with hemispherical ends, the minimum mass of the pressure vessel is

$M = 2 \pi R^2 (R + W) P \rho/\sigma$

M is the minimum pressure vessel mass (kg), R is the cylinder radius (m), W is the cylinder width (m), P is the gauge pressure above ambient (Pa), ρ is the density of the pressure vessel material (kg/m^3), and σ is the maximum working stress that the material can tolerate, (Pa). The term σ/ρ is the strength to weight ratio of the pressure vessel's material. The Pascal, Pa, is used to measure pressure, stress, and ultimate tensile strength. A Pascal is $kg/m\text{-}s^2$ in SI base units. (Wikipedia, Pressure vessel) (fxsolver, Mass+) (One standard atmosphere, 14.7 psi, is equal to 101.3 kPa.)

The derivation of this formula for the mass of a cylindrical pressure vessel provides some additional insight.

M = cylinder material volume * ρ, where ρ is the density of the pressure vessel material.

M = surface area * thickness * ρ

The walls of a cylindrical pressure vessel experience different stresses and therefore are designed to have different thickness.

The stress in a spherical pressure vessel is:

σ sphere = P R/2T, where T is the thickness of the wall (m).

This result is obtained by setting the internal force, the pressure times the internal area, $P \pi R^2$, equal to the resisting force, the wall stress times wall cross sectional area, σ sphere 2 π R T.

The stresses in a cylinder wall of a cylindrical pressure vessel are:

σ hoop = P R /T, measured around the circumference of the cylinder, and,

σ long = P R /2T, measured down the length of the cylinder. (Wikipedia, Pressure vessel)

Note that the cylinder hoop stress is twice the cylinder axial stress and also twice the hemispherical end cap spherical stress. To equalize the stresses at the joint of the cylinder and the hemispherical end caps, the cylinder walls are made twice as thick as the hemispherical cap walls. (Wikipedia, Pressure vessel) (Roylance, 2001) (Megyesy, 2008)

T sphere = P R /2 σ

T cylinder = P R/σ

Note that the wall thickness is proportional to the cylinder radius. Thus the mass is

M = spherical surface area * spherical wall thickness * ρ + cylinder surface area * cylinder wall thickness * ρ

$M = 4 \pi R^2 * T_{sphere} * \rho + 2 \pi R W * 2 T_{sphere} * \rho = 4 \pi R * (R + W) * T_{sphere} * \rho$

$M = 4 \pi R^2 * P R/2 \sigma * \rho + 2 \pi R W * P R/\sigma * \rho = 2 \pi R^2 (R + W) P \rho/\sigma$

This formula applies to thin walled cylinders, R > 10 or 20 T. For steel cylinders, the cylinder walls are often made thicker to reduce deformation at the joints. (Roylance, 2001)

C. Pressure vessel design – gas and tank mass and scaling

"No matter what shape it takes, the minimum mass of a pressure vessel scales with the pressure and volume it contains and is inversely proportional to the strength to weight ratio of the construction material." (Wikipedia, Pressure vessel) If the temperature is constant, a fixed pressure and volume implies a fixed mass of gas, so the mass of the tank is proportional to the mass of gas stored.

The ideal gas equation is:

P V = n R T, where n is the number of moles of gas and a mole is the mass equal to the atomic weight in grams, R is the ideal gas constant in units of liters kPa/moles K, and T here is the temperature in Kelvin (K).

The mass of gas in a tank is:

Mgas = n * atomic weight = P V/R T * atomic weight

At a fixed temperature and pressure, the mass of gas in a tank is directly proportional to the tank volume.

The volume of a cylindrical tank with hemispherical ends is

$V = 4/3\ \pi\ R^3 + \pi\ R^2\ W = \pi\ R^2\ (4/3\ R + W)$, where V is volume.

The mass of a cylindrical tank with hemispherical ends is

$Mtank = 2\ \pi\ R^2\ (R + W)\ P\ \rho/\sigma$

$Mgas \sim \pi\ R^2\ (4/3\ R + W)$,

Mgas has a factor of 4/3 R + W rather than the R + W in Mtank, but W > R and tank mass should scale quite closely with the mass of gas the tank contains.

The mass of a pressure vessel is closely proportional to the mass of the gas it contains. The mass efficiency of gas storage, measured as the mass of the gas stored divided by the mass of the gas plus the storage tank, is roughly constant for different size tanks of the same shape. There are no economies of scale for increasing pressure or for increasing tank mass to stored gas mass. For storing gases, "tankage efficiency" is independent of pressure at a given temperature. Colder temperatures would allow greater stored gas mass. (Wikipedia, Pressure vessel)

D. Pressure vessel material – steel or composite

Most commercial tanks are made of steel. To manufacture a cylindrical tank with hemispherical ends, rolled parts must be welded together, and the welding must be done carefully. The steel must have high strength and a high impact resistance, especially for low temperatures. Special alloy steel should be used where ordinary carbon steel would corrode. Thicker walls and higher mass may be used to reduce deformation at the end joints. (Wikipedia, Pressure vessel)

If low tank mass is required, such as in space, the pressure vessels can be made of layered light weight composite materials, often with a metal liner. They can be reinforced using high tensile strength carbon fiber held in place with a polymer. The fiber can be oriented to counter the different cylinder wall stresses. An infinitely long cylinder would be wound at an optimal winding angle of 54.7 degrees, as this gives the necessary double strength in the circular hoop direction compared to that in the length direction. Fiber wound composite material tanks can be very light, but are much more difficult to manufacture. (Wikipedia, Pressure vessel)

III. Pressure vessel failures, reliability, and cost

Failures of pressure vessels are unusual, but pressure vessels are so common that many failures have occurred and been analyzed. This section discusses the pressure vessel failure modes and causes, failure prevention, and historical failure rates. Cost is also discussed.

A. Pressure vessel failure modes and causes

Pressure vessels can fail to hold their contained gases either by a slow leak or a sudden rupture. They sometimes experience slow deformation or degradation that can lead to failure. Some pressure vessel failure modes are shown in Table 1.

Table 1. Pressure vessel failure modes. (Simonen, 2002)

Severity	Failure mode
Major failures	Fracture/catastrophic rupture
	Excessive leakage
Minor problems and warnings	Leaking through cracks
	Wall corrosion and thinning
	Tank deformation
	Small cracks

The failure modes are listed in order of decreasing severity and increasing likelihood. Small cracks are much more common than major leaks or ruptures. However, in long term installations, a minor degradation such as small cracks can progress to leakage through cracks and ultimately even to a catastrophic failure. (Simonen, 2002) Table 2 shows possible pressure vessel failure causes.

Table 2. Pressure vessel failure causes. (Simonen, 2002)

Failure cause	Sudden	Long term
Pressure over design limit	x	
Temperature over design limit	x	
Temperature below brittle fracture limit	x	
Improper design and fabrication	x	
Improper operation, repair, and maintenance	x	
External event damage	x	
Excessive vibration	x	x
Material or welding defects	x	x
Corrosion		x
Wear		x
Thermal fatigue cracking		x
Vibration fatigue cracking		x
Stress corrosion cracking		x
High-temperature creep		x
Long-term embrittlement		x

Some failure causes can occur suddenly, in response to some event. These include overpressure, extreme overheating, external events such as earthquakes, and human errors such as improper design and fabrication including material or welding defects and also improper operation, repair, and maintenance. (Simonen, 2002) (TWI, 2016)

Other failure modes only occur after a long period of time in service, such as corrosion, wear, fatigue cracking, stress corrosion cracking, creep, and hydrogen embrittlement. Years can go by before a leak or rupture. Metal fatigue is common. Small-diameter piping is often subject to vibrational that causes cracking. Large vessels can suffer fatigue due to cyclic thermal stresses due to hot and cold flows. Corrosion is also common and causes wall thinning, pitting, and cracking. (Simonen, 2002) (TWI, 2016)

B. Pressure vessel failure prevention

Most sudden failures can be prevented by ensuring proper design, fabrication, inspection, operation, repair, and maintenance. Good engineering procedures should be used, possibly following a recognized code. The approach is to ensure adequate material strength, to prevent high stress, to stress relieve by post-weld heat-treatment, to fabricate using qualified welders and procedures, to inspect to minimize the number of defects, and finally to proof test. (TWI, 2016)

Proof testing is the traditional method to demonstrate that pressure vessels do not contain flaws that can cause catastrophic failure. The vessel is pressurized with water to more than the maximum service stress, and if the component survives it is expected to be safe. (TWI, 2016)

Proof testing does not take account of any crack growth during the service life of the component. Long term failures can be due to cyclic stresses or environmental conditions, causing fatigue or corrosion. Cracking can be monitored and inspection results used to predict greater or lesser reliability than previously expected. (TWI, 2016)

C. Stress induced failures and failure prediction theory

A pressure vessel can be expected to fail when the load or induced stress is greater than the material strength, measured in terms of the allowable stress. A tank material such as steel under increasing stress will first deform elastically but still be able to return to its original shape when the applied stress is removed. Greater stress beyond the yield point will cause the material to deform plastically. If plasticity occurs over a full load bearing area, collapse occurs. If the load stress exceeds the tensile strength of the material, the material will fail by breaking or rupturing. If lesser loads are applied for many cycles, a failure may occur due to fatigue. Sustained loads at low temperatures could result in brittle fracture. (Arnold, 1972) (Chattopadhyay, 2005)

These failures in pressure vessels are stress dependent. For high reliability, the induced stress level must be maintained below the allowable material stress level. The induced stress level must be less than the allowable level for all the relevant failure modes, such as plastic collapse, rupture, fatigue, and brittle fracture. For a given pressure vessel shape and content, the induced stress level in the walls can be reduced by increasing the shell thickness and vessel mass. (Arnold, 1972) (Chattopadhyay, 2005)

The typical industrial design process required by code is to assign a safety factor so that the induced stress level is some fraction of the allowable material stress level. For example, the ASME Code requires that the allowable stress intensity should not be higher than two-thirds of the minimum specified yield strength of the material or one-third of the minimum specified ultimate tensile strength of the material. (Arnold, 1972) (Chattopadhyay, 2005) In a cylindrical pressure vessel, the hoop stress is the highest stress. The shear stress, the difference between opposing stresses, is also important. Failure is governed by the combination of all stress components. (Arnold, 1972) (Chattopadhyay, 2005)

A theoretical model can be used to predict failure probability, but calibrating it would be difficult. The probability of failure is roughly the probability that an induced stress will exceed the allowable stress. Probability distributions can be constructed for both the induced stress and the allowable stress. The hoop stress can be determined as the function of the pressure and the geometry of the vessel. The expected variations in pressure and dimensions determine the probability distribution of the induced stress. The distribution functions of yield strength and ultimate tensile strength can be measured and are typically normal. "In practice, the radius and shell thickness of a pressure vessel are held to rather close tolerances (about 2%) when compared with the expected variation in loads and material strengths (about 15%)." (Arnold, 1972) In practice, the safety factors are much larger than the expected variations in stresses and the usual failure probability is very low.

D. Pressure vessel failure rates

Lees has extensive material on pressure vessel design and he describes many failure rate surveys. Smith and Warwick found 229 potentially dangerous failures, including 206 cracks, and 13 catastrophic failures in 20,000 high quality vessels over 310,000 vessel-years, corresponding to failure rates of $7.4 * 10^{-4}$ and $4.2 * 10^{-5}$ per year. Other surveys of 100,000's of vessel years found no catastrophic failures, indicating that the catastrophic failure rate is less than 1 in 100,000, $1 * 10^{-5}$, per year. Davenport surveyed 360,000 mostly thin walled lower quality pressure vessels over $1.8 * 10^{6}$ vessel years and found 60 cracks in 92 total failures, a total failure rate of $5 * 10^{-5}$ per year. In general hazard assessments, values of 10^{-6}, 10^{-5}, and 10^{-4} failures per year are typically used respectively for catastrophic failure, leakage, and worst case. (Lees, 2012)

The Flemish Government has provided a summary and analysis of the Smith and Warwick pressure vessel failure survey. The 229 failures included 216 cracks due to split propagation, 5 defects before delivery, 1 corrosion, 3 malfunction and human error, 3 creep, and 1 unverified. The 216 splits included 52 due to material fatigue, 30 corrosion, 63 manufacturing defects, 61 unknown, and 10 miscellaneous. The most significant failures occurred during the first years of operation. Because of the large data set the overall failure rate of $7.4 * 10^{-4}$ has a very narrow 99% confidence interval of $6.2 * 10^{-4}$ to $8.7 * 10^{-4}$. (Flemish Government, 2009)

E. Pressure vessel costs

Pressure vessels are commonly used and cost estimates can be obtained from on-line calculators, commercial software, and a cost estimating relation given below. The cost of a pressure vessel increases as some fractional power of its mass. For a given material and shape, such as carbon steel in a cylinder with hemispherical ends, the internal pressure and dimensions determine the required shell thickness and the total pressure vessel mass.

A chemical encyclopedia article reports the pressure vessel cost estimating relations developed for use in ASPEN and widely used in the industry. (Mulet et al., 1993) ASPEN's material and energy balance calculations can be used to size equipment and estimate capital and operating costs. Cost data was gathered for shop fabricated pressure vessels built to code. The vessel cost correlated well with the shell weight and total weight including nozzles, man holes, and supports. For a given material, assumed to be carbon steel for the base vessel, the vessel shell weight can be calculated from the diameter, length, and pressure. Adjustments are applied for other materials.

The cost of a horizontal pressure vessel is

$$\text{Cost} = \exp\,[8.114 - 0.16449 \ln M + 0.04333 (\ln M)^2]$$

The formula applies to steel tanks from one thousand to one million pounds. M is mass in kg. The standard deviation of the cost was 8.7% and the estimator is close to the data. Cost adjustments are available for other materials. (Mulet et al., 1993)

Since the cost of a pressure vessel increases more slowly than the mass of the tank and the mass of the gas stored, storing a given amount of gas in several tanks is more expensive than one big tank. This is shown in Table 3.

Table 3. The cost of storing a fixed amount of gas in N or N + 1 tanks.

N, number of tanks	Normalized cost for 1	Normalized cost for N	Normalized cost for N + 1
1	1.00	1.00	2.00
2	0.60	1.19	1.79
3	0.45	1.35	1.80
4	0.37	1.49	1.86
5	0.32	1.61	1.93
6	0.29	1.73	2.01
10	0.21	2.12	2.33
15	0.17	2.54	2.71
20	0.15	2.91	3.06

Since the mass of a tank is proportional to the mass of the gas it contains, 20 small tanks weigh roughly as much as one full size one containing the same gas. However, the cost of a smaller tank does not decrease as rapidly as its mass, per the formula, so the 20 small tanks cost 2.91 times as much as the one full size tank. However, adding one full size spare doubles the cost, while adding one spare to five or six smaller ones is a one-fifth or one-sixth cost increase and the total cost is no more than two full size tanks. The cost of a larger number of tanks would be further reduced if the learning curve reduction in cost is also considered. And the cost of developing the tanks is likely to be small compared to the cost of launching the tanks and the mass they contain into space. This suggests that the number of tanks can be optimized considering reliability and operations as more important than launch mass or development cost. However, developing a new tank larger than those now available could have much larger costs for design, tooling, and manufacturing than using currently available smaller tanks.

IV. Pressure vessel types

Pressure vessels have been classified using five categories or types based on their construction. Each higher type is more advanced, lighter, and more expensive. (LeGault, 2012)

Type I pressure vessels have all-metal construction, usually carbon steel, and are widely available. Commercial code Type I vessels are inexpensive, costing about five dollars per liter of volume. Type I vessels are the heaviest, weighing approximately 1.4 kg/liter.

Type II pressure vessels are typically steel or aluminum with a glass-fiber composite overwrap in the hoop direction. "The metal vessel and composite materials share about equal structural loads. Type II vessels cost about 50 percent more to manufacture than Type I vessels, but they weigh 30 to 40 percent less." (LeGault, 2012)

Type III vessels are COPVs. They have a metal liner, usually aluminum but titanium for space, with a full carbon fiber or other composite overwrap. The composite wrap carries the structural load.

Type IV vessels are all-composite, featuring a polymer liner, typically high-density polyethylene, with carbon fiber or hybrid carbon/glass composite fiber.

Type III and Type IV vessels reduce mass further than Type II vessels, to 0.3 to 0.45 kg/liter. The cost of Type III and Type IV vessels is about two times greater than Type II vessels and 3.5 times greater than the all-metal Type I tanks. Composite vessels have higher corrosion resistance, fatigue resistance, service life, and overall safety. For high-pressure applications to 5,000 psi or higher, Type III and Type IV vessels usually are the most practical solution. Type III and Type IV pressure vessels can remain in use for up to 30 years before replacement, twice the time allowed for Type I and Type II vessels. (LeGault, 2012)

Type V vessels are all-composite and linerless. The “Type V tank has been the pressure vessel industry’s holy grail for years.” (Composites World, 2014) Recently a Type V tank was designed, built, tested, and flown for gas storage on a student satellite. The 1.9 liter tank weighed only 0.2 kg. It was carbon fiber and epoxy resin. “It had an operational pressure of 200 psi, a proof pressure of 1,000 psi, and a burst pressure between 2,000 and 2,500 psi.” (Composites World, 2014) Linerless tanks are expected to be 15 to 20 percent lighter than the nearest Type IV equivalents. (LeGault, 2012)

NASA has developed and tested a Type V propellant tank for cryogenic liquid hydrogen.

> “In 2013, The National Aeronautics and Space Admin. (NASA, Washington, D.C.) announced on July 2 that it recently completed a major space technology development milestone by successfully testing a large, pressurized cryogenic propellant tank made of composite materials. The almost 8-ft/2.4m diameter composite tank will hold cryogenic propellants (gasses chilled to subfreezing temperatures and condensed to form highly combustible liquids) critical to future long-term human exploration missions beyond low-Earth orbit. In the past, propellant tanks have been fabricated from metals. Switching from metallic to composite construction holds the potential to dramatically increase the performance of future space systems through a dramatic reduction in weight. A potential initial target application for the composite technology is an upgrade to the upper stage of NASA’s Space Launch System (SLS) heavy-lift rocket.” (Composites World, 2014)

V. Composite overwrapped pressure vessels (COPVs)

A composite overwrapped pressure vessel (COPV) has a very thin, impermeable liner wrapped with load bearing fibers held in a matrix. The liner does not support load or pressure but prevents leaks through microcracks in the matrix. A shell can be used to protect against impact damage. The fibers, usually carbon and kevlar, are wrapped around the liner and embedded in a polymer matrix. COPVs have lower weight than metallic pressure vessels but are more expensive and difficult to design. (Wikipedia, Composite overwrapped pressure vessel)

COPVs have been used in aerospace applications for decades and are considered safe and cost effective. “COPVs are currently used at NASA to contain high-pressure fluids in propulsion, science experiments and life support applications. These COPVs have a significant weight advantage over all-metal vessels; but, as compared to all-metal vessels, COPVs require unique design, manufacturing, and test requirements.” (McLaughlan et al., 2011)

A. COPV design

The composite in a COPV is formed of structural fibers and a resin that are overwrapped on a liner. Long fibers provide tensile strength and the resin holds the fibers and carries the shear loads. This composite is applied over an interior liner of rubber, plastic, or thin ductile metal. The fiber and wet resin are wrapped on the liner to form the composite structure. The liner prevents leaks and usually provides little structural support, but some are load-sharing. “On most ISS and Shuttle COPVs, the vessel liner is substantial and serves as a partial structural element by carrying a portion of the pressure load.” (McLaughlan et al., 2011)

Both metal vessels and COPVs are used for weight limited rocket and spacecraft applications. Typically, a COPV will have approximately one-half the weight of a comparable metal tank. A heavier all-metal vessel usually has a more straightforward design, lower manufacturing cost, and well understood verification of fracture control by analysis. “(E)ach application of a pressure vessel should have a mass, performance, cost and risk trade.” (McLaughlan et al., 2011)

COPV design includes analysis of the liner, the fiber overwrap, and their interaction. The liner may be of ductile aluminum, with no load-sharing, or steel, titanium, or cryogenic stainless steel for a load-sharing. Plastic-lined COPVs can save weight. The fiber is generally applied as a ribbon of multiple fibers that passes through a bath for resin application and is wound on the liner. Cylindrical vessels are wound in both the longitudinal and circumferential or hoop directions. In a process called autofretage, the COPV is pressurized above the liner yield strength, causing it to permanently expand and induce stress in the fiber composite and compressive strain in the liner. This improves the cycle life performance of the liner. (McLaughlan et al., 2011)

The COPV factors of safety should be higher than for metal vessels to compensate for design unknowns, manufacturing variability, and less conclusive inspection and test. Factors of safety should also be adjusted according to usage, which can vary from single-pressurization, brief, low risk orbital missions to long-term critical applications requiring many pressurization cycles. (McLaughlan et al., 2011)

B. COPV failure modes

COPVs have different failure modes than metal vessels, and the failures are less well understood and manageable. It is difficult to predict the expected failure mode due to the interaction between the liner and the fiber-matrix composite. The overpressure testing used to detect flaws in metal vessels is generally not applicable to

COPVs. Composites may fail due to stress rupture or static fatigue after a long time at operating pressure. Surface impacts and even minor surface damage can reduce the burst strength of carbon fiber composites, but kevlar is more damage tolerant. (McLaughlan et al., 2011)

The four major potential COPV failure modes are:

1) Burst from over-pressurization. The pressurization source must be controlled.

2) Fatigue failure of the liner. The design should ensure an adequate number of pressure cycles.

3) Burst resulting from damage. Protection from handling damage is needed.

4) Stress rupture of the composite overwrap. Stress rupture occurs when the composite degrades over time and the vessel suddenly bursts, possibly causing injury and damage. (McLaughlan et al., 2011)

"Pressure, duration of time at pressure, and temperature experienced contribute to the degradation of the fiber and/or the fiber-matrix interface, particularly around accumulations of fiber breaks, and these increase the probability of COPV stress rupture." (McLaughlan et al., 2011)

VI. NASA shuttle COPVs

The NASA space shuttle orbiter has twenty-four internal Kevlar COPVs, six 26 inch COPVs for nitrogen for life support and eighteen 19, 20, and 40 inch COPVs for helium for maneuvering and propulsion. These were designed in the 1970s and built during the late 1970's and into the early 1980's. The shuttle COPVs have operated reliably but with some concerns. (McLaughlan et al., 2011) (Kezirian, 2010) Newer NASA COPVs have carbon/epoxy overwraps. (Thesken et al., 2009) The space shuttle uses some metallic tanks. Eighteen tanks store liquid oxygen for atmosphere and liquid oxygen and liquid hydrogen for propulsion and fuel cells.

A. Shuttle COPV description

When the space shuttle COPVs were designed in the 1970's, COPVs were new and the design approaches for metal vessels were still used. The design included a load-sharing metal liner. The composite wrap was considered to be a highly reliable supplement to the metal liner performance. The load sharing between the metal liner and the overwrap was poorly understood. "The factor-of-safety margins, development testing, burst test articles, manufacturing inspections, and acceptance procedures did not fully address the unique, and generally unknown, composite characteristics." (McLaughlan et al., 2011)

The shuttle COPVs have titanium liners, 0.104 inch thick, and titanium bosses. The composite overwrap is Kevlar49 fiber in epoxy, 0.739 inch thick. The composite carries seventy or eighty percent of the load at the operating pressure. Using the 24 Kevlar COPVs saved approximately 752 pounds on each shuttle compared to an all metal tank design. (Kezirian, 2010)

The design requirement for the liner was "leak before burst," so that if a crack occurs it would grow slowly enough for the gas to gradually escape. Tanks were pressure cycled to confirm this. (Kezirian et al., 2011)

B. Shuttle COPV reliability

The major concern in space shuttle COPV performance has been the expected time to stress rupture failure. A stress rupture is a sudden and catastrophic failure of the overwrap after holding pressure at a stress level below the ultimate strength over an extended time. Currently there is no simple method of determining the stress rupture life of a COPV, nor is there a screening technique to determine if a particular COPV is close to the time of a stress rupture failure. (Russell et al., 2010) A stress rupture failure could be catastrophic. Despite this concern, shuttle experience, analysis, and test have all indicated excellent reliability. "To date, there have been zero stress rupture failures of COPVs in NASA spaceflight applications." (McLaughlan et al., 2011)

Specifically, the stress rupture life of NASA's kevlar fiber COPVs was a concern due to their long usage and the lack of understanding of stress rupture in kevlar fibers. The data show that the rupture process is a function of stress, temperature, and time. However due to the load sharing liner, the manufacturing induced stresses, and the design details, the actual fiber stress was not clearly known. (Thesken et al., 2009)

After the Columbia accident, shuttle engineers reexamined the COPV flight certification. The initial estimate of the probability of a catastrophic failure was one in five through STS-107. Replacing all existing flight COPVs was considered unfeasible. Two COPVs identified as high risk were replaced. Improvements were made in ground procedures to reduce risk. Pressure loading was done in stages to reduce temperature. The maximum load was reduced when possible. The reliability model was updated using a Kevlar database and a flight vessel burst test, which had a lower than expected burst pressure. The reliability was estimated at 0.998 for the planned remaining flights of the shuttle program, STS-118 through STS-135. (Kezirian et al., 2011) The stress rupture reliability model predicted that each shuttle was flying with a tank reliability of greater than 0.999 per flight. (Russell et al., 2010)

Additional confidence was gained by an accelerated stress rupture test that was performed on one of the high risk tanks removed from a shuttle. Phase I was conducted at flight pressure, 4,850 psi, with age accelerated at 130°F, out to 38,000 total effective hours. The reliability model predicted a 50% chance of failure but the tank passed with no issues. Phase II was conducted at flight pressure and 160°F to 87,000 total effective hours. The reliability model predicted a 95% chance of failure but none occurred. Phase III included an increase in pressure above flight limits to 5,200 psi and age acceleration at 160°F to 113,000 total effective hours. The model predicted a 99% chance of tank failure but the tank performed well. The last phase IV was performed at a higher pressure and temperature of 5,400 psi and 174°F. The COPV tank finally failed after accumulating a total of 3,100,000 effective hours, roughly 350 years. And this was for one of the two flown tanks that were removed because they had expected high risk. "(T)he model was shown to have significant conservatism." "Test was first experimental determination of tank lifetime (industry wide)." "Test of a Flight article (exposed to space environments) proves no missed physics (confirms analysis)." (Gebhardt, 2010) (Russell et al., 2010)

VII. International Space Station (ISS) on board COPVs

The International Space Station (ISS) has many pressure vessels used to store oxygen and other gases. The High Pressure Gas Tanks (HPGTs) store oxygen and nitrogen to maintain the atmosphere. The Nitrogen Tank Assemblies (NTAs) store nitrogen for thermal control. Eleven smaller Composite Overwrapped Pressure Vessels (COPVs) store various gases. The ISS on-board COPVs are shown in Table 4.

Table 4. International Space Station (ISS) on-board COPVs. (Kezirian, 2010)

System	Diameter, in	Gas	Volume, in^3	Maximum operating pressure, psig
HPGT	37.89	Oxygen, nitrogen	26,093	3,400
NTA	45 L x 19.7	Nitrogen	12,000	3,000
PCU	15.37	Xenon	1,680	3,000
SAFER	9 L x 6	Nitrogen	170	10,000
VGA	7.22 L x 3.55	Air	44.6	3,000
GBA	17.1 L x 8.5	Argon	655	3,000
AMS	15.37	Xenon	1,680	3,000
AMS	12.4	Carbon dioxide	813	3,200
AMS	21.7 L x 6.6	Helium	505	3,538
VCAM	8.1 L x 3.68	Helium	47.8	2,150
GBU	9.8	Argon	467	2,630
GBU	9.8	Helium	467	2,630
GBU	9.8	Carbon dioxide	467	2,630

Table 4 only nomenclature.
AMS = Alpha Magnetic Spectrometer
GBA = Gas Bottle Assembly
GBU = Gas bottle Unit
NTA = Nitrogen Tank Assembly
PCU = Plasma Contactor Unit
SAFER = Simplified Aid for Extravehicular Activity Rescue.
VCAM = Vehicle Cabin
VGA = Verification Gas Assembly

None of the COPV tanks has experienced a stress rupture failure so far in the history of ISS. (Groome, 2012)

A. High Pressure Gas Tanks (HPGTs) and Nitrogen Tank Assemblies (NTAs)

The HPGTs are located near the airlock. There are two oxygen HPGTs and two nitrogen HPGTs with one oxygen and one nitrogen on-orbit spare. Nitrogen is also stored in the external Thermal Control System in two Nitrogen Tank Assemblies (NTAs) located on two different trusses. (Dick, 2011-5226) (Dick et al., 2009-01-2413)

The oxygen HPGTs have a maximum design pressure of 3,000 psia, but are normally pressurized to 2,400 psia maximum. A full oxygen tank has approximately 94.3 kg of oxygen. The nitrogen HPGTs have a maximum design pressure of 3,400 psia, but are also normally pressurized to 2,400 psia maximum. A full nitrogen tank has approximately 84.4 kg of nitrogen. (Dick et al., 2009-01-2413) The HPGTs weigh 544 kg, empty. (Carrasquillo et al., 1997) The HPGT mass and efficiency are shown in Table 5.

Table 5. HPGT mass and efficiency.

System	Dry mass, kg	Gas mass, kg	Mass efficiency = gas/total	Mass multiple = total/gas
HPGT, oxygen	544	94.3	0.148	6.77
HPGT, nitrogen	544	84.4	0.134	7.45

VIII. Orbital ATK COPVs

The ISS COPVs were made by Orbital ATK, as have been most other space COPVs. An on-line data sheet describes 20 different COPVs. Table 6 shows some of the Orbital ATK COPVs.

Table 6. Orbital ATK COPVs. (Orbital-ATK data sheet, 2016)

Tank mass, kg	Volume, liters	Operating pressure, psi	Oxygen mass, kg	Mass efficiency = gas/total	Mass multiple = total/gas
6.4	32.1	2,500	7.3	0.53	1.88
7.0	50.0	2,176	9.9	0.58	1.71
10.0	67.3	4,500	27.4	0.73	1.36
10.5	67.3	4,500	27.4	0.72	1.38
10.7	67.3	4,500	27.4	0.72	1.39
12.2	54.1	2,875	14.1	0.54	1.87
12.7	81.4	4,800	35.4	0.74	1.36
16.8	87.0	4,496	35.5	0.68	1.47
19.1	119.7	2,875	31.2	0.62	1.61
20.4	132.8	2,875	34.6	0.63	1.59

There are only 10 entries because similar items have been combined. For all the COPVs, the mass efficiency averages 0.65 and the mass multiple 1.56. The higher pressure COPVs, 4,500 psi or near, have a mass efficiency of about 0.72 and a mass multiple of about 1.38. The least efficient higher pressure COPV, with mass efficiency of 0.68 and mass multiple of 1.47, is heavier and stronger than the others with higher proof pressure and higher burst pressure. Since the mass of gas in a tank is proportional to pressure, increasing pressure increases the mass contained. The least efficient higher pressure COPV is essentially equivalent to the others. The best Orbital ATK COPV is roughly two times more mass efficient than the NORS COPVs described below.

The best existing Orbital AKT COPV design for Mars transit would be the one with 12.7 kg tank mass and 35.4 kg of oxygen contained. It has the highest efficiency, 0.74, and lowest mass multiple, 1.36.

The Orbital ATK COPVs can be expected to be very reliable.

> "Orbital ATK is the world's leading producer of titanium propellant tanks used in military, scientific and commercial satellites, space-launch vehicles, and space-exploration vehicles ... The tanks have been a part of nearly every large U.S. launch vehicle and geosynchronous earth-orbit satellite, with 100 percent reliability. Orbital ATK propellant tanks have landed on Mars, Venus and the Moon, and have visited every planet in the solar system. They have been an integral part of nearly every major space-exploration vehicle, including Cassini, Mariner, Pioneer and Voyager." (Orbital-ATK, Propellant Tanks, 2016)

IX. International Space Station (ISS) Nitrogen Oxygen Recharge System (NORS)

The Nitrogen Oxygen Recharge System (NORS) is used to transport oxygen and nitrogen to ISS. The NORS tank is a COPV contained in the Recharge Tank Assembly (RTA).

A. NORS design specifications

The NORS COPV design specifications are given in Table 7.

Table 7. NORS COPV design specifications. (Kezirian et al, 2012)

Specification	Value
Maximum design pressure	7,000 psia
Working fill pressure	6,000 psia (41.4 MPa)
Minimum volume	2.43 cu ft (68.8 L)
Maximum empty weight	104 lbm (47.2 kg)
Maximum envelope	31" L x 18.5" D

The NORS COPV tank is designed and manufactured by Orbital ATK. The COPV is designed to hold approximately 27.2 kg (60 lbm) of nitrogen or 36.3 kg (80 lbm) of oxygen. (Dick, 2011-5226) The COPV has a metal liner and carbon-composite overwrap. Some actual values differ from the design plan. The COPV is a cylindrical tank with an actual volume of approximately 2.68 cubic feet (75.9 L). (Dick and Griffin, 2012-3614) The RTAs are filled with 38.1 kg (84 lbm) of oxygen or 28.6 kg (63 lbm) nitrogen. The RTAs also contain a valve assembly with a high pressure quick disconnect, isolation valve, vent valve to enable venting of the quick disconnect to cabin before mate/demate, and a rough pressure gauge. (Schaezler and Cook, 2015)

The best current values for RTA dry mass and content mass are 55.5 kg empty, 38.3 kg of oxygen, and 28.7, kg of nitrogen. (Duchesne, 2016) The NORS mass and mass efficiency are shown in Table 8.

Table 8. NORS mass and mass efficiency.

System	Dry mass, kg	Gas mass, kg	Mass efficiency = gas/total	Mass multiple = total/gas
RTA, oxygen	55.5	38.3	0.41	2.45
RTA, nitrogen	55.5	28.7	0.34	2.93

The NORS COPV is roughly three times more mass efficient than the HPGT, but only about half as efficient as the best Orbital ATK COPVs.

B. Use of NORS tanks on ISS and in the future

The first NORS oxygen and nitrogen RTAs were flown to ISS together on August 19, 2015 and installed January 19, 2016. They contained 84 lbm (38.2 kg) of oxygen and 63 lbm (28.6 kg) of nitrogen. Oxygen has been transferred from an RTA to an HPGT. “The empty NORS RTAs will be returned to earth on a subsequent SpaceX flight for re-fill and re-launch. NORS tanks can be re-used up to 10 times.” (Gentry, 2016-406)

The ISS atmosphere control and supply system includes a Pressure Control Assembly (PCA), the HPGTs and NORS, and various regulators and valves. “They are not generally gravity sensitive and have proven to be very robust and dependable components on Apollo, Shuttle and ISS. … it is expected that NORS will be the gas transport standard for the foreseeable future.” (West et al., 2016-226)

X. Nitrogen Oxygen Recharge System (NORS) design

The NORS has five components: the Ground Fill Assembly (GFA), the Recharge Tank Assembly (RTA), the Internal Fill Assembly (IFA), the External Fill Assembly (EFA), and the Airlock Installation Kit (AIK). The Recharge Tank Assembly (RTA) is the pressure vessel used to transport pressurized oxygen and nitrogen to the ISS. (Dick et al., 2009-01-2413) The Internal Fill Assemblies (IFA) regulate the flow of gas from the RTA. The RTA and IFA are discussed.

A. Recharge Tank Assembly (RTA)

The Recharge Tank Assembly (RTA) is shown in Figure 1.

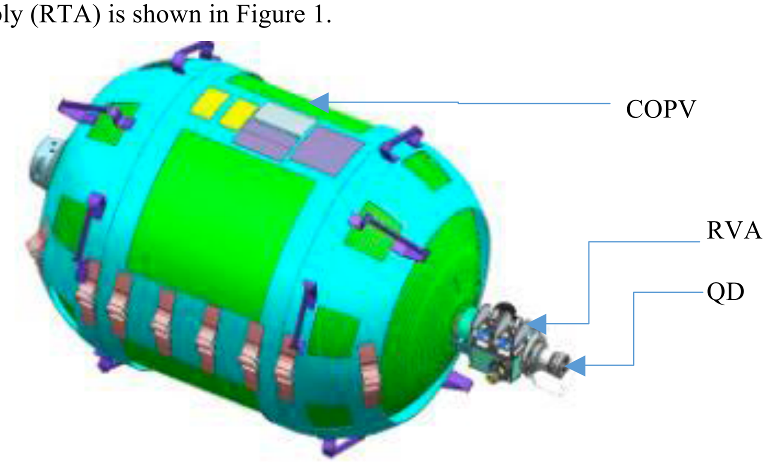

Figure 1. The Recharge Tank Assembly (RTA). (Schaezler and Cook 2015-146)

The RTA consists of three parts: a composite overwrap pressure vessel (COPV), the RTA Valve Assembly (RVA), and a high pressure Quick Disconnect (QD). The tank has a single port for filling and emptying, but has an opposed boss for handling purposes. (Dick, 2011-5226)

The RTA Valve Assembly (RVA)was designed and manufactured by Cobham. The RVA isolates the flow of gas from the COPV and provides a connection to the Internal Fill Assembly (IFA) thought the Quick Disconnect (QD). To allow easier QD operation by avoiding the need to connect and disconnect under pressure, the RVA includes a line depress valve. Additionally, the RVA includes a pressure gauge to measure the quantity of gas contained in the COPV and a burst disk required for air transport. (Dick, 2011-5226) (Dick and Griffin, 2012-3614) The RVA is shown in Figure 2.

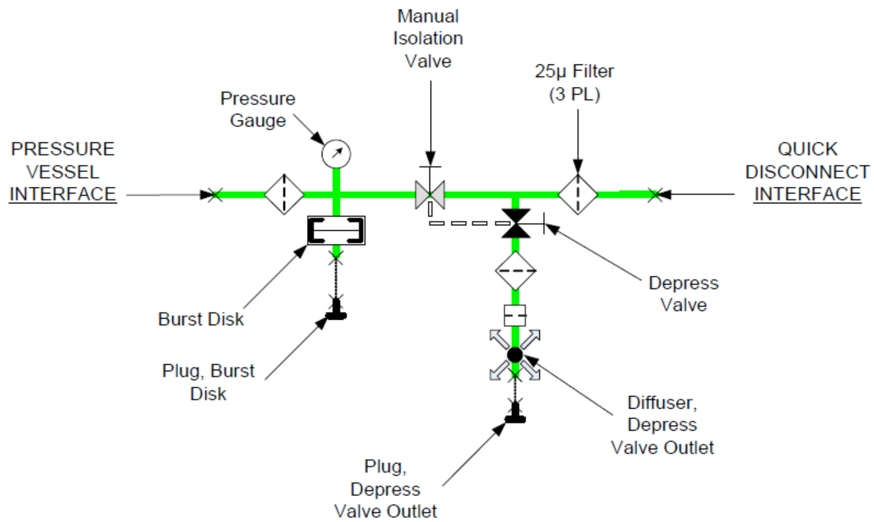

Figure 2. The RTA Valve Assembly (RVA). (Dick et al., 2013-3499)

The RVA includes two filters, a pressure gauge, a burst disk, a manual isolation valve, and a manual depressurization valve. (Dick et al., 2013-3499)

B. Internal Fill Assemblies (IFAs)

Fill assemblies interface between the RVA and gas destinations and regulate the pressure below the Maximum Design Pressure (MDP). The Internal Fill Assemblies (IFA) regulate the pressure of the gas from the RTA to the airlock interface to the HPGTs. At the outlet of the IFA, a Medium Pressure QD (MPQD) provides a connection between the RVA and the destination interface. (Dick, 2011-5226) The IFA is shown in Figure 3.

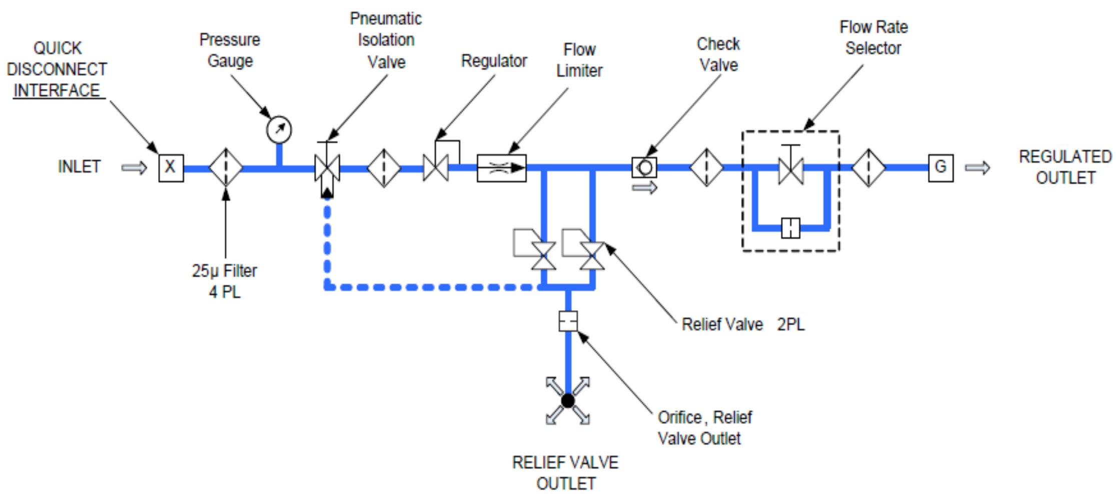

Figure 3. The Internal Fill Assembly (IFA). (Dick et al., 2013-3499)

The IFA includes four filters, a pressure gauge, an isolation valve, a regulator, a flow limiter, dual relief valves, a check valve, and a flow rate selector. (Dick et al., 2013-3499)

C. NORS design issues

The first task in designing the NORS was determining the pressure vessel size and fill pressure. The RTA must fit through a hatch that is 31.5 inches in diameter. The RTA must also have protection against loads and impacts experienced during shipping and handling. The pressure vessel had to be no larger than 24 inches in diameter. (Dick et al., 2009-01-2413) The final diameter was 18.5 inches.

Next the tank volume and pressure needed to be established. An analysis was made of spherical tanks with diameters of 12, 18, and 24 inches at pressures from 2,000 psia to 10,000 psia. The mass of gas transferred was compared to the mass of the tank to determine mass efficiency. This analysis showed that a 20 inch pressure vessel charged to 7,000 psia was the optimum size. The need to accommodate a 10 degrees C increase in temperature within the Maximum Design Pressure (MDP) led to reducing the fill pressure to 6,000 psia. (Dick et al., 2009-01-2413) Because of the different uses of the oxygen and nitrogen, a regulator assembly is needed with the ability to lower the pressure of gases and provide for variable flow rates. (Dick et al., 2009-01-2413)

Vessels with pressures ranging from 6,000 to 7,000 psia are nearly unprecedented on-orbit. High pressure oxygen means that stainless steel cannot be used since it would be consumed in an ignition. Oxygen compatible materials such as Monel or brass must be used. (Dick et al., 2009-01-2413)

The original NORS architecture included a regulator with a single relief valve on the outlet to prevent over pressurizing the downstream system. "However, upon review with the Safety organization, this architecture was deemed to be unacceptable. … NASA requires two fault tolerance against any catastrophic hazard. This means that if a hazard is considered catastrophic there must be three controls to prevent the hazard from occurring. … Therefore, the NORS architecture was altered to use redundant relief valves at the outlet of the oxygen and nitrogen internal regulators." (Dick, 2011-5226)

XI. Mars transit oxygen tank new design approach

How should the Mars transit oxygen tank be developed? The space tank industry has accumulated a great deal of design knowledge and flight experience, and has many flight qualified tank designs.

The most direct and least expensive approach would be to use a qualified tank as is. The additional engineering effort may be only a simple qualification-by-similarity report or could extend to a full stress and fracture analysis and some protoflight testing. Also for relatively low cost, an existing tank can be adapted. It can be modified without affecting the tank shell qualification status, perhaps by changing the support structure or the size of the inlet or outlet. (Tam et al., 2008-4940)

To implement an optimal tank solution, it is almost always necessary to develop and qualify 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." (Tam et al., 2008-4940) This is the most expensive and highest risk option, but it should be considered and may be justified for the unique mission of a human Mars transit.

A design trade study should be conducted to determine the best Mars transit oxygen tank design. (Tam et al., 2008-4940) Some of the steps are as follows:

1. Prepare a preliminary specification, to be modified according to study results.
2. Develop a trade study methodology, including criteria and weights, again to be revised.
3. Assess existing tank designs and identify best candidates.
4. Consider tank shell configuration. Probably a central cylinder with hemispherical heads rather than fully spherical or cylindrical with space saving ellipsoidal heads.
5. Consider tank construction. Probably a COPV with titanium shell and full wrap rather than all titanium, all composite, or hybrid with metal heads and composite overwrapped cylinder section. Include inlet, boss, and mounting.
6. Consider tank size. Titanium plate sizes and increasing cost of tooling limit tank diameter. More smaller tanks reduce the size and cost of spares.
7. Consider impact of higher-level, system-wide trades. Mass, volume, reliability, safety, risk.

> "(T)he 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. ... 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 … 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." (Tam et al., 2008-4940)

A new tank designed for Mars transit would probably more mass efficient than existing tanks. The large expense of a Mars mission and the relatively low cost of a tank development could justify an extensive design effort. COPVs are highly reliable, so it could be possible to reduce the tank mass while retaining less but sufficient reliability. The overall reliability can be restored by adding filled spare tanks, which would increase mass. It is not clear what tank mass and reliability would give the minimum overall mass for the required reliability. The oxygen storage tanks for Mars transit should have extensive reliability testing and analysis.

XII. Mars transit oxygen storage system requirements

This section considers the requirements for an oxygen storage system design for a Mars transit mission. The basic mission parameters include the transit duration, the number of crew, and the daily oxygen consumption per crewmember. These together determine the quantity of oxygen required. Another basic mission requirement is the acceptable Probability of Loss of Crew, Pr(LOC), due to a failure of the oxygen supply.

A. The Mars transit mission duration

Oxygen storage tanks could be used for the Mars transit portion of a Mars surface mission. This is an alternative system design to be traded off against the use of a redesigned ISS Oxygen Generation Assembly (OGA) or perhaps a new Mars specific design for a different oxygen electrolysis system. An important question is how long the oxygen supply must last.

The transit mission would consist of the trip to Mars, a non-operating wait either brief or extended in Mars orbit, and the return trip to Earth. Each leg of the Mars transit can last from 200 to 270 days. The typical outbound and return transit times are 225 days each, so oxygen must be supplied to the crew for 450 days. The typical total mission time is 935 days, with 485 days on the surface. (Boden and Hoffman, 2000)

Two similar but separate oxygen tank assemblies will be used, one for the trip to Mars and one for the return to Earth. The empty outbound tanks will be allowed to fly out past Mars, so the outbound tanks must supply oxygen only for the first 225 days. The full return trip tanks must be captured in Mars orbit and then sent back toward Earth. The return trip oxygen tanks provide oxygen for the last 225 days of the typical 935-day mission, so their required life is longer, the full 935 days.

B. Oxygen requirement for Mars transit

The amount of oxygen required is about 0.84 kg per crewmember per day. (Weiland, 1994) It is assumed that there are four crew, and that all descend to the surface. The oxygen requirement is given in Table 9.

Table 9. Mars transit oxygen requirement.

Requirement	
Number of crew	4
Trip out duration	225 days
Trip out oxygen	756 kg
Quiescent operation	485 days
Trip back duration	225 days
Trip back oxygen	756 kg
Total oxygen	1,512 kg

The outbound and return oxygen requirements are shown separately since the outbound tanks will be empty and can be allowed to fly by Mars, while the full return trip tanks must be captured into Mars orbit and sent back towards Earth, as would an oxygen generation system.

C. Probability of Loss of Crew, Pr(LOC), for the Mars transit oxygen supply

The Probability of Loss of Crew, Pr(LOC), on a space mission was about one percent for launch and one percent for reentry during the shuttle era. The Pr(LOC) due to a life support failure has been roughly similar. (Jones, 2013-

3315) For Mars exploration, a reasonable initial assumption would be that we should not exceed the past one percent Pr(LOC) for life support failures. Allocating the Pr(LOC) < 0.01 between water, oxygen, carbon dioxide, pressure, food, fire suppression, and other vital life support systems, we can assume that the Mars transit oxygen system must have Pr(LOC) < 0.001. Since storage systems have had high reliability, it might be overall cost effective to have an even lower Pr(LOC) for the oxygen system, so that more Pr(LOC) could be allocated to other more risky mission elements.

XIII. Tanks for Mars transit oxygen storage

The tanks that could be used for Mars transit oxygen storage are all Composite Overwrapped Pressure Vessels (COPVs). They include the ISS High Pressure Gas Tanks (HPGTs), the Orbital ATK COPV space tanks, the ISS Nitrogen Oxygen Recharge System (NORS) tanks, and a possible new oxygen tank designed for Mars transit.

Table 10 shows the tank oxygen mass, empty mass, total mass, mass increase ratio, one way and round trip mass, and number of tanks for the ISS HPGT tanks, Orbital tanks, ISS NORS tanks, and possible new design Mars tanks.

Table 10. Tank oxygen and total masses.

	ISS HPGT tank	Orbital tank	ISS NORS tank	New Mars tank
Single tank oxygen mass, kg	94.3	35.4	38.3	75
Single tank empty mass, kg	544	12.7	55.5	15
Single tank oxygen and tank mass, kg	638.3	48.1	93.8	90
Mass increase ratio	6.77	1.36	2.45	1.20
One way oxygen mass, kg	756	756	756	756
One way number of tanks (rounded)	8	21	20	10
One way tank and oxygen mass, kg	5,106	1,010	1,876	900
Round trip number of tanks	16	42	40	20
Round trip tank and oxygen mass, kg	10,212	2,020	3,752	1,800

The HPGT tank is the oxygen tank from Table 5. The Orbital tank is the 12.7 kg tank from Table 6. The NORS tank is the oxygen RTA from Table 8. The HPGT is large and rugged but inefficient, while the more efficient Orbital and NORS tanks are so small that about 20 would be required for oxygen on a one-way transit to Mars. A larger and more efficient design seems called for, so a hypothetical improved new Mars tank is shown in Table 10. The assumed new design would have about twice the oxygen content of the Orbital and NORS tanks but a relatively smaller empty tank mass. The tankage over head of the new Mars tank is assumed to be only 20%, much less than the 36% of the Orbital tank. Such a mass efficiency improvement may not be achievable. The purpose of assuming this advanced new Mars tank is to see how it would improve oxygen storage system performance, and the round trip mass is reduced 10%. The next section surprisingly shows this gain disappears. Since a storage tank system requires one or two spares regardless of tank size, the larger new Mars tanks increase the mass needed for spares.

XIV. Number of spare tanks for Mars transit oxygen storage

The number of spare tanks required depends on the overall requirement on the Probability of Loss of Crew, Pr(LOC), which would occur if the oxygen supply fails, and on the expected tank reliability. It is assumed that the Mars transit oxygen system must have Pr(LOC) < 0.001.

A. Expected COPV tank reliability and need for spares

The analysis of the accelerated life testing on a used shuttle COPV tank found an estimated life of 350 years for the worst shuttle tank the testers could obtain. This would indicate the probability of a tank failure is less than 1/350 = 0.0028 per year. If the outbound Mars transit is 225 days long, the probability of any tank failing going to Mars is estimated as 225/365 * (1/350) = 0.0017. Ten or twenty tanks will have ten or twenty times this failure probability, roughly one or two percent. As the requirement is a failure probability of less than 0.001, one-tenth of one percent, spare tanks are needed.

The need for spares is greater on the return trip. The return trip to Earth lasts until the last day of the mission, 935 days. The probability of any tank failing on the round trip is estimated as 935/365 * (1/350) = 0.0073. Ten or twenty tanks will have ten or twenty times this failure probability, roughly seven or fourteen percent.

B. Computing the number of spare tanks

The number of tanks required to hold the oxygen for a one way transit to or from Mars is 8, 21, 20, and 10 in Table 10. If the number of required tanks is r and the number of spares is s, the total number of tanks is n = r + s. To provide the needed oxygen, r out of the n tanks must not fail on the trip.

This is an "r out of n" redundancy problem. The reliability and failure probability are found using the binomial distribution. For general r and n, the system reliability, R, is the probability that r, r+1, … up to n subsystems survive to time t. This is the cumulative binomial distribution from i = r to n. Using a sufficient number of spares, s = n – r, any theoretical reliability can be attained. The cost is the added mass of the filled spare tanks.

C. The number of spares for the outbound transit tank assembly

The number of spares to achieve an overall failure rate of 0.001 is computed for the outbound transit tank assembly, assuming the probability of a single tank failure is 1/350 = 0.0028 per year. For an outbound Mars transit of 225 days, the probability of one tank failing going to Mars is (1/350) * (225/365) = 0.0017. The required number of tanks, the number of spares, the mass increase, and failure probability is shown in Table 11 for the candidate tanks of Table 10.

Table 11. The required number of tanks, the number of spare tanks, the mass increase ratio, the failure probability, and the one-way mass for the candidate tanks for the outbound transit.

r, required tanks	s, spare tanks	n = r + s, total tanks	Mass increase ratio, n/r	Failure probability	One way mass
ISS HPGT tank					
8	0	8	1.00	0.0135	5,106
8	1	9	1.13	0.0001	5,744
Orbital tank					
21	0	21	1.00	0.0351	1,010
21	1	22	1.05	0.0007	1,058
ISS NORS tank					
20	0	20	1.00	0.0335	1,876
20	1	21	1.05	0.0006	1,970
New Mars tank					
10	0	10	1.00	0.0169	900
10	1	11	1.10	0.0002	990

For all the candidate tanks, only one spare is required to achieve the required failure probability of less than 0.001. The overall mass increase is 13% for the ISS HPGT, 5% for the Orbital AKT and ISS NORS tanks, and 10% for the new Mars tanks. The new Mars tanks lose much of their mass advantage over the Orbital AKT tanks because each is about twice as big, including the spare.

D. The number of spares for the return transit tank assembly

The number of spares to achieve an overall failure rate of 0.001 is computed for the return transit tank assembly, assuming the probability of a single tank failure is 1/350 = 0.0028 per year. For the full Mars mission duration of 935 days, the probability of one tank failing going to Mars is (1/350) * (935/365) = 0.0073. The required number of tanks, the number of spares, the mass increase, and failure probability is shown in Table 12 for the candidate tanks of Table 10.

Table 12. The required number of tanks, the number of spare tanks, the mass increase ratio, the failure probability, and the one-way mass for the candidate tanks for the return transit.

r, required tanks	s, spare tanks	n = r + s, total tanks	Mass increase ratio, n/r	Failure probability	One way mass
ISS HPGT tank					
8	0	8	1.00	0.0569	5,106
8	1	9	1.13	0.0019	5,744
8	2	10	1.25	0.0000	6,383
Orbital tank					
21	0	21	1.00	0.1426	1,010
21	1	22	1.05	0.0112	1,058
21	2	23	1.10	0.0006	1,106
ISS NORS tank					
20	0	20	1.00	0.1363	1,876
20	1	21	1.05	0.0102	1,970
20	2	22	1.10	0.0005	2,064
New Mars tank					
10	0	10	1.00	0.0706	900
10	1	11	1.10	0.0028	990
10	2	12	1.20	0.0001	1,080

For all the candidate tanks, two spares are required to achieve the required failure probability of less than 0.001. The overall mass increase is 25% for the ISS HPGT, 10% for the Orbital AKT and ISS NORS tanks, and 20% for the new Mars tanks. The new Mars tanks have little mass advantage over the Orbital AKT tanks because each spare is larger.

E. Tank reliability and spares

The number of spares depends on the expected tank reliability. The 350 year expected life number that was used depends on a single test of a shuttle tank. These early tanks had additional strength due to a load bearing inner liner, so later tank designs may be less robust. The space shuttle had 24 internal COPVs and typically three were operational from 1981 to 2011, so the total failure free experience was about 24 * 3 * 30 = 2,160 vessel-years. This would indicate a roughly six times longer life and one-sixth the failure rate that was used above.

The ISS has about twenty COPVs, counting multiple HPGTs and NTAs. It has been operational about fifteen years, indicating about 300 vessel-years of failure free operation. The 350 year expected life used to compute the number of spares seems reasonable, even conservative since no failures have occurred.

XV. Conclusion

The paper reviewed pressure vessel design, failure modes, reliability, and cost. Pressure vessel types were described, including the COPVs used by NASA. The oxygen requirements and possible tank designs for Mars transit were given and the required mass was computed, including spares.

The mass of a pressure vessel is proportional to the mass of the gas it contains. The mass of gas depends on the tank's pressure, volume, and temperature. The mass of a pressure vessel depends on its surface area, wall thickness, and the density of the wall material. The wall thickness is determined by the tank pressure and the stress tolerance of the wall material. It was shown that the mass of a pressure vessel scales with the pressure and volume it contains, which determines the mass of the gas it contains, and it also scales with the ratio of the wall material's density to stress tolerance.

Given the same tank material and shape, a given mass of gas will require the same mass of tankage, regardless of the number of larger or smaller tanks that are used. Increasing tank pressure increases gas mass and equally increases wall stress, wall thickness, and tank mass. Lighter tanks require lighter and stronger wall materials.

Pressure vessels fail due to rupture and leakage but failure rates are low. Fewer, larger tanks would cost less per kg of gas contained, but adding the cost of one spare tank significantly cuts the total cost saving of larger tanks. The size and number of the tanks used is not a significant cost determinant.

Pressure vessels can be all steel, combined metal and fiberglass overwrap, or COPVs with a metal and composite overwrap that carries the structural load. COPVs have a significant weight advantage over all-metal vessels. Titanium lined COPVs have been used in space for decades on almost all missions. The shuttle and ISS have used many produced by Orbital ATK. They are considered safe, robust, dependable, and cost effective. None have failed and the expected life based on experience is 100's of years. The best existing tank or possibly a similar improved tank could be used for Mars transit.

For a 450 day Mars transit out and back, a crew of four will need 1,512 kg of oxygen. The best Orbital tank would require 42 tanks and a total mass of 2,020 kg without spares. An improved similar tank with about twice the capacity and half the tank mass overhead would require 20 tanks and a total mass of 1,800 kg. This small 10% mass saving becomes much smaller when one spare tank is added for the outbound trip and two spares for the return. The cost of designing and qualifying a new tank design may not be needed. Using existing COPVs is feasible for Mars transit.

Previous work found that the current ISS OGA is not feasible for Mars transit. (Jones, 2016-103) This result was initially indicated by the large mass of the OGA and its spares, which is more than the mass of the oxygen it would provide. The total mass of the ISS OGA plus three sets of onboard spare subsystems would be 4,119 lbs or 1,872 kg. (Jones, 2016-103) The mass of the oxygen to be consumed is 1,512 kg, 19% lower. The total mass of 45 filled oxygen tanks similar to the Orbital tank, 42 containing the needed oxygen and 3 spares, would be 2,164 kg, 13 % higher. However, orbital mechanics give a strong mass advantage to using tanks. On the outbound trip, 21 tanks will be emptied and can be allowed to fly by Mars, but the 21 return trip tanks and 2 or 3 spares must be captured into Mars orbit and sent back towards Earth. Only about half the oxygen tanks requite many times their mass in rockets and propulsion gas to return them to Earth, but the entire oxygen generation system must make the return trip. Using the ISS OGA for Mars transit would require about twice the mass as using the best current oxygen tanks.

The OGA would not save mass or reduce launch cost, but launch cost has declined in size and relative importance. (Jones, 2017-87) Other factors are more important. Mars requires higher reliability than ISS and deep space radiation hardening. The cost of designing and developing an OGA similar to the ISS design would be much larger than for using existing or developing new tanks. Compared to tanks, the OGA is very complex and has many more failure modes. Tanks need little crew time to operate or or maintain. Tank storage is highly reliable and can easily increase reliability using a few more spares. Tanks easily operate in microgravity and do not produce contamination or noise. Existing oxygen storage tanks are feasible for Mars transit and are attractive compared to the ISS OGA.

References

Arnold, H. G., "Pressure vessel reliability as a function of allowable stress," thesis, Oak Ridge National Laboratory, 1972, web.ornl.gov/info/reports/1972/3445605147677.pdf, accessed April 1, 2016.

Boden, D. G., and Hoffman, S. J., "Orbit Selection and Astrodynamics," in Larson, W. K., and Pranke, L. K, eds., *Human Spaceflight: Mission Analysis and Design*, McGraw-Hill, New York, 2000.

Carrasquillo, R. L., Reuter, J. L., and Philistine, C. L., "Summary of Resources for the International Space Station Environmental Control and Life Support System," Proceedings of the 27th International Conference on Environmental Systems, SAE 972332, 1997.

Chattopadhyay, S., Pressure Vessels Design and Practice, CRC press, 2005.

Composites World, The markets: Pressure vessels (2014), Jan. 1, 2014. http://www.compositesworld.com/articles/the-markets-pressure-vessels-2012, accessed 4/1/2016.

Dick, B. N., and Griffin, T. E., "International Space Station Nitrogen Oxygen Recharge System," AIAA 2012-3614, 42nd International Conference on Environmental Systems, 2012.

Dick, B. N., Tokasz, S., and Griffin, T. E., "Development of the International Space Station Nitrogen Oxygen Recharge System," AIAA 2013-3499, 43rd International Conference on Environmental Systems (ICES), July 14-18, 2013, Vail, CO, 2013.

Dick, B., "Current Status of the Nitrogen Oxygen Recharge System," AIAA 2011-5226, 41st International Conference on Environmental Systems, 2011.

Dick, B., Cook, T., and Leonard, D., "Nitrogen Oxygen Recharge System (NORS) for the International Space Station," 2009-01-2413, 39th International Conference on Environmental Systems, 2009.

Duchesne, S. M., email, May 10, 2016.

Flemish Government, BACKGROUND INFORMATION: APPENDIX TO HANDBOOK FAILURE FREQUENCIES, 2009. vr_rlbvr_rl_hbff_background_information_EN.pdf, downloaded April 6, 2016.

fxsolver, Mass+, http://www.fxsolver.com/browse/formulas/Mass+of+pressure+Cylindrical+vessel+with+hemispherical+ends%28+capsule%29, accessed 3/31/2016.

Gebhardt, C., "NASA Reviews COPV Reliability Concerns for Final Program Flights," NASASpaceFlight.com, July 18, 2010, https://www.nasaspaceflight.com/2010/07/nasa-reviews-copv-for-final-program-flights/, accessed April 6, 2016.

Gentry, G. J., 'International Space Station (ISS) Environmental Control and Life Support (ECLS) System Overview of Events: 2015-2016," ICES-2016-406, 46th International Conference on Environmental Systems, Vienna, 2016.

Groome, W. C. A., Ripple, Tate Publishing, 2012.

Jones, H. W., "Much Lower Launch Costs Make Resupply Cheaper Than Recycling for Space Life Support," Submitted as ICES-2017-87, 47th International Conference on Environmental Systems, 16-20 July 2017, Charleston, South Carolina.

Jones, H. W., "Space Life Support Risk and Reliability," 2013-3315, AIAA, Washington, DC, 43rd International Conference on Environmental Systems, 2013.

Jones, H. W., "Using the International Space Station (ISS) Oxygen Generation Assembly (OGA) Is Not Feasible for Mars Transit," ICES-2016-103, 46th International Conference on Environmental Systems, 10-14 July 2016, Vienna, Austria.

Kezirian, M. T., Johnson, K. L., and Phoenix, S. L., "Composite overwrapped pressure vessels (COPV): Flight rationale for the Space Shuttle Program." AIAA, 2011, ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110015972.pdf, downloaded April 6, 2016.

Kezirian, M., "Composite Overwrapped Pressure Vessels (COPV): Developing Flight Rationale for the Space Shuttle Program," Boeing, November 3, 2010. ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100036778.pdf, accessed April 6, 2016.

Kezirian, M., Cook, A., Dick, B., and Phoenix, S. L., "Providing Pressurized Gasses to the International Space Station (ISS): Developing a Composite Overwrapped Pressure Vessel (COPV) for the Safe Transport of Oxygen and Nitrogen," Composites Conference 2012, August 15, 2012.

Lees, F., *Lees' Loss Prevention in the Process Industries: Hazard Identification, Assessment, and Control*, Elsevier, Butterworth-Heinmann, Oxford, 2012.

LeGault, M., "Pressure vessel tank types," Composites World, Jul. 2, 2012, http://www.compositesworld.com/articles/pressure-vessel-tank-types, accessed 4/1/2016.

McLaughlan, P. B., Forth, S. C., and Grimes, L. R., *Composite Overwrapped Pressure Vessels, A Primer,* NASA/SP–2011–573, March, 2011.

Megyesy, E. F., *Pressure Vessel Handbook*, PV Publishing, Oklahoma City, www.pressurevesselhandbook.com. 2008, downloaded 3/31/2016.

Mulet, A., Corripio, A. B., and Evans, L. B., "Pressure Vessel Costs," in *Encyclopedia of Chemical Processing and Design: Volume 42 – Pressure-Relieving Devices, Rupture Disks: Selection of Process Control and Dynamics: Savings from Upgrading*, McKetta, J. J., ed., Marcel Dekker, New York, 1993. (Also CRC Press, 1992.)

Orbital AKT data sheet, http://www.psi-pci.com/Data_Sheet_Index_Pressurant-PN.htm, retrieved April 21, 2016.

Orbital-ATK, Propellant Tanks, https://www.orbitalatk.com/space-systems/space-components/propellant-tanks/, accessed June 6, 2016.

Roylance, D., "Pressure vessels," August 23, 2001, web.mit.edu/course/3/3.11/www/modules/pv.pdf, downloaded 3/31/2016.

Russell, R., Flynn, H., Forth, S., Greene, N., Kezirian, M., Varanauski, D., Leifeste, M., Yoder, T., and Warren Woodworth, W., "Composite Overwrapped Pressure Vessels (COPV) Stress Rupture Test Part 2," 2010.

Schaezler, R. N., and Cook, A. J., "Report on ISS O2 Production, Gas Supply & Partial Pressure Management," ICES-2015-146, 45th International Conference on Environmental Systems, Bellevue, Washington

Simonen, F. A., "Pressure Vessels and Piping Systems: Reliability, Risk and Safety Assessment," ANCILLARY EQUIPMENT AND ELECTRICAL EQUIPMENT, *Encyclopedia of Desalination and Water Resources* (DESWARE), 2002, www.desware.net/Sample-Chapters/D09/E6-165-07-00.pdf, accessed April 4, 2016.

Tam, W. H., Ballinger, I., and Jaekle, D. E., Jr., "Tank Trade Studies – An Overview," AIAA 2008-4940, 2008.

Thesken, J. C., Murthy, P. L. N., Phoenix, S. L., Greene, N., Palko, J. L., Eldridge, J., Sutter, J., Saulsberry, R., and Beeson, H., "A Theoretical Investigation of Composite Overwrapped Pressure Vessel (COPV) Mechanics Applied to NASA Full Scale Tests," NASA/TM —2009-215684, 2009.

TWI, The Welding Institute, "How can failure of pipelines and pressure vessels be prevented?" 2016, http://www.twi-global.com/technical-knowledge/faqs/structural-integrity-faqs/faq-how-can-failure-of-pipelines-and-pressure-vessels-be-prevented/, accessed April 4, 2016.

West, W., Samplatsky, D., Gentry, G. J., and Duggan, M., "Lunar Surface Habitats as a Development Opportunity for Mars Surface Life Support Systems," ICES-2016-226, 46th International Conference on Environmental Systems, Vienna, 2016.

Wieland, P. O., *Designing for Human Presence in Space: An Introduction to Environmental Control and Life Support Systems*, NASA Reference Publication RP-1324, 1994.

Wikipedia, Composite overwrapped pressure vesselhttps://en.wikipedia.org/wiki/Composite_overwrapped_pressure_vessel, accessed 3/31/2016.

Wikipedia, Pressure vessel, https://en.wikipedia.org/wiki/Pressure_vessel, accessed 3/31/2016.