Analysis of a Low-Vapor-Pressure Cryogenic Propellant Tankage System

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One potential technology for a fully reusable and permanently space-based cryogenic upper stage rocket is the use of liquid hydrogen and liquid oxygen propellants in less than atmospheric condition—a "low-vapor-pressure" system. This enables the use of lighter weight tank shells and higher density fluids, two features that can reduce the quantity of costly propellants consumed by the vehicle in performing a payload delivery mission. The fluids must have their saturation conditions lowered from the levels produced today. Five conditioning techniques and important issues relevant to the structural design of very thin-gage tanks are discussed; e.g., fracture mechanics, thin-gage formability, inspection, and weights. An important conclusion is that significant structural inert weight can be saved with further manufacturing technology development of large-scale, thin-gage shells.

Nomenclature

E	= modulus of elasticity, psi
F_a	= allowable stress, psi
F_{tu}	= tensile ultimate strength, psi
F_{ty}	= tensile yield strength, psi
g	= acceleration due to gravity, ft/s^2
H	= height, in.
K_{IC}	= stress intensity factor, ksi (in.)$^{1/2}$
m	= mass flow rate, lb/min
P	= pressure, psia
R	= radius, in.
t	= thickness, in.
ρ	= density, lb/in.^{3}

Introduction

SUBATOMSPHERIC (<14.7 psia) liquid hydrogen (LH_2) and liquid oxygen (LO_2) are particularly attractive for use on a space-based orbital transfer vehicle (SBOTV) designed to operate solely in the vacuum environment of space. Weight savings could be realized for the vehicle tank structure if liquid vapor pressures are lowered from the current commercially produced value of 18–20 psia down to approximately 5 psia. In addition, the LH_2 density increases by 5.2% and the LO_2 density by 5.0%. This reduces the amount of propellants required for the SBOTV to perform any given mission, which, in turn, provides cost savings per single mission and throughout the entire lifetime mission model.

To reduce tank pressures below Earth atmospheric requires that the propellant saturation condition be lowered so that the fluids remain in the liquid phase. Liquid hydrogen and liquid oxygen produced on the ground are stored and maintained at pressures slightly above 1 atm and are normally used in this condition (e.g., Saturn, Centaur, and the Space Transportation System external tank). In this study, such propellants are referred to as "nonconditioned" in that no unusual thermodynamic requirements are imposed on producing, storing, and handling them. To operate the SBOTV at a subatmospheric tank pressure, the liquid propellants must be "conditioned" to reduce their saturation pressures to the tank operating levels. Balanced against the advantage of conditioned propellants for the vehicle is the complication of having to provide liquid hydrogen and liquid oxygen for use on orbit at the lower saturation pressures and temperatures. This conditioning process can take place either on the ground or on orbit at the long-term cryogenic storage facility (LTCSF) depot, which could be located either at an orbiting orbital transportation and staging facility, the space station orbital transfer vehicle servicing facility, or the orbital refueling platform.[1-2] This paper describes the results of an analysis of tank operating pressure levels and a trade of propellant conditioning alternatives. A concept for lightweight vehicle tankage structure is proposed for a vehicle design that offers the least-weight system required to use the low-vapor pressure cryogens and satisfy structural design criteria. Although this discussion is oriented toward an SBOTV application, much of the material is general in nature and could be developed for use on other cryogenic tankage systems where requirements permit.

Baseline Vehicle

The baseline vehicle for this study is a SBOTV concept known as the S-4C. The structural arrangement (Fig. 1) consists of spherical LO_2 and LH_2 tanks mounted in a composite tubular trusswork between fore and aft polygonal composite frames. The aft frame supports twin 5000-lbf thrust engines and the aerobrake structure. The forward frame mates with a modularized avionics ring and payload adapter. Outrigger tanksets can be added radially onto the core propellant tank structure to tailor vehicle capability to mission needs. Figure 2 shows such a vehicle configured with twin outrigger tanksets.

Fluid Systems

Propellant Conditioning

The amount of specific energy required to be removed from the fluids to condition them to a lower saturation pressure is shown in Fig. 3.

The following conditioning cases were developed and compared to the nonconditioned alternative to determine which offered the greatest performance advantages for the SBOTV and had the lowest total cost (from purchase of propellant on the ground to final SBOTV usage):

1) Ground-conditioned propellant (cryogenic, 5 psia vapor pressure).

2) Ground-conditioned propellant (cryogenic, <5 psia vapor pressure, no solid).

3) Ground-conditioned propellant (cryogenic slush).

4) On-orbit conditioned propellant (cryogenic delivery).

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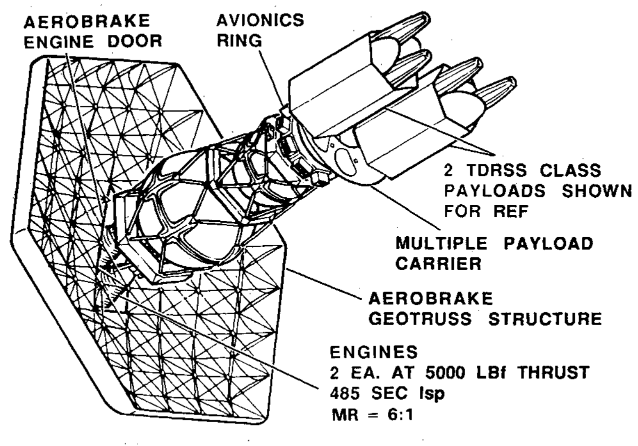

Fig. 1 S-4C SBOTV core propellant vehicle.

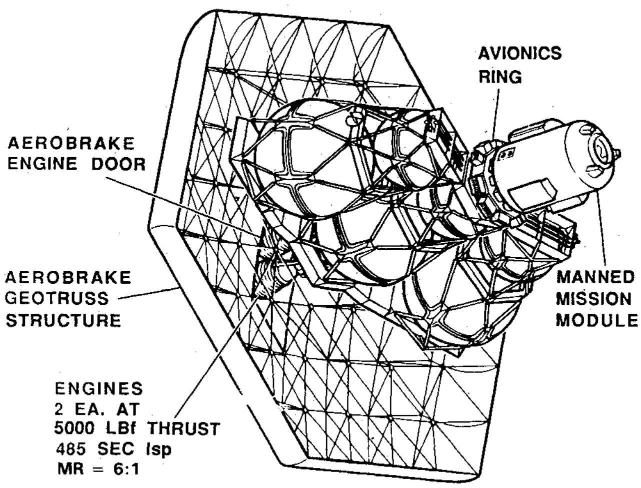

Fig. 2 Twin-outrigger tankset configuration.

5) On-orbit conditioned propellant (water delivery).
6) Nonconditioned propellant (cryogenic).

Case 1: Ground-Conditioned Propellant (Cryogenic, 5 psia Vapor Pressure)

Propellant conditioned on the ground will take advantage of power costs that are lower than on orbit, as well as minimizing the amount and size of equipment at the LTCSF. However, heat addition during delivery will increase the vapor pressure of the propellant, and some on-orbit reconditioning will be required. If the propellant is reconditioned using the boiloff technique to lower the liquid vapor-pressure level, then the amount of deliverable propellant is decreased. Refrigeration or venting with reliquefaction will increase the size (and cost) of the LTCSF equipment. Scavenged propellant must be refrigerated (increase LTCSF capability) or boiled down. Overall, this concept will transfer some of the higher cost, on-orbit operations to the ground but will still require some on-orbit conditioning equipment.

Case 2: Ground-Conditioned Propellant (Cryogenic, <5 psia Vapor Pressure, No Solid)

Further conditioning of the propellant from 5 psia down to a pressure just above the triple point extracts more energy from the propellant (Fig. 3) while marginally increasing ground-conditioning costs. If the delivery system is designed so that the leak during transport is less than this stored energy, then <5 psia liquid vapor pressure propellant can be delivered to the orbiting propellant depot (LTCSF). Thus, no on-orbit reconditioning would be required. In addition, if the heat leak to the delivery tank is small, some scavenged propellant can be mixed with the delivered propellant giving a final vapor pressure of 5 psia at the depot. Since this concept could be designed so that no on-orbit reconditioning is required, minimum on-orbit power and energy requirements can be obtained.

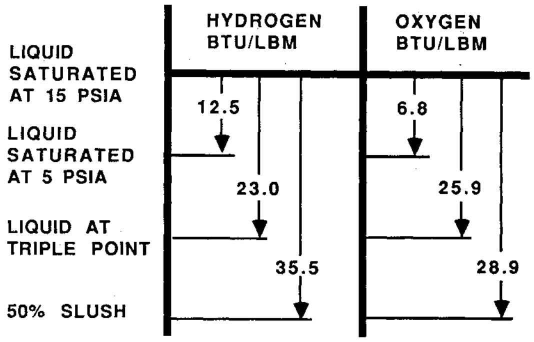

Fig. 3 Specific energy (Btu/lbm) to be removed to condition LO_2 and LH_2.

Case 3: Ground-Conditioned Propellant (Cryogenic Slush)

A potential major improvement in ground-conditioned propellant operations involves use of slush cryogens. Slush is the term used to describe a mixture of solid and liquid phases. The advantage of slush over liquid cryogens is that the latent heat of the solid in the slush increases the storage time before vapor pressure rise (or venting) occurs. The improved storage time may allow delivery of ground-conditioning propellant with no vapor pressure increase or loss of propellant due to venting. In addition, conditioning of scavenged propellant to 5 psia via mixing is possible. Also, a higher stored mass for the same occupied volume in the storage tank can be obtained because of the higher density of the slush (although pressure increase as a result of volume expansion due to heat addition must be limited). This improved capacity may allow for increased delivery capability if the vehicle is volume-limited.

The slush concept has the advantage of stored energy, as in case 2. Since even more stored energy is stored in slush, lighter weight insulation delivery systems and/or a higher percentage of conditioning scavenged propellants via mixing are possible. Note that the additional energy extracted in making slush oxygen is small compared with the energy removed in reducing liquid vapor pressure from 5 psia to just above the triple point. For slush hydrogen, the opposite is true. Thus, the advantages of slush will be greater for hydrogen applications. Balancing the conditioning advantages of slush cryogens are the costs associated with developing a new technology. Although slush as been made at the laboratory batch level and behaves much like liquids at quantities of up to 50%, it has never been produced in the quantities necessary to meet the SBOTV mission model. It is anticipated that the technology advances necessary for a large-scale slush system would be warranted only if case 2 proved feasible.

Case 4: On-Orbit Conditioned Propellant (Cryogenic Delivery)

A disadvantage of ground-conditioned propellant is that tanks must be pressurized with a noncondensible gas to prevent leakage of the atmosphere into the tank. As the tank is heated, the vapor pressure rises, and the propellants eventually require further conditioning. By launching the propellants at a vapor pressure above 1 atm, this problem is avoided. In addition, scavenged propellants pose no conditioning problem, since all liquid is conditioned at the depot. On the other hand, conditioning time and equipment downtime can potentially impact SBOTV operation schedules. Two depot tanks and peripheral equipment are likely to be required.

As an alternative, boiling down the propellant could reduce the amount of conditioning equipment and the time to condition. However, since 10% of the propellants are vaporized in reducing liquid vapor from 20 to 5 psia by boiling down and a 5-6% propellant saving is realized from a low-pressure SBOTV, boildown is not expected to be a viable option (only large space station or platform gaseous propellant requirements would allow the boildown option to be feasible). Overall, launching a nonconditioned propellant and conditioning on orbit is not expected to be cost-effective, since power and energy requirements on orbit will be much higher than on the ground.

Case 5: On-Orbit Conditioned Propellant (Water Delivery)

Water is a desirable payload since it is 2.89 times more dense than an equivalent quantity of liquid hydrogen/oxygen propellants. Water also has a very simple container requirement, has no boiloff losses, and causes no additional launch vehicle safety concern. The concept has been analyzed for a 1×10^6 lb storage depot.[3] Results of that study show that large power and energy requirements exist for the production of cryogens by electrolysis, dehumidification, and liquefaction. These requirements are in addition to the costs associated with conditioning the propellants to 5 psia and the complications of on-orbit conditioning. An additional problem is that the 8:1 ratio of oxygen to hydrogen produced by the processing does not match the most efficient SBOTV mixture ratio of 6:1. Total costs will likely be highest for this concept. Safety benefits and ease of delivery will have to be traded against the risks associated with cryogenic delivery to determine if the additional cost is warranted.

Case 6: Nonconditioned Propellant (Cryogenic)

Nonconditioned propellants have the advantage of requiring no special ground or on-orbit conditioning and can be mixed with scavenged propellant with little effect on the resultant vapor pressure. This cost advantage is balanced against the increased cost of operating a heavier SBOTV. With respect to on-orbit propellant maintenance, Ref. 1 indicates that a thermodynamic vent system (TVS) with reliquefaction capability is the preferred mode. Comparison of this concept with the lowest cost conditioned propellant concept determines whether a low- or high-pressure system should be recommended for SBOTV operation.

Table 1 summarizes the relative differences among the five conditioning options in comparison to the nonconditioned case 6. Ground electrical power consumption, orbit electrical power consumption, and life cycle cost (LCC) deltas were calculated based on an orbital transfer vehicle (OTV) mission model.[4] Results indicate that case 2—ground conditioning (cryogenic, <5 psia vapor pressure, no solid)—is likely to be the lowest-cost approach for a low-pressure SBOTV.

Figure 4 is a thermodynamic schematic of the low-vapor-pressure cryogenic fluid delivery-to-orbit condition in a separate propellant resupply tankage delivery system for use on an expendable heavy-lift rocket. LH_2 and LO_2 are placed in their respective delivery tanks at a saturated 5-psia condition. Positive tank pressure is necessary to maintain positive internal pressure on tank walls and prevent leakage from the outer atmosphere into the tank, so tank ullage is pressurized to 20 psia to maintain positive tank pressure above atmospheric. This is a nonequilibrium condition since the ullage pressure is higher than the liquid vapor pressure, so the liquid vapor pressure will tend to resaturate at a higher pressure over a long period of time. This condition requires fluid recycling up to launch. Although the fluid will heat up during the short period between launch and parking orbit, preliminary analysis indicates that the fluid's liquid vapor pressure level will change very little in that length of time. Once on orbit, the ullage pressure level can be reduced to a small fraction above the liquid vapor pressure level.

Table 1 Five propellant conditioning scenarios for the SBOTV compared to the nonconditional case

Operation	Case 1: ground condition cryo 5 psia	Case 2: ground condition cryo <5 psia	Case 3: ground condition cryo slush	Case 4: orbit condition cryo delivery	Case 5: orbit condition water delivery	Case 6: orbit condition cryo delivery
Start condition	Liquid saturated at 18 psia	Liquid saturated at 18 psia	Liquid saturated at 18 psia	Liquid saturated at 18 psia	Purified water	Liquid saturated at 18 psia
Ground condition	Lower liquid vapor pressure to 5 psia	Lower liquid vapor pressure to <5 psia	Lower liquid vapor pressure to 50% slush	Liquid saturated at 18 psia	Purified water	Liquid saturated at 18 psia
Delivery to orbit preparations	Delivery tank fluid recirculation prior to liftoff	Delivery tank fluid recirculation prior to liftoff	Delivery tank fluid recirculation prior to liftoff	Liquid saturated at 18 psia	Purified water	Liquid saturated at 18 psia
On-orbit conditioning	Delivery tank fluid recirculation prior to liftoff	Delivery tank fluid recirculation prior to liftoff	Delivery tank fluid recirculation prior to liftoff	Lower liquid vapor pressure to 5 psia	Electrolysis dehumidification & liquefaction at 5 psia	Liquid saturated at 18 psia
Annual ground elect. power, normalized	2.3×10^5	6.4×10^5	1×10^6	1	1	1
Annual orbital elect. power, normalized	1.2	1.2	1.2	9.7	92.1	1
LCC deltas, normalized	-4.7×10^8	-4.7×10^8	-5.6×10^8	1.7×10^8	1.2×10^{10}	1
OTV propellant consumption	5-6% propellant savings over 18 psia vehicle	5-6% propellant savings over 18 psia vehicle	5-6% propellant savings over 18 psia vehicle	5-6% propellant savings over 18 psia vehicle	5-6% propellant savings over 18 psia vehicle	—
OTV inert weight—1 tankset	6912 lb	6912	6912	6912	6912	7575
OTV inert weight—3 tanksets	11,540 lb	11,540	11,540	11,540	11,540	13,529
OTV inert weight—4 tanksets	13,348 lb	13,348	13,348	13,348	13,348	16,000
OTV inert weight—5 tanksets	15,152 lb	15,152	15,152	15,152	15.152	18,467
OTV inert weight—7 tanksets	18,765 lb	18,765	18,765	18,765	18,765	22,743

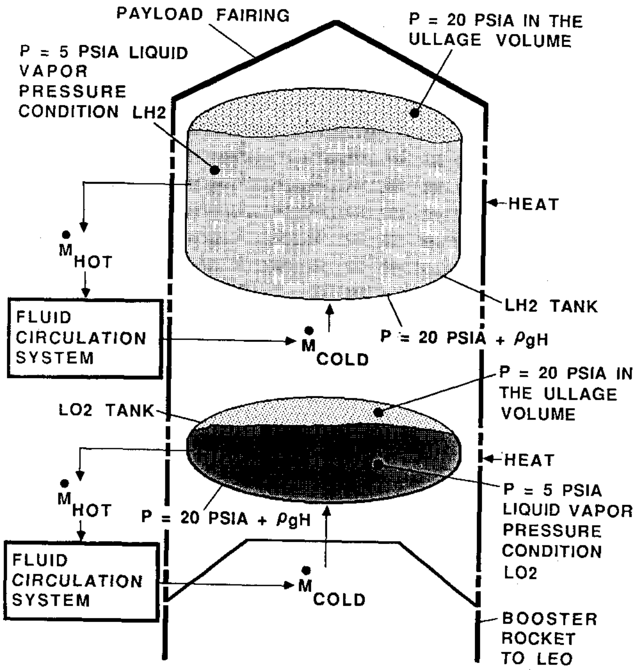

Fig. 4 Low-vapor-pressure cryogenic fluid delivery-to-orbit condition.

Tank Pressure Level Derivation

For any vessel, tank pressure must be controlled within the structural limits of the design. In a typical flight pressure control system, control transducers input information into computers, which in turn open and close various fluid systems at predetermined pressure levels to maintain pressure within design limits. The baseline SBOTV configuration has redundant autogenous pressurization, vent, and engine feed systems to perform these pressure-control functions: 1) Pressurize during engine burn to provide saturated (or low quality) fluid to the boost pumps, 2) vent during coast periods to accommodate tank heating, and 3) control tank pressure in the event of failures.

Control bands are used to actuate the various systems. One pressure limit of the band closes the system; the other limit opens the system. At a minimum, the open and close levels must be separated so that random noise will not cause valves to chatter between open and closed. The number of cycles the valve is capable of withstanding may also limit the minimum bandwidth. The maximum separation is restricted by the tank design pressure and may also be restricted by tank fatigue considerations. In selecting the control band pressure levels, the following must be considered:

1) Safety factor—The vehicle shall be designed so that the tank design pressure is 1.4 times the maximum operating presure. This safety factor accounts for uncertainties in load definition, material properties, dimensional discrepancies, etc.

2) Measurement system uncertainty—Transducer uncertainty, random noise, and analog-to-digital data conversion are all components of measurement system uncertainty. Transducer uncertainty is assumed to be 0.25% of the total transducer range of 0–20 psia (0.05 psia), based on production experience with Atlas and Centaur vehicles. The total of all other uncertainty components is assumed to be 0.05 psia.

3) Overshoot and undershoot—A finite amount of time exists between the time when tank pressure reaches an actuation level and when the valve is fully opened or closed. During this time, tank pressure will continue to change in the undesired direction. These undershoots and overshoots must be accounted for in proper tank pressure control so that systems are not inadvertaently actuated or structural requirements violated. Pressurization overshoots and vent system undershoots are assumed to be 0.20 psia. Undershoot due to propellant outflow during engine burn is assumed to be 0.05 psig. Undershoot due to propellant outflow during engine burn is assumed to be 0.05 psig, while overshoot due to tank heating is assumed to be negligible. High and low pressure values are assumed to be equal with the exception of the vent undershoot. Since vent rate is directly proportional to tank pressure, high-pressure vent undershoot is taken to be 4.0 times that of the low-pressure system.

4) Margin—Critical functions should include some degree of margin to insure vehicle safety. Using this method, tank pressurization and vent bands for engine burn and coast periods can be determined for two types of vehicles. For the low-pressure, conditioned-propellant vehicle, a maximum liquid vapor pressure of 5 psia was selected as the lowest practical pressure to: 1) allow no vent-propellant transfer, 2) permit use of the thinnest manufacturable aluminum tank gage, 3) potentially allow for operation of a thermodynamic vent system, and to 4) insure tank pressure remains above the triple point.

For the high-pressure vehicle, 20-psia liquid vapor pressure will meet the above requirements for nonconditioned propellant, with the exception that higher pressure tanks affect tank wall thicknesses and increase vehicle weight.

For engine burn (Fig. 5), the tanks must be pressurized above the liquid vapor pressure to provide a low-quantity fluid at the boost pump inlet. Engine feed system analysis for the low-pressure system identified the differential pressure required to provide saturated liquid to the boost pump inlet (2.0 psig LH_2; 1.5 psig LO_2). Since the boost pumps will operate with some vapor at the inlet, margin exists for this critical function.

Because configuration is likely to dominate engine feed line loss coefficients, it is assumed that the pressure drop for the high-vapor-pressure system is the same as that of the low-pressure system. Accounting for measurement system uncertainty and pressurization system undershoot, the pressurization bands are defined as 7.15–7.25 psia LH_2 and 6.65–7.00 psia LO_2 for the low-pressure system.

The vent band must be set high enough above the pressurization band so that, nominally, the vent will never be actuated. The vent band is also set so that if venting should occur in the event of a failure, undershoot and measurement uncertainty would not activate the pressurization branch. In addition, the pressurization and vent bands are separated by more than the minimum requirements, when possible. Thus, the vent bands are defined as 7.55–7.65 psia LH_2 and 7.85–8.35 psia LO_2. Maximum operating pressure is the vent-open level increased by overshoot and measurement system uncertainty. The design pressure must be at least 1.4 times the maximum operating pressure.

The high-pressure system requires a maximum operating pressure of 23.60 psia LH_2 and 24.25 psia LO_2. The low-pressure system can operate below 8 psia for the hydrogen tank and 8.65 psia for the oxygen tank. Note, however, that the LH_2 tank pressurization and vent bands are as narrow as possible and very near to each other. Fast-acting valves to minimize overshoots and undershoots and low-pressure-drop engine feed components to minimize pressurization requirements are necessary to function with these compressed levels. In addition, pressure transients such as those that can occur when cold liquid sloshes into a warm ullage must be accommodated.

For coast periods between engine burns (Fig. 6), periodic venting may be required to accommodate tank heating. In addition, since the maximum liquid vapor pressure during engine burn is 5.0 psia (to maintain pressure control below 11.20 psia LH_2 and 12.11 psia LO_2), the levels during coast must allow the tank to be vented to 5.0 psia. (Software logic that will initiate a vent cycle immediately before every burn if tank pressure is above 5.0 psia is likely to be required to condition the propellant for engine burn.) A vent band of 1.5 psig will require venting about every 40 h. Also, tank pressure must nominally remain above the triple-point pressure.

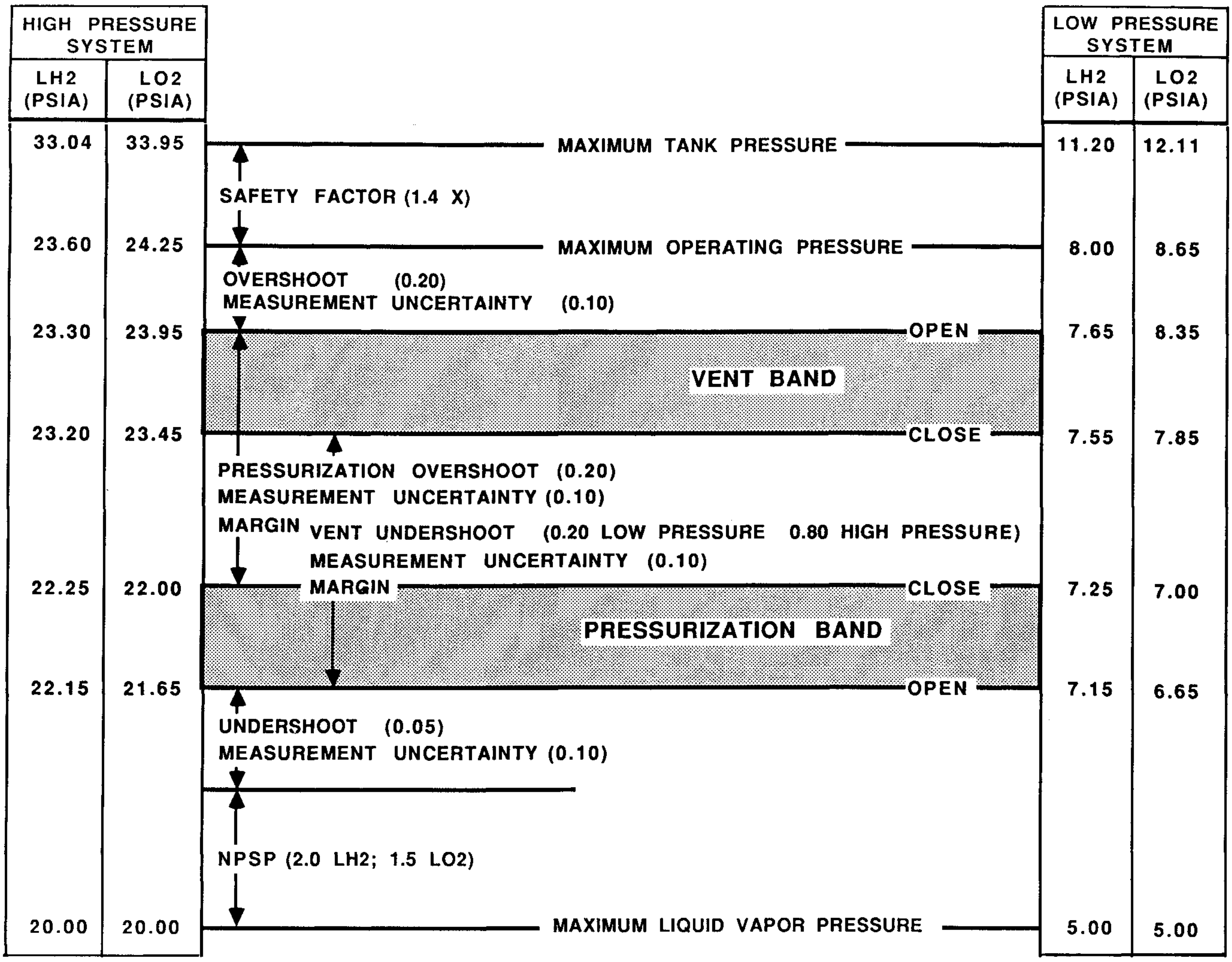

Fig. 5 Tank pressure control for engine burn.

These requirements set the vent bands at 4.90 to 6.40 psia for both LH_2 and LO_2 tanks. Since the tank membrane is structurally stable at 0 psia, and two failures must occur before the triple point is reached and freezing begins to occur (safe vehicle but probable loss of return capability), a pressurization band is not required. Since pressurization is not required during coast, an autogenous system can meet all pressurization requirements. This enhances vehicle safety since a pressurization branch failing to open will not affect tank pressure during coast. An additional level of protection is required to prevent tank overpressurization in the event of a dual failure that renders the vent system inoperable. At this level, the engine feed system is opened to reduce pressure by expanding the ullage volume. The band must be set high enough above the vent system to prevent inadvertent actuation of the engine feed system during nominal venting. In addition, since dumping propellant overboard could result in loss of return capability, the engine feed band is set as high as possible to delay liquid loss. Thus, the engine feed bands are defined as 7.70–7.90 psia LH_2 and 8.35–8.55 psia LO_2.

The maximum operating pressure is the engine feed open level increased by overshoot and measurement system uncertainty. And again, design pressure must be at least 1.4 times the maximum operating pressure. Figure 6 shows that significant margin exists between control bands for the coast periods. Therefore, engine burn drives tank pressure control design.

Pressure History Modeling

Pressurization profiles of the LH_2 and LO_2 propellant tanks for this vehicle configuration were determined for a 72-h, single-tankset mission and for 17- and 30-day, triple-tankset configurations. An existing computer code called Hydrogen Pressurization System (HYPRS) is used to perform these analyses. This program was originally written to model the Centaur hydrogen tank pressurization system. Pertinent tank heating rates, propellant outflow rates, pressurant conditions, and flow rates are employed. The code also considers liquid propellant/ullage and wall/ullage heat transfer. The analyses are based on the tank pressure control levels previously recommended. For a given mission scenario, the venting requirements, residuals, and pressurant requirements depend on the type of pressurization system used. The following pressurization systems were studied:

1) Autogenous—Hot propellant gas is bled from the engine feed lines and recycled into the propellant tanks to provide the required net positive suction pressure (NPSP) for main engine start (MES) and for steady-state operation during the burns. Autogenous pressurant is provided before engine firing by taking advantage of the bootstrapping capability for pre-MES pressurization.

2) Helium bubbler pressurization—Ambient helium gas is supplied to the LO_2 tank through a bubbler ring. Bubbling helium through only the LO_2 propellant tank at typical LO_2 tank conditions is more efficient than ullage pressurization because LO_2 boiloff into the helium bubbles contributes significantly to tank pressurization. Bubbler efficienty has been determined from Centaur flight data.

3) Helium ullage pressurization—Bubbler pressurization considerably increases helium usage at typical LH_2 propellant tank conditions. Consequently, helium pressurization of the LH_2 tank is accomplished by injecting helium into the ullage

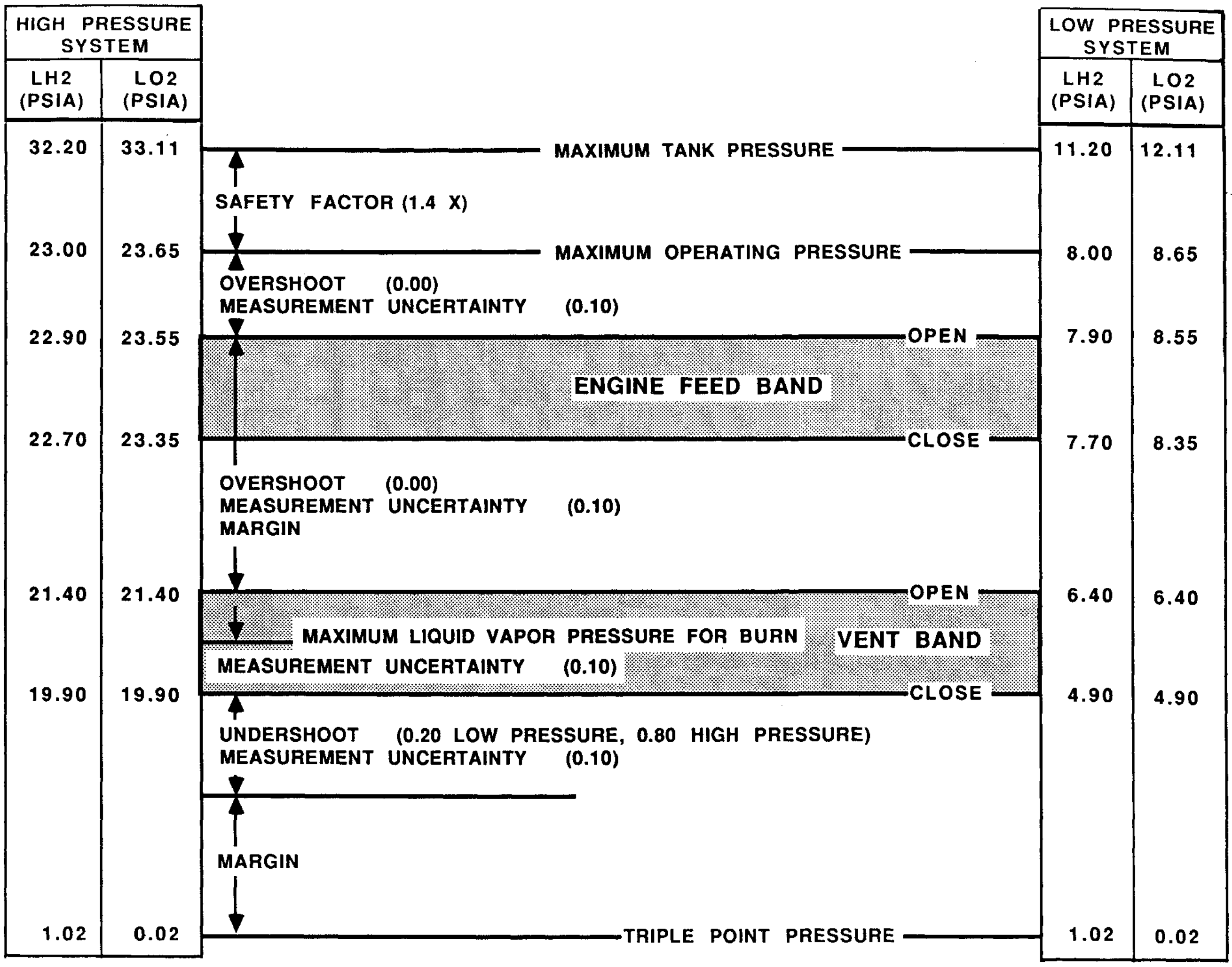

Fig. 6 Tank pressure control for coast.

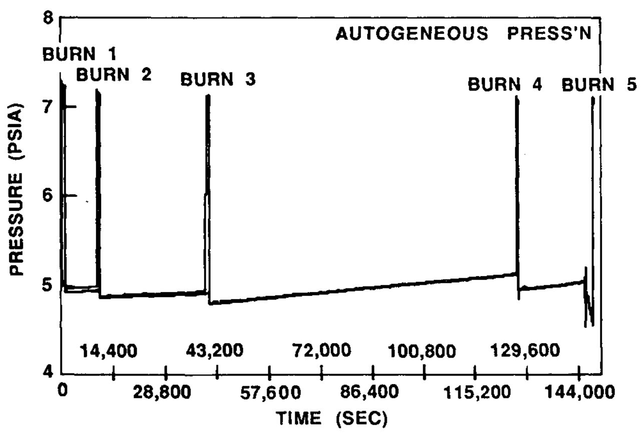

Fig. 7 LH_2 tank autogenous pressurization profile for a single-tankset SBOTV—72-h mission.

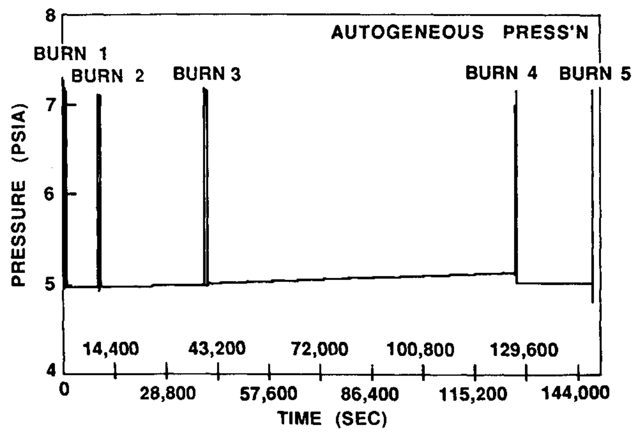

Fig. 8 LO_2 tank autogenous pressurization profile for a single-tankset SBOTV—72-h mission.

via an energy dissipater. The dissipater forces the helium to flow along the tank wall, decreasing disturbance of the liquid's surface by lowering the velocity at which it impinges on the liquid surface. In this study, a system involving helium pressurization for pre-MES operations and autogenous pressurization during engine burns was analyzed for both the LH_2 and LO_2 tanks.

As detailed previously, tank pressures are maintained near 7 psia during the engine burns to satisfy NPSP requirements. During coast periods, the propellant tanks are vented to 5.0 psia to condition propellants for the subsequent burns. Figures 7 and 8 show LH_2 and LO_2 pressurization profiles for a 72-h mission. Similar pressurization profiles were made for 17- and 30-day missions. Tank blowdown will be accomplished by TVS operation. Further investigation into TVS operations at low tank pressures is required to insure adequate capability and tank pressure control.

Changes in vehicle accelerations at main engine cutoff will cause propellants to oscillate in the propellant tanks. Propellant sloshing up the warm sidewalls produces additional boiloff. Propellants may also be thrown forward into the ullage, chilling the ullage and generally causing a collapse in tank pressure. This quench/mix sequence is assumed following each burn to maximum propellant boiloff. During coast periods, the propellants are also measured to mix with the tank ullage (zero-*g* conditions). An equilibrium pressure is assumed during these times; this maximizes propellant boiloff and pressurant requirements for each burn.

The optimum pressurization system is determined by evaluating overall system weight penalties. Propellant vent masses, pressurant requirements, and overall system weight penalties for the pressurization systems were studied. The results indicate that an entirely autogenous system for both tanks is the most efficient in terms of weight savings and/or payload capability. The high LO_2 vent masses and LO_2 tank helium usages are the greatest differences in determining an optimum system. The substantial increase in coast time for the 30-day mission results in an increase in the total heating, which increases propellant vent requirements.

Tankage Structural Design Criteria

There are specific design criteria relevant to the basing mode of each OTV concept. However, it is beyond the scope of this paper to address all criteria, such as slosh loads, asymmetric pressure loads, and specific point loads, that would be required in the detail design criteria of tankage structure. For conceptual or preliminary design studies, a brief list of major criteria can be established to size the tank structure based on loads. For the baseline vehicle in this study, design criteria include:

1) 5-psia tank quiescent ullage pressure of the low-liquid-vapor-pressure system: 8.00 (LH_2), 8.65 (LO_2) psia maximum operating pressure during engine burn; and 8.00 (LH_2), 8.65 (LO_2) psia during coast.

2) 20-psia tank quiescent ullage pressure for the high-liquid-vapor-pressure system: 23.60 (LH_2), 24.25 (LO_2) psia maximum operating pressure during burn; and 23.00 (LH_2), 23.65 (LO_2) psia during coast.

3) Safety factor of 1.4 on material ultimate strength.

4) Safety factor of 1.1 on material yield strength.

5) Design life of 40 flight mission with a scatter factor of 4 (the number of actual full pressurization cycles in the tanks is greater).

6) Leak-free containment.

7) Micrometeoroid and debris protection for a 0.999 probability that no debris will impact the tank wall on a given mission and 0.96 probability over the design life of 40 missions.

8) Ground rules for system failure tolerance: 0 failures = mission success, 1 failure = safe return, and 2 failures = safe vehicle, no return.

9) A mission model was provided for vehicle sizing and to establish mission timelines.[4]

10) Tank shells must be structurally stable at 0.00 psig across the membrane since on-orbit propellant loading and tank conditioning require complete draining of all residual gases and fluids.

Materials

The cryogenic propellants LO_2 and LH_2, at temperatures of 145.8 and 30.8°R, respectively, at 5 psia, must be contained by compatible materials. The choice of materials is critical because many materials are LO_2-sensitive and/or embrittled by hydrogen. The low-temperature environment may also reduce ductility and fracture toughness of the tank materials to unacceptably low levels. There is a structural design criterion that fatigue resistance be provided to preclude failure for 40 missions. When accounting for the actual number of full pressurization cycles in the tanks, this may grow to an estimated 400–1000 leak-free pressurization cycles. Leak-tight tanks require that no cracks grow through the thickness on the tank structural wall for the life of the tank. In cryogenic tanks, a crack through the thickness, while not of critical size structurally, can be catastrophic because leaking propellants pose a fire/explosion hazard.

For lightweight welded structures that must operate at cryogenic temperatures, aluminum alloy 2219 is generally the preferred material of construction. Aluminum alloys possess high specific strength and stiffness, excellent fabricability and corrosion resistance, ready availability in many product forms, and low cost. In addition to these desirable characteristics, alloy 2219 is also easily welded and has superior cryogenic toughness in both unwelded and welded conditions. Several aluminum alloys are weldable, but none is currently capable of developing the cryogenic weld strength levels of 2219, particularly in the aged condition.

Because low vehicle weight is of prime importance in space structures, the low-density aluminum-lithium (Al-Li) alloys currently under development by major aluminum producers are potential competitors to 2219. These alloys have shown encouraging properties in studies to date. Lower density accompanied by higher strength and modulus show the possibility of structural weight reductions of 15% or more. Preliminary data show specific strength values at room temperature for one of these alloys, 2090-T8E41 plate, that are more than 10% higher than 7075-T651 and 40% higher than 2219-T851. Specific modulus values are about 20% higher for the Al-Li alloy.

However, before the Al-Li alloys can be used efficiently as replacements for 2219, a number of requirements must be satisfied. Fracture toughness, particularly at cryogenic temperatures, must be investigated and satisfactory values obtained. Encouraging results have already been found with data to −452°F that appear to indicate the 2090 alloy to be superior to 2219 in the T8 temper.[5] Manufacturability must also be determined, particularly a capability for producing sound welds with adequate cryogenic toughness. Preliminary results indicate that Al-Li alloy 2090 has welding characteristics similar to 2219.[6] Initial welding studies have shown some microcracking in the heat-affected zone, but a solution to this problem is expected through a careful study of weld filler alloy selection and a thorough investigation of weld process parameters. Finally, an extensive data base of both mechanical properties and physical property values is of utmost importance before the design and fabrication of space structures is possible.

All major aluminum producers have research programs underway to speed development of these low-density alloys using ingot metallurgy. Two of the alloys are currently available on a limited basis: 2090 and 8090. Table 2 compares some of the mechanical properties at room temperature and, where available, at cryogenic temperatures of the two alloys with the 2219 alloy.[5,7]

Analytical Procedure

It is necessary to establish a procedure[8] for estimating OTV tank wall thicknesses, since the need to minimize structural in-

Table 2 Properties of 2090, 8090, and 2219 aluminum alloys

Property	E	F_{tu}[a]	Density	F_{ty}[a]			K_{IC}			F_{tu}/density
Units	MSI	KSI	lb/in.[b]	KSI			KSI × (in.)$^{1/2}$			in. × 10[c]
Temp., °F	70	70	70	70	−320	−423	70	−320	−423	70
2090-T8E41[b]	11.0	82	0.092	77.6	87.0	89.2[d]	31	47	59[d]	8.91
8090-T8[c]	—	70	0.092	60	—	—	55	—	—	7.6
2219-T87	10.5	63	0.102	56.0	66.9	74.3[d]	33	39	44[d]	6.17
2219-T62	10.5	54	0.102	36.0	42.8	48.6	32	35.5[e]	35.5[e]	5.29

[a]Longitudinal data. [b]Data from Ref. 5. [c]Data from Ref. 7. [d]Data at −425°F. [e]Data at −320°F.

ert weight and propellant consumption entails critical assessment of tank wall thickness. An initial sizing can be based on membrane load and material allowables for the burst pressure design. Initial flaw sizes needed to calculate the number of pressurization cycles to failure can be found by one of two methods: setting the initial flaw size to the smallest inspectable by nondestructive evaluation techniques, or using proof tests to screen out the largest flaw size in the tank wall.[9] By inspection techniques, for the very thin gages under consideration for the low-pressure cryogenic tanks, these flaw sizes will be greater than the wall thickness.[10] Requiring the wall thickness to exceed the crack length or be greater than the largest undetectable crack/flaw may impose an unnecessary weight penalty on the vehicle. Therefore, proof tests are necessary.

Proof testing is performed to insure that the largest flaws existing in the vessel are below the size that would grow to the critical length during the operating lifetime and to establish tank wall thicknesses.[8]

Results from either method are used in a flaw growth, service life analysis to determine three things: 1) Final crack length after four lifetimes, 2) critical crack length for failure, and 3) number of flights to failure. Finite-element models can then be built for static and stability analyses of tanks. Dynamic analysis can determine vehicle mode shapes and natural frequencies. Finally, a check on tank wall gages to satisfy dynamic, static, and stability conditions could be performed before recommending a final design.

Tank Wall Sizing

Ullage pressure and dynamic pressure head induced by flight acceleration levels, plus fracture mechanics fatigue life requirements, and the need to minimize structural inert weight (which increases the mass fraction) are considered in sizing a tank wall structure that will meet the tank design life.

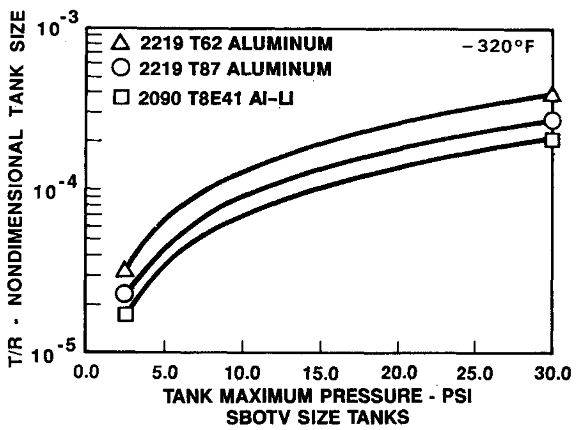

Fig. 9 Nondimensionalized tank features vs pressure for spherical LO_2 tanks.

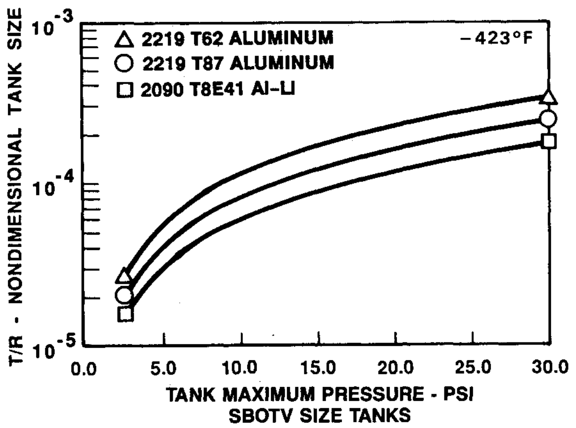

Fig. 10 Nondimensionalized tank features vs pressure for spherical LH_2 tanks.

Pressure Loads

Cryogenic propellant tanks must be pressurized above the liquid vapor pressure to provide proper engine inlet conditions. This pressure is used in initially sizing the tank membrane thickness. Vehicle acceleration levels are low (about 0.2 *g*), so the resultant dynamic pressure head is not a significant contribution to the wall thickness, as indicated in finite-element modeling.[11] Figure 9 is a graph of LO_2 spherical tank wall dimensions for a spectrum of pressures spanning from the low vapor pressure levels through the high pressure levels. Figure 10 is a graph of LH_2 spherical tank dimensions for the same span of pressures. The ordinate on each has been nondimensionalized by showing t/R. The t/R value is calculated from:

$$t/R = P/2F_a$$

The tank wall allowable stress F_a is determined from the lesser of the yield strength divided by 1.1 or the ultimate strength divided by 1.4.

The graphs are thus generally applicable to a broad spectrum of spherical tank radii at these pressure levels, and indicate that wall thicknesses can be extremely thin if sizing is based only on the pressure load requirements of this analysis. For example, an 80.0-in.-radius spherical LH_2 tank needs a wall thickness of only 0.010 in. in 2090-T8E41 when operating at 20 psia and a thickness of only 0.003 in. when operating at 5 psia in the same material. Similarly, a 60.0-in.-radius spherical LO_2 tank of 2090-T8E41 operating at a pressure of 20 psia needs a wall thickness of only 0.009 in. and for operations of 5 psia, a wall thickness of 0.002 in.

The wall thicknesses are much thinner than current state-of-the-art manufacturing processes permit, given the tolerances required in the chemical milling process. Therefore, the results shown in Figs. 9 and 10 are initial membrane-sizing estimations only, based on strength analyses. Chemical milling of sample aluminum sheets has indicated that the minimum practically achievable thicknesses are on the order of 0.008 in. This fact, when combined with a knowledge of contemporary manufacturing processes and tolerances on the chemical milling process of ±0.002, imposes a minimum thickness of 0.008 in., irrespective of strength analyses. However, these are not the only requirements establishing wall thicknesses.

Fracture Mechanics

Fracture mechanics analyses are required on all cryogenic tanks to demonstrate that the maximum size flaw or crack-like defect that could exist after proof testing and nondestructive evaluation will not grow to critical size and cause premature failure during the required service life.[12]

The service life of a structural member above its endurance limit is dominated by its fatigue and fracture mechanics properties. Fatigue occurs when a crack forms at or below the surface of the structural member, while fracture mechanics describes the growth of existing cracks. For space vehicle structures, the flaw is assumed to be present before flight service and that the life is the number of missions it takes to grow this flaw to a critical crack size. The computer program FLAGRO is an automated procedure that predicts the propagation of various flaw shapes in structural members under variable-amplitude spectral loading environments.[13]

Fracture analysis of the very thin 2090-T8E41 Al-Li tanks demonstrates that initial cracks too small to be through cracks have negligible growth during one service life. Further, for these very thin gages, any initial cracks from manufacturing would almost surely be through cracks that would be detected during leak testing. However, fracture analysis of the tanks is performed using much larger cracks to demonstrate a reasonable amount of tank damage tolerance. This means that the

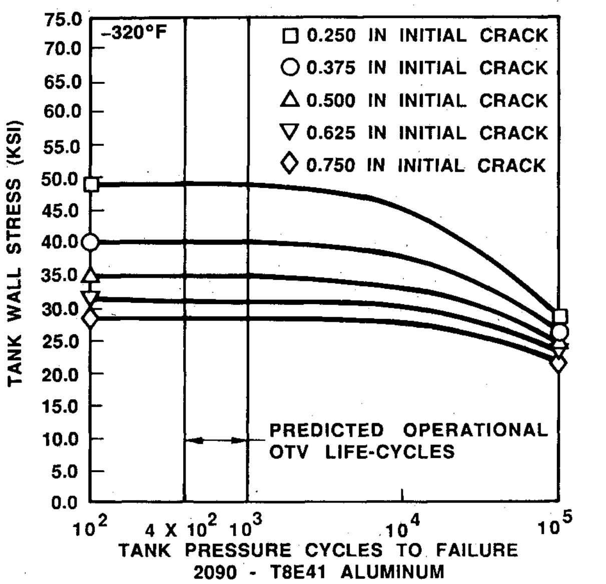

Fig. 11 Fracture life of tank walls/tank pressure cycles to failure for 2090-T8E41 aluminum.

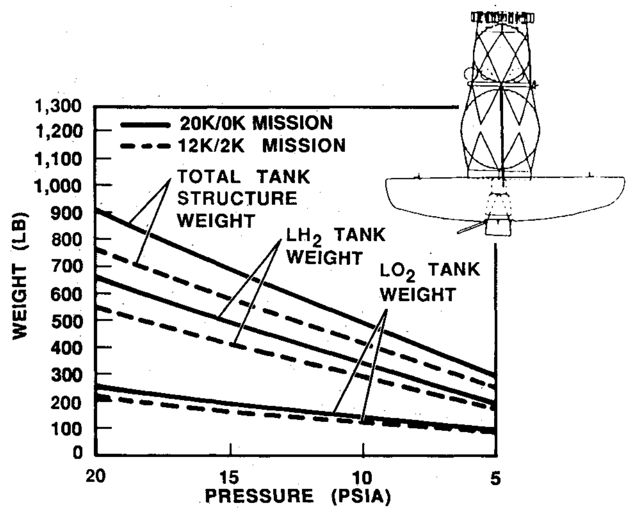

Fig. 12 Influence of tank pressure on tank structure weight of S-4C SBOTV vehicle concept.

tank would survive a small penetration by space debris or from servicing without catastrophic failure.

The FLAGRO program was used to generate the curves in Fig. 11 of the fracture fatigue life for 2090-T8E41 Al-Li tanks. These curves show the tank wall stress vs the number of cycles to failure based on initial crack lengths varying from 0.25–0.75 in. The curves were based on the number of full pressure cycles at a given stress level that would be required to grow the initial through crack to rupture. These curves were generated from fracture data for 0.5-in.-thick 2090-T8E41 plate at $-320°F$ (Table 2) from the curves of Ref. 5, Fig. 6. The program used the data directly to calculate the crack growths rather than attempting to fit the data to a Paris or Collipriest equation. The curves here would be somewhat conservative, since the fracture toughness for the very thin tanks would be higher than the fracture toughness for 0.5-in. plate. On the other hand, there may be some nonconservatism, since the fracture toughness at $-452°F$ may be lower than given a $-320°F$.

This approach demonstrates by analysis that the service life requirement is met. But, the assumptions regarding the initial flaw sizes selected and the capability to inspect for very small flaws in thin-gage tanks must be evaluated. For example, analyses show that critical flaw sizes are much greater than the tank wall thickness for these alloys, thereby imposing a new constraint on the applicability of existing nondestructive inspection techniques. This is just the opposite of cases in which computed critical crack size is much smaller than potential cracks resulting by either choosing an alternative material having a higher fracture toughness or using a lower operating stress level with the same material.

Weights

Lowering the level of the LH_2 and LO_2 liquid vapor pressure level in the SBOTV propellant tanks permits the use of thinner shell wall thicknesses, which, in turn, reduces the structural inert weight of the vehicle and raises its mass fraction. This factor can reduce propellant consumption by the vehicle to perform any particular mission and reduce total propellant consumed over the lifetime of the vehicle's mission model. Propellant delivery-to-orbit costs constitute a significant fraction of the total LCC of a reusable SBOTV system. Thus, reducing propellant consumption translates into cost savings. A weight trade study is performed to quantify the amount of weight savings potentially available when cryogenic tank pressures are varied incrementally from 5–10 to 15–20 psia.

For a 20,000-lb delivery to geosynchronous Earth orbit (GEO) with 0-lb return (20 K/0) mission, 466.7 lb can be saved in the LH_2 tanks shell if the operating pressure is reduced from 20 to 5 psia; 156.4 lb can be removed from the LO_2 tank shell for the same mission. For a 12,000-lb delivery to GEO with 2,000-lb return (12 K/2 K) mission, 385.3 lb can be saved in the LH_2 tank if the operating pressure is reduced from 20 psia to 5 psia; 125.7 lb can be saved in the LO_2 tank for this mission.

This weight trend is graphically represented in Fig. 12 for both missions, both LO_2 and LH_2 tanks, and the cumulative tanks' structure weight for the S-4C vehicle configuration. A total of 623.1 lb of combined LH_2 and LO_2 tank structure weight can be saved on the core tankset of the S-4C when sized for the 20 K/0 mission. And 511 lb of combined LH_2 and LO_2 tank structure weight can be saved in the core tankset of the S-4C when sized for the 12 K/2 K mission.

Representative Tank Design Concept

A set of initial tank wall gage thicknesses can be recommended for both the low- and high-pressure cryogenic systems based on the salient finding of this study:

1) Thickness-to-radius relationships have been developed for spherical tanks for two different aluminum alloys for both LO_2 and LH_2 temperatures, as shown in Figs. 9 and 10.

2) Fracture fatigue life analysis shows sufficient pressurization cycle life in these thin gages.

3) A few test aluminum specimens plus consultations with manufacturing representatives indicate that minimum manufacturable gages by chemical milling are on the order of 0.008 in. for flat sheet specimens.

Figures 13 and 14 compile these findings into a set of recommended tank wall gages for the S-4C SBOTV vehicle concept 166.0-in.-diam LH_2 tank and the 119.0-in.-diam LO_2 tank, along with the potential to manufacture tanks using either of the two alloys. Note that the minimum thickness, 0.008 in., is established for both tanks irrespective of strength requirements, which are proportional to pressure level. Two particular pressure levels are delineated: maximum tank operating pressure for both the low-vapor-pressure system and the high-vapor-pressure system for both LO_2 and LH_2 tanks. The 2090-T8E41 curve allows thinner gages than the 2219-T87 alloy because of its higher tensile strength. However, full cryogenic compatability of this material with LO_2 and LH_2 is yet to be developed to thoroughly support its selection. The 2219-T62 alloy and final condition give the thickest gages of the three. A manufacturing process that can produce tanks of the higher-strength tempers would be preferable to reduce weight.

Figure 15 is an overview of the core propellant tank structure design of this vehicle configuration. Interior reinforcement structure is needed for the membrane (regardless of membrane thickness). On-orbit propellant transfer operations for a fully reusable SBOTV require a complete purge of all residual warm gases and liquids in the tanks before refilling with LH_2 and LO_2. A prechill operation cools the tank walls to the appropriate temperature by injecting a small amount of LH_2 and LO_2 into the respective tanks. The liquids "flash" in the warm tanks and cool the walls. This gas is then purged before filling operations begin. For this operational reason, it is unacceptable to leave an unreinforced, thin-skin tank in an upressurized state. The vacuum condition of space does not necessitate reinforcement of thin skins. However, the danger of gas and fluid transients within the tank walls together with unforeseen momentary movements at the propellant docking/loading facility indicate the need for interior reinforcement.

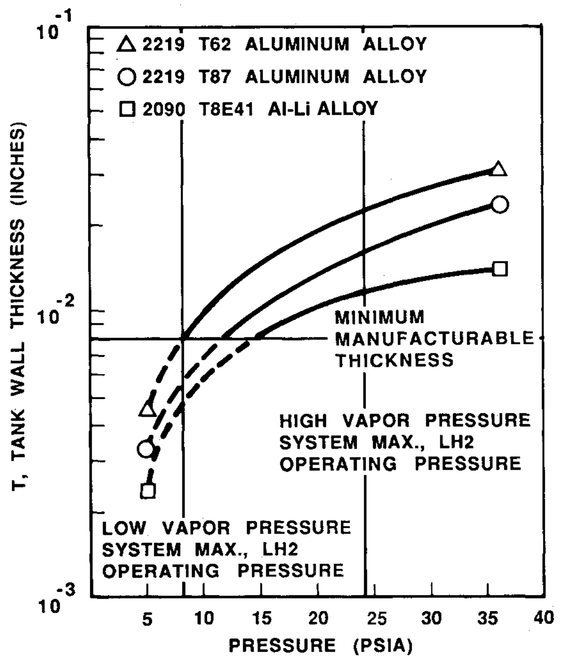

Fig. 13 S-44C SBOTV LH_2 tank wall thickness for 166-in.-diam spherical tank.

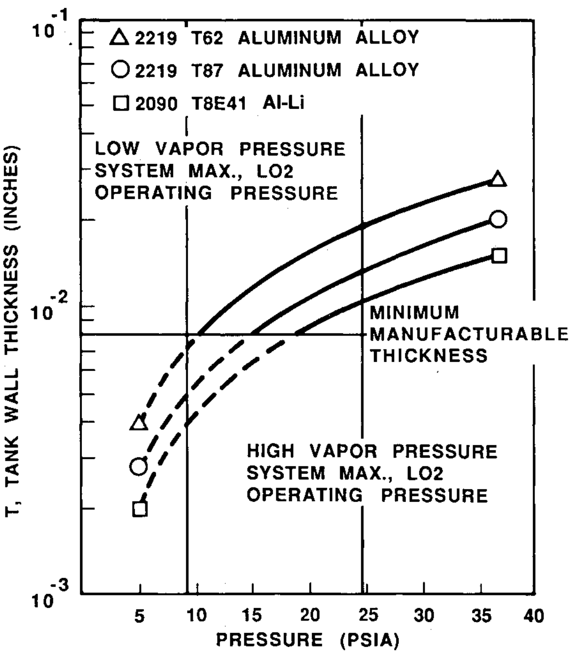

Fig. 14 S-4C SBOTV LO_2 tank wall thickness for 119-in.-diam spherical tank.

To satisfy this requirement, reinforcing structure is designed into the shell to support the skin while unpressurized. Also, tank skins are designed to not carry any axial or moment loads from the flight vehicle. Axial and bending moment loads from the flight vehicle are carried through the load carrythrough structure, not the tank wall membrane, in this design. Shell membranes carry pressure loads only from tank ullage pressure plus sloshing and dynamic pressure head from accelerations. To meet these requirements, a series of longitudinal and latitudinal interior rings supports the tank skin. Longitudinal rings follow the gore sections' weld line perimeters. The rings are slender "I" sections with web member thicknesses calculated to provide stiff support with minimal deflection of skins. A series of small longitudinal stringers span the distances between the longitudinal rings and thereby provide needed skin support. These interior structural support members also provide reinforcement during ground transportation, the Earth-to-orbit launch environment, multi-*g* launch loads, accelerations due to reaction and attitude control system firing, and due to hard dockings. The cryotankage wall construction may be envisioned as a system composed of internal reinforcement members, the fluid containment and pressure membrance, the multilayer aluminized Kapton insulation system, and finally the outermost face sheet for high-temperature protection and micrometerioid/debris shielding.

The composite support struts attach to the exteriors of the tanks at brackets welded onto thicker chem-milled lands. All vehicle axial loads resulting from thrust accelerations pass through this strut system. Since the axial centerlines of the struts are tangential to the tanks, radii or curvature and the corresponding rod ends are some distance apart, as shown in Fig. 15, a system was designed that would pass the loads from one strut to the next, independent of any need to maintain tank pressurization to control strut position. Accordingly, in addition to the interior rings and stringers that support the skin, two exterior rings are installed to maintain the spacing between the six strut attachment brackets around the perime-

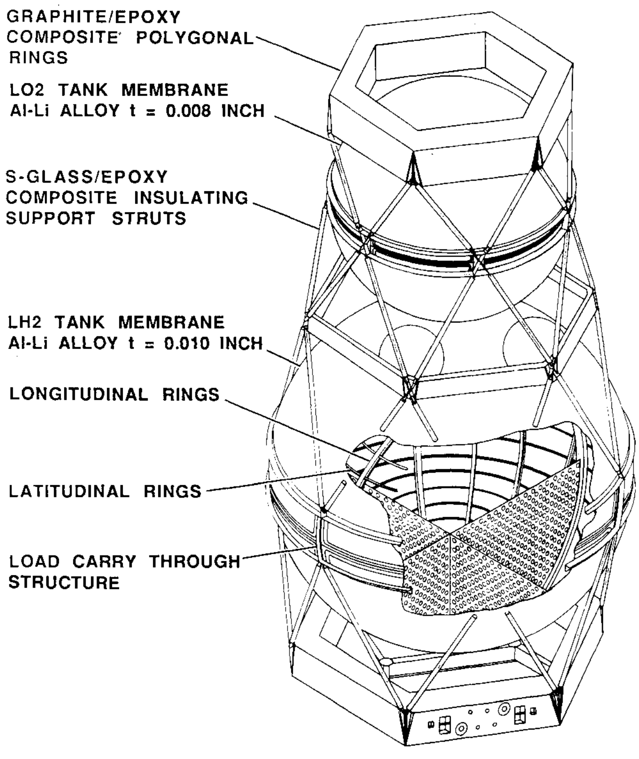

Fig. 15 S-4C SBOTV core propellant tank structure. (Micrometeoroid shielding and insulation not shown for clarity.)

ter of the tank. The tank interior stucture supports a full-channel liquid acquisition device (LAD), fluid baffles, and a main feed outlet at the junction of the LAD channels.

Conclusions

The opportunity to design cryogenic propellant tanks for a new, fully reusable, on-orbit-serviced upper stage imposes some new design constraints—not all of which have been addressed by prior cryogenic missile systems. The tank shells must be very lightweight to minimize costly propellant consumption, yet be durable enough to provide fatigue life extending beyond the predicted service life. These needs prompt an investigation of low-vapor-pressure cryogenic fluids, lower-density aluminum-lithium alloys, fracture control, and inspection technique to detect very small flaw sizes, and an evaluation of operational safety issues. The required analytical design techniques appear close at hand.

The manufacturability and inspectability of full-scale shells in the thin gages discussed herein need considerably more work. Chemical milling processes may be capable of yielding tank skins about 0.008-in. thick. Consequently, this process may be the limiting factor in producing thin-skin aluminum tank unless alternative thin-gage forming methods are explored.

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