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High-Payoff Space Transportation Design Approach with a Technology Integration Strategy

C. M. McCleskey[1] and R. E. Rhodes[2]
NASA Kennedy Space Center, Florida 32899

T. T. Chen[3]
NASA Marshall Space Flight Center, Huntsville, Alabama 35812

J. W. Robinson[4]
Propellant Supply Technology, Seal Beach, California 90740

This paper describes a general approach for creating architectural concepts that are highly efficient, operable, and supportable, in turn achieving affordable, repeatable, and sustainable space transportation. The paper focuses on the following: (1) vehicle architectural concept (including important strategies for greater reusability), (2) vehicle element propulsion system packaging, including integrated main and auxiliary propulsion systems, (3) vehicle element functional integration, (4) ground element functional integration, (5) simplified and automated electrical power and avionics integration, and (6) ground and flight testing before production commitments. We also provide four essential technologies that enable the high-payoff design approach: (a) parallel-tank propellant storage, such as concentric-nested tanks, for more efficient space vehicle design and operation, (b) high-thrust, LO_2-rich, LO_2-cooled first-stage earth-to-orbit main engine, (c) nontoxic, day-of-launch-loaded propellants for upper stages and in-space propulsion, and (d) electric controls for propulsion.

Nomenclature

CH_4	=	methane
EHA	=	electrohydrostatic actuator
EMA	=	electromechanical actuators
GSE	=	ground support equipment
I_{sp}	=	specific impulse
LH_2	=	liquid hydrogen
LO_2	=	liquid oxygen
LRU	=	line replacement unit
psi	=	pound per square inch
RP-1	=	Rocket Propellant - 1
SCAPE	=	self-contained atmospheric protective ensembles
SPST	=	Space Propulsion Synergy Team
TPS	=	thermal protection system
TVC	=	thrust vector control

[1] Aerospace Technologist, Engineering Directorate, NASA Kennedy Space Center, mail code NE-D1, and AIAA Senior Member.
[2] Aerospace Technologist, Engineering Directorate, NASA Kennedy Space Center, mail code NE-D1, and AIAA Senior Member.
[3] Lead Aerospace Engineer, Spacecraft and Vehicle Systems Department, NASA Marshall Space Flight Center, mail code EV-91, and AIAA Senior Member.
[4] Propellant Supply Technology; chairman, Space Propulsion Synergy Team, and AIAA Associate Fellow.

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Introduction

A six-step process is suggested to provide a general architectural design sequence to create a highly efficient, operable, and supportable design that achieves an affordable and economically sustainable transportation function.

Six Critical Steps to an Affordable, Economically Sustainable System Design

1. *Simplify the vehicle/ground system architecture.*
2. *Efficiently package the propulsion system of each vehicle element (e.g., tank, engine, and compartment layouts).*
3. *Integrate vehicle element functions into the lowest number of subsystems/components with minimum ground support requirements.*
4. *Integrate ground element functions into the lowest number of workstations, facilities, and items of support equipment.*
5. *Simplify avionics and flight control design into minimum components; then, power and automate what's left.*
6. *Extensively flight-test to demonstrate accomplishment of all production and operations needs and objectives for full operational system capability within the cost objective.*

These steps are important to perform during early conceptual design to avoid the accumulation of unaffordable design, development, production, and ground operations work. Through adherence to these steps, one can also avoid delays that increase costs and thus achieve the objectives of life cycle affordability and operational sustainability.

A separate section for each step discusses the specifics of the approach and how each step addresses technical criteria that influence space transportation affordability and sustainability. This paper uses the criteria developed by the Space Propulsion Synergy Team (SPST), a NASA-sponsored volunteer group of experienced government, industry, and academia colleagues in the space propulsion community.[1]

Specifically, the SPST identified 18 highly influential criteria as design drivers of space transportation affordability and sustainability. These 18 criteria and their influence on life cycle affordability and sustainability are examined in depth by Rhodes et al.[2]

This paper adds another criterion—*reusability:* the ability of a system, or parts of a system, to be reused for multiple flights.

A system with low reusability requires a high degree of work for its next flight. A system with high reusability is assumed to be one that fully retains its functional integrity between flights, and thus little or no work is required other than handling payloads and servicing propellants. Highly reusable systems are more affordable by (1) minimizing routine purchases of expensive flight equipment by its owner-operator, (2) reducing routine maintenance expense, and (3) increasing system productivity through quicker processing. Therefore, we can logically conclude that highly reusable system designs and advanced technologies are needed to enable affordable and sustainable space transportation.

The savings from reusability become less clear when low-reusability systems (e.g., ocean-retrieved elements) are compared with fully expendable systems.

The 19 criteria and their correlation with key life cycle affordability parameters are shown in Table 1. The paper concludes by identifying specific technologies and design approaches that support the steps described in achieving the overall objectives of affordability and economic sustainability.

Step 1. Simplify the vehicle architecture.

A. Discussion/Specifics

Simplify the vehicle by minimizing the number of unique vehicle elements, and maximize reusability in those that remain in the concept.

This keeps the number of production and operation ground stations to a minimum and therefore holds the marginal and fixed operating costs to a minimum. A high degree of reusability precludes the need for the owner-

operator to routinely purchase expensive flight equipment and replacement parts. The minimum number of elements minimizes annual fixed costs associated with producing, supplying, servicing, and maintaining each unique stage or element. Finally, a simplified flight system made up of a minimum number of elements enables a simplified ground system. A simplified ground system not only reduces fixed costs for infrastructure support but also decreases direct operating costs per flight by reducing work content and eliminating many time-consuming tasks. Savings in work and time increase the use, affordability, and sustainability of the system for the equipment owner-operator.

B. Specific Engineering Criteria Addressed for Improvement

Step 1 directly addresses about half of the 19 engineering criteria for achieving affordable and sustainable space transportation systems (see Table 1 for specific correlations to affordability):

- *Percentage of elements and systems that are highly reusable*
- *Total number of separate identified vehicle propulsion systems or separate stages*
- *Total number of flight tanks in the architecture*
- *Number of unplanned maintenance actions before or between missions*
- *Number of planned maintenance actions before or between missions*
- *Total number of traditional ground interface functions required*
- *Total number of vehicle element-to-element support systems*
- *Number of flight vehicle servicing interfaces*
- *Number of confined/closed compartments*
- *Number of mechanical element-mating operations*

Step 2. Efficiently package each vehicle element's propulsion system.

A. Discussion/Specifics

Design a far more compact vehicle, whose cryogenic propulsion systems are far simpler to operate in flight and on the ground than those of current designs.

1. *Use the minimum number of main- and auxiliary-propellant commodities, preferably only oxygen and hydrogen loaded on the day of launch*. The idea is to minimize the design effort, recurring production work, and ground processing time and expense. Separate propulsion systems increase costs throughout the life cycle.
2. *Keep ground interface connections close to ground level to avoid a series of elevated, articulating umbilicals—particularly, liftoff umbilicals (i.e., T-0 umbilicals or those that remain connected until vehicle first motion).* Avoiding large structures keeps ground system development and maintenance costs down. When such systems are outfitted with active mechanical, plumbing, and electrical systems, the development, maintenance, and operations costs go up and the responsiveness of the system goes down.
3. *Avoid complexities for production and propellant-loading operations, and avoid safety risks of specifying common-bulkhead, tandem tank arrangements, and separate auxiliary propulsion systems*.
4. *Use concentric-nested propellant tanks arranged to preclude complex feed systems and other external subsystems.* (*Concentric-nested* means one tank is concentrically arranged inside another, but the tanks have no common walls.) This approach eliminates long feed lines and a number of active support subsystems for the propulsion function (e.g., long propellant feed lines for the pump feed system, liquid oxygen [LO_2] "pogo" suppression system, and anti-geysering and thermal-conditioning subsystems). Furthermore, concentric-nested tanks minimize the volume and weight of the total system. As such, the approach has wide and far-reaching architectural implications across a number of space transportation applications and across the space transportation life cycle. It also allows the incorporation of advanced concepts such as integrating the turbo-pump into the main propellant tank sump, further reducing the need for added subsystems.
5. *Use a minimum number of main engines with a minimum amount of turbo-machinery and interconnecting main propulsion system plumbing*. The more main engines (meaning devices incorporating feed turbo-machinery, combustion chambers, and exhaust nozzles) there are in the system, the more interconnecting plumbing, avionics, software, and opportunities for reliability problems to accumulate. This rapidly expands the effort necessary to design the main propulsion system, develop and test, continually manufacture (particularly if hardware is expended with each flight), process on the ground, and control risk in flight.
6. *Use electric propellant valve actuation and eliminate distributed hydraulic and pneumatic primary and back-up systems from all engine and propellant system controls (including thrust vector control, but only if differential required).* This approach avoids numerous support systems for the propellant valve controls

and/or gimbaled engines and reduces the number of support systems for the flight vehicle and ground support equipment (GSE). It also means fewer parts to produce and less assembly work, leading to more flights in shorter times with less effort.

7. *In the longer term, consider using LO_2-rich, LO_2-cooled main engine combustion for first-stage earth-to-orbit propulsion that adjusts the mixture ratio back toward stoichiometric ratio as the thrust requirement is reduced during ascent.* This concept reduces the combined propellant tank volume and hence reduces vehicle length and dry weight. This allows a more efficient design for both flight and ground operations. It also promotes the design criteria of a minimum number of propellants since it avoids having to use unique, high-thrust propellant combinations applicable to only lower-altitude, first-stage flight. Use of solid boosters or kerosene is generally considered beneficial for low-altitude, first-stage flight where specific impulse (I_{sp}) is traded for higher thrust. This concept uses a common set of propellants throughout the ascent phase and varies the thrust and I_{sp} characteristics during flight with a minimum number of dedicated systems.

B. Specific Engineering Criteria Addressed for Improvement

Step 2 enables or directly addresses at least 12 of the 19 engineering criteria for achieving affordable and sustainable space transportation systems (see Table 1 for specific correlations to affordability):

- *Total number of separate identified vehicle propulsion systems or separate stages*
- *Percentage of elements and systems that are highly reusable*
- *Total number of traditional ground interface functions required*
- *Number of flight vehicle servicing interfaces*
- *Number of different fluids required*
- *Number of safety-driven functional requirements to maintain safe control of systems during flight and ground operations*
- *Number of confined/closed compartments*
- *Number of safety-driven limited-access control operations*
- *Number of unplanned maintenance actions before or between missions*
- *Number of planned maintenance actions before or between missions*
- *Number of commodities used that require medical support operations and routine training*
- *Number of Criticality 1 system and failure analysis modes*

Step 3. Integrate vehicle element functions into the lowest number of subsystems/components.

A. Discussion/Specifics

Create a generic functional system breakdown structure for each conceived vehicle element, and combine (or integrate) as many functions as possible into singular systems to achieve a minimum of stand-alone, dedicated subsystems.[3] This will minimize the number of accumulated subsystems and supporting components for a given set of required functions. For example, combine various propulsion and power functions with common propellants and fluid commodities to avoid separate fill and drain, storage and distribution subsystems, ground interfaces, and GSE. Also, use technical approaches that inherently require fewer separate support subsystems to perform the function (e.g., use electric actuation to displace distributed hydraulics and its support subsystems and GSE). In so doing, the cumulative design and development effort for both flight and ground support systems is greatly reduced. The recurring production effort is likewise reduced, along with the attendant number of separate suppliers necessary to sustain the system. The recurring ground operations work and processing time are reduced, as well as recurring labor, materials, and other direct costs.

B. Specific Engineering Criteria Addressed for Improvement

Step 3 enables or directly addresses many of the 19 engineering criteria for achieving affordable and sustainable space transportation systems (see Table 1 for specific correlations to affordability):

- *Total number of flight tanks in the architecture*
- *Total number of separate identified vehicle propulsion systems or separate stages*
- *Total number of traditional ground interface functions required*
- *Number of flight vehicle servicing interfaces*
- *Number of different fluids required*

- *Number of safety-driven functional requirements to maintain safe control of systems during flight and ground operations*
- *Number of confined/closed compartments*
- *Number of safety-driven limited-access control operations*
- *Number of unplanned maintenance actions before or between missions*
- *Number of planned maintenance actions before or between missions*
- *Number of commodities used that require medical support operations and routine training*
- *Number of Criticality 1 system and failure analysis modes*
- *Number of safing operations at landing (for reusable elements)*

Step 4. Integrate ground element functions into the lowest number of work stations, facilities, and support equipment.

A. Discussion/Specifics

Keep routine external ground servicing and access requirements simple and to a minimum (e.g., strive for simple turnaround, no masts or towers, and little or no offline processing).

1. *Avoid breaking the functional integrity of any flight systems during ground turnaround operations*. For highly reusable system designs, the objective is to avoid electrical and plumbing disconnections, along with mechanical system disconnections that would require rerigging, recalibration, realignment, and functional checkout. Minimize any operator "closeout" activity by design. This will significantly reduce the routine ground operations work and time necessary to produce a flight.
2. *Require the flight systems to be designed for maintainability as a means of achieving reliability and safety objectives*. This avoids the need to go into a maintenance station during ground turnaround operations.
3. *Locate internal line replacement units (LRUs) near the outer mold line to avoid all internal access for installation or routine change-out.* Doing so eliminates the need for internal access kits for routine operations, conditioned air, controlled personnel entry, and drag-on lighting.
4. *Remove as many closed vehicle compartments as possible.* This approach minimizes subsystem hardware and routine ground operations necessary in such compartments (e.g., purges and hazardous gas detection subsystems). This helps avoid the need to go into a dedicated maintenance station for routine ground turnaround operations (see Figure 1).
5. *Avoid vehicle element design complexity when other passive system design techniques can achieve the same results, potentially with a net weight reduction.* Examples: (1) open truss vs. enclosed compartment, (2) radiation-cooling vs. forced cooling, and (3) main propulsion system tank head start vs. ground-supplied turbine spin start system. Retaining existing functional and hardware complexity also reduces the overall system reliability and safety of flight.
6. *Integrate and use main propellant tanks for auxiliary propulsion and power services wherever practical. Avoid dedicated tank sets.* These require separate subsystem designs; added design, integration, and ground operations; and an associated logistics chain, all of which accumulate both production and ground operations work content. The design objective is to keep the number of plumbing systems that the production line and the operator encounter to an absolute minimum. Provide enough margins to fully account for plumbing interconnects.
7. *Minimize the number of dedicated fluids and gases, as well as the number of separate specialized fluid purities required. All subsystems must be coordinated on this during design definition.*
8. *Locate the remaining vehicle ground servicing points near ground level and avoid elevated fluid system servicing and purge points that require towers with dedicated service arms and access platforms.*
9. *Avoid T-0 umbilicals. However, all unavoidable day-of-launch propellants should have their flight-to-ground interfaces at ground level to avoid system complexities associated with elevated services, umbilicals, etc.*
10. *Load all stage propellants (including spacecraft modules) on day of launch. Avoid assembly operations involving stages and modules with loaded and fully pressurized fluid systems that are considered unsafe. Nonpropellant fluids (e.g., life support fluids and gases) should be loaded before the day of launch.*

B. Specific Engineering Criteria Addressed for Improvement

Step 4 enables or directly addresses many of the 19 engineering criteria for achieving affordable and sustainable space transportation systems (see Table 1 for specific correlations to affordability):

- *Percentage of elements and systems that are highly reusable*
- *Number of unplanned maintenance actions before or between missions*
- *Number of planned maintenance actions before or between missions*
- *Total number of flight tanks in the architecture*
- *Total number of traditional ground interface functions required*
- *Number of flight vehicle servicing interfaces*
- *Number of different fluids required*
- *Number of safety-driven functional requirements to maintain safe control of systems during flight and ground operations*
- *Number of confined/closed compartments*
- *Number of safety-driven limited-access control operations*
- *Number of commodities used that require medical support operations and routine training*
- *Number of Criticality 1 system and failure analysis modes*
- *Number of safing operations at landing (for reusable elements)*

Step 5. Simplify avionics and flight control design into minimum components; then, power and automate what's left.

A. Discussion/Specifics

Steps 1 through 4 have set the stage for a vehicle design that maximizes functionality with a minimum of hardware systems. The next step is to bring those systems to life by powering them, enabling them to communicate with other flight and ground systems and crews. This step also requires attention to the principles of minimizing complexity. Finally, automate what is left by applying savings gained in the first four steps of this process.

1. *Use simple and dependable flight control mechanisms that do not require routine fluid or gas servicing during ground operations.* This is similar to the approach in Step 3 but applies to electric power support of flight controls that are less expensive to design, produce, operate, and sustain than existing fluid- and gas-powered systems for flight control actuation.
2. *Limit the number of dedicated avionics boxes (achievable if all of the above is adhered to) so that no dedicated active avionics cooling subsystems are required.* The thermal threshold that drives passive cooling to active cooling for a suite of avionics components must be understood, managed, and constantly monitored and controlled throughout the design process. Attention and visibility must involve all subsystem designers and be made a hard and fast design requirement. An avionics system requiring no added active thermal control can help keep the cumulative costs of DDT&E, production, and operations to a minimum. Without such attention, avionics systems are likely to require the use of complex cold plates, supporting working fluids, flight equipment, and GSE, all of which increase the design, production, operation, and maintenance effort.
3. *Build in enough mass margins to account for the lengths of avionics cable and interconnectivity hardware.* Not doing so requires added effort and increases the risk of expensive design, production, and ground operations rework. This can delay operational deployment and limit flexibility for the owner-operator to leave the cabling alone for a variety of customers. With little or no margin, the operator is often forced to spend time and money optimizing the cabling to maintain propulsion margin for a particular payload.
4. *Avoid specialized ground power. Standardize the ground power to a single interface and build in, from the beginning, enough mass margins to convert power onboard.* The time and expense involved in ground systems design and development can be reduced, along with added hook-ups to ground services (see Figure 2).
5. *Build in remote autonomous verification of avionics functions every time the systems are powered up*. This can dramatically increase the efficiency of ground operations for launch vehicles and spacecraft. Without this built-in design feature, the ground operators are left to play a game of "twenty questions," so to speak, just to determine whether functional integrity is available to continue with critical servicing and launch operations. This strategy provides autonomous verification that the vehicle's active systems have retained functional integrity (i.e., that full electrical power, electronic signal, and software integrity exist upon power-up before continuing critical operations). Modern computer peripherals and automobiles do more of

this upon power-up than most modern launch vehicles and spacecraft. The objective is to automatically determine that there are no electrical shorts or opens and that no inadvertent software errors have been introduced. Increased vehicle availability, achieved through more responsive flight system power-up times, increases affordability by increasing the flight rate for a given set of fixed and variable operating costs.

B. Specific Engineering Criteria Addressed for Improvement

Step 5 enables or directly addresses many of the 19 engineering criteria for achieving affordable and sustainable space transportation systems (see Table 1 for specific correlations to affordability):

- *Number of separate electrical supply interface functions required*
- *Percentage of elements and systems that are highly reusable*
- *Percentage of all systems not automated*
- *Number of unplanned maintenance actions before or between missions*
- *Number of planned maintenance actions before or between missions*

Step 6. Extensively test/adjust the design to qualify the system and achieve the objectives.

A. Discussion/Specifics

Extensively qualify the components, verify and validate the systems, and flight-test the vehicle to prove accomplishment of all needs and objectives before commitment to full operational capability or production.

1. *Prove out design assumptions for simplicity and build technical and managerial confidence in a simple, robust system before committing to production.*
2. *Allow the flight test program to schedule improvements in the system design before committing to production.*
3. *Maintain a separate, developmental component, subsystem, system, and flight test capability that is offline from operational transportation service; do not put these in the serial critical path of the owner-operator of the system.* The owner-operator should not be expected to interrupt its transportation service to make risky changes and conduct flight experiments. Nor should technical changes to the system design (which should have been identified in the offline test mode) be allowed to increase production costs. A separate effort to demonstrate upgraded capabilities will mitigate any added operational program risk from design improvement changes.

B. Specific Engineering Criteria Addressed for Improvement

Step 6 enables or directly addresses a many of the 19 engineering criteria for achieving affordable and sustainable space transportation systems (see Table 1 for specific correlations to affordability):

- *Percentage of elements and systems that are highly reusable*
- *Number of unplanned maintenance actions before or between missions*
- *Number of planned maintenance actions before or between missions*
- *Number of Criticality 1 system and failure analysis modes*

Four Essential Technologies Enabling the High-Payoff Design Approach

A. Concentric-Nested Propellant Tanks for Launch Vehicle Stages and Spacecraft

To simply the architectural design, in-depth consideration should be given to using concentric-nested main propellant tanks, where the inner wall of the external of the two tanks is integral to the structure of the space vehicle. Such configurations would use at least one toroidal tank configuration located on the exterior to bear the structural loads of the vehicle and engine (depending on how many stages employ this technique). This enables a far more compact vehicle structure whose cryogenic propulsion system is far simpler to operate, in flight and on the ground, than today's more complex systems.

The "stack height," or total integrated space vehicle height, can be a real cost driver to launch system designs for a number of ground system processing stations and elements. For example, the total stack height drives the designs of assembly facilities, launch towers (both mobile and fixed), and launch pad structures (see Figure 3). Advanced development investments for innovative parallel tanks for cryogenic systems will give the designer more tank arrangement options to consider during conceptual design.

Tandem tank arrangements can also drive the concept toward slender dimensions with large overall length-to-diameter ratios. This creates problems for the structural dynamic stability of the vehicle during flight. In addition, tandem tank arrangement lengthens the propellant feed line, protrudes the vehicle outer mold line, increases thermal-conditioning requirements for the engine start box, creates "pogo" effects, and requires added geyser protection systems. This increases the design, production, and ground operations cost for stabilizers, dampeners, and so forth. Finally, tandem vehicle arrangements cause problems with liftoff drift and launch tower recontact.

Toroidal tank arrangements for space vehicles and stages can greatly improve the length-to-diameter ratio and achieve far more inherent structural stiffness of the stage (as opposed to traditional tandem tank and tandem-common-bulkhead arrangements). This not only reduces the complexities of the vehicle's flexible-body stability and its control dynamics in flight, but also improves its handling and access characteristics during ground operations. As with the common-bulkhead arrangement, toroidal tank arrangement inherently avoids the need for routine ground access because it eliminates the compartment between tanks that traditional, tandem tank arrangements require.

To date, concentric-nested tanks, such as toroidal tank configurations, have been used only seldom in conceptual designs for main-propellant containment. However, a number of Russian launch systems (e.g., the Briz-M upper stage) employ toroidal tanks to store propellants. The second and third stages of the Sea Launch Zenit 3SL also use toroidal kerosene fuel tanks with an LO_2 propellant combination.

One drawback of a longitudinally arranged intertank compartment is the temptation of locating functional hardware and ground interfaces within such a compartment. This immediately creates an opportunity for locating flight hardware functions that require routine ground servicing at this location. Routine access by personnel may come in two forms: external access for mold line connections/disconnections (which may have some potential for automation) and internal access. Internal access requires added mass and complexity for entry hatches. However, if full personnel entry is necessary and not just a partial reach inside an opening, the design, budget, and schedule for the compartment will need to account for the following:

- Lighting.
- Time and effort to install and remove work platforms and various protective caps, covers, and remove-before-flight items strictly there to protect critical and delicate flight hardware from inadvertent damage.
- Ground-supplied purge systems to convert the inert intertank atmosphere (gaseous nitrogen) to breathable air. These active purge systems are costly and time-consuming to design and operate.

Another benefit of the toroidal tank arrangement is greater thermodynamic efficiency. Liquid hydrogen (LH_2) has a lower boiling point than LO_2. Therefore, if the LO_2 tank is the outer tank in a toroidal configuration, and a traditional cylindrical LH_2 tank is nested inside, the configuration can dramatically reduce hydrogen boiloff because the outer LO_2 tank insulates against thermal radiation better than a traditional tank arrangement does. This reduces the weight of the vehicle's thermal protection system (TPS) on the LH_2 tank and could be especially beneficial in space or on an extraterrestrial surface.

For surface landing applications, the use of LH_2 as a fuel for the propulsion function has been avoided because of boiloff during a medium stay time (say, a month). This boiloff rate can be reduced by use of concentric-tank arrangements where an outer LO_2 tank insulates an inner LH_2 tank.

Another cryogenic use for this tank arrangement involves LO_2/methane (CH_4) propulsion, perhaps taking advantage of the availability of CH_4 on Mars. In this case, the boiling temperatures are very similar, offering a different set of design circumstances and considerations. Since LO_2 is denser than CH_4, it should be in the outer tank, which should be an integral part of the structure and carry the load of the stage or vehicle.

A commonly raised problem to be addressed is that the inner cylindrical wall of an elongated toroidal tank will be in radial compression when pressurized. Typically, the cylindrical wall of a pressure vessel is mostly in tension. Being primarily in compression, the inner cylindrical wall must be designed for high strength. However, the mass and strength required of such a wall, as part of the pressure vessel, can also carry the majority of vehicle's weight and thrust loads. The architectural implications are quite profound if the life cycle costs and ownership benefits are fully considered. The payoff may be well worth the investment to explore innovations that overcome the perceived difficulties.

A promising configuration to be explored uses a traditional cylindrical cryogenic tank inside another concentric toroidal cryogenic tank. The two parallel "nested" tanks are separated by compliant filler material as the two cryogenic tanks expand and contract between ambient and cryogenic temperatures. Use of a common-barrel section (similar to common-bulkhead arrangements) to reduce weight is not what is envisioned. This is primarily because of concerns for operational safety, along with the production and propellant loading/offloading complexities that arise when a common structural face encounters two different cryogenic fluids, each having unique thermal-transport properties. Also, in this configuration, the outer propellant tank is integral to the vehicle, whereas the interior tank (either cylindrical or toroidal) is a non-load-bearing structure. Whether the interior hydrogen tank is toroidal or a

standard cylindrical design depends on the application. The interior wall of the LO_2 tank should carry the longitudinal load of the vehicle. If so, the interior hydrogen tank can be lightweight and cylindrical with standard end domes. If, however, the interior tank is also toroidal, a crew access airlock can be inserted in the interior space created in a spacecraft application.

A concentric-nested-tank arrangement, with pliant insulation and an adequately sized annulus within the interstitial volume between the tanks allows a purge gas to flow freely from one compartment to another. This arrangement eliminates one of the ground-supplied compartment purges from the traditional tank design. It also relieves the procedural constraints required of the common bulkhead dome (sometimes called the "crotch" area) during cryogenic loading because major stresses in the face sheets are eliminated. These problems are avoided in the concentric-tank approach. (Production complexities with use of a common bulkhead are likewise avoided but are not addressed here.) The insulation between the interior and exterior tanks needs to be pliant and allow for expansion and contraction with changes in the tank diameters.

B. LO_2-Rich/LO_2-Cooled First-Stage Earth-to-Orbit Main Engine

This proposed technology uses large-scale thrust cryogenic engines (say 1-million to 2-million-pound thrust class) with an oxidizer-rich (LO_2-rich), rather than the traditional fuel-rich (LH_2-rich), main-combustion mixture ratio. A promising approach would set the mixture ratio at ~12:1 at liftoff and reduce it during ascent. This technology would then allow a much higher propellant bulk density for the first-stage propellant tanks or a greatly increased mass fraction over traditional configurations.

As with concentric-nested tanks, this technology allows a far more compact vehicle structure. This is the result of a favorable volume ratio: the substantial reduction in volume of the hydrogen tank overcomes the increase in volume of the oxygen tank, which was necessary in order to supply the oxygen-rich engine (due to the relative densities of the propellants). This technology also results in a cryogenic propulsion system that is far simpler to operate in flight and on the ground than today's more complex systems. This approach will achieve the required thrust at liftoff with fewer main engines and will decrease the safety risk at ignition or in an abort shutdown at the launch pad. Ignition overpressure will also be eliminated, in turn eliminating the need for the ground hydrogen burnoff system at liftoff.

1. Engine Combustion Mixture Ratio Considerations

In the Space Shuttle main engine and the Delta IV's RS-68 applications, the ratio of the LO_2 mass to the LH_2 mass is 6:1.The stoichiometric ratio of burning hydrogen and oxygen to produce water (i.e., neither fuel-rich nor oxidizer-rich) is 8:1, by mass. The hydrogen-rich 6:1 ratio requires a vehicle hydrogen tank with high volume.

If the mixture ratio is 12:1 (i.e., LO_2-rich) for first-stage operation in the atmosphere, then the size of the main fuel tank, and thus the total dry mass fraction of the vehicle, is substantially increased.

2. Engine (Combustion Chamber) Cooling Considerations During Combustion

Since the feasibility of LO_2 cooling has been tested for both LO_2/LH_2 and LO_2/RP-1 engines by NASA's Lewis Research Center (now Glenn Research Center), it is proposed to cool the combustion chamber with LO_2. Cooling propellant must be present for both the start of the engine ("*lead*") and its shutdown ("*lag*"), and will increase the safety of launch operations by eliminating the excess free hydrogen both at start and during shutdown. This condition of gaseous hydrogen lead during engine start and lag during shutdown is much more severe with the RS-68 rocket engine and would be considered a safety risk with a crewed vehicle.

LO_2 should be more advantageous from a cooling standpoint, and may be needed since the heat flux of the much higher-mass-flow (higher thrust) engine is much greater than that of the traditional 6:1 mixture ratio LO_2/LH_2 engine.

3. Combined High-Payoff

When combined with the concentric-nested tank design approach, the design space for Earth-to-orbit launch systems opens up new and innovative configurations—ones that can offer far more utility, efficiency, and value to the owner-operator. Specifically, a configuration based on these design approaches, and using these high-payoff technologies, will allow elimination of long engine feed lines and active engine conditioning systems. Without a concerted effort to remove these complexities, support systems will continue to accumulate in designs presently caused by conditioning requirements for starting the engine. It also allows the designer freedom to eliminate LO_2 "pogo" suppression systems, elevated ground servicing fill and drain systems, additional compartment conditioning, and hazardous gas leak detection systems. For example, a trade study using the Delta IV 5-meter-diameter first stage shows that a combined benefit can be achieved, shortening the first-stage vehicle by as much as 50% (see Figure 6 and Figure 7).

C. Nontoxic, Day-of-Launch-Loaded Propellants (LO_2/CH_4, or LO_2/LH_2, for example)

This technology enables the spacecraft main and auxiliary propellants to be loaded on the day of launch. On a small scale, this was accomplished for the DC-X vehicle (see Figure 2). Advancements and investments can bring this design technique to full scale and bring about many affordable system attributes.

Specification of traditional toxic hypergolic bipropellants has led to complex and time-consuming operations that drive up recurring production and ground operations costs. Impediments to efficient and affordable ground operations are the added personnel protection suit infrastructure; the time required for manual propellant operations; and serial loading operations that require "stop work" on all other vehicle systems (often for weeks for propellants to be loaded and systems to be pressurized). Separate auxiliary propulsion servicing at the pad, even when automated and performed remotely, adds a considerable expense to the design, fabrication, and maintenance of the pad systems. Alternatively, an entire launch site processing station dedicated to the hypergolic fuel-loading function can be designed, constructed, maintained, and operated offline from the rest of the vehicle operations, but also with significant added cost. Offline facility stations of this complexity often consider separate dedicated ground operations control rooms and facility systems to manage containment of emergency fluid spills, toxic vapor control, waste management systems, and offline operations. These added systems for facility safety involve complex scrubbers, underground containment, exhaust systems, extremely tall pipes and vents, and so forth.

Toxic propellants also require technicians to wear self-contained atmospheric protective ensembles (SCAPE) while performing operations and maintenance. All these attributes of toxic systems add a significant burden to the design effort for flight and ground systems and to the recurring cost of their production and operation.

Use of nontoxic propellant combinations also eliminates the dedicated infrastructure, operations, and maintenance for the hazardous facilities; and, also specialized GSE (both fixed and mobile support equipment), such as SCAPE vans, SCAPE maintenance facilities, and personnel that support the SCAPE technicians and their suits. Further, it eliminates the added waste management function and its burden and the logistics cost of the unique hypergolic bipropellants. Other than the Long March system of launch vehicles, very few, if any, modern launch systems use hypergolic propellants in large quantities anymore. Finally, the burdens imposed by personnel health monitoring, safety training overhead, recordkeeping, and health industry personnel to support the SCAPE technicians are avoided.

D. Electric Propulsion/Thrust Vector Control System

Propellant control valves and thrust vector control (TVC) systems often use a small quantity of hydrazine and distributed high-pressure (3,000 psi) hydraulics to control the combustion process and to gimbal the nozzle for ascent flight control. An alternative to hydrazine is the use of main propulsion ullage gas to drive a high-speed turbine, combined with high-pressure distributed hydraulics, as well as a high-voltage electrical subsystem to actuate the engine for ascent flight control. A much simpler and cheaper approach is to use only electromechanical actuators (EMAs) and electrohydrostatic actuators (EHAs), which eliminates the need for distributed hydraulics and distributed pneumatic systems altogether. This enabling technology would considerably reduce the ground support systems, equipment, procedures, remanufacturing purchases, disassembly, refurbishment, reassembly, and workforce necessary to support the extra subsystems (e.g., hydrazine, high-pressure hydraulics, and pneumatic systems).

In an evolutionary sense, use of all-electric approaches in recoverable systems that subsequently require remanufacturing would eliminate the need for any dedicated test facilities to protect personnel during system testing before element assembly. It would also eliminate numerous fluid and pneumatic GSE and facility systems requirements. It would reduce recurring production costs, streamline the propellant loading operations at the pad before launch countdown, and simplify the procurement and control of these additional fluid commodities. The hazards and expense of pad-clear loading operations and use of the SCAPE infrastructure can be avoided by using both nontoxic propellants and electric TVC. It also eliminates the use of distributed hydraulic systems that require considerable launch site equipment, GSE, and labor to maintain and operate. To gain this benefit, the use of nontoxic propellants with EMA/EHA TVC for high-thrust engines must be refined and implemented in the design process together.

All of these techniques would reduce design and recurring production cost, ground operations, GSE (and in the case of hydrazine, some dedicated hazardous facilities and rooms), operations work content, and the serial critical time necessary to produce a space flight.

Conclusions and Recommendations

Investing in and implementing the essential technologies presented and using the six-step process suggested in this paper would benefit the major contributors to life cycle cost: (1) work effort and time involved with the design development, testing, and evaluation phase, (2) the recurring production and vendor supply in sustaining the system by design, (3) flight and ground operations work accumulation by design, and (4) overall launch productivity through major reduction in the critical-path time necessary to produce a space flight. The six-step approach, suggested technologies, and advanced design techniques represent a very high-payoff design approach that would enable an affordable and sustainable space transportation system.

Table 1. **Criteria correlations with various components of life cycle affordability.**

AFFORDABILITY CRITERIA	DESIGN LABOR	DEVELOPMENT & TEST LABOR	DEVELOPMENT & TEST MATERIALS & OTHER DIRECT COSTS	DESIGN & DEVELOPMENT TIME	RECURRING PRODUCTION & VENDOR-SUPPLIEDSUPPLIED LABOR	RECURRING PRODUCTION, VENDOR-SUPPLIED MATERIALS & OTHER DIRECT COSTS	ANNUAL FIXED COSTS OF FLIGHT & GROUND OPERATIONS	RECURRING FLIGHT & GROUND OPERATIONS COST PER FLIGHT	FLIGHT RATE CAPABILITY / THROUGHPUT / PRODUCTIVITY
Percentage of elements and systems that are highly reusable					X	X	X	X	X
Total number of flight tanks in the architecture	X	X	X	X	X	X	X	X	X
Total number of separate identified vehicle propulsion systems and/or separate stages	X	X	X	X	X	X	X	X	X
Number of safety-driven functional requirements to maintain safe control of systems during flight and ground operations		X	X	X	X	X	X	X	X
Number of unplanned maintenance actions before or between missions	X	X	X	X	X	X	X	X	X
Number of planned maintenance actions before or between missions					X	X	X	X	X
Total number of traditional ground interface functions required	X	X	X	X	X	X	X	X	X
Percent of all systems not automated					X	X	X	X	X
Number of different fluids required	X	X	X	X	X	X	X	X	X
Total number of vehicle element-to-element support systems	X	X	X	X	X	X	X	X	X
Number of flight vehicle servicing interfaces	X	X	X	X	X	X	X	X	X
Number of confined/closed compartments	X	X	X	X	X	X	X	X	X
Number of commodities used that require medical support operations and routine training		X		X	X	X	X	X	X
Number of safety-driven limited-access control operations		X	X	X			X	X	X
Number of safing operations at landing (for reusable elements)	X	X	X	X	X	X	X	X	X
Number of mechanical element mating operations		X	X	X			X	X	X
Number of separate electrical supply interfaces	X	X	X	X	X	X	X	X	X
Number of intrusive data-gathering devices		X	X	X	X	X	X	X	X
Number of Criticality 1 system and failure analysis modes	X	X	X	X	X	X	X	X	X

Figure 1. *Closed-compartment entry for personnel requiring design and operations effort, resulting lost time and productivity.*

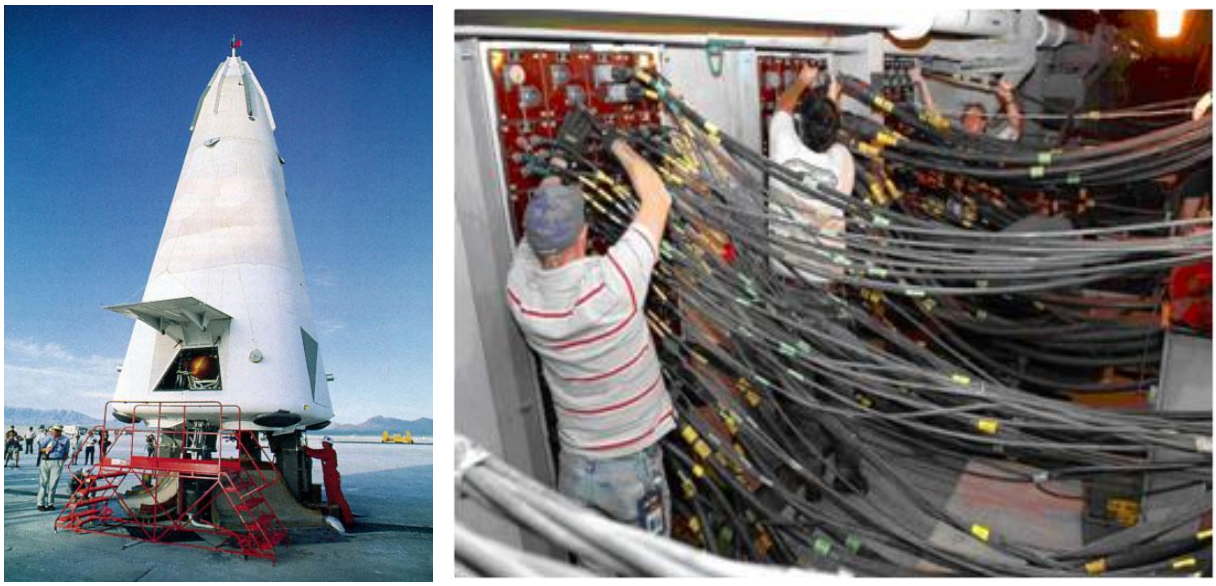

Figure 2. *(Left) DC-X used a common commodity for both main and auxiliary propulsion, which would have reduced the overall ground operations work involved had a dedicated commodity been used. (Right) a high degree of dedicated, specialized power and signal requirements can be seen for a large-scale mobile launch system. Greater design integration can reduce design, development, fabrication, testing, and ground operations.*

Figure 3. *(Left) A typical interstage design mock-up requires routine internal personnel access. (Right) The Zenit SeaLaunch interstage, including the upper-stage engine nozzle, is encapsulated within a concentric-nested-stage design (described in Step 2, item 4). None of the following are required: routine personnel entry; environmental control system; personnel work platform installation and removals; installation of lighting and oxygen deficiency monitoring equipment; and compartment closeout work, including hatch removal, installation, sealing, and thermal protection. The difference in stack height and implied mass savings also are apparent. Also note the propellant feed-line extending from the lower stage, through the interstage, and into the upper stage for fill and drain. This eliminates the need for side-mounted service umbilicals and large service towers to support them.*

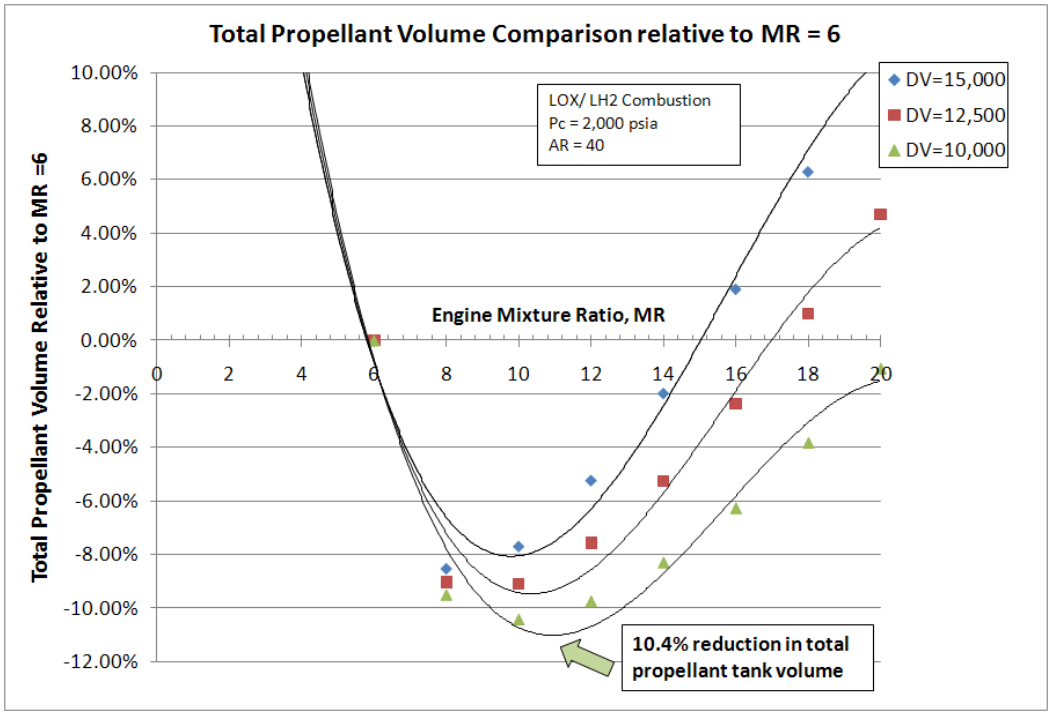

Figure 4. *Vehicle propellant tank volume reduction with LO_2-rich combustion engine.*

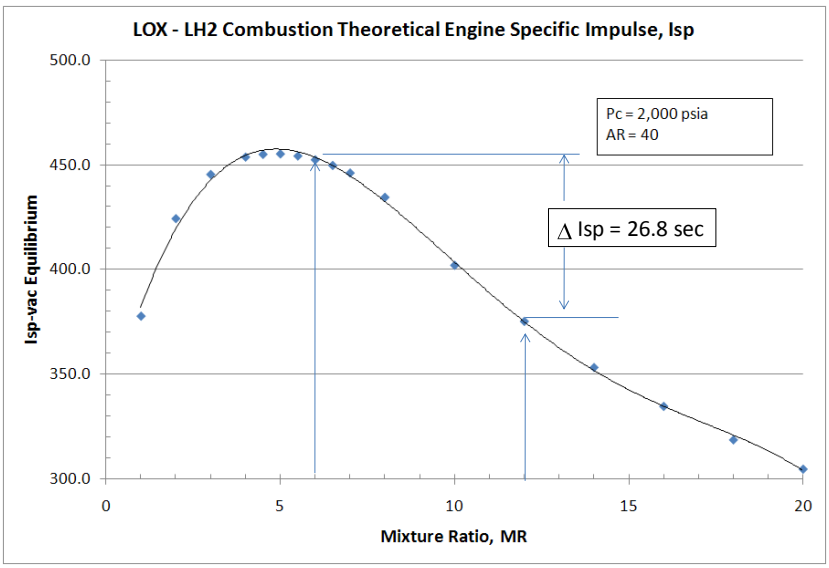

Figure 5. *Theoretical engine specific impulse for LO_2-LH_2 combustion.*

Total Tank volume =	ft^3	20,510.38		
Fuel tank volume =	ft^3	15,002.90		
Oxid tank volume =	ft^3	5,507.48		
d1, Tank diameter	m	3.80		note 1
Tank diameter	ft	12.47		
Tank diameter	in.	149.61		
A1, Cylindrical cross-sect area	ft^2	488.30		
Equiv cylindrical length, h =	ft	30.72	66.99%	note 2
A-tot, Cylindrical cross-sect ar	ft^2	667.55		
d2 =	ft	29.15		
d2, Outer tank diameter =	m	8.89		
note:				
1) CBC baseline tank diameter is 5 meter				
2) % tank length from vertical stack				

Figure 6. *Delta IV Medium Common Booster Core (CBC) nested-tank calculation for baseline configuration.*

Total Tank volume =	ft^3	18,435.5	89.88%	note 1
Fuel tank volume =	ft^3	10,672.74		
Oxid tank volume =	ft^3	7,762.76		
d1, Tank diameter	m	3.80		note 2
Tank diameter	ft	12.47		
Tank diameter	in.	149.61		
A1, Cylindrical cross-sect area	ft^2	488.30		
Equiv cylindrical length, h =	ft	21.86	50.35%	note 3
A-tot, Cylindrical cross-sect area	ft^2	843.46		
d2 =	ft	32.77		
d2, Outer tank diameter =	m	9.99		
note:				
1) % from MR =6 total tank volume				
2) CBC baseline tank diameter is 5 meter				
3) % tank length from vertical stack				

Figure 7. *Delta IV Medium Common Booster Core (CBC) nested-tank calculation for LO_2-rich configuration.*

NOTES

[1] Space Propulsion Synergy Team (SPST) web site: http://spacepropulsion.us [link available as of June 23, 2011].

[2] Rhodes, R. E., Zapata, E., Levack, D. J. H., Robinson, J. W., and Donahue, B. B., members Space Propulsion Synergy Team (SPST), "Concepts for Life Cycle Cost Control Required to Achieve Space Transportation Affordability and Sustainability," AIAA 2009-5345, *45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Denver, Colorado, 2-5 August 2009.

[3] DeHoff, B., Levack, D. J. H., and Rhodes, R. E., members Space Propulsion Synergy Team (SPST), "The Functional Breakdown Structure (FBS) and Its Relationship to Life Cycle Cost," AIAA 2009-5344, *45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Denver, Colorado, 2-5 August 2009.